

HYPERKÄHLER MANIFOLDS

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ABSTRACT. These are personal notes for the course on hyperkähler manifolds taught by Alessio Bottini at Universität Bonn in the Winter 2025-2026 semester. Please email me at s37mbrai@uni-bonn.de if you notice any typo.

1. FIRST LECTURE

We first review some complex geometry.

Definition 1.0.1. A **complex manifold** is a locally ringed space (X, \mathcal{O}_X) such that

- X is Hausdorff and second countable (this part is to ensure we actually have a topological manifold);
- (X, \mathcal{O}_X) is locally isomorphic to $(\Delta, \mathcal{O}_\Delta)$, where $\Delta \subset \mathbb{C}^n$ is the polydisc.

Example 1.0.2. Let $f_1, \dots, f_d \in \mathbb{C}[z_1, \dots, z_n]$ be complex polynomials such that the Jacobian of

$$f = (f_1, \dots, f_d) : \mathbb{C}^n \rightarrow \mathbb{C}^d$$

has everywhere full rank on the vanishing set $V = V(f) \subset \mathbb{C}^n$. By the holomorphic implicit function theorem (regular value theorem), V is a complex manifold.

Example 1.0.3. If X is a smooth algebraic variety over \mathbb{C} , we may cover it by affines V_i which are of the same form as in [Example 1.0.2](#). We may consider the analytic topology X^{an} obtained by gluing the different charts V_i . Similarly, we may define the sheaf \mathcal{O}_X^{an} on X^{an} by considering the sheaf of holomorphic functions on each V_i (the transitions $V_i \rightarrow V_j$ are regular algebraic, hence holomorphic, so that this gluing makes sense). Then, $(X^{an}, \mathcal{O}_X^{an})$ is a complex manifold.

Note that in [Example 1.0.3](#), we obtain a natural map of ringed spaces

$$\alpha : (X^{an}, \mathcal{O}_X^{an}) \rightarrow (X, \mathcal{O}_X)$$

since the analytic topology is finer than the Zariski topology, and regular functions are holomorphic. In particular, we obtain a functor between abelian categories:

$$\alpha^* : \mathcal{O}_X\text{-mod} \rightarrow \mathcal{O}_X^{an}\text{-mod}$$

restricting to

$$\alpha^* : \text{Coh}(X) \rightarrow \text{Coh}(X^{an}).$$

Theorem 1.0.4 (Géométrie algébrique géométrie analytique; [Ser56]). *If X is smooth¹ and proper functor $\alpha^* : \text{Coh}(X) \rightarrow \text{Coh}(X^{an})$ is an equivalence, which moreover induces an isomorphism of sheaf cohomology.*

1.1. Almost complex structures. A complex manifold (X, \mathcal{O}_X) has an underlying smooth manifold (X, C_X^∞) , where C_X^∞ denotes the sheaf of smooth functions on X ; indeed, if X has complex charts $U_i \subset \mathbb{C}^n$, the transitions are holomorphic, hence C^∞ .

Notation 1.1.1. Since the indices i will be ubiquitous, ι shall denote the root of -1 for these notes (this spares the cumbersome $\sqrt{-1}$ alternative).

On each chart U_i , we have multiplication by ι , but this does not globalise, as ι does not commute with holomorphic functions: in the Taylor expansion, we have terms which are of degree m where $m \not\equiv 1 \pmod{4}$. However, the differential of ι may be globalised, as we get rid of the higher order terms. In a local chart $U_i \subset \mathbb{C}^n$, the (real) tangent bundle has a local frame

$$T_{\mathbb{R}}U_i = \langle \partial_{x_j}, \partial_{y_j} : 1 \leq j \leq n \rangle,$$

on which $I := d\iota$ acts by

$$\begin{cases} \partial_{x_j} \mapsto \partial_{y_j} \\ \partial_{y_j} \mapsto -\partial_{x_j}. \end{cases}$$

Definition 1.1.2. An **almost complex structure** on a smooth manifold X is an endomorphism $I \in \text{End}(T_{\mathbb{R}}X)$ such that $I^2 = -1$. We say that I is integrable if X is a complex manifold and I is obtained by locally differentiating ι .

Question 1.1.3. Given I an almost complex structure, when is it integrable?

