

M 392C Representation Theory, Fall 2025: Dr. David Ben-Zvi's lectures, T<sub>E</sub>Xed by Sai Sivakumar. The main goal of these notes was to clarify and even expand on several of the points David made during the lectures. As a warning, I made minimal effort to reorder the content of the course, and many digressions in these notes have additional details not discussed in class.

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**Lecture 1 08/26****Definitions**

Let  $G$  be a group and  $k$  be a field. A representation of  $G$  is a vector space  $V \in \mathbf{Vect}_k$  with a linear action of  $G$  on  $V$ . (For convenience, let's assume representations are finite-dimensional vector spaces unless otherwise stated.)

This is to say there is a homomorphism  $G \xrightarrow{\rho} \text{Aut}(V)$  so that we may define the action of  $G$  on  $V$  to be  $g \cdot v := \rho(g)v$  or alternatively a product  $G \times V \rightarrow V$  given by  $(g, v) \mapsto \rho(g)v$  that is linear in  $V$  and associative in  $G$ , among other properties. (We often suppress the  $\cdot$  in the action/product.)

Note  $\text{Aut}(V) =: \text{GL}(V) \cong \text{GL}_{\dim V}(k)$ , so we could even think of the elements of  $G$  as matrices if we fix a basis of  $V$ .

The (finite-dimensional) representations  $(V, \rho)$  of  $G$  over a field  $k$  form the objects of a category  $\mathbf{Rep}_k(G)$  whose morphisms are linear transformations which commute with the action of  $G$ ; i.e.,  $\text{Hom}_G(V, W)$  consists of the linear transformations  $T: V \rightarrow W$  for which  $g(Tv) = T(gv)$  for all  $g \in G$  and  $v \in V$ . (These are also called intertwining operators,  $G$ -linear maps, or  $G$ -equivariant maps, etc. Also note that  $\text{Hom}_G(V, W)$  is merely a vector space, but see this MSE post.)

The field  $k$  does matter, but for the majority of what follows  $k$  will be  $\mathbb{C}$ . Sometimes it may be possible to replace  $\mathbb{C}$  with any algebraically closed field, but the characteristic of the field is rather important (see modular representation theory for example).

**Variants of representations**

We can add adjectives in various places to the definitions above to get different kinds of representations.

For example, if  $V$  has an inner product we can ask about linear actions of  $G$  on  $V$  that preserve that inner product. If  $V$  is a Hilbert space we can ask about linear actions of  $G$  on  $V$  for which  $\rho(g)$  is a unitary operator; these are the unitary representations of  $G$ .

If  $G$  has a topology and  $V$  is a topological vector space, we say  $(V, \rho)$  is a continuous representation if the product map  $G \times V \rightarrow V$  defined before is continuous. If  $G$  has a smooth structure (e.g. is a Lie group) or is an algebraic group, we can ask about smooth or algebraic representations, respectively.

## Aspects of representations we study

1. Irreducible representations (henceforth called “irreps”): An irrep of  $G$  are the representations  $V$  which have no invariant (or stable some might say) subspaces under the group action; that is, if  $W$  is a  $G$ -invariant subspace of  $V$  then  $W$  is either 0 or  $V$ . These are like the “atoms” in representation theory.

For a given group  $G$  one goal of representation theory is to classify up to isomorphism its irreps. One approach is to try to attach numerical invariants to representations and see if they help to classify irreps, and generalizations of this idea lead to character theory. Sometimes there are “isotopes” that are not isomorphic but nevertheless cannot be distinguished by certain invariants.

Another thing we do is to take a subgroup  $H$  of  $G$  and study how irreps of  $G$  decompose when the group action is restricted to  $H$ . On the other hand, we can also look at how to build bigger representations or “molecules” out of the atomic irreps via extension. Of course, it is easy to take direct sums of irreps but depending on the context it may be possible to obtain indecomposable reps which are extensions of irreps but do not decompose into a direct sum of irreps (so to summarize, irreducible implies indecomposable but not the other way around in general).

Maschke’s theorem implies that indecomposable representations of finite groups over fields with characteristic not dividing the order of the group are irreducible. Alternatively, the theorem implies that in this setting, all short exact sequences of representations split.

For example, the indecomposable representations over  $\mathbb{C}$  coincide with the irreps when  $G$  is finite. On the other hand, the shearing representation

$$\begin{aligned}\mathbb{Z} &\rightarrow \mathrm{GL}_2(\mathbb{R}) \\ 1 &\mapsto \begin{pmatrix} 1 & 1 \\ 0 & 1 \end{pmatrix}\end{aligned}$$

preserves the horizontal axis, so it is not an irrep, but is not decomposable since  $\begin{pmatrix} 1 & 1 \\ 0 & 1 \end{pmatrix}$  is not diagonalizable. The representations  $(k^n, \rho)$  of  $\mathbb{Z}$  are given by specifying an invertible  $n \times n$  matrix, and any two such representations are isomorphic if the matrices specifying them are conjugate. If  $k$  is algebraically closed, the indecomposable representations in this setting correspond to Jordan blocks. Of course, every representation is the direct sum of indecomposables, and in this setting the Jordan normal form of an  $n \times n$  matrix would describe the decomposition of  $k^n$  into indecomposables.

2. Harmonic analysis is the study of naturally appearing “large” representations; we would like to perform some kind of “spectroscopy” to determine what representations appear within them.

If a group  $G$  acts on some object  $X$  (which could be a set, manifold, or otherwise a “geometric” object), we say  $X$  has some symmetries which we would like to “linearize”. We achieve this by considering the  $k$ -valued functions on  $X$  for some field  $k$ ; if  $X$  has additional structure we can restrict to functions on  $X$  which interact with that structure (e.g. measurable/continuous/etc maps)

From a right action of  $G$  on  $X$ , function spaces on  $X$  inherit a natural linear left action of  $G$ ; one is given by  $gf(x) = f(xg)$ . These representations are typically very decomposable or reducible.

3. Different groups give rise to different phenomena. Below are some examples of groups we will see again.

	compact	noncompact
Abelian	$S^1$	$\mathbb{R}$
non-Abelian	$\mathrm{SO}(3)$	$\mathrm{SL}_2(\mathbb{R}), \mathrm{SL}_2(\mathbb{C})$

It is a theorem that irreps of compact groups coincide with their indecomposables, and that irreps of Abelian groups are all one-dimensional.

The representation theory of  $S^1$  leads to the theory of Fourier series, and in a similar way we can recover the Fourier transform from the representation theory of  $\mathbb{R}$ .

The Lie group  $\mathrm{SO}(3)$  can be thought of as the group of rotations of a 2-sphere. One nice result is that the spherical harmonics are basis functions for the irreps of  $\mathrm{SO}(3)$ , which occur naturally as the atomic orbitals (see the Wikipedia article on spherical harmonics).

The representations of the groups  $\mathrm{SL}_2(k)$  for various fields  $k$  appear all over math. We can study special functions like the Bessel or hypergeometric functions, or even modular forms. The hard Lefschetz theorem in algebraic geometry says that  $\mathrm{SL}_2(\mathbb{C})$  acts on  $H^*(X, \mathbb{C})$  for  $X$  a nice enough smooth projective variety. In physics, the special linear group sort of appears in the Lorentz group  $\mathrm{SO}(1, 3)^+ = \mathrm{PSL}_2(\mathbb{C})$ .

## Spectral theory

A slogan for what is to come: “commutativity implies geometry”.

Let  $k = \mathbb{C}$  and  $X$  a set. Then the complex-valued functions on  $X$  form a commutative algebra. This is some example of a functor suggestively called  $\mathcal{O}$  from the category of some kind of geometric objects to commutative algebras.

To expand on the previous idea, here is a motto originating from Gelfand and Grothendieck’s work:

1. Any commutative ring should be thought of as functions on some space.

That is, there is some functor going from commutative rings to some category of geometric objects that realizes this idea. In particular we should be able to adjust the functor and its source/target to obtain an equivalence of categories.

$$\text{commutative rings} \longleftrightarrow \text{geometry}$$

2. Once we are in the situation where we have an equivalence of categories between commutative rings and geometric objects, we should further obtain a correspondence between the modules over a ring  $R$  and sheaves (special families of vector spaces or Abelian groups) on the corresponding geometric object  $X$  to  $R$ .

$$R\text{-modules} \longleftrightarrow \text{sheaves on } X$$

For example, if  $X$  is a finite set, the corresponding ring  $R$  is the finite-dimensional commutative algebra of complex-valued functions on  $X$ . This algebra is semisimple with  $R = \bigoplus_i \mathbb{C}e_i$  where  $e_i e_j = \delta_{ij}$ . We can think of the  $e_i$  as delta/indicator functions on points of  $X$ .

An  $R$ -module  $M$  has the decomposition  $M = \bigoplus_i e_i M$ , which corresponds to a sheaf on  $X$  where at each point of  $X$  we imagine the corresponding module  $e_i M$  lying on it:

$$\begin{array}{ccccccc} M & e_1 M & e_2 M & \cdots & e_n M \\ X & \bullet & \bullet & \cdots & \bullet \end{array}$$

### A short word about the group algebra

A representation  $V$  of a group  $G$  is given by a group homomorphism  $G \xrightarrow{\rho} \text{Aut}(V)$ . Since  $\text{Aut}(V)$  is contained in  $\text{End}(V)$ , a  $k$ -algebra, there is an object  $k[G]$  called the group algebra for which the homomorphism  $\rho$  factors through  $k[G]$ ; that is, the diagram

$$\begin{array}{ccc} G & \xrightarrow{\rho} & \text{End}(V) \\ \downarrow & \nearrow \bar{\rho} & \\ k[G] & & \end{array}$$

commutes. One explicit description of  $k[G]$  is the set of finite linear combinations of elements of  $G$  with coefficients in  $k$ :

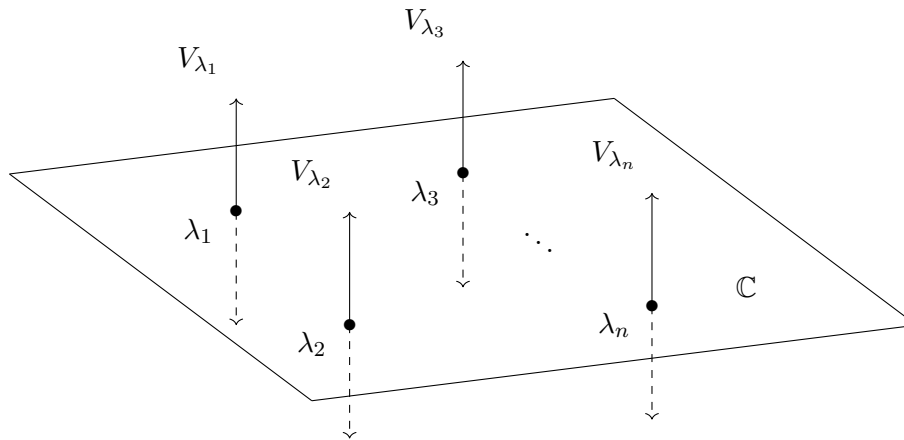
$$k[G] = \left\{ \sum_{g \in G} c_g g \mid c_g \in k, \text{ all but finitely many } c_k \text{ are zero} \right\}.$$

The addition and multiplication in  $k[G]$  are defined using the addition in  $k$  and multiplication in  $G$ , respectively. We will return to the group algebra when investigating representations from a module-theoretic point of view.

## Lecture 2 08/28

Spectral theory over  $\mathbb{C}$ 

Consider an operator  $T$  on a finite-dimensional complex vector space  $V$ . The spectrum of  $T$ ,  $\sigma(T)$ , is a finite subset of  $\mathbb{C}$  consisting of the eigenvalues of  $T$ . To each  $\lambda \in \sigma(T)$  there is a corresponding eigenspace  $V_\lambda$  of  $V$ , and  $V = \bigoplus_{\lambda \in \sigma(T)} V_\lambda$ . We can visualize placing each of the eigenspaces  $V_\lambda$  above each point  $\lambda$  in the spirit of sheaf theory:



On  $\mathbb{C}$ , the coordinate function  $x$  where  $x(z) = z$  has the same action as  $T$  on the eigenspaces  $V_\lambda$ :

$$Tv = \sum_{\lambda \in \sigma(T)} T v_\lambda = \sum_{\lambda \in \sigma(T)} \lambda v_\lambda = \sum_{\lambda \in \sigma(T)} x(\lambda) v_\lambda = x \cdot \left( \sum_{\lambda} v_\lambda \right) = x \cdot v$$

In this sense  $T$  corresponds to  $x \in \text{Fun}(\mathbb{C})|_{\sigma(T)}$  (complex-valued functions on  $\mathbb{C}$ , restricted to  $\sigma(T)$ ).

Now consider the commutative ring  $R = k[T_1, \dots, T_n]/(f_1, \dots, f_m)$  and an  $R$ -module  $M$ . We would like to simultaneously diagonalize the action of the  $T_i$  on  $M$ , or rather, diagonalize the action of  $R$  on  $M$ , which amounts to finding a basis of  $M$  where  $R$  acts diagonally. Assume we can do this.

We should attach a set  $X = \text{Spec}(R)$  to  $R$  called the spectrum of  $R$  for which we can decompose  $M$  into a direct sum of modules  $M_{x_i}$ , each summand lying over their corresponding point  $x_i \in X$ :

$$\begin{array}{ccccccc} M & = & M_{x_1} & \oplus & M_{x_2} & \oplus & \cdots \oplus M_{x_\ell} \\ X & & x_1 & & x_2 & & \cdots & x_\ell \end{array}$$

Furthermore, we form an assignment  $R \xrightarrow{\varphi} \text{Fun}(X)$  for which we can recast the action of  $R$  on  $M$  through this assignment:

$$rm = \varphi(r) \sum_{x \in X} m_x = \sum_{x \in X} \varphi(r)|_{\{x\}} m_x$$

The idea here is to turn what was an algebraic notion of rings acting on modules to thinking about sheaves on a particular space which “diagonalize” the ring action.

## Some examples of the algebra-geometry dictionary

An important philosophy we've been looking at the broad strokes of is this dictionary between algebra and geometry, specifically the two following ideas coming from Gelfand and Grothendieck:

1. Commutative rings correspond to geometric objects via functors

$$\text{commutative rings} \begin{array}{c} \xrightarrow{\text{Spec}} \\ \xleftarrow{\mathcal{O}} \end{array} \text{geometric objects}$$

In this vague setting we should think of  $\text{Spec}$  as in taking the spectrum of some collection of simultaneously diagonalized operators coming from the ring and  $\mathcal{O}$  as returning the space of functions on these geometric objects. Again we should think of  $R$  as being the space of functions on  $\text{Spec } R$  in this correspondence.

2. Modules over rings  $R$  correspond to sheaves on the corresponding geometric object  $\text{Spec } R$  via

$$\text{modules} \begin{array}{c} \xrightarrow{\text{spectral decomposition}} \\ \xleftarrow{\text{global sections}} \end{array} \text{sheaves}$$

In particular in the previous examples we have that taking global sections amounts to taking the direct sum of modules, but this can also appear as a direct integral of modules in continuous versions of the previous examples. Spectral decomposition as we have seen is to break up a module into submodules where the ring action is pointwise multiplication.

We look at some examples of part 1. of the above philosophy.

Grothendieck's version of this idea is the heart of modern algebraic geometry. One correspondence is

$$\text{commutative rings} \longleftrightarrow \text{affine schemes}$$

but an earlier version might have been

$$\text{finitely presented, reduced, etc. } \mathbb{C}\text{-algebras} \longleftrightarrow \text{complex affine varieties}$$

In both correspondences, the  $\text{Spec}$  functor is given by taking the set of prime ideals. In the top correspondence,  $\mathcal{O}$  is taking the structure sheaf of a scheme, but this amounts to taking polynomial functions on a space in the bottom correspondence.

Gelfand's version of this idea is the correspondence

$$\text{commutative } C^*\text{-algebras} \longleftrightarrow \text{Hausdorff locally compact topological spaces}$$

The functor  $\text{Spec}$  in this case is the eponymous Gelfand spectrum and  $\mathcal{O}$  takes the continuous compactly supported functions on Hausdorff, locally compact spaces.



A special case of the above is the correspondence

$$\text{commutative von Neumann algebras} \longleftrightarrow \text{measure spaces}$$

One direction is some kind of spectrum, but the other direction is taking  $L^\infty$  functions on a measure space. As a side remark, there are only five commutative von Neumann algebras up to equivalence; they are  $L^\infty$  of: finite sets,  $\mathbb{N}$ ,  $[0, 1]$ ,  $[0, 1]$  union a finite set, and  $[0, 1]$  union a countably infinite set.

There is a version of part 2. for each of the above examples involving modules and sheaves, but we will not discuss them here, aside from mentioning that we can talk about algebraic, continuous, or measurable families of vector spaces (sheaves) in the various settings above.

### The group algebra (over $\mathbb{C}$ )

Let  $G$  be any group and  $(V, \rho)$  any complex representation of  $G$  (the below discussion would work for other fields instead of  $\mathbb{C}$ ). Recall that  $\mathbb{C}[G]$  is the unique object for which the diagram

$$\begin{array}{ccccc} G & \xrightarrow{\rho} & \text{Aut}(V) & \hookrightarrow & \text{End}(V) \\ \downarrow & & & \nearrow \bar{\rho} & \\ \mathbb{C}[G] & & & & \end{array}$$

commutes; moreover, we think of  $\mathbb{C}[G]$  as a “free”  $\mathbb{C}$ -algebra on  $G$ . This is because the functor taking  $G$  to  $\mathbb{C}[G]$  is the left adjoint to the forgetful functor from  $\mathbb{C}\text{-alg}$  to **Group** (given by taking the group of units).

An explicit description of  $\mathbb{C}[G]$  is the  $\mathbb{C}$ -vector space generated by the elements of  $G$  with multiplication induced by the products in  $\mathbb{C}, G$ . An alternative description of  $\mathbb{C}[G]$  is the set of finitely supported functions from  $G$  to  $\mathbb{C}$ , with multiplication given by convolution:

$$(f * h)(g) = \sum_{\substack{(x,y) \\ xy=g}} f(x)h(y) = \sum_x f(x)h(x^{-1}g) \quad (\text{defined since } f, h \text{ are finitely supported})$$

This product is no different from the product defined in the first description of  $\mathbb{C}[G]$ .

What is really happening is that we can take  $f, h$  from above and form the box product  $f \boxtimes h: G \times G \rightarrow \mathbb{C}$ , which is just the map  $(x, y) \mapsto f(x)h(y)$ . We want to form a map from  $G$  to  $\mathbb{C}$ , so consider  $G \times G \xrightarrow{m} G$ , the product in  $G$ . The pushforward of  $f \boxtimes h$  via  $m$  is  $f * h$ :

$$m_*(f \boxtimes h) \quad \text{also denoted} \quad \int_m f \boxtimes h = \sum_{\substack{(x,y) \\ xy=-}} f(x)h(y) = f * h$$

An important observation to make is that complex representations of  $G$  coincide with  $\mathbb{C}[G]$ -modules.

## Representation theory of finite Abelian groups and the dual group

If  $G$  is Abelian, then  $\mathbb{C}[G]$  is a commutative ring. So representation theory may be thought of as a special case of the study of modules over commutative rings. Using language from earlier, note that the corresponding geometric object to  $\mathbb{C}[G]$  is  $\text{Spec}(\mathbb{C}[G])$ , and representations of  $G$  correspond to vector bundles or sheaves over  $\text{Spec}(\mathbb{C}[G])$ .

Let  $G$  be a finite Abelian group, and let  $\widehat{G} := \text{Spec}(\mathbb{C}[G])$ ; we call this the dual of  $G$ . Then  $\mathbb{C}[G]$  (functions on  $G$ ) with multiplication given by convolution is isomorphic as an algebra to  $\mathbb{C}[\widehat{G}]$  (functions on  $\widehat{G}$ , which we will see is a finite set) with pointwise multiplication. This isomorphism is usually given by some kind of finite Fourier transform. On the other hand, representations of  $G$  correspond to vector bundles (sheaves) on  $\widehat{G}$ , and this is some kind of finite spectral theorem.

Let  $G = \langle x \rangle$  be a cyclic group of order  $n$ . The dual object  $\widehat{G}$  is given by the  $n$ -th roots of unity in  $\mathbb{C}$ : (the picture is for  $n = 6$ )

$$\widehat{G} = \text{Spec}(\mathbb{C}[G]) = \begin{array}{ccccc} & & \bullet & & \bullet \\ & & & & \\ & & & & \\ \bullet & & & & \bullet \\ & & & & \\ & & \bullet & & \bullet \end{array}$$

In this case,  $\text{Spec}$  is taking the maximal ideals of rings. With  $\mathbb{C}[G] \cong \mathbb{C}[x]/(x^n - 1)$ , it is equivalent to describe the elements in  $\text{Hom}_{\mathbb{C}\text{-alg}}(\mathbb{C}[x]/(x^n - 1), \mathbb{C})$ , which are characterized by each of the  $n$ -th roots of unity.

We take a small detour to discuss Schur's lemma, which states that for any group  $G$ , that any  $\mathbb{C}[G]$ -module homomorphisms between simple  $\mathbb{C}[G]$ -modules are either 0 or are isomorphisms of  $\mathbb{C}[G]$ -modules. This follows by investigating kernels and images since they are submodules of  $V, W$  respectively. In particular, any  $\mathbb{C}[G]$ -module endomorphism of a simple  $\mathbb{C}[G]$ -module is a scalar multiple of the identity, since for any nonzero endomorphism  $T$  we can consider  $T - \lambda \text{id}_V$ , which is no longer an isomorphism and hence must be zero. Here we used the algebraic closedness of  $\mathbb{C}$ , and in fact we could have replaced  $\mathbb{C}$  by any algebraically closed field  $k$ .

Schur's lemma is used to prove that if  $G$  is Abelian then any finite-dimensional irrep of  $G$  is one-dimensional. If such an irrep  $V$  had finite dimension greater than or equal to 2, then left multiplication  $V \xrightarrow{g} V$  by any element  $g \in G$  must be a scalar multiple of  $\text{id}_V$ , which contradicts the irreducibility of  $V$  (since we assumed  $\dim V \geq 2$ ).

