EULERIAN GRADED $\mathcal{D}$-MODULES

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Abstract. Let $R = K[x_1, \ldots, x_n]$ with $K$ a field of arbitrary characteristic and $\mathcal{D}$ be the ring of differential operators over $R$. Inspired by Euler formula for homogeneous polynomials, we introduce a class of graded $\mathcal{D}$-modules, called Eulerian graded $\mathcal{D}$-modules. It is proved that a vast class of $\mathcal{D}$-modules, including all local cohomology modules $H^s_1 \cdots H^s_s(R)$ where $J_1, \ldots, J_s$ are homogeneous ideals of $R$, are Eulerian. As an application of our theory of Eulerian graded $\mathcal{D}$-modules, we prove that all socle elements of each local cohomology module $H^i_0 \cdots H^i_s(R)$ must be in degree $-n$ in all characteristic. This answers a question raised in [12]. It is also proved that graded $F$-modules are Eulerian and hence the main result in [12] is recovered. An application of our theory of Eulerian graded $\mathcal{D}$-modules to the graded injective hull of $R/P$, where $P$ is a homogeneous prime ideal of $R$, is discussed as well.

1. Introduction

Let $R = K[x_1, \ldots, x_n]$ be a polynomial ring in $n$ indeterminates over a field $K$ with the standard grading, i.e., $\deg(x_i) = 1$ for each $x_i$ and $\deg(c) = 0$ for each nonzero $c \in K$. Let $\partial_i^{[j]}$ denote the $j$th order differential operator $\frac{1}{j!} \partial_i^j$ with respect to $x_i$ for each $0 \leq i \leq n$ and $j \geq 1$. By [4, Théorème 16.11.2], $\mathcal{D} = R(\partial_i^{[j]} | 1 \leq i \leq n, 1 \leq j)$ is the ring of $K$-linear differential operators of $R$ (note if $K$ has characteristic 0, $\mathcal{D}$ is the same as the Weyl algebra $R(\partial_1, \ldots, \partial_n)$). The ring of $K$-linear differential operators $\mathcal{D}$ has a natural $\mathbb{Z}$-grading given by $\deg(x_i) = 1$, $\deg(\partial_i^{[j]}) = -j$, and $\deg(c) = 0$ for each $x_i, \partial_i^{[j]}$ and each nonzero $c \in K$.

The classical Euler formula for homogeneous polynomials says that

$$\sum_{i=1}^{n} x_i \partial_i f = \deg(f) f$$

for each homogeneous polynomial $f \in R$. Inspired by Euler formula, we introduce a class of $\mathcal{D}$-modules called Eulerian graded $\mathcal{D}$-modules: the graded $\mathcal{D}$-modules whose homogeneous elements satisfy a series of “higher order Euler formulas” (cf. Definition 2.1). One of our main results concerning Eulerian graded $\mathcal{D}$-modules is the following (proved in Sections 2 and 5):

**Theorem 1.1.** Let $R = K[x_1, \ldots, x_n]$, $\mathfrak{m} = (x_1, \ldots, x_n)$, and $J_1, \ldots, J_s$ be homogeneous ideals of $R$. Then

1. $R(\ell)$ is Eulerian if and only if $\ell = 0$.
2. Let $^*E$ be the graded injective hull of $R/\mathfrak{m}$. Then $^*E(\ell)$ is Eulerian if and only if $\ell = n$.

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(3) Each local cohomology module $H_{J_1}^{i_1}(\cdots (H_{J_s}^{i_s}(R)))$ is Eulerian for all $i_1, \ldots, i_s$.

As an application of our theory of Eulerian graded $\mathcal{D}$-modules, we have the following result on local cohomology (proved in Section 5):

**Theorem 1.2.** Let notations be as in the previous theorem. Then all socle elements of each $H_{m}^{i_0}(H_{J_1}^{i_1}(\cdots (H_{J_s}^{i_s}(R)))$ must have degree $-n$, and consequently each $H_{m}^{i_0}(H_{J_1}^{i_1}(\cdots (H_{J_s}^{i_s}(R)))$ is isomorphic (as a graded $\mathcal{D}$-module) to a direct sum of copies of $^*E(n)$.

This result is characteristic-free, in particular it gives a positive answer to a question stated in [12] and recovers the main theorem in [12].

The paper is organized as follows. In Section 2, Eulerian graded $\mathcal{D}$-modules are defined over an arbitrary field and some basic properties of these modules are discussed. In Sections 3 and 4, we consider Eulerian graded $\mathcal{D}$-modules in characteristic 0 and characteristic $p$, respectively; in particular, we show in Section 4 that each graded $F$-module (introduced in [12]) is Eulerian. In Section 5, we apply our theory of Eulerian graded $\mathcal{D}$-modules to local cohomology modules; Theorem 1.2 is proved in this section. Finally, in Section 6, an application of our theory to graded injective hull of $R/P$, where $P$ is a homogeneous prime ideal, is considered.

We finish our introduction by fixing our notation throughout the paper as follows. $R = K[x_1, \ldots, x_n]$ denotes the polynomial ring in $n$ indeterminates over a field $K$. The $j$th order differential operator $\frac{1}{j!} \cdot \frac{\partial^j}{\partial x_i^j}$ with respect to $x_i$ is denoted by $\partial_i^{[j]}$ and $\mathcal{D} = R(\partial_i^{[j]} | 1 \leq i \leq n, 1 \leq j)$ denotes the ring of differential operators over $R$. It follows from [10, Corollary 2.2] that every element of $\mathcal{D}$ may be uniquely written as a linear combinations of monomials in $x$’s and $\partial$’s. The natural $\mathbb{Z}$-grading on $R$ and $\mathcal{D}$ is given by

$$\deg(x_i) = 1, \quad \deg(\partial_i^{[j]}) = -j, \quad \deg(c) = 0$$

for each $x_i, \partial_i^{[j]}$ and nonzero $c \in K$ (it is evident that $R$ is a graded $\mathcal{D}$-module).

A graded $\mathcal{D}$-module is a left $\mathcal{D}$-module with a $\mathbb{Z}$-grading that is compatible with the natural $\mathbb{Z}$-grading on $\mathcal{D}$. Given any graded $\mathcal{D}$-module $M$, the module $M(\ell)$ denotes $M$ with degree shifted by $\ell$, i.e., $M(\ell)_i = M_{\ell+i}$ for each $i$.

For each integer $a$ and a nonnegative integer $b$, we will use $\binom{a}{b}$ to denote

$$\frac{a \cdot (a - 1) \cdots (a - b + 1)}{b!}$$

(note that this number is still well-defined when $\text{char}(K) = p > 0$).

