

Berger classification and remarks on parallel structures

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Our story so far

De Rham decomposition theorem allows us to split a Riemannian manifold under certain conditions (complete and connected) as Riemannian product of complete connected manifold with *irreducible holonomy representation*. We will now interest in manifolds with irreducible holonomies. If the manifold is *locally symmetric* then one can prove that it is isometric to the homogeneous space G/H with H (the holonomy) a closed Lie subgroup of G . The theory of Lie groups developed by E. Cartan gave a complete list of these spaces.

Berger classification for non-symmetric manifolds

Theorem 1 (Berger classification). *For the non-symmetric irreducible manifold, the holonomy representation has to be one of the following*

1. $SO(n)$
2. $U(m) \subset SO(2m)$
3. $SU(m) \subset SO(2m)$
4. $Sp(r) \subset SO(4r)$
5. $SO(r)Sp(1) \subset SO(4r)$
6. $G_2 \subset SO(7)$

7. $Spin(7) \subset SO(8)$.

where $n = 2m = 4r$ is the dimension.

Here are some notations, note always that

$$Sp(m) \subset SU(2m) \subset U(2m) \subset SO(4m)$$

1. If $Hol(g) \subset U(m) \subset SO(2m)$, g is called a *Kähler metric*.
2. If $Hol(g) \subset SU(m) \subset SO(2m)$, g is called a *Calabi-Yau metric*. We will see that a Calabi-Yau metric is a Kähler metric that is also Ricci-flat.
3. If $Hol(g) \subset Sp(m) \subset SO(4m)$ then g is called a *hyperkahler metric*.
4. G_2 and $Spin(7)$ are called *exceptional holonomies*

To sum up: hyperkahler \longrightarrow Calabi-Yau \longrightarrow Kähler.

But what do we mean by $U(n) \subset SO(2n)$? To embed $U(n)$ in $SO(2n)$ one needs to identify \mathbb{C} and \mathbb{R}^{2n} , this can be done using an almost complex structure J of \mathbb{R}^{2n} . We will prove that when we change the almost complex structure, the embedded image of $U(n)$ in $SO(2n)$ always remains in the same conjugacy class, which corresponds to the fact that while holonomy representation is well-defined, the holonomy group in $SO(2n)$ is only defined up to its conjugacy class.

Almost complex structure

Definition 1. A (almost) complex structure J on a vector space V is an automorphism $J : V \longrightarrow V$ with $J^2 = -Id_V$. If V has a scalar product g , we suppose in addition that $g \circ J = J$.

A (almost) complex structure J on manifold M is a vector bundle automorphism $J : TM \longrightarrow TM$ that satisfies $J_x^2 = -Id_{T_x M}$ for every $x \in M$. If M is a Riemannian manifold, we assume in addition that $g \circ J = g$.

Let us first have a look at a complex structure J on a fiber (vector space) V . Here are some direct consequences:

Complexification. g and J extend in an unique way over $V_{\mathbb{C}}$ to a hermitian product $g_{\mathbb{C}}$ and a \mathbb{C} -linear automorphism (also noted by J). One also has $g_{\mathbb{C}} \circ J = g_{\mathbb{C}}$.

Eigenspaces. The complexified space $V_{\mathbb{C}}$ is decomposed to $V_{\mathbb{C}} = V^{1,0} \oplus V^{0,1}$ where $V^{1,0}$ and $V^{0,1}$ are eigenspaces (complex vector space) corresponding to eigenvalues i and $-i$ of J on $V_{\mathbb{C}}$. The orthogonality is by $g_{\mathbb{C}}$. The complex conjugate $\sum z_i x_i \mapsto \sum \bar{z}_i x_i$ where $z_i \in \mathbb{C}$ and $x_i \in V$ maps $V^{1,0}$ to $V^{0,1}$. Their dimensions are therefore the same.

Hermitian form. The fundamental form ω of (V, J) is defined by

$$\omega(a, b) = g(Ja, b) = -g(a, Jb) \quad \text{on } V$$

which is an antisymmetric real 2-form with $\omega \circ J = \omega$. V equipped with the following Hermitian form

$$h(a, b) = g(a, b) - i\omega(a, b) \quad \text{on } V$$

in the sense that $h(.,.)$ is \mathbb{R} -linear with $h(Ja, b) = ih(a, b)$ and $h(a, Jb) = -ih(a, b)$.

