Algebraic geometry

Lecture 6: tensor product of rings

Misha Verbitsky

Université Libre de Bruxelles

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Tensor product (reminder)

DEFINITION: Let R be a ring, and M, M' modules over R. We denote by $M \otimes_R M'$ an R-module generated by symbols $m \otimes m'$, $m \in M, m' \in M'$, modulo relations
$r(m \otimes m') = (rm) \otimes m' = m \otimes (rm')$,
$(m + m_1) \otimes m' = m \otimes m' + m_1 \otimes m'$,
$m \otimes (m' + m'_1) = m \otimes m' + m \otimes m'_1$. Such an R-module is called **the tensor product of M and M' over R.**

REMARK: Suppose that M is generated over R by a set $\{m_i \in M\}$, and M' generated by $\{m'_j \in M'\}$. **Then $M \otimes_R M'$ is generated by $\{m_i \otimes m'_j\}$.**

EXERCISE: Find two non-zero R-modules A, B such that $A \otimes_R B = 0$ when

a. $R = \mathbb{Z}$.

b. $R = C^\infty M$ the ring of smooth functions on a manifold.

c. $R = \mathbb{C}[t]$ (polynomial ring).

Bilinear maps (reminder)

DEFINITION: Let M_1, M_2, M be modules over a ring R. **Bilinear map** $\mu(M_1, M_2) \xrightarrow{\varphi} M$ is a map satisfying $\varphi(rm, m') = \varphi(m, rm') = r\varphi(m, m')$, $\varphi(m + m_1, m') = \varphi(m, m') + \varphi(m_1, m')$, $\varphi(m, m' + m'_1) = \varphi(m, m') + \varphi(m, m'_1)$.

THEOREM: (Universal property of the tensor product)
For any bilinear map $B: M_1 \times M_2 \longrightarrow M$ **there exists a unique homomorphism $b: M_1 \otimes M_2 \longrightarrow M$, making the following diagram commutative:**

$$\begin{tikzcd}
M_1 \times M_2 \arrow[r, "B"] \arrow[dr] & M_1 \otimes M_2 \arrow[d, "b"] \\
& M
\end{tikzcd}$$

■

REMARK: If R is the field k, R-modules are vector spaces, and the previous theorem proves that $\mathrm{Bil}(M_1 \times M_2, k) = (M_1 \otimes M_2)^*$. For finite-dimensional M_i, it gives $M_1 \otimes M_2 = (M_1 \otimes M_2)^{**} = \mathrm{Bil}(M_1 \times M_2, k)^*$.

Universal property of the tensor product and categories

DEFINITION: Initial object of a category $\mathcal{C}$ is an object $X \in \mathcal{O}b(\mathcal{C})$ such that for any $Y \in \mathcal{O}b(\mathcal{C})$ there exists a unique morphism $X \longrightarrow Y$.

EXAMPLE: Zero space is an initial object in the category of vector spaces. The ring $\mathbb{Z}$ is an initial object in the category of rings with unit.

EXERCISE: Prove that **initial object is unique.**

DEFINITION: Let M_1, M_2 are R-modules, and $\mathcal{C}$ the following category. Objects of $\mathcal{C}$ are pairs (R-module M, bilinear map $M_1 \times M_2 \longrightarrow M$). Morphisms of $\mathcal{C}$ are homomorphisms $M \xrightarrow{\varphi} M'$ making the following diagram commutative:

$$\begin{array}{ccc} M_1 \times M_2 & \longrightarrow & M \\ \downarrow{\scriptstyle \mathrm{Id}} & & \downarrow{\scriptstyle \varphi} \\ M_1 \times M_2 & \longrightarrow & M' \end{array}$$

CLAIM: (Universal property of the tensor product)
Tensor product $M_1 \times M_2$ is the initial object in $\mathcal{C}$.

COROLLARY: Tensor product is uniquely determined by the universal property.

Indeed, the initial object is unique.

Exactness of the tensor product (reminder)

THEOREM: Let $M_1 \longrightarrow M_2 \longrightarrow M_3 \longrightarrow 0$ be an exact sequence of R-modules. **Then the sequence**

$$M_1 \otimes_R M \longrightarrow M_2 \otimes_R M \longrightarrow M_3 \otimes_R M \longrightarrow 0 \qquad (*)$$

is exact.