Let us first set up some tools in order to address this question appropriately. Assume only for now that X is a smooth manifold and I is an almost complex structure. We can consider the complexified tangent bundle

$$T_{\mathbb{C}}X := T_{\mathbb{R}}X \otimes_{\mathbb{R}} \mathbb{C},$$

¹This can be dropped by considering complex analytic spaces (rather than manifolds).

to which we can extend the action of I . Since $I^2 = -1$, the minimal polynomial of I is $x^2 + 1$, which is separable over \mathbb{C} , meaning that I is diagonalisable, with eigenvalues $\pm i$. The eigenspaces must have the same dimension as I acts on the *real* tangent space. We thus obtain a decomposition

$$T_{\mathbb{C}}X = T^{1,0}X \oplus T^{0,1}X = T^{1,0}X \oplus \overline{T^{1,0}X}.$$

Note that we have

$$T^{1,0}X = \{(v - iIv) : v \in T_{\mathbb{C}}X\} \quad T^{0,1}X = \{(v + iIv) : v \in T_{\mathbb{C}}X\}.$$

Notation 1.1.4. We will use the following notation

- $\mathcal{A}^0(X) := C_X^\infty$;
- $\mathcal{A}^k(X)$ denotes the sheaf of (smooth) degree k real forms;
- $\mathcal{A}^k(X, \mathbb{C}) = \bigoplus_{p+q=k} \mathcal{A}^{p,q}(X)$ denotes the sheaf of sections of $\bigwedge^k T_{\mathbb{C}}^*X$ (i.e. smooth complex degree k forms) and $\mathcal{A}^{p,q}(X)$ denotes the sheaf of sections of $\bigwedge^p T^{1,0}X \otimes \bigwedge^q T^{0,1}X$;
- $d : \mathcal{A}^k(X, \mathbb{C}) \rightarrow \mathcal{A}^{k+1}(X, \mathbb{C})$ denotes the complexification of the usual exterior derivative, and can be decomposed by types as $d = \partial + \bar{\partial}$, where ∂ denotes the part corresponding to the differentiation in holomorphic coordinates, and similarly $\bar{\partial}$ for anti-holomorphic coordinates.
- $A^k(X)$, $A^k(X, \mathbb{C})$, and $A^{p,q}(X)$ denotes the global sections of $\mathcal{A}^k(X)$, $\mathcal{A}^k(X, \mathbb{C})$, and $\mathcal{A}^{p,q}(X)$ respectively.
- \mathcal{T}_X denotes the sheaf of homolorphic vector fields, i.e. $\mathcal{T}_X := \text{Der}(\mathcal{O}_X, \mathcal{O}_X)$;
- $\Omega_X := \mathcal{T}_X^*$ denotes the cotangent sheaf.

The following theorem answers [Question 1.1.3](#).

Theorem 1.1.5 (Newlander-Niremberg). *I is integrable if and only if $\bar{\partial}^2 = 0$.*

Note that this is equivalent to $T^{1,0}X$ being closed under the (complex) Lie bracket (this is much related to the Frobenius theorem of differential geometry), and also equivalent of the vanishing of a certain tensor N_I called the *Nijenhuis* tensor.

1.2. Metrics. Let E be a real vector bundle on (X, C_X^∞) . A **Riemannian metric** g on E is a section of $\text{Sym}^2 E^\vee$ such that for all $p \in X$, g_p is positive definite. If E is a complex bundle, a **Hermitian metric** h is a map of sheaves $E \otimes \bar{E} \rightarrow C^\infty(X, \mathbb{C})$ such that each h_p is Hermitian, i.e. $h_p(e, f) = \overline{h_p(f, e)}$ and $h_p(e, e) > 0$ for all $e, f \in E_p$. When $E = T_{\mathbb{R}}X$, we say that g (resp. h) is a **Riemannian** (resp. **Hermitian**) **metric** on X (here, the almost complex structure I is used to put a \mathbb{C} -structure on $T_{\mathbb{R}}X$).

If X is a complex manifold and h is a Hermitian metric, then we can write

$$h = g - i\omega$$

where $g = \Re(h)$ and $\omega = -\Im(h)$. We obtain that g is a Riemannian metric, and ω is skew-symmetric since

$$\omega(X, Y) = \frac{i}{2}(h(X, Y) - \bar{h}(X, Y))$$

and h is conjugate skew-symmetric. Thus, $\omega \in A^2(X)$.

