

THE DIFFERENTIAL GEOMETRY DIFFERENTIAL TOPOLOGY DUMP			
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0.0.1. *Application to Occupancy Problems; binomial coefficients.* cf. Sec. 5 Application to Occupancy Problems of Feller (1968) [1].

Consider randomly placing r balls into n cells.
Let r_k = occupancy number = number of balls in k th cell.
Every n -tuple of integers satisfying $r_1 + r_2 + \cdots + r_n = r$; $r_k \geq 0$. describes a possible configuration of occupancy numbers.
With indistinguishable balls 2 distributions are distinguishable only if the corresponding n -tuples (r_1, \dots, r_n) are not identical.

- (i) number of distinguishable distributions is
- (3)
$$A_{r,n} = \binom{n+r-1}{r} = \binom{n+r-1}{n-1}$$
- cf. Eq. (5.2) of Feller (1968) [1]
- (ii) number of distinguishable distributions in which no cell remains empty is $\binom{r-1}{n-1}$.

Proof. Represent balls by stars, indicate n cells by n spaces between $n+1$ bars. e.g. $r = 8$ balls .
 $n = 6$ cells

3 10 00 4
| * * * | * | || | * * * * |

Such a symbol necessarily starts and ends with a bar, but remaining $n-1$ bars and r stars appear in an arbitrary order. In this way, it becomes apparent that the number of distinguishable distributions equals the number of ways of selecting r places out of $n+r-1$, $\frac{(n+r-1)!}{(n-1)!r!} = \binom{n-1+r}{r}$

|||| ... || $n+1$ bars
* * * ... * * r stars leave $r-1$ spaces

Condition that no cell be empty imposes the restriction that no 2 bars be adjacent. r stars leave $r-1$ spaces of which $n-1$ are to be occupied by bars. Thus $\binom{r-1}{n-1}$ choices.

□

Probability to obtain given occupancy numbers $r_1, \dots, r_n = \frac{r!}{r_1!r_2!\dots r_n!}/n^r$, with r balls given by Thm. 4.2. of Feller (1968)
 n cells

[1], which is the Maxwell-Boltzmann distribution.

- (a) Bose-Einstein and Fermi-Dirac statistics. Consider r indistinguishable particles, n cells, each particle assigned to 1 cell.
State of the system - random distribution of r particles in n cells.
If n cells distinguishable, n^r arrangements equiprobable \rightarrow Maxwell-Boltzmann statistics.
Bose-Einstein statistics: only distinguishable arrangements are considered, and each assigned probability $\frac{1}{A_{r,n}}$

- (4)
$$A_{r,n} = \binom{n+r-1}{r} = \binom{n-1+r}{n-1}$$

- cf. Eq. 5.2 of Feller (1968) [1]
Fermi-Dirac statistics.
(1) impossible for 2 or more particles to be in the same cell. $\rightarrow r \leq n$.
(2) all distinguishable arrangements satisfying the first condition have equal probabilities.
 \rightarrow an arrangement is completely described by stating which of the n cells contain a particle
 r particles $\rightarrow \binom{n}{r}$ ways r cells chosen.
Fermi-Dirac statistics, there are $\binom{n}{r}$ possible arrangements, prob. $1/\binom{n}{r}$.

pp. 39. Feller (1968) [1]. Consider cells themselves indistinguishable! Disregard order among occupancy numbers.
cf. Feller (1968) [1]

Part 2. Linear Algebra Review

cf. *Change of Basis*, of Appendix B of John Lee (2012) [3].

Exercise B.22. Suppose V, W, X finite-dim. vector spaces
 $S : V \rightarrow W, \quad T : W \rightarrow X$

- (a) $\text{rank } S \leq \dim V$ with $\text{rank } S = \dim V$ iff S injective
(b) $\text{rank } S \leq \dim W$ with $\text{rank } S = \dim W$ iff S surjective
(c) if $\dim V = \dim W$ and S either injective or surjective, then S isomorphism
(d) $\text{rank } TS \leq \text{rank } S$ $\text{rank } TS = \text{rank } S$ iff $\text{im } S \cap \ker T = 0$
(e) $\text{rank } TS \leq \text{rank } T$ $\text{rank } TS = \text{rank } T$ iff $\text{im } S + \ker T = W$
(f) if S isomorphism, then $\text{rank } TS = \text{rank } T$
(g) if T isomorphism, then $\text{rank } TS = \text{rank } S$

EY : Exercise B.22(d) is useful for showing the chart and atlas of a Grassmannian manifold, found in the More examples, for smooth manifolds.

Proof. (a) Recall the **rank-nullity theorem**:

Theorem 2 (Rank-Nullity Theorem).

(5)
$$\dim(\text{im}(S)) + \dim(\ker(S)) = \dim V$$

Now
$$\text{rank}(S) + \dim(\ker(S)) \equiv \dim(\text{im}(S)) + \dim(\ker(S)) = \dim V$$
$$\implies \boxed{\text{rank}(S) \leq \dim V}$$

- If $\text{rank}(S) = \dim V$,
then by rank-nullity theorem, $\dim(\ker(S)) = 0$, implying that $\ker S = \{0\}$.
Suppose $v_1, v_2 \in V$ and that $S(v_1) = S(v_2)$. By linearity of S , $S(v_1) - S(v_2) = S(v_1 - v_2) = 0$, which implies, since $\ker S = \{0\}$, that $v_1 - v_2 = 0$.
 $\implies v_1 = v_2$. Then by definition of injectivity, S injective.
If S injective, then $S(v) = 0$ implies $v = 0$. Then $\ker S = \{0\}$. Then by rank-nullity theorem, $\text{rank}(S) = \dim V$.
(b) $\forall w \in \text{im}(S), w \in W$. Clearly $\text{rank } S \leq \dim W$.
If S surjective, $\text{im}(S) = W$. Then $\dim(\text{im}(S)) = \text{rank } S = \dim W$.

If $\text{rank } S = \dim W = m$, then $\text{im}(S)$ has basis $\{y_i\}_{i=1}^m, y_i \in \text{im}(S)$, so $\exists x_i \in V, i = 1 \dots m$ s.t. $S(x_i) = y_i$, with $\{S(x_i)\}_{i=1}^m$ linearly independent.
Since $\{S(x_i)\}_{i=1}^m$ linearly independent and $\dim W = m, \{S(x_i)\}_{i=1}^m$ basis for W .
 $\forall w \in W, w = \sum_{i=1}^m w^i S(x_i) = S(\sum_{i=1}^m w^i x_i)$. $\sum_{i=1}^m w^i x_i \in V$. S surjective.

- (c)
(d) Now
$$\dim V = \text{rank } TS + \text{nullity } TS$$
$$\dim V = \text{rank } S + \text{nullity } S$$

$\ker S \subseteq \ker TS$, clearly, so $\text{nullity } S \leq \text{nullity } TS$
$$\implies \boxed{\text{rank } TS \leq \text{rank } S}$$

If $\text{rank } TS = \text{rank } S$,
then $\text{nullity } S = \text{nullity } TS$
Suppose $w \in \text{Im } S \cap \ker T, w \neq 0$
Then $\exists v \in S$, s.t. $w = S(v)$ and $T(w) = 0$
Then $T(w) = TS(v) = 0$. So $v \in \ker TS$
 $v \notin \ker S$ since $w = S(v) \neq 0$
This implies $\text{nullity } TS > \text{nullity } S$. Contradiction.

$$\implies \text{Im}S \cap \ker T = 0$$

If $\text{Im}S \cap \ker T = 0$,

Consider $v \in \ker TS$. Then $TS(v) = 0$.

. Then $S(v) \in \ker T$

$S(v) = 0$; otherwise, $S(v) \in \text{Im}S$, contradicting given $\text{Im}S \cap \ker T = 0$

$v \in \ker S$

$$\ker TS \subseteq \ker S$$

$$\implies \ker TS = \ker S$$

So nullity $TS = \text{nullity} S$

$$\implies \text{rank} TS = \text{rank} S$$

(e)

(f)

(g)

Part 3. Manifolds

1. INVERSE FUNCTION THEOREM

Shastri (2011) had a thorough and lucid and explicit explanation of the Inverse Function Theorem [5]. 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 3 (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).

$$x_1 = \phi(x_0)$$

$$x_2 = \phi(x_1)$$

$\forall x_0 \in X$, Define \vdots

$$x_j = \phi(x_{j-1})$$

\vdots

$$x_n = \phi(x_{n-1})$$

$$d(x_{n+1}, x_n) = d(\phi(x_n), \phi(x_{n-1})) \leq cd(x_n, x_{n-1}) \leq \cdots \leq c^n d(x_1, x_0)$$

for some $0 < c < 1$.

$$d(x_m, x_n) \leq d(x_n, x_{n-1}) + d(x_{n-1}, x_m) \leq d(x_n, x_{n-1}) + d(x_{n-1}, x_{n-2}) + \cdots + d(x_{m+1}, x_m) \leq \sum_{k=n-1}^m c^k d(x_1, x_0)$$

Thus, $\forall \epsilon > 0$, $\exists n_0 > 0$, (n_0 large enough) s.t. $\forall m, n \in \mathbb{N}$ s.t. $n_0 < n < m$,

$$d(x_m, x_n) \leq \sum_{k=n-1}^m c^k d(x_1, x_0) < \epsilon d(x_1, x_0)$$

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

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

Since by def. of y limit pt. of $\{x_n\}$, $\forall \epsilon > 0$, then $\{n \mid |x_n - y| \leq \epsilon, n \in \mathbb{N}\}$ is infinite.

Consider $\delta > 0$. Consider $\{n \mid |x_n - y| \leq \delta, n \in \mathbb{N}\}$

$\exists N_\delta \in \mathbb{N}$ s.t. $\forall n > N_\delta$, $|x_n - y| < \delta$; otherwise, $\forall N_\delta$, $\exists n > N_\delta$ s.t. $|x_n - y| \geq \delta$. Then $\{n \mid |x_n - y| \leq \delta, n \in \mathbb{N}\}$ finite.

Contradiction.

ϕ cont. so by def. $\forall \epsilon > 0$, $\exists \delta > 0$ s.t. if $|x_n - y| < \delta$, then $|\phi(x_n) - \phi(y)| < \epsilon$.

Pick N_δ s.t. $\forall n > N_\delta$, $|x_n - y| < \delta$, and so $|\phi(x_n) - \phi(y)| < \epsilon$. There are infinitely many $\phi(x_n)$'s that satisfy this, and so $\phi(y)$ is a limit pt.

□

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 4 (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

(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

$$\tilde{f}(0) = 0 \text{ and}$$

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

$$D\tilde{f}(0) = (Df(x_0))^{-1}Df(x_0) = 1$$

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 $\phi_y : V \rightarrow \mathbb{R}^n$

$$\phi_y(x) = x + (y - f(x))$$

$$D(\phi_y)(x) = 1 + -Df(x) \quad \forall x \in V$$

$$\|D(\phi_y)(x)\| = \|1 - Df(x)\| \leq \epsilon < 1$$

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

$$\phi_y(x_1) = x_1$$

$$\phi_y(x_2) = x_2$$

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

$\implies f|_U$ 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 $y \in B_{r\epsilon}(y_0)$.

$$r\epsilon > \|y - y_0\| = \|y - f(x_0)\| = \|\phi_y(x_0) - x_0\| \text{ with}$$

$$\phi_y(x) = x + (y - f(x))$$

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 $\phi(B_r(x_0)) = B_{r\epsilon}(y_0)$.

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) [5], but I found Wienhard's Handout 4 for Math 327 to be clearer.¹

Theorem 5 (Implicit Function Theorem). *Let open $U \subset \mathbb{R}^{m+n} \equiv \mathbb{R}^m \times \mathbb{R}^n$*

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

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

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

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

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

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

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 $f(x, g(x)) = 0$,

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

□

2. IMMERSIONS

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

□ Absil, Mahony, and Sepulchre [7] pointed out that another definition for a *immersion* can utilize the theorem that rank of $Df \equiv DF = \dim T_p M$. Indeed, recall these facts from linear algebra:
for $T : V \rightarrow W$,

It's always true that $\text{rank} T \leq V$, and

$$\text{rank} T \leq W$$

$\text{rank} T = \dim V$ iff T injective.

$\text{rank} T = \dim W$ iff T surjective.

$$\begin{array}{ccc} T_x M & \xrightarrow{DF(x)} & T_{F(x)} N = T_y N \\ \uparrow & & \uparrow \\ x \in M & \xrightarrow{F} & y = F(x) \in N \end{array}$$

$$M \xrightarrow{F} N$$

Now

$$\dim T_x M = \dim M$$

$$\dim T_{F(x)} N = \dim N$$

And

$$\text{rank}(DF(x)) \equiv \text{rank of } F$$

I know that the notation above is confusing, but this is what all Differential Geometry books apparently mean when they say "rank of F ".

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

Now

$$\text{rank}(DF(x)) = \dim(\text{im}(DF(x))) = \dim T_x M \text{ iff } DF(x) \text{ injective}$$

If $\forall x \in M$, this is the case, then F an **immersion**.

Apply the rank-nullity theorem in this case:

$$\begin{aligned} \text{rank}(DF(x)) + \dim \ker(DF(x)) &= \dim T_x M = \dim M \\ \implies \text{rank}(DF(x)) &= \dim M \leq \dim T_{F(x)} N = \dim N \text{ or } \dim M \leq \dim N \end{aligned}$$

Now

$$\text{rank}(DF(x)) = \dim T_{F(x)} N \text{ iff } DF(x) \text{ surjective}$$

If $\forall x \in M$, this is the case, then F an **submersion**.

$$\text{rank}(DF(x)) = \dim T_{F(x)} N = \dim N \leq \dim M$$

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” [4].

Theorem 6 (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

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

$D(\psi f \phi^{-1}) \equiv Df$. $Df(p)$ 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.

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

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

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 7 (Implicit Function Thm.). *Let open subset $U \subseteq \mathbb{R}^n \times \mathbb{R}^d$, $(x, y) = (x^1 \dots x^n, y^1 \dots y^d)$ 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 $y = F(x)$.

3. SUBMERSIONS; RANK THEOREM

cf. pp. 20, Sec. 4 ”Submersions”, Ch. 1 of Guillemin and Pollack (2010) [4].

Consider $X, Y \in \mathbf{Man}$, s.t. $\dim X \geq \dim Y$.

Definition 3 (submersion). *If $f : X \rightarrow Y$, if $Df_x \equiv df_x$ is surjective, $f \equiv$ **submersion** at x .*

Recall that,

$$Df_x : T_x X \rightarrow T_{f(x)} Y$$

$$\dim T_x X \geq \dim T_{f(x)} Y$$

$\text{rank } Df_x \leq \dim T_{f(x)} Y$, in general, while

$\text{rank } Df_x = \dim T_{f(x)} Y$ iff Df_x surjective

Canonical submersion is standard projection:

If $\dim X = k$, $k \geq l$,

$\dim Y = l$

$$(a_1 \dots a_k) \mapsto (a_1 \dots a_l)$$

Theorem 8 (Local Submersion Theorem). *Suppose $f : X \rightarrow Y$ submersion at x , and $y = f(x)$, Then \exists local coordinates around x, y s.t.*

$$f(x_1 \dots x_k) = (x_1 \dots x_l)$$

i.e. f locally equivalent to canonical submersion near x

Proof. I’ll have a side-by-side comparison of my notation and the 1 used in Guillemin and Pollack (2010) [4] where I can.

For charts $(U, \phi), (V, \psi)$ for X, Y , respectively, $y = f(x)$ for $x \in X$,

$$\begin{array}{ccc} U \subseteq X & \xrightarrow{f} & Y \supseteq V \\ \downarrow \phi & & \downarrow \psi \circ G \\ \mathbb{R}^k & \xrightarrow{\mathbf{i}} & \mathbb{R}^l \end{array} \quad \begin{array}{ccc} x & \xrightarrow{f} & f(x) = y \\ \downarrow \phi & & \downarrow \psi \\ \phi(x) = (a^1 \dots a^k) & \xrightarrow{g} & g(\phi(x)) = g(a^1 \dots a^k) = \psi(y) \end{array}$$

Dg_x surjective, so assume it’s a $l \times k$ matrix $[\mathbf{1}_l \quad 0]$.

Define

$$G : U \subset \mathbb{R}^k \rightarrow \mathbb{R}^k$$

(6)

$$G(a) \equiv G(a^1 \dots a^k) := (g(a), a_{l+1}, \dots, a_k)$$

Now

$$(7) \quad DG(a) = \begin{bmatrix} \mathbf{1}_l & 0 \\ & \mathbf{1}_{k-l} \end{bmatrix} = \mathbf{1}_k$$

so G local diffeomorphism (at 0).

So $\exists G^{-1}$ as local diffeomorphism of some U' of a into $U \subset \mathbb{R}^k$.

By construction,

$$(8) \quad g = \mathbb{P}_l \circ G$$

where \mathbb{P}_l is the *canonical submersion*, the projection operator onto \mathbb{R}^l .

$$g \circ G^{-1} = \mathbb{P}_l$$

(since G diffeomorphism)

$$\begin{array}{ccc} U \subseteq X & \xrightarrow{f} & V \subseteq Y \\ \phi^{-1} \circ G^{-1} \uparrow & & \uparrow \psi^{-1} \\ \mathbb{R}^k & \xrightarrow{\mathbb{P}_l} & \mathbb{R}^l \end{array} \quad \text{for}$$

$$\begin{array}{ccc} \phi^{-1} \circ G^{-1}(a) \equiv \phi^{-1} \circ G^{-1}(a^1 \dots a^k) = x & \xrightarrow{f} & f(x) = y = \psi^{-1}(a^1 \dots a^l) \\ \phi^{-1} \circ G^{-1} \uparrow & & \uparrow \psi^{-1} \\ (a^1 \dots a^k) & \xrightarrow{\mathbb{P}_l} & (a^1 \dots a^l) \end{array}$$

$$\implies$$

”An obvious corollary worth noting is that if f is a submersion at x , then it is actually a submersion in a whole neighborhood of x .” Guillemin and Pollack (2010) [4]

Suppose f submersion at $x \in f^{-1}(y)$.

By local submersion theorem

$$f(x_1 \dots x_k) = (x_1 \dots x_l)$$

Choose $y = (0, \dots, 0)$.

Then, near x , $f^{-1}(y) = \{(0, \dots, 0, x_{l+1} \dots x_k)\}$ i.e. let $V \ni x$ neighborhood of x , define $(x_1 \dots x_k)$ on V .

Then $f^{-1}(y) \cap V = \{(0 \dots 0, x_{l+1}, \dots x_k) | x_1 = 0, \dots x_l = 0\}$.

Thus $x_{l+1}, \dots x_k$ form a coordinate system on open set $f^{-1}(y) \cap V \subseteq f^{-1}(y)$.

Indeed,

$$\begin{array}{ccc} U \subseteq X & \xrightarrow{f} & V \subseteq Y \\ \downarrow \phi & & \downarrow \psi \\ \mathbb{R}^k & \xrightarrow{\mathbb{P}_l} & \mathbb{R}^l \end{array} \quad \begin{array}{ccc} x & \xrightarrow{f} & f(x) = y \\ \downarrow \phi & & \downarrow \psi \\ \phi(x) = (x^1 \dots x^k) & \xrightarrow{\mathbb{P}_l} & (x^1 \dots x^l) \end{array}$$

and now

$$\begin{array}{ccc} f^{-1}(y) & \xleftarrow{f^{-1}} & y \\ \phi^{-1} \uparrow & & \downarrow \psi \\ \{(0, \dots, 0, x^1 \dots x^k)\} & \xleftarrow{\mathbb{P}_l^{-1}} & (0 \dots 0) \end{array}$$

3.1. Rank Theorem. Lee (2012) [3] in pp. 85, Ch. 4 Submersions, Immersions, and Embeddings, combines Theorems 6, 8 (local immersion and local submersion theorems, respectively) into the ”Rank Theorem” (cf. Thm 4.12 ”Rank Theorem” of Lee (2012)):

Theorem 9 (Rank Theorem). *Suppose smooth manifolds M, N , $\dim M = m$, $\dim N = n$, smooth map $F : M \rightarrow N$, F has constant rank r .*

$\forall p \in M$, \exists smooth charts (U, φ) for M , centered at p , (V, ψ) for N , centered at $F(p)$, s.t.

$$F(U) \subseteq V$$

in which F has coordinate representation of form

$$(9) \quad \widehat{F}(x^1 \dots x^r, x^{r+1} \dots x^m) = (x^1 \dots x^r, 0 \dots 0)$$

Particularly, if F smooth submersion,

$$\widehat{F}(x^1 \dots x^n, x^{n+1} \dots x^m) = (x^1 \dots x^n)$$

and if F smooth immersion

$$\widehat{F}(x^1 \dots x^m) = (x^1 \dots x^m, 0 \dots 0)$$

$$\begin{array}{ccc} \mathbb{R}^m & \xrightarrow{\psi F \varphi^{-1}} & \mathbb{R}^n \\ \uparrow \varphi & & \uparrow \psi \\ U \subset M & \xrightarrow{F} & V \subset N \end{array}$$

Also remember that $DF(p) : T_p M \rightarrow T_{F(p)} N$

Proof. $DF(p)$ has rank r (given). Then $DF(p)$ is some $r \times r$ submatrix of a $n \times m$ matrix s.t. $\det DF(p)$ nonzero.

By change of basis in \mathbb{R}^n , or reordering coordinates, assume $DF(p)$ is upper left submatrix $\left(\frac{\partial F^i}{\partial x^j} \right) \quad \forall i, j = 1, \dots, r$.

