McKay correspondence

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Abstract

The goal of this thesis is to establish a 1-1 correspondence between quivers created from the four following sets whenever G is a finite subgroup of $SL(2,\mathbb{C})$ and S is the power series ring $\mathbb{C}[\![x,y]\!]$

- The Maximal Cohen-Macaulay modules of the fixed ring S^G.
- The indecomposable projective modules of the skew group algerba $S\#G$.
- The indecomposable projective modules of $End_{S^G}(S)$.
- The irreducible representations of G (indecomposable $\mathbb{C}G$-modules).

Much of the thesis will be used to define these four quivers and to develope tools to establish such a correspondence. A similar correspondence can be established for a general field k and a finite subgroup of $GL(n,k)$ with order nonzero in k, but the case for $SL(2,\mathbb{C})$ is the most interesting as the quivers will be extended Dynkin diagrams.

Finite subgroups of SL(2,C)

characters and irreducible representations

Recall that the trace of a matrix is defined to be the sum of its diagonal element and that the trace satisfies two important equations. Namely

$$tr(A+B) = tr(A) + tr(B) \text{ and } tr(AB) = tr(BA)$$

For a given representation of G, $\rho : G \to GL_n(\mathbb{C})$ we define its characther by $\chi_\rho : G \to \mathbb{C}$, $\chi_\rho(g) = tr(\rho(g))$.

Proposition. *Conjugate elements in G take the same value under a character.*

Proof. Let g and g' be in the same conjugacy class. Then there exists an element h such that $h^{-1}gh = g'$. Then we have

$$\chi(g') = \chi(h^{-1}gh) = tr(\rho(h)^{-1}\rho(g)\rho(h)) \stackrel{*}{=} tr(\rho(g)\rho(h)\rho(h)^{-1}) = tr(\rho(g)) = \chi(g)$$

In (*) we use the fact that $tr(AB) = tr(BA)$. $\square$

Lemma. *For a finite abelian group G any irreducible representation must be 1-dimensional.*

Proof. Let $\rho : G \to GL(V)$ be an irreducible representation. Since G is abelian we have that $\rho(g)\rho(h)v = \rho(h)\rho(g)v$, and thus $\rho(g)$ is a homomorphism of G-representations. Then by Schur's lemma $\rho(g)$ must be a scalar multiplication. This implies that ρ can be written as a direct sum of 1-dimensional representations, but since ρ is irreducible ρ must be 1-dimensional. $\square$

Proposition. *If χ is the character of a representation, ρ, with dimension n of a group G, and g is an element of G with order m, then the following holds*

(1) $\chi(1) = n$

(2) $\chi(g)$ *is the sum of m-th roots of unity.*

(3) $chi(g^{-1}) = \overline{\chi(g)}$

Proof.

(1) The first result is immidiate.

$$\chi(1) = tr\left(\begin{bmatrix} 1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & 1 \end{bmatrix}\right) = n$$

(2) Since $\langle g \rangle$ is an abelian group, rho decomposes into n 1-dimensional $\langle g \rangle$-representations. Then there is a basis such that $\rho(g)$ is diagonal. Since g has order m it follows that the diagonal entries of $\rho(g)$ must be m-th roots of unity. Thus $\chi(g) = tr(\rho(g))$ must be the sum of m-th roots of unity.

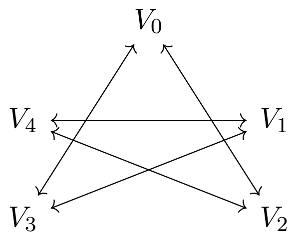
(3) Using the same basis as above and the fact that $\omega^{-1} = \overline{\omega}$ when ω is a root of unity we see that $\chi(g^{-1}) = tr(\rho(g)^{-1}) = \overline{tr(\rho(g))} = \overline{\chi(g)}$.

$\square$

The McKay quiver

Definition. *Let G be a finite subgroup of $GL(n, \mathbb{C})$, and let V be the canonical representation (the one that sends g to g). Then we define the McKay quiver of G to be the quiver with verticies the irreducible representations of G, denoted V_i. For two irreducible representations V_i and V_j we say there is an arrow from the former to the latter if and only if V_j is a direct summand of $V \otimes V_i$.*

Example. *Let G be the group generated by $g = \begin{bmatrix} \omega^2 & 0 \\ 0 & \omega^3 \end{bmatrix}$, where ω is the primitive fifth root of unity. Then there are five different irreducible representations, the one sending g to ω, ω^2, ω^3, ω^4 respectively, and the trivial representation. Denote the representation sending g to ω^i by V_i, and let $V = V_2 \oplus V_3$ be the cannonical representation. Note that $V_i \otimes V_j = V_{i+j}$, where $i+j$ is understood to be modulo 5. Then we get the following McKay-quiver*



Skew algebra S#G indecomposable projectives

Definition. *If G is a subgroup of $GL_n(\mathbb{C})$, we can extend the group action of G to $\mathbb{C}[\![x_1, \cdots, x_n]\!]$. We then define the skew algebra $\mathbb{C}[\![x_1, \cdots, x_n]\!]\#G$ to be the algebra generated by elements of the form $f \cdot g$ with $f \in \mathbb{C}[\![x_1, \cdots, x_n]\!]$ and $g \in G$, and we define the multiplication by*

$$(f_1 \cdot g_1) \cdot (f_2 \cdot g_2) = (f_1 \cdot f_2^{g_1}) \cdot (g_1 \cdot g_2)$$

Where f^g denotes the image of f under the action of g.