Definition 1.2.1. (X, h) is **Kähler** if $d\omega = 0$.

That h is linear in the first variable and anti-linear in the second ensures that $h(I-, I-) = h(-, -)$, implying that $g(I-, I-) = g(-, -)$, a property that is sometimes called **compatibility** of the metric with I . We have

$$\omega(-, -) = \frac{i}{2}(h(-, -) - \bar{h}(-, -)) = \frac{1}{2}(h(I-, -) + \bar{h}(I-, -)) = g(I-, -),$$

which also implies

$$\omega(-, I-) = g(-, -).$$

Definition 1.2.2. A form $\omega \in A^2(X)$ is called **positive** if $\omega(u, Iu) > 0$ for all $u \in T_{\mathbb{R}}X$. We see that a de Rham cohomology class in $H^2(X, \mathbb{C})$ is **positive** if it can be represented by a positive form. If moreover ω is I -invariant (or equivalently, of type $(1, 1)$ after embedding $A^2(X) \subset A(X, \mathbb{C})$), we say ω is **Kähler**.

If ω is Kähler, we may define the hermitian metric $h_\omega = \omega(-, I-) - i\omega$, and we have that ω is Kähler if and only if (X, h_ω) is Kähler.

Example 1.2.3. Let $X = \mathbb{P}^n$, with projective coordinates Z_0, \dots, Z_n . Let U_i be the $Z_i \neq 0$ chart, and define $z_j = \frac{Z_j}{Z_i}$. We may define on U_i the metric

$$\omega_{FS} = \omega = i\partial\bar{\partial} \log \left(1 + \sum_j z_j \bar{z}_j \right),$$

and one checks that these glue to a global form, which we call the **Fubini-Study metric**. Written as a Kähler potential this way shows that it is a Kähler metric.

Note that if (X, ω) is Kähler, restricting the metric to a complex submanifold Y preserves all properties of [Definition 1.2.2](#), and so (Y, ω_Y) is Kähler. Thus, any projective manifold is Kähler.

1.3. Connections. Let E be a complex (the real case is identical) vector bundle on (X, C_X^∞) . A **complex connection** in E is a \mathbb{C} -linear map

$$\nabla : \mathcal{A}^0(E, \mathbb{C}) \rightarrow \mathcal{A}^1(E, \mathbb{C}),$$

(here $\mathcal{A}^i(E, \mathbb{C}) = \mathcal{A}^i(X, \mathbb{C}) \otimes \Gamma(E)$) such that

$$\nabla(f \cdot s) = df \otimes s + f \cdot \nabla s$$

for all section s of E and $f \in C_X^\infty$.

If E is a holomorphic bundle on a complex manifold, we can define the operator

$$\bar{\partial} : \mathcal{A}^0(E) \rightarrow \mathcal{A}^{0,1}(E)$$

as follows: if σ_i is a local frame, and $s = s^i \sigma_i$ a section, we let

$$(1.1) \quad \bar{\partial}(s^i \sigma_i) := (\bar{\partial}s^i) \otimes \sigma_i.$$

Indeed, given another frame τ_j related by $\sigma_i = g_{ij} \tau_j$, we have

$$\bar{\partial}(s^i) \otimes \sigma_i = \bar{\partial}(s^i) \otimes g_{ij} \tau_j = \bar{\partial}(g_{ij} s^i) \otimes \tau_j$$

since the transitions g_{ij} are holomorphic by assumption.

A (complex) connection being valued in $\mathcal{A}^1(E, \mathbb{C}) = \mathcal{A}^{1,0}(E) \oplus \mathcal{A}^{0,1}(E)$, we may split $\nabla = \nabla^{1,0} + \nabla^{0,1}$.

Definition 1.3.1. The complex connection ∇ in E is said to be **compatible** with the holomorphic structure if $\nabla^{0,1} = \bar{\partial}$. Suppose E has a hermitian metric h . We say ∇ is **compatible** with h if for any sections e, f , we have equality of forms

$$d(h(e, f)) = h(\nabla e, f) + h(e, \nabla f).$$

More geometrically, this says that h is parallel to the connection, i.e. constant along parallel transport, i.e. the connection has $U(n)$ -holonomy. We say ∇ is a **Chern connection** if it is both compatible with the holomorphic structure and the hermitian metric.

