

§5. Geometrie applications of the flatness criteria

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Proof: $\text{Tor}_1^A(k, F) = \text{Tor}_1^B(\bar{B}, F)$, by prop. 7.

§ 5. Geometric applications of the flatness criterions

A) Flatness for finite morphisms

Proposition 1: Let $\pi: X \rightarrow S$ be a finite morphism (i.e. proper with finite fibres) of analytic spaces. Then $\pi_*(\mathcal{O}_X)$ is a coherent analytic sheaf over S . The following conditions are equivalent:

- (a) π is flat (i.e. for every $x \in X$, $\mathcal{O}_{X,x}$ is a flat $\mathcal{O}_{S,s}$ -module, $s = \pi(x)$).
- (b) For every s , $(\pi_* \mathcal{O}_X)_s$ is a flat $\mathcal{O}_{S,s}$ -module.
- (c) $\pi_* \mathcal{O}_X$ is a locally free sheaf.

Proof: Because π is finite $\pi_*(\mathcal{O}_X)_s = \bigoplus_{x \in \pi^{-1}(s)} \mathcal{O}_{X,x}$, thus the only point to prove is (b) \Rightarrow (c).

Now if $\mathcal{O}_{X,x}$ is a flat $\mathcal{O}_{S,s}$ -module, then (by theorem 2) $\mathcal{O}_{X,x}$ is free, and a coherent sheaf whose fibers are free is a locally free sheaf.

Proposition 2: Let S be a reduced analytic space and \mathcal{E} a coherent \mathcal{O}_S -module. Let $E(s)$ be the finite dimensional vector space (over \mathbb{C}) $\mathcal{E}_s \otimes_{\mathcal{O}_{S,s}} \mathbb{C}_s$. \mathcal{E} is a locally free $\mathcal{O}_{S,s}$ -module if and only if $\dim_{\mathbb{C}} E(s)$ is locally constant.

Proof: If \mathcal{E} is locally free, then $\dim_{\mathbb{C}} E(s)$ is locally constant. Suppose now that $\dim_{\mathbb{C}} E(s)$ is locally constant in an open set $U \subset S$, and that $\mathcal{O}_U^p \xrightarrow{d} \mathcal{O}_U^q \rightarrow \mathcal{E}_U \rightarrow 0$ is exact. d is determined by a $p \times q$ matrix of analytic functions on U , so it gives a morphism $\mathbb{C}_U^p \xrightarrow{d} \mathbb{C}_U^q$ of trivial vector bundles over U .

From the exact sequence $\mathcal{O}_S^p \xrightarrow{d_s} \mathcal{O}_S^q \rightarrow \mathcal{E}_S \rightarrow 0$, we get (by making tensor-products with \mathbb{C}_s) the exact sequence:

$$\mathbb{C}_s^p \xrightarrow{d(s)} \mathbb{C}_s^q \rightarrow E(s) \rightarrow 0,$$

which shows that d has constant rank in U . Thus $\text{Ker } d$ and $\text{Im } d$ are vector bundles, and we can write

$$\mathbb{C}_U^p = F_1 \oplus G_1, \quad \mathbb{C}_U^q = F_0 \oplus G_0,$$

$$d : \begin{cases} F_1 \rightarrow 0 \\ G_1 \simeq F_0 \end{cases}.$$

Now $\mathcal{E} \simeq$ the sheaf of analytic sections of G_0 , therefore \mathcal{E} is locally free.

Definition 1: Let $\pi : X \rightarrow S$ be a finite morphism of analytic spaces, and $s \in S$. For each $x \in X(s) = \pi^{-1}(s)$, $\mathcal{O}_{X(s),x} = \mathbf{C} \otimes_{\mathcal{O}_{S,s}} \mathcal{O}_{X,x}$ is finite dimensional vectorspace over \mathbf{C} . Denote its dimension by $v(x)$. Then the degree $v(s)$ of s is defined by $v(s) = \sum_{x \in X(s)} v(x)$.

Theorem 1: Let $\pi : X \rightarrow S$ be a finite morphism of analytic space and let S be a reduced space. Then X is flat over S if and only if $v(s)$ is locally constant function of s .

$$\begin{aligned} \text{Proof: } v(s) &= \sum_{x \in X(s)} \dim_{\mathbf{C}} \mathcal{O}_{X(s),x} = \dim_{\mathbf{C}} \left(\bigoplus_{x \in X(s)} \mathcal{O}_{X(s),x} \right) \\ &= \dim_{\mathbf{C}} \left(\bigoplus_{x \in X(s)} (\mathbf{C} \otimes_{\mathcal{O}_{S,s}} \mathcal{O}_{X,x}) \right) \\ &= \dim_{\mathbf{C}} \mathbf{C} \otimes_{\mathcal{O}_{S,s}} \pi_* (\mathcal{O}_X)_s = \dim_{\mathbf{C}} E(s). \end{aligned}$$

The theorem follows from propositions 1 and 2.

