Holomorphic Morse Inequalities and the Green-Griffiths-Lang conjecture

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Entire curves

- **Definition.** By an entire curve we mean a non constant holomorphic map $f : \mathbb{C} \to X$ into a complex n-dimensional manifold.
  X is said to be (Brody) hyperbolic if $\nexists$ such $f : \mathbb{C} \to X$.
- If X is a bounded open subset $\Omega \subset \mathbb{C}^n$, then there are no entire curves $f : \mathbb{C} \to \Omega$ (Liouville's theorem),
  $\Rightarrow$ every bounded open set $\Omega \subset \mathbb{C}^n$ is hyperbolic
- $X = \overline{\mathbb{C}} \smallsetminus \{0, 1, \infty\} = \mathbb{C} \smallsetminus \{0, 1\}$ has no entire curves, so it is hyperbolic (Picard's theorem)
- A complex torus $X = \mathbb{C}^n/\Lambda$ (Λ lattice) has a lot of entire curves. As $\mathbb{C}$ simply connected, every $f : \mathbb{C} \to X = \mathbb{C}^n/\Lambda$ lifts as $\tilde{f} : \mathbb{C} \to \mathbb{C}^n$, $\tilde{f}(t) = (\tilde{f}_1(t), \ldots, \tilde{f}_n(t))$, and $\tilde{f}_j : \mathbb{C} \to \mathbb{C}$ can be arbitrary entire functions.

Projective algebraic varieties

- Consider now the complex projective n-space

$$\mathbb{P}^n = \mathbb{P}^n_{\mathbb{C}} = (\mathbb{C}^{n+1} \smallsetminus \{0\})/\mathbb{C}^*, \qquad [z] = [z_0 : z_1 : \ldots : z_n].$$

- An entire curve $f : \mathbb{C} \to \mathbb{P}^n$ is given by a map

$$t \longmapsto [f_0(t) : f_1(t) : \ldots : f_n(t)]$$

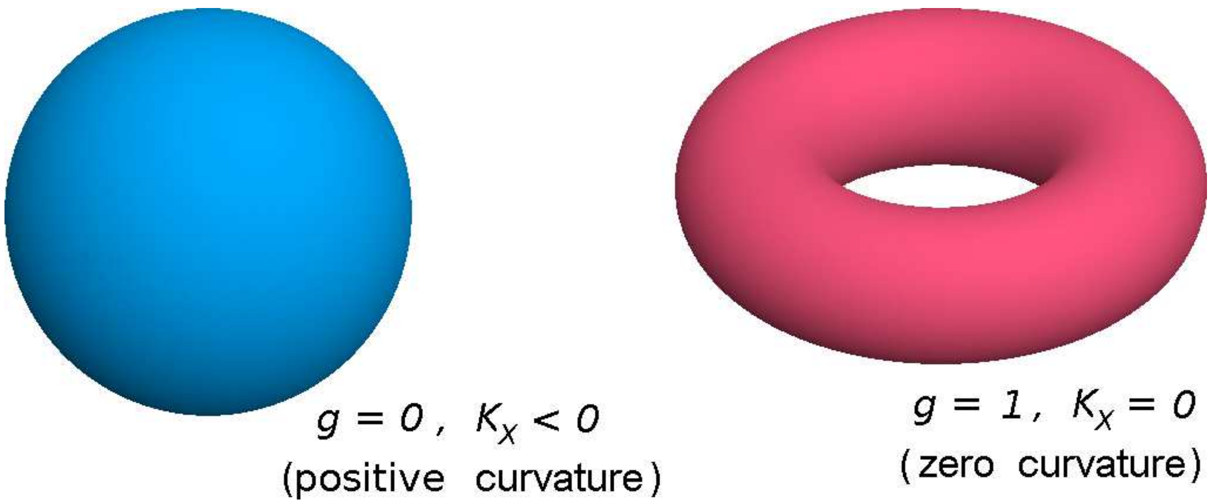
  where $f_j : \mathbb{C} \to \mathbb{C}$ are holomorphic functions without common zeroes (so there are a lot of them).

- More generally, look at a (complex) projective manifold, i.e.

$$X^n \subset \mathbb{P}^N, \qquad X = \{[z]\,;\ P_1(z) = ... = P_k(z) = 0\}$$

  where $P_j(z) = P_j(z_0, z_1, \ldots, z_N)$ are homogeneous polynomials (of some degree d_j), such that X is non singular.