Identification. One usually identifies (V, J) and $(V^{1,0}, i)$ as vector spaces equipped with complex structure, using the following map:

$$\iota_J : x \mapsto \frac{1}{2}(x - iJ(x))$$

which is \mathbb{C} -linear in the sense of complex structure $\iota_J(Jx) = i\iota_J(x)$. Note that one $(V, -J)$ is also isomorphic to $(V^{0,1}, i)$ by the conjugate of ι_J : $x \mapsto \frac{1}{2}(x + iJ(x))$.

Now note that on we have on (V, J) an hermitian product $h(.,.)$ and on $(V^{1,0}, i)$ the restricted hermitian product $g_{\mathbb{C}}$ of $V_{\mathbb{C}}$. The following lemma gives their relation (the proof is straightforward computation, see Manuscript).

Lemma 2. *The identification $(V, J) = (V^{1,0}, i)$ by ι_J gives*

$$\frac{1}{2}h = g_{\mathbb{C}}|_{V^{1,0}}$$

We can now embed $U(n)$ to $SO(2n)$, in other words $U(V^{1,0})$ to $SO(V)$

by the map $\phi \mapsto \tilde{\phi}$ as follow:

$$\begin{array}{ccc} V & \xrightarrow{\tilde{\phi}} & V \\ \downarrow \iota_J & & \downarrow \iota_J \\ V^{1,0} & \xrightarrow{\phi} & V^{1,0} \end{array}$$

Note that the correspondance $\phi \leftrightarrow \tilde{\phi}$ is one-to-one between $\{\phi : V^{1,0} \longrightarrow V^{1,0} \mathbb{R}\text{-linear}\}$ and $\{\tilde{\phi} : V \longrightarrow V \mathbb{R}\text{-linear}\}$. Then

1. ϕ is \mathbb{C} -linear if and only if $\tilde{\phi}J = J\tilde{\phi}$.
2. ϕ preserves $g_{\mathbb{C}}$ if and only if $\tilde{\phi}$ preserves h . Taking the real and imaginary part, the latter is equivalent to the fact that $\tilde{\phi}$ preserves g and ω .
3. Every \mathbb{C} -linear $\tilde{\phi}$ preserves orientation of $V^{1,0}$ as \mathbb{R}^{2n} (note that the fact that $\tilde{\phi}$ preserves orientation or not is independent of how one identifies $V^{1,0}$ and \mathbb{R}^{2n}).

Hence for every J , $\phi \mapsto \tilde{\phi}$ gives an embedding of $U(V^{1,0})$ to $SO(V)$. By each an orthonormal base of $V^{1,0}$ and that of V give an embedding $U(n) \subset SO(2n)$.

Remark 1. *The image of $U(n)$ in $SO(2n)$ may depend on J and the orthonormal base of V , but its conjugacy class in $SO(2n)$ is uniquely defined. This is because every complex structure J is, up to an orthonormal conjugation,*

$$J_0 = \begin{pmatrix} 0 & I_n \\ -I_n & 0 \end{pmatrix}.$$

Complexified dual and forms, prelude to Kähler geometry

We state first some linear algebra facts, whose proofs are tedious and can be consulted in the Manuscript.

Lemma 3 (Linear algebra facts). *1. Let $V = W_1 \oplus W_2$ be an R -module then the exterior algebra of V splits into*

$$\wedge^n V = \bigoplus_{p+q=n} \wedge^p W_1 \otimes \wedge^q W_2$$

We remark that the tensor product here is formal, and not related to the tensor product defining the exterior algebra.

2. *If V has a complex structure J then J gives a complex structure on $V^* = \text{Hom}_{\mathbb{R}}(V, \mathbb{R})$, naturally by $\phi \mapsto \phi \circ J$.*

One has

$$(V^*)_{\mathbb{C}} = \text{Hom}_{\mathbb{R}}(V, \mathbb{C}) \equiv \text{Hom}_{\mathbb{C}}(V_{\mathbb{C}}, \mathbb{C})$$

and

$$(V^*)^{1,0} = \text{Hom}_{\mathbb{C}}((V, J), \mathbb{C}), \quad (V^*)^{0,1} = \text{Hom}_{\mathbb{C}}((V, -J), \mathbb{C})$$

$$\begin{array}{ccc}
(V, J) & \xrightarrow{dz_i} & \mathbb{C} \\
\downarrow \iota_J & \nearrow dz_i & \\
(V^{1,0}, i) & &
\end{array}
\quad
\begin{array}{ccc}
V & \xrightarrow{dz_i} & \mathbb{C} \\
\downarrow \mathbb{C}\text{-lin} & \nearrow dz_i & \\
V_{\mathbb{C}} & &
\end{array}$$

