

LEARNING MATHEMATICS

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ABSTRACT. To record many interesting things I learned in case I forgot. To keep myself busy ...

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1. JUNE 2021

Something I would like to get done this month:

- (1) Learn how much 2-dimensional gauge theory of finite group G tells us about representation of G . This is firstly motivated by Frobenius formula that Nam showed few months ago, interpreting number $\text{Hom}(\pi_1(\Sigma), G)$ as sum over irreducible representations of G where Σ is (closed, compact?) Riemann surface. I then found a "topological" proof using topological field theory <https://math.berkeley.edu/~qchu/TQFT.pdf> and <https://upennig.weebly.com/uploads/7/4/0/3/74037187/2d-tqft.pdf> and <https://www.math.ru.nl/~mueger/TQFT/FQ.pdf>. In topological field theory language, there is a functor Z from category of 2-cobordisms to category of vector spaces. And in our situation, it sends a manifold M to $\text{Map}(\text{Bun}_G(M), \mathbb{C})$ where $\text{Bun}_G(M)$ is the groupoid of principal G -bundles over M , which can then be identified with $\text{Hom}(\pi_1(M), G)/G$ quotient by conjugation. Roughly in the proof of Frobenius using TQFT, somehow one can cut and glue M to get the desired formula. The further question is how much $Z(M)$ tells us about representation of G , when one varies the manifold M .

More to read from: "Bartlett Categorical aspects of topological quantum field theories" (arxiv); <https://arxiv.org/abs/1705.05734v1> and Kock "Frobenius algebra and 2D topological quantum field theory" <https://www.mat.uab.cat/~kock/TQFT/FS.pdf> this has book version; https://golem.ph.utexas.edu/category/2008/06/teleman_on_topological_constru.html.

One can also ask why we choose $\text{Bun}_G(M)$ as target for our cobordism functor and expect it to tell something about representations of G . I think this is because one can interpret representations of G as bundles of some sort (see wikipedia of "induced representations").

- (2) For my thesis, I am trying to understand certain self-adjoint operator in Langlands' computation of volume of fundamental domain $G(\mathbb{Z}) \backslash G(\mathbb{R})$. I don't understand this operator and all and how it is linked to Eisenstein series.
- (3) Gauge theory in representation theory, geometric representation theory: <https://people.maths.ox.ac.uk/tillmann/ASPECTSbenzvi.pdf> and <https://web.ma.utexas.edu/users/benzvi/GRASP/lectures/NWTFT/nwtft.pdf>, also <https://ncatlab.org/nlab/files/BenZviGeometric.pdf>.

Daily learning

02/06/2021 Today I learnt roughly what is a "rigid symmetric monoidal category" and how category of n -dimensional cobordisms $n\text{Cob}$ is one, following <https://arxiv.org/abs/q-alg/9503002>. To explain roughly, "monoidal" means the category has a product \otimes operation, "symmetric" means we have a map $a \otimes b \rightarrow b \otimes a$, "rigid" means every object x has a dual object x^* . The main point to take away is that one can visualise the relations/commutative diagrams in the category via cobordisms, which make it easier to remember. For example, relations between counit and unit maps is seen as straightening the curve S (see p. 5). For more examples of this, see p. 21 of <https://arxiv.org/pdf/math/0512103v1.pdf>.

Another note, on p. 4, it mentions that relations between morphisms in $n\text{Cob}$ can be understood using Morse theory, where we can stratify a bordism N (i.e. a n -manifold N) by giving a Morse function on N to pick up critical points (something relates to handle decomposition in Morse theory). *I see some familiar words like "stratification" and "Morse function" when reading about symplectic geometry, would like to learn more about this at some point*

06/06/2021 I am trying to understand first few sections of <https://ncatlab.org/nlab/files/BenZviGeometricFunction.pdf> (with the hope of getting to know more about <https://ncatlab.org/nlab/show/geometric+infinity-function+theory>). Here is what I have so far:

Given two sets X, Y with a G -action on these two and a G -equivariant map $\phi : X \rightarrow Y$. We can pullback to give a map ϕ^* of G -equivariant complex-valued functions $Fun_G(Y)$ on Y to that $Fun_G(X)$ on X . Pushforward $\phi_* : Fun_G(X) \rightarrow Fun_G(Y)$ is a bit more tricky. Firstly, it is better to view X, Y as groupoids, then

$$\phi^* : f \in Fun_G(X) \mapsto \left(y \mapsto \sum_{x \in |\phi^{-1}(y)|} \frac{f(x)}{\#Aut_{\phi^{-1}(y)}(x)} \right).$$

Here $|X|$ refers to isomorphic classes of objects in groupoid X . Note $\phi^{-1}(y)$ is also a groupoid with natural automorphisms. *How to come up with this pushforward? What condition should a good pushforward satisfy? Usually pushforward is very nontrivial to realise, unlike pullback. Is there a general rule to come up with something like this?*

The two are adjoint in following sense: One can define inner product on $Fun_G(X)$ by $(f, g) = \sum_{x \in X} \frac{f(x)\overline{g(x)}}{\#Aut(x)}$ then ϕ^* and ϕ_* are adjoint with respect to this inner product. *What is the relation of this with adjointness as functors? Do we have something like Frobenius reciprocity in representation theory, where adjointness in inner product is the same as adjointness as adjoint functors due to semisimplicity of representations? What constitutes a good inner product?*

Perhaps this would help: https://golem.ph.utexas.edu/category/2007/03/canonical_measures_on_configur_1.html or https://golem.ph.utexas.edu/category/2011/09/universal_measures.html or https://golem.ph.utexas.edu/category/2008/07/news_on_measures_on_groupoids.html.

06/06/2021 Regarding item 1, I managed to figure out how to describe $Z_G(\mathbb{O}) : Z_G(pt) \rightarrow Z_G(S^1)$ where $N = \mathbb{O}$ is a half-sphere with boundaries pt (a point) and S^1 . To do this, start with the more geometric correspondence

$$Bun_G(pt) \longleftarrow Bun_G(N) \longrightarrow Bun_G(S^1)$$

obtained by restricting G -bundles to corresponding boundaries (i.e. pull back). This gives us morphism of groupoids

$$pt \xleftarrow{p} pt \xrightarrow{q} G/G.$$

Indeed, N is just a disk so $Bun_G(N) = Bun_G(pt) = pt$, a point with a G action on it. We know $\pi_1(S^1) = \mathbb{Z}$ so $Bun_G(S^1) = \text{Hom}(\mathbb{Z}, G)/G = G/G$, groupoid with elements in G and automorphisms are conjugations by G . Then p is the identity map, q sends to the identity 1 in G (as we have group hom $\pi_1(S^1) \rightarrow 1 = \pi_1(N)$ inducing $Bun_G(N) \rightarrow Bun_G(S^1)$).

By definition, $Z_G(N) = \text{Hom}_{\mathbb{C}}(Bun_G(N), \mathbb{C})$ so this gives $Z_G(N) := q_* \circ p^* : Z_G(pt) \rightarrow Z_G(S^1)$. Note $Z_G(pt) = \mathbb{C}$, $Z_G(S^1) = \text{Hom}(G/G, \mathbb{C}) = \mathbb{C}[G]^G$ so from pushforward described in 06/06/2021 for groupoids, we find $Z_G(N)$ sends $\lambda \in \mathbb{C}$ to $g \mapsto \lambda \delta_{g,1}/|G|$ in $\mathbb{C}[G]^G$.

A remark: Bun_G is a geometric object, but doing computation it seems to be easier to deal with $\text{Hom}(\pi_1(\cdot), G)/G$.

16/06/2021 (Continued from 06/06/2021) It seems the idea of TQFT has been applied to study character varieties $\text{Hom}(\pi_1(\Sigma), G)$ by Angel Gonzalez Prieto in <https://arxiv.org/abs/1812.11575> (his PhD thesis) or <https://arxiv.org/abs/1810.09714> (a relevant paper), <http://www.mat.ucm.es/~joseag12/investigacion/documentos/SeminarioTesis.pdf> (PhD presentation), <http://www.mat.ucm.es/~joseag12/investigacion/documentos/TFMJAngelGonzalez.pdf> (his master thesis),... It seems there are many things unexplored here.

17/06/2021 (Continued from 06/06) Understand most of the computations in <https://math.berkeley.edu/~qchu/TQFT.pdf> and <https://upennig.weebly.com/uploads/7/4/0/3/74037187/2d-tqft.pdf>.

pdf. These two notes present a "topological" proof of

$$(1) \quad \frac{\# \text{Hom}(\pi_1(\Gamma_g), G)}{|G|} = \frac{1}{|G|^{\chi(\Gamma_g)}} \sum_V (\dim V)^{\chi(\Gamma_g)}.$$

Here G is a finite group, Γ_g is a closed connected orientable surface of genus g , $\chi(\Gamma_g)$ is Euler characteristic of Γ_g , the sum is over all complex irreducible representations of G .

Here are the main computations:

- $Z_G(\mathbb{O}) : Z_G(pt) \rightarrow Z_G(S^1)$. We did this on 06/06/2021. This map sends $\lambda \in \mathbb{C} = Z_G(pt)$ to $\lambda \delta_{g,1}/|G|$.
- $Z_G(\mathbb{O}) : Z_G(S^1) \rightarrow Z_G(pt)$ sends $f \in Z_G(S^1) = \mathbb{C}[G]^G$ to $f(1)$.
- $Z_G(\text{figure 8}) : Z(S^1) \otimes Z(S^1) \rightarrow Z(S^1)$ sends $f \otimes g \in \mathbb{C}[G]^G \otimes \mathbb{C}[G]^G$ to the convolution product $f * g \dots$
- $Z_G(\text{figure 8}) : Z(S^1) \rightarrow Z(S^1) \otimes Z(S^1)$
- $Z_G(M_1 \sqcup_{M'} M_2) = Z(M_2) \circ Z(M_1)$ for surfaces M_1, M_2 with common boundary M' .
- As $Z_G(M) = \text{Map}(\text{Bun}_G(M), \mathbb{C})$ so if M is homotopic to M' then $Z_G(M) = Z_G(M')$.

From this, to compute $Z_G(\Gamma_g)$, it suffices to chop Γ_g into pieces and compute each piece, then compose everything together. On the other hand, $Z_G(\Gamma_g) = \text{Hom}(\pi_1(\Gamma_g), G)/G$ so we can obtain (1).

We also have general formula when G is a Lie group (due to Witten 1991) or a quantum group (Rouchet-Szenes 2000) (I learnt this info from reading the slide https://www2.ist.ac.at/fileadmin/user_upload/group_pages/hausel/Aarhus07.pdf).

22/06/2021 (Things I would like to understand in a far way future) In this paper <https://arxiv.org/pdf/1511.06271.pdf> of Michael Groechenig claimed to give a generalisation to Weil's description of correspondence between groupoid of vector bundles on algebraic curve X (defined over algebraically closed field) and groupoid of the double quotient.

My impression of adeles is that it seems to be the right notion to study analysis on moduli space of bundles?

22/06/2021 (Things I would like to understand in a far way future) There seems to be some mysterious applications of p -adic integrations (and furthermore, motivic integrations) to various sorts of problems: equal Betti numbers of birational Calabi-Yau n folds <https://www.math.uni-bonn.de/people/huybrech/Magni.pdf>, Fundamental Lemma in Langlands program <https://arxiv.org/abs/1810.06739>, Topological Mirror Symmetry Conjecture by HauselThaddeus for smooth moduli spaces of Higgs bundles <https://arxiv.org/abs/1707.06417v3>.

22/06/2021 I attend lectures of Geordie Williamson about Spectra in representation theory and of Anna Romanov about Whittaker categories. I just want to write down what I understand (no matter how vague and imprecise it can be).

- (a) In Geordie's talk: There are three ways to define cohomology $H^i(X, \mathbb{Z})$, one is via map $\Delta^n \rightarrow X$ ("maps in to X "), second is via Eilenberg-MacLane space $K(\mathbb{Z}, i)$ as $H^i(X, \mathbb{Z}) = [X, K(\mathbb{Z}, i)]$ (maps out of X), third is via constant sheaf $\underline{\mathbb{Z}}_X$, i.e. $H^i(X, \mathbb{Z}) = H^i(R\Gamma(X, \underline{\mathbb{Z}}_X))$ ("on X ").

Geordie said that Grothendieck-Quillen's dream is that every generalised cohomology theory can be described as in the third way (i.e. "on X ", without replying on $\Delta^n X$ or $K(\mathbb{Z}, i)$). He said Lurie has achieved this dream for K -theory. Then he goes to define spectra, which should be seen as an analogue of \mathbb{Z} . Then he mentioned that there is on going research trying to generalised Geometric Satake over spectra KU (instead of over

\mathbb{Z}) which gives the quantum group version on the RHS (instead of just representation of Langlands dual group).

What is spectra, KU rigorously? Do we have a visual(?) easier(?) explanation on why KU is an analogue of \mathbb{Z} ? Why do we expect quantum groups on the RHS of geometric Satake, or is there some sort of deformation from \mathbb{Z} to KU that explains this?

Some notes about spectra (other than Lurie ...): by Rok Gregoric <https://web.ma.utexas.edu/users/gregoric/Spectra%20Are%20Your%20Friends.pdf>, his summary of higher algebra <https://web.ma.utexas.edu/users/gregoric/Appendix.pdf>. I found a table giving the analogy between Lurie's theory and classical theory in <https://sites.duke.edu/scshgaf/files/2018/05/Pandit-Imperial.pdf>.

Actually, there is an even elementary question I don't know how to answer, as I don't know anything about K -theory: Why K -theory is considered to be an upgraded version of cohomology theory? (or something along this question...)

- (b) In Anna's talk: There is a lot of technical details going on so I didn't get much out of it. But here it is: A Whittaker module is the induced representation from the upper Borel \mathfrak{n} to \mathfrak{g} from some character of \mathfrak{n} . The motivation for Whittaker model is that one has an "explicit" (?) description of representation as functions on some space. The motivation for Whittaker module (I think explained by Masoud in the talk but I may need to hear it again) is that Whittaker module of $GL_n(\mathbb{F}_q)$ gives almost all the irrep(?). *What is the motivation of Whittaker story here? In what sense it is a good generalisation of irreducible representations?*

Whittaker module contains all the finite-dimensional rep of \mathfrak{g} then she studies category \mathcal{N} , roughly similar to category \mathcal{O} but with simple objects being Whittaker modules.

Travis told me that the motivation of category \mathcal{O} is that it is the nicest (?) category that contains finite-dimensional rep of \mathfrak{g} and the Verma module. *Why Verma module? is it because all irrep of \mathfrak{g} (even infinite one) can be described from Verma module? What sort of results do people expect when studying this category? Something like characters of irreducible modules, Kazhdan Lusztig theory?*

23/06/2021 I learnt about some geometric constructions of representation of a group G . Let's just say G is finite for simplicity. Let X be a space with an action of G .

To obtain a representation of G , one can linearise by considering a vector space $Fun(X)$ of complex-valued functions on X (one can also choose $Fun(X, V)$ of V -valued functions on X , where V is any vector space). Then G acts on $f \in Fun(X)$ by $(g \cdot f)(x) = f(g^{-1}x)$. We will explain a geometric analogue of this construction as follows. Again, we are given a space X with an action of G . The process of "linearising", i.e. associating X with $Fun(X)$, requires the language of vector bundles.

First, we recall notion of a vector bundle of rank n . It is a surjective map $\pi : V \rightarrow X$ satisfying local triviality condition: for every $x \in X$, there exists open neighborhood U of X containing x and a homeomorphism $\pi^{-1}(U) \rightarrow U \times \mathbb{C}^n$ compatible with projections to U , such that its restriction to x induces a vector space isomorphism $V_x := \pi^{-1}(x) \cong \{x\} \times \mathbb{C}^n$. Intuitively, a vector bundle associate each point $x \in X$ a vector space of dimension n . To see vector bundles as $Fun(X, \mathbb{C}^n)$, we consider its global section $\Gamma(X, V)$, which is a vector space because the fibers are vector spaces. Hence, one can think of vector bundle on X as vector-valued functions on X . Then line bundle (i.e. vector bundle of rank 1) is \mathbb{C} -valued functions on X .

Now, go back to the definition of G action on $Fun(X)$ and we want to interpret this in the language of vector bundles, i.e. how much information is needed to associate an action of G on sections $\Gamma(X, V)$ of a vector bundle $\pi : V \rightarrow X$? Note that if $s \in \Gamma(X, V)$ then $s(x) \in V_x$. Now we want to say something like " $(g \cdot s)(x) = s(g^{-1} \cdot x)$ " but LHS is in V_x ,

while the RHS is in $V_{g \cdot x}$. Hence, what we need is a linear isomorphism $g : V_x \rightarrow V_{g \cdot x}$ for every $g \in G$, so that we can write the action as $(g \cdot s)(x) = g \cdot s(g^{-1}x)$. This motivates the notion of G -equivariant vector bundles:

A G -equivariant vector bundle over X is a vector bundle $\pi : V \rightarrow X$ with an action of G on V such that π is G -equivariant and the induced map $g : V_x \rightarrow V_{gx}$ is a linear map (a priori this is just a bijection).

Thus, we have obtained a map

$$\{G\text{-equivariant vector bundles over } X\} \longrightarrow \{G\text{-representations}\}.$$

More questions:

- (a) *How to motivate notion of equivariant sheaf as generalisation of equivariant vector bundle? See Chriss Ginzburg or Achar book, wikipedia.*
- (b) *What choice of space X gives you irreducible representations or all representations? For example, in Bott-Weil theory, X is a flag variety (so why flag varieties? Masoud told me that on the Lie algebra version, irreducible representations appear as quotients of Verma module, which is the induced representation from the Borel \mathfrak{b} ; hence we expect irreducible representations to appear in bundle over $X = G/B$, which is the geometric way to describe induced representation) then considering certain line bundles over it (why line bundles but not general vector bundles? Is it because the regular representation of G on $\text{Fun}(G, \mathbb{C})$ contains all irreducible representations?) give you irreducible representations. What about Ginzburg construction of irreducible representations?*
- (c) *Is there a map going backwards? Starting from a G -representation, how to get a G -equivariant vector bundle over some space X . Some ideas: Given G -module V , then $V \times G \rightarrow V$ is a principal G -bundle. Try to obtain a vector bundle out of this (for example, using associated bundle construction, or replace G with vector space $\text{Fun}(G)$, as we know action of G on V induces action of $\text{Fun}(G)$ on V).*
- (d) *What representations will appear if we consider higher cohomology groups? Global sections is H^0 .*

From this perspective, the construction of induced representation is quite natural. Consider a representation $\rho : H \rightarrow \text{GL}(V)$ of subgroup H of G . Then we can construct a G -equivariant vector bundle as follows. Note $\pi : G \rightarrow G/H$ is a principal H -bundle, so to get a vector bundle, we use associated bundle construction: define $G \times_\rho V = G \times V / \sim$ where $(g(g')^{-1}, v) \sim (g, \rho(g')v)$ then $G \times_\rho V \rightarrow G/H$ is a vector bundle with fiber V . Note that G acts on $G \times_\rho V$ by $g(g', v) = (gg', v)$, making it into a G -equivariant vector bundle over G/H . In our analogy, this corresponds to $\text{Fun}(G/H, V)$. Taking global sections should give us back to the (analytic?) construction of induced representation.

Question:

- (a) *I am still a bit confused about associated bundle construction. In particular, would the following construction be the same as associated bundle construction: Given group hom $f : G \rightarrow H$ then we have morphism $Bf : BG \rightarrow BH$ of classifying spaces, which induces a map from principal G -bundles to principal H -bundles. Now if we let $H = \text{GL}(V)$ then is this the same as associated bundle construction?*
- (b) *Check the details of the induced representation construction above. More is said here <https://mathoverflow.net/q/5772/89665> and here <https://math.stackexchange.com/q/1704622/58951>.*

We also have the correspondence

$$\{\text{principal } G\text{-bundles over } X\}/G \longleftrightarrow \{\text{group hom } \pi_1(X) \rightarrow G\}/G.$$

I know one direction from left to right: a principal G -bundle over X corresponds to homotopy $\phi : X \rightarrow BG$, taking fundamental group induces $\pi_1(X) \rightarrow \pi_1(BG) = G$.

Another way to describe this without using BG : consider principal G -bundle $\pi : P \rightarrow X$. Pick $x \in X, p \in P$ so $\pi(p) = x$. Consider a closed loop $\gamma : [0, 1] \rightarrow X$ in X at x , i.e. $[\gamma] \in \pi_1(X, x)$. Then there exists a unique lift of γ to a curve $\tilde{\gamma}$ on P starting at p (but not necessarily closed curve). Then as $\tilde{\gamma}(1) = q$ and $\tilde{\gamma}(0) = p$ have the same fiber over x , and π is a principal G -bundle, there exists $g \in G$ so $q = p \cdot g$. We define $\pi_1(X) \rightarrow G$ by sending $[\gamma]$ to g .

Questions:

- (a) *What is the reverse direction of this correspondence?*
- (b) *If I choose $G = GL(V)$, $X = BG$ then the RHS is representation of G . Compare with previous correspondence, can I associate principal $GL(V)$ -bundle over BG with G -equivariant vector bundles this way?*
- (c) *This seems to be irrelevant, but what is the connection between principal GL_n -bundle and vector bundle? How to get one from the other?*

See more connection between vector bundles and representation theory at http://www.numdam.org/item/PMIHES_1961__9_23_0.pdf.

23/06/2021 For a Lie group G , I learnt how to describe a connection of a principal G -bundle $\pi : P \rightarrow X$ as \mathfrak{g} -valued 1-form on P .

First, we can define a vertical tangent bundle $T^v P = \{(p, v_p) : d\pi(v_p) = 0\}$. This gives us short exact sequence $0 \rightarrow T^v P \xrightarrow{f} TP \xrightarrow{g} \pi^* TX \rightarrow 0$. A connection on $P \rightarrow X$ is a choice of splitting of this short exact sequence. We have three equivalent ways to describe this:

- (a) A map $s : TP \rightarrow T^v P$ s.t. $s \circ f = \text{id}_{T^v P}$.
- (b) A map $t : TX \rightarrow TP$ s.t. $g \circ t = \text{id}_{TX}$.
- (c) A direct sum decomposition $TP = T^v P \oplus H$.

If we use (a), then note that $T^v P$ can be identified with $P \times \mathfrak{g}$, i.e. $(T^v P)_p$ can be identified with \mathfrak{g} via the linear isomorphism $v_p \mapsto \left. \frac{d}{dt} \right|_{t=0} p \cdot \exp(tv_p)$.

What is the geometric intuition of a connection for principal G -bundle?

Read more from chapter "Moduli Spaces of Flat Connections" of the book *Torus Actions on Symplectic Manifolds* by Audin.

2.1. 07/07/2021: Kemp-Ness theorem. From 01/07 till 07/07, we have a workshop on Heron island <https://sites.google.com/view/hiwgrt/home> about Kempf-Ness theorem, which gives a link between Geometric Invariant Theory and Symplectic Geometry.

Here are some unresolved thoughts I have during this workshop:

2.1.1. $\mathrm{GL}_n(\mathbb{C})$ acts by conjugation on $\mathfrak{gl}_n(\mathbb{C})$. One of the main example is letting $G = \mathrm{GL}_n(\mathbb{C})$ acting on $\mathfrak{gl}_n(\mathbb{C})$ by conjugation then stability of the action can be described as follows. Let $0 \neq V \in \mathfrak{gl}_n(\mathbb{C})$ then V can be written as $V = D + N$ where D is a diagonalisable matrix and N is nilpotent.

- (1) V is unstable, i.e. $0 \notin \overline{G \cdot V}$ iff $D = 0 \neq N$,
- (2) V is polystable, i.e. $\overline{G \cdot V}$ is closed, iff $N = 0 \neq D$.
- (3) V is semistable ($0 \notin \overline{G \cdot V}$) but is not polystable (note polystable implies semistable as $V \neq 0$) iff $D \neq 0 \neq N$.

Here the topology of $\mathfrak{gl}_n(\mathbb{C})$ is the classical topology of \mathbb{C}^{n^2} . I can show the following:

- (1) If V is nilpotent then $0 \in \overline{G \cdot V}$. Indeed, because $G = \mathrm{GL}_n(\mathbb{C})$ acts on V by conjugation, every matrix is conjugate to an upper triangular matrix, we can assume V is upper triangular with 0's on the diagonal, $V = (a_{ij})$ where $a_{ij} = 0$ for $i \geq j$. Let $f(t)$ be a diagonal matrix whose (i, i) th entry is t^i . Then $f(t)Vf(t)^{-1} = (t^{i-j}a_{ij})_{1 \leq i, j \leq n}$. Hence, as $|t| \rightarrow \infty$ in \mathbb{C}^\times , $f(t)Vf(t)^{-1} \rightarrow 0$. Hence, $0 \in \overline{G \cdot V}$.
- (2) If V is not nilpotent then V is semistable, i.e. $0 \notin \overline{G \cdot V}$. Indeed, V has nonzero eigenvalue $\lambda \in \mathbb{C}$ and hence gVg^{-1} also has nonzero eigenvalue λ for any $g \in \mathrm{GL}_n(\mathbb{C})$. Because all norm on a finite dimensional vector space is equivalent, we can choose the operator norm $\|\cdot\|$ on $\mathfrak{gl}_n(\mathbb{C})$, giving $\|gVg^{-1}\| \geq |\lambda| > 0$ for all $g \in \mathrm{GL}_n(\mathbb{C})$ (operator norm of a matrix is at least the spectral radius, i.e. largest eigenvalue, of that matrix). Thus $0 \notin \overline{G \cdot V}$.

I don't know how to show that if V is diagonalisable (hence we can assume V is a diagonal matrix) with at least one nonzero eigenvalue, then $G \cdot V$ is closed (and vice versa).

I can do for example when $n = 2$, $V = \mathrm{diag}(\lambda, 0)$ with $\lambda \neq 0$. Then

$$\begin{pmatrix} a & b \\ c & d \end{pmatrix} V \begin{pmatrix} a & b \\ c & d \end{pmatrix}^{-1} = \frac{\lambda}{ad - bc} \begin{pmatrix} ad & -ab \\ cd & -bc \end{pmatrix}.$$

Then $G \cdot V = \left\{ \begin{pmatrix} x_{11} & x_{12} \\ x_{21} & x_{22} \end{pmatrix} \in \mathfrak{gl}_2(\mathbb{C}) : x_{11} + x_{22} = \lambda, x_{11}x_{22} = x_{21}x_{12} \right\}$, which is closed in $\mathfrak{gl}_2(\mathbb{C})$.

What is the moment map here? Can I draw a picture for this example, showing that the moment map is some kind of critical point of some norm?

2.1.2. Torus acting on a vector space. Another example is letting $T = (\mathbb{C}^\times)^n$ acting on a (finite dimensional?) complex vector space V , equipped with a Hermitian inner product. Then V can be decomposed as direct sum of orthogonal vector spaces $\bigoplus_{\chi \in X^*(T)} V_\chi$ where $V_\chi = \{v \in V : t \cdot v = \chi(t)v\}$. Let $v \in V$ and $v = \sum_{i=1}^r v_i$ where $v_i \in V_{\chi_i}$, where $\chi_1, \dots, \chi_r \in X^*(T)$ are distinct characters. Note that each character can be identified with an element in \mathbb{Z}^n as $X^*(T) \cong \mathbb{Z}^n$ by sending $(m_1, \dots, m_n) \in \mathbb{Z}^n$ to $(t_1, \dots, t_n) \in (\mathbb{C}^\times)^n \mapsto \prod_{i=1}^n t_i^{m_i}$. Then the stability of the action can be described as follows:

- (1) $v \in V$ is unstable, i.e. $0 \in \overline{T \cdot v}$, iff 0 does not lie in the convex hull of χ_1, \dots, χ_r .
- (2) v is polystable, i.e. $T \cdot v$ is closed, iff 0 lies in the interior of the convex hull of χ_1, \dots, χ_r .

I can prove (a). It essentially lies in the proof of Hilbert-Mumford criterion <https://www.isibang.ac.in/~sury/hilbmumf.pdf> by B.Sury that I read in order to present to the workshop.

Let me try to decode the definition of convex hull to see why it is essentially in B. Sury's paper. One definition is that it is the set $\{\sum_{i=1}^r b_i \chi_i \in \mathbb{R}^n : 0 \leq b_i \leq 1, \sum b_i = 1\}$. Another way to think about this is that 0 does not lie in the convex hull iff there exists a hyperplane passing through 0, i.e. $\sum_i c_i x_i = 0$, such that χ_i 's lie on the same half-plane separated by that hyperplane, i.e. $\langle \chi_i, (c_1, \dots, c_n) \rangle > 0$. With this, we can choose $t_\ell = (\ell^{c_1}, \dots, \ell^{c_n})$ then $\|t_\ell \cdot v\|^2 = \sum_{i=1}^r |\ell|^{2\langle \chi_i, (c_1, \dots, c_n) \rangle} \|v_i\|^2$, which goes to 0 as $\ell \rightarrow 0$. Conversely, if $0 \in \overline{T \cdot v}$ then this is Sury's proof of Hilbert Mumford criterion for $\mathrm{GL}_n(\mathbb{C})$. *Need to write this down in case I forgot.*

How to prove (b)? Can I draw a picture of this example?

Maybe two subexamples we can draw are

(1) \mathbb{C}^\times acts on \mathbb{C}^2 by multiplication via $t \mapsto \begin{pmatrix} t & 0 \\ 0 & t^{-1} \end{pmatrix}$. The orbits are $O_\lambda = \{(x, y) \in \mathbb{C}^2 : xy = \lambda\}$ for $\lambda \in \mathbb{C}^\times$, $\{(x, 0) : x \neq 0\}$ and $\{(0, y) : y \neq 0\}$. One can see that the quotient topology of this action is not Hausdorff. Ramiro mentioned that the moment map is then somesort of shortest distance to each orbit. *Need to work this out.* The non-closed orbits are the x, y -axes without the origin. If we throw out these two orbits, we expect to get a nicer topology when taking quotient. *What does this mean? Can you draw it?*

(2) \mathbb{C}^\times acts on \mathbb{C}^2 by multiplication $t \mapsto \begin{pmatrix} t & 0 \\ 0 & t \end{pmatrix}$. Then the orbits are $\{(0, 0)\}$ and lines through the origin but minus the origin. When we take out the bad orbit $((0, 0))$ we get \mathbb{P}^1 .

2.1.3. *Kempf-Ness fancy version.* I don't think I have seen the relation between Kempf-Ness theorem in Kempf-Ness paper and the fancy version of this (i.e. a homeomorphism between some GIT quotient and symplectic reduction). I would like to learn this someday. For example, I don't know much about the process of throwing away bad orbits to get better quotient topology. *Maybe work out the examples above or read this paper <https://arxiv.org/pdf/math/0512411.pdf> in more details.* Geordie mentions that this Kempf-Ness paper essentially embeds in Atiyah-Bott paper and I would like to understand more what did he mean by this.

2.1.4. *Complexification, real vs complex.* This is about complexification, real form, compact form, \mathbb{R} vs \mathbb{C} structure, reductive etc... of Lie groups. During the workshop, we have done this for torus, i.e. what is the most natural way to get a compact torus from a complex torus and vice versa?

There are two ways to define compact torus. A non-canonical way is that it is a real Lie group diffeomorphic to $U(1)^n$ for some n , where $U(1) = S^1 = \{z \in \mathbb{C} : z\bar{z} = 1\}$. A canonical definition is that it is a connected compact abelian real Lie group.

There are also two ways to define complex torus. A noncanonical way is that it is a complex Lie group diffeomorphic to $(\mathbb{C}^\times)^n$. A canonical definition is that it is a connected reductive abelian complex Lie group (see how compact is replaced by reductive when comparing with compact torus definition, i.e. one can think of reductive complex Lie group as complexification of compact real Lie group).

From a complex torus, you can take its maximal compact real Lie subgroup, which will be unique up to conjugation (every Lie group has a unique maximal compact subgroup up to conjugation?). From a compact torus T then the exponential map $\exp : \mathfrak{t} \rightarrow T$ is surjective, i.e. $T = \exp(\mathfrak{t})$. Indeed, $\exp(\mathfrak{t})$ is a subgroup of T (as T is abelian) and contains a neighborhood of the identity. Hence, T is a disjoint union of cosets of $\exp(\mathfrak{t})$. But as T is connected so $T = \exp(\mathfrak{t})$. Hence, if $\Gamma = \ker(\exp)$ then T is diffeomorphic and group isomorphic to \mathfrak{t}/Γ . The complexification of T is then $T_{\mathbb{C}} = (\mathfrak{t} \otimes_{\mathbb{R}} \mathbb{C})/\Gamma$. This way of defining complexification seems to work only for torus. In general, it is more complicated. *How to define complexification in general?* Ramiro mentioned there is a universal property about this. Masoud told us another way to define complexification, which is based on the idea that categories of representations of compact Lie group and of its complexification are the same (?).

Rohin told me that real/compact form is some sort of reverse process of complexification. From a compact Lie group, you can get a complex Lie group unique in some sense, but the reverse process is not unique, and a real form refers to a "real"isation of that ...

In the first line of Kemp-Ness proof for theorem in section 4: For $\mathrm{GL}_n(\mathbb{C})$, one can give it an algebraic structure over \mathbb{R} such that its real locus is $U(n)$. Indeed, write down the equation $AA^* = I$ of $U(n)$ as polynomials over \mathbb{R} . The claim is that over \mathbb{C} , this gives $\mathrm{GL}_n(\mathbb{C})$. For example, when $n = 1$, then $U(1) = \{(x, y) \in \mathbb{R}^2 : x^2 + y^2 = 1\}$. And we can identify $\left\{ \begin{pmatrix} x & y \\ y & x \end{pmatrix} : x^2 + y^2 = 1 \right\}$ being isomorphic to \mathbb{C}^\times over \mathbb{C} . *Need to write this down. I have done this before but I forgot.*

2.2. 19/07/2021: Line bundles on \mathbb{P}^1 . Past few days I have been trying to learn about line bundles on \mathbb{P}^1 , how to classify topological/ holomorphic/ algebraic line bundles on \mathbb{P}^1 , how to describe their (global) sections, to compute their transition functions, how to draw some of them.

2.2.1. Transition functions of $\mathcal{O}(-1)$. First is the (topological) canonical line bundle $\mathcal{O}(-1)$ on \mathbb{P}^1 over \mathbb{C} . Since each point in \mathbb{P}^1 corresponds to a line in \mathbb{C}^2 , as a set $\mathcal{O}(-1) = \{(\ell, x) \in \mathbb{P}^1 \times \mathbb{C}^2 : x \in \ell\}$ with the obvious projection p to \mathbb{P}^1 .

Now, I want to compute the transition functions of this line bundle. \mathbb{P}^1 can be thought abstractly as open cover of $U_0 = \{[x, y] \in \mathbb{P}^1 : x \neq 0\}$ and $U_1 = \{[x, y] : y \neq 0\}$. Each U_i is isomorphic to affine space \mathbb{C} , for example, $U_0 \cong \mathbb{C}$ via $[x, y] \mapsto y/x$.

We have an isomorphism $\pi_0 : p^{-1}(U_0) \rightarrow U_0 \times \mathbb{C}$ sending $([1 : z_\ell], (x, y))$ to $([1 : z_\ell], x)$. The inverse π_0^{-1} sends $([1 : z_\ell], c)$ to $([1 : z_\ell], c(1, z_\ell))$. Notice that here we have picked a representative $(1, z_\ell) \in \mathbb{C}^2$ of $\ell = [1 : z_\ell]$ to define π_0 . The reason for this is that we want our map to be a homeomorphism. Visually, imagine $\mathcal{O}(-1)$ as collection of lines on \mathbb{C}^2 passing through 0. Choosing representatives for elements in U_0 as above means the representatives lie on the line $x = 1$ in \mathbb{C}^2 , which guarantee continuity (i.e. if $|z_\ell| < 1$ and $|c| < 1$ then the image $c(1, z_\ell)$ is open in \mathbb{C}^2 , looking like a paper fan).

Similarly, $\pi_1 : p^{-1}(U_1) \rightarrow U_1 \times \mathbb{C}$ sends $([z_\ell, 1], (x, y))$ to $([z_\ell, 1], y)$ and π_1^{-1} sends $([z_\ell, 1], c)$ to $([z_\ell, 1], c(z_\ell, 1))$.

The transition function $g_{01} : U_1 \cap U_0 \rightarrow \mathrm{GL}_1(\mathbb{C})$ is defined via

$$\begin{aligned} (U_1 \cap U_0) \times \mathbb{C} &\xrightarrow{\pi_0^{-1}} p^{-1}(U_1 \cap U_0) \xrightarrow{\pi_1} (U_1 \cap U_0) \times \mathbb{C} \\ (\ell = [1, z_\ell], c) &\mapsto ([1, z_\ell], c(1, z_\ell)) \mapsto ([1, z_\ell], cz_\ell) \end{aligned}$$

Hence, g_{01} sends $\ell = [1, z_\ell] \in U_1 \cap U_0$ to $(c \mapsto cz_\ell)$ in $\mathrm{GL}_1(\mathbb{C})$. Under identification of $U_1 \cap U_0$ with \mathbb{C}^\times via identification $U_0 \cong \mathbb{C}$, i.e. $\ell = [1, z_\ell] \mapsto z_\ell$ (we choose $U_0 \cong \mathbb{C}$ instead of $U_1 \cong \mathbb{C}$ because our map is $\pi_1 \circ \pi_0^{-1}$ so the domain $U_1 \cap U_0$ lies in U_0 originally) and $\mathrm{GL}_1(\mathbb{C})$ with \mathbb{C}^\times , g_{01} can be view simply as a map $\mathbb{C}^\times \rightarrow \mathbb{C}^\times$ sending z to z .

Similarly, one can check the other transition function $g_{10} : U_1 \cap U_0 \rightarrow \mathrm{GL}_1(\mathbb{C})$ defined by $\pi_0 \circ \pi_1^{-1}$ sends $z \mapsto z$, under identification of spaces $U_1 \cap U_0$ with \mathbb{C}^\times via $U_1 \cong \mathbb{C}$. Let me spell this out. We have

$$\begin{aligned} (U_1 \cap U_0) \times \mathbb{C} &\xrightarrow{\pi_1^{-1}} p^{-1}(U_1 \cap U_0) \xrightarrow{\pi_0} (U_1 \cap U_0) \times \mathbb{C} \\ (\ell = [z_\ell, 1], c) &\mapsto ([z_\ell, 1], c(z_\ell, 1)) \mapsto ([z_\ell, 1], cz_\ell) \end{aligned}$$

Notice that it is true $g_{01}(\ell)g_{10}(\ell) = 1$ for all $\ell \in U_1 \cap U_0$, but upon correct identification of spaces, both these maps can be viewed as $z \mapsto z$ from \mathbb{C}^\times to \mathbb{C}^\times .