The irrelevant maximal ideal $(x_1, \ldots, x_n)$ of $R$ is denoted by $m$. The graded injective hull of $R/m$ is denoted by $^*E$. It may be identified with the $K$-vector space with a basis $\left\{ \frac{1}{x_1 \cdots x_n} e_1, \ldots, e_n \geq 1 \right\}$ and it has a natural $\mathcal{D}$-module structure given by

$$\partial_i^{[j]} \cdot \frac{1}{x_1 e_1 \cdots x_n e_n} = \binom{-e_i}{j} \frac{1}{x_1^{e_1} \cdots x_j^{e_j} \cdots x_n^{e_n}}.$$

$^*E$ is graded to the effect that the element $\frac{1}{x_1 \cdots x_n}$ has degree 0 (cf. [2, Example 13.3.9]).
2. Eulerian graded \( \mathcal{D} \)-modules

In this section, we introduce Eulerian graded \( \mathcal{D} \)-modules and discuss some of their basic properties. We begin with the following definition.

**Definition 2.1.** The \( r \)th Euler operator, denoted by \( E_r \), is defined as

\[
E_r : = \sum_{i_1 + i_2 + \cdots + i_n = r, i_1 \geq 0, \ldots, i_n \geq 0} x_1^{i_1} \cdots x_n^{i_n} \partial_1^{[i_1]} \cdots \partial_n^{[i_n]}.
\]

In particular, \( E_1 \) is the usual Euler operator \( \sum_{i=1}^n x_i \partial_i \).

A graded \( \mathcal{D} \)-module \( M \) is called Eulerian, if each homogeneous element \( z \in M \) satisfies

\[
E_r \cdot z = \left( \frac{\deg(z)}{r} \right) z
\]

for every \( r \geq 1 \).

We start with an easy lemma.

**Lemma 2.2.** For all positive integers \( s \) and \( t \), we have

\[
\partial_i^{[s]} \partial_i^{[t]} = \binom{s + t}{s} \partial_i^{[s+t]}.
\]

**Proof.** It is easy to check that (in all characteristic)

\[
\partial_i^{[s]} \partial_i^{[t]} = \frac{s! \ t!}{s! \ t!} \partial_i^{s+t} = \binom{s + t}{s} \partial_i^{[s+t]}.
\]

\( \Box \)

The following lemma is a special case of [10, Proposition 2.1] (with \( f = x_1^t \)), which will be needed in the sequel.

**Lemma 2.3.** For all positive integers \( s \) and \( t \), we have

\[
\partial_i^{[s]} x_i^t = \sum_{j=0}^{\min\{s,t\}} \binom{t}{j} x_i^{t-j} \partial_i^{[s-j]}
\]

for each \( i \).

The following proposition indicates a connection among Euler operators.

**Proposition 2.4.** For every \( r \geq 1 \), we have

\[
E_1 \cdot E_r = (r + 1) E_{r+1} + r E_r.
\]
Proof. By Lemma 2.2 we know $\partial_i \partial_j^{[j]} = (j+1) \partial_i^{[j+1]}$. Now we have

$$E_1 \cdot E_r = \sum_j x_j \partial_j \cdot \sum_{i_1 + i_2 + \ldots + i_n = r} x_1^{i_1} x_2^{i_2} \ldots x_n^{i_n} \partial_1^{[i_1]} \partial_2^{[i_2]} \ldots \partial_n^{[i_n]}$$

$$= \sum_j \sum_{i_1 + i_2 + \ldots + i_n = r} x_j^{i_j} x_1^{i_1} \ldots x_n^{i_n} \partial_1^{[i_1]} \partial_2^{[i_2]} \ldots \partial_n^{[i_n]}$$

by Lemma 2.3

$$= \sum_{i_1 + i_2 + \ldots + i_n = r} \sum_j x_1^{i_1} \ldots x_j^{i_j+1} \ldots x_n^{i_n} \partial_1^{[i_1]} \ldots (\partial_j \partial_j^{[i_j]} \ldots \partial_n^{[i_n]})$$

$$+ \sum_{i_1 + i_2 + \ldots + i_n = r} \sum_j i_j x_1^{i_1} \ldots x_n^{i_n} \partial_1^{[i_1]} \ldots \partial_n^{[i_n]}$$

$$= \sum_{i_1 + i_2 + \ldots + i_n = r} \sum_j (i_j + 1) x_1^{i_1} \ldots x_j^{i_j+1} \ldots x_n^{i_n} \partial_1^{[i_1]} \ldots \partial_j^{[i_j+1]} \ldots \partial_n^{[i_n]} + r E_r$$

$$= (r+1) E_{r+1} + r E_r.$$

\[\square\]

Some remarks are in order.

Remark 2.5. (1) If $M$ is an Eulerian graded $\mathcal{D}$-module, then $M(\ell)$ is Eulerian if and only if $\ell = 0$ (consequently, for any graded $\mathcal{D}$-module $M$, $M(\ell)$ is Eulerian graded for at most one $\ell$). This follows from the following claim.

Claim 2.5.1. $\left(\begin{array}{c} a \\ r \end{array}\right) = \left(\begin{array}{c} b \\ r \end{array}\right)$ for all $r \in \mathbb{N}$ if and only if $a = b$.

Proof. The claim is trivial in characteristic 0 (by simply setting $r = 1$). Next, we consider the case in characteristic $p > 0$. Assume that $\left(\begin{array}{c} a \\ r \end{array}\right) = \left(\begin{array}{c} b \\ r \end{array}\right)$ for all $r \in \mathbb{N}$ and we wish to show that $a = b$. If one of $a, b$ is 0, the conclusion is clear. Hence, there are three possibilities:

(i) $a, b > 0$;
(ii) $a, b < 0$;
(iii) $ab < 0$.

(i) If both $a$ and $b$ are positive, then by a theorem of Lucas [6], we have

$$\left(\begin{array}{c} a \\ r \end{array}\right) = \prod_{i} \left(\begin{array}{c} a_i \\ r_i \end{array}\right),$$

where $a = \sum a_i p^i$ and $r = \sum r_i p^i$ are the $p$-adic decompositions of $a$ and $r$.

In particular, if we apply $\left(\begin{array}{c} a \\ r \end{array}\right) = \left(\begin{array}{c} b \\ r \end{array}\right)$ to $r = p^i$, we get $a_i = b_i$ for every $i$, hence $a = b$.