Relabel standard coordinate as

$$(x, y) = (x^1 \dots x^r, y^1 \dots y^{m-r}) \in \mathbb{R}^m$$

$$(v, w) = (v^1 \dots v^r, w^1 \dots w^{n-r}) \in \mathbb{R}^n$$

By initial translations of coordinates, assume without loss of generality $p = (0, 0)$, $F(p) = (0, 0)$

Suppose

$$F(x, y) = (Q(x, y), R(x, y))$$

for some smooth maps $Q : U \rightarrow \mathbb{R}^r$, $R : U \rightarrow \mathbb{R}^{n-r}$

Define

$$\varphi : U \rightarrow \mathbb{R}^m$$

$$\varphi(x, y) = (Q(x, y), y)$$

so

$$D\varphi(0,0) = \begin{pmatrix} \frac{\partial Q^i}{\partial x^j}(0,0) & \frac{\partial Q^i}{\partial y^j}(0,0) \\ 0 & \delta_j^i \end{pmatrix}$$

$D\varphi(0,0)$ nonsingular, since $\det \frac{\partial Q^i}{\partial x^j} \neq 0$ (by hypothesis).

By inverse function thm., \exists connected neighborhoods U_0 of $(0,0)$, \tilde{U}_0 of $\varphi(0,0) = (0,0)$ s.t.

$$\varphi : U_0 \rightarrow \tilde{U}_0$$

is a diffeomorphism.

By shrinking U_0, \tilde{U}_0 , assume \tilde{U}_0 open cube.

Write $\varphi^{-1}(x,y) = (A(x,y), B(x,y))$, for some smooth functions $A : \tilde{U}_0 \rightarrow \mathbb{R}^r$,
 $B : \tilde{U}_0 \rightarrow \mathbb{R}^{m-r}$

$$\begin{aligned} (x,y) &= \varphi(A(x,y), B(x,y)) = (Q(A(x,y), B(x,y)), B(x,y)) \\ \implies B(x,y) &= y \\ \varphi^{-1}(x,y) &= (A(x,y), y) \\ \varphi\varphi^{-1} &= 1 \implies x = Q(A(x,y), y) \end{aligned}$$

Recall that we had hypotehsized that

$$F(x,y) = (Q(x,y), R(x,y))$$

Then

$$F \circ \varphi^{-1}(x,y) = F(A(x,y), y) = (Q(A(x,y), y), R(A(x,y), y)) = (x, R(A(x,y), y))$$

and so

$$F \circ \varphi^{-1}(x,y) = (x, \tilde{R}(x,y))$$

where $\tilde{R} : \tilde{U}_0 \rightarrow \mathbb{R}^{n-r}$

$$\tilde{R}(x,y) = R(A(x,y), y)$$

Compute

$$D(F \circ \varphi^{-1})(x,y) = \begin{pmatrix} \delta_j^i & 0 \\ \frac{\partial \tilde{R}^i}{\partial x^j}(x,y) & \frac{\partial \tilde{R}^i}{\partial y^j}(x,y) \end{pmatrix}$$

Since composing with a diffeomorphism doesn't change rank of map, $D(F \circ \varphi^{-1})$ has rank r everywhere in \tilde{U}_0 .

$\begin{pmatrix} \delta_j^i \\ \frac{\partial \tilde{R}^i}{\partial x^j}(x,y) \end{pmatrix} j = 1 \dots r$ are linearly independent, so $\frac{\partial \tilde{R}^i}{\partial y^j}(x,y) = 0$ on \tilde{U}_0 , so \tilde{R}^i independent of y^j .

Let $S(x) = \tilde{R}(x,0)$, then

$$F \circ \varphi^{-1}(x,y) = (x, S(x))$$

Let open $V_0 \subseteq V$, $(0,0) \in V$ be an open subset $V_0 = \{(v,w) \in V : (v,0) \in \tilde{U}_0\}$.

Then V_0 is a neighborhood of $(0,0)$.

Because \tilde{U}_0 is a cube, $F \circ \varphi^{-1}(x,y) = (x, S(x))$,

$$F \circ \varphi^{-1}(\tilde{U}_0) \subseteq V_0$$

so $F(U_0) \subseteq V_0$.

Define $\psi : V_0 \rightarrow \mathbb{R}^n$

$$\psi(v,w) = (v, w - S(v))$$

Because $\psi^{-1}(s,t) = (s, t + S(s))$,

it is a diffeomorphism.

Thus (V_0, ψ) is a smooth chart.

$$\psi \circ F(\varphi^{-1}(x,y)) = \psi(x, S(x)) = (x, S(x) - S(x)) = (x, 0)$$

□

Definition 4 (regular value). *For smooth $f : X \rightarrow Y$, $X, Y \in \mathbf{Man}$,*

*$y \in Y$ is a **regular value** for f if $Df_x : T_x X \rightarrow T_y Y$ surjective $\forall x$ s.t. $f(x) = y$.*

*$y \in Y$ **critical value** if y not a regular value of f .*

Absil, Mahony, and Sepulchre [7] pointed out that another definition for a *regular value* can utilize the theorem that rank of $Df \equiv DF = \dim T_p N = \dim N$, iff $DF(p)$ surjective, for $p \in M$, $F : M \rightarrow N$. Then

regular value $y \in N$, of F , if rank of $F \equiv \text{rank}(DF(x)) = \dim N$, $\forall x \in F^{-1}(y)$, for $F : M \rightarrow N$.

Theorem 10 (Preimage theorem). *If y regular value of $f : X \rightarrow Y$, $f^{-1}(y)$ is a submanifold of X , with $\dim f^{-1}(y) = \dim X - \dim Y$*

Proof. Given y is a regular value of $f : X \rightarrow Y$,

$\forall x \in f^{-1}(y)$, $Df_x : T_x X \rightarrow T_y Y$ is surjective. By local submersion theorem,

$$f(x^1 \dots x^k) = (x^1 \dots x^l) = y$$

Since $x \in f^{-1}(y)$, $(x^1 \dots x^k) = (y^1 \dots y^l, x^{l+1} \dots x^k)$.

For this chart for (U, φ) , $U \ni x$, consider $(U \cap f^{-1}(y), \psi)$ with $\psi(x) = (x^{l+1} \dots x^k) \quad \forall x \in U \cap f^{-1}(y)$.

$\forall f^{-1}(y)$ submanifold with $\dim f^{-1}(y) = k - l = \dim X - \dim Y$.

□

Examples for emphasis

If $\dim X > \dim Y$,

if $y \in Y$, regular value of $f : X \rightarrow Y$,
 f submersion, $\forall x \in f^{-1}(y)$

If $\dim X = \dim Y$,

f local diffeomorphism $\forall x \in f^{-1}(y)$

If $\dim X < \dim Y$, $\forall y \in f(X)$ is a critical value.

Example: $O(n)$ as a submanifold of $\mathbf{Mat}(n, n)$

Given $\mathbf{Mat}(n, n) \equiv M(n) = \{n \times n \text{ matrices}\}$ is a manifold; in fact $\mathbf{Mat}(n, n) \cong \mathbb{R}^{n^2}$,

Consider $O(n) = \{A \in \mathbf{Mat}(n, n) | AA^T = 1\}$.

$$(10) \quad AA^T \in \text{Sym}(n) \equiv S(n) = \{S \in \mathbf{Mat}(n, n) | S^T = S\} = \{\text{symmetric } n \times n \text{ matrices}\}$$

$\text{Sym}(n)$ submanifold of $\mathbf{Mat}(n, n)$, $\text{Sym}(n)$ diffeomorphic to \mathbb{R}^k (i.e. $\text{Sym}(n) \cong \mathbb{R}^k$), $k := \frac{n(n+1)}{2}$.

$$f : \mathbf{Mat}(n, n) \rightarrow \text{Sym}(n)$$

$$f(A) = AA^T$$

Notice f is smooth,

$$f^{-1}(1) = O(n)$$

$$Df_A(B) = \lim_{s \rightarrow 0} \frac{f(A + sB) - f(A)}{s} = \lim_{s \rightarrow 0} \frac{(A + sB)(A^T + sB^T) - AA^T}{s} = AB^T + BA^T$$

If $Df_A : T_A \mathbf{Mat}(n, n) \rightarrow T_{f(A)} \text{Sym}(n)$ surjective when $A \in f^{-1}(1) = O(n)$ (???).

Proposition 1. *If smooth $g_1 \dots g_l \in C^\infty(X)$ on X are independent $\forall x \in X$, s.t. $g_i(x) = 0$, $\forall i = 1 \dots l$,*

then $Z = \{x \in X | g_1(x) = \dots = g_l(x) = 0\}$ is a submanifold of X s.t. $\dim Z = \dim X - l$.

Take note that $g_1 \dots g_l$ are independent at x means, really, that $D(g_1)_x \dots D(g_l)_x$ are linearly independent on $T_x X$.

Proof. Suppose smooth $g_1 \dots g_l \in C^\infty(X)$ on manifold X s.t. $\dim X = k \geq l$.

Consider $g = (g_1 \dots g_l) : X \rightarrow \mathbb{R}^l$, $Z \equiv g^{-1}(0)$.

Since $\forall g_i$ smooth, $D(g_i)_x : T_x X \rightarrow \mathbb{R}$ linear.

Now for

$$Dg_x = (D(g_1)_x \dots D(g_l)_x) : T_x X \rightarrow \mathbb{R}^l$$

By rank-nullity theorem (linear algebra), Dg_x surjective iff $\text{rank} Dg_x = l$ i.e. l functionals $D(g_1)_x \dots D(g_l)_x$ are linearly independent on $T_x X$.

”We express this condition by saying the l functions $g_1 \dots g_l$ are independent at x .” (Guillemin and Pollack (2010) [4])

□

4. SUBMANIFOLDS; IMMERSED SUBMANIFOLD, EMBEDDED SUBMANIFOLDS, REGULAR SUBMANIFOLDS

Definition 5 (Embedded Submanifold).

Recall immersion:

$F : M \rightarrow N$ immersion iff DF injective, i.e. iff $\text{rank} DF = \dim M$.

Consider manifolds $M \subseteq N$.

Consider inclusion map $i : M \rightarrow N$.

$$i : x \mapsto x$$

If i immersion, $Di(x) = \frac{\partial y^i}{\partial x^j} = \delta_j^i$ if $y^i = x^i$, $\forall i = 1, \dots, \dim M$.

Definition 6 (immersed submanifold). ***immersed submanifold** $M \subseteq N$ if inclusion $i : M \rightarrow N$ is an immersion.*

cf. 3.3 Embedded Submanifolds of Absil, Mahony, and Sepulchre [7], also Ch. 5 Submanifolds, pp. 108, **Immersed Submanifolds** of John Lee (2012) [3].

Immersed submanifolds often arise as images of immersions.

Proposition 2 (Images of Immersions as submanifolds). *Suppose smooth manifold M , smooth manifold with or without boundaries N ,*

injective, smooth immersion $F : M \rightarrow N$ (F injective itself, not just immersion)

Let $S = F(M)$.

Then S has unique topology and smooth structure of smooth submanifolds of N s.t. $F : M \rightarrow S$ diffeomorphism.

cf. Prop. 5.18 of John Lee (2012) [3].

Proof. Define topology of S : set $U \subseteq S$ open iff $F^{-1}(U) \subseteq M$ open ($F^{-1}(U \cap V) = F^{-1}(U) \cap F^{-1}(V)$, $F^{-1}(U \cup V) = F^{-1}(U) \cup F^{-1}(V)$).

Define smooth structure of S : $\{F(U), \varphi \circ F^{-1} | (U, \varphi) \in \text{atlas for } M, \text{ i.e. } (U, \varphi) \text{ any smooth chart of } M\}$.

”smooth compatibility condition”:

$$(\varphi_2 \circ F^{-1})(\varphi_i F^{-1})^{-1} = \varphi_2 \circ F^{-1} F \varphi_1^{-1} = \varphi_2 \varphi_1^{-1}$$

since $\varphi_2 \varphi_1^{-1}$ diffeomorphism ($\varphi_2 \varphi_1^{-1}$ bijection and it and inverse is differentiable)

F diffeomorphism onto $F(M)$.

and these are the only topology and smooth structure on S with this property:

$$S \xrightarrow{F^{-1}} M \xrightarrow{F} N = S \hookrightarrow M$$

and F^{-1} diffeomorphism, F smooth immersion, so $i : S \rightarrow M$ smooth immersion.

5. TENSORS

I’ll go through Ch.7 *Tensors* of Jeffrey Lee (2009) [2].

Definition 7 (7.1[2]). *Let V, W be modules over commutative ring R , with unity.*

Then, algebraic W -valued tensor on V is multilinear map.

$$(11) \quad \tau : V_1 \times V_2 \times \dots \times V_m \rightarrow W$$

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

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

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^{**} .
 $v \mapsto \tilde{v}$

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 $(\pi \circ s)(u) = u$, $\forall u \in U$.

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

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

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

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

$$(12) \quad (\otimes_{i=1}^r V) \otimes (\otimes_{j=1}^s V^*) \rightarrow T_s^r(V; R)$$

$$u_1 \otimes \dots \otimes u_r \otimes \beta^1 \otimes \dots \otimes \beta^s \in (\otimes^r V) \otimes (\otimes^s V^*) \mapsto (\alpha^1 \dots \alpha^r, v_1 \dots v_s) \mapsto \alpha^1(u_1) \dots \alpha^r(u_r) \beta^1(v_1) \dots \beta^s(v_s)$$

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

$$\alpha^i = \alpha_\mu^i e^\mu, \quad i = 1, 2, \dots, r, \mu = 1, 2, \dots, \dim V^* \quad \alpha^i(u_i) = \alpha_\mu^i u_i^\mu$$

$$v_i = v_i^\mu e_\mu, \quad i = 1, 2, \dots, s, \mu = 1, 2, \dots, \dim V \quad \beta^i(v_i) = \beta_\mu^i v_i^\mu$$

So that

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

$$= (u_1^{\alpha_1} \dots u_r^{\alpha_r} \beta_{\mu_1}^1 \dots \beta_{\mu_s}^s)(\alpha_{\alpha_1}^1 \dots \alpha_{\alpha_r}^r v_1^{\mu_1} \dots v_s^{\mu_s})$$

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

Proposition 4. *If V is finite-dim. vector space, or if $V = \Gamma(E)$, for vector bundle $E \rightarrow M$, map*

$$(13) \quad (\otimes_{i=1}^r V) \otimes (\otimes_{j=1}^s V^*) \rightarrow T_s^r(V; R)$$

□ *is an isomorphism.*

Definition 8. *tensor that can be written as*

$$(14) \qquad \qquad \qquad u_1 \otimes \cdots \otimes u_r \otimes \beta^1 \otimes \cdots \otimes \beta^s \equiv u_1 \otimes \cdots \otimes \beta^s$$

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

Now well that not *all* tensors are simple.

Definition 9 (7.7[2], tensor product). $\forall S \in T_{s_1}^{r_1}(V), \forall T \in T_{s_2}^{r_2}(V)$,
define *tensor product*

$$(15) \qquad \qquad \qquad S \otimes T \in T_{s_1+s_2}^{r_1+r_2}(V) \\ S \otimes T(\theta^1 \ldots \theta^{r_1+r_2}, v_1 \ldots v_{s_1+s_2}) := S(\theta^1 \ldots \theta^{r_1}, v_1 \ldots v_{s_1})T(\theta^{r_1+1} \ldots \theta^{r_1+r_2}, v_{s_1+1} \ldots v_{s_1+s_2})$$

Proposition 5 (7.8[2]).

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

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

Exercise 7.11. Let basis for V $e_1 \ldots e_n$, corresponding dual basis for V^* $e^1 \ldots e^n$
Let basis for V $\bar{e}_1 \ldots \bar{e}_n$, corresponding dual basis for V^* $\bar{e}^1 \ldots \bar{e}^n$
s.t.

$$\bar{e}_i = C^k_i e_k$$

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

EY:20170404, keep in mind that

$$\begin{aligned} Ax &= e_i A^i_k e^k (x^j e_j) = e_i A^i_j x^j = A^i_j x^j e_i \\ Ae_j &= e_k A^k_i e^i (e_j) = A^k_j e_k = \bar{e}_j \\ \bar{\tau}^i_{jk} \bar{e}_i \otimes \bar{e}^j \otimes \bar{e}^k &= \bar{\tau}^i_{jk} C^l_i e_l (C^{-1})^j_m e^m (C^{-1})^k_n e^n = \bar{\tau}^i_{jk} C^l_i (C^{-1})^j_m (C^{-1})^k_n = \tau^l_{mn} \\ \bar{\tau}^i_{jk} &= C^c_k C^b_j (C^{-1})^i_a \tau^a_{bc} \end{aligned}$$

On Remark 7.13 of Jeffrey Lee (2009) [2]: 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,

$$(16) \qquad \qquad \qquad {}_R \mathbf{Mod} \ni {}_{\text{Mat}_{\mathbb{K}}(N, M)} \mathbb{K}^N$$

where

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

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

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

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

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

Consider

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

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

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

(remember, isomophrism 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 10 (7.20[2], **contraction**). *Let $(e_1, \ldots e_n)$ basis for V , $(e^1 \ldots e^n)$ dual basis.*
If $\tau \in T_s^r(V)$, then for $k \leq r, l \leq s$, define

$$(17) \qquad \qquad \qquad C_l^k \tau \in T_{s-1}^{r-1}(V) \\ C_l^k \tau(\theta^1 \ldots \theta^{r-1}, w_1 \ldots w_{s-1}) := \\ \sum_{a=1}^n \tau(\theta^1 \ldots \underbrace{e^a}_{kth \ position} \ldots \theta^{r-1}, w_1 \ldots \underbrace{e_a}_{ith \ position} \ldots w_{s-1})$$

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.

$$(C_l^k \tau)^{i_1 \ldots \widehat{i_k} \ldots i_r}_{j_1 \ldots \widehat{j_l} \ldots j_s} := \tau^{i_1 \ldots a \ldots i_r}_{j_1 \ldots a \ldots j_s}$$

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

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

so that

$$\begin{aligned} v_j &= v_j^\mu e_\mu & j &= 1 \ldots s, & \mu &= 1, \ldots \dim V \\ \alpha^i &= \alpha_\mu^i e^\mu & i &= 1 \ldots r, & \mu &= 1 \ldots \dim V^* \end{aligned}$$

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

$$\begin{aligned} \tau(\alpha^1 \ldots \alpha^r, v_1 \ldots v_s) &= \tau(\alpha_{\mu_1}^1 e^{\mu_1} \ldots \alpha_{\mu_r}^r e^{\mu_r}, v_1^{\nu_1} e_{\nu_1} \ldots v_s^{\nu_s} e_{\nu_s}) = \\ &= \alpha_{\mu_1}^1 \ldots \alpha_{\mu_r}^r v_1^{\nu_1} \ldots v_s^{\nu_s} \tau(e^{\mu_1} \ldots e^{\mu_r}, e_{\nu_1} \ldots e_{\nu_s}) = \alpha_{\mu_1}^1 \ldots \alpha_{\mu_r}^r v_1^{\nu_1} \ldots v_s^{\nu_s} \tau^{\mu_1 \ldots \mu_r}_{\nu_1 \ldots \nu_s} \end{aligned}$$

which is equivalent to

$$\begin{array}{ccc} \tau \in T_s^r(V) & \xrightarrow{\alpha^1 \otimes \cdots \otimes \alpha^r \otimes v_1 \otimes \cdots \otimes v_s \otimes} & \alpha^1 \otimes \cdots \otimes \alpha^r \otimes v_1 \otimes \cdots \otimes v_s \otimes \tau \\ & & \downarrow \\ & & \tau(\alpha^1 \dots \alpha^r, v_1 \dots v_s) \in R \end{array}$$

$$C_{s+1}^1 C_{s+2}^2 \cdots C_{r+s}^r C_1^r C_2^{r+1} \cdots C_s^{r+s}$$

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

Conlon (2008) [16]

Part 4. Lie Groups, Lie Algebra

6. LIE GROUPS

- : Lie Groups
- : Groups
- : Ring
- : group algebra
- : Group Ring
- : Representation Theory
- : Modules
- : kG -modules

From Sec. 8.1 "Noncommutative Rings" of Rotman (2010) [9]:

Definition 11. *ring R - additive abelian group equipped with multiplication $R \times R \rightarrow R$ s.t. $\forall a, b \in R$*
 $(a, b) \mapsto ab$

- (i) $a(bc) = (ab)c$
- (ii) $a(b+c) = ab+ac$, $(b+c)a = ba+ca$
- (iii) $\exists 1 \in R$ s.t. $\forall a \in R$, $1a = a = a1$

Example 8.1[9]

- (ii) group algebra kG , k commutative ring, G group, "its additive abelian group is free k -module having basis labeled by elements of G ,
- i.e. $\forall a \in kG$, $a = \sum_{g \in G} a_g g$, $a_g \in k$, $\forall g \in G$, $a_g \neq 0$ for only finitely many $g \in G$.

define (ring) multiplication $kG \times kG \rightarrow kG$ $\forall a, b \in kG$,

$$a = \sum_{g \in G} a_g g \quad \text{to be}$$

$$ab = \sum_{h \in G} b_h g$$

$$\left(\sum_{g \in G} a_g g \right) \left(\sum_{h \in G} b_h h \right) = \sum_{z \in G} \left(\sum_{gh=z} a_g b_h \right) z$$

Definition 12. *Given R ring, left R -module is (additive) abelian group M equipped with*

scalar multiplication $R \times M \rightarrow M$ s.t. $\forall m, m' \in M$, $\forall r, r', 1 \in R$

$$(r, m) \mapsto rm$$

- (i) $r(m+m') = rm+rm'$
- (ii) $(r+r')m = rm+r'm$
- (iii) $(rr')m = r(r'm)$
- (iv) $1m = m$

EY : 20150922 Example : for kG -module V^σ , for $r \in kG$, so $r = \sum_{g \in G} a_g g$

$$\begin{array}{ccc} R \times M \rightarrow M & & kG \times V \rightarrow V \\ (r, m) \mapsto rm & \xRightarrow{\quad} & (r, v) \mapsto tv \end{array}$$

For some representation $\sigma : G \rightarrow GL(V)$,

$$rv = \sum_{g \in G} a_g g \cdot v = \sum_{g \in G} a_g \sigma_g(v)$$

So a kG -module needs to be associated with some chosen representation.

