MAT1191 - Algebraic Geometry Curves and Surfaces

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Contents

Throughout these notes, [HA] refers to Hartshorne, [MA] refers to Commutative Ring Theory by Matsumura, and [STA] refers to the stacks project.

1 Curves

1.1 Lecture 1 - Line bundles and divisors

Def: An "equation" for a scheme X is a map $X \to \mathbb{P}^n$. In turn these correspond to a choice of $n + 1$ global sections which globally generate a line bundle $\mathscr{L}$ on X.

Def: A *nice curve* over k is a smooth, proper, geometrically integral k-scheme of dimension 1.

Def: A *curve* over k is a geometrically integral k-scheme of dimension 1.

(The following definition was assumed but will be included for completeness)

Def: A scheme X of finite type over a field k is *geometrically integral* (resp. *reduced, irreducible*) if $X \times_k \bar{k}$ is integral (resp. reduced, irreducible). See [HA, Ex II.3.15] for some equivalent properties.

Def: The *arithmetic genus* of a nice curve X/k, denoted $p_a(X)$ or $g(X)$, is $1 - \chi(\mathcal{O}_X) = \dim H^1(X, \mathcal{O}_X) = \dim H^0(X, \omega_X)$.

Recall that the geometric genus of a scheme X/k is $\dim_k \Gamma(X, \omega_X)$. In general, the arithmetic genus of X/k is given by $p_a(X) = (-1)^{\dim X}(\chi(\mathcal{O}_X) - 1)$. If X is a proper integral curve over an algebraically closed field, then $\Gamma(X, \mathcal{O}_X) = k$ [HA, Ex II.4.5d]. If X is nice, then it is geometrically integral and thus $\Gamma(X, \mathcal{O}_X) = k$ still holds (Why?). Therefore $\dim_k H^0(X, \mathcal{O}_X) = 1$, so $p_a(X) = \dim_k H^1(X, \mathcal{O}_X) = \dim_k H^0(X, \omega_X)$ by Serre duality. So for nice curves, arithmetic genus and geometric genus coincide.

Def: A *Weil divisor* on a scheme X is a $\mathbb{Z}$-linear combination of integral codimension 1 subschemes. The free abelian group of Weil divisors is denoted $\operatorname{Div} X$.

If X is a nice curve over $k = \bar{k}$ then $\operatorname{Div}(X) = \bigoplus_{p \in X^{cl}} \mathbb{Z}p$

Def: Let X be is a nice curve$/k$, $D = \sum_{p \in X^{cl}} n_p p$, we define the degree of D to be

$$\deg D = \sum_{p \in X^{cl}} n_p [k(p) : k]$$

Here, X^{cl} is the set of closed points of X.

It follows easily that deg is a morphism and that it is stable under base change with a careful definition of the base change morphism).

Let Y be a normal integral finite type k-scheme, regular in codimension 1 (e.g. a nice curve).

Def: Let Y be as above. A *Cartier divisor* on X is a global section of $\mathscr{K}_X^* / \mathcal{O}_X^*$.

$\mathscr{K}_X^*$ is the sheaf of invertible elements of the field of fractions of $\mathcal{O}_X$. $\mathscr{K}_X$ can alternatively be defined as $\iota_* \iota^{-1} \mathcal{O}_X$ where $\iota : \operatorname{Spec} K(X) \to X$ is the natural inclusion. Cartier divisors can be defined more generally, if you care you can look in [HA II.6].

> ### Theorem 1.1.1 (Equivalence of Divisors)
>
> If Y as above and furthermore is locally factorial, then
>
> 1. $\operatorname{Div}(Y) \to \Gamma(Y, \mathscr{K}_Y^* / \mathcal{O}_Y^*)$ is an isomorphism.
>
> 2. $\Gamma(Y, \mathscr{K}_Y^* / \mathcal{O}_Y^*) \to \{(\mathscr{L}, s) | \mathscr{L} \text{ line bundle}, s \in \Gamma(Y, \mathscr{L} \otimes \mathscr{K}_Y) - \{0\}\} / \sim$ is an isomorphism. Here $\sim$ is an isomorphism of the line bundle mapping the distinguished sections to each other (???).

Proof. 1) Note: this proof is not the one given in class, since it seems we assumed Y had a cover by UFDs which is not generally true. To get the map $\operatorname{Div} Y \to \Gamma(Y, \mathscr{K}^*/\mathcal{O}_X^*)$, we consider a divisor $D \in \operatorname{Div} Y$. Now let $p \in Y$ and consider the inclusion $\iota_p : \operatorname{Spec} \mathcal{O}_{Y,p} \to Y$, then this induces a divisor $D_p = \iota_p^* D$ (recall, the pullback is given by taking preimages). Since $\mathcal{O}_{Y,p}$ is a UFD, then all divisors are principal [HA II.6.2], therefore $D_p = \operatorname{div}(f_p)$ for some $f_p \in \mathcal{O}_{Y,p}$. Now $\mathcal{O}_{Y,p} \subseteq K(Y)$, then for any point z of codimension 1, the multiplicity of D along z and of f_p along z agree as long as z passes through p. Now there are only finitely many z of codimension 1 such that z does not pass through p and $\nu_z(f_p) \neq 0$ or D has nonzero multiplicity along z (finiteness is from Y being Noetherian, although this is not a trivial consequence). Therefore excluding these codimension 1 subschemes, we obtain an open set U_z on which $\operatorname{div}(f_p)|_{U_p} = D|_{U_p}$. Now $p \in U_p$, so $\{U_p\}$ covers Y and therefore we want to show $\{(U_p, f_p)\}$ is a Cartier divisor. To do so, we just want to show that for any p, p', we have that $f_p/f_p' \in \mathcal{O}_Y^*$ locally. To do so we cover $U_p \cap U_{p'}$ by affine opens. Now in any open affine $\operatorname{Spec} R$ we have some element $h = f_p/f_p' \in \operatorname{Frac}(R)$ such that $\nu_{\mathfrak{p}}(h) = 0$ for all $\mathfrak{p}$ of height 1. Since R is normal, then $R = \bigcap_{\operatorname{ht}(\mathfrak{p})=1} R_{\mathfrak{p}}$ and therefore $h \in R$. Similarly $h^{-1} \in R$, so $h \in \mathcal{O}_Y^*(\operatorname{Spec} R)$. It follows that $\{(U_p, f_p)\}$ is a Cartier divisor.

The inverse map is much easier. Given any Cartier divisor $\{(U_i, f_i)\}$, we let $D = \sum_z \nu_z(f_i) z$ where $z \in U_i$. Note that if $z \in U_i \cap U_j$, then f_i/f_j is a unit in $\mathcal{O}_X(U_i \cap U_j)$, thus $\nu_z(f_i) = \nu_z(f_j)$, so D is well-defined. One (not me) checks that this is the inverse to the previously described map.

2) We have an exact sequence,

$$0 \to \mathcal{O}_Y^* \to \mathcal{K}_Y^* \to \mathcal{K}_Y^*/\mathcal{O}_Y^* \to 0$$

Now notice that $\mathcal{K}_Y^*$ is a constant sheaf and thus flasque, therefore $H^1(X, \mathcal{K}_Y^*) = 0$. Now we can take a long exact sequence of cohomology and get a surjective map $\delta : \Gamma(Y, \mathcal{K}_Y^*/\mathcal{O}_Y^*) \to H^1(Y, \mathcal{O}_Y^*)$. Now taking an affine open cover $\{U_i\}$ of Y, we can compute $H^1(Y, \mathcal{O}_Y^*)$ using Čech cohomology as we have maps

$$\bigoplus_i \mathcal{O}_Y^*(U_i) \to \bigoplus_{i,j} \mathcal{O}_Y^*(U_i \cap U_j) \to \bigoplus_{i,j,k} \mathcal{O}_Y^*(U_i \cap U_j \cap U_k)$$

we compute $H^1(Y, \mathcal{O}_X^*)$ as the kernel of the second modulo the image of the first. It follows that we have sections $f_{ij} \in \mathcal{O}_Y^*(U_i \cap U_j)$ which thus describe isomorphisms $f_{ij} : \mathcal{O}_Y|_{U_i \cap U_j} \to \mathcal{O}_Y|_{U_i \cap U_j}$. Since the collections of sections is in the kernel of the boundary map, then they satisfy the cocycle condition, so $f_{ij}f_{jk} = f_{ik}$ on $U_i \cap U_j \cap U_k$. It follows that these isomorphisms define a line bundle $\mathcal{L}$ on Y. We now want to exhibit a global section s of $\mathcal{L} \otimes \mathcal{K}$ which determines the embedding into $\mathcal{K}$. To do so, consider the global section given by $1 \otimes f_{ij}$ in $\mathcal{O}_X(U_{ij}) \otimes \mathcal{K}(U_{ij})$ and then taking the image in $(\mathcal{L} \otimes \mathcal{K})(U_{ij})$. We need to check that $1 \otimes f_{ij} = 1 \otimes f_{kl}$ on any quadruple intersection, however it suffices to just show it in the case where $k = j$, since then we can use the same argument twice. So we want to show that applying the transition map to $1 \otimes f_{ij}$ yields $1 \otimes f_{jl}$. The transition map is exactly multiplication by the restriction of f_{il} and thus $f_{il}(1 \otimes f_{ij}) = 1 \otimes (f_{il}f_{ij}) = 1 \otimes f_{jl}$ as desired. $\qquad\square$

> **Remark**
>
> If Y is a curve, then $\mathcal{K}^*/\mathcal{O}^* \cong \sum_{p \in Y^{cl}} i_* \mathbb{Z}$. The isomorphism comes from the valuation on the stalks $(\mathcal{K}^*/\mathcal{O}^*)_p$ as a normal curve Y is locally a DVR [HA I.6.2A or MA 11.2].

1.2 Lecture 2 - Maps into $\mathbb{P}^n$, Riemann-Roch, and Serre Duality

Let k be a field and X a nice curve $/k$. Note that X is then locally factorial since X smooth, then X is geometrically regular at any point [STA, 33.12.6] and therefore X is regular. Since X is one-dimensional, then one dimensional regular local rings are UFDs (in fact, they are PIDs). Therefore X is locally factorial.

We have the map of thm 1.1.1 from $\mathrm{Div}\, X \to \{(\mathcal{L}, s) | \mathcal{L} \text{ line bundle}, s \in \Gamma(X, \mathcal{L} \otimes_{\mathcal{O}_X} \mathcal{K})\} / \sim$. This is an isomorphism when X is nice by the above discussion. Two line bundles are isomorphic $\mathcal{L} \cong \mathcal{L}'$ iff they differ by an element of k^* (this is true for line bundles contained in $\mathcal{K}$, I think).

How can we explicitly describe this map? We may define it on the generators of $\mathrm{Div}\, X$, i.e. all closed points of X, then the rest of the map will be given by taking duals and tensor products. We map $p \mapsto \mathcal{O}_X(p) := \mathcal{I}_p^\vee$ where $\mathcal{I}_p$ is the ideal sheaf of p.

To see that $\mathcal{I}_p$ is a line bundle, we want to show that it is locally free of rank 1. To show that a coherent module is locally free, it suffices to show that it is free on stalks (idk if this is true for quasi-coherent modules). For any point $z \in X$, then $(\mathcal{I}_p)_z \subseteq \mathcal{O}_{X,z}$ which is a DVR, then picking a uniformizing parameter t, we have that $(\mathcal{I}_p)_z = (t^n)$ for some n and therefore $(\mathcal{I}_p)_z = t^n \mathcal{O}_{X,z}$ is free. Alternatively, $\mathcal{O}_{X,z}$ is a DVR and thus a PID, and $(\mathcal{I}_p)_z$ is clearly torsion-free ($\mathcal{O}_{X,z}$ is integral) and therefore by the structure theorem for modules over a PID, $(\mathcal{I}_p)_z$ is free.

We have an inclusion $\iota : \mathscr{I}_p \hookrightarrow \mathcal{O}_X$, which is an element of $\check{\mathscr{I}_p}(X) = \mathscr{H}om(\mathscr{I}_p, \mathcal{O}_X)(X)$. The distinguished section to which we map $p \in X$ is the section $\iota \otimes 1 \in \mathscr{I}_p \otimes_{\mathcal{O}_X} \mathscr{K}$ (do you have to sheafify $\mathscr{I}_p \otimes_{\mathcal{O}_X} \mathscr{K}$ or is the tensor product presheaf already a sheaf?).

> **Def:** Let $\mathcal{O}_X(D) = \bigotimes_{p \in X^{cl}} \mathcal{O}_X(p)^{n_p}$ where $D = \sum n_p p$.

Let X be a nice curve, then the map of thm 1.1.1 is given by $D \mapsto \mathcal{O}_X(D)$. Here $\mathcal{O}_X(p)^n$ is the n-fold tensor product or the n-fold tensor product of the dual. For locally free sheaves, the tensor product and dual commute. Given φ, ψ functionals on M, N, $\varphi \otimes \psi$ is a functional on $M \otimes N$ and is an isomorphism in the case of free modules.

For $\mathcal{O}_X(-p) = \mathscr{I}_p$, the distinguished section is the inverse of the morphism $s \otimes \mathrm{id} : \mathscr{I}_p \otimes \mathscr{K} \to \mathcal{O}_X \otimes \mathscr{K}$. Note that $\mathscr{I}_p \to \mathcal{O}_X$ is in general not an isomorphism, but after tensoring with $\mathscr{K}$ it becomes an isomorphism and thus has an inverse $s^{-1} : \mathcal{O}_X \otimes \mathscr{K} \to \mathscr{I}_p \otimes \mathscr{K}$, then this is given by a global section of $\mathscr{I}_p \otimes \mathscr{K}$.

$\Gamma(U, \mathcal{O}_X(D)) = \{t \in \Gamma(U, \mathscr{K}) \,|\, \mathrm{Div}\, t \geqslant -D|_U\}$ and the distinguished global section is $s = 1$.

> **Def:** $D = \sum_p n_p p \in \mathrm{Div}(X)$ is *effective* if $n_p \geqslant 0$ for all p.

> **Remark**
>
> D is effective iff the distinguished section $s \in \Gamma(X, \mathcal{O}_X(D) \otimes \mathscr{K})$ is regular, i.e. $s \in \Gamma(X, \mathcal{O}_X(D))$

> **Def:** Two divisors D, D' are *linearly equivalent* if $D - D' = div(s)$ for some $s \in \Gamma(X, \mathscr{K})$.

> **Claim 1.2.1 (Linear Equivalence is Isomorphism)**
>
> Let X be a smooth, integral scheme. Two divisors $D \sim_{lin} D'$ iff $\mathcal{O}_X(D) \cong \mathcal{O}_X(D')$.

Proof. First suppose that $f \in \hom(\mathcal{O}_X(D), \mathcal{O}_X(D')) \cong \hom(\mathcal{O}_X, \mathcal{O}_X(D' - D))$ is an isomorphism. Then $1/f(1) \in \Gamma(X, \mathscr{K}^*)$ has divisor $D' - D$ since $f(1)$ generates $\mathcal{O}(D' - D)$.

Now suppose that $D \sim_{lin} D'$ so that $D - D' \sim 0$. It suffices to show that $\mathcal{O}(D' - D) \cong \mathcal{O}_X$. There is some $s \in \Gamma(X, \mathscr{K})$ with $D - D' = div(s)$. Then $\mathcal{O}(div s)$ is globally generated by $\frac{1}{s}$, so $1 \mapsto s^{-1}$ is the desired isomorphism. $\qquad\square$

> **Def:** Let $Pic(X)$ be the group of line bundles on X up to isomorphism with operation given by tensor product.

We content ourselves with a reference [HA, II.6.10]

Corollary:

The set of effective divisors linearly equivalent to a given divisor D is in bijection with $\mathbb{P}\Gamma(X, \mathcal{O}_X(D))(\bar{k})$ (the $\bar{k}$-valued points of the projective space).

I don't know where this $\bar{k}$-values points comes into this, so I will pretend that $k = \bar{k}$. The divisor of zeros D_0 of $D = \sum_p n_p p$ is $D_0 = \sum_{n_p \geqslant 0} n_p p$. [HA, II.7.7]

Proof. First let $s \in \mathbb{P}\Gamma(X, \mathcal{O}_X(D))$ then s corresponds to an element t of $\Gamma(X, \mathcal{O}_X(D)) \subset \Gamma(X, \mathcal{K})$. If D is locally given as a cartier divisor with $\{(U_i, f_i)\}$ with $f_i \in K^*$. Then $\mathcal{L}(D)$ is locally generated by f_i^{-1} so we get a local isomorphism $\varphi : \mathcal{O}_X(D) \to \mathcal{O}_X$ by multiplying s by f_i (this gives a map by the cocyle condition). Then $D = \operatorname{div}_0 t = D' + \operatorname{div} s$ so $D \geqslant 0$ and $D \sim D'$. It is clear that you get the same divisor if you replace t by another representative λt, so it is well defined.
Now, given $D' \geqslant D$ and $D \sim D'$, we have $D' = D + \operatorname{div} f$ for some $f \in \mathcal{K}$. Thus $f \geqslant -D$ since $D' \geqslant 0$. Thus $f \in \Gamma(X, \mathcal{O}_X(D))$ has divisor of zeros D'. You can check that any two f_1, f_2 you get from the second map are related by $f_1 = \lambda f_2$ and that these two maps are inverses. $\qquad \square$

Mappings to $\mathbb{P}V$

Thm 1.2.2 (Maps into Projective Space)

Let V be a vector space over a field k and X a scheme, then

$$\operatorname{Hom}(X, \mathbb{P}V) = \left\{ V \otimes \mathcal{O}_X \xrightarrow{\varphi} \mathcal{L} \,\middle|\, \varphi \text{ surjection}, \mathcal{L} \in \operatorname{Pic}(X) \right\} / \sim$$

Note: V is a k-vector space, so V is a module on $\operatorname{Spec} k$ and we thus denote by V the pull-back along the structure map $X \to \operatorname{Spec} k$

Proof. Pick a basis $e_1, \cdots, e_n$ of V with images $s_1, \cdots, s_n \in \Gamma(X, \mathcal{L})$. Let $D_{s_i} = \left\{ p \in X \,\middle|\, (s_i)_p \notin \mathfrak{m}_p \mathcal{L}_p \right\}$. In general, such sets are not open, but since $\mathcal{L}$ is locally free, then for any point $p \in D_{s_i}$, take a nbhd U of p such that $\mathcal{L}|_U \cong \mathcal{O}_X|_U$, then let t be the image of s_i in $\mathcal{O}_X|_U$, then $D_{s_i} \cap U = D(t)$ is open. Since we have a surjection, then $\mathcal{L}$ is globally generated by the s_i which is to say that $X = \bigcup D_{s_i}$. On any D_{s_i}, the morphism $\varphi_i : \mathcal{O}_X|_{D_{s_i}} \to \mathcal{L}|_{D_{s_i}}$ given by $x \mapsto x s_i$ is an isomorphism on stalks and thus expresses the freeness of $\mathcal{L}$ on D_{s_i}. It follows that s_j / s_i makes sense as an element of $\mathcal{O}_X(D_{s_i})$ by this isomorphism (it is just $\varphi^{-1}(s_j)$).