(ii) When $a$ and $b$ are both negative, we look at the $p$-adic expansions of $-a - 1$ and $-b - 1$:

$$-a - 1 = \sum_i a_i p^i,$$
$$-b - 1 = \sum_i b - ip^i.$$
Setting \( r = p^i \), we get

\[
(-1)^{p^i} \cdot (a_i + 1) = (-1)^{p^i} \left( -a + p^i - 1 \right) = \left( \frac{a}{p^i} \right) = \left( \frac{b}{p^i} \right) = \left( \frac{-b + p^i - 1}{p^i} \right) = (-1)^{p^i} \cdot (b_i + 1).
\]

Hence we have \( a_i = b_i \) for every \( i \). Therefore \( -a - 1 = -b - 1 \) whence \( a = b \).

(iii). If \( a > 0 \) and \( b < 0 \), we can pick \( r = p^j \gg a - b \), then direct computation (or using the theorem of Lucas [6]) gives \( \left( \frac{a}{p^j} \right) = 0 \) while \( \left( \frac{b}{p^j} \right) = (-1)^{p^j} \), which is a contradiction. Likewise, it is also impossible to have \( a < 0, b > 0 \). This finishes the proof of our claim. \( \square \)

(2) Definition 2.1 does not depend on the characteristic of \( K \). However, we will see in Section 3 that, in characteristic 0, we only need to consider \( E_1 \), the usual Euler operator.

(3) \( R \) is Eulerian and a proof goes as follows. For each monomial \( x_1^{j_1} x_2^{j_2} \cdots x_n^{j_n} \), where \( j_n \)'s are arbitrary integers (we allow negative integers), we have (for each \( r \geq 1 \))

\[
E_r \cdot x_1^{j_1} x_2^{j_2} \cdots x_n^{j_n} = \left( \sum_{i_1 + i_2 + \cdots + i_n = r} x_1^{i_1} x_2^{i_2} \cdots x_n^{i_n} \partial_1^{i_1} \partial_2^{i_2} \cdots \partial_n^{i_n} \right) \cdot (x_1^{j_1} x_2^{j_2} \cdots x_n^{j_n}) = \sum_{i_1 + i_2 + \cdots + i_n = r} \binom{j_1}{i_1} \cdots \binom{j_n}{i_n} \cdot x_1^{j_1} x_2^{j_2} \cdots x_n^{j_n}.
\]

We explain the last equality: we use an induction argument. It is clear when \( r = 1 \), now suppose we have the equality for \( r - 1 \). Then

\[
\sum_{i_1 + i_2 + \cdots + i_n = r} \binom{j_1}{i_1} \cdots \binom{j_n}{i_n} = \sum_{i_n = 0}^{r} \binom{j_n}{i_n} \sum_{i_1 + i_2 + \cdots + i_{n-1} = r - i_n} \binom{j_1}{i_1} \cdots \binom{j_{n-1}}{i_{n-1}} = \sum_{i_n = 0}^{r} \binom{j_n}{i_n} \binom{j_1 + \cdots + j_{n-1}}{r - i_n} = \binom{j_1 + \cdots + j_n}{r},
\]
where the second equality is by induction hypothesis for \( r - 1 \), and the last equality is by the Chu–Vandermonde identity (see [3, page 44])

\[
\binom{a}{r} = \sum_{k=0}^{r} \binom{j}{k} \binom{a-j}{r-k}.
\]

Since \( x_1^{j_1} x_2^{j_2} \cdots x_n^{j_n} \) clearly has degree \( j_1 + \cdots + j_n \) in \( R \) and the \( E_r \)'s clearly preserve addition, we can see from the computation above that \( E_r \cdot z = \left( \deg(z) \right) \cdot z \) for every homogeneous \( z \in R \). Therefore, \( R \) is Eulerian.

(4) \( \mathcal{D} \) is not Eulerian. It is clear that the identity \( 1 \in \mathcal{D} \) is homogeneous with degree 0, but \( E_1 \cdot 1 = \left( \sum_{i=1}^{n} x_i \partial_i \right) \cdot 1 = \sum_{i=1}^{n} x_i \partial_i \neq 0 \).

One of the main results in this section is that, to check whether a graded \( \mathcal{D} \)-module is Eulerian, it suffices to check whether each element of any set of homogeneous generators satisfies (1).

**Theorem 2.6.** Let \( M \) be a graded \( \mathcal{D} \)-module. Assume that \( \{g_1, g_2, \ldots\} \) is a set of homogeneous \( \mathcal{D} \)-generators of \( M \). Then, \( M \) is Eulerian if and only if each \( g_j \) satisfies Euler formula (1) for every \( r \).

**Proof.** If \( M \) is Eulerian, then it is clear that each \( g_j \) satisfies Euler formula (1) for every \( r \). Assume that each \( g_j \) satisfies Euler formula (1) for every \( r \) and we wish to prove that \( M \) is Eulerian. To this end, it suffices to show that, if a homogeneous element \( z \in M \) satisfies Euler formula (1) for every \( r \), then so does \( x_1^{s_1} \cdots x_n^{s_n} \partial_1^{[j_1]} \cdots \partial_n^{[j_n]} \cdot z \).

And it is clear that it suffices to consider \( x_1^{s_1} \partial_1^{[j]} \cdot z \). Without loss of generality, we may assume that \( i = 1 \). We will prove this in two steps; first we consider \( \partial_1^{[j]} \cdot z \) and then \( x_1^{s} \cdot z \) (once we finish our first step, we may replace \( \partial_1^{[j]} \cdot z \) by \( z \) and then our second step will finish the proof).

First we will use induction on \( r \) to show that \( \partial_1^{[j]} \cdot z \) satisfies Euler formula (1) for each \( r \). When \( r = 1 \), we compute