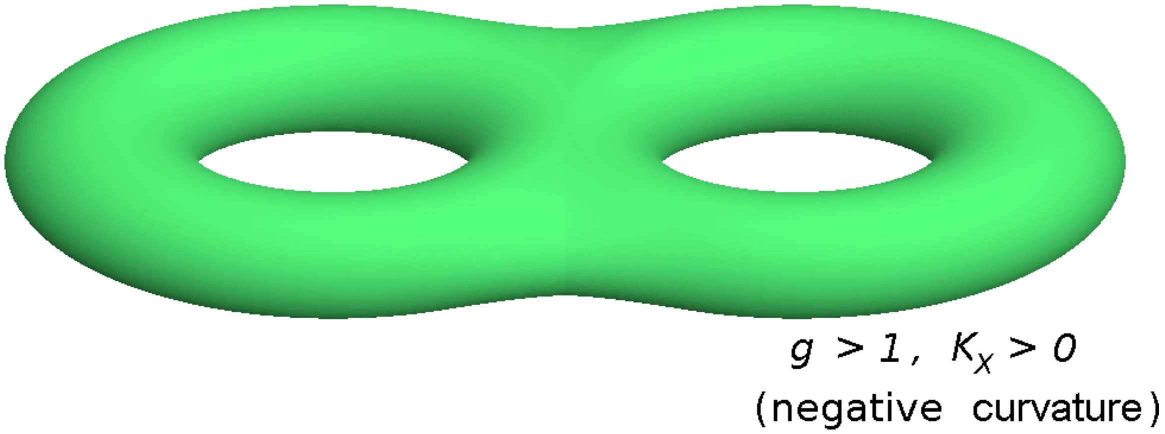
Complex curves (genus 0 and 1)



Canonical bundle $K_X = \Lambda^n T^*_X$ (here $K_X = T^*_X$)

- $g = 0 :\ X = \mathbb{P}^1$ courbure $T_X > 0$ not hyperbolic
- $g = 1 :\ X = \mathbb{C}/(\mathbb{Z} + \mathbb{Z}\tau)$ courbure $T_X = 0$ not hyperbolic

Complex curves (genus $g \geq 2$)



$\deg K_X = 2g - 2$

If $g \geq 2$, $X \simeq \mathbb{D}/\Gamma$ $(T_X < 0)$ $\Rightarrow$ X is hyperbolic.

In fact every curve $f : \mathbb{C} \to X \simeq \mathbb{D}/\Gamma$ lifts to $\widetilde{f} : \mathbb{C} \to \mathbb{D}$, and so must be constant by Liouville.

Kobayashi metric / hyperbolic manifolds

- For a complex manifold, $n = \dim_{\mathbb{C}} X$, one defines the Kobayashi pseudo-metric : $x \in X$, $\xi \in T_X$
  $\kappa_x(\xi) = \inf\{\lambda > 0\,;\ \exists f : \mathbb{D} \to X,\ f(0) = x,\ \lambda f_*(0) = \xi\}$
  On $\mathbb{C}^n$, $\mathbb{P}^n$ or complex tori $X = \mathbb{C}^n/\Lambda$, one has $\kappa_X \equiv 0$.
- X is said to be hyperbolic in the sense of Kobayashi if the associated integrated pseudo-distance is a distance (i.e. it separates points – i.e. has Hausdorff topology).
- **Examples.** $*$ $X = \Omega/\Gamma$, Ω bounded symmetric domain.
  $*$ any product $X = X_1 \times \ldots \times X_s$ where X_j hyperbolic.
- **Theorem (dimension *n* arbitrary)** (Kobayashi, 1970)
  T_X negatively curved ($T_X^* > 0$, i.e. ample) $\Rightarrow$ X hyperbolic.
  Recall that a holomorphic vector bundle E is ample iff its symmetric powers $S^m E$ have global sections which generate 1-jets of (germs of) sections at any point $x \in X$.

The proof of the above Kobayashi result depends crucially on:

Ahlfors-Schwarz lemma. Let $\gamma = i\sum \gamma_{jk} dt_j \wedge d\overline{t}_k$ be an almost everywhere positive hermitian form on the ball $B(0,R) \subset \mathbb{C}^p$, such that $-\mathrm{Ricci}(\gamma) := i\,\partial\overline{\partial}\log\det\gamma \geq A\gamma$ in the sense of currents, for some constant $A > 0$ (this means in particular that $\det\gamma = \det(\gamma_{jk})$ is such that $\log\det\gamma$ is plurisubharmonic). Then the γ-volume form is controlled by the Poincaré volume form :

$$\det(\gamma) \leq \Big(\frac{p+1}{AR^2}\Big)^p \frac{1}{(1-|t|^2/R^2)^{p+1}}.$$

Brody reparametrization Lemma. *Assume that X is compact, let ω be a hermitian metric on X and $f : \mathbb{D} \to X$ a holomorphic map. For every $\varepsilon > 0$, there exists a radius $R \geq (1-\varepsilon)\|f'(0)\|_\omega$ and a homographic transformation ψ of the disk $D(0,R)$ onto $(1-\varepsilon)\mathbb{D}$ such that $\|(f\circ\psi)'(0)\|_\omega = 1$ and $\|(f\circ\psi)'(t)\|_\omega \leq (1-|t|^2/R^2)^{-1}$ for every $t \in D(0,R)$.*
$\Rightarrow$ if f' unbounded, $\exists g = \lim f\circ\psi_\nu : \mathbb{C} \to X$ with $\|g'\|_\omega \leq 1$.