Theorem 1.3.2 (Chern). *There exists a unique Chern connection.*

When $E = T_{\mathbb{R}}X$, the Chern connection ought to be regarded as the complex geometric analogue of the Levi-Civita connection from Riemannian geometry. In fact this is more than an analogy. If h is a hermitian metric, the Levi-Civita connection of $g = \Re(h)$ can be complexified to a complex connection. It is a theorem that the Levi-Civita connection is the Chern connection if and only if (X, h) is Kähler.

We can extend the connection $\nabla : \mathcal{A}^0(E, \mathbb{C}) \rightarrow \mathcal{A}^1(E, \mathbb{C})$ to a connection

$$\nabla : \mathcal{A}^p(E, \mathbb{C}) \rightarrow \mathcal{A}^{p+1}(E, \mathbb{C})$$

for all positive p via

$$\nabla(\omega \otimes s) = d\omega \otimes s + (-1)^p \omega \wedge \nabla s,$$

where ω is a p -form and s is a section of E .

Remark 1.3.3. Note that this is different from the usual extension of a connection to tensors since we are dealing with skew-symmetric forms. In particular, this satisfies a different Leibniz rule:

$$\nabla(fs) = df \wedge s \otimes d\nabla s.$$

Definition 1.3.4. We define the **curvature** of ∇ to be the composition $\nabla^2 = \nabla \circ \nabla = F_\nabla$.

Note that

$$\begin{aligned}\nabla(\nabla f s) &= \nabla(df \otimes s + f \nabla s) = ddf - df \wedge \nabla s + \nabla(f \nabla s) \\ &= -df \wedge \nabla s + df \wedge \nabla s + f \nabla^2 s = f \nabla^2 s\end{aligned}$$

so that F_∇ is C_X^∞ -linear, that is a section of $\mathcal{A}^2(\text{End}(E), \mathbb{C})$.

We may also define

$$F_\nabla^k := \underbrace{F_\nabla \circ \dots \circ F_\nabla}_k \in \mathcal{A}^{2k}(\text{End}(E), \mathbb{C}).$$

We define the **k th Chern character** of ∇ to be

$$\text{ch}_k(E, \nabla) := \text{Tr} \left(\frac{1}{k!} \left(\frac{\iota}{2\pi} F_\nabla^k \right) \right) \in A^{2k}(X, \mathbb{C}).$$

Theorem 1.3.5 (Chern-Weil). *The following is true about the Chern character.*

- (1) $ch_k(E, \nabla)$ is closed;
- (2) The cohomology class $ch_k(E) := [ch_k(E, \nabla)] \in H_{dR}^{2k}(X, \mathbb{C})$ is independent of ∇ ;
- (3) $ch_k(E)$ is real, i.e. in $H_{dR}^{2k}(X, \mathbb{R})$ (in fact, it is integral);
- (4) The total Chern character $\sum_k ch_k(E)$ is equal to the cohomology class of $\text{Tr}(\exp(\frac{\iota}{2\pi} F_\nabla))$ (this one directly follows from developing the exponential).

2. SECOND LECTURE

2.1. Chern classes. Let V be a vector space over \mathbb{C} of dimension r . Let $P \in \mathbb{C}[End(V)]$ be a homogeneous polynomial of degree k . Assume moreover P is $GL(V)$ invariant, that is $P(A^{-1}BA) = P(B)$ for any $A \in GL(V)$.

Let now E be a complex vector bundle and ∇ a connection. By $GL(V)$ invariance, $P(\frac{1}{2\pi}F_\nabla)$ is well-defined, and lives in $A^{2k}(X, \mathbb{C})$.

Fact 2.1.1 (Chern-Weil). $P(\frac{1}{2\pi}F_\nabla)$ is closed, and the class $[P(\frac{1}{2\pi}F_\nabla)] \in H^{2k}(X, \mathbb{C})$ is independent of ∇ .

Consider now the $GL(V)$ -invariant homogeneous polynomials P_k returning the coefficients of the characteristic polynomials (i.e. P_k k th elementary symmetric polynomial on the eigenvalues). We can explicitly define P_k by the formula:

$$\det(I + tB) = \sum_k P_k(B)t^k.$$

We define the **k th Chern class** of E to be the cohomology class of $P_k(\frac{i}{2\pi}F_\nabla)$, and the **total Chern class** of E to be $c(E) := \sum_{i=0}^k c_i(E)$.

