Lectures on quasi-invariants of Coxeter groups and the Cherednik algebra

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Introduction

This paper arose from a series of three lectures given by the first author at Università di Roma “Tor Vergata” in January 2002, when the second author extended and improved her notes of these lectures. It contains an elementary introduction for non-specialists to the theory of quasi-invariants (but no original results).

Our main object of study is the variety $X_m$ of quasi-invariants for a finite Coxeter group. This very interesting singular algebraic variety arose in a work of O.Chalykh and A.Veselov about 10 years ago, as the spectral variety of the quantum Calogero-Moser system. We will see that despite being singular, this variety has very nice properties (Cohen-Macaulay, Gorenstein, simplicity of the ring of differential operators, explicitly given Hilbert series). It is interesting that although the definition of $X_m$ is completely elementary, to understand the geometry of $X_m$ it is helpful to use representation theory of the rational degeneration of Cherednik’s double affine Hecke algebra, and the theory of integrable systems. Thus, the study of $X_m$ leads us to a junction of three subjects – integrable systems, representation theory, and algebraic geometry.

The content of the paper is as follows. In Lecture 1 we define the ring of quasi-invariants for a Coxeter group, and discuss its elementary properties (with proofs), as well as deeper properties, such as Cohen-Macaulay, Gorenstein prop-
erty, and the Hilbert series (whose proofs are partially postponed until Lecture 3). In Lecture 2, we explain the origin of the ring of quasi-invariants in the theory of integrable systems, and introduce some tools from integrable systems, such as the Baker-Akhieser function. Finally, in Lecture 3, we develop the theory of the rational Cherednik algebra, the representation-theoretic techniques due to Opdam and Rouquier, and finish the proofs of the geometric statements from Chapter 1.

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1 Lecture 1

1.1 Definition of quasi-invariants

In this lecture we will define the ring of quasi-invariants $Q_m$ and discuss its main properties.

We will work over the field of complex numbers $\mathbb{C}$. Let $W$ be a finite Coxeter group i.e. a finite group generated by reflections. Let us denote by $\mathfrak{h}$ its reflection representation. A typical example is the Weyl group of a simple Lie algebra acting on a Cartan subalgebra $\mathfrak{h}$. In the case the Lie algebra is $\mathfrak{sl}(n)$, we have that $W$ is the symmetric group $S_n$ on $n$ letters and $\mathfrak{h}$ is the space of diagonal traceless $n \times n$ matrices.

Let $\Sigma \subset W$ denote the set of reflections. Clearly, $W$ acts on $\Sigma$ by conjugation. Let $m : \Sigma \rightarrow \mathbb{Z}_+$ be a function on $\Sigma$ taking non negative integer values, which is $W$-invariant. The number of orbits of $W$ on $\Sigma$ is generally very small. For example, if $W$ is the Weyl group of a simple Lie algebra of ADE type, then $W$ acts transitively on $\Sigma$, so $m$ is a constant function.

For each reflection $s \in \Sigma$, choose $\alpha_s \in \mathfrak{h}^* - \{0\}$ so that $\alpha_s(sx) = -\alpha_s(x)$ (this means that the hyperplane given by the equation $\alpha_s = 0$ is the reflection hyperplane for $s$).

**Definition 1.1** [CV1, CV2] A polynomial $q \in \mathbb{C}[\mathfrak{h}]$ is said $m$-quasiinvariant with respect to $W$, if for any $s \in \Sigma$, the polynomial $q(x) - q(sx)$ is divisible by $\alpha_s(x)^{2m+1}$.

We will denote by $Q_m$ the space of $m$-quasiinvariant polynomials for $W$.

Notice that every element of $\mathbb{C}[\mathfrak{h}]$ is a 0-quasiinvariant, and that every $W$ invariant is an $m$-quasiinvariant for any $m$. Indeed if $q \in \mathbb{C}[\mathfrak{h}]^W$, then we have $q(x) - q(sx) = 0$ for all $s \in \Sigma$, and 0 is divisible by all powers of $\alpha_s(x)$. Thus in a way, $\mathbb{C}[\mathfrak{h}]^W$ can be viewed as the set of $\infty$-quasivariants.
Example 1.2 The group $W = \mathbb{Z}/2$ acts on $\mathfrak{h} = \mathbb{C}$ by $s(v) = -v$. In this case $m \in \mathbb{Z}_+$ and $\Sigma = \{s\}$. So this definition says that $q$ is in $Q_m$ iff $q(x) - q(-x)$ is divisible by $x^{2m+1}$. It is very easy to write a basis of $Q_m$. It is given by the polynomials $\{x^{2i}i \geq 0\} \cup \{x^{2i+1}i \geq m\}$.

1.2 Elementary properties of $Q_m$.

Some elementary properties of $Q_m$ are collected in the following proposition.

Proposition 1.3 (See [FV] and references therein).

1) $\mathbb{C}[\mathfrak{h}]^W \subset Q_m \subset \mathbb{C}[\mathfrak{h}]$, $Q_0 = \mathbb{C}[\mathfrak{h}]$, $Q_m \subset Q_{m'}$ if $m \geq m'$, $\cap_m Q_m = \mathbb{C}[\mathfrak{h}]^W$.

2) $Q_m$ is a subring of $\mathbb{C}[\mathfrak{h}]$.

3) The fraction field of $Q_m$ is equal to $\mathbb{C}(\mathfrak{h})$.

4) $Q_m$ is a finite $\mathbb{C}[\mathfrak{h}]^W$-module and a finitely generated algebra. $\mathbb{C}[\mathfrak{h}]$ is a finite $Q_m$-module.

Proof. 1) is immediate and has partly been remarked already.

2) Clearly $Q_m$ is closed under sum. Let $p, q \in Q_m$. Let $s \in \Sigma$. Then

$$p(x)q(x) - p(sx)q(sx) = p(x)q(x) - p(sx)q(x) + p(sx)q(x) - p(sx)q(sx) =$$

$$= (p(x) - p(sx))(q(x) + p(sx)(q(x) - q(sx)))$$

Since both $p(x) - p(sx)$ and $q(x) - q(sx)$ are divisible by $\alpha_s^{2m+1}$, we deduce that $p(x)q(x) - p(sx)q(sx)$ is also divisible by $\alpha_s^{2m+1}$, proving the claim.

3) Consider the polynomial

$$\delta_{2m+1}(x) = \prod_{s \in \Sigma} \alpha_s(x)^{2m+1}$$

This polynomial is uniquely defined up to scaling. One has $\delta_{2m+1}(sx) = -\delta_{2m+1}(x)$. Take $f(x) \in \mathbb{C}[\mathfrak{h}]$. We claim that $f(x)\delta_{2m+1}(x) \in Q_m$. As a matter of fact,

$$f(x)\delta_{2m+1}(x) - f(sx)\delta_{2m+1}(sx) = (f(x) + f(sx))\delta_{2m+1}(x).$$

and by its definition $\delta_{2m+1}(x)$ is divisible by $\alpha_s(x)^{2m+1}$ for all $s \in \Sigma$. This implies 3).

4) By Hillbert’s theorem on the finiteness of invariants, we get that $\mathbb{C}[\mathfrak{h}]^W$ is a finitely generated algebra over $\mathbb{C}$ and $\mathbb{C}[\mathfrak{h}]$ is a finite $\mathbb{C}[\mathfrak{h}]^W$-module and hence a finite $Q_m$-module, proving the second part of 4).

Now $Q_m \subset \mathbb{C}[\mathfrak{h}]$ is a submodule of the finite module $\mathbb{C}[\mathfrak{h}]$ over the Noetherian ring $\mathbb{C}[\mathfrak{h}]^W$. Hence it is finite. This immediately implies that $Q_m$ is a finitely generated algebra. $\square$

Remark. In fact, since $W$ is a finite Coxeter group, a celebrated result of Chevalley says that the algebra $\mathbb{C}[\mathfrak{h}]^W$ is not only a finitely generated $\mathbb{C}$-algebra
but actually a free (=polynomial) algebra. Namely, it has the form \( \mathbb{C}[q_1, \ldots, q_n] \), where the \( q_i \) are homogeneous polynomials of some degrees \( d_i \). Furthermore, if we denote by \( H \) the subspace of \( \mathbb{C}[h] \) of harmonic polynomials, i.e. of polynomials killed by \( W \) invariant differential operators with constant coefficients without constant term, then the multiplication map

\[
\mathbb{C}[h]^W \otimes H \to \mathbb{C}[h]
\]

is an isomorphism of \( \mathbb{C}[h]^W \)- and of \( W \)-modules. In particular, \( \mathbb{C}[h] \) is a free \( \mathbb{C}[h]^W \) module of rank \( |W| \).

### 1.3 The variety \( X_m \) and its bijective normalization

Using Proposition 1.3, we can define the irreducible affine variety \( X_m = \text{Spec}(Q_m) \).

The inclusion \( Q_m \subset \mathbb{C}[h] \) induces a morphism

\[
\pi : h \to X_m
\]

which again by Proposition 1.3, is birational and surjective. (Notice that in particular this implies that \( X_m \) is singular for all \( m \neq 0 \).

In fact, not only is \( \pi \) birational, but a stronger result is true.