Figure 1: Two natural ways to define dz_i on $V^{1,0}$

where $Hom_{\mathbb{C}}(V, \mathbb{C})$ denotes the set of \mathbb{R} -linear morphisms that preserves complex structures (\mathbb{C} is implicitly with the complex structure $z \mapsto iz$)

Therefore $(V^*)_{\mathbb{C}} = (V^*)^{1,0} \oplus (V^*)^{0,1}$ is rewritten as

$$Hom_{\mathbb{R}}(V, \mathbb{C}) = Hom_{\mathbb{C}}((V, J), \mathbb{C}) \oplus Hom_{\mathbb{C}}((V, -J), \mathbb{C})$$

Using the first point of Lemma 3, one has

$$\wedge^n (V^*)_{\mathbb{C}} = \oplus_{p+q=n} \wedge^{p,q} (V^*)_{\mathbb{C}}$$

where $\wedge^{p,q} T_{\mathbb{C}}^* M$ denotes the \mathbb{C} -vector space of forms that are p times \mathbb{C} -linear and q times \mathbb{C} -antilinear.

Note one can easily find in V an orthonormal basis $\partial_{x_i}, \partial_{y_i}$ with $J(\partial_{x_i}) = \partial_{y_i}$. We clarify here the definition and implicit identifications of basic objects such as dz_i and $d\bar{z}_i$.

Object	Where it belongs/ properties	\mathbb{C} -linear extension/ properties
$\partial_{z_i} = \iota_J(\partial_{x_i}) = \frac{1}{2}(\partial_{x_i} - i\partial_{y_i})$	$V^{1,0}$	$dz_i(\partial_{z_j}) = \delta_{i,j}, dz_i(\partial_{\bar{z}_j}) = 0$
$\partial_{\bar{z}_i} = \iota_{-J}(\partial_{x_i}) = \frac{1}{2}(\partial_{x_i} + i\partial_{y_i})$	$V^{0,1}$	$d\bar{z}_i(\partial_{z_j}) = 0, d\bar{z}_i(\partial_{\bar{z}_j}) = \delta_{i,j}$
$dz_i = dx_i + idy_i$	$Hom_{\mathbb{C}}((V, J), \mathbb{C}), \mathbb{C}$ -linear	$Hom_{\mathbb{C}}(V_{\mathbb{C}}, \mathbb{C}),$ null on $V^{0,1}$,
$d\bar{z}_i = dx_i - idy_i$	$Hom_{\mathbb{C}}((V, -J), \mathbb{C}), \mathbb{C}$ -antilinear	$Hom_{\mathbb{C}}(V_{\mathbb{C}}, \mathbb{C}),$ null on $V^{1,0}$

Remark 2. One can note a subtlety here: there are two natural ways to extend dz_i to $V^{1,0}$

1. by first make a \mathbb{C} -linear extension on $V_{\mathbb{C}}$, then make a restriction on $V^{1,0}$

2. using the identification $(V, J) \equiv (V^{1,0}, i)$

but these two coincide, as they are all \mathbb{C} -linear and satisfy $dz_i(\partial_{z_j}) = \delta_{i,j}, dz_i(\partial_{\bar{z}_j}) = 0$. Same story with $d\bar{z}_i$. See Figure and Figure

$$\begin{array}{ccc}
(V, -J) & \xrightarrow{d\bar{z}_i} & \mathbb{C} \\
\downarrow \iota_J & \nearrow d\bar{z}_i & \\
(V^{0,1}, i) & &
\end{array}
\qquad
\begin{array}{ccc}
V & \xrightarrow{d\bar{z}_i} & \mathbb{C} \\
\downarrow \mathbb{C}\text{-lin} & \nearrow d\bar{z}_i & \\
V_{\mathbb{C}} & &
\end{array}$$

Figure 2: Two natural ways to define $d\bar{z}_i$ on $V^{0,1}$

Definition 2 (Theorem). *The following properties are equivalent and X is called a Kähler manifold if one of them is satisfied.*

1. X is a complex manifold, equipped with a Hermitian structure $h(.,.)$ compatible with the complex structure J , and a fundamental form ω , and $d\omega = 0$.
2. X is a Riemannian manifold equipped with a parallel complex structure.
3. X is a complex manifold, equipped with a Hermitian structure such that the Chern connection on $T^{1,0}X$ is, up to an identification by ι_J , the Levi-Civita connection
4. X is a complex manifold, equipped with a Hermitian structure such that the Chern connection on $T^{1,0}X$ is torsionless

We call a complex manifold X of Kähler type if there exists a Hermitian structure under which X is Kähler.

The proof is straightforward, see Manuscript for details.