

Concise AG Notes - UofT MAT1190

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1 Lecture Notes

1.1 Lecture 1 (Sept 3, 2025)

Theorem 1. (Gelfond-Neymark) A compact topological space is determined by its ring of smooth functions. In particular if the ring $C(X) := C(X, \mathbb{R})$ and $C(X) \cong C(Y)$, then $X \cong Y$.

Proposition 1. Each point in X corresponds to a maximal ideal of $C(X)$, moreover if X is compact, then the correspondence is 1-1.

Proof. the evaluation at a point gives a surjective homomorphism $C(X) \rightarrow \mathbb{R}$, the image is a field, hence the kernel is a maximal ideal corresponding to the point.

Now in the compact case, (assume X is Hausdorff?), then X is Hausdorff and compact hence normal. We can use Urysohn's lemma to get a function vanishing at x but not y . Now suppose that for some maximal ideal $\mathfrak{m} \subset C(X)$ for any point $p \in X$ there is a continuous function with $f(p) \neq 0$, then the set $U_f = \{x \in X \mid f(x) \neq 0\}$ is open, and $\bigcup_{f \in C(X)} U_f = X$, so we get a finite subcover. Take a linear combination of the functions in this subcover to complete the proof. \square

definition 1. The Zariski Topology on $\text{Spec}_{\max}(R)$ is the coarsest topology such that when $\mathfrak{m} \leftrightarrow x$ $f : \mathfrak{m} \rightarrow f(x)$ is continuous, where the topology on \mathbb{R} is taken as the cofinite topology. The closed sets in this topology are the vanishing loci of $f \in C(X)$.

- Exercise 1, complete Hartshorne exercise 1.4

1.2 Lecture 2 (Sept 5, 2025)

definition 2. For $T \subset R_n := k[x_1, \dots, x_n]$ and $S \subset k^n$ we define

$$V(T) = \{x \in k^n \mid f(x) = 0, \forall f \in T\} \text{ and } I(S) = \{f \in R_n \mid f(x) = 0, \forall x \in S\}$$

Proposition 2. Suppose k is an uncountable field, and L/k is an extension with $[L : k] \leq \aleph_0$, then $L = k$.

Proof. Suppose not, then let $x \in L \setminus k$, we find that $\{\frac{1}{x-\lambda} \mid \lambda \in k\}$ is uncountable, so that there must be an algebraic relation. Thus there exist $\mu_i \in k$ with $\sum_1^n \frac{\mu_i}{x-\lambda_i} = 0$, so that $\sum_1^n \mu_j \prod_{i \neq j} (x - \lambda_i) = 0$, but then x is algebraic over k , hence $x \in k$, contradiction. \square

Theorem 2. (Nullstellensatz - weak form) $V(T) = \emptyset \implies (T) = R_n$

Proof. We assume here that k is uncountable (this is unnecessary- use Noether Normalization). Since $J := (T) \subset R_n$ is an ideal it is contained in a maximal ideal \mathfrak{m} . Then R_n/\mathfrak{m} is a field extension of k with countable dimension, by the previous proposition it is equal to k . It follows that each $x_i \mapsto a_i \in k$ when taking the quotient $R_n \rightarrow R_n/\mathfrak{m} = k$, it follows that I vanishes on (a_1, \dots, a_n) , so I cannot be contained in a maximal ideal. \square

Theorem 3. (Nullstellensatz)

$$IV(J) = \sqrt{J}$$

Proof. By Hilbert's basis theorem, we reduce to the finitely generated case. Let $f \in IV(\{f_1, \dots, f_r\})$, then $(1 - tf, f_1, \dots, f_r) \subset R_n[t]$ has no common zero. Then $g_0(1 - tf) + g_1f_1 + \dots + g_rf_r = 1$, and let $N = \max_i \{\deg_t g_i\}$. Taking $t = f^{-1}$, we get $\sum_1^r g_i f_i = 1$, so that for $h_i = f^N g_i \in R_n$ we get $\sum_1^r h_i f_i = f^N \in I \implies f \in \sqrt{I}$. \square

The Nullstellensatz gives a bijection

$$\{\text{Affine algebraic varieties}\} \longleftrightarrow \{\text{Finitely generated reduced k-algebras}\}$$

$$V(\sqrt{J}) \longleftrightarrow R_n/\sqrt{J}$$

Moreover, this is a categorical equivalence

$$\text{Var}_k \cong \left(\text{Alg}_k^{\text{reduced}} \right)^{\text{op}}$$

1.3 Lecture 3 (Sept 8, 2025)

definition 3. Let $\pi : S \rightarrow X$ be a local homeomorphism, then S is called an étalé space, or a sheaf on X .