The Chern classes and characters satisfy certain properties:

- $c_0(E) = 1$ and $ch_0 = r$;
- $c_d = 0$ if $d > r$. In particular, if L is a line bundle, $c(L) = 1 + c_1(L)$;
- $ch(L) = \exp(c_1(L)) := 1 + c_1(L) + \frac{c_1(L)^2}{2!} + \dots \in H^{2\bullet}(X, \mathbb{C})$.

To derive further elementary properties of the Chern characters and classes, let us first observe how we can assemble connections into new connections

Let E_1 and E_2 be vector bundles with respective (complex) connections ∇_1 and ∇_2 . Then,

- $\nabla_{E_1 \oplus E_2} := \nabla_1 \oplus \nabla_2$ is a connection on $E_1 \oplus E_2$, and $F_{\nabla_1 \oplus \nabla_2} = F_{\nabla_1} \oplus F_{\nabla_2}$, where this is seen as a block matrix

$$\begin{pmatrix} F_{\nabla_1} & \\ & F_{\nabla_2} \end{pmatrix};$$

- $\nabla_{E_1 \otimes E_2} := \nabla_1 \otimes \text{id}_{E_2} + \text{id}_{E_1} \otimes \nabla_2$ is a connection on $E_1 \otimes E_2$;
- the assignment

$$(\nabla^\vee \phi)(s) := d(\phi(s)) - \phi(\nabla(s))$$

where $s \in E$ and $\phi \in E^\vee$ defines a connection on E^\vee (note that this is the usual way to extend connections on tensors). In other words, if $\langle -, - \rangle$ denotes the natural pairing on $E \otimes E^\vee$, the dual connection is defined by

$$d\langle s, \phi \rangle = \langle \nabla s, \phi \rangle + \langle s, \nabla^\vee \phi \rangle.$$

Let us try to compare the two curvatures. Given s_i and t_j frames of E , we consider the connection form $A = (A_i^j)$ satisfying $\nabla s_i = A_i^j \otimes t_j$. Let s^i and t^j be the dual frames. We obtain

$$\begin{aligned} d\langle s_i, t^j \rangle &= 0 = \langle \nabla s_i, t^j \rangle + \langle s_i, \nabla^\vee t^j \rangle \\ &= \langle A_i^k \otimes t_k, t^j \rangle + \langle s_i, B_k^j \otimes s^k \rangle \\ &= A_i^j + B_i^j, \end{aligned}$$

where $B = (B_i^j)$ is the connection form of ∇^\vee . And so we have $B = -A^t$ as sections of $\mathcal{A}^2(End(E), \mathbb{C}) = \mathcal{A}^2(End(E^\vee), \mathbb{C})$. Using Cartan's formula for the curvature of a connection, we conclude

$$F_{\nabla^\vee} = d(-A^t) + (-A^t) \wedge (-A^t) = -(dA + A \wedge A)^t = -F_\nabla^t.$$

- connections pull back, that is if $f : Y \rightarrow X$ is a smooth map and E is a bundle on X with connection ∇_E , we may define the connection ∇_{f^*E} by *locally* demanding

$$\nabla_{f^*E}(f^*s) = f^*\nabla s.$$

Corollary 2.1.2. Let E_1, E_2 be complex vector bundles on X . The following hold:

- (1) $ch(E_1 \oplus E_2) = ch(E_1) + ch(E_2)$ and $c(E_1 \oplus E_2) = c(E_1) \cup c(E_2)$;
- (2) $ch(E_1 \otimes E_2) = ch(E_1) \cup ch(E_2)$;
- (3) $c_k(E^\vee) = (-1)^k c_k(E)$
- (4) $ch_k(f^*E) = f^*(ch_k(E))$ and $c_k(f^*E) = f^*(c_k(E))$.