Note for V as an additive abelian group, $\forall u, v, w \in V$,

$$v+w = w+v, (u+v)+w = u+(v+w)$$

$$v+0 = v \quad \forall v \in V \text{ for } 0 \in V$$

$$v+(-v) = 0 \quad \forall v \in V$$

So a vector space can be an additive abelian group.

Note that

$$r(v+w) = \left(\sum_{g \in G} a_g g \right) (v+w) = \left(\sum_{g \in G} a_g \sigma_g \right) (v+w) = \sum_{g \in G} a_g \sigma_g(v) + \sum_{g \in G} a_g \sigma_g(w) = rv + rw$$

$$(r+r')v = \left(\sum_{g \in G} a_g g + b_g g \right) v = \sum_{g \in G} (a_g \sigma_g + b_g \sigma_g) v = \sum_{g \in G} a_g \sigma_g(v) + \sum_{g \in G} b_g \sigma_g(v) = rv + r'v$$

$$(rr')v = \left(\sum_{g \in G} a_g g \sum_{h \in G} b_h h \right) v = \left(\sum_{z \in G} \sum_{gh=z} a_g b_h z \right) v = \sum_{z \in G} \sum_{gh \in z} a_g b_h \sigma_z(v) = \sum_{g \in G} \sum_{h \in G} a_g b_h \sigma_g \sigma_h(v)$$

since $\sigma(gh) = \sigma(g)\sigma(h) = \sigma_g \sigma_h = \sigma_{gh}$ (σ homomorphism)

$$1v = \sigma(1)v = 1v = v$$

From Sec. 8.3 "Semisimple Ring" of Rotman (2010) [9]:

Definition 13. *k -representation of group G is homomorphism*

$$\sigma : G \rightarrow GL(V)$$

where V is vector field over field k

Proposition 6 (8.37 Rotman (2010)[9]). $\forall k$ -representation $\sigma : G \rightarrow GL(V)$ equips V with structure of left kG -module, denote module by V^σ .

Conversely, \forall left kG -module V determines k -representation $\sigma : G \rightarrow GL(V)$

Proof. Given $\sigma : G \rightarrow GL(V)$,

$$\sigma_g =: \sigma(g) : V \rightarrow V$$

define

$$kG \times V \rightarrow V$$

$$\left(\sum_{g \in G} a_g g \right) v = \sum_{g \in G} a_g \sigma_g(v)$$

$v, w \in V$
Let $r, r', 1 \in kG$

$$r = \sum_{g \in G} a_g g$$

$$r(v + w) = \left(\sum_{g \in G} a_g g \right) (v + w) = \left(\sum_{g \in G} a_g \sigma_g \right) (v + w) = \sum_{g \in G} a_g \sigma_g(v) + \sum_{g \in G} a_g \sigma_g(w) = rv + rw$$

$$(r + r')v = \left(\sum_{g \in G} a_g g + b_g g \right) v = \sum_{g \in G} (a_g \sigma_g + b_g \sigma_g) v = \sum_{g \in G} a_g \sigma_g(v) + \sum_{g \in G} b_g \sigma_g(v) = rv + r'v$$

$$(rr')v = \left(\sum_{g \in G} a_g g \sum_{h \in G} b_h h \right) v = \left(\sum_{z \in G} \sum_{gh=z} a_g b_h z \right) v = \sum_{z \in G} \sum_{gh \in z} a_g b_h \sigma_z(v) = \sum_{g \in G} \sum_{h \in G} a_g b_h \sigma_g \sigma_h(v)$$

since $\sigma(gh) = \sigma(g)\sigma(h) = \sigma_g \sigma_h = \sigma_{gh}$ (σ homomorphism)

$$1v = \sigma(1)v = 1v = v$$

Conversely, assume V left kG -module.

If $g \in G$, then $v \mapsto gv$ defines $T_g : V \rightarrow V$. T_g nonsingular since $\exists T_g^{-1} = T_{g^{-1}}$

Define $\sigma : G \rightarrow GL(V)$

$$\sigma : g \mapsto T_g$$

σ k -representation

$$\sigma(gh) = T_{gh} = T_g T_h = \sigma(g)\sigma(h)$$

$$\sigma(gh)(v) = T_{gh}v = ghv = T_g T_h v = \sigma(g)\sigma(h)v \quad \forall v \in V$$

Proposition 7. Let group G , let $\sigma, \tau : G \rightarrow GL(V)$ be k -representations, field k .

If V^σ, V^τ corresponding kG -modules in Prop. 6 (Prop. 8.37 in Rotman (2010) [9]), then

$V^\sigma \simeq V^\tau$ as kG -modules iff \exists nonsingular $\varphi : V \rightarrow V$ s.t.

$$\varphi\tau(g) = \sigma(g)\varphi \quad \forall g \in G$$

Proof. If $\varphi : V^\tau \rightarrow V^\sigma$ kG -isomorphism, then $\varphi : V \rightarrow V$ isomorphism s.t.

$$\varphi(\sum a_g gv) = (\sum a_g g)\varphi(v) \quad \forall v \in V, \forall g \in G$$

in V^τ , $kG \times V \rightarrow V$

$$gv = \tau(g)(v)$$

in V^σ , $kG \times V \rightarrow V$ scalar multiplication

$$gv = \sigma(g)(v)$$

$$\implies \forall g \in G, v \in V, \quad \varphi(\tau(g)(v)) = \sigma(g)(\varphi(v))$$

I think

$$\varphi(gv) = \varphi(\tau(g)(v)) = g\varphi(v) = \sigma(g)\varphi(v)$$

$$\implies \varphi\tau(g) = \sigma(g)\varphi \quad \forall g \in G$$

Conversely, if \exists nonsingular $\varphi : V \rightarrow V$ s.t. $\varphi\tau(g) = \sigma(g)\varphi \quad \forall g \in G$

$$\varphi\tau(g)v = \varphi(\tau(g)v) = \sigma(g)\varphi(v) \quad \forall g \in G, \forall v \in V$$

Consider scalar multiplication

$$kG \times V \rightarrow V$$

$$\sum_{g \in G} a_g g(v) = \sum_{g \in G} a_g \tau_g(v)$$

$$\varphi \left(\sum_{g \in G} a_g \tau_g(v) \right) = \varphi \left(\sum_{g \in G} a_g \tau(g)v \right) = \sum_{g \in G} a_g \sigma(g)\sigma(g)\varphi(v) = \left(\sum_{g \in G} a_g g \right) \varphi(v)$$

□

Admittedly, after this exposition from Rotman (2010) [9], I still didn't understand how kG -modules relate to representation theory and group rings. I turned to Baker (2011) [10], which we'll do right now. Note that I found a lot of links to online resources on representation theory from Khovanov's webpage <http://www.math.columbia.edu/~khovanov/resource/>.

Note,

Definition 14. vector subspace $W \subseteq V$ is called a

G -submodule, G -subspace, EY : 20150922 “invariant” subspace?

if $\forall g \in G$, for representation $\rho : G \rightarrow GL_k(V)$, $\rho_g(w) \in W$, $\forall w \in W$, $\forall g \in G$ i.e. closed under “action of elements of G ” with

$$\rho_g =: \rho(g) : V \rightarrow V$$

Given basis $\mathbf{v} = \{v_1 \dots v_n\}$ for V , $\dim_k V = n$, $\forall g \in G$,

$$\rho_g v_j = \rho(g)v_j = r_{kj}(g)v_k$$

for, indeed,

$$\rho_g x^j v_j = \rho(g)x^j v_j = x^j \rho(g)v_j = x^j r_{kj}(g)v_k = r_{kj}x^j v_k$$

so that

□

$$\rho : G \rightarrow GL_k(V)$$

$$\rho(g) = [r_{ij}(g)]$$

Example 2.1 (Baker (2011) [10]): Let $\rho : G \rightarrow GL_k(V)$ where $\dim_k V = 1$

$$\forall v \in V, v \neq 0, \forall g \in G, \lambda_g \in k \text{ s.t. } g \cdot v = \rho_g(v) = \lambda_g v$$

$$\rho(hg)v = \rho_h \rho_g v = \lambda_{hg}v = \lambda_h \lambda_g v \implies \lambda_{hg} = \lambda_h \lambda_g$$

$\implies \exists$ homomorphism $\Lambda : G \rightarrow k^\times$

$$\Lambda(g) = \lambda_g$$

From Sec. 2.2 “ G -homomorphisms and irreducible representations” of Baker (2011) [10], suppose $\rho : G \rightarrow GL_k(V)$ are 2 representations $\sigma : G \rightarrow GL_k(W)$

Many names for the same thing: G -equivalent, G -linear, G -homomorphism, EY : 20150922 kG -isomorphic?

If $\forall g \in G$,

$$\begin{array}{ccc}
 V & \xrightarrow{\varphi} & V \\
 \tau_g \downarrow & & \downarrow \sigma_g \\
 V & \xrightarrow{\varphi} & V
 \end{array}
 \iff V^\tau \xrightarrow{\varphi} V^\sigma$$

Indeed, define

$$\begin{aligned}
 \varphi : V^\tau &\rightarrow V^\sigma \\
 \varphi(v + w) &= \varphi(v) + \varphi(w) \\
 \varphi(rv) &= \varphi\left(\sum_{g \in G} a_g g \cdot v\right) = \varphi\left(\sum_{g \in G} a_g \tau_g(v)\right) = \sum_{g \in G} a_g \varphi(\tau_g(v)) = \sum_{g \in G} a_g \sigma_g \cdot \varphi(v) = r\varphi(v)
 \end{aligned}$$

EY : 20150922 So φ is a kG -isomorphism between left kG modules V^τ and V^σ if it's bijective and is “linear” in “scalars” $r \in kG$, i.e. $\varphi(rv) = r\varphi(v)$.

Define action of G on $\text{Hom}_k(V, W)$ ($\text{Hom}_k(V, W)$ is the vector space of k -linear transformations $V \rightarrow W$)

$$\begin{array}{ccc}
 V & \xrightarrow{f} & W \\
 v \mapsto f & \longrightarrow & f(v)
 \end{array}$$

$\forall f \in \text{Hom}_k(V, W), f : V \rightarrow W$
 $f(v) \in W$

Consider

$$\begin{aligned}
 G \times \text{Hom}_k(V, W) &\rightarrow \text{Hom}_k(V, W) \\
 (g \cdot f) &\mapsto (\sigma_g f) \circ \rho_{g^{-1}} \text{ i.e. } (g \cdot f)(v) = \sigma_g f(\rho_{g^{-1}} v) \quad (f \in \text{Hom}_k(V, W))
 \end{aligned}$$

Let $g, h \in G$,

$$(gh \cdot f)(v) = g \cdot \sigma_h f(\rho_{h^{-1}} v) = \sigma_g \sigma_h f \rho_{h^{-1}} \rho_{g^{-1}}(v) = (\sigma_{gh} f \rho_{(gh)^{-1}})(v)$$

Thus, $G \times \text{Hom}_k(V, W) \rightarrow \text{Hom}_k(V, W)$ is thus another G -representation of G .

$$(g \cdot f) \mapsto (\sigma_g f) \circ \rho_{g^{-1}}$$

For k -representation ρ , if the only G -subspaces of V are $\{0\}$, V , ρ **irreducible** or **simple**.

$$\begin{aligned}
 \rho_g(\{0\}) &= \{0\} \\
 \rho_g(V) &= V
 \end{aligned}$$

given subrepresentation $W \subseteq V$, V/W admits linear action of G , $\bar{\rho}_W : G \rightarrow GL_k(V/W)$ quotient representation

$$\bar{\rho}_W(g)(v + W) = \rho(g)(v) + W$$

if $v' - v \in W$

$$\rho(g)(v') + W = \rho(g)(v + (v' - v)) + W = (\rho(g)(v) + \rho(g)(v' - v)) + W = \rho(g)(v) + W$$

Proposition 8 (2.7 Baker (2011)[10]). *if $f : V \rightarrow W$ G -homomorphism, then*

- (a) *$\ker f$ is G -subspace of V*
- (b) *$\text{im} f$ is G -subspace of W*

$$\begin{array}{ccc}
 V & \xrightarrow{f} & W \\
 \rho_g \downarrow & & \downarrow \sigma_g \\
 V & \xrightarrow{f} & W
 \end{array}$$

Proof. Recall

- (a) Let $v \in \ker f$. Then $\forall g \in G$,

$$f(\rho_g v) = \sigma_g f(v) = 0$$

so $\rho_g v \in \ker f, \forall g \in G$. So $\ker f$ is G -subspace of V

- (b) Let $w \in \text{im} f$. So $w = f(u)$ for some $u \in V$

$$\sigma_g w = \sigma_g f(u) = f(\rho_g u) \in \text{im} f$$

So $\text{im} f$ is G -subspace of W

□

Theorem 11 (Schur's Lemma). *Let $\rho : G \rightarrow GL_{\mathbb{C}}(V)$ be irreducible representations of G over field $k = \mathbb{C}$; let $f : V \rightarrow W$ be $\sigma : G \rightarrow GL_{\mathbb{C}}(W)$*

G -linear map.

- (a) *if $f \neq 0$, f isomorphism. True $\forall k$ field, not just \mathbb{C}*
- (b) *if $V = W$, $\rho = \sigma$, then for some $\lambda \in \mathbb{C}$, f given by $f(v) = \lambda v$ ($v \in V$) (true for algebraically closed fields)*

Proof. (a) By Prop. 8, $\ker f \subseteq V$, $\text{im} f \subseteq W$ are G -subspaces.

For ρ , only G -subspaces are 0 or V , so if $\ker f = V$, $f = 0$. If $\ker f = 0$, f injective.

For σ , only G -subspaces are 0 or V , so $\text{im} f = 0$, $f = 0$. If $\text{im} f = V$, f surjective.

$\implies f$ isomorphism.

- (b) Let $\lambda \in \mathbb{C}$ be an eigenvalue of f , $f(v_0) = \lambda v_0$ eigenvector, $v_0 \neq 0$.

Let linear $f_\lambda : V \rightarrow V$ s.t.

$$f_\lambda(v) = f(v) - \lambda v \quad (v \in V)$$

$\forall g \in G$

$$\rho_g f_\lambda(v) = \rho_g f(v) - \rho_g \lambda v = f(\rho_g v) - \lambda \rho_g v = f_\lambda(\rho_g v)$$

So f_λ is G -linear, for

$$\begin{array}{ccc}
 V & \xrightarrow{f} & V \\
 \rho_g \downarrow & & \downarrow \rho_g \\
 V & \xrightarrow{f} & V
 \end{array}$$

Since $f_\lambda(v_0) = 0$, by Prop. 8, $\ker f_\lambda = V$, (for $\ker f_\lambda \neq 0$ and so $\ker f_\lambda = V$)

By rank-nullity theorem, $\dim V = \dim \ker f_\lambda + \dim \text{im} f_\lambda$.

So $\text{im} f_\lambda = 0$, and so $f_\lambda(v) = 0$ ($\forall v \in V$) $\implies f(v) = \lambda v$

□

Schur's lemma, at least the first part, implies that the left kG -modules associated with representations ρ, σ are kG -isomorphic, i.e.

Proof.

$$\begin{array}{ccc} V & \xrightarrow{f} & W \\ \rho_g \downarrow & & \downarrow \sigma_g \\ V & \xrightarrow{f} & W \end{array} \iff V^\rho \stackrel{f}{\simeq} V^\sigma$$

with f being an isomorphism between V^ρ and V^σ s.t.

$$\begin{aligned} f(v+w) &= f(v) + f(w) \quad \forall v, w \in (V^\sigma, +) \\ f(rv) &= rf(v) \quad \forall r = \sum_{g \in G} a_g g \in kG \end{aligned}$$

Kosmann-Schwarzbach's **Groups and Symmetries**[11] is a very lucid text that's mathematically rigorous enough and practical for physicists. It's really good and very clear. Let's follow its development for $SU(2)$, $SO(3)$, $SL(2, \mathbb{C})$ and corresponding Lie algebras $\mathfrak{su}(2)$, $\mathfrak{so}(3)$, $\mathfrak{sl}(2, \mathbb{C})$.

From Chapter 2 “Representations of Finite Groups” of Kosmann-Schwarzbach (2010) [11]

Definition 15 (2.1 Kosmann-Schwarzbach (2010)[11]). *On $L^2(G)$, scalar product defined by*

$$\langle f_1 | f_2 \rangle = \frac{1}{|G|} \sum_{g \in G} \overline{f_1(g)} f_2(g)$$

$f_1, f_2 \in \mathcal{F}(G) \equiv \mathbb{C}[G]$ vector space of functions on G taking values on \mathbb{C}

Definition 16 (2.3 Kosmann-Schwarzbach (2010)[11]). *Let (E, ρ) be representation of G*

character of $\rho \equiv \chi_\rho : G \rightarrow \mathbb{C}$

$$\chi_\rho(g) = \text{tr}(\rho(g)) = \sum_{i=1}^n (\rho(g))_{ii}$$

*Note: equivalent representations have same character
each conjugacy class of G , function χ_ρ is constant*

Looking at Def. 15

$$\langle \chi_{\rho_1} | \chi_{\rho_2} \rangle = \frac{1}{|G|} \sum_{g \in G} \chi_{\rho_1}(g^{-1}) \chi_{\rho_2}(g)$$

since $\overline{\chi_{\rho_1}(g)} = \chi_{\rho_1}(g^{-1})$ by unitarity of representation with respect to scalar product \langle , \rangle

Proposition 9 (2.7 Kosmann-Schwarzbach (2010)[11]). *Let (E_1, ρ_1) be representations of G , let linear $u : E_1 \rightarrow E_2$.
(E_2, ρ_2)*

Then \exists linear T_u s.t.

$$(18) \quad \begin{aligned} T_u &: E_1 \rightarrow E_2 \\ T_u &= \frac{1}{|G|} \sum_{g \in G} \rho_2(g) u \rho_1(g)^{-1} \end{aligned}$$

so that $\rho_2(g) T_u = T_u \rho_1(g) \quad \forall g \in G$

$$\rho_2(g) T_u = \frac{1}{|G|} \sum_{h \in G} \rho_2(gh) u \rho_1(h^{-1}) = \frac{1}{|G|} \sum_{k \in G} \rho_2(k) u \rho_1(k^{-1}g) = T_u \rho_1(g)$$

□

Thus, diagrammatically, we have that

$$E_1 \xrightarrow{u} E_2 \implies \begin{array}{ccc} E_1 & \xrightarrow{T_u} & E_2 \\ \rho_1(g) \downarrow & & \downarrow \rho_2(g) \\ E_1 & \xrightarrow{T_u} & E_2 \end{array}$$

From Definition 1.12 of Kosmann-Schwarzbach [11], “representations ρ_1 and ρ_2 are called **equivalent** if there is a bijective intertwining operator for ρ_1 and ρ_2 .” So I will interpret this as if an intertwining operator is not bijective, then the representations ρ_1 , ρ_2 are not equivalent.

Proposition 10 (2.8 Kosmann-Schwarzbach (2010)[11]). *Let (E_1, ρ_1) be irreducible representations of G , let linear $u : E_1 \rightarrow E_2$,
(E_2, ρ_2)*

define T_u by $T_u = \frac{1}{|G|} \sum_{g \in G} \rho_2(g) u \rho_1(g)^{-1}$ by Eq. 18.

- (i) *If ρ_1, ρ_2 inequivalent, then $T_u = 0$*
- (ii) *If $E_1 = E_2 = E$ and $\rho_1 = \rho_2 = \rho$, then*

$$T_u = \frac{\text{tr}(u)}{\dim E} 1_E$$

Proof. (i) if ρ_1, ρ_2 are inequivalent, by definition, T_u is not isomorphic. Then by Schur's lemma (first part), $T_u = 0$
(ii) By Schur's lemma, $T_u(v) = \lambda v \quad \forall v \in E = E_1 = E_2$. So $T_u = \lambda 1_E$. $\text{tr} T_u = \lambda \dim E$ or $\lambda = \frac{\text{tr} T_u}{\dim E}$. Thus, $T_u = \frac{\text{tr} T_u}{\dim E} 1_E$ □

Let $(e_1 \dots e_n)$ basis of E

$(f_1 \dots f_p)$ basis of F

$$\forall u \in \mathcal{L}(E, F), \quad \begin{aligned} u &: E \rightarrow F \\ u(x) &= u(x^j e_j) = x^j u(e_j) = x^j u^i_j f_i \quad \text{for } x = x^j e_j \in E \\ u &= u^i_j e^j \otimes f_i \quad y = y^i f_i \in F \end{aligned}$$

For

$$T : E^* \otimes F \rightarrow \mathcal{L}(E, F)$$

$$T(\xi \otimes y) = u^i_j e^j \otimes f_i \text{ i.e. set } T(\xi \otimes y) \text{ to this } u$$

$$T(\xi \otimes y) = T(\xi_l e^l \otimes y^k f_k) = \xi_l y^k T(e^l \otimes f_k) = (\xi_l y^k T_{kj}^{li}) e^j \otimes f_i \implies \xi_l y^k T_{kj}^{li} = u^i_j$$

Exercises. Exercises of Ch. 2 Representations of Finite Groups [11]

Exercise 2.6. [11] *The dual representation.*

Let (E, π) representation of group G .