Now consider maps $f_i : D_{s_i} \to \mathbb{A}_k^{n-1}$ given by the ring maps $k[x_1, \cdots, x_n] \mapsto \Gamma(D_{s_i}, \mathcal{O}_X)$ by $x_j \mapsto s_j/s_i$. Note that D_{s_i} is not affine, but these ring maps still define scheme maps [HA, Ex II.2.4]. Now we have an open cover of $\mathbb{P}V$ given by $n + 1$ copies of $\mathbb{A}_k^{n-1}$, so to check that the f_i yield a map from X to $\mathbb{P}V$, we need only check that they glue. On $D_{s_i} \cap D_{s_k}$ we have two maps f_i and f_k. The transition map from $\mathbb{A}_k^{n-1} = \operatorname{Spec} k[x_0, \cdots, \hat{x}_i, \cdots, x_n] \to \operatorname{Spec} k[y_0, \cdots, \hat{y}_k, \cdots, y_n]$ is given by thinking of x_j and y_j as z_j/z_i and z_j/z_k respectively. With this, the map is then obvious: $y_j = z_j/z_i \cdot z_i/z_k = x_j/x_k$ and $x_j = z_j/z_i = z_j/z_k \cdot z_k/z_i = y_j/y_i$ defined on the localizations at x_k and y_i respectively. To check gluing, we map $x_j \to s_j/s_i$ in $\mathcal{O}_X(D_{s_i} \cap D_{s_k})$ under f_i and under f_k, we apply the transition map $x_j \to y_j/y_i$ which under f_k maps to $s_j/s_k \cdot s_k/s_i = s_j/s_i$. There is slightly more to check than I let on since s_j/s_k and s_k/s_i are defined by isomorphisms, so a priori we don't know that they multiply like rationals, although that is a simple check using the isomorphisms. Therefore the maps glue and we obtain a well-defined morphism $f : X \to \mathbb{P}V$. $\qquad\square$

This shows that more properly, $\mathbb{P}V$ corresponds naturally with 1 dimensional quotients of V with the correspondence

$$p \mapsto \operatorname{coker}(V \to \mathscr{L}_p)$$

This should again be thinking of V as an $\mathcal{O}_X$-module given by a pullback.

> **Def:** A *linear system* $(V, \mathscr{L})$ is a line bundle $\mathscr{L}$ along with a subspace $V \subseteq \Gamma(X, \mathscr{L})$. The *complete linear system* $|\mathscr{L}|$ is $(\Gamma(X, \mathscr{L}), \mathscr{L})$. The dimension of $(V, \mathscr{L})$ is $\dim V - 1$.

Given a linear system $(V, \mathscr{L})$, there exists a natural map

$$V \otimes \mathcal{O}_X \hookrightarrow \Gamma(X, \mathscr{L}) \otimes \mathcal{O}_X \to \mathscr{L}$$

the second map being given by evaluation, since $\Gamma(X, \mathscr{L}) \cong \operatorname{Hom}(\mathcal{O}_X, \mathscr{L})$ naturally. Equivalently we get the second map from the adjunction $\pi^*\pi_*\mathscr{L} \to \mathscr{L}$ where $\pi : X \to \operatorname{Spec} k$ is the structure map.

> **Def:** $(V, \mathscr{L})$ is *basepoint free* (bpf) if $V \otimes \mathcal{O}_X \to \mathscr{L}$ is surjective. Equivalently, $\forall p \in X, \exists s \in V$ such that s does not vanish at p (i.e. s_p is not in $\mathfrak{m}_p\mathscr{L}_p$ where $\mathfrak{m}_p$ is the maximal ideal of $\mathcal{O}_{X,p}$).

> **Def:** $(V, \mathscr{L})$ is *very ample* if the induced map $X \xrightarrow{(V,\mathscr{L})} \mathbb{P}V$ is an embedding.

Riemann-Roch

How can we get a handle on $\dim |\mathscr{L}| = \dim H^0(X, \mathscr{L}) - 1$. When can we figure out if $\mathscr{L}$ is bpf or very ample?

Theorem 1.2.3 (Riemann-Roch)

Let X be a nice curve and $\mathscr{L}$ a line bundle, then,

$$\chi(\mathscr{L}) = \deg\mathscr{L} + 1 - g$$

Equivalently, for a Weil divisor D, $\chi(\mathcal{O}_X(D)) = \deg D + 1 - g$.

Proof. We first show this is true for $\mathcal{O}_X$, then show that it is true when we tensor with $\mathcal{O}_X(p)$ for a point p at which point the rest of the proof will follow easily.

Step 1: If $\mathscr{L} = \mathcal{O}_X$, then $h^0(X, \mathcal{O}_X) = 1, h^1(X, \mathcal{O}_X) = g$ and $\deg\mathcal{O}_X = 0$, so the claim holds trivially.

Step 2: Suppose the claim holds for $\mathcal{O}_X(D)$, then let p be any point. We want to show that the claim also holds for $\mathcal{O}_X(D + p)$. We see that $\deg(D + p) = \deg D + [k(p) : k]$, so we just need to show that $\chi(\mathcal{O}_X(D)) = \chi(\mathcal{O}_X(D + p)) - [k(p) : k]$. We have a short exact sequence,

$$0 \to \mathscr{I}_p = \mathcal{O}_X(-p) \to \mathcal{O}_X \to \iota_* k(p) \to 0$$

where ι is the inclusion $p \to X$. Now $\mathcal{O}_X(D + p)$ is locally free, so tensoring is exact, thus we obtain,

$$0 \to \mathcal{O}_X(D) \to \mathcal{O}_X(D + p) \to \iota_* k(p) \to 0$$

Note that $\iota_* k(p) \otimes \mathscr{F} = \iota_* k(p)$ for any sheaf $\mathscr{F}$ which is locally free of rank 1 on a nbhd of p. Now ι is a closed immersion, so it induces an isomorphism on cohomology groups, $H^n(X, \iota_* k(p)) = H^n(p, k(p))$, so $\chi(\iota_* k(p)) = [k(p) : k]$. Note that you can see a closed immersion induces isomorphisms since it is locally a quotient and thus affine, so the pushforward is exact and thus $R^i \iota_* = 0$ for $i > 0$ from which the claim follows. Now the Euler characteristic is additive (by the LES of cohomology), so $\chi(\mathcal{O}_X(D + p)) = \chi(\mathcal{O}_X(D)) + [k(p) : k]$ as desired. Now since any line bundle is of the form $\mathcal{O}_X(D)$ an easy induction shows that Riemann-Roch holds for all $\mathcal{O}_X(D)$ as desired. $\qquad\square$

Corollary: (Riemann's inequality)

$h^0(X, \mathscr{L}) \geqslant \deg\mathscr{L} + 1 - g$ i.e. $\dim|\mathscr{L}| \geqslant \deg\mathscr{L} - g$.

Theorem 1.2.4 Serre Duality

Let X/k be a smooth, proper, of pure dimension n, geometrically connected. Let $\omega_X = \bigwedge^{top}\Omega_{X/k}$. Then,

1. There is a canonical isomorphism $tr : H^n(X, \omega_X) \to k$.

2. For $\mathscr{E}$ locally free, the cup product,

$$H^i(X, \mathscr{E}) \times H^{n-i}(X, \check{\mathscr{E}} \otimes \omega_X) \to H^n(X, \mathscr{E} \otimes \check{\mathscr{E}} \otimes \omega_X) \to H^n(X, \omega_X) = k$$

   is a perfect pairing (i.e. a bilinear map $\varphi : M \times N \to k$ such that $m \mapsto \varphi(m, \cdot)$ is an isomorphism).

A proof of Serre Duality in the projective case is given in [HA III.7.5]. A general proof can probably be found in EGA.

> **Corollary:**
>
> For $\mathscr{E}$ locally free, $h^i(X, \mathscr{E}) = h^{n-i}(X, \check{\mathscr{E}} \otimes \omega_X)$.

> **Theorem 1.2.5 (Serre Duality for nice curves)**
>
> $$h^1(X, \mathscr{L}) = h^0(X, \omega_X \otimes \check{\mathscr{L}}).$$
>
> If $\mathscr{L} = \mathcal{O}_X(D)$ this becomes
>
> $$h^1(X, \mathcal{O}_X(D)) = h^0(X, \omega_X(-D))$$

Daniel alluded to a nice description of the Serre duality cup product in Čech cohomology. I could not find a reference, but in principle you can just find Čech cocycle representations of each group via the natural isomorphisms between sheaf and Čech cohomology.

1.3 Lecture 3 - Computing the Serre Duality maps and some basic application of R.R.

For the rest of the lecture X will be a nice curve $/k$.

> **R.R. + Serre Duality**
>
> If $\mathscr{L} \in \mathrm{Pic}(X)$,
>
> $$\dim H^0(X, \mathscr{L}) - \dim H^0(X, \omega_X \otimes \check{\mathscr{L}}) = \deg \mathscr{L} + 1 - g$$
>
> if $\mathscr{L} = \mathcal{O}(D)$ we can write the left hand side as $\ell(D) - \ell(K - D)$.

How to Compute Serre Duality for Curves:

Let P be a closed point of X, then we get a SES

$$0 \to \omega_X \to \omega_X(P) \to \omega_X(P)|_P \to 0$$

where $\omega_X(P)|_P = \omega_X(P) \otimes k(P)$ is the fibre at P and we often write $(D) = \otimes \mathcal{O}(\mathcal{D})$ for a divisor D and line bundle . Then taking the LES in cohomology we get a boundary map

$$k \cong H^0(X, \omega_X(P)|_P) \to^d H^1(X, \omega_X)$$

which sends $\frac{dz}{z}$ to 1 where z is a local parameter at P.

> **Claim: (Daniel said this)**
>
> $\frac{dz}{z} = \frac{dt}{t}$ in $\omega_X(P)|_P$ for any local parameters z, t at P.

We then consider how to compute the trace map in Čech Cohomology. As we will see in the next lecture, all nice curves are projective, so by Ex III.4.8(d), we can cover X by to open affines $\mathfrak{U} = \{U_1, U_2\}$. Then the Čech complex corresponding to $\mathfrak{U}$

$$C^\bullet(\mathfrak{U}, \omega_X) : H^0(U_1, \omega_X) \oplus H^0(U_2, \omega_X) \xrightarrow{\delta} H^0(U_1 \cap U_2, \omega_X)$$

has only two nontrivial terms, where $\delta(s,t) = s - t$ restricted to $U_1 \cap U_2$. Then $H^0(X, \omega_X) = \ker \delta$ and $H^1(X, \omega_X) = \mathrm{coker}\delta$. So we can define the trace map from the following diagram

$$
\begin{array}{ccc}
H^1(X, \omega_X) \dashrightarrow k & & \sum_{P \notin U_1 \cap U_2} \mathrm{res}_P \eta \\
\pi \uparrow \quad \nearrow & & \nearrow \\
H^0(U_1 \cap U_2, \omega_X) & \eta \, \searrow &
\end{array}
$$

From this point there are a couple of things left to check, which Daniel left to us as a Fun™ Exercise. (e.g. that $\ker(H^0(U_1 \cap U_2, \omega_X) \to k) \supseteq \ker \pi$).

The following is an aside, the contents of which are mainly relevant if you know more about complex manifold theory than scheme theory. (In which case you likely know more than the one writing this.)

Remark

Let X be a compact Riemann Surface and $\mathscr{E}$ a holomorphic vector bundle on X.
Then there is a very natural complex with which we can compute cohomology, namely the Dolbeault complex $C^\bullet_{dol}(X, \mathscr{E})$:

$$C^\infty(X, \mathscr{E}) \xrightarrow{\bar{\partial}} C^\infty(X, \mathscr{E} \otimes \Omega^{0,1}).$$

If $\mathscr{E} = \omega_X$, then the trace map tr is given by

$$C^\infty(X, \mathscr{E} \otimes \Omega^{0,1}) = C^\infty(\text{2-forms}) \to \mathbb{C}$$

$$\eta \mapsto \int_X \eta$$

We now consider the cup product map. In Čech cohomology the map corresponds to

$$H^0(X, \mathscr{E}) \otimes H^0(U_1 \cap U_2, \check{\mathscr{E}} \otimes \omega_X) \to H^0(U_1 \cap U_2, \omega_X)$$

But there are the natural maps

$$H^0(X, \mathscr{E}) \otimes H^0(U_1 \cap U_2, \check{\mathscr{E}} \otimes \omega_X) \to H^0(U_1 \cap U_2, \mathscr{E} \otimes \check{\mathscr{E}} \otimes \omega_X) \xrightarrow{ev} H^0(U_1 \cap U_2, \omega_X) \xrightarrow{tr} k$$

giving us the cup product upon taking the appropriate quotients.

Corollary

$\deg \omega_X + 1 - g = \dim H^0(X, \omega_X) - \dim H^1(X, \omega_X) = g - 1$, so $\deg \omega_X = 2g - 2$.

> **Def:** If $\omega_X = \mathcal{O}_X(D)$, then we say D is a *canonical divisor* and K_X is the linear equivalence class of D.

Theorem 1.4.1 (Cohomology vanishing by degree)

Let $\mathscr{L}$ be a line bundle on X.

1. If $\deg \mathscr{L} < 0$, then $\dim H^0(X, \mathscr{L}) = 0$.

2. If $\deg \mathscr{L} = 0$, then $\dim H^0(X, \mathscr{L}) \neq \iff \mathscr{L} \cong \mathcal{O}_X$.

3. If $\deg \mathscr{L} > 2g - 2$, then $H^1(X, \mathscr{L}) = 0$.

4. If $\deg \mathscr{L} = 2g - 2$, then $H^1(X, \mathscr{L}) = 0 \iff \mathscr{L} \cong \omega_X$

Proof.

1. If $\mathcal{O}_X(D)$ were an effective divisor linearly equivalent to $\mathscr{L}$, then we would have that $\deg \mathscr{L} = \deg \mathcal{O}_X(D) \geqslant 0$ which is impossible. It follows that there are no effective divisors linearly equivalent to $\mathscr{L}$. Since $H^0(X, \mathscr{L})$ is in bijection with effective divisors linearly equivalent to $\mathscr{L}$ up to multiplication by k^*, then $\dim H^0(X, \mathscr{L}) = 0$.

2. If $\mathscr{L} = \mathcal{O}_X$, then $H^0(X, \mathscr{L}) = 1 \neq 0$. Conversely, if $H^0(X, \mathscr{L}) \neq 0$, then there is an effective divisor D linearly equivalent to $\mathscr{L}$, so $\mathscr{L} \cong \mathcal{O}_X(D)$, but then $\mathcal{O}_X(D)$ is a degree 0 effective divisor. Since effective divisors are non-negative sums of prime divisors, then the only degree 0 effective divisor is $\mathcal{O}_X$. It follows that $\mathscr{L} \cong \mathcal{O}_X(D) \cong \mathcal{O}_X$.

3. This is essentially the same as 1 using Serre duality. Since $\deg \mathscr{L} > 2g-2$, then $\deg(\omega_X \otimes \check{\mathscr{L}}) = 2g - 2 - \deg \mathscr{L} < 0$, thus $\dim H^0(X, \omega_X \otimes \check{\mathscr{L}}) = 0$ by 1. By Serre duality, we then get $\dim H^1(X, \mathscr{L}) = 0$.

4. This again follows from 2 using Serre duality. We get that $\deg \omega_X \otimes \check{\mathscr{L}} = 0$, so $\dim H^0(X, \omega_X \otimes \check{\mathscr{L}}) \neq 0$ iff $\omega_X \otimes \check{\mathscr{L}} = \mathcal{O}_X$, i.e. iff $\mathscr{L} \cong \omega_X$. Now we just use Serre duality once more, so $\dim H^1(X, \mathscr{L}) \neq 0 \iff \mathscr{L} \cong \omega_X$.

$\square$

1.4 Lecture 4 - Bpf and very ample divisors and genus 0 curves

Recall that $\operatorname{Hom}(X, \mathbb{P}V) = \{V \otimes_k \mathcal{O}_X \twoheadrightarrow \mathscr{L} | \mathscr{L} \text{ line bundle }\}$ where $\mathbb{P}V = \operatorname{Proj} \operatorname{Sym}^* V$. Given $V \otimes \mathcal{O}_X \twoheadrightarrow \mathscr{L}$, we want to get a map $X \to \mathbb{P}V$ given by taking a point $x \in X$ and mapping it to $V \otimes k(x) \to \mathscr{L} \otimes k(x)$ which is the fiber over the point x, the cokernel of which is then a point in $\mathbb{P}V$.

The one dimensional subspaces of V are in correspondence with hyperplanes in $\mathbb{P}V$ given by taking a 1-dim subspace $\ell \subseteq V$ and sending it to $\{f : V \to k | f(\ell) = 0\}$. The quotient map $V \to V/\ell$ induces a map $\mathbb{P}(V/\ell) \to \mathbb{P}V$ which is the map $V \otimes \mathcal{O}_{\mathbb{P}(V/\ell)} \to (V/\ell) \otimes \mathcal{O}_{\mathbb{P}(V/\ell)} \xrightarrow{ev} \mathcal{O}(1)$.

We can specialize to the case of a complete linear system: $H^0(X, \mathscr{L}) \otimes \mathcal{O}_X \xrightarrow{ev} \mathscr{L}$ given by taking $x \mapsto (s \to s(x))$.

There is a bijection,

$$\left\{ \begin{matrix} \text{effective divisors} \\ D, \ \mathscr{L} \cong \mathcal{O}(D) \end{matrix} \right\} \leftrightarrow \left\{ \begin{matrix} \text{hyperplanes of functions } H^0(X, \mathscr{L}) \to k \\ \text{vanishing on } s, \text{ where } \mathrm{div}_0 s = D \end{matrix} \right\}$$

The map is given by sending an effective divisor D to H_D, the hyperplane of functions vanishing on D.

If $s(x) = 0$, then $x \in V(s) = D$, so for any $x \in f^{-1}(H_D)$ we have that $s(x) = 0$, thus $x \in D$, so set theoretically, $D = f_{|\mathscr{L}|}^{-1}(H_D)$.