Example(s). 1. $\rightarrow X$

2. $1 : X \rightarrow X$

3. I a set with the discrete topology and the projection $X \times I \rightarrow X$

4. A covering space, more explicitly the mobious covering

$$S^1 \rightarrow S^1$$

$$z \mapsto z^2$$

5. $U \subset X$ an open set, $\iota : U \rightarrow X$

6. If $x \in X$ is a closed point, then we can construct the space $X \sqcup_{X \setminus \{x\}} X = X \times \{1, 2\} / \sim$ where $(y, 1) \sim (y, 2)$ when $y \neq x$. This comes with the codiagonal map $\nabla : X \sqcup_{X \setminus \{x\}} X \rightarrow X$, where $\nabla|_{X \times \{i\}} = 1_X, i \in \{1, 2\}$.

This is a generalization of the line with two origins.

7. $I \neq \emptyset$, then take $\bigsqcup_{X \setminus \{x\}} X \xrightarrow{\nabla} X$

definition 4. If $U \subset X$ is an open set, then a section on U is a continuous map $s : U \rightarrow S$ such that the following commutes:

$$\begin{array}{ccc} & S & \\ & \downarrow \pi & \\ U & \xrightarrow{\iota} & X \end{array} \quad \begin{array}{c} \nearrow s \\ \searrow \end{array}$$

The set of sections is denoted $S(U)$ or $\Gamma(U, S)$. If $U = X$, then s is called a global section with notation $S(X)$ or $\Gamma(S)$.

Example(s). (Revisited)

1.

$$S(U) = \begin{cases} 1_\emptyset & U = \emptyset \\ \emptyset & \text{else} \end{cases}$$

2.

$$S(U) = \{\iota_U\}$$

3.

$$S(U) = \text{hom}_{\text{set}}(\pi_0(U), I)$$

4.

$$S(U) = \{f : U \rightarrow \mathbb{C} \mid f(z^2) = z\}$$

5.

$$S(U) = \begin{cases} \{\iota\} & x \notin U \\ \{1, 2\} & x \in U \end{cases}$$

6.

$$S(U) = \begin{cases} \{\iota\} & x \notin U \\ I & x \in U \end{cases}$$

This particular example is called the “sky-scraper sheaf”

Proposition 3. There is a étalé space \mathcal{H} over \mathbb{C}_{EUC} with sections corresponding to holomorphic functions on \mathbb{C} .

Proof. The construction of \mathcal{H} as a set is given, alongside its topology. Verifying the claim is exercise 2.

$$\mathcal{H} := \bigsqcup_{z_0 \in \mathbb{C}} \left\{ \sum_{n=1}^{\infty} c_n (z - z_0)^n \mid \text{the series converges in some neighborhood of } z_0 \right\}$$

And define the topology on \mathcal{H} as the strongest topology such that for any open set U , and holomorphic $f : U \rightarrow \mathbb{C}$ we have the following map is continuous

$$\begin{aligned} \mathcal{H}f : U &\rightarrow \mathcal{H} \\ z_0 &\mapsto \text{The Taylor expansion of } f \text{ at } z_0 \end{aligned}$$

□

1.4 Lecture 4 (Sept 10, 2025)

definition 5. Let $\pi : S \rightarrow X$ be étalé, then $S_x := \pi^{-1}(x)$ is called the stalk of x .

Example(s). 1. $1 : X \rightarrow X$, $S_x = \{x\}$

2. $X \times I \rightarrow X$, $S_x \cong I$

3. $\bigsqcup_{X \setminus \{x\}} X \xrightarrow{\nabla} X$, then $S_y \cong \begin{cases} I & y = x \\ \{\bar{y}\} & y \neq x \end{cases}$

4. $\mathcal{H} \rightarrow \mathbb{C}$ \mathcal{H}_{z_0} is locally convergent power series at z_0 .