$\forall g \in G, \xi \in E^*, x \in E$, set $\langle \pi^*(g)(\xi), x \rangle = \langle \xi, \pi(g^{-1})(x) \rangle$

(a) *dual* (or *contragredient*) of π , $\pi^* : G \rightarrow \text{End}(E^*)$, π^* is a representation, since

$$\begin{aligned} \langle \pi^*(gh)(\xi), x \rangle &= \langle \xi, \pi((gh)^{-1})(x) \rangle = \langle \xi, \pi(h^{-1}g^{-1})(x) \rangle = \langle \xi, \pi(h^{-1})\pi(g^{-1})(x) \rangle = \langle \xi, \pi(h^{-1})(\pi(g^{-1})(x)) \rangle = \\ &= \langle \pi^*(h)(\xi), \pi(g^{-1})(x) \rangle = \langle \pi^*(g)\pi^*(h)(\xi), x \rangle \end{aligned}$$

since this is true, $\forall x \in E, \forall \xi \in E^*, \pi^*(gh) = \pi^*(g)\pi^*(h)$.

dual π^* of π is a representation.

(b) Consider $G \times \mathcal{L}(E, F) \rightarrow \mathcal{L}(E, F)$.

$$g \cdot u = \rho(g) \circ u \circ \pi(g^{-1})$$

Define

$$\sigma : G \rightarrow \text{End}(\mathcal{L}(E, F))$$

$$\sigma(g) : \mathcal{L}(E, F) \rightarrow \mathcal{L}(E, F)$$

$$\sigma(g)(u) = \rho(g) \circ u \circ \pi(g^{-1})$$

Let $(e_1 \dots e_n)$ be a basis of E . Let $\xi = \xi_i e^i \in E^*, x = x^j e_j \in E$.

Consider the isomorphism $T : E^* \otimes F \rightarrow \mathcal{L}(E, F)$ defined as²

$$T : E^* \otimes F \rightarrow \mathcal{L}(E, F) = \text{Hom}(E, F)$$

$$\xi \otimes y \mapsto (x \mapsto \xi(x)y)$$

Choose bases $(e_1 \dots e_n)$ of E
 $(e^1 \dots e^n)$ of E^* . Then
 $(f_1 \dots f_p)$ of F

$$T(e^j \otimes f_i)(x) = T(e^j \otimes f_i)(x^k e_k) = \delta_k^j x^k f_i = x^j f_i$$

$$T(e^j \otimes f_i)(e_k) = \delta_k^j f_i$$

Consider

$$u \in \mathcal{L}(E, F)$$

$$u : E \rightarrow F$$

$$u(x) = u(x^j e_j) = x^j u(e_j) = x^j u^i_j f_i$$

$$u(e_j) = u^i_j f_i \text{ i.e. } u : e_j \rightarrow u^i_j f_i$$

Then $\forall u \in \mathcal{L}(E, F)$,

$$T(u^i_j e^j \otimes f_i)(e_k) = u^i_j \delta_k^j f_i = u^i_k f_i = u(e_k) \implies u = T(u^i_j e^j \otimes f_i)$$

so T is surjective.

With $T(\xi \otimes y) = T(\xi' \otimes y')$,

$$T(\xi \otimes y)(x) = T(\xi' \otimes y')(x)$$

$$\xi(x)y = \xi'(x)y' \implies \xi(x)y - \xi'(x)y' = 0$$

which implies that $\xi \otimes y = \xi' \otimes y'$. So T is injective. Or, one could consider that $T^{-1} : \mathcal{L}(E, F) \rightarrow E^* \otimes F$, $T^{-1} : u \mapsto u^i_j e^j \otimes f_i$, which is the inverse of T .

Remark 1.

$$E^* \otimes F \xrightarrow{T} \mathcal{L}(E, F) = \text{Hom}(E, F)$$

$$(\xi, y) \mapsto (x \mapsto \xi(x)y)$$

and so $(e^j \otimes f_i) \mapsto (x \mapsto e^j(x)f_i = x^j f_i)$

So $E^* \otimes F$ is isomorphic to $\mathcal{L}(E, F) = \text{Hom}(E, F)$

For representation π ,

$$\pi : G \rightarrow \text{End}(E)$$

$$\pi(g) : E \rightarrow E$$

$$\pi(g)(x) = \pi(g)(x^j e_j) = x^j \pi(g)(e_j) = x^j \pi(g)^i_j e_i = (\pi(g)^i_j x^j e_i$$

Consider this matrix formulation:

$$\pi^*(g)(\xi) = \pi^*(g)(\xi_i e^i) = \xi_i \pi^*(g)(e^i) = \xi_i (\pi^*(g))^i_j e^j$$

$$\implies \langle \pi^*(g)(\xi), x \rangle = \xi_i (\pi^*(g))^i_j x^j$$

and

$$\langle \xi, \pi(g^{-1})(x) \rangle = \xi_i \pi(g^{-1})^i_j x^j$$

so that

$$\langle \pi^*(g)(\xi), x \rangle = \langle \xi, \pi(g^{-1})(x) \rangle \implies \pi(g^{-1})^i_j = (\pi^*(g))^i_j$$

Thus, given a choice of basis for E , the *dual* of π , $\pi^*(g)^i_j$, and $\pi(g^{-1})^i_j$ are formally equal.

So for a choice of basis of E and of F ,

$$(\pi^* \otimes \rho)(g)(\xi, y) = (\pi^*(g) \otimes \rho(g))(\xi, y) = \pi^*(g)\xi \otimes \rho(g)y = \xi_l \pi(g^{-1})^l_j e^j \otimes \rho(g)^i_k y^k f_i = \rho(g)^i_k y^k \xi_l \pi(g^{-1})^l_j e^j \otimes f_i$$

Applying T ,

$$T(\pi^* \otimes \rho)(g)(\xi, \rho) = \rho(g)^i_k y^k \xi_l \pi(g^{-1})^l_j = \rho(g)T(\xi, y)\pi(g^{-1})$$

$$\begin{array}{ccc} E^* \otimes F & \xrightarrow{T} & \mathcal{L}(E, F) \\ \downarrow (\pi^* \otimes \rho)(g) & & \downarrow \sigma(g) \\ E^* \otimes F & \xrightarrow{T} & \mathcal{L}(E, F) \end{array} \quad \begin{array}{ccc} (\xi, y) & \xrightarrow{T} & (x \mapsto \xi(x)y) = y^i \xi_j \\ \downarrow (\pi^* \otimes \rho)(g) & & \downarrow \sigma(g) \\ \pi^*(g)(\xi) \otimes \rho(g)y & \xrightarrow{T} & \rho(g)y^i \xi_j \pi(g^{-1}) = \rho(g)T(\xi, y)\pi(g^{-1}) \end{array}$$

Thus

Thus, representation $\sigma(g)$ is equivalent to representation $(\pi^* \otimes \rho)$, a tensor product of representations.

Exercise 2.15. *Representation of $GL(2, \mathbb{C})$ on the polynomials of degree 2*

Let group G , let representation ρ of G on $V = \mathbb{C}^n$, i.e. $\rho : G \rightarrow \text{End}(V)$

Let $P^{(k)}(V)$ vector space of complex polynomials on V that are homogeneous of degree k .

For $f \in P^{(k)}(V)$, the general form is

$$f = \sum_{\substack{i_1+i_2+\dots+i_n=k \\ 0 \leq i_j \leq k}} a_{i_1 i_2 \dots i_n} x_1^{i_1} x_2^{i_2} \dots x_n^{i_n}$$

²Mathematics stackexchange Isomorphism between Hom and tensor product [duplicate] <http://math.stackexchange.com/questions/428185/isomorphism-between-hom-and-tensor-product>

<http://math.stackexchange.com/questions/57189/understanding-isomorphic-equivalences-of-tensor-product>

Given

$$\binom{n+k}{k} = \binom{k-1}{k-1} + \binom{k}{k-1} + \cdots + \binom{n+k-1}{k-1} = \sum_{i=0}^n \binom{k-1+i}{k-1}$$

$\binom{k+n-1}{n-1}$ is number of monomials of degree k .

So $\dim P^{(k)}(V) = \binom{k+n-1}{n-1}$. This is a very lucid and elementary exposition on the basics of polynomials which I found was useful for the basic facts I forgot³.

So we have the graded algebra

$$P(V) = \bigoplus_{k=0}^{\infty} P^{(k)}(V)$$
$$\rho^{(k)} : G \rightarrow \text{End}(P^{(k)}(V))$$
$$\rho^{(k)}(g) : P^{(k)}(V) \rightarrow P^{(k)}(V)$$
$$\rho^{(k)}(g)(f) = f \circ \rho(g^{-1})$$

This is a representation of G since

- (a)
- $$\rho^{(k)}(gh)(f) = f \circ \rho((gh)^{-1}) = f \circ \rho(h^{-1}g^{-1}) = f \circ \rho(h^{-1})\rho(g^{-1}) \implies \rho^{(k)}(gh) = \rho^{(k)}(g)\rho^{(k)}(h)$$
- $$\rho^{(k)}(g)\rho^{(k)}(h)(f) = \rho^{(k)}(g)(f \circ \rho(h^{-1})) = f \circ \rho(h^{-1}) \circ \rho(g^{-1})$$
- (b) Choose basis $(e_1 \dots e_n)$ of V , $x = x^j e_j \in V$, $\rho : G \rightarrow \text{End}(V)$, and so $\rho(g)(x) = \rho(g)(x^j e_j) = x^j \rho(g)(e_j) = x^j (\rho(g))^i_j e_i$.
With $\xi(e_i) = \xi_i \implies \langle \xi, \rho(g^{-1})x \rangle = \xi_i x^j (\rho(g^{-1}))^i_j$
 $\forall \xi \in V^*, \xi = \xi_i e^i,$

$$\rho^*(g)(\xi) = \rho^*(g)(\xi_i e^i) = \xi_i \rho^*(g)^i_j e^j$$
$$\implies \langle \rho^*(g)(\xi), x \rangle = \xi_i x^j (\rho^*(g))^i_j \implies (\rho^*(g))^i_j = (\rho(g^{-1}))^i_j$$

So $\forall f \in P^{(1)}(V)$, $x \in V$, $\rho(g^{-1})x = x^j (\rho(g^{-1}))^i_j e_i$. So $f \circ \rho(g^{-1})(x) = \sum_{i=1}^n a_i (\rho(g^{-1}))^i_j x^j = \sum_{i=1}^n a_i (\rho^*(g))^i_j x^j$
 $\implies \rho^{(1)}(g)(f) = f \circ \rho^*(g)$

- (c) Suppose $G = GL(2, \mathbb{C})$, $V = \mathbb{C}^2$, ρ fundamental representation $g = \begin{pmatrix} a & b \\ c & d \end{pmatrix}$, $g^{-1} = \frac{1}{\det g} \begin{pmatrix} d & -b \\ -c & a \end{pmatrix}$ for $\det g = ad - bc$.

Let $k = 2$, $\dim P^{(2)}(\mathbb{C}^2) = \binom{2+2-1}{2-1} = \binom{3}{1} = 3$

$\forall f \in P^{(2)}(\mathbb{C}^2)$, $f(x, y) = Ax^2 + 2Bxy + Cy^2$

Let

$$P^{(2)}(\mathbb{C}^2) \rightarrow \mathbb{C}^3$$
$$f(x, y) = Ax^2 + 2Bxy + Cy^2 \mapsto \begin{pmatrix} A \\ B \\ C \end{pmatrix} \in \mathbb{C}^3$$

Call this transformation T , $T : P^{(2)}(\mathbb{C}^2) \rightarrow \mathbb{C}^3$.

$$\forall \begin{pmatrix} A \\ B \\ C \end{pmatrix} \in \mathbb{C}^3, f(x, y) = Ax^2 + 2Bxy + Cy^2 \text{ and } Tf(x, y) = \begin{pmatrix} A \\ B \\ C \end{pmatrix}. \text{ } T \text{ surjective.}$$

Suppose $Tf(x, y) = Tf'(x, y)$,

$$\implies Ax^2 + 2Bxy + Cy^2 = A'x^2 + 2B'xy + C'y^2$$
$$\implies (A - A')x^2 + 2(B - B')xy + (C - C')y^2 = 0$$

Then since the monomials form a basis, and its basis elements are independent (by definition), then $A = A'$, $B = B'$, $C = C'$. T injective. So T is bijective, an isomorphism.

(This is all in `groups.sage`)

```
sage: P2CC.<x,y> = PolynomialRing(CC,2) # this declares a PolynomialRing of field of complex numbers,
# of order 2 (i.e. only 2 variables for a polynomial, such as x, y)
sage: A = var('A')
sage: assume(A, 'complex')
sage: B = var('B')
sage: assume(B, 'complex')
sage: C = var('C')
sage: assume(C, 'complex')
sage: f(x,y) = A*x**2 +2*B*x*y + C*y**2

sage: a = var('a')
sage: assume(a, 'complex')
sage: b = var('b')
sage: assume(b, 'complex')
sage: c = var('c')
sage: assume(c, 'complex')
sage: d = var('d')
sage: assume(d, 'complex')
sage: g = Matrix([[a,b],[c,d]] )
sage: X = Matrix([[x],[y]])
sage: f( (g.inverse()*X)[0,0], (g.inverse()*X)[1,0] ).expand()
sage: f( (g.inverse()*X)[0,0], (g.inverse()*X)[1,0] ).expand().coefficient(x^2).full_simplify()
(C*c^2 - 2*B*c*d + A*d^2)/(b^2*c^2 - 2*a*b*c*d + a^2*d^2)
sage: f( (g.inverse()*X)[0,0], (g.inverse()*X)[1,0] ).expand().coefficient(x*y).full_simplify()
-2*(C*a*c + A*b*d - (b*c + a*d)*B)/(b^2*c^2 - 2*a*b*c*d + a^2*d^2)
sage: f( (g.inverse()*X)[0,0], (g.inverse()*X)[1,0] ).expand().coefficient(y^2).full_simplify()
(C*a^2 - 2*B*a*b + A*b^2)/(b^2*c^2 - 2*a*b*c*d + a^2*d^2)
```

So

$$\rho^{(2)}(g)(f)(x, y) = f \circ \rho(g^{-1})(x, y) =$$
$$= \frac{Cc^2 - 2Bcd + Ad^2}{(ad - bc)^2}x^2 + -2\frac{(Cac + Abd - (bc + ad)B)}{(ad - bc)^2}xy + \frac{Ca^2 - 2Bab + Ab^2}{(ad - bc)^2}y^2$$

So define $\tilde{\rho} : G \rightarrow \text{End}(\mathbb{C}^3)$. $\tilde{\rho}$ is a representation, for

$$\forall v = \begin{pmatrix} A \\ B \\ C \end{pmatrix} \in \mathbb{C}^3, \quad \tilde{\rho}(gh)(v) = T \circ f \circ \rho((gh)^{-1}) = T \circ f \circ \rho(h^{-1}g^{-1}) = T \circ f \circ \rho(h^{-1})\rho(g^{-1})$$

Now $\tilde{\rho}(h)(v) = T \circ f \circ \rho(h^{-1})$
 $\implies \tilde{\rho}(g)\tilde{\rho}(h)(v) = T \circ (f \circ \rho(h^{-1})) \circ \rho(g^{-1}) = T \circ f \circ \rho(h^{-1})\rho(g^{-1})$ and so
 $\tilde{\rho}(gh) = \tilde{\rho}(g)\tilde{\rho}(h)$

And so

$$\tilde{\rho}^*(g)(v) = Tf\rho(g^{-1})$$

and consider this commutation diagram, that (helped me at least and) clarifies the relationships:

³Polynomials. Math 4800/6080 Project Course <http://www.math.utah.edu/~bertram/4800/PolyIntroduction.pdf>

$$\begin{array}{ccc}
P^{(2)}(\mathbb{C}^2) & \xrightarrow{T} & \mathbb{C}^3 \\
\rho^{(2)}(g) \downarrow & & \downarrow \tilde{\rho}(g) \\
P^{(2)}(\mathbb{C}^2) & \xrightarrow{T} & \mathbb{C}^3
\end{array}
\qquad
\begin{array}{ccc}
f & \xrightarrow{T} & \begin{pmatrix} A \\ B \\ C \end{pmatrix} \\
\rho^{(2)}(g) \downarrow & & \downarrow \tilde{\rho}(g) \\
f \circ \rho(g^{-1}) & \xrightarrow{T} & \begin{pmatrix} D \\ E \\ F \end{pmatrix}
\end{array}$$

with

$$\begin{pmatrix} D \\ E \\ F \end{pmatrix} = \begin{pmatrix} \frac{C^2 - 2Bcd + Ad^2}{(ad-bc)^2} \\ -2 \frac{(Cac + Abd - (bc+ad)B)}{(ad-bc)^2} \\ \frac{Ca^2 - 2Bab + Ab^2}{(ad-bc)^2} \end{pmatrix}$$

Now define the dual $\tilde{\rho}^*$ as such:

$$\begin{aligned}
\tilde{\rho}^*(g) &: (\mathbb{C}^3)^* \rightarrow (\mathbb{C}^3)^* \\
\tilde{\rho}^*(g) &= \tilde{\rho}(g^{-1}) \\
&\forall \xi \in (\mathbb{C}^3)^* \\
\tilde{\rho}^*(g)\xi &= \xi_i(\tilde{\rho}^*(g))_j^i e^j = \xi_i(\tilde{\rho}(g^{-1}))_j^i e^j
\end{aligned}$$

$$\text{So for } v = \begin{pmatrix} A \\ B \\ C \end{pmatrix} \in \mathbb{C}^3, f = T^{-1}v = Ax^2 + 2Bxy + Cy^2 \in P^2(\mathbb{C}^2),$$

$$\tilde{\rho}(g^{-1})(v) = T \circ (f\rho(g)) = \begin{bmatrix} Aa^2 + 2Bac + Cc^2 \\ Aab + Bbc + Bad + Ccd \\ Ab^2 + 2Bbd + Cd^2 \end{bmatrix}$$

which was found using Sage Math:

```

sage: f((g*X)[0,0],(g*X)[1,0])
(a*x + b*y)^2*A + 2*(a*x + b*y)*(c*x + d*y)*B + (c*x + d*y)^2*C
sage: f((g*X)[0,0],(g*X)[1,0]).expand()
A*a^2*x^2 + 2*B*a*c*x^2 + C*c^2*x^2 + 2*A*a*b*x*y + 2*B*b*c*x*y + 2*B*a*d*x*y + 2*C*c*d*x*y + A*b^2*y^2 + 2*B*b*d*y^2 + C*d^2*y^2
sage: f((g*X)[0,0],(g*X)[1,0]).expand().coefficient(x^2)
A*a^2 + 2*B*a*c + C*c^2
sage: f((g*X)[0,0],(g*X)[1,0]).expand().coefficient(x*y)
2*A*a*b + 2*B*b*c + 2*B*a*d + 2*C*c*d
sage: f((g*X)[0,0],(g*X)[1,0]).expand().coefficient(y^2)
A*b^2 + 2*B*b*d + C*d^2

```

or

```

sage: T( f((g*X)[0,0],(g*X)[1,0]).expand() )
[A*a^2 + 2*B*a*c + C*c^2,
2*A*a*b + 2*B*b*c + 2*B*a*d + 2*C*c*d,
A*b^2 + 2*B*b*d + C*d^2]

```

So then

$$\tilde{\rho}(g^{-1}) = \begin{bmatrix} a^2 & 2ac & c^2 \\ 2ab & 2(ad+bc) & 2cd \\ b^2 & 2bd & d^2 \end{bmatrix}$$

So then

$$\tilde{\rho}^*(g) = \begin{bmatrix} a^2 & 2ac & c^2 \\ 2ab & 2(ad+bc) & 2cd \\ b^2 & 2bd & d^2 \end{bmatrix}$$

and operate on row vectors $\xi \in (\mathbb{C}^3)^*$ with $\tilde{\rho}^*(g)$ from the row vector's right.

$$\text{More: Let } G = SU(2). \text{ Then } U = e^{i\phi} \begin{bmatrix} a & b \\ -\bar{b} & \bar{a} \end{bmatrix}$$

$$\tilde{\rho}: SU(2) \rightarrow \text{End}(\mathbb{C}^3)$$

$$\tilde{\rho}(U): \mathbb{C}^3 \rightarrow \mathbb{C}^3$$

$$\tilde{\rho}(U)(v) = e^{-2i\varphi} \begin{bmatrix} A\bar{a}^2 + 2B\bar{a}\bar{b} + C\bar{b}^2 \\ -A\bar{a}b + B + C\bar{a}\bar{b} \\ Ab^2 - 2Bab + Ca^2 \end{bmatrix}$$

$$\implies \tilde{\rho}(U) = e^{-2i\varphi} \begin{bmatrix} -\bar{a}^2 & 2\bar{a}\bar{b} & \bar{b}^2 \\ -\bar{a}b & 1 & \bar{a}\bar{b} \\ b^2 & -2ab & a^2 \end{bmatrix}$$

cf. Ch. 5 Lie Groups of Jeffrey Lee (2009) [2]

Definition 17 (Lie Group). ***Lie Group** $G := \text{smooth manifold } G \text{ is a } \mathbf{Lie \ Group}$ if G is a group (abstract group), s.t.*

multiplication map $\mu: G \times G \rightarrow G$

$$\mu(g, h) = gh$$

inverse map $inv: G \rightarrow G$

$$inv(g) = g^{-1}$$

are C^∞ maps.