Theorem 1.4.2 (Bpf/Very Ample Criterion)

Let X be a nice $/k$, where k is algebraically closed. Let $\mathscr{L}$ be a line bundle on X then

1. $|\mathscr{L}|$ is base-point-free (bpf) iff $\forall p \in X(k), h^0(X, \mathscr{L}) = h^0(X, \mathscr{L}(-p)) + 1$.

2. $|\mathscr{L}|$ is very ample iff $\forall p, q \in X(k)$, (not necessarily distinct) $h^0(X, \mathscr{L}) = h^0(X, \mathscr{L}(-p-q)) + 2$.

Remark

For $k \neq \bar{k}$ it is enough to base change to $\bar{k}$ then check the conditions ([Daniel mentioned this very loosely, so this is our interpretation] because $\bar{k}/k$ is a faithfully flat base change so we get an iff for surjective before and after the base change).

---

1. *Proof.* We want $H^0(X, \mathscr{L}) \otimes \mathcal{O}_X \xrightarrow{ev} \mathscr{L}$ to be surjective iff the stated condition holds. Surjectivity of a map of sheaves is equivalent to surjectivity at all closed points.[1] By Nakayama's Lemma, it is thus equivalent to check surjectivity on fibers at all closed points $p \in X$. So

$$ev \text{ surjective} \iff H^0(X, \mathscr{L}) \twoheadrightarrow^{ev_p} \mathscr{L}|_p, \qquad \forall p \in X$$

iff $H^0(X, \mathscr{L}(-p)) = \ker ev_p \subsetneq H^0(X, \mathscr{L})$. But we have a SES

$$0 \to \mathscr{L}(-p) = \mathscr{I}(p) \to \mathscr{L} \to \mathscr{L} \otimes k(p) \to 0$$

which gives the LES

$$0 \to H^0(X, \mathscr{L}(-p)) \to H^0(X, \mathscr{L}) \xrightarrow{ev_p} \mathscr{L} \otimes k(p) \to \cdots$$

So we have $H^0(X, \mathscr{L}(-p)) \subsetneq H^0(X, \mathscr{L}), \iff \mathrm{rk}\, ev_p = 1$ for all $p \in X(k) \iff h^0(X, \mathscr{L}) = h^0(X, \mathscr{L}(-p)) + 1$. $\qquad\square$

Remark

The proof also shows that it suffices that $h^1(X, \mathscr{L}(-p)) = 0$ for all closed points p.

---

[1] Every point is a further localization of a closed point, and localization preserves surjections since it is exact.

2. Invoking II.7.3 would substantially simplify this proof, but we do it in detail because that's what Daniel did. We also only prove that the given condition implies that $\mathscr{L}$ is very ample, the other direction being in Hartshorne, for instance.

Proof. We first show that $\mathscr{L}$ is bpf so that $\mathscr{L}$ defines a map from X to a projective space. Let $p \neq q$ be closed points. The assumption gives us that

$$H^0(X, \mathscr{L}) \twoheadrightarrow (k(p) \oplus k(q)) \otimes \mathscr{L}$$

So in particular

$$H^0(X, \mathscr{L}) \twoheadrightarrow \mathscr{L} \otimes k(p)$$

so $\mathscr{L}$ is bpf. Thus $\mathscr{L}$ induces a map $f : X \to \mathbb{P}H^0(X, \mathscr{L})$. To show that $\mathscr{L}$ is very ample, we must show that f is a closed immersion, for which we need to check that (a) f is a homeomorphism onto its image and (b) $\mathcal{O}_{\mathbb{P}} \twoheadrightarrow f_*\mathcal{O}_X$.

(a) Because X is proper, it is enough to check that f is injective and indeed for that it is enough to check that f is injective on closed points. Therefore, given $p \neq q$, we need to show that $f(p) \neq f(q)$ so by "previous remarks" (I'm not clear on what this was), it is ETS that $t \in H^0(X, \mathscr{L})$ with $t(p) = 0$ and $t(q) \neq 0$. But this is the case since by the assumption

$$H^0(X, \mathscr{L}) \twoheadrightarrow (k(p) \oplus k(q)) \otimes \mathscr{L}$$

(b) Since f has closed image, then $f_*\mathcal{O}_X$ is supported on the image so it is enough to check surjectivity on points of $f(X)$. Since f is homeomorphism, for any closed point p the map on stalks is

$$\mathcal{O}_{\mathbb{P}, f(p)} \to (f_*\mathcal{O}_X)_{f(p)} = \mathcal{O}_{X,p}$$

By 7.4, it is enough to check that $\mathfrak{m}_{f(p)} \twoheadrightarrow \mathfrak{m}_p/\mathfrak{m}_p^2$. [2] $\mathcal{O}_{X,p}$ is a DVR since X is a nice curve so it is enough to check that the map is nonzero, i.e. that there is a $s \in H^0(X, \mathscr{L})$ vanishing at P to order 1.

Unwinding definitions: $\mathscr{L} = f^*\mathcal{O}(1)$ so $H^0(\mathbb{P}, \mathcal{O}(1)) = H^0(X, \mathscr{L})$, which is true because $\mathbb{P} = \operatorname{Proj} \operatorname{Sym}_\bullet H^0(X, \mathscr{L})$ and $\Gamma(\mathbb{P}, \mathcal{O}(n))$ is nice for polynomial rings by II.5.13. We know $h^0(X, \mathscr{L}(-2p)) = 2 + h^0(X, \mathscr{L})$ so $h^0(X, \mathscr{L}(-p)) = 1 + h^0(X, \mathscr{L})$ (each twist changes it by at most one). Thus we have

$$H^0(X, \mathscr{L}(-2p)) \subsetneq H^0(X, \mathscr{L}(-p)) \subsetneq H^0(X, \mathscr{L})$$

which is exactly what we need.

$\square$

> **Corollary**
>
> Let X be a nice curve of genus g, then
>
> 1. All line bundles $\mathscr{L}$ with $\deg \mathscr{L} > 2g - 1$.
>
> 2. All line bundles $\mathscr{L}$ with degree $\deg \mathscr{L} > 2g$ are very ample.

---

[2] (a) follows since $k = k(f(p)) \to k(p) = k$ is an isomorphism since k is algebraically closed and (c) is trivial since everything is f.g. $/k$

Proof. First pass to the algebraic closure, then for any point p, we have a LES:

$$0 \to H^0(X, \mathcal{L}(-p)) \to H^0(X, \mathcal{L}) \to k(p) \to H^1(X, \mathcal{L}(-p)) \to \cdots$$

Since $\deg \mathcal{L}(-p) = \deg \mathcal{L} - 1 > 2g - 2$, then $H^1(X, \mathcal{L}(-p)) = 0$ by theorem 1.4.1. It follows that we actually have a short exact sequence,

$$0 \to H^0(X, \mathcal{L}(-p)) \to H^0(X, \mathcal{L}) \to k(p) \to 0$$

Now taking the dimension of this, we get $h^0(X, \mathcal{L}) = h^0(\mathcal{L}(-p)) + 1$. Now by the previous theorem, 1.4.2, we get that $\mathcal{L}$ is bpf.

If we have that $\deg \mathcal{L} > 2g$, then $\deg \mathcal{L}(-p) > 2g - 1$, so we can twist down again, so $h^0(\mathcal{L}(-p - q)) + 2 = h^0(\mathcal{L}(-p)) + 1 = h^0(\mathcal{L})$. It follows that $\mathcal{L}$ is very ample. $\square$

> **Corollary**
>
> If $\deg \mathcal{L} > 0$, some power is very ample, i.e. $\mathcal{L}$ is ample.

Curves of genus 0

Let X be a nice curve of genus 0. Examples include $\mathbb{P}^1_k$ or if $k = \mathbb{R}$, then we can consider the projective vanishing of $x^2 + y^2 + z^2$ in $\mathbb{P}^2_{\mathbb{R}}$.

> **Claim**
>
> If $s \in H^0(\mathbb{P}^2, \mathcal{O}(2))$ such that $V(s)$ is smooth, then $V(s)$ is a nice curve of genus 0.

Proof. Consider the exact sequence of the ideal and structure sheaf of $X = V(s)$,

$$0 \to \mathcal{O}(-2) \xrightarrow{\times s} \mathcal{O}_{\mathbb{P}^2} \to \mathcal{O}_X \to 0$$

We can apply the Euler characteristic to get:

$$\chi(\mathcal{O}_{\mathbb{P}^2}) = \chi(\mathcal{O}(-2)) + \chi(\mathcal{O}_X)$$

Now from the computation of cohomology of projective space [HA III.5.1], we know that

$$h^0(X, \mathcal{O}_{\mathbb{P}^2}) = 1, h^1(\mathcal{O}_{\mathbb{P}^2}) = 0, h^2(\mathcal{O}_{\mathbb{P}^2}) = 0$$

the last computation of $h^2(\mathcal{O}_{\mathbb{P}^2})$ is by Serre duality, $h^2(\mathcal{O}_{\mathbb{P}^2}) = h^0(\omega_{\mathbb{P}^2})$ and $\omega_{\mathbb{P}^2} = \mathcal{O}_{\mathbb{P}^2}(-3)$. For $\mathcal{O}(-2)$, we have $h^0(\mathcal{O}(-2)) = 0, h^1(\mathcal{O}(-2)) = 0, h^2(\mathcal{O}(-2)) = h^0(\mathcal{O}(-1)) = 0$ the last is again by Serre duality. It follows that $\chi(\mathcal{O}_X) = 1$, so X has genus 0.

To see that X is connected, we take the long exact sequence of cohomology, then we compute the following, $H^0(\mathbb{P}^2, \mathcal{O}_{\mathbb{P}^2}(-2)) = H^1(\mathbb{P}^2, \mathcal{O}_{\mathbb{P}^2}(-2)) = 0$ we get $H^0(\mathbb{P}^2, \mathcal{O}_{\mathbb{P}^2}) = H^0(X, \mathcal{O}_X) = k$, so X is connected. Since X is smooth and connected, then X is integral and therefore X is a nice curve of genus 0. $\square$

> **Theorem 1.4.3 (Coarse classification of genus 0 curves)**
>
> Let X/k be a nice curve.
>
> 1. If $X(k) \neq \varnothing$, then $X \cong \mathbb{P}^1$
>
> 2. X is isomorphic to a conic in $\mathbb{P}^2$, i.e. there is some $\mathscr{L}$ on X which is very ample of degree 2.

> **Remark**
>
> 1. There is a finer classification of isomorphism types of genus 0 curves in terms of the Brauer group.
>
> 2. Maps $\mathbb{P}^1 \xrightarrow{|\mathscr{L}|} \mathbb{P}^N$ of high degree are still interesting.

Proof. 1) If $X(k) \neq 0$, then choose a point $P \in X(k)$ and consider $\mathscr{L} = \mathcal{O}(p)$, then,

$$h^0(X, \mathcal{O}(P)) - h^1(X, \mathcal{O}(P)) = 1 + 1 - g = 2$$

Since $\deg \mathcal{O}(P) = 1 > 2g - 2$, then $h^1(X, \mathcal{O}(P)) = 0$, thus $h^0(X, \mathcal{O}(P)) = 2$. Similarly $\mathcal{O}(P)$ is very ample since $1 > 0$, so we get $f : X \to \mathbb{P}H^0(X, \mathcal{O}(P)) = \mathbb{P}^1$ which is a closed immersion. Now X is a one-dimensional so it is defined by some ideal sheaf, then since $\mathbb{P}^1$ is reduced we have $X = \mathbb{P}^1$.

2) Let $\mathscr{L} = \check{\omega_X}$, $\deg \omega_X = 2g - 2 = -2$, so $\deg \mathscr{L} = 2$. Then $h^0(X, \mathscr{L}) - h^1(X, \mathscr{L}) = 2 + 1 = 3$ by Riemann-Roch. Since $\deg \mathscr{L} = 2$, then $h^1(X, \mathscr{L}) = 0$. $\mathscr{L}$ is very ample since $\deg \mathscr{L} = 2 > 0$. It follows that $\mathscr{L}$ defines a closed immersion $f_{|\mathscr{L}|} : X \to \mathbb{P}H^0(X, \mathscr{L}) = \mathbb{P}^2$.

By definition, $\mathbb{P}H^0(X, \mathscr{L}) = \operatorname{Proj} \operatorname{Sym}^* H^0(X, \mathscr{L})$. $f_{|\mathscr{L}|} : X \to \mathbb{P}H^0(X, \mathscr{L})$ gives $\mathscr{L} = f_{|\mathscr{L}|}^* \mathcal{O}(1) = \mathcal{O}_X(1)$. Now let $X = \operatorname{Proj} S \subseteq \mathbb{P}H^0(X, \mathscr{L})$, then $\widetilde{S} = \mathcal{O}_X$ and $\widetilde{S}(d) = \mathcal{O}_X(d) = (\mathcal{O}_X(1))^{\otimes d} = \mathscr{L}^{\otimes d}$. By [HA Ex II.5.9b], we have $S_d = H^0(X, \widetilde{S}(d)) = H^0(X, \mathscr{L}^{\otimes d})$ in sufficiently high degrees. It follows by [HA Ex II.2.14c] that $X = \operatorname{Proj} S = \operatorname{Proj} \bigoplus_n H^0(X, \mathscr{L}^{\otimes d})$. It follows that the map $X \to \mathbb{P}^2$ induces a map of graded algebras

$$\operatorname{Sym}^* H^0(X, \mathscr{L}) \to \bigoplus_n H^0(X, \mathscr{L}^n)$$

The equations cutting out X in $\mathbb{P}^2$ are the kernel of this map. We want to show that the kernel is generated by a single degree 2 element.

Notice that $\operatorname{Sym}^2 H^0(X, \mathscr{L})$ has dimension 6 (if x, y, z is a basis of $H^0(X, \mathscr{L})$, then Sym^2 is generated by $x^2, y^2, z^2, xy, xz, yz$). By Riemann-Roch, $\deg \mathscr{L}^2 = 4$, so $h^1(\mathscr{L}^2) = 0$ and therefore $h^0(\mathscr{L}^2) = 4 + 1 - 0 = 5$. It follows that the map $\operatorname{Sym}^2 H^0(X, \mathscr{L}) \to H^0(X, \mathscr{L}^2)$ has a nontrivial kernel, so we may pick a degree 2 element g in the kernel.

Since g is in the kernel of the morphism of graded algebras, then g vanishes along X, thus $X \subseteq V(g) \subseteq \mathbb{P}^2$. Suppose that $X \neq V(g)$, then we may find another $h \in \operatorname{Sym}^* H^0(X, \mathscr{L})$ such h is not a multiple of g and that h vanishes along X, then $X \subseteq V(h) \cap V(g)$ which by Bézout's theorem has dimension 0 which is a contradiction. Therefore $X = V(g)$ is a plane conic. $\square$

Def: $f_{|\omega_X|}$, the map given by the complete linear system of ω_X is called that *Canonical Map*.

Example

1. If $g(X) = 0$, then $\deg \omega_X = 2g - 2 = -2$ so ω_X is not bpf.

2. If $g(X) = 1, \deg \omega_X = 0$ so $h^0(X, \omega_X) = g = 1$ so $\omega_X = \mathcal{O}_X$. Therefore, the canonical map $X \to \mathbb{P}^0$ is trivial.

1.5 Lecture 5 - Introduction to hyperelliptic curves

Theorem 1.5.1 Curves of genus at least 2

Let C/k be a nice curve of genus $g \geqslant 2$,

1. $|\omega_C|$ is bpf

2. ω_C is very ample or then $C_{\bar{k}} := C \times_k \bar{k}$ is hyperelliptic.

Remark

If $k \neq \bar{k}$, in (b) then we can still a degree 2 map from C to some genus 0 curve. (Although this does not quite prove it yet)

Lemma 1.5.2

Let C/k be a nice curve, $\mathscr{L}$ a line bundle on C of degree $\geqslant 0$, then $h^0(\mathscr{L}) \leqslant \deg \mathscr{L} + 1$ with equality iff $g(C) = 0$.

Proof. If $h^0(\mathscr{L}) = 0$, then we are done. If $h^0(\mathscr{L}) \neq 0$, then $\mathscr{L}$ is linearly equivalent to an effective divisor, so we may assume that $\mathscr{L}$ is effective. We may further assume that $k = \bar{k}$. Let $\mathscr{L} = \mathcal{O}(D)$, D effective, then we have a short exact sequence,

$$0 \to \mathcal{O}_X \xrightarrow{\times s} \mathcal{O}(D) \to \mathcal{O}(D)|_D \to 0$$

Where s is an element of $K(X)$ yielding D as its divisor. Taking the LES of cohomology, we get:

$$0 \to H^0(\mathcal{O}) \to H^0(\mathcal{O}(D)) \to H^0(\mathcal{O}(D)|_D)$$

So $h^0(\mathcal{O}(D)) \leqslant 1 + h^0(\mathcal{O}(D)|_D) = 1 + \deg D$.

If we have equality, then let $D = \sum i = 1^n x_i$ where the x_i may be non-distinct. Removing a point from D drops $h^0(\mathcal{O}(D))$ by at most one, therefore $h^0(\mathcal{O}(x_1)) = h^0(\mathcal{O}(D)) - (\deg D - 1) = 2$. Now $\deg \mathcal{O}(x_1 - p - q) = -1$, so $h^0(\mathcal{O}(x_1 - p - q)) = 0 = h^0(\mathcal{O}(x_1)) - 2$, so $\mathcal{O}(x_1)$ is very ample. It follows that we have a closed immersion $f : C \to \mathbb{P}H^0(\mathcal{O}(x_1)) = \mathbb{P}^1$. Since this is a closed immersion and nonconstant, then $C = \mathbb{P}^1$, so C has genus 0. $\qquad\square$

Now we prove the theorem.