**Proposition 1.4** *(Berest, see [BEG])* \( \pi \) is a bijection.

**Proof.** By the above remarks, we only have to show that \( \pi \) is injective. In order to achieve this, we need to prove that quasi-invariants separate points of \( h \), i.e. if \( z, y \in h \) and \( z \neq y \), then there exist \( p \in Q_m \) such that \( p(z) \neq p(y) \). This is obtained in the following way. Let \( W_z \subset W \) be the stabilizer of \( z \) and choose \( f \in \mathbb{C}[h] \) such that \( f(z) \neq 0 \), \( f(y) = 0 \). Set

\[
p(x) = \prod_{s \in \Sigma, s \neq z} \alpha_s(x)^{2m_s+1} \prod_{w \in W_z} f(wx).
\]

We claim that \( p(x) \in Q_m \). Indeed, let \( s \in \Sigma \) and assume that \( s(z) \neq z \).

We have by definition \( p(x) = \alpha_s(x)^{2m_s+1} \tilde{p}(x) \), with \( \tilde{p}(x) \) a polynomial. So

\[
p(x) - p(sx) = \alpha_s(x)^{2m_s+1} \tilde{p}(x) - \alpha_s(sx)^{2m_s+1} \tilde{p}(sx) = \alpha_s(x)^{2m_s+1}(\tilde{p}(x) + \tilde{p}(sx))
\]

If on the other hand, \( sz = z \), i.e. \( s \in W_z \), then \( s \) preserves the set \( W \setminus W_z \), and hence preserves \( \prod_{s \in W \setminus W_z} \alpha_s(x)^{2m_s+1} \) (as it acts by \(-1\) on the products of the same terms both over \( W \) and over \( W_z \)). Since \( \prod_{w \in W_z} f(wx) \) is \( W_z \) invariant, we deduce that \( p(x) - p(sx) = 0 \), so that in this case \( p(x) - p(sx) \) also is divisible by \( \alpha_s(x)^{2m_s+1} \).

To finish, notice that \( p(z) \neq 0 \). Indeed, for a reflection \( s \), \( \alpha_s \) vanishes exactly on the fixed points of \( s \), so that \( \prod_{s \in \Sigma, s \neq z} \alpha_s(z)^{2m_s+1} \neq 0 \). Also for all \( w \in W_z \), \( f(wz) = f(z) \neq 0 \). On the other hand, it is clear that \( p(y) = 0 \). \( \square \)
Example 1.5 \( W = \mathbb{Z}/2 \). As we have already seen, \( Q_m \) has a basis given by the monomials \( \{ x^{2i} | i \geq 0 \} \cup \{ x^{2i+1} | i \geq m \} \). From this we deduce that setting \( z = x^2 \) and \( y = x^{2m+1} \), \( Q_m = \mathbb{C}[y, z]/(y^2 - z^{2m+1}) = \mathbb{C}[K] \), where \( K \) is the plane curve with a cusp at the origin, given by the equation \( y^2 = z^{2m+1} \). The map \( \pi : \mathbb{C} \to K \) is given by \( \pi(t) = (t^2, t^{2m+1}) \) which is clearly bijective.

1.4 Further properties of \( X_m \)

Let us get to some deeper properties of quasi-invariants. Let \( X \) be an irreducible affine variety over \( \mathbb{C} \) and \( A = \mathbb{C}[X] \). Recall that, by Noether normalization Lemma, there exists \( f_1, \ldots, f_n \in \mathbb{C}[X] \) which are algebraically independent over \( \mathbb{C} \) and such that \( \mathbb{C}[X] \) is a finite module over the polynomial ring \( \mathbb{C}[f_1, \ldots, f_n] \). This means that we have a finite morphism of \( X \) onto an affine space.

Definition 1.6 A (and \( X \)) is said to be Cohen-Macaulay if there exist \( f_1, \ldots, f_n \) as above, with the property that \( \mathbb{C}[X] \) is a locally free module over \( \mathbb{C}[f_1, \ldots, f_n] \).

(Notice that by the Quillen-Suslin theorem, this is equivalent to saying that \( A \) is a free module).

Remark. If \( A \) is Cohen-Macaulay, then for any \( f_1, \ldots, f_n \) which are algebraically independent over \( \mathbb{C} \) and such that \( \mathbb{C}[X] \) is a finite module over the polynomial ring \( \mathbb{C}[f_1, \ldots, f_n] \), \( A \) is a locally free \( \mathbb{C}[f_1, \ldots, f_n] \)-module.

Theorem 1.7 ([EG2], [BEG], conjectured in [FV]) \( Q_m \) is Cohen-Macaulay.

Notice that, using Chevalley’s result that \( \mathbb{C}[h]^W \) is a polynomial ring, in order to prove Theorem 1.7 it will suffice to prove:

Theorem 1.8 ([EG2], [BEG], conjectured in [FV]) \( Q_m \) is a free \( \mathbb{C}[h]^W \) module.

A proof of this theorem will be given at the end of Lecture 3. This proof follows [BEG] (the original proof of [EG2] is shorter but somewhat less conceptual).

1.5 The Poincaré series of \( Q_m \)

Consider now the Poincaré series

\[
h_{Q_m}(t) = \sum_{r \geq 0} \dim Q_m[r] t^r
\]

\( Q_m[r] \) denoting the graded component of \( Q_m \) of degree \( r \).

For every irreducible representation \( \tau \in \hat{W} \), define

\[
\chi_{\tau}(t) = \sum_{r \geq 0} \dim \text{Hom}_W(\tau, \mathbb{C}[h][r]) t^r.
\]
Consider the element in the group ring $\mathbb{Z}[W]$ 

$$\mu_m = \sum_{s \in \Sigma} m_s (1 - s).$$

The $W$ invariance of $m$ implies that $\mu_m$ lies in the center of $\mathbb{Z}[W]$. Hence it is clear that $\mu$ acts as a scalar, $\xi_m(\tau)$, on $\tau$.

**Lemma 1.9** The scalar $\xi_m(\tau)$ is an integer.

**Proof.** $\mathbb{Z}[W]$ and hence also its center, is a finite $\mathbb{Z}$-module. This clearly implies that $\xi_m(\tau)$ is an algebraic integer. Thus to prove that $\xi_m(\tau)$ is an integer, it suffices to see that $\xi_m(\tau)$ is a rational number. Set $d_\tau$ equal to the degree of $\tau$ and $d_{\tau,s}$ equal to the dimension of space of $s$ invariants in $\tau$. Taking traces we get

$$d_\tau \xi_m(\tau) = \sum_{s \in \Sigma} 2m_s (d_\tau - d_{\tau,s})$$

which gives the rationality of $\xi_m(\tau)$. \qed

One has:

**Theorem 1.10**

$$h_{Q_m}(t) = \sum_{\tau \in \hat{W}} d_\tau t \xi_m(\tau) \chi_{\tau}(t)$$

(1)

**Remark.** This theorem was proved in [FeV] modulo Theorem [L7] (conjectured in [FV]) using the Matsuo-Cherednik correspondence. Thus, Theorem 1 follows from [FeV] and [EG2]. Another proof of this theorem is given in [BEG]; this is the proof we will discuss below.

**Example 1.11** If $m = 0$, since $Q_0 = \mathbb{C}[h]$, the theorem says that

$$h_{Q_0}(t) = \frac{1}{(1 - t)^n} = \sum_{\tau \in \hat{W}} d_\tau \chi_{\tau}(t)$$

Indeed, as a $W$-module one has

$$\mathbb{C}[h] = \oplus_{\tau} \tau \otimes \text{Hom}_W(\tau, \mathbb{C}[h]).$$

**Example 1.12** If $W = \mathbb{Z}/2$, then $\hat{W} = \{+, -\}$, $+$ (respectively $-$) denoting the trivial (respectively the sign) representation. One has

$$\mathbb{C}[x] = \mathbb{C}[x^2] \oplus \mathbb{C}[x^2]x$$
where $\mathbb{C}[x^2] = \mathbb{C}[x]^W$ and $\mathbb{C}[x^2]x$ is the isotypic component of the sign representation. Thus

\[
\chi_+(t) = \frac{1}{1-t^2}, \quad \chi_-(t) = \frac{t}{1-t^2},
\]

$\mu_m = m(1-s)$. Thus $\xi_m(+) = 0$, $\xi_m(-) = 2m$. We deduce that

\[
h_{Q_m}(t) = \frac{1}{1-t^2} + \frac{t^{2m+1}}{1-t^2}
\]
as we already know.

Recall now that as a graded $W$-module $\mathbb{C}[h]$ is isomorphic to $\mathbb{C}[h]^W \otimes H$, $H$ being the space of harmonic polynomials. We deduce that the $\tau$-isotypic component in $\mathbb{C}[h]$ is isomorphic to $\mathbb{C}[h]^W \otimes H_{\tau}$. Set $K_\tau(t) = \sum_{\tau \geq 0} \dim \text{Hom}(\tau, H_{[\tau]}) t^\tau$. This is a polynomial called the Kostka polynomial relative to $\tau$. We deduce that

\[
\chi_\tau(t) = \frac{K_\tau(t)}{\prod_{i=1}^n (1-t^{d_i})}
\]

(2)

Also, if $\tau' = \tau \otimes \varepsilon$, $\varepsilon$ being the sign representation, one has

\[
K_{\tau'}(t) = K_\tau(t^{-1}) t^{[\Sigma]}
\]

Set now

\[
P_m(t) = \sum_{\tau \in \hat{W}} d_\tau t^{\xi_m(\tau)} K_\tau(t)
\]

We have

Proposition 1.13 \cite{FeV}

\[
h_{Q_m}(t) = \frac{P_m(t)}{\prod_{i=1}^n (1-t^{d_i})}.
\]

Furthermore $P_m(t) = t^{\xi_m(\varepsilon)+|[\Sigma]|} P_m(t^{-1})$.