If group is abelian, use additive notation $g + h$ for group operation.

Definition 18 ($GL(n, \mathbb{R})$). $GL(n, \mathbb{R}) := \text{group of all invertible real } n \times n \text{ matrices.}$

global chart on $GL(n, \mathbb{R}) = \{x_j^i\}$, n^2 functions x_j^i , where if $A \in GL(n, \mathbb{R})$, then $x_j^i(A)$ is ij th entry of A .

Claim: $GL(n, \mathbb{R})$ is a Lie group.

Proof. multiplication is clearly smooth: $(AB)_{ij} = A_{ik}B_{kj}$,

$$\frac{\partial}{\partial x_m^l}(x_k^i(A)x_j^k(B)) = \delta_l^i \delta_k^m x_j^k(B) + x_k^i(A) \delta_l^k \delta_j^m$$

inversion map; appeal to formula for A^{-1} , $A^{-1} = \text{adj}(A)/\det(A)$, $\text{adj}(A) \equiv \text{adjoint matrix}$ (whose entries are cofactors).

$\implies A^{-1}$ depends smoothly on entries of A .

Similarly, $GL(n, \mathbb{C})$, group of invertible $n \times n$ complex matrices, is a Lie group. □

Exercise 5.5. Let subgroup H of G , consider cosets gH , $g \in G$.

Recall G is disjoint union of cosets of H .

Claim: if H open, so are all its cosets. And H closed.

Proof. cf. [stackexchange: Open subgroups of a topological group are closed](#)

$gH = \{gh|h \in H\}$ is an open neighborhood of g (since $1 \in H$, and mapping $h \mapsto gh$ sends open sets to open sets, since its inverse, $gh \mapsto h$, is C^∞ (so continuous)).

$$\begin{array}{ll} gH \rightarrow H & H \rightarrow gH \\ gh \xrightarrow{g^{-1}} h = \mu(g^{-1}, gh) & h \xrightarrow{g} gh = \mu(g, h) \end{array}$$

Then \forall coset gH , gH is open.

Suppose $g' \in H^c \equiv G - H \equiv G \setminus H$.

Consider $h \in H$, if $g'h \in H$, then $g' = (g'h)h^{-1} \in H$ (recall $h^{-1} \in H$, and H is a subgroup).

Contradiction.

$\implies \forall g' \in H^c$, \exists open neighborhood $g'H \subset H^c$, so H^c open (by definition). Then H closed.

cf. Thm. 5.6 in Jeffrey Lee (2009) [2].

Theorem 12. *If G connected Lie group, U neighborhood of identity element e , then U generates the group, i.e. $\forall g \in G$, g is a product of elements of U .*

Proof. Note $V = \text{inv}(U) \cap U$ is an open neighborhood of e . Note $\text{inv}(V) = V$. $\text{inv}(V) \equiv V^{-1} = \{V^{-1} | v \in V\}$. We say that V is *symmetric*.

Claim: V generates G .

\forall open W_1 , open $W_2 \subset G$,

$W_1 W_2 = \{w_1 w_2 | w_1 \in W_1, w_2 \in W_2\}$ is an open set being a union of open sets $\bigcup_{g \in W_1} g W_2$.

Thus, inductively defined sets

$$V^n = V V^{n-1}, \quad n = 1, 2, 3, \dots$$

are open.

$$e \in V \subset V^2 \subset \dots V^n \subset \dots$$

It's easy to check that each V^n is symmetric.

$$\text{inv}(V) = V$$

$$\text{inv}(V^2) = \text{inv}\left(\bigcup_{v \in V} vV\right) = V \text{inv}(V) = V = V^2$$

$$\text{inv}(V^{n+1}) = \text{inv}\left(\bigcup_{v \in V} vV^n\right) = V \text{inv}(V^n) = V V^n = V^{n+1}$$

so $V^\infty := \bigcup_{n=1}^\infty V^n$ is symmetric.

V^∞ closed under inversion, also multiplication. Thus V^∞ is an open subgroup.

From Exercise 5.5, Jeffrey Lee (2009) [2], i.e. Exercise 6, V^∞ also closed, since G is connected, $V^\infty = G$. (a topological space X is **connected** iff the only open and closed (clopen) sets are \emptyset and X).

Definition 19. *Identity component of G, G_0 .*

$G_0 :=$ connected component of Lie group G that contains identity;

G_0 is a Lie group, and is generated by any open neighborhood of the identity.

Definition 20. *For Lie group G , fixed element $g \in G$,*

left translation (by g) $L_g : G \rightarrow G$, $L_g x = gx$, $\forall x \in G$

right translation (by g) $R_g : G \rightarrow G$, $R_g x = xg$, $\forall x \in G$

$$L_g, R_g \text{ are diffeomorphisms with } L_g^{-1} = L_{g^{-1}}, R_g^{-1} = R_{g^{-1}}.$$

⁴<https://faculty.math.illinois.edu/~lerman/519/s12/427notes.pdf>

Definition 21 (Product Lie group). *If G, H are Lie groups, then product manifold $G \times H$ is a Lie group, where multiplication*

$$(g_1, h_1) \cdot (g_2, h_2) = (g_1 g_2, h_1 h_2)$$

*Lie group $G \times H$ is called **product Lie group***

e.g. product group $S^1 \times S^1 \equiv$ 2-torus group.

Generally, higher torus groups $T^n = S^1 \times \dots \times S^1$ (n factors).

Definition 22 (Lie subgroup of G, H). *Let H be an abstract subgroup of Lie group G .*

If H is a Lie group s.t. inclusion map $i : H \rightarrow G \equiv H \hookrightarrow G$ is an immersion, then H is a

Lie subgroup of G .

Recall $i : H \rightarrow G$ immersion iff Di injective, i.e. iff $\text{rank } Di = \dim H$

cf. Prop. 5.9 in Jeffrey Lee (2009) [2].

Proposition 11. *If H abstract subgroup of Lie group G , that's also a regular submanifold \equiv embedded submanifold, then H closed Lie subgroup.*

Recall that

embedded submanifold \equiv regular submanifold

Each name is used frequently and we shouldn't be biased against one or the other; we'll have to refer to both, to emphasize they're *exactly the same*.

embedded submanifold \equiv regular submanifold is an immersed submanifold s.t. inclusion map i is a topological embedding,

i.e. embedded submanifold \equiv regular submanifold $S \subset M$,

immersed submanifold S if $i : S \rightarrow M \equiv S \hookrightarrow M$ is an immersion, i.e. Di injective, i.e. $\text{rank } Di \equiv \dim S$.

topological embedding $:=$ homeomorphism onto its image, i.e.

injective cont. map $f : X \rightarrow Y$, X, Y topological spaces, is a **topological embedding**

if f is a homeomorphism between X and $f(X)$.

f homeomorphism is a bijection, continuous, and f^{-1} continuous.

e.g. \forall embedding $f : M \rightarrow N$, $f(M) \subset N$ naturally has the structure of an embedding submanifold \equiv regular submanifold.

Useful, intrinsic definition of **embedded submanifold** \equiv regular submanifold.

Let manifold M , $\dim M = n$, let $k \in \mathbb{Z}^+$, s.t. $0 \leq k \leq n$.

A k -dim. embedded submanifold \equiv regular submanifold S is subset $S \subset M$ s.t. $\forall p \in S$, \exists chart $(U \subset M, \varphi : U \rightarrow \mathbb{R}^n \ni 0)$, s.t. $\varphi(S \cap U)$ is the intersection of a k -dim. plane with $\varphi(U)$.

(pairs $(S \cap U, \varphi|_{S \cap U})$ form an atlas for differential structure on S).

Proof 1:

cf. 9.2 The Closed Subgroup Theorem I of 427 Notes⁴

Proof. Claim: If H abstract subgroup of Lie group G , that's also an embedded submanifold \equiv regular submanifold, then H is a Lie subgroup.

Recall that by definition, Lie group has group multiplication and inverse map to be C^∞ . Then, just show group multiplication is C^∞ , first.

Since G is a Lie group, then

$$\mu : G \times G \rightarrow G$$

$$\mu(x, y) = xy$$

is C^∞ (by definition).

Then $\mu : G \times G \rightarrow G$ cont.

Consider subgroup $H \subseteq G$ and $\mu : H \times H \rightarrow H$.

Since $H \times H \subseteq G \times G$, $\forall (x, y) \in H \times H$ (fix $(x, y) \in H \times H$), \forall neighborhood V of $\mu(x, y) = xy$, $V \subset G$, \exists neighborhood U of (x, y) s.t. $\mu(U) \subseteq V$ (by $\mu : G \times G \rightarrow G$ cont.).

Since H embedded submanifold \equiv regular submanifold of G ,
 \exists neighborhood $V' \subseteq V$ of $xy \in G$, coordinate map $\varphi : V' \rightarrow \mathbb{R}^n$ ($n = \dim G$) s.t.

$$\varphi(H \cap V') = \varphi(V') \cap (\mathbb{R}^k \times \{0\})$$

where $k = \dim H$
(since H is a k -dim. embedded submanifold \equiv regular submanifold, $H \subseteq G$, s.t. $\forall p \in H$, \exists chart $(V \subset G, \varphi : U \rightarrow \mathbb{R}^n \ni 0)$,
s.t. $\varphi(U \cap V) = \varphi(V) \cap (\mathbb{R}^k \times \{0\})$).
Now

$$\varphi \circ \mu : \mu^{-1}(V') \cap U \rightarrow \mathbb{R}^n \text{ is } C^\infty, \text{ and } \varphi \circ \mu(\mu^{-1}(V') \cap U) \subseteq \mathbb{R}^k \times \{0\}$$

Let projection $\pi : \mathbb{R}^n \rightarrow \mathbb{R}^k$ be the standard projection,

$$\pi \circ \varphi \circ \mu : \mu^{-1}(V') \cap U \rightarrow \mathbb{R}^k \text{ is } C^\infty$$

$\implies \mu$ is C^∞

From Chapter 4 “Lie Groups and Lie Algebras” of Kosmann-Schwarzbach (2010) [11]
While Proposition 2.6 of Kosmann-Schwarzbach (2010) [11] states that

$$\det(\exp(X)) = \exp(\operatorname{tr} X)$$

here are some other resources online that gave further discussion on the characteristic polynomial, $\det(A - \lambda 1)$ and the different terms of it, called Newton identities:

- http://scipp.ucsc.edu/~haber/ph116A/charpoly_11.pdf
- <http://math.stackexchange.com/questions/1126114/how-to-find-this-lie-algebra-proof-that-mathfraksl-is-trace-zero-matrice>
- <http://mathoverflow.net/questions/131746/derivative-of-a-determinant-of-a-matrix-field>

Theorem 13 (5.1 [11]). *Consider $\mathfrak{g} = \{X = \gamma'(0) | \gamma : 1 \rightarrow G \text{ of class } C^1, \gamma(0) = 1\}$*

Let Lie group G

- (i) \mathfrak{g} vector subspace of $\mathfrak{gl}(n, \mathbb{R})$
- (ii) $X \in \mathfrak{g}$ iff $\forall t \in \mathbb{R}, \exp(tX) \in G$
- (iii) if $X \in \mathfrak{g}$, if $g \in G$, then $gXg^{-1} \in \mathfrak{g}$
- (iv) \mathfrak{g} closed under matrix commutator, i.e. if $X, Y \in \mathfrak{g}$, $[X, Y] \in \mathfrak{g}$

Proof. (i)
(ii) If $\exp(tX) \in G$, then $X \frac{d}{dt} \exp(tX) \Big|_{t=0} \in \mathfrak{g}$ (by def.)
If $X \in \mathfrak{g}$, then by def., $X = \frac{d}{dt} \gamma(t) \Big|_{t=0}$ with $\gamma(t) \in G$.
Now Taylor expand; $\forall k \in \mathbb{Z}^+$

$$\begin{aligned} \gamma\left(\frac{t}{k}\right) &= 1 + \frac{t}{k}X + O\left(\frac{1}{k^2}\right) = \exp\left(\frac{t}{k}X + O\left(\frac{1}{k^2}\right)\right) \\ &\implies \left(\gamma\left(\frac{t}{k}\right)\right)^k = \exp(tX) \\ \gamma\left(\frac{t}{k}\right) &\in G \quad \forall k \in \mathbb{Z}^+ \end{aligned}$$

G closed subgroup, so $\lim_{k \rightarrow \infty} (\gamma(\frac{t}{k}))^k = \exp(tX) \in G$

- (iii)
- (iv)

Definition 23 (Lie algebra). *Lie algebra \mathfrak{g} , tangent space to G at 1, i.e. $\mathfrak{g} := T_1G$ is called Lie algebra of Lie group G .*

$$\mathfrak{g} := \{X = \gamma'(0) | \gamma : 1 \rightarrow G \text{ of class } C^1, \gamma(0) = 1\} = T_1G$$

This is based on Proposition 5.3 of Kosmann-Schwarzbach (2010) [11].
For Lie group

$$U(n) = \{U \in GL(n, \mathbb{C}) | UU^\dagger = 1\}$$

If $X \in \mathfrak{u}(n)$, then $\exp(tX) \in U(n)$. Then

$$\exp(tX) \exp(tX)^\dagger = (1 + tX + O(t^2))(1 + tX^\dagger + O(t^2)) = 1 + t(X + X^\dagger) + O(t^2) = 1 \forall t \in \mathbb{R} \implies X + X^\dagger = 0$$

i.e. $X \in \mathfrak{u}(n)$ is an anti-Hermitian complex $n \times n$ matrix.
 $\mathfrak{u}(n) = \{X \in \mathfrak{gl}(n, \mathbb{C}) | X + X^\dagger = 0\}$
Physicists: $X = iA$ and so $A - A^\dagger$. $A \in \mathfrak{u}(n)$ is a Hermitian complex $n \times n$ matrix.
 $\mathfrak{u}(n) = \{A \in \mathfrak{gl}(n, \mathbb{C}) | A - A^\dagger = 0\}$
Regardless, $\dim_{\mathbb{R}} \mathfrak{u}(n) = n^2 = 2n^2 - n^2$
 \square For Lie group

$$SU(n) = \{U \in GL(n, \mathbb{C}) | UU^\dagger = 1, \det U = 1\}$$

Then

$$\mathfrak{su}(n) = \{X \in \mathfrak{gl}(n, \mathbb{C}) | X + X^\dagger = 1, \operatorname{tr} X = 0\}$$

is the Lie algebra of traceless anti-Hermitian complex $n \times n$ matrices, and that

$$\dim_{\mathbb{R}} \mathfrak{su}(n) = n^2 - 1$$

In summary,

$$\begin{array}{ccc} \mathfrak{u}(n) = \{X \in \mathfrak{gl}(n, \mathbb{C}) | X + X^\dagger = 0\} & & \mathfrak{su}(n) = \{X \in \mathfrak{gl}(n, \mathbb{C}) | X + X^\dagger = 0, \operatorname{tr} X = 0\} \\ \exp(tX) \downarrow & & \exp(tX) \downarrow \\ U(n) = \{U \in GL(n, \mathbb{C}) | UU^\dagger = 1\} & & SU(n) = \{U \in GL(n, \mathbb{C}) | UU^\dagger = 1, \det U = 1\} \\ \dim_{\mathbb{R}} \mathfrak{u}(n) = n^2 & & \dim_{\mathbb{R}} \mathfrak{su}(n) = n^2 - 1 \end{array}$$

From Chapter 5 “Lie Groups $SU(2)$ and $SO(3)$ ” of Kosmann-Schwarzbach (2010) [11],

6.0.1. *Bases of $\mathfrak{su}(2)$, Subsection 1.1 of Chapter 5 of Kosmann-Schwarzbach (2010) [11].* Recall that

$$\begin{array}{ccc} \mathfrak{su}(n) = \{X \in \mathfrak{gl}(n, \mathbb{C}) | X + X^\dagger = 0, \operatorname{tr} X = 0\} & & \\ \exp(tX) \downarrow & & \\ SU(n) = \{U \in GL(n, \mathbb{C}) | UU^\dagger = 1, \det U = 1\} & & \end{array}$$

\square

$$\dim_{\mathbb{R}} \mathfrak{su}(n) = n^2 - 1$$

and so

$$\begin{array}{c} \mathfrak{su}(2) = \{X \in \mathfrak{gl}(2, \mathbb{C}) | X + X^\dagger = 0, \text{tr} X = 0\} \\ \exp(tX) \downarrow \\ SU(2) = \{U \in GL(n, \mathbb{C}) | UU^\dagger = 1, \det U = 1\} \end{array}$$

$$\dim_{\mathbb{R}} \mathfrak{su}(2) = 3$$

Also, recall that $\mathfrak{g} \subseteq \mathfrak{gl}(n, \mathbb{C})$ is a vector subspace (13) and that $X \in \mathfrak{g}$ iff $\forall t \in \mathbb{R}, \exp(tX) \in G$.
if $X \in \mathfrak{g}$, if $g \in G$, then $gXg^{-1} \in \mathfrak{g}$

\mathfrak{g} closed under $\mathfrak{g} \times \mathfrak{g} \rightarrow \mathfrak{g}$

$$(X, Y) \mapsto [X, Y]$$

and so with \mathfrak{g} as a vector space, we can have a choice of bases.

$$\begin{array}{l} \xi_1 = \frac{i}{2} \begin{pmatrix} & 1 \\ 1 & \end{pmatrix} \\ \text{(a) } \xi_2 = \frac{1}{2} \begin{pmatrix} & -1 \\ 1 & \end{pmatrix} \\ \xi_3 = \frac{i}{2} \begin{pmatrix} 1 & \\ & -1 \end{pmatrix} \\ \text{satisfying} \end{array}$$

$$[\xi_k, \xi_l] = \epsilon_{klm} \xi_m$$

(b) *Physics*

$$\begin{array}{l} \sigma_1 = -2i\xi_1 = \begin{pmatrix} & 1 \\ 1 & \end{pmatrix} \\ \sigma_2 = 2i\xi_2 = \begin{pmatrix} & -i \\ i & \end{pmatrix} \\ \sigma_3 = -2i\xi_3 = \begin{pmatrix} 1 & \\ & -1 \end{pmatrix} \end{array}$$

satisfying

$$[\sigma_k, \sigma_l] = 2i\epsilon_{klm} \sigma_m$$

EY : 20151001 Sage Math 6.8 doesn’t run on Mac OSX El Capitan: I suspect that it’s because in Mac OSX El Capitan, /usr cannot be modified anymore, even in an Administrator account. The TUG group for MacTeX had a clear, thorough, and useful (i.e. copy UNIX commands, paste, and run examples) explanation of what was going on:

<http://tug.org/mactex/elcapitan.html>

So keep in mind that my code for Sage Math is for Sage Math 6.8 that doesn’t run on Mac OSX El Capitan. I’ll also use sympy in Python as an alternative and in parallel.

One can check in sympy the traceless anti-Hermitian (or Hermitian) property of the bases and Pauli matrices, and the commutation relations (see groups.py):

```
import itertools
from itertools import product, permutations
```

```
import sympy
from sympy import I, LeviCivita
from sympy import Rational as Rat

from sympy.physics.matrices import msigma # <class 'sympy.matrices.dense.MutableDenseMatrix'>

def commute(A,B):
    """
    commute = commute(A,B)
    commute takes the commutator of A and B
    """
    return (A*B - B*A)

def xi(i):
    """
    xi = xi(i)
    xi is a function that returns the independent basis for
    Lie algebra su(2)\equiv su(2.\mathbb{C}) of Lie group SU(2) of
    traceless anti-Hermitian matrices, based on msigma of sympy
    cf. http://docs.sympy.org/dev/_modules/sympy/physics/matrices.html#msigma
    """
    if i not in [1,2,3]:
        raise IndexError("Invalid_Pauli_index")
    elif i==1:
        return I/Rat(2)*msigma(1)
    elif i==2:
        return -I/Rat(2)*msigma(2)
    elif i==3:
        return I/Rat(2)*msigma(3)

## check anti-Hermitian property and commutation relations with xi
# xi is indeed anti-Hermitian
xi(1) == -xi(1).adjoint() # True
xi(2) == -xi(2).adjoint() # True
xi(3) == -xi(3).adjoint() # True

# xi obeys the commutation relations

for i,j in product([1,2,3],repeat=2): print i,j

for i,j in product([1,2,3],repeat=2): print i,j, "\tCommutator:", commute(xi(i),xi(j))

## check traceless Hermitian property and commutation relations with Pauli matrices
# Pauli matrices i.e. msigam is indeed traceless Hermitian

msigma(1) == msigma(1).adjoint() # True
msigma(2) == msigma(2).adjoint() # True
msigma(3) == msigma(3).adjoint() # True

msigma(1).trace() == 0 # True
msigma(2).trace() == 0 # True
msigma(3).trace() == 0 # True

# Pauli matrices obey commutation relation
print "For_Pauli_matrices, the_commutation_relations_are:\n"
for i,j in product([1,2,3],repeat=2): print i,j, "\tCommutator:", commute(msigma(i),msigma(j))

for i,j,k in permutations([1,2,3],3): print "Commute:", i,j,k, msigma(i), msigma(j), \
":_and_is_2*i_of_", msigma(k), commute(msigma(i),msigma(j)) == 2*I*msigma(k)*LeviCivita(i,j,k)
```

And finally the traceless property of the Pauli matrices:

```
>>> msigma(1).trace()
0
>>> msigma(2).trace()
```

```
0
>>> msigma(3).trace()
0
```

6.1. **Spin.** Let’s follow the development by Baez and Muniain (1994) on pp. 175 of the Section II.1 “Lie Groups”, the second (II) chapter on “Symmetry” [8].