\[
E_1 \cdot (\partial_1^{[j]} z) = \sum_{i=1}^{n} x_i \partial_i \cdot (\partial_1^{[j]} z)
= x_1 \partial_1^{[j]} \partial_1 z + \partial_1^{[j]} \sum_{i \geq 2} x_i \partial_i \cdot z
= \partial_1^{[j]} x_1 \partial_1 z - \partial_1^{[j-1]} \partial_1 z + \partial_1^{[j]} \sum_{i \geq 2} x_i \partial_i \cdot z
= \partial_1^{[j]} \sum_{i=1}^{n} x_i \partial_i \cdot z - j \partial_1^{[j]} z
= (\deg(z) - j) \cdot \partial_1^{[j]} z.
\]
Now for general $r$, suppose we know that $E_{r-k} \cdot (\partial_1^{[j]} z) = \binom{\deg(z) - j}{r - k} \cdot \partial_1^{[j]} z$ for every $1 \leq k \leq r - 1$. Then we have
\[
\left( \sum_{i_1 + i_2 + \cdots + i_n = r} x_1^{i_1} x_2^{i_2} \cdots x_n^{i_n} \partial_1^{[i_1]} \partial_2^{[i_2]} \cdots \partial_n^{[i_n]} \right) \cdot (\partial_1^{[j]} z) = \sum_{i_1 + i_2 + \cdots + i_n = r} (x_1^{i_1} \partial_1^{[j]} z) x_2^{i_2} \cdots x_n^{i_n} \partial_1^{[i_1]} \partial_2^{[i_2]} \cdots \partial_n^{[i_n]} \cdot z
\]
(1)
\[
= \sum_{i_1 + i_2 + \cdots + i_n = r} (\partial_1^{[j]} x_1^{i_1} z) x_2^{i_2} \cdots x_n^{i_n} \partial_1^{[i_1]} \partial_2^{[i_2]} \cdots \partial_n^{[i_n]} \cdot z
\]
\[
- \sum_{i_1 + i_2 + \cdots + i_n = r} \min\{i_1, j\} k \sum_{k=1}^{\min\{i_1, j\}} x_1^{i_1 - k} x_2^{i_2} \cdots x_n^{i_n} \partial_1^{[i_1]} \partial_2^{[i_2]} \cdots \partial_n^{[i_n]} \cdot z
\]
\[
= \binom{\deg(z)}{r} \cdot (\partial_1^{[j]} z) - \sum_{i_1 + i_2 + \cdots + i_n = r} \binom{\min\{i_1, j\}}{k} x_1^{i_1 - k} x_2^{i_2} \cdots x_n^{i_n} \partial_1^{[i_1]} \partial_2^{[i_2]} \cdots \partial_n^{[i_n]} \cdot z
\]
(2)
\[
\cdots \partial_n^{[i_n]} \cdot (\partial_1^{[j - k]} z)
\]
\[
= \binom{\deg(z)}{r} \cdot (\partial_1^{[j]} z) - \sum_{i_1 + i_2 + \cdots + i_n = r} \binom{\min\{i_1, j\}}{k} x_1^{i_1 - k} x_2^{i_2} \cdots x_n^{i_n} \partial_1^{[i_1]} \partial_2^{[i_2]} \cdots \partial_n^{[i_n]} \cdot (\partial_1^{[k]} \partial_1^{[j - k]} z)
\]
\[
= \binom{\deg(z)}{r} \cdot (\partial_1^{[j]} z) - \sum_{i_1 + i_2 + \cdots + i_n = r} \binom{\min\{i_1, j\}}{k} x_1^{i_1 - k} x_2^{i_2} \cdots x_n^{i_n} \partial_1^{[i_1]} \partial_2^{[i_2]} \cdots \partial_n^{[i_n]} \cdot (\partial_1^{[k]} \partial_1^{[j - k]} z)
\]
(3)
\[
\cdot \left( \frac{j}{k} \right) (\partial_1^{[j]} z)
\]
\[
= \binom{\deg(z)}{r} \cdot (\partial_1^{[j]} z) - \sum_{k=1}^{\min\{i_1, j\}} \binom{j}{k} x_1^{i_1} x_2^{i_2} \cdots x_n^{i_n} \partial_1^{[i_1]} \partial_2^{[i_2]} \cdots \partial_n^{[i_n]}
\]
(4)
\[
\cdot (\partial_1^{[j]} z)
\]
(5)
\[
= \binom{\deg(z) - j}{r} \cdot (\partial_1^{[j]} z) - \sum_{k=1}^{j} \binom{j}{k} \binom{\deg(z) - j}{r - k} \cdot (\partial_1^{[j]} z)
\]
(6)
where (1) follows from Lemma 2.3:
\[ x_1^{i_1} \partial_1^{[j]} = \partial_1^{[j]} x_1^{i_1} - \sum_{k=1}^{\min\{i_1,j\}} \binom{i_1}{k} x_1^{i_1-k} \partial_1^{[j-k]}; \]

(2) and (3) follow from Lemma 2.2;
(4) is obtained by setting \( i_1' = i_1 - k; \)
(5) is true by induction on \( r; \)
(6) follows from the Chu–Vandermonde identity ([3, page 44])
\[ \binom{a}{r} = \sum_{k=0}^{j} \binom{j}{k} \binom{a-j}{r-k}. \]

This completes our first step.

Next we consider \( x_1 \cdot z \) and we have
\[
\left( \sum_{i_1+i_2+\ldots+i_n=r} x_1^{i_1} x_2^{i_2} \ldots x_n^{i_n} \partial_1^{[i_1]} \partial_2^{[i_2]} \ldots \partial_n^{[i_n]} \right) \cdot (x_1 \cdot z) = \left( \sum_{i_1+i_2+\ldots+i_n=r} x_1^{i_1} x_2^{i_2} \ldots x_n^{i_n} (\partial_1^{[i_1]} x_1) \partial_2^{[i_2]} \ldots \partial_n^{[i_n]} \right) \cdot z.
\]
\[
= \left( \sum_{i_1+i_2+\ldots+i_n=r, i_1 \geq 1} x_1 x_2^{i_2} \ldots x_n^{i_n} (x_1 \partial_1^{[i_1]} + \partial_1^{[i_1-1]} \partial_2^{[i_2]} \ldots \partial_n^{[i_n]}) + x_1 \right) \cdot z
\]
\[
= x_1 \left( \sum_{i_1+i_2+\ldots+i_n=r} x_1^{i_1} x_2^{i_2} \ldots x_n^{i_n} \partial_1^{[i_1]} \partial_2^{[i_2]} \ldots \partial_n^{[i_n]} + \sum_{i_1+i_2+\ldots+i_n=r, i_1 \geq 1} x_2^{i_2} \ldots x_n^{i_n} \partial_1^{[i_1-1]} \partial_2^{[i_2]} \ldots \partial_n^{[i_n]} \right) \cdot z.
\]
\[
= x_1 \left( \binom{\deg(z)}{r} + \binom{\deg(z)}{r-1} \right) \cdot z = \left( \binom{\deg(z) + 1}{r} \right) (x_1 \cdot z) = \left( \binom{\deg(x_1 \cdot z)}{r} \right) (x_1 \cdot z).
\]

This finishes our second step in the case when \( s = 1. \)

Now we consider \( x_1^s \cdot z \) when \( s \geq 2. \) By an easy induction we may assume that \( x_1^{s-1}z \) satisfies (1), now we have
\[
E_r(x_1^s z) = E_r(x_1 x_1^{s-1} z) = \left( \binom{\deg(x_1(x_1^{s-1} z))}{r} \right) (x_1 (x_1^{s-1} z)) = \left( \binom{\deg(x_1^s z)}{r} \right) (x_1^s z),
\]
where the second equality is the case when \( s = 1 \) (because we assume that \( x_1^{s-1}z \) satisfies (1)). This completes the proof of our theorem. \( \square \)

An immediate consequence of Theorem 2.6 on cyclic \( \mathcal{D} \)-modules is the following.