Proof. Substituting the expression (2) for $\chi_\tau(t)$ in (1) and using the definition of $P_m(t)$, we get

\[
h_{Q_m}(t) = \sum_{\tau \in \hat{W}} d_\tau t^{\xi_m(\tau)} \frac{K_\tau(t)}{\prod_{i=1}^n (1-t^{d_i})} = \frac{P_m(t)}{\prod_{i=1}^n (1-t^{d_i})}
\]
as desired.

Now notice that

\[
\xi_m(\tau) + \xi_m(\tau') = \sum_{s \in \Sigma} 2m_s = \xi_m(\varepsilon)
\]
Using this we get
\[ t^{\xi_m(\varepsilon)+|\Sigma|} P_m(t^{-1}) = \sum_{\tau \in W} d^{\xi_m(\varepsilon)-\xi_m(\tau)} t^{|\Sigma|} K_\tau(t^{-1}) = \sum_{\tau' \in \hat{W}} d^{\xi_m(\tau')} K_{\tau'}(t) = P_m(t) \]
as desired. 

From this we deduce

**Theorem 1.14** ([EG2, BEG, FeV], conjectured in [FV]) The ring \( Q_m \) of \( m \)-quasi-invariants is Gorenstein.

**Proof.** By Stanley’s theorem (see [Eis]), a positively graded Cohen-Macaulay domain \( A \) is Gorenstein iff its Poincare series is a rational function \( h(t) \) satisfying the equation \( h(t^{-1}) = (-1)^n t^l h(t) \), where \( l \) is an integer and \( n \) the dimension of the spectrum of \( A \). Thus the result follows immediately from Proposition 1.13.

\[ \square \]

1.6 The ring of differential operators on \( X_m \)

Finally, let us introduce the ring \( D(X_m) \) of differential operators on \( X_m \), that is the ring of differential operators with coefficients in \( \mathbb{C}(\hbar) \) mapping \( Q_m \) to \( Q_m \). It is clear that this definition coincides with the well known Grothendieck’s definition.

**Theorem 1.15** ([BEG]) \( D(X_m) \) is a simple algebra.

**Remark 1.16** a) The ring of differential operators on a smooth affine algebraic variety is always simple.

b) By a result of M. van den Bergh [VdB], for a non-smooth variety, the simplicity of the ring of differential operators implies the Cohen-Macaulay property of this variety.

2 Lecture 2

We will now see how the ring \( Q_m \) appears in the theory of completely integrable systems.

2.1 Hamiltonian mechanics and integrable systems

Recall the basic setup of Hamiltonian mechanics [Ar]. Consider a mechanical system with configuration space \( X \) (a smooth manifold). Then the phase space of this system is \( T^*X \), the cotangent bundle on \( X \). The space \( T^*X \) is naturally a symplectic manifold, and in particular we have an operation of Poisson bracket on functions on \( T^*X \). A point of \( T^*X \) is a pair \( (x, p) \), where \( x \in X \) is the position
and $p \in T^*_x X$ is the momentum. Such pairs are called states of the system. The dynamics of the system $x = x(t), p = p(t)$ depends on the Hamiltonian, or energy function, $E(x, p)$ on $T^* X$. Given $E$ and the initial state $x(0), p(0)$, one can recover the dynamics $x = x(t), p = p(t)$ from Hamilton’s differential equations $\frac{df(x, p)}{dt} = \{E, f\}$. If $X$ is locally identified with $\mathbb{R}^n$ by choosing coordinates $x_1, \ldots, x_n$, then $T^* X$ is locally identified with $\mathbb{R}^{2n}$ with coordinates $x_1, \ldots, x_n, p_1, \ldots, p_n$. In these coordinates, Hamilton’s equations may be written in their standard form:

$$\dot{x}_i = \frac{\partial E}{\partial p_i}, \quad \dot{p}_i = -\frac{\partial E}{\partial x_i}.$$ 

A function $I(x, p)$ is called an integral of motion for our system if $\{I, E\} = 0$. Integrals of motion are useful, since for any such integral $I$ the function $I(x(t), p(t))$ is constant, which allows one to reduce the number of variables by 2. Thus, if we are given $n$ functionally independent integrals of motion $I_1, \ldots, I_n$ with $\{I_l, I_k\} = 0$ for all $1 \leq l, k \leq n$, then all $2n$ variables $x_i, p_i$ can be excluded, and the system can be completely solved by quadratures. Such situation is called complete (or Liouville) integrability.

### 2.2 Classical Calogero-Moser system

Quasi-invariants are related to many-particle systems. Consider a system of $n$ particles on the real line $\mathbb{R}$. A potential is an even function

$$U(x) = U(-x).$$

Two particles at points $a, b$ have energy of interaction $U(a - b)$. The total energy of our system of particles is

$$E = \sum_{i=1}^{n} \frac{p_i^2}{2} + \sum_{i<j} U(x_i - x_j).$$

Here, $x_i$ are the coordinates of the particles, $p_i$ their momenta. The dynamics of the particles $x_i = x_i(t), p_i = p_i(t)$ is governed by the Hamilton equations with energy function $E$.

This is a system of nonlinear differential equations, which in general may be difficult to solve explicitly. However, for special potentials this system may be completely integrable. For instance, we will see that it is so for the Calogero-Moser potential,

$$U(x) = \frac{\gamma}{x^2},$$

$\gamma$ being a constant.

The Calogero-Moser system has a generalization to arbitrary Coxeter groups. Namely, consider a finite group $W$ generated by reflections acting on the space $\mathfrak{h}$,
and keep the notation of the previous section. Fix a $W$-invariant nondegenerate scalar product $(-,-)$ on $\mathfrak{h}$. It determines a scalar product on $\mathfrak{h}^*$. Define the “energy function”

$$E(x,p) = \frac{(p,p)}{2} + \frac{1}{2} \sum_{s \in \Sigma} \frac{\gamma_s(\alpha_s, \alpha_s)}{\alpha_s(x)^2}.$$ 

on $T^*\mathfrak{h} = \mathfrak{h} \times \mathfrak{h}^*$, where $\gamma : \Sigma \to \mathbb{C}$ is a $W$-invariant function. Notice that although $\alpha_s$ is defined up to a non zero constant, by homogeneity, $E$ is independent of the choice of $\alpha_s$. We will call the system defined by $E$ the Calogero-Moser system for $W$.

If $W$ is the symmetric group $S_n$, $\mathfrak{h} = \mathbb{C}^n$, then $\Sigma$ is the set of transpositions $s_{i,j}$, $i < j$ and we can take $\alpha_s = e_i - e_j$. Then we clearly obtain the usual Calogero-Moser system.

Below we will see that the Calogero-Moser system for $W$ is completely integrable.

### 2.3 Quantum Calogero-Moser system

Let us now discuss quantization of the Calogero-Moser system. We start by quantizing the energy $E$ by formally making the substitution

$$p_j \Rightarrow i\hbar \frac{\partial}{\partial x_j}$$

where $\hbar$ is a parameter (Planck constant). This yields the Schrödinger operator

$$\hat{E} := -\frac{\hbar^2}{2} \Delta + \frac{1}{2} \sum_{s \in \Sigma} \frac{\gamma_s(\alpha_s, \alpha_s)}{\alpha_s^2(x)},$$

where $\Delta$ denotes the Laplacian.

In particular, in the case of $W = S_n$ we have

$$\hat{E} = -\frac{\hbar^2}{2} \Delta + \sum_{i < j} \frac{c}{(x_i - x_j)^2},$$

where $\Delta = \sum_i \frac{\partial^2}{\partial x_i^2}$.

Setting $\beta_s = \frac{\gamma_s}{2\hbar^2}$, we will from now on consider the operator

$$H := -\frac{2}{\hbar^2} \hat{E} = \Delta - \sum_{s \in \Sigma} \frac{\beta_s(\alpha_s, \alpha_s)}{\alpha_s^2(x)}.$$ 

This operator is called the Calogero-Moser operator.

We want to study the stationary Schrödinger equation:

$$H \psi = \lambda \psi, \quad \lambda \in \mathbb{C}. \quad (3)$$
Similarly to the classical case, for a general Schrödinger operator $H$, it is hard to say anything explicit about solutions of this equation, but for the Calogero-Moser operator the situation is much better.

**Definition 2.1** A quantum integral of $H$ is a differential operator $M$ such that

$$[H, M] = 0.$$ We are going to show that there are plenty of quantum integrals of $H$, namely that there are $n$ commuting algebraically independent quantum integrals $M_1, \ldots, M_n$ of $H$. By definition, this means that the quantum Calogero-Moser system is completely integrable.

Once we have found $M_1, \ldots, M_n$, remark that for fixed constants $\mu_1, \ldots, \mu_n$, the space of solutions of the system

$$\begin{cases} M_1 \psi = \mu_1 \psi \\ \ldots \\ M_n \psi = \mu_n \psi \end{cases}$$

is clearly stable under $H$. We will see that this space is in fact finite dimensional. Therefore, the operators $M_i$ allow one to reduce solving the partial differential equation $H \psi = \lambda \psi$ to solving a system of ordinary linear differential equations. This phenomenon is called quantum complete integrability.

### 2.4 The algebra of differential-reflection operators

We are now going to explain how to find quantum integrals for $H$, using the Dunkl-Cherednik method.