Let $V = \mathbb{C}^2$, $G = SU(2)$. Then consider the graded algebra of polynomials on $V = \mathbb{C}^2 \ni (x, y)$

$$P(V) = \bigoplus_{k=0}^{\infty} P^{(k)}(V) = \bigoplus_{\substack{j=0 \\ 2j \in \mathbb{Z}}}^{\infty} P^{(2j)}(V) = \bigoplus_{\substack{j=0 \\ j \in \mathbb{Z}}}^{\infty} P^{(2j)}(V) \oplus \bigoplus_{\substack{j=1/2 \\ 2j \text{ odd}}}^{\infty} P^{(2j)}(V)$$
$$P^{(2j)}(V) \equiv \text{vector space of complex polynomials of degree } 2j$$

and recall this representation on $P^{(2j)}(V)$

$$\begin{aligned} \rho^{(2j)} : G &\rightarrow \text{End}(P^{(2j)}(V)) \\ \rho^{(2j)} : P^{(2j)}(V) &\rightarrow P^{(2j)}(V) \\ \rho^{(2j)}(g)(f) &= f \circ \rho(g^{-1}) \text{ where } \rho \text{ is the fundamental representation of } G = SU(2) \\ \rho^{(2j)}(g)(f)(v) &= f \circ \rho(g^{-1})(v) \quad \forall f \in P^{(2j)}(V), \forall v \in V = \mathbb{C}^2 \end{aligned}$$

Note,
 $\dim P^{(2j)} = \binom{2j+2-1}{2-1} = 2j + 1$

Exercise 21. [8] *spin-0* Consider the trivial representation τ :

$$\begin{array}{ccc} \mathbb{C} & \xrightarrow{T} & P^{(0)}(V) \\ \tau(g) \downarrow & & \downarrow \rho^{(0)}(g) \\ \mathbb{C} & \xrightarrow{T} & P^{(0)}(V) \end{array}$$
$$\begin{aligned} \tau : G &\rightarrow \text{End}(\mathbb{C}) \\ \tau(g) : \mathbb{C} &\rightarrow \mathbb{C} \\ \tau(g) &= 1_{\mathbb{C}} \end{aligned}$$

Clearly, $P^{(0)}(V) = \mathbb{C}$, since $P^{(0)}(V)$ consists of polynomials of constants in \mathbb{C} .
Consider $c_0 \in \mathbb{C}$, $f = k_0 \in P^{(0)}(V)$
 $\rho^{(0)}(g)(f) = f \circ \rho(g^{-1}) = k_0$
 $\implies \rho^0(g)T(c_0) = T \circ \tau(g)c_0 = T(c_0)$. Let $T = 1_{\mathbb{C}} = 1_{P^0(V)}$
So $\rho^{(0)}(g) = \tau(g) = 1$. $T = 1$. So representations $\rho^{(0)}$ and trivial representation τ on G are equivalent.

Exercise 22. [8] *spin- $\frac{1}{2}$* For spin- $\frac{1}{2}$, $j = \frac{1}{2}$, $2j = 1$.

$\forall f \in P^{(1)}(V)$, $V = \mathbb{C}^2$. So in general form, $f(x, y) = ax + by \in P^{(1)}(V)$, $\begin{pmatrix} x \\ y \end{pmatrix} \in V = \mathbb{C}^2$

$$\begin{aligned} \text{Recall the fundamental representation} \quad \rho : G &\rightarrow GL(2, \mathbb{C}) \equiv GL(\mathbb{C}^2) \\ \rho(g) : \mathbb{C}^2 &\rightarrow \mathbb{C}^2 \\ \rho(g) &= g \end{aligned}$$

So consider T such that

$$\begin{array}{ccc} \mathbb{C}^2 & \xrightarrow{T} & P^{(1)}(V) \\ \rho(g) \downarrow & & \downarrow \rho^{(1)}(g) \\ \mathbb{C}^2 & \xrightarrow{T} & P^{(1)}(V) \end{array}$$

Consider $\forall v \in \mathbb{C}^2$, $v = \begin{pmatrix} x \\ y \end{pmatrix}$, then

$$\rho(g)v = gv = \begin{bmatrix} ax + by \\ cx + dy \end{bmatrix}$$

```
sage: g*X
[a*x + b*y]
[c*x + d*y]
```

For notation, let $U \in G = SU(2)$ s.t. $UU^\dagger = 1$.
Consider $(\rho^{(2j)}(U)(f))(x) = f(U^{-1}x)$, $\forall x \in \mathbb{C}^2$.

Choose $f(x, y) = x$. So for $f(x, y) = Ax + By$, $A = 1, B = 0$. Choose $U = \begin{pmatrix} a & b \\ -\bar{b} & \bar{a} \end{pmatrix}$ so $U^{-1} = \begin{pmatrix} \bar{a} & -b \\ \bar{b} & a \end{pmatrix}$. Then

$$U^{-1}x = \begin{pmatrix} \bar{a}x - by \\ \bar{b}x + ay \end{pmatrix}$$

So

$$\begin{aligned} (\rho^{(1)}(U)(f))(x) &= f(U^{-1}x) = \bar{a}x - by \\ (\rho^{(1)}(U)(f))(x) &= f(U^{-1}x) = \bar{b}x + ay \text{ for } f(x, y) = y \end{aligned}$$

Let $f(x, y) = Ax + By$

$$(\rho^{(1)}(U)(f))(x) = f(U^{-1}x) = (A\bar{a} + B\bar{b})x + (Ba - Ab)y = (\bar{a}x - by)A + (\bar{b}x + ay)B = (A\bar{a} + B\bar{b})x + (Ba - Ab)y$$

which was calculated with the assistance of Sage Math:

```
sage: U_try1 = Matrix( [[a.conjugate(), -b],[b.conjugate(), a] ] )
sage: f1( U_try1*X).coefficient(x)
A*conjugate(a) + B*conjugate(b)
sage: f1( U_try1*X).coefficient(y)
B*a - A*b
```

Treating $P^{(1)}(\mathbb{C}^2)$ as a vector space, in its matrix formulation, then $f(x, y) = Ax + By \in P^{(1)}(\mathbb{C}^2)$ is treated as $\begin{bmatrix} A \\ B \end{bmatrix}$, then $(\rho^{(1)}(U)f)$ is

$$\implies \begin{bmatrix} \bar{a} & \bar{b} \\ -b & a \end{bmatrix} \begin{bmatrix} A \\ B \end{bmatrix} = \begin{bmatrix} A\bar{a} + B\bar{b} \\ -Ab + Ba \end{bmatrix}$$

so conclude in general that $\rho^{(1)}(U) = (U^\dagger)^T$.

Now, as Kosmann-Schwarzbach (2010) [11] says, on pp. 13, Chapter 2 Representations of Finite Groups, “Two representations (E_1, ρ_1) and (E_2, ρ_2) are equivalent if and only if there is a basis B_1 of E_1 and a basis B_2 of E_2 such that for every $g \in G$, the matrix of $\rho_1(g)$ in the basis B_1 is equal to the matrix of $\rho_2(g)$ in the basis B_2 . In particular, if the representations (E_1, ρ_1) and (E_2, ρ_2) are equivalent, then E_1 is isomorphic to E_2 .” So we need a change of basis between $\rho(U) = U$ and $\rho^{(1)}(U)$. What’s the linear transformation T s.t.

$$T^{-1}\rho^{(1)}(U)T = U?$$

By intuition,

$$T = \sigma_x \sigma_z \equiv \sigma_1 \sigma_3$$

where σ_i ’s are Pauli matrices.
Indeed,


```
sage: Paulimat [3] * Paulimat [1]*U_try*Paulimat [1] * Paulimat [3]
[conjugate(a) conjugate(b)]
[ -b a]
```

Then $\rho^{(1)}(U) \circ T = TU$, so this $T = \sigma_1 \sigma_3$ is an “intertwining operator” between $\rho^{(1)}(U)$ and fundamental representation $\rho(U) = U$, with $T = \begin{bmatrix} & -1 \\ 1 & \end{bmatrix}$, and $T^{-1} = \begin{bmatrix} & 1 \\ -1 & \end{bmatrix}$.

T is an isomorphism between \mathbb{C}^2 and $P^{(1)}(\mathbb{C}^2)$. So fundamental representation ρ of $G = SU(2)$ is equivalent to $\rho^{(1)}(U)$ on $P^{(1)}(\mathbb{C}^2)$.

Exercise 23. [8] (Also from Exercise 2.6 of Kosmann-Schwarzbach (201) [11])

Let (E, π) representation of group G .

$\forall g \in G, \xi \in E^*, x \in E$, set $\langle \pi^*(g)(\xi), x \rangle = \langle \xi, \pi(g^{-1})(x) \rangle$

dual (or *contragredient*) of π , $\pi^* : G \rightarrow \text{End}(E^*)$, π^* is a representation, since

$$\begin{aligned} \langle \pi^*(gh)(\xi), x \rangle &= \langle \xi, \pi((gh)^{-1})(x) \rangle = \langle \xi, \pi(h^{-1}g^{-1})(x) \rangle = \langle \xi, \pi(h^{-1})\pi(g^{-1})(x) \rangle = \langle \xi, \pi(h^{-1})(\pi(g^{-1})(x)) \rangle = \\ &= \langle \pi^*(h)(\xi), \pi(g^{-1})(x) \rangle = \langle \pi^*(g)\pi^*(h)(\xi), x \rangle \end{aligned}$$

since this is true, $\forall x \in E, \forall \xi \in E^*, \pi^*(gh) = \pi^*(g)\pi^*(h)$.

dual π^* of π is a representation.

6.2. Adjoint Representation. I will first follow Sec. 7.3 The Adjoint Representation of Ch. 4 Lie Groups and Lie Algebras of Kosmann-Schwarzbach (201) [11]).

The *conjugation action* $\mathcal{C}_g : G \rightarrow G$ is defined as

$$\mathcal{C}_g : G \rightarrow G$$

$$\mathcal{C}_g : h \mapsto ghg^{-1}$$

So

$$\mathcal{C} : G \rightarrow \text{Aut}(G)$$

$$\mathcal{C}g = \mathcal{C}_g$$

Now define the *adjoint action* of g as the differential or push forward of \mathcal{C}_g :

$$\text{Ad}_g := D_1\mathcal{C}_g \equiv (\mathcal{C}_g)_{*1} \equiv (\mathcal{C}_g)_*|_{g=1} \quad (\text{adjoint action of } g)$$

Now $\text{Ad}_g : \mathfrak{g} \rightarrow \mathfrak{g}$, so $\text{Ad} : G \rightarrow \text{End}(\mathfrak{g})$

$$\text{Ad}(g) \equiv \text{Ad}_g$$

Note $\mathcal{C}_{gg'} = \mathcal{C}_g\mathcal{C}_{g'} \equiv \mathcal{C}(gg') = \mathcal{C}(g) \circ \mathcal{C}(g')$ and so

$$\xrightarrow{D_1} \text{Ad}_{gg'} = \text{Ad}_g \circ \text{Ad}_{g'}$$

Kosmann-Schwarzbach (201) [11]) claims, because $\text{Ad}_g = 1_{\mathfrak{g}}$ when $g = 1$,

$\text{Ad} : G \rightarrow GL(\mathfrak{g})$ is a representation of G on \mathfrak{g} . (EY : 20160505 ???)

$\text{Ad} : g \mapsto \text{Ad}_g$

Definition 24. *representation* Ad of G on $V = \mathfrak{g}$ is called *adjoint representation of Lie group* G .

Denote adjoint representation of Lie algebra \mathfrak{g} , ad .

By definition, $\text{Ad}_{\exp(tX)} = \exp(\text{tad}_X)$

cf. Prop. 7.8 of Kosmann-Schwarzbach (201) [11])

Proposition 12. (1) *Let A invertible matrix, $A \in \text{Lie group } G$.*

Let X matrix s.t. $X \in \mathfrak{g}$. Then

$$\text{Ad}_A(X) = AXA^{-1}$$

(2) *Let $X, Y \in \mathfrak{g}$. Then*

$$\text{ad}_X(Y) = [X, Y]$$

(3) *Let $X, Y \in \mathfrak{g}$. Then*

$$\text{ad}_{[X, Y]} = [\text{ad}_X, \text{ad}_Y]$$

Proof. (1) By def., $\forall B \in G, \mathcal{C}_A(B) = ABA^{-1}$, and thus

$$\text{Ad}_A(X) = \left. \frac{d}{dt} A \exp(tX) A^{-1} \right|_{t=0} = AXA^{-1}$$

(2)

$$\begin{aligned} \text{ad}_X(Y) &= \left. \frac{d}{dt} \text{Ad}_{\exp(tX)}(Y) \right|_{t=0} = \left. \frac{d}{dt} \exp(tX) Y \exp(tX) \right|_{t=0} = \\ &= XY - YX = [X, Y] \end{aligned}$$

(3) Use Jacobi identity:

$$[A, [B, C]] + [B, [C, A]] + [C, [A, B]] = 0 \text{ or}$$

$$[[A, B], C] = [A, [B, C]] - [B, [A, C]]$$

$\text{ad}_{[X, Y]}C = [[X, Y], C] = [X, [Y, C]] - [Y, [X, C]] = [X, \text{ad}_Y C] - [Y, \text{ad}_X C]$ and that

$$\text{ad}_X \text{ad}_Y C = [X, [Y, C]] \implies \text{ad}_{[X, Y]}C = [\text{ad}_X, \text{ad}_Y]C$$

□

Part 5. Cohomology; Stoke’s Theorem

7. STOKE’S THEOREM

Theorem 14 (Stoke’s Theorem). *Let M be oriented, smooth n -manifold with boundary, let ω be a compactly supported smooth $(n-1)$ -form on M , or if $\omega \in A_c^{n-1}(M)$, Then*

$$(19) \quad \int_M d\omega = \int_{\partial M} \omega$$

If $\partial M = \emptyset$, then $\int_{\partial M} \omega = 0$

$\int_{\partial M} \omega$ interpreted as $\int_{\partial M} i_{\partial M}^ \omega = \int_{\partial M} i^* \omega$ so*

$$(20) \quad \int_M d\omega = \int_{\partial M} i^*(\omega)$$

where inclusion $i : \partial M \hookrightarrow M$

Proof. Begin with very special case:

Suppose $M = \mathbb{H}^n$ (upper half space), $\partial M = \mathbb{R}^{n-1}$

ω has compact support, so $\exists R > 0$ s.t. $\text{supp } \omega \subseteq \text{rectangle } A = [-R, R] \times \cdots \times [-R, R] \times [0, R]$.

$$\forall \omega \in A_c^{n-1}(\mathbb{H}^n)$$

$$(21) \quad \omega = \sum_{j=1}^n (-1)^{j-1} f_j dx^1 \wedge \cdots \wedge \widehat{dx^j} \wedge \cdots \wedge dx^n \equiv \sum_{i=1}^n \omega_i dx^1 \wedge \cdots \wedge \widehat{dx^i} \wedge \cdots \wedge dx^n$$

with Conlon (2008) [16] and John Lee (2012) [3]’s notation, respectively, and where f_j has compact support.

$$i^* \omega = (f_1 \circ i) dx^2 \wedge \cdots \wedge dx^n \in A_c^{n-1}(\partial \mathbb{H}^n)$$

$$\begin{aligned} d\omega &= \sum_{i=1}^n d\omega_i \wedge dx^1 \wedge \cdots \wedge \widehat{dx}^i \wedge \cdots \wedge dx^n = \sum_{i,j=1}^n \frac{\partial \omega_i}{\partial x^j} dx^j \wedge dx^1 \wedge \cdots \wedge \widehat{dx}^i \wedge \cdots \wedge dx^n = \\ &= \sum_{i=1}^n (-1)^{i-1} \frac{\partial \omega_i}{\partial x^i} dx^1 \wedge \cdots \wedge dx^n \end{aligned}$$

i.e. (for another notation)

$$\begin{aligned} d\omega &= \left(\sum_{j=1}^n \frac{\partial f_j}{\partial x^j} \right) dx^1 \wedge \cdots \wedge dx^n \in A_c^n(\mathbb{H}^n) \\ d\omega &= \left(\sum_{j=1}^n \frac{\partial f_j}{\partial x^j} \right) dx^1 \wedge \cdots \wedge dx^n \in A_c^n(\mathbb{H}^n) \end{aligned}$$

$$\int_{\mathbb{H}^n} d\omega = \sum_{i=1}^n (-1)^{i-1} \int_A \frac{\partial \omega_i}{\partial x^i} dx^1 \wedge \cdots \wedge dx^n = \sum_{i=1}^n (-1)^{i-1} \int_0^R \int_{-R}^R \cdots \int_{-R}^R dx^1 \cdots dx^n \frac{\partial \omega_i}{\partial x^i}(x)$$

We can change order of integration in each term so to do x^i integration first.

By fundamental thm. of calculus, terms for which $i \neq n$ reduce to

$$\begin{aligned} \sum_{i=1}^{n-1} (-1)^{i-1} \int_0^R \int_{-R}^R \cdots \int_{-R}^R \frac{\partial \omega_i}{\partial x^i}(x) dx^1 \cdots dx^n &= \sum_{i=1}^{n-1} (-1)^{i-1} \int_0^R \int_{-R}^R \cdots \int_{-R}^R \frac{\partial \omega_i}{\partial x^i}(x) dx^i dx^1 \cdots \widehat{dx}^i \cdots dx^n = \\ &= \sum_{i=1}^{n-1} (-1)^{i-1} \int_0^R \int_{-R}^R \cdots \int_{-R}^R [\omega_i(x)]_{x^i=-R}^{x^i=R} dx^1 \cdots \widehat{dx}^i \cdots dx^n = 0 \end{aligned}$$

because we've chosen R large enough that $\omega = 0$ when $x^i = \pm R$.

Part 6. Prástaro

Prástaro (1996) [12]

7.0.1. *Affine Spaces.* cf. Sec. 1.2 - *Affine Spaces* of Prástaro (1996) [12]

Definition 25 (affine space).

$$\begin{aligned} &\text{affine space} \quad (M, \mathbf{M}, \alpha) \\ &\quad \text{with} \\ (22) \quad &M \equiv \text{set (set of pts.)} \\ &\mathbf{M} \equiv \text{vector space (space of free vectors)} \\ &\alpha \equiv \mathbf{M} \times M \rightarrow M \equiv \text{translation operator} \\ &\alpha : (v, p) \mapsto p' \equiv p + v \end{aligned}$$

Note: α is a **transitive** action and without fixed pts. (free).

i.e. $\forall p \in M$,

$$\begin{aligned} &\forall \text{ pt. } O \in M, \alpha : (v, O) \mapsto O' \equiv O + v, \alpha(\cdot, O) \equiv \alpha_O \equiv \alpha(O). \quad \alpha_O(v) = O' = O + \mathbf{v} \quad \forall O' \in M, \exists \mathbf{v} \in \mathbf{M} \text{ s.t. } O' = O + \mathbf{v} \\ &\implies M \equiv \mathbf{M}. \\ &\forall (O, \{e_i\})_{1 \leq i \leq n}, \text{ where } \{e_i\} \text{ basis of } \mathbf{M}, M \equiv \mathbf{M} = \mathbb{R}^n \text{ so isomorphism } M \simeq \mathbb{R}^n \end{aligned}$$

i.e. α is **without fixed pts.**, meaning,

Given pointed space (M, O) , where base pt. $O \in M$, we can associate $\forall p \in M$, vector $\mathbf{x} \in \mathbf{M}$, by 1-to-1 mapping $M \rightarrow \mathbf{M}$.

So for

$$\alpha : \mathbf{M} \times M \rightarrow M$$

$$\alpha(\mathbf{x}, p) = p' = p + \mathbf{x}$$

Consider

$$\alpha(\mathbf{x}, O) = p = \alpha_O(\mathbf{x}) = p \implies \exists \alpha_O^{-1}(p) = \mathbf{x} \in \mathbf{M}$$

- (1) tangent space of M in $p \in M$ is vector space $T_p M \equiv (\mathbf{M}, p) \cong M$
- (2) If \mathbf{M} Euclidean space, affine space (M, \mathbf{M}, α) is Euclidean
- (3) Call dim. of affine space (M, \mathbf{M}, α) , dim. of $\mathbf{M} \equiv \dim \mathbf{M}$

$\{\mathbf{e}_i\}$ basis of \mathbf{M}

Definition 26. $(O, \{e_i\}) \equiv \text{affine frame.}$

\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 $p - O$

Proposition 13 (1.6, Prástaro (1996) [12]). $\forall O \in M$, we have canonical identification $M \equiv \mathbf{M}$, since

$$\begin{aligned} \alpha_O^{-1} : M &\rightarrow \mathbf{M} & \alpha_O : \mathbf{M} &\rightarrow M \\ \alpha_O^{-1}(p) &= \mathbf{x} & \alpha_O : \mathbf{x} &= \alpha(\mathbf{x}, O) = p \end{aligned}$$

Furthermore,

\forall **affine frame** $(O, \{\mathbf{e}_i\})_{1 \leq i \leq d}$, where $\{\mathbf{e}_i\}$ basis of \mathbf{M} ,

\exists isomorphism $M \cong \mathbb{R}^d$,

Then, $\forall (O, \{\mathbf{e}_i\})_{1 \leq i \leq d}$,

\exists coordinate system $x^\alpha : M \rightarrow \mathbb{R}$,

where $x^\alpha(p)$ is α th component, in basis $\{\mathbf{e}_i\}$, of vector $p - O$.