Brody theorem (1978). *If X is compact then X is Kobayashi hyperbolic if and only if there are no entire holomorphic curves $f : \mathbb{C} \to X$ (Brody hyperbolicity).*

Hyperbolic varieties are especially interesting for their expected diophantine properties :

Conjecture (S. Lang, 1986) *An arithmetic projective variety X is hyperbolic iff $X(\mathbb{K})$ is finite for every number field $\mathbb{K}$.*

- **Definition** *A non singular projective variety X is said to be of general type if the growth of pluricanonical sections*

$$\dim H^0(X, K_X^{\otimes m}) \sim cm^n, \qquad K_X = \Lambda^n T_X^*$$

is maximal.

(sections locally of the form $f(z)\,(dz_1 \wedge \ldots \wedge dz_n)^{\otimes m}$)

Example: A non singular hypersurface $X^n \subset \mathbb{P}^{n+1}$ of degree d satisfies $K_X = \mathcal{O}(d-n-2)$,
X is of general type iff $d > n+2$.

- **Conjecture CGT.** *If a compact variety X is hyperbolic, then it should be of general type, and if X is non singular, then $K_X = \Lambda^n T_X^*$ should be ample, i.e. $K_X > 0$ (Kodaira) (equivalently $\exists$ Kähler metric ω such that Ricci$(\omega) < 0$).*

- **Theorem.** *Let X be projective algebraic. Consider the following properties :*
(GT) *Every subvariety Y of X is of general type.*
(AH) $\exists\varepsilon > 0$, $\forall C \subset X$ *algebraic curve*

$$2g(\bar{C}) - 2 \geq \varepsilon \deg(C).$$

(X *"algebraically hyperbolic"*)
(HY) X *is hyperbolic*
(JC) X *possesses a jet-metric with negative curvature on its k-jet bundle X_k [to be defined later], for $k \geq k_0 \gg 1$.*
Then (JC) $\Rightarrow$ (GT), (AH), (HY),
(HY) $\Rightarrow$ (AH),
and if Conjecture CGT holds, (HY) $\Rightarrow$ (GT).

- It is expected that all 4 properties are in fact equivalent for projective varieties.

- **Conjecture** (Green-Griffiths-Lang = GGL) *Let X be a projective variety of general type. Then there exists an algebraic variety $Y \subsetneq X$ such that for all non-constant holomorphic $f : \mathbb{C} \to X$ one has $f(\mathbb{C}) \subset Y$.*
- Combining the above conjectures, we get :
  Expected consequence (of CGT + GGL) Properties:
  (HY) *X is hyperbolic*
  (GT) *Every subvariety Y of X is of general type*
  are equivalent if CGT + GGL *hold.*
- **Arithmetic counterpart** (Lang 1987). *If X is a variety of general type defined over a number field and Y is the Green-Griffiths locus (Zariski closure of $\bigcup f(\mathbb{C})$), then $X(\mathbb{K}) \smallsetminus Y$ is finite for every number field $\mathbb{K}$.*

- Using "jet technology" and deep results of McQuillan for curve foliations on surfaces, D. – El Goul proved
  Theorem (solution of Kobayashi conjecture, 1998).
  A very generic surface $X \subset \mathbb{P}^3$ of degree ≥ 21 is hyperbolic.
  Independently McQuillan got degree ≥ 35.
  Recently improved to degree ≥ 18 (Păun, 2008).

  For $X \subset \mathbb{P}^{n+1}$, the optimal bound should be degree $\geq 2n+1$ for $n \geq 2$ **(Zaidenberg)**.
- **Generic GGL conjecture for** $\dim_{\mathbb{C}} X = n$
  (S. Diverio, J. Merker, E. Rousseau, 2009).
  If $X \subset \mathbb{P}^{n+1}$ is a generic n-fold of degree $d \geq d_n := 2^{n^5}$,
  [*also* $d_3 = 593$, $d_4 = 3203$, $d_5 = 35355$, $d_6 = 172925$] then
  $\exists Y \subsetneq X$ s.t. $\forall$ non const. $f : \mathbb{C} \to X$ satisfies $f(\mathbb{C}) \subset Y$
  Moreover (S. Diverio, S. Trapani, 2009) $\operatorname{codim}_{\mathbb{C}} Y \geq 2 \Rightarrow$ generic hypersurface $X \subset \mathbb{P}^4$ of degree ≥ 593 is hyperbolic.