First let us fix some notation. Given a smooth affine variety $X$, we will denote by $\mathcal{D}(X)$ the ring of differential operators on $X$. We are going to consider the case in which $X$ is the open set $U$ in $\mathfrak{h}$ which is the complement of the divisor of the equation $\prod_{s \in \Sigma} \alpha_s(x)$. Clearly $\mathcal{D}(U) = \mathcal{D}(\mathfrak{h})[1/\delta(x)]$.

**Lemma 2.2** An element of $\mathcal{D}(U)$ is completely determined by its action on $\mathbb{C}[U]^W = \mathbb{C}[U/W]$.

**Proof.** Recall that the quotient map $\pi : U \to U/W$ is finite and unramified. This implies that

$$\mathcal{D}(U) = \mathbb{C}[U] \otimes_{\mathbb{C}[U/W]} \mathcal{D}(U/W).$$

From this we obtain that if $P \in \mathcal{D}(U)$ is such that $Pf = 0$ for all $f \in \mathbb{C}[U/W]$ then $P = 0$.

We also have the operators on $\mathbb{C}[U]$ given by the action of $W$. We will denote by $\mathcal{A}$ the algebra of operators on $U$ generated by $\mathcal{D}(U)$ and $W$. We have:
Proposition 2.3 \( A = D(U) \rtimes W \) i.e. every element in \( A \in A \) can be uniquely written as a linear combination

\[
A = \sum_{w \in W} P_w w
\]

with \( P_w \in D(U) \).

**Proof.** The fact that every element in \( A \) can be expressed as a linear combination \( \sum_{w \in W} P_w w \) is clear. To show that such an expression is unique, assume \( \sum_{w \in W} P_w w f^i w = 0 \) for all \( i \geq 0 \). We deduce that given \( g \in \mathbb{C}[U/W] \) one has

\[
(\sum_{w \in W} P_w w f^i)(g) = 0.
\]

Thus by Lemma 2.2, \( \sum_{w \in W} P_w w f^i = 0 \) for all \( i \). Therefore, \( P_w \prod_{w \not= u} (w f - u f) = 0 \) and hence \( P_w = 0 \), for all \( w \in W \), as desired. \( \square \)

We set \( m(A) = \sum_{w \in W} P_w \in D(U) \). Notice that if \( f \) is a \( W \)-invariant function, then clearly \( A(f) = m(A)(f) \) and that, by what we have seen in the proof of the above proposition, \( m(A) \) is completely determined by its action on invariant functions.

In general, \( m \) is not a homomorphism. However:

**Proposition 2.4** Let \( A^W \subset A \) denote the subalgebra of \( W \)-invariant elements. Then the restriction of \( m \) to \( A^W \) is an algebra homomorphism.

**Proof.** If \( A \in A^W \), then clearly \( m(A) \) is \( W \)-invariant. Now if we take \( A, B \in A^W \) and \( f \) a \( W \)-invariant function we have that \( B(f) \) is also \( W \)-invariant. So

\[
m(AB)(f) = (AB)(f) = A(B(f)) = A(m(B)(f)) = m(A)(m(B)(f)).
\]

Thus \( m(AB) \) and \( m(A)m(B) \) coincide on \( W \)-invariant functions and hence coincide. \( \square \)
2.5 Dunkl operators and symmetric quantum integrals

Fix a $W$ invariant function $c : \Sigma \to \mathbb{C}$ such that $\beta_s = c_s(c_s + 1)$ for each $s \in \Sigma$. Set

$$L = \delta_c(x)H\delta_c(x)^{-1}.$$  

Then an easy computation shows that

$$L = \Delta - \sum_{s \in \Sigma} \frac{2c_s}{\alpha_s(x)} \partial_{\alpha_s}$$

where, for a vector $y \in \mathfrak{h}$, as usual the symbol $\partial_y$ denotes the partial derivative in the $y$ direction (notice that using the scalar product we are viewing $\alpha_s$ as a vector in $\mathfrak{h}$ orthogonal to the hyperplane fixed by $s$).

From now on we will work with $L$ instead of $H$ and study the eigenvalue problem

$$L\psi = \lambda \psi \quad (4)$$

It is clear that $\psi$ is a solution of this equation if and only if $\delta_c(x)^{-1}\psi$ is a solution of (3).

Since for any $s \in \Sigma$ and $f \in \mathbb{C}[\mathfrak{h}]$ we have that $f(sx) - f(x)$ is divisible by $\alpha_s(x)$, we get that the operator

$$\frac{1}{\alpha_s(x)}(s - 1) \in \mathcal{A}$$

maps $\mathbb{C}[\mathfrak{h}]$ to itself.

**Definition 2.5** Given $y \in \mathfrak{h}$, we define the Dunkl operator $D_y$ on $\mathbb{C}[\mathfrak{h}]$ by

$$D_y := \partial_y + \sum_{s \in \Sigma} c_s \frac{(\alpha_s, y)}{\alpha_s(x)}(s - 1)$$

We have the following very important theorem.

**Theorem 2.6** [Du] Let $y, z \in \mathfrak{h}$, Then

$$[D_y, D_z] = 0.$$  

**Proof.** See [Du], [Op].  

**Proposition 2.7** (Cherednik) Let $\{y_1, \ldots, y_n\}$ be an orthonormal basis of $\mathfrak{h}$. Then we have

$$m \left( \sum_{i=1}^n D_{y_i}^2 \right) = L.$$
Proof. Observe that $m(\sum_{i=1}^{n} D_{y_i}^{2}) = \sum_{i=1}^{n} m(D_{y_i}^{2})$, so we need to compute $m(D_{y}^{2})$ for $y \in \mathfrak{h}$. We have $m(D_{y}^{2}) = m(D_{y} m(D_{y})) = m(D_{y} \partial_{y})$. A simple computation shows that

$$D_{y} \partial_{y} = \partial_{y}^{2} + \sum_{s \in \Sigma} c_{s} \frac{\alpha_{s} y}{\alpha_{s}(x)} (\partial_{y} s - 1) - \frac{2(\alpha_{s} y)}{(\alpha_{s}, \alpha_{s})} \partial_{\alpha_{s}}.$$ 

Thus

$$m(D_{y}^{2}) = \partial_{y}^{2} - 2 \sum_{s \in \Sigma} c_{s} \frac{(\alpha_{s}, y)^{2}}{(\alpha_{s}, \alpha_{s}) \alpha_{s}(x)} \partial_{\alpha_{s}},$$

We get

$$m(\sum_{i=1}^{n} D_{y_{i}}^{2}) = \sum_{i} \partial_{y_{i}}^{2} - 2 \sum_{s \in \Sigma} c_{s} \sum_{i=1}^{n} (\alpha_{s}, y_{i})^{2} \partial_{\alpha_{s}} = L$$

since $\sum_{i=1}^{n} (\alpha_{s}, y_{i})^{2} = (\alpha_{s}, \alpha_{s})$. \hfill \(\square\)

We are now ready to give the construction on quantum integrals of $L$. Consider the symmetric algebra $S_{\mathfrak{h}} = \mathbb{C}[y_{1}, \ldots, y_{n}]$ which we can identify, using the fact that the Dunkl operators commute, with the polynomial ring $\mathbb{C}[D_{y_{1}}, \ldots, D_{y_{n}}] \subset \mathfrak{A}$. The restriction of $m$ to $S_{\mathfrak{h}}^{W}$ is an algebra homomorphism into the ring $\mathcal{D}(U)$ (and in fact into $\mathcal{D}(U/W)$). Since $S_{\mathfrak{h}}^{W}$ is itself a polynomial ring $\mathbb{C}[q_{1}, \ldots, q_{n}]$, with $q_{1}, \ldots, q_{n}$ of degree $d_{1}, \ldots, d_{n}$, $d_{i}$ being the degrees of basic $W$-invariants, we obtain a polynomial ring of commuting differential operators in $\mathcal{D}(U)$. Given $q \in \mathbb{C}[q_{1}, \ldots, q_{n}]$ we will denote by $L_{q}$ the corresponding differential operator. We can assume that $q_{1} = \sum_{i=1}^{n} y_{i}^{2}$ so that $L = L_{q_{1}}$. Thus for every $q \in \mathbb{C}[q_{1}, \ldots, q_{n}]$, $L_{q}$ is a quantum integral of the quantum Calogero-Moser system. In particular, the operators $L_{q_{1}}, \ldots, L_{q_{n}}$ are $n$ algebraically independent pairwise commuting quantum integrals.

Now the eigenvalue problem (4) may be replaced by

$$L_{p} \psi = \lambda_{p} \psi$$

for $p \in \mathbb{C}[q_{1}, \ldots, q_{n}]$, where the assignment $p \rightarrow \lambda_{p}$ is a algebra homomorphism $\mathbb{C}[q_{1}, \ldots, q_{n}] \rightarrow \mathbb{C}$. In other words, we may say that since $\mathbb{C}[q_{1}, \ldots, q_{n}] = \mathbb{C}[\mathfrak{h}^{*}/W] = \mathbb{C}[\mathfrak{h}/W]$, for every point $k \in \mathfrak{h}/W$, we have the eigenvalue problem

$$L_{p} \psi = p(k) \psi. \quad (5)$$

Proposition 2.8 Near a generic point $x_{0} \in \mathfrak{h}$, the system $L_{p} \psi = p(k) \psi$ has a space of solutions of dimension $|W|$. \hfill \(\square\)

Proof. The proposition follows easily from the fact that the symbols of $L_{q_{i}}$ are $q_{i}(\partial)$, and that $\mathbb{C}[y_{1}, \ldots, y_{n}]$ is a free module over $\mathbb{C}[q_{1}, \ldots, q_{n}]$ of rank $|W|$. \hfill \(\square\)
2.6 Additional integrals for integer $c$

If $c_s \notin \mathbb{Z}$, the analysis of the solutions of the equations $L_p \psi = p(k) \psi$ is rather difficult (see [10]). However, in the case $c : W \rightarrow \mathbb{Z}$, the system can be simplified. Let us consider this case. First remark the since $\beta_s = c_s(c_s + 1)$, by changing $c_s$ to $-1 - c_s$ if necessary, we can assume that $c$ is non-negative. So we will assume that $c$ takes non-negative integral values and we will denote it by $m$.