**Proposition 2.7.** Let \( J \) be a homogeneous left ideal in \( \mathcal{D} \). Then \( \mathcal{D} / J \) is Eulerian if and only if \( E_r = \sum_{i_1+i_2+\cdots+i_n=r} x_1^{i_1} x_2^{i_2} \cdots x_n^{i_n} \partial_1^{[i_1]} \partial_2^{[i_2]} \cdots \partial_n^{[i_n]} \in J \) for every \( r \).

**Proof.** According to Theorem 2.6, \( \mathcal{D} / J \) is Eulerian if and only if \( 1 \in \mathcal{D} / J \) satisfies Euler’s formula (1). Since \( 1 \) has degree 0, \( 1 \in \mathcal{D} / J \) satisfies Euler’s formula (1) if and only if \( E_r \cdot 1 = 0 \in \mathcal{D} / J \), which holds if and only if \( E_r \in J \) for every \( r \). \( \square \)

**Proposition 2.8.** If a graded \( \mathcal{D} \)-module \( M \) is Eulerian, so are each graded submodule of \( M \) and each graded quotient of \( M \).

**Proof.** Let \( N \) be a graded submodule of \( M \). Since each homogeneous element is also a homogeneous element in \( M \), it is clear that \( N \) is also Eulerian. Given a \( \mathcal{D} \)-linear degree-preserving surjection \( \psi : M \to M' \) and a homogeneous element \( z' \in M' \), there is a homogeneous \( z \in M \) with the same degree such that \( \psi(z) = z' \) and hence we have (for every \( r \))

\[
E_r \cdot z' = E_r \cdot \psi(z) = \psi(E_r \cdot z) = \psi\left( \binom{\deg(z)}{r} \cdot z \right) = \binom{\deg(z')}{r} \cdot z'.
\]

This proves that \( M' \) is also Eulerian. \( \square \)

We end this section with the following result which is one of the key ingredients for our application to local cohomology.

**Theorem 2.9.**

1. The graded \( \mathcal{D} \)-module \( R(\ell) \) is Eulerian if and only if \( \ell = 0 \).
2. The graded \( \mathcal{D} \)-module \( ^*E(\ell) \) is Eulerian if and only if \( \ell = n \).

**Proof.** By Remark 2.5 (1), it suffices to show that \( R(0) \) and \( ^*E(n) \) are Eulerian graded. It is clear that \( R = R(0) \) is Eulerian by Remark 2.5 (3). Since \( ^*E(\ell) \) is spanned over \( K \) by \( x_1^{j_1} x_2^{j_2} \cdots x_n^{j_n} \) with each \( j_i \leq -1 \). By the computation in Remark 2.5 (3), it is clear that \( ^*E(n) \) is Eulerian graded (because in \( ^*E(n) \), the element \( x_1^{j_1} x_2^{j_2} \cdots x_n^{j_n} \) has degree \( j_1 + \cdots + j_n \)). \( \square \)

3. Eulerian graded \( \mathcal{D} \)-modules in characteristic 0

Throughout this section \( K \) will be a field of characteristic 0. In this section, we collect some properties of Eulerian graded \( \mathcal{D} \)-modules when \( \text{char}(K) = 0 \). The main result is that, if a graded \( \mathcal{D} \)-module \( M \) is Eulerian, then so is \( M_f \) for each \( f \in R \). This is one of the ingredients for our application to local cohomology in Section 5. First we observe that, in characteristic 0, if each homogeneous element \( z \) in a graded \( \mathcal{D} \)-module \( M \) satisfies (1) for \( r = 1 \) (instead of for all \( r \geq 1 \)), then \( M \) is Eulerian.

**Proposition 3.1.** Let \( M \) be a graded \( \mathcal{D} \)-module. If \( E_1 \cdot z = \deg(z) \cdot z \) for every homogeneous element \( z \in M \). Then \( M \) is Eulerian.
Proof. We prove by induction that $E_r \cdot z = \binom{\deg(z)}{r} \cdot z$ for every $r \geq 1$. When $r = 1$ this is exactly $E_1 \cdot z = \deg(z) \cdot z$ which is given. Now suppose we know $E_r \cdot z = \binom{\deg(z)}{r} \cdot z$. By Proposition 2.4, we know that $E_{r+1} = \frac{1}{r+1} (E_1 \cdot E_r - rE_r)$. So we have

$$E_{r+1} \cdot z = \frac{1}{r+1} (E_1 \cdot E_r - rE_r) \cdot z$$

$$= \frac{1}{r+1} \left( E_1 \cdot \binom{\deg(z)}{r} \cdot z - r \cdot \binom{\deg(z)}{r} \cdot z \right)$$

$$= \frac{1}{r+1} \cdot \binom{\deg(z)}{r} \cdot (\deg(z) \cdot z - rz)$$

$$= \frac{1}{r+1} \cdot \binom{\deg(z)}{r} (\deg(z) - r) \cdot z$$

$$= \binom{\deg(z)}{r+1} \cdot z,$$

where the second equality uses the induction hypothesis. This finishes the proof. □

Remark 3.2. As we have seen, Lemma 2.4 is quite useful when char($K$) = 0. Unfortunately, this is no longer the case once we are in characteristic $p$. For instance, when $r \equiv -1 \pmod{p}$, we cannot link $E_{r+1}$ and $E_r$ via Lemma 2.4. This is one of the reasons that we treat characteristic 0 and characteristic $p$ separately in two different sections.

Corollary 3.3. Let $J$ be a homogeneous left ideal in $\mathcal{D}$. Then $\mathcal{D}/J$ is Eulerian if and only if $\sum_{i=1}^{n} x_i \partial_i \in J$.