Definition of algebraic differential operators

The main idea in order to attack GGL is to use differential equations. Let

$$\mathbb{C} \to X, \quad t \mapsto f(t) = (f_1(t), \ldots, f_n(t))$$

be a curve written in some local holomorphic coordinates $(z_1, \ldots, z_n)$ on X.

Consider algebraic differential operators which can be written locally in multi-index notation

$$\begin{aligned} P(f_{[k]}) &= P(f', f'', \ldots, f^{(k)}) \\ &= \sum a_{\alpha_1\alpha_2\ldots\alpha_k}(f(t))\, f'(t)^{\alpha_1} f''(t)^{\alpha_2} \ldots f^{(k)}(t)^{\alpha_k} \end{aligned}$$

where $a_{\alpha_1\alpha_2\ldots\alpha_k}(z)$ are holomorphic coefficients on X and $t \mapsto z = f(t)$ is a curve, $f_{[k]} = (f', f'', \ldots, f^{(k)})$ its k-jet. Obvious $\mathbb{C}^*$-action :

$$\lambda \cdot f(t) = f(\lambda t), \quad (\lambda \cdot f)^{(k)}(t) = \lambda^k f^{(k)}(\lambda t)$$

$\Rightarrow$ weighted degree $m = |\alpha_1| + 2|\alpha_2| + \ldots + k|\alpha_k|$.

Vanishing theorem for differential operators

- **Definition.** $E^{\mathrm{GG}}_{k,m}$ *is the sheaf (bundle) of algebraic differential operators of order k and weighted degree m.*
- **Fundamental vanishing theorem**
  [Green-Griffiths 1979], [Demailly 1995], [Siu-Yeung 1996]
  Let $P \in H^0(X, E^{\mathrm{GG}}_{k,m} \otimes \mathcal{O}(-A))$ be a global algebraic differential operator whose coefficients vanish on some ample divisor A. Then $\forall f : \mathbb{C} \to X$, $P(f_{[k]}) \equiv 0$.
- *Proof.* One can assume that A is very ample and intersects $f(\mathbb{C})$. Also assume f' bounded (this is not so restrictive by Brody !). Then all $f^{(k)}$ are bounded by Cauchy inequality. Hence

  $$\mathbb{C} \ni t \mapsto P(f', f'', \ldots, f^{(k)})(t)$$

  is a bounded holomorphic function on $\mathbb{C}$ which vanishes at some point. Apply Liouville's theorem ! □

Geometric interpretation of vanishing theorem

- Let $X_k^{\rm GG} = J_k(X)^*/\mathbb{C}^*$ be the projectivized k-jet bundle of X = quotient of non constant k-jets by $\mathbb{C}^*$-action.
Fibers are weighted projective spaces.
Observation. *If $\pi_k : X_k^{\rm GG} \to X$ is canonical projection and $\mathcal{O}_{X_k^{\rm GG}}(1)$ is the tautological line bundle, then*

$$E_{k,m}^{\rm GG} = (\pi_k)_* \mathcal{O}_{X_k^{\rm GG}}(m)$$

- Saying that $f : \mathbb{C} \to X$ satisfies the differential equation $P(f_{[k]}) = 0$ means that

$$f_{[k]}(\mathbb{C}) \subset Z_P$$

where Z_P is the zero divisor of the section

$$\sigma_P \in H^0(X_k^{\rm GG}, \mathcal{O}_{X_k^{\rm GG}}(m) \otimes \pi_k^* \mathcal{O}(-A))$$

associated with P.

Consequence of fundamental vanishing theorem

- **Consequence of fundamental vanishing theorem.**
If $P_j \in H^0(X, E_{k,m}^{\rm GG} \otimes \mathcal{O}(-A))$ is a basis of sections then the image $f(\mathbb{C})$ lies in $Y = \pi_k(\bigcap Z_{P_j})$, hence property asserted by the GGL conjecture holds true if there are "enough independent differential equations" so that

$$Y = \pi_k(\bigcap_j Z_{P_j}) \subsetneq X.$$

- However, some differential equations are not very useful. On a surface with coordinates (z_1, z_2), a Wronskian equation $f_1' f_2'' - f_2' f_1'' = 0$ tells us that $f(\mathbb{C})$ sits on a line, but $f_2''(t) = 0$ says that the second component is linear affine in time, an essentially meaningless information which is lost by a change of parameter $t \mapsto \varphi(t)$.