This is the point that confuses me the most because it seems many other sources claiming that the transition map should send $z \mapsto z^{-1}$ (for example, this and this, p.30 while one reference agrees with my choice). The reason for this ambiguity seems to be because there are two ways to identify $U_1 \cap U_1$ with \mathbb{C}^\times , one via $U_0 \cong \mathbb{C}$ and the second via $U_1 \cong \mathbb{C}$ (see how I get g_{01} as $z \mapsto z$). To avoid

ambiguity, the best way to phrase this is that g_{01} sends $[x_0, x_1] \rightarrow x_1/x_0$ and g_{10} sends $[x_0, x_1]$ to x_0/x_1 (later we will see that we can define line bundle $\mathcal{O}(k)$ with $k \in \mathbb{Z}$ with transition functions $g_{01}([x_0, x_1]) = (x_1/x_0)^k$).

One may then ask why name the bundle to be $\mathcal{O}(-1)$ instead of $\mathcal{O}(1)$? One reason, as we will later see that algebraic/holomorphic $\mathcal{O}(-1)$ has no nontrivial global section, while algebraic/holomorphic $\mathcal{O}(1)$ has global section being a \mathbb{C} -vector space of degree 1 homogeneous polynomials in two variables x_0, x_1 . For more reasons, see <https://math.stackexchange.com/q/256482/58951>.

2.2.2. $\mathcal{O}(-1)$ as a Mobius strip. How do you visualise $\mathcal{O}(-1)$? I claim that you can draw this as an "infinite" Mobius strip. At least this is the picture over \mathbb{R} , but as a drawing, you can just pretend that any field k is just a line.

Before drawing it out, let me first explain why $\mathcal{O}(-1)$ over \mathbb{R} is the infinite Mobius strip, i.e. $[0, 1] \times \mathbb{R} / \sim$ where $(0, t) \sim (1, -t)$. Over \mathbb{R} , every line in \mathbb{R}^2 intersects the circle S^1 at exactly two points, so we will define a map sending $x \in [0, 1]$ to $e^{\pi i x} \in S^1$ to indicate our line. Hence, $(x, t) \in [0, 1] \times \mathbb{R}$ is sent to a line ℓ in \mathbb{R}^2 passing through $e^{\pi i x}$ and the corresponding point $te^{\pi i x}$ on that line. To get a bijection, we need identification $(0, t) \sim (1, -t)$ because both represent the same point on the x -axis.

Now, let's try to draw this out for $1 < t < 2$. We would get fig. 1 where under $(0, t) \sim (1, -t)$ we

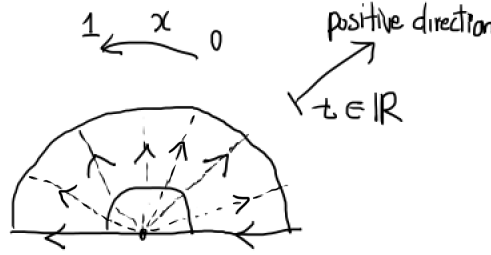


FIGURE 1. Visualise $\mathcal{O}(-1)$

need to glue the paper fan above along the arrows on the x -axis. As you let x goes from 0 to 1 to get back to the x -axis, by looking at the positive direction of each line, you can notice the twist.

Let me offer another explanation of $\mathcal{O}(-1)$ being the Mobius bundle. In the previous explanation, I take the definition of $\mathcal{O}(-1)$ as lines on \mathbb{R}^2 , this time I want to view $\mathcal{O}(-1)$ abstractly via its transition functions. The goal would be the same, i.e. how to see the twist in $\mathcal{O}(-1)$, but I don't want to describe the homeomorphism explicitly (because it relies too much of the fact that we are in \mathbb{R}). If successful, I want an argument that works for any topological field.

Now, $\mathcal{O}(-1)$ is defined via its transition function $g_{01} : U_0 \cap U_1 \rightarrow \text{GL}_1(\mathbb{R})$ sending $[x_0, x_1] \mapsto x_1/x_0$. This means that $\mathcal{O}(-1)$ is obtained by glueing $U_1 \times \mathbb{R}$ and $U_0 \times \mathbb{R}$ via $(U_1 \cap U_0) \times \mathbb{R} \rightarrow (U_1 \cap U_0) \times \mathbb{R}$ sending $([1, z], c) \mapsto ([1, z], zc)$. Now, I would draw $U_0 \cong \mathbb{R}$ as a circle with a point $[0, 1]$ removed and $U_1 \cong \mathbb{R}$ as a circle with a point $[1, 0]$ removed.

In U_0 , on one side of $[1, 0]$ are points $[1, z]$ with $z < 0$ and on the other side are those $[1, z]$ with $z > 0$. On each fiber of $U_0 \times \mathbb{R} \rightarrow U_0$, we choose the positive directions as pointing outwards from the circle. This choice is possible because we are working over \mathbb{R} . Now we look at those fibers in the circle of U_1 via the glueing $([1, z], c) \mapsto ([1, z], zc)$, keeping in mind of the positive direction of each fiber (see fig. 2).

With this, we observe that we have twisted one connected component of $(U_0 \cap U_1) \times \mathbb{R}$ by half.

Is there an easier way to see why $\mathcal{O}(-1)$ is not the trivial line bundle $\mathbb{P}^1 \times \mathbb{C}$? I would say that intuitively, because all lines/fibers of $\mathcal{O}(-1)$ "have a common point 0", while for $\mathbb{P}^1 \times \mathbb{C}$, the fibers do not intersect each other. *How to rigorously describe this phenomenon?*

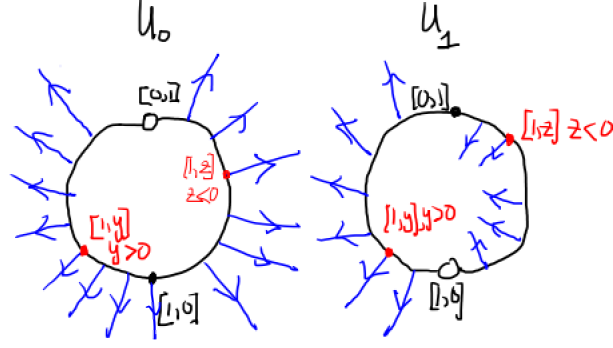


FIGURE 2. Visualise $\mathcal{O}(-1)$

2.2.3. *Dual line bundle $\mathcal{O}(1)$.* The line bundle $\mathcal{O}(1)$ is the dual line bundle to $\mathcal{O}(-1)$. What does this mean? One could guess that it means the fibers of $\mathcal{O}(1)$ are the dual spaces to the fibers of $\mathcal{O}(-1)$. But this is not a good enough description. To describe this vector bundle, we need to determine its transition functions.

In general, the dual vector bundle E^* of $E \rightarrow V$ is the vector bundle whose fibers are the dual spaces to the fibers of E . From this information, I will (heuristically) derive that the most natural vector bundle E^* that has this property is the one that has transition functions $g_{ij}^* = (g_{ij}^T)^{-1}$. Because $\pi_j \circ \pi_i^{-1} : \{u\} \times \mathbb{C}^n \xrightarrow{\sim} E_u \xrightarrow{\sim} \{u\} \times \mathbb{C}^n$ is an isomorphism of vector spaces so $f_{ij} := \pi_j^{-1} \circ (g_{ij} u) \circ \pi_i \in \text{GL}(E_u)$. We want the transition functions for E^* , i.e. how to cook up $\{u\} \times \mathbb{C}^n \xrightarrow{\sim} E_u^* \xrightarrow{\sim} \{u\} \times \mathbb{C}^n$? This is not possible as we don't know local trivialisations of E^* , but we can guess $f_{ij}^* : E_u^* \xrightarrow{\sim} \{u\} \times \mathbb{C}^n \xrightarrow{\sim} E_u^*$ in $\text{GL}(E_u^*)$, i.e. the most natural one is $(\phi \in E_u^*) \mapsto ((v \in E_u) \mapsto \phi(f_{ij}^{-1}v))$. Notice I put f_{ij}^{-1} instead of f_{ij} because f_{ij}^* needs to satisfy the cocycle condition $f_{jk}^* f_{ij}^* = f_{ik}^*$. We will show that $f_{ij}^* = (f_{ij}^{-1})^T$ (note that for $\phi \in \text{GL}(V)$ then ϕ^T means $\phi^T \in \text{GL}(V^*)$ sending $f \in V^*$ to $f \circ \phi$) and therefore implying $g_{ij}^* = (g_{ij}^{-1})^T$.

2.2.4. *Line bundles $\mathcal{O}(k)$.* We define $\mathcal{O}(k)$ to be $|k|$ -times tensor product of $\mathcal{O}(1)$ if $k > 0$ or $\mathcal{O}(-1)$ if $k < 0$. We want to compute the transition functions of these bundles.

For vector bundles E_1, E_2 over V with transition functions $g_{ij} : U_i \cap U_j \rightarrow \text{GL}_m(\mathbb{C}^m)$, $f_{ij} : U_i \cap U_j \rightarrow \text{GL}_n(\mathbb{C}^n)$, the transition functions of $E_1 \otimes E_2$ are $g_{ij} \otimes f_{ij} : U_i \cap U_j \rightarrow \text{GL}_{mn}(\mathbb{C}^m \otimes_{\mathbb{C}} \mathbb{C}^n)$.

We show $\mathcal{O}(-1) \otimes \mathcal{O}(1)$ is the trivial line bundle $\mathbb{P}^1 \otimes \mathbb{C}$. The transition function of $\mathcal{O}(-1) \otimes \mathcal{O}(1)$ is $g_{01} \otimes g_{01}^* : U_0 \cap U_1 \rightarrow \text{GL}_1(\mathbb{C})$, sending $[x_0, x_1]$ to $\frac{x_1}{x_0} \otimes \frac{x_0}{x_1} = 1$ and similarly for the other transition function.

The transition function of $\mathcal{O}(2)$ is $g_{01} \otimes g_{01}$, sending $[x_0, x_1]$ to $(x_1/x_0)^2$. Now, if you try to draw out $\mathcal{O}(2)$ as I did for $\mathcal{O}(-1)$, you will notice that topologically, it is just the trivial line bundle $\mathbb{P}^1 \times \mathbb{R}$. Similarly, $\mathcal{O}(1)$ over \mathbb{R} is also just a Mobius bundle. In fact, over \mathbb{P}^1 (or S^1), there are just two topological line bundles up to isomorphism!

Can I interpret $\mathcal{O}(k)$ where k means number of twists? Just like $\mathcal{O}(-1)$ is the Mobius strip over \mathbb{R} (and I think $\mathcal{O}(1)$ over \mathbb{R} is also a Mobius strip)? See <https://math.stackexchange.com/q/220203/58951> or <https://math.stackexchange.com/q/2219539/58951> for example. For example, can you draw $\mathcal{O}(2)$ or $\mathcal{O}(-2)$?

2.2.5. *Only two topological line bundles over $\mathbb{P}^1(\mathbb{R})$.* Read <https://ayouc.is.wordpress.com/2014/12/12/line-bundles-on-the-circle/>.

2.2.6. *What about topological line bundles over other fields?*

2.2.7. $\mathcal{O}(-1)$ as an algebraic line bundle over \mathbb{C} . So far, we have describe $\mathcal{O}(-1)$ as a topological line bundle, i.e. a continuous map $p : \mathcal{O}(-1) \rightarrow \mathbb{P}^1$ with local trivialisations $\pi_0 : p^{-1}(U_0) \xrightarrow{\sim} U_0 \times \mathbb{C}$ and $\pi_1 : p^{-1}(U_1) \xrightarrow{\sim} U_1 \times \mathbb{C}$ that commutes with projections to U_0, U_1 , respectively. Furthermore, these local trivialisations must induce isomorphisms of vector spaces $p^{-1}(\ell) \cong \{\ell\} \times \mathbb{C}$ of each fiber of p .

How do we describe $\mathcal{O}(-1)$ as an algebraic/holomorphic/smooth/etc line bundle?

<https://math.stackexchange.com/q/3481443/58951>.

2.2.8. \mathbb{P}^1 as a scheme. Before, we describe \mathbb{P}^1 abstractly as a topological space over \mathbb{C} , in fact the construction works over any field k , by glueing two k 's, namely $\mathbb{A}_0 = k$ and $\mathbb{A}_1 = k$. This is glued via $\mathbb{A}_0 \setminus \{0\} = k^\times \rightarrow k^\times = \mathbb{A}_1 \setminus \{0\}$ sending $z \mapsto z^{-1}$. In particular, U is open in \mathbb{P}^1 if $U \cap \mathbb{A}_0$ and $U \cap \mathbb{A}_1$ are both open.

Now we wish to equip \mathbb{P}^1 with an extra structure, i.e. \mathbb{P}^1 as a scheme. I will explain how to construct \mathbb{P}^1 over field k as a sheaf of rings by glueing two affine pieces $\mathbb{A}_0 = \text{Spec } k[t_0]$ and $\mathbb{A}_1 = \text{Spec } k[t_1]$. By gluing, I mean we have to do two things: glue two topological spaces \mathbb{A}_0 and \mathbb{A}_1 and then glue their structure sheaves $\mathcal{O}_{\mathbb{A}_1}$ and $\mathcal{O}_{\mathbb{A}_0}$.

Compute global section of $\mathcal{O}_{\mathbb{P}^1}$.

2.2.9. *Classifying algebraic vector bundles on \mathbb{P}^1 via double cosets.* Algebraic vector bundles on \mathbb{P}^1 of degree n are classified via the transition functions $g_{ij} : \text{Spec } k[t, t^{-1}] \rightarrow \text{Spec } \mathcal{O}(\text{GL}_n)$ which corresponds to a point in $\text{GL}_n(k[t, t^{-1}])$...

2.2.10. $\mathcal{O}(2)$ as tangent bundle of \mathbb{P}^1 .

2.2.11. *Global sections of algebraic bundles.*

2.3. **23/07/2021: Categorical measure theory.** Masoud mentioned that I only defined push-forward measures but not pullback measures in my thesis. When I googled, I found this explanation <https://mathoverflow.net/q/122704/89665> saying there is no pullback of general maps. One needs extra conditions, such as being able to integrate on fibers. There is also a way to develop measure theory categorically with pushforward and pullback available this way, from <https://mathoverflow.net/a/20820/89665>. But the language is quite foreign to me. *Need to read more at some point.*

2.4. **23/07/2021: Sheaf of solutions of ODE is a local system.** I want to claim that local existence and uniqueness of a differential equation is the same as saying that its sheaf of solutions is a constant sheaf.

We have the following result for local existence and uniqueness of ODEs (cited from <https://www.math.utah.edu/~milicic/Eprints/de.pdf>, theorem 1.2): Let Ω be a simply connected region in \mathbb{C} , $z_0 \in \Omega$ and $A : \Omega \rightarrow \text{GL}_n(\mathbb{C})$ a holomorphic map. For any $Y_0 \in \mathbb{C}^n$, there exists a unique holomorphic function $Y : \Omega \rightarrow \mathbb{C}^n$ such that $\frac{dY}{dz} = AY$ in Ω , and $Y(z_0) = Y_0$.

First, we can construct a sheaf \mathcal{F} of solutions over Ω for this equation by letting $\mathcal{F}(U)$ to be set of all $Y : U \rightarrow \mathbb{C}^n$ satisfying the ODE. The claim is that \mathcal{F} is a constant sheaf \mathbb{C}^n (note that because Ω is simply connected so any continuous $\Omega \rightarrow \mathbb{C}^n$ with \mathbb{C}^n having the discrete topology must be a constant function, meaning $\underline{\mathbb{C}^n}_\Omega(\Omega) = \mathbb{C}^n$). Indeed, $\mathcal{F}(\Omega) \rightarrow \mathbb{C}^n$ sending $Y \mapsto Y(z_0)$.

Now, if Ω is not simply connected then \mathcal{F} is a \mathbb{C} -local system, i.e. Ω is union of its connected components and \mathcal{F} restricted to each component is a constant sheaf, as shown below.

2.5. **23/07/2021: Shrawan Kumar's SMRI talk.** I attend Shrawan Kumar's talk "Root components for tensor product of affine Kac-Moody Lie algebra modules" for the Sydney Mathematical Research Institute. Here are something news I learnt:

- (1) Some history about tensor product decomposition problem for finite/affine/Kac-Moody Lie algebras.
- (2) There is a problem that I think I can work out the proof: For integral dominant weight λ, μ , let $V(\lambda), V(\mu)$ be the corresponding highest weight reps. By complete irreducibility, we can decompose $V(\lambda) \otimes V(\mu)$ as direct sum of $V(\nu)$. Let $n_{\lambda, \mu}^{\nu}$ be the multiplicity of $V(\nu)$ in $n_{\lambda, \mu}^{\nu}$. The problem is that:

Show, if $n_{\lambda, \mu}^{\nu} \neq 0$ then $n_{m\lambda, m\mu}^{m\nu} \neq 0$ for all positive integer m .

Kumar claimed that there are two proofs of this, one use standard representation theoretic method and the second via Borel-Weil theorem, and I would like to know how to prove this for the above two methods.

- (3) Do some google on "ample line bundle" as this terminology is mentioned in the talk. Roughly, a line bundle L on a proper ¹ scheme X over field k is ample if $L^{\otimes n}$ has enough global sections to give a closed immersion (i.e. closed embedding) $X \rightarrow \mathbb{P}^N$ where $N = \dim H^0(X, L^{\otimes n}) - 1$. From what I know, this definition is important in order to classify algebraic varieties, i.e. describe a variety with certain properties as subvariety of certain projective space defined by equations of certain degrees. See https://www.math.ucla.edu/~totaro/papers/public_html/algebraic.pdf for example.

Now, let me try to explain more about the part of "having enough global sections gives a morphism $X \rightarrow \mathbb{P}^N$ ". I read this from wikipedia https://en.wikipedia.org/wiki/Ample_line_bundle. Choose global sections $a_0, \dots, a_{N-1} \in H^0(X, L)$ then we can defined $f: X \rightarrow \mathbb{P}^N$ sending $x \mapsto [a_0(x), \dots, a_{N-1}(x)]$. Note that this is well-defined if over any $x \in X$, at least one of $a_i(x)$ is non-zero, i.e. intersection of zero sets of all global sections is empty. This is what is called "basedpoint-free" line bundle. "Semi-ample" line bundle L is when $L^{\otimes n}$ is basedpoint-free for some n . "Very-ample" L is when $X \rightarrow \mathbb{P}^N$ is a closed immersion. "Ample" L is when $L^{\otimes r}$ is very-ample. So it's a bunch of definitions. *Workout the examples in wikipedia: $\mathcal{O}(d)$ on \mathbb{P}^1 is based-point free iff $d \geq 0$, and very ample iff $d \geq 1$.*

What is the role of being "ample" in representation theory, Kumar mentioned that $L(\lambda)$ as ample line bundle corresponding to a dominant weight λ , what does this mean?

2.6. **27/07/2021: Discriminant and different of field extension.** Let A be a Dedekind domain with field of fraction K , L/K is a finite separable extension and B is integral closure of A in L . Recall a prime $\mathfrak{q}|\mathfrak{p}$ of L is unramified if $e_{\mathfrak{q}} = 1$ and B/\mathfrak{q} is separable extension of A/\mathfrak{p} . A prime \mathfrak{p} of K is unramified if every prime $\mathfrak{q}|\mathfrak{p}$ lying above it are unramified.

In this notes, we will define *different* $\mathcal{D}_{B/A}$ and *discriminant* $D_{B/A}$ and show that these encodes information about ramification of L/K . In particular, we would like to explain the following:

The different is B -ideal that is divisible by the ramified primes \mathfrak{q} of L , and the discriminant is A -ideal that is divisible by the ramified primes \mathfrak{p} of K . The valuation $v_{\mathfrak{q}}(\mathcal{D}_{B/A})$ will give us information about the ramification index $e_{\mathfrak{q}}$ and its exact value when \mathfrak{q} is tamely ramified.

This is created to summarised Lecture 12 in <https://math.mit.edu/classes/18.785/2019fa/lectures>.

2.6.1. *The different.* First, we need to define these two objects. We have trace pairing $L \times L \rightarrow K$ defined by $(x, y) \mapsto \text{Trace}_{L/K}(xy)$. When L/K is separable, this is a perfect pairing (i.e. it induces K -module isomorphism L with $L^{\vee} = \text{Hom}_K(L, K)$). B is a A -lattice in L (i.e. finitely generated

¹finite dimensional of global section of line bundles on X ?

A -module that spans L as K -vector space) and we have a corresponding *dual lattice* for B , defined as

$$B^* := \{x \in L : \text{Trace}_{L/K}(xb) \in A \forall b \in B\}.$$

It is an A -lattice in L isomorphic to dual A -module $M^\vee := \text{Hom}_A(M, A)$. One can show $B^* \in \mathcal{I}_B$ (\mathcal{I}_B is the *ideal class group* of B , i.e. group of invertible fractional ideals of B , i.e. finitely generated B -submodules lying of L ; here fractional ideal I being invertible means $IJ = B$ for some fractional ideal J). We define the *different* $\mathcal{D}_{L/K}$ of L/K (or the different $\mathcal{D}_{B/A}$ of B/A) to be the inverse of B^* in \mathcal{I}_B . Explicitly, we have

$$\mathcal{D}_{L/K} := \mathcal{D}_{B/A} := (B^*)^{-1} = \{x \in L : xB^* \subset B\}.$$

Note $B \subset B^*$ as $\text{Trace}_{L/K}(ab) \in A$ for any $a, b \in B$, we find that the different is an ideal of B , not just fractional ideal.

Different respects localisation and completion:

- Let S be multiplicative subset of A . Then $S^{-1}\mathcal{D}_{B/A} = \mathcal{D}_{S^{-1}B/S^{-1}A}$. To prove this, it suffices to show inverses and duals commutes with localisation.
- Let $\mathfrak{q}|\mathfrak{p}$ be a prime of B . Then $\mathcal{D}_{\hat{B}_{\mathfrak{q}}/\hat{A}_{\mathfrak{p}}} = \mathcal{D}_{B/A}\hat{B}_{\mathfrak{q}}$ as $\hat{B}_{\mathfrak{q}}$ -ideals. Here $\hat{B}_{\mathfrak{q}}$ and $\hat{A}_{\mathfrak{p}}$ are completions of B and A at $\mathfrak{q}, \mathfrak{p}$, respectively.

2.6.2. The discriminant. Let $n := [L : K]$. For B an A -lattice in L , we can define the *discriminant* of L/K (or of B/A) to be the A -module $D_{L/K}$ (or $D_{B/A}$) generated by

$$\text{disc}(x_1, \dots, x_n) := \det[\text{Trace}_{B/A}(x_i x_j)]_{ij} \in A$$

where $x_1, \dots, x_n \in B$. This is infact a fractional ideal of A . When B is free A -lattice in L (such as when $A = \mathbb{Z}$) then $D_{B/A}$ is a principal fractional ideals, generated by $\text{disc}(e_1, \dots, e_n)$ where e_1, \dots, e_n is K -basis for L in B .

Depending on the situations, we have few ways to compute the discriminant:

- Let Ω/K be field extension for which there are discint $\sigma_1, \dots, \sigma_n \in \text{Hom}_K(L, \Omega)$ then for any $e_1, \dots, e_n \in L$, we have

$$\text{disc}(e_1, \dots, e_n) = \det[\sigma_i(e_j)]_{ij}^2,$$

- For polynomial $f(x) = \prod_i (x - \alpha_i)$ of degree n , then the discriminant of extension $A[x]/(f)$, where α is the image of x in $A[x]/(f)$, is generated by

$$\text{disc}(1, \alpha, \dots, \alpha^{n-1}) = \prod_{i < j} (\alpha_i - \alpha_j)^2.$$

People also define this to be the *discriminant of f* .

Discriminant also respects localisation and completion:

- For S multiplicative subset of A then $S^{-1}D_{B/A} = D_{S^{-1}B/S^{-1}A}$.
- For prime $\mathfrak{q}|\mathfrak{p}$ of B then *Need to learn more ... Check Serre after this.*

2.7. 28/07/2021: Representations of \mathfrak{sl}_2 . Recall on 23/07/2021, I found the following question on Kumar's talk that he mentioned as an "easy observation" (see <https://youtu.be/gph8XNkpdBM?t=368>):

Problem 1. *Show that if $V(\nu)$ appears in the direct sum decomposition of $V(\lambda) \otimes V(\mu)$ into irreducible representations, then $V(m\nu)$ appears in the direct sum decomposition of $V(m\lambda) \otimes V(m\mu)$ for any positive integer m .*

As a first step to answer a question, I just want to review the construction of irreducible representations of $\mathfrak{sl}_2(\mathbb{C})$ via Verma modules.

The Lie algebra \mathfrak{sl}_2 has basis $h = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}, e = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}, f = \begin{bmatrix} 0 & 0 \\ 1 & 0 \end{bmatrix}$ with relations $[h, e] = 2e, [h, f] = -2f, [e, f] = h$.

The adjoint representation $\text{ad} : \mathfrak{g} \rightarrow \text{GL}(\mathfrak{g})$ taking $(x \in \mathfrak{g}) \mapsto (\text{ad } x : y \mapsto [x, y])$ gives us the root system Φ for \mathfrak{g} and the Cartan decomposition $\mathfrak{g} = \mathfrak{h} \oplus \bigoplus_{\alpha \in \Phi} \mathfrak{g}_\alpha$. For \mathfrak{sl}_2 , we find $\mathfrak{sl}_2 = \mathfrak{h} \oplus \mathfrak{g}_\alpha \oplus \mathfrak{g}_{-\alpha} = \mathbb{C}h \oplus \mathbb{C}e \oplus \mathbb{C}f$ where $\alpha \in \Phi = \{\pm\alpha\} \subset \mathfrak{h}^*$ is defined by $\alpha(h) = 2$ (because $[h, e] = 2e$). We choose α to be a simple root, so $\Phi^+ = \{\alpha\}$.

Next, I want to determine the coroots, (co)weights. In order to do this, I first need an identification between \mathfrak{h} and \mathfrak{h}^* . We have the Killing form $\kappa : \mathfrak{g} \times \mathfrak{g} \rightarrow \mathbb{C}$ sending $\kappa(a, b) = \text{Trace}(\text{ad } a \circ \text{ad } b)$ which is nondegenerate when restricting to $\mathfrak{h} \times \mathfrak{h}$. This gives us an inner product on \mathfrak{h} . In our case of \mathfrak{sl}_2 , we find $\kappa(h, h) = 8$.

Because of nondegeneracy of κ , we have an isomorphism $\mathfrak{h}^* \cong \mathfrak{h}$ sending $\lambda \mapsto t_\lambda \in \mathfrak{h}$ defined by $\lambda(h) = \kappa(t_\lambda, h)$. Hence, we can turn κ into an inner product (\cdot, \cdot) on \mathfrak{h}^* by $(\alpha, \beta) := \kappa(t_\alpha, t_\beta)$. In the literatures, there are two ways to define coroots. One is Bourbaki style, where the coroots lying inside \mathfrak{h} while in Humphreys' style, the coroots lying in \mathfrak{h}^* . In Bourbaki's style, the coroot h_λ of $\lambda \in \Phi$ (in Bourbaki, this notation is λ^\vee , but we will save this for Humphreys style) is the unique element in \mathfrak{h} such that $\lambda(h_\lambda) = 2$ (in particular, $h_\lambda = 2t_\lambda / (\kappa(t_\lambda, t_\lambda))$). In Humphreys style, coroot of $\lambda \in \Phi$ is $\lambda^\vee := \frac{2\lambda}{(\lambda, \lambda)}$. One can show that $\langle \alpha, \beta^\vee \rangle = \frac{2(\alpha, \beta)}{(\beta, \beta)} = \alpha(h_\beta) \in \mathbb{Z}$ for all $\beta \in \Phi$. In our case of \mathfrak{sl}_2 , with simple root $\alpha \in \Phi$, we find $t_\alpha = \frac{h}{4}$ as $\alpha(h) = 2$. Hence $h_\alpha = h$ and $\alpha^\vee = \alpha$.

From now on, we will stick to Humphreys style. We can then define the (integral) weight lattice by

$$\Lambda := \{\alpha \in \mathfrak{h}^* \mid \langle \alpha, \beta^\vee \rangle \in \mathbb{Z} \forall \beta \in \Phi\}.$$

In the case of \mathfrak{sl}_2 , we find $\Lambda = \frac{1}{2}\mathbb{Z}\alpha$. Let $\omega = \alpha/2$ then ω is the fundamental weight of α , i.e. $\langle \omega, \alpha^\vee \rangle = 1$. Upon a choice of positive roots Φ^+ , we can define the dominant (integral) weight lattice $\Lambda^+ := \{\alpha \in \mathfrak{h}^* \mid \langle \alpha, \beta^\vee \rangle \in \mathbb{Z}_{>0} \forall \beta \in \Phi^+\}$. In the case of \mathfrak{sl}_2 , we find $\Lambda^+ = \mathbb{Z}_{>0}\omega$.

Next, we will construct the Verma module $M(\lambda)$ for every $\lambda \in \mathfrak{h}^*$. Let $\mathfrak{b} = \mathfrak{h} \oplus \bigoplus_{\alpha \in \Phi^+} \mathfrak{g}_\alpha = \mathfrak{h} \oplus \mathfrak{n}$ to be the Borel subalgebra corresponding to the Cartan subalgebra \mathfrak{h} . In \mathfrak{sl}_2 , $\mathfrak{b} = \mathbb{C}h \oplus \mathbb{C}e, \mathfrak{n} = \mathbb{C}e, \mathfrak{n}^- = \mathbb{C}f$. We define $M(\lambda) := U(\mathfrak{g}) \otimes_{U(\mathfrak{b})} \mathbb{C}_\lambda$ where \mathbb{C}_λ is a 1-dimensional representation of \mathfrak{b} with a trivial action by \mathfrak{n} and \mathfrak{h} acts on \mathbb{C}_λ by λ . Concretely, let $v^+ := 1 \otimes 1 \in M(\lambda)$ then $M(\lambda)$ has \mathbb{C} -basis $U(\mathfrak{n}^-)v^+$, with $\mathfrak{n} \cdot v^+ = 0$ and $h \cdot v^+ = \lambda(h)v^+$. For the case \mathfrak{sl}_2 , $M(\lambda) = \text{span}_{\mathbb{C}}\{f^i v^+\}$, $e \cdot v^+ = 0$ and $h \cdot v^+ = \lambda(h)v^+$. Letting $v_i := \frac{f^i v^+}{i!}$ for $i = 0, 1, \dots$ then we can show that (here we have abused of notation to write λ for $\lambda(h)$):

$$\begin{aligned} h \cdot v_i &= (\lambda - 2i)v_i, \\ e \cdot v_i &= (\lambda - i + 1)v_{i-1}, \\ f \cdot v_i &= (i + 1)v_{i+1}. \end{aligned}$$

$M(\lambda)$ always has a maximal proper submodule $L(\lambda)$ with quotient being a simple module $V(\lambda)$. $V(\lambda)$ is finite dimensional iff $\lambda \in \Lambda^+$. To see this for the case of \mathfrak{sl}_2 , we observe:

- (1) If $\lambda \notin \mathbb{Z}_{\geq 1}$ then $\lambda - i + 1 \neq 0$ for all $i = 1, \dots$, implying $M(\lambda)$ is irreducible. Indeed, starting with any $v \in M(\lambda)$, one can keep applying e to get v_0 .
- (2) If $\lambda \in \mathbb{Z}_{\geq 1}$ then $e \cdot v_{\lambda+1} = 0$. This means $U(\mathfrak{g}) \cdot v_{\lambda+1} = \text{span}_{\mathbb{C}}(v_{\lambda+1}, v_{\lambda+2}, \dots)$ is a maximal submodule of $M(\lambda)$ that is isomorphic to $M(-\lambda - 2) \cong V(-\lambda - 2)$. Its quotient $V(\lambda)$ has dimension $\lambda + 1$ and is irreducible. In $V(\lambda)$, we have $f^{\langle \lambda, \alpha^\vee \rangle + 1} v_0 = f^{\lambda+1} v_0 = 0$.

Now, coming back to Kumar's problem on 23/07/2021:

Problem 2. Show that if $V(\nu)$ appears in the direct sum decomposition of $V(\lambda) \otimes V(\mu)$ into irreducible representations, then $V(m\nu)$ appears in the direct sum decomposition of $V(m\lambda) \otimes V(m\mu)$ for any positive integer m .

I want to do an example for \mathfrak{sl}_2 , based on the description of $V(\lambda)$ above.

Example 3. For \mathfrak{sl}_2 , I will show that $V(1) \otimes V(2) = V(3) \oplus V(1)$. From the problem, I then should have $V(2)$ in $V(2) \otimes V(4)$.

Denote $V(m) := \text{span}_{\mathbb{C}}\{v_{im} : i = 0, 1, \dots\}$ where the v_{im} 's are defined above. Then $v_{01} \otimes v_{02}$ is a highest weight vector in $V(1) \otimes V(2)$ of weight 3, implying $V(3)$ appears in $V(1) \otimes V(2)$. Because $V(1) \otimes V(2)$ has dimension $2 \times 3 = 6$, $V(3)$ has dimension 4 so it can only be $V(1) \otimes V(2) = V(3) \oplus V(1)$. In fact, we can describe $V(1)$ explicitly as a submodule of $V(1) \otimes V(2)$. Note that $v_{01} \otimes v_{12}$ and $v_{11} \otimes v_{02}$ have weight 1. When applying e to both of these, we find a highest weight vector $v_{01} \otimes v_{12} - 2v_{11} \otimes v_{02}$ of weight 1.

We can play the same game to see how $V(2)$ appears in $V(2) \otimes V(4)$. In particular, $v_{i2} \otimes v_{j4}$ for $i + j = 2, 0 \leq i \leq 2, 0 \leq j \leq 4$ are weight vectors of weight 2 in $V(2) \otimes V(4)$. By applying e to these vectors:

- (1) $e(v_{02} \otimes v_{24}) = (4 - 2 + 1)v_{02} \otimes v_{14},$
- (2) $e(v_{12} \otimes v_{14}) = (2 - 1 + 1)v_{02} \otimes v_{14} + (4 - 1 + 1)v_{12} \otimes v_{04},$
- (3) $e(v_{22} \otimes v_{04}) = (2 - 2 + 1)v_{12} \otimes v_{04}.$

Hence, $2v_{02} \otimes v_{24} - 3v_{12} \otimes v_{14} + 12v_{22} \otimes v_{04}$ is a highest weight vector of weight 2.

However, I don't know how to see $V(2)$ lying inside $V(2) \otimes V(4)$ from the fact that $V(1)$ lies inside $V(1) \otimes V(2)$.

Maybe it will help if I go a bit more general, suppose $V(c)$ appears in $V(a) \otimes V(b)$ for \mathfrak{sl}_2 . This means there exists a highest weight vector of weight c in $V(a) \otimes V(b)$. Such vector has the form $\sum_{i+j=(a+b-c)/2} c_{ij} v_{ia} \otimes v_{jb}$. For this to be a highest weight vector, we need

$$\begin{aligned} 0 &= e \cdot \left(\sum_{i+j=(a+b-c)/2} c_{ij} v_{ia} \otimes v_{jb} \right), \\ &= \sum_{i+j=\ell} c_{ij} ((a-i+1)v_{i-1,a} \otimes v_{j,b} + (b-j+1)v_{i,a} \otimes v_{j-1,b}), \quad \ell = (a+b-c)/2 \\ &= \sum_{i+j=\ell-1} (c_{i+1,j}(a-i) + c_{i,j+1}(b-j)) v_{i,a} \otimes v_{j,b}. \end{aligned}$$

To show $V(mc)$ appears in $V(ma) \otimes V(mb)$ for some positive integer m , I want to find a weight vector $\sum_{i+j=m\ell} d_{ij} v_{i,ma} \otimes v_{j,mb}$ of weight mc in $V(ma) \otimes V(mb)$, where $d_{ij} \in \mathbb{C}, \ell = m(a+b-c)/2$, such that it is of highest weight, i.e. for all $i+j = m\ell - 1$ then $d_{i+1,j}(ma-i) + d_{i,j+1}(mb-j) = 0$.

Now this is where I got stuck for the \mathfrak{sl}_2 case ...

2.8. More unresolved questions.

2.8.1. Functional equation of Riemann zeta function. What is the proof of the functional equation of the Riemann zeta function using Poisson summation formula. I read the proof from Terence Tao's blog <https://terrytao.wordpress.com/2008/07/27/tates-proof-of-the-functional-equation/>, <https://math.bu.edu/people/jsweinst/Teaching/MA843/TatesThesis.pdf> or <https://people.reed.edu/~jerry/361/lectures/mats.html> (the continuation and functional equation sections).

Need to explain Mellin transform is Fourier transform on $(\mathbb{R}_{>0}, \cdot)$ by transferring the usual Fourier transform via $\exp : \mathbb{R} \rightarrow \mathbb{R}_{>0}$. To learn more, read <https://people.reed.edu/~jerry/>

361/lectures/mats.html (the Mellin transform section), <https://people.mpim-bonn.mpg.de/zagier/files/tex/MellinTransform/fulltext.pdf>, <https://mathoverflow.net/q/79868/89665>.

Relate this with Tate's thesis, read Fourier analysis on Number fields, <https://math.stackexchange.com/q/25090/58951>.

2.8.2. *Grothendieck's proof of classification of line bundles on \mathbb{P}^1* . See Marielle Ong's <https://drive.google.com/file/d/1yfe91TjF48a0UiZJqEqb8PvRY5yUC20s/view> or Sabin Cautis notes Vector bundles on Riemann surfaces.

See more things about \mathbb{P}^1 at <https://math.berkeley.edu/~qchu/Notes/256B.pdf> or <https://math.stanford.edu/~vakil/725/class21.pdf>.