The action of  $G$  on the irrep  $V$  is given by scalar multiplication by  $\chi_V(g) \in \mathbb{C}^\times$  since  $V$  is one-dimensional. More importantly, the assignment  $g \rightarrow \chi_V(g)$  is a group homomorphism  $G \rightarrow \mathbb{C}^\times$ , called a character of  $G$ .

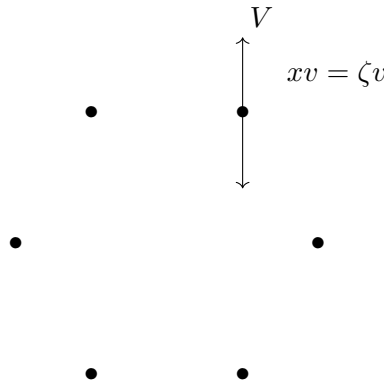
For  $G$  Abelian,  $\widehat{G}$  is the set of maximal ideals of  $\mathbb{C}[G]$ , which is in bijection with  $\text{Hom}_{\mathbb{C}\text{-alg}}(\mathbb{C}[G], \mathbb{C})$ . By the

universal property of the group algebra,  $\text{Hom}_{\mathbb{C}\text{-alg}}(\mathbb{C}[G], \mathbb{C})$  is in bijection with  $\text{Hom}_{\mathbf{Group}}(G, \mathbb{C}^\times)$ :

$$\begin{array}{ccccc} G & \xrightarrow{f} & \text{Aut}(\mathbb{C}) \cong \mathbb{C}^\times & \hookrightarrow & \text{End}(\mathbb{C}) \cong \mathbb{C} \\ \downarrow & & & \nearrow \bar{f} & \\ \mathbb{C}[G] & & & & \end{array}$$

So in general we can also think of  $\widehat{G}$  as the collection of irreps of  $G$ .

Given an irrep  $V$  of  $G$  (i.e. a simple  $\mathbb{C}[G]$ -module), we can try to form a sheaf out of  $V$  on  $\widehat{G}$ . Since  $V$  is irreducible, this sheaf has to be concentrated at only one of the points of  $\widehat{G}$ , and this point is the point corresponding to the irrep  $V$  itself. So in the example where  $G = \langle x \rangle$  has order  $n$ , the point at which an irrep  $V$  lies on is the root of unity  $\zeta$  for which the action of  $x$  on an irrep  $V$  is given by multiplication by  $\zeta$ .



Since  $\widehat{G}$  is in bijection with  $\text{Hom}_{\mathbf{Group}}(G, \mathbb{C}^\times)$ , we can equip  $\widehat{G}$  with a group operation; by doing so,  $G$  and  $\widehat{G}$  are non-canonically isomorphic as groups. So in particular finite cyclic groups are (non-canonically) self-dual.

Next time, we will explore the Fourier transform, which for  $G$  finite Abelian is a  $\mathbb{C}[G]$ -module isomorphism

$$\text{Fun}(G) \xrightarrow{\widehat{\phantom{x}}} \text{Fun}(\widehat{G})$$

where  $\text{Fun}(G)$ ,  $\text{Fun}(\widehat{G})$  are function spaces on  $G$ ,  $\widehat{G}$  and are given convolution and pointwise multiplication, respectively. Note that in this case  $\text{Fun}(G) \cong \mathbb{C}[G]$ , so we give  $\text{Fun}(G)$  the corresponding action, which is given by  $gf(x) = f(g^{-1}x)$ . We will look at the action of  $G$  on  $\text{Fun}(\widehat{G}) \cong \mathbb{C}[\widehat{G}]$  next time. This isomorphism has some symmetry which is part of the statement of Pontryagin duality.

**Lecture 3 09/02****More on the structure of  $\widehat{G}$** 

For  $G$  a finite Abelian group, we saw/will see four equivalent descriptions of  $\widehat{G}$ :

$$\begin{aligned}\widehat{G} &= \text{set of irreps of } G \\ &= \text{Hom}_{\mathbf{Group}}(G, \mathbb{C}^\times) \\ &= \text{unitary irreps of } G = \text{Hom}_{\mathbf{Group}}(G, \text{U}(1)) \\ &= \text{Spec}(\mathbb{C}[G]) = \text{maximal ideals of } \mathbb{C}[G] = \text{Hom}_{\mathbb{C}\text{-alg}}(\mathbb{C}[G], \mathbb{C})\end{aligned}$$

Some of these descriptions for  $\widehat{G}$  stop becoming equivalent to each other if we remove the adjectives finite or Abelian from  $G$ .

For any commutative ring  $R$ , recall that we think of  $R$  as functions on  $\text{Spec}(R)$  with pointwise multiplication. In general there is no reason to expect  $\text{Spec}(R)$  to be a group, but we were able to give  $\text{Spec}(\mathbb{C}[G])$  a group operation when  $G$  is Abelian. So in this situation something special is happening.

The deeper lesson: Suppose now that  $G$  is any group (not necessarily Abelian). If  $V, W$  are representations of  $G$  then we can form a new representation  $V \otimes_{\mathbb{C}} W$  where  $g(v \otimes w) = gv \otimes gw$ . This comes from the diagonal embedding  $\mathbb{C}[G] \xrightarrow{\Delta} \mathbb{C}[G] \otimes_{\mathbb{C}} \mathbb{C}[G]$  given by  $\mathbb{C}$ -linearly extending the assignment  $g \mapsto g \otimes g$ . By doing so  $\Delta$  is a  $\mathbb{C}$ -algebra homomorphism; it suffices only to check that it respects the group multiplication:

$$\Delta(hg) = hg \otimes hg = (h \otimes h)(g \otimes g) = \Delta(h)\Delta(g)$$

The natural action of  $\mathbb{C}[G] \otimes_{\mathbb{C}} \mathbb{C}[G]$  on  $V \otimes_{\mathbb{C}} W$  given by  $(f \otimes g)(v \otimes w) = fv \otimes gw$  can be pulled back along the diagonal embedding  $\Delta$  to give  $V \otimes_{\mathbb{C}} W$  the action of  $G$  mentioned above.

If  $A$  is a  $\mathbb{C}$ -algebra and  $V, W$  are  $A$ -modules, there is a natural action of  $A \otimes_{\mathbb{C}} A$  on  $V \otimes_{\mathbb{C}} W$  given by  $(a \otimes a')(v \otimes w) = av \otimes a'w$ . But the diagonal map  $A \rightarrow A \otimes_{\mathbb{C}} A$  might not be a  $\mathbb{C}$ -algebra homomorphism, but only  $\mathbb{C}$ -linear. In this case there may not be a natural way for  $A$  to act on  $V \otimes_{\mathbb{C}} W$  like in the case of the group algebra. That the diagonal map  $\mathbb{C}[G] \xrightarrow{\Delta} \mathbb{C}[G] \otimes_{\mathbb{C}} \mathbb{C}[G]$  for the group algebra is a  $\mathbb{C}$ -algebra homomorphism is part of the group algebra really being a Hopf algebra (see Wikipedia), and in this setting  $\Delta$  is the comultiplication map.

If  $V$  is a representation of  $G$ , another representation of  $G$  we can form is the dual space  $V^* := \text{Hom}_{\mathbb{C}}(V, \mathbb{C})$ , where the action of  $G$  on  $\mathbb{C}$  is the trivial action. The action of  $G$  on  $V^*$  is  $(gf)(v) = f(g^{-1}v)$ . We may not be able to construct dual modules for an arbitrary  $\mathbb{C}$ -algebra  $A$  and  $A$ -module  $V$ , since we need some way to invert the action of  $A$  when “passing the action inside the function”. This is related to one other datum that Hopf algebras have, which is their coinverse (also called antipode) map. In the case of the group algebra  $\mathbb{C}[G]$ , the coinverse map is  $g \mapsto g^{-1}$  and this actually gives an isomorphism of  $\mathbb{C}[G]$  and its opposite ring  $\mathbb{C}[G]^{\text{op}}$  (the ring where  $g \cdot_{\text{op}} h = hg$ ).

If  $A$  is a Hopf algebra over  $\mathbb{C}$  and  $V, W$  are  $A$ -modules it is possible to define actions of  $A$  on  $V \otimes_{\mathbb{C}} W$  and on  $V^* := \text{Hom}_{\mathbb{C}}(V, \mathbb{C})$  in a manner analogous to the above by using the comultiplication and antipode maps on  $A$ , respectively.

If we want to think of the tensor product as giving a monoid structure to  $\mathbf{Rep}_{\mathbb{C}}(G)$  (the category of dimensional representations of  $G$ ), we might wonder if there is a way to obtain inverses in this category. So far, being able to take tensor products and duals of representations make  $\mathbf{Rep}_{\mathbb{C}}(G)$  a rigid symmetric monoidal category; see the nLab. Another question is when the irreps of  $G$  form a monoid or even a group; in the case that  $G$  is not Abelian the tensor product of irreps need not be an irrep...

Returning to  $G$  finite Abelian, in the description of  $\widehat{G}$  as the collection of irreps of  $G$ , the group operation in  $\widehat{G}$  is given by the tensor product of representations and inverses are given by taking dual spaces. Of course, the tensor product is associative and commutative in this case, and observe that  $V \otimes_{\mathbb{C}} V^* \cong \text{End}(V) \cong \mathbb{C}$  (since  $V$  is one-dimensional). The action of  $G$  on  $V \otimes_{\mathbb{C}} V^*$  is also trivial:  $g(v \otimes f) = gv \otimes gf = \chi_V(g)v \otimes \chi_V^{-1}(g)f = v \otimes f$ .

### The Fourier transform on finite Abelian groups

Let  $G$  be a finite Abelian group. Then  $G \times \widehat{G}$  has a distinguished complex-valued function  $G \times \widehat{G} \xrightarrow{\chi} \mathbb{C}^\times$  called the universal character, defined by

$$\chi(g, \hat{g}) = \chi_{\hat{g}}(g) \quad (= \hat{g}(g) \text{ if we think of } \hat{g} \text{ as a character})$$

where  $\chi_{\hat{g}}$  is the character corresponding to  $\hat{g} \in \widehat{G}$  (here  $\widehat{G}$  is thought of as a set of points). Observe that  $\chi$  is multiplicative in each component; that is,

$$\chi(hg, \hat{h}\hat{g}) = \chi_{\hat{h}\hat{g}}(hg) = \chi_{\hat{h}\hat{g}}(h)\chi_{\hat{h}\hat{g}}(g) = \chi_{\hat{h}}(h)\chi_{\hat{g}}(h)\chi_{\hat{h}}(g)\chi_{\hat{g}}(g)$$

To each  $g \in G$ , the function  $\chi_g := \chi(g, -): \widehat{G} \rightarrow \mathbb{C}^\times$  is a group homomorphism:

$$\chi_g(\hat{h}\hat{g}) = \chi(g, \hat{h}\hat{g}) = \chi_{\hat{h}}(g)\chi_{\hat{g}}(g) = \chi_g(\hat{h})\chi_g(\hat{g})$$

The assignment  $g \mapsto \chi_g$  is a group homomorphism  $G \xrightarrow{\chi_-} \text{Hom}_{\mathbf{Group}}(\widehat{G}, \mathbb{C}^\times)$  that informally speaking, takes an element  $g$  to the map  $\widehat{G} \rightarrow \mathbb{C}^\times$  which evaluates a character at  $g$ :

$$\chi_{gh}(\hat{g}) = \chi(gh, \hat{g}) = \chi(g, \hat{g})\chi(h, \hat{g}) = \chi_g(\hat{g})\chi_h(\hat{g}) \quad \text{Thus } \chi_{gh} = \chi_g \cdot \chi_h \text{ (pointwise multiplication)}$$

Denote by  $\widehat{\widehat{G}}$  the group  $\text{Hom}_{\mathbf{Group}}(\widehat{G}, \mathbb{C}^\times)$ . Since the kernel of  $\chi_-$  is trivial and the image of  $\chi_-$  is all of  $\widehat{\widehat{G}}$ , we obtain a (canonical) isomorphism of  $G$  with  $\widehat{\widehat{G}}$ . This is the content of Pontryagin duality for finite Abelian groups. The same result is true for locally compact Abelian groups, but requires some more tools to prove.

An analyst cannot help but think of the universal character  $\chi(-, -)$  as being similar to kernels of integral operators (which are usually denoted  $K(-, -)$  for example), or in this finite setting it might be more accurate to think of

the universal character as similar to a matrix. The similarity is no coincidence. The universal character  $\chi(-, -)$  is the kernel for the Fourier transform.

The Fourier transform is a map  $\text{Fun}(G) \xrightarrow{\widehat{\phantom{x}}} \text{Fun}(\widehat{G})$  which we think of as a linear transformation with matrix  $\chi(-, -)$ . The Fourier transform is given by the formula

$$\widehat{f}(\widehat{g}) = \sum_{g \in G} \chi(g, \widehat{g}) f(g)$$

For infinite groups that admit a Fourier transform like this, the sum is replaced by an integral of some kind and the kind of function spaces we consider may need adjustment.

One other perspective of this map is that it comes from a pullback and a pushforward. Consider the diagram

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

and consider a function  $f \in \text{Fun}(G)$ . The Fourier transform  $\widehat{f}$  is given by pulling back  $f$  along  $\pi_1$ , multiplying by  $\chi(-, -)$ , and then pushing forward along  $\pi_2$ . That is,

$$\widehat{f} = \pi_{2*}(\pi_1^* f \cdot \chi)$$

The pushforward just means to sum (integrate) over fibers, and fiber of  $\widehat{g}$  is  $\{(g, \widehat{g}) \mid g \in G\}$ . Pulling back  $f$  along this projection does nothing but view  $f$  as a function on  $G \times \widehat{G}$ ; that is,  $(\pi_1^* f)(g, \widehat{g}) = f(g)$ . This recovers the first formula above for the Fourier transform.

As a fun fact, we can think about matrix multiplication this way. An  $n \times m$  matrix  $A = (A_{ij})$  is a function on the set  $\{1, \dots, m\} \times \{1, \dots, n\}$  and a vector  $v$  in  $\mathbb{C}^m$  is a function on  $\{1, \dots, m\}$ . There is a diagram

$$\begin{array}{ccc} & \{1, \dots, m\} \times \{1, \dots, n\} & \\ \pi_1 \swarrow & & \searrow \pi_2 \\ \{1, \dots, m\} & & \{1, \dots, n\} \end{array}$$

So  $Av$  coincides with  $\pi_{2*}(\pi_1^* v \cdot A)$ ; that is,  $(Av)_j = \sum_{i=1}^m A_{ij} v_i$  as expected. The same thing can be done for integral operators with kernel  $K(-, -)$ .

Denote by  $\delta_g$  the Kronecker delta or the delta function(al) at  $g$ , or also the indicator function of  $\{g\}$ :

$$\delta_g(h) = \delta_{gh} = \begin{cases} 1 & \text{if } g = h \\ 0 & \text{otherwise} \end{cases}$$

Since  $G$  is finite, these delta functions span  $\text{Fun}(G)$ . The Fourier transform of the delta function is calculated by

$$\widehat{\delta_g}(\widehat{g}) = \sum_{h \in G} \chi(h, \widehat{g}) \delta_g(h) = \chi(g, \widehat{g}), \quad \text{so } \widehat{\delta_g} = \chi_g$$

which we summarize by saying that Fourier transforms of delta functions are characters.

From the calculation

$$(\delta_g * \delta_h)(x) = \sum_y \delta_g(y) \delta_h(y^{-1}x) = \delta_h(g^{-1}x) = \begin{cases} 1 & \text{if } x = gh \\ 0 & \text{otherwise} \end{cases}$$

we have  $\delta_g * \delta_h = \delta_{gh}$ . Recalling that  $\chi_{gh} = \chi_g \cdot \chi_h$ , conclude from the linearity of convolution that for any  $f, h \in \text{Fun}(G)$  that  $\widehat{f * h} = \hat{f} \cdot \hat{h}$ , which is summarized by saying that the Fourier transform turns convolution to pointwise multiplication. In other words, the Fourier transform diagonalizes the action of  $G$  on  $\text{Fun}(G)$  since  $gf = \delta_g * f$ . So in order for the Fourier transform to be a  $\mathbb{C}[G]$ -module homomorphism,  $G$  should act on  $\text{Fun}(\widehat{G})$  by pointwise multiplication by  $\chi_g$ ; that is,  $gF(x) = \chi_g(x)F(x)$  for  $F \in \text{Fun}(\widehat{G})$ .

### Fourier inversion on finite Abelian groups

We will show that the Fourier transform has a  $G$ -linear inverse and hence is an isomorphism.

From some of the above calculations, we have that  $g\delta_h = \delta_g * \delta_h = \delta_{gh}$ . This equation shows that the action of  $G$  on the delta functions is by pushforward via left multiplication. So in reality the delta function in this case is a distribution or measure as opposed to a function.

Let  $G$  be any finite group. The left multiplication of  $G$  on itself gives rise to a natural right action on functions by pullback along the left multiplication map and a natural left action on distributions (or measures) by pushforward via the right action map on  $\text{Fun}(G)$ . That is, given a complex-valued function  $G \xrightarrow{f} \mathbb{C}$ , the right action of  $G$  on  $f$  is given by  $fg = (g \cdot)^* f = f(g \cdot)$ :

$$\begin{array}{ccc} G & \xrightarrow{g \cdot} & G \\ & \searrow & \downarrow f \\ & f(g \cdot) = (g \cdot)^* f & \mathbb{C} \end{array} \quad \text{pulling back } f \text{ along } g \cdot$$

The right action on  $\text{Fun}(G)$  defines a map  $\text{Fun}(G) \xrightarrow{\cdot g} \text{Fun}(G)$ , by which we will pushforward distributions. Given a distribution on  $G$ ; that is, a linear function  $\text{Fun}(G) \xrightarrow{T} \mathbb{C}$ , the left action of  $G$  on  $T$  is given by  $gT = (\cdot g)_* T = T(-g^{-1})$ :

$$\begin{array}{ccc} \text{Fun}(G) & \xrightarrow{\cdot g} & \text{Fun}(G) \\ T \downarrow & \swarrow & \\ \mathbb{C} & (\cdot g)_* T = T(-g^{-1}) & \end{array} \quad \text{pushing forward } T \text{ by } \cdot g$$

Here,  $(\cdot g)_* T = T(-g^{-1})$  because

$$(\cdot g)_* T(f) = \sum_{\substack{h \\ hg=f}} T(h) = T(fg^{-1}) \quad (\text{only one element in the fiber})$$

Typically, for a function  $f: X \rightarrow Y$  and a distribution  $F: \text{Fun}(X) \rightarrow \mathbb{C}$ , the pushforward  $(f^* \cdot)_* F$  is denoted by  $f_* F$ , and this is what is meant by the pushforward of the distribution  $F$  by  $f$  (similarly for measures).

It is instructive to look at the left action of  $G$  on the regular distributions, which are the distributions  $T_f$  obtained by integration against  $f \in \text{Fun}(G)$ :

$$T_f(h) = \sum_{g \in G} f(g)h(g)$$

and the action of  $G$  on a regular distribution looks like

$$\begin{aligned} (gT_f)(h) &= ((\cdot g)_* T_f)(h) = T_f(hg) = T_f(h(g-)) \\ &= \sum_{x \in G} f(x)h(gx) = \sum_{x \in G} f(g^{-1}x)h(x) = \sum_{x \in G} (fg^{-1})(x)h(x) = T_{fg^{-1}}(h) \end{aligned}$$

To summarize, for any  $f \in \text{Fun}(G)$ ,  $gT_f = T_{fg^{-1}}$ . For finite groups, every distribution on  $G$  is a regular distribution. Given a distribution  $T$  on  $G$ , define  $f \in \text{Fun}(G)$  by  $f(g) = T(\delta_g)$ . Then by linearity of  $T$  the calculation

$$T_f(\delta_h) = \sum_{x \in G} f(x)\delta_h(x) = \sum_{x \in G} T(\delta_x)\delta_h(x) = T(\delta_h)$$

implies that  $T = T_f$  (and that  $f$  is unique).

Compare the original left action of  $G$  (not the natural one defined by pullbacks above) on the function  $\delta_h$  with the left action of  $G$  on the regular distribution  $T_{\delta_h}$ :

$$g\delta_h = \delta_{gh} \quad \text{and} \quad gT_{\delta_h} = T_{\delta_{hg^{-1}}} = T_{\delta_{gh}}$$

So this is a reason for why we mentioned above that the delta function was really a distribution or measure. The original definition of the left action of  $G$  on  $\text{Fun}(G)$  may be thought of as turning the natural right action of  $G$  on  $\text{Fun}(G)$  into a left action by being clever with signs, or more interestingly as identifying all functions with their corresponding regular distributions.

Now return to the case when  $G$  is finite Abelian. View  $\chi_{\hat{g}}$  as an element of  $\text{Fun}(G)$ . The calculation

$$g\chi_{\hat{g}}(h) = \chi_{\hat{g}}(g^{-1}h) = \chi_{\hat{g}}(g^{-1})\chi_{\hat{g}}(h) = \chi_{\hat{g}}(g)^{-1}\chi_{\hat{g}}(h) = \overline{\chi_{\hat{g}}(g)}\chi_{\hat{g}}(h)$$

shows that under the action of  $G$  on  $\text{Fun}(G)$ ,  $\chi_{\hat{g}}$  is an eigenvector with eigenvalue  $\chi_{\hat{g}}(-)^{-1} = \overline{\chi_{\hat{g}}(-)}$ . In the theory of Fourier series (which we will see more later), a character of  $\text{U}(1) = \mathbb{R}/\mathbb{Z}$  is of the form  $x \mapsto \exp(2\pi i n x)$ . The action of  $\mathbb{R}/\mathbb{Z}$  on  $\text{Fun}(\mathbb{R}/\mathbb{Z})$  is given by  $(x \cdot f)(\theta) = f(\theta - x)$ , so

$$y \cdot \exp(2\pi i n x) = \exp(2\pi i n(x - y)) = \overline{\exp(2\pi i n y)} \exp(2\pi i n x)$$

(See Terence Tao's blog.)

