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The set of “ nice ” fibers is dense in X , so we cannot remove the z -axis and still get a closed subspace of \mathbf{C}_3 .

§ 4. Algebraic study of flatness

In the following all rings are commutative, with 1, and all modules are unitary.

Definition 1: An A -module E is *flat*, if for every exact sequence of A -modules

$$0 \rightarrow F' \rightarrow F \rightarrow F'' \rightarrow 0,$$

the sequence $0 \rightarrow E \otimes F' \rightarrow E \otimes F \rightarrow E \otimes F'' \rightarrow 0$ is also exact. We can also say, because \otimes is right exact, that E is flat, if for every injective homomorphism $F' \rightarrow F$, $E \otimes F' \rightarrow E \otimes F$ is also injective.

Examples of modules which are not flat:

- (1) if $A = \mathbf{Z}$, $E = \mathbf{Z}_2 = \mathbf{Z}/2\mathbf{Z}$, $F = F' = \mathbf{Z}$; then the sequence $0 \rightarrow \mathbf{Z} \xrightarrow{2I} \mathbf{Z} (2I : x' \rightarrow 2x)$ is exact. But now $\mathbf{Z}_2 \otimes \mathbf{Z} = \mathbf{Z}_2$, and the homomorphism $\mathbf{Z}_2 \xrightarrow{2I} \mathbf{Z}_2$ is the zero homomorphism, which is not injective. So \mathbf{Z}_2 is not a flat \mathbf{Z} module.
- (2) If $A = \mathbf{C}\{x\}$, $E = \mathbf{C} = \mathbf{C}\{x\}/(x)$, $F = F' = \mathbf{C}\{x\}$, then the sequence $0 \rightarrow F \xrightarrow{xI} F' (xI : p(x) \rightarrow xp(x))$ is exact. But the homomorphism $E \xrightarrow{xI} E$ is not injective.

Proposition 1: If A is an integral domain and E a flat A -module, then E is torsion-free.

Proof: Let $a \in A$, $a \neq 0$. Because A is an integral domain, the sequence $0 \rightarrow AA \xrightarrow{aI} (aI : x \rightarrow ax)$ is exact. Since E is flat, the sequence $0 \rightarrow E \xrightarrow{aI} E$ is also exact. In other words E has no torsion elements.

Proposition 2: If A is a principal-ideal domain, then E is flat if and only if E is torsionfree.

Proof: See corollary of prop. 6.

Examples of flat modules:

- (1) The inductive limit of flat modules is flat, because the inductive limit preserves exactness, and it commutes with the tensor product.

- (2) Every free module is flat. In fact, if E is free and finite type, then $E = A^n$ and $E \otimes F = F^n$. If $F' \rightarrow F$ is injective, so is $F'^n \rightarrow F^n$ too.

If E is an arbitrary free module, then it is an inductive limit of free modules of finite type, and the flatness of E follows from (1).

- (3) Let S be a multiplicative system in A . Then the ring of fractions $S^{-1}A$ is a flat A -module. In fact the ring $S^{-1}A$ can be identified with an inductive limit of free modules, so it is flat ((1) (2)). We assume for simplicity that S has only regular elements. We can define in the set S a partial order in the following way:

$$s' \geq s \Leftrightarrow \exists t \in A, \quad ts = s' \quad (\text{such a } t \text{ is then unique}).$$

Let $E_s = A$ for every $s \in S$, and if $s' \geq s$ (i.e. $s' = ts$) then let $f_s^{s'}$ be the homomorphism $t \cdot I_A : E_s \rightarrow E_{s'}$. The family $(E_s)_{s \in S}$ with the homomorphisms $(f_s^{s'})$ is an inductive system.

Let $E = \lim_{\rightarrow} E_s$ be the inductive limit of this system, and φ_s the canonical homomorphism $E_s \rightarrow E$. We shall define an isomorphism $\psi : E \rightarrow S^{-1}A$.