Proof: Follows from the universal property and left exactness of the interior $\mathcal{H}om$ functors. ■

COROLLARY: Let $I \subset R$ be an ideal in a ring. **Then** $M \otimes_R (R/I) = M/IM$**.**

Proof: Apply the functor $\otimes_R M$ to the exact sequence $0 \longrightarrow I \longrightarrow R \longrightarrow R/I \longrightarrow 0$. We obtain $IM \longrightarrow M \longrightarrow (R/I) \otimes_R M \longrightarrow 0$. ■

Tensor product of rings: geometric meaning

EXERCISE: Let $f: X \longrightarrow Y$ be a morphism of algebraic varieties, $y \in Y$ a point. **Prove that $f^{-1}(y)$ is affine.**

QUESTION: How one describes the ring of regular functions on $f^{-1}(y)$?

HINT: Use the tensor product of rings!

EXERCISE: Let $X \subset \mathbb{C}^n$, $Y \subset \mathbb{C}^k$ be algebraic subvarieties. **Prove that $X \times Y$ is also algebraic.**

HINT: Use the tensor product of rings!

Tensor product of rings

DEFINITION: Let A, B be rings, $C \longrightarrow A$, $C \longrightarrow B$ homomorphisms. Consider A and B as C-modules, and let $A \otimes_{\mathbb{C}} B$ be their tensor product. Define the ring multiplication on $A \otimes_C B$ as $a \otimes b \cdot a' \otimes b' = aa' \otimes bb'$. This defines **tensor product of rings**.

EXAMPLE: $\mathbb{C}[t_1, ..., t_k] \otimes_{\mathbb{C}} \mathbb{C}[z_1, ..., z_n] = \mathbb{C}[t_1, ..., t_k, z_1, ..., z_n]$. Indeed, if we denote by $\mathbb{C}_d[t_1, ..., t_k]$ the space of polynomials of degree d, then $\mathbb{C}_d[t_1, ..., t_k] \otimes_{\mathbb{C}} \mathbb{C}_{d'}[z_1, ..., z_n]$ is polynomials of degree d in $\{t_i\}$ and d' in $\{z_i\}$.

EXAMPLE: For any homomorphism $\varphi : \mathbb{C} \longrightarrow A$, **the ring $A \otimes_C (C/I)$ is a quotient of A by the ideal $A \cdot \varphi(I)$**. This follows from $M \otimes_R (R/I) = M/IM$.

PROPOSITION: (associativity of $\otimes$)
Let $C \longrightarrow A, C \longrightarrow B, C' \longrightarrow B, C' \longrightarrow D$ be ring homomorphisms. Then $(A \otimes_C B) \otimes_{C'} D = A \otimes_C (B \otimes_{C'} D)$.

Proof: Universal property of $\otimes$ implies that $\operatorname{Hom}((A \otimes_C B) \otimes_{C'} D, M) = \operatorname{Hom}(A \otimes_C (B \otimes_{C'} D), M)$ is the space of polylinear maps $A \otimes B \otimes D \longrightarrow M$ satisfying $\varphi(ca, b, d) = \varphi(a, cb, d)$ and $\varphi(a, c'b, d) = \varphi(a, b, c'd)$. However, an object X of category is defined by the functor $\operatorname{Hom}(X, \cdot)$ uniquely **(prove it)**.
■

Tensor product of rings and preimage of a point

DEFINITION: Recall that **the spectrum** of a finitely generated ring R is the corresponding algebraic variety, denoted by Spec(R)

PROPOSITION: Let $f: X \longrightarrow Y$ be a morphism of affine varieties, $f^*: \mathcal{O}_Y \longrightarrow \mathcal{O}_X$ the corresponding ring homomorphism, $y \in Y$ a point, and $\mathfrak{m}_y$ its maximal ideal. **Denote by R_1 the quotient of $R := \mathcal{O}_X \otimes_{\mathcal{O}_Y} (\mathcal{O}_Y/\mathfrak{m}_y)$ by its nilradical. Then Spec$(R_1) = f^{-1}(y)$.**

Proof. Step 1: If $\alpha \in \mathcal{O}_Y$ vanishes in y, $f^*(\alpha)$ vanishes in all points of $f^{-1}(y)$. This implies that **the set V_I of common zeros of the ideal $I := \mathcal{O}_X \cdot f^*\mathfrak{m}_y$ contains $f^{-1}(y)$.**

Step 2: If $f(x) \neq y$, take a function $\beta \in \mathcal{O}_Y$ vanishing in y and non-zero in $f(x)$. Since $\varphi^*(\beta)(x) \neq 0$ and $\beta(y) = 0$, this gives $x \notin V_I$. **We proved that the set of common zeros of the ideal $I = \mathcal{O}_X \cdot f^*\mathfrak{m}_y$ is equal to $f^{-1}(y)$.**

Step 3: Now, strong Nullstellensatz implies that $\mathcal{O}_{f^{-1}(y)}$ is a quotient of $R = \mathcal{O}_X/I$ by nilradical. ■

EXERCISE: Give an example when $R = \mathcal{O}_X/I$ is non-reduced (contains nilpotents).