Earlier we showed that  $\widehat{\delta_g} = \chi_g$ , and that extending this linearly produces the Fourier transform. We would like for the inverse Fourier transform to send  $\delta_{\hat{g}}$ , the indicator function of  $\hat{g}$ , to a character, to match the Fourier transform. (Note that the space  $\text{Fun}(\widehat{G})$  has basis the indicator functions  $\delta_{\hat{g}}$ .) But the inverse Fourier transform should also respect the group action on the function spaces. Compared to the action of  $G$  on  $\text{Fun}(G)$ , the action of  $G$  on



$\text{Fun}(\widehat{G})$  is given by identifying  $G$  with  $\widehat{\widehat{G}} \subset \text{Fun}(\widehat{G})$  and using pointwise multiplication. That is,  $gf = \chi_g \cdot f$ . We should try another calculation to see if that provides a clue; in particular, if we want to have a chance at defining the inverse Fourier transform we should try to take Fourier transforms of characters. The Fourier transform of  $\chi_{\hat{g}} \in \text{Fun}(G)$  is given by

$$\widehat{\chi_{\hat{g}}}(\hat{h}) = \sum_{h \in G} \chi(h, \hat{h}) \chi_{\hat{g}}(h) = \sum_{h \in G} \chi(h, \hat{h} \hat{g}) = |G| \delta_{\hat{g}^{-1}},$$

where in the last equality we used the following result:

$$\sum_{g \in G} \chi_g(\hat{h}) = \begin{cases} 0 & \text{if } \hat{h} \neq 1_{\widehat{G}} \\ |G| & \text{otherwise} \end{cases}$$

Indeed, since  $\widehat{\widehat{G}}$  is a group, if  $\hat{h} \neq 1_{\widehat{G}}$ , then choose  $h \in G$  for which  $\chi_{\hat{h}}(h) = \chi_h(\hat{h}) \neq 1$  (we can do this since  $\chi_{\hat{h}}$  is not the trivial character). Then with  $\chi_h \in \widehat{\widehat{G}}$ , we have

$$\chi_h(\hat{h}) \sum_{g \in G} \chi_g(\hat{h}) = \sum_{g \in G} \chi_{hg}(\hat{h}) = \sum_{g \in G} \chi_g(\hat{h}),$$

but  $\chi_h(\hat{h}) \neq 1$ , so  $\sum_{g \in G} \chi_g(\hat{h}) = 0$ . If  $\hat{h} = 1_{\widehat{G}}$ , then  $\sum_{g \in G} \chi_g(\hat{h}) = \sum_{g \in G} 1 = |G|$ . A similar argument may be done to evaluate the sum  $\sum_{\hat{g} \in \widehat{G}} \chi_{\hat{g}}(h)$ .

Based on the calculations above, one might try to calculate the Fourier transform of  $\overline{\chi_{\hat{g}}}$ , to obtain  $|G| \delta_{\hat{g}}$ . So the inverse Fourier transform should send  $\delta_{\hat{g}}$  to  $\chi_{\hat{g}}/|G|$ , and by extending linearly we find that the inverse Fourier transform  $\text{Fun}(\widehat{G}) \xrightarrow{\vee} \text{Fun}(G)$  is given by

$$F^{\vee}(g) = \frac{1}{|G|} \sum_{\hat{g} \in \widehat{G}} \overline{\chi(g, \hat{g})} F(\hat{g})$$

One can calculate that for any  $f \in \text{Fun}(G)$  that

$$f(g) = \frac{1}{|G|} \sum_{\hat{g} \in \widehat{G}} \overline{\chi(g, \hat{g})} \hat{f}(\hat{g})$$

which is the Fourier inversion theorem for finite Abelian groups.

By endowing  $\text{Fun}(G)$  with the Hermitian  $L^2$  inner product

$$\langle f, h \rangle = \sum_{g \in G} f(g) \overline{h(g)}$$

it turns out that the characters  $\chi_{\hat{g}}$  form an orthonormal basis (use one of the earlier calculations to do this). A similar statement is true for  $\text{Fun}(\widehat{G})$ , and by scaling the Fourier transform, the inverse Fourier transform, and possibly the inner products correctly, we obtain an unitary isomorphism of the Hilbert spaces  $\text{Fun}(G)$  and  $\text{Fun}(\widehat{G})$  (i.e., the inner product is preserved).

## A preview for locally compact Abelian groups

Some examples of locally compact Abelian (LCA) groups are the finite Abelian groups,  $\mathbb{Z}$ ,  $U(1)$ ,  $\mathbb{R}$ ,  $\mathbb{Z}_p$  (the  $p$ -adic integers), and  $\mathbb{Q}_p$  (the  $p$ -adic numbers). In this setting  $\widehat{G}$  is defined to be the set of unitary irreps, otherwise given by  $\text{Hom}_{\mathbf{Group}}(G, U(1))$ .

Pontryagin duality still holds in this setting. The result encapsulates the following statements:

1. The canonical map  $G \rightarrow \widehat{\widehat{G}}$  (where  $\widehat{\widehat{G}} = \text{Hom}_{\mathbf{Group}}(\widehat{G}, U(1))$ ) is an isomorphism.
2. The Fourier transform and its inverse are Hilbert space isomorphisms (i.e. unitary isomorphisms) of  $L^2(G)$  with  $L^2(\widehat{G})$  (with the correct measures on  $G, \widehat{G}$ ). The transforms interchange convolution with pointwise multiplication, and sends delta “functions” to characters (neither of which are  $L^2$  functions, so this is meant in the sense of distributions).
3. A spectral theorem: Representations of LCA groups are in correspondence with sheaves of vector spaces on  $\widehat{G}$ . Given a finite-dimensional representation  $V$  of  $G$ , decompose  $V$  into its invariant subspaces (otherwise called isotypic components)  $V = \bigoplus_{\hat{g}} V_{\hat{g}}$  where  $V_{\hat{g}} = \{v \in V \mid gv = \chi_{\hat{g}}(g)v\}$ . The Fourier transform in this setting takes the representation (sheaf)  $\text{Fun}(G)$  and spits out the representation (sheaf)  $\text{Fun}(\widehat{G}) = \bigoplus_{\hat{g} \in \widehat{G}} \mathbb{C} \dots$

Soon we will look at the LCA groups  $U(1)$  and  $\mathbb{R}$ . There we can recover the usual Fourier series and real Fourier transform theory.

## Lecture 4 09/04

### Unitarizable representations and semisimplicity

A category is called semisimple if every object is the direct sum of finitely many simple objects. We will show that  $\mathbf{Rep}_{\mathbb{C}}(G)$  is semisimple for  $G$  finite.

A complex representation of a group  $G$  is unitarizable if there exists a Hermitian inner product (non-degenerate, sesquilinear, positive definite bilinear form)  $\langle -, - \rangle$  on  $V$  for which

$$\langle gv, gw \rangle = \langle v, w \rangle$$

In other words,  $V$  is unitarizable if it can be endowed with a Hermitian inner product that is invariant under the group action, or otherwise we can say that the group acts by unitary transformations on  $V$  with this inner product. In the language of diagrams, given the representation  $(V, \rho)$ , there exists an inner product  $\langle -, - \rangle$  and the map  $G \xrightarrow{\rho} \mathrm{U}(V, \langle -, - \rangle)$  (with the same definition as  $G \xrightarrow{\rho} \mathrm{GL}(V)$ ) for which the following diagram commutes

$$\begin{array}{ccc} G & \xrightarrow{\rho} & \mathrm{GL}(V) \\ & \searrow \rho & \uparrow \\ & & \mathrm{U}(V, \langle -, - \rangle) \end{array}$$

A non-example of a unitarizable representation: If  $\mathbb{Z}$  acts on a one-dimensional vector space  $V$  and  $1 \in \mathbb{Z}$  acts by an operator outside of  $\mathrm{U}(V)$ , then there is no way to unitarize  $V$ .

Given a representation  $(V, \rho)$ , recall we can define the dual representation  $V^*$  where  $gf(v) = f(g^{-1}v)$ . In this case we think of the action of  $G$  as being inverted since we use the inversion map on  $G$  to define the action on  $V^*$ . On the other hand, since the action of  $G$  on  $V$  is by complex-valued matrices, we can pointwise conjugate these matrices to obtain a representation  $(\bar{V}, \bar{\rho})$  where the underlying Abelian group  $\bar{V}$  coincides with the Abelian group  $V$  but the scalar multiplication is given by  $c \cdot_{\bar{V}} v = \bar{c} \cdot_V v$ . Extending this, the group  $G$  acts on  $\bar{V}$  by  $gv = \overline{\rho(g)}v$ , and in this case we think of the action as being conjugated as opposed to inverted in the case with the dual vector space.

A Hermitian inner product  $\langle -, - \rangle$  on any complex vector space  $V$  corresponds to an isomorphism of  $\bar{V}$  with  $V^*$  given by  $v \mapsto \langle -, v \rangle$ , and from any isomorphism  $\bar{V} \xrightarrow{H} V^*$ , define the inner product  $\langle -, - \rangle$  by  $\langle v, w \rangle = H(v)(w)$ .

That a representation  $V$  is unitarizable is a property of  $V$  as opposed to being part of the structure. On the other hand, if  $W$  is a unitary representation, part of the data of  $W$  is a fixed  $G$ -invariant inner product  $\langle -, - \rangle$ , as opposed to a unitarizable representation  $V$  for which we do not specify any one  $G$ -invariant inner product. Of course, once we do specify a  $G$ -invariant inner product  $\langle -, - \rangle_0$ , we can speak of the unitary representation  $(V, \langle -, - \rangle_0)$ , which is different from the unitary representation  $(V, \langle -, - \rangle_1)$  for a different  $G$ -invariant inner product  $\langle -, - \rangle_1$ .

If  $V$  is a finite-dimensional unitarizable representation, then  $V$  is a semisimple representation; that is,  $V$  is the direct sum of irreps/simples. Assume  $V$  is already not simple, and fix a  $G$ -invariant inner product  $\langle -, - \rangle$  on  $V$ . Let  $W \subset V$  be any  $G$ -invariant subspace, and see that  $W^\perp = \{v \in V \mid \langle v, w \rangle = 0 \text{ for all } w \in W\}$  is a  $G$ -invariant subspace of  $V$  since the  $W$  and the inner product  $\langle -, - \rangle$  are  $G$ -invariant:

$$\langle gv, w \rangle = \langle v, g^{-1}w \rangle \quad \text{implies } gv \in W^\perp \text{ whenever } v \in W^\perp$$

Then induction proves the result (this amounts to iterating this procedure on  $W^\perp$  and repeating on each of the resulting subspaces until it cannot be done, which happens because  $V$  is finite-dimensional).

Another nice result is that if  $G$  is finite, then a finite-dimensional representation  $V$  is unitarizable and hence semisimple. The heart of this result is due to the existence of an averaging element  $av \in \mathbb{C}[G]$  given by

$$av = \frac{1}{|G|} \sum_{g \in G} g$$

Note that  $av \in Z(\mathbb{C}[G])$ . To define this averaging element, it is crucial that  $G$  is finite and that the characteristic of the field  $\mathbb{C}$  (zero) does not divide the order of the group. The existence of an averaging operator is the content of Maschke's theorem from earlier, since we can use this averaging element to form a projector needed to form complements of  $G$ -stable subspaces, as we will see.

Let  $V$  be any finite-dimensional representation. Then we can define the subspace of  $G$ -fixed points,  $V^G$ , by

$$V^G = \{v \in V \mid gv = v \text{ for all } g \in G\}$$

The subspace  $V^G$  is the part of  $V$  that  $G$  acts trivially on, or in other words is the trivial representation part of  $V$  when broken into irreps. For any  $v \in V$ ,  $av \cdot v \in V^G$  since for any  $h \in G$  we have

$$h(av \cdot v) = h\left(\frac{1}{|G|} \sum_{g \in G} gv\right) = \left(\frac{1}{|G|} \sum_{g \in G} hgv\right) = \left(\frac{1}{|G|} \sum_{g \in G} gv\right) = av \cdot v$$

Observe further that because the sum is normalized with the factor  $1/|G|$ , multiplication by  $av$  defines a projection map to  $V^G$ , since  $av^2 = av$ , so  $av-$  is an idempotent. The complementary idempotent is  $(1 - av)-$ , and see that it squares to itself as well. It is complementary since  $av(1 - av) = 0$ . It follows that  $V = avV \oplus (1 - av)V = V^G \oplus (1 - av)V$ .

An aside: To prove Maschke's theorem, we do a similar trick. Given any  $G$ -invariant subspace  $H$  of a representation  $V$ , consider the space  $\text{Hom}_{\mathbb{C}}(V, H)$ , which contains many projections since short exact sequences in  $\mathbf{Vect}_{\mathbb{C}}$  always split, or this is just true from linear algebra. What we want to find is a projector  $\pi$  which is  $G$ -intertwining; that is,  $(g \cdot) \pi (g^{-1} \cdot) = \pi$ . Considering the action of  $G$  on  $\text{Hom}_{\mathbb{C}}(V, H)$  by conjugation, finding a  $G$ -intertwining projector  $\pi$  amounts to finding a projector that is fixed under conjugation. Pick any one projector  $V \xrightarrow{\pi_0} H$ , and average  $\pi_0$  using  $av$  to get the projector

$$\pi = av \cdot \pi_0 = \frac{1}{|G|} \sum_{g \in G} (g \cdot) \pi_0 (g^{-1} \cdot)$$

Hence  $\pi$  is a fixed point under the conjugation action and thus is a desired  $G$ -equivariant projector.

Returning to showing that a finite-dimensional representation  $V$  is unitarizable and hence semisimple, it amounts to finding a  $G$ -invariant inner product  $\langle -, - \rangle$ . Pick any inner product  $\langle -, - \rangle_0$  on  $V$  and make it  $G$ -invariant by averaging it via  $\text{av}$ . Define the inner product  $\langle -, - \rangle$  by

$$\langle -, - \rangle = \text{"av}(\langle -, - \rangle_0)" = \frac{1}{|G|} \sum_{g \in G} \langle g-, g- \rangle_0$$

Observe that this new inner product is  $G$ -invariant as desired, and is really a Hermitian inner product because  $\langle -, - \rangle_0$  was to begin with. (In other words, we have found an isomorphism  $H \in \text{Hom}_{\mathbb{C}}(\overline{V}, V^*)^G$  by applying the projection  $\text{Hom}_{\mathbb{C}}(\overline{V}, V^*) \rightarrow \text{Hom}_{\mathbb{C}}(\overline{V}, V^*)^G$  obtained via averaging to any isomorphism  $H_0 \in \text{Hom}_{\mathbb{C}}(\overline{V}, V^*)$ .) Since  $V$  is unitarizable,  $V$  is semisimple. This shows that  $\mathbf{Rep}_{\mathbb{C}}(G)$  is semisimple. The slickness of the argument above gives a compelling reason to use the group algebra  $\mathbb{C}[G]$ .

## Distributions and measures

When  $G$  is finite, then the group algebra  $\mathbb{C}[G]$  can be identified with the algebra  $\text{Fun}(G)$  with convolution, and we identify  $\text{av}$  with  $\mathbf{1}_G/|G|$  ( $\mathbf{1}_G$  is the indicator function on  $G$ ) and identify  $\mathbf{1}_{\mathbb{C}[G]}$  with  $\delta_{1_G}$ , and everything in between. If  $G$  is also Abelian, then  $\text{Fun}(G)$  with convolution is isomorphic to  $\text{Fun}(\hat{G})$  with pointwise multiplication via the Fourier transform. A short calculation shows that the Fourier transform of  $\delta_{1_G}$  is  $\mathbf{1}_{\hat{G}} = \sum_{\hat{g} \in \hat{G}} \delta_{\hat{g}}$ , which can be thought of as some version of Plancherel's theorem.

So if  $G$  acts on  $V$ , then we know that  $V$  decomposes as  $V = \bigoplus_{\hat{g} \in \hat{G}} V_{\hat{g}}$ , where  $V_{\hat{g}} = \delta_{\hat{g}}V$ , where we think of the delta functions as being projectors onto subspaces of  $V$  for which  $G$  acts by multiplication by characters. The notation is suggestive:  $g \cdot \delta_{\hat{g}}V = \chi_{\hat{g}}(g)\delta_{\hat{g}}V$ .

When we consider groups  $G$  that are not finite, we may need to consider a smaller function space than all of  $\text{Fun}(G)$  in order for the theory to be nicer. In doing so, the functions  $\delta_{1_G}$ ,  $\mathbf{1}_G/|G|$  cease to belong in these new function spaces or even in  $\text{Fun}(G)$  to begin with, and should be thought of as distributions or measures. For example, this will happen with  $G = \text{U}(1)$  or  $\mathbb{R}$  since we will look at  $L^2(G)$  primarily. For example, we think of  $\mathbf{1}_G/|G|$  more accurately as the distribution  $1/\mu(G) \int_G -d\mu$  for a correctly chosen measure  $\mu$  on  $G$ , for  $G$  compact, and  $\delta_{1_G}$  as the functional which evaluates functions at  $1_G$ .

Because the convolution of two functions is given by an integral or otherwise a pushforward, secretly somehow what is actually happening is that we are pushing forward a particular distribution or measure. "You don't integrate functions, you integrate measures." So this is more evidence that we should see if we can do an analysis of the representations of infinite Abelian groups using distributions instead of functions.

Let  $G$  be a locally compact Hausdorff topological group. Then Haar's theorem (see Wikipedia) states that there is a measure  $\mu$  on the Borel subsets of  $G$ , called the Haar measure, which is:

1. Left-translation invariant under the left multiplication action of  $G$ ; that is, the pushforward measure  $(g\cdot)_*\mu$  agrees with  $\mu$ .
2. Finite on compact sets of  $G$ .
3. Outer regular on Borel sets; that is,  $\mu(S) = \inf\{\mu(U) \mid S \subseteq U \text{ with } U \text{ open}\}$  for  $S$  a Borel set.
4. Inner regular on open sets; that is,  $\mu(U) = \sup\{\mu(K) \mid K \subseteq U \text{ with } K \text{ compact}\}$  for  $U$  an open set.
5. Unique up to positive scaling.

If  $G$  is compact then we can normalize the Haar measure on  $G$  to produce a unique Haar measure for which  $\mu(G) = 1$ . This measure is provided by  $\text{av}$ , viewed as a measure by the formula  $\text{av}(E) = \frac{1}{\mu(G)} \int_E 1 d\mu$  where  $\mu$  is any Haar measure, or as the regular distribution  $T_{\text{av}}$  where  $T_{\text{av}}(f) = \int_G f(g) \text{av}(g) d\mu = \frac{1}{\mu(G)} \int_G f(g) d\mu$  where  $\mu$  is any Haar measure. So for example, the normalized Haar measure on  $U(1)$  is  $d\theta/2\pi$ .

On a manifold, to be able to integrate we need to be able to find a top differential form. So if  $G$  is a Lie group, consider the tangent space  $\mathfrak{g} = T_G(1_G)$ , which is the only one we need to consider since all other tangent spaces are obtained via translation of the tangent space at the identity. Then the space of top differential forms  $\bigwedge^{\dim \mathfrak{g}} \mathfrak{g}^*$  is a 1-dimensional vector space. The normalized Haar measure is the measure induced by the normalized top form in this vector space.

The requirement that  $G$  is locally compact probably comes from wanting to be able to approximate integrals using compact exhaustions. The Hausdorff requirement is a consequence of the following result of topological groups: For  $G$  a topological group, let  $H$  be the closure of the set  $\{1_G\}$ . Then  $H$  is a normal subgroup and the quotient  $G/H$  is the largest quotient of  $G$  that is Hausdorff. Furthermore, every continuous map of  $G$  to a Hausdorff space factors through the quotient  $G/H$ . So in our setting, we will be considering continuous maps from  $G$  to the complex numbers, so in this setting  $G$  is indistinguishable from its largest Hausdorff quotient. As a consequence, there is no loss in defining LCA groups to be locally compact, Abelian, and Hausdorff.

A fun fact is that if  $G$  is compact, then the Haar measure on  $G$  is automatically both left and right-translation invariant, even if  $G$  is not Abelian. For any Haar measure  $\mu$  on  $G$  and  $g \in G$ , the pushforward of  $\mu$  by right multiplication by  $g^{-1}$  produces another left invariant Haar measure  $(\cdot g)_*\mu$ . So  $\mu$  is some multiple of  $(\cdot g)_*\mu$ , denote this multiple by  $\text{mod}(g)$ , called the modulus character of  $G$ . It turns out that this quantity does not depend on the choice of Haar measure  $\mu$  we started with, and is also a group homomorphism  $G \rightarrow \mathbb{R}_{>0}$ , which measures how much the left and right-translation invariance of the Haar measure disagree. The modulus character is trivial if  $G$  is Abelian. For  $G$  compact, there are no compact subgroups of  $\mathbb{R}_{>0}$  aside from  $\{1\}$ , so in this case the modulus character is also trivial, and hence Haar measures on compact groups are bi-invariant. In other words, the Haar measure is a  $G \times G$ -invariant measure on  $G$  (where  $(g, h) \in G \times G$  acts by left translation by  $g$  and by right translation by  $h^{-1}$ ). This is because the element  $\text{av} \in \mathbb{C}[G]$  is  $G \times G$ -invariant (where  $(g, h) \in G \times G$  acts by left multiplication by  $g$  and by right multiplication by  $h^{-1}$ ); this is stronger than just being invariant under conjugation by  $G$ .

### A tiny preview of LCA groups

Let  $G$  be compact. Then finite-dimensional representations of  $G$  are semisimple. The proof follows the same ideas as in the finite case, but we replace all sums with integrals using the normalized Haar measure. Note that the normalization of the Haar measure is what will ensure that our desired projector actually is an idempotent as we did in the finite case.

