

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 $\mathfrak{m} \leftrightarrow x : \mathfrak{m} \rightarrow f(x)$ 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 $[L : k] \leq \#\mathbb{N}$, 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

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

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

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 $\sqcup_I X \xrightarrow{\nabla} X$

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:

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

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.

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

6.

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

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 $S_y \cong \begin{cases} I & y = x \\ \{\overline{y}\} & y \neq x \end{cases}$

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 $U \ni \{x\}$ 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.

□

Proposition 5.

$$\varinjlim_{x \in U} \Gamma(U, S) \xrightarrow{s \mapsto s(x)} S_x$$

is a bijection.

Proof. This is onto since every element of the stalk has a section mapping to it, and injective by uniqueness of such an element up to the equivalence relation in the colimit. This is essentially restating the previous proposition. \square

Proposition 6. $f : X \rightarrow Y, g : Y \rightarrow Z$ continuous maps, then

- f and g being local homeomorphisms implies $g \circ f$ is.
- g and $f \circ g$ being local homeomorphisms implies f is.

definition 6. (The Category of Sheaves on X) The objects are étalé spaces $\pi : S \rightarrow X$, and the morphisms are $\varphi : S_1 \rightarrow S_2$ continuous maps where the following commutes:

$$\begin{array}{ccc} S_1 & \xrightarrow{\varphi} & S_2 \\ \pi_1 \searrow & & \swarrow \pi_2 \\ & X & \end{array}$$

Note that φ continuous and the diagram commuting implies it is a local homeomorphism, and hence morphisms are actually sheaves on sheaves.

Proposition 7. (Isomorphism Criterion) A morphism $\varphi \in \text{Sh}(X)$ is an isomorphism if and only if the induced map $(S_1)_x \rightarrow (S_2)_x$ is bijective for all $x \in X$.

Proof. One direction is easy since stalks get mapped to stalks, and an inverse map must be a bijection. In the converse direction, we know that it must be a local homeomorphism by proposition 6, hence since its invertible as a set function, its inverse is a local homeomorphism. \square

Proposition 8. (Monomorphism Criterion) A morphism $\varphi \in \text{Sh}(X)$ is a monomorphism if and only if the induced map $(S_1)_x \rightarrow (S_2)_x$ is injective for all $x \in X$.

Proof. Once again, one direction is easy. For the other direction, if $\varphi(x_1) = \varphi(x_2)$, then $\pi_2 \varphi(x_1) = \pi_2 \varphi(x_2)$, so that $\varphi(x_1)$ and $\varphi(x_2)$ are in the same element of the stalk, by injectivity on stalks we are done. \square

Proposition 9. (Isomorphism Criterion for Sections) If $\varphi : S_1 \rightarrow S_2$ is a morphism in $\text{Sh}(X)$ such that for any open set the induced map $\Gamma(U, S_1) \rightarrow \Gamma(U, S_2)$ is a bijection, then φ is an isomorphism. Moreover, the converse is true.

Proof. The main thing to check here is that a bijection for all U gives a bijection on the colimits. Assuming this for now we get that as sets:

$$(S_1)_x \cong \varinjlim_{x \in U} \Gamma(U, S_1) \cong \varinjlim_{x \in U} \Gamma(U, S_2) \cong (S_2)_x$$

So that applying the Isomorphism Criterion we find that φ is an isomorphism. Now if φ is an isomorphism, then $\varphi : \Gamma(U, S_1) \rightarrow \Gamma(U, S_2)$ via $s_1 \mapsto \varphi s_1$, this has map inverse φ^{-1} , so these sets are in bijective correspondence which suffices to prove the converse. \square

Note that the same proof works for injections.

Warning \triangle . If $\varphi : S_1 \rightarrow S_2$, $\varphi \in \text{Sh}(X)$ is surjective this does not imply that the induced map on $\Gamma(U, S)$ is in general surjective. A counter example is the Mobius covering of S^1 , i.e. $X = S = S^1$ with $\pi_S = \varphi : S \rightarrow X$ via $z \mapsto z^2$ and $\pi_X = 1_X$. Then $\Gamma(X, S) = \emptyset$, since there is no globally continuous square root on S^1 . This implies that there is no surjection

$$\emptyset = \Gamma(X, S) \rightarrow \Gamma(X, X) = \{1_X\}$$

The upshot is that local lifts do exist.

Proposition 10. (Local Lifts) Let S_1, S_2 be étalé over X , and $\varphi : S_1 \rightarrow S_2$ a surjective morphism. Then given a section $s \in S_2$, there is an open cover $\bigcup_I U_i$ with sections $t_i \in S_1(U_i)$ such that $\varphi \circ t_i = s|_{U_i}$ for all i .