Proof. This is clear from Proposition 3.1 and (the proof of) Proposition 2.7. □

Remark 3.4. One particular case of Corollary 3.3 is when $J = \mathcal{D} \cdot E_1$, the left ideal generated by the Euler operator $E_1$. It was pointed out to the authors by Professor Mircea Mustață that, according to [1, VII, 9.2], the ring of differential operators $\mathcal{D}(\mathbb{P}^{n-1})$ on $\mathbb{P}^{n-1}$ can be identified with $(\mathcal{D}/\mathcal{D} \cdot E_1)^{\mathbb{C}^n}$.

Proposition 3.5. If $M$ is an Eulerian graded $\mathcal{D}$-module, so is $S^{-1}M$ for each homogeneous multiplicative system $S \subseteq R$. In particular, $M_f$ is Eulerian for each homogeneous polynomial $f \in R$. 
Proof. By Proposition 3.1, it suffices to show for each homogeneous \( f \in S \) and \( z \in M \), we have \( E_1 \cdot \frac{z}{f^t} = \deg \left( \frac{z}{f^t} \right) \cdot \frac{z}{f^t} \). Now we compute

\[
E_1 \cdot \frac{z}{f^t} = \sum_{i=1}^{n} x_i \partial_i \cdot \frac{z}{f^t}
\]

\[
= \sum_{i=1}^{n} x_i \cdot \frac{f^t \sum_{i=1}^{n} x_i \partial_i(z) - \sum_{i=1}^{n} x_i \partial_i(f^t) \cdot z}{f^{2t}}
\]

\[
= \frac{1}{f^{2t}} \left( f^t \sum_{i=1}^{n} x_i \partial_i(z) - \sum_{i=1}^{n} x_i \partial_i(f^t) \cdot z \right)
\]

\[
= \frac{1}{f^t} \cdot \deg(z) \cdot z - \frac{1}{f^{2t}} \cdot \deg(f^t) \cdot f^t \cdot z
\]

\[
= (\deg(z) - \deg(f^t)) \cdot \frac{z}{f^t}
\]

\[
= \deg \left( \frac{z}{f^t} \right) \cdot \frac{z}{f^t}.
\]

This finishes the proof. \( \square \)

Remark 3.6. (1) It turns out that Eulerian graded \( \mathcal{D} \)-modules are not stable under extension because of the following short exact sequence of graded \( \mathcal{D} \)-modules:

\[
0 \rightarrow \frac{\mathcal{D}}{\langle \sum_{i=1}^{n} x_i \partial_i \rangle} \rightarrow \frac{\mathcal{D}}{\langle \sum_{i=1}^{n} x_i \partial_i \rangle^2} \rightarrow \frac{\mathcal{D}}{\langle \sum_{i=1}^{n} x_i \partial_i \rangle} \rightarrow 0,
\]

where the map \( \frac{\mathcal{D}}{\langle \sum_{i=1}^{n} x_i \partial_i \rangle} \rightarrow \frac{\mathcal{D}}{\langle \sum_{i=1}^{n} x_i \partial_i \rangle^2} \) is the multiplication by \( \sum_{i=1}^{n} x_i \partial_i \), i.e., \( a \mapsto a \cdot \langle \sum_{i=1}^{n} x_i \partial_i \rangle \).

(2) Since \( \dim \left( \frac{\mathcal{D}}{\langle \sum_{i=1}^{n} x_i \partial_i \rangle} \right) = 2n - 1 \) and \( \frac{\mathcal{D}}{\langle \sum_{i=1}^{n} x_i \partial_i \rangle} \) is Eulerian, finitely generated (even cyclic) Eulerian graded \( \mathcal{D} \)-modules may not be holonomic when \( n \geq 2 \).

(3) When \( n = 1 \), it is rather straightforward to check that each finitely generated Eulerian graded \( \mathcal{D} \)-module is holonomic.

(4) As we will see in Section 5, in characteristic 0, a vast class of graded \( \mathcal{D} \)-modules (namely local cohomology modules of \( R \)) are both Eulerian and holonomic.

4. Eulerian graded \( \mathcal{D} \)-module in characteristic \( p > 0 \)

Throughout this section \( K \) will be a field of characteristic \( p > 0 \). In this section, we prove that being Eulerian is preserved under localization. The proof is quite different from that in characteristic 0. We also show that each graded \( F \)-module is always an Eulerian graded \( \mathcal{D} \)-module, which will enable us to recover the main result in [12] in Section 5.

Proposition 4.1. If \( M \) is an Eulerian graded \( \mathcal{D} \)-module, so is \( S^{-1}M \) for each homogeneous multiplicative system \( S \subseteq R \). In particular, \( M_f \) is Eulerian for each homogeneous polynomial \( f \in R \).
Proof. First notice that, \( \partial_i^{[j]} \) is \( R^{p^e} \)-linear if \( p^e \geq j + 1 \). So we have
\[
\partial_i^{[j]}(z) = \partial_i^{[j]} \left( f^{p^e} \cdot \frac{z}{f^{p^e}} \right) = f^{p^e} \cdot \partial_i^{[j]} \left( \frac{z}{f^{p^e}} \right).
\]
This tells us that, if \( p^e \geq r + 1 \) and \( f \in S \), then \( \partial_i^{[j]} \left( \frac{z}{f^{p^e}} \right) = \frac{1}{f^{p^e}} \partial_i^{[j]}(z) \) for every \( j \leq r \) in \( S^{-1}M \). In particular, we have
\[
E_r \cdot \frac{z}{f^{p^e}} = \frac{1}{f^{p^e}} E_r \cdot z.
\]
For any homogeneous \( \frac{z}{f^t} \in S^{-1}M \), we can multiply both the numerator and denominator by a large power of \( f \) and write \( \frac{z}{f^t} = \frac{f^{p^e-t}z}{f^{p^e}} \) for some \( p^e \geq \max\{r + 1, t\} \). So we have
\[
E_r \cdot \frac{z}{f^t} = E_r \cdot \frac{f^{p^e-t}z}{f^{p^e}} = \frac{1}{f^{p^e}} E_r \cdot f^{p^e-t}z
\]
\[
= \frac{1}{f^{p^e}} \left( \deg(f^{p^e-t}) + \deg(z) \right) f^{p^e-t}z
\]
\[
= \left( p^e \cdot \deg(f) - \deg(f^t) + \deg(z) \right) \frac{f^{p^e-t}z}{f^{p^e}}
\]
\[
= \left( \frac{\deg(z)}{r} \right) \cdot \frac{z}{f^t},
\]
where the last equality is because \( p^e \geq r + 1 \) and we are in characteristic \( p > 0 \). This finishes the proof. \( \square \)

Recall the definition of a graded \( F \)-module as follows.