For LCA groups, it is also true that finite-dimensional representations are semisimple, and from before we know the irreps are one-dimensional. If  $G = \mathrm{U}(1) = S^1$ , then we obtain the theory of Fourier series, since the dual group  $\widehat{S^1}$  is isomorphic to  $\mathbb{Z}$ ; each character of  $S^1$  is of the form  $z \mapsto z^n$  (or  $x \mapsto \exp(2\pi i n x)$  if we think of  $S^1$  as  $\mathbb{R}/\mathbb{Z}$ ) for some integer  $n$ .

## Lecture 5 09/09

## Fourier series

Let  $G = \mathrm{U}(1)$ , which we know familiarly as the circle. Since  $G$  is compact, representations of  $G$  are semisimple, and since  $G$  is Abelian, irreps of  $G$  are one-dimensional. We could decide to stop with the theory here, since at this point we have classified all of the finite-dimensional representations using the dual group  $\widehat{G}$  from before.

The dual group of the circle  $\widehat{\mathrm{U}(1)}$  is  $\mathbb{Z}$ , where  $n \in \mathbb{Z}$  corresponds to the character  $z \mapsto z^n$ , or if we think of  $\mathrm{U}(1)$  as  $\mathbb{R}/\mathbb{Z}$ , the character  $x \mapsto \exp(2\pi i n x)$ . We will think of the circle as  $\mathbb{R}/\mathbb{Z}$  usually, to appease the analysts (this is a joke). In this setting, the universal character  $\chi(-, -)$  is the map  $(x, n) \mapsto \exp(2\pi i n x)$  (so  $\chi_x = \chi(x, -)$  and  $\chi_n = \chi(-, n)$ ). Then the Fourier transform as we mentioned before is obtained from the maps in the diagram

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

by pulling back  $f \in \mathrm{Fun}(G)$  along  $\pi_1$ , multiplying by  $\chi(-, -)$ , and then pushing forward along  $\pi_2$ . That is,

$$\hat{f} = \pi_{2*}(\pi_1^* f \cdot \chi) \quad \text{so} \quad \hat{f}(n) = \int_0^1 f(x) \exp(2\pi i n x) dx$$

The Fourier inversion theorem in this setting is

$$f(x) \approx \sum_{n \in \mathbb{Z}} \hat{f}(n) \exp(-2\pi i n x)$$

where the  $\approx$  means that we should worry about convergence. It ends up being the case that we get convergence in the  $L^2$  norm, but more analysis is needed for better results.

Another point of view of the Fourier transform is to look at  $G = \mathrm{U}(1) = \mathbb{R}/\mathbb{Z}$  acting on  $L^2(G)$  by translation. The action is

$$y \cdot f =: \tau_y f = f((-) - y) \quad \text{for } y \in \mathbb{R}/\mathbb{Z}$$

The group action preserves each of the subspaces  $\mathbb{C}\chi_n$  since like before, we have  $\tau_y \chi_n(x) = \chi_{-n}(y) \chi_n(x)$ . We can think of the Fourier transform in linear algebra terms, since  $L^2(G)$  has the Hermitian inner product  $\langle f, g \rangle = \int_0^1 f(x) \overline{g(x)} dx$ . Some analysis shows that the characters  $\chi_n$  form an orthonormal basis of  $L^2(G)$ , so the Fourier transform finds the components of any  $f \in L^2(G)$  using the inner product:

$$\hat{f}(n) = \langle f, \chi_{-n} \rangle = \int_0^1 f(x) \exp(2\pi i n x) dx$$

The inverse Fourier transform reassembles  $f$  from its projections onto each of the subspaces  $\mathbb{C}\chi_n$ , but as we noted before, we might need to worry about convergence:

$$f(x) \approx \sum_{n \in \mathbb{Z}} \langle f, \chi_{-n} \rangle \chi_{-n} = \sum_{n \in \mathbb{Z}} \hat{f}(n) \exp(-2\pi i n x)$$



Analysts are likely used to the characters being maps  $x \mapsto \exp(inx)$  and the Fourier transform of  $f \in L^2(U(1))$  as  $\frac{1}{2\pi} \int_0^{2\pi} f(x) \exp(-inx) dx$ ; to obtain this form we can present  $U(1)$  not by  $\mathbb{R}/\mathbb{Z}$  but as unimodular points in  $\mathbb{C}$ , with the Haar measure given by arclength measure, and by reindexing the characters by interchanging  $n$  with  $-n$ .

## Function spaces

An algebraic point of view is to view the algebra spanned by all of the characters as the algebraic functions on the circle; that is,

$$\bigoplus_{n \in \mathbb{Z}} \mathbb{C} \chi_n \cong \mathbb{C}[z, z^{-1}] \quad \text{where } z = \exp(2\pi i x) \text{ since } x \in \mathbb{R}/\mathbb{Z}$$

The coordinate ring of the affine space  $\mathbb{C}$  is  $\mathbb{C}[z]$ . By localizing the coordinate ring at the maximal ideal  $m_0 = \{f \in \mathbb{C}[z] \mid f(0) = 0\} = (z)$ , we obtain the algebraic functions on  $\mathbb{C}^\times$ , which agree with the algebraic functions on the circle if we restrict  $z$  to  $z = \exp(2\pi i x)$  for  $x \in \mathbb{R}/\mathbb{Z}$ .

An analytic point of view is to see this space of algebraic functions as being dense in function spaces like  $L^2(G)$ ,  $L^1(G)$ ,  $C^\infty(G)$ ,  $C^\omega(G)$  (analytic functions),  $C^{-\infty}(G)$  (distributions), or even  $C^{-\omega}(G)$  (hyperfunctions?). Let us suppress the  $(G)$  for now. Each of these spaces has the algebraic functions above as an “algebraic core”, for which we understand the Fourier transform on. The question is how the action of the Fourier transform extends to the rest of the function spaces, and this requires analysis. The Fourier transform exchanges the following spaces (this is not to say the Fourier transform is always an isomorphism of these spaces!):

$$\begin{array}{ll} L^2 \longleftrightarrow \ell^2 & L^1 \longleftrightarrow c_0 \\ C^\infty \longleftrightarrow \{f \rightarrow 0 \text{ faster than } 1/\text{polynomial}\} & C^\omega \longleftrightarrow \{f \rightarrow 0 \text{ faster than } 1/\text{exponential}\} \\ C^{-\infty} \longleftrightarrow \{f \rightarrow \infty \text{ polynomial order}\} & C^{-\omega} \longleftrightarrow \{f \rightarrow \infty \text{ exponential order?}\} \end{array}$$

It is actually the case that the Fourier transform gives an isomorphism of  $L^2$  with  $\ell^2$ . Harish-Chandra studied similar function spaces for non-Abelian groups and found similar exchanges as above.

More than just an orthonormal basis, the algebraic core of characters is the basis in which the action of  $G$  is diagonalized via the Fourier transform. This is due to the property that the Fourier transform interchanges convolution of functions with pointwise multiplication of functions. In the setting of the circle group, this is to recast the action of translation as convolution against a delta distribution and to use the Fourier transform to obtain pointwise multiplication by a scalar:

$$\tau_y f = \delta_y * f \xrightarrow{\widehat{\phantom{x}}} \widehat{\delta_y * f} = \exp(2\pi i(-)y) \hat{f}.$$

If  $f$  is the character  $\chi_n$ , then  $\tau_y$  acts on  $f$  by multiplication by the scalar  $\exp(-2\pi i n y)$ , and this action commutes with the Fourier transform. In general we should worry about what functions it makes sense to convolve against; after all, we are convolving functions with distributions, so some analysis must be done. If we restrict to continuous functions, then the analysis of  $C^*$ -algebras will appear, for example.

Since  $U(1)$  is thought of as continuous as opposed to discrete, there is an “infinitesimal” action of  $U(1)$  on functions given by taking the derivative. The Fourier transform takes differentiation to multiplication by a multiple of the identity function:

$$\widehat{\frac{d}{dx}f}(n) = -2\pi i n \hat{f}$$

If  $f$  is the character  $\chi_m$ , then the derivative of  $f$  is  $2\pi i m f$ . The Fourier transform of  $2\pi i m f$  is  $2\pi i m \delta_{-m}$ , so the action of the derivative commutes with the Fourier transform.

What is meant by the “infinitesimal” action  $\frac{d}{dx}$ ? From the action of  $U(1) = \mathbb{R}/\mathbb{Z}$ , we define an action of its Lie algebra  $\mathbb{R}$  (the tangent space at the identity 0 of  $\mathbb{R}/\mathbb{Z}$ ) on a function by  $y \cdot f = \frac{d}{dt}(\tau_{ty}f)|_{t=0}$ . In this case,  $\frac{d}{dx}$  agrees with the action of  $-1$  on functions; that is,  $\frac{d}{dx}f = \frac{d}{dt}(\tau_{-t}f)|_{t=0}$ . If we want to insist on working in  $U(1)$  given by the unimodular complex numbers, then the Lie algebra of  $U(1)$  in this case is  $i\mathbb{R}$ . The action of  $i\mathbb{R}$  on  $g$  (here  $g$  is a function of  $\theta$ ; if  $g$  is a function of  $z$ , put  $z = \exp(i\theta)$ ) is given by  $iy \cdot g = \frac{d}{dt}(\exp(iyt) \cdot g)|_{t=0}$ . In this case  $\frac{d}{d\theta}$  is given by the action of  $-i$  on functions; that is,  $\frac{d}{d\theta}g = \frac{d}{dt}(\exp(-it) \cdot g)|_{t=0}$ .

Due to Pontryagin duality, we can mirror the above theory by considering taking Fourier transforms of functions on  $\mathbb{Z}$  to get functions on  $\widehat{\mathbb{Z}} = U(1)$ . The universal character  $\chi(-, -)$  in this case is the same map (but we should flip the inputs)  $(n, x) \mapsto \exp(2\pi i n x)$ . Even though  $\mathbb{Z}$  is a discrete group, we can still think about difference operators in place of derivatives (these are just linear combinations of differences of translation operators). As desired, the action of  $\mathbb{Z}$  on a function is given by translation, and the Fourier transform exchanges this action with multiplication by a character. That is, for  $n \in \mathbb{Z}$

$$n \cdot g =: \tau_n g = \delta_n * g = g((-) - n) \xrightarrow{\widehat{\phantom{x}}} \widehat{\delta_n * g} = \exp(2\pi i n (-)) \hat{g}$$

As before, we should also expect difference operators to correspond to a multiplier operator after taking the Fourier transform.

The Fourier transform on  $\mathbb{Z}$ , which we also denote by  $\mathcal{F}_{\mathbb{Z}}$ , is given by  $\hat{g}(x) = \sum_{n \in \mathbb{Z}} g(n) \exp(2\pi i n x)$ , which is different from the inverse Fourier transform of the Fourier transform  $\mathcal{F}_{U(1)}$  from  $U(1)$  to  $\mathbb{Z}$ . Each Fourier transform has order four. Note also that by composing the two Fourier series together, we get  $\mathcal{F}_{\mathbb{Z}}\mathcal{F}_{U(1)}f(x) = f(-x)$ . Similarly,  $\mathcal{F}_{U(1)}\mathcal{F}_{\mathbb{Z}}g(n) = g(-n)$ .

Even though we understand well how the Fourier transform acts on delta distributions and characters, there is the issue of figuring out how the Fourier transforms extend to larger function spaces. There should be a nice way to package the theory together nicely, in a way that is agnostic to the exact functions appearing in the larger spaces. A nice way to package everything together is via the spectral theorem for the group  $U(1)$ .

### The spectral theorem for $U(1)$

Let  $\mathcal{H}$  be any unitary representation of  $U(1)$  (note that some of the function spaces we mentioned earlier are not Hilbert spaces!). Since we have diagonalized the action of  $U(1)$ , it acts on  $\mathcal{H}$  by compact operators (in this case the

operators are approximated by finite-rank diagonal operators). By the spectral theorem for compact operators, we can find countably many eigenspaces of  $\mathcal{H}$  whose direct sum is dense in  $\mathcal{H}$ . We find these eigenspaces explicitly using the characters  $\chi_n$ .

The first part of this is to find analogues of the group algebra in this setting. On one hand, compactly supported functions on  $G = \mathbb{R}/\mathbb{Z}$  would be a good starting place, but we can choose even larger spaces for which the product, convolution, still makes sense. For example, suitable candidates for a group algebra might be the space of continuous or even  $L^1$  functions on  $G$ . For now, consider the continuous functions on  $G$  with convolution, denoted by  $(C(G), *)$ . A unitary representation  $(\mathcal{H}, \rho)$  of  $G$  is in correspondence with a non-degenerate, bounded  $*$ -representation (whatever this means, but note that this new representation is not unitary)  $\pi_\rho$  of the algebra  $C(G)$ . Define  $\pi_\rho$  by the Bochner integral

$$\pi_\rho(f) = \int_0^1 f(x)\rho(x)dx$$

In other words,  $f$  acts on  $v$  by “convolution against  $v$ ”:

$$f \cdot v = “f * v” = \int_0^1 f(x)(x \cdot v)dx$$

In this setting the action of the character  $\chi_n$  (which is an element of  $C(G)$ ) on  $\mathcal{H}$  is an orthogonal idempotent; that is, the map  $\chi_n * -$  satisfies

$$(\chi_m * -)(\chi_n * -) = (\chi_m * \chi_n) * - = \delta_{mn}\chi_n * -$$

To see this, use the Fourier transform: It suffices to see that  $\widehat{\chi_m * \chi_n} = \delta_m \cdot \delta_n = \delta_{mn}\delta_n$  (here  $\delta_{mn}$  is the usual Kronecker delta).

The subspaces  $\mathcal{H}_n = \chi_n * \mathcal{H}$  of  $H$  combine to form  $\mathcal{H}^{\text{alg}} = \bigoplus_{n \in \mathbb{Z}} \mathcal{H}_n$ . It turns out that  $\mathcal{H}^{\text{alg}}$  is dense in  $\mathcal{H}$ . As expected,  $U(1)$  acts by pointwise multiplication by characters on the isotypic components of  $\mathcal{H}$ , the summands in  $\mathcal{H}^{\text{alg}}$ . Like before, we can get a sheaf picture where to each point  $n$  of  $\mathbb{Z}$  we place above it the vector space  $\mathcal{H}_n$ . The picture is a little different since the Hilbert space  $\mathcal{H}$  is the closure of  $\mathcal{H}^{\text{alg}}$ .

$$\begin{array}{ccccccc} \mathcal{H} & = & \overline{\mathcal{H}_1 \oplus \mathcal{H}_2 \oplus \cdots \oplus \mathcal{H}_\ell} \\ \mathbb{Z} & & 1 & & 2 & & \cdots & & \ell \end{array}$$

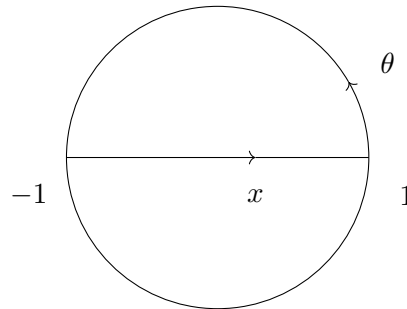
The density of  $\mathcal{H}^{\text{alg}}$  is due to some version of Plancherel’s theorem in this setting. The algebra  $C(G)$  does not have a unit, but if it did, it should have been the delta function  $\delta_{1_G}$  (which is not a continuous function, or much less a function at all). This is evidence that we should have taken some larger space to be the analogue of the group algebra in this setting; that is, perhaps some space of distributions (with convolution as product) would have been a better choice. If we believe that such an analogue exists, then  $\delta_{1_G}$  acts as the identity operator on  $\mathcal{H}$ :

$$\text{id}_{\mathcal{H}} v = v = \delta_{1_G} * v$$

But by the Fourier transform  $\delta_{1_G}$  corresponds to the unit for multiplication in the analogue of the group algebra for  $\mathbb{Z}$  with pointwise multiplication, which is the constant function  $\mathbf{1}_{\mathbb{Z}}$  ( $\mathbf{1}_{\mathbb{Z}}(n) = 1$ , notably not finitely supported). Since  $\mathbf{1}_{\mathbb{Z}} = \sum_{n \in \mathbb{Z}} \delta_n$ , taking the inverse Fourier transform shows that  $\text{id}_{\mathcal{H}} = \sum_{n \in \mathbb{Z}} \chi_n * -$ ; this shows that  $\mathcal{H}^{\text{alg}}$  is dense in  $\mathcal{H}$ .

### Chebyshev polynomials of the first kind

The Chebyshev polynomials (of the first kind) are special functions, like the characters given by either  $n$  or  $x$  maps to  $\exp(2\pi i n x)$  that play nice with the Fourier theory.



Comparing the real and imaginary parts in de Moivre's formula  $(\cos(\theta) + i \sin(\theta))^n = \cos(n\theta) + i \sin(n\theta)$ , one can prove that  $\cos(n\theta)$  is a polynomial in  $\cos(\theta)$ . The change of coordinates  $x = \cos(\theta) = (\exp(i\theta) + \exp(-i\theta))/2$  can now be used to turn power series in  $\exp(i\theta), \exp(-i\theta)$  (Fourier series) representing even functions on the circle to power series in  $x$ . We can use a different change of coordinates  $\sin(\theta) = (\exp(i\theta) - \exp(-i\theta))/2i$  to handle odd functions on the circle; these will lead to Chebyshev polynomials of the second kind.

The  $n$ -th Chebyshev polynomial of the first kind  $T_n(x)$  is defined to be the polynomial for which

$$T_n(\cos(\theta)) = \cos(n\theta)$$

That  $\{\cos(n\theta)\}$  is an orthogonal basis for a suitable space of even functions on the circle corresponds to  $\{T_n(x)\}$  being an orthogonal basis of a suitable space of functions on  $[-1, 1]$  with weighted  $L^2$  inner product  $\langle f, g \rangle = \int_{-1}^1 f(x)g(x)/\sqrt{1-x^2}dx$ . Some of the first few Chebyshev polynomials of the first kind are

$$\begin{array}{ll} T_0(x) = 1 & T_1(x) = x \\ T_2(x) = 2x^2 - 1 & T_3(x) = 4x^3 - 3x \\ T_4(x) = 8x^4 - 8x^2 + 1 & T_5(x) = 16x^5 - 20x^3 + 5x \end{array}$$

We should think of the  $T_n(x)$  as characters; in particular we can undo the change of coordinates  $x = \cos(\theta)$  to obtain the universal character  $(n, \theta) \mapsto T_n(\cos(\theta)) = \cos(n\theta) = (\exp(in\theta) + \exp(-in\theta))/2$ .

These polynomials satisfy the recurrence relation

$$T_{n+1}(x) = 2xT_n(x) - T_{n-1}(x)$$

which should be thought of as a second order difference equation in  $n$ ; that is, a discrete or otherwise integral version of a second order ODE. The Fourier transform takes shift operators to multiplier operators, so in this setting, undoing the change of coordinates  $x = \cos(\theta)$  and applying a suitable Fourier transform to the resulting recurrence relation would return a second order algebraic equation (a quadratic equation) for  $\cos(n\theta)$  in  $\theta$ .

These polynomials also satisfy the differential equation

$$(1 - x^2) \frac{d^2}{dx^2} T_n(x) - x \frac{d}{dx} T_n + n^2 T_n = 0$$

in  $x$ , so we should obtain a second order algebraic equation in  $n$  after applying a suitable Fourier transform to the above differential equation. That the above difference equation and differential equation are of second order should not be surprising since the universal character is  $\cos(n\theta)$  in this setting.

From the point of view of trigonometric polynomials, for some space of functions the set

$$\{\underline{1}, \underline{\cos(\theta)}, \underline{\sin(\theta)}, \underline{\cos(2\theta)}, \underline{\sin(2\theta)}, \dots\}$$

is an orthogonal basis. The underlined groups of functions are eigenspaces for the Laplacian  $\Delta_{U(1)} = \frac{\partial^2}{\partial \theta^2}$  on the circle. We can obtain these functions in a different way by first considering harmonic polynomials in the plane; that is, polynomials  $p(x, y)$  for  $x, y$  real which satisfy  $\Delta_{\mathbb{R}^2} p = \left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right) p = 0$ . Then consider the homogeneous polynomials in the plane; these are the polynomials  $p$  for  $p(kx, ky) = k^{\deg(p)} p(x, y)$ ; in polar coordinates these polynomials are separable with  $p(r, \theta) = r^{\deg p} \tilde{p}(\theta)$  for some function  $\tilde{p}(\theta)$  ( $\deg p$  is the homogeneous degree of  $p$ ). If  $p$  is a harmonic homogeneous polynomial,

$$0 = \Delta_{\mathbb{R}^2} p(r, \theta) = \left( \frac{d^2}{dr^2} + \frac{1}{r} \frac{d}{dr} + \frac{1}{r^2} \frac{d^2}{d\theta^2} \right) r^{\deg p} \tilde{p}(\theta) = r^{\deg p - 2} \left( (\deg p)^2 \tilde{p}(\theta) + \frac{d^2}{d\theta^2} \tilde{p}(\theta) \right)$$

By restricting to the circle  $r = 1$ , observe that  $\tilde{p}$  is an eigenfunction of the Laplacian on the circle, which by the theory of ordinary differential equations tells us that  $\tilde{p}$  is some linear combination of  $\cos(n\theta)$  and  $\sin(n\theta)$  for  $n = \deg p$ .

That the real eigenspaces (that aren't  $\mathbb{R}\{1\}$ ) for the Laplacian on the circle are two-dimensional comes from the action of the Laplacian on a suitable function space on the circle. Other differential operators may have different eigenspaces, of possibly different dimensions. In a Lie algebra, there is no notion of squaring elements, only taking their bracket. The universal enveloping algebra for a Lie algebra is an algebra which makes it possible to multiply elements of the Lie algebra together, and from a representation of a Lie group we should obtain a module over the universal enveloping algebra in a similar way to how we did so with the group algebra. We saw before how to obtain the derivative  $\frac{d}{d\theta}$  from the action of the Lie algebra of  $U(1)$  on functions. In the universal enveloping algebra it makes sense to square the element producing the derivative (it was  $-1$  for the Lie algebra of  $\mathbb{R}/\mathbb{Z}$  or  $-i$  for the Lie algebra of  $U(1)$ ), which would then act on functions as the Laplacian.