Proposition 4. If $\pi : S \rightarrow X$ is étalé and $y \in \pi^{-1}(x)$, then there is an open set $U \supset \{x\}$ and a section $s : U \rightarrow S$ with $s(x) = y$. Moreover, given two sections $s_i \in \Gamma(U_i, S)$ there is some $V \subset U_1 \cap U_2$ containing x , such that $s_1|_V = s_2|_V$.

Proof. The proof is exercise 3.

□

2 Exercises

exercise 1. (Hartshorne Exercise 1.4) An algebraically closed field is infinite, moreover the zero sets of polynomials are either k or a finite subset of k . Consider the closed set $V(x - y) \subset \mathbb{A}^2$, then it is an infinite set so if $\mathbb{A}^1 \times \mathbb{A}^1 = \mathbb{A}^2$, then it must be of the form $\mathbb{A}^1 \times F \cup E \times \mathbb{A}^1$, where $E, F \subset \mathbb{A}^1$ are closed. But for a fixed x or y we have $V(x - y)$ has cardinality 1 which makes this impossible. \square

exercise 2. (Show that $\mathcal{H}(U) = \{f : U \rightarrow \mathbb{C} \mid f \text{ holomorphic}\}$) where we define \mathcal{H} in proposition 3.

We first check that it is a local homeomorphism, for $z \in \mathbb{C}$ and $U \supset z$, we can take a function f holomorphic on U , then $\mathcal{H}f$ has only one Taylor expansion for f at each z_0 and is continuous. Since there is only one Taylor expansion at each z_0 the map π taking Taylor series centered at z_0 to z_0 is injective, π is continuous because for an open set V we have $\pi^{-1}(V) = \bigsqcup_{z_0 \in V} \mathcal{H}f(z_0)$, which has open preimage under all of the $\mathcal{H}f$. Since $\mathcal{H}f\pi = 1_S, \pi\mathcal{H}f = 1_X$ we are done this step.

Now $\pi \circ \mathcal{H}f|_U = \iota_U$ and $\mathcal{H}f$ continuous suffices to show that every holomorphic function is a section. Conversely, suppose $g : X \rightarrow \mathcal{H}$ is not induced by a holomorphic function. The first case is g maps some z_1 to a Taylor expansion around $z_0 \neq z_1$, this cannot be a section since then the diagram won't commute. In the second case, there are distinct points $\{z_\alpha\}_{\alpha \in I}$ in the same connected component of U each Taylor series $g(z_\alpha)$ determining a different holomorphic function (near that point) f_α , denote the set of points that determines f_α as V_α , it is immediate that the V_α are disjoint. We know that $\mathcal{H}f_\alpha(U)$ is open in \mathcal{H} for each α (Check!), but if $g^{-1}(\mathcal{H}f_\alpha(U)) = V_\alpha$ is open for each $\alpha \in I$, then $U = \bigsqcup V_\alpha$ is not connected, violating our earlier assumption. Hence for some open $\mathcal{H}f_\alpha(U)$ we have that $g^{-1}(\mathcal{H}f_\alpha(U))$ is not open and g is not continuous. \square

Check: If two holomorphic functions have the same Taylor series at a point they are equal so

$$\mathcal{H}\phi^{-1}(\mathcal{H}f_\alpha(U)) = \begin{cases} U & \text{or the domain of definition for } f & \phi = f_\alpha \\ \emptyset & \text{else} \end{cases}$$

In either case the preimage is an open set.

exercise 3. (Show the existence and uniqueness of sections for each element in the stalk)

Existence is not too bad, since π is a local homeomorphism, hence we can choose some neighborhood $y \in U$ with $\pi|_U$ a homeomorphism. Then define $s : \pi(U) \rightarrow U$ via $x \mapsto \pi|_U^{-1}(x)$. Now assume that s_1, s_2 are two such sections associated to open sets U_1, U_2 , then $y \in \pi^{-1}(U_1) \cap \pi^{-1}(U_2)$, and hence some open set $y \in \tilde{V} \subset \pi^{-1}(U_1) \cap \pi^{-1}(U_2)$ such that $\pi|_{\tilde{V}}$ is a homeomorphism.

A Assigned Readings

B Misc.

definition 6. A ring or algebra is called reduced when it has no non-zero nilpotents.