1. *Proof.* Wlog $k = \bar{k}$ since we can check dimensions of global sections after base change. By a previous result, it suffices to show that $\forall p \in C(k), h^0(C, \omega_C(-p)) = g - 1$. We have the SES

$$0 \to \omega_C(-p) \to \omega_C \to \omega_C|_p \to 0.$$

It suffices to show that $H^0(\omega_C(-p)) \to H^0(\omega_C)$ is not surjective. Looking at a part of the LES in cohomology,

$$\omega_C|_p \to H^1(\omega_C(-p)) \to H^1(\omega_C) \to 0$$

we see that if the map were surjective, then we would have $h^1(\omega_C(-p)) = h^1(\omega_C) + 1 = 2$. Since $h^1(\omega_C(-p)) = h^0(\mathcal{O}(p)) = 2$ it follows by the above lemma that we must have $g = 0$. This contradicts the assumption that $g \geqslant 2$ so we conclude that ω_C is bpf. $\qquad\square$

2. *Proof.* Wlog $k = \bar{k}$ since whether the canonical map (which we now know is well-defined) is a closed immersion can be checked after base change to $\bar{k}$. (Hyperellipticity cannot which is why the statement only involves $C_{\bar{k}}$) Assume that ω_C were not very ample. Then there would be $p, q \in C(k)$ with $h^0(\omega_C(-p-q)) \geqslant g - 1$. By base-point freeness, we must have $h^0(\omega_C(-p-q)) = g - 1$ since $h^0(\omega_C(-p-q)) \leqslant h^0(\omega_C(-p)) = g - 1$. Considering the SES

$$0 \to \omega_C(-p-q) \to \omega_C \to \mathcal{O}_{p+q} \to 0$$

we get the LES (using Serre duality)

$$0 \to H^0(\omega_C(-p-q))) \to H^0(\omega_C) \to \mathcal{O}_{p+q} \to H^0(\mathcal{O}(p+q)) \to H^0(\mathcal{O}) \to 0$$

Since $h^0(\omega_C(-p-q)) = g-1$ and $h^0(\omega_C) = g$, the first map has corank 1. The second then has rank 1, so the third does as well since $h^0(\mathcal{O}_{p+q}) = 2$. The last map has rank 1 by surjectivity. Thus we deduce that $h^0(\mathcal{O}(p+q)) = 2$. If $h^0(\mathcal{O}(p+q-r)) = 2 = \deg(\mathcal{O}(p+q-r)+1$ then by the above lemma we would have $g = 0$, contrary to assumption. Therefore $|\mathcal{O}(p+q)|$ is bpf dimension 1 and of degree 2, which gives us a degree 2 map $\mathbb{P}^1$. That is, C is hyperelliptic. $\qquad\square$

> **Corollary**
>
> Let $k = \bar{k}$, then,
>
> - If $g = 2$, then C is hyperelliptic (this works without $k = \bar{k}$, but we did not prove it).
>
> - If $g = 3$, C s hyperelliptic or plane quartic.

Proof. Suppose that $g = 2$. It is enough to show that ω_C is not very ample, for then C will necessarily be hyperelliptic. Notice that $h^0(\omega_C) = 2$ and therefore we obtain $f_{|\omega_C|} : C \to \mathbb{P}^1$. C cannot be a closed subscheme of $\mathbb{P}^1$ since C has genus 2, therefore $f_{|\omega_C|}$ is not a closed immersion and therefore ω_C is not very ample.

If $g = 3$. Either C is hyperelliptic or $f_{|\omega_C|}$ is a closed immersion with image of degree $\deg \omega_C = 4$, i.e. C is a plane quartic. $\qquad\square$

1.6 Lecture 6 - Hyperelliptic curves, Riemann-Hurwitz, and cyclic covers

Question

Does there exist a nice of every genus?
Answer: Yes, we will see how below.

Thm

Suppose C/k is nice and C admits a finite degree 2 morphism to $\mathbb{P}^1_k$ and char $k \neq 2$. We show that C admits an involution over $\mathbb{P}^1_k$.

Proof. The map $f : C \to \mathbb{P}^1_k$ is finite of degree 2 and therefore induces a map $K(\mathbb{P}^1_k) \hookrightarrow K(C)$ which makes $K(C)$ a degree 2 extension. It follows that the extension is Galois. $K(C)$ therefore admits a non-trivial automorphism $\sigma : K(C) \to K(C)$ of order 2. Let η be the generic point of C, then we have a map $\eta \to C$. The map $\eta \to C$ extends to a nbhd U of C since $K(C)$ is a finitely generated field. Since U is open and C is proper, then by the valuative criterion, we may extend the map from $U \to C$ to a map from $C \to C$. This yields a map $\tilde{\sigma} : C \to C$. Furthermore $\sigma^2 = $ id since it is the identity at η, then looking at an affine open Spec $R \subseteq C$ with preimage Spec S, we have that $\mathrm{Frac}(R) = \mathcal{O}_{C,\eta} = K(C)$ and so $\tilde{\sigma}^2 : $ Spec $S \to $ Spec R inducing the identity map on the generic point and since S, R are integral, then it induces the identity map on U. Since C is reduced and separated, then two maps that agree on an open set are the same, thus $\sigma^2 = $ id. Furthermore, the map $\tilde{\sigma}$ is a map over $\mathbb{P}^1_k$, i.e. $f\tilde{\sigma} = \tilde{\sigma}f$ where $f : C \to \mathbb{P}^1_k$ is our degree 2 finite morphism. This follows from the fact that σ fixes $K(\mathbb{P}^1_k)$ and the equivalence of complete nonsingular curves and function fields. $\square$

Claim:

There exists a $0 \to \mathcal{O}_{\mathbb{P}^1} \to \pi_* \mathcal{O}_C \to \mathscr{L} \to 0$.

Proof. Let $\tau : \pi_* \mathcal{O}_C \to \pi_* \mathcal{O}_C$ be map induced by $\tilde{\sigma}$ on $\pi_* \mathcal{O}_C$. Then $\mathcal{O}_{\mathbb{P}^1} = (\pi_* \mathcal{O}_C)^\tau$ (fixed subsheaf), as this is "obviously" true on fibres. Therefore, the exact sequence splits with the splitting map $f \mapsto \frac{1}{2}(f + \tau f)$ using that char $k \neq 2$. $\square$

Indeed we then have $\pi_* \mathcal{O}_C = \mathcal{O}_{\mathbb{P}^1} \oplus \mathscr{L}$ where $\mathscr{L} = (\pi_* \mathcal{O}_C)^{\tau = -1}$.

Claim:

$\pi_* \mathcal{O}_C = \mathcal{O}_{\mathbb{P}^1} \oplus \mathscr{L}$ as a $\mu_2 = \{\pm 1\}$-graded sheaf of algebras.

Proof. $\mathscr{L}^2 \subset \mathcal{O}_{\mathbb{P}^1}$ since as noted above $\mathcal{O}_{\mathbb{P}^1} = (\pi_* \mathcal{O}_C)^\tau$, τ acts as -1 on $\mathscr{L}$, and for any $s, t \in \mathscr{L}(U)$ over an open $U, \tau(st) = \tau(s)\tau(t) = (-s)(-t) = st$. $\square$

Claim:

Let $\pi : C \to \mathbb{P}^1$ be a hyperelliptic curve. Then $C = \mathbf{Spec}_{\mathbb{P}^1}(\mathcal{O}_{\mathbb{P}^1} \oplus \mathscr{L})$, where $\mathcal{O} \oplus \mathscr{L}$ has a product structure induces by a map $\mathscr{L}^2 \to \mathcal{O}$ and $V(\mathscr{L}^2 \to \mathcal{O})$ is reduced.

Proof. Here's a sketch of a trace of the idea of the proof. Working (étale)-locally this reduces to the computation that $k[x,y]/(y^2 - f(x)) \supset k[x]$ is smooth when f is separable. This is also true Zariski-locally for the specific case of $\mathbb{P}^1$. $\qquad \square$

> **Def:** Let X, Y be nice curves, and $f : X \to Y$ a non-constant map. f is *cyclic* if $k(X)/k(Y)$ is a cyclic Galois extension.

The same "argument" gets you the following.

Thm

Let $f : X \to Y$ be cyclic. If $(\deg f, \operatorname{char} k) = 1$ then $X \cong \mathbf{Spec}\,_Y \mathscr{A}$, where $\mathscr{A} = \mathcal{O} \oplus \mathscr{L} \oplus \mathscr{L}^2 \oplus \cdots \oplus \mathscr{L}^{\deg f - 1}$ is μ_n-graded with a multiplication induced by $\mathscr{L}^{\deg f} \to \mathcal{O}$. X is smooth if $V(\mathscr{L}^{\deg f} \to \mathcal{O})$ is smooth.

Example

Let $\mathscr{L} = \mathcal{O}(-5)$, then $\mathscr{L}^2 = \mathcal{O}(-10)$, so map $\mathscr{L}^2 = \mathcal{O}(-10) \to \mathcal{O}$ is given by an element of $\Gamma(\mathbb{P}^1, \mathcal{O}(10)) = \operatorname{Sym}^{10} \langle x, y \rangle$. Choose $f = x^{10} + y^{10}$ which has no double roots over a field of characteristic not 2 or 5. Therefore $\mathbf{Spec}\,_{\mathbb{P}^1}(\mathcal{O} \oplus \mathcal{O}(-5))$ is a double cover of $\mathbb{P}^1$ "branched" (we will soon learn what this means) at the tenth roots of unity.

How to write equations for the above curve:

Let $f : X \to Y$ be a cyclic cover. We want to embed X in some natural space, namely $\operatorname{Tot}(\mathscr{L})$, the total space of the line on Y.

We recall that $\operatorname{Tot}(\mathscr{L}) = \mathbf{Spec}\,_Y(\operatorname{Sym}^\bullet \mathscr{L})$. Thus we have the following property

$$\operatorname{Hom}_Y(Y, \operatorname{Tot} \mathscr{L}) = \operatorname{Hom}(\mathscr{L}, \mathcal{O}_Y) = \operatorname{Hom}(\mathcal{O}_Y, \check{\mathscr{L}})$$

We get a natural map from $\operatorname{Sym}^\bullet \mathscr{L} = \bigoplus_{n \geq 0} \mathscr{L}^n$ to $\bigoplus_{0 \leq n < \deg f}$ induced by $id_{\mathscr{L}}$ and $f : \mathscr{L}^{\deg f} \to \mathcal{O}$. By applying the relative spec functor, this gets us a closed immersion $X \hookrightarrow \operatorname{Tot}(\mathscr{L})$.

Choosing a trivialization U of $\mathscr{L}$, (i.e. $t \in \Gamma(U, \mathscr{L})$ which vanishes nowhere), we have

$$\operatorname{Tot}(\mathscr{L}|_U \check{)} = U \times \mathbb{A}^1_t$$

Then t^n trivializes $\mathscr{L}^n$ over U so we get $f|_U : \mathscr{L}|_U^{\deg f} = \operatorname{Sym}^n \mathcal{O}_U \cong \mathcal{O}_U \to \mathcal{O}_U$ is represented by some polynomial g. Then $X_U \subset U \times \mathbb{A}^1$ is cut out by $t^{\deg f} - g$ (where g is separable if X is smooth) giving us the normal local representation of hyperelliptic curves.

Riemann-Hurwitz formula

Let $f : X \to Y$ be degree d. Using $g(Y)$, d, and some auxiliary data, can we compute $g(X)$? The answer is yes.

> **Def:** Let X, Y be nice curves, then a morphism is *separable* $f : X \to Y$ if it induces a separable extension of function fields $K(X)$ over $K(Y)$.

> **Claim 1.6.1: SES of Kähler differentials**
>
> Let X, Y be nice curves and $f : X \to Y$ a separable morphism, then we have a SES
>
> $$0 \to f^*\omega_Y \to \omega_X \to \omega_{X/Y} \to 0$$

Proof. By [HA II.8.11], we have an exact sequence,

$$f^*\Omega_Y \to \Omega_X \to \Omega_{X/Y} \to 0$$

and since X, Y are curves, then Ω and ω are the same since everything is dimension 1. We want to show that this is in fact a short exact sequence, i.e. we need to show that it is exact no the left. We can check that the morphism of locally free sheaves $f^*\omega_Y \to \omega_X$ is injective by checking it generically. This follows in greater generality. If $\mathscr{F}, \mathscr{G} \in \mathfrak{Qco}(X)$ with $\mathscr{F}$ torsion-free, if $f : \mathscr{F} \to \mathscr{G}$ is generically injective, then it is actually injective. Suppose that there is some point x such that $f_x : \mathscr{F}_x \to \mathscr{G}_x$ is not injective, then we have two elements $a, b \in \mathscr{F}_x$ such that $f_x(a) = f_x(b)$, then since $\mathscr{F}$ is quasi-coherent, $\mathscr{F}_\eta$ is a further localization of $\mathscr{F}$ and since $\mathscr{F}$ is torsion-free, then $\mathscr{F}_x \hookrightarrow \mathscr{F}_\eta$ and therefore $f_\eta(a) = f_\eta(b)$, so f is not generically injective. It follows that we need only show $f^*\omega_Y \to \omega_X$. $f^*\omega_Y$ is a line bundle, so it is torsion-free. Taking stalks at the generic point, f is separated and $(\omega_{X/Y})_\eta = \Omega_{K(X)/K(Y)} = \text{tr.d.}\, K(X)/K(Y) = 0$ by [HA II.8.6A]. It follows that $f^*\omega_Y \to \omega_X$ is generically surjective but they are also fields generically, so it is also injective as desired. $\square$

> **Theorem 1.6.2 Riemann-Hurwitz**
>
> Let X, Y be nice curves over k, let $f : X \to Y$ be a degree d separable morphism, then
>
> $$2g(X) - 2 = d\,(2g(Y) - 2) + \ell(\omega_{X/Y})$$
>
> where $\ell(\omega_{X/Y})$ is the length of $\omega_{X/Y}$ i.e. the length of the longest filtration by $\mathcal{O}_X$-modules with nonzero quotients. Furthermore $\ell(\omega_{X/Y}) = h^0(X, \omega_{X/Y})$.

Proof. We have a SES,

$$0 \to f^*\omega_Y \to \omega_X \to \omega_{X/Y} \to 0$$

then taking the Euler characteristic, we have $\chi(\omega_X) = \chi(\omega_{X/Y}) + \chi(f^*\omega_Y)$. $\omega_{X/Y}$ is supported on a dimension 0 set, so $\chi(\omega_{X/Y}) = h^0(\omega_{X/Y})$. By Riemann-Roch,

$$\chi(f^*\omega_Y) = \deg(f^*\omega_Y) + 1 - g(X) = d(2g(Y) - 2) + 1 - g(X)$$

Putting this together, we get that,

$$g(X) - 1 = d(2g(Y) - 2) + 1 - g(X) + h^0(\omega_{X/Y})$$

Rearranging this yields the desired result. It remains just to show that $h^0(\omega_{X/Y}) = l(\omega_{X/Y})$ which follows from noticing that $\omega_{X/Y}$ is a direct sum of skyscraper sheaves at the points of ramification (i.e. $\text{Supp}\,\omega_{X/Y}$). On a local ring $\mathcal{O}_{X,p}$, a module over the local ring has length equal to the dimension of as a $k = \mathcal{O}_{X,p}/\mathfrak{m}_p$ vector space (Nakayama's lemma). Then since $\omega_{X/Y}$ is a direct sum of skyscraper sheaves, its h^0 and length agree. $\square$

> **Thm**
>
> $f^*\mathcal{O}(D) = \mathcal{O}(f^{-1}(D))$ so $\deg f^*\mathscr{L} = \deg f \deg \mathscr{L}$

Proof. Hartshorne Ex II.6.8 and Prop 6.9. □

> **Question**
>
> What is $\mathrm{len}_R \omega_{X/Y}$?

> **Example**
>
> Since this is a local question we consider
> $$\omega_{\mathbb{C}[x^{1/n}]/\mathbb{C}[x]} = \omega_{\mathbb{C}[x,t]/(x^n-t)/\mathbb{C}[x]} = \mathbb{C}[x,t]dt/nt^{n-1}dt$$
> which has length $n-1$, as it is supported at $t = 0$ dimension $n - 1/\mathbb{C}$.

> **Example**
>
> Let $S = \mathbb{F}_p[x], R = S[t]/(t^p - t^{p-1} - f(x))$. Then $\omega_{R/S} = Rdt/t^{p-2}dt$ has length $p - 2$.

> **Remark**
>
> WARNING: As written this fact is likely wrong. If you have the correct statement, please let us know. If $k = \bar{k}$ is of characteristic 0, all finite extensions of $k((t))$ are of the form $k((t^{1/n}))$ and if R is a domain and $R/k((t))$ is finite flat and normal, then $\omega_{R/k((t))}$ has length $[R : k((t))] - 1$.

> **Claim:**
>
> Let $f : X \to Y, x \in \mathrm{Supp}\,\omega_{X/Y}, y = f(x)$. Then
> $$\omega_{\hat{\mathcal{O}}_{X,x}/\hat{\mathcal{O}}_{Y,y}} = \omega_{X/Y}|_{\hat{\mathcal{O}}_{X,x}} = \widehat{(\omega_{X/Y})_x}$$

Proof. Formation of the module of differentials commutes with base change and $\hat{\mathcal{O}}_{X,x}$ is flat over $\mathcal{O}_{X,x}$. □

The upshot of this is that then
$$l(\omega_{X/Y}) = \sum_{x \in \mathrm{Supp}\omega_{X/Y}} l(\omega_{X/Y})_x = \sum_{x \in \mathrm{Supp}\omega_{X/Y}} l(\omega_{X/Y})_{\hat{x}}$$

which in characteristic 0 can also be computed as $\sum_{x \in \mathrm{Supp}\omega_{X/Y}} [\mathrm{Frac}\hat{\mathcal{O}}_{X,x} : \mathrm{Frac}\hat{\mathcal{O}}_{Y,y}] - 1$.

Recall: If $f : X \to Y$ is cyclic of degree d, defined by $f : \mathscr{L}^d \to \mathcal{O}_Y$ in local coordinates:
$$R = k[x,t]/(t^n - f(x))$$

We want to figure out what $\omega_{X/Y}$ looks like. If $(n, \operatorname{char} k) = 1$, then

$$\omega_{X/Y} = R dt / (n t^{n-1} dt)$$

If we choose a point $z \in X$, i.e. a point $(x, t) \in R$ such that $t^n = f(x)$, then

1. 1) If $f(x) \neq 0$, then $t = f(x)$ is invertible in the local ring, so $\omega_{X,Y}$ is 0 at z.

2. 2) If $f(x) = 0$, then t is nilpotent of degree n and the length over $\mathcal{O}_{X,z}$ of $(\omega_{X/Y})_z$ is $n - 1$.

> **Corollary**
>
> Let $X \to \mathbb{P}^1$ hyperelliptic and $X = \mathbf{Spec}_{\mathbb{P}^1}(\mathcal{O} \oplus \mathcal{O}(-d))$, then $g(X) = d - 1$.

Proof. We have $\mathcal{O}(-2d) \to \mathcal{O}$ is given by an element $f \in \Gamma(\mathbb{P}^1, \mathcal{O}(2d))$ so there are $2d$ points in $\omega_{X/Y}$, i.e. the zeros of f and at each point, the curve locally looks like $k[x, t]/(t^2 - f(x))$, so the length is $2 - 1 = 1$. By Riemann-Hurwitz,

$$2g(X) - 2 = 2(0 - 2) + 2d = 2d - 4$$

Therefore $2g(X) = 2d - 2$, so $g(X) = d - 1$ as desired. $\qquad\square$

> **Corollary 1.6.3: $\mathbb{P}^1$ is simply connected**
>
> If X is a nice curve over k and $f : X \to \mathbb{P}^1$ is étale then f is an isomorphism.