**Lecture 6 09/11****The Fourier transform on  $\mathbb{R}$** 

Let  $G$  be the real line  $\mathbb{R}$ , which henceforth we will denote by  $\mathbb{R}_x$  to indicate that the coordinate on  $\mathbb{R}$  is  $x$ . Like before, because  $G$  is an LCA group we know that the irreps of  $G$  are its one-dimensional unitary representations, which are parameterized by  $\widehat{G} = \mathbb{R}_t$  (again, this notation means the real line with coordinate  $t$ , to distinguish this real line with the real line defining  $G$ ). The universal character  $\chi$  in this setting is the map  $(x, t) \mapsto \exp(ixt)$ .

Let  $\mathcal{H}$  be a unitary representation of  $G$ ; that is,  $\mathcal{H}$  is a Hilbert space that the real line acts on by unitary operators. In this case, the image of  $\mathbb{R}$  in  $U(\mathcal{H})$  is a one-parameter subgroup  $\{U_x\}_{x \in \mathbb{R}_x}$  of  $U(\mathcal{H})$ . By Stone's theorem on one-parameter unitary groups (Wikipedia), it follows that  $U_x = \exp(ixH)$  for some self-adjoint operator  $H$  on  $\mathcal{H}$ . So the data of a unitary representation  $\mathcal{H}$  of  $G$  corresponds to the data of a single self-adjoint operator on  $\mathcal{H}$ . By differentiating this action, that is, passing to the action of the Lie algebra of  $G$  on  $\mathcal{H}$ , we find that the Lie algebra of  $G$  acts by the operator  $iH$  on  $\mathcal{H}$ ; this element (in physics, just  $H$ ) is called the infinitesimal generator for the group  $\{U_x\}_{x \in \mathbb{R}_x}$ .

One example of this story is in quantum mechanics, where  $\mathcal{H}$  is the space of states for a quantum mechanical system and  $\mathbb{R}$  acts on  $\mathcal{H}$  by time evolution. The infinitesimal generator of the one-parameter group  $\{U_x\}_{x \in \mathbb{R}_x}$  in this setting is the system's Hamiltonian.

From the spectral theorem for self-adjoint operators on Hilbert spaces, we obtain a kind of dictionary between

$$\{\text{irreps of unitary reps}\} \longleftrightarrow \{\text{eigenvalues in } \mathbb{R}\}$$

where the left side lives in the world of representation theory and the right side lives in the world of self-adjoint operator theory. Specifically, for a fixed unitary representation  $\mathcal{H}$  of  $G$ , decomposing  $\mathcal{H}$  into its irreps amounts to finding the eigenvalues of the operator  $H$  defining the representation. More generally, the decomposition of unitary representations  $\mathcal{H}$  of  $G$  corresponds to the spectrum of the operator  $H$  defining the representation. We will see this later.

The universal character  $\chi$  is used to obtain the Fourier transform  $\text{Fun}(G) \rightarrow \text{Fun}(\widehat{G})$  as usual. It is given by  $f \mapsto \hat{f}$  where

$$\hat{f}(t) = \int_{\mathbb{R}_x} f(x) \exp(itx) dx,$$

and the Fourier inversion theorem in this setting is

$$f(x) \approx \int_{\mathbb{R}_t} \hat{f}(t) \exp(-itx) dt,$$

where as usual we should worry about convergence. We should also care about what functions we apply the Fourier transform to. For example, a nice result from analysis is that the Fourier transform defines a unitary isomorphism of  $L^2(\mathbb{R}_x)$  with  $L^2(\mathbb{R}_t)$  (that the isomorphism is unitary is usually known as Plancherel's theorem).

The Fourier transform diagonalizes the translation operators like before. The group  $G$  acts naturally on  $\text{Fun}(G)$  by translation:

$$y \cdot f =: \tau_y f = f((-) - y) \quad \text{for } y \in \mathbb{R}_x$$

and one can calculate the infinitesimal version of this as differentiation. The group algebra version of this action is given by convolution; that is, an element  $f$  in the group algebra acts on  $\text{Fun}(G)$  by the operator  $f * -$ . By group algebra we might mean a nicer function space like continuous or smooth functions with compact support or even  $L^1$  functions, so it makes sense to convolve, but these are matters of analysis. The point is that the Fourier transform takes these translation actions and simultaneously diagonalizes them, turning them into multiplication operators on  $\text{Fun}(\widehat{G})$ . In particular, translation  $\tau_y$  is sent to pointwise multiplication by  $\chi_y$ , differentiation is sent to multiplication by  $-it$  (meaning pointwise multiplication by the map  $-i(t \mapsto t)$ ), and convolution against  $f$  is sent to pointwise multiplication by  $\hat{f}$ .

The statement that  $L^2(\mathbb{R}_x)$  is isomorphic to  $L^2(\mathbb{R}_t)$  can instead be thought of as a consequence of the spectral theory of the operator  $H = i\frac{d}{dx}$ . This operator should be thought of as an infinitesimal translation operator, which under the Fourier transform is sent to multiplication by  $t$  (a diagonal operator). The exponential of  $iH$ ,  $\exp(-y\frac{d}{dx})$ , is the translation operator  $\tau_y$ ; the exponential of  $it$ ,  $\exp(iyt)$ , is the multiplication operator  $\chi_y$ .

### An algebraic version of spectral theory

Let  $V$  be a complex vector space, and fix an element  $T \in \text{End}(V)$ . Then regard  $V$  as a  $\mathbb{C}[t]$ -module, where  $tv = Tv$  (this formalism is the prototype for the functional calculus). The action of  $\mathbb{C}[t]$  on  $V$  factors through  $\mathbb{C}[t]/\text{Ann}_{\mathbb{C}[t]}(V)$ , but this ring is isomorphic to  $\mathbb{C}[\text{Spec}(T)]$ , the ring of regular functions on the spectrum of the operator  $T$ , a subset of  $\mathbb{C}$ . The isomorphism is to take a polynomial  $f(t)$  and send it to the function  $f$  as a function of  $t \in \mathbb{C}$ . These regular functions remember the multiplicities of elements of  $\text{Spec}(T)$ . If the factor  $(t - \lambda)^n$  appears in  $m(t) \in \text{Ann}_{\mathbb{C}[t]}(V)$ , then the polynomials  $f(t), (t - \lambda)f(t), \dots, (t - \lambda)^{n-1}f(t)$  do not vanish at  $t = \lambda$  when viewed as functions on  $\mathbb{C}$ . In other words,  $f$  may have poles (so maybe these are not called regular functions).

The action of  $f$  on  $V$  will be more clear later, but here is part of it: We have  $f \cdot v = f(\lambda)v$  for  $v \in V_\lambda$  and  $\lambda \in \text{Spec}(T)$ , where  $V_\lambda$  is the  $\lambda$ -isotypic component of  $V$ . The decomposition of  $V$  in this setting is nicest if  $T$  is diagonalizable.

Suppose now that  $V$  is finitely generated as a  $\mathbb{C}[t]$ -module. Since  $\mathbb{C}[t]$  is a principal ideal domain, we can use the structure theorem for finitely generated modules over principal ideals domains to obtain a “spectral decomposition” of  $V$ :

$$V \cong V^{\text{free}} \oplus V^{\text{torsion}} \quad (\text{as } \mathbb{C}[t]\text{-modules})$$

The free part of  $V$  corresponds to the continuous spectrum of  $T$  and the torsion part of  $V$  corresponds to the discrete spectrum of  $T$ . Note that so far we have not thought about whether  $T$  was self-adjoint or not yet; this is all happening purely algebraically. Assume now that  $V$  is finite-dimensional so that  $V^{\text{free}}$  in the decomposition

above is trivial ( $\mathbb{C}[t]$  is infinite-dimensional as a complex vector space). Then from the same structure theorem for finitely generated modules over principal ideals we have

$$V \cong \bigoplus_{i=1}^m \frac{\mathbb{C}[t]}{(t - \lambda_i)^{n_i}},$$

where the  $\lambda_i$  may repeat. This decomposition of  $V$  is called the primary decomposition of  $V$ , from which we can obtain the Jordan normal form of  $T$ . The Jordan normal form of  $T$  is a block matrix

$$\begin{pmatrix} J_1 & & \\ & J_2 & \\ & & \ddots \\ & & & J_m \end{pmatrix}$$

where each  $J_i$  is the  $n_i \times n_i$  matrix

$$\begin{pmatrix} \lambda_i & 1 & & \\ & \lambda_i & \ddots & \\ & & \ddots & 1 \\ & & & \lambda_i \end{pmatrix}$$

If  $n_i > 1$ , we say that  $\lambda_i$  is a generalized eigenvalue of  $T$ .

For example, the natural action of  $t$  on the  $\mathbb{C}[t]$ -module  $\mathbb{C}[t]/(t - \lambda)^n$  with  $\mathbb{C}$ -basis  $\{1, (t - \lambda), \dots, (t - \lambda)^{n-1}\}$  as a linear operator is given by the  $n \times n$  Jordan block with diagonal entries  $\lambda$ .

An analyst's point of view on this spectral decomposition is that the module  $\mathbb{C}[t]/(t - \lambda)^n$  is isomorphic to the  $\mathbb{C}[t]$ -module generated by the  $(n - 1)$ -th distributional derivative of the delta distribution concentrated at  $\lambda$ . The action of  $f \in \mathbb{C}[t]$  on a distribution  $\phi$  is given by  $(f\phi)(\varphi) = \phi(f\varphi)$ , which is usually written in analysis as  $\langle f\phi, \varphi \rangle = \langle \phi, f\varphi \rangle$ .

The defining property of the delta distribution  $\delta_\lambda$ , which evaluates functions at  $\lambda$ , is that it is annihilated by the ideal  $(t - \lambda)$ ; that is,  $(t - \lambda)\delta_\lambda$  is the zero distribution. In other words, these delta distributions are eigenvectors for the action of  $t$ . By the  $n$ -th distributional derivative of  $\delta_\lambda$ , denoted  $\delta_\lambda^{(n)}$ , we mean the distribution that acts on test functions by the formula  $\delta_\lambda^{(n)}(\varphi) = (-1)^n \delta_\lambda(\varphi^{(n)}) = (-1)^n \varphi^{(n)}(\lambda)$ . The calculations

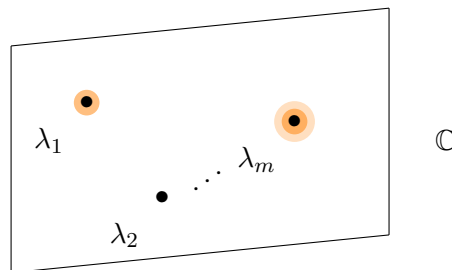
$$\begin{aligned} t\delta_\lambda(\varphi) &= (t\varphi)(\lambda) = \lambda\varphi(\lambda) = \lambda\delta_\lambda \\ t\delta'_\lambda(\varphi) &= -(t\varphi)'(\lambda) = -\lambda\varphi'(\lambda) - \varphi(\lambda) = \lambda\delta'_\lambda(\varphi) - \delta_\lambda(\varphi) \\ t\delta''_\lambda(\varphi) &= (t\varphi)''(\lambda) = \lambda\varphi''(\lambda) + 2\varphi'(\lambda) = \lambda\delta''_\lambda(\varphi) - 2\delta'_\lambda(\varphi) \\ &\vdots \end{aligned}$$

show that derivatives of delta distributions are generalized eigenvectors for the action of  $t$ ; that is,  $(t - \lambda)^k \delta_\lambda^{(k-1)} = 0$ . As a result the action of  $t$  on the complex vector space spanned by  $\{\delta'_\lambda, -\delta_\lambda\}$  is given by the matrix  $\begin{pmatrix} \lambda & 1 \\ 0 & \lambda \end{pmatrix}$ . Thus for the case  $n = 1$ , we have an isomorphism of  $\mathbb{C}[t]$ -modules  $\mathbb{C}[t]/(t - \lambda)^2 \rightarrow \mathbb{C}[t]\delta'_\lambda$  given by  $1 \mapsto \delta'_\lambda$ . In general,  $t$  acts on the complex vector space spanned by  $\{(-1)^n \delta_\lambda^{(n-1)}/(n - 1)!, \dots, \delta'_\lambda, -\delta_\lambda\}$  by the  $n \times n$  Jordan block with



diagonal entries  $\lambda$ . Like before, we obtain an isomorphism of  $\mathbb{C}[t]$ -modules  $\mathbb{C}[t]/(t - \lambda)^n \rightarrow \mathbb{C}[t]\delta_\lambda^{(n-1)}$  given by  $1 \mapsto \delta_\lambda^{(n-1)}$ .

So the discrete spectrum of an operator should correspond to derivatives of delta distributions supported at generalized eigenvalues of  $T$ . But even though these distributions are supported at points, their values on a test function  $\varphi$  depend on the values of the derivatives of  $\varphi$  (in general distributions may depend on the Taylor series for  $\varphi$ ), so the delta distributions are “localized” in this sense. This story can be retold in the language of sheaf theory by thinking of the delta distributions as a sheaf supported at the generalized eigenvalues of  $T$ ; that is, on  $\text{Spec}(\mathbb{C}[t]/\text{Ann}_{\mathbb{C}[t]}(V))$  (here  $\text{Spec}$  takes the prime spectrum of a ring). The higher the order of the generalized eigenvalue, the higher its “multiplicity” is in this setting (and in the picture below, the multiplicity is indicated by concentric disks).



The infinitesimal action of  $G = \mathbb{R}_x$  on  $\text{Fun}(\widehat{G})$  by pointwise multiplication by  $t$  comes from the Fourier transform of the infinitesimal action of  $G$  on  $\text{Fun}(G)$  by differentiation. The eigenfunctions of these actions are also expected to be interchanged via the Fourier transform. The delta functions  $\delta_\lambda$  for  $\lambda \in \mathbb{R}_t$  are eigenfunctions for pointwise multiplication by  $t$ ; and on the other side of the Fourier transform, the exponentials  $\exp(-i\lambda x)$  for  $\lambda \in \mathbb{R}_x$  are eigenfunctions of  $i \frac{d}{dx}$ . Some analysis is needed to make this rigorous, but thinking of  $\exp(-i\lambda x)$  as a regular distribution (i.e. as an element of a suitably chosen candidate for the group algebra) we have

$$\langle \widehat{\exp(-i\lambda(-))}, \varphi \rangle = \langle \exp(-i\lambda(-)), \hat{\varphi} \rangle = \int_{\mathbb{R}_x} \hat{\varphi}(x) \exp(-i\lambda x) dx = \varphi(\lambda) = \langle \delta_\lambda, \varphi \rangle$$

so indeed the Fourier transform of  $\exp(-i\lambda(-))$  is  $\delta_\lambda$ .

Since  $G = \mathbb{R}_x$  is not compact, indecomposable representations of  $G$  need not coincide with the irreps of  $G$ . One way to obtain these is by taking the inverse Fourier transform of derivatives of delta distributions. Some calculations show that the Fourier transform of the function given by  $(ix)^k \exp(-i\lambda x)$  is  $\delta_\lambda^{(k)}$ . By taking the inverse Fourier transform of the calculations from before involving  $t\delta_\lambda^{(k)}$ , we obtain the equations

$$\begin{aligned} i \frac{d}{dx} [\exp(-i\lambda x)] &= \lambda \exp(-i\lambda x) \\ i \frac{d}{dx} [(ix) \exp(-i\lambda x)] &= \lambda(ix) \exp(-i\lambda x) - \exp(-i\lambda x) \\ i \frac{d}{dx} [(ix)^2 \exp(-i\lambda x)] &= \lambda(ix)^2 \exp(-i\lambda x) - 2(ix) \exp(-i\lambda x) \\ &\vdots \end{aligned}$$

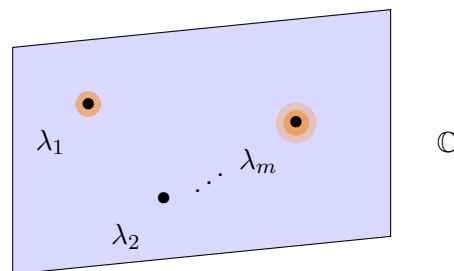
from which we can see that  $i\frac{d}{dx}$  acts on the complex vector space spanned by  $\{(-1)^n(ix)^{n-1}\exp(-i\lambda x)/(n-1)!, \dots, (ix)\exp(-i\lambda x), -\exp(-i\lambda x)\}$  by the  $n \times n$  Jordan block with diagonal entries  $\lambda$ . Similarly, if we think of this vector space instead as a  $\mathbb{C}[X]$ -module where  $X$  acts by  $i\frac{d}{dx}$ , there is an isomorphism  $\mathbb{C}[X]/(X-\lambda)^n \rightarrow \mathbb{C}[X](ix)^{n-1}\exp(-i\lambda x)$  given by  $1 \mapsto (ix)^{n-1}\exp(-i\lambda x)$ . Notice this is all completely symmetric to what we did earlier with the delta distributions. The indecomposable representation we have obtained is the  $n$ -dimensional representation of the Lie algebra of  $\mathbb{R}_x$  given by the  $\mathbb{C}$ -span of  $\{(ix)^{n-1}\exp(-i\lambda x), \dots, (ix)\exp(-i\lambda x), \exp(-i\lambda x)\}$  (this is the induced Lie algebra representation given by acting by scalar multiples of  $\frac{d}{dx}$ ). It is the case that this vector space is also an indecomposable representation of the original group  $\mathbb{R}_x$  under translation.

So in the usual sheaf picture, given a finite-dimensional representation  $V$  of  $\mathbb{R}_x$ , we can decompose  $V$  into the direct sum of indecomposable subrepresentations isomorphic to the ones in the previous paragraph (of possibly different dimensions of course), and each subspace should be viewed as living over the corresponding generalized eigenvalue of the operator  $H$  defining the action of  $\mathbb{R}_x$  on  $V$ .

One objection to the arguments from before is that none of these functions (the exponential, the delta distribution) belong to  $L^2(\mathbb{R}_x)$  or are even functions. So these representations above are not necessarily unitary representations; somehow the Fourier theory is able to see non-unitary representations...

To address the continuous spectrum, we return to the setting where  $V$  is a finitely generated  $\mathbb{C}[t]$ -module (where  $t$  acts by an operator  $T \in \text{End}(V)$ ), so that  $V$  decomposes as  $V = V^{\text{free}} \oplus V^{\text{torsion}}$ . We saw earlier that the  $V^{\text{torsion}}$  summand corresponds to the discrete spectrum of the operator  $T$ , so on the other side the  $V^{\text{free}}$  summand corresponds to the continuous spectrum of  $T$ .

Since  $V$  is finitely generated as a  $\mathbb{C}[t]$ -module,  $V^{\text{free}} \cong \mathbb{C}[t]^\ell$  for  $\ell$  finite. Note that  $\text{Spec}(\mathbb{C}[t]/(t-\lambda)^n)$  is the point  $\{\lambda\}$  (thought of as having multiplicity  $n$ ), and that  $\text{Spec}(\mathbb{C}[t])$  is the affine line  $\mathbb{C}$ . So in contrast to the discrete spectrum, the continuous spectrum in this setting “lives everywhere” over  $\mathbb{C}$  (in blue).



There are no eigenvectors under the action of  $t$  in the free module  $\mathbb{C}[t]$ ; that is, there are no annihilators of  $V^{\text{free}}$  under the action of  $T$ . However, there will be “co-eigenvectors” or eigenfunctionals belonging to  $\mathbb{C}[t]^* = \text{Hom}_{\mathbb{C}}(\mathbb{C}[t], \mathbb{C})$ ; for example, the delta distribution  $\delta_\lambda$ . This is to say there are no subspaces of  $\mathbb{C}[t]$  that are eigenspaces under the action of  $t$ , but there are quotients of  $\mathbb{C}[t]$  that are eigenspaces: The functional  $\delta_\lambda$  defines a surjection  $\mathbb{C}[t] \xrightarrow{\delta_\lambda} \mathbb{C}$ , and by the first isomorphism theorem we obtain the quotient eigenspace  $\mathbb{C}[t]/(t-\lambda)$ . Indeed,  $t = (t-\lambda) + \lambda$  acts on the  $\mathbb{C}[t]$ -module  $\mathbb{C}[t]/(t-\lambda)$  by scalar multiplication by  $\lambda$ . So in some sense this sheaf that

“lives everywhere” is some kind of direct integral of delta sheaves living at every point.

Here are some examples that illustrate why  $V$  should be finitely generated as a  $\mathbb{C}[t]$ -module. Think of the ring  $\mathbb{C}[t]$  as an  $\mathbb{N}$ -graded ring consisting of  $\mathbb{C}$  in each degree or graded component, where  $t$  acts by moving elements of  $\mathbb{C}$  up one degree:

$$\begin{array}{ccccccc} & 0 & & 1 & & 2 & & 3 \\ \mathbb{C} & \xrightarrow{t \cdot} & \mathbb{C} & \xrightarrow{t \cdot} & \mathbb{C} & \xrightarrow{t \cdot} & \mathbb{C} & \xrightarrow{t \cdot} \dots \end{array}$$

In contrast the ring  $\mathbb{C}[t, t^{-1}]$  can be thought of a  $\mathbb{Z}$ -graded ring consisting of  $\mathbb{C}$  in each degree, where  $t$  acts by moving elements of  $\mathbb{C}$  up one degree, and  $t^{-1}$  acts by moving elements of  $\mathbb{C}$  down one degree:

$$\begin{array}{ccccccc} & -2 & & -1 & & 0 & & 1 \\ \dots & \xrightleftharpoons[t^{-1} \cdot]{t \cdot} & \mathbb{C} & \xrightleftharpoons[t^{-1} \cdot]{t \cdot} & \mathbb{C} & \xrightleftharpoons[t^{-1} \cdot]{t \cdot} & \mathbb{C} & \xrightleftharpoons[t^{-1} \cdot]{t \cdot} & \mathbb{C} & \xrightleftharpoons[t^{-1} \cdot]{t \cdot} & \dots \end{array}$$

As a  $\mathbb{C}[t]$ -module,  $\mathbb{C}[t, t^{-1}]$  is not finitely generated due to the uncountably many copies of  $\mathbb{C}$  in negative degrees. Further, there is no  $\mathbb{C}[t]$ -module quotient of  $\mathbb{C}[t, t^{-1}]$  that is concentrated exactly in degree zero (that is, no eigenquotients under the action of  $t$ ); that is, there is no evaluation map  $\mathbb{C}[t, t^{-1}] \rightarrow \mathbb{C}$  that sends  $t$  to zero. The algebraic dual space of  $\mathbb{C}[t, t^{-1}]$  is the ring of formal power series over  $\mathbb{Z}$ , denoted  $\mathbb{C}[[t, t^{-1}]]$ . The delta functional  $\delta_\lambda$  lives in this ring for  $\lambda \neq 0$ , so we obtain a sheaf that lives everywhere except at the origin; we know this because  $\text{Spec}(\mathbb{C}[t, t^{-1}])$  is  $\mathbb{C}^\times$  (since  $\mathbb{C}[t, t^{-1}]$  is the localization of  $\mathbb{C}[t]$  at the ideal  $(t)$ ).