System (5) can be further simplified, if we can find a differential operator $M$ (not a polynomial of $L_{q_1}, \ldots, L_{q_n}$) such that $[M, L_p] = 0$ for all $p \in \mathbb{C}[q_1, \ldots, q_n]$. Then the operator $M$ will act on the space of solutions of (5), hopefully with distinct eigenvalues. So, if $\mu$ is such an eigenvalue, the system

\[
\begin{cases}
L_p \psi = p(k) \psi \\
M \psi = \mu \psi
\end{cases}
\]

will have a one dimensional space of solutions and we can find the unique up to scaling solution $\psi$ using Euler formula.

Such an $M$ exists if and only if $c = m$ has integer values. Namely, we will see that one can extend the homomorphism $\mathbb{C}[q_1, \ldots, q_n] \rightarrow D(U)$ mapping $q \rightarrow L_q$ to the ring of $m$-quasi-invariants $Q_m$.

We start by remarking that under some natural homogeneity assumptions, if such an extension exists, it is unique.

**Proposition 2.9** 1) Assume that $q \in \mathbb{C}[y_1, \ldots, y_n]$ is a homogeneous polynomial of degree $d$. If there exists a differential operator $M_q$ with coefficients in $\mathbb{C}(\h)$ of the form

$$M_q = q(\partial_{y_1}, \ldots, \partial_{y_n}) + \text{l.o.t.}$$

such that $[M_q, L] = 0$, whose homogeneity degree is $-d$, then $M_q$ is unique.

2) Let $\mathbb{C}[q_1, \ldots, q_n] \subseteq B \subseteq \mathbb{C}[y_1, \ldots, y_n]$ be a graded ring. Assume that we have a linear map $M : B \rightarrow D(U)$ such that, if $q \in B$ is homogeneous of degree $d$, then $[M_q, L] = 0$, $M_q$ has homogeneity degree $-d$, and

$$M_q = q(\partial_{y_1}, \ldots, \partial_{y_n}) + \text{l.o.t.}$$

Then $M$ is a ring homomorphism and $M_q = L_q$ for all $q \in \mathbb{C}[q_1, \ldots, q_n]$.

**Proof.** 1) If there exist two different operators $M_q$ and $M'_q$ with these properties, take $M_q - M'_q$. This operator has degree of homogeneity $-d$, but order smaller than $d$. Therefore, its symbol $S(x, y)$ is not a polynomial. On the other hand, since the symbol of $L$ is $\sum y_i^2$, we get that $[L, M_q - M'_q] = 0$ implies $\{\sum y_i^2, S(x, y)\} = 0$. Write $S$ in the form $K(x, y)/H(x)$ with $K$ is a polynomial, and $H(x)$ a homogeneous polynomial of positive degree $t$ (we assume that $K(x, y)$ and $H(x)$ have no common irreducible factors). Then

$$0 = \{\sum y_i^2, S(x, y)\} = 2 \sum_{i=1}^n y_i K_{x_i}(x, y) H(x) - \sum_{i=1}^n y_i H_{x_i}(x) K(x, y)$$

$$H(x)^2$$

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Since $\sum_{i=1}^{n} x_i H_{x_i}(x) = tH(x)$, we have that $\sum_{i=1}^{n} y_i H_{x_i}(x) K(x, y) \neq 0$. So $H(x)$ must divide this polynomial and, by our assumptions, this implies that it must divide the polynomial $\sum_{i=1}^{n} y_i H_{x_i}(x)$ whose degree in $x$ is $t - 1$. This is a contradiction.

2) Let $q, p \in B$ be two homogeneous elements. Then $M_q M_p$ and $M_{pq}$ both satisfy the same homogeneity assumptions. Hence they are equal by 1).

Finally if $q \in \mathbb{C}[q_1, \ldots, q_n]$, both $M_q$ and $L_q$ satisfy the same homogeneity assumptions. Hence they are equal by 1).

The required extension to the ring of $m$-quasi-invariants is then provided by the following:

**Theorem 2.10** ([CV1, CV2]) Let $c = m : \Sigma \to \mathbb{Z}_+$. The following two conditions are equivalent for a homogeneous polynomial $q \in \mathbb{C}[\hbar^*]$ of degree $d$.

1) There exists a differential operator

$$L_q = q(\partial y_1, \ldots, \partial y_n) + \text{l.o.t.}$$

of homogeneity degree $-d$, such that $[L_q, L] = 0$.

2) $q$ is an $m$-quasiinvariant homogeneous of degree $d$.

Using this, we can extend system (5) to the system

$$L_p \psi = p(k) \psi, \quad p \in Q_m, \quad k \in \text{Spec } Q_m = X_m$$

(Recall that, as a set, $X_m = \mathfrak{h}$). Near a generic point $x_0 \in \mathfrak{h}$, system (6) has a one dimensional space of solutions, thus there exists a unique up to scaling solution $\psi(k, x)$, which can be expressed in elementary functions. This solution is called the Baker-Akhiezer function, and has the form

$$\psi(k, x) = P(k, x) e^{(k, x)}$$

with $P(k, x)$ a polynomial of the form $\delta(x)\delta(k) + \text{l.o.t.}$. Furthermore, it can be shown that $\psi(k, x) = \psi(x, k)$ (see [CV1, CV2, PV]).

These results motivate the following terminology. The variety $X_m$ is called the spectral variety of the Calogero-Moser system for the multiplicity function $m$, and $Q_m$ is called the spectral ring of this system.

### 2.7 An example

**Example 2.11** Let $W = \mathbb{Z}/2$, $\hbar = \mathbb{C}$, $m = 1$. As we have seen, $Q_m$ has a basis given by the monomials $\{x^{2i}\} \cup \{x^{2i+3}\}, i \geq 0$. Let us set for such a monomial, $L_x = L_x$, and $\partial = \frac{d}{dx}$. Then we have

$$L_0 = 1, \quad L_2 = \partial^2 - \frac{2}{x} \partial, \quad L_3 = \partial^3 - \frac{3}{x} \partial^2 + \frac{3}{x^2} \partial$$
As for the others, \( L_{2j} = L_j^2 \), \( L_{2j+3} = L_j^2 L_3 \). (Note that \( L_1 \) is not defined). The system in this case is

\[
\begin{align*}
\psi'' - \frac{2}{x} \psi' &= k^2 \psi, \\
\psi''' - \frac{2}{x} \psi'' + \frac{3}{x^2} \psi' &= k^3 \psi
\end{align*}
\]

The solution can easily be computed by first differentiating the first equation and subtracting the second, thus obtaining the new system

\[
\begin{align*}
\psi'' - \frac{2}{x} \psi' &= k^2 \psi \\
\psi'' - \left( \frac{1}{x} + k^2 x \right) \psi' &= -k^3 x \psi
\end{align*}
\]

Taking the difference, we get the first order equation

\[
\psi' = \frac{k^2 x}{k x - 1} \psi
\]

whose solution (up to constants) is given by \( \psi = (k x - 1)e^{k x} \).

In fact, one can easily calculate \( \psi_m \) for a general \( m \).

**Proposition 2.12**

\[
\psi_m(k, x) = (x \partial - 2m + 1)(x \partial - 2m - 1) \cdots (x \partial - 1)e^{k x}
\]

**Proof.** We could use the direct method of Example \([2.11] \), but it is more convenient to proceed differently. Namely, we have

\[
(\partial^2 - \frac{2m}{x} \partial)(x \partial - 2m + 1) = (x \partial - 2m + 1)(\partial^2 - \frac{2(m - 1)}{x} \partial)
\]

as it is easy to verify directly. So using induction in \( m \) with base \( m = 0 \), we get

\[
(\partial^2 - \frac{2m}{x} \partial)\psi_m(k, x) = (x \partial - 2m + 1)(\partial^2 - \frac{2(m - 1)}{x} \partial)\psi_{m-1}(k, x) = k^2 \psi_m(k, x),
\]

and \( \psi_m(k, x) \) is our solution.

\[ \Box \]

3 Lecture 3

3.1 Shift operator and construction of the Baker-Akhiezer function

In Lecture 2, we have introduced the Baker-Akhiezer function \( \psi(k, x) \) for the operator

\[
L = \Delta - \sum_{s \in \Sigma} \alpha_s(x) \partial_{a_s}.
\]
The way to construct \( \psi(k, x) \) is via Opdam shift operator. Given a function \( m : \Sigma \to \mathbb{Z}_+ \), Opdam showed in [Op1] that there exists a unique \( W \)-invariant differential operator \( S_m \) of the form 

\[
\delta_m(x) \delta_m(\partial_x) + l.o.t.,
\]

such that

\[
L_q S_m = S_m q(\partial)
\]

for every \( q \in \mathbb{C}[q_1, ..., q_n] \). From this, if we set

\[
\psi(k, x) = S_m e^{(k, x)},
\]

we get

\[
L_q \psi = S_m q(\partial) e^{(k, x)} = q(k) \psi,
\]

where \( q \in \mathbb{C}[q_1, ..., q_n] \).