We first define for every s a homomorphism $\psi_s : E_s = A \rightarrow S^{-1}A$; $x \rightarrow x/s$. Now if $s' \geq s$, then

$$(\psi_{s'} \circ f_s^{s'})(x) = \psi_{s'}(tx) = \frac{tx}{s'} = \frac{tx}{ts} = \frac{x}{s} = \psi_s(x).$$

Therefore there exists a homomorphism $\psi : E \rightarrow S^{-1}A$, satisfying $\psi_s = \psi \circ \varphi_s$ for every $s \in S$.

Because every element of $S^{-1}A$ has the form a/s , ψ is surjective. On the other hand if $\psi(\varphi_s(x)) = 0$, then $\psi_s(x) = x/s = 0$. Thus $x = 0$, and ψ is also injective.

The above proof can be extended to the general case, not assuming that the elements of S are regular. The extended proof involves the notion of inductive limit of an inductive system indexed by a category instead of an ordered set.

From (1) and (2) above, any module which is the inductive limit of free modules, is flat. Conversely:

Theorem 1 : (Daniel, Lazard)

Any flat module is a inductive limit of free modules.

For the proof: See *C.R. Acad. Sci. Paris*, 258 (1964), pp. 6313-6316.

Some elementary properties of flat modules :

- (1) If E and F are flat A -modules, then $E \otimes_A F$ is also flat. In fact, if $G' \rightarrow G$ is injective, then $F \otimes_A G' \rightarrow F \otimes_A G$ is injective, and also $E \otimes_A (F \otimes_A G') \rightarrow E \otimes_A (F \otimes_A G)$ is injective. The result follows from the associativity of the tensor product.
- (2) Let $\phi : A \rightarrow B$ be a ring homomorphism, and E a flat A -module. The module $B \otimes_A E$ is a flat B -module.

If F is a B -module, then $F \otimes_B (B \otimes_A E) = (F \otimes_B B) \otimes_A E = F \otimes_A E$ further if F' and F are B -modules, and $F' \rightarrow F$ an injective homomorphism of B -modules, we can consider this homomorphism as an injective homomorphism of A -modules. Because E is A -flat,

$$F' \otimes_A E \rightarrow F \otimes_A E \text{ is injective.}$$

- (3) Let $\phi : A \rightarrow B$ be a ring homomorphism, such that B is a flat A -module. If F is a flat B -module, then F is a flat A -module. In fact: if $E' \rightarrow E$ is injective, then $E' \otimes_A B \rightarrow E \otimes_A B$ is injective, and also $(E' \otimes_A B) \otimes_B F' \rightarrow (E \otimes_A B) \otimes_B F$ is injective. But $(E' \otimes_A B) \otimes_B F' = E' \otimes_A F$; $(E \otimes_A B) \otimes_B F = E \otimes_A F$.
If an A -module E is not flat, we want to measure how far it is from being flat. For this purpose we introduce the functor Tor .

Definition 2 : A free resolution of E is an exact sequence: $\dots \rightarrow L_n \rightarrow L_{n-1} \rightarrow \dots \rightarrow L_1 \rightarrow L_0 \rightarrow E \rightarrow 0$, where all L_i are free A -modules.

The complex of the resolution is the sequence

$$(L.) \dots \rightarrow L_n \rightarrow L_{n-1} \rightarrow \dots \rightarrow L_1 \rightarrow L_0 \rightarrow 0.$$

Every module has a free resolution. Two resolutions are algebraically homotopy-equivalent. Forming the tensor products $L_i \otimes F$, we get

$$(L. \otimes F) \dots \rightarrow L_n \otimes F \rightarrow L_{n-1} \otimes F \rightarrow \dots \rightarrow L_1 \otimes F \rightarrow L_0 \otimes F \rightarrow 0.$$

Definition 3 :

$$\text{Tor}_n^A(E, F) = H_n(L. \otimes F) = \frac{\text{Ker}(L_n \otimes F \rightarrow L_{n-1} \otimes F)}{\text{Im}(L_{n+1} \otimes F \rightarrow L_n \otimes F)}$$

if $n \geq 1$, and $\text{Tor}_0^A(E, F) = \text{Coker}(L_1 \otimes F \rightarrow L_0 \otimes F) = E \otimes F$.

Basic properties of Tor :

- (1) $\text{Tor}_n(E, F)$ is independent of the choice of the resolution (up to a canonical isomorphism).