Tensor product of rings and product of varieties

LEMMA: $A \otimes_C B \otimes_B B' = A \otimes_C B'$.
Proof: Follows from associativity of tensor product and $B \otimes_B B' = B'$. ■

LEMMA: $A \otimes_C (B/I) = A \otimes_C B/(1 \otimes I)$, where $1 \otimes I$ denotes the ideal $A \otimes_C I$.
Proof: Using $M \otimes_R (R/I) = M/IM$, we obtain

$$A \otimes_C (B/I) = (A \otimes_C B) \otimes_B (B/I) = (A \otimes_C B)/(1 \otimes I) \quad \blacksquare$$

Lemma 1: Let A, B be finitely generated rings without nilpotents, $R := A \otimes_{\mathbb{C}} B$, and $N \subset R$ nilradical. **Then** Spec$(R/N) = $ Spec$(A) \times$ Spec(B).

Proof. Step 1: Let $A = \mathbb{C}[t_1, ..., t_n]/I, B = \mathbb{C}[z_1, ..., z_k]/J$. Then $\mathbb{C}[t_1, ..., t_n] \otimes_{\mathbb{C}} \mathbb{C}[z_1, ..., z_k] = \mathbb{C}[t_1, ..., t_n, z_1, ..., z_k]$. Applying the previous lemma twice, **we obtain** $A \otimes_{\mathbb{C}} B = \mathbb{C}[t_1, ..., t_n, z_1, ..., z_k]/(I + J)$. Here $I + J$ means $I \otimes 1 \oplus 1 \otimes J$.

Step 2: The set V_{I+J} of common zeros of $I + J$ is Spec$(A) \times$ Spec$(B) \subset \mathbb{C}^n \times \mathbb{C}^k$.

Step 3: Hilbert Nullstellensatz implies Spec$(R/N) = V_{I+J} = $ Spec$(A) \times$ Spec(B). ■

REMARK: We shall see that **a tensor product $R := A \otimes_{\mathbb{C}} B$ of reduced rings is reduced.**

Tensor product of rings and product of varieties (2)

LEMMA: For any finitely-generated ring A over $\mathbb{C}$, **intersection P of all its maximal ideals is its nilradical.**

Proof: Let $A = \mathbb{C}[t_1, ..., t_n]/I$, and $Z = V_I$ the set of common zeros. Strond Nullstellensatz implies that $f \in A$ **is nilpotent if and only ig $f = 0$ in each point of Z.** This is equivalent to $f \in P$. ∎

EXERCISE: Prove this lemma without Nullstellensatz and not assuming that A is finitely generated.

REMARK: Let A, B be finite generated rings over $\mathbb{C}$m $B \longrightarrow A$ a homomorphism, and $\mathfrak{m} \subset B$ a maximal ideal. Then the ring $A \otimes_B (B/\mathfrak{m})$ **can contain nilpotents**, even if A and B have no zero divisors.

EXERCISE: Give an example of such rings A, B.

THEOREM: Let A, B be finitely-generated, reduced rings over $\mathbb{C}$, and $R := A \otimes_{\mathbb{C}} B$ their product. **Then R is reduced** (that is, has no nilpotents).

Proof: see the next slide.

COROLLARY: Spec$(A) \times$ Spec$(B) =$ Spec$(A \otimes_{\mathbb{C}} B)$.

Tensor product of rings and product of varieties (2)

THEOREM: Let A, B be finitely-generated, reduced rings over $\mathbb{C}$, and $R := A \otimes_{\mathbb{C}} B$ their product. **Then R is reduced**.