2.8.3. *Fourier transform*. I want to first explain that Poisson transform is some sort of change of basis formula, i.e. given $f(x)$, we want to write it with respect to some basis $e^{2\pi i x}$ (this choice of basis is invariant under translation in some sense) and this is what the Fourier transform indicates Where can I read more something along this line? See Jacob Lurie <https://www.youtube.com/watch?v=w3f8KEcv4RE&t=2497s>.

2.8.4. *Algebraic groups*. I just want to verify the following facts: SO_n is connected semisimple but is not simply connected.

Some more things to learn

- (1) Learn Langlands' proof of Tamagawa: Fourier inversion <https://people.reed.edu/~jerry/311/mats.html>, Mellin transform <https://people.reed.edu/~jerry/361/lectures/mats.html> <https://people.mpim-bonn.mpg.de/zagier/files/tex/MellinTransform/fulltext.pdf>, Riemann-Zeta functions, spectral theory <https://www.math.nagoya-u.ac.jp/~richard/teaching/s2019/Operators.pdf>, <https://mtaylor.web.unc.edu/wp-content/uploads/sites/16915/2018/04/specthm.pdf>, https://en.wikipedia.org/wiki/Spectral_theorem.
- (2) Geometry:
 - (a) Learn about classification of vector bundles (Hatcher <http://pi.math.cornell.edu/~hatcher/VBKT/VBpage.html>), characteristic classes (e.g. Tu's book, https://web.ma.utexas.edu/users/a.debray/lecture_notes/u17_characteristic_classes.pdf), connections, equivariant cohomology (Tu's book, Geordie's note, see folder) -> Read Atiyah, Bott paper.

3. AUGUST 2021

3.1. 04/08/2021: Tamagawa number for GL_1 over \mathbb{Q} . I will define Tamagawa measure for GL_1 over \mathbb{Q} and then compute its Tamagawa number.

The ideles $\mathrm{GL}_1(\mathbb{A}) = \mathbb{A}^\times$ is the restricted product of \mathbb{Q}_v^\times 's with respect to its compact open \mathbb{Z}_v^\times . We have a norm map

$$|\cdot| : \mathbb{A}^\times \rightarrow \mathbb{R}_{>0}$$

defined by sending $a = (a_v) \in \mathbb{A}^\times$ to $\prod_v |a_v|_v$. The product is well-defined because $a_v \in \mathbb{Z}_v^\times$ for almost all places v of \mathbb{Q} . Its kernel is denoted \mathbb{A}^1 , which is closed in \mathbb{A}^\times . In fact, we have a homeomorphism

$$\begin{aligned} \phi : \mathbb{A}^\times &\rightarrow \mathbb{A}^1 \times \mathbb{R}_{>0}, \\ a = (a_v) &\mapsto ((a_\infty/|a|, a_2, a_3, \dots), |a|), \\ ra &\mapsto (a, r). \end{aligned}$$

Proof that ϕ is a homeomorphism. The map $(a, r) \mapsto ra$ from $\mathbb{A}^1 \times \mathbb{R}_{>0} \rightarrow \mathbb{A}^\times$ is continuous because \mathbb{A}^\times is a topological ring with multiplication map being continuous, and that the two maps $\mathbb{A}^1 \hookrightarrow \mathbb{A}^\times$ and $\mathbb{R}_{>0} \hookrightarrow \mathbb{A}^\times$ are continuous.

We just need to show its inverse ϕ is also continuous. \mathbb{A}^1 has basis of open sets

$$U_S := \left\{ a = (a_v) \in U_\infty \times \prod_{p \in S \setminus \{\infty\}} b_p(1 + p^{k_p} \mathbb{Z}_p) \times \prod_{v \notin S} \mathbb{Z}_v^\times : \prod_{v \in S} |a_v|_v = 1 \right\}.$$

where S is a finite set of places of \mathbb{Q} containing the infinite place. Let U be an open subset in $\mathbb{R}_{>0}$. Then the preimage $\phi^{-1}(U_S \times U)$ is

$$U_\infty U \times \prod_{p \in S \setminus \{\infty\}} b_p(1 + p^{k_p} \mathbb{Z}_p) \times \prod_{v \notin S} \mathbb{Z}_v^\times$$

which is open. □

To define the Tamagawa measure $\mu_{\mathrm{GL}_1, \mathbb{Q}}$ on \mathbb{A}^\times , we choose a left-invariant differential form $\omega = x^{-1}dx$ on $\mathrm{GL}_1(\mathbb{Q})$. It is left-invariant because left-multiplication by $a \in \mathbb{Q}$ gives $L_a(x^{-1}dx) = (ax)^{-1}d(ax) = x^{-1}dx$. Over each completion of \mathbb{Q} , this induces a left-invariant Haar measure $\mu_{\mathrm{GL}_1(\mathbb{Q}_v), \omega} = d|\omega|_v$ on \mathbb{Q}_v^\times by integrating over ω . It is left-invariant because we have the change of variables formula, even over \mathbb{Q}_p , i.e.

$$\int_{\mathbb{Q}_v^\times} f(x) |x|_v^{-1} d|x|_v = \int_{\mathbb{Q}_v^\times} f(x) d|\omega|_v = \int_{\mathbb{Q}_v^\times} f(ax) d|L_a \omega|_v = \int_{\mathbb{Q}_v^\times} f(ax) |x|_v^{-1} d|x|_v,$$

where $f(x)$ is a complex-valued continuous function with compact support on \mathbb{Q}_v^\times , $d|x|_v$ is the Haar measure on \mathbb{Q}_v . Here \mathbb{Q}_∞^\times means \mathbb{R}^\times . For example, we can compute

$$\mu_{\mathbb{Q}_p^\times, \omega}(\mathbb{Z}_p^\times) = \int_{\mathbb{Z}_p^\times} |x|_p^{-1} d|x|_p = \int_{\mathbb{Z}_p^\times} d|x|_p = \sum_{i=1}^{p-1} \int_{i+p\mathbb{Z}_p} d|x|_p = (p-1) \int_{p\mathbb{Z}_p} d|x|_p = \frac{p-1}{p}.$$

Let the Tamagawa measure on \mathbb{A}^\times over \mathbb{Q} to be essentially the product measure

$$\mu_{\mathbb{R}^\times, \omega} \times \prod_p \left(1 - \frac{1}{p}\right)^{-1} \mu_{\mathbb{Q}_p^\times, \omega}$$

In other words, there is a unique Haar measure on \mathbb{A}^\times such that over the open set $\prod_{v \in S} U_v \times \prod_{v \notin S} \mathbb{Z}_v^\times$ where S is a finite set of places of \mathbb{Q} containing the infinite place, the measure is by taking the product of measures of each local part.

Because of the homeomorphism $\mathbb{A}^\times \cong \mathbb{A}^1 \times \mathbb{R}_{>0}$, if we give $\mathbb{R}_{>0}$ the natural Haar measure obtained by integrating $x^{-1}dx$, this determines a Haar measure da_1 on \mathbb{A}^1 satisfying

$$\int_{\mathbb{A}^\times} f(x) \mu_{\mathrm{GL}_1, \mathbb{Q}}(x) = \int_{\mathbb{R}_{>0}} \int_{\mathbb{A}^1} f(a_1 t) t^{-1} da_1 dt.$$

As \mathbb{Q}^\times is discrete in \mathbb{A}^1 , this induces a measure $\mu'_{\mathrm{GL}_1, \mathbb{Q}}$ on $\mathbb{Q}^\times \setminus \mathbb{A}^1$. We define the Tamagawa number for GL_1 over \mathbb{Q} to be

$$\tau(\mathrm{GL}_1, \mathbb{Q}) := \int_{\mathbb{Q}^\times \setminus \mathbb{A}^1} \mu'_{\mathrm{GL}_1, \mathbb{Q}}.$$

To compute $\tau(\mathrm{GL}_1, \mathbb{Q})$, we will determine a fundamental domain for $\mathbb{Q}^\times \setminus \mathbb{A}^1$, based on the following proposition:

Proposition 4. *We have*

- (a) \mathbb{Q}^\times is dense in $\mathrm{GL}_1(\mathbb{A}^\infty)$, implying $\mathbb{Q}^\times \setminus (\mathbb{A}^\times)^\infty / \widehat{\mathbb{Z}}^\times = \{1\}$.
- (b) We have a homeomorphism $\mathbb{Q}^\times \setminus \mathbb{A}^\times \cong (\{\pm 1\} \setminus \mathbb{R}^\times) \times \widehat{\mathbb{Z}}^\times$.

Proof. (a) We need to show every basis of open sets of $\mathrm{GL}_1(\mathbb{A}^\times)$ contains an element in \mathbb{Q}^\times . A basis of open sets of $\mathrm{GL}_1(\mathbb{A}^\times)$ consists of $\prod_{p \in S \setminus \{\infty\}} a_p (1 + p^{k_p} \mathbb{Z}_p) \times \prod_{p \notin S \cup \{\infty\}} \mathbb{Z}_p^\times$, where S is a finite set of places of \mathbb{R} containing the infinite place, $k_p \in \mathbb{Z}_{\geq 1}$ (as then $1 + p^{k_p} \mathbb{Z}_p$ is open neighborhood of 1 in \mathbb{Q}_p^\times), $a_p \in \mathbb{Q}^\times$ (for any $a_p \in \mathbb{Q}_p^\times$, you can always find $a'_p \in \mathbb{Q}^\times$ so $a_p - a'_p \in p^{k_p} \mathbb{Z}_p$). By Chinese Remainder Theorem, there exists $q \in \mathbb{Q}^\times$ such that $q \equiv a_p \pmod{p^{k_p}}$ for all $p \in S \setminus \{\infty\}$ and q only has primes $p \in S \setminus \{\infty\}$ in its prime factorisation. This implies q lies in the desired open set.

To see $(\mathbb{A})^\infty = \mathbb{Q}^\times \cdot \widehat{\mathbb{Z}}^\times$, as $\widehat{\mathbb{Z}}^\times$ is compact open in $(\mathbb{A})^\times$, any $a \in (\mathbb{A})^\infty$ then the open set $a\widehat{\mathbb{Z}}^\times$ must contains an element in \mathbb{Q}^\times , as desired.

(b) We define the map

$$\begin{aligned} \phi : (\{\pm 1\} \setminus \mathbb{R}^\times) \times \widehat{\mathbb{Z}}^\times &\rightarrow \mathbb{Q}^\times \setminus \mathbb{A}^\times, \\ (r + \{\pm 1\}, z) &\mapsto rz. \end{aligned}$$

Note that $\{\pm 1\} = \widehat{\mathbb{Z}}^\times \cap \mathbb{Q}^\times$, one can then show that ϕ is indeed a homeomorphism. Be careful that $\widehat{\mathbb{Z}}^\times$ and \mathbb{Q}^\times are embedded differently into \mathbb{A}^\times . \square

From this proposition, as $\mathbb{A}^1 \cong \mathbb{A}^\times / \mathbb{R}_{>0}$ so $\mathbb{Q}^\times \setminus \mathbb{A}^1 \cong \mathbb{Q}^\times \setminus \mathbb{A} / \mathbb{R}_{>0} \cong \widehat{\mathbb{Z}}^\times$. Thus, we have

$$\begin{aligned} \tau(\mathrm{GL}_1, \mathbb{Q}) &= \int_{\widehat{\mathbb{Z}}^\times} \mu_{\mathrm{GL}_1, \mathbb{Q}}, \\ &= \prod_p \left(1 - \frac{1}{p}\right)^{-1} \int_{\mathbb{Z}_p^\times} \mu_{\mathbb{Q}_p^\times, \omega}, \\ &= \prod_p \left(1 - \frac{1}{p}\right)^{-1} \frac{p-1}{p}, \\ &= 1. \end{aligned}$$

Now, something I would like to learn next:

- (1) How to write the above description but for GL_n .
- (2) What happen over other number fields/function fields?

3.2. 07/08/2021: Global left-invariant top form of SL_2 . GL_2 has a global left-invariant top form $\det(x_{ij})^{-2} dx_{11} \wedge dx_{12} \wedge dx_{21} \wedge dx_{22}$. I want to use this and the map $\mathrm{SL}_2 \times \mathbb{G}_m \rightarrow \mathrm{GL}_2$ to find a global left-invariant top form of SL_2 .

3.2.1. *Sheaf of differentials.* We want to mimic the following construction in differential geometry to algebraic geometry language: Given a smooth map $\phi : X \rightarrow Y$ of smooth manifolds, this induces map $\phi^* : T^*Y \rightarrow T^*X$ of cotangent bundles.

I read this from Neron models book, chapter 2, p. 33.

First, we will describe the sheaf of differentials (i.e. the cotangent bundles in differential geometry) $\Omega_{X/k}$ for an affine scheme $X = \text{Spec } A$. To do this, I will need to introduce the *module of differentials* $\Omega_{A/k}$. It is an A -module equipped with a k -derivation $d : A \rightarrow \Omega_{A/k}$ (i.e. a k -linear map such that $d(fg) = fd(g) + gd(f)$ for $g, f \in A$) such that it is universal among those A -modules M with A -derivation $d_M : A \rightarrow M$. The *sheaf of differentials* $\Omega_{X/k}$ is then the sheaf of \mathcal{O}_X -modules corresponding to the module of differential $\Omega_{A/k}$. In particular, over open set $D(f)$ of X where $f \in A$, its sections are $\Gamma(D(f), \Omega_{X/k}) = (\Omega_{A/k})_f$.

We start with $\phi : X = \text{Spec } A \rightarrow Y = \text{Spec } B$ a morphism of affine schemes over k . This gives us a ring map $B \rightarrow A$ and a morphism $\mathcal{O}_Y \rightarrow \phi_*\mathcal{O}_X$ of sheaves of rings over Y ².

I claim that we have a morphism

$$\Phi : \phi^*\Omega_{Y/k} \rightarrow \Omega_{X/k}$$

of sheaves of \mathcal{O}_X -modules that resembles $T^*Y \rightarrow T^*X$ in differential geometry.

I will describe $\phi_*\Omega_{Y/k}$ first. It is a sheaf of \mathcal{O}_X -modules obtained by pulling back $\Omega_{Y/k}$ along $\phi : X \rightarrow Y$. Its sections over open U of X forms a $\mathcal{O}_X(U)$ -module $\Omega_{Y/k}(\phi^{-1}(U)) \otimes_{\mathcal{O}_Y(\phi^{-1}(U))} \mathcal{O}_X(U)$. In other words, it is a sheaf of \mathcal{O}_X -modules corresponding to the A -module $\Omega_{B/k} \otimes_B A$.

Thus, to describe Φ , we just need to know a map $\Omega_{B/k} \otimes_B A \rightarrow \Omega_{A/k}$ of A -modules.

By composing the ring map $B \rightarrow A$ with d_A , we get a k -derivation map corresponding to the B -module $\Omega_{A/k}$, hence by universal property of $\Omega_{B/k}$, this induces a map of B -modules

$$\begin{aligned} \Omega_{B/k} &\rightarrow \Omega_{A/k} \\ fd_B(g) &\mapsto \phi(f)d_A(\phi(g)), \quad f, g \in B. \end{aligned}$$

We then also have a morphism of A -modules

$$\Omega_{B/k} \otimes_B A \rightarrow \Omega_{A/k}.$$

3.2.2. *Global left-invariant top form of GL_2 .* I want to determine a left-invariant global differential form of top degree for GL_2 .

Firstly, the module of differential $\Omega_{\mathcal{O}(\text{GL}_2)/k}$ is the $\mathcal{O}(\text{GL}_2)$ -module generated by dx_{ij}, dt for $1 \leq i, j \leq 2$, modulo the relation

$$0 = d(t(x_{11}x_{22} - x_{21}x_{12}) - 1) = td(x_{11}x_{22} - x_{21}x_{12}) + (x_{11}x_{22} - x_{12}x_{21})dt.$$

As in $\mathcal{O}(\text{GL}_2)$, $(x_{11}x_{22} - x_{12}x_{21})t = 1$ so we can write

$$(2) \quad dt = -t^2 d(x_{11}x_{22} - x_{21}x_{12}).$$

Consider left-multiplication by $a = \begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix} \in \text{GL}_2(k)$ via

$$\begin{aligned} L_a : \mathcal{O}(\text{GL}_2) &\rightarrow \mathcal{O}(\text{GL}_2), \\ x_{ij} &\mapsto a_{i1}x_{1j} + a_{i2}x_{2j}, \\ t &\mapsto (a_{11}a_{22} - a_{12}a_{21})^{-1}t. \end{aligned}$$

²At some point, I was confused on whether the arrow should be $\mathcal{O}_Y \rightarrow \phi_*\mathcal{O}_X$ or the other way around. To convince myself on this, just view \mathcal{O}_Y as functions on Y and \mathcal{O}_X as functions on X , and we know a function on Y induces a function on X by precomposing with ϕ .

This induces a morphism of $\mathcal{O}(\mathrm{GL}_2)$ -modules

$$L_a : \bigwedge_{i,j=1}^2 \Omega_{\mathcal{O}(\mathrm{GL}_2)/k} \rightarrow \bigwedge_{i,j=1}^2 \Omega_{\mathcal{O}(\mathrm{GL}_2)/k},$$

$$f \bigwedge_{i,j=1}^2 dx_{ij} \mapsto L_a(f) \bigwedge_{i,j=1}^2 (a_{i1}dx_{1j} + a_{i2}dx_{2j}).$$

Note that we only need to specify what $\bigwedge_{i,j} dx_{ij}$ is sent to because dt is determined from (2). I want to find $f \in \mathcal{O}(\mathrm{GL}_2)$ so $L_a(f \bigwedge_{i,j} dx_{ij}) = f \bigwedge_{i,j} dx_{ij}$, or

$$L_a(f) \det(a_{ij})^2 dx_{11} \wedge dx_{12} \wedge dx_{21} \wedge dx_{22} = f dx_{11} \wedge dx_{12} \wedge dx_{21} \wedge dx_{22}.$$

Thus, we want $f \in \mathcal{O}(\mathrm{GL}_2)$ such that $L_a(f) \det(a_{ij})^2 = f$ for all $a \in \mathrm{GL}_2(k)$. Note that $f = t^2$ satisfies this.

3.2.3. Global left-invariant top form of SL_2 . Now, I want to focus on an example $\phi : \mathrm{SL}_2 \times \mathbb{G}_m \rightarrow \mathrm{GL}_2$, defined by

$$\left(\begin{pmatrix} x_{11} & x_{12} \\ x_{21} & x_{22} \end{pmatrix}, t \right) \mapsto \begin{pmatrix} tx_{11} & tx_{12} \\ x_{21} & x_{22} \end{pmatrix}.$$

From this map and the corresponding left-invariant top form of GL_2 , I want to obtain a left-invariant global top differential form of SL_2 .

We first have an isomorphism $\phi' : \mathcal{O}(\mathrm{GL}_2) \rightarrow \mathcal{O}(\mathrm{SL}_2) \otimes \mathcal{O}(\mathbb{G}_m)$ of k -algebras given by

$$\begin{aligned} \phi' : k[x_{ij}, t] / (t(x_{11}x_{22} - x_{21}x_{12}) - 1) &\rightarrow k[x_{ij}] / (x_{11}x_{22} - x_{21}x_{12} - 1) \otimes_k k[t, t^{-1}], \\ x_{11} &\mapsto tx_{11}, \\ x_{12} &\mapsto tx_{12}, \\ x_{21} &\mapsto x_{21}, \\ x_{22} &\mapsto x_{22}, \\ t &\mapsto t^{-1}. \end{aligned}$$

The module of differentials $\Omega_{\mathcal{O}(\mathrm{SL}_2)/k}$ is the $\mathcal{O}(\mathrm{SL}_2)$ -module generated by dx_{ij} for $1 \leq i, j \leq 2$, modulo the relation

$$0 = d(x_{11}x_{22} - x_{12}x_{21} - 1) = x_{11}dx_{22} + x_{22}dx_{11} - x_{12}dx_{21} - x_{21}dx_{12}.$$

And $\Omega_{\mathcal{O}(\mathbb{G}_m)/k}$ is the $\mathcal{O}(\mathbb{G}_m)$ -module generated by dt with the k -derivation $dt^{-1} := -t^{-2}dt$.

The module of differentials $\Omega_{\mathcal{O}(\mathrm{SL}_2 \times \mathbb{G}_m)/k}$ is the $\mathcal{O}(\mathrm{SL}_2) \otimes_k \mathcal{O}(\mathbb{G}_m)$ -module generated by dx_{ij} for $1 \leq i, j \leq 2$ and dt modulo the relation $d(x_{11}x_{22} - x_{21}x_{12}) = 0$, with the differential $dt^{-1} := -t^{-2}dt$. In particular, one can show that

$$\Omega_{\mathcal{O}(\mathrm{SL}_2 \times \mathbb{G}_m)/k} \cong \Omega_{\mathcal{O}(\mathrm{SL}_2)/k} \otimes_{\mathcal{O}(\mathrm{SL}_2)} \mathcal{O}(\mathrm{SL}_2 \times \mathbb{G}_m) \oplus \Omega_{\mathcal{O}(\mathbb{G}_m)/k} \otimes_{\mathcal{O}(\mathbb{G}_m)} \mathcal{O}(\mathrm{SL}_2 \times \mathbb{G}_m),$$

which we will write $\Omega_{\mathcal{O}(\mathrm{SL}_2 \times \mathbb{G}_m)/k} \cong \Omega_{\mathcal{O}(\mathrm{SL}_2)/k} \oplus \Omega_{\mathcal{O}(\mathbb{G}_m)/k}$ for convenience. This induces an isomorphism of $\mathcal{O}(\mathrm{SL}_2) \otimes_k \mathcal{O}(\mathbb{G}_m)$ -modules

$$\bigwedge^4 \Omega_{\mathcal{O}(\mathrm{SL}_2 \times \mathbb{G}_m)/k} \cong \Omega_{\mathcal{O}(\mathbb{G}_m)/k} \wedge \bigwedge^3 \Omega_{\mathcal{O}(\mathrm{SL}_2)/k}.$$

From ϕ' , we have a morphism of $\mathcal{O}(\mathrm{GL}_2)$ -module

$$\Omega_{\mathcal{O}(\mathrm{GL}_2)/k} \rightarrow \Omega_{\mathcal{O}(\mathrm{SL}_2 \times \mathbb{G}_m)/k},$$

inducing a morphism of $\mathcal{O}(\mathrm{SL}_2) \otimes_k \mathcal{O}(\mathbb{G}_m)$ -module

$$\Omega_{\mathcal{O}(\mathrm{GL}_2)/k} \otimes_{\mathcal{O}(\mathrm{GL}_2)/k} (\mathcal{O}(\mathrm{SL}_2) \otimes_k \mathcal{O}(\mathbb{G}_m)) \rightarrow \Omega_{\mathcal{O}(\mathrm{SL}_2 \times \mathbb{G}_m)/k}.$$

This is the map obtained by taking global sections of

$$\Phi : \phi^* \Omega_{\mathrm{GL}_2/k} \rightarrow \Omega_{\mathrm{SL}_2 \times \mathbb{G}_m/k}.$$

With this, we have a morphism of top forms $\bigwedge^4 \phi^* \Omega_{\mathrm{GL}_2/k} \rightarrow \bigwedge^4 \Omega_{\mathrm{SL}_2 \times \mathbb{G}_m/k}$, whose global sections sends

$$\begin{aligned} \bigwedge_{i,j=1}^2 dx_{ij} &\mapsto d(tx_{11}) \wedge d(tx_{12}) \wedge dx_{21} \wedge dx_{22}, \\ &= (tdx_{11} + x_{11}dt) \wedge (tdx_{12} + x_{12}dt) \wedge dx_{21} \wedge dx_{22}, \\ &= t^2 dx_{11} \wedge dx_{12} \wedge dx_{21} \wedge dx_{22} \\ &\quad + tx_{11}dt \wedge dx_{12} \wedge dx_{21} \wedge dx_{22} \\ &\quad - tx_{12}dt \wedge dx_{11} \wedge dx_{21} \wedge dx_{22}. \end{aligned}$$

Note that $x_{11}x_{22} - x_{21}x_{12} = 1$ in the $\mathcal{O}(\mathrm{SL}_2) \otimes_k \mathcal{O}(\mathbb{G}_m)$ -module $\bigwedge^4 \Omega_{\mathcal{O}(\mathrm{SL}_2 \times \mathbb{G}_m)/k}$ and that $d(x_{11}x_{22} - x_{21}x_{12}) = 0$ so

$$dx_{11} \wedge dx_{12} \wedge dx_{21} \wedge dx_{22} = (x_{11}x_{22} - x_{21}x_{12})dx_{11} \wedge dx_{12} \wedge dx_{21} \wedge dx_{22} = 0.$$

In the end, we find

$$t^2 \bigwedge_{i,j=1}^2 dx_{ij} \mapsto t^{-1}dt \wedge (x_{11}dx_{12} \wedge dx_{21} \wedge dx_{22} - x_{12}dx_{11} \wedge dx_{21} \wedge dx_{22}).$$

From previous section, $t^2 \bigwedge_{i,j} dx_{ij}$ is a global left-invariant top form of GL_2 . We also know $t^{-1}dt$ is the global left-invariant top form of \mathbb{G}_m . This should imply that

$$\omega = x_{11}dx_{12} \wedge dx_{21} \wedge dx_{22} - x_{12}dx_{11} \wedge dx_{21} \wedge dx_{22}$$

is a global left-invariant top form of SL_2 Is this correct? If yes, what is the quickest way to check this?

3.3. 11/08/2021: $V(m\nu)$ in $V(m\lambda) \otimes V(m\mu)$. I want to continue to solve the problem I had on 28/07/2021. I learnt this proof from Travis.

Lemma 5. *There is a unique copy $V(m\lambda)$ in $V(\lambda)^{\otimes m}$ that contains $v^{\otimes m}$ for every $v \in V(\lambda)$.*

Proof. We denote v_λ to be the highest weight vector of weight λ in $V(\lambda)$. Then $v_\lambda^{\otimes m}$ is a highest weight vector of weight $m\lambda$ in $V(\lambda)^{\otimes m}$ so $V(\lambda)^{\otimes m}$ contains a copy of $V(m\lambda)$.

There is only one copy of $V(m\lambda)$ in $V(\lambda)^{\otimes m}$ because $v_\lambda^{\otimes m}$ is the only vector of highest weight λ in $V(\lambda)^{\otimes m}$ (up to linear independence). Indeed, suppose $\sum_{i=1}^n c_i v_{i1} \otimes v_{i2} \otimes \cdots \otimes v_{im}$ is a highest weight vector of weight $m\lambda$ where $0 \neq c_i \in \mathbb{C}$ and v_{ik} is a weight vector of weight λ_{ik} , then from $h \cdot \sum_{i=1}^n c_i v_{i1} \otimes v_{i2} \otimes \cdots \otimes v_{im} = (m\lambda)(h) \sum_{i=1}^n c_i v_{i1} \otimes v_{i2} \otimes \cdots \otimes v_{im}$, we find $m\lambda = \sum_{k=1}^m \lambda_{ik}$ for every $1 \leq i \leq n$. Because $\lambda_{ik} \leq \lambda$ for every i, k so we find $\lambda_{ik} = \lambda$ for every i, k , as desired.

$V(m\lambda)$ in $V(\lambda)^{\otimes m}$ contains $v^{\otimes m}$ for every $v \in V(\lambda)$ because $U(\mathfrak{g}) \cdot v^{\otimes m}$ contains $v_\lambda^{\otimes m}$. Indeed, let $v = \sum_{i=1}^\ell a_i v_i$ where v_i is a weight vector of weight $\mu_i \leq \lambda$ ($\mu_i \neq \mu_j$ for $i \neq j$) and $a_i \in \mathbb{C} \setminus \{0\}$. Let $\lambda - \mu_j = \sum_{i=1}^k c_{ij} \alpha_i$ where α_i 's are the simple roots, $c_{ij} \in \mathbb{Z}_{\geq 1}$.

We can choose a μ_1 among μ_j 's such that $c_{11} = \max_j \{c_{1j}\}$; c_{21} is maximal among those c_{2j} 's of μ_j 's satisfying $c_{1j} = c_{11}$; c_{31} is maximal among those c_{3j} 's of μ_j 's satisfying $c_{1j} = c_{11}, c_{21} = c_{2j}$; ...

With this, by letting $e_i \in \mathfrak{n}$ that corresponds to the simple root α_i , we find $e_1^{c_{11}} \cdots e_k^{c_{k1}} v_j = 0$ for $j \neq 1$ and $0 \neq e_1^{c_{11}} \cdots e_k^{c_{k1}} v_1 \in \mathbb{C}v_\lambda$. Thus, when $g = e_1^{c_{11}} \cdots e_k^{c_{k1}}$ then $gv \in \mathbb{C}v_\lambda$, while $g^2v = 0$. This follows $g^m v^{\otimes m} = m!(gv)^{\otimes m}$, as desired. \square

Lemma 6. *For \mathfrak{g} -modules V, W then $V \otimes W \cong W \otimes V$ by sending $v \otimes w \mapsto w \otimes v$.*

Proof. It suffices to check that the map $f : V \otimes W \rightarrow W \otimes V$ is a \mathfrak{g} -module homomorphism. Indeed, $f(g(v \otimes w)) = f((gv) \otimes w + v \otimes (gw)) = w \otimes (gv) + (gw) \otimes v = g(w \otimes v) = g \cdot f(v \otimes w)$. This argument is the same as saying that $U(\mathfrak{g})$ is cocommutative, i.e. comultiplication $\Delta : U(\mathfrak{g}) \rightarrow U(\mathfrak{g}) \otimes U(\mathfrak{g})$, defined by $\Delta(g) = g \otimes 1 + 1 \otimes g$ for $g \in \mathfrak{g}$, commutes with $\tau : U(\mathfrak{g}) \otimes U(\mathfrak{g}) \rightarrow U(\mathfrak{g}) \otimes U(\mathfrak{g})$, where τ is the permutation map. \square

Back to the problem, we want to show that $V(m\lambda) \otimes V(m\mu)$ contains a copy of $V(m\nu)$. There exists a highest weight vector of $V(\nu)$ in $V(\lambda) \otimes V(\mu)$. By the construction of tensor product, we can write it as $v \otimes w$ where $v \in V(\lambda), w \in V(\mu)$.

We also know that $(V(\lambda) \otimes V(\mu))^{\otimes m} \cong V(\lambda)^{\otimes m} \otimes V(\mu)^{\otimes m}$ sends $(v \otimes w)^{\otimes m}$ to $v^{\otimes m} \otimes w^{\otimes m}$. We have $(v \otimes w)^{\otimes m}$ is of highest weight $m\nu$. From the previous lemma, we know $v^{\otimes m} \in V(m\lambda)$ and $w^{\otimes m} \in V(m\mu)$ so $U(\mathfrak{g}) \cdot v^{\otimes m} \otimes w^{\otimes m}$ is a submodule of $V(m\lambda) \otimes V(m\mu)$ in $V(\lambda)^{\otimes m} \otimes V(\mu)^{\otimes m}$. With this, we conclude $V(m\lambda) \otimes V(m\mu)$ contains a copy of $V(m\nu)$.

3.4. 12/08/2021: Tate vector spaces. I read something interesting called Tate vector spaces. It refers to an infinite dimensional vector space V equipped with a set of lattices in V such that V is isomorphic to the inverse limit of V/L where L runs through lattices in V .

This notion generalises other spaces such as the Grassmannians, adeles, $k((t))$.

There are dimension theory (i.e. assign each lattice in V a number, called dimension) and determinant theory (i.e. assign each each lattice in V a line) for Tate vector space V generalise certain constructions in the above mentioned examples. For the determinant theory, one can use it to construct central extensions of $GL(V)$ and somehow people want to do this ...

Need to read more at <http://page.mi.fu-berlin.de/groemich/chicago.pdf> by Michael Groechenig and [https://people.math.harvard.edu/~gaitsgde/grad_2009/SeminarNotes/Nov3-10\(CentExt\).pdf](https://people.math.harvard.edu/~gaitsgde/grad_2009/SeminarNotes/Nov3-10(CentExt).pdf) by Dustin Clausen.

3.5. 13/08/2021: Inner product and Hom. Madeline pointed out to the category theory reading group that in Etingof's book on representation theory (p. 189 of <http://www-math.mit.edu/~etingof/reprbook.pdf>), there is a myterious dictionary between a category and a vector space V equipped with a nondegenerate inner product. In particular, an inner product (x, y) in V is analogous to $\text{Hom}(X, Y)$ in a category. I wonder if we can make this analogy more formal. I suspect it is some sort of (de)categorification, although I am not too sure about this.

Let me try to describe this analogy in the case our category is $\text{Rep}(G)$, i.e. the category of finite-dimensional complex representations of a finite group G . Then the vector space is vector space V of class functions, i.e. complex-valued functions on G that is invariant under conjugation action of G . This the space where all characters of representations live. One can equipp V with a Hermitian inner product. For example, if χ_V, χ_W are characters of representations V, W of G , then $\langle \chi_V, \chi_W \rangle = \dim \text{Hom}(V, W)$. In some sense, $\text{Rep}(G)$ is the categorification of V , where orthonormal basis of V corresponds to irreducible representations.

This reminds me of a question I had on 06/06/2021 about the relation between adjoint operators and adjoint functors.

Nasos told us that John Baez have done something related to this dictionary in this paper of his: Higher-Dimensional Algebra II: 2-Hilbert Spaces <https://arxiv.org/pdf/q-alg/9609018.pdf>.

3.6. 14/08/2021: Principal G -bundles. I want to digest the definition of principal G -bundles, as it seems to me that there are many ways to phrase this notion and different sources define principal bundles differently, depending on how nice the space of consideration is.

Update 30/09/2021: Brian Conrad wrote some notes with many examples on taking quotient by a group action <https://math.stanford.edu/~conrad/diffgeomPage/handouts/qtmanifold.pdf>.

In this discussion, every topological space is assumed to be Hausdorff.

We start off with one definition of principal G -bundles, taken from Cohen's lecture notes on The Topology of Fiber Bundles or Stephen A. Mitchell's notes <https://sites.math.washington.edu/~mitchell/Notes/prin.pdf>.

Definition 7. For a topological group G , a principal G -bundle P over X is a (surjective) continuous map $\pi : P \rightarrow X$ satisfying the following conditions:

- (1) G acts on the right on P ;
- (2) Local trivialisation: There is an open cover $\{U\}$ of X such that for each such U , we have a homeomorphism $\pi_U : \pi^{-1}(U) \rightarrow U \times G$ that is G -equivariant satisfying

$$\begin{array}{ccc} \pi^{-1}(U) & \xrightarrow[\pi_U]{\sim} & U \times G \\ & \searrow \pi \quad \swarrow & \\ & U & \end{array}$$

Here g acts on $U \times G$ by $(u, g)g' = (u, gg')$.

Firstly, π_U being G -equivariant tells us that G acts on fiber P_x . Indeed, for a local trivialisation (U, π_U) at x , if $p \in P_x$ so $\pi_U(p) = (x, g)$, we find $\pi_U(pg') = \pi_U(p)g' = (x, gg')$. Hence, $pg' \in P_x$. To say G acts on fibers is the same as saying $\pi : P \rightarrow X$ is G -equivariant with trivial G -action on X .

Furthermore, π_U being bijective implies G acts simply transitively on P_x . Indeed, choose a local trivialisation (U, π_U) of x , for any $y, z \in P_x$, let $\pi_U(y) = (x, g_y)$ and $\pi_U(z) = (x, g_z)$ then there exists a unique $g \in G$ so $g_y g = g_z$, implying $\pi_U(z) = \pi_U(y)g = \pi_U(yg)$. Hence, there exists unique $g \in G$ so $z = yg$.

On the other hand, π_U being a G -equivariant bijection implies that G acts freely (i.e. trivial stabiliser) on P . Indeed, if we have $p \in P$ and $g \in G$ so $pg = p$ then by choosing a local trivialisation (U, π_U) of $\pi(p)$, we find $(\pi(p), g') = \pi_U(p) = \pi_U(pg) = \pi_U(p)g = (\pi(p), g'g)$. Hence, $g' = g'g$ so $g = 1$.

Because G acts simply transitively on P_x , we know that for any $y \in P_x$, the map $G \rightarrow P_x$ defined by $g \mapsto yg$ is a continuous bijection³. However, we cannot say anything more than this. In particular, this does not imply that G is homeomorphic to P_x , i.e. P_x is a G -torsor, which is what we want when we define principal G -bundles⁴. Hence, we would like to add the following condition to the definition

Definition 8. We add the following condition to our definition of principal G -bundle $\pi : P \rightarrow X$.

- (1) For every $y \in P_x$, the morphism $G \rightarrow P_x$ defined by $g \mapsto yg$ is a homeomorphism.

In the case where our spaces are smooth manifolds and G is a Lie group, this condition automatically holds, see p.5 <https://www.mathi.uni-heidelberg.de/~lee/MenelaosSS16.pdf>. The reason roughly is that the map $G \rightarrow P_x$ is of constant rank and bijective, hence a diffeomorphism.

³One can show $f_y : G \rightarrow P_x$ is continuous when assuming P_x (or P) is Hausdorff. Indeed, since G acts continuously on P_x via $\phi : P_x \times G \rightarrow P_x$, for any closed subset U of P_x , we know $\phi^{-1}(U) \cap (\{y\} \times G)$ is closed, implying $\phi_y : G \rightarrow P_x$, defined by $\phi_y(g) = yg$, is continuous

⁴For example, consider $G = \mathbb{R}$ with discrete topology acts on $P = \mathbb{R}$ with the usual topology, then G is not homeomorphic to $P_x = \mathbb{R}$.

An equivalent way to phrase this condition is that the map $\phi : P \times G \rightarrow P \times P$, defined by $(x, g) \mapsto (x, xg)$, is a homeomorphism. Indeed, for closed subset U in G then $\phi(\{x\} \times U)$ is closed. Hence, $\phi_x : g \mapsto xg$ is a closed map. We know ϕ_x is a continuous bijection so this implies ϕ_x is a homeomorphism.

An equivalent way to say $\pi : P \rightarrow X$ has local trivialisations is to say it has local sections.

