

# De Rham decomposition

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## 1 Decomposition theorem of de Rham

We observe that if a manifold  $(M, g)$  is globally a product  $(M_1, g_1) \times (M_2, g_2)$  then  $Hol_g(M) = Hol_{g_1}(M_1) \times Hol_{g_2}(M_2)$  and the holonomy representation of  $M$  is reducible. A result of de Rham says that one can decompose a Riemannian manifold as product of ones with irreducible holonomy representation.

**Theorem 1** (De Rham decomposition). *Given  $(M, g)$  a simply connected and complete Riemannian manifold, there exists a unique decomposition up to isometry and permutation of factors*

$$(M, g) = \prod_{i=1}^n (M_i, g_i)$$

where  $(M_i, g_i)$  are complete, simply connected Riemannian irreducible manifolds. Moreover the holonomy representation of  $M$  over  $T_x M$  is the product of holonomy representations of  $M_i$  over  $T_{x_i} M_i$  where  $x = (x_1, \dots, x_n)$

*Sketch of proof.* The proof of this theorem contains two steps:

1. Remark that if the holonomy group is reducible then locally  $M$  is a product of Riemannian manifolds, i.e. for every  $x \in M$  there exists a neighborhood  $U$  containing  $x$  with  $(U, g) = (M_1, g_1) \times (M_2, g_2)$ .
2. Obtain the global product structure from local one. This is where completeness is used.

We now discuss the first point with a bit more details. Suppose that  $T_x M = U_x \oplus^\perp V_x$  where  $U_x, V_x$  are stable under action of holonomy group, then by transporting  $U_x, V_x$  to the tangent space of any point  $y$  (as they are stable by holonomy, the result is independent of the curve along which the transport is taken), we obtain then two sub fibers  $A$  and  $B$  of  $TM$  over  $M$  that are stable by transport. Then for every vector field  $u_A$  in  $A$  and  $v$  in  $TM$ ,  $\nabla_v u_A \in A$ , as the Levi-Civita connection is torsionless, one deduces  $[u_A, v_A] = \nabla_{u_A} v_A - \nabla_{v_A} u_A$  remains in  $A$ . By Frobenius theorem, locally at a point  $x \in M$ , there exist manifolds  $M_1, M_2$  whose tangent spaces are  $A$  and  $B$ .

**Theorem 2** (Frobenius). *Given distribution  $D$  which to each point  $x$  associates a  $k$  -dimensional hyperplanes of  $T_x M$  which satisfies:*

1.  *$D$  varies smoothly by  $x$ , i.e. there exist  $k$  smooth vector fields that at each point  $x$  form a base of  $D(x)$ .*
2.  *$D$  is stable by Lie bracket, i.e. for every vector fields  $X, Y$  on  $M$  that take value in  $D$ ,  $[X, Y]$  takes value in  $D$ .*

*Then at each point  $x \in M$ , there exists a maximal  $k$  -dimension sub-manifold  $N$  of  $M$  containing  $x$  such that  $D(y)$  is the tangent of  $N$  at  $y$ . The maximality means that every sub-manifold of  $M$  that satisfies this condition is an open sub-manifold of  $N$ .*

For a complete proof that  $M$  is isometric to  $M_1 \times M_2$ , see Takashi Sakai, *Riemannian geometry*.  $\square$

## 2 Uniqueness

We note that the decomposition is unique in the following sense:

**Proposition 2.1** (Uniqueness of de Rham decomposition). *If  $M$  is decomposed as  $E \times \prod M_i$  and  $E' \times \prod M'_j$  where  $M_i, M'_j$  are irreducible and  $E, E'$  are maximal Euclidean components (i.e. none of  $M_i, M'_j$  are isometric to  $\mathbb{R}$ ). Then up to a rearrangement of indice  $j$  the composed map*

$f : E \times \prod M_i \longrightarrow E' \times \prod M'_i$  are product of the isometries  $f_E : E \longrightarrow E'$  and  $f_i : M_i \longrightarrow M'_i$ .

We first explain the appearance of Euclidean components  $E, E'$ . They come from the parallel transport of trivial representations  $T_{x_i}M_i$  appeared in the decomposition on each fiber. We call them Euclidean because they are, up to an isometric,  $\mathbb{R}^k$  with the usual metric. This follows from the fact that  $\mathbb{R}$  with any Riemannian metric is isometric to  $\mathbb{R}$  with Euclidean metric.

We first note that the uniqueness stated in Proposition 2.1 comes from the uniqueness of the decomposition of each tangent fiber to irreducible representation of holonomy group, we have the following lemma.

**Lemma 3** (Uniqueness of fiber decomposition). *Let  $f : M \longrightarrow M'$  be an isometry that send  $x \in M$  to  $y \in M'$ . Let*

$$T_x M = E \oplus^\perp \bigoplus_i V_i, \quad T_y M' = E' \oplus^\perp \bigoplus_j V'_j$$

*be a decomposition of  $T_x M$  and  $T_y M'$  as direct sum of trivial subspaces  $E, E'$  and irreducible subspaces  $V_i, V'_j$  under holonomy action. Then up to a rearrangement of  $j$ ,  $f_*$  send  $E$  to  $E'$  and  $V_i$  to  $V'_i$ .*

**Remark 1.** *One may note that a similar result is not true for general representations: one can only prove the uniqueness of the irreducible factors up to isomorphism and their multiplicity. But the individual irreducible summands might not map to individual summands (However if one groups all irreducible summands of the same type, then each group maps to another).*