Examples of flat morphisms

Example 1: If $\pi : X \rightarrow S$ is a local isomorphism near x , then π is flat at x .

Example 2: Consider § 2, Ex. 1. Here $v(x) = 1$.

Examples of non-flat morphisms

Examples 1: If $X \subset S$ is a closed subspace, not open, $v(s)$ is not locally constant.

Example 2: Let X be a subspace of \mathbf{C}^4 defined by the ideal intersection of (x_3, x_4) and $(x_1 - x_1, x_4 - x_2)$ (which is equal to the product ideal) and let π be the projection onto the (x_1, x_2) -plane \mathbf{C}^2 . Then X is a union of two 2-planes in \mathbf{C}^4 , whose intersection is (0) . When $s \neq 0$, $X(s)$ consists of two simple points, so $v(s) = 2$. $X(0)$ is given by the ideal $(x_1, x_2, x_3^2, x_3x_4, x_4^2)$, thus $v(0) = 3$.

Example 3: Let $S = \{(u, v, w) \in \mathbf{C}^3 \mid v^2 = uw\}$ and $\pi : \mathbf{C}^2 \rightarrow S$ be the map $(x, y) \rightarrow (x^2, xy, y^2)$. This map identifies S with the quotient of \mathbf{C}^2 by the equivalence relation identifying (x, y) with $(-x, -y)$. However, π is not flat, since for $s \in S$, $v(s) = 2$ if $s \neq 0$ and $v(s) = 3$ if $s = 0$.

B) Projection of a product of analytic spaces

Theorem 2: Let S and X be analytic spaces. If $\pi : S \times X \rightarrow S$ is the projection morphism, then π is flat, i.e. $\mathcal{O}_{S \times X, (s, x)}$ is a flat $\mathcal{O}_{S, s}$ module for every $(s, x) \in S \times X$.

To prove this theorem we need first some homological algebra. Then we shall show it in the particular case, when S is a manifold, and finally in the general case.

(a) Koszul complex

Let A be a ring, M an A -module and h_1, \dots, h_n homomorphisms $M \rightarrow M$, which commute with each other, i.e. $h_i h_j = h_j h_i$ for every i, j .

If $1 \leq k \leq n$, set $Q_k = M/h_1(M) + \dots + h_k(M)$, and $Q_0 = M$, thus, in particular, $Q_n = Q = M/\sum_{i=1}^n h_i(M)$. Every h_k induces a map $\tilde{h}_k : Q_{k-1} \rightarrow Q_{k-1}$.

Definition 2: The sequence (h_1, \dots, h_n) is called regular if each of the mappings \tilde{h}_k ($1 \leq k \leq n$) is injective.

The Koszul complex of the module M and of the mappings h_k ($1 \leq k \leq n$) $K. = K. [M; h_1, \dots, h_n]$ is defined in the following way:

$$K_i = \wedge^{n+i} A^n \otimes M \simeq M^{(i)}, \quad 0 \leq i \leq n.$$

We define the homomorphisms $d_i : K_i \rightarrow K_{i-1}$ ($i > 0$) by $\lambda \otimes x \rightarrow \sum_i (e_i \wedge \lambda) \otimes \otimes h_i(x)$, where (e_i) is the natural base of A^n . We also define $\varepsilon : K_0 \rightarrow Q$ as the natural map $: K_0 = M \rightarrow M/\sum_{i=1}^n h_i(M) = Q$. Using the fact that h_1, \dots, h_n commute with each other, it is easy to verify that

$$(d_{i-1} \circ d_i)(\lambda \otimes x) = \sum_{i,j} (e_j \wedge e_i \wedge \lambda) \otimes h_j(h_i(x)) = 0;$$

also $\varepsilon d_1 = 0$. Thus $K.$ is really a complex.

Theorem 3 (Poincaré-Koszul).

If (h_1, \dots, h_n) is a regular sequence, then

$$H_i(K.) = \begin{cases} Q & \text{if } i = 0 \\ 0 & \text{if } i > 0 \end{cases}.$$

If $h_i \in A$, it defines the map: $A \xrightarrow{h_i I} A$, which we denote also by h_i . We say that (h_1, \dots, h_n) is a regular sequence of elements if $(h_1 I, \dots, h_n I)$ is a regular sequence.

Corollary. If (h_1, \dots, h_n) is a regular sequence of elements, then the Koszul complex $K. = K. [A; h_1, \dots, h_n] = \{ \wedge^{n-1} A^n \simeq A^{(n)} \}$ is a free resolution of $Q = A/(h_i)$ ((h_i) is the ideal generated by h_1, \dots, h_n).

Example: If $A = \mathbb{C}\{x_1, \dots, x_n\}$; $h_i = x_i$, then $Q_k = A/(x_1, \dots, x_k) = \mathbb{C}\{x_{k+1}, \dots, x_n\}$ and $Q = Q_n = \mathbb{C}$. The complex $K. = K. [A; x_1, \dots, x_n]$ is a free resolution of \mathbb{C} .