- (2) If we take a free resolution of F , we get $\text{Tor}_n(F, E) = \text{Tor}_n(E, F)$ (Symmetry of the Tor). We can also define $\text{Tor}_n(E, F)$ by taking two free resolutions, one of E and one of F .
- (3) If $0 \rightarrow E' \rightarrow E \rightarrow E'' \rightarrow 0$ is a short exact sequence, then we get a long exact sequence:

$$\begin{aligned} & \text{Tor}_n(E', F) \rightarrow \text{Tor}_n(E, F) \rightarrow \text{Tor}_n(E'', F) \rightarrow \\ & \rightarrow \text{Tor}_{n-1}(E', F) \rightarrow \text{Tor}_{n-1}(E, F) \rightarrow \text{Tor}_{n-1}(E'', F) \rightarrow \\ & \rightarrow \text{Tor}_1(E', F) \rightarrow \text{Tor}_1(E, F) \rightarrow \text{Tor}_1(E'', F) \rightarrow \\ & \rightarrow E' \otimes F \rightarrow E \otimes F \rightarrow E'' \otimes F \rightarrow 0. \end{aligned}$$

- (4) Tor is compatible with inductive limit, i.e. if $E = \lim (E_i)$, then

$$\text{Tor}_n(\lim E_i, F) = \lim (\text{Tor}_n(E_i, F)).$$

- (5) We can define $\text{Tor}_n(E, F)$ by taking a flat resolution of E .

Proposition 3: Let E be an A -module. Then the following conditions are equivalent:

- (a) E is flat.
- (b) For all A -modules F , and for all $n \geq 1$, $\text{Tor}_n(E, F) = 0$.
- (c) For all A -modules F , $\text{Tor}_1(E, F) = 0$.

Proof: (a) \Rightarrow (b). If $\dots \rightarrow L_n \rightarrow L_{n-1} \rightarrow \dots \rightarrow L_1 \rightarrow L_0 \rightarrow F \rightarrow 0$ is a free resolution of F , then the sequence

$$\dots \rightarrow E \otimes L_n \rightarrow E \otimes L_{n-1} \rightarrow \dots \rightarrow E \otimes L_1 \rightarrow E \otimes L_0 \rightarrow E \otimes F \rightarrow 0$$

is exact, thus $\text{Tor}_n(E, F) = 0$ for all $n \geq 1$.

(b) \Rightarrow (c) clear. (c) \Rightarrow (a): If the sequence $0 \rightarrow F' \rightarrow F \rightarrow F'' \rightarrow 0$ is exact, so is also (by (3) above) $\text{Tor}_1(E, F'') \rightarrow E \otimes F' \rightarrow E \otimes F \rightarrow E \otimes F'' \rightarrow 0$. Now $\text{Tor}_1(E, F'') = 0$, thus E is flat.

Proposition 4: If I and J are two ideals in A , then $\text{Tor}_1^A(A/I, A/J) = I \cap J / I \cdot J$.

Proof: From the exact sequence $0 \rightarrow I \rightarrow A \rightarrow A/I \rightarrow 0$, we get the exact sequence:

$$\text{Tor}_1(A, A/J) \rightarrow \text{Tor}_1(A/I, A/J) \rightarrow I \otimes A/J \rightarrow A \otimes A/J \rightarrow A/I \otimes A/J \rightarrow 0.$$

But now $\text{Tor}_1(A, A/J) = 0$ (A being A -free), and $I \otimes A/J = I/I \cdot J$; $A \otimes A/J = A/J$. Therefore the sequence $0 \rightarrow \text{Tor}_1(A/I, A/J) \rightarrow I/I \cdot J \rightarrow A/J$ is exact, and $\text{Tor}_1(A/I, A/J) = \text{Ker}(I/I \cdot J \rightarrow A/J) = I \cap J / I \cdot J$.