- The k-th order Wronskian operator

$$W_k(f) = f' \wedge f'' \wedge \ldots \wedge f^{(k)}$$

(locally defined in coordinates) has degree $m = \frac{k(k+1)}{2}$ and

$$W_k(f \circ \varphi) = \varphi'^m W_k(f) \circ \varphi.$$

- **Definition.** *A differential operator P of order k and degree m is said to be invariant by reparametrization if*

$$P(f \circ \varphi) = \varphi'^m P(f) \circ \varphi$$

for any parameter change $t \mapsto \varphi(t)$. Consider their set

$$E_{k,m} \subset E^{\mathrm{GG}}_{k,m} \quad (\textit{a subbundle})$$

(Any polynomial $Q(W_1, W_2, \ldots W_k)$ is invariant, but for $k \geq 3$ there are other invariant operators.)

- **Goal.** We are interested in curves $f : \mathbb{C} \to X$ such that $f'(\mathbb{C}) \subset V$ where V is a subbundle (or subsheaf) of T_X.
- **Definition.** *Category of directed manifolds :*
  – Objects : pairs (X, V), X manifold/$\mathbb{C}$ and $V \subset \mathcal{O}(T_X)$
  – Arrows $\psi : (X, V) \to (Y, W)$ holomorphic s.t. $\psi_* V \subset W$
  – "Absolute case" (X, T_X)
  – "Relative case" $(X, T_{X/S})$ where $X \to S$
  – "Integrable case" when $[V, V] \subset V$ (foliations)
- **Fonctor "1-jet" :** $(X, V) \mapsto (\tilde{X}, \tilde{V})$ where :

$$\tilde{X} = P(V) = \text{bundle of projective spaces of lines in } V$$
$$\pi : \tilde{X} = P(V) \to X, \quad (x, [v]) \mapsto x, \quad v \in V_x$$
$$\tilde{V}_{(x,[v])} = \{\xi \in T_{\tilde{X},(x,[v])} \,;\, \pi_* \xi \in \mathbb{C}v \subset T_{X,x}\}$$

- For every entire curve $f : (\mathbb{C}, T_{\mathbb{C}}) \to (X, V)$ tangent to V

$$f_{[1]}(t) := (f(t), [f'(t)]) \in P(V_{f(t)}) \subset \tilde{X}$$
$$f_{[1]} : (\mathbb{C}, T_{\mathbb{C}}) \to (\tilde{X}, \tilde{V}) \quad \text{(projectivized 1st-jet)}$$

- **Definition.** *Semple jet bundles :*
  – $(X_k, V_k) =$ k-th iteration of fonctor $(X, V) \mapsto (\tilde{X}, \tilde{V})$
  – $f_{[k]} : (\mathbb{C}, T_{\mathbb{C}}) \to (X_k, V_k)$ is the projectivized k-jet of f.
- **Basic exact sequences**

$$0 \to T_{\tilde{X}/X} \to \tilde{V} \xrightarrow{\pi_\star} \mathcal{O}_{\tilde{X}}(-1) \to 0 \qquad \Rightarrow \text{rk}\,\tilde{V} = r = \text{rk}\,V$$
$$0 \to \mathcal{O}_{\tilde{X}} \to \pi^\star V \otimes \mathcal{O}_{\tilde{X}}(1) \to T_{\tilde{X}/X} \to 0 \quad \text{(Euler)}$$
$$0 \to T_{X_k/X_{k-1}} \to V_k \xrightarrow{(\pi_k)_\star} \mathcal{O}_{X_k}(-1) \to 0 \qquad \Rightarrow \text{rk}\,V_k = r$$
$$0 \to \mathcal{O}_{X_k} \to \pi_k^\star V_{k-1} \otimes \mathcal{O}_{X_k}(1) \to T_{X_k/X_{k-1}} \to 0 \quad \text{(Euler)}$$

- For $n = \dim X$ and $r = \text{rk}\,V$, get a tower of $\mathbb{P}^{r-1}$-bundles

$$\pi_{k,0} : X_k \xrightarrow{\pi_k} X_{k-1} \to \cdots \to X_1 \xrightarrow{\pi_1} X_0 = X$$

with $\dim X_k = n + k(r-1)$, $\text{rk}\,V_k = r$,
and tautological line bundles $\mathcal{O}_{X_k}(1)$ on $X_k = P(V_{k-1})$.

- **Theorem.** *X_k is a smooth compactification of*

$$X_k^{\mathrm{GG,reg}}/G_k = J_k^{\mathrm{GG,reg}}/G_k$$

where G_k is the group of k-jets of germs of biholomorphisms of $(\mathbb{C}, 0)$, acting on the right by reparametrization: $(f, \varphi) \mapsto f \circ \varphi$, and J_k^{reg} is the space of k-jets of regular curves.