Note that $c_k(E) \in H^{2k}(X, \mathbb{C})$ is in fact real: indeed, conjugation acts via $\overline{F_\nabla} = F_{\overline{\nabla}}$, and up to choosing a hermitian metric, we have $E^\vee \simeq \overline{E}$ and $F_{\overline{\nabla}} = -F_\nabla^t$, and in a Chern splitting, the eigenvalues $\omega_1, \dots, \omega_r$ are purely imaginary. We obtain

$$c_k(E) = P_k\left(\frac{\iota}{2\pi} F_\nabla\right) = \left[\frac{\iota^k}{(2\pi)^k} P_k(F_\nabla) \right] = \left[\frac{\iota^k}{(2\pi)^k} \sigma_k(\omega_1, \dots, \omega_r) \right]$$

while

$$\overline{c_k(E)} = \left[\frac{(-1)^k \iota^k}{(2\pi)^k} \sigma_k(-\omega_1, \dots, -\omega_r) \right] = \left[\frac{(-1)^{2k} \iota^k}{2\pi} \sigma_k(\omega_1, \dots, \omega_r) \right] = c_k(E)$$

where σ_k denotes the k th standard symmetric polynomial, so that $c_k(E) \in H^{2k}(X, \mathbb{R})$. The k th Chern class is also $(1, 1)$. Indeed, consider the Chern connection $\nabla = \nabla^{1,0} + \nabla^{0,1} = \nabla^{1,0} + \bar{\partial}$. From this decomposition, we see that the $(0, 2)$ -part of the curvature is $\bar{\partial}^2 = 0$. Similarly, one can use the fact that the hermitian metric is parallel to show that the $(2, 0)$ part vanishes so that all ω_i are of type $(1, 1)$, from which one obtains that $c_k(E)$ is of type (k, k) .

Let $D \subset X$ be a divisor. It is a fact that the fundamental class of D is the Chern class of $\mathcal{O}(D)$, i.e.

$$[D] = c_1(\mathcal{O}(D)) \in H^2(X, \mathbb{C}),$$

showing that the first — and therefore any — Chern class is integral.

An important theorem relating to chern classes is Kodaira's embedding theorem.

Theorem 2.1.3 ([Kod54]). *A (holomorphic) line bundle L on a complex manifold X is ample (i.e. induces an embedding in projective space) if and only if it admits a metric h such that $\frac{\iota}{2\pi} F_{D_h}$ is a positive form.*

In particular, let h_0 be any hermitian metric on L , and let $\omega_0 = \frac{\iota}{2\pi} F_{D_{h_0}}$. Assuming X is Kähler, if $c_1(L) = [\omega_0]$ is positive, i.e. if it has a positive form ω as representative of the cohomology class, then we can write $\omega = \omega_0 + \frac{\iota}{2\pi} \partial\bar{\partial}\phi$ for some function ϕ by the $\partial\bar{\partial}$ -lemma. Then, one may compute that the metric $h := e^{-\phi} \cdot h_0$ satisfies $\frac{\iota}{2\pi} F_{D_h} = \omega$; indeed the $(1, 0)$ -part of the Chern of the connection is

$$h^{-1} \partial h = \partial \log h = \partial \log(e^{-\phi} h_0) = \partial \log h_0 + \partial(-\phi)$$

so that the curvature is given by

$$F_{D_{h_0}} + \bar{\partial} \partial(-\phi) = F_{D_{h_0}} + \partial \bar{\partial} \phi.$$

In particular, a line bundle L is ample if and only if $c_1(L)$ is positive, i.e. is represented by a Kähler form. Now, on a compact manifold, slightly perturbing a Kähler form inside $H^{1,1}(X, \mathbb{R})$ still yields a Kähler form, since it preserves the positivity criterion. Thus, Kähler forms form an open positive cone \mathcal{K}_X inside of $H^{1,1}(X, \mathbb{R})$ (scaling by a positive real preserves Kählerness). Moreover, by the Lefschetz theorem on $(1, 1)$ classes, the Chern map $\text{Pic}(X) \rightarrow H^{1,1}(X, \mathbb{Z})$ is surjective. Thus, we conclude that a compact complex manifold is projective if and only if \mathcal{K}_X intersects with $H^{1,1}(X, \mathbb{Z})$ inside of $H^{1,1}(X, \mathbb{R})$.