**Definition 4.2** (cf. Definitions 2.1 and 2.2 in [12]). For each integer \( e \geq 1 \), let \( eR \) denote the \( R \)-bimodule that is the same as \( R \) as a left \( R \)-module and whose right \( R \)-module structure is given by \( r' \cdot r = r''r' \) for all \( r' \in eR \) and \( r \in R \). An \( F \)-module is an \( R \)-module \( M \) equipped with an \( R \)-module isomorphism \( \theta : M \to F(M) = \frac{1}{1} R \otimes R M \). An \( F \)-module \( (M, \theta) \) is called a graded \( F \)-module if \( M \) is graded and \( \theta \) is degree-preserving.

**Remark 4.3.** It is clear from the definition that, if \( (M, \theta) \) is an \( F \)-module, the map
\[
\alpha_e : M \xrightarrow{\theta} F(M) \xrightarrow{F(\theta)} F^2(M) \xrightarrow{F^2(\theta)} \cdots \xrightarrow{F^e(\theta)} F^e(M)
\]
induced by \( \theta \) is also an isomorphism.

This induces a \( \mathcal{D} \)-module structure on \( M \). To specify the induced \( \mathcal{D} \)-module structure, it suffices to specify how \( \partial_1^{[i_1]} \cdots \partial_n^{[i_n]} \) acts on \( M \). Choose \( e \) such that \( p^e \geq (i_1 + \cdots + i_n) + 1 \). Given each element \( z \), we consider \( \alpha_e(z) \) and we will write it as \( \sum y_j \otimes z_j \) with \( y_j \in eR \) and \( z_j \in M \). And we define
\[
\partial_1^{[i_1]} \cdots \partial_n^{[i_n]} z := \alpha_e^{-1} \left( \sum \partial_1^{[i_1]} \cdots \partial_n^{[i_n]} y_j \otimes z_j \right).
\]
See [5, Section 1] for more details.
When an $F$-module $(M, \theta)$ is graded, the induced map $\alpha_e$ is also degree-preserving. And hence $M$ is naturally a graded $\mathcal{D}$-module. It turns out that each graded $F$-module is Eulerian as a graded $\mathcal{D}$-module.

**Theorem 4.4.** If $M$ is a graded $F$-module, then $M$ is Eulerian graded as a $\mathcal{D}$-module.

**Proof.** Pick any homogeneous element $z \in M$, we want to show $E_r \cdot z = \left( \frac{\deg(z)}{r} \right) \cdot z$ for each $r \geq 1$. Pick $e$ such that $p^e \geq r + 1$. Since $M$ is a graded $F$-module, we have a degree-preserving isomorphism $M \xrightarrow{\alpha_e} F^e_R(M)$. Assume that $\alpha_e(z) = \sum_i y_i \otimes z_i$ where $y_i \in R$ and $z_i \in M$ are homogeneous and $\deg(z) = \deg(y_i \otimes z_i) = p^e \deg(z_i) + \deg(y_i)$ for each $i$. In particular, we have $\left( \frac{\deg(y_i)}{r} \right) = \left( \frac{\deg(z)}{r} \right)$ for every $i$ (because we are in characteristic $p > 0$). So we know

$$ E_r \cdot z = \alpha_e^{-1} \left( \sum_i (E_r \cdot y_i) \otimes z_i \right) $$

$$ = \alpha_e^{-1} \left( \sum_i \left( \frac{\deg(y_i)}{r} \right) y_i \otimes z_i \right) $$

$$ = \alpha_e^{-1} \left( \left( \frac{\deg(z)}{r} \right) \sum_i y_i \otimes z_i \right) $$

$$ = \left( \frac{\deg(z)}{r} \right) \cdot z. $$

This finishes the proof. \qed

---

5. An application to local cohomology

Let $R$ be an arbitrary commutative Noetherian ring and $I$ be an ideal of $R$. We recall that if $I$ is generated by $f_1, \ldots, f_l \in R$ and $M$ is any $R$-module, we have the Čech complex:

$$ 0 \to M \to \bigoplus_j M_{f_j} \to \bigoplus_{j,k} M_{f_j f_k} \to \cdots \to M_{f_1 \cdots f_l} \to 0 $$

whose $i$th cohomology module is $H^i_I(M)$. Here the map $M_{f_{j_1} \cdots f_{j_i}} \to M_{f_{k_1} \cdots f_{k_{i+1}}}$ induced by the corresponding differential is the natural localization (up to sign) if \{j_1, \ldots, j_i\} is a subset of \{k_1, \ldots, k_{i+1}\} and is 0 otherwise.

When $R$ is graded and $I$ is a homogeneous ideal (i.e., $f_1, \ldots, f_l$ are homogeneous elements in $R$) and $M$ is a graded $R$-module, each differential in the Čech complex is degree-preserving because natural localization is so. It follows that each cohomology module $H^i_I(R) = \cdots (H^i_I(R))$ for each $i$ is a graded $R$-module.

When $R = \mathcal{K}[x_1, \ldots, x_n]$ with $\mathcal{K}$ a field of characteristic $p > 0$ and $\mathfrak{m} = (x_1, \ldots, x_n)$, it is proven in [12] (using the theory of graded $F$-modules) that
Theorem 5.1 (Theorem 3.4 in [12]). Let $R = K[x_1, \ldots, x_n]$ be a polynomial ring over a field $K$ of characteristic $p > 0$ and $J_1, \ldots, J_s$ be homogeneous ideals of $R$. Each local cohomology module $H^i_\mathfrak{m}(H^{i_1}_{J_1} \cdots (H^{i_s}_{J_s}(R)))$ is isomorphic to a direct sum of copies of $^*E(n)\,$ (i.e., all socle elements of $H^i_\mathfrak{m}(H^{i_1}_{J_1} \cdots (H^{i_s}_{J_s}(R)))$ must have degree $-n$).

It is a natural question (and is asked in [12]) whether the same result holds in characteristic 0. Using our theory of Eulerian graded $\mathcal{D}$-module, we can give a characteristic-free proof of the same result. In particular, we answer the question in characteristic 0 in the affirmative.

We begin with the following easy observation.

Proposition 5.2. Let $J_1, \ldots, J_s$ be homogeneous ideals of $R$, then each local cohomology module $H^i_{J_1}(\cdots (H^i_{J_s}(R)))$ is a graded $\mathcal{D}$-module.

Proof. Since natural localization map is $\mathcal{D}$-linear (and so is each differential in the Čech complex), our proposition follows immediately from the Čech complex characterization of local cohomology.