□

Theorem 15 (1.4 Prástaro (1996) [12]). Let $(x^\alpha), (\bar{a}^\alpha)$ 2 coordinate systems correspond to affine frames $(O, \{e_i\}), (\bar{O}, \{\bar{e}_i\})$, respectively.

$$(23) \quad \bar{x}^\alpha = A^\alpha_\beta x^\beta + y^\alpha$$

where

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

Definition 27 (1.10 Prástaro (1996) [12]).

$$(24) \quad A(n) \equiv Gl(n, \mathbb{R}) \times \mathbb{R}^n$$

affine group of dim. n

Theorem 16 (1.5). symmetry group of n -dim. affine space, called affine group $A(M)$ of M . \exists isomoprhism,

$$(25) \quad A(M) \simeq A(n), \quad f \mapsto (f^\alpha_\beta, y^\alpha); \quad f^\alpha \equiv x^\alpha \circ f = f^\alpha_\beta x^\beta + y^\alpha$$

cf. Eq. 1.4 Prástaro (1996) [12]

Definition 28 (metric). Let smooth manifold M , $\dim M = n$, $\forall p \in M$, \exists vector space $T_p M$, and so for

$$\begin{aligned} (26) \quad &g_p(T_p M)^2 \rightarrow \mathbb{R} \\ &g_p : (X_p, Y_p) \mapsto g_p(X_p, Y_p) \in \mathbb{R} \end{aligned}$$

with g_p being bilinear, symmetric (in X_p, Y_p), nondegenerate (i.e. if $g_p(X_p, Y_p) = 0$, then X_p or $Y_p = 0$)

Note that

$$g \in \Gamma((TM \otimes TM)^*)$$

and that for $X = X^i \frac{\partial}{\partial x^i}$ so

$$Y = Y^i \frac{\partial}{\partial x^i}$$

$$g(X, Y) = g_{ij} X^i Y^j$$

Now for

$$\begin{aligned} F : M &\rightarrow N & DF &\equiv F_* : T_p M \rightarrow T_{F(p)} N \\ F : x &\mapsto y = y(x) & DF : X_p &\mapsto (DF)(X^j \frac{\partial}{\partial x^j}) = X^j \frac{\partial y^i}{\partial x^j} \frac{\partial}{\partial y^i} \\ (F^* g')(X, Y) &= (F^* g')(X^i \frac{\partial}{\partial x^i}, Y^j \frac{\partial}{\partial x^j}) = (F^* g')_{ij} X^i Y^j = g'(F_* X, F_* Y) = \\ &= \end{aligned}$$

Part 7. Holonomy

Definition 29 (Conlon, 10.1.2). If $X, Y \in \mathfrak{X}(M)$, $M \subset \mathbb{R}^m$, **Levi-Civita connection** on $M \subset \mathbb{R}^m$

$$\begin{aligned} \nabla : \mathfrak{X}(M) : \mathfrak{X}(M) &\rightarrow \mathfrak{X}(M) \\ (27) \quad \nabla_X Y &:= p(D_X Y) \end{aligned}$$

with

$$\begin{aligned} D_X Y &:= \sum_{j=1}^m X(Y^j) \frac{\partial}{\partial x^j} = \sum_{i,j=1}^m X^i \frac{\partial Y^j}{\partial x^i} \frac{\partial}{\partial x^j} & \forall X &= \sum_{i=1}^m X^i \frac{\partial}{\partial x^i}, \\ & & \forall Y &= \sum_{i=1}^m Y^i \frac{\partial}{\partial x^i} \end{aligned}$$

$$\nabla_{fX} Y = f(D_{fX} Y) = p(f D_X Y) = f p D_X Y = f \nabla_X Y$$

$$\nabla_X fY = p(D_X fY) = p\left(\sum_{i,j=1}^m \left(X^i f \frac{\partial Y^j}{\partial x^i} + X^i Y^j \frac{\partial f}{\partial x^i}\right) \frac{\partial}{\partial x^j}\right) = f \nabla_X Y + p \sum_{j=1}^m X(f) Y^j \frac{\partial}{\partial x^j} = f \nabla_X Y + X(f) p(Y)$$

Definition 30 (Conlon, 10.1.4; Christoffel symbols).

$$\begin{aligned} \nabla_{\frac{\partial}{\partial x^i} \frac{\partial}{\partial x^j}} &= \Gamma_{ij}^k \frac{\partial}{\partial x^k} & (\text{Conlon's notation}) \\ \nabla_{\frac{\partial}{\partial x^j} \frac{\partial}{\partial x^i}} &= \Gamma_{ij}^k \frac{\partial}{\partial x^k} & (F. Schuller's notation) \end{aligned} \quad (28)$$

Definition 31 (torsion).

$$\begin{aligned} T : \mathfrak{X}(M) \times \mathfrak{X}(M) &\rightarrow \mathfrak{X}(M) \\ (29) \quad T(X, Y) &= \nabla_X Y - \nabla_Y X - [X, Y] \end{aligned}$$

If $T = 0$, ∇ torsion-free or symmetric.

$$\begin{aligned} T(fX, Y) &= f \nabla_X Y - (f \nabla_Y X + Y(f)X) - \{(fXY - (Y(f)X + fYX))\} = fT(X, Y) \\ T(X, fY) &= f \nabla_X Y + X(f)Y - f \nabla_Y X - \{((X(f)Y + fXY) - fYX)\} = fT(X, Y) \end{aligned}$$

Thus, $T(X, Y)$ $C^\infty(M)$ -bilinear.

$$T \in \tau_1^2(M).$$

$$T(v, w) \in T_x M \text{ defined, } \forall v, w \in T_x M, \forall x \in M.$$

Thus, torsion is a **tensor**.

Exercise 10.1.7 Conlon (2008)[16] . .

If $T(X, Y) = 0$,

$$T(e_i, e_j) = \Gamma_{ji}^k e_k - \Gamma_{ij}^k e_k - 0 = 0 \implies \Gamma_{ji}^k = \Gamma_{ij}^k$$

If $\Gamma_{ij}^k = \Gamma_{ji}^k$, $T(e_i, e_j) = 0$.

Exercise 10.1.8, Conlon (2008)[16].

If $M \subset \mathbb{R}^m$ smoothly embedded submanifold, $\forall \frac{\partial}{\partial x^j}, \frac{\partial}{\partial x^i} \in T_x M$, spanning $T_x M$, consider $\frac{\partial}{\partial x^j} = X_j^k \frac{\partial}{\partial \tilde{x}^k}$, $\frac{\partial}{\partial x^i} = X_i^k(\tilde{x}) \frac{\partial}{\partial \tilde{x}^k}$

$$\begin{aligned} \nabla_{\frac{\partial}{\partial x^j} \frac{\partial}{\partial x^i}} &= p D_{X_j^k \frac{\partial}{\partial \tilde{x}^k}} X_i^l \frac{\partial}{\partial \tilde{x}^l} = p \left(X_j^k \frac{\partial X_i^l}{\partial \tilde{x}^k} \frac{\partial}{\partial \tilde{x}^l} \right) = X_j^k p \left(\frac{\partial X_i^l}{\partial \tilde{x}^k} \frac{\partial}{\partial \tilde{x}^l} \right) \\ \nabla_{\frac{\partial}{\partial x^i} \frac{\partial}{\partial x^j}} &= X_i^k p \left(\frac{\partial X_j^l}{\partial \tilde{x}^k} \frac{\partial}{\partial \tilde{x}^l} \right) \end{aligned}$$

If $X \in \mathfrak{X}(M)$, smooth $s : [a, b] \rightarrow M$, then $\forall s(t)$,

$$X'_{s(t)} = \nabla_{\dot{s}(t)} X \in T_{s(t)} M$$

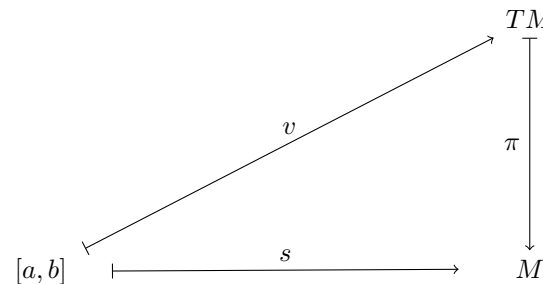
In fact, it's often natural to consider fields $X_{s(t)}$ along s , parametrized by parameter t , allowing

$$X_{s(t_1)} \neq X_{s(t_2)}$$

each of $s(t_1) = s(t_2)$.

Definition 32 (10.1.9). Let smooth $s : [a, b] \rightarrow M$.

Vector field along s is smooth $v : [a, b] \rightarrow TM$ s.t.



commutes.

Note that $v \in \mathfrak{X}(s) \subset \mathfrak{X}(M)$

e.g. $(Y|s)(t) = Y_{s(t)}$, restriction of $Y \in \mathfrak{X}(M)$ to s .

e.g. $\dot{s}(t) \in \mathfrak{X}(M)$.

$\forall v, w \in \mathfrak{X}(s)$, $v + w \in \mathfrak{X}(s)$,

$$(fv + gw)(t) := (f(s(t)) + g(s(t)))v(t) = f(s(t))v(t) + g(s(t))v(t) = (f + g)v(t)$$

Likewise,

$$f(v + w) = fv + fw$$

$\mathfrak{X}(s)$ is a real vector space and $C^\infty[a, b]$ -module.

Definition 33 (10.1.10). Let conection ∇ on M .

Associated covariant derivative is operator

$$\frac{\nabla}{dt} \mathfrak{X}(s) \rightarrow \mathfrak{X}(s)$$

\forall smooth s on M , s.t.

- (1) $\frac{\nabla}{dt}$ \mathbb{R} -linear
- (2) $\left(\frac{\nabla}{dt}\right)(fv) = \frac{df}{dt}v + f\frac{\nabla}{dt}v$, $\forall f \in C^\infty[a, b]$, $\forall v \in \mathfrak{X}(s)$
- (3) If $Y \in \mathfrak{X}(M)$, then

$$\frac{\nabla}{dt}(Y|s)(t) = \nabla_{\dot{s}(t)}Y \in T_{s(t)}M, \quad a \leq t \leq b$$

Theorem 17 (Conlon Thm. 10.1.11[16]). \forall connection ∇ on M , $\exists!$ associated covariant derivative $\frac{\nabla}{dt}$

Proof. Consider arbitrary coordinate chart $(U, x^1 \dots x^n)$.

Consider smooth curve $s : [a, b] \rightarrow U$.

Let $v \in \mathfrak{X}(s)$, $v(t) = v^i(t)\frac{\partial}{\partial x^i}$; $\dot{s}(t) = s^j\frac{\partial}{\partial x^j}$.

$$\frac{\nabla v}{dt} = \frac{dv^i(t)}{dt}\frac{\partial}{\partial x^i} + v^i(t)\frac{\nabla}{dt}\frac{\partial}{\partial x^i} = \frac{dv^i}{dt}\frac{\partial}{\partial x^i} + v^i\nabla_{\dot{s}(t)}\frac{\partial}{\partial x^i} = v^i\frac{\partial}{\partial x^i} + v^i\dot{s}^j\Gamma_{ij}^k\frac{\partial}{\partial x^k} = (\dot{v}^k + v^i\dot{s}^j\Gamma_{ij}^k)\frac{\partial}{\partial x^k}$$

This is an explicit, local formula in terms of connection, proving uniqueness.

Existence: \forall coordinate chart $(U, x^1 \dots x^n)$, $(\dot{v}^k + v^i\dot{s}^j\Gamma_{ij}^k)\frac{\partial}{\partial x^k} =: \frac{\nabla v}{dt}$.

$$\frac{\nabla}{dt}(fv) = \dot{f}v^k + f\dot{v}^k + f v^i\dot{s}^j = \dot{f}v + f\frac{\nabla v}{dt}$$

If f constant, then $\frac{\nabla}{dt}$ is \mathbb{R} -linear.

Definition 34 (10.1.12 Conlon (2008)[16]). Let (M, ∇) . Let $v \in \mathfrak{X}(s)$ for smooth $s : [a, b] \rightarrow M$.

If $\frac{\nabla v}{dt} \equiv 0$ on s , then v is **parallel** along s .

Theorem 18 (10.1.13). Let (M, ∇) , smooth $s : [a, b] \rightarrow M$, $c \in [a, b]$, $v_0 \in T_{s(c)}M$.

Then $\exists!$ parallel field $v \in \mathfrak{X}(s)$ s.t. $v(c) = v_0$.

v parallel transport along s .

Proof.

$$\dot{s}(t) = \dot{s}^j(t)e_j$$

$$v(t) = v^i(t)e_i$$

$$v_0 = a^i e_i$$

$$0 = \left(\frac{dv^k}{dt}(t) + v^i(t)\dot{s}^j(t)\Gamma_{ij}^k(s(t)) \right) e_k$$

or equivalently

$$(30) \quad \frac{dv^k}{dt} = -v^i\dot{s}^j\Gamma_{ij}^k, \quad 1 \leq k \leq n \quad (10.1)$$

with initial conditions $v^k(c) = a^k$, $1 \leq k \leq n$.

By existence and uniqueness of solutions of O.D.E.

$\exists \epsilon > 0$ s.t. $\exists!$ solutions $v^k(t)$. For $c - \epsilon < t < c + \epsilon$.

In fact, these ODEs being linear in v^k , by ODE theory (Appendix C, Thm. C.4.1).

\nexists restriction on ϵ , so $\exists! v^k(t) \quad \forall t \in [a, b]$, $1 \leq k \leq n$

7.0.2. *Principal bundle, vector bundle case for parallel transport.* Recall the 2 different forms or viewpoints for Lie-algebra valued 1-forms, or vector-valued 1-forms, or sections of 1-form-valued endomorphisms:

$$\omega_{i\mu}^k dx^\mu \equiv \omega_i^k \in \Omega^1(M, \mathfrak{gl}(n, \mathbb{F})) = \Gamma(\mathfrak{gl}(n, \mathbb{R} \otimes T^*M|_U))$$

for $i, k = 1 \dots n = \dim E$.

$$\mu = 1 \dots d = \dim E$$

Now

$$D_X\mu = X^\mu D_{\frac{\partial}{\partial x^\mu}}\mu = X^\mu \left[\left(\frac{\partial}{\partial x^\mu} \mu^k \right) e_k + \mu^i \omega_{i\mu}^k e_k \right] = (X(\mu^k) + \mu^i \omega_i^k(X)) e_k = (d\mu^k(X) + \mu^i \omega_i^k(X)) e_k$$

So then define

$$(31) \quad \begin{aligned} D : \Gamma(E) &\rightarrow \Gamma(E) \otimes \Gamma(T^*M) \\ D\mu &= D(\mu^i e_i) = e_k(d\mu^k + \mu^i \omega_i^k) \equiv (d + A)\mu \end{aligned}$$

Also, D can be defined for this case:

$$D : \Gamma(\text{End}(E)) \rightarrow \Gamma(\text{End}E) \otimes \Gamma(T^*M)$$

Let $\sigma = \sigma_j^i e_i \otimes e^j \in \Gamma(\text{End}(E))$

□

$$(32) \quad \begin{aligned} D\sigma &= D(\sigma_j^i e_i) \otimes e^j + \sigma_j^i e_i \otimes D^*e^j = (d\sigma_j^k + \sigma^i A_i^k) e_k \otimes e^j + \sigma_j^i e_i \otimes (A^*)^j_k e^k = \\ &= (d\sigma_j^k + \sigma_j^i A_i^k) e_k \otimes e^j + \sigma_i^k e_j \otimes (-A_j^i) e^j = (d\sigma_j^k + [A, \sigma]_j^k) e_k \otimes e^j \end{aligned}$$

cf. Def. 4.1.4 of Jost (2011), pp. 138.

For $\mu \in \Gamma(E)$, smooth $s : [a, b] \rightarrow M$, $X(t) = \dot{s}(t)$,

$$(33) \quad D_{\dot{s}(t)}\mu = \dot{s}^\mu D_{\frac{\partial}{\partial x^\mu}}\mu = \dot{s}^\mu \left[\frac{\partial \mu^k}{\partial x^\mu} e_k + \mu^i \omega_{i\mu}^k e_k \right] = \left[\dot{s}^\mu \frac{\partial \mu^k}{\partial x^\mu} + \dot{s}^\mu \mu^i \omega_{i\mu}^k \right] e_k = \frac{d}{dt}\mu(s(t)) + \mu^i \dot{s}^\mu \omega_{i\mu}^k e_k$$

Let $D_{\dot{s}(t)}\mu = 0$. Then,

$$(34) \quad \frac{d}{dt}\mu(s(t)) = -\mu^i \dot{s}^\mu \omega_{i\mu}^k e_k$$

Recall, given vector bundle $E \xrightarrow{\pi} N$, given $\varphi : M \rightarrow N$, then pullback

$$(35) \quad \varphi^*E \rightarrow M$$

i.e.

$$\begin{array}{ccc} \varphi^*E & \xleftarrow{\varphi^*} & E \\ \downarrow \psi & & \downarrow \pi \\ M & \xrightarrow{\varphi} & N \end{array} \quad \begin{array}{c} (\varphi^*E)_x = E_{\varphi(x)} \\ \uparrow \\ x \in M \end{array}$$

i.e. if $s \in \Gamma(E)$,

□

$$\varphi^*s = s \circ \varphi \in \Gamma(\varphi^*E)$$

Thus,

$$\begin{array}{ccc} \gamma^*E & \xleftarrow{\gamma^*} & E \\ \downarrow & & \downarrow \pi \\ [a, b] & \xrightarrow{\gamma} & M \end{array} \quad (\varphi^*E)_c = E_{\gamma(c)} \quad \begin{array}{c} \uparrow \\ c \in [a, b] \end{array}$$

For

$$\begin{aligned} \dot{v}^k &= -v^i \dot{s}^j \Gamma_{ij}^k \\ v^k(c) &= v_0^k \quad 1 \leq k \leq m \\ \dot{v} &= -v^i \dot{s}^j \Gamma_{ij} \\ (v + w)^\cdot &= -(v^i + w^i) \dot{s}^j \Gamma_{ij}(v + w)(c) = v(c) + w(c) = v_0 + w_0 \end{aligned}$$

so $v + w \in \mathfrak{X}(s)$ is parallel transport of $v_0 + w_0$.

Likewise, $\forall a \in \mathbb{F}$, $av \in \mathfrak{X}(s)$ is the parallel transport of av_0 .

$$\dot{\mu}^k = -\mu^i \dot{s}^\mu \omega_{i\mu}^k = -\mu^i \omega_i^k(\dot{s}^\mu)$$

Suppose γ^*E trivialized over $[a, b]$.

Closed interval is contractible, so this is always possible.

For chart (U, φ) ,

$$\begin{array}{ccc} \gamma^*E & \xleftarrow{\gamma^*} & E \\ \downarrow & & \downarrow \pi \\ [a, b] & \xrightarrow{\gamma} & M \end{array} \quad \begin{array}{ccc} E|_U & \xrightarrow{\psi} & U \times V \\ \pi^{-1} \uparrow & \nearrow & \\ U \subset M & & \end{array}$$

Consider

$$\begin{aligned} \varphi : [a, b] \times V &\rightarrow \gamma^*E \\ \varphi(t, \cdot) &= \gamma^* \circ \psi^{-1}(\gamma(t), \cdot) \end{aligned}$$

$$\forall \mu \in \Gamma(E|_{x \in M}),$$

$$\mu = \mu^i e_i.$$

$$\varphi(t, e_i) = \epsilon_i \text{ is a basis for } \gamma^*E.$$

$$\forall \sigma \in \Gamma(\gamma^*E),$$

$$\begin{aligned} \sigma &= \sigma^i \epsilon_i, \quad \sigma^i : [a, b] \rightarrow \mathbb{F} \\ \nabla_{\frac{\partial}{\partial x^\mu}} \sigma &= \frac{\partial \sigma^k}{\partial x^\mu} \epsilon_k + \omega_{j\mu}^k \sigma^j \epsilon_k = \left(\frac{\partial \sigma^k}{\partial x^\mu} + \omega_{j\mu}^k \sigma^j \right) \epsilon_k \\ \nabla \sigma &= \epsilon_k \otimes (d\sigma^k + \omega_{j\mu}^k dx^\mu \sigma^j) = \epsilon_k \otimes (d\sigma^k + \omega_{j\mu}^k \sigma^j) \\ \nabla_{\frac{d}{dt}} \sigma &= \epsilon_k \otimes \left(\frac{d\sigma^k}{dt} + \omega_{j\mu}^k \dot{x}^\mu \sigma^j \right) \end{aligned}$$

Now

$$\frac{d}{dt} = \dot{x}^\nu \frac{\partial}{\partial x^\nu}$$

Then σ parallel along γ if

$$\frac{d\sigma^k}{dt} + \omega_{j\mu}^k \dot{x}^\mu \sigma^j = 0$$

Definition 35 (3.1.4 [17]). *Parallel transport along γ is*

$$(36) \quad \begin{aligned} P_\gamma : E_{\gamma(a)} &\rightarrow E_{\gamma(b)} \\ P_\gamma(v) &\mapsto \sigma(b) \end{aligned}$$

where $\sigma \in \Gamma(\gamma^*E)$, σ unique and s.t. $\sigma(a) = v$.

Lemma 1 (10.1.16[16]). *holonomy*

$$h_s : T_x M \rightarrow T_{x_0} M$$

if ∇ around piecewise smooth loop s is a linear transformation.

Lemma 2 (10.1.18 Conlon (2008)[16]). *Let piecewise smooth loop $s : [a, b] \rightarrow M$ at x_0 .*

Let weak reparametrization $\tilde{s} = s \circ r : [c, d] \rightarrow M$.