2.2. Hirzebruch-Riemann-Roch.

Definition 2.2.1. Let X be a compact complex manifold. Let ∇ be a connection in the tangent bundle. We define the **Todd class** of X to be

$$td(X) := \left[\det \left(\frac{\frac{\iota}{2\pi} F_\nabla}{1 - \exp(\frac{-\iota}{2\pi} F_\nabla)} \right) \right] \in H^{2\bullet}(X, \mathbb{C})$$

In terms of Chern roots $\omega_1, \dots, \omega_r$, we have that

$$td(X) = \prod_{i=1}^r \frac{\omega_i}{1 - e^{-\omega_i}}$$

It can be computed that we have

$$td_0(X) = 1; \quad td_1(X) = \frac{c_1}{2}; \quad td_2(X) = \frac{1}{12}(c_1^2 + c_2); \quad td_3(X) = \frac{c_1 c_2}{24} \quad td_4(X); = \frac{-c_1^4 + 4c_2 + c_1 c_3 + 3c_2^2 - c_4}{720}; \quad \dots$$

where $td_k(X)$ denotes the k th homogeneous component of $td(X)$ and $c_i = c_i(X) := c_i(\mathcal{T}_X)$.

Theorem 2.2.2 (Hirzebruch-Riemann-Roch). *Let E be a holomorphic vector bundle on a compact complex manifold X . Then, we have equality*

$$(2.1) \quad \chi(X, E) := \sum_k (-1)^k h^k(X, E) = \int_X ch(E) \cup td(X).$$

Note that since we are integrating over X , we only need to consider the top degree parts.

Example 2.2.3. Let $X = C$ be a compact Riemann surface and L be a line bundle on X . we have $ch(E) = 1 + c_1(L)$ and $td(1) = 1 + \frac{c_1(X)}{2}$. thus, we have

$$\chi(X, L) = \int_X 1 + c_1(L) + \frac{c_1(X)}{2} = \int_X c_1(L) + \frac{c_1(X)}{2} = \deg(L) + \frac{\deg(\mathcal{T}_C)}{2}.$$

What is remarkable about this theorem is that the left-hand side of (2.1) is purely holomorphic (or algebraic) whilst the right-hand side is purely topological. Another similar theorem is the algebro-geometric Gauss-Bonnet theorem.

Theorem 2.2.4. *Let X be a compact complex dimension of dimension n . Then,*

$$\chi_{top}(X) := \sum_i (-1)^i b_i(X) = \int_X c_n(X).$$

Recall the classical relation between the Euler characteristic χ_{top} and the genus g of a topological surface: $\chi_{top} = 2 - 2g$. In particular, this implies for a compact Riemann surface C as above, that

$$\int_X c_1(X) = \deg(\mathcal{T}_C) = 2 - 2g.$$

In particular, in light of what we found in [Example 2.2.3](#), we recover the classical Riemann-Roch theorem:

$$\chi(X, L) = \deg(L) - g + 1.$$

2.3. Kähler-Einstein manifolds.

Question 2.3.1. When does a smooth projective variety over \mathbb{C} admit a “canonical” metric?

Definition 2.3.2. Let (X, ω) be a compact Kähler manifold, and let D_ω be the corresponding Chern connection. We define the **Ricci form** $\text{Ric}(\omega)$ of ω to be

$$\text{Ric}(\omega) = i\text{Tr}(F_{D_\omega}) \in A^2(X, \mathbb{C}).$$

We say that (X, ω) is **Kähler-Einstein** if $\text{Ric}(\omega) = \lambda\omega$ for some constant $\lambda \in \mathbb{R}$.

Remark 2.3.3. We make the following comments.

- (1) Recall that we argued earlier that all the Chern roots of F_{D_ω} were pure imaginary of type $(1, 1)$ so that $\text{Ric}(\omega)$ is real of type $(1, 1)$.
- (2) Note also that D_ω is invariant under rescaling ω by some $\lambda > 0$ (indeed, parallelness of h is unaffected so we get the same connection). Thus, we may always assume that $\lambda = -1, 0, 1$.
- (3) since $c_1(X) = [\frac{i}{2\pi} \text{Tr} F_{D_\omega}]$ by definition, we have $[\text{Ric}(\omega)] = 2\pi c_1(X) \in H^2(X, \mathbb{R})$.
- (4) λ is proportional to the scalar curvature, and so (X, ω) being Kähler-Einstein implies that the scalar curvature with respect to $g_\omega = \omega(I-, -)$ is constant.
- (5) If X is Kähler-Einstein, then we have

$$c_1(X) = \begin{cases} 0 \\ \pm \text{positive form.} \end{cases}$$

Definition 2.3.4. We say that a complex manifold X is **Calabi-Yau** if $c_1(X) = 0$, **Fano** if $c_1(X)$ is positive, of **general type** (or **canonically polarised**) if $-c_1(X)$ is positive.

Note that by Kodaira’s embedding theorem, Fano and general type manifolds are projective.