Proof. Since φ is surjective, it must also be surjective on stalks $S_x \rightarrow S_x$. Then for any x , we have some (t_x, V_x) so that $\varphi \circ t_x(x) = s(x)$, it follows by the existence part of proposition 4 that we can choose a neighborhood $x \in U_x \subset V_x$ so that $\nu p : (t_x, U_x) \rightarrow (s, U)$. \square

Remark 1. (An abstract perspective on lifts) Given the setup

$$\begin{array}{ccc} S_1 & \xrightarrow{\varphi} & S_2 \\ & \searrow \pi_1 & \swarrow \pi_2 \\ & X & \end{array}$$

and a global section $s \in \Gamma(X, S_2)$, we get a sheaf from the fibered product $s^{-1}S_1 := S_1 \times_{S_2} X$ (this of course means its points are $\{(t, x) \mid \varphi(t) = s(x)\}$). From this perspective, s having a lift to $\Gamma(X, S_1)$ is equivalent to $s^{-1}S_1$ having a global section.

1.5 Lecture 5 (Sept 12, 2025)

definition 7. If $f : X \rightarrow Y$ and $g : Z \rightarrow Y$ are morphisms, then we define the fiber product by the universal property

$$\begin{array}{ccccc} T & & \xrightarrow{\beta} & & Z \\ & \searrow \exists! & & \searrow \pi_Z & \\ & X \times_Y Z & \xrightarrow{\pi_Z} & Z & \\ & \downarrow \pi_X & & \downarrow g & \\ & X & \xrightarrow{f} & Y & \end{array}$$

α (curved arrow from T to X)

Example(s).

$$\begin{array}{ccc} X \times Z & \longrightarrow & Z \\ \downarrow & & \downarrow \\ X & \longrightarrow & \{\cdot\} \end{array} \quad \begin{array}{ccc} f^{-1}(y) & \longrightarrow & \{y\} \\ \downarrow & & \downarrow \\ X & \longrightarrow & Y \end{array}$$

So that products and fibers are special cases.

definition 8. (Pre-Image Sheaf) Given a continuous map $f : X \rightarrow Y$, there is a functor $f^{-1} : \text{Sh}(Y) \rightarrow \text{Sh}(X)$ via $(\pi : S \rightarrow Y) \mapsto (\pi_Y : S \times_X Y \rightarrow Y)$. This is given in the following diagram,

$$\begin{array}{ccc} S \times_X Y & \longrightarrow & S \\ \downarrow \pi_Y & & \downarrow \pi \\ Y & \xrightarrow{f} & X \end{array}$$

Proposition 11. In the pre-image sheaf diagram, π_Y is a local homeomorphism when π is.

Proof. \square

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 $U \ni z$, 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. Now let $V = s_1^{-1}(\tilde{V}) \cap s_2^{-1}(\tilde{V})$ which is nonempty since it contains x , and open. Since the inclusions are injective, we can say the same about sections, hence $s_1, s_2: V \rightarrow \tilde{V}$, and for $z \in V$ we have $\pi|_{\tilde{V}} s_i(z) = \iota(z) = z$ and hence $s_i(z) = \pi|_{\tilde{V}}^{-1}(z)$. \square

A Problem Sets

A.1 Problem set 1.

Problem 1. (a) For a topological space X , define a sheaf \mathcal{C}_X of continuous real valued functions on X .

Proof. Consider the set

$$\bigsqcup_{x \in X} \{(f, U) \mid x \in U \text{ open and } f: U \rightarrow \mathbb{R} \text{ continuously}\} / \sim$$

Where $(f, U) \sim (g, U')$ when there is some $x \in V \subset U \cap U'$ such that $f|_V = g|_V$. With the final topology generated by the functions $\mathcal{C}f: x \mapsto [f]_x$ (the germ of f at x), with the covering map $\pi: [f]_x \mapsto x$. From the definition of the topology, we find that π is continuous with $\pi^{-1}(x) = \bigcup_{(U,f)} [f]_x$. Moreover each $\mathcal{C}f$ is a section by definition, and if $s: U \rightarrow \mathcal{C}_X$ is not induced in this fashion, then \square

B Assigned Readings

C Misc.

definition 9. A ring or algebra is called reduced when it has no non-zero nilpotents.

definition 10. A map is a monomorphism when it has the left cancellation property $f g_1 = f g_2 \implies g_1 = g_2$.