If reparametrization is orientation-preserving, then $h_{\tilde{s}} = h_s$,

If reparametrization is orientation-reversing, then $h_{\tilde{s}} = h_s^{-1}$,

Proof. Without loss of generality, assume smooth s, r

$$\tilde{s}(\tau) = s(r(\tau))$$

$$\tilde{v}(\tau) = v(r(\tau))$$

$$\tilde{u}^j(\tau) = \frac{dt}{d\tau}(\tau) u^j(r(\tau))$$

$$\frac{d\tilde{v}^k}{d\tau}(\tau) = \frac{dr}{d\tau}(\tau) \frac{dv^k}{dt}(r(\tau))$$

$$\frac{d\tilde{v}^k}{d\tau} = -\tilde{v}^i \tilde{u}^j \Gamma_{ij}^k$$

since

$$\frac{dv^k}{dt} = -v^i u^j \Gamma_{ij}^k; \quad 1 \leq k \leq n$$

$$v^k(c) = a^k; \quad 1 \leq k \leq a$$

$$\frac{dr}{d\tau} \frac{dv^k}{dt} = -v^i \frac{dr}{d\tau} u^j \Gamma_{ij}^k = \frac{d\tilde{v}^k}{d\tau} = -\tilde{v}^i \tilde{u}^j \Gamma_{ij}^k$$

Thus, if $r(c) = a$, $r(d) = b$

If $r(c) = a$, $r(d) = b$, then

$$h_{\tilde{s}}(v_0) = \tilde{v}(d) = v(b) = h_s(v_0)$$

and

$$h_{\tilde{s}}(h_s(v_0)) = h_{\tilde{s}}(v(b)) = \tilde{v}(d) = v(a) = v_0$$

At this point, I will switch to my notation because it clarified to me, at least, what was going on, in that a holonomy h_s is *invariant* under orientation-preserving reparametrization, and its inverse is well-defined.

For $\tilde{s} = s \circ t : [c, d] \rightarrow M$,

piecewise smooth t is reparametrized, i.e.

$$(37) \quad t : [c, d] \rightarrow [a, b]$$

Now,

$$\frac{d}{d\tau} \tilde{s}(\tau) = \frac{d}{d\tau} \tilde{s}(t(\tau)) = \dot{s}(t) \frac{dt}{d\tau}(\tau) \equiv \dot{s} \frac{dt}{d\tau}$$

$$v^k(t) = v^k(t(\tau)) = v^k(\tau)$$

$$\frac{dv^k}{d\tau}(t(\tau)) = \frac{dv^k}{dt} \frac{dt}{d\tau} = \frac{dt}{d\tau} (-v^i(\tau) \dot{s}^j(t) \Gamma_{ij}^k) = -v^i(\tau) \frac{d\tilde{s}^j}{d\tau} \Gamma_{ij}^k$$

Consider

$$h_s(v_0) = v(b)$$

$$\begin{aligned} \text{If } t(c) &= a, \\ t(d) &= b \end{aligned}$$

$$h_{\tilde{s}}(v_0) = \tilde{v}(d) = v(t(d)) = v(b) = h_s(v_0)$$

$$\begin{aligned} \text{If } t(c) &= b, \\ t(d) &= a \end{aligned}$$

$$\begin{aligned} h_{\tilde{s}}(h_s(v_0)) &= h_{\tilde{s}}(v(b)) = h_{\tilde{s}}(v(t(c))) = h_{\tilde{s}}(\tilde{v}(c)) = \\ &= \tilde{v}(d) = v(t(d)) = v(a) = v_0 \end{aligned}$$

Thus,

$$\boxed{h_{\tilde{s}} = h_s^{-1}}$$

I am working through Conlon (2008) [16], Clarke and Santoro (2012) [17], and Schreiber and Waldorf (2007)[18], concurrently, for holonomy.

8. PATH GROUPOID OF A SMOOTH MANIFOLD; GENERALIZATION OF PATHS

cf. Schreiber and Waldorf (2007)[18].

Definition 36 (path). ***path** is a smooth map $\gamma : [0, 1] \rightarrow M$, between 2 pts. $x, y \in M$, which has a sitting instant; i.e. number $0 < \epsilon < \frac{1}{2}$ s.t.*

$$(38) \quad \gamma(t) = \begin{cases} x & \text{for } 0 \leq t < \epsilon \\ y & \text{for } 1 - \epsilon < t \leq 1 \end{cases}$$

Denote the set of such paths by PM ,

$$(39) \quad PM \equiv \{\gamma \in \Gamma(M) \mid \text{smooth } \gamma : [0, 1] \rightarrow M \text{ s.t. } \exists 0 < \epsilon < \frac{1}{2} \text{ s.t. } \begin{cases} x & \text{for } 0 \leq t < \epsilon \\ y & \text{for } 1 - \epsilon < t \leq 1 \end{cases}\}$$

cf. Def. 2.1. of Schreiber and Waldorf (2007)[18]

Define *composition*:

$$\begin{aligned} \text{Given paths } \gamma_1, \gamma_2; \quad \gamma_1(0) &= x, \quad \gamma_2(0) = y, \\ \gamma_1(1) &= y \quad \gamma_2(1) = z \end{aligned}$$

define composition to be path

$$(40) \quad \begin{aligned} &\gamma_2 \circ \gamma_1 \\ (\gamma_2 \circ \gamma_1)(t) &:= \begin{cases} \gamma_1(2t) & \text{for } 0 \leq t \leq \frac{1}{2} \\ \gamma_2(2t - 1) & \text{for } \frac{1}{2} \leq t \leq 1 \end{cases} \end{aligned}$$

$\gamma_2 \circ \gamma_1$ smooth since γ_1, γ_2 both constant near gluing pt., due to sitting instants ϵ_1, ϵ_2 , respectively.

Define *inverse*:

$$(41) \quad \begin{aligned} \gamma^{-1} &: [0, 1] \rightarrow M \\ \gamma^{-1}(t) &:= \gamma(1 - t) \end{aligned}$$

$$(\text{so that } \gamma^1(t) = \begin{cases} y & \text{for } 1 - \epsilon < 1 - t \leq 1 \text{ or } 0 \leq t < \epsilon \\ x & \text{for } 0 \leq 1 - t < \epsilon \text{ or } 1 - \epsilon < t \leq 1 \end{cases})$$

Definition 37 (thin homotopy equivalent). *2 paths γ_1, γ_2 s.t. $\gamma_1(0) = \gamma_2(0) = x$, γ_1, γ_2 are thin homotopy equivalent, $\gamma_1(1) = \gamma_2(1) = y$*

if \exists smooth $h : [0, 1] \times [0, 1] \rightarrow M$ s.t.

$$(1) \quad \exists 0 < \epsilon < \frac{1}{2} \text{ with}$$

$$\begin{aligned} \text{(a)} \quad &h(s, t) = x \text{ for } 0 \leq t < \epsilon \\ &h(s, t) = y \text{ for } 1 - \epsilon < t \leq 1 \\ \text{(b)} \quad & \end{aligned}$$

$$\begin{aligned} \text{(c)} \quad &h(s, t) = \gamma_1(t) \text{ for } 0 \leq s < \epsilon \\ &h(s, t) = \gamma_2(t) \text{ for } 1 - \epsilon < s \leq 1 \end{aligned}$$

□

(2) *differential of h has at most rank 1 everywhere, i.e.*

$$(42) \quad \text{rank}(dh|_{(s,t)}) \leq 1 \quad \forall (s, t) \in [0, 1] \times [0, 1]$$

cf. Def. 2.2. of Schreiber and Waldorf (2007)[18]

$$\begin{aligned} h(s, t) &= \gamma_1(t) \text{ for } 0 \leq s < \epsilon \quad \text{is the homotopy from } \gamma_1 \text{ to } \gamma_2, \text{ i.e. } h(0, t) = \gamma_1(t) \\ h(s, t) &= \gamma_2(t) \text{ for } 1 - \epsilon < s \leq 1 \quad h(1, t) = \gamma_2(t) \end{aligned}$$

and define an equivalence relation on PM .

Note that for $h : [0, 1] \times [0, 1] \rightarrow M$,

$$(Dh)|_{(s,t)} = \left[\frac{\partial h^i}{\partial s}, \frac{\partial h^i}{\partial t} \right]$$

$P^1M \equiv$ set of thin homotopy classes of paths, i.e.

$$(43) \quad P^1M = \{[\gamma] \mid \gamma_1 \in PM, \text{ if } \exists \text{ smooth } h : [0, 1] \times [0, 1] \rightarrow M \text{ s.t. } h \text{ thin homotopy of } \gamma_1 \text{ and } \gamma_2, \gamma_1 \sim \gamma_2\}$$

$\text{pr} : PM \rightarrow P^1M$ is projection to classes.

Denote thin homotopy class of path γ , $\gamma(0) = x$, by $\bar{\gamma}$, or $[\gamma]$.

$$\gamma(1) = y$$

8.1. Reparametrization of thin homotopies. Let $\beta : [0, 1] \rightarrow [0, 1]$, $\beta(0) = 0$, $\beta(1) = 1$

$$\begin{aligned} \text{Then } \forall \text{ path } \gamma, \quad \gamma(0) &= x, \gamma \circ \beta \text{ is also a path } \gamma \circ \beta(0) = x \text{ and} \\ \gamma(1) &= y \quad \gamma \circ \beta(1) = y \end{aligned}$$

$$(44) \quad h(s, t) := \gamma(t\beta(1 - s) + \beta(t)\beta(s))$$

defines a homotopy from γ to $\gamma \circ \beta$.

$$\gamma_1 \circ \gamma_2 \in PM \xrightarrow{\text{pr}} [\gamma_1 \circ \gamma_2] = [\gamma_1][\gamma_2] \in P^1M$$

Composition of thin homotopy classes of paths obeys following rules:

Lemma 3. \forall path γ , $\gamma(0) = x$

$$\gamma(1) = y$$

$$(1) \quad \bar{\gamma} \circ \overline{id_x} = \bar{\gamma} = \overline{id_y} \circ \bar{\gamma} \equiv [\gamma]1_x = [\gamma] = 1_y[\gamma]$$

$$(2) \quad \text{for paths } \gamma'; \quad \gamma'(0) = y, \quad \gamma''(0) = z \\ \gamma'(1) = z \quad \gamma''(1) = w$$

$$(45) \quad (\bar{\gamma}'' \circ \bar{\gamma}') \circ \bar{\gamma} = \bar{\gamma}'' \circ (\bar{\gamma}' \circ \bar{\gamma}) \equiv ([\gamma''][\gamma'])[\gamma] = [\gamma'']([\gamma'][\gamma])$$

$$(3) \quad \bar{\gamma} \circ \bar{\gamma}^{-1} = \overline{id_y} \text{ and } \overline{\gamma^{-1}} \circ \bar{\gamma} = \overline{id_x} \equiv [\gamma][\gamma^{-1}] = 1_y \text{ and } [\gamma^{-1}][\gamma] = 1_x$$

cf. Lemma 2.3. of Schreiber and Waldorf (2007)[18]

Definition 38 (path groupoid). \forall smooth manifold M , consider category whose set of objects is M ,

whose set of morphisms is P^1M , where class $[\gamma]$, $[\gamma](0) = x$ is a morphism from x to y and

$$[\gamma](1) = y$$

composition $[\gamma_1][\gamma_2] = [\gamma_1 \circ \gamma_2] \in P^1M$ Lemma 3 are axioms of a category, 3rd. property says \forall morphism is invertible.

Hence, we've defined a groupoid, called **path groupoid** of M , $\mathcal{P}_1(M)$.

So

$$\text{Obj}(\mathcal{P}_1(M)) = M$$

$$\text{Mor}(\mathcal{P}_1(M)) = P^1M$$

\forall smooth $f : M \rightarrow N$, denote functor f_*

$$(46) \quad f_* : \mathcal{P}_1(M) \rightarrow \mathcal{P}_1(N)$$

with

$$f_*(x) = f(x)$$

$$(f_*)([\gamma]) := [f \circ \gamma]$$

If $\gamma \sim \gamma'$, for $f \circ \gamma$, $f \circ \gamma'$,

$f \circ h(s, t)$ with $f \circ h(0, t) = f \circ \gamma(t)$,

$$f \circ h(1, t) = f \circ \gamma'(t)$$

so $f \circ h$ is a thin homotopy between $f \circ \gamma$, $f \circ \gamma'$ and so $[f \circ \gamma]$ well-defined.

Part 8. 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) [13]

[Lectures on Riemannian Geometry, Part II: Complex Manifolds](#) by Stefan Vandoren

Vandoren (2008) [14]

Part 9. Jets, Jet bundles, h -principle, h -Prinzipien

cf. Eliashberg and Misahchev (2002) [19]

cf. Ch. 1 Jets and Holonomy, Sec. 1.1 Maps and sections of Eliashberg and Misahchev (2002) [19].

Visualize $f : \mathbb{R}^n \rightarrow \mathbb{R}^q$ as graph $\Gamma_f \subset \mathbb{R}^n \times \mathbb{R}^q$.

Consider this graph as image of $\mathbb{R}^n \rightarrow \mathbb{R}^n \times \mathbb{R}^q$, i.e.

$$x \mapsto (x, f(x))$$

$\mathbb{R}^n \rightarrow \mathbb{R}^n \times \mathbb{R}^q$ is called section (by mathematicians),

$$x \mapsto (x, f(x))$$

is called *field* or \mathbb{R}^q -valued field (by physicists).

cf. Ch. 1 Jets and Holonomy, Sec. 1.2 Coordinate definition of jets of Eliashberg and Misahchev (2002) [19].

Definition 39 (r -jet). Given (smooth) $f : \mathbb{R}^n \rightarrow \mathbb{R}^q$, given $x \in \mathbb{R}^n$.

r -jet of f at x - sequence of derivatives of f , up to order r , \equiv

$$(47) \quad J_f^r(x) = (f(x), f'(x) \dots f^{(r)}(x))$$

$f^{(q)}$ consists of all partial derivatives $D^\alpha f$, $\alpha = (\alpha_1 \dots \alpha_n)$, $|\alpha| = \alpha_1 + \dots + \alpha_n = s$, ordered lexicographically.

e.g. $q = 1$,

$f : \mathbb{R}^n \rightarrow \mathbb{R}$.

1-jet of f at $x = J_f^1(x) = (f(x), f^{(1)}(x))$.

$$f^{(1)}(x) = \{D^\alpha f | \alpha = (\alpha_1 \dots \alpha_n), |\alpha| = \alpha_1 + \dots + \alpha_n = 1\} = \left(\frac{\partial f}{\partial x^1}, \frac{\partial f}{\partial x^2}, \dots, \frac{\partial f}{\partial x^n} \right)$$

Let $d_r = d(n, r)$ = number of all partial derivatives D^α of order r of function $\mathbb{R}^n \rightarrow \mathbb{R}$.

Consider r -jet $J_f^r(x)$ of map $f : \mathbb{R}^n \rightarrow \mathbb{R}^q$ as pt. of space $\mathbb{R}^q \times \mathbb{R}^{qd_1} \times \mathbb{R}^{qd_2} \times \dots \times \mathbb{R}^{qd_r} = \mathbb{R}^{qN_r}$, where $N_r = N(n, r) = 1 + d_1 + d_2 + \dots + d_r$, i.e.

$$J_f^r(x) = (f(x), f^{(1)}(x), \dots, f^{(r)}(x)) \in \mathbb{R}^q \times \mathbb{R}^{qd_1} \times \dots \times \mathbb{R}^{qd_r} = \mathbb{R}^{qN_r}$$

Exercise 1.

Given order r , consider n -tuple of (positive) integers $(r_1, r_2 \dots r_n)$ s.t. $r_1 + r_2 + \dots + r_n = r$, and $r_k \geq 0$.

Imagine r_k = occupancy number, num ber of balls in k th cell. $(r_1 \dots r_n)$ describes a positive ocnfiguration of occupancy numbers, with indistinguishable balls; 2 distributions are distinguishable only if corresponding n -tuples $(r_1 \dots r_n)$ not identical.

Represent balls by stars, and indicate n cells by n spaces between $n + 1$ bars.

With $n + 1$ bars, r stars, 2 bars are fixed. $n - 1$ bars and r stars to arrange linearly, so a total of $n - 1 + r$ objects to arrange. r stars indistinguishable amongst themselves, so choose r out of $n - 1 + r$ to be stars.

$$(48) \quad \implies d_r = d(n, r) = \binom{n-1+r}{r}$$

Use *induction* (cf. [Ch. 4 Binomial Coefficients](#)).

$$N_0 = N(n, 0) = \binom{n-1+0}{0} = 1$$

$$N_1 = N(n, 1) = 1 + \binom{n-1+1}{1} = 1 + n = \frac{(n+1)!}{n!1!}$$

Induction step:

$$N_{r-1} = N(n, r-1) = \sum_{k=1}^{r-1} d_k + 1 = \binom{n+r-1}{r-1}$$

Definition 41. *critical point* x of f is zero of Df , i.e.

$$(52) \qquad \qquad \qquad Df(x) = 0$$

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 42. *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) [6]

Lemma 4 (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.*

$$(53) \qquad \qquad \qquad f\varphi^{-1}(u_1 \dots u_n) = f(p) - \sum_{i=1}^k u_i^2 + \sum_{i=k+1}^n u_i^2$$

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

Lemma 5. *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

$$(54) \qquad \qquad \qquad P : N \rightarrow GL(n, \mathbb{R})$$

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 $x = T y$ where

$$x_1 = \left[y_1 - \frac{b_{12}}{b_{11}} y_2 - \dots - \frac{b_{1n}}{b_{11}} y_n \right] / \sqrt{|b_n|}$$

$$x_k = y_k \text{ for } k = 2, \dots n$$

□

10. 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](#)

Part 11. Classical Mechanics applications

cf. Arnold, Kozlov, Neishtadt (2006) [20].

If known forces $\mathbf{F}_1 \dots \mathbf{F}_n$ acts on points, then

$$(55) \qquad \qquad \qquad \sum_{i=1}^n \langle m_i \ddot{\mathbf{r}}_i - \mathbf{F}_i, \xi_i \rangle = 0$$

cf. Eq. (1.26) of Arnold, Kozlov, Neishtadt (2006) [20], where $\xi_1, \dots \xi_n$ are arbitrary tangent vectors to M , $\xi_i, \dots \xi_n \in TM$.

$\sum_{i=1}^n \langle m_i \ddot{\mathbf{r}}_i - \mathbf{F}_i, \xi_i \rangle$ called "general equation of dynamics" or d'Alembert-Lagrange principle.

Part 12. Classical Mechanics

11. CLASSICAL MECHANICS

11.1. Structure of Galilean Space-Time. cf. Sec. 3.1 - *Structure of Galilean Space-Time* of Prástaro (1996) [12].

Mechanics assumes a particular simple formulation if formulated with respect to some spacetime manifold.

In Galilean spacetime, it's possible to naturally recognize absolute objects, and others that depend on frames.

cf. Def. 3.1 of Prástaro (1996) [12]

Definition 43 (Galilean spacetime structure). (1) *Galilean spacetime structure* $:= (\mathcal{G}, g)$ where \mathcal{G} is (fiber bundle space-time)

$$(56) \qquad \qquad \qquad \mathcal{G} \equiv \{ \tau : M \rightarrow T \}$$

where

$M = 4\text{-dim. affine manifold}$ (**space-time**); corresponding structure is (M, \mathbf{M}, α) ,

(2) $T = 1\text{-dim. affine space}$ (**time**), corresponding affine structure is (T, \mathbf{T}, β)

(3) $\tau =$ surjective affine mapping, of constant rank 1, s.t. $\forall p \in M$ associates its time $\tau(p) \in T$
Put $\mathbf{S} = \ker(\underline{\tau}) \equiv \ker(D\tau) \in M$,
where $\underline{\tau} \equiv D\tau$, D is symbol of derivative.
Define

$$g : M \rightarrow vS_2^0(M) \equiv M \times S_2^0(\mathbf{S})$$
$$g(p) = (p, \underline{g}) \equiv (p, Dg), \forall p \in M$$

where $\underline{g} \equiv Dg$ is a Euclidean structure on \mathbf{S} . g is called vertical metric field.

Thus, given (M, \mathbf{M}, α) , $\forall (O, \{\mathbf{e}_i\}_{1 \leq i \leq d}, \{\mathbf{e}_i\}_{i=1\dots d})$, is basis of \mathbf{M} ,

$$M \cong \mathbb{R}^4, \text{ and } \exists \{x^\alpha : M = \mathbb{R}^4 \rightarrow \mathbb{R}\}_{\alpha=1\dots 4}$$

11.2. **Fundamental Theorems of (Classical) Dynamics.** cf. Sec. 3.4 - *Fundamental Theorems of Dynamics* of Prástaro (1996) [\[12\]](#).
cf. Thm. 3.20 of Prástaro (1996) [\[12\]](#)

Theorem 19 ((Momentum Theorem)). *Variation of the free part of momentum of the observed motion of 1 body, in time interval $\Delta t \equiv [0, t]$ is equal to the corresponding impulse:*

(57)

$$I[0, t] \equiv \int_0^t F dt \equiv \left(\int_0^t F^j dt \right) \mathbf{e}_j$$

where $\{\mathbf{e}_j\}_{1 \leq j \leq 3}$ is a fixed basis of \mathbf{S}

(58)

$$\bar{p}_\psi(t) - \bar{p}_\psi(0) = I[0, t]$$

Proof.

$$\bar{p}_\psi = \mu \ddot{m}_\psi = \bar{f}_\psi \implies \dot{\bar{p}}_\psi = \dot{p}^j \mathbf{e}_j = F^j \mathbf{e}_j \implies \int_{[0, t]} \dot{p}^j dt = \int_{[0, t]} F^j dt$$

□

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