Theorem 5.3. Let $J_1, \ldots, J_s$ be homogeneous ideals of $R$, then each local cohomology module $H^i_{J_1}(\cdots (H^i_{J_s}(R)))$ (considered as a graded $\mathcal{D}$-module) is Eulerian.

Proof. This follows immediately from Propositions 3.5, 4.1 and 2.8, and the Čech complex characterization of local cohomology.

Proposition 5.4 (cf. Proposition 2.3 in [7] in characteristic 0 and Lemma (b) on page 208 in [9] in characteristic $p > 0$). Let $R = K[x_1, \ldots, x_n]$ and $\mathfrak{m} = (x_1, \ldots, x_n)$. There is a degree-preserving isomorphism

\[ \mathcal{D}/\mathcal{D}\mathfrak{m} \to ^*E. \]

Proof. It is proven in Proposition 2.3 in [7] in characteristic 0 and Lemma (b) on page 208 in [9] in characteristic $p > 0$. Let $R = K[x_1, \ldots, x_n]$ and $\mathfrak{m} = (x_1, \ldots, x_n)$. There is a degree-preserving isomorphism

\[ \mathcal{D}/\mathcal{D}\mathfrak{m} \to ^*E. \]

Proposition 5.5 (cf. Theorem 2.4(a) in [7] in characteristic 0 and Lemma (c) on page 208 in [9] in characteristic $p > 0$). Let $M$ be a graded $\mathcal{D}$-module. If $\text{Supp}_R(M) = \{\mathfrak{m}\}$, then as a graded $\mathcal{D}$-module $M \cong \bigoplus_j \mathcal{D}_{\mathfrak{m}}(n_j) \cong \bigoplus_j ^*E(n_j)$.

Proof. $M$ is a graded $\mathcal{D}$-module hence also graded as an $R$-module. We first claim that the socle of $M$ can be generated by homogeneous elements and we reason as follows. Pick a generator $g$ of the socle, we can write it as a sum of homogeneous elements $g = \sum_{i=1}^t g_i$ where each $g_i$ has a different degree. For every $x_j \in \mathfrak{m}$, we have $\sum_{i=1}^t x_j \cdot g_i = x_j \cdot g = 0$ (since $g$ is killed by $\mathfrak{m}$), hence $x_j \cdot g_i = 0$ for every $i$.

\[ ^1 \text{when } s = 1, \text{ this is also proved in [11, page 615].} \]
(because each \(x_j \cdot g_i\) has a different degree). Therefore \(g_i\) is killed by every \(x_j\), hence is killed by \(m\), so \(g_i\) is in the socle for each \(i\). This proves our claim. We also note that since the socle is killed by \(m\), a minimal homogeneous set of generators is actually a homogeneous \(K\)-basis.

Let \(\{e_j\}\) be a homogeneous \(K\)-basis of the socle of \(M\) with \(\deg(e_j) = -n_j\). There is a degree-preserving homomorphism of \(\mathcal{D}\)-modules \(\bigoplus_j \mathcal{D}_{\mathfrak{m}}(n_j) \to M\) which sends 1 of the \(j\)th copy to \(e_j\). This map is injective because it induces an isomorphism on socles and \(\bigoplus_j \mathcal{D}_{\mathfrak{m}}(n_j)\) is supported only at \(m\) (as an \(R\)-module). By 5.4, \(\bigoplus_j \mathcal{D}_{\mathfrak{m}}(n_j) \cong \bigoplus_j ^*E(n_j)\) is an injective \(R\)-module. So \(M = \bigoplus_j \mathcal{D}_{\mathfrak{m}}(n_j) \oplus N\) where \(N\) is some graded \(R\)-module supported only at \(m\). Since the map on the socles is an isomorphism, \(N = 0\), so \(M = \bigoplus_j \mathcal{D}_{\mathfrak{m}}(n_j) \cong \bigoplus_j ^*E(n_j)\). \(\square\)

**Theorem 5.6.** Let \(M\) be an Eulerian graded \(\mathcal{D}\)-module. If \(\text{Supp}_R(M) = \{m\}\), then \(M\) is isomorphic (as a graded \(\mathcal{D}\)-module) to a direct sum of copies of \(^*E(n)\).

**Proof.** Since \(M\) is supported only at \(m\), we know it is isomorphic to \(\bigoplus_j ^*E(n_j)\) as a graded \(\mathcal{D}\)-module by Proposition 5.5. By our assumption, \(M\) is Eulerian, so is \(\bigoplus_j ^*E(n_j)\). It follows from Theorem 2.9 that \(n_j = n\) for each \(j\), i.e., \(M\) is isomorphic (as a graded \(\mathcal{D}\)-module) to a direct sum of copies of \(^*E(n)\). This finishes the proof. \(\square\)

**Corollary 5.7.** Let \(J_1, \ldots, J_s\) be homogeneous ideals of \(R\), then \(H^0_\mathfrak{m}H^{i_1}_{J_1} \cdots H^{i_s}_{J_s}(R)\) is isomorphic (as a graded \(\mathcal{D}\)-module) to a direct sum of copies of \(^*E(n)\) (or equivalently, all socle elements of each \(H^0_\mathfrak{m}H^{i_1}_{J_1} \cdots H^{i_s}_{J_s}(R)\) must have degree \(-n\)).

**Proof.** This follows immediately from Theorems 5.3 and 5.6. \(\square\)

**Remark 5.8.** It is proven in [7] (resp, [8]) that every \(H^{i_1}_{J_1} \cdots (H^{i_s}_{J_s}(R))\) is holonomic (resp, \(F\)-finite) as a \(\mathcal{D}\)-module (resp, \(F\)-module) in characteristic 0 (resp, characteristic \(p > 0\)). Therefore in any case we know \(H^{i_1}_{J_1} \cdots (H^{i_s}_{J_s}(R))\) has finite Bass numbers (cf. Theorem 3.4(d) in [7] and Theorem 2.11 in [8]). It follows from this and Corollary 5.7 that \(H^0_\mathfrak{m}H^{i_1}_{J_1} \cdots H^{i_s}_{J_s}(R) \cong ^*E(n)c\) for some integer \(c < \infty\).

### 6. Remarks on the graded injective hull of \(R/P\) when \(P\) is a homogeneous prime ideal

We have seen in Theorem 2.9 that \(^*E(\ell) = ^*E(R/m)(\ell)\) is Eulerian graded if and only if \(\ell = n\). In this section, we wish to extend this result to \(^*E(R/P)\) where \(P\) is a non-maximal homogeneous prime ideal (here \(^*E(R/P)\) denotes the graded injective hull of \(R/P\), see cf. [2, Chapter 13.2]). To this end, we