If $\pi : P \rightarrow X$ admits local sections, i.e. for every x there is a continuous section $s : U \rightarrow P$ on some open neighborhood U of x , then this will imply local trivialisation condition. Indeed, we can define $\pi_U^{-1}(u, g) = s(u) \cdot g$. The map is bijective since G acts simply transitively on fibers. Indeed, if $s(u')g = s(u)g'$ then $u = u'$ and for any $p \in \pi^{-1}(U)$, there exists a unique $g \in G$ so $s(\pi(p)) \cdot g = p$. The map is continuous as it is the composition of $U \times G \xrightarrow{s \times \text{id}_G} P \times G \rightarrow P$. *I cannot seem to show that this map is a homeomorphism, i.e. it is open/closed with the current assumption on X, P ?* It seems for this to be true, s needs to be homeomorphic onto its image, then π_U^{-1} is an open map. For this to work, I can assume extra condition that X is locally compact Hausdorff, which means we can assume U is compact (or restrict U to a compact neighborhood). Then we have $s : U \rightarrow s(U)$ is a bijective continuous map from compact U to Hausdorff $s(U)$, implying s is a homeomorphism onto its image. Thus, π_U is a local trivialisation.

Conversely, if we are given a local trivialisation (U, π_U) of a principal G -bundle $\pi : P \rightarrow X$, we can define a local section $s : U \rightarrow P$ by $s(u) := \pi_U^{-1}(u, 1)$. To check s is a continuous map, given a closed set $V \subset \pi^{-1}(U)$ of $p \in \pi^{-1}(U)$, $V \cap P_{\pi(p)}$ is also a closed set of p , we have $s^{-1}(V \cap P_{\pi(p)})$ is either $\{\pi(p)\}$ or \emptyset , hence is closed.

We know if $\pi : P \rightarrow X$ is a principal G -bundle then G acts freely on P . In the other direction, if we are given a space P with a free G -action on the right of P , it is not enough to say $\pi : P \rightarrow P/G$ is a principal G -bundle. For example, let \mathbb{R} acts on the torus $\mathbb{R}^2/\mathbb{Z}^2$ by translating $(1/2, a)$ where a is an irrational number. Even though the action is free, the orbits are dense and the quotient space is not even Hausdorff. One needs to add extra condition, for example, π having local sections. Some references would call P a (right) *free* G -space if $\pi : P \rightarrow P/G$ is a principal G -bundle.

Given a principal G -bundle $\pi : P \rightarrow X$ then by the universal property of quotient spaces, this induces a continuous bijective map $\phi : P/G \rightarrow X$, defined by $[p] \in P/G \mapsto \pi(p)$. In our setup, I don't think we can show ϕ is a homeomorphism. However, if we assume our spaces are smooth manifolds, G is a Lie group, then ϕ is a diffeomorphism (see for example <https://www.mathi.uni-heidelberg.de/~lee/MenelaosSS16.pdf>).

Some more references <https://web.ma.utexas.edu/users/dafr/M392C-2017/Notes/lecture13.pdf>, <https://ncatlab.org/nlab/show/principal+bundle>

Principal G -bundles in topological setting is discussed at Tammo tom Dieck's book *Algebraic Topology*

3.7. 14/08/2021: Gufang Zhao's first lecture: Bundles as double quotient space. Just want to take some notes on Gufang Zhao lectures. The summary of his lecture series is as follows: One can construct certain bundles on Riemann surfaces (bundles of conformal blocks on the configuration space of points of the Riemann surface), equipped it with a flat connection, called Knizhnik-Zamolodchikov (KZ) connection. The solution of the KZ equations can be obtained by counting algebraic curves.

His first lecture is about constructing such bundles.

3.7.1. Representations from sections of equivariant vector bundles. Given a space X with a free (right) G -action (i.e. so that $\pi : X \rightarrow X/G$ is a principal G -bundle) and a representation $\rho : G \rightarrow \text{GL}(V)$ of G , we can construct a vector bundle $X \times_G V \rightarrow X/G$ by letting $X \times_G V := (X \times V)/\sim$

where the equivalence relation is $(xg, v) \sim (x, \rho(g^{-1})v)$ ⁵. It has a natural projection $p : X \times_G V \rightarrow X/G$, making it a vector bundle over X/G with fiber isomorphic to V . We can describe its global sections $H^0(X/G, X \times_G V)$ as the space of G -equivariant functions $s : X \rightarrow V$, i.e. $s(xg) = g \cdot s(x)$ for all $g \in G$. Indeed, given such s , we can define $\bar{s} : X/G \rightarrow X \times_G V$ by $\bar{s}(\bar{x}) = (x, s(x))$ where $\pi(x) = \bar{x}$. This is well-defined because $(xg^{-1}, s(xg^{-1})) \sim (x, g \cdot s(xg^{-1})) \sim (x, s(x))$.

If we also have an action of a group H on X that commutes with the G -action, we can turn $X \times_G V \rightarrow X/G$ into a H -equivariant vector bundle by letting H act on $X \times_G V$ by $h(x, v) := (hx, v)$ and on X/G by $h(xG) = hxG$. This is well-defined because the action of H on X commutes with action of G on X . This induces a representation of H on the space of global sections $H^0(X/G, X \times_G V)$. Indeed, let $\bar{s} : X/G \rightarrow X \times_G V$ be in $H^0(X/G, X \times_G V)$ then $(h \cdot \bar{s})(x) := h \cdot s(h^{-1}x)$. As \bar{s} corresponds to a G -equivariant $s : X \rightarrow V$, we have $(h \cdot s)(x) = s(h^{-1}x)$.

Example 9. Consider $X = \mathbb{C}^2 \setminus \{0\}$ and $G = \mathbb{C}^\times$ acts on X by $t(x, y) = (tx, ty)$, then X/G is $\mathbb{P}^1(\mathbb{C})$.

For every $d \in \mathbb{Z}$, we can construct a representation $\mathbb{C}(d)$ of $G = \mathbb{C}^\times$ on $V = \mathbb{C}$ by $t \cdot x = t^d x$.

Thus, this gives us a vector bundle $\mathcal{O}(d) := \mathbb{C}^2 \setminus \{0\} \times_{\mathbb{C}^\times} \mathbb{C}(d)$ over \mathbb{P}^1 . Its global sections can be described as

$$H^0(\mathbb{P}^1, \mathcal{O}(d)) = \{f : \mathbb{C}^2 \setminus \{0\} \rightarrow \mathbb{C} \mid f(tx, ty) = t^d f(x, y) \forall t \in \mathbb{C}^\times\}.$$

When we only care about holomorphic/algebraic sections then

$$H^0(\mathbb{P}^1, \mathcal{O}(d)) = \{f \in \mathbb{C}[x, y] : f(tx, ty) = t^d f(x, y) \forall t \in \mathbb{C}^\times\}.$$

This is the space of homogeneous polynomials of degree d over two variables x, y .

Let $H = \mathrm{SL}_2(\mathbb{C})$ acts on $X = \mathbb{C}^\times \setminus \{0\}$ by left-multiplication. Then $\mathrm{SL}_2(\mathbb{C})$ acts on $H^0(\mathbb{P}^1, \mathcal{O}(d))$ by $(a \cdot f)(x, y) = f(a^{-1}(x, y))$.

3.8. 15/08/2021: Tamagawa number for SL_n over \mathbb{Q} . I would like to sketch the computation that the Tamagawa number of SL_n over \mathbb{Q} is 1, i.e. $\mu_{\mathrm{SL}_n, \mathbb{Q}}(\mathrm{SL}_n(\mathbb{Q}) \setminus \mathrm{SL}_n(\mathbb{A})) = 1$. I learnt this from Garrett's notes <https://www-users.cse.umn.edu/~garrett/m/v/volumes.pdf> and Andre Weil's book *Adeles and Algebraic Groups* (p. 47, §3.4). From these sources, I know that Siegel came up with this proof for $\mathrm{SL}_n(\mathbb{Z}) \setminus \mathrm{SL}_n(\mathbb{R})$, which was then adapted by Weil to prove it for $\mathrm{SL}_n(\mathbb{Q}) \setminus \mathrm{SL}_n(\mathbb{A})$.

At the moment, to focus on describing the main idea of the proof, I will avoid analytic issues such as convergence of integrals, measure-preserving homeomorphisms and normalisations of measures. This is also because I haven't managed to figure out all these technical details.

For $G_n = \mathrm{SL}_n$, we are able to find a copy of SL_{n-1} in SL_n via the action of SL_n on k^n . This then allows us to use induction on n . More precisely, let $G_n(k)$ acts on k^n by left-multiplication. Let $G'_n(k)$ be the stabiliser of $e_1 = (1, 0, 0, \dots, 0)^t \in k^n$ in $G(k)$. We then have the following identification of spaces

- (1) $G'_n(k) \setminus G_n(k)$ is continuously bijective to $G_n(k)e_1$ for $k = \mathbb{Q}_v$ or \mathbb{A} . When k is a division algebra, $G_n(k)e_1 = k^n \setminus \{0\}$ as one can write out explicitly $M \in G_n(k)$ such that $Me_1 = y$ for any $y \in k^n \setminus \{0\}$. Note that \mathbb{A} is not a division algebra, but if we only care about integrating over this quotient space, then it is good enough to know that the set $\mathbb{A}^n - G_n(\mathbb{A})e_1$ has measure 0.
- (2) G'_n is the semidirect product of G_{n-1} with \mathbb{G}_a^{n-1} . In particular, elements in $G'_n(k)$ can be described as

$$\begin{pmatrix} 1 & 0 \\ 0 & x \end{pmatrix} \begin{pmatrix} 1 & u \\ 0 & 1 \end{pmatrix}$$

where $u \in k^{n-1}$, $x \in G_{n-1}(k)$.

⁵Some references define this equivalence relation as $(xg, v) \sim (x, \rho(g), v)$. I don't think it matters which one we choose, but we need to modify this discussion accordingly

We start with the following formula that describe integration over $G'_n(\mathbb{Q}) \setminus G_n(\mathbb{A})$ in two ways

$$(3) \quad \int_{x \in G_n(\mathbb{Q}) \setminus G_n(\mathbb{A})} \int_{y \in G'_n(\mathbb{Q}) \setminus G_n(\mathbb{Q})} f(xy) dx dy = \int_{z \in G'_n(\mathbb{A}) \setminus G_n(\mathbb{A})} \int_{t \in G'_n(\mathbb{Q}) \setminus G'_n(\mathbb{A})} f(zt) dz dt.$$

As $G'_n = \mathbb{G}_a^{n-1} \ltimes G_{n-1}$, by inductive hypothesis on G_n , we find the Tamagawa number of G'_n (i.e. the volume of $G'_n(\mathbb{Q}) \setminus G'_n(\mathbb{A})$) is

$$\tau(G'_n) = \tau(\mathbb{G}_a^{n-1})\tau(G_{n-1}) = 1.$$

Therefore, if we choose f to be a function on $G'_n(\mathbb{A}) \setminus G_n(\mathbb{A})$, i.e. trivial on $G'_n(\mathbb{A})$, and from the identification of $G'_n(k) \setminus G_n(k)$, we can rewrite (4) as

$$(4) \quad \int_{x \in G_n(\mathbb{Q}) \setminus G_n(\mathbb{A})} \sum_{y \in \mathbb{Q}^n \setminus \{0\}} f(yx) dx dy = \int_{\mathbb{A}^n} f(z) dz.$$

The Fourier transform of $f : \mathbb{A}^n \rightarrow \mathbb{C}$ is

$$\widehat{f}(y) = \int_{\mathbb{A}^n} f(x) \chi_{\mathbb{A}}(y^t \cdot x) dx,$$

where $\chi_{\mathbb{A}}$ is the standard unitary character on \mathbb{A} . Applying (4) for \widehat{f} , we find

$$\int_{x \in G_n(\mathbb{Q}) \setminus G_n(\mathbb{A})} \sum_{y \in \mathbb{Q}^n \setminus \{0\}} \widehat{f}(yx) dx = \int_{\mathbb{A}^n} f(z) dz.$$

On the other hand, noting that for $x \in G_n(\mathbb{A})$, as $\det x = 1$, we find $f(yx) = \widehat{f}(y(x^t)^{-1})$ for $y \in \mathbb{A}^n$. Thus, combining the above two equations, we find

$$\int_{\mathbb{A}^n} (f(x) - \widehat{f}(x)) dx = \int_{G_n(\mathbb{Q}) \setminus G_n(\mathbb{A})} (\widehat{f}(0) - f(0)) dx.$$

By Fourier inversion formula, the left-hand side is $\widehat{f}(0) - f(0)$. One can choose f such that $f(0) \neq \widehat{f}(0)$, giving $G_n(\mathbb{Q}) \setminus G_n(\mathbb{A})$ volume 1, as desired.

Remark 10. What I found surprising about this proof is the following:

- (1) It works (almost) verbatim if we work with $\mathrm{SL}_n(\mathbb{Z}) \setminus \mathrm{SL}_n(\mathbb{R})$ instead. An induction argument can be used to show the answer is $\zeta(1)\zeta(2) \cdots \zeta(n)$.
- (2) Comparing this proof with the one given by describing a fundamental domain for $\mathrm{SL}_n(\mathbb{Q}) \setminus \mathrm{SL}_n(\mathbb{A})$, for the later one, we need to compute the volume of $\mathrm{SL}_n(\mathbb{Z}_p)$, but this is nowhere to be seen for this proof. In some sense, the appearance of \mathbb{Q}_p is completely suppressed.
- (3) It seems to me that because this is an inductive argument, one does not have to make an explicit choice of a left-invariant top form for G . This proof also works for any global field I believe.
- (4) The proof works mainly because for $G_n = \mathrm{SL}_n$, one can find a nice subgroup $G'_n = \mathbb{G}_a^{n-1} \ltimes G_{n-1}$. I wonder if this phenomenon holds for other groups. For example, it is mentioned in the references that the inductive strategy of this proof works for Sp_{2n} , (any more?)

Update 22/09/2021: The group G_n is called the mirabolic subgroup of SL_n (mirabolic = miraculous parabolic). It is important in establishing "multiplicity-one" results in automorphic representation theory, (see <https://mathoverflow.net/q/196006/89665>).

3.9. 22/08/2021: Tamagawa number of Sp_{2n} . Let $J_n = \begin{pmatrix} 0 & I_n \\ -I_n & 0 \end{pmatrix}$ be a $2n$ -by- $2n$ matrix.

The symplectic group Sp_{2n} is defined as

$$\mathrm{Sp}_{2n}(k) = \{M \in M_{2n \times 2n}(k) : M^t J_n M = J_n\}.$$

In this section, we show that the Tamagawa number of the symplectic group Sp_{2n} is 1. We prove this by induction on n . For $n = 1$ then $\mathrm{Sp}_2 = \mathrm{SL}_2$ so $\tau(\mathrm{Sp}_2) = \tau(\mathrm{SL}_2) = 1$.

Let $G_n = \mathrm{Sp}_{2n}$ acts on k^{2n} by left-multiplication. Let $G'_n(k)$ be the stabiliser of $e = (1, 0, \dots, 0)^t \in k^{2n}$. Elements in $G'_n(k)$ can be written as

$$\begin{pmatrix} 1 & * & * & * \\ 0 & a & * & b \\ 0 & 0 & 1 & 0 \\ 0 & c & * & d \end{pmatrix}$$

where $\begin{pmatrix} a & b \\ c & d \end{pmatrix} \in G_{n-1}(k)$ and other entries are suitably chosen.

Determine elements in G'_n . To determine other entries, let $X = \begin{pmatrix} A & B \\ C & D \end{pmatrix}$ where $A, B, C, D \in M_{n \times n}$, then such matrix lies in Sp_{2n} iff $A^t C - C^t A = B^t D - D^t B = 0$ and $A^t D - C^t B = I_n$. For X to stabilise e means $A = \begin{pmatrix} 1 & * \\ 0 & * \end{pmatrix}$ and $C = \begin{pmatrix} 0 & * \\ 0 & * \end{pmatrix}$. Hence, we find $\begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} 1 & x_1 & x & x_2 \\ 0 & a & y_1 & b \\ 0 & 0 & 1 & 0 \\ 0 & c & y_2 & d \end{pmatrix}$

where $(x_1, x_2) = \begin{pmatrix} y_1 \\ y_2 \end{pmatrix}^t \begin{pmatrix} 0 & I_{n-1} \\ -I_{n-1} & 0 \end{pmatrix} \begin{pmatrix} a & b \\ c & d \end{pmatrix}$ and $\begin{pmatrix} a & b \\ c & d \end{pmatrix} \in \mathrm{Sp}_{2n-2}$. \square

The set g of elements in $G'_n(k)$ so $\begin{pmatrix} a & b \\ c & d \end{pmatrix} = I_{(2n-2) \times (2n-2)}$ is a normal subgroup of $G'_n(k)$. The set of elements in g so $(x_1, x_2) = 0$ is a normal subgroup of g . Thus, we find that G'_n is isomorphic to the semidirect product $(\mathbb{G}_a \times \mathbb{G}_a^{2n-2}) \rtimes G_{n-1}$. Thus, by inductive hypothesis, the Tamagawa number of G'_n is $\tau(G'_n) = \tau(G_{n-1})\tau(\mathbb{G}_a)^{2n-1} = 1$.

We can identify $G'_n(k) \setminus G_n(k)$ with $G'_n(k)e$. When k is a division algebra, $G'_n(k)e = k^{2n} \setminus \{0\}$. When $k = \mathbb{A}$ then $\mathbb{A}^{2n} \setminus G'_n(\mathbb{A})e$ has measure 0. Proceeding exactly as in SL_n case, we obtain $\tau(\mathrm{Sp}_{2n}) = 1$.

3.10. 22/08/2021: Tamagawa measure and restriction of scalars. I will discuss on how to define a measure on the adelic points of a variety. After this, we will focus on the case for linear algebraic groups and define the Tamagawa measure on the adelic points of such groups.

The references we follow are: Weil's Adeles and Algebraic Groups, first chapter of Gaitsgory and Lurie's book Weils Conjecture for Function Fields I.

3.10.1. Tamagawa measure on smooth schemes. Let X be a separated ⁶ smooth (affine) scheme of finite type over k . A *volume form* on X is a nowhere-vanishing algebraic differential form of top degree on X . Suppose X has a volume form ω (in other words, the canonical line bundle on X has a nonzero global section).

Over a complete valued field k , $X(k)$ has a canonical structure of a k -analytic manifold. When k is a local field equipped with a Haar measure, from the volume form of X , one can define a measure on $X(k)$.

⁶I don't know that well of this separatedness condition for schemes but it will guarantee that over complete valued field k , $X(k)$ is Hausdorff

Let k be now a global field. Let k_v to be the completion of k with respect to a place v of k . Let \mathcal{O}_{k_v} to be the ring of integers of k_v . Let μ_{k_v} to be standard Haar measure on k_v (i.e. when k_v is a nonarchimedean local field, we normalise μ_{k_v} so $\mu_{k_v}(\mathcal{O}_v) = 1$; when $k_v = \mathbb{R}$ then it is the Lebesgue measure; when $k_v = \mathbb{C}$ then μ_{k_v} is twice the Lebesgue measure).

From a volume form ω on X , we can define a measure ω_v on $X(k_v)$, where v is a place of k and k_v is the completion of k with respect to v . Denote \mathcal{O}_{k_v} to be the ring of integers of k_v .

Let S be a nonempty finite set of places of k that contains every archimedean places of k and let $\mathcal{O}_S := \{x \in k : x \in \mathcal{O}_{k_v} \forall v \notin S\}$. Suppose there exists a smooth scheme \overline{X} over \mathcal{O}_S such that $\overline{X}_k = X$ (here \overline{X}_k is an affine scheme over k such that its coordinate ring is $\mathcal{O}(\overline{X}_k) = \mathcal{O}(\overline{X}) \otimes_{\mathcal{O}_S} k$)⁷, and suppose that \overline{X} has a volume form $\overline{\omega}$. Then this induces a volume form $\overline{\omega}|_X$ for X . As $\mathcal{O}_S \hookrightarrow \mathcal{O}_v$ or $\text{Spec } \mathcal{O}_v \rightarrow \text{Spec } \mathcal{O}_S$ ⁸, we can make sense of $\mu_{\omega,v}(\overline{X}(\mathcal{O}_v))$ where $\mu_{\omega,v}$ is the induced measure from ω on $X(k_v) \supset \overline{X}(\mathcal{O}_v)$. We can also regard

$$\prod_{v \notin S} \overline{X}(\mathcal{O}_v) \times \prod_{v \in S} X(k_v)$$

as an open subgroup of $X(\mathbb{A}_k)$.

If the product

$$\prod_{v \notin S} \mu_{\omega,v} \overline{X}(\mathcal{O}_v)$$

converges absolutely to a nonzero real number, we say X admits a Tamagawa measure.

If X admits a Tamagawa measure, a Tamagawa measure μ_ω on $X(\mathbb{A}_k)$ with respect to ω is such that over open sets $\prod_{v \notin S} \overline{X}(\mathcal{O}_v) \times \prod_{v \in S} X(k_v)$ of $X(\mathbb{A}_k)$, μ_ω is the product measure

$$\tau(\mathbb{G}_a)^{-\dim X} \prod_v \mu_{\omega,v}.$$

Here $\tau(\mathbb{G}_a)$ is the Tamagawa number for \mathbb{A} (i.e. we define the measure $\mu_{\mathbb{A}}$ on \mathbb{A} to be the one such that over open sets $\prod_{v \notin S} \mathcal{O}_v \times \prod_{v \in S} k_v$, it is the product measure. We then let $\tau(\mathbb{G}_a) = \int_{\mathbb{Q} \setminus \mathbb{A}} \mu_{\mathbb{A}}$, which is well-defined because $\mathbb{Q} \setminus \mathbb{A}$ is compact).

This definition of μ_ω does not depend on the choice of a set S of places of k or the choice of an integral model \overline{X} for X (because two choice of integral models become isomorphic after enlarging S).

The reason why we add a factor $\tau(\mathbb{G}_a)^{-\dim X}$ is because of the following result⁹

Theorem 11. *Let K/k be a finite and separable extension. Let V be a separated smooth scheme of finite type over K . Let W to be the Weil's restriction of scalars of V with respect to K/k , i.e. W is a scheme over k such that $W(R) := V(R \otimes_k K)$ where R is a k -algebra. Under the restriction of scalars, there is a canonical isomorphism $W(\mathbb{A}_k) \cong V(\mathbb{A}_K)$. We then have*

- (1) *W admits a Tamagawa measure iff V admits a Tamagawa measure.*
- (2) *If the previous condition holds, the canonical isomorphism $W(\mathbb{A}_k) \cong V(\mathbb{A}_K)$ is a measure preserving map.*

What to do next:

⁷One says \overline{X} is a *model* for X over \mathcal{O}_S . So the point of a model is as follows: for a linear algebraic group G over \mathbb{Q} . We would like to describe $G(\mathbb{Z})$ without having to embed G to GL_n and write $G(\mathbb{Z}) = G(\mathbb{Q}) \cap \text{GL}_n(\mathbb{Z})$, which is less functorial

⁸For example, when $k = \mathbb{Q}$, $S = \{\infty, 2, 3\}$ then $\mathcal{O}_S = \mathbb{Z}[1/2, 1/3]$ and for $v = 5 \notin S$, as $1/2$ and $1/3$ are invertible in \mathbb{Z}_5 , we have a map $\mathbb{Z}[1/2, 1/3] \rightarrow \mathbb{Z}_5$.

⁹Another way for people to define Tamagawa measure is to choose Haar measures on local fields k_v such that $\tau(\mathbb{G}_a) = 1$. A natural choice of Haar measures on k_v would be the one that is self-dual with respect to its Pontryagin dual $\widehat{k_v}$.

- (1) Do some more examples over number fields and function fields.
- (2) Examples with restriction of scalars.

3.10.2. *Tamagawa measure for semisimple algebraic groups.* Let G be a connected semisimple linear algebraic group over a global field k . The above discussion of Tamagawa measure applies for ω being a left-invariant volume form for G . In particular, G does admit a Tamagawa measure (in this case, Tamagawa measure for G is a Haar measure) and furthermore, such measure does not depend on the choice of ω .

3.11. **27/08/2021: Affine Grassmannian.** Today I attend a WiSe talk about affine Grassmannian by Alex Weeks <https://sites.google.com/view/mathwise> and I just want to write down something I learnt from this talk.

We start by defining the ring of formal power series $\mathcal{O} = \mathbb{C}[[z]] = \{a_0 + a_1z + a_2z^2 + \dots | a_i \in \mathbb{C}\}$ and its fraction field, the field of formal Laurent series $K = \mathbb{C}((z)) = \{a_nz^n + a_{n+1}z^{n+1} + \dots | n \in \mathbb{Z}, a_i \in \mathbb{C}\}$.

An \mathcal{O} -lattice $L \subset K^n$ is a finitely-generated \mathcal{O} -module¹⁰ such that $K \otimes_{\mathcal{O}} L \cong K^n$. As a set, the affine Grassmannian of GL_n is defined to be

$$\mathrm{Gr}_{\mathrm{GL}_n} = \{L \subset K^n : L \text{ is an } \mathcal{O}\text{-lattice}\}.$$

We will later see that $\mathrm{Gr}_{\mathrm{GL}_n}$ has more structure.

For example, let $n = 1$, then $\mathrm{Gr}_{\mathrm{GL}_1} \cong \mathbb{Z}$, where $n \in \mathbb{Z} \mapsto z^n \mathcal{O}$. The set $\{z^n \mathcal{O} : n \in \mathbb{Z}\}$ are all the \mathcal{O} -lattices in K because if L is an \mathcal{O} -lattice, there exists an element of lowest degree $a_nz^n + a_{n+1}z^{n+1} + \dots$ in L , where $a_n \neq 0$. This follows $z^n \in L$ and hence $L = z^n \mathcal{O}$.

We can construct \mathcal{O} -lattice L_λ , where $\lambda = (\lambda_1, \dots, \lambda_n) \in \mathbb{Z}^n$, in K^n , by $L_\lambda = z^{\lambda_1} \mathcal{O} e_1 \oplus \dots \oplus z^{\lambda_n} \mathcal{O} e_n$. Here $e_i = (0, \dots, 1, 0, \dots, 0)$.

The ind-scheme structure of $\mathrm{Gr}_{\mathrm{GL}_n}$ comes from the following observation: For any $L_1, L_2 \in \mathrm{Gr}_{\mathrm{GL}_n}$, we can find $a, b \in \mathbb{Z}_{\geq 0}$ such that $z^a L_1 \subset L_2 \subset z^{-b} L_1$. To see this, we can choose \mathcal{O} -basis $\{v_1, \dots, v_n\}$ for L_2 and \mathcal{O} -basis $\{w_1, \dots, w_n\}$ for L_1 . We then can write $w_i = \sum a_{ij} v_j$ with $a_{ij} \in K$. We can choose sufficiently large $n \in \mathbb{Z}$ such that $z^n w_i \in L_2$ for every $1 \leq i \leq n$. This implies $z^n L_1 \subset L_2$. For the case $n = 1$, the following observation just says that for any integer n , there exists $a, b \in \mathbb{Z}$ so $a \leq n \leq b$ (which trivially holds ...).

From this observation, given $z^a \mathcal{O}^n \subset L \subset z^{-b} \mathcal{O}^n$, we find $L/z^a \mathcal{O}^n \subset z^{-b} \mathcal{O}^n / z^a \mathcal{O}^n$. Furthermore, $z^{-b} \mathcal{O}^n / z^a \mathcal{O}^n$ is a finite dimensional complex vector space of dimension $(a+b)n$. Indeed, it has basis $z^{-b} e_i, z^{-b+1} e_i, \dots, z^{a-1} e_i$ over all i . If we write $d = \dim_{\mathbb{C}}(L/z^a \mathcal{O}^n)$, we find $L/z^a \mathcal{O}^n \in \mathrm{Gr}(d, z^{-b} \mathcal{O}^n / z^a \mathcal{O}^n)$, our usual Grassmannian of d -dimensional subspaces in $z^{-b} \mathcal{O}^n / z^a \mathcal{O}^n$.

Now, we wonder if a d -dimensional subspace $U \in \mathrm{Gr}(d, z^{-b} \mathcal{O}^n / z^a \mathcal{O}^n)$ can be used to build an \mathcal{O} -lattice in K^n ?

To see this, we first can define an operator T on $z^{-b} \mathcal{O}^n / z^a \mathcal{O}^n$ by multiplying by z . This operator T is nilpotent with Jordan type $(a+b, \dots, a+b)$. Indeed, $T^{a+b}(z^j e_i) = 0$ where $1 \leq i \leq n, -b \leq j \leq a$ and $T(z^j e_i) = z^{j+1} e_i$ for $-b \leq j \leq a-2$.

If L is an \mathcal{O} -lattice where $z^a \mathcal{O}^n \subset L \subset z^{-b} \mathcal{O}^n$ then $L/z^a \mathcal{O}^n$ is a T -invariant subspace of $z^{-b} \mathcal{O}^n / z^a \mathcal{O}^n$. Back to our question: The converse also holds, i.e. $U \in \mathrm{Gr}(d, z^{-b} \mathcal{O}^n / z^a \mathcal{O}^n)$ defines an \mathcal{O} -lattice in K^n if it is T -invariant.

Indeed, let L to be the kernel of

$$L := \ker \left(z^b \mathcal{O}^n \rightarrow z^{-b} \mathcal{O}^n / z^a \mathcal{O}^n \rightarrow \left(z^{-b} \mathcal{O}^n / z^a \mathcal{O}^n \right) / U \right)$$

¹⁰Zhu's note on affine Grassmannian put finitely generated *projective* \mathcal{O} -module, which is a free module as any finitely generated projective module over a PID (e.g. \mathcal{O}) is free. This then means we can choose an \mathcal{O} -basis e_1, \dots, e_n for L , i.e. $L = \mathcal{O} e_1 \oplus \dots \oplus \mathcal{O} e_n$.

We claim that L is a \mathcal{O} -lattice in K^n . Firstly, L is an \mathcal{O} -module because U is T -invariant. It is finitely generated because it is an \mathcal{O} -submodule of finitely generated module $z^b\mathcal{O}^n$ ($\mathcal{O} = \mathbb{C}[[z]]$ is Noetherian as \mathbb{C} is, and any submodule of finitely generated module over a Noetherian ring is also finitely generated). L contains $z^a\mathcal{O}^n$ so $L \otimes_{\mathcal{O}} K = K^n$, as desired.

In summary, we have a bijection from d -dimensional \mathcal{O} -lattices $z^a\mathcal{O}^n \subset L \subset z^{-b}\mathcal{O}^n$ to d -dimensional subspaces of $z^{-b}\mathcal{O}^n/z^a\mathcal{O}^n$.

Thus, the task of finding an \mathcal{O} -lattice L (of dimension d) between $z^a\mathcal{O}^n$ and $z^{-b}\mathcal{O}^n$ boils down to find a d -dimensional subspace of $z^{-b}\mathcal{O}^n/z^a\mathcal{O}^n$.

Example 12. When $n = 2, a = 2, b = 0$ then $T = \begin{pmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \end{pmatrix}$ by identifying basis ze_1, e_1, ze_2, e_2

of $z^2\mathcal{O}^2/\mathcal{O}^2$ with (e_1, e_2, e_3, e_4) of \mathbb{C}^4 . To find \mathcal{O} -lattices $z^2\mathcal{O}^2 \subset L \subset \mathcal{O}^2$ of dimension 2, we want to find T -invariant 2-dimensional subspaces of \mathbb{C}^4 . Note that $\ker T$ is 2-dimensional, so it is one candidate. If T -invariant subspace U is not $\ker T$, then there exists $v \in U$ so $T(v) \neq 0$. Then $U = \text{span}_{\mathbb{C}}(v, Tv)$ because T has only eigenvalue 0 with eigenvector Tv , but $v \notin \ker T$ so v and Tv are linearly independent.

These are all the 2-dimensional subspaces of \mathbb{C}^4 that are T -invariant.

Our problem of finding 2-dimensional T -invariant subspaces is related to the nilpotent cone. Let Nil_2 to be the set of all 2×2 nilpotent matrices over \mathbb{C} . Equivalently, we can write

$$\text{Nil}_2 = \left\{ \begin{pmatrix} a & b \\ c & -a \end{pmatrix} \in \text{SL}_2(\mathbb{C}) : a^2 + bc = 0 \right\}.$$

It is called a "cone" because under change of variables $b = x - y, c = x + y$ then the equation becomes $a^2 + x^2 = y^2$, which is a cone over the real points.

We can define a map

$$\begin{aligned} \text{Nil}_2 &\rightarrow \text{Gr}_{\text{GL}_2} \\ \begin{pmatrix} a & b \\ c & -a \end{pmatrix} &\mapsto L := \mathcal{O}(z + a, c) \oplus \mathcal{O}(b, -a + z). \end{aligned}$$

We notice $z^2\mathcal{O}^2 \subset L \subset \mathcal{O}^2$. L is a free \mathcal{O} -module because $a^2 + bc = 0$. To see $\dim_{\mathbb{C}}(L/z^2\mathcal{O}^2) = 2$, by identifying $z^2\mathcal{O}^2/\mathcal{O}^2 \cong \mathbb{C}^4$ via $(ze_1, e_1, ze_2, e_2) \mapsto (e_1, e_2, e_3, e_4)$, we can write

$$L/z^2\mathcal{O}^2 = \mathbb{C}(1, a, 0, c) \oplus \mathbb{C}(0, b, 1, -a).$$

This vector space is T -invariant because $a^2 + bc = 0$.

3.12. Some unanswered questions.

- (1) Masoud asked what happen if we do not choose the standard character in identifying k with \widehat{k} where k is a local field, what would be the dual Haar measure on k and \widehat{k} in the Fourier inversion formula.
- (2) What happen to Haar measure on local field under field extension. For example \mathbb{C}/\mathbb{R} ?
- (3) Learn Borel-Weil-Bott construction of irreducible representations. See book Complex geometry and Representation theory. See notes by Joel Kammitzer (already print out).
- (4) Why the non-split maximal torus of $\mathrm{GL}_2(\mathbb{F}_q)$ is $\left\{ \begin{pmatrix} x & \varepsilon y \\ y & x \end{pmatrix} \right\}$ where $x, y, \varepsilon \in \mathbb{F}_q$ and ε is non-square.
- (5) Learn about moduli (very short note by Ivan Mirkovic algebraic geometry course).
- (6) Why adeles can be used to compute cohomology? See 12/08/2021 and <https://webusers.imj-prg.fr/~matthew.morrow/Morrow,%20M.,%20Introduction%20to%20HLF.pdf>.

4.1. 01/09/2021: Algebraic function fields. I want to take some notes on ways to describe algebraic function fields. I learned this from Salvador's book Topics in the Theory of Algebraic Function Fields.

A global function field k is a field of characteristic p that is a finitely generated extension of transcendental degree 1 over \mathbb{F}_p .

Some digestion on the definition of transcendence: Let L/K be a field extension. A *transcendental basis* of L over K is a maximal subset of L algebraically independent over K (i.e. for any n elements s_1, \dots, s_n in the basis, there does not exist $f \in K[x_1, \dots, x_n]$ so that $f(s_1, \dots, s_n) = 0$). One can show that S is a transcendental basis of L over K iff $L/K(S)$ is an algebraic extension¹¹, and the cardinality of S is called the *transcendental degree of L over K* . For example, the field $L = K(X)[Y]/(X^2 - Y - 1)$ has transcendental basis $\{x\}$ or $\{y\}$, where $x = X \bmod (X^2 - Y - 1)$, as there does not exist $f \in K[x]$ so $f(x) = 0$ in L . Furthermore, $L/K(x)$ is algebraic as $y^2 = x + 1$.

Back to our global function field k/\mathbb{F}_p . If $T \in k$ is transcendental over \mathbb{F}_p then $k/\mathbb{F}_p(T)$ is a finite (algebraic) extension¹². If we choose a different transcendental basis T' for k/\mathbb{F}_p then $[k : \mathbb{F}_p(T)]$ does not necessarily equal to $[k : \mathbb{F}_p(T')]$. This is one of the principal differences with number fields, i.e. there is no natural choice of a base field. For example, take $L = \mathbb{Q}(x)[z]/(x^2 + z^4 - 1)$ then $[L : \mathbb{Q}(x)] = 4$, $[L : \mathbb{Q}(z)] = 2$, $[L : \mathbb{Q}(x^2)] = 8$.

4.2. 03/09/2021: Tamagawa number of orthogonal groups. In this section, we will show that the Tamagawa number of orthogonal group is 2. We follow Igusa's chapter 4 of Lectures on Forms of Higher Degrees and Hida's notes on Siegel-Weil Formulas.

4.2.1. Orthogonal groups. Let V be a vector space over \mathbb{Q} of dimension $n \geq 3$. A map $q : V \rightarrow \mathbb{Q}$ is called a *quadratic form on V over \mathbb{Q}* if it satisfies the following conditions:

- (1) The function $b : V \times V \rightarrow \mathbb{Q}$, defined by

$$b(x, y) := q(x + y) - q(x) - q(y),$$

is a symmetric bilinear form.

- (2) For $\lambda \in \mathbb{Q}$ and $x \in V$, we have $q(\lambda x) = \lambda^2 q(x)$.

Throughout this section, we will always assume that q is nondegenerate, i.e. b is nondegenerate.

A morphism between two quadratic forms q, q' is a linear map $f : V \rightarrow V$ such that $q' \circ f = q$. The automorphism group of a quadratic form q over \mathbb{Q} is denoted as $O_q(\mathbb{Q})$, called the *orthogonal group* of (V, q) .

For any \mathbb{Q} -algebra R , q induces a quadratic form $q_R : V \otimes_{\mathbb{Q}} R \rightarrow R$ over R by extension of scalars. Its automorphism group is denoted by $O_q(R)$. Thus, we have defined an algebraic group O_q over \mathbb{Q} corresponding to the quadratic form $q : V \rightarrow \mathbb{Q}$.

Furthermore, O_q is an affine algebraic group. Indeed, we fix a choice of basis $\{e_1, \dots, e_n\}$ for V , a quadratic form q on V then corresponds to a symmetric matrix B_q defined by $(B_q)_{ij} := \frac{1}{2}(q(e_i + e_j) - q(e_i) - q(e_j))$. One can show that two quadratic forms q, q'' on V are isomorphic over \mathbb{Q} if $B_{q'} = T^t B_q T$ for some $T \in \mathrm{GL}_n(\mathbb{Q})$. Thus, for any \mathbb{Q} -algebra R , we can describe $O_q(R)$ as

$$O_q(R) = \{x \in \mathrm{GL}_n(R) : B_q = x^t B_q x\}.$$

¹¹If $L/K(S)$ is an algebraic extension then for any $x' \notin S$, there exists $f \in K(S)[x]$ so $f(x') = 0$, i.e. $\sum_i f_i(s_1, \dots, s_n)x'^i = 0$ for some $s_1, \dots, s_n \in S$ and $f_i \in K[x_1, \dots, x_n]$. This means $\{x'\} \cup S$ is algebraically dependent, i.e. if S is an algebraically independent set of L/K , then S is a transcendental basis of L .