Proof. Step 1: By the previous lemma, it suffices to show that the **intersection P of maximal ideals of R is 0.**

Step 2: Let X, Y denote the varieties $\operatorname{Spec}(A), \operatorname{Spec}(B)$. Lemma 1 implies that **maximal ideals of R are points of $X \times Y$.**

Step 3: Every such ideal is given as $\mathfrak{m}_x \otimes \mathcal{O}_Y + \mathcal{O}_X \otimes \mathfrak{m}_y$, where $x \in X, y \in Y$. Then

$$P = \bigcap_{X \times Y} (\mathfrak{m}_x \otimes \mathcal{O}_Y + \mathcal{O}_X \otimes \mathfrak{m}_y) = \bigcap_Y \left(\left(\bigcap_X \mathfrak{m}_x \otimes \mathcal{O}_Y \right) + \mathcal{O}_X \otimes \mathfrak{m}_y \right) = \bigcap_Y \mathcal{O}_X \otimes \mathfrak{m}_y = 0.$$

This follows from $\bigcap_Y 1 \otimes \mathfrak{m}_y = \bigcap_X \mathfrak{m}_x \otimes 1 = 0$ since A and B are reduced. ■

Preimage and diagonal

Claim 2: Let $f: X \longrightarrow Y$ be a morphism of algebraic varieties, $f^*: \mathcal{O}_Y \longrightarrow \mathcal{O}_X$ the corresponding ring homomorphism, $Z \subset Y$ a subvariety, and I_Z its ideal. Denote by R_1 the quotient of a ring $R := \mathcal{O}_X \otimes_{\mathcal{O}Y} (\mathcal{O}_Y/I_Z) = \mathcal{O}_X/f^*(I_Z)$ by its nilradical. **Then** Spec$(R_1) = f^{-1}(Z)$.

Proof: Clearly, the set of common zeros of the ideal $J := f^*(I_Z)$ contains $f^{-1}(Z)$. On the other hand, for any point $x \in X$ such that $f(x) \notin Z$ there exist a function $g \in J$ such that $g(x) \neq 0$. Therefore, $f^{-1}(Z) = V_J$, and strong Nullstellensatz implies that $\mathcal{O}_{f^{-1}(Z)} = R_1$. ■

Claim 3: Let M be an algebraic variety, and $\Delta \subset M \times M$ the diagonal, and $I \subset \mathcal{O}_M \otimes_{\mathbb{C}} \mathcal{O}_M$ the ideal generated by $r \otimes 1 - 1 \otimes r$ for all $r \in \mathcal{O}_M$. **Then** $\mathcal{O}_\Delta$ **is** $\mathcal{O}_M \otimes_{\mathbb{C}} \mathcal{O}_M/I$.

Proof. Step 1: By definition of the tensor product, $\mathcal{O}_M \otimes_{\mathbb{C}} \mathcal{O}_M/I = \mathcal{O}_M \otimes_{\mathcal{O}_M} \mathcal{O}_M = \mathcal{O}_M$, hence it is reduced. If we prove that $\Delta = V_I$, the statement of the claim would follow from strong Nullstellensatz.

Step 2: Clearly, $\Delta \subset V_I$. To prove the converse, let $(m, m') \in M \times M$ be a point not on diagonal, and $f \in \mathcal{O}_M$ a function which satisfies $f(m) = 0, f(m') \neq 0$. Then $f \otimes 1 - 1 \otimes f$ is non-zero on (m, m'). ■

Fibered product

DEFINITION: Let $X \xrightarrow{\pi_X} M, Y \xrightarrow{\pi_Y} M$ be maps of sets. **Fibered product** $X \times_M Y$ is the set of all pairs $(x, y) \in X \times Y$ such that $\pi_X(x) = \pi_Y(y)$.

CLAIM: Let $X \xrightarrow{\pi_X} M, Y \xrightarrow{\pi_Y} M$ be morphism of algebraic varieties, $R := \mathcal{O}_X \otimes_{\mathcal{O}_M} \mathcal{O}_Y$, and R_1 the quotient of R by its nilradical. **Then** Spec$(R_1) = X \times_M Y$.

Proof: Let I be the ideal of diagonal in $\mathcal{O}_M \otimes_{\mathbb{C}} \mathcal{O}_M$. Since I is generated by $r \otimes 1 - 1 \otimes r$ (Claim 3), $R = \mathcal{O}_X \otimes_{\mathbb{C}} \mathcal{O}_Y / (\pi_X \times \pi_Y)^*(I)$. Applying Claim 2, we obtain that Spec$(R_1) = (\pi_X \times \pi_Y)^{-1}(\Delta)$. ■