Proof. By Riemann-Hurwitz, $2g(X) - 2 = -2 \deg f + \ell(\omega_{X/Y})$. Since f is étale, then $\omega_{X/Y} = 0$, therefore $\deg(f) = 1 - g(X) \leqslant 1$ but we also have that $1 \leqslant \deg(f)$. Therefore f has degree 1 so f is an isomorphism. $\qquad\square$

> **Corollary**
>
> There is a bijective correspondence
>
> $$\{f : X \to Y \text{ cyclic étale of degree } d\} \cong \{\mathscr{L} \text{ line bundle } \mathscr{L}^d \cong \mathcal{O}\}$$

Proof sketch: Let σ be an involution of X/Y of order d (which exists for the same reason as the involution from the start of lecture / there is an equivalence of categories between nice curves and their function fields) and ζ a d-th root of unity. Let $f : X \to Y$ as in the left side. Then $f_* \mathcal{O}_X \cong \mathcal{O}_Y \oplus \mathscr{L} \oplus \cdots \oplus \mathscr{L}^{d-1}$ where $\mathscr{L}$ is ζ^d-eigenspace of σ. This gives us $\mathscr{L}^d \to \mathcal{O}$, which is an isomorphism iff f is étale.

Reversing this process combined with the earlier result from lecture gives us the other map. Since every automorphism of $\mathcal{O}$ is given by multiplication by a scalar, the isomorphism $\mathscr{L}^d \to \mathcal{O}$ is just as unique. Hence it suffices to show that scaling the isomorphism gives an isomorphic $f : X \to Y$. $\qquad\square$

For line bundles on $\mathbb{P}^1$ we have the following table due to R.R.,

deg	h^0	h^1
-4	0	3
-3	0	2
-2	0	1
-1	0	0
0	1	0
1	2	0
2	3	0
3	4	0
4	5	0

Thm

$\mathcal{O}_{\mathbb{P}^1}(d)$ is very ample for $d \geqslant 1$

Proof. Let $p, q \in \mathbb{P}^1$, then look at $h^0(\mathcal{O}(d) \otimes \mathcal{O}(-p-q))$ in the table above and observe that it goes down by 2. Thus $\mathcal{O}(d)$ is very ample by thm 1.4.2. $\qquad\square$

The map $f_{|\mathcal{O}(d)|} : \mathbb{P}^1 \to \mathbb{P}^d$ is a morphism of degree d, i.e. $f^*_{|\mathcal{O}(d)|}\mathcal{O}(1) = \mathcal{O}(d)$ i.e. $f^{-1}H$ is a degree d divisor for a hyperplane H. We get a map $\operatorname{Sym}^d \Gamma(\mathbb{P}^1, \mathcal{O}(1)) \xrightarrow{\sim} \Gamma(\mathbb{P}^1, \mathcal{O}(d))$, i.e. elements in $\Gamma(\mathbb{P}^1, \mathcal{O}(d))$ are degree d two variables polynomials. We then get $f_{|\mathcal{O}(d)|} : \mathbb{P}^1 \to \mathbb{P}^d$ and $[x:y] \mapsto [x^d : x^{d-1}y : \cdots : xy^{d-1} : y^d]$.

Def: The image of $f_{|\mathcal{O}(d)|}$ is a *Rational Normal Curve* (RNC).

1.7 Lecture 7 - Rational normal curves

We want to find a nice surface in which hyperelliptic curves of genus g live. This will turn out to be a so called "ruled surface".

Thm

Suppose $k = \bar{k}$ and char $k \neq 2$. Let C/k be hyperelliptic, then $f_{|\omega_C|} : C \to \mathbb{P}^{g-1}$ is $2-1$ onto its image, which is a rational normal curve.

We postpone the proof to first see some corollaries and then build up lemmas to tackle the proof.

Corollary

The $2:1$ map $C \to \mathbb{P}^1$ is canonical

Proof. The "canonical" nature of this is up to automorphism of $\mathbb{P}^1$. This will follow by a commutative diagram we will get in thm 1.7.1. $\qquad\square$

> **Corollary**
>
> If C is hyperelliptic, then the hyperelliptic involution is in the center of $\mathrm{Aut}\,C$.

Proof. Since the involution over $\mathbb{P}^1$ is uniquely determined by the hyperelliptic 2:1 map, it is sent to the canonical involution of an automorphic image of C. □

> **Corollary**
>
> If $C_{\overline{k}}$ is hyperelliptic, then C admits a $2:1$ map to a smooth conic.

Proof. The canonical map from $C \to \mathbb{P}_k^{g-1}$ base changes to the canonical map out of $C_{\overline{k}}$ which is a $2:1$ map to a rational normal curve. It follows that the image of the canonical map out of C is a genus 0 curve, i.e. a smooth conic. □

> **Prop**
>
> Given coordinates $x_0, \dots, x_d$ on $\mathbb{P}^d$. A rational normal curve is cut out by the 2x2 minors of the matrix
> $$\begin{pmatrix} x_0 & x_1 & \cdots & x_{d-1} \\ x_1 & x_2 & \cdots & x_d \end{pmatrix}$$

Proof. Let I be the ideal generated by the 2x2 minors of the above matrix. Let $X = V(I)$ be the curve cut out by I. Then we define $\varphi : S(X) = k[x_0, \dots, x_d]/I \to k[s,t]_{\times d} = S(\mathrm{im} f_{|\mathcal{O}(d)})$ by sending x_i to $s^{d-i}t^i$. φ is well defined by looking at the generators of I and seeing that our definition respects them. It is clear that φ is a graded map so it suffices to show that φ is an isomorphism.

φ is clearly surjective in degree "1" (really degree d of $k[s,t]$ but the homogeneous coordinate ring is $k[s,t]_{\times d}$) and $k[s,t]_{\times d}$ is generated in degree "1."

Therefore we show injectivity. It suffices to show injectivity in degree n. Since the map is surjective we can just compute dimensions where it suffices to show that

$$\dim S(X)_n \leqslant \dim k[s,t]_{nd} = nd + 1$$

It is easy to see using the relations in I that every monomial of degree n in $(k[x_0, \dots, x_d]/I)_n$ is equivalent to one of the form $x_0^a x_1^{\epsilon_1} \cdots x_{d-1}^{\epsilon_{d-1}} x_d^b$ where $\epsilon_i \in \{0, 1\}$ and at most one is non-zero. There are $nd + 1$ of there so we are done (this only shows the upper bound to an equality, but that's all we need).

□

> **Def:** A curve $C \subseteq \mathbb{P}^n$ is called *non-degenerate* if it is not contained in any hyperplane.

> **Thm**
>
> Let $k = \overline{k}$. Any non-degenerate geometrically integral curve in $\mathbb{P}^d$ of degree $\leqslant d$ is a rational normal curve.

Proof. Let $C \subseteq \mathbb{P}^d$ satisfy the hypotheses. Let $\widetilde{C}$ be the normalization of C. Then $\widetilde{C}$ is smooth and hence nice since C is geometrically integral. We have $\widetilde{C} \xrightarrow{\pi} C \to \mathbb{P}^d$, so we get a map $f : \widetilde{C} \to \mathbb{P}^d$ given by a line bundle $\mathscr{L}$ on $\widetilde{C}$ and a surjective map $V \otimes \mathcal{O}_X \to \mathscr{L}$. This map being nondegenerate means that the map on global sections $V \to \Gamma(\widetilde{C}, \mathscr{L})$ is an injection. If it is not an injection, then suppose $x \in V$ gets sent to 0, choosing a basis of V containing x, we get that the image of $\widetilde{C}$ in $\mathbb{P}V$ is contained in the hyperplane cut out by x. It follows that $h^0(\mathscr{L}) = d$, but $\deg \mathscr{L} \leqslant d$ (since π is degree 1). It follows by lemma 1.5.2 that $\widetilde{C}$ has genus 0, so $\widetilde{C} = \mathbb{P}^1$. Therefore $\widetilde{C} \to \mathbb{P}^d$ is a d-uple embedding. C has the same scheme theoretic image as $\widetilde{C}$ and is therefore a rational normal curve. $\qquad\square$

Projections

Given a point $p \in \mathbb{P}^n$, the lines through p correspond exactly to a copy of $\mathbb{P}^{n-1}$.

$$p \in \mathbb{P}V \leftrightarrow H \subseteq V \text{ hyperplane}$$
$$\text{line through } p \in \mathbb{P}V \leftrightarrow H' \subseteq V \text{codim 2 w}/H' \subseteq H \leftrightarrow \mathbb{P}H$$

Suppose we have a map $f_{(V,\mathscr{L})} : C \to \mathbb{P}V$. Let $W \subseteq V$ be a subspace. Then the inclusion $W \subseteq V$ yields an inclusion $W \otimes \mathcal{O}_X \to V \otimes \mathcal{O}_X$. It follows that maps from $V \otimes \mathcal{O}_X$ to $\mathscr{L}$ yield, by way of composition, maps from $W \otimes \mathcal{O}_X \to \mathscr{L}$. Note however, that this map may no longer be surjective, therefore we obtain only a rational map $C \dashrightarrow \mathbb{P}W$.

Recall that a rational map out of a curve can be upgraded to a map from the whole curve. This corresponds to the fact that we may replace $\mathscr{L}$ with the image of $W \otimes \mathcal{O}_X$ which is a torsion free rank 1 subsheaf of $\mathscr{L}$ which is therefore locally free since C is locally a DVR.

> **Claim 1.7.2: Maps from $\mathbb{P}^1$ to $\mathbb{P}^n$**
>
> Any map $\mathbb{P}^1 \to \mathbb{P}^n$ with non-degenerate image is obtained by projection from a rational normal curve.

Proof. Let $f = f_{V,\mathscr{L}}$, the non-degeneracy means that $V \otimes \mathcal{O}_X \to \mathscr{L}$ yields an injection $V \to \Gamma(\mathbb{P}^1, \mathscr{L})$. $\mathscr{L} = \mathcal{O}(d)$ for some d, so we have a map $\Gamma(P^1, \mathscr{L}) \otimes \mathcal{O}_X \to \mathscr{L}$ which kills the elements outside of V. Now $V \otimes \mathcal{O}_X \to \mathscr{L}$ factors through the map from $\Gamma(\mathbb{P}^1, \mathscr{L}) \otimes \mathcal{O}_X$ as a projection. It follows that f is a projection after the map $f_{|\mathscr{L}|}$ is a rational normal curve. $\qquad\square$

1.8 Lecture 8 - g_d^rs and better bounds on $h^0(\mathscr{L})$

> **Theorem 1.8.1: Hyperelliptic curve canonical map**
>
> Let C/k be hyperelliptic with $g \geqslant 2$, i.e. $\pi : C \to \mathbb{P}^1$ is 2-to-1. Then the canonical map $f_{|\omega_C|} : C \to \mathbb{P}^{g-1}$ is 2:1 onto its image - a RNC - and factors through π.

Proof. Let $p + q$ be the fiber over ∞ of π (possibly with $p = q$). Since C is reduced it suffices to show that show that $f_{|\omega_C|}(p) = f_{|\omega_C|}(q)$ (this is essentially by the Reduced-to-Separated theorem).

1. $\pi = f_{|\mathcal{O}(p+q)|} : \dim |\mathcal{O}(p + q)| = 1$ because $g > 0$ so $\dim |\mathcal{O}(p + q)| < \deg \mathcal{O}(p + q) = 2$ and $\dim |\mathcal{O}(p + q)| \geqslant 1$ since $\mathcal{O}$ is BPF. π is given by some line-bundle and hence it must be given by $|\mathcal{O}(p + q)|$.

2. We WTS that $p + q$ imposes 1 condition on ω_C, i.e. $h^0(\omega_C(-p - q)) = h^0(\omega_C) - 1 = g - 1$. This means any 1-form vanishing at p also vanishes at q (if $p = q$ then take this to mean that any 1-form vanishing at p vanishes to order 2), or equivalently the natural map

$$H^0(\omega_C(-p - q)) \hookrightarrow H^0(\omega_C(-p))$$

is an quality.

Proof of 2. Start with the SES

$$0 \longrightarrow \mathcal{O}_C \longrightarrow \mathcal{O}_C(p + q) \longrightarrow \mathcal{O}_{p+q} \longrightarrow 0$$
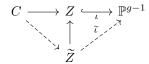
giving the LES

$$0 \longrightarrow H^0(\mathcal{O}_C) \longrightarrow H^0(\mathcal{O}_C(p + q)) \longrightarrow H^0(\mathcal{O}_{p+q})$$

$$H^1(\mathcal{O}_C) \longleftarrow H^1(\mathcal{O}_C(p + q)) \longrightarrow 0$$

since $p + q$ is 0-dimensional. $h^0(\mathcal{O}_C) = 1$ and $h^0(\mathcal{O}(p + q)) = 2$ because $f_{|\mathcal{O}(p+q)|}$ maps to $\mathbb{P}^1$. Therefore $\mathrm{rk}(H^0(\mathcal{O}_C(p + q)) \to H^0(\mathcal{O}_{p+q})) = 1$ and since $h^0(\mathcal{O}_{p+q}) = \deg p + q = 2$, so does $\mathrm{rk}(H^0(\mathcal{O}_{p+q}) \to H^1(\mathcal{O}_C)) = 1$ hence $h^1(\mathcal{O}_C(p + q)) = h^1(\mathcal{O}_C) - 1 = g - 1$. The result follows by Serre duality. $\qquad\square$

3. Let $Z = f_{|\omega_C|}(C)$ be the image of C under the cannonical map. We then get the following diagram by the universal property of the normalization.

$$C \longrightarrow Z \overset{\iota}{\hookrightarrow} \mathbb{P}^{g-1}$$
$$\widetilde{Z}$$
with $\widetilde{\iota}$

Then $\deg \widetilde{\iota} \leqslant \frac{\deg f_{|\omega_C|}}{\deg(C \to Z)} \leqslant \frac{2g-2}{2} = g - 1$ and $\widetilde{\iota}$ has image Z which is nondegenerate. Therefore by the big theorem from lecture 7, Z is a rational normal curve and so $Z = \widetilde{Z}$ and has degree exactly $g - 1$. Therefore $\deg f_{|\omega_C|} : C \to Z$ is 2 and the fibers of $f_{|\omega_C|} =$ fibers of π. (Since they are of the same degree / this means scheme theoretically). $\qquad\square$

> **Corollary**
>
> The $2 : 1$ map π is determined entirely by $f_{|\omega_C|}$, so it is unique up to an isomorphism of $\mathbb{P}^1$.

Originally our goal was to understand maps from curves to $\mathbb{P}^n$. We now understand $2:1$ maps to $\mathbb{P}^1$ at least in the case where $g(C) \neq 1$ and we understand $1:1$ maps to $\mathbb{P}^1$, i.e. genus 0 curves.

Def: We want to more generally understand degree d maps to $\mathbb{P}^n$, i.e. linear systems of dimension r and degree d which we denote g_d^r's

---

Example

A hyperelliptic curve is a curve with a g_2^1.
A curve with a g_3^1 is called trigonal. For example take $X = \mathrm{Spec}_{\mathbb{P}^1}(\mathcal{O}_{\mathbb{P}^1} \oplus \mathcal{O}_{\mathbb{P}^1}(-d) \oplus \mathcal{O}_{\mathbb{P}^1}(-2d))$ where we put an algebra structure by choosing a map $\mathcal{O}_{\mathbb{P}^1}(-3d) \to \mathcal{O}_{\mathbb{P}^1}$, i.e. a degree $3d$ separable homogeneous polynomial.

Claim:

Any non-hyperelliptic genus 3 curve has a g_3^1.

Proof. Let X be a genus 3 non-hyperelliptic, then the canonical map is an embedding. $f_{|\omega_X|} : X \to \mathbb{P}H^0(X, \omega_X) = \mathbb{P}^2$ embeds X as a plane quartic. We can now project away from a point p in X which comes from a map

$$H^0(X, \omega_X(-p)) \otimes \mathcal{O}_X \to \omega_X(-p)$$

This is surjective since for any point q, $h^0(X, \omega_X(-p-q)) = h^0(X, \omega_X(-p)) - 1$ since ω_X is very ample. Therefore there is a section of $H^0(\omega_X(-p))$ vanishing at q, so it surjects. Note that $\omega_X(-p)$ has degree 3 so this is a g_3^1. $\qquad\square$

We will later show the following:

Thm

Any non-hyperelliptic $g = 4$ is trigonal.

Question

Which curves have very ample g_d^2's?

Thm

Let $C \subset \mathbb{P}^2$ and ι be the inclusion. Suppose that C is a very nice cuve of degree d. Then $g(C) = \frac{1}{2}(g-1)(g-2)$.

Proof. Let

$$0 \longrightarrow \mathcal{O}_{\mathbb{P}^2}(-C) = \mathcal{O}_{\mathbb{P}^2}(-d) \longrightarrow \mathcal{O}_{\mathbb{P}^2} \longrightarrow \mathcal{O}_C \longrightarrow 0$$

be the natural SES for the structure sheaf of C. We then get that $H^1(\mathcal{O}_C) \to H^2(\mathcal{O}_{\mathbb{P}^2}(-d))$ is an isomorphism from the LES in cohomology since $h^1(\mathbb{P}^2) = h^2(\mathbb{P}^2) = 0$ by the cohomology of projective space. But $h^2(\mathcal{O}_{\mathbb{P}^2}(-d)) = h^0(\omega_{\mathbb{P}^2}(d)) = h^0(\mathcal{O}(d-3))$ by Serre Duality. We then recall

that $H^0(\mathcal{O}(d-3))$ are the homogeneous polynomials in degree $d-3$ so $h^1(\mathcal{O}_C) = \binom{d-1}{2}$ by stars and bars. $\qquad\square$

Better bounds on h^0

For genus 0, $h^0(\mathcal{L}) = 1 + h^1(\mathcal{L}) + \deg\mathcal{L}$ and for $\deg\mathcal{L} \geqslant 0$ $h^1(\mathcal{L}) = 0$.

For genus 1:

deg	h^0	h^1
-3	0	3
-2	0	2
-1	0	1
0	$\begin{cases} 1 & \text{if } \mathcal{O} \\ 0 & \text{else} \end{cases}$	$\begin{cases} 1 & \text{if } \mathcal{O} \\ 0 & \text{else} \end{cases}$
1	1	0
2	2	0
3	3	0

In general we understand $h^0(\mathcal{L})$ perfectly for $\deg\mathcal{L} \geqslant 2g-2$. If $\deg\mathcal{L} \geqslant 2g-2$ and $\mathcal{L} \neq \omega_C$ then $h^0(\mathcal{L}) = \deg\mathcal{L} + 1 - g$ since h^1 vanishes. This is linear of slope 1.