We claim that equation (7) must in fact hold for all \( q \in Q_m \). Indeed, near a generic point \( x \), the functions \( \psi(wk, x) \) are obviously linearly independent and satisfy (7) for symmetric \( q \). Thus, they are a basis in the space of solutions (we know that this space is \( |W| \)-dimensional). Consider the matrix of \( L_q \) in this basis for any \( q \in Q_m \). Since \( \psi(k, x) \) is a polynomial times \( e^{(k, x)} \), this matrix must be diagonal with eigenvalues \( q(k) \), as desired.

**Example 3.1** As we have seen in the previous section, for \( W = \mathbb{Z}/2 \) and \( \mathfrak{h} = \mathbb{C} \),

\[
S_m = (x \partial - 2m + 1)(x \partial - 2m - 1) \cdots (x \partial - 1)
\]

**3.2 Berest’s formula for \( L_q \)**

We are now going to give an explicit construction of the operators \( L_q \) for any \( q \in Q_m \).

Let us identify, using our \( W \)-invariant scalar product, \( \mathfrak{h} \) with \( \mathfrak{h}^* \), and let us choose an orthonormal basis \( x_1, ..., x_n \) in \( \mathfrak{h}^* \). If \( x \in \mathfrak{h}^* \), we will write \( D_x \) for the Dunkl operator relative to the vector in \( \mathfrak{h} \) corresponding to \( x \) under our identification. Thus

\[
L = \sum_{i=1}^n D_{x_i}^2
\]

**Proposition 3.2** (Berest [Be]) If \( q \in Q_m \) is a homogeneous element of degree \( d \), then

\[
(adL)^{d+1} q = 0.
\]
Proof. It is enough to prove that

\[((adL)^{d+1}q)^{(x)}\psi(k,x) = 0.\]

Indeed, by the definition of \(\psi(k,x)\), we get that this implies that in the ring \(D(U)\),

\[((adL)^{d+1}q)S_m = 0,\] since \(D(U)\) is a domain.

Given \(q \in Q_m\), we will denote by \(L_q^{(k)}\) the operator \(q(D_{k_1}, \ldots, D_{k_n})\). Notice that since \(\psi(k,x) = \psi(x,k)\), we have that \(L_q^{(k)} \psi = q(x)\psi\). Thus we deduce, for \(p, q, r \in Q_m\),

\[L_q^r(x)L_p \psi = L_q^r(x)p(k)\psi = p(k)L_q^r(x)\psi = p(k)L_qL_r^{(k)}\psi =\]

\[= p(k)L_r^{(k)}L_q \psi = p(k)L_r^{(k)}q(k)\psi\]

It follows that

\[(adL)^{d+1}q\psi = (-1)^{d+1}(ad(\sum_{i=1}^{n} k_i^2))^{d+1}L_q^{(k)}\psi\]

Since \(L_q\) is a differential operator of degree \(d\), we get that \(ad(\sum_{i=1}^{n} k_i^2)d+1L_q^{(k)} = 0\), as desired. \(\square\)

Notice now that the operator \((adL)^dq(x)\) commutes with \(L\). Its symbol is given by \((ad\Delta)^dq(x) = 2^d d! q(\partial)\). So we deduce the following:

**Corollary 3.3** (Berest’s formula, [BM]) If \(q \in Q_m\) is homogeneous of degree \(d\), then

\[L_q = \frac{1}{2^d d!}(adL)^d q(x).\]

Proof. This is clear from Proposition 2.8, once we remark that \((adL)^dq(x)\) has the required homogeneity. \(\square\)

We want to give a representation theoretical interpretation of what we have just seen. Consider the three operators

\[F = \sum_{i=1}^{n} x_i^2, \quad E = -\frac{L}{2}, \quad H = [E,F]\]

It is easy to check that \([H,E] = 2E, [H,F] = -2F\). We deduce that the elements \(E,F,H\) span an \(sl(2)\) Lie subalgebra of \(D(U)\). Thus \(sl(2)\) acts by conjugation on \(D(U)\). We can then reformulate Proposition 3.2 as follows:

**Proposition 3.4** Any polynomial \(q \in Q_m\) of degree \(d\) is a lowest weight vector for the \(sl(2)\)-action of weight \(-d\) and generates a finite dimensional module (necessarily of dimension \(d+1\)) for which \(L_q\) is a highest weight vector.
Proof. An easy direct computation shows that

$$H = [E, F] = -\sum_{i=1}^{n} x_i \frac{\partial}{\partial x_i} + C$$

where $C$ is a constant. Thus if $q$ is homogeneous of degree $d$, we have $[H, L_q] = dL_q$.

This and the fact that $[L, L_q] = 0$, implies that $L_q$ is a highest weight vector of weight $d$. Also since $F$ is a polynomial, we deduce that $adF^{d+1}L_q = 0$, so that $L_q$ generates a $d + 1$ dimensional irreducible $\mathfrak{sl}(2)$-module.

One last property about these operators is given by:

**Proposition 3.5** [FV] For any $q \in Q_m$, the operator $L_q$ preserves $Q_m$.

Proof. Let us begin by proving that $L$ preserves $Q_m$.

Take $f \in Q_m$, so that for any $s \in \Sigma$, $f - sf = \alpha_s^{2m_s+1}t$, $t \in \mathbb{C}[\mathfrak{h}]$. Let us start by showing that $Lf$ is a polynomial. Clearly $Lf = \delta_s^{-1}q$, with $q \in \mathbb{C}[\mathfrak{h}]$, and $\delta_s = \prod_{s:m_s \neq 0} \alpha_s$. Since $L$ is $W$-invariant, $Lf - \gamma(Lf) = L(f - sf)$ is clearly divisible by $\alpha_s^{2m_s-1}$ if $m_s > 0$. In particular, it always is regular along the reflection hyperplane of $s$. On the other hand, since $Lf - \gamma(Lf) = \delta_s^{-1}(q + \gamma q)$, we deduce that $q + \gamma q$ is divisible by $\alpha_s$ if $m_s > 0$. But then $q = ((q + \gamma q) + (q - \gamma q))/2$ is divisible by $\alpha_s$ if $m_s > 0$, hence it is divisible by $\delta_s$, so that $Lf$ lies in $q \in \mathbb{C}[\mathfrak{h}]$.

We have already remarked that $L(f - sf)$ is divisible by $\alpha_s^{2m_s-1}$ if $m_s > 0$. In fact

$$L(f - sf) = (L\alpha_s^{2m+1})t + \alpha_s^{2m}\tilde{t}$$

$\tilde{t}$ being a suitable polynomial.

But since

$$L\alpha_s^{2m+1} = 2m_s(2m_s + 1)(\alpha_s, \alpha_s)\alpha_s^{2m_s-1} - 2m_s'(2m_s + 1)\sum_{s' \in \Sigma}(\alpha_{s'}, \alpha_s)\frac{\alpha_s^{2m_s}}{\alpha_{s'}} =$$

$$= -2m_s'(2m_s + 1)\sum_{s' \in \Sigma, s' \neq s}(\alpha_{s'}, \alpha_s)\frac{\alpha_s^{2m_s}}{\alpha_{s'}},$$

we deduce that $L(f - sf)$ is divisible by $\alpha_s^{2m_s}$. On the other hand, since $Lf - \gamma(Lf) = L(f - sf)$, this polynomial is either zero or it must vanish to odd order on the reflection hyperplane of $s$. We deduce that it must be divisible by $\alpha_s^{2m_s+1}$, proving that $Lf \in Q_m$.

We now pass to a general $L_q$, $q \in Q_m$. We can assume that $q$ is homogeneous of, say, degree $d$. By Corollary 3.3 we have that $L_q$ is a non zero multiple of $(adL)^d(q)$. Since both $q$ and $L$ preserve $Q_m$, our claim follows. $\square$
3.3 Differential operators on $X_m$

Now let us return to the algebra of differential operators $\mathcal{D}(X_m)$. Notice that $\mathcal{D}(X_m)$ contains two commutative subalgebras (both isomorphic to $Q_m$). The first is $Q_m$ itself, the second is the subalgebra $Q^\dagger_m$ consisting of the differential operators of the form $L_q$ with $q \in Q_m$. It is possible to show that:

**Theorem 3.6** [BEG] $\mathcal{D}(X_m)$ is generated by $Q_m$ and $Q^\dagger_m$.

Notice that by Corollary 3.3 we in fact have that $\mathcal{D}(X_m)$ is generated by $Q_m$ and by $L$.

**Example 3.7** If $W = \mathbb{Z}/2$, $\mathfrak{h} = \mathbb{C}$ we get that $\mathcal{D}(X_m)$ is generated by the operators

$$x^2, x^{2m+1}, \frac{d^2}{dx^2} - \frac{2m}{x} \frac{d}{dx}.$$ 

Theorem 3.6 together with Proposition 3.4, imply:

**Corollary 3.8** [BEG] $\mathcal{D}(X_m)$ is locally finite dimensional under the action of the Lie algebra $\mathfrak{sl}(2)$ defined in [8].