¹²finitely generated algebraic extension is finite

4.2.2. *Tamagawa measure of O_q .* As an algebraic group, $O_{q,\mathbb{Q}}$ has an algebraic left-invariant differential form ω of top degree over \mathbb{Q} . Hence, for each place v of \mathbb{Q} , ω defines a left-invariant Haar measure $\mu_{O_q(\mathbb{Q}_v),\omega}$ on $O_q(\mathbb{Q}_v)$. As we know that **Need to state this for general semisimple group**

$$\prod_{p<\infty} \mu_{O_q(\mathbb{Q}_p),\omega}(O_q(\mathbb{Z}_p)) < \infty$$

so this defines a Tamagawa measure $\mu_{O_q,\mathbb{Q}}$ on $O_q(\mathbb{A})$.

4.2.3. *Tamagawa number of O_q .* In this section, we will prove the following result

Theorem 13. $\tau_{\mathbb{Q}}(O_q) = 2$.

To prove this, we induct on $n = \dim V$. We will take for granted that $\tau_{\mathbb{Q}}(O_q) = 2$ for $n = 3, 4$. The proof for these cases can be found at Weil's book, p. 65, theorem 3.7.1.

4.2.4. *Stabilisers of the action of O_q on \mathbb{G}_a^n .* For any \mathbb{Q} -algebra R , we denote

$$O_{v,q}(R) = \{g \in O_q(R) : vg = v\}$$

to be the stabiliser of $v \in V_R := V \otimes_{\mathbb{Q}} R$. In particular, for $v \in V_{\mathbb{Q}}$, $O_{v,q}$ is an affine algebraic group over \mathbb{Q} . In this section, we will describe the structure of $O_{v,q}(R)$ in the two cases where $q(v) = 0$ and $q(v) \neq 0$. For convenience, we will restrict the discussion for $O_{v,q}(\mathbb{Q})$, as the case $O_{v,q}(R)$ for any \mathbb{Q} -algebra R is completely similar.

If $q(v) \neq 0$ then we will show O_v is an orthogonal group of dimension $n - 1$. Let $W_v = (\mathbb{Q}v)^{\perp} := \{v' \in V : q(v, v') = 0\}$ then W_v is a \mathbb{Q} -vector space of dimension $n - 1$. Indeed, we know $q(v) \neq 0$ so $q(v, v) \neq 0$. Hence, for any basis v, v_1, \dots, v_{n-1} of V , one can choose $c_i \in \mathbb{Q}$ so that $q(v, v_i + c_i v) = 0$. This means $W_v = \text{span}_{\mathbb{Q}}\{v_1 + c_1 v, \dots, v_{n-1} + c_{n-1} v\}$.

We note that if $g \in O_v$ then g preserves W_v , as $0 = q(v, v') = q(gv, gv') = q(v, gv')$ for $v' \in W_v$. This means $O_v \subset O_{q|_{W_v}}$. Conversely, given $g \in O_{q|_{W_v}}$ then we can extend g to action on V by letting $gv = v$, as $v \notin W_v$. Thus, $O_v = O_{q|_{W_v}}$, i.e. O_v is the orthogonal group corresponding to the quadratic form $q|_{W_v}$.

If $q(v) = 0$ but $v \neq 0$, q restricts to $\mathbb{Q}v$ is trivial. Since q is nondegenerate, there exists $v' \in V$ independent from v such that $q(v, v') = 1$. Then $q(v' - xv) = \frac{1}{2}q(v' - xv, v' - xv) = q(v') - x$ for $x \in \mathbb{Q}$. Thus, by taking $x = q(v')$ and replace v' by $v' - xv$, we may assume that $q(v') = 0$. This follows $W = (\mathbb{Q}v \oplus \mathbb{Q}v')^{\perp}$ has dimension $n - 2$, as for any $w \in W$, we can find $c, c' \in \mathbb{Q}$ so $q(w + cv + c'v', v) = q(w + cv + c'v', v') = 0$. Thus, under a choice of basis $v, v_1, \dots, v_{n-2}, v'$ of V where v_1, \dots, v_{n-2} is a basis of W , q has the matrix form

$$B_q = \begin{pmatrix} 0 & 0 & 1 \\ 0 & S & 0 \\ 1 & 0 & 0 \end{pmatrix}$$

where S is a $(n - 2) \times (n - 2)$ symmetric matrix corresponding to $q|_W$. From this, one can show that $O_{v,q}$ is the semidirect product $\mathbb{G}_a^{n-2} \ltimes O_{q|_W}$, i.e. element in $O_{v,q}(\mathbb{Q})$ has the form

$$\begin{pmatrix} 1 & w & -\frac{1}{2}w^t S w \\ 0 & 1 & -S^t w \\ 0 & 0 & 1 \end{pmatrix}$$

where $w \in \mathbb{G}_a^{n-2}(\mathbb{Q})$.

4.2.5. *An evaluation of integral.* We will assume the following results

- (1) Hasse-Minkowski theorem: For every $n \geq 1$, if $q_{\mathbb{A}}^{-1}(x) \neq \emptyset$ then $q_{\mathbb{Q}}^{-1}(x) \neq \emptyset$ for every $x \in \mathbb{Q}$.
- (2) Witt's theorem: For $n \geq 3$, if we have $0 \neq v_i \in q_{\mathbb{Q}}^{-1}(i)$ then $v_i \cdot O_q(\mathbb{Q}) = q_{\mathbb{Q}}^{-1}(i) - \{0\}$ and $v_i \cdot O_q(\mathbb{A}) = q_{\mathbb{A}}^{-1}(i) - \{0\}$ for every $i \in \mathbb{Q}$.

Next, similarly to the case of SL_n and Sp_{2n} , we want to rewrite the following integral

$$\int_{O_q(\mathbb{Q}) \backslash O_q(\mathbb{A})} \left(\sum_{x \in \mathbb{Q}^n} f(xg) \right) d\mu_{O_q}(g).$$

where $f : V_{\mathbb{A}} \rightarrow \mathbb{C}$ is a Schwartz-Bruhat function, so that we can see the appearance of $\tau_{\mathbb{Q}}(O_q)$.

From Witt's theorem, we have

$$V_{\mathbb{Q}} - \{0\} = \bigsqcup_{i \in \mathbb{Q}} (q_{\mathbb{Q}}^{-1}(i) - \{0\}) = \bigsqcup_{i \in \mathbb{Q}} v_i \cdot O_q(\mathbb{Q}).$$

Furthermore, $O_{v_i}(\mathbb{Q}) \backslash O_q(\mathbb{Q}) \cong v_i \cdot O_q(\mathbb{Q})$ via $\gamma \mapsto v_i \gamma$, we find

$$\begin{aligned} \int_{O_q(\mathbb{Q}) \backslash O_q(\mathbb{A})} \left(\sum_{x \in V_{\mathbb{Q}} \backslash \{0\}} f(xg) \right) d\mu_{O_q}(g) &= \int_{O_q(\mathbb{Q}) \backslash O_q(\mathbb{A})} \sum_{i \in \mathbb{Q}} \sum_{v \in q_{\mathbb{Q}}^{-1}(i) - \{0\}} f(vg) d\mu_{O_q}(g), \\ &= \sum_{i \in \mathbb{Q}} \sum_{\gamma \in O_{v_i}(\mathbb{Q}) \backslash O_q(\mathbb{Q})} \int_{O_q(\mathbb{Q}) \backslash O_q(\mathbb{A})} f(v_i \gamma g) d\mu_{O_q}(g), \\ &= \sum_{i \in \mathbb{Q}} \int_{O_{v_i}(\mathbb{Q}) \backslash O_q(\mathbb{A})} f(v_i g) d\mu_{O_q}(g), \\ &= \sum_{i \in \mathbb{Q}} \tau_{\mathbb{Q}}(O_{v_i}) \int_{O_{v_i}(\mathbb{A}) \backslash O_q(\mathbb{A})} f(v_i g) d\mu_{O_q}(g), \\ &= \sum_{i \in \mathbb{Q}} \tau_{\mathbb{Q}}(O_{v_i}) \int_{q_{\mathbb{A}}^{-1}(i) \backslash \{0\}} f(v) dv, \\ &= \sum_{i \in \mathbb{Q}} \tau_{\mathbb{Q}}(O_{v_i}) \int_{q_{\mathbb{A}}^{-1}(i)} f(v) dv \end{aligned}$$

By induction on n and from the previous descriptions of O_{v_i} , we find $\tau_{\mathbb{Q}}(O_{v_i}) = 2$ for all $0 \neq v_i$, implying

$$(5) \quad \int_{O_q(\mathbb{Q}) \backslash O_q(\mathbb{A})} \left(\sum_{x \in \mathbb{Q}^n} f(xg) \right) d\mu_{O_q}(g) = f(0) \tau_{\mathbb{Q}}(O_q) + 2 \sum_{i \in \mathbb{Q}} \int_{q_{\mathbb{A}}^{-1}(i)} f(v) dv.$$

4.2.6. *A second evaluation of integral.* We show that

$$\sum_{i \in \mathbb{Q}} \int_{q_{\mathbb{A}}^{-1}(i)} f(v) dv = \sum_{i \in \mathbb{Q}} \int_{V_{\mathbb{A}}} f(v) \exp_{\mathbb{A}}(q(v)x) dv.$$

For any $x, y \in \mathbb{A}^{\times}$ and $0 \neq v \in q_{\mathbb{A}}^{-1}(x)$, there exists $g \in GL_n(\mathbb{A})$ such that $q(vg) = y$. Hence, $q_{\mathbb{A}}^{-1}(x) \times \mathbb{A}^{\times} \xrightarrow{\sim} V_{\mathbb{A}} - q_{\mathbb{A}}^{-1}(0)$ by sending $(v, y) \mapsto vg$. This follows that from a volume form $\omega = dx_1 \wedge \cdots \wedge dx_n$ on $V_{\mathbb{A}}$, one can split $\omega = \omega_x \wedge dx$ where ω_x is the volume form on $q_{\mathbb{A}}^{-1}(x)$.

For $x = 0$, if there exists $0 \neq v \in V_{\mathbb{A}}$ so $q(v) = 0$, then there also exists a volume form on $q_{\mathbb{A}}^{-1}(0)$. Indeed, ... **Need to learn this**

With this, we can define $F_f(x) = \int_{q_{\mathbb{A}}^{-1}(x)} f d|\omega_x|$, we find that

$$\widehat{F}_f(x) = \int_{\mathbb{A}} F_f(y) \exp(yx) dx = \int_{V_{\mathbb{A}}} f(v) \exp_{\mathbb{A}}(q(v)x) dv.$$

By the Poisson summation formula, we find

$$\sum_{i \in \mathbb{Q}} F_f(i) = \sum_{i \in \mathbb{Q}} \widehat{F}_f(i).$$

Thus, (5) can be rewritten as

$$(6) \quad \int_{O_q(\mathbb{Q}) \backslash O_q(\mathbb{A})} \left(\sum_{x \in \mathbb{Q}^n} f(xg) \right) d\mu_{O_q}(g) = f(0)\tau_{\mathbb{Q}}(O_q) + 2 \sum_{i \in \mathbb{Q}} \int_{V_{\mathbb{A}}} f(v) \exp_{\mathbb{A}}(q(v)i) dv.$$

4.2.7. *A Poisson summation formula.* Letting $\phi_g(x) := f(xg)$, we have

$$\begin{aligned} \widehat{\phi}_g(x) &:= \int_{V_{\mathbb{A}}} f(yg) \exp_{\mathbb{A}}(q(x, y)) dy, \\ &= \int_{V_{\mathbb{A}}} f(yg) \exp_{\mathbb{A}}(q(xg, yg)) dy \quad (y \mapsto yg^{-1}), \\ &= \int_{V_{\mathbb{A}}} f(y) \exp_{\mathbb{A}}(q(xg, y)) dy, \\ &= \widehat{\phi}(xg) \end{aligned}$$

By the Poisson summation formula, we find

$$\sum_{x \in V_{\mathbb{Q}}} f(xg) = \sum_{x \in V_{\mathbb{Q}}} \widehat{f}(xg).$$

This says that the left hand side of (6) is invariant under $f \mapsto \widehat{f}$.

On the other hand, we know that

$$\int_{V_{\mathbb{A}}} \widehat{f}(v) \exp_{\mathbb{A}}(q(v)i) dv = \int_{V_{\mathbb{A}}} \widehat{f}(v) \exp_{\mathbb{A}}(-i^{-1}q(v)) dv.$$

This follows

$$\begin{aligned} \sum_{i \in \mathbb{Q}} \int_{V_{\mathbb{A}}} f(v) \exp_{\mathbb{A}}(iq(v)) dv - \sum_{i \in \mathbb{Q}} \int_{V_{\mathbb{A}}} \widehat{f}(v) \exp_{\mathbb{A}}(iq(v)) dv &= \int_{V_{\mathbb{A}}} (f(v) - \widehat{f}(v)) dv, \\ &= \widehat{f}(0) - f(0). \end{aligned}$$

Hence, it follows from (6) that

$$(\tau_{\mathbb{Q}}(O_q) - 2)(f(0) - \widehat{f}(0)) = 0.$$

We can choose $f \in \mathcal{S}(V_{\mathbb{A}})$ such that $f(0) \neq \widehat{f}(0)$, implying $\tau_{\mathbb{Q}}(O_q) = 2$.

4.3. 05/09/2021: Holomorphic maps between Riemann surfaces. I want to give a summary of properties of holomorphic maps between two Riemann surfaces, learned from Forster's Lectures on Riemann Surfaces.

Our Riemann surfaces are always assumed to be connected and Hausdorff.

4.3.1. Global behaviour. There are a few results on the global behaviour of a holomorphic function, obtained by looking at its domain of definition:

- (1) Riemann's Removable Singularities Theorem: Let U be an open subset of a Riemann surface X and $a \in U$. Suppose f is a holomorphic function on $U \setminus \{a\}$ that is bounded on some neighborhood of a . Then f can be extended uniquely to a holomorphic function \tilde{f} on U .
- (2) Identity theorem: Let f_1, f_2 be two holomorphic maps which coincide on a set A having a limit point $a \in X$. Then f_1 and f_2 are identically equal.

These properties can be obtained via similar results for holomorphic functions on \mathbb{C} .

What are the higher dimensional results for the above?

4.3.2. Local behaviour: Ramification. Let $f : X \rightarrow Y$ be a non-constant holomorphic map. We would like to study the behaviour of f locally at a point in X . A point $a \in X$ is called a *ramification point* of f if f is not locally injective at a . We call $b \in Y$ a *branch point* of f if $f^{-1}(b)$ has a ramification point. If f has no ramification point then f is called *unramified/unbranched*¹³.

There is another way to describe ramification for non-constant holomorphic maps by noting that for any $a \in X$, there exists $k \in \mathbb{Z}_{\geq 1}$ such that under certain choices of charts near a and $f(a)$, f is given by $z \mapsto z^k$ (Forster §2.1). Then f is ramified at $a \in X$ iff $k \geq 2$, and such k is called the *ramification index* of $a \in X$. Indeed, observe that the map $p_k : \mathbb{C} \rightarrow \mathbb{C}$, defined by $z \mapsto z^k$ for $k \in \mathbb{Z}_{\geq 2}$, has only one ramification point 0, as for any $\varepsilon > 0$, if $a \in B_{\varepsilon>0}(0)$ then $ae^{2\pi in/k} \in B_\varepsilon(0)$ where $n \in \mathbb{Z}, 1 \leq n \leq k$.

An example of an unramified map is the exponential map $\exp : \mathbb{C} \rightarrow \mathbb{C}^\times$. This map is unramified because for any $a \in \mathbb{C}$, one can choose $\varepsilon > 0$ so $B_\varepsilon(a)$ does not contain any two points that differ by an integer multiple of $2\pi i$. Here is another example of unramified morphism: Let Γ be a lattice in \mathbb{C} , i.e. $\Gamma = \mathbb{Z}\omega_1 + \mathbb{Z}\omega_2$ where $\omega_1, \omega_2 \in \mathbb{C}$ are linearly independent over \mathbb{R} , then the projection $p : \mathbb{C} \rightarrow \mathbb{C}/\Gamma$ is a local homeomorphism under the quotient topology on \mathbb{C}/Γ . One can equip \mathbb{C}/Γ with a complex structure inherited from \mathbb{C} via p , making it into a Riemann surface and p is then unramified (as p is a local homeomorphism).

The local behaviour $z \mapsto z^k$ of f allows one to deduce many local properties of f . For example, we find that f is an open map. Some more properties from this local behaviour when you add extra conditions of f, X and Y :

- (1) If f is injective and holomorphic, then $f : X \rightarrow f(X)$ is biholomorphic.
- (2) If X is compact then f is surjective and Y compact. Indeed, as $f(X)$ is both open (since f is open) and closed (since X is compact) and Y is connected, we find $f(X) = Y$ is compact.

In particular, every holomorphic function on a compact Riemann surface is constant.

Study some more specific examples of holomorphic functions: Why meromorphic functions on \mathbb{P}^1 is rational?; What do functions $f : \mathbb{C}/\Gamma \rightarrow \mathbb{P}^1$ on the torus look like?; What is Weierstrass functions?; What are some example of ramified morphism?

4.3.3. Local behaviour: Covering maps. Let $f : X \rightarrow Y$ be a non-constant holomorphic map. In contrast to the previous section, we would like to study the behaviour of f locally at a point in Y . Firstly, f is a discrete map, i.e. the fiber $f^{-1}(y)$ for any $y \in Y$ is discrete in X , or else f would be equal to y by the Identity theorem.

¹³Some references such as Griffiths and Harris or Forster would not distinguish between branch points and ramification points, i.e. both are elements in X that are not locally injective

Locally at a ramification point $x \in X$, f can be represented by $z \mapsto z^k$ for some $k \in \mathbb{Z}_{>1}$, and as that 0 is the only ramification point of $p_k : \mathbb{C} \rightarrow \mathbb{C}, p_k(z) = z^k$, the set A of all ramification points of f is discrete and closed in X .

If we require that f is *proper*¹⁴ i.e. the preimage of every compact set is compact, then the set $B := f(A)$ of branch points of f is also closed and discrete in Y ¹⁵. Let $Y' := Y \setminus B$ and $X' := X \setminus f^{-1}(B)$ then $f : X' \rightarrow Y'$ is an unramified proper holomorphic map.

A proper, non-constant unramified holomorphic map $f : X \rightarrow Y$ is a *n-sheeted covering map*, i.e.

- (1) There exists a positive integer n such that for any $y \in Y$, $f^{-1}(y)$ is a discrete set consisting of n points.
- (2) For any $y \in Y$ and $f^{-1}(y) = \{x_1, \dots, x_n\}$, there exists an open neighborhood U of y so that $f^{-1}(U)$ is a disjoint union of open neighborhoods U_i 's of x_i 's, and $f|_{U_i}$ is a homeomorphism for every $1 \leq i \leq n$.

We give a brief explanation on why a proper, non-constant, unramified holomorphic map $f : X \rightarrow Y$ has these properties:

- (1) Because f is proper and discrete, we find $f^{-1}(y)$ is finite for every $y \in Y$. In particular, this does not use the unramified condition.
- (2) Because f is unramified, f is a local homeomorphism. Combining with the fact that $f^{-1}(y)$ is finite and discrete, we find that f is a (finite) covering map.
- (3) Our Riemann surface Y is connected (hence path connected because Y is locally path connected) and f is a finite covering map so from the theory of covering maps (where one has curve lifting properties), $f^{-1}(y)$ and $f^{-1}(y')$ have the same cardinality for any $y, y' \in Y$. (See Forster §4 for more elaborations).

Thus, for a non-constant proper surjective holomorphic map $f : X \rightarrow Y$, by removing all the branch points, we find that $f : X' \rightarrow Y'$ is a n -sheeted covering map. One may wonder if $f^{-1}(y)$ also has cardinality n for a branch point $y \in Y$. If one takes into account of ramification index, the answer is yes. For $x \in X$, we let $\nu(f, x)$ to be the ramification index of $x \in X$ with respect to f .

Theorem 14. *Let $f : X \rightarrow Y$ be a proper, non-constant holomorphic maps between connected Riemann surfaces, then there exists a positive integer n , called the number of sheets of f , such that*

$$n = \sum_{x \in f^{-1}(y)} \nu(f, x)$$

for any $y \in Y$.

Proof. Note that if $x \in X$ is unramified then $\nu(f, x) = 1$. Hence, we let n be the number of sheets for the unramified map $f : X' \rightarrow Y'$ that is obtained from $f : X \rightarrow Y$.

Let $y \in Y$ be a branched point, $f^{-1}(y) = \{x_1, \dots, x_r\}$ and $k_j := \nu(f, x_j)$. From the local behaviour of non-constant holomorphic map, for any $1 \leq j \leq r$, there exists disjoint neighborhoods U_j of x_j and V_j of y such that for any $c \in V_j \setminus \{y\}$, the set $f^{-1}(c) \cap U_j$ contains exactly k_j points.

¹⁴See https://en.wikipedia.org/wiki/Proper_map for the motivation of properness

¹⁵ $f(A)$ is closed because any proper mapping between locally compact spaces $f : X \rightarrow Y$ is closed. Indeed, let C be a closed subset of X , we want to show $f(C)$ is closed in Y or $Y \setminus f(C)$ is open. Let $y \in Y \setminus f(C)$ and because Y is locally compact, y has an open neighborhood V with compact closure \bar{V} . Because f is proper, $f^{-1}(\bar{V})$ is compact, hence $E = f^{-1}(\bar{V}) \cap C$ is also compact (it is closed in the compact set $f^{-1}(\bar{V})$). It follows that $f(E)$ is compact, hence closed in Y (as Y is Hausdorff). Let $U = V \setminus f(E)$ then U is a neighborhood of y that is disjoint from $f(C)$, as desired.

On the other hand, as A is discrete, every subset of A is closed, hence every subset of $f(A)$ is closed, meaning $f(A)$ is discrete.

Because f is proper, hence closed, we can find a neighborhood $V \subset V_1 \cap \cdots \cap V_r$ of y such that $f^{-1}(V) \subset U_1 \cup \cdots \cup U_r$. Indeed, let $X \setminus \cup_j U_j$ is closed in X , hence $f(X \setminus \cup_j U_j)$ is closed and does not contain y , implying $V := Y \setminus f(X \setminus \cup_j U_j)$ is the desired open neighborhood of y .

This means for every unbranch point $c \in V$, $f^{-1}(c)$ consists of $k_1 + \cdots + k_r$ points, which should be n . We are done. \square

To do: Learn some examples and calculations:

- (1) <https://math.stackexchange.com/q/403923/58951>
- (2) <https://math.stackexchange.com/q/702538/58951>
- (3) <https://math.stackexchange.com/q/119699/58951>
- (4) <https://math.stackexchange.com/q/144748/58951>
- (5) <https://math.stackexchange.com/q/740414/58951>
- (6) https://en.wikipedia.org/wiki/Analytic_continuation
- (7) https://en.wikipedia.org/wiki/Covering_space
- (8) <https://people.math.wisc.edu/~robbin/951dir/algebraicCurves.pdf>
- (9) http://www.tjsullivan.org.uk/pdf/MA475_Riemann_Surfaces.pdf
- (10) https://people.brandeis.edu/~igusa/Math101bS07/Math101b_notesB2.pdf
- (11) <https://users.math.yale.edu/~td276/lecture3.pdf>

4.4. **07/09/2021: Adeles over function fields.** Need to define this from perspective of \mathbb{P}^1 over \mathbb{F}_p .

4.4.1. *Completions of $\mathbb{F}_p(T)$.* The rational function field $\mathbb{F}_p(T)$ over \mathbb{F}_p has the following equivalence classes of nontrivial absolute values and completions

- (1) Fix a monic irreducible polynomial $Q \in \mathbb{F}_p[T]$. Any $f \in \mathbb{F}_p(T)$ is uniquely written as $f = Q^r g$ for some $r \in \mathbb{Z}$ and $g \in \mathbb{F}_p(T)$ such that Q does not divide the numerator or denominator of g . We can define an absolute value $|\cdot|_Q$ on $\mathbb{F}_p(T)$ by $|f|_Q = p^{-r \deg(Q)}$ and $|0|_Q = 0$.

The completion of $\mathbb{F}_p(T)$ with respect to $|\cdot|_Q$ is the field of formal Laurent series $\mathbb{F}_q((Q))$ in the variable Q with coefficients in \mathbb{F}_q , where $q = p^{\deg Q}$:

$$\mathbb{F}_q((Q)) = \left\{ \sum_{i=N}^{\infty} a_i Q^i : N \in \mathbb{Z}, a_i \in \mathbb{F}_q \right\}.$$

The absolute value on $\mathbb{F}_q((Q))$ is defined by

$$\left| \sum_{i=N}^{\infty} a_i Q^i \right|_Q = q^{-N} \quad (a_N \neq 0).$$

- (2) For $f = P_1/P_2 \in \mathbb{F}_p(T)$ where $P_1, P_2 \in \mathbb{F}_p(T)$ then we define

$$|f|_{\infty} = p^{\deg(P_1) - \deg(P_2)}, \quad |0|_{\infty} = 0.$$

The completion of $\mathbb{F}_p(T)$ with respect to this absolute value $|\cdot|_{\infty}$ is $\mathbb{F}_p((1/T))$, the field of formal Laurent series in the variable $1/T$. This field has an absolute value defined by

$$\left| \sum_{i=N}^{\infty} a_i \left(\frac{1}{T} \right)^i \right|_{\infty} = p^{-N} \quad (a_N \neq 0).$$

For any $f \in \mathbb{F}_p(T)^{\times}$, one can check that $\prod_v |f|_v = 1$ where the product runs over all places v of $\mathbb{F}_p(T)$. In fact, this is simply a restatement of the fact that if $f = \prod_Q Q^{e_Q} \in \mathbb{F}_p(T)^{\times}$, then $\deg f = \sum_Q e_Q \deg Q$, where the sum/product is over all monic irreducible polynomials in $\mathbb{F}_p[T]$.

4.4.2. *Adeles over $\mathbb{F}_p(T)$.* For a place v of $k = \mathbb{F}_p(T)$, denote $\mathcal{O}_v := \{x \in k_v : |x|_v \leq 1\}$ to be the valuation ring of k_v . In particular, we find

$$\begin{aligned} \mathcal{O}_Q &= \left\{ \sum_{i=0}^{\infty} a_i Q^i : a_i \in \mathbb{F}_q \right\}, \\ \mathcal{O}_{\infty} &= \left\{ \sum_{i=0}^{\infty} a_i \left(\frac{1}{T} \right)^i : a_i \in \mathbb{F}_p \right\}, \end{aligned}$$

where $Q \in \mathbb{F}_p[T]$ is a monic irreducible polynomial. We define the adeles $\mathbb{A}_{\mathbb{F}_p(T)}$ over $\mathbb{F}_p(T)$ to be the restricted product of $\mathbb{F}_p(T)_v$'s with respect to the subgroups \mathcal{O}_v . We can embed $\mathbb{F}_p(T) \hookrightarrow \mathbb{A}_{\mathbb{F}_p(T)}$ diagonally.

Proposition 15. *Under the action of $\mathbb{F}_p(T)$, $\mathbb{F}_p(T) \setminus \mathbb{A}_{\mathbb{F}_p(T)}$ has a fundamental domain*

$$(T^{-1}\mathcal{O}_{\infty}) \times \prod_Q \mathcal{O}_Q.$$

Proof. We will first show that $\mathbb{F}_p(T)$ is dense in $\mathbb{A}_{\mathbb{F}_p(T)}^\infty$, i.e. for any non-empty finite set S of monic irreducible polynomials in $\mathbb{F}_p[T]$, then any open set

$$\prod_{Q \in S} (a_Q + b_Q \mathcal{O}_Q) \times \prod_{Q \notin S \cup \{\infty\}} \mathcal{O}_Q$$

of $\mathbb{A}_{\mathbb{F}_p(T)}^\infty$, where $a_Q, b_Q \in \mathbb{F}_q((Q))$, contains an element of $\mathbb{F}_p(T)$. Without loss of generality, we can assume that $b_Q = Q^{c_Q}$ for $c_Q \in \mathbb{Z}$, and $a_Q \in \mathbb{F}_p(T)$. By the Chinese Riemander Theorem, there exists $f \in \mathbb{F}_p(T)$ such that $f \equiv a_Q \pmod{Q^{c_Q}}$ for all $v \in S$ and f does not have monic irreducible polynomials $Q \notin S$ as factors. This implies f lies in the desired open set.

Because $\mathbb{F}_p(T)$ is dense in $\mathbb{A}_{\mathbb{F}_p(T)}^\infty$, and $\prod_Q \mathcal{O}_Q$ is an open set of $\mathbb{A}_{\mathbb{F}_p(T)}^\infty$, we find

$$\mathbb{F}_p(T) + \prod_Q \mathcal{O}_Q = \mathbb{A}_{\mathbb{F}_p(T)}^\infty.$$

Next, we will show that

$$\mathbb{F}_p(T) + (T^{-1}\mathcal{O}_\infty) \times \prod_Q \mathcal{O}_Q = \mathbb{A}_{\mathbb{F}_p(T)}.$$

Indeed, we consider $(x_\infty, x) \in \mathbb{A}_{\mathbb{F}_p(T)}$, where $x_\infty \in \mathbb{F}_p((1/T))$ and $x \in \mathbb{A}_{\mathbb{F}_p(T)}^\infty$. We can write $x = x_1 + x_2$ where $x_1 \in \mathbb{F}_p(T)$ and $x_2 \in \prod_Q \mathcal{O}_Q$. Furthermore, we can choose $x_3 \in \mathbb{F}_p(T)$ such that $x_3 - x_\infty \in T^{-1}\mathcal{O}_\infty$ and $x_3 - x_1 \in \mathbb{F}_p[T]$, i.e. there exists a positive integer N and $x_3 = \sum_{i=-N}^N a_i T^i$ with $a_i \in \mathbb{F}_p$ so that $\sum_{i=-N}^{-1} a_i T^i - x_1 \in \mathbb{F}_p[T]$ and $\sum_{i=0}^N a_i T^i - x_\infty \in T^{-1}\mathcal{O}_\infty$. Thus, we find $(x_\infty, x) = x_3 + (x_\infty - x_3, x_1 - x_3 + x_2)$ lies in $\mathbb{F}_p(T) + (T^{-1}\mathcal{O}_\infty) \times \prod_Q \mathcal{O}_Q$, as desired.

Finally, note that if $x, x' \in (T^{-1}\mathcal{O}_\infty) \times \prod_Q \mathcal{O}_Q$ and $x - x' \in \mathbb{F}_p(T)$ then as $\mathbb{F}_p(T) \cap (T^{-1}\mathcal{O}_\infty) \times \prod_Q \mathcal{O}_Q = \{0\}$, we find $x = x'$. \square

4.4.3. Unitary characters. For a place v of $\mathbb{F}_p(T)$, we can define the standard unitary characters on $\mathbb{F}_p(T)_v$ and on $\mathbb{A}_{\mathbb{F}_p(T)}$ as follows:

- (1) If $v = \infty$ then $\psi_\infty : \mathbb{F}_p((1/T)) \rightarrow \mathbb{C}^\times$ is defined by

$$\psi_\infty \left(\sum_{i=N}^{\infty} a_i (1/T)^i \right) = e^{-2\pi i a_1 / p}.$$

In this definition, a_1 is any lift of $a_1 \in \mathbb{F}_p$ to \mathbb{Z} . Note that $\psi_\infty(T^{-2}\mathcal{O}_\infty) = 1$.

- (2) If v corresponds to a monic irreducible polynomial $Q \in \mathbb{F}_q[T]$ then $\psi_Q : \mathbb{F}_q((Q)) \rightarrow \mathbb{C}^\times$ is defined by

$$\psi_Q \left(\sum_{i=N}^{\infty} a_i Q^i \right) = e^{2\pi i (a_{-1} \bmod T) / p}.$$

In this definition, we have identified $a_{-1} \in \mathbb{F}_q$ with an element in $\mathbb{F}_p[T]/(Q(T))$, then $a_{-1} \bmod T \in \mathbb{F}_p$. Note that $\psi_Q(\mathcal{O}_Q) = 1$.

- (3) For $x = (x_v) \in \mathbb{A}_{\mathbb{F}_p(T)}$, we can define an adelic unitary character $\psi : \mathbb{A}_{\mathbb{F}_p(T)} \rightarrow \mathbb{C}^\times$ by

$$\psi(f) = \prod_v \psi_v(x_v),$$

where ψ_v 's are the local characters on $\mathbb{F}_p(T)_v$ as defined before. It is clear that ψ is nontrivial.

Proposition 16. For $f \in \mathbb{F}_p(T)$, we have $\psi(f) = 1$.

Proof. Observe that $\psi_\infty(f)$ only carries the information about the coefficient of $1/T$ in the expansion of f with respect to the variable $1/T$. To see how this relates to ψ_Q , we first write f as

$$f(T) = \sum_Q \frac{b_Q(T)}{Q(T)^{e_Q}} = \sum_Q \sum_{i=1}^{e_Q} \frac{b_{i,Q}(T)}{Q(T)^i}$$

where the finite sum is over all monic irreducible polynomials such that the order of Q in the factorisation of f into irreducible polynomials is $-e_Q < 0$; $\deg b_{i,Q}(T) < \deg Q(T)$.

Note that $\psi_Q(f) = e^{2\pi i \cdot [T^{\deg Q-1}]b_{1,Q}/p}$, where $[T^{\deg Q-1}]b_{1,Q} \in \mathbb{F}_p$ denotes the coefficient of $T^{\deg Q-1}$ in $b_{1,Q}$. **This does not look right**

We have $Q(T) = T^{\deg Q} F_Q(1/T)$ for some $F_Q \in \mathbb{F}_p[T]$, hence

$$\frac{b_{i,Q}(T)}{Q(T)^i} = \frac{b_{i,Q}(T) T^{-i \deg Q}}{F_Q(1/T)^i}$$

As $F_Q(1/T)^{-i} \in \mathcal{O}_\infty$ (furthermore, as Q is monic, $F_Q(1/T)^{-i}$ has constant coefficient 1 in the expansion with respect to the variable $1/T$) and as $\deg b_{i,Q}(T) < \deg Q(T)$, we find that the coefficient of $1/T$ in the expansion of $b_{i,Q}(T) Q(T)^{-i}$ with respect to $1/T$ is 0 if $i \geq 2$ and if $i = 1$, it is the coefficient of $T^{\deg(Q)-1}$ in $b_{1,Q}(T)$. \square

4.4.4. *Fourier transform.* From the standard unitary characters ψ_v on $\mathbb{F}_p(T)_v$, we can define the Fourier transforms on $\mathbb{F}_p(T)_v$ as follows:

Proposition 17. *Let μ_∞ be a Haar measure on $\mathbb{F}_p((1/T))$ so that $\mu_\infty(\mathcal{O}_\infty) = p$ and for each monic irreducible polynomial $Q \in \mathbb{F}_p[T]$, let μ_Q be a Haar measure on $\mathbb{F}_q((Q))$ such that $\mu_Q(\mathcal{O}_Q) = 1$. For each place v of $\mathbb{F}_p(T)$, we can define the Fourier transform of a Bruhat-Schwartz function $f : \mathbb{F}_p(T)_v \rightarrow \mathbb{C}$ by*

$$\hat{f}(x) = \int_{\mathbb{F}_p(T)_v} f(y) \psi_v(xy) d\mu_v(y).$$

Then $\hat{\hat{f}}$ is Bruhat-Schwartz and that the Fourier inversion formula holds

$$\hat{\hat{f}}(x) = f(-x) \quad \forall x \in \mathbb{F}_p(T)_v.$$

Proof. A Bruhat-Schwartz function $f : \mathbb{F}_p(T)_v \rightarrow \mathbb{C}$ is a locally constant compactly supported function. Every such function on $\mathbb{F}_p(T)_v$ is a finite linear combination of characteristic functions on compact open sets $a + Q^n \mathcal{O}_Q$ with $a \in \mathbb{F}_p(T)_Q$ and $n \in \mathbb{Z}$ (when $v = \infty$ then the open sets are $a + (1/T)^n \mathcal{O}_\infty$). Hence, it suffices to prove this proposition for the case $f = 1_{a+Q^n \mathcal{O}_Q}$ when $v = Q$ or $f = 1_{a+(1/T)^n \mathcal{O}_\infty}$ when $v = \infty$.

We check this for the case $v = Q$. The other case $v = \infty$ is completely similar. Firstly, we will show that

$$\int_{Q^n \mathcal{O}_Q} \psi_Q(xy) d\mu_Q(x) = \begin{cases} q^{-n} & y \in Q^{-n} \mathcal{O}_Q, \\ 0 & \text{otherwise.} \end{cases}$$

Indeed, if $y \in Q^{-n} \mathcal{O}_Q$ then $xy \in \mathcal{O}_Q$ for all $x \in Q^n \mathcal{O}_Q$. As $\psi_Q(\mathcal{O}_Q) = 1$, the integral becomes $\mu_Q(Q^n \mathcal{O}_Q) = q^{-n}$. If $y \notin Q^{-n} \mathcal{O}_Q$ then there exists $x_0 \in \mathbb{F}_q((Q))$ such that $\psi_Q(x_0 y)$ is nontrivial. By invariance of the Haar measure μ_Q , we find

$$\int_{Q^n \mathcal{O}_Q} \psi_Q(xy) d\mu_Q(x) = \int_{Q^n \mathcal{O}_Q} \psi_Q((x+x_0)y) d\mu_Q(x) = \psi_Q(x_0 y) \int_{Q^n \mathcal{O}_Q} \psi_Q(xy) d\mu_Q(x).$$

As $\psi_Q(x_0 y)$ is nontrivial, we find the integral for $y \notin Q^{-n} \mathcal{O}_Q$ is 0.