In particular, if $\mathcal{L} = 2g-1$ then $h^0(\mathcal{L}) = g$ always holds. We also know that $h^0(\mathcal{L}) \leqslant \deg\mathcal{L}$ for $\deg\mathcal{L} > 0$ and $g > 0$.

Now suppose that $x_1, x_2, \ldots, x_{2g-1} \in X(k)$ are closed points. Consider the sequence

$$1 = h^0(\mathcal{O}(x_1)) \leqslant h^0(\mathcal{O}(x_1 + x_2)) \leqslant \cdots \leqslant h^0(\mathcal{O}(\sum_i x_i)) = g$$

so there are exactly $g-1$ jumps.

> **Theorem 1.8.2: Clifford**
>
> If $0 \leqslant \deg\mathcal{L} \leqslant 2g-2$ then $h^0(\mathcal{L}) \leqslant \frac{\deg\mathcal{L}}{2} + 1$.

We first prove a lemma

> **Lemma**
>
> If D, D' are disjoint (we need to get rid of the disjoint assumption, this is given next lecture) effective divisors, then
>
> $$h^0(\mathcal{O}(D + D')) + 1 \geqslant h^0(\mathcal{O}(D)) + h^0(\mathcal{O}(D'))$$

Proof. The SES $0 \to \mathcal{O} \to \mathcal{O}(D) \to \mathcal{O}(D)|_D \to 0$ gives a LES:

$$0 \to H^0(\mathcal{O}) \to H^0(\mathcal{O}(D)) \to H^0(\mathcal{O}(D)|_D) \xrightarrow{\varphi} H^1(\mathcal{O}) \to H^1(\mathcal{O}(D)) \to 0$$

We have another SES $0 \to \mathcal{O}(D') \to \mathcal{O}(D + D') \to \mathcal{O}(D + D')|_D \to 0$ which gives another LES,

$$0 \to H^0(\mathcal{O}(D')) \to H^0(\mathcal{O}(D + D')) \to H^0(\mathcal{O}(D + D')|_D) \xrightarrow{\varphi} H^1(\mathcal{O}(D')) \to H^1(\mathcal{O}(D + D')) \to 0$$

It follows that $h^0(\mathcal{O}(D + D')) \geqslant h^0(\mathcal{O}(D)) + \dim \ker \varphi$. We now have $\dim \ker \varphi = \dim h^0(\mathcal{O}(D)) - 1$ so we win if $\dim \ker \psi \geqslant \dim \ker \varphi$.

$$
\begin{array}{ccc}
H^0(\mathcal{O}(D)|_D) & \xrightarrow{\ \varphi\ } & H^1(\mathcal{O}) \\
\downarrow{\scriptstyle \cdot s_{D'}} & & \downarrow{\scriptstyle \cdot s_{D'}} \\
H^0(\mathcal{O}(D + D')|_D) & \xrightarrow{\ \psi\ } & H^1(\mathcal{O}(D'))
\end{array}
$$

Where $s_{D'}$ is a global section of D' whose vanishing is exactly D'. Since $D \cap D' = \varnothing$, then the LHS is an isomorphism so the inequality holds. $\qquad\square$

We can now prove Clifford's theorem:

Proof. If $h^1(\mathscr{L}) = 0$, then $h^0(\mathscr{L}) = \deg \mathscr{L} + 1 - g$ by Riemann-Roch and $g - 1 \geqslant \frac{\deg \mathscr{L}}{2}$, so $h^0(\mathscr{L}) \leqslant \frac{\deg \mathscr{L}}{2}$.

If $h^1(\mathscr{L}) = h^0(\omega \otimes \check{\mathscr{L}}) \neq 0$, then by Riemann-Roch $h^0(\mathscr{L}) - h^0(\omega \otimes \check{\mathscr{L}}) = \deg \mathscr{L} + 1 - g$.

Claim: If $\mathscr{L} = \mathcal{O}(D)$, then there exists a divisor $D' \in \left|\omega_X \otimes \mathscr{L}\right|$ disjoint from D.

Assuming the above we get $\mathcal{O}(D + D') = \omega_X$, so

$$h^0(\omega_X) + 1 = g + 1 \geqslant h^0(\mathscr{L}) + h^0(\omega_X \otimes \check{\mathscr{L}})$$

Adding this to Riemann-Roch we get:

$$2h^0(\mathscr{L}) \leqslant \deg \mathscr{L} + 2 \Rightarrow h^0(\mathscr{L}) \leqslant \frac{\deg \mathscr{L}}{2} + 1$$

Thus Clifford's theorem holds, modulo proving the claim that was assumed true, or removing the disjoint requirement. $\qquad\square$

Genus 1 curves:

Let E genus 1, $p \in E^{cl}.\deg \mathcal{O}(p) = [k(p) : k] =$?????????????? could be anything if $k \neq \bar{k}$.

> **Def:** $\mathrm{Gcd}(\{\deg D | D \geqslant 0\})$ is index of an genus 1 curve.

Assume that $E(k) \neq \varnothing$ and the let $p \in E(k).|\mathcal{O}(p)| = 0$ and $\dim|\mathcal{O}(2p)| = 1$ so we get a 2-1 map to $\mathbb{P}^1$ by BPF-ness of $\mathcal{O}(2p)$. This map is not necessarily unique as E is not hyper-elliptic. We will soon show that $|\mathcal{O}(3p)|$ gives an embedding to $\mathbb{P}^2$ as a cubic equation.

1.9 Lecture 9 - Some random stuff

We start by removing the disjointness assumption from the previous lecture.

> **Lemma**
>
> Given two effective divisors D, D' we have that $h^0(\mathcal{O}(D + D')) + 1 \geqslant h^0(\mathcal{O}(D)) + h^0(\mathcal{O}(D'))$.

Proof. We first show that $h^0(\mathcal{O}(D)) \geqslant m + 1$ if for any m points, $x_1, \cdots, x_m \in X(\bar{k})$ there exists a section of $\mathcal{O}(D)$ vanishing at all x_i. In particular, it suffices to show that $h^0(\mathcal{O}(D)) = m_{\max} + 1$ where $m_{\max}$ is the largest m for which the property holds.

Let $n = h^0(\mathcal{O}(D)) - 1$. We want to show that for point $x_1, \cdots, x_n \in X(\bar{k})$, there is a nonzero section vanishing at all of them. We have a map

$$H^0(X, \mathcal{O}(D)) \to \oplus_i \mathcal{O}(D)_{x_i}$$

of vector vector spaces given by the evaluation map. Since the dimension of the LHS is $n + 1$ and the dimension of the RHS is n, then there is a nonzero kernel, i.e. a nonzero section of $\mathcal{O}(D)$ vanishing at each x_i as desired.

Conversely, choose x_1 such that some section of $\mathcal{O}(D)$ doesn't vanish at x_1. Choose x_i such that some nonzero section of $\mathcal{O}(D - x_1 - \cdots - x_{i-1})$ doesn't vanish at x_i. We can continue choosing such points as long as $h^0(X, \mathcal{O}(D - x_1 - \cdots - x_{i-1})) \geqslant 1$. Since each point drops the dimension by at most 1, then we can do this at least $n + 1$ times. We have a SES,

$$0 \to \mathcal{O}(-x_1 - \cdots - x_i) \to \mathcal{O}_X \to \mathcal{O}_{x_1 + \cdots + x_i} \to 0$$

Now tensoring with $\mathcal{O}(D)$ and taking the global sections, we get that $H^0(X, \mathcal{O}(D - x_1 - \cdots - x_i))$ injects into $H^0(X, \mathcal{O}(D))$. Let $s_i \in H^0(X, \mathcal{O}(D - x_1 - \cdots - x_{i-1}))$ be a section which does not vanish at x_i, then $s_i \in H^0(X, \mathcal{O}(D))$ vanishes at all $x_1, \cdots, x_{i-1}$ and not at x_i. It follows that $\{s_i\}_{i=1}^{n+1}$ forms a basis of $H^0(X, \mathcal{O}(D))$. Therefore an element $s \in H^0(X, \mathcal{O}(D))$ vanishing at all x_i has coefficients of 0 for each s_i and hence $s = 0$.

We can now prove the lemma: Let $h^0(\mathcal{O}(D)) = m_D + 1, h^0(\mathcal{O}(D')) = m_{D'} + 1$. For any $m_D + m_{D'}$ points, there is a nonzero section x of $\mathcal{O}(D)$ vanishing at the first m_D and $y \in H^0(X, \mathcal{O}(D'))$ vanishing at last $m_{D'}$ and therefore $x \otimes y$ is a nonzero section of $\mathcal{O}(D + D')$ vanishing at all the points. It follows that $h^0(\mathcal{O}(D + D')) \geqslant m_D + m_{D'} + 1$. $\qquad\square$

Back to Curves of Genus 1:

There are many 2:1 maps from a genus 1 curve, E, to $\mathbb{P}^1$. For example for any $P \in E, f_{|\mathcal{O}(2P)|}$ is ramified at P and 4 other points. In fact (we don't know enough to prove this yet) those 4 points are exactly the points differing from P by a 2-torsion element of E.

If $\deg \mathscr{L} = 3$ then $|\mathscr{L}|$ represents E as a plane cubic by looking at the table in 1.8.1.
Similarly, $\deg \mathscr{L} = 4$ represents E as a quartic in $\mathbb{P}^3$. The image of $f_{|\mathscr{L}|}$ in $\mathbb{P}^3$ has homogeneous coordinate ring given by $\bigoplus_{n \geqslant 0} \Gamma(E, \mathscr{L}^{\otimes n})$. We get a surjective graded map

$$\mathbb{C}[x_0, x_1, x_2, x_3] \to \bigoplus_{n \geqslant 0} \Gamma(E, \mathscr{L}^{\otimes n})$$

by the embedding.
For $n = 1$, both sides have dimension 4, LHS by counting and RHS by R.R.
For $n = 2$, the RHS has dimension 10 by counting. The LHS has dim 8 by R.R. Therefore there are two linearly independent quadrics Q_1, Q_2 vanishing on E. Since $\deg E = 4, E = V(Q_1, Q_2)$ since there is a containment and both have the same degree.

> **Question**
>
> Suppose $Q_1, Q_2 \subset \mathbb{P}^3$ are quadrics which intersect in a nice curve X. What is $g(X)$?

Answer. We have the following exact sequence (which is one example of a Koszul complex)

$$0 \longrightarrow \mathcal{O}_{\mathbb{P}^3}(-4) \xrightarrow{(Q_2, -Q_1)} \mathcal{O}_{\mathbb{P}^3}(-2)^{\oplus 2} \xrightarrow{\begin{pmatrix} Q_1 \\ Q_2 \end{pmatrix}} \mathcal{O}_{\mathbb{P}^3} \longrightarrow \mathcal{O}_X \longrightarrow 0$$

Then by additivity of χ we get

$$\chi(\mathcal{O}_X) = 1 - 2\chi(\mathcal{O}(-2)) + \chi(\mathcal{O}(-4)) = 1 - 0 + \chi(\omega_X)) = 1 - 1 = 0.$$

Therefore $g(X) = 1 - \chi(\mathcal{O}_X) = 1$ so X is genus 1. $\qquad \square$

We now sketch the construction of the Koszul complex in greater generality.

> **Claim**
>
> Let X be smooth, and $\mathcal{E}$ s vector bundle on X. Let $s \in \Gamma(X, \mathcal{E})$ be such that $\mathrm{codim}V(s) = \mathrm{rk}\mathcal{E}$. Then we can resolve $\mathcal{O}_X$ as follows:
>
> $$0 \to \overset{top}{\bigwedge} \check{\mathcal{E}} \xrightarrow{\cdot s} \cdots \xrightarrow{\cdot s} \overset{2}{\bigwedge} \check{\mathcal{E}} \xrightarrow{\cdot s} \check{\mathcal{E}} \xrightarrow{\cdot s} \mathcal{O}_X \to \mathcal{O}_{V(s)} \to 0$$

Sketches of an idea of a proof. Since we defined the maps globally we can show exactness locally. Thus wlog $\mathcal{E} = \mathcal{O}_X^{\oplus d}, s = (s_1, \ldots, s_d)$. Consider the chain complex (concentrated in degrees 0 and 1)

$$C_i^{\bullet} = (\mathcal{O}_X \xrightarrow{\cdot s_i} \mathcal{O}_X)$$

we then get another chain complex by setting

$$D^{\bullet} = \bigotimes_{i=1}^{d} C_i^{\bullet}$$

which is then obviously exact in degree > 0 as a tensor product of complexes exact in degree > 0. Also $H^0(D^{\bullet}) = \mathcal{O}_{V(s)}$.

Claim: $D^{\bullet}$ is the Koszul complex earlier defined.
When $d = 2, H^i(C_1^{\bullet} \otimes C_2^{\bullet}) = \underline{Tor}_i(\mathcal{O}_{V(s_1)}, \mathcal{O}_{V(s_2)})$ as we have an isomorphism of total complexes between the two (bounded) double chain complexes

$$\begin{array}{ccc} \mathcal{O}_X & \xrightarrow{\cdot s_1} & \mathcal{O}_X \\ {\scriptstyle \cdot s_2} \downarrow & & \downarrow {\scriptstyle \cdot -s_2} \\ \mathcal{O}_X & \xrightarrow{\cdot s_2} & \mathcal{O}_X \end{array} \qquad \begin{array}{c} \mathcal{O}_{V(s_1)} \\ \downarrow \\ \mathcal{O}_{V(s_2)} \end{array}$$

here is where we use the assumptions on the codimension of $V(s)$. This is where the lecture ended.

$\qquad \square$

1.10 Lecture 10 - Curves of genus 4 and the Picard scheme/functor

Let $C/\mathbb{C}$ be a non-hyperelliptic curve of genus 4, then we have the canonical map $f_{|\omega_C|} : C \to \mathbb{P}^3$. This induces a map of projective schemes which comes from a graded map of rings:

$$\mathbb{C}[x_0, \cdots, x_3] \to \bigoplus_{n \geqslant 0} H^0(C, \omega_C^{\otimes n})$$

If you care to see why C is Proj of the RHS refer to the proof of part 2 of thm 1.4.3. The degree of ω_C is 6 and so for all its tensor powers will have $H^1 = 0$. It follows by Riemann-Roch, that $h^0(\omega_C^{\otimes n}) = 6n - 3$ for $n \geqslant 2$ and for $n = 1$, it $h^0 = 1$, and for $n = 2$, $h^0 = 4$. The dimension of the degree n component of $\mathbb{C}[x_0, \cdots, x_3]$ is $\binom{n+3}{3}$. It follows that in degree 2, we have 10 dimensions on the LHS and 9 on the RHS so there is a quadric Q vanishing on C. Then since the LHS has dimension 4 in degree 1, this quadric gives 4 dimensions worth of elements in degree 3 which vanish on C. Since in degree 3, the LHS has dimension 20 and the RHS has dimension 15 and we already know 4 dimensions of the kernel, then there is at least one cubic F_3 which vanishes on C and not on Q.

Since F_3 is degree 3 and Q is degree 2, then $F_3 \cap Q$ has degree 6 and contains C which also has degree 6. It follows that $F_3 \cap Q = C$. Therefore we have proven

---

Prop

A canonically embedded genus 4 curve is the intersection of a unique quadric and a non-unique cubic.

Theorem 1.10.1: Curves have a g_d^3

Let C/k be a nice curve with k an infinite field. Then C has a closed embedding into $\mathbb{P}^3$, i.e. C has a very ample g_d^3.

Proof. Let P be a closed point of C, then $\mathcal{O}(P)$ is a line bundle of degree $[k(P) : k] > 0$ and therefore $\mathcal{O}(P)$ is ample, so $C \hookrightarrow \mathbb{P}^N$ for some N. We now want to repeatedly project down from $\mathbb{P}^N$ until we get to $\mathbb{P}^3$.

Claim: If $N > 3$, there is a point $p \in \mathbb{P}^N(k)$ such that $proj_p : \mathbb{P}^N \dashrightarrow \mathbb{P}^{N-1}$ which induces a closed immersion of C into $\mathbb{P}^{N-1}$. Note that $proj_p$ fails to be a closed immersion iff p lies on a secant/tangent line to C.
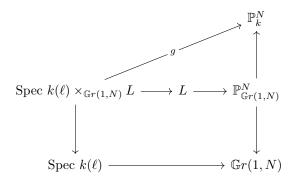
To prove this claim, it suffices to find a point which is on neither the secant variety or the tangent variety to C. To do this, it suffices to show that the secant variety has dimension $\leqslant 3$, as then it is a proper closed subscheme of $\mathbb{P}^N$ so there is a rational point not contained in the secant variety by infiniteness of k. To construct $\mathrm{Sec}(C)$, we first consider $\mathbb{G}r(1, N) = Gr(2, N+1)$, the Grassmannian of all lines in $\mathbb{P}^N$. We have $L \subseteq \mathbb{G}r(1, N) \times_k \mathbb{P}^N$, the universal family of lines in $\mathbb{P}^N$, i.e. over any line $\ell \in \mathbb{G}r(1, N)$, the preimage under the projection map of ℓ in L is the line ℓ in $\mathbb{P}^N$.