The supplementary property of holonomy representation put into use here is the following:

**Remark 2.** *The holonomy representation  $H \subset SO(V)$  on a fiber  $V = T_x M$  satisfies the property (H): if  $V = V_1 \oplus^\perp V_2$  where  $V_i$  are stable by  $H$  then  $H = H_1 \times H_2$  where  $H_i := \{h \in H : h|_{V_j} = Id, j \neq i\}$  is the action of  $H$  on  $V_i$ . This property is a consequence of de Rham decomposition along  $V_1, V_2$  and the fact that  $Hol(M_1 \times M_2) = Hol(M_1) \times Hol(M_2)$ .*

An example of representation that do satisfies this property (H) is the group  $G = \{\pm I_2\}$ . Take  $V_i = \mathbb{R}e_i$ , then  $G_1 = G_2 = \{I_2\}$  therefore  $G_1 \times G_2 \neq G$ . This also illustrates the fact that not every group (representation) are holonomy group (representation).

We prove the following lemma, which is more general than Lemma 3.

**Lemma 4** (Uniqueness of representation decomposition). *Let  $G \subset SO(V)$  be an orthonormal representation over a finite dimensional vector space  $V$  with property (H), given any two decompositions*

$$V = E \times \prod V_i = E' \times \prod V'_j$$

*where  $G$  acts trivially on  $E, E'$ ,  $V_i, V'_j$  are irreducible and of dimension larger than 2, one has  $E = E'$  and  $V_i = V'_j$  up to a rearrangement of index  $j$ .*

*Moreover, given  $J \in \text{Hom}_G(V, V) \cap SO(V)$  then  $J$  sends  $E$  and  $V_i$  to themselves.*

*Proof.* Note that since action of  $G$  is special orthonormal, any one dimensional subspace of  $V$  stable by  $G$  are trivial under  $G$ , that explains why we supposed  $V_i, V'_j$  are of dimension larger than 2. It suffices to see that every irreducible subspace  $N$  of  $V$  is either in  $E$  or equal to  $V_i$ .

Let  $pr_i$  and  $pr_E$  be orthogonal projection of  $V$  to  $V_i$  and  $E$ . As  $E$  and  $V_i$  are  $G$ -stable, these projections are  $G$ -invariant. Let  $N_i = pr_i(N)$ , then  $N_i$  is a subspace of  $V_i$  stable by  $G$ , hence either 0 or all  $V_i$ . If all  $N_i = 0$  then clearly  $N$  is perpendicular to  $\bigoplus_i V_i$ , that is  $N \subset E$ . If  $pr_E(N) \neq 0$  then  $\text{Hom}_G(N, E) \neq 0$  since it contains  $pr_E$ . Since  $N$  is irreducible,  $N$  is  $G$ -isomorphic to a irreducible component of  $N$  by  $pr_E$ , therefore  $N$  is  $G$ -invariant hence  $N \subset E$ . Therefore one can suppose that at least one  $N_i = V_i$  and  $pr_E(N) = 0$ . The second condition means  $E \perp N$ .

Note that  $pr_i$  is bijective (Schur lemma). Let  $G_i = \{g \in G : g|_{V_j} = Id \ \forall j \neq i\}$  the action of  $G$  on  $V_i$  then  $\text{Fix}(\prod_{j \neq i} G_j) = E \oplus V_i$ , in fact each  $v = e + \sum v_i \in \text{Fix}(\prod_{j \neq i} G_j)$  where  $e \in E, v_i \in V_i$ , one has  $g_i v_i = v_i \forall g_i \in G_i$ , hence  $g_i v_i = v_i \forall g_i \in G$ , hence  $v_i = 0$ . It remains to note that as  $pr_i$  is  $G$ -invariant,  $N_i$  is also fixed by  $\prod_{j \neq i} G_j$ , therefore  $N_i \subset E \oplus^\perp V_i$ . Therefore  $N_i = V_i$  as  $N_i \perp E$ .

For the last point, note that as  $J$  commutes with all elements of  $G$ ,  $J$  sends  $\text{Fix}(\prod_{j \in A} G_j)$  to itself. Therefore  $J|_E : E \rightarrow E$  and  $J|_{E \oplus V_i} : E \oplus V_i \rightarrow E \oplus V_i$ , hence by orthogonality  $J$  sends  $E$  and  $V_i$  to themselves.  $\square$

### 3 Application of uniqueness lemma: decomposition for Kähler manifold

Now let apply the de Rham decomposition to a complete Riemannian manifold  $M$  with holonomy  $SU(n) \subset SO(2n)$  (called a *Kähler manifold*). There exists on a fixed fiber  $T_x M$  an automorphism  $J$  that preserve the riemannian

metric and satisfies  $J^2 = -1$ . By transporting  $J$  to every other fibers of  $TM$  one obtains a *almost complex structure* on  $M$ .

Apply Lemma 4 to  $J$  which is obviously  $G$  -invariant and orthonormal, one see that such structure  $J$  passes to every manifold  $M_i$  and the Euclidean component  $\mathbb{R}^n$  and remains parallel on these manifolds. We proved that  $M$  is decomposed to  $\mathbb{C}^{n/2} \times \coprod M_i$  where  $M_i$  are Kähler manifold. The decomposition map is both a Riemannian isometry and a isomorphism between complex manifold (morphism that preserves complex structure).