From this calculation, we find

$$\begin{aligned}
\hat{1}_{a+Q^n\mathfrak{o}_Q}(x) &= \int_{\mathbb{F}_q((Q))} 1_{a+Q^n\mathfrak{o}_Q}(y) \psi_Q(xy) d\mu_Q(y), \\
&= \int_{a+Q^n\mathfrak{o}_Q} \psi_Q(xy) d\mu_Q(y), \\
&= \int_{Q^n\mathfrak{o}_Q} \psi_Q(x(y+a)) d\mu_Q(y), \\
&= \psi_Q(xa) q^{-n} \cdot 1_{Q^{-n}\mathfrak{o}_Q}(x)
\end{aligned}$$

Hence, we have

$$\begin{aligned}
\hat{1}_{a+Q^n\mathfrak{o}_Q}(x) &= \int_{\mathbb{F}_q((Q))} \hat{1}_{a+Q^n\mathfrak{o}_Q}(y) \psi_Q(xy) d\mu_Q(y), \\
&= q^{-n} \int_{Q^{-n}\mathfrak{o}_Q} \psi_Q(x(y+a)) d\mu_Q(y), \\
&= 1_{Q^n\mathfrak{o}_Q}(y+a) = 1_{a+Q^n\mathfrak{o}_Q}(-y).
\end{aligned}$$

We are done. \square

This proposition allows us to define a Haar measure on $\mathbb{A}_{\mathbb{F}_p}(T)$ and define the Fourier transform on the space of Bruhat-Schwartz functions on $\mathbb{A}_{\mathbb{F}_p}(T)$. We also have the Fourier inversion formula, which gives us the Poisson summation formula.

Proposition 18 (Poisson summation formula). *Let $f \in \mathcal{S}(\mathbb{A}_{\mathbb{F}_p}(T))$ be a Bruhat-Schwartz function on $\mathbb{A}_{\mathbb{F}_p}(T)$. Then*

$$\sum_{x \in \mathbb{F}_p(T)} f(x) = \sum_{x \in \mathbb{F}_p(T)} \hat{f}(x).$$

Similar to the number field case, the Poisson summation formula implies that the volume of $\mathbb{F}_p(T) \setminus \mathbb{A}_{\mathbb{F}_p}(T)$ (with respect to the Haar measure on $\mathbb{A}_{\mathbb{F}_p}(T)$) is 1.

4.4.5. Riemann-Roch theorem. We will prove the Riemann-Roch theorem for \mathbb{P}^1 over \mathbb{F}_p using the Poisson summation formula.

The *divisor group* of \mathbb{P}^1 is the free abelian group generated by the the places v of $\mathbb{F}_p(T)$. A divisor D can be written $\sum_v n_v v$ with $d_v \in \mathbb{Z}$ and $d_v = 0$ for all but finitely many v . We define the *degree* of a place v to be

$$\deg(v) := \begin{cases} 1, & v = \infty, \\ \deg(Q), & v = Q \text{ is a monic irreducible polynomial.} \end{cases}$$

The degree of a divisor $D = \sum_v n_v v$ is defined by

$$\deg(D) := \sum_v n_v \deg(v).$$

Any nonzero $\omega \in \Omega_{\mathbb{P}^1/\mathbb{F}_p}$ corresponds to a divisor $K = \sum_v \kappa_v v$, where κ_v is the “order of vanishing of ω at v ” **Need to find the precise definition of κ_v** . For example, $\omega \in \Omega_{\mathbb{P}^1/\mathbb{F}_p}$ defined by $-du \in \Gamma(U_0, \Omega_{\mathbb{P}^1/\mathbb{F}_p})$ and $w^{-2}dw \in \Gamma(U_1, \Omega_{\mathbb{P}^1/\mathbb{F}_p})$ gives rise to a divisor $K_\omega = -2 \cdot \infty$.

For a divisor $D = \sum_v n_v v$, we can define $\mathcal{O}_{\mathbb{A}}(D) := \prod_v \mathfrak{p}_v^{-n_v} \subset \mathbb{A}$. Let $L(D) := K \cap \mathcal{O}_{\mathbb{A}}(D)$ then $L(D)$ is \mathbb{F}_q -vector space of functions on \mathbb{P}^1 having at worst a pole of order n_v at v for each v . Indeed, for $f, g \in L(D)$ and $\alpha \in \mathbb{F}_p$ then

$$v_v(f+g) \geq \min\{v_v(f), v_v(g)\} = -n_v, v_v(\alpha f) = v_v(f).$$

Furthermore, $L(D)$ is finite-dimensional since for $f \in L(D)$ with factorisation $f = \prod_Q Q^{e_Q}$ into irreducible monic polynomials, then

$$e_Q \geq -n_Q, \deg(f) = \sum_Q e_Q \deg(Q) \leq n_\infty.$$

We can then let $\ell(D) = \dim_{\mathbb{F}_p} L(D)$. For example, $\ell(K_\omega) = 0$ is the *genus* of \mathbb{P}^1 .

Theorem 19 (Riemann-Roch). *Let $K = -2 \cdot \infty$ to be the divisor corresponding to the differential $\omega \in \Omega_{\mathbb{P}^1/\mathbb{F}_p}$, defined by $-du \in \Gamma(U_0, \Omega_{\mathbb{P}^1/\mathbb{F}_p})$ and $w^{-2}dw \in \Gamma(U_1, \Omega_{\mathbb{P}^1/\mathbb{F}_p})$. Then for any divisor D on \mathbb{P}^1 ,*

$$\ell(D) - \ell(K - D) = \deg(D) + 1.$$

Proof. For a divisor $D = \sum_v n_v v$, we find that

$$\hat{1}_{\mathfrak{p}_v^{-n_v}} = p^{n_v \deg v - \kappa_v/2} 1_{\mathfrak{p}_v^{n_v - \kappa_v}},$$

which implies

$$\hat{1}_{\mathcal{O}_{\mathbb{A}}(D)} = p^{\deg D - \deg(K)/2} 1_{\mathcal{O}_{\mathbb{A}}(K-D)},$$

as $\mathcal{O}_{\mathbb{A}} = \prod_v \mathfrak{p}_v^{-n_v}$. On the other hand, as $L(D)$ has $p^{\ell(D)}$ elements so

$$\sum_{x \in \mathbb{F}_p(T)} 1_{\mathcal{O}_{\mathbb{A}}(D)}(x) = p^{\ell(D)}.$$

Similarly, we can also compute

$$\sum_{x \in \mathbb{F}_p(T)} \hat{1}_{\mathcal{O}_{\mathbb{A}}(D)} = p^{\deg D - \deg(K)/2} \sum_{x \in L(K-D)} 1 = p^{\deg D - \deg(K)/2 + \ell(K-D)}.$$

Thus, by Poisson summation formula, we find

$$\ell(D) = \ell(K - D) + \deg(D) + 1.$$

□

Can one write this in such a way that does not depend on the choice of charts?

4.5. 10/09/2021: The theta correspondence and the Siegel-Weil formula. I want to take a quick notes on the theta correspondences and the Siegel-Weil formula. At the moment, I just want to sketch the big picture (so some of what I write below may be incorrect), and leave the technical details later in the future. Some references

- (1) Proof of a simple case of the Siegel-Weil formula by Paul Garrett, https://www-users.cse.umn.edu/~garrett/m/v/easy_siegel_weil.pdf
- (2) A brief survey on the theta correspondence by Dipendra Prasad <http://www.math.tifr.res.in/~dprasad/dp.pdf>
- (3) On the local theta correspondence <https://www.math.u-bordeaux.fr/~ybilu/algant/documents/theses/Zou.pdf>.

We start with a symplectic vector space W over a global/local field k . Reductive dual pairs (G_1, G_2) are certain pairs of subgroups of $\mathrm{Sp}(W)$. For example, if V is an orthogonal vector space then $V \otimes W$ is a symplectic vector space, and we have a pair $(O(V), \mathrm{Sp}(W))$ as a reductive dual pair of $\mathrm{Sp}(V \otimes W)$. So we have a correspondence $O(V) \leftarrow \mathrm{Sp}(V \otimes W) \rightarrow \mathrm{Sp}(W)$ (I think this is true only when we consider two fold covers of these groups but let me ignore this at the moment).

The (lobal) theta correspondence roughly says that there is a one-to-one correspondence between certain irreducible representations of $O(V)$ and certain irreducible representations of $\mathrm{Sp}(W)$ from the Weil representations of $\mathrm{Sp}(V \otimes W)$.

For the global theta correspondence, one can realise Weil representation of $\mathrm{Sp}(V \otimes W)$ as a representation of $\mathrm{Sp}(V \otimes W)$ on the space of nice functions on $V(\mathbb{A})^n$. Then the theta correspondence is roughly obtained by push-pull functions from the correspondence $O(V) \leftarrow \mathrm{Sp}(V \otimes W) \rightarrow \mathrm{Sp}(W)$, i.e. how to get a function on $O(V)$ to a function on $\mathrm{Sp}(W)$ given a function on $\mathrm{Sp}(V \otimes W)$. This is called the *theta lifts* (i.e. it maps automorphic forms on $O(V)$ to automorphic forms on $\mathrm{Sp}(W)$).

The Siegel-Weil formula says that this theta lift at the constant function 1 on $O(V)$ is the Siegel Eisenstein series on $\mathrm{Sp}(W)$.

4.6. 13/09/2021: Mystery point counting. From my naive point of view, there is something so mysterious of doing counting points over finite fields. Let me try to give out some links this time, as I am unable to explain much

- (1) Hausel and Rodriguez-Villegas: <https://arxiv.org/pdf/math/0612668.pdf> (look more into papers of these two), “counting absolutely indecomposable quiver representations, vector bundles with parabolic structure on a projective curve, and irreducible etale local systems”, <https://arxiv.org/pdf/1612.01733.pdf>
- (2) Motivic integration: A theorem of Weil relates p -adic integration with point counting over finite fields; p -adic integration is used to prove many conjectures
 - (a) Birational Calabi-Yau n -folds have equal Betti numbers, <https://arxiv.org/abs/alg-geom/9710020>
 - (b) Topological Mirror Symmetry Conjecture by HauselThaddeus for SL_n and PGL_n , <https://arxiv.org/abs/1707.06417>; Later these people use p -adic integration to reprove Ngo’s fundamental lemma <https://arxiv.org/abs/1810.06739>
 - (c) Igusa’s theory of local zeta functions. <https://people.math.harvard.edu/~mpopa/571/chapter3.pdf>, <https://link.springer.com/book/10.1007/978-1-4939-7887-8> chapter 0
 - (d) What is the relation between p -adic integration with p -adic Hodge theory <https://mat.uab.cat/~masdeu/wp-content/uploads/2017/04/padicint.pdf>?

Motivic integration is some kind of generalisation of p -adic integration. In one direction, it seems people are trying to use this to define nonabelian Fourier transform (see Kazhdan, Braveman, ...) , also orbital integrals in the Langlands program.

- (3) Weil's conjecture and this Weil's conjecture <https://www.math.ias.edu/~lurie/papers/tamagawa-abridged.pdf>, point counting via ℓ -adic cohomology.
- (4) Topological Quantum Field Theory: This reminds me of my digging around what's called "geometric function theory" by David Ben-Zvi on 02-06/06/2021 and 16-17/06/2021. My question back then is roughly like this: Given a map $\phi : X \rightarrow Y$, it is usually easy to define pullback $\phi^* : \text{Fun}(Y) \rightarrow \text{Fun}(X)$, but what characterise a nice pushforward $\phi_* : \text{Fun}(X) \rightarrow \text{Fun}(Y)$? In the discrete case, 06/06/2021, I think this is doing some sort of weight count. In the other case(?), I think this is some sort of integration along fibers as pullback, something like this https://golem.ph.utexas.edu/category/2010/11/integral_transforms_and_pullpu.html. Overall, it certainly relates point counting and integration, and I think it relates to the theory of sheaves with better operations of pushforward (and hence relates to Weil's conjecture?).

4.7. 17/09/2021: Again with left-invariant differential form of SL_2 . On 07/08/2021, I used a map $\text{SL}_2 \times \mathbb{G}_m \rightarrow \text{GL}_2$ to find a global left-invariant top form for SL_2 from a global left-invariant top form of GL_2 . To be honest, I am not satisfied with this computation as I suspect there is a different way to do this without relying on GL_2 (because the way I found a left-invariant top form for GL_2 is an educated guess, i.e. it should have the form $f(x)dx_{11} \wedge dx_{12} \wedge dx_{21} \wedge dx_{22}$, and $f(x) = \det(x_{ij})^{-2}$ is guessed from the left-invariant property).

Masoud pointed out a Math Stack Exchange answer <https://math.stackexchange.com/q/2907521/58951> saying that the k -vector space of left-invariant differential forms of SL_2 has basis $x_{22}dx_{11} - x_{12}dx_{21}, x_{22}dx_{12} - x_{12}dx_{22}$ and $-x_{21}dx_{11} + x_{11}dx_{21}$. Upon taking exterior product, this should gives us the global left-invariant top form of SL_2 . Today, I want to explain a way to get this basis. In particular, I want to explain a natural way to get from an element of the dual Lie algebra \mathfrak{sl}_2^* to a left-invariant differential form of SL_2 , following a proof on page 100 of the book Neron models. This also helps me to digest this proof in the book (although I cannot understand it completely, at least now I can follow it with an example of SL_2 in mind).

I will use the same notation as on 07/08/2021. Let's start. The group scheme SL_2 over $\text{Spec } k$ is a group object in the category of k -schemes (equivalently, it gives $\mathcal{O}(\text{SL}_2)$ the structure of a Hopf algebra). In particular, we have

- (1) A unit section $\varepsilon : \text{Spec } k \rightarrow \text{SL}_2$ is given by the algebra map $\mathcal{O}(\text{SL}_2) \rightarrow k$, defined by sending $x_{ij} \mapsto \delta_{ij}$ (to see this, view x_{ij} as function on $\text{SL}_2(k) \rightarrow k$ output the (i, j) -th position, by precomposing with the unit map $1 \rightarrow \text{SL}_2(k)$, we get a map $1 \rightarrow k$ that either is 0 if $i \neq j$ or 1 if $i = j$).
- (2) The multiplication $m : \text{SL}_2 \times \text{SL}_2 \rightarrow \text{SL}_2$ is given by the algebra map $\mathcal{O}(\text{SL}_2) \rightarrow \mathcal{O}(\text{SL}_2) \otimes_k \mathcal{O}(\text{SL}_2)$, sending $f \in \mathcal{O}(\text{SL}_2)$ (viewed as function $\text{SL}_2(k) \rightarrow k$) to a function $\text{SL}_2(k) \times \text{SL}_2(k) \rightarrow k$, defined by $(a, b) \mapsto f(ab)$. For example, $x_{11} \mapsto (yz)_{11} := y_{11}z_{11} + y_{12}z_{21}$ where (y_{ij}) are generators for the first $\mathcal{O}(\text{SL}_2)$ in $\mathcal{O}(\text{SL}_2) \otimes_k \mathcal{O}(\text{SL}_2)$.

We can pullback $\Omega_{\text{SL}_2/k}$ along ε to get a sheaf $\varepsilon^*\Omega_{\text{SL}_2/k}$ of $\mathcal{O}_{\text{Spec } k}$ -modules. Its global section is the k -module $\Omega_{\mathcal{O}(\text{SL}_2)/k} \otimes_{\mathcal{O}(\text{SL}_2)} k$, defined by $\mathcal{O}(\text{SL}_2) \rightarrow k$ by ε . In particular, it is a k -module generated by dx_{ij} , modulo the relation $dx_{11} + dx_{22}$ (this is obtained from the relation $x_{22}dx_{11} + x_{11}dx_{22} - x_{12}dx_{21} - x_{21}dx_{12} = 0$ in $\Omega_{\mathcal{O}(\text{SL}_2)/k}$ by letting $x_{ij} \mapsto \delta_{ij}$). This is isomorphic to the dual Lie algebra \mathfrak{sl}_2^* .

Now, I want to identify an element in $\Gamma(\text{Spec } k, \varepsilon^*\Omega_{\text{SL}_2/k}) \cong \mathfrak{sl}_2^*$ with a left-invariant differential form of SL_2 . Let's choose $dx_{11} \in \Gamma(\text{Spec } k, \varepsilon^*\Omega_{\text{SL}_2/k})$. One can view dx_{11} as an element in $\Gamma(\text{SL}_2, \Omega_{\text{SL}_2/k})$. On the other hand, from the multiplication map $m : \text{SL}_2 \times \text{SL}_2 \rightarrow \text{SL}_2$, we can pullback to obtain a section $m^*(dx_{11})$ of $\Omega_{\text{SL}_2 \times \text{SL}_2/k}$, i.e.

$$m^*(dx_{11}) = d(y_{11}z_{11} + y_{12}z_{21}) = y_{11}dz_{11} + z_{11}dy_{11} + y_{12}dz_{21} + z_{21}dy_{12}.$$

We also have $\Omega_{\mathrm{SL}_2 \times \mathrm{SL}_2 / k} \cong p_y^* \Omega_{\mathrm{SL}_2 / k} \oplus p_z^* \Omega_{\mathrm{SL}_2 / k}$ where p_y, p_z is the projection of $\mathrm{SL}_2 \times \mathrm{SL}_2$ to the first and second factor, respectively. This means

$$m^*(dx_{11}) = \omega_y + \omega_z = (z_{11}dy_{11} + z_{21}dy_{12}) + (y_{11}dz_{11} + y_{12}dz_{21}).$$

Now, consider the twist diagonal map $\delta : \mathrm{SL}_2 \rightarrow \mathrm{SL}_2 \times \mathrm{SL}_2$ given by $\delta \mapsto (\delta^{-1}, \delta)$. The claim in the proof is that $\delta^*\omega_z$ is a left-invariant different form for SL_2 . Let's describe $\delta^*\omega_z$ explicitly.

First, note that δ corresponds to the map $\delta' : \mathcal{O}(\mathrm{SL}_2) \otimes_k \mathcal{O}(\mathrm{SL}_2) \rightarrow \mathcal{O}(\mathrm{SL}_2)$, defined by sending $y_{ij} \otimes z_{kl}$ to the function $\mathrm{SL}_2(k) \rightarrow k$, taking $a \mapsto (a^{-1}, a) \mapsto (a^{-1})_{ij}a_{kl}$. In particular, it sends

$$\delta^*\omega_z = \delta^*(y_{11}dz_{11} + y_{12}dz_{21}) = \delta'(y_{11})d(\delta'(z_{11})) + \delta'(y_{12})d(\delta'(z_{21})) = x_{22}dx_{11} + (-x_{12})dx_{21}.$$

This is one of the left-invariant differential form for SL_2 given in the Math Stack Exchange answer. I will stop here for today.

A further note that in differential geometry, to find left-invariant differential form of a Lie group, there is something called the Maurer-Cartan equations/form that can be used. But I haven't had the time to understand what this means, so I will refer to p.190 of the book *Differential Geometry and Lie Groups* by Jean Gallier and Jocelyn Quaintance for the future.

4.8. 19/09/2021: Tamagawa measure on function fields.

4.8.1. *Function field of \mathbb{P}^1 .* In this section, we aim to describe \mathbb{P}^1 over a field k as a smooth, projective, geometrically connected algebraic curves. We then define the function field $k_{\mathbb{P}^1}$ of \mathbb{P}^1 and completions of $k_{\mathbb{P}^1}$.

The projective k -scheme $\mathbb{P}_k^1 := \text{Proj } k[x_0, x_1]$ can be described as follows:

- (1) The points of \mathbb{P}^1 consist of homogeneous prime ideals of the \mathbb{Z} -graded ring $k[x_0, x_1]$ ¹⁶.
- (2) For a homogeneous polynomial of positive degree $f \in k[x_1, x_2]$, let $D(f)$ be the set of homogeneous prime ideals of $k[x_0, x_1]$ not containing f . These sets form a basis of open sets for \mathbb{P}^1 . Furthermore, one can think of $D(f)$ as $\text{Spec}(k[x_0, x_1]_f)_0$, the spectrum of the algebra of elements in $k[x_0, x_1]_f$ having degree 0. For example, one can identify $D(x_i)$ with the affine scheme $\text{Spec } k[x_{0/i}, x_{1/i}]/(x_{i/i} - 1)$, where $x_{i/j}$ is identified with x_i/x_j .
- (3) The structure sheaf of \mathbb{P}^1 is obtained by giving $D(f)$ the structure sheaf of $\text{Spec}(k[x_0, x_1]_f)_0$. In particular, $\mathcal{O}_{\mathbb{P}^1}(D(x_0)) = k[x_{1/0}]$, $\mathcal{O}_{\mathbb{P}^1}(D(x_1)) = k[x_{0/1}]$ and the glueing of the structure sheaves on $D(x_0) \cap D(x_1) = D(x_0x_1)$ is obtained by sending $x_{0/1} \mapsto x_{1/0}$.

Being an integral scheme (i.e. $\mathcal{O}_{\mathbb{P}^1}(U)$ is an integral domain for every nonempty subset U of \mathbb{P}^1), \mathbb{P}^1 has a generic point η (i.e. a point that is dense in \mathbb{P}^1), corresponding to the homogeneous prime ideal (0) in $\mathbb{F}_p[x_0, x_1]$ (because every open set $D(f)$ contains (0)). The stalk $\mathcal{O}_{\mathbb{P}^1, \eta}$ of \mathbb{P}^1 at η , and hence the residue field $\kappa(\eta)$, is noncanonically isomorphic to $k(T)$ (i.e. if we view η as an element of $\text{Spec } \mathbb{F}_p[x_{0/1}] \hookrightarrow \mathbb{P}^1$, its stalk is then $k[x_{0/1}]_{(0)} = k(x_{0/1})$). We denote this as $k_{\mathbb{P}^1}$ and call it the *function field* of \mathbb{P}^1 over k .

A point in \mathbb{P}^1 is closed if it is closed in each open set $D(x_i)$ of \mathbb{P}^1 . Furthermore, a point in an affine scheme $\text{Spec } A$ is closed if it corresponds to a maximal ideal in A , and the maximal ideals of $k[x]$ are in bijection with monic irreducible polynomials in $k[x]$. Thus, closed points of \mathbb{P}^1 corresponds to homogeneous polynomials $Q(x_0, x_1) \in k[x_0, x_1]$ so that either $Q(x_{0/1}, 1)$ is monic irreducible in $x_{0/1}$ or $Q(1, x_{1/0})$ is monic irreducible in $x_{1/0}$.

For a closed point $x \in \mathbb{P}^1$ corresponding to a homogeneous polynomial $Q(x_0, x_1) \in k[x_0, x_1]$, the stalk $\mathcal{O}_{\mathbb{P}^1, x}$ of \mathbb{P}^1 at x is $k[x_{0/1}]_{(Q(x_{0/1}, 1))} \cong k[x_{1/0}]_{(Q(1, x_{1/0}))}$. The residue field $\kappa(x)$ at x is then noncanonically isomorphic to $k[t]/(Q(t, 1))$, which is a finite extension k . We denote \mathcal{O}_x to be the completion of the local ring $\mathcal{O}_{\mathbb{P}^1, x}$ then \mathcal{O}_x is a complete discrete valuation ring with residue field $\kappa(x)$, noncanonically isomorphic to the power series ring $\kappa(x)[[t]]$. Let k_x be the fraction field of \mathcal{O}_x .

4.8.2. *Group scheme over \mathbb{P}^1 .* Let $X = \mathbb{P}_{\mathbb{F}_p}^1$. Let G_0 be a linear algebraic group over k_X .

Definition 20. An integral model of G_0 is an affine and smooth group scheme $\pi : G \rightarrow X$ whose generic fiber (i.e. let η be a generic point of X then we have a morphism $\text{Spec } \kappa(\eta) \rightarrow \text{Spec } \mathcal{O}_{X, \eta} \rightarrow X$, giving us the generic fiber $G \times_X \text{Spec } \kappa(\eta)$ as a scheme over $\kappa(\eta)$) is isomorphic to G_0 .

Example 21. An integral model $\overline{\text{SL}}_2 \rightarrow \mathbb{P}^1$ for SL_2 can be obtained by base change $\overline{\text{SL}}_2 = \text{SL}_2 \times_{\text{Spec } \mathbb{F}_q} \mathbb{P}^1$.

Example 22. Masoud mentioned that a nontrivial example of an integral model is parahoric group scheme. I couldn't understand that much from googling around, but let me put something down first and leave this for later.

Question: Give an example of a parahoric group scheme \mathcal{P} over \mathbb{P}^1 whose generic fiber is a linear algebraic group G .

Most references refer to Bruhat Tits papers http://www.numdam.org/item/PMIHES_1972__41__5_0/. Benedict Gross wrote an expository paper about parahoric subgroups at <https://abel.>

¹⁶an ideal of $k[x_0, x_1]$ is homogeneous if it is generated by homogeneous polynomials

math.harvard.edu/~gross/preprints/parahorics.pdf. There are also some answers on Math-Overflow about this. I want to construct one from the suggestions given in <https://www.math.lsu.edu/~pramod/selie/10/mcninch.pdf>, i.e. from what I read, the $\kappa(x)[[t]] = \mathcal{O}_x$ -points of a parahoric group scheme is the stabiliser of x in the Bruhat-Tits building (some geometric gadget that $G(k_X)$ acts).

Given such a group scheme, for every commutative ring R equipped with a map $u : \text{Spec}(R) \rightarrow X$, we can associate a group $G(R)$. If u factors through the generic point η of X , we can equip R with the structure of k_X -algebra via u , and $G(R)$ can be identified with $G_0(R)$. A choice of integral model gives additional structures:

- (1) For each closed point $x \in X$, we have a morphism $\text{Spec } \mathcal{O}_x \rightarrow \text{Spec } \mathcal{O}_{X,x} \rightarrow X$ ¹⁷, so we can consider the group $G(\mathcal{O}_x)$ of \mathcal{O}_x -valued points of G .
- (2) For a closed point $x \in X$, we have a morphism $\text{Spec } \kappa(x) \rightarrow \text{Spec } \mathcal{O}_{X,x} \rightarrow X$, so we can consider the group $G(\kappa(x))$ of $\kappa(x)$ -valued point of G . We have a surjective map $G(\mathcal{O}_x) \rightarrow G(\kappa(x))$ because G is smooth¹⁸.
- (3) For a finite set S of closed points of X , we have a morphism $\text{Spec } \mathbb{A}_X^S \rightarrow X$ so we can consider the group $G(\mathbb{A}_X^S)$ of \mathbb{A}_X^S -valued point of G . It is an open subgroup of $G(\mathbb{A}_X) = G_0(\mathbb{A}_X)$ and as $\text{Spec } \mathbb{A}_X^S = \prod_{x \in S} \text{Spec } k_x \times \prod_{x \notin S} \text{Spec } \mathcal{O}_x$, $G(\mathbb{A}_X^S)$ is isomorphic to the direct product $\prod_{x \in S} G(k_x) \times \prod_{x \notin S} G(\mathcal{O}_x)$.

4.8.3. p -adic integration and point counting over finite fields. In this section, we will focus on explaining a theorem of Weil that links between p -adic integrations and point counting of algebraic varieties over finite fields. We follow the following reference

- (1) p -adic Integration and Birational Calabi-Yau Varieties by Pablo Magni.
- (2) First chapter about p -adic integration of the book Motivic Integration by A. Chambert-Loir, J. Nicaise, and J. Sebag.

Let k be a nonarchimedean local field, \mathcal{O}_k be its ring of integers, \mathbb{F}_q be the residue field where q is a prime power of a prime p . Let X be a smooth scheme of relative dimension n over \mathcal{O}_k and Ω_{X/\mathcal{O}_k} be the sheaf of differentials.

We will define a canonical measure on $X(\mathcal{O}_k)$, called the *Weil measure*. Because X is smooth over \mathcal{O}_k , $\Omega_{X/\mathcal{O}_k}^n$ is a locally free sheaf of \mathcal{O}_X -modules of rank 1, there exists an affine open cover $\{U_i\}$ of \mathcal{O}_k -schemes of X such that we have a trivialisation $\Omega_{X/\mathcal{O}_k}^n|_{U_i} \cong \mathcal{O}_X|_{U_i}$ over each U_i . A trivialisation of $\Omega_{X/\mathcal{O}_k}^n|_{U_i}$ corresponds to a nowhere-vanishing differential form $\omega_i \in \Gamma(U_i, \Omega_{X/\mathcal{O}_k}^n)$. From this, we can define a (Radon) measure $d|\omega_i|$ on $U_i(\mathcal{O}_k)$ by integrating with respect to ω_i . We also have $X(\mathcal{O}_k) = \bigcup_i U_i(\mathcal{O}_k)$, so in order to define a (Radon) measure on $X(\mathcal{O}_k)$, the measures $d|\omega_i|$'s must agree on overlaps. This is true because for two nowhere-vanishing differential forms $\omega_i|_{U_i \cap U_j}$ and $\omega_j|_{U_i \cap U_j}$ on $U_i \cap U_j$, there exists a nowhere-vanishing function $f \in \mathcal{O}_X|_{U_i \cap U_j}$ (hence invertible) so that $\omega_i = f\omega_j$ on $U_i \cap U_j$. This gives us the relation $d|\omega_i|(x) = |f(x)|_k d|\omega_j|(x)$ of measures on $U_j(\mathcal{O}_k) \cap U_i(\mathcal{O}_k) = (U_i \cap U_j)(\mathcal{O}_k)$. However, as $f : (U_i \cap U_j)(\mathcal{O}_k) \rightarrow \mathcal{O}_k$ is invertible, $|f(x)|_k = 1$ for all $x \in (U_i \cap U_j)(\mathcal{O}_k)$, meaning $d|\omega_i| = d|\omega_j|$ on $(U_i \cap U_j)(\mathcal{O}_k)$.

Remark 23. The Weil measure is canonical in the sense that its construction does not depend on the existence of a global differential form. The main reason for this is because our scheme X is

¹⁷For example, let $X = \text{Spec } \mathbb{Z}$, a prime number in \mathbb{Z} corresponds to a closed point of X , we find $\mathcal{O}_{X,p} = \mathbb{Z}_{(p)}$ is a local ring with maximal ideal $\mathfrak{m}_{X,p} = p\mathbb{Z}_{(p)}$. The completion of $\mathcal{O}_{X,p}$ with respect to this maximal ideal is $\mathcal{O}_p = \mathbb{Z}_p$. Thus, we have $\mathbb{Z} \rightarrow \mathbb{Z}_{(p)} \rightarrow \mathbb{Z}_p$, giving us $\text{Spec } \mathcal{O}_x \rightarrow \text{Spec } \mathcal{O}_{X,x} \rightarrow X$

¹⁸Smoothness implies a condition on the Jacobian of the local coordinates at a point, and by a generalisation of Hensel's lifting lemma, we have surjectivity. For more details, see p.20 of See Weil's book Adeles and Algebraic Groups

over \mathcal{O}_k , hence any invertible function f , defined on an open set U of X , must have $|f(x)|_k = 1$ for all $x \in U(\mathcal{O}_k)$. This also means that one may not be able to repeat this construction to define a measure on $X(k)$. However, if we have a global differential form $\omega \in \Gamma(X, \Omega_{X/\mathcal{O}_k}^n)$, we can define a measure on $X(k)$ whose restriction to $X(\mathcal{O}_k)$ is the Weil measure.

In the literature (see Batyrev's paper *Birational Calabi-Yau n -folds have equal Betti numbers*), it seems that the name Weil measure is given when X has a global nowhere-vanishing differential form, and the measure we have constructed is called the canonical measure, and in fact, the two measures are the same if the Weil measure (as defined in the literature) exists. Thus, for convenience, we will stick with our definition of Weil measure.

Theorem 24 (Weil). *Let X be a smooth scheme of dimension n over \mathcal{O}_k . Let μ be the Weil measure on $X(\mathcal{O}_k)$, then*

$$\int_{X(\mathcal{O}_k)} d\mu = \frac{|X(\mathbb{F}_q)|}{q^n}.$$

Sketch. Consider the surjective reduction map $\varphi : X(\mathcal{O}_k) \rightarrow X(\mathbb{F}_q)$ sending $x \mapsto \bar{x}$, we then have

$$\int_{X(\mathcal{O}_k)} d\mu = \sum_{\bar{x} \in X(\mathbb{F}_q)} \int_{\varphi^{-1}(\bar{x})} d\mu.$$

It suffices to show $\int_{\varphi^{-1}(\bar{x})} d\mu = q^{-n}$ for all $\bar{x} \in X(\mathbb{F}_q)$. We view $\bar{x} \in X(\mathbb{F}_q)$ as an element of X by taking the value $\bar{x}(\eta)$ at the generic point $\eta \in \text{Spec } \mathbb{F}_q$. Because X is smooth and Ω_{X/\mathcal{O}_k} is locally free, there exists an affine open set $U \cong \text{Spec } \mathcal{O}_k[x_1, \dots, x_{n+m}]/(f_1, \dots, f_m)$ of \bar{x} such that $\Omega_{X/\mathcal{O}_k}|_U$ is trivialised and the Jacobian matrix $(\partial f_i / \partial x_{n+j})_{1 \leq i, j \leq m}$ is invertible at $\varphi^{-1}(\bar{x}) \subset U(\mathcal{O}_k)$ ($\varphi^{-1}(\bar{x}) \subset U$ as any open set of \bar{x} contains $x \in \varphi^{-1}(\bar{x})$, viewed an element of X by evaluating at the generic point $\eta \in \text{Spec } \mathcal{O}_k$). We consider the map $g : U(\mathcal{O}_k) \rightarrow \mathbb{A}_{\mathcal{O}_k}^{n+m}$ defined by $g(x_1, \dots, x_{n+m}) = (x_1, \dots, x_n, f_1(x), \dots, f_m(x))$. Observe that the Jacobian of g at $\varphi^{-1}(\bar{x})$ is a unit in \mathcal{O}_k . Therefore, by forgetting the last m coordinates, g induces an étale morphism $h : U \rightarrow \mathbb{A}_{\mathcal{O}_k}^n$, which induces a k -analytic isomorphism from $\varphi^{-1}(\bar{x})$ to \mathfrak{p}^n by Hensel's lemma, where \mathfrak{p} is the maximal ideal of \mathcal{O}_k . Furthermore, because $\Omega_{X/\mathcal{O}_k}|_U \cong \mathcal{O}_X^n|_U$, we can find a global nowhere-vanishing differential form $\omega \in \Gamma(U, \bigwedge^n \Omega_{X/\mathcal{O}_k}|_U)$. We then have $h^*(dt_1 \wedge dt_2 \wedge \dots \wedge dt_n) = f\omega$, where f is invertible in U , hence has p -adic norm 1 when viewed as a function $f : U(\mathcal{O}_k) \rightarrow \mathcal{O}_k$. By definition, $f\omega$ defines a Weil measure on the neighborhood $U(\mathcal{O}_k)$. Thus, we find

$$\int_{\varphi^{-1}(\bar{x})} d\mu = \int_{\mathfrak{p}^n} dt_1 \wedge \dots \wedge dt_n = q^{-n}$$

by the change of variables formula. □

4.8.4. Tamagawa measure for function fields. For a linear algebraic group G_0 over k_X , we will define the Tamagawa measure on $G_0(\mathbb{A}_X)$ in this section. We follow §1.3 of Gaitsgory and Lurie's book <https://www.math.ias.edu/~lurie/papers/tamagawa-abridged.pdf>.

Let $\pi : G \rightarrow X$ be an integral model of G_0 (such an integral model always exists), let $\Omega_{G/X}$ be the relative cotangent bundle of π . Then $\Omega_{G/X}^n := \bigwedge^n \Omega_{G/X}$ is a line bundle on G , where $n = \dim(G_0)$. Let \mathcal{L} be the pullback of $\Omega_{G/X}^n$ along the identity section $e : X \rightarrow G$. Sections of \mathcal{L} can be identified with left-invariant differential forms on G via the canonical isomorphism $\pi^* \mathcal{L} \cong \Omega_{G/X}^n$ (see Neron models p.100). Let $\mathcal{L}_0 := \text{Spec } k_X \times_X \mathcal{L}$ be the generic fiber of \mathcal{L} , whose global sections form a 1-dimensional k_X -vector space. A non-zero global section ω of \mathcal{L}_0 can be viewed as a global left-invariant nowhere-vanishing algebraic differential form on G_0 . For every closed point $x \in X$, ω induces a left-invariant Haar measure $d\mu_{\omega, x}$ on $G(k_x)$.

For an invertible sheaf \mathcal{L} of \mathcal{O}_X -modules and a nonzero global section ω of its generic fiber \mathcal{L}_0 , one can associate a divisor on X as follows. For a closed point $x \in X$, we consider the stalk $\mathcal{L}_x \subset \mathcal{L}_0$ at x , which is a \mathcal{O}_x -module of rank 1 inside a 1-dimensional k_X -vector space. Then $\omega\mathcal{O}_x$ is also a rank 1 \mathcal{O}_x -submodule of \mathcal{L}_0 . Let $t_x \in \mathcal{O}_x$ be a uniformiser element then $\omega\mathcal{O}_x = t_x^{-n_x} \mathcal{L}_x$ for some integer n_x . We define $v_x(\omega) := n_x$ to be the *order of vanishing* of ω at x .

Proposition 25. *For every closed point $x \in X$, We have*

$$\mu_{\omega,x} G(\mathcal{O}_x) = \frac{|G(\kappa(x))|}{|\kappa(x)|^{n+v_x(\omega)}},$$

where $v_x(\omega) \in \mathbb{Z}$ denotes the order of vanishing of ω at x .