Example : Let U be an open set in \mathbb{C}^n , and $x \in U$. Further let $X, Y \subset U$ be two hypersurfaces, defined by $I = (f)$ and $J = (g)$. Supposing that f and g do not have common factors: $I_x \cap J_x = I_x J_x$, and

$$\text{Tor}_1(\mathcal{O}_{X,x}, \mathcal{O}_{Y,x}) = \text{Tor}_1(\mathcal{O}_{U,x}/I_x, \mathcal{O}_{U,x}/J_x) = \frac{I_x \cap J_x}{I_x \cdot J_x} = 0.$$

Heuristic remark : The formula $\text{Tor}_1(\mathcal{O}_{X,x}, \mathcal{O}_{Y,x}) = 0$ expresses the fact that X and Y are “in general position”. If for example X and Y are two linear subspaces in \mathbb{C}^n of dimensions p and q , we have $\text{Tor}_1(\mathcal{O}_{X,x}, \mathcal{O}_{Y,x}) = 0$ if $\dim(X \cap Y) = p + q - n$, and $\text{Tor}_1(\mathcal{O}_{X,x}, \mathcal{O}_{Y,x}) \neq 0$ otherwise.

Next we shall prove an elementary flatness criterion.

Proposition 5 : Let E be an A -module. The following conditions are equivalent:

- (a) E is flat.
- (b) For all finitely generated ideals I of A , $\text{Tor}_1(E, A/I) = 0$.
- (c) For all monogenous A -modules F , $\text{Tor}_1(E, F) = 0$.

Proof : (a) \Rightarrow (b), by prop. 3.

(b) \Rightarrow (c): Because Tor is compatible with inductive limit, we can suppose, that $\text{Tor}_1(E, A/I) = 0$ for an arbitrary ideal I of A . But every monogenous A -module F can be represented by A/I .

(c) \Rightarrow (a). By prop. 3 it is sufficient to prove that $\text{Tor}_1(E, F) = 0$ for any A -module F .

First consider the case, where F is finitely generated. We use induction, supposing that $\text{Tor}_1(E, F) = 0$, when F has n generators. Let F have $(n+1)$ generators x_1, \dots, x_n, x_{n+1} . If F' is the submodule generated by $\{x_1, \dots, x_n\}$, then $F' \subset F$ and $F'' = F/F'$ is monogenous. The exact sequence $0 \rightarrow F' \rightarrow F \rightarrow F'' \rightarrow 0$ gives the exact sequence $\text{Tor}_1(E, F') \rightarrow \text{Tor}_1(E, F) \rightarrow \text{Tor}_1(E, F'')$. Now $\text{Tor}_1(E, F') = \text{Tor}_1(E, F'') = 0$, thus $\text{Tor}_1(E, F) = 0$. In the general case, F can be considered as an inductive limit of finitely generated modules, and because Tor is compatible with inductive limits, $\text{Tor}_1(E, F) = 0$.

Proposition 6 : Let A be an integral domain, and E an A -module. Then E is torsionfree if and only if $\text{Tor}_1(E, A/(a)) = 0$, for any element $a \in A$.

Proof : If E is A -module, $a \in A$, then the exact sequence $0 \rightarrow A \xrightarrow{aI} A \rightarrow A/(a) \rightarrow 0$ gives the exact sequence $0 \rightarrow \text{Tor}_1(E, A/(a)) \rightarrow E \xrightarrow{aI} E$. In other words $\text{Tor}_1(E, A/(a)) = \{x \in E \mid ax = 0\}$, from which the result follows.

Corollary: Let A be a principal ideal domain. E is flat if and only if E is torsionfree.

Proof: We have already proved that, if E is flat, then it is torsion free. The converse follows from prop. 6 and prop. 5.

The first flatness criterion for noetherian local rings is the following:

Theorem 2: Let A be a noetherian local ring with maximal ideal m ; $k = A/m$, and E a finitely generated A -module. The following conditions are equivalent:

- (a) E is free.
- (b) E is flat.
- (c) $\text{Tor}_1^A(E, k) = 0$.

Proof: We have already proved $(a) \Rightarrow (b) \Rightarrow (c)$.

$(c) \Rightarrow (a)$: We recall first Nakayma's lemma. If A is a local ring with maximal ideal m ; $k = A/m$, and E is a finitely generated A -module, such that $k \otimes_A E = E/mE = 0$, then $E = 0$.