Another example is the ring  $\mathbb{C}(t)$ , which is not finitely generated as a  $\mathbb{C}[t]$ -module. There are no  $\mathbb{C}[t]$ -submodules or quotients of  $\mathbb{C}(t)$  concentrated in degree 0 (no eigenspaces or eigenquotients under the action of  $t$ ). The spectrum of  $\mathbb{C}(t)$  is the origin, because it is a field; or observe that we have inverted too many elements in  $\mathbb{C}[t]$  (localized away from the zero ideal), so the sheaf we obtain in this case lives over the origin. By assuming  $V$  is finitely generated as a  $\mathbb{C}[t]$ -module, we are led to study a quasicoherent sheaf over  $\text{Spec}(\mathbb{C}[t]/\text{Ann}_{\mathbb{C}[t]}(V))$  whose global sections are  $V$ .

### An analytic version of spectral theory

Let  $\mathcal{H}$  be a Hilbert space. The spectral theorem for self-adjoint operators on Hilbert spaces gives a correspondence

$$\{\text{self-adjoint operators } H \text{ on } \mathcal{H}\} \longleftrightarrow \{\text{measurable fields of Hilbert spaces } \{\mathcal{H}_t \mid t \in \mathbb{R}\} \text{ over } \mathbb{R}\}$$

A measurable field over  $\mathbb{R}$  is a family of Hilbert spaces  $\mathcal{H}_t$  for each  $t \in \mathbb{R}$  together with a subspace  $M$  of  $\prod_{t \in \mathbb{R}} \mathcal{H}_t$  which denote the measurable sections (the elements of  $m$  should be thought of as functions), which satisfy a few properties involving measurability (see the nLab). In some sense the assignment  $t \mapsto \mathcal{H}_t$  should be measurable and  $\mathcal{H} = \int_{\mathbb{R}}^{\oplus} \mathcal{H}_t dt$ , a direct integral (a continuous analogue of a direct sum).

One idea in functional calculus is to make a commutative algebra out of an operator; this is analogous to the idea of a group algebra. This leads to an action of the von Neumann algebra  $L^\infty(\mathbb{R})$  on  $\mathcal{H}$  by integrating functions against a projection-valued measure and applying the resulting projection; in this way  $\mathcal{H}$  becomes a  $W^*$ -module.

A projection-valued measure on a measure space  $X$  is a function that takes in measurable sets  $E$  of  $X$  and returns orthogonal projectors  $\pi_E$  onto certain subspaces of a Hilbert space  $\mathcal{H}$ . This function needs to take the empty set to the zero operator,  $X$  to the identity map, disjoint unions to sums of projectors, and finite intersections to products of projections (compositions of projections; which commute). If  $H$  is a self-adjoint operator on  $\mathcal{H}$ , then there is a unique projection-valued measure  $\pi_H$  on  $\mathbb{R}$  for which  $H = \int_{\mathbb{R}} \lambda d\pi_H(\lambda)$  (and this integral is actually just taken over the spectrum of  $H$ , which is compact).

It turns out that the map  $f \mapsto \int_{\mathbb{R}} f(\lambda) d\pi_H(\lambda)$  from  $L^\infty(\mathbb{R})$  to bounded operators on  $\mathcal{H}$  is a homomorphism of  $C^*$ -algebras, so in particular the product of functions goes to the composition of the resulting operators (and the composition commutes; we should think of this map as returning diagonal operators).

Returning to our unitary representation  $\mathcal{H}$ , the action of  $\mathbb{R}_x$  on  $\mathcal{H}$  is determined by the self-adjoint operator  $H$  for which  $x \in \mathbb{R}_x$  acts by  $U_x = \exp(ixH)$ . Then such an  $H$  gives us a unique projection-valued measure  $\pi_H$  which we use to define the action of  $L^\infty(\mathbb{R})$  on  $\mathcal{H}$ .

For example, if  $I$  is an interval in  $\mathbb{R}$ , then the characteristic function  $\chi_I \in L^\infty(\mathbb{R})$  acts on  $\mathcal{H}$  by the operator  $\int_I d\pi_H(\lambda)$ , which is an idempotent since  $\chi_I^2 = \chi_I$  and integration against  $\pi_H$  preserves products. Compare this with the operator given by convolution against a character in the case when  $G = \mathrm{U}(1)$ . Think of the operator  $\int_I d\pi_H(\lambda)$  as projecting onto the piece of  $\mathcal{H}$  that lives over the interval  $I$ .

Compare this with the case where  $\mathcal{H}$  is finite-dimensional and  $H$  is diagonalizable, in which case the direct integral is reduced to the direct sum and the projection we get by integrating the characteristic function of an eigenvalue  $\lambda$  against the projection-valued measure  $\pi_H$  is the projection to the eigenspace  $\mathcal{H}_\lambda$ . If we like we can integrate other characteristic functions to get direct sums of eigenspaces.

In general  $\mathcal{H}$  need not have eigenspaces or eigenquotients, and the spectral theory of the operator  $H$  coming from the group action will tell us how  $\mathcal{H}$  is smeared over the spectrum of  $H$ , and by using  $\pi_H$  we can obtain projections to parts of  $\mathcal{H}$  living over the continuous spectrum. Notice that if  $t$  belongs to the continuous spectrum of  $H$ , we cannot obtain a projection onto  $\mathcal{H}_t$  since such an operator would have to come from integrating a function concentrated at  $\lambda = t$  against  $\pi_H$ , which yields the zero operator since the measure of a point is zero.

The way  $\mathcal{H}$  is smeared over the spectrum of  $H$  can be thought of as an analyst's version of a sheaf. We can think of the atoms of the sheaf as eigenspaces (from delta functions), and the molecules as the spaces coming from generalized eigenvalues (from derivatives of delta functions). Unitary representations need not have either of these in the case the discrete spectrum of the operator  $H$  defining the representation is empty, but in general the representation is smeared over the continuous spectrum of  $H$ .

### A tiny preview of the Heisenberg group

The group  $\mathbb{R}_x$  acts on  $L^2(\mathbb{R}_x)$  by translations  $\tau_y = \delta_y * -$  for  $y \in \mathbb{R}_x$ , and on the other side of the Fourier transform,  $\mathbb{R}_x$  acts on  $L^2(\mathbb{R}_t)$  by pointwise multiplication by characters  $\chi_y = \chi(y, -)$ . Due to Pontryagin duality we can also think about the action of the dual group  $\mathbb{R}_t$  on  $L^2(\mathbb{R}_t)$  by translation and on the other side of the Fourier transform on  $\mathbb{R}_t$  (not the inverse Fourier transform!),  $\mathbb{R}_t$  acts on  $L^2(\mathbb{R}_x)$  by pointwise multiplication by characters  $\chi_t = \chi(-, t)$  for  $t \in \mathbb{R}_t$ .

These observations may be collected on the side  $G = \mathbb{R}_x$  to see that the group  $G \times \widehat{G}$  acts on  $L^2(G)$ . One natural question is to ask if the action of  $G$  commutes with the action of  $\widehat{G}$  on  $L^2(G)$  (where  $G, \widehat{G}$  are henceforth viewed as subgroups of  $G \times \widehat{G}$ ). The actions of  $G, \widehat{G}$  on  $L^2(G)$  should be thought of as belonging to the multiplicative group  $\text{Aut}(\text{Fun}(G))$ , so to ask if they commute is to calculate the commutator of the action of group elements  $g \in G$  and  $\hat{g} \in \widehat{G}$  denoted by  $[g, \hat{g}] = [g, \hat{g}] \cdot$ . On a test function, we have

$$\begin{aligned} [g, \hat{g}] \cdot f &= g^{-1} \hat{g}^{-1} g \hat{g} \cdot f \\ &= g^{-1} \hat{g}^{-1} g(\chi(-, \hat{g})f) \\ &= g^{-1} \hat{g}^{-1} (\overline{\chi(g, \hat{g})} \chi(-, \hat{g}) f(g^{-1} -)) \\ &= g^{-1} (\chi(-, \hat{g}^{-1}) \overline{\chi(g, \hat{g})} \chi(-, \hat{g}) f(g^{-1} -)) \\ &= \overline{\chi(g, \hat{g})} f(gg^{-1} -) \\ &= \overline{\chi(g, \hat{g})} f \end{aligned}$$

So the action of  $G$  and  $\widehat{G}$  differ by multiplication by  $\overline{\chi(g, \hat{g})} \in \text{U}(1)$ . To account for these additional symmetries, we form the Heisenberg group by forming the central extension of  $G \times \widehat{G}$  by  $\text{U}(1)$  (or if  $G$  is instead a finite Abelian group, we only instead use the roots of unity that  $\overline{\chi(g, \hat{g})}$  lie in). The central extension is specifically the short exact sequence of groups

$$1 \rightarrow \text{U}(1) \rightarrow \text{Heis} \rightarrow G \times \widehat{G} \rightarrow 1$$

Note that  $\text{U}(1)$  is central in  $\text{Heis}$ , that is, viewing  $\text{U}(1)$  as a subgroup of  $\text{Heis}$ , the elements in  $\text{U}(1)$  belong to the center  $Z(\text{Heis})$  of the Heisenberg group (since the action of multiplication by scalars commuted with the actions of  $G, \widehat{G}$  to begin with).

The Heisenberg group acts on  $L^2(G)$  in three ways: by scalar multiplication, by translation, and by multiplication by characters (coming from  $\text{U}(1), G, \widehat{G}$  respectively). One advantage of forming the Heisenberg group this way is that it will be easy to show that  $L^2(G)$  is actually an irreducible representation of the Heisenberg group, and many results surrounding harmonic analysis are much easier to prove.

The discussion above about the commutator of the group actions of  $G, \widehat{G}$  can be differentiated to recover a fundamental commutation relation the physicists and analysts are deeply familiar with. Let  $\mathfrak{g}, \widehat{\mathfrak{g}}$  denote the Lie algebras of  $G, \widehat{G}$  respectively. The infinitesimal actions of  $\mathfrak{g}, \widehat{\mathfrak{g}}$  on  $\text{Fun}(G)$  are given by the following:  $y \in \mathfrak{g}$  acts on  $f \in \text{Fun}(G)$  by  $y \cdot f = \frac{d}{dt}(\exp(yt) \cdot f)|_{t=0} = Df(-y)$  and  $\hat{y} \in \widehat{\mathfrak{g}}$  acts on  $f \in \text{Fun}(G)$  by  $\hat{y} \cdot f = \frac{d}{dt}(\exp(\hat{y}t) \cdot f)|_{t=0} = (D_{\hat{g}}\chi(-, 1_{\widehat{G}}))(\hat{y})f$ . View  $\mathfrak{g}, \widehat{\mathfrak{g}}$  as subspaces of the Lie algebra  $\mathfrak{g} \oplus \widehat{\mathfrak{g}}$ .

In general, a representation of a Lie group  $G$  given by  $G \xrightarrow{\rho} \mathrm{GL}(V)$  gives rise to a Lie algebra representation  $\mathfrak{g} \xrightarrow{d\rho} \mathfrak{gl}(V) = \mathrm{End}(V)$  by the above formulas. What is meant by the commutation relation of the actions of  $y, \hat{y}$ , we mean the commutation relation as operators in  $\mathrm{End}(V)$ , so we calculate the ordinary commutator of operators. On a test function, we have

$$\begin{aligned} [y \cdot, \hat{y} \cdot]f &= y \cdot (\hat{y} \cdot f) - \hat{y} \cdot (y \cdot f) \\ &= D_g(D_{\hat{g}}\chi(-, 1_{\hat{G}}))(\hat{y})(-y)f + (D_{\hat{g}}\chi(-, 1_{\hat{G}}))(\hat{y})Df(-y) - (D_{\hat{g}}\chi(-, 1_{\hat{G}}))(\hat{y})Df(-y) \\ &= D_g(D_{\hat{g}}\chi(-, 1_{\hat{G}}))(\hat{y})(-y)f \end{aligned}$$

So the commutation relation is  $[y \cdot, \hat{y} \cdot] = D_g(D_{\hat{g}}\chi(-, 1_{\hat{G}}))(\hat{y})(-y)$  (the right hand side is a number, so we mean scalar multiplication by this number). In the case that  $G = \mathbb{R}_x$  and  $\hat{G} = \mathbb{R}_t$ ,  $\chi(x, t) = \exp(ixt)$  so by choosing  $y = -1$ ,  $\hat{y} = -i$  we obtain the anticipated commutation relation

$$[(-1) \cdot, (-i) \cdot] = \left[ \frac{d}{dx} \cdot, x \cdot \right] = 1$$

**Lecture 7 09/16****Central extensions**

We slowly transition away from Abelian groups by first discussing a slightly non-Abelian group, the Heisenberg group. It is only “slightly” non-Abelian because it is formed as a central extension of two Abelian groups.

In general, a central extension of the group  $H$  (which need not be Abelian) by an Abelian group  $A$  is a group  $\tilde{H}$  which fits in the short exact sequence of groups

$$1 \rightarrow A \rightarrow \tilde{H} \rightarrow H \rightarrow 1$$

(so  $A \rightarrow \tilde{H}$  is injective and  $\tilde{H} \rightarrow H$  is surjective) with  $A \hookrightarrow Z(\tilde{H})$ . If  $H$  is Abelian then the group  $\tilde{H}$  is close to being Abelian in the sense that it is a nilpotent group with nilpotency class 2 (Abelian groups have nilpotency class 1).

A nilpotent group  $G$  of nilpotency class  $n$  is a group whose central series of shortest length terminates in the whole group after  $n$  many steps; that is, there is a series of normal subgroups  $G_i$

$$1 = G_0 \triangleleft G_1 \triangleleft \cdots \triangleleft G_n = G$$

with  $G_{i+1}/G_i \leq Z(G/G_i)$  (or equivalently  $[G, G_{i+1}] \leq G_i$ ). With this definition it is clear that if  $H$  is Abelian, then  $\tilde{H}$  is of nilpotency class 2 since its upper central series is

$$1 \triangleleft A \triangleleft \tilde{H}$$

To classify central extensions of  $H$  (which need not be Abelian) by  $A$ , we turn to group cohomology. By some process in group cohomology, we can produce a set (really a group) denoted  $H^2(H, A)$ , which classifies central extensions of  $H$  by  $A$  up to isomorphism. As a set,  $\tilde{H} \cong H \times A$ . The multiplication in  $\tilde{H}$  is given by

$$(g, a)(h, b) = (gh, f(g, h)ab)$$

where  $f: H \times H \rightarrow A$  is a set map satisfying the 2-cocycle conditions

$$f(1_H, 1_H) = 1_A \quad \text{and} \quad f(g, h)f(gh, j) = f(g, hj)f(h, j)$$

for  $g, h, j \in H$ . The first condition is needed if we want the restriction of the product to  $A$  viewed as a subgroup of  $\tilde{H}$ , as  $\{1_H\} \times A \subseteq \tilde{H}$ , to agree with the product in  $A$ . The second condition is to ensure the multiplication is associative. (See this MSE question.)

It is important to note that a central extension is not necessarily a semidirect product of  $H$  and  $A$ ; the semidirect products of  $H$  and  $A$  are the split extensions; that is, the extensions

$$1 \rightarrow A \rightarrow \tilde{H} \xrightarrow{p} H \rightarrow 1$$

where we do not assume  $A \hookrightarrow Z(\tilde{H})$  (or that  $A$  is Abelian; i.e., a possibly non-central extension) but there is a homomorphism  $s: H \rightarrow \tilde{H}$  that is a section; that is,  $ps = \text{id}_H$ . A central extension of  $H$  by  $A$  that is also a split extension makes  $\tilde{H}$  isomorphic to the direct product of  $H$  and  $A$ ; that is,  $\tilde{H} \cong H \times A$  (see this MSE question). The split central extensions correspond to the identity element in the group  $H^2(H, A)$ .

### The Heisenberg group

We return to the Heisenberg group. Let  $G$  be an LCA group and let  $\hat{G} = \text{Hom}_{\mathbf{Group}}(G, \text{U}(1))$ . Then the universal character  $\chi(-, -)$  is a map from  $G \times \hat{G}$  to  $\text{U}(1)$ , and if  $G$  is finite the universal character really maps into a finite set of roots of unity  $\mu_n$  for some  $n$ . The Heisenberg group  $\text{Heis}$  is obtained as a central extension

$$1 \rightarrow \text{U}(1) \rightarrow \text{Heis} \rightarrow G \times \hat{G} \rightarrow 1$$

(where if  $G$  is finite, we could replace  $\text{U}(1)$  by  $\mu_n$  if desired) and the 2-cocycle  $f: (G \times \hat{G}) \times (G \times \hat{G}) \rightarrow \text{U}(1)$  appearing in the multiplication formula

$$(g, \hat{g}, z)(h, \hat{h}, w) = (gh, \hat{g}\hat{h}, f(g, \hat{g}, h, \hat{h})zw)$$

in  $\text{Heis}$  (viewed as the set  $(G \times \hat{G}) \times \text{U}(1)$ ) is given by

$$f(g, \hat{g}, h, \hat{h}) = \overline{\chi(g, \hat{h})}$$

By comparing the results of the following calculations it follows that  $f$  really is a 2-cocycle:

$$\begin{aligned} f(g, \hat{g}, h, \hat{h})f(gh, \hat{g}\hat{h}, j, \hat{j}) &= \overline{\chi(g, \hat{h})\chi(gh, \hat{j})} \\ f(g, \hat{g}, hj, \hat{h}\hat{j})f(h, \hat{h}, j, \hat{j}) &= \overline{\chi(g, \hat{h}\hat{j})\chi(h, \hat{j})} \end{aligned}$$

We can obtain an isomorphic group by using the 2-cocycle  $\tilde{f}$  given by  $\tilde{f}(g, \hat{g}, h, \hat{h}) = \chi(h, \hat{g})$  instead of  $f$  in the multiplication formula above. Results from group cohomology imply that we obtain isomorphic groups if  $f$  and  $\tilde{f}$  differ by a 2-coboundary, which is the case:

$$\tilde{f}(g, \hat{g}, h, \hat{h})^{-1}f(g, \hat{g}, h, \hat{h}) = \chi(h, \hat{h})\overline{\chi(gh, \hat{g}\hat{h})}\chi(g, \hat{g})$$

The 2-coboundary in this situation is the image of  $\chi: G \times \hat{G} \rightarrow \text{U}(1)$  under a particular differential  $d^1$  coming from a bar complex, that is, the 2-coboundary is  $d^1\chi: (G \times \hat{G}) \times (G \times \hat{G}) \rightarrow \text{U}(1)$  given by  $d^1\chi(g, \hat{g}, h, \hat{h}) = \chi(h, \hat{h})\chi(gh, \hat{g}\hat{h})^{-1}\chi(g, \hat{g})$ .

As an aside, some Abelian subgroups of  $\text{Heis}$  are  $G \times \{1_{\hat{G}}\} \times \text{U}(1)$ ,  $\{1_G\} \times \hat{G} \times \text{U}(1)$ ,  $G \cong G \times \{1_{\hat{G}}\} \times \{1_{\text{U}(1)}\}$ , and  $\hat{G} \cong \{1_G\} \times \hat{G} \times \{1_{\text{U}(1)}\}$ . The subgroups  $G \times \{1_{\hat{G}}\} \times \text{U}(1)$  and  $\{1_G\} \times \hat{G} \times \text{U}(1)$  do not commute with each other!