Sketch. If we view ω as a left-invariant differential form on $G(k_x)$ via the isomorphism $\pi^* \mathcal{L} \cong \Omega_{G/X}^n$, $v_x(\omega)$ can be described as follows. At the neighborhood U of the identity e of $G(k_x)$, ω can be written as $\omega = f(t) dt_1 \wedge \cdots \wedge dt_n$ where t_1, \dots, t_n are the local coordinates at e , $f : U \rightarrow k_x$ is an invertible rational function. Then $f(e)\mathcal{O}_x = t_x^{-v_x(\omega)} \mathcal{O}_x$. In other words, the image of $\omega(e) \in \bigwedge^n T_e^*(G(\mathcal{O}_x))$ under $\bigwedge^n T_e(G(\mathcal{O}_x))$ generates a fractional ideal $\mathfrak{p}^{-v_x(\omega)}$ of k_x . Because ω is left-invariant so for any $g \in G(\mathcal{O}_x)$, the image of $\omega(g) \in \bigwedge^n T_g^*(G(\mathcal{O}_x))$ under $\bigwedge^n T_g(G(\mathcal{O}_x))$ generates the fractional ideal $\mathfrak{p}^{-v_x(\omega)}$ of k_x . In other words, under a new local coordinates y_1, \dots, y_n at the neighborhood of $g \in G(\mathcal{O}_x)$, $\omega = f'(y) dy_1 \wedge \cdots \wedge dy_n$ where f' is a rational function so that $f'(g)\mathcal{O}_x = t_x^{-v_x(\omega)} \mathcal{O}_x$. By the definition of Weil measure, we then find that $t_x^{v_x(\omega)} \omega$ defines the Weil measure on $G(\mathcal{O}_x)$, or ω defines a measure $|\kappa(x)|^{-v_x(\omega)} \mu_{\text{Weil}}$ on $G(\mathcal{O}_x)$. Thus, by Weil's theorem, we find

$$\mu_{\omega,x}(G(\mathcal{O}_x)) = |\kappa(x)|^{-v_x(\omega)} \mu_{\text{Weil}}(G(\mathcal{O}_x)) = \frac{|G(\kappa(x))|}{|\kappa(x)|^{n+v_x(\omega)}}.$$

□

The Tamagawa measure $\mu_{G_0,X}$ of $G(\mathbb{A}_X) = G_0(\mathbb{A}_X)$ is

$$\tau_X(\mathbb{G}_a)^{-n} \prod_{x \in X}' \mu_{\omega,x}.$$

We have $\tau_X(\mathbb{G}_a) = q^{g-1}$, where g is the genus of X **need to learn this**. We also have

$$\prod_{x \in X} |\kappa(x)|^{v_x(\omega)} = \prod_{x \in X} q^{\deg(x)v_x(\omega)} = q^{\sum_{x \in X} \deg(x)v_x(\omega)} = q^{\deg \mathcal{L}} = q^{\deg \Omega_{G/X}}.$$

Here $\deg(x) := [\kappa(x) : \mathbb{F}_q]$, $\deg \mathcal{L} := \sum_{x \in X} \deg(x)v_x(\omega)$ where the sum is over all closed points of X ¹⁹, $\deg \mathcal{L} = \deg \Omega_{G/X} = n$ because of the isomorphism $\pi^* \mathcal{L} \cong \Omega_{G/X}^n$ (see Stack project <https://stacks.math.columbia.edu/tag/0AYQ>, we have $\deg \mathcal{L} = \deg \pi^* \mathcal{L} = \deg \Omega_{G/X}^n = \deg \Omega_{G/X}$). Thus, we find

$$\mu_{G_0,X}(G(\mathbb{A}_X^\emptyset)) = q^{n(1-g)-\deg(\Omega_{G/X})} \prod_{x \in X} \frac{|G(\kappa(x))|}{|\kappa(x)|^n}.$$

4.9. 22/09/2021: Cayley transform carries conjugacy classes in G to adjoint orbits in \mathfrak{g} . The classical Cayley transform gives a bijection between the real skew-symmetric matrices ($A^t = -A$) to the orthogonal matrices ($A^t A = I$) by sending

$$A \mapsto \frac{I - A}{I + A}.$$

¹⁹note that this does not depend on the choice of ω because for any two nonzero global sections ω and ω' of \mathcal{L} , there exists a nowhere-vanishing function $f \in \mathcal{O}_X(X)$ so $\omega = f\omega'$, and one can show $\sum_{x \in X} v_x(f) \deg(x) = 0$.

One define this Cayley transform for other classical groups (and I think for reductive groups?). In general, a Cayley transform is a bijection from a (reductive) group G to its Lie algebra \mathfrak{g} (see <https://www.mat.univie.ac.at/~michor/kostant.pdf> The Generalized Cayley Map from an Algebraic Group to its Lie Algebra by Bertram Kostant and Peter W. Michor for complex, reductive, which says that we have the Cayley map whenever we have a faithful representation of our group G). One property of this map is that it carries conjugacy classes in G to adjoint orbits in \mathfrak{g} , allowing one to study conjugation action of G via the adjoint action in \mathfrak{g} .

It seems that this transform plays some role in the theory of Harish-Chandra characters, Fourier analysis on orbital integrals (see <https://arxiv.org/abs/1111.7057>, which is where I first found the term). I am intestered in the application of this to the study of orbital integrals appearing in the Fundamental lemma of the Langlands program. It seems to me that this is a way to reduce the group theoretic version about orbits to the Lie algebra theoretic version about orbits. But I cannot make it more precise than this.

I don't know if this has anything to do with the orbit method of Kirillov (<https://ncatlab.org/nlab/show/orbit+method>) in representation theory?

4.10. 22/09/2021: Category theory: Adjunctions and String diagrams. Some notes on what I have learn from the category theory reading group, following Tom Leinster, Basic Category Theory.

There are many ways to describe adjoint functors F, G between two categories \mathcal{A}, \mathcal{B} (where $F : \mathcal{A} \rightarrow \mathcal{B}$ is left-adjoint to $G : \mathcal{B} \rightarrow \mathcal{A}$):

- (1) First way: For any $A \in \mathcal{A}, B \in \mathcal{B}$, we have bijections $\text{Hom}_{\mathcal{B}}(FA, B) \cong \text{Hom}_{\mathcal{A}}(A, GB)$ (called this taking conjugations) satisfying some natural compatibility conditions.
- (2) Second way: We have units $\eta : 1_{\mathcal{A}} \Rightarrow GF$ and counits $\varepsilon : FG \Rightarrow 1_{\mathcal{B}}$ satisfying triangle identities.
- (3) Third way: We have unit η such that for any $A \in \mathcal{A}$, $\eta_A : A \rightarrow GF(A)$ is an initial object in the comma category $(1_A \Rightarrow G)$, where $1_A : 1 \rightarrow \mathcal{A}$ is a functor defined by A . To define the comma category: For functors $P : \mathcal{A} \rightarrow \mathcal{C}$ and $Q : \mathcal{B} \rightarrow \mathcal{C}$, the comma category $(P \Rightarrow Q)$ is the ‘pullback’ of the diagram of categories

$$\begin{array}{ccc} (P \Rightarrow Q) & \longrightarrow & \mathcal{B} \\ \downarrow & \nearrow & \downarrow Q \\ \mathcal{A} & \xrightarrow{P} & \mathcal{C} \end{array}$$

Concretely, it consists of a category $(P \Rightarrow Q)$ with projections functors $p_{\mathcal{B}} : (P \Rightarrow Q) \rightarrow \mathcal{B}$ and $p_{\mathcal{A}} : (P \Rightarrow Q) \rightarrow \mathcal{A}$, together with a natural transformation $Pp_{\mathcal{A}} \Rightarrow Qp_{\mathcal{B}}$ (Search ‘2-limit’ for more of this).

In the category theory reading group, we learn how to draw functors between categories and natural transformations between functors as string diagrams. I am a bit lazy to write down the way to see this but let me link to the videos by TheCatsters <https://youtube.com/playlist?list=PL50ABC4792BD0A086>. The main idea is that one can turn a natural transformation to a string diagram by Poincare duality, treating 2-morphisms (i.e. natural transformations) as points, 1-morphisms (i.e. functors) as a line and 0-morphisms (objects) as 2-dimensional spaces.

Although up to this point, I am still not that convinced on how one can see triangle identities in adjunctions as string diagrams, i.e. <https://ncatlab.org/nlab/show/triangle+identities> with the above rules of drawings?

What is the relation of string diagrams with Feymann diagrams?

I think I refer to the following reference on June 2021 already (related to Topological QFT) but let me link it again: <https://arxiv.org/abs/math/0512103>.

4.11. **22/09/2021: Characters in representation theory.** I read the section about trace formula in representation theory from <https://arxiv.org/abs/1009.1862v3>

Some things I don't understand: For a finite-dimensional representation π of a finite group G , one can define the character of π by taking the trace of your representation, which can be viewed as a linear functional on $\mathbb{C}[G]$. One can generalise the definition of character for compact G and the application of characters in representation theory in both cases are similar: irreducible characters are orthonormal basis of the space of class functions; knowing these irreducible characters help to determine decomposition of any G -representation V into irreducibles (see Folland, Abstract harmonic analysis, §5.3 for example). A generalisation of this for semisimple G is Harish-Chandra character, i.e. it is a distribution of G , defined by

$$\Theta_\pi : f \mapsto \text{Tr} \left(\int_G f(x) \pi(x) dx \right).$$

What is the role of this character theory in representation theory of G ? Is there an even more general context of character theory? e.g. categorical version, locally compact version, p -adic version? Is there a conceptual explanation of why taking trace is a natural thing to do? Update 28/09/2021: See Terence Tao's comment in <https://mathoverflow.net/a/13527/89665>, where he said trace is a linearised version of dimension-counting operator. So I guess some sort of decategorification functor (if this makes any sense) ... See also the comment on how this idea fails in characteristic $p > 0$.

Maybe this has something to do with the discussion on 13/08/2021, where character theory is some sort of decategorification of the category $\text{Rep}(G)$.

Another related thing is that I don't know too much of the analytic side of representation theory: distributions, Plancherel formula, ... *Hopefully, this will motivate me to read something like <http://math.uchicago.edu/~ngo/Rep-p-adic.pdf> more carefully.*

4.12. More things to learn.

- (1) From 19/09/2021: What is the definition of divisors, the correspondence between divisors and invertible sheaves, Weil divisors, Cartier divisors ? Divisors of locally free sheaves over a curves? See Vakil's book or Wedhorn's book on AG.
- (2) Analogy of $\text{Spec } \mathbb{Z}$ as a 3-manifold? <https://mathoverflow.net/q/4075/89665> See also Ben-Zvi's Relative Geometric Langlands duality from <https://www.msri.org/workshops/918/schedules/28233> and <https://math.ucr.edu/home/baez/week257.html>.
- (3) Motivic characters of SL_2 : <https://arxiv.org/abs/math/0609260>, see also 22/09/2021.
- (4) Just found some links <https://ncatlab.org/nlab/show/functorial+field+theory> to topological QFT, functorial field theory. This is something I managed to learn a bit on 06/2021, hopefully I have later time to revisit this. See also string diagrams on 22/09/2021. The book "Towards the Mathematics of Quantum Field Theories" is also following this direction I believe (probably the best place to learn).
- (5) (22/09/2021) I found a very nice notes by David Nadler in <https://arxiv.org/abs/1009.1862v3>, titled 'The Geometric Nature of the Fundamental Lemma'. I only managed to read the first three sections of his notes, but even so, I loved the way he presented the materials on these sections.
Need to write some notes on what I learnt from this notes. In particular,
 - (a) Trace formula in representation theory, starting from finite group example (see also 22/09/2021).
 - (b) Chevalley restriction theorem and characteristic polynomials.
 - (c) Reductive groups generality.
 - (d) A study of orbits under group action.

5.1. 01/10/2021: Hecke algebra, groupoid version. I learnt how to describe the Hecke algebra as a groupoid from David Ben-Zvi's lectures Between electric-magnetic duality and the Langlands program (p. 122). I remembered trying to understand something like this on 06/06/2021 (what Ben-Zvi called 'geometric function theory'), but at the time I couldn't figure out what pt/G means in Ben-Zvi's notes back then. Now thanks to the category theory reading group (see 22/09/2021), I can make some sense out of this (at least when G is finite).

First, let me try to restate the question in Ben-Zvi's lectures: Let G be a finite group acting on a space X , and let $K \subset G$ be a subgroup.

What is the symmetry of $\mathbb{C}[X/K]$, i.e. what acts on $\mathbb{C}[X/K]$?

One views $\mathbb{C}[X/K]$ as K -invariant functions $\mathbb{C}[X]^K$ on X , and we have a K -invariant functor of G -representations

$$(-)^K : \text{Rep } G \rightarrow \text{Vect}.$$

To study the action on $(-)^K$ means to understand its endomorphism $\text{End}((-)^K)$. By Frobenius reciprocity (or Hom- \otimes adjunction), the functor $(-)^K$ is representable by

$$V_{G,K} = \text{Ind}_K^G \mathbb{C} = \mathbb{C}[G] \otimes_{\mathbb{C}[K]} \mathbb{C} = \mathbb{C}[G/K].$$

The Hecke algebra $\mathcal{H}_{G,K}$ is

$$\mathcal{H}_{G,K} := \text{End}((-)^K) = \text{End}_{\text{Rep}(G)}(V_{G,K}, V_{G,K}) = (V_{G,K})^K = \mathbb{C}[K \backslash G / K].$$

Have I really answered the question of what is the symmetry of $\mathbb{C}[X/K]$? The third equal sign follows from the fact that a G -homomorphism $\phi : V_{G/K} \rightarrow V_{G/K}$ is determined by the image $\phi(1_K)$, where $1_K \in \mathbb{C}[G/K]$. We also know K fixes 1_K when acting on $\mathbb{C}[G/K]$. This description tells us that the double coset has a canonical algebra structure via the endomorphism ring.

The functor $(-)^K$ factors through $\mathcal{H}_{G,K}\text{-mod}$, which is equivalent to the subcategory of $\text{Rep}(G)$, consisting of spherical G -representations, i.e. its irreducible components V has non-trivial K -invariants $V^K \neq \emptyset$. The word 'spherical' goes back to the study of spherical harmonics, i.e. $L^2(S^2)$ being acted on by SO_3 , where noting that $S^2 = \text{SO}_3 / \text{SO}_2$.

One has a concrete way to describe the algebra structure of $\mathcal{H}_{G,K}$ as follows. We first start by describing the algebra structure of the group algebra $\mathbb{C}[G]$.

In fact,

Now, we want to describe a canonical algebra structure on $\mathbb{C}[G]$ from the multiplication map $\mu : G \times G \rightarrow G$. We first write down all the information we know about G : **Technically this is not all information, we are missing something about identity map, associativity, ... but why are they missing when defining the algebra structure on $\mathbb{C}[G]$?**

$$\begin{array}{ccc} & G \times G & \\ \swarrow \pi_1 & \downarrow \mu & \searrow \pi_2 \\ G & & G \\ & \downarrow & \\ & G & \end{array}$$

Does this link to finite Fourier transform?

Remark 26. We start of by discussing pullback and pushforward of a given map $f : X \rightarrow Y$ between two spaces X and Y . For convenience, we take X, Y to be finite.

For a map $\Phi : X \rightarrow Y$, it is not hard to define pullback $\Phi^* : \mathbb{C}[Y] \rightarrow \mathbb{C}[X]$, when we view $\mathbb{C}[Y]$ as the space of functions on Y . However, to define pushforward $\Phi_* : \mathbb{C}[X] \rightarrow \mathbb{C}[Y]$, a natural

definition of $\Phi_*(f)$ for $f \in \mathbb{C}[X]$ is sending

$$y \mapsto \int_{\Phi^{-1}(y)} f dx := \sum_{x \in \Phi^{-1}(y)} f(x).$$

From this, to define pushforward, it is better to view $\mathbb{C}[X]$ as the space of measures on X , i.e. given $f \in \mathbb{C}[X]$, one can (noncanonically) associate a measure on X by sending open $U \subset X$ to $\int_U f dx$. Now $\Phi^*(f)$ is a measure on Y , defined by sending open $V \subset Y$ to $\int_{\Phi^{-1}(V)} f dx \in \mathbb{C}$.

When X is locally compact Hausdorff, by Riesz representation theorem, there is a canonical way to view a measure on X as a linear functional $\mathbb{C}[X] \rightarrow \mathbb{C}$. In other words, to identify measures and functions on X , we have essentially identify $\mathbb{C}[X]$ with its dual $\mathbb{C}[X]^*$.²⁰ In our case where X is finite, to see the duality between functions $\mathbb{C}[X]$ on X and measures $\mathbb{C}[X]^*$ on X , we have fixed a measure on X , i.e. a linear functional $\int_X : \mathbb{C}[X] \rightarrow \mathbb{C}$, defined by $f \mapsto \sum_{x \in X} f(x)$. From this, recall we have noncanonically identified a function $f \in \mathbb{C}[X]$ with a measure μ_f on X , sending open $U \subset X$ to $\mu_f(U) = \int_U f dx$. One view this measure as a linear functional $\mathbb{C}[X] \rightarrow \mathbb{C}$ by $g \mapsto \int_X g(x) \mu_f(x) = \int_X f(x) g(x) dx$. Thus, in other words, the duality between $\mathbb{C}[X]$ and $\mathbb{C}[X]^*$ is obtained by choosing a linear functional $\int_X : \mathbb{C}[X] \rightarrow \mathbb{C}$ (i.e. a measure on X) by $f \mapsto \sum_X f(x)$ and then define an inner product on $\mathbb{C}[X]$ by

$$\langle f, g \rangle = \int_X f(x) g(x) dx := \sum_{x \in X} f(x) g(x).$$

I don't see the point where the Hermitian condition of the inner product comes in naturally This inner product also gives the compatibility between pullback and pushforward, where they are adjoint with respect to this inner product.

So the duality allows one to work with one space (instead of with itself and its dual). Usually it is easier to define pullback on the spaces X and easier to define pushforward on the dual spaces. Having a self-duality allows one to define pullback and pushforward on the same space.^{21 22}

This then reminds me of the discussion on 13/08/2021 and 22/09/2021.

Under the identification $\mathbb{C}[X]$ with $\mathbb{C}[X]^*$, we want to check that the pushforward Φ_* is really coming from $\mathbb{C}[X]^* \rightarrow \mathbb{C}[Y]^*$. **Need to check this**

A final comment: A lesson I learnt from this computation is that adjointness is like an approximation for duality. Normally it is difficult to determine left-adjoint of some operator/functor, but once we have duality (between $\mathbb{C}[X]$ and $\mathbb{C}[X]^*$) then constructing the adjoint is easier.

Remark 27. We would like to discuss the G -equivariant case of the previous remark, i.e. we would like to describe pullback and pushforward of $\Phi : X \rightarrow Y$ when we have an action of G on X and Y . Again, we assume X, Y are finite first, and we consider G -equivariant functions on X and Y , denoted $\mathbb{C}[X/G]$ or $\mathbb{C}[X]^G$. If Φ is G -equivariant then one can define pullback $\Phi^* : \mathbb{C}[Y/G] \rightarrow \mathbb{C}[X/G]$.

One should view pushforward as something coming from taking the dual of pullback, i.e. $\mathbb{C}[X/G]^* \rightarrow \mathbb{C}[Y/G]^*$. Thus, to define pushforward $\Phi_* : \mathbb{C}[X/G] \rightarrow \mathbb{C}[Y/G]$, our task is to find a way to identify $\mathbb{C}[X/G]^*$ with $\mathbb{C}[X/G]$. Similar to the previous remark, we first need to choose a linear functional

²⁰In functional analysis language, a linear functional $\text{Fun}(X) \rightarrow \mathbb{C}$ is called a distribution (or generalised function)

²¹ Another remark: I think another place where we have the duality between measures and functions on X is when X is a smooth manifold. A tangent vector is roughly a linear map $C^\infty(X) \rightarrow \mathbb{C}$, a differential form is dual to a tangent vector, so something like $\text{Func}(C^\infty(X)) \rightarrow \mathbb{C}$. One can define a measure with respect to a differential form. We can then define pullback and pushforward of differential forms as analogues of pullback and pushforward of measures.

Make precise

²² Another place where we have that self-duality is the case of Hilbert space, where we are given a Hermitian inner product that identifies the Hilbert space H with its dual.

$\int_{X/G} : \mathbb{C}[X/G] \rightarrow \mathbb{C}$. We define $f \mapsto \sum_{x \in |X/G|} \frac{f(x)}{\#\text{Aut}(x)}$ for the case X is finite. Here $|X/G|$ is the set of isomorphism classes of elements in X , $\#\text{Aut}(x)$ is the size of the isotropy group of x .

After identifying $\mathbb{C}[X/G]$ with $\mathbb{C}[X/G]^*$, we will now define the pushforward map. **Need to do**

The algebra structure on $\mathbb{C}[G]$ (called convolution) can be described in terms of the multiplication map μ as follows.

$$f_1 * f_2 := \mu_*(f_1 \boxtimes f_2) := \mu_*(\pi_1^* f_1 \cdot \pi_2^* f_2).$$

5.2. 05/10/2021: References: Aaron Mazel-Gee, factorisation homology, ∞ -categories.

The website of Aaron Mazel-Gee has many good notes about ∞ -categories. For example his introductory lecture notes to Higher Algebra <https://etale.site/teaching/w21/math-128-lecture-notes.pdf>, his guidelines for topics in ∞ -category <https://etale.site/teaching/f16-infty/seminar-infty-2.pdf>, a syllabus about factorisation homology <https://etale.site/teaching/s19-fact-hlgy/fact-hlgy-outline.pdf> and his lecture notes.

What caught my interest is that he mentioned factorisation homology as *generalised integration theory*. **I would like to learn on what he meant by that.**

Some more references about factorisation homology:

- (1) Lectures on Factorization Homology, Infinity-Categories, and Topological Field Theories: <https://arxiv.org/abs/1907.00066>
- (2) Claudia Isabella Scheimbauer PhD thesis <http://www.scheimbauer.at/ScheimbauerThesis.pdf>

5.3. 19/10/2021: Tamagawa number as Pic/Sha. So for connected reductive group over number field, we have $\tau(G) = \frac{\text{Pic}(G)}{\text{III}(G)}$.

See discussion at <https://mathoverflow.net/q/44184/89665>.

I would like to understand this statement for SL_n or GL_n .

5.3.1. *Picard group.* Let G be a (split) connected semisimple linear algebraic group over a (algebraically closed) field k (of characteristic 0). The Picard group $\text{Pic } G$ of G is the group of isomorphism classes of line bundles on X . In this section, we will focus on proving the following

Theorem 28. *If G is simply connected then $\text{Pic } G = 0$.*

Trying for SL_2 . One way to show $\text{Pic}(\text{SL}_2)$ is to show $\mathcal{O}(\text{SL}_2) = k[x_{ij}]/(x_{11}x_{22} - x_{12}x_{21} - 1)$ is a unique factorisation domain, and the fact that the Picard group of $\text{Spec } A$ for a unique factorisation domain A is trivial. But proving $\mathcal{O}(\text{SL}_2)$ is a UFD for any k seems to be nontrivial (in fact this is usually considered as a consequence of the theorem proved via other methods). See <https://math.stackexchange.com/q/173021/58951>.

A second way, following Milne p. 69 <https://www.jmilne.org/math/CourseNotes/RG.pdf>, is as follows: Consider $T \subset B \subset \text{SL}_2$. We have a group homomorphism

$$\begin{aligned} X^*(T) &\rightarrow \text{Pic}(\text{SL}_2/B) \\ \chi &\mapsto L(\chi) \end{aligned}$$

A character $\chi : T \rightarrow \mathbb{G}_m$ induces a B -equivariant line bundle $\text{SL}_2 \times^B \mathbb{A}^1$ on SL_2 by letting B acts on $\text{SL}_2 \times \mathbb{A}^1$ by

$$(g, x)b = (gb, \chi(b^{-1})x), g \in G, x \in \mathbb{A}^1, b \in B.$$

This descends to a line bundle $L(\chi) = \text{SL}_2 \times_{\text{SL}_2} \mathbb{A}^1$ on $G/B = \mathbb{P}^1$. In fact, this is an isomorphism $X^*(T) \cong \text{Pic}(G/B) = \text{Pic}(\mathbb{P}^1) \cong \mathbb{Z}$.

Milne claimed that the following sequence is exact

$$0 \rightarrow X^*(\text{SL}_2) \rightarrow X^*(T) \rightarrow \text{Pic}(\text{SL}_2/B) \rightarrow \text{Pic}(\text{SL}_2) \rightarrow 0$$

Milne didn't prove this. I tried to look elsewhere for the proof of exactness of this sequence and found this <https://www-fourier.ujf-grenoble.fr/~mbrion/enney.pdf>, which I couldn't understand ... For example, is there a way to see $\text{Pic}(\text{SL}_2/B) \rightarrow \text{Pic}(\text{SL}_2)$ is surjective?

From the exactness of the above sequence, we find $\text{Pic}(\text{SL}_2) = 0$.

Trying to understand the general proof. I found the proofs to be given in:

- (1) Section 4 (Proposition 4.6) of Local properties of algebraic group actions by F. Knop, H. Kraft, D. Luna and T. Vust [in: "Algebraische Transformationsgruppen und Invariantentheorie" (H. Kraft, P. Slodowy, T. Springer eds.) DMV-Seminar 13, Birkhuser Verlag (Basel-Boston) (1989), pp. 63-76]
- (2) Another proof by Iversen 19 sketched in p.70 Milne Reductive groups notes. There are some similarities between the two proofs.
- (3) Another proof in Voskresenskii's Algebraic Groups and Their Birational Invariants, p. 45 using Kummer exact sequence and etale cohomology.

A sketch of what I understand about the first two proofs:

- (1) Show $\text{Pic } G$ is finite.

An 'independent' proof I found in Voskresenskii's Algebraic Groups and Their Birational Invariants, p. 45: By the theory of split semisimple group, there exists $g \in G(k)$ so NgB is open in G (N is a nilpotent group, B is a Borel) and $V = G \setminus NgB$ is the union $\bigcup_{i=1}^l F_i$ of closed irreducible subsets of G of codimension 1 (i.e. prime divisors of G), where $l = \text{rank } G = \dim T$. Because G is smooth, $\text{Pic } G$ can be identified with (Weil?Cartier?) divisors, so the above implies (see p.312 of the book Ulrich Grtz, Torsten Wedhorn, Algebraic Geometry I: Schemes) an exact sequence

$$\bigoplus_{i=1}^l \mathbb{Z} \cdot [F_i] \rightarrow \text{Pic}(G) \rightarrow \text{Pic}(NgB) \rightarrow 0$$

As $NgB \cong N \times T \times N$ so $\text{Pic}(U) = 0$ (I think this goes roughly as $\text{Pic}(\mathbb{G}_a) = \text{Pic}(\mathbb{G}_m) = 0$?). This means $\text{Pic}(G)$ is the quotient of \mathbb{Z}^l by principal divisors on U , i.e. regular invertible functions on U , which is $k(U)^* \cong k^* \times X^*(T)$ (Voskresenskii didn't explain this but I guess it roughly goes like this: N is \mathbb{G}_a^r so invertible functions on $U = N \times T \times N$ are the same as invertible functions on T because invertible function on \mathbb{G}_a is trivial?).

All of this implies $\text{Pic}(G)$ is finite.

- (2) Identify $\text{Pic}(G)$ with central extensions $\text{Ext}(G, \mathbb{G}_m)$ of G by \mathbb{G}_m . This implies for any $L \in \text{Pic}(G)$, there exists a finite covering $\pi : G' \rightarrow G$ of algebraic groups so $\pi^*(L) = 0$.

I am still trying to understand this step. For example, in Lemma 4.3 of Knop, Kraft, Luna, I don't understand the definition of $\mu : L \times L \rightarrow L$, i.e. how to map $L \times L \rightarrow p_1^*(L) \otimes p_2^*(L)$.

People commented that this step is similar to the abelian variety case. See Serre Algebraic groups and class fields VII. §16.

- (3) Because $\text{Pic}(G)$ is finite with elements L_1, \dots, L_k . By previous step, there exists finite covering $G'_i \rightarrow G$ of G , then $\prod G'_i \rightarrow G$ is a finite covering of G such that the induced map $\text{Pic}(G) \rightarrow \text{Pic}(\prod G'_i) = 0$.
- (4) If G is simply connected, meaning any finite covering $G' \rightarrow G$ is an isomorphism, giving an isomorphism $\text{Pic}(G) \rightarrow \text{Pic}(G')$ Hence, we can choose $G' = \prod G'_i$ from previous step to get $\text{Pic}(G) = 0$.

For more general G . There is a formula of $\text{Pic}(G)$ for more general reductive G . See <https://mathoverflow.net/q/296965/89665> or <https://mathoverflow.net/a/297093/89665>.

A discussion of the proof is given in <https://mathoverflow.net/a/273883/89665>.

See also Voskresenskii's p. 45.

5.3.2. *Tate-Shafarevich set.* I would like to mention of historial facts I learnt about this.

For a global field k and algebraic group G , there is a natural map

$$H^1(k, G) \rightarrow \prod_v H^1(k_v, G)$$

The kernel of this map is called Tate-Shafarevich set, denoted $\text{III}(G)$. Its geometric meaning is all G -torsors X so $X(k_v) \neq 0$ for all places v .

- (1) When G is a linear algebraic group, $\text{III}(G)$ is shown to be finite in

J-J. Sansuc, Groupe de Brauer et arithmetique des groupes algebriques lineaires sur un corps de nombres

- (2) When G is an abelian variety, this is a group. But it seems that the finiteness of this is still a conjecture, and this directly ties with the Birch and Swinnerton-Dyer conjecture.
(3) When $G = \text{SL}_n$ or GL_n , there is a simple proof that $H^1(k, \text{SL}_n) = 1$ given in Voskresenskii p 28 but I didn't have enough time to learn this.
(4) For simply-connected algebraic group, $\text{III}(G) = 0$ and this is the Hasse principle for algebraic groups.

5.4. **21/10/2021: Mednykh's formula, TQFT, character varieties, skein algebra.** The story from 06/06/2021, 13/09/2021 and 01/10/2021 again, about Mednykh's formula and TQFT. Maybe also 05/10/2021.

There is an open question on MathOverflow asking a modular analogue of Mednykh's formula <https://mathoverflow.net/q/313599/89665>.

Until now, I still don't understand the proof of this seminar and historical background (<https://arxiv.org/pdf/math/0703073.pdf>), what kind of generalisations can it get.

Sam Gunningham asked what aspects of character theory that can be simplified using TQFT.

I get a bit more motivated about this topic because I just learned about Madeline's research which is Temperley Lieb algebra, which leads me to related topics like skein theory: <https://arxiv.org/pdf/1908.05233.pdf>.

I wonder if one can always described this sort of algebra (Hecke, Temperley Lieb) as some TQFT? What advantage can this point of view give?

Another link between skein algebra as quantization of algebra of functions on a character varieties: <https://youtu.be/GF5PXRkEn3w>. There are connections to mirror symmetry but I don't understand this.

What is the precise relation here between TQFT, skein, character varieties, Mednykh's formula?

5.5. **23/10/2021: Condensed mathematics and functional analysis.** Peter Scholze and Dustin Clausen are using condensed mathematics to rewrite the theory of functional analysis that have better functional properties. Condensed sets are analogues of compactly generated space (which includes locally compact topological spaces). **I wonder what is the right notion of measures of a (locally comact) topological spaces in this setting, and then Fourier transform? What is adeles in this setting? What is \mathbb{R} ? What is the difference between \mathbb{R} and \mathbb{Q}_p in this setting?** For a talk, see <https://youtu.be/cDkuhXD7hn0>. See also Scholze's notes <https://www.math.uni-bonn.de/people/scholze/Condensed.pdf> for locally compact abelian groups. Here we have Pontryagin duality.

5.6. **23/10/2021: How to discover Hecke algebras: Knot invariants.** First motivation is through the study of the algebra of B -equivariant functions on $G = \mathrm{GL}_n(\mathbb{F}_q)$. See 01/10/2021. A blog post here explains how to categorify this idea <https://sbseminar.wordpress.com/2009/04/09/interpreting-the-hecke-algebra-ii-the-sheafification/>.

Second motivation is through knot invariants <https://sbseminar.wordpress.com/2009/04/13/how-to-get-an-algebra-from-a-knot-invariant/> and <https://mathoverflow.net/a/12986/89665>. What exactly does this mean? i.e. how to one sees the quadratic relation of the Hecke algebra from knot invariants? It seems the quadratic relation comes from skein relation? And then what is the motivation for skein relation? What is the stuff about fundamental groups of a torus mentioned in <https://mathoverflow.net/a/13461/89665>?

5.7. More things to learn.

- (1) For a Lie group G , let $LG = \mathrm{Map}(S^1, G)$ be a Lie group of all morphisms between manifolds $f : S^1 \rightarrow G$. The group structure is given by pointwise multiplication. Why the Lie algebra of this is $L\mathfrak{g} = \mathfrak{g} \otimes \mathbb{C}((t))$. Why does this group has trivial central extension? Taking the Lie algebra of the central extensions, we should get affine Lie algebras.
- (2) Principles between cohomology as classifying obstructions: <https://math.stanford.edu/~conrad/210BPage/handouts/gpext.pdf> (Brian Conrad has so many good notes)
- (3) Spectral sequences, computing cohomology. What is a good motivation to do this? Perverse sheaves?

6. MORE THINGS TO LEARN

- (1) Everthing about SL_2, GL_2 : Representations of $SL_2(\mathbb{R}), SL_2(\mathbb{F}_q), SL_2(\mathbb{Q}_p), U(\mathfrak{sl}_2)$, quantum affine \mathfrak{sl}_2 , ... Some links:
 - (a) <https://jenseberhardt.com/teaching/S21Seminar/plan.pdf>, <https://jenseberhardt.com/teaching/W2021Seminar/plan.pdf>, <https://www.maths.usyd.edu.au/u/romanova/Talks/TwistSheavess12.pdf>
 - (b) Rep of $SL_2(\mathbb{F}_q)$, book by Cedric Bonnafé (see rep lie group of finite type folder).
 - (c) automorphic representations of SL_2, GL_2 over adeles <https://virtualmath1.stanford.edu/~conrad/conversesem/refs/NgoGL2.pdf>, trace formula <https://www.math.stonybrook.edu/~aknapp/pdf-files/355-405.pdf> (see more at folder about automorphic forms), Anton Deitmar book Automorphic forms looks very introductory
 - (d) More general refs: <https://virtualmath1.stanford.edu/~conrad/conversesem/>,
 - (e) Langlands fundamental lemma for SL_2 (Bill Casselman Essays on the Fundamental Lemma).
- (2) Geometric Langlands and its connection to mathematical physics: https://web.ma.utexas.edu/users/vandyke/notes/langlands_sp21/langlands.pdf; Quantization problem <https://arxiv.org/pdf/math/0210466.pdf>.
- (3) Perverse sheaves, Kazhdan-Lusztig conjectures. See Archar's book, Chriss Ginzburg, Goerdie and Anna's notes, Humphreys book, <https://chenhi.github.io/math7390-s21/>, Gelfand and Manin books, any many more ...
- (4) Algebraic geometry, complex geometry
 - (a) do Vakil exercises. Learn sheaf cohomology in more details.
 - (b) Moduli space of vector bundles over Riemann surfaces, over \mathbb{P}^1 (see Sabin Cautis notes).
- (5) Something is mysterious to me about "hypergeometric", as it seems appear in many areas. Some references: Zoladek The Monodromy Group (see Geometry folder), Kapranov Hypergeometric functions on reductive groups (Hypergeometric folder), Macdonald hypergeometric functions, Hypergeometric functions over finite fields by Jenny Fuselier, Ling Long, Ravi Ramakrishna, Holly Swisher, Fang-Ting Tu.

I would like to at least understand all the application in terms of the ${}_2F_1$ hypergeometric function.

7. NOVEMBER 2021

7.1. **07/11/2021: Coxeter systems.** Today I read the book Introduction to Soergel bimodules, up to §1.1.5. Learnt some interesting ways to describe Coxeter systems type A,B,D via strand diagrams.

7.2. **08/11/2021: Stoke's theorem.** Read Bott Tu Differential forms in Algebraic topology. Learn about Stoke's theorem and its proof.

Learn how to compute De Rham cohomology of \mathbb{R}^2 minus one/two points.

Proposition 29. *We will compute $H_{dR}^*(\mathbb{R}^2 - \{0\})$.*

Proof.

□

7.3. 10/11/2021: Valuation theory. Revise about valuation theory of fields, in particular nonarchimedean valuation from the book Introduction to non-Archimedean Geometry by Piotr Achinger. The goal would be to learn some nonarchimedean geometry and its applications.

7.4. 11/11/2021: Poincare lemmas: De Rham and compactly supported cohomology of \mathbb{R}^n . Today I read some more pages of Bott Tu's book. In particular, I learned on how one computes De Rham and compactly supported cohomology of \mathbb{R}^n . Importantly, one needs to prove the Poincare lemma, saying that

$$H_{dR}^*(\mathbb{R}^n \times \mathbb{R}) \cong H_{dR}^*(\mathbb{R}^n)$$

and

$$H_c^*(\mathbb{R}^n \times \mathbb{R}) \cong H_c^{*-1}(\mathbb{R}^n).$$

For the de Rham cohomology, one can show that the projection map $\mathbb{R}^n \times \mathbb{R} \rightarrow \mathbb{R}$ and the inclusion $\mathbb{R} \hookrightarrow \mathbb{R}^n \times \mathbb{R}$ via $r \mapsto (r, 0)$ induce the isomorphism in cohomology, i.e. p^*e^* and e^*p^* are homotopic to the identity map.

For the compactly supported cohomology, we have the integration-over-fibers map that induces map $H_c^*(\mathbb{R}^n \times \mathbb{R}) \rightarrow H_c^{*-1}(\mathbb{R}^n)$ on cohomology. Together with the map $\Omega_c^*(\mathbb{R}^n) \rightarrow \Omega_c^{*+1}(\mathbb{R}^n \times \mathbb{R})$ by adding dt in the \mathbb{R} component of $\mathbb{R}^n \times \mathbb{R}$, these two map induces the isomorphism $H_c^*(\mathbb{R}^n \times \mathbb{R}) \cong H_c^{*-1}(\mathbb{R}^n)$ on cohomology. The compositions of these two maps are homotopic to the identity maps, although the construction of homotopic operators doesn't seem to be trivial to me.

Poincare lemma also holds for any smooth manifold M instead of \mathbb{R}^n .

I also learned about degree map: given a proper map of smooth real manifolds $f : \mathbb{R}^n \rightarrow \mathbb{R}^n$, one can define pullback of compactly supported cohomology $f^* : \Omega_c^*(\mathbb{R}^n) \rightarrow \Omega_c^*(\mathbb{R}^n)$. Choose a compactly supported n -form $\alpha \in \Omega_c^n(\mathbb{R}^n) \cong \mathbb{R}$ with volume 1 when integrating over \mathbb{R}^n . The degree map is $\deg f := \int_{\mathbb{R}^n} f^*\alpha$. Surprisingly, this turns out to be an integer. The proof uses Sard's theorem. Actually this situation is very much the same as the compact Riemann surface case, see 05/09/2021.

7.5. 16/11/2021: Tamagawa numbers and unfinished questions. I finished my honours about Tamagawa numbers today. I still have quite a lot of questions unanswered regarding this topic (see Tamagawa folder). I just want to record some of those questions here and move on first. Hopefully when I get back I can understand more.