Theorem. *We have an isomorphism of rings*

$$e\mathbb{C}[\![x, y]\!]\#Ge \simeq \mathbb{C}[\![x, y]\!]^G$$

where $e = \frac{1}{|G|} \sum_{g \in G} g$.

Proof. Let f^g denote the image of f under the action of g. Then if we let $f(x, y)g$ be an element of the skew algebra we get that $ef(x, y)ge = f(x, y)^e \cdot ege = f(x, y)^e \cdot e$. It then follows that $e\mathbb{C}[\![x, y]\!]\#Ge$ is isomorphic to the image of e. Since $ge = g$ for all $g \in G$ it is clear that the image of e is contained in the fixed ring. For the converse you just need to notice that the fixed ring is fixed under e and thus is contained in the image. $\square$

Lemma. *Let $S = \mathbb{C}[\![x, y]\!]$. An $S\#G$-modulo is projective if it is projective as an S-module.*

Proof. First we need to see that an $S\#G$-linear map is just an S-linear map such that $f(g(m)) = g(f(m))$ for all $g \in G$. Equivalently $f(m) =$

$g(f(g^{-1}(m)))$. This allows us to define a group action $f^g(m) = g(f(g^{-1}(m)))$. Then we can restate it as

$$\mathrm{Hom}_{S\#G}(M,N) = \mathrm{Hom}_S(M,N)^G$$

Clearly if f is $S\#G$-linear then it's in $\mathrm{Hom}_S(M,N)^G$. To see the other inclusion, let f be an S-linear map such that fixed under G. Then $f(s\cdot gm) = sf(gm) = s\cdot g(f(g^{-1}gm)) = s\cdot gf(m)$, and hence f is $S\#G$-linear. Nextly I want to show that $-^G$ is an exact functor.

If K is the kernel of a map $f : M \to N$, then the kernel of the inuced map $f^G : M^G \to N^G$ is of course just $K \cap M^G$ which equals K^G. Assume f is epi and let $n \in N^G$. Consider a preimage m such that $f(m) = n$. Let $\theta = \frac{1}{|G|}\sum_{g\in G} g(m)$. Then θ is in M^G and $f(\theta) = \frac{1}{|G|}\frac{1}{|G|}\sum_{g\in G} g(f(m)) = \frac{1}{|G|}\frac{1}{|G|}\sum_{g\in G} n = n$.

This implies that if $\mathrm{Hom}_S(P,-)$ is exact then $\mathrm{Hom}_S(P,-)^G = \mathrm{Hom}_{S\#G}(P,-)$ is exact and our lemma follows. $\square$

Theorem. *Let $S = \mathbb{C}[\![x,y]\!]$ and let $\mathfrak{m} = \langle x,y\rangle_S$. Then there are bijections between the indecomposable projective $S\#G$-modules and the indecomposable $\mathbb{C}G$-modules given by*

$$\mathcal{F} : P \mapsto P/\mathfrak{m}P$$
$$\mathcal{G} : W \mapsto S \otimes_{\mathbb{C}} W$$

Where the $S\#G$-module structure on $S \otimes_{\mathbb{C}} W$ is given by $(s\cdot g)\cdot f\otimes v = sf^g \otimes g(v)$.

Proof. To see that this are bijections we will show that they are mutuall inverses. First to see that $\mathcal{F}(\mathcal{G}(W)) \cong W$ we simply look at the definition

$$\frac{S\otimes_{\mathbb{C}} W}{\mathfrak{m}S\otimes_{\mathbb{C}} W} \cong S/\mathfrak{m}\otimes_{\mathbb{C}} W \cong \mathbb{C}\otimes_{\mathbb{C}} W \cong W$$

Next we consider $\mathcal{G}(\mathcal{F}(P)) = S\otimes_{\mathbb{C}} P/\mathfrak{m}P$. Notice that the top of $S\otimes_{\mathbb{C}} P/\mathfrak{m}P$ is isomorphic to $P/\mathfrak{m}P$. Then by the uniquness of tops we have that $S\otimes_{\mathbb{C}} P/\mathfrak{m}P \cong P$.

The only thing that remains to show is that $\mathcal{F}$ and $\mathcal{G}$ are well-defined maps with the correct images. Namely that $\mathcal{F}(P)$ is an indecomposable $\mathbb{C}G$-module and that $\mathcal{G}(W)$ is an indecomposable projective $S\#G$-module.

Since P is an indecomposable projective we have that $\mathcal{F}(P)$ is a simple $S\#G$-module. By the natural inclusion $\mathbb{C}G \hookrightarrow S\#G$ $\mathcal{F}(P)$ becomes a $\mathbb{C}G$-module. Assume that $\mathcal{F}(P)$ decomposes as $P_1 \oplus P_2$ as a $\mathbb{C}G$-module. Then since the action of x and y are trivial on $\mathcal{F}(P)$, $P_1\oplus P_2$ is a decomposition of $S\#G$-modules. This implies that $P_1 = 0$ or $P_2 = 0$, and we have that $\mathcal{F}(P)$ is indecomposable.

Lastly we want to show that $\mathcal{G}(W)$ is projective and indecomposable. $\square$

$End_{S^G}(S)$

MCM modules

Definition. *If R is a local ring with residual field k we define the depth of a module, M, to be the minimal n such that the extension $Ext^n_R(k, M)$ is non-zero.*

Definition. *If M is a module over a local ring R with Krull-dimension d we say that M is maximal Cohen Macaulay (MCM) if the depth of M equals d.*