This Corollary implies that our $\mathfrak{sl}(2)$ action on $\mathcal{D}(X_m)$ can be integrated to an action of the group $SL(2)$. In particular we have that

$$\begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} q = L_q.$$ 

for all $q \in Q_m$. This transformation is a generalization of the Fourier transform, since it reduces to the usual Fourier transform on differential operators on $\mathfrak{h}$ when $m = 0$.

**Example 3.9** If $W = \mathbb{Z}/2$, $\mathfrak{h} = \mathbb{C}$, we get that the monomials $\{x^{2i}\} \cup \{x^{2i+2m+1}\}$ are (up to constants) all lowest weight vectors for the $\mathfrak{sl}(2)$ action on $\mathcal{D}(X_m)$. $x^n$ has weight $-n$. We deduce that $\mathcal{D}(X_m)$ is isomorphic as a $\mathfrak{sl}(2)$-module to the direct sum of the irreducible representations of dimension $n+1$ for $n$ even or $n = 2(m + i) + 1$, each with multiplicity one.

3.4 The Cherednik algebra

Let us now go back to the algebra $\mathcal{A}$ of operators on $U$ generated by $\mathcal{D}(U)$ and $W$. This algebra contains the Dunkl operators

$$D_y := \partial_y + \sum_{s \in \Sigma} c_s \frac{\alpha_s(y)}{\alpha_s} (s - 1).$$
Lemma 3.10 The following relations hold:

\[ [x_i, x_j] = [D_{x_i}, D_{x_j}] = 0, \quad \forall 1 \leq i, j \leq n \]

\[ [D_{x_i}, x_j] = \delta_{i,j} + \sum_{s \in \Sigma} c_s \frac{(x_i, \alpha_s)(x_j, \alpha_s)}{(\alpha_s, \alpha_s)} s, \quad \forall 1 \leq i, j \leq n \]

\[ wxw^{-1} = w(x), \quad wD_y w^{-1} = D_{w(y)}, \quad \forall w \in W, x \in h^*, y \in h \]

Proof. The proof is an easy computation, except the relations \([D_{x_i}, D_{x_j}] = 0\), which follow from Theorem 2.6.

Thus lemma motivates the following definition.

Definition 3.11 (see e.g. [EG]) The Cherednik algebra \(H_c\) is an associative algebra with generators \(x_i, y_i, i = 1, \ldots, n\), and \(w \in W\), with defining relations

\[ [x_i, x_j] = [y_i, y_j] = 0, \quad \forall 1 \leq i, j \leq n \]

\[ [y_i, x_j] = \delta_{i,j} + \sum_{s \in \Sigma} c_s \frac{(x_i, \alpha_s)(x_j, \alpha_s)}{(\alpha_s, \alpha_s)} s, \quad \forall 1 \leq i, j \leq n \]

\[ wxw^{-1} = w(x), \quad wyw^{-1} = w(y), \quad w \cdot w' = ww', \quad \forall w, w' \in W, x \in h^*, y \in h, \]

This algebra was introduced by Cherednik as a rational limit of his double affine Hecke algebra defined in [Ch]. Notice that if \(c = 0\) then \(H_c = D(h) \rtimes \mathbb{C}[W]\).

Lemma 3.11 implies that the algebra \(H_c\) is equipped with a homomorphism \(\phi : H_c \rightarrow A\), given by \(w \rightarrow w, x_i \rightarrow x_i, y_i \rightarrow D_{x_i}\).

Cherednik proved the following theorem.

Theorem 3.12 (Poincaré-Birkhoff-Witt theorem) The multiplication map

\[ \mu : \mathbb{C}[h] \otimes \mathbb{C}[h^*] \otimes \mathbb{C}[W] \]

given by \(\mu(f(x) \otimes g(y) \otimes w) = f(x)g(y)w\) is an isomorphism of vector spaces.

Proof. It is easy to see that the map \(\mu\) is surjective. Thus, we only have to show that it is injective. In other words, we need to show that monomials \(x_{i_1}^{j_1} \cdots x_{i_n}^{j_n} y_{i_1}^{j_1} \cdots y_{i_n}^{j_n} w\) are linearly independent in \(H_c\). To do this, it suffices to show that the images of these monomials under the homomorphism \(\phi\), i.e. \(x_{i_1}^{j_1} \cdots x_{i_n}^{j_n} D_{x_{i_1}}^{j_1} \cdots D_{x_{i_n}}^{j_n} w\), are linearly independent.

Given an element \(A \in A\), writing \(A = \sum_{w \in W} P_w w\) with \(P_w \in D(U)\) we define the order of \(A\), \(\text{ord}A\), as the maximum of the orders of the \(P_w\)'s. Notice that \(\text{ord}AB \leq \text{ord}A + \text{ord}B\). We now remark that for any sequence of non negative indices, \((i_1, \ldots, i_n)\),

\[ D_{x_{i_1}}^{j_1} \cdots D_{x_{i_n}}^{j_n} = \partial_{x_{i_1}}^{j_1} \cdots \partial_{x_{i_n}}^{j_n} + \text{l.o.t.} \]
Indeed this is true for \( D_{x_i} \). We proceed by induction on \( r = i_1 + \cdots + i_n \). We can clearly assume \( i_1 > 0 \), so by induction,

\[
D_{x_1}^{i_1} \cdots D_{x_n}^{i_n} = (\partial_{x_1} + \text{l.o.t.})(\partial_{x_1}^{i_1-1} \cdots \partial_{x_n}^{i_n} + \text{l.o.t.}) = \partial_{x_1}^{i_1} \cdots \partial_{x_n}^{i_n} + \text{l.o.t.}
\]

From this we deduce that for any pair of multiindices \( I = (i_1, \ldots, i_n) \), \( J = (j_1, \ldots, j_n) \), \( w \in W \), setting \( x_I = x_1^{i_1} \cdots x_n^{i_n} \), \( D_J = D_{x_1}^{j_1} \cdots D_{x_n}^{j_n} \), \( \partial_J = \partial_{x_1}^{j_1} \cdots \partial_{x_n}^{j_n} \), we have

\[
x_I D_J w = x_I \partial_J w + \text{l.o.t.}
\]

Using this and the linear independence of the elements \( x_I \partial_J w \), it is immediate to conclude that the elements \( x_I D_J w \) are linearly independent, proving our claim. 

\( \square \)

**Remark 1.** We see that the homomorphism \( \phi \) identifies \( H_c \) with the subalgebra of \( \mathcal{A} \) generated by \( \mathbb{C}[h] \), the Dunkl operators \( D_y \), \( y \in h \) and \( W \).

**Remark 2.** Another way to state the PBW theorem is the following. Let \( F^\bullet \) be a filtration on \( H_c \) defined by \( \deg(x_i) = \deg(y_i) = 1 \), \( \deg(w) = 0 \). Then we have a natural surjective mapping from \( \mathbb{C}[h \times h^\ast] \times W \) to the associated graded algebra \( \text{gr}(H_c) \). The PBW theorem claims that this map is in fact an isomorphism.

### 3.5 The spherical subalgebra

Let us now introduce the idempotent

\[
e = \frac{1}{W} \sum_{w \in W} w = \in \mathbb{C}[W].
\]

**Definition 3.13** The spherical subalgebra of \( H_c \) is the algebra \( eH_c e \).

Notice that \( 1 \notin eH_c e \). On the other hand, since \( ex = xe = e \) for \( x \in eH_c e \), \( e \) is the unit for the spherical subalgebra. We can embed both \( \mathbb{C}[h^\ast]^W \) and \( \mathbb{C}[h]^W \) in the spherical subalgebra as follows. Take \( f \in \mathbb{C}[h^\ast]^W \) (the other case is identical) and set \( m_e(f) = fe \). Since \( f \) is invariant, we have \( efe = e^2 = e = m_e(f) \), so that \( m_e \) actually maps \( \mathbb{C}[h^\ast]^W \) to \( eH_c e \). The injectivity is clear from the PBW-theorem. As for the fact that \( m_e \) is a homomorphism, we have \( m_e(fg) = fge = fge^2 = fege = m_e(f)m_e(g) \). From now on, we will consider both \( \mathbb{C}[h^\ast]^W \) and \( \mathbb{C}[h]^W \) as subalgebras of the spherical subalgebra.

### 3.6 Category \( O \)

We are now going to study representations of the algebras \( H_c \) and \( eH_c e \).
Definition 3.14 The category $\mathcal{O}(H_c)$ (resp. $\mathcal{O}(eH_c,e)$) is the full subcategory of the category of $H_c$-modules (resp. $eH_c,e$-modules) whose objects are the modules $M$ such that
1) $M$ is finitely generated.
2) For all $v \in M$, the subspace $\mathbb{C}[\mathfrak{h}^*]Wv \subset M$ is finite dimensional.

We can define a functor
$$F : \mathcal{O}(H_c) \to \mathcal{O}(eH_c,e)$$
by setting $F(M) = eM$. It is easy to show that $F(M)$ is a object of $\mathcal{O}(eH_c,e)$.