In the past, we had three group actions on  $\text{Fun}(G)$ . One was the action of  $G$  by translation, another was the action of  $\hat{G}$  by multiplication by characters, and lastly the usual scalar multiplication by  $\text{U}(1)$ . The action of  $\text{U}(1)$



commutes with the first two group actions (and of course with its own group action). We saw before that the actions of  $G, \widehat{G}$  do not commute, which was why we formed the Heisenberg group in the first place. These three group actions can be thought of as living in  $\text{Aut}(\text{Fun}(G))$ . The Heisenberg group collects all the commutation relations between the different group actions, and so we can say that the Heisenberg group can be presented as generated by the group actions of  $G, \widehat{G}$ , and  $\text{U}(1)$  modulo their relations in  $\text{Aut}(\text{Fun}(G))$ . For example, we recover the commutation relation  $[g \cdot, \hat{g} \cdot] = \overline{\chi(g, \hat{g})}$  as the commutator of the corresponding elements in Heis:

$$\begin{aligned} [(g, 1, 1), (1, \hat{g}, 1)] &= (g^{-1}, 1, 1)(1, \hat{g}^{-1}, 1)(g, 1, 1)(1, \hat{g}, 1) \\ &= (g^{-1}, \hat{g}^{-1}, \overline{\chi(g, \hat{g})})(g, \hat{g}, \overline{\chi(g, \hat{g})}) \\ &= (1, 1, \overline{\chi(g, \hat{g})}) \end{aligned}$$

One particular form of the Heisenberg group for  $G = \mathbb{R}_x^n$  that may be familiar is as a matrix group. To make this identification, first see that the dual group  $\widehat{G} = \mathbb{R}_t^n$  is really the dual vector space to  $G$ ; that is, there is a natural isomorphism between  $\widehat{G} = \text{Hom}_{\text{Group}}(\mathbb{R}_x^n, \text{U}(1))$  and  $G^* = \text{Hom}_{\mathbb{R}}(\mathbb{R}_x^n, \mathbb{R})$  that identifies  $x \mapsto \exp(i\langle x, t \rangle)$  with  $x \mapsto \langle x, t \rangle$  for  $t \in \mathbb{R}_t$ . Then the Heisenberg group for  $G = \mathbb{R}_x$  (i.e.,  $n = 1$ ) is obtained from the central extension

$$1 \rightarrow \text{U}(1) \rightarrow \text{Heis} \rightarrow \mathbb{R}_x \times \mathbb{R}_x^* \rightarrow 0$$

Further identifications of

$$\text{U}(1) \quad \text{with} \quad \left\{ \begin{pmatrix} 1 & 0 & z \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \mid z \in \mathbb{R}/\mathbb{Z} \right\}$$

and

$$\mathbb{R}_x \times \mathbb{R}_x^* \quad \text{with} \quad \left\{ \begin{pmatrix} 1 & x & 0 \\ 0 & 1 & t \\ 0 & 0 & 1 \end{pmatrix} \mid x \in \mathbb{R}_x, t \in \mathbb{R}_t \right\}$$

imply that Heis can be identified with the matrix “group”

$$\left\{ \begin{pmatrix} 1 & x & z \\ 0 & 1 & t \\ 0 & 0 & 1 \end{pmatrix} \mid x \in \mathbb{R}_x, t \in \mathbb{R}_t, z \in \mathbb{R}/\mathbb{Z} \right\}$$

where the multiplication law is matrix multiplication but we reduce modulo  $\mathbb{Z}$  in the top right entry. Somehow the 2-cocycle appearing after multiplying two elements doesn't exactly match the sign conventions in the usual 2-cocycle we use for the Heisenberg group, but nevertheless we recover the commutation relation

$$\left[ \begin{pmatrix} 1 & x & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}, \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & t \\ 0 & 0 & 1 \end{pmatrix} \right] = \begin{pmatrix} 1 & 0 & -xt \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Then in general the Heisenberg group for  $G = \mathbb{R}_x^n$  can be thought of as the matrix “group”

$$\left\{ \begin{pmatrix} 1 & x & z \\ 0 & 1 & t \\ 0 & 0 & 1 \end{pmatrix} \mid x \in \mathbb{R}_x, t \in \mathbb{R}_t, z \in \mathbb{R}/\mathbb{Z} \right\}$$

where the multiplication law is given by

$$\begin{pmatrix} 1 & x & z \\ 0 & 1 & t \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & y & w \\ 0 & 1 & s \\ 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} 1 & x+y & z+w+\langle x, s \rangle \\ 0 & 1 & t+s \\ 0 & 0 & 1 \end{pmatrix}$$

where the top right entry is reduced modulo  $\mathbb{Z}$ . In any case, this point of view is very coordinate-ful and thus might not be a good way to think about the Heisenberg group in general.

## Representation theory of the Heisenberg group

The representation theory of the Heisenberg group can be used to obtain slick proofs of results in Fourier analysis.

One important result in this vein is that  $\text{Fun}(G)$  is an irrep of Heis (it will not be exactly  $\text{Fun}(G)$  but some analysis is needed to get the function space correct; we need to have an inner product, for example, so we should think of  $L^2(G)$  instead). This is to say that  $\text{Fun}(G)$  is a simple  $\mathbb{C}[\text{Heis}]$ -module, and again what is meant by the group algebra is not clear, but it should include things like delta distributions and other odd elements that might not be nice functions. Contained inside this group algebra are the group algebras  $(\mathbb{C}[G], *)$  and  $(\mathbb{C}[\widehat{G}], *)$ . The action of  $\mathbb{C}[G]$  on  $\text{Fun}(G)$  is given by convolution; that is,

$$F \cdot f = F * f$$

for  $F \in \mathbb{C}[G]$ . Indeed, thinking of  $g \in G$  as the element  $\delta_g \in \mathbb{C}[G]$ , we recover the usual action  $g \cdot f = \delta_g * f = f(g^{-1}-)$ . The action of  $\mathbb{C}[\widehat{G}]$  on  $\text{Fun}(G)$  is given by first identifying  $(\mathbb{C}[\widehat{G}], *)$  with  $(\mathbb{C}[G], \cdot)$  by taking the inverse Fourier transform and then pointwise multiplying. Specifically this is

$$H \cdot f = (H * \hat{f})^\vee = H^\vee \cdot f$$

for  $H \in \mathbb{C}[\widehat{G}]$ . Indeed, thinking of  $\hat{g} \in \widehat{G}$  as the element  $\delta_{\hat{g}}$ , we recover the usual action  $\hat{g} \cdot f = (\delta_{\hat{g}} * \hat{f})^\vee = \chi(-, \hat{g})f$ .

To show that  $\text{Fun}(G)$  is an irrep of Heis we show that any nonzero function  $f$  can be sent to  $\delta_{1_G}$  by acting on  $f$  by elements of the group algebra of Heis (and from the delta function we can reconstruct any other function in  $\text{Fun}(G)$ ). Indeed, given any  $f \in \text{Fun}(G)$  that is not the zero function, we can act on  $f$  by elements of  $\mathbb{C}[\text{Heis}]$  which take  $f$  to  $\delta_{1_G}$ . Since  $f(g) \neq 0$  for some  $g \in G$ , translate and scale  $f$  so that  $f(1_G) = 1$ . We would like to take the pointwise product  $\delta_{1_G} \cdot f$  to obtain  $\delta_{1_G}$ , but we obtain this product by taking the inverse Fourier transform of convolution against the character  $\chi(1_G, -) \in \mathbb{C}[\widehat{G}]$ . That is,

$$\chi(1_G, -) \cdot f = (\chi(1_G, -) * \hat{f})^\vee = \delta_{1_G} \cdot f = \delta_{1_G}$$

In general we need some analysis to approximate these delta distributions with nice enough functions to obtain the result, but this is a good enough sketch of a proof.

The action of the Heisenberg group on  $L^2(\widehat{G})$  is given by swapping the roles of  $G$  and  $\widehat{G}$  up to a sign since we want the action to commute with taking the Fourier transform. The element  $(g, \hat{g}, z) \in \text{Heis}$  acts on  $f \in \text{Fun}(G)$  by

$$(g, \hat{g}, z) \cdot f = z\chi(-, \hat{g})f(g^{-1}-)$$

and on  $F \in \text{Fun}(\widehat{G})$  by

$$(g, \hat{g}, z) \cdot F = z\chi(g, \hat{g})\chi(g, -)F(\hat{g}-)$$

(this is just interchanging the roles of  $G$  and  $\widehat{G}$  in some sense.) Then the Fourier transform (and hence also the inverse Fourier transform) intertwines with this action:

$$\widehat{(g, \hat{g}, z) \cdot f} = z\widehat{\chi(g, -)\delta_{\hat{g}} * f} = z\delta_{\hat{g}^{-1}} * (\chi(g, -)\hat{f}) = z\chi(g, \hat{g})\chi(g, -)\hat{f}(\hat{g}-) = (g, \hat{g}, z) \cdot \hat{f}$$

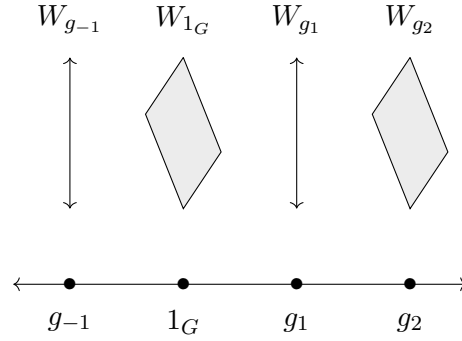
Since this action is not really any different than the original action we defined,  $\text{Fun}(\widehat{G})$  is also an irrep of Heis (and we can repeat this as well for  $\text{Fun}(\widehat{\widehat{G}})$ ).

Let  $G = \mathbb{R}_x$ . That the Fourier transform is a unitary isomorphism of  $L^2(G)$  with  $L^2(\widehat{G})$  can also be proved knowing some kind of unitary Schur's lemma, which comes from analysis. Identify  $G$  and  $\widehat{G}$ , as well as  $L^2(G)$  with  $\overline{L^2(G)}$  and  $L^2(G)^*$ . The argument in analysis is that the Fourier transform is densely defined and can be closed (we can take limits of Fourier transforms), so its adjoint is also densely defined so the Fourier transform must be unitary up to a constant multiple. Morally what is happening is that intertwining operators of unitary representations are typically unitary operators (they would “have to be terrible not to be unitary” according to Howe). This is usually known as Plancherel's theorem. (See p.452 in Real and Functional Analysis by Lang.) In other words, the Fourier transform takes an invariant Hermitian form  $\langle -, - \rangle$  on  $L^2(G)$ ; that is, an isomorphism of Heis-representations  $\overline{L^2(G)} \rightarrow L^2(G)^*$  to another invariant Hermitian form  $\langle \widehat{ }, \widehat{ } \rangle$  on  $L^2(G)$ ; that is, to another isomorphism  $\overline{L^2(G)} \rightarrow L^2(G)^*$ . But by Schur's lemma these two forms should only differ by a constant multiple and to find out which multiple it suffices to calculate the new Hermitian form on a convenient element to see that the Fourier transform is unitary.

To prove that  $\widehat{\widehat{f}}(g) = f(g^{-1})$ , observe that applying the Fourier transform twice intertwines with correctly chosen actions of the Heisenberg groups. The reflection map  $\text{Fun}(G) \xrightarrow{R} \text{Fun}(G)$  given by  $Rf = f((-)^{-1})$  also intertwines with the action of the Heisenberg group, so applying the Fourier transform twice is a scalar multiple of  $R$ . To find out what the multiple is, it suffices to calculate the twice Fourier transform of a single element; usually we pick a convenient element. In the case when  $G = \mathbb{R}$ , the Gaussian  $f(x) = \exp(-x^2/2)$  is self-dual, meaning  $\widehat{\widehat{f}}(t) = \exp(-t^2/2)$  from which it follows that taking the Fourier transform twice really does agree with the reflection map. But this is not too bad to do since  $f$  satisfies the differential equation  $\frac{d}{dx}u + xu = 0$ . The Fourier transform of this differential equation is  $-it\widehat{u} - i\frac{d}{dt}\widehat{u} = 0$ ; that is,  $\frac{d}{dt}\widehat{u} + t\widehat{u} = 0$ , from which it follows that the Fourier transform of the aforementioned Gaussian is itself.

One of the most important results about the Heisenberg group is the Stone-von Neumann theorem, which roughly says that  $\text{Fun}(G)$  is the only genuine irrep of the Heisenberg group up to isomorphism, where by a genuine representation  $V$  we mean that the subgroup  $U(1) \subset \text{Heis}$  acts on  $V$  by the usual scalar multiplication of complex numbers on  $V$ .

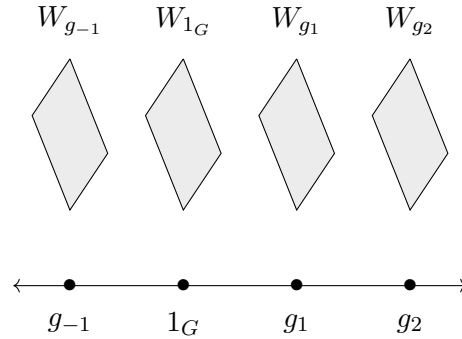
A stronger result is that the categories  $\mathbf{Rep}_{\text{genuine}}(\text{Heis})$  and  $\mathbf{Vect}_{\mathbb{C}}$  are equivalent, which implies the Stone-von Neumann theorem since in this setting  $\text{Fun}(G)$  corresponds to the one-dimensional vector space  $\mathbb{C}$ . Let  $W$  be a genuine representation of Heis. Restricting to the action of  $G, \widehat{G}$  in Heis, view  $W$  as a representation of  $\widehat{\widehat{G}}$ , which from before it follows that  $W$  can be thought of as global sections of a sheaf over  $\widehat{\widehat{G}} \cong G$ . The following picture is slightly inaccurate but we will fix it shortly: (The inaccuracy is that the vector spaces  $W_g$  have different dimensions; the picture is an example where the drawn vector spaces have dimension 1 or 2.)



On  $W_g$ , the group  $\widehat{G}$  acts by multiplication by  $\chi(g, \hat{g})$ . Think of  $W_g$  as the  $\chi(g, -)$ -eigenspace for the  $\widehat{G}$ -action on  $W$ . On the other hand,  $G$  acts on  $w \in W_g$  by translation, specifically by translating the eigenspace  $w$  belongs to. That is, if  $h \in G$  and  $w \in W_g$ , then by the commutation relation of  $G$  and  $\widehat{G}$  in Heis we have

$$\hat{g}(hw) = (\hat{g}h)w = \chi(h, \hat{g})(h\hat{g})w = \chi(hg, \hat{g})(gw)$$

So  $h \in G$  sends  $w \in W_g$  to  $hw \in W_{hg}$ . Since multiplication by group elements in  $G$  is invertible, the eigenspaces  $W_g$  are all isomorphic to each other (i.e. for any  $h, g \in G$ ,  $W_g \cong W_{hg}$  as  $\widehat{G}$ -representations), so the picture from earlier is more accurately depicted with each stalk the same dimension.



The equivalence  $\mathbf{Rep}_{\text{genuine}}(\text{Heis}) \rightarrow \mathbf{Vect}_{\mathbb{C}}$  is given by taking the stalk of the sheaf we get by smearing a representation  $W$  at  $1_G$ . The functor going the other way is given by taking a complex vector space  $V$ , letting  $\widehat{G}$  act on it by multiplication by  $\chi(1_G, -)$ ; that is, thinking of  $V$  as the stalk of a sheaf at  $1_G$ . Then “translate”  $V_{1_G} = V$  by  $G$  to form copies  $V_g$  for which  $\widehat{G}$  acts by multiplication by  $\chi(g, -)$ . The global section of the sheaf we obtain by translating  $V$  this way is a genuine representation of Heis if throughout we let  $U(1)$  act by usual scalar multiplication. The only way to obtain an irrep of Heis through this functor is by starting with  $V = \mathbb{C}$ , which when translated over  $G$  yields a sheaf whose global sections is exactly  $\text{Fun}(G)$ .

So the role of  $\widehat{G}$  in this picture is to spectrally decompose a representation  $W$  and  $G$  translates the eigenspaces around. Of course, there is a symmetric picture if we swap the roles of  $G$  and  $\widehat{G}$  around.

In physics, we look at the infinitesimal actions of translation from  $G = \mathbb{R}_x$  and multiplication from  $\widehat{G} = \mathbb{R}_t \cong \mathbb{R}_x$ . From some calculations from earlier, we saw that these correspond to  $\frac{d}{dx}$  and  $x$ ; the observables of position and

momentum (in physics some additional constants are present). These two operators do not commute, and hence cannot be simultaneously diagonalized, which is the content of the Heisenberg uncertainty principle. The Stone-von Neumann theorem says that this is pretty much the only case up to scale.

### A short preview of the Weyl algebra

Let  $G = \mathbb{R}_x$ . The Weyl algebra is a non-commuting  $\mathbb{C}$ -algebra of polynomial differential operators:

$$D = \frac{\mathbb{C}\langle x, \partial_x \rangle}{(\partial_x x - x \partial_x - 1)}$$

The Weyl algebra naturally acts on  $\text{Fun}(G)$  or rather  $L^2(G)$  by unbounded operators, and Hermann Weyl used this algebra and related algebras to study the Heisenberg uncertainty principle in quantum mechanics. It is related to the Heisenberg group from earlier since differentiation and multiplication by  $x$  are the infinitesimal actions of  $G, \hat{G}$  on  $L^2(G)$ , but there are very interesting differences in the theories surrounding representations of the Weyl algebra and of the Heisenberg group.

The Weyl algebra appears in the theory of  $D$ -modules, which from one point of view is a way to study the theory of systems of linear partial differential equations using algebra and algebraic geometry. It is (one of) David's favorite algebras.

**Lecture 8 09/18****The Heisenberg group and the Weyl algebra**

The Heisenberg group is not a semidirect product of  $U(1)$  and  $G \times \widehat{G}$ , but by breaking the symmetry of the pair  $G, \widehat{G}$ , it is a semidirect product of  $\widehat{G} \times U(1)$  and  $G$ . That is,

$$\text{Heis} \cong G \ltimes_{\varphi} \widehat{G} \times U(1)$$

where  $\varphi: G \rightarrow \text{Aut}(\widehat{G} \times U(1))$  is given by  $\phi(g)(\hat{h}, w) = (\hat{h}, \overline{\chi(g, \hat{h})}w)$ . Hence the group multiplication is given by

$$(g, \hat{g}, z)(h, \hat{h}, w) = (gh, \hat{g}\hat{h}, \overline{\chi(g, \hat{h})}zw)$$

and agrees with the usual one on  $\text{Heis}$ .

The observations we made last time about viewing genuine representations of  $\text{Heis}$  as a sheaf over  $G$  in which  $\widehat{G}, U(1)$  act in a manner that preserve stalks and  $G$  acts by moving vectors between stalks can be recast using the above isomorphism. Genuine irreps of  $\widehat{G} \times U(1)$  of a fixed dimension are in correspondence with (or live over) the elements of  $G$ , and  $G$  acts on the set of irreps by changing the action of  $\widehat{G}$  on them; that is, by exchanging irreps (last time, this was to exchange  $W_g$  with  $W_{hg}$ ).

Last time, we saw that the Weyl algebra  $D$  on  $\mathbb{R}_x$  was the noncommutative  $\mathbb{C}$ -algebra generated by  $x$  and  $\partial_x$ , subject to the relation  $\partial_x x - x \partial_x = 1$ . It acts on  $L^2(\mathbb{R})$ , but a better space for the Weyl algebra to act on is the Schwartz space  $\mathcal{S}(\mathbb{R})$ . The Schwartz space contains the  $C^\infty$  functions on  $\mathbb{R}$  whose derivatives of all orders decay faster than the reciprocal of any polynomial as  $x$  tends to  $\pm\infty$ . A precise definition of the Schwartz space and its topology is rather cumbersome, so it suffices to think of the functions living in the Schwartz space as “rapidly decaying smooth functions”. For example, the Gaussian  $\exp(-x^2/2)$  belongs to  $\mathcal{S}(\mathbb{R})$ .

By design, the Schwartz space is a module for the Weyl algebra, since the functions in the Schwartz space and their derivatives rapidly decrease, multiplication by  $x$  and differentiation really define an action on  $\mathcal{S}(\mathbb{R})$ . By taking the continuous dual of the Schwartz space, we obtain the tempered distributions, denoted  $\mathcal{S}'(\mathbb{R})$ . The tempered distributions  $\mathcal{S}'(\mathbb{R})$  is another candidate for the group algebra for  $G = \mathbb{R}_x$ .

From analysis, the Fourier transform defines operators on  $L^2(\mathbb{R})$  and on  $\mathcal{S}(\mathbb{R})$ . By taking adjoints, the Fourier transform also defines an operator on  $\mathcal{S}'(\mathbb{R})$ . So the space of tempered distributions is a very nice place to do harmonic analysis on, and we would like to do something similar in the future for non-Abelian groups.

There are no nonzero finite-dimensional  $D$ -modules. Suppose  $V$  is a finite-dimensional  $D$ -module. Then

$$\dim(V) = \text{Tr}_V(1) = \text{Tr}_V(\partial_x x - x \partial_x) = \text{Tr}_V(\partial_x x) - \text{Tr}_V(x \partial_x) = \text{Tr}_V(\partial_x x) - \text{Tr}(\partial_x x) = 0$$

This result may be thought of as an algebraic version of the Heisenberg uncertainty principle, since not only can we not simultaneously diagonalize  $\partial_x$  and  $x$ , but we cannot have these operators act on finite dimensional vector spaces.

The exponentials  $\exp(iy-)$  of  $i\partial_x$  and of  $x$  give the translation  $\tau_y$  and multiplication by the character  $\exp(iyx)$ , and these generate the Heisenberg group. By starting with a  $D$ -module, we can obtain a module over Heis by differentiating the action of  $G, \widehat{G}$  to obtain differentiation and multiplication by  $x$ . To be careful, we need analysis because  $D$ -modules are not finite-dimensional.

### Quick introduction to $D$ -modules

The data of a finitely presented  $D$ -module is the same as a system of linear differential equations with polynomial coefficients. We will come back to this claim after looking at small examples.