(b) *Proof of theorem 2, when S is a complex manifold*

In this case we can take $\mathcal{O}_{S,s} = \mathbb{C}\{t_1, \dots, t_m\} = A$ and if $\mathcal{O}_{X,x} = \mathbb{C}\{x_1, \dots, x_n\}/(f_1, \dots, f_p)$, then

$$\mathcal{O}_{S \times X, (s,x)} = \mathbb{C}\{t_1, \dots, t_m, x_1, \dots, x_n\}/(f_1, \dots, f_p) = B.$$

B is an A -module in a natural way.

By the corollary of the Poincaré-Koszul theorem $K. = K. [A; t_1, \dots, t_m]$ in a free resolution of \mathbb{C} . We want to compute the modules $\text{Tor}_i^A(\mathbb{C}, B) = H_i(K. \otimes B)$ ($i > 0$).

It's easily seen, that we can consider the complex $K. \otimes B$ as a Koszul

complex $K'. = K. [B; t_1, \dots, t_m]$ (where $t_i : B \xrightarrow{t_i I} B$). But now the sequence (t_1, \dots, t_m) is regular, thus by the Poincaré-Koszul theorem $H_i[K'] = 0$ if $i > 0$.

In particular: $\text{Tor}_1^A(\mathbb{C}, B) = H_1[K. \otimes B] = H_1[K'] = 0$. By the second flatness criterion B is A -flat.

(c) *The general case*

The question being local, we can suppose that $S \subset W \subset \mathbb{C}^n$, where W is open, and S an analytic subspace of W . Let S be defined by g_1, \dots, g_r . Then $S \times X \subset W \times X$ and $\mathcal{O}_S = \mathcal{O}_W/(g_1, \dots, g_r)$. On the other hand $\mathcal{O}_{S \times X} = \mathcal{O}_{W \times X}/(g_1, \dots, g_r) = \mathcal{O}_S \otimes_{\mathcal{O}_W} \mathcal{O}_{W \times X}$. The last equality follows from

the fact, that if $\pi : X \rightarrow S$ is a morphism, and $S' \subset S$ a subspace, $X' = \pi^{-1}(S')$,

$$\text{then } \mathcal{O}_{X'} = \mathcal{O}_{S'} \otimes_{\mathcal{O}_S} \mathcal{O}_X.$$

Remark : This a particular case of the following proposition: if π and π' are two morphisms of which at least one is finite, then

$$\begin{array}{ccc} X & & Y \\ \pi \searrow & & \swarrow \pi' \\ & S & \end{array} \quad \mathcal{O}_{X \times_S Y} = \mathcal{O}_X \otimes_{\mathcal{O}_S} \mathcal{O}_Y.$$

We have proved that $\mathcal{O}_{W \times X}$ is \mathcal{O}_W -flat, so by scalar extension $\mathcal{O}_{S \times X}$ is \mathcal{O}_S flat.

Corollary : If X and S are two manifolds and $\pi : X \rightarrow S$ is a submersion, then π is flat.

III. PRIVILEGED POLYCYLINDERS

§ 1. Banach vector bundles over an analytic space

Let E be a Banach space and X an analytic space. We denote then by E_X the trivial bundle $X \times E$ over X .

To define bundle morphisms, we first define the sheaf $\mathcal{H}_X(E)$ of germs of analytic morphisms from X to E . If $U \subset \mathbb{C}^n$ is open, then the set $\mathcal{H}(U, E)$ of analytic morphisms from U into E consists of all functions $g : U \rightarrow E$ having at every point $x \in U$ a converging power series expansion.

Let now X' be a local model for X , i.e. X' is the support of the quotient sheaf \mathcal{O}_U/J , where $U \subset \mathbb{C}^n$ is open and J is a coherent sheaf of ideals of \mathcal{O}_U , then $\mathcal{H}_{X'}(E)$ is the sheaf associated to the presheaf $V \rightarrow \mathcal{H}(V, E)/J_V \cdot \mathcal{H}(V, E)$ ($V \subset U$, V -open).

Remark : If X' is reduced, the sections of $\mathcal{H}_{X'}(E)$ are just the functions from X' to E which are locally induced by analytic functions on open sets in U .

The sheaf $\mathcal{H}_X(E)$ is constructed with help of the local models X' of X , i.e. $\mathcal{H}_X(E)|_{X'} = \mathcal{H}_{X'}(E)$, for every local model X' .

Definition 1 : The set of *analytic morphisms* from an analytic space X into a Banach space E is the set $\mathcal{H}(X; E)$ of sections of the sheaf $\mathcal{H}_X(E)$.

Let $\mathcal{L}(E, F)$ be the Banach space of all continuous linear mappings from the Banach space E into the Banach space F .

Definition 2 : An *analytic vector bundle morphism* from E_X into F_X is an analytic morphism from X into $\mathcal{L}(E, F)$.