The module $\bar{E} = k \otimes_A E = E/mE$ is a finitely generated vector space over k . Let $\{\bar{x}_1, \dots, \bar{x}_r\}$ be a base of \bar{E} (over k), and $\{x_1, \dots, x_r\}$ E representatives of \bar{x}_i : s . Consider the homomorphism $\phi : A^r \rightarrow E$, $\phi(a_1, \dots, a_r) = \sum a_i x_i$. Denoting by R and Q the kernel and the cokernel of ϕ , we get an exact sequence:

$$(*) \quad 0 \rightarrow R \rightarrow A^r \rightarrow E \rightarrow Q \rightarrow 0$$

and R, Q are finitely generated A -modules. From $(*)$ we get the exact sequence

$$A^r \otimes_A k \rightarrow E \otimes_A k \rightarrow Q \otimes_A k \rightarrow 0.$$

But $\bar{E} = E \otimes_A k \simeq k^r = A^r \otimes_A k$, so $Q \otimes_A k = 0$, and by Nakayama's lemma $Q = 0$.

Therefore we have an exact sequence

$$0 \rightarrow R \rightarrow A^r \rightarrow E \rightarrow 0.$$

From this we get: $\text{Tor}_1(E, k) \rightarrow k \otimes_A R \rightarrow k^r \rightarrow \bar{E} \rightarrow 0$ (exact). Now: $\bar{E} \simeq k^r$, $\text{Tor}_1(E, k) = 0$ (by assumption). Therefore $k \otimes_A R = 0$, and once more by Nakayama's lemma $R = 0$, thus $E \simeq A^r$, i.e. E is free.

Proposition 7: Let $\phi : A \rightarrow B$ be a ring homomorphism, and let B be A -flat. If I is an ideal of A , we write $\bar{A} = A/I$, $\bar{B} = B/IB = \bar{A} \otimes_A B$. Let F be a B -module, then: $\text{Tor}_i^A(\bar{A}, F) = \text{Tor}_i^B(\bar{B}, F)$ ($i \geq 0$).

Proof: We choose first a B -free resolution of F

$$\rightarrow L_{n+1} \rightarrow L_n \rightarrow \dots \rightarrow L_1 \rightarrow L_0 \rightarrow F \rightarrow 0.$$

If L is the respective complex of resolution, then

$$\bar{B} \otimes_B L = B/IB \otimes_B L = \bar{A} \otimes_A (B \otimes_B L) = \bar{A} \otimes_A L.$$

Because every L_i is B -free, and B is A -flat, every L_i is A -flat (Property 3 after Th. 1). Thus L is a flat A -resolution, and

$$\text{Tor}_i^A(\bar{A}, F) = H_i(\bar{A} \otimes_A L) = H_i(\bar{B} \otimes_B L) = \text{Tor}_i^B(\bar{B}, F).$$

We shall next state the second flatness criterion for noetherian local rings.

Theorem 3: Let A and B be two noetherian local rings, with maximal ideals \underline{m} , \underline{n} ; $k = A/\underline{m}$. If $\phi : A \rightarrow B$ is a local homomorphism (i.e. $\phi(\underline{m}) \subset \underline{n}$), and F finitely generated B module then

$$F \text{ is } A\text{-flat} \Leftrightarrow \text{Tor}_1^A(k, F) = 0.$$

The proof of this theorem is much more difficult than that of th. 20 see for example:

Bourbaki: *Algèbre commutative*, Chapter III § 5, th1, (i) \Leftrightarrow (iii), p. 98.

The conditions in Bourbaki's theorem are here fulfilled:

- 1° A finitely generated module F over a noetherian local ring B is idealwise separated for \underline{n} . (*Ibid.*, § 5. 1. Ex. 1, p. 97.)
- 2° If $\phi : A \rightarrow B$ is a local homomorphism, F is also idealwise separated for \underline{m} . (*Ibid.*, § 5, prop. 2, p. 101.)
- 3° Also the flatness condition is fulfilled, because k is a field.

Remark: The main interest of the theorem lies in the fact, that it is true without any assumption of finiteness on B .

Corollary: If the assumptions are the same as in the theorem 3, and if moreover B is A -flat, then

$$F \text{ is } A\text{-flat} \Leftrightarrow \text{Tor}_1^B(\bar{B}, F) = 0,$$

where $\bar{B} = B/\underline{m}B$.

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

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

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