Caution 2.3.5. It is not because a manifold fits in this trichotomy that it admits a Kähler-Einstein metric. In fact, there exist Fano varieties with no Kähler-Einstein metric. Whether a Fano variety admits such metric is equivalent to K -stability, a purely algebro-geometric notion. Nonetheless, Yau (cf. [Yau78]) proved that any Calabi-Yau manifold admits a Kähler-Einstein metric, and Aubin–Yau (cf. [Aub76; Yau78]) proved the same for general type manifolds.

Note also that not all manifolds fit in this trichotomy.

Example 2.3.6 (Curves). Let us see how these categories apply to curves.

- $g = 0$ gives only \mathbb{P}^1 . Since it is diffeomorphic to a sphere, we have positive scalar curvature. And indeed, the Fubini-Study metric is Kähler-Einstein with $\lambda = 1$. Note also that \mathbb{P}^1 is Fano.
- The $g = 1$ case corresponds to elliptic curves. These are Ricci-flat and Calabi-Yau.
- The case $g > 1$ are of general type, and there exists a Kähler-Einstein metric with negative scalar curvature.

For Fano manifolds, here is a summary of the known classifications:

- (1) In dimension 1 there is only the projective line.
- (2) In dimension 2, they are called *del Pezzo* surfaces. There are 10 different deformation families. First, \mathbb{P}^2 and $\mathbb{P}^1 \times \mathbb{P}^1$ which are isolates. The other 8 families are obtained by blowing up \mathbb{P}^2 at d points in general position, where $1 \leq d \leq 8$.
- (3) In dimension 3, Mukai proved there are 105 families.
- (4) In dimension 4, we know there are finitely many families but it remains open to know how many.

For Calabi-Yau manifolds, there is the following structural theorem.

Theorem 2.3.7 (Beauville–Bogomolov; Bog74 and Bea83). *Let X be Kähler and Calabi-Yau. Then, there exists an étale cover $\tilde{X} \rightarrow X$ such that*

$$\tilde{X} = T \times \prod_j X_j \times \prod_i V_i$$

where T is a torus, X_j is **hyperkähler** for all j , and V_i are **strict Calabi-Yau** for all i .

We now define the terms.

Definition 2.3.8. A compact Kähler manifold V is called **strict Calabi-Yau** if

- $K_V \simeq \mathcal{O}_V$ is trivial, where K_V denotes the canonical bundle;
- V is simply connected;
- $H^i(V, \mathcal{O}_V) = 0$ for all $0 < i < \dim V$.

A complex manifold X is **hyperkähler** if

- it is simply connected;
- $H^0(X, \Omega_X^2) \simeq \mathbb{C}\sigma$ where σ is holomorphic symplectic (in particular, it induces an isomorphism $\mathcal{T}_X \simeq \Omega_X$).

Remark 2.3.9. If V is a strict Calabi-Yau of dimension greater than two, then $h^{2,0} = h^{0,2} = 0$. In particular, $H^{1,1}(X, \mathbb{C}) = H^2(X, \mathbb{C})$, and so $H^{1,1}(X, \mathbb{R}) = H^2(X, \mathbb{R}) = H^{1,1}(X, \mathbb{Z}) \otimes_{\mathbb{Z}} \mathbb{R}$. Since the Kähler cone is not empty by assumption, we conclude that it intersects $H^{1,1}(X, \mathbb{Z})$, so that V is projective by our discussion on Kodaira’s embedding theorem. In dimension 2, non-projective K3 surfaces yield an example of non-projective strict Calabi-Yau manifolds.

Remark 2.3.10. Theorem 2.3.7 has an important corollary. Namely, if X is a Kähler, we have a degree n étale map $f : \tilde{X} \rightarrow X$ with the canonical bundle $K_{\tilde{X}}$ of \tilde{X} trivial. Since f is étale, $f^*K_X = K_{\tilde{X}}$, which implies that $nK_X = 0$ (this follows from existence of a norm map $\mathcal{O}_{\tilde{X}} \rightarrow \mathcal{O}_X$ mapping $f^*g \mapsto g^n$; see [Stacks, Tag 0BD3 and Tag 0BCY] for the algebraic case). Thus, for Kähler manifolds, being Calabi-Yau and that $nK_X = 0$ for some $n \geq 0$ are equivalent conditions.

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