To construct L, recall that the Grassmannian $Gr(k, n)$ represents the functor

$$F(X) = \left\{ V \otimes \mathcal{O}_X \twoheadrightarrow \mathscr{E} \mid \mathscr{E} \text{ locally free of rank } k, \dim_k V = n \right\}$$

We can now consider the identity map $id : \mathbb{G}r(1, N) \to \mathbb{G}r(1, N)$ which by the above corresponds to some map $\varphi : V \otimes \mathcal{O}_{\mathbb{G}r(1,N)} \to \mathscr{E}$ where $\mathscr{E}$ is some rank 2 locally free sheaf on $\mathbb{G}r(1, N)$ and $\dim_k V = N + 1$. We then get a map $\mathrm{Sym}\,\varphi : \mathrm{Sym}(V \otimes \mathcal{O}) \to \mathrm{Sym}\,\mathscr{E}$ which yields a map of relative

proj, $f : \text{Proj}_{\mathbb{G}r(1,N)} \text{Sym}(\mathscr{E}) \to \text{Proj}_{\mathbb{G}r(1,N)} \text{Sym}(V \otimes \mathcal{O})$. Since $V \otimes \mathcal{O}_{\mathbb{G}r(1,N)}$ is just a free sheaf of rank $N + 1$, then the RHS is exactly $\mathbb{P}^N_{\mathbb{G}r(1,N)} = \mathbb{P}^N_k \times_k \mathbb{G}r(1,N)$. We will call the LHS L. Since the map of $\mathcal{O}_X$-algebras was surjective, then this map is a closed immersion. We want to show that L is this universal family of lines. For any point $\text{Spec } k(\ell) \to \mathbb{G}r(1,N)$ corresponding to a line ℓ in $\mathbb{P}^N_k$, we have the following commutative diagram,

$$
\begin{array}{ccc}
& & \mathbb{P}^N_k \\
& \nearrow^{g} & \uparrow \\
\text{Spec } k(\ell) \times_{\mathbb{G}r(1,N)} L \longrightarrow & L \longrightarrow & \mathbb{P}^N_{\mathbb{G}r(1,N)} \\
\downarrow & & \downarrow \\
\text{Spec } k(\ell) \longrightarrow & & \mathbb{G}r(1,N)
\end{array}
$$

The fiber product on the left is the preimage of ℓ under the projection map $L \to \mathbb{G}r(1,N)$. It follows that we want the map g to have image exactly ℓ. Since L is the proj of a rank 2 line bundle on $\mathbb{G}r(1,N)$, then the fibers of the structure map $L \to \mathbb{G}r(1,N)$ will be $\mathbb{P}^1_k$. The map $\text{Spec } k(\ell) \to \mathbb{G}r(1,N)$ corresponds to a surjective map $\psi : k^{N+1} \to k^2$. Now map $\text{Spec } k(\ell) \to \mathbb{P}^1_k$ to an arbitrary point, then consider $\psi \otimes \text{id} : k^{N+1} \otimes \mathcal{O}_{\mathbb{P}^1_k} \to k^2 \otimes \mathcal{O}_{\mathbb{P}^1_k}$. This is a surjective map $\widetilde{\psi} : \mathcal{O}^{N+1}_{\mathbb{P}^1_k} \to \mathcal{O}^2_{\mathbb{P}^1_k}$. The identity map $\mathbb{P}^1_k \to \mathbb{P}^1_k$ corresponds to the map $\mathcal{O}_{\mathbb{P}^1_k} \to \mathcal{O}_{\mathbb{P}^1_k}(1)$ the sheafification of the map $k[x_0, x_1]^2 \to k[x_0, x_1]$ by $(x, y) \mapsto x_0 x + x_1 y$. One checks that at the point $\mathfrak{p} = (x_0 - a, x_1 - b)$ $\overline{x}_0 = a, \overline{x}_1 = b$, so the map becomes $k^2 \to k$ by $(x, y) \mapsto ax + by$ which corresponds exactly to the point $[a : b]$ as one expects. Composing with $\widetilde{\psi}$, we obtain a map $\gamma : \mathcal{O}^{N+1}_{\mathbb{P}^1_k} \to \mathcal{O}_{\mathbb{P}^1_k}(1)$ corresponding to a map $\mathbb{P}^1_k \to \mathbb{P}^N_k$. The image of this map is exactly the line corresponding to the element $\ell \in \mathbb{G}r(1,N)$. Since $\text{Spec } k(\ell) \times_{\mathbb{G}r(1,N)} L \cong \mathbb{P}^1_k$, we want to show that g is the same map $g : \mathbb{P}^1_k \to \mathbb{P}^N_k$ as ℓ, up to an automorphism of $\mathbb{P}^1$. We may assume that we embed $k(\ell)$ at the point $1 \in \mathbb{P}^1_k$, then $\gamma : k[x_0, x_1]^{N+1} \to k[x_0, x_1]$ maps the standard basis $(e_0, \cdots, e_n)$ to $e_i \mapsto x_0 \psi(e_i)_0 + x_1 \psi(e_i)_1$. We now want to pull $\mathcal{O}_{\mathbb{P}^N_k}(1)$ back along g, which we can do in steps and show that the pullbacks of x_i agree with $\gamma(e_i)$. I will leave this as an exercise, since it is kind of convoluted.

Now consider $\pi_{1*}(\pi_2^* \mathcal{O}_C \otimes \mathcal{O}_L)$. The rank of this sheaf at any point $[\ell] \in \mathbb{G}r(1, N($ is the multiplicity of the intersection $\ell \in C$. Now consider $Z \subseteq \mathbb{G}r(1, N)$ to be the closed subset $\{[\ell] \, \big| \, \text{rank}_{[\ell]} \, \pi_{1*}(\pi_2^* \mathcal{O}_C \otimes \mathcal{O}_L) \geqslant 2\}$ with the reduced induced structure. Note that it is closed by upper semicontinuity of rank. We now define $\text{Sec}(C) = \pi_2(\pi_1^{-1}(Z))$. $\qquad \square$

Picard scheme/functor

The Picard group of a scheme X/k, denoted $\text{Pic}(X)$, is the collection of all line bundles on X up to isomorphism with the composition being the tensor product.

> **Question**
>
> If X/k is sufficiently nice, then is $\text{Pic}(X)$ the points of a k-scheme?

For references on this, look in FGA explained, chapter 9, or Néron Models, chapter 7.

We want to guess what the functor we should be representing is. A reasonable guess would be the following: Let X/k be a scheme and consider the function $T \mapsto \mathrm{Pic}(X \times_k T)$ from k-schemes to Gp. The problem with this functor is that it is not a Zariski sheaf and therefore cannot be representable.

For example, if $X = k$, then if $\mathscr{L}$ is any element of $\mathrm{Pic}_{k/k}(T) = \mathrm{Pic}(T)$, then we may cover T by open sets $\{U_i\}$ such that $\mathscr{L}|_{U_i} = \mathcal{O}_T|_{U_i}$. If $\mathrm{Pic}_{X/k}$ were now a Zariski sheaf, then the fact that $\mathscr{L}$ is trivial on an open cover means that $\mathscr{L} = 0$ in $\mathrm{Pic}_{k/k}(T)$ and so we would have that $\mathrm{Pic}_{k/k}$ is the 0 functor. Since this is not the case, then $\mathrm{Pic}_{X/k}$ is not a Zariski sheaf and therefore cannot be representable.

Another problem is given as follows: Fix T such that $\mathrm{Pic}(T) \neq 0$, then there is an action of $\mathrm{Pic}(T)$ on $\mathrm{Pic}(X \times_k T)$. For any $\mathscr{L} \in \mathrm{Pic}(T)$ and any $\mathscr{E} \in \mathrm{Pic}(X \times_k T)$, we let $\mathscr{L} \cdot \mathscr{E} = \mathscr{E} \otimes \pi_1^* \mathscr{L}$. This action is locally trivial. In other words, we may take an open cover $\{U_i\}$ of T such that $\mathscr{L}|_{U_i} = \mathcal{O}_T|_{U_i}$, then the action of $\mathrm{Pic}(T)$ on $\mathrm{Pic}(X \times_k T)$ restricts to an action $\mathrm{Pic}(U_i) \curvearrowright \mathrm{Pic}(X \times_k U_i)$. Now suppose that the action commutes with restriction, then the fact that the action of each $\mathrm{Pic}(U_i)$ is trivial for $\mathscr{L}$ means that the action of $\mathscr{L} \in \mathrm{Pic}(T)$ should be trivial, but it is not.

> **Remark**
>
> $\mathrm{Hom}_{\mathbf{Sch}/S}(-, Z)$ is a sheaf in the fppf (faithfully flat finite presentation) site:
> Given any flat, surjective, finite presented morphism $U \to X$, we get an equalizer diagram
>
> $$\mathrm{Hom}(X, Z) \to \mathrm{Hom}(U, Z) \rightrightarrows \mathrm{Hom}(U \times_X U, Z)$$
>
> That is to say that given a morphism from $U \to Z$ if both projections agree, then it glues to a morphism on X. In the case of the Zariski site, which is just the Zariski topology, if we have an open cover U_i, then taking $U = \bigsqcup_i U_i$, $U \times_X U = \bigsqcup_{i,j} U_i \cap U_j$ and so this is just the statement that the morphisms from the U_i agree on intersections.

This is called fppf descent.

> **Def:** If X/S is an S-scheme, we let $\mathrm{Pic}_{X/S}$ be the sheafification w.r.t. the fppf site of the naïve Picard presheaf we defined above.

> **Example**
>
> If $X = S = \mathrm{Spec}\, k$, then $\mathrm{Pic}_{X/S}$ is represented by $\mathrm{Spec}\, k$ since it is trivial (since any map of a k-scheme into $\mathrm{Spec}\, k$ is just the structure morphism).

> **Theorem 1.10.2: Existence of Pic scheme**
>
> Let $f : X \to S$ be projective, finitely presented, and flat, with integral geometric fibers, then $\mathrm{Pic}_{X/S}$ is representable.

Thm

If $f : X \to S$ has a section s and $\operatorname{Pic}_{X/S}$ is representable, then it also represents $\operatorname{Pic}^{rig}_{X/S,s}$.

Example

Let $X/\mathbb{R} = \{x^2 + y^2 + z^2 = 0\} \subseteq \mathbb{P}^2_{\mathbb{R}}$.
Q: What represents $\operatorname{Pic}_{X/\mathbb{R}}$?
Warm up: What is $\operatorname{Pic}_{\mathbb{P}^1/\mathbb{C}}$? A: $\bigsqcup_{k \in \mathbb{Z}} \operatorname{Spec} \mathbb{C}$ (one for each degree).

We must have
$$\operatorname{Pic}_{X/\mathbb{R}} \times \mathbb{C} = \operatorname{Pic}_{X \times \mathbb{C}/\mathbb{C}} = \operatorname{Pic}_{\mathbb{P}^1/\mathbb{C}}$$

so therefore
$$\operatorname{Pic}_{X/\mathbb{R}} = \bigsqcup_{k \in \mathbb{Z}} \operatorname{Spec} \mathbb{R}.$$

However, X has no line bundles of degree 1 so this is weird. [Daniel mentioned something about galois actions here that I did not write in great detail]

Quick and dirty detour into riemann surfaces

Let X be a compact Riemann surface. We recall that in a great level of generality $\operatorname{Pic}(X) = H^1(X, \mathcal{O}_X^*)$ by $\check{C}ech$ cohomology, the same proof works as in the algebraic case. (This is apparently true in very many different topologies on a scheme).
We recall the exponential exact sequence

$$0 \to \underline{2\pi i \mathbb{Z}} \to \mathcal{O}_X \xrightarrow{\exp} \mathcal{O}_X^* \to 0$$

which yields the LES in cohomology

$$
\begin{array}{ccccc}
0 \longrightarrow & H^0(\mathbb{Z}) \longrightarrow & H^0(\mathcal{O}_X) \longrightarrow & H^0(\mathcal{O}_X^*) & \\
& H^1(\mathbb{Z}) \xleftarrow{\ } & H^1(\mathcal{O}_X) \longrightarrow & H^1(\mathcal{O}_X^*) & \\
& H^2(\mathbb{Z}) \xleftarrow{\ } & 0 & &
\end{array}
$$

Where you can see that $H^i(\mathscr{F}) = 0$ for coherent $\mathscr{F}$ and $i > \dim X$ by Dolbeaut cohomology (or for projective manifolds by GAGA). We also recall that $H^i(\mathbb{Z}) = H^i(X, \mathbb{Z})$ as singular cohomology

agrees with sheaf cohomology of constant sheaves for sufficiently nice (locally contractible) spaces (see Voisin Hodge Theory 4.47 or Bredon Sheaf theory III.1.1). It is also (non-trivially) the case that the genus of X in the algebraic sense is the same an in the topological sense. Therefore the above sequence reduces to

$$\mathbb{Z}^{2g} \xrightarrow{\alpha} \mathbb{C}^g \longrightarrow \text{Pic}(X) \longrightarrow \mathbb{Z} \longrightarrow 0$$

where the map $\text{Pic}(X) \to \mathbb{Z}$ is actually the degree map we have come to know and love. Thus since $\mathbb{Z}$ is free, $\text{Pic}(X) \cong \mathbb{C}^g/\mathbb{Z}^{2g} \oplus \mathbb{Z}$ as abelian groups.

$$H^1(X, \mathcal{O}_X) = H^0(X, \omega_X)^{\vee} \supseteq H_1(X, \mathbb{Z})$$

where we get an the inclusion by mapping a cycle γ to integration over γ. The map is well defined by stokes theorem and injective.

> **Fact**
>
> $\mathbb{Z}^{2g} \subset \mathbb{C}^g$ is honestly a lattice so $H^0(X, \omega_X)^{\vee}/H_1(X, \mathbb{Z})$ is a complex torus T^g and, furthermore, is isomorphic to $(\text{Pic}^0_{X/\mathbb{C}})^{an}$ (if X is algebraic and we consider the associated compact Riemann surface X^{an} in the above).

> **Question**
>
> $X/\mathbb{C}$ a nice curve. What is $T_{[\mathscr{L}]} \text{Pic}_{X/\mathbb{C}}$?

Answer. We know it should be $H^1(\mathcal{O}_X)$ by the analytic description. Now we "prove" this algebraically. We first remark that by Hartshorne Ex II.2.8, $T_{[\mathscr{L}]} \text{Pic}_{X/\mathbb{C}}$ are just the maps of $\mathbb{C}[\epsilon]/\epsilon^2$ sending the closed point to $[\mathscr{L}]$.

Alternatively, we get the tangent space at a point $p \in Z(k)$ (which is a map from $\text{Spec } k \to Z$) as the fiber over p of the map

$$\text{Hom}(\text{Spec } k[\epsilon]/\epsilon^2, Z) \to \text{Hom}(\text{Spec } k, Z)$$

which sends $v \in T_p Z$ to p.

Question: Can we understand $\text{Pic}_{X/\mathbb{C}}(\mathbb{C}[\epsilon]/\epsilon^2)$?
Yes,
$$\text{Pic}_{X/\mathbb{C}}(\mathbb{C}[\epsilon]/\epsilon^2) = \text{Pic}(X_{\mathbb{C}[\epsilon]/\epsilon^2}) = H^1(X_{\mathbb{C}[\epsilon]/\epsilon^2}, \mathcal{O}^*_{\mathbb{C}[\epsilon]/\epsilon^2}) = H^1(X, \mathcal{O}^*_{\mathbb{C}[\epsilon]/\epsilon^2})$$

We get a SES (the fake exponential exact sequence)

$$a + b\epsilon \longmapsto a$$

$$0 \longrightarrow \mathcal{O}_X \longrightarrow \mathcal{O}^*_{X_{\mathbb{C}[\epsilon]/\epsilon^2}} \longrightarrow \mathcal{O}^*_X \longrightarrow 0$$

$$f \longmapsto 1 + f\epsilon$$

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yielding the following exact sequence

$$0 \to H^1(\mathcal{O}_X) \to \mathrm{Pic}(X_{\mathbb{C}[\epsilon]/\epsilon^2}) \to \mathrm{Pic}(X) \to 0$$

$\square$

1.11   Lecture 11 - Abel-Jacobi map

If X is a nice curve over k, with $X(k) \neq \varnothing$, then $\mathrm{Pic}_{X/k} = \mathbb{Z} \times \mathrm{Pic}^0_{X/k}$ where $\mathrm{Pic}^0_{X/k}$ is the connected component of $\mathcal{O}_X$.

More canonically, there is a short exact sequence,

$$0 \to \mathrm{Pic}^0_{X/k} \to \mathrm{Pic}_{X/k} \xrightarrow{\deg} \mathbb{Z} \to 0$$

Where we associate $\mathbb{Z}$ with

$$\mathbb{Z} = \bigsqcup_{n \in \mathbb{Z}} \mathrm{Spec}\ k$$

Whence the above SES is a SES of algebraic groups. Moreover, $\mathrm{Hom}(T, \mathrm{Pic}_{X/k})$ is all rigidified line bundles on $X \times_k T$ up to isomorphism. That is to say there is a section $T \to X \times_k T$ since $X(k) \neq \varnothing$.

Given $\mathscr{L} \in \mathrm{Pic}(X \times_k T)$, we get a map $T \to \mathrm{Pic}_{X/k}$ by $\mathscr{L} \otimes (\pi^* s^* \mathscr{L})^{\vee}$.

Def: $\mathrm{Pic}^d_{X/k} = \deg^{-1}(d)$.

Construction: Let X be a nice curve, then we want to find a map $AJ^1 : X \to \mathrm{Pic}^1_{X/k}$ corresponding set theoretically to the map $p \mapsto \mathcal{O}(p)$. A map $X \to \mathrm{Pic}^1_{X/k}$ is a line bundle on $X \times_k X$ by the functorial definition of Pic. We choose the line bundle $\mathscr{L} = \mathcal{O}_{X \times_k X}(\Delta) = \mathscr{I}_{\Delta}^{\vee}$. For any slice $X \times \{p\}$, we have $\mathscr{L}|_{X \times \{p\}} = \mathscr{I}_p^{\vee} = O(p)$.

Hard exercise: $dAJ^1 \to T_p X \to T_{[\mathcal{O}(p)]} \mathrm{Pic}^1_{X/k}$. We know that the latter is $H^1(X, \mathcal{O}_X)$ which by Serre duality means we have a map $(dAJ^1)^{\vee} : H^0(X, \omega_X) \to (T_p X)^{\vee}$ which maps $\eta \mapsto \eta_p$ where η is a differential, so η_p is a derivation at p, i.e. an element in $(T_p X)^{\vee}$.

Since we know what dAJ^1 is, then we obtain AJ^1 by integrating. Fix $p \in X(\mathbb{C})$, then we define $AJ_p : X \to \mathrm{Pic}^0_{X/k}$ by $AJ^1 \otimes \mathcal{O}(-p)$, then this sends p to $\mathcal{O}_X$.

Claim

$$AJ_p(q) = \left[\eta \mapsto \int_p^q \eta \right].$$

Proof. It is well-defined, i.e. it is independent of the curve from p to q. This follows from the fact that in the complex construction of $\mathrm{Pic}_{X/\mathbb{C}}$, we mod out by the image of $H^1(X, \mathbb{Z})$, i.e. integrals along loops, so two curves give the same value. Then $dAJ_p = dAJ^1$ by FTOC. It follows that they are equal since they give the same value at $q = p$. $\square$

AJ^1 is a closed immersion for $g \geqslant 1$ since then ω_X is globally generated. Since the cotangent space, $(T_pX)^\vee$ is just derivations at p, then being globally generated means that $H^0(X, \omega_X) \to (T_pX)^\vee$ is surjective and since this is the dual $(dAJ^1)^\vee$, then dAJ^1 is injective. Therefore AJ^1 separates tangent vectors. To show that it is a closed immersion, it therefore suffices to show that it is injective on points. Suppose that $\mathcal{O}(p) = \mathcal{O}(q)$, then the genus would be 0. Therefore AJ^1 is a closed immersion.

> **Remark**
>
> The map AJ^1 exists even if $X(k) = \varnothing$.