- (1) Learn Weil's computation of Tamagawa for other groups.
- (2) Learn Langlands's proof of computation of Tamagawa number
 - Eisenstein series, then explicit computations in the notes
 - Rewrite Langlands proof in functorial point of view to see the main idea. See Braveman, Kazhdan Representations of affine Kac-Moody groups over local and global fields: a survey of some recent results.
 - geometric Eisenstein series? There is a notion of geometric Eisenstein series, can this be used to compute Tamagawa <https://web.ma.utexas.edu/users/benzvi/GRASP/lectures/drinfeldEisen.pdf>?
- (3) Yang-Mills theory and Tamagawa Numbers: Read Atiyah Bott paper, Harder -j. What is the connection with Tamagawa?
 - Connections on principal bundles, Yang Mills, <https://www.math.toronto.edu/mein/teaching/moduli.pdf> and <http://www.math.columbia.edu/~thaddeus/papers/odense.pdf>
 - Equivariant cohomology -j. Tu's book, Goergie's book.
- (4) Lurie Gaitsgory proof:
 - Moduli stack of vector bundles. Weil's conjecture -j. Frank Neumann; Behrend, The Lefschetz trace formula for algebraic stacks; Algebraic stacks and moduli of vector bundles Frank Neumann; Alper Introduction to Stacks and Moduli.

- Higher algebra: Lurie's lecture notes on Tamagawa. <https://web.ma.utexas.edu/users/gregoric/Appendix.pdf>
- (5) (3.5) More: affine Tamagawa (Braveman, Kazhdan), Tate-Shafarevich groups, condensed mathematics (it seems to define better space to do Haar measure), Tamagawa in Higgs bundles, characteristic varieties, Siegel Weil Formula <https://www.math.ucdavis.edu/~mulase/texfiles/charvar.pdf>, p-adic integration, motivic integration, height zeta functions <https://www.youtube.com/watch?v=ngwax1V1Bgg&t=1529s>,
 - (6) condensed mathematics: how to test this with Tamagawa numbers? Class field theory? Langlands' proof? Adeles? Cohomology using adeles? The point of condensed set is to have good cohomology theory, where do we use cohomology theory in the proof of Tamagawa number? How Haar measures change under exactness of functions? Can we use Lurie Gaitsgory proof for the number field case? Can we use Langlands proof for number field case? What is analogue of Haar measures here? Can we define Haar measure for not just locally compact? For example $G(\mathbb{C}((t)))$? See Frenkel Analytic theory of langlands over complex curves, section 3,4. "The representation theories of the corresponding groups, such as $G(\mathbb{Q}_p)$ and $G(\mathbb{C})$, are known to follow different paths: for the former we have, in the unramified case, the spherical Hecke algebra and the Satake isomorphism. For the latter, instead of a spherical Hecke algebra one usually considers the center of $U(\mathfrak{g})$ (or, more generally, the convolution algebra of distributions on $G(\mathbb{C})$ supported on its compact subgroup K)"
 - (7) Relative Langlands: The principle of Tamagawa numbers is that integrating over adelic quotient gives you values of L -functions. This has another name of 'periods in automorphic forms', where we integrate a function instead of just taking the volume. Recently, Yiannis Sakellaridis and Akshay Venkatesh define periods this for spherical varieties, <https://arxiv.org/pdf/1203.0039.pdf>. The question is whether there is a Tamagawa number formula for general spherical varieties.
 - (8) There is a general formula $\tau(G) = |Pic(G)|/|Sha(G)|$. Is it valid over function fields? Do we have a description of this in terms of G -bundles? Just like for semisimple simply connected G , we can formulate $\tau(G) = 1$ in terms of G -bundles.

Now, let's learn something different!

7.6. 17/11/2021: Poincare duality, Kunneth formula and Poincare duals. Last few days I read about Poincare duality, Kunneth formula and Poincare duals from Bott and Tu book. A few technical points:

- (1) For oriented manifold (without boundary) M of dimension n , we have a pairing $H^q(M) \otimes H_c^{n-q}(M) \rightarrow \mathbb{R}$, obtained by taking wedge product and then integrating over M . Poincare duality states that this pairing induces an isomorphism $H^q(M) \cong (H_c^{n-q}(M))^*$. Bott and Tu only proved this for the case M has finite good cover and use Mayer-Vietoris in §5. Interestingly, one does not always have $H_c^q(M) \cong (H^{n-q}(M))^*$. But in the case of M having finite good cover (cover of M where intersection of any two is \mathbb{R}^k), we do have this.
- (2) Kunneth formula says that $H^*(M \times F) = H^*(M) \otimes H^*(F)$ as graded \mathbb{R} -vector spaces for manifolds M, F where one of them has finite good cover. This can be generalised to Leray-Hirsch theorem about cohomology of fiber bundle where the base space has a finite good cover.
- (3) For any closed submanifold S of manifold M of dimension n , via Poincare duality, one can associate to S a Poincare dual $[\eta_S] \in H^{n-k}(M)$ for any $0 \leq k \leq n$. If S is compact, one can associate compact Poincare dual $[\eta'_S] \in H_c^{n-k}(M)$ to S .

7.7. 24/11/2021: Fourier analysis and rep theory. I read a nice overview from <https://mathoverflow.net/a/37189/89665>, which describes Fourier analysis in a representation theoretic viewpoint.

- (1) For locally compact group G , we want to describe $L^2(G)$ as Hilbert space direct integral of matrix coefficients of irreducible unitary reps (not sure what this means), and for this, one has to find the correct measure (Plancherel measure) on set \widehat{G} of irreducible unitary reps.
- (2) When G is “Type I”, we have such measure of \widehat{G} and a decomposition of $L^2(G)$, but such measure is not explicitly given.
- (3) When G is a real semisimple Lie group, Harish-Chandra describes Plancherel measure explicitly. Those irreducible unitary reps appearing in the spectral decomposition of $L^2(G)$ are called *tempered*. Among those tempered, a rep that have positive spectral measure is called *discrete series* rep. The *principal series* representations are non-discrete tempered and account for the spectral decomposition of functions supported on the hyperbolic elements of the group. The *complementary series* are those irreducible unitary reps that are not tempered.

7.8. 28/11/2021: Tate’s thesis I: From Dirichlet characters to quasicharacters on $\mathbb{Q}^\times \backslash \mathbb{A}^\times$. I read this from Stephen S. Kudla notes on Tate’s thesis. From Dirichlet characters to quasicharacters on $\mathbb{Q}^\times \backslash \mathbb{A}^\times$:

- (1) A classical Dirichlet character $\underline{\chi}_N : \mathbb{Z} \rightarrow \mathbb{C}$ modulo N is a function obtained from a character $\chi_N : (\mathbb{Z}/n)^\times \rightarrow \mathbb{C}^\times$ by extending to 0 on \mathbb{Z}/n and then pulling back to \mathbb{Z} .
- (2) Every Dirichlet character $\underline{\chi}_N$ can be viewed as a continuous character χ on $\widehat{\mathbb{Z}}^\times$ by pulling back via $\widehat{\mathbb{Z}}^\times = \varprojlim_n (\mathbb{Z}/n)^\times \rightarrow (\mathbb{Z}/n)^\times$.
- (3) As $\mathbb{A}^\times \cong \mathbb{Q}^\times \times \mathbb{R}_+^\times \times \widehat{\mathbb{Z}}^\times$ so any Dirichlet character defines a continuous character $\omega : \mathbb{Q}^\times \backslash \mathbb{A}^\times \rightarrow \mathbb{C}^\times$, called a quasicharacter. An example of a quasicharacter is $\omega_s(x) = |x|_\mathbb{A}^s$ for $s \in \mathbb{C}$.
- (4) A character $\omega_p : \mathbb{Q}_p^\times \rightarrow \mathbb{C}^\times$ is *unramified* if it is trivial on \mathbb{Z}_p^\times , hence can be written in the form $\omega_p(x) = t_p^{\text{ord}_p(x)}$ for some $t_p = t_p(\omega) \in \mathbb{C}^\times$.
- (5) A quasicharacter on $\mathbb{Q}^\times \backslash \mathbb{A}^\times$ induces quasicharacters ω_p on \mathbb{Q}_p^\times via the embedding $\mathbb{Q}_p^\times \hookrightarrow \mathbb{A}^\times$. There are finite set of places $S(\omega)$ containing the archimedean places such that ω_v is unramified for all $v \notin S(\omega)$. If ω corresponds to a Dirichlet character $\underline{\chi}_N$ then $S(\omega) = \infty \cup \{p : p \mid N\}$.
- (6) It is harder to define Dirichlet character when the number field is not \mathbb{Q} , as one does not simply have $\mathbb{A}^\times = \mathbb{Q}^\times \times \mathbb{R}_+^\times \times \widehat{\mathbb{Z}}^\times$ but need to take into account of global units and ideal class group being nontrivial. This is why the adelic point of view is better.
- (7) For a quasicharacter ω , one can associate a partial L -function by taking the Euler product

$$L^S(s, \omega) = \prod_{v \notin S(\omega)} (1 - t_v(\omega) q_v^{-s})^{-1},$$

which is absolutely convergent in the half plane $\text{Re}(s) > 1$. The factors

$$L_v(s, \omega_v) := (1 - t_v(\omega) q_v^{-s})^{-1}$$

are called *local L-factors* associated to ω_v .

- (8) The goals are to complete L_S to include local L -factors for $v \in S(\omega)$, and then to prove meromorphic analytic continuation and functional equation of the completed L -function.

Some more definition: The *conductor* of $\chi : \widehat{\mathbb{Z}}^\times \rightarrow \mathbb{C}^\times$ is the smallest N_0 for which χ is trivial on the kernel of $\widehat{\mathbb{Z}}^\times \rightarrow (\mathbb{Z}/N_0)^\times$, i.e. χ is the pullback of a unique Dirichlet character χ_{N_0} .

7.9. 28/11/2021: Torus, elliptic curves and double cover of \mathbb{CP}^1 . A very rough ideas of what I learned today. We have the correspondences between:

$$A = \{\text{torus}\}$$

with

$$B = \{\text{elliptic curve}\}$$

with

$$C = \{\text{double cover of } \mathbb{P}^1 \text{ ramified at four points}\}.$$

- (1) To go between A and B , one uses Weierstrass function: for an elliptic curve $y^2 = (x - a)(x - b)(x - c)$, one can parametrise its points by $(x, y) = (P(t), P'(t))$ for $t \in \mathbb{C}$ where P is Weierstrass function of this curve, which is doubly periodic. Hence, the map $t \mapsto [P(t), P'(t), 1] \in E \cup \{\infty\}$ defines isomorphism between a torus and an (compactified) elliptic curve. See <https://www.math.purdue.edu/~arapura/graph/elliptic.html> for more details.
- (2) To go between B and C : Take the projection to x -axis. Then the ramified points are a, b, c and infinity (after compactifying elliptic curve). A more detailed check that this is indeed a ramified covering is at <https://math.stackexchange.com/a/177564/58951>. A rough idea is that the fiber at $x = a, b, c$ gives $y^2 = 0$.
- (3) To go between A and C : Quotient the torus $T = \mathbb{C}/\Lambda$ by relation $z \sim -z$ to get \mathbb{CP}^1 . This gives a double cover $T \rightarrow \mathbb{CP}^1$ ramified at 4 points (these 4 coincide at "infinity" in T). A segment between two of these points form a loop in the torus. For the converse, one can use branch-cut constructions, which I still don't quite understand. See for example <https://math.stackexchange.com/q/3474041/58951>.

7.10. 28/11/2021: Construction of derived categories. The classical way to define derived functors: For a left exact functor $F : \mathcal{C} \rightarrow \mathcal{D}$ where \mathcal{C} has enough injectives, its i -th derived functor $R^i F : \mathcal{C} \rightarrow \mathcal{D}$ applied to $A \in \mathcal{C}$ is the i th cohomology of $0 \rightarrow F(I^0) \rightarrow F(I^1) \rightarrow \dots$ where $0 \rightarrow A \rightarrow I^0 \rightarrow I^1 \rightarrow \dots$ is an injective resolution of A .

Two fundamental examples of this:

- (1) For R -modules A, B , the functor $Tor(\cdot, B)$ is the left derived functor of $\cdot \otimes_R B$ and $Ext(A, \cdot)$ is the right derived functor of $\text{Hom}(A, \cdot)$.
- (2) Category $Sh(X)$ of sheaves of vector spaces/abelian groups over X has enough injectives. Since taking global section Γ is left exact, it has a right derived functor $R^i \Gamma$. When X is Hausdorff and paracompact, $R^i \Gamma(\mathcal{F})$ can be seen to be the Čech cohomology $H^i(X, \mathcal{F})$.

The goal of derived categories is to find a better way to talk about derived functors, i.e. we want to compute cohomology in terms of complexes and neglect morphisms between complexes that induce isomorphisms on cohomology.

- (1) We start with an abelian category \mathcal{A} . We define category $C(\mathcal{A})$ as category of complexes in \mathcal{A} . We have cohomology functor $H^i : C(\mathcal{A}) \rightarrow \mathcal{A}$.
- (2) As two homotopic morphisms in $C(\mathcal{A})$ induce the same cohomology map, and as we only care about cohomology map, we define the *homotopy category* $K(\mathcal{A})$ over \mathcal{A} as: objects same as $C(\mathcal{A})$, but morphisms are morphisms in $C(\mathcal{A})$ modulo $f : A^\bullet \rightarrow B^\bullet$ that is homotopic to 0. The cohomology functor descends to $H^i : K(\mathcal{A}) \rightarrow \mathcal{A}$.
- (3) $K(\mathcal{A})$ is additive but not abelian, so one cannot speak of short exact sequences in the category. However, $K(\mathcal{A})$ is close to being abelian in the sense that it is a *triangulated category*.
- (4) $K(\mathcal{A})$ can be seen as a triangulated category as follows:
 - (a) We have a *suspension functor* $\Sigma^n : K(\mathcal{A}) \rightarrow K(\mathcal{A})$ sending $A^\bullet \mapsto A[n]^\bullet$ which is the shift functor of complexes: $(A[n])^i = A^{i+n}$ and differential $d_{A[n]^\bullet}^i = (-1)^n d_{A^\bullet}^i$.

- (b) In general, a triangulated category consists a class of distinguished triangles, i.e. sequences $X \rightarrow Y \rightarrow Z \rightarrow X[1]$ where composition of any two adjacent arrows is 0, that satisfy 4 axioms. If one sees $Z[-1] \rightarrow X$ as homotopy kernel of $X \rightarrow Y$ and $Y \rightarrow Z$ as homotopy cokernel of $X \rightarrow Y$, these four axioms will say that

- (i) The identity map has zero homotopy kernel and cokernel.
- (ii) Every map has a homotopy kernel and cokernel.
- (iii) Any map is the homotopy kernel of its homotopy cokernel and every map is the homotopy cokernel of its kernel.
- (iv) Homotopy kernels and cokernels are ‘functorial’.

A morphism $f : A^\bullet \rightarrow B^\bullet$ in $K(\mathcal{A})$, induces a distinguished triangle

$$A^\bullet \xrightarrow{f} B^\bullet \rightarrow \text{cone}(f) \rightarrow A[1]^\bullet,$$

hence giving $K(\mathcal{A})$ the structure of a triangulated category.

- (5) Lastly, we would like to consider quasi-isomorphism on $K(\mathcal{A})$ to be invertible, as those induces isomorphism on cohomology. This uses localisation construction of category: take S the set of all quasi-isomorphisms in $K(\mathcal{A})$, one can define a unique localisation category $K(\mathcal{A})[S^{-1}]$ of $K(\mathcal{A})$ at S with a functor $Q : K(\mathcal{A}) \rightarrow K(\mathcal{A})[S^{-1}]$, that satisfy the similar localisation property for modules. This gives us the *derived category* $D(\mathcal{A})$ of \mathcal{A} .
- (6) In this case of taking localisation of a triangulated category $K(\mathcal{A})$, we can describe $D(\mathcal{A})$ quite explicitly as follows: Its objects are the same as $C(\mathcal{A})$, but morphisms are given by equivalence classes of *roofs*. A roof from X^\bullet to Y^\bullet is a diagram

$$\begin{array}{ccc} & X^\bullet & \\ f \swarrow & & \searrow g \\ A^\bullet & & B^\bullet \end{array}$$

where $f, g \in K(\mathcal{A})$, f is a quasi-isomorphism. Two roofs $A^\bullet \rightarrow B^\bullet$ are equivalent if there is a third roof such that we have a commutative diagram

$$\begin{array}{ccccc} & & Z^\bullet & & \\ & \swarrow & & \searrow & \\ X^\bullet & & & & Y^\bullet \\ \downarrow & & \swarrow & \searrow & \downarrow \\ A^\bullet & & & & B^\bullet \end{array}$$

Note that there is some checking needed for the above description of $D(\mathcal{A})$ to make sense.

7.11. 30/11/2021: Mayer-Vietoris argument. I noticed many results (Poincare duality, Kuneth formula) have two main ingredients in their proofs: first is to establish the result in the case of \mathbb{R}^n (Poincare lemma), then use the Mayer-Vietoris argument to deal with the general case (given that the manifold has finite good cover).

After realising the importance of the Mayer-Vietoris argument, I want to sketch it here.

First is the case of de Rham cohomology,

8.1. 06/12/2021: Sato's hyperfunctions. Today I read a bit about Sato's hyperfunctions that somehow generalise distribution theory of Schwarz et al. The hyperfunctions $\mathcal{B}(U)$ on $U \subset \mathbb{R}$ are defined by holomorphic functions on $\tilde{U} \setminus U$ for open $\tilde{U} \subset \mathbb{C}$ satisfying $\tilde{U} \cap \mathbb{R} = U$, modulo holomorphic functions on \tilde{U} . This definition does not depend on \tilde{U} , so one should think of hyperfunctions as “boundary values” of holomorphic functions.

This \mathcal{B} is actually a sheaf of modules over sheaf of real analytic functions. There is a linear injection from the space of distributions $\mathcal{D}'(\mathbb{R})$ to the space of hyperfunctions $\mathcal{B}(\mathbb{R})$. So hyperfunctions includes Schwartz distributions as a special case and is more explicit in the sense that it is not based on some dual spaces of some smooth functions. Furthermore, with the definition of hypergeometric functions, one can make sense of differentiation and integration using complex analysis. This means one can make sense of integration of distributions, which seem to be of use to physicists.

Some references to read more. What are the applications of these functions to the theory of differential equations? How to define Fourier transform on these? What are the differences between distribution theory and hyperfunctions?

- (1) Urs Graf Introduction to Hyperfunctions and Their Integral Transforms
- (2) Henrik Schlichtkrull Hyperfunctions and Harmonic Analysis on Symmetric Spaces.

8.2. 15/12/2021: Connection and curvature. Given a vector bundle $\pi : V \rightarrow M$ of (C^∞ -real manifolds, complex analytic, smooth algebraic varieties, smooth rigid analytic variety). I learnt of various ways to interpret/define connection and curvature (see wikipedia on connection):

- (1) A connection (in the sense of Ehresmann connection) on π tells you how to move between fibers of the bundle in a horizontal direction, i.e. tells you what paths in V are considered ‘horizontal’. This is achieved by identifying a ‘horizontal’ subspace H_x of V_x for each $x \in M$. If one starts with a path on the base M then a horizontal lift of this path on V is not unique, and the failure of uniqueness is measured by curvature. If curvature vanishes, we say the connection is integrable. This interpretation allows one to link integrable connection with monodromy representations. This interpretation of connection is more topological and is in fact valid for any fiber bundle.

Equivalently, Ehresmann connection is a vector bundle hom $v : TV \rightarrow TV$ that is a projection (i.e. $v^2 = v$). The ‘horizontal’ subbundle can then be identified with $\ker v$. One should view this v as TV -valued 1-form on V , i.e. v as section of $TV \otimes (TV)^* = TV \otimes \Omega(V)^1$.

- (2) A connection (in the sense of Koszul/linear connection) as family of differential operators acting on sections of V : by choosing open U of M so $V|_U$ is affine, with local coordinates x_1, \dots, x_n on U of M , one can define action of $\frac{\partial}{\partial x_i}$ on $\Gamma(U, V)$. Curvature is then the measure of commutativity of these differential operators, i.e. curvature vanishes if $\frac{\partial}{\partial x_i}$ commute with each other.

A more formal definition: A connection on V is a bundle map $\nabla : V \rightarrow V \otimes \Omega_M^1$ which is additive and satisfies Leibniz rule: for any open $U \subset X$, any $f \in \Gamma(U, \mathcal{O}_U)$ and $s \in \Gamma(U, V)$,

$$\nabla(fs) = f\nabla(s) + s \otimes df.$$

A section s is called horizontal if $\nabla(s) = 0$.

Let T_X be the tangent bundle on X then for $\xi \in T_X(U)$, we can define a (differential) operator

$$\nabla_\xi : \Gamma(U, V) \rightarrow \Gamma(U, V), \nabla_\xi(\phi) = \langle \nabla\phi, \xi \rangle.$$

We view ∇_ξ as differentiating sections of V along vector fields ξ . This is the global version of differential operator as defined before. A connection is said to be integrable if the map $\xi \mapsto \nabla_\xi$ is a Lie algebra homomorphism $T_X \rightarrow \text{End}(V)$.

Let $\nabla_1 : V \otimes \Omega_M^1 \rightarrow V \otimes \Omega_M^2$ be the map

$$s \otimes w \mapsto \nabla(s) \wedge w + s \otimes dw.$$

The curvature is the map $\nabla_1 \circ \nabla$. A connection is integrable is same as saying curvature vanishes (actually I haven't check this).

- (3) A connection as vector-valued differential forms (Cartan connection): Note that (Koszul) connection is a map $V \rightarrow V \otimes \Omega_M^1$, where one should view $\Omega_M^p(V) := V \otimes \Omega_M^p$ as V -valued p -form on M . Similar to how we define ∇_1 in the definition of curvature, we can define

$$d_\nabla : \Omega^r(V) \rightarrow \Omega^{r+1}(V)$$

by

$$d_\nabla(s \otimes \omega) = s \otimes d\omega + (-1)^{\deg \omega} \omega \wedge \nabla s.$$

In this sense, a connection defines a sequence of morphisms $\Omega^*(V)$. It is not a complex as $d_\nabla^2 \neq 0$. In fact, $d_\nabla^2 = 0$ is equivalent to the fact that the curvature vanishes (see more at wikipedia vector bundle). So, **if the connection is integrable, how much de-Rham theory can be applied to flat connection?**

8.3. 17/12/2021: Algebraic de Rham and Hodge-de Rham spectral sequence. I learned about the algebraic de Rham and the Hodge-de Rham spectral sequence from Kiran S. Kedlaya notes 'p-adic cohomology: from theory to practice' (see more technical notes at the edited pdf file). The main example would be to use the Hodge-de Rham spectral sequence to compute de Rham cohomology of projective spaces.

8.3.1. Algebraic de Rham. Let X be a smooth variety over a field k of relative dimension n (smooth scheme of finite type which is reduced and separated). We have the de Rham complex of sheaves on X :

$$0 \rightarrow \Omega_{X/k}^0 \rightarrow \Omega_{X/k}^1 \rightarrow \cdots \rightarrow \Omega_{X/k}^n \rightarrow 0.$$

We define the *algebraic de Rham cohomology* of X , denoted $H_{dR}^i(X)$, as the hypercohomology of the de Rham complex.

- (1) By definition, take any quasi-isomorphism $\Omega_{X/k}^* \rightarrow I^*$ where I^* is a complex of injective elements. The hypercohomology $H^i(\Omega_{X/k}^*)$ is defined to be the cohomology of the complex $\Gamma(I^*)$ where Γ is the global section functor.
- (2) Instead of using injective resolution to compute de Rham, one can use acyclic resolution. The point is that it is easier to construct acyclic resolution by using Čech complexes.
- (3) For a quasi-coherent sheaf \mathcal{F} of \mathcal{O}_X -modules on X , we can construct an acyclic resolution of \mathcal{F} as follows: Let $\{U_i\}_{i \in I}$ be a finite open cover of X by affine open subschemes with I a totally ordered set. Since X is separated, any nonempty finite intersection of U_i 's is affine. For $J \subset I$, let $U_J = \bigcap_{i \in J} U_i$. Let $j_J : U_J \rightarrow X$ be the open submersion, which is affine and hence, $(j_J)_*$ is exact. Since every quasi-coherent sheaf on affine space is acyclic, $(j_J)_* j_J^* \mathcal{F}$ is acyclic on X . The acyclic resolution \mathcal{F}^* of \mathcal{F} is then
 - (a) $\mathcal{F}^i = \bigoplus_J (j_J)_* j_J^* \mathcal{F}$ over all $(i+1)$ -elements subset J of I .
 - (b) The map $\mathcal{F}^i \rightarrow \mathcal{F}^{i+1}$, sends $x_J \in (j_J)_* j_J^* \mathcal{F}$ to element of \mathcal{F}^{i+1} whose component in $(j_L)_* j_L^* \mathcal{F}$ with $L = \{j_0 < \cdots < j_{i+1}\}$ is

$$\sum_{h=0}^{i+1} (-1)^h x_{L \setminus \{j_h\}}.$$

In particular, the sheaf cohomology of \mathcal{F} is the given cohomology of this complex after taking global sections. In i th position of this complex is the direct sum of $\Gamma(U_J, j_J^* \mathcal{F})$ over all $(i+1)$ -elements subsets J of I .

- (c) From the previous point, we have an acyclic resolution $D^{i,\bullet}$ for each $\Omega_{X/k}^i$. This gives us a double complex $D^{p,q} = \bigoplus_J \Gamma(U_J, \Omega_{X/k}^p)$ where the sum is over all $(q+1)$ -element subsets J of I . To construct an complex of acyclic objects to $\Omega_{X/k}^*$: Let $D^i = \bigoplus_{j+k=i} D^{j,k}$, define $D^i \rightarrow D^{i+1}$ by sending an element of D^i with component $x_{j,k} \in D^{j,k}$ to one with component in $D^{j,k}$ being $d_{\text{horizontal}}(x_{j-1,k}) + (-1)^j d_{\text{vertical}}(x_{j,k-1})$ (here vertical is just restriction maps, horizontal is the differential). Then D^\bullet is an acyclic resolution of $\Omega_{X/k}^\bullet$.
- (d) An example of a computation using this method is given by Kedlaya: Suppose $P(x) = x^3 + ax + b \in k[x]$ has no repeated roots. Let $X = \text{Proj } k[X, Y, W]/(Y^2W - X^3 - aXW^2 - bW^3)$ be the complete elliptic curve. Compute de Rham cohomology of X .

8.3.2. *Hodge-de Rham spectral sequence.* We continue our theme of developing methods to compute the de Rham cohomology. Recall we have reduced the task to computing the cohomology of D^\bullet .

The complex D^\bullet has a filtration, i.e. a decreasing sequence of complexes:

$$D^\bullet = F^0 D^\bullet \supset F^1 D^\bullet \supset \dots \supset F^n D^\bullet \supset F^{n+1} D^\bullet = 0,$$

where $F^p D^i = \bigoplus_{p'+q=i, p' \geq p} D^{p',q}$. From a filtered complex $F^\bullet D^\bullet$, we can construct a *spectral sequence* in the following sense: it is a sequence $\{E_r, d_r\}_{r=r_0}^\infty$ where each E_r is a bigraded group

$$E_r = \bigoplus_{p,q \geq 0} E_r^{p,q}$$

and

$$d_r : E_r^{p,q} \rightarrow E_r^{p+r, q-r+1}, d_r^2 = 0$$

is a map such that $E_{r+1}^{p,q} = H^{p,q}(E_r^{p,q}, d_r)$. In particular, from our filtered complex $F^\bullet D^\bullet$, we get

$$E_0^{p,q} = \frac{F^p D^{p+q}}{F^{p+1} D^{p+q}}, E_1^{p,q} = H^{p+q}(\text{Gr}^p D^\bullet), \dots$$

where $\text{Gr}^p D^\bullet = \frac{F^p D^\bullet}{F^{p+1} D^\bullet}$.

In fact, this spectral sequence converges to E_∞ , i.e. there exists $r > 0$ s.t. $E_r = E_{r+1} = \dots = E_\infty$. And we can describe E_∞ as *associated graded cohomology*

$$E_\infty^{p,q} := \text{Gr}^p H^{p+q}(D^\bullet) := \frac{F^p H^{p+q}(D^\bullet)}{F^{p+1} H^{p+q}(D^\bullet)},$$

where $F^p H^q(D^\bullet)$ is the *filtered cohomology* of D^\bullet , defined as

$$F^p H^q(D^\bullet) = \text{image}(H^q(F^p D^\bullet) \rightarrow H^q(D^\bullet)).$$

In our case where D^\bullet comes from the de Rham complex, we find

$$E_1^{p,q} = H^q(X, \Omega_{X/k}^p)$$

and it is a theorem that this *Hodge-de Rham spectral sequence* degenerates at E_1 (i.e. $E_1 = E_2 = \dots = E_\infty$). Therefore, if we know the sheaf cohomology of $\Omega_{X/k}^i$, we know E_∞ . Then, by using the formula for E_∞ and that $F^{n+1} = 0$, we can compute the filtered cohomology, in particular, we know $F^0 H^q(D^\bullet) = H^q(D^\bullet)$.

An exercise of this method would be to compute the de Rham cohomology of \mathbb{P}^n .

8.3.3. More things.

- (1) See more of algebraic de Rham at Stack Project: <https://stacks.math.columbia.edu/tag/0FK4>
- (2) A blog post of Alex Youcis: <https://ayoucis.wordpress.com/2015/07/22/algebraic-de-rham-cohomology/>
- (3) Future exercise: Deduce Picard-Fuchs equations from Gauss-Manin connection. Why do we care about these? A reference <https://virtualmath1.stanford.edu/~conrad/shimsem/2013Notes/Littvhs.pdf>.

8.4. **17/12/2021: Derived functors of sheaves.** Just want to make a summary about the story of derived functors of sheaves. For the reference, say I learned this from Konstanze Rietsch, An introduction to perverse sheaves, Achar Introduction to Perverse sheaves. You can say it is a continuation from 28/11/2021.

We always assume X is a nice topological space (locally compact, Hausdorff, paracompact, with a countable basis, locally simply connected).

- (1) The right-derived functor $RF : D^b(\mathcal{A}) \rightarrow D^b(\mathcal{B})$ (of bounded derived categories) of a left-exact functor $F : \mathcal{A} \rightarrow \mathcal{B}$ is defined as $RF(\mathcal{F}^\bullet) = F(\mathcal{I}^\bullet)$, where $\mathcal{F}^\bullet \rightarrow \mathcal{I}^\bullet$ is an injective resolution (i.e. a quasi-isomorphism with \mathcal{I}^\bullet consists of injective elements). For this to make sense, we also need \mathcal{A} to have enough injectives.
- (2) The category of sheaves of vector spaces/abelian groups/modules on X has enough injectives. This is done by using Godement resolution. It follows that every complex of sheaves has an injective resolution (Cartan-Eilenberg resolution).
- (3) Some example of functors: Let $f : X \rightarrow Y$ be a continuous map. We can define *push-forward* (or *direct image*) functor f_* , *push-forward with proper supports* functor $f_!$ by

$$(f_*\mathcal{X})(U) = \mathcal{X}(f^{-1}(U)),$$

$$(f_!\mathcal{X})(U) = \{s \in \mathcal{X}(f^{-1}(U)) : f : \text{supp}(s) \rightarrow U \text{ is proper}\}.$$

These are left-exact functors. If $\pi : X \rightarrow \{pt\}$, we find $\pi_* = \Gamma$, the global section functor and $\pi_! = \Gamma_c$, compactly supported global section functor. If $j : X \hookrightarrow Y$ is an inclusion of locally closed subset, $j_!$ is the *extension by 0* functor, and is exact.

We can also define *pull-back* functor $f^* : \text{Sh}(Y) \rightarrow \text{Sh}(X)$ (some people denote this f^{-1} in order to distinguish with pull-back of sheaf of \mathcal{O}_X -modules) The key property of this functor is that $(f^*\mathcal{Y})_x = \mathcal{Y}_{f(x)}$. It is an exact functor. Achar notes has a table on more of this.

- (4) To compute derived functor RF , injective resolutions are not practical tools. Instead, one use a large class of sheaves, called *F-acyclic* (it is a theorem that derived functor can be computed by acyclic resolution): For left-exact functor $F : \text{Sh}(X) \rightarrow \text{Sh}(Y)$. A sheaf $\mathcal{A} \in \text{Sh}(X)$ is *F-acyclic* if $R^i F(\mathcal{A}) = 0$ for all $i \neq 0$. So, if $\mathcal{F}^\bullet \in D^b(X)$ is quasi-isomorphic to *F-acyclic* complex \mathcal{A} , then $RF(\mathcal{F}^\bullet) = F(\mathcal{A}^\bullet)$.
- (5) In the context of sheaves and $F = f_*, f_!, \dots$, there are ways to characterise *F-acyclic* sheaf. For example, injective \subset flabby \subset soft are all f_* -acyclic sheaf. When I mean ‘characterise’, I mean something like: a sheaf \mathcal{F} is flabby (or flasque) if the restriction map $\mathcal{F}(X) \rightarrow \mathcal{F}(U)$ is surjective for all open $U \subset X$. Now I know why there are so many adjectives to describe sheaves ...

OK, now I want to see some computations ...

8.5. **31/12/2021: Van Kampen theorem.** I learned about some applications of Van Kampen theorem from <https://people.math.harvard.edu/~hirolee/pdfs/231a-35-van-kampen.pdf> notes by Omar Antolin Camarena.

Let $\pi_{\leq 1}(X)$ be the fundamental groupoid of X , i.e. a category whose objects are the points of X and whose morphisms from p to q are the homotopy classes of paths in X from p to q . The classical fundamental group of X at the based point $x_0 \in X$ is $\text{Hom}_{\pi_{\leq 1}(X)}(x_0, x_0)$.

Here is the statement of the theorem, in the language of groupoids:

- (1) No based points version: Let X be a topological space and U, V be open subsets of X such that $X = U \cup V$. Then the following diagram is a pushout of groupoids

$$\begin{array}{ccc} \pi_{\leq 1}(U \cap V) & \longrightarrow & \pi_{\leq 1}(U) \\ \downarrow & & \downarrow \\ \pi_{\leq 1}(V) & \longrightarrow & \pi_{\leq 1}(X) \end{array}$$

In other words, $\pi_{\leq 1}$ preserves pushout square. To generalise this over any open cover \mathcal{U} of X where any finite intersection of elements in \mathcal{U} belongs in \mathcal{U} , $\pi_{\leq 1}X = \text{colim}_{U \in \mathcal{U}} \pi_{\leq 1}(U)$.

- (2) Based points version: For $A \subset X$, let $\pi_{\leq 1}(X, A)$ denotes the full subcategory of $\pi_{\leq 1}(X)$ whose objects are in A . To have a pushout square of $\pi_{\leq 1}(\cdot, A)$, we need an extra condition: A contains at least one point in each connected component of each of $U \cap V, U$ and V . Then we have a pushout of groupoids

$$\begin{array}{ccc} \pi_{\leq 1}(U \cap V, A) & \longrightarrow & \pi_{\leq 1}(U, A) \\ \downarrow & & \downarrow \\ \pi_{\leq 1}(V, A) & \longrightarrow & \pi_{\leq 1}(X, A) \end{array}$$

Some applications

- (1) Compute $\pi_1(S^1)$: Take U, V two open intervals s.t. $S^1 = U \cup V$ and $U \cap V$ is a union of two disjoint open intervals in which lies points p, q , respectively. Let $A = \{p, q\}$. As U is contractible, $\pi_{\leq 1}(U, A)$ consists of two points p, q with a unique morphism from p to q and only identity map from p to itself. Similarly for $\pi_{\leq 1}(V, A)$. $\pi_{\leq 1}(U \cap V, A)$ consists of two points p, q with no morphism from p to q or from q to p . By Van Kampen, there are only two morphisms from p to q in $\pi_{\leq 1}(X, A)$, taken from those in $\pi_{\leq 1}(U, A)$ and $\pi_{\leq 1}(V, A)$, denoted as u, v . As $\pi_{\leq 1}(X, A)$ is the initial object in the pushout square, $(v^{-1} \circ u)^n$ are all distinct as all morphisms from p to itself in $\pi_{\leq 1}(X, A)$. Thus, $\pi_1(S^1) = \mathbb{Z}$.
- (2) Compute π_1 of Klein bottle: The Klein bottle K is obtained from the square

$$\begin{array}{ccc} & \xrightarrow{a} & \\ \downarrow b & & \downarrow b \\ & \xleftarrow{a} & \end{array}$$

by glueing paths a and b . To compute $\pi_1(K)$, draw a smaller square inside this square. Let U be the smaller square and its interior, V be the area between two squares. Then $U \cap V$ is the smaller square and is homotopy equivalent to S^1 , U is contractible and V is wedge of two circles formed by a and b (V is essentially the larger square without its interior, and when one glues a and b together, we get two circles with a common point). Thus, $\pi_1(V)$ is a free group with generators a, b , the generator of $\pi_1(U \cap V)$ is sent to the loop $b^{-1}aba$ in $\pi_1(V)$. Thus, by Van Kampen, $\pi_1(K)$ is $\langle a, b \rangle *_{\mathbb{Z}} 1 = \langle a, b | b^{-1}aba \rangle$.

- (3) Similarly, for the torus T of genus 1, we find $\pi_1(T) = \langle a, b | [a, b] = 1 \rangle$. And for real projective space P , we find $\pi_1(P) = \langle a, |a^2 = 1 \rangle$.
- (4) π_1 behaves well with respect to taking wedge of spaces and taking connected sums.

- (5) Attaching cells of dimension at least 3 to a CW complex X do not affect the fundamental group of that complex. Attaching a 2-cell to X then the new space has fundamental group being the quotient of $\pi_1(X)$ the relation formed by the boundary of that 2-cell. See <https://www.homepages.ucl.ac.uk/~ucahjde/tg/html/vkt02.html> for a more detailed explanation.
- (6) Compute fundamental group of mapping tori: See <https://www.homepages.ucl.ac.uk/~ucahjde/tg/html/vkt03.html>. I haven't read this. A particular example is fundamental group of Klein bottle (as in the link), or fundamental group of knots complements (see <https://www.homepages.ucl.ac.uk/~ucahjde/tg/html/braids03.html>, key words: braid). *I haven't read this.*