Let  $M = D/D(\partial_x - \lambda)$  be a left  $D$ -module (left, right are important since  $D$  is not commutative). Then for some other left  $D$ -module  $F$ , which is typically a nice function space,  $f \in \text{Hom}_D(M, F)$  can be thought of as a solution to the differential equation  $(\partial_x - \lambda)u = 0$  living in  $F$ . This is because any  $f \in \text{Hom}_D(M, F)$  is zero on  $D(\partial_x - \lambda)$  and any  $f \in \text{Hom}_D(D, F)$  which is zero on  $D(\partial_x - \lambda)$  descends to a well defined homomorphism  $f \in \text{Hom}_D(M, F)$ . That is,

$$\text{Hom}_D(M, F) \cong \{f \in \text{Hom}_D(D, F) \mid f(\partial_x - \lambda) = 0\}$$

The map  $f \mapsto f(1_M)$  defines an isomorphism of  $\text{Hom}_D(D, F)$  with  $F$ , so in particular

$$\{f \in \text{Hom}_D(D, F) \mid f(\partial_x - \lambda) = (\partial_x - \lambda)f(1_M) = 0\} \cong \{f \in F \mid (\partial_x - \lambda)f = 0\}$$

So if  $F$  is a  $D$ -module that contains  $\exp(\lambda x)$ , then  $\text{Hom}_D(M, F)$  is  $\mathbb{C}\exp(\lambda x)$ , otherwise  $\text{Hom}_D(M, F)$  is zero. One example of a  $D$ -module  $F$  that has exponentials is the continuous dual of  $C_c^\infty(\mathbb{R})$ , the usual space of distributions on  $\mathbb{R}$  (analysis shows that  $\exp(\lambda x)$  does not define a tempered distribution on  $\mathbb{R}$ ). As a vector space (or  $\mathbb{C}[x]$ -module), the module  $M$  is isomorphic to the graded vector space  $\mathbb{C}[x]1_M$ . The calculation  $(\partial_x - \lambda)x = 1 - x\partial_x - x\lambda = 1$  shows that left multiplication by  $(\partial_x - \lambda)$  gives maps between graded components of  $\mathbb{C}[x]1_M$ :

$$\begin{array}{c} 0 \\ (\partial_x - \lambda) \nearrow \\ \mathbb{C}1_M \\ (\partial_x - \lambda) \nearrow \\ \mathbb{C}x \\ (\partial_x - \lambda) \nearrow \\ \vdots \end{array}$$

This graded point of view is interesting because now we can see that if  $f \in F$  is a solution to  $(\partial_x - \lambda)u = 0$ ; that is,  $f$  is a homomorphism of  $D$ -modules  $D/D(\partial_x - \lambda) \rightarrow F$ , then  $x^n f(x)$  is a solution to  $(\partial_x - \lambda)^{n+1}u = 0$ . This is because  $(\partial_x - \lambda)x^n = 0$  in  $M$ . So in particular, we recover the expected solutions  $x^n \exp(\lambda x)$ .

Consider the left  $D$ -module  $M = D/D(x - \lambda)$ . Its solutions in  $\mathcal{S}'(\mathbb{R})$  are  $\mathbb{C}\delta_\lambda$ . As a vector space (or  $\mathbb{C}[\partial_x]$ -module), the module  $M$  is isomorphic to the graded vector space  $\mathbb{C}[\partial_x]1_M$ . We obtain a similar picture as above, with  $x$

and  $\partial_x$  interchanged. Similarly, solutions to the equation  $(x - \lambda)^n u = 0$  are derivatives of  $\delta_\lambda$ . We actually already observed these facts when discussing the indecomposable representations of  $\mathbb{R}$ , from the point of view of Jordan blocks and Fourier duality, so this is just another perspective.

A finitely presented left  $D$ -module  $M$  is a module with the free resolution

$$0 \rightarrow D^n \xrightarrow{P} D^m \rightarrow M \rightarrow 0$$

where  $m$  denotes the number of generators of  $M$  and the map  $P$ , which can be thought of as right multiplication by an  $n \times m$  matrix  $P$  (with entries in  $D$ ), encodes the  $n$  relations that the  $m$  generators of  $M$  are subject to. In other words,  $M$  is isomorphic to the left  $D$ -module  $D^m/D^n P$ . Like before, if  $F$  is a left  $D$ -module, then  $f \in \text{Hom}_D(M, F)$  can be identified with solutions  $f = (f_1, \dots, f_m)$  to the system of differential equations

$$\sum_{i=1}^n P_{ij} f_j = 0 \quad \text{for } j = 1, \dots, m$$

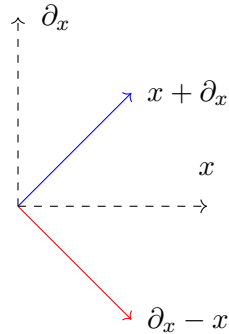
This is because  $f = (f_1, \dots, f_m) \in \text{Hom}_D(M, F)$  is really a homomorphism  $f = (f_1, \dots, f_m)$  from  $D^m$  to  $F$  vanishing on  $1_{D^n} P = (\sum_{i=1}^n P_{i1}, \dots, \sum_{i=1}^n P_{im})$ , and we identify  $\text{Hom}_D(D, F)$  with  $F$  in the same way as before.

If  $D = \mathbb{C}\langle x_1, \dots, x_n, \partial_{x_1}, \dots, \partial_{x_n} \rangle / ([x_i, x_j], [\partial_{x_i}, \partial_{x_j}], [\partial_{x_i}, x_j] - \delta_{ij} \mid 1 \leq i, j \leq n)$ , then the data of a finitely presented  $D$ -module is the same as a system of linear partial differential equations with polynomial coefficients.

The Fourier transform takes  $\frac{d}{dx}$  to  $-it$  and  $x$  to  $-i\frac{d}{dt}$ . It follows that  $1 = \partial_x x - x \partial_x$  is sent to  $1 = (-it)(-i\partial_t) - (-i\partial_t)(-it) = \partial_t t - t \partial_t$ , so the Fourier transform negates the commutation relation between differentiation and multiplication by the coordinate. Since  $\mathcal{S}'(\mathbb{R})$  is a  $D$ -module, the Fourier transform of  $\mathcal{S}'(\mathbb{R})$ , which is itself  $\mathcal{S}'(\mathbb{R})$ , is a  $\widehat{D} = \mathbb{C}\langle t, \partial_t \rangle / ([\partial_t, t] + 1)$ -module (a module for some kind of opposite version of  $D$ ). So if  $f$  satisfies a linear differential equation with polynomial coefficients  $Pu = 0$  for a left  $D$ -module  $M$ , then  $\hat{f}$  satisfies the Fourier transformed partial differential equation  $\hat{P}\hat{u} = 0$ , so for the left  $D$ -module  $\widehat{M}$  which is  $M$  with  $\partial_x, x$  replaced by  $-it, -i\partial_t$ .

Indeed, the Gaussian  $g = \exp(-x^2/2)$  satisfies the differential equation  $(\partial_x + x)u = 0$ . It defines a tempered distribution as well; that is,  $g \in \mathcal{S}'(\mathbb{R})$ . The Fourier transform takes this differential equation to  $(-it - i\partial_t)\hat{u} = 0$ , so  $(\partial_t + t)\hat{u} = 0$ . So the Fourier transform of the Gaussian is itself (we did this calculation before). Consider the element  $(\partial_x - x)$  in  $M$ . Suggestively, it is “orthogonal” to the element  $(x + \partial_x)$ : The corresponding  $D$ -module for  $g$  is  $M = D/D(\partial_x + x)$ , which is isomorphic as a vector space to  $\mathbb{C}[x - \partial_x]1$  (the  $(x - \partial_x)^i$  form a basis for  $M$ ). The calculation  $(\partial_x + x)(x - \partial_x) = 1 + x^2 - \partial_x^2 = 2 + (x - \partial_x)(\partial_x + x) = 2$  shows that left multiplication by  $(\partial_x + x)$





gives maps between graded components of  $\mathbb{C}[x - \partial_x]1$ :

$$\begin{array}{c}
 0 \\
 \uparrow (\partial_x + x) \\
 \mathbb{C}1 \\
 \uparrow (\partial_x + x) \\
 \mathbb{C}(x - \partial_x) \\
 \uparrow (\partial_x + x) \\
 \vdots
 \end{array}$$

The homomorphism  $S_g: M \rightarrow \mathcal{S}'(\mathbb{R})$  corresponding to the solution  $g$  of the differential equation  $(\partial_x + x)u = 0$  is the one where  $1 \in M$  is sent to  $g \in \mathcal{S}'(\mathbb{R})$ . Then  $(x - \partial_x)$  is sent to  $(x - \partial_x)g = 2xg$ , and  $(x - \partial_x)^2$  is sent to  $(x - \partial_x)^2g = (4x^2 - 2)g$ . By continuing this process we recover the physicist's Hermite polynomials  $H_n(x)$ : the image of  $(x - \partial_x)^n$  is  $H_n(x)g$ , where the first few Hermite polynomials are

$$\begin{array}{ll}
 H_0(x) = 1 & H_1(x) = 2x \\
 H_2(x) = 4x^2 - 2 & H_3(x) = 8x^3 - 12x \\
 H_4(x) = 16x^4 - 48x^2 + 12 & H_5(x) = 32x^5 - 160x^3 + 120x
 \end{array}$$

The Hermite polynomials, like the Chebyshev polynomials of the first kind we found earlier, are special functions. They satisfy nice orthogonality relations and recurrence relations which can of course be obtained through the lens of representation theory. The Hermite polynomials form a basis of  $L^2(\mathbb{R})$  with weighted inner product  $\langle -, - \rangle_g = \langle -g, -g \rangle_{L^2(\mathbb{R})}$  because they form a maximal orthogonal family. To see this, observe that

$$(\partial_x + x)(x - \partial_x) = 2 + (x - \partial_x)(\partial_x + x)$$

and that the adjoint differential operator of  $(x - \partial_x)$  is  $(\partial_x + x)$ ; that is,

$$\langle (x - \partial_x)f, h \rangle_{L^2(\mathbb{R})} = \langle f, (\partial_x + x)h \rangle_{L^2(\mathbb{R})}$$

Repeated application of these identities will show that

$$\langle H_j(x), H_i(x) \rangle_g = \langle H_j(x)g, H_i(x)g \rangle_{L^2(\mathbb{R})} = \langle (x - \partial_x)^j g, (x - \partial_x)^i g \rangle_{L^2(\mathbb{R})}$$

is nonzero only if  $j = i$ .

## Introduction to $SU_2$

The main groups we would like to get to are  $SU_2(\mathbb{R})$ ,  $SO_3(\mathbb{R})$ , and of course,  $SL_2(\mathbb{R})$ . For now, we suppress notating the field  $\mathbb{R}$  and refer to these groups by  $SU_2$ ,  $SO_3$ , and  $SL_2$ . By studying the representation theory of the first two groups (which are subgroups of  $SL_2$ ), we will gain some insight for how to study the representation theory of  $SL_2$ .

By identifying complex numbers  $z = x + iy$  with real matrices  $\begin{pmatrix} x & y \\ -y & x \end{pmatrix}$ , we can identify  $U(1) = \{z \in \mathbb{C} \mid |z| = 1\}$  with the real matrix group  $\{\begin{pmatrix} x & y \\ -y & x \end{pmatrix}\} \cap SL_2$ . There is a natural complexification of this idea (it's unclear whether this was a pun or not).

One way to describe the quaternions is as a complex matrix group; that is,

$$\mathbb{H} = \left\{ \begin{pmatrix} z & w \\ -\bar{w} & \bar{z} \end{pmatrix} \right\}$$

viewed as a subgroup of the  $2 \times 2$  complex matrices. The quaternions form an associative, non-commutative  $\mathbb{C}$ -algebra which may also be described as an  $\mathbb{R}$ -algebra spanned by  $\{1, i, j, k\}$  subject to the relations  $i^2 = j^2 = k^2 = -1$ ,  $ij = k$ ,  $jk = i$ ,  $ki = j$ . The description of  $\mathbb{H}$  as an  $\mathbb{R}$ -algebra is convenient since there is a nice way to write the conjugation involution and norm on  $\mathbb{H}$ : For  $a + bi + cj + dk \in \mathbb{H}$ ,  $\overline{a + bi + cj + dk} = a - bi - cj - dk$  and  $\|a + bi + cj + dk\|^2 = (a + bi + cj + dk)(\overline{a + bi + cj + dk}) = a^2 + b^2 + c^2 + d^2$ . We can also view the quaternions as the complex matrix algebra generated by the matrices  $1 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$ ,  $i = \begin{pmatrix} i & 0 \\ 0 & -i \end{pmatrix}$ ,  $j = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$ ,  $k = \begin{pmatrix} 0 & i \\ i & 0 \end{pmatrix}$ .

In the same way that we think of  $U(1)$  as the determinant 1 matrices in  $SL_2$ , we can define  $SU_2$  as the unit quaternions; that is,

$$SU_2 = \mathbb{H} \cap SL_2(\mathbb{C})$$

The determinant 1 matrices  $\begin{pmatrix} z & w \\ -\bar{w} & \bar{z} \end{pmatrix}$  are those with  $|z|^2 + |w|^2 = 1$ ; if  $z = z_1 + iz_2$  and  $w = w_1 + iw_2$ , then  $z_1^2 + z_2^2 + w_1^2 + w_2^2 = 1$ . So the elements of  $SU_2$ , the unit quaternions, can be thought of the 3-sphere  $S^3$ .

Related is the group of  $2 \times 2$  unitary matrices  $U(2)$ , whose elements satisfy  $U\bar{U}^\top = \bar{U}^\top U = 1$  (so  $|\det U| = 1$ ). The group  $SU_2$  is a subgroup of  $U(2)$ , and we can also write  $SU_2 = U(2) \cap SL_2(\mathbb{C})$ .

That we can identify the unit quaternions with  $S^3$  shows that we can endow  $S^3$  with a group structure. Similarly, the unit magnitude elements of  $\mathbb{C}$  may be identified with  $S^1$  to give  $S^1$  a group structure, and the same can be said about  $S^0$  and the unit magnitude elements  $\{-1, 1\}$  of  $\mathbb{R}$ .

Some easy complex representations of  $SU_2$  are  $\mathbb{H} \cong \mathbb{C}^2$ , one where  $SU_2$  acts by left multiplication and another where  $SU_2$  acts by conjugation. The first representation is irreducible, since any element of a proper subspace of  $\mathbb{H}$  can be translated out of that subspace by a suitably chosen element of  $SU_2$ . The conjugation representation viewed as a real representation is reducible, since by viewing  $\mathbb{H}$  as  $\mathbb{R}^4$ , the subspace  $\mathbb{R}1$  is preserved under conjugation by unit quaternions. It is also the case that the complement of  $\mathbb{R}1$ , the pure quaternions (which we identify as  $\mathbb{R}^3$  so that  $\mathbb{H} = \mathbb{R}1 \oplus \mathbb{R}^3$  as a real vector space), is also preserved under conjugation by unit quaternions. This is because

for a unit quaternion  $q$  and quaternions  $g, h$ , the real part of  $h$  is  $(h + \bar{h})/2$  and the pure quaternion part of  $h$  is  $(h - \bar{h})/2$ , conjugation of a product is order-reversing:  $\overline{gh} = \bar{h}\bar{g}$ , and conjugation by  $q$  commutes with conjugation  $q\bar{h}q^{-1} = q\bar{h}\bar{q} = \overline{qh\bar{q}} = \overline{qh}q^{-1}$ .

That the pure quaternions are a 3-dimensional real representation of  $SU_2$  under conjugation is to say there is a particular homomorphism  $SU_2 \rightarrow GL(\mathbb{R}^3)$  which manifests the conjugation action. Conjugation by (nonzero) quaternions preserves the norm of any quaternion (it is easier to see this by returning to the matrix form of quaternions and observing that conjugation by a quaternion preserves the determinant, since the determinant of a matrix is invariant under conjugation). A calculation (not shown here, but see Wikipedia) shows that the orientation of a pure quaternion viewed as an element of  $\mathbb{R}^3$  is also preserved under conjugation. It follows that the image of the homomorphism  $SU_2$  to  $GL(\mathbb{R}^3)$  is a subgroup of  $SO_3$ . This amounts to viewing conjugation of pure quaternions by a unit quaternion as rotations of vectors in  $\mathbb{R}^3$ .

The map from  $SU_2$  to  $SO_3$  is actually a surjective two-to-one map with kernel  $\{\pm 1\} \cong \mathbb{Z}/2\mathbb{Z}$ . So we get an exact sequence

$$1 \rightarrow \{\pm 1\} \rightarrow SU_2 \rightarrow SO_3 \rightarrow 1$$

where  $SO_3 = SU_2 / \{\pm 1\}$ . By identifying  $SU_2$  with  $S^3$ , quotienting out by  $\{\pm 1\}$  amounts to identifying antipodal points of  $S^3$ , so as a topological space,  $SO_3$  is identified with  $\mathbb{RP}^3$ . We say that  $SU_2$  is a double cover of  $SO_3$ .

David brought an interesting prop made of a belt and a piece of cardboard that represents the double cover of  $SO_3$  by  $SU_2$ . The belt is supposed to keep track of the twisting by  $\{\pm I\}$  and the cardboard is supposed to keep track of the position of an element of  $SO_3$ . I would like to make a video about this that I can link here. **TODO**

A fun fact: Let  $u$  be a pure quaternion of unit length and let  $g_\theta = \cos(\theta/2) + \sin(\theta/2)u$ . Then  $g_\theta$  is a unit quaternion and conjugation of a pure quaternion  $v$  by  $g_\theta$  (or  $-g_\theta$ ) can be viewed in  $\mathbb{R}^3$  (viewing  $u, v$  as elements of  $\mathbb{R}^3$ ) as rotating  $v$  by  $\theta$  radians about the axis  $u$  (i.e. counterclockwise about  $u$  if we move our point of view so that  $u$  points towards us).

By letting  $\theta$  vary, we can identify  $\{g_\theta\} \subset SU_2 = S^3$  with a copy of  $U(1) = U(1)$ . Then we can draw the commutative cube

$$\begin{array}{ccccc}
 & & \mathbb{C}^\times & \xrightarrow{\quad\quad\quad} & SL_2(\mathbb{C}) \\
 & \nearrow & \downarrow & & \downarrow \\
 U(1) & \xrightarrow{\quad\quad\quad} & SU_2 \cong S^3 & \xrightarrow{\quad\quad\quad} & \\
 \downarrow & & \downarrow & & \downarrow \\
 & \nearrow & \mathbb{C}^\times / \{\pm 1\} & \xrightarrow{\quad\quad\quad} & SL_2(\mathbb{C}) / \{\pm 1\} \cong PSL_2(\mathbb{C}) \\
 \downarrow & & \downarrow & & \downarrow \\
 U(1) / \{\pm 1\} & \xrightarrow{\quad\quad\quad} & SO_2 \cong \mathbb{RP}^1 & \xrightarrow{\quad\quad\quad} & 
 \end{array}$$

We will try to study the representation theory of  $SU_2$  and  $SO_3$  by first using the representation theory of  $U(1)$ , which we have already studied in detail.

## References

The references below were from the course page. (There are other references throughout the text that I should put in here?)

### Basic Lie theory

R. Carter, G. Segal and I. MacDonald: Lectures on Lie Groups and Lie Algebras. London Math. Society Student Texts 32. The lectures by Segal are a beautiful overview of the fundamental ideas of Lie groups and algebras, with geometry and examples emphasized.

W. Fulton and J. Harris: Representation Theory. Springer GTM 129. The canonical reference for representations, especially for the (Lie) algebraic point of view and basic algebro-geometric aspects.

D. Milicic, The Weyl Character Formula. Explicit derivation for  $SU_2$  not using anything “external” (Part of a course on representation theory.)

### Review articles

G. Mackey: Harmonic Analysis as the Exploitation of Symmetry. Bull. Amer. Math. Soc. 3/1 (1980) 543-699. Reprinted in: The Scope and History of Commutative and Noncommutative Harmonic Analysis. History of Math Vol.5, Amer. Math Soc./London Math Soc. 1992. My favorite (and first) introduction to representation theory, emphasizing its history and origins in probability, number theory and physics. The reprint appears in a volume devoted to Mackey’s wonderful representation theory survey articles.

Other Mackey surveys (besides those in the book above): Unitary Group Representations in physics, probability and number theory (Addison-Wesley 1989) – a book delving deeper into the ideas of the above survey article.

W. Schmid: Representations of semi-simple Lie groups. In: Atiyah et al., Representation Theory of Lie Groups. London Math Society Lecture Notes 34. Cambridge U. Press 1979. Excellent overview by a master, in a volume full of useful reviews (also Mackey, Bott, Kostant, Kazhdan..)

W. Schmid: Analytic and Geometric Realization of Representations. In: Tirao and Wallach (eds.), New Developments in Lie Theory and their Applications. Lecture notes overviewing the subject in the title, with a strong emphasis on  $SL_2$ .

R. Howe, On the role of the Heisenberg group in harmonic analysis.

### More advanced, $SL_2$ specific references

K. Vilonen: Representations of  $SL_2$ . Course Notes, Northwestern University.

R. Howe and E.C. Tan: Non-abelian harmonic analysis - applications of  $SL(2, \mathbb{R})$ . Springer Universitext. A very nice introduction to representations of  $SL(2, \mathbb{R})$ , with interesting applications to classical analysis.

V.S. Varadarajan: An Introduction to Harmonic Analysis on Semisimple Lie Groups. Cambridge Studies in advanced math 16. Nice textbook, with an emphasis on  $SL_2$  and good introductions to various topics.

S. Lang:  $SL(2, \mathbb{R})$ . Springer GTM. Fairly analytical introduction, alas not very coherent – read the review by Robert Langlands

**Other**

D. Ramakrishnan and R. Valenza: Fourier Analysis on Number Fields. Springer GTM 186. Contains an introduction to the Pontrjagin duality theory for locally compact abelian groups, and its applications to number theory (Tate's thesis).

J. Arthur: Harmonic Analysis and Group Representations. Notices of the AMS. Gorgeous introduction to the ideas of Harish-Chandra. Available off AMS website.

I. Gelfand, M. Graev and I. Piatetskii-Shapiro: Representation Theory and Automorphic Functions. Academic Press. A classic thorough study of representations of  $SL_2$  over real,  $p$ -adic and adelic fields.

D. Bump: Automorphic Forms and Representations. Cambridge Studs. Advanced Math. 55. A good and detailed introduction to Langlands program ideas focussed on representations of  $GL_2$ .

T. Bailey and A. Knapp (eds): Representation Theory and Automorphic Forms. Proc. Symp. Pure Math 61. Proceedings of an instructional conference, with a variety of great introductory articles. (In particular Schmid, Knapp and Langlands).

J. Bernstein and S. Gelbart (eds): An Introduction to the Langlands Program. Birkhauser. A very timely collection of introductions to the basic constituents of the Langlands program.

A. Borel and W. Casselman (eds): Automorphic Forms, Representations and L-functions (the Corvallis volumes). The standard source of information about the Langlands program. Available off the AMS website (see e.g. Arinkin's webpage, below).

J. Bernstein, Courses on Eisenstein Series and Representations of  $p$ -adic Groups. Beautiful expositions. Available at Dima Arinkin's Langlands page

Wee Teck Gan, Automorphic Forms and Automorphic Representations: slides for a series of five lectures given in Hangzhou, China giving an excellent overview of the basic theory (available on his web page).