We are now going to explain how to construct some modules in $\mathcal{O}(H_c)$ which, by analogy with the case of enveloping algebras of semisimple Lie algebras, we will call Whittaker and Verma modules. First, take $\lambda \in \mathfrak{h}^*$. Denote by $W_\lambda \subset W$ the stabilizer of $\lambda$. Take an irreducible $W_\lambda$ module $\tau$. We define a structure of $C[\mathfrak{h}^*] \rtimes C[W_\lambda]$-module on $\tau$ by
$$(fw)v = f(\lambda)(wv), \forall v \in \tau, w \in W_\lambda, f \in C[\mathfrak{h}^*].$$
It is easy to see that this action is well defined and we call this module $\lambda\#\tau$. We can then consider the $H_c$-module
$$M(\lambda, \tau) = H_c \otimes_{C[\mathfrak{h}^*] \rtimes C[W_\lambda]} \lambda\#\tau$$
This is called a Whittaker module. In the special case $\lambda = 0$ (and hence $W_\lambda = W$), the module $M(0, \tau)$ is called a Verma module. It is clear that these are objects of $\mathcal{O}$. Notice that as $C[\mathfrak{h}] \rtimes C[W]$-module, $M(\lambda, \tau) = C[\mathfrak{h}] \otimes C[W] \otimes C[W_\lambda] \tau$.

Example 3.15 If $\lambda = 0$ and $\tau = 1$ is the trivial representation of $W$, the Verma module $M(0, 1) = C[\mathfrak{h}]$. The action of $C[\mathfrak{h}]$ is given by multiplication, the one of $C[\mathfrak{h}^*]$ is generated by the Dunkl operators and $W$ acts in the usual way.

3.7 Generic $c$

Opdam and Rouquier have recently studied the structure of the categories $\mathcal{O}(H_c)$, $\mathcal{O}(eH_c,e)$, and found that it is especially simple if $c$ is “generic” in a certain sense. Namely, recall that for a $W$-invariant function $q : \Sigma \to \mathbb{C}^*$ one may define the Hecke algebra $H_\mathfrak{q}(W)$ to be the quotient of the group algebra of the fundamental group of $U/W$ by the relations $(T_s - 1)(T_s + q_s) = 0$, where $T_s$ is the image in $U/W$ of a small half-circle around the hyperplane of $s$ in the counterclockwise direction. It is well known that $H_\mathfrak{q}(W)$ is an algebra of dimension $|W|$, which coincides with $C[W]$ if $q = 1$. It is also known that $H_\mathfrak{q}(W)$ is semisimple (and isomorphic to $C[W]$ as an algebra) unless $q_s$ for some $s$ belongs to a finite set of roots of unity depending on $W$. 

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Definition 3.16 The function $c$ is said to be generic if for $q = e^{2\pi ic}$, the Hecke algebra $He_q(W)$ is semisimple.

In particular, any irrational $c$ is generic, and (more importantly for us) an integer valued $c$ is generic (since in this case $q = 1$).

We can now state the following central result:

**Theorem 3.17** (Opdam-Rouquier [OR]; see also [BEG] for an exposition) If $c$ is generic (in particular, if $c$ takes non negative integer values), then the irreducible objects in $\mathcal{O}$ are exactly the modules $M(\lambda, \tau)$. Moreover, the category $\mathcal{O}$ is semisimple.

We also have

**Theorem 3.18** ([OR]) If $c$ is generic then the functor $F$ is an equivalence of categories.

From Theorem 3.17 we can deduce:

**Theorem 3.19** [BEG] If $c$ is generic then $H_c$ is a simple algebra.

In the case $c = 0$, we get the simplicity of $\mathbb{C}[\mathfrak{h} \otimes \mathfrak{h}^*] \rtimes \mathbb{C}[W]$, which is well known.

### 3.8 The Levasseur-Stafford theorem and its generalization

Let us now recall a result of Levasseur and Stafford:

**Theorem 3.20** [LS] If $G$ is a finite group acting on a finite dimensional vector space $V$ over the complex numbers, then the ring $D(V)^G$ is generated by the subrings $\mathbb{C}[V]^G$ and $\mathbb{C}[V^*]^G$.

As an example, notice that if we let $\mathbb{Z}/n\mathbb{Z}$ act on the complex line by multiplication by the $n$-th roots of 1, we deduce that the operator $x \frac{d}{dx}$ can be expressed as a non commutative polynomial in the operators $x^n$ and $\frac{d}{dx}$, a non-obvious fact. We note also that this theorem has a purely “quantum” nature, i.e. the corresponding “classical” statement, saying that the Poisson algebra $\mathbb{C}[V \times V^*]^G$ is generated, as a Poisson algebra, by $\mathbb{C}[V]^G$ and $\mathbb{C}[V^*]^G$, is actually false, already for $V = \mathbb{C}$ and $G = \mathbb{Z}/n\mathbb{Z}$.

One can prove a similar result for the algebra $eH_c e$. Namely, recall that the algebra $eH_c e$ contains the subalgebras $\mathbb{C}[\mathfrak{h}]^W$, and $\mathbb{C}[\mathfrak{h}^*]^W$.

**Theorem 3.21** [BEG] If $c$ is generic then the two subalgebras $\mathbb{C}[\mathfrak{h}]^W$ and $\mathbb{C}[\mathfrak{h}^*]^W$ generate $eH_c e$. 

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Notice that if \( c = 0 \), then \( eH_0e = D(h)^W \), so Theorem 3.21 reduces to the Levasseur-Stafford theorem.

Remark. It is believed that this result holds without the assumption of generic \( c \). Moreover, it is known to be true for all \( c \) if \( W \) is a Weyl group not of type \( E \) and \( F \), since in this case Wallach proved that the corresponding classical statement for Poisson algebras holds true. Nevertheless, the genericity assumption is needed for the proof, because, similarly to the proof of the Levasseur-Stafford theorem, it is based on the simplicity of \( H_c \).

### 3.9 The action of the Cherednik algebra to quasi-invariants

We now go back to the study of \( Q_m \). Notice that the algebra \( eH_m e \) acts on \( C[h]^W \), since \( e \) gives the \( W \)-equivariant projection of \( C[h] \) onto \( C[h]^W \). It is clear that this action is by differential operators. For instance, the subalgebra \( C[h]^W \subset eH_m e \) acts by multiplication. Also, an element \( q \in C[h^*]^W \subset eH_m e \) acts via the operator \( q(D_{x_1}, \ldots D_{x_n}) \). By definition this operator coincides with \( L_q \) on \( C[h]^W \).

The following important theorem shows that this action extends to \( Q_m \).

**Theorem 3.22** [BEG] There exists a unique representation of the algebra \( eH_m e \) on \( Q_m \) in which an element \( q \in C[h]^W \) acts by multiplication and an element \( q \in C[h^*]^W \) by \( L_q \).

**Proof.** Since by Proposition 3.5, \( L_q \) preserve \( Q_m \), we get a uniquely defined representation of the subalgebra of \( eH_m e \) generated by \( C[h]^W \) and \( C[h^*]^W \) on \( Q_m \). The result now follows from Theorem 3.21. \(\square\)

### 3.10 Proof of Theorem 1.8

Finally we can prove Theorem 1.8.

To do this, observe that as an \( eH_m e \)-module, \( Q_m \) is in the category \( O(eH_m e) \), and \( C[h^*]^W \) acts locally nilpotently in \( Q_m \) (by degree arguments). We can now apply Theorem 3.18 and Theorem 1.17 and deduce that \( Q_m \) is a direct sum of modules of the form \( eM(0, \tau) \). As a \( C[h] \times C[W] \)-module, \( M(0, \tau) = C[h] \otimes \tau \). On the other hand, by Chevalley theorem, there is an isomorphism \( C[h] \simeq C[h]^W \otimes C[W] \), commuting with the action of \( W \) and \( C[h]^W \). Thus we get an isomorphisms of \( C[h]^W \)-modules

\[
eM(0, \tau) \simeq (M(0, \tau))^W \simeq C[h]^W \otimes (C[W] \otimes \tau)^W \simeq C[h]^W \otimes \tau
\]

proving that \( eM(0, \tau) \) and hence \( Q_m \) is a free \( C[h]^W \)-module. \(\square\)

**Example 3.23** For \( W = \mathbb{Z}/2 \) and \( h = \mathbb{C} \), take the polynomials \( 1, x^{2m+1} \). Notice that \( L(1) = L(x^{2m+1}) = 0 \) while \( s(1) = 1, s(x^{2m+1}) = -x^{2m+1}, s \in \mathbb{Z}/2 \) being the
element of order two. It follows that $Q_m$ as an $eH_m e$-module is the direct sum of $\mathbb{C}[x^2] \oplus x^{2m+1} \mathbb{C}[x^2]$. These modules are irreducible. Moreover, $\mathbb{C}[x^2] \simeq eM(0, 1)$, $x^{2m+1} \mathbb{C}[x^2] \simeq eM(0, \varepsilon)$, $\varepsilon$ being the sign representation.

3.11 Proof of Theorem 1.15

Let $I$ be a nonzero two-sided ideal in $\mathcal{D}(X_m)$. First we claim that $I$ nontrivially intersects $Q_m$. Indeed, otherwise let $K \in I$ be a lowest order nonzero element in $I$. Since the order of $K$ is positive, there exists $f \in Q_m$ such that $[K, f] \neq 0$. Then $[K, f] \in I$ is of smaller order than $K$. Contradiction.

Now let $f \in Q_m$ be an element of $I$. Then $g = \prod_{w \in W} w f \in I$. But $g$ is $W$-invariant. This shows that the intersection $J$ of $I$ with the subalgebra $H_m$ in $\mathcal{D}(X_m)$ is nonzero. But $H_m$ is simple, so $J = H_m$. Hence, $1 \in J \subset I$, and $I = \mathcal{D}(X_m)$.

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