We now want to construct a map AJ^d which should map from the space of degree d effective divisors over X to the degree d component, $\mathrm{Pic}^d_{X/k}$.

From AJ^1, we can take $(AJ^1)^d : X^d \to (\mathrm{Pic}^1_{X/k})^d$, then we have a map $\Sigma : (\mathrm{Pic}^1_{X/k})^d \to \mathrm{Pic}^d_{X/k}$ given by taking the tensor product of the line bundles. The map Σ is commutative, i.e. invariant under the natural S_d action on X^d given by permuting the factors. It follows that if X^d/S_d exists, then the map $X^d \to \mathrm{Pic}^d_{X/k}$ given by composing $\Sigma \circ (AJ^1)^d$ factors through X^d/S_d.

> **Fact**
>
> The quotient $\mathrm{Sym}^d X = X^d/S_d$ exists in $\mathbf{Sch}_k$.

In general, the quotient of a sufficiently nice scheme by a finite group will always exist.

> **Example**
>
> $(\mathrm{Spec}\, R)/G \cong \mathrm{Spec}\, R^G$ where R^G is the ring of invariants under the action of G.
> $\mathbb{A}^d/S_d = \mathrm{Spec}\, k[x_1, \cdots, x_d]^{S_d} = \mathrm{Spec}\, k[\sigma_1, \cdots, \sigma_n]$ where $\sigma_1, \cdots, \sigma_d$ are the elementary symmetric polynomials. Therefore $\mathbb{A}^d/S_d$ is also a copy of $\mathbb{A}^d$ but the quotient map $\mathbb{A}^d \to \mathbb{A}^d/S_d$ is $d!$ to 1 and given by interpreting a point x in A^d as the roots of a polynomial and then sending it to the point $(\sigma_1(x), \sigma_2(x), \cdots \sigma_d(x))$.

> **Def:** The map AJ^d is the quotient map induced by $\Sigma \circ (AJ^1)^d$ from $\mathrm{Sym}^d X \to \mathrm{Pic}^d_{X/k}$.

Note that the points of $\mathrm{Sym}^d X$ are collections of d points of X without order, so their sum determines a degree d effective divisor. All degree d effective divisors are sums of d points, so the points of Sym^d are exactly the effective divisors over X.

We now look at the Hilbert scheme. The Hilbert functor over X is given by,

$$\mathrm{Hilb}^d(X)(T) = \left\{ \begin{matrix} Z \subseteq X \times T \text{ flat } /T \text{ s.t.} \\ Z_{\overline{t}} \text{ has length } d \text{ for all } \overline{t} \in T(\overline{k}) \end{matrix} \right\}$$

> **Grothendieck**
>
> If X is projective, then Hilb^d is representable.

> **FGA explained**
>
> X is a nice curve, then $\mathrm{Hilb}^d(X)$ is smooth projective and isomorphic to $\mathrm{Sym}^d(X)$.

It follows that we can understand AJ^d as a map from $\mathrm{Hilb}^d(X) \to \mathrm{Pic}^d_{X/k}$. To understand what this is given by, we have a universal object $Z_{univ} \subseteq X \times \mathrm{Hilb}^d(X)$ which is the closed subscheme, flat over $\mathrm{Hilb}^d(X)$ corresponding to the identity map from $\mathrm{Hilb}^d(X) \to \mathrm{Hilb}^d(X)$. Then we know that $Z_{\bar{t}}$ has length d for all geometric points $\bar{t} \in \mathrm{Hilb}^d(X)(\bar{k})$. That is to say that $Z_{\bar{t}}$ parameterizes the collections of d geometric points in X.

> **Prop**
>
> $(AJ^d)^{-1}([\mathscr{L}]) = \mathbb{P}H^0(X, \mathscr{L})$.

Proof. Set-theoretically we have that $(AJ^d)^{-1}([\mathscr{L}])$ is the collection of all effective divisors linearly equivalent to $\mathscr{L}$, i.e. $|\mathscr{L}| = \mathbb{P}H^0(X, \mathscr{L})$. $\square$

> **Prop**
>
> $\mathrm{Sym}^d(X)$ is a projective space bundle over $\mathrm{Pic}^d_{X/k}$ for $d > 2g - 2$ and $X(k) \neq \varnothing$.

Proof. $h^1(\mathscr{L})$ vanishes in degree $> 2g - 2$, so $h^0(\mathscr{L}) = d + 1 - g$ and therefore the fibers at every point are exactly $\mathbb{P}^{d-g}$. Note that we have not defined a projective space bundle. $\square$

> **Remark**
>
> If $X(k) \neq \varnothing$, then AJ^d is a Zariski-locally trivial $\mathbb{P}^{d-g}$-bundle for $d > 2g - 2$.

1.12 Lecture 12 - Stronger Vanishing Results and Zeta Functions

Recall the Abel Jacobi map $AJ_d : \mathrm{Sym}^d C \to \mathrm{Pic}^d_{C/k}$ and that $AJ_d^{-1}([\mathscr{L}]) = \mathbb{P}H^0(C, \mathscr{L})$.

> **Corollary**
>
> For $d > 2g - 2, C(k) \neq 0, \mathrm{Sym}^d C$ is a $\mathbb{P}^{d-2}$-bundle over $\mathrm{Pic}^d_{C/k}$. (We might come back to this when we know the proper definition of a projective space bundle).

In fact this theorem implies the case where $k \neq \bar{k}$ by base changing.

1. *Proof.* Consider $W_d = \{\mathscr{L} \in \operatorname{Pic}^d_{C/k} \,|\, h^0(\mathscr{L}) > 0\}$. W_d is closed by upper-semicontinuity of cohomology. Alternatively W_d can be seen to be the image of $\operatorname{Sym}^d C$ under C as

$$(AJ^d)^{-1}(\mathscr{L}) = \mathbb{P}H^0(C, \mathscr{L}) \neq 0 \iff \mathscr{L} \text{ has a global section}$$

Thus W_d closed and irreducible. Therefore to show that W_d^c is generic, it suffices to show that $W_d \neq \operatorname{Pic}^d_{C/k}$.

We have that $\dim W_d \leqslant \dim \operatorname{Sym}^d C = d$ but $\dim \operatorname{Pic}^d_{C/k} = \dim T_{\mathscr{L}} \operatorname{Pic}^d_{C/k} = h^1(\mathcal{O}_C) = g$ (from lecture 11) as $\operatorname{Pic}^d_{C/k}$ is smooth.

As $\operatorname{Pic}^d_{C/k}$ is an algebraic group this is always true in characteristic 0. If $\operatorname{char} k > 0$ then in fact (due to some deformation theory facts and functor of points nonsense) this is also true since $H^2(C, \mathcal{O}_C) = 0$. Thus by dimension considerations $W_d \subsetneq \operatorname{Pic}^d_{C/k}$ is a proper closed subset and so we win. $\square$

2. *Proof.* It is equivalent to show that $\operatorname{Sym}^d C \to W_d$ is injective on an open subset as $(AJ^d)^{-1}([\mathscr{L}]) = \mathbb{P}H^0(\mathscr{L})$ is finite iff it is a single point iff $h^0(\mathscr{L}) = 1$. But (by Hartshorne Ex II.3.22(e)) $\dim$ general fiber $= \dim \operatorname{Sym}^d C - \dim \dim W_d = d - \dim W_d$ it suffices to show that $\dim W_d \geqslant d$ (and therefore exactly d).

   (a) If $d = g$ then R.R. says that $\chi(\mathscr{L}) = 1$ so $h^0(\mathscr{L}) > 0$ for all $\mathscr{L}$. Therefore $W_g = \operatorname{Pic}^g_{C/k}$ so we win.

   (b) It suffices to prove that $\dim W_d > \dim W_{d-1}$ for $1 \leqslant d \leqslant g$, for then $\dim W_d \geqslant d + \dim W_0 = d$. As notes above W_d is irreducible as it is the image of the irreducible spaces $\operatorname{Sym}^d C$ under a continuous map. Now choose $p \in C(k)$. Let $\iota_p : \operatorname{Pic}^{d-1}_{C/k} \to \operatorname{Pic}^d_{C/k}$ be the map induced by twisting with p. Then ι_p is an isomorphism (with inverse given by twisting down by p). In particular ι_p maps W_{d-1} into W_d as effective line bundles remain so after being twisted by a point. Since ι_p is injective, then, $\dim W_d \geqslant \dim W_{d-1}$ with equality iff $W_d = \iota_p(W_{d-1})$ as $\iota_p(W_{d-1})$ is a closed subset of the irreducible space W_d.
   But now suppose that ι_p is an iso for some d. Then ι_x will be an iso for all $x \in X(k), i > d$. It suffices to check surjectivity; for any $\mathscr{L} \in W_{i+1}$, we have $\mathscr{L} = \mathscr{L}' \otimes \mathcal{O}(p)$ (since $\mathscr{L}$ is effective). Then $\mathscr{L}' \in W_i$, so $\mathscr{L}' = \mathscr{L}'' \otimes \mathcal{O}(x)$, then $\mathscr{L} = (\mathscr{L}'' \otimes \mathcal{O}(p)) \otimes \mathcal{O}(x)$, so ι_x is surjective.
   But we know that $\dim W_g = g$ so either equality holds, and then $\dim W_d = \dim W_g = g \geqslant d$ or equality does not hold for and $i \leqslant d$ and we win.

□

For an example look up "generic vanishing theorem."

Example

$C = \operatorname{Sym}^1 C \to \operatorname{Pic}^1_{C/k}$ is a closed immersion for $g > 0$.

$C = \operatorname{Sym}^2 C \to \operatorname{Pic}^2_{C/k}$ is a closed immersion for $g \geqslant 2$ and non-hyperelliptic C. Injectivity is clear as existence of a degree 2 effective divisor with more than one global section is equivalent to being hyperelliptic.

If C is hyperelliptic then there is a unique 1 dimensional fiber so the map is birational onto its image.

$\operatorname{Sym}^{g-1} C \to \operatorname{Pic}^{g-1}_{C/k}, W_{g-1}$ is a divisor called Θ. There is lots of theory about this guy. Daniel proceeded to talk about Brill-Noether theory in generality for another few minutes.

Zeta Functions

Def: Let $X/\mathbb{F}_q$ a variety. Set

$$Z_X(t) = \exp\left(\sum_{n\geqslant 1} \frac{\#X(\mathbb{F}_{q^n})t^n}{n}\right)$$

But why should we care about this function?

Motivation

$\frac{\partial}{\partial t}\log Z_X(t) \sum_{n\geqslant 1} \#X(\mathbb{F}_{q^n})t^{n-1}$ is the normal generating functions for $\#X(\mathbb{F}_{q^n})$.

This lets us bring in ideas from analytic number theory:

Slogan

Growth of Taylor series coeffs of $\frac{\partial}{\partial z}\log f(z)$ is controlled by the zeros and poles of $f(z)$.

Let us justify this idea, at least in the only case that will matter to us: rational functions.

Example

If $f(t) = \frac{\prod_i (1 - a_i t)}{\prod_j (1 - b_j t)}$ then

$$
\begin{aligned}
\frac{\partial}{\partial t} \log f(t) &= \sum_i \frac{-a_i}{1 - a_i t} - \sum_j \frac{-b_j}{1 - b_j t} \\
&= -\sum_i a_i \sum_{n \geqslant 0} (a_i t)^n - \sum_j b_j \sum_{n \geqslant 0} (b_j t)^n \\
&= \sum_{n \geqslant 0} \left(\sum_j b_j^{n+1} - \sum_i a_i^{n+1} \right)
\end{aligned}
$$

We now state the Weil conjectures.

Weil conjectures {Now theorems :)}

1. (Dwark) $Z_X(t)$ is rational.

2. (Grothendieck) If X is smooth and proper then Z_X satisfies a functional equation (not to be stated here).

3. Riemann hypothesis: All roots and poles α of Z_X in $\bar{\mathbb{Q}}$ and for any $\bar{Q} \hookrightarrow \mathbb{C} |\alpha| = q^{-j/2}$ for j depending only on α. (Such an α is called a q-Weil number.)

4. Set $p_j(t) = \prod_{|\alpha_i| = q^{-j/2}} (1 - \alpha_i^{-1} t)$. If X is smooth and proper, then

$$
Z_X(t) = \prod_{j=0}^{2 \dim X} p_j(t)^{(-1)^{j+1}}
$$

and $\deg p_j(t) = h_{\mathrm{sing}}^j(X(\mathbb{C}), \mathbb{Q})$ if X "lifts to a complex model".

3 & 4 are due to Deligne. We prove 1) today for curves, 2 might be a nice presentation topic, we will prove 3& 4 when we know about surfaces and intersection theory.

1. $Z_{\operatorname{Spec} \mathbb{F}_q}(t) = \exp\left(\sum_{n \geqslant 0} \frac{t^n}{n}\right) = \exp(-\log(1-t)) = \frac{1}{1-t}$ as $\operatorname{Spec} \mathbb{F}_q(K)$ has a single point for any extension $K/\mathbb{F}_q$.

2. $Z_{\mathbb{A}^1}(t) = \exp\left(\sum_{n \geqslant 0} \frac{q^n t^n}{n}\right) = \frac{1}{1-qt}$ by counting polynomials.

3. $Z_{\mathbb{A}^1}(t) = \frac{1}{1-q^n t}$ in the same way.

4. $Z_{\mathbb{P}^1}(t) = Z_{\operatorname{Spec} \mathbb{F}_q}(t) Z_{\mathbb{A}^1}(t) = \frac{1}{1-qt}\frac{1}{1-t}$ as $\mathbb{P}^1$ is a disjoint union of a closed point and a copy of $\mathbb{A}^1$.

5. $Z_{\mathbb{P}^n}(t) = \prod_{j=0}^{n} Z_{\mathbb{A}^j}(t) = \prod_{j=0}^{n} \frac{1}{1-q^j t}$.

6. $Z_{\mathbb{F}_{q^n}}(t) = \frac{1}{1-t^k}$ as there is a map $\mathbb{F}_{q^n} \to \mathbb{F}_{q^m}$ iff $n|m$.

If $X = Y \sqcup W$ with W closed then $Z_X = Z_Y Z_W$ as $\#X(K) = \#Y(K) + \#W(K)$ and then the exponential turns the addition to multiplication.

Claim:

$$Z_X(t) = \prod_{x \in X^{\mathrm{cl}}} Z_x(t) = 1 + \sum_{n \geqslant 1} \# \operatorname{Sym}^n(X)(\mathbb{F}_q) t^n.$$

Proof. Set-theoretically, $X = \bigsqcup_{x \in X^{\mathrm{cl}}} \{x\}$ and for each $\mathbb{F}_{q^n}$ there are only finitely many closed points with F_{q^n} points. It follows that $\sum \frac{\#X(\mathbb{F}_{q^n}) t^n}{n}$ can be written as a sum over all the closed points of X, therefore,

$$Z_X(t) = \exp\left(\sum_{n \geqslant 1} \frac{\#X(\mathbb{F}_{q^n}) t^n}{n}\right)$$

$$= \exp\left(\sum_{x \in X^{\mathrm{cl}}} \sum_{n \geqslant 1} \frac{\#x(\mathbb{F}_{q^n}) t^n}{n}\right)$$

$$= \prod_{x \in X^{\mathrm{cl}}} \frac{1}{1 - t^{[k(x):\mathbb{F}_q]}}$$

$$= \prod_{x \in X^{\mathrm{cl}}} \left(1 + t^{[k(x):\mathbb{F}_q]} + t^{2[k(x):\mathbb{F}_q]} + \cdots\right)$$

It follows that the coefficient on t^n in the final expansion will be the number of collections of points whose degrees add up to n. This is the number of effective divisors of degree n on X. This is exactly the $\mathbb{F}_q$ points of $\operatorname{Sym}^n X$. It follows that,

$$Z_X(t) = 1 + \sum_{n \geqslant 1} \# \operatorname{Sym}^n(X)(\mathbb{F}_q) t^n$$

$\square$

In the following theorem we assume that $X(\mathbb{F}_q) \neq \varnothing$, but Daniel claims the reduction to that case is not that hard.

Thm

Let X be a nice curve over $\mathbb{F}_q$ with a rational point. Then $Z_X(t)$ is rational.

Proof.

$$
\begin{aligned}
Z_X(t) &= \sum_{n=0}^{\infty} \# \operatorname{Sym}^n X(\mathbb{F}_q) t^n \\
&= \sum_{n=0}^{2g-2} \# \operatorname{Sym}^n X(\mathbb{F}_q) t^n + \sum_{n>2g-2} \# \operatorname{Sym}^n X(\mathbb{F}_q) t^n \\
&= p(t) + \sum_{n>2g-2} \# \mathbb{P}^{n-g}(\mathbb{F}_q) \# \operatorname{Pic}_{X/k}^n(\mathbb{F}_q) t^n && \operatorname{Sym}^n X \text{ is a } \mathbb{P}^{n-g}\text{-bundle} \\
&= p(t) + \# \operatorname{Pic}_{X/k}^0(\mathbb{F}_q) \sum_{n>2g-2} \# \mathbb{P}^{n-g}(\mathbb{F}_q) t^n && \operatorname{Pic}^n \cong \operatorname{Pic}^0 \text{ if } X \text{ has a } \mathbb{F}_q \text{ point}
\end{aligned}
$$

set $\widetilde{p}(t) = \sum_{n>2g-2} \# \mathbb{P}^{n-g}(\mathbb{F}_q) t^n$.

Exercise

$(1-t)(1-qt)\widetilde{p}(t)$ can be seen to be polynomial using the given formulae.

$\square$

Thm

$Z_X(t) = \frac{p(t)}{(1-t)(1-qt)}$ for some $p(t) \in \mathbb{Z}[t]$ of degree $2g$.

2 Surfaces

2.1 Lecture 12 Cont. - Intro to surfaces

Def: A ruled surface is a smooth projective variety S of dimension 2 with a rational map $S \dashrightarrow C$ with C a nice curve s.t. the generic fiber is genus 0.

Example

If C is a curve and $\mathscr{E}$ is a rank 2 vector bundle on C, then $\mathbb{P}\mathscr{E} = \mathrm{Proj}_C \mathrm{Sym}\, \mathscr{E}$ is a ruled surface.

Thm

Let $k = \bar{k}$ be an algebraically closed field and $S \dashrightarrow C$ be a ruled surface, then S is birational to $C \times \mathbb{P}^1$.

Example

$\mathbb{P}^2$ and $\mathbb{P}^1 \times \mathbb{P}^1$ both contain a copy of $\mathbb{A}^2$ as a dense open subset, then this yields a birational map. If $g(C) > 0$ or $g(D) > 0$, then $C \times D$ is not birational to $\mathbb{P}^2$.