- **Direct image formula.** $(\pi_{k,0})_* \mathcal{O}_{X_k}(m) = E_{k,m} V^* =$ *invariant algebraic differential operators $f \mapsto P(f_{[k]})$ acting on germs of curves $f : (\mathbb{C}, T_{\mathbb{C}}) \to (X, V)$.*

- Although very interesting, results are currently limited by lack of knowledge on jet bundles and differential operators
- Theorem (Bérczi-Kirwan, 2009). *The ring of germs of invariant differential operators on* $(\mathbb{C}^n, T_{\mathbb{C}^n})$ *at the origin* $\mathcal{A}_{k,n} = \bigoplus_m E_{k,m} T^*_{\mathbb{C}^n}$ *is finitely generated.*
- Checked by direct calculations $\forall n$, $k \leq 2$ and $n = 2$, $k \leq 4$:

$$\mathcal{A}_{1,n} = \mathcal{O}[f'_1, \ldots, f'_n]$$
$$\mathcal{A}_{2,n} = \mathcal{O}[f'_1, \ldots, f'_n, W^{[ij]}], \quad W^{[ij]} = f'_i f''_j - f'_j f''_i$$
$$\mathcal{A}_{3,2} = \mathcal{O}[f'_1, f'_2, W_1, W_2][W]^2, \quad W_i = f'_i DW - 3f''_i W$$
$$\mathcal{A}_{4,2} = \mathcal{O}[f'_1, f'_2, W_{11}, W_{22}, S][W]^6, \quad W_{ii} = f'_i DW_i - 5f''_i W_i$$

where $W = f'_1 f''_2 - f'_2 f''_1$, $S = (W_1 DW_2 - W_2 DW_1)/W$.

- **Generalized GGL conjecture.** *If* (X, V) *is directed manifold of general type, i.e.* det V^* *big, then* $\exists Y \subsetneq X$ *such that* $\forall f : (\mathbb{C}, T_{\mathbb{C}}) \to (X, V)$ *non const.,* $f(\mathbb{C}) \subset Y$.
- **Remark.** Elementary by Ahlfors-Schwarz if $r = \mathrm{rk}\, V = 1$. $t \mapsto \log \|f'(t)\|_{V,h}$ is strictly subharmonic if $r = 1$ and (V^*, h^*) has > 0 curvature in the sense of currents.
- **Strategy.** Try some sort of induction on $r = \mathrm{rk}\, V$. First try to get differential equations $f_{[k]}(\mathbb{C}) \subset Z \subsetneq X_k$. Take minimal such k. If $k = 0$, we are done! Otherwise $k \geq 1$ and $\pi_{k,k-1}(Z) = X_{k-1}$, thus $V' = V_k \cap T_Z$ has rank $< \mathrm{rk}\, V_k = r$ and should have again det V'^* big (unless some unprobable geometry situation occurs ?).
- **Needed induction step.** *If* (X, V) *has* det V^* *big and* $Z \subset X_k$ *irreducible with* $\pi_{k,k-1}(Z) = X_{k-1}$, *then* (Z, V'), $V' = V_k \cap T_Z$ *has* $\mathcal{O}_{Z_\ell}(1)$ *big on* (Z_ℓ, V'_ℓ), $\ell \gg 0$.

Holomorphic Morse inequalities (D-, 1985) Let $L \to X$ be a holomorphic line bundle on a compact complex manifold X, h a smooth hermitian metric on L and

$$\Theta_{L,h} = \frac{i}{2\pi}\nabla^2_{L,h} = -\frac{i}{2\pi}\partial\overline{\partial}\log h$$

its curvature form. Then $\forall q = 0, 1, \ldots, n = \dim_{\mathbb{C}} X$

$$\sum_{j=0}^{q}(-1)^{q-j}h^j(X, L^{\otimes k}) \le \frac{k^n}{n!}\int_{X(L,h,\le q)}(-1)^q\Theta^n_{L,h} + o(k^n).$$

where

$$X(L, h, q) = \{x \in X\,;\ \Theta_{L,h}(x) \text{ has signature } (n-q, q)\}$$

(q-index set), and

$$X(L, h, \le q) = \bigcup_{0\le j\le q} X(L, h, \le j)$$

As a consequence, one gets an upper bound

$$h^0(X, L^{\otimes k}) \le \frac{k^n}{n!}\int_{X(L,h,0)}\Theta^n_{L,h} + o(k^n)$$

and a lower bound

$$h^0(X, L^{\otimes k}) \ge h^0(X, L^{\otimes k}) - h^1(X, L^{\otimes k}) \ge$$

$$\ge \frac{k^n}{n!}\Big(\int_{X(L,h,0)}\Theta^n_{L,h} - \int_{X(L,h,1)}|\Theta^n_{L,h}|\Big) - o(k^n)$$

and similar bounds for the higher cohomology groups H^q:

$$h^q(X, L^{\otimes k}) \le \frac{k^n}{n!}\int_{X(L,h,q)}|\Theta^n_{L,h}| + o(k^n)$$

$$h^q(X, L^{\otimes k}) \ge \frac{k^n}{n!}\Big(\int_{X(L,h,q)} - \int_{X(L,h,q-1)} - \int_{X(L,h,q+1)}|\Theta^n_{L,h}|\Big) - o(k^n)$$

Finsler metric on the k-jet bundles

Let J_kV be the bundle of k-jets of curves $f : (\mathbb{C}, T_{\mathbb{C}}) \to (X, V)$
Assuming that V is equipped with a hermitian metric h, one defines a "weighted Finsler metric" on J^kV by taking $p = k!$ and

$$\Psi_{h_k}(f) := \Big(\sum_{1\le s\le k} \varepsilon_s \|\nabla^s f(0)\|_{h(x)}^{2p/s}\Big)^{1/p}, \quad 1 = \varepsilon_1 \gg \varepsilon_2 \gg \cdots \gg \varepsilon_k.$$

Letting $\xi_s = \nabla^s f(0)$, this can actually be viewed as a metric h_k on $L_k := \mathcal{O}_{X_k^{\rm GG}}(1)$, with curvature form $(x, \xi_1, \ldots, \xi_k) \mapsto$

$$\Theta_{L_k,h_k} = \omega_{{\rm FS},k}(\xi) + \frac{i}{2\pi} \sum_{1\le s\le k} \frac{1}{s} \frac{|\xi_s|^{2p/s}}{\sum_t |\xi_t|^{2p/t}} \sum_{i,j,\alpha,\beta} c_{ij\alpha\beta} \frac{\xi_{s\alpha}\overline{\xi}_{s\beta}}{|\xi_s|^2} dz_i \wedge d\overline{z}_j$$

where $(c_{ij\alpha\beta})$ are the coefficients of the curvature tensor Θ_{V^*,h^*} and $\omega_{{\rm FS},k}$ is the vertical Fubini-Study metric on the fibers of $X_k^{\rm GG} \to X$. The expression gets simpler by using polar coordinates $x_s = |\xi_s|_h^{2p/s}$, $u_s = \xi_s/|\xi_s|_h = \nabla^s f(0)/|\nabla^s f(0)|$.

Probabilistic interpretation of the curvature

In such polar coordinates, one gets the formula

$$\Theta_{L_k,h_k} = \omega_{{\rm FS},p,k}(\xi) + \frac{i}{2\pi} \sum_{1\le s\le k} \frac{1}{s} x_s \sum_{i,j,\alpha,\beta} c_{ij\alpha\beta}(z)\, u_{s\alpha}\overline{u}_{s\beta}\, dz_i \wedge d\overline{z}_j$$

where $\omega_{{\rm FS},k}(\xi)$ is positive definite in ξ. The other terms are a weighted average of the values of the curvature tensor $\Theta_{V,h}$ on vectors u_s in the unit sphere bundle $SV \subset V$. The weighted projective space can be viewed as a circle quotient of the pseudosphere $\sum |\xi_s|^{2p/s} = 1$, so we can take here $x_s \ge 0$, $\sum x_s = 1$. This is essentially a sum of the form $\sum \frac{1}{s}\gamma(u_s)$ where u_s are random points of the sphere, and so as $k \to +\infty$ this can be estimated by a "Monte-Carlo" integral

$$\Big(1 + \frac{1}{2} + \ldots + \frac{1}{k}\Big) \int_{u\in SV} \gamma(u)\, du.$$

As γ is quadratic here, $\int_{u\in SV} \gamma(u)\, du = \frac{1}{r}\,{\rm Tr}(\gamma)$.

It follows that the leading term in the estimate only involves the trace of Θ_{V^*,h^*}, i.e. the curvature of $(\det V^*, \det h^*)$, which can be taken to be > 0 if $\det V^*$ is big.

Corollary (D-, 2010) Let (X, V) be a directed manifold, $F \to X$ a $\mathbb{Q}$-line bundle, (V, h) and (F, h_F) hermitian. Define

$$L_k = \mathcal{O}_{X_k^{\mathrm{GG}}}(1) \otimes \pi_k^* \mathcal{O}\Big(\frac{1}{kr}\Big(1 + \frac{1}{2} + \ldots + \frac{1}{k}\Big)F\Big),$$
$$\eta = \Theta_{\det V^*, \det h^*} + \Theta_{F,h_F}.$$

Then for all $q \geq 0$ and all $m \gg k \gg 1$ such that m is sufficiently divisible, we have

$$h^q(X_k^{\mathrm{GG}}, \mathcal{O}(L_k^{\otimes m})) \leq \frac{m^{n+kr-1}}{(n+kr-1)!} \frac{(\log k)^n}{n!\,(k!)^r}\Big(\int_{X(\eta,q)} (-1)^q \eta^n + \frac{C}{\log k}\Big)$$
$$h^0(X_k^{\mathrm{GG}}, \mathcal{O}(L_k^{\otimes m})) \geq \frac{m^{n+kr-1}}{(n+kr-1)!} \frac{(\log k)^n}{n!\,(k!)^r}\Big(\int_{X(\eta,\leq 1)} \eta^n - \frac{C}{\log k}\Big).$$

Using the above cohomological estimate, we obtain:

Theorem (D-, 2010) Let (X, V) be of general type, i.e. $K_V = (\det V)^*$ is a big line bundle. Then there exists $k \geq 1$ and an algebraic hypersurface $Z \subsetneq X_k$ such that every entire curve $f : (\mathbb{C}, T_{\mathbb{C}}) \mapsto (X, V)$ satisfies $f_{[k]}(\mathbb{C}) \subset Z$ (in other words, f satisfies an algebraic differential equation of order k).

Another important consequence is:

Theorem (D-, 2012) A generic hypersurface $X \subset \mathbb{P}^{n+1}$ of degree $d \geq d_n$ with

$$d_2 = 286, \quad d_3 = 7316, \quad d_n = \left\lfloor \frac{n^4}{3}\big(n \log(n \log(24n))\big)^n \right\rfloor$$

(for $n \geq 4$) satisfies the Green-Griffiths conjecture.

A differentiation technique by Yum-Tong Siu

The proof of the last result uses an important idea due to Yum-Tong Siu, itself based on ideas of Claire Voisin and Herb Clemens, and then refined by M. Păun [Pau08], E. Rousseau [Rou06b] and J. Merker [Mer09].
The idea consists of studying vector fields on the relative jet space of the universal family of hypersurfaces of $\mathbb{P}^{n+1}$.

Let $\mathcal{X} \subset \mathbb{P}^{n+1} \times \mathbb{P}^{N_d}$ be the universal hypersurface, i.e.

$$\mathcal{X} = \{(z,a)\,;\ a = (a_\alpha) \text{ s.t. } P_a(z) = \sum a_\alpha z^\alpha = 0\},$$

let $\Omega \subset \mathbb{P}^{N_d}$ be the open subset of a's for which $X_a = \{P_a(z) = 0\}$ is smooth, and let

$$p : \mathcal{X} \to \mathbb{P}^{n+1}, \quad \pi : \mathcal{X}_{|\Omega} \to \Omega \subset \mathbb{P}^{N_d}$$

be the natural projections.

Meromorphic vector fields on jet spaces

Let

$$p_k : \mathcal{X}_k \to \mathcal{X} \to \mathbb{P}^{n+1}, \quad \pi_k : \mathcal{X}_k \to \Omega \subset \mathbb{P}^{N_d}$$

be the relative Green-Griffiths k-jet space of $\mathcal{X} \to \Omega$. Then J. Merker [Mer09] has shown that global sections η_j of

$$\mathcal{O}(T_{\mathcal{X}_k}) \otimes p_k^*\mathcal{O}_{\mathbb{P}^{n+1}}(k^2+2k) \otimes \pi_k^*\mathcal{O}_{\mathbb{P}^{N_d}}(1)$$

generate the bundle at all points of $\mathcal{X}_k^{\rm reg}$ for $k = n = \dim X_a$.
From this, it follows that if P is a non zero global section over Ω of $E_{k,m}^{\rm GG} T_{\mathcal{X}}^* \otimes p_k^*\mathcal{O}_{\mathbb{P}^{n+1}}(-s)$ for some s, then for a suitable collection of $\eta = (\eta_1, \ldots, \eta_m)$, the m-th derivatives

$$D_{\eta_1} \ldots D_{\eta_m} P$$

yield sections of $H^0(\mathcal{X}, E_{k,m}^{\rm GG} T_{\mathcal{X}}^* \otimes p_k^*\mathcal{O}_{\mathbb{P}^{n+1}}(m(k^2+2k)-s))$ whose joint base locus is contained in $\mathcal{X}_k^{\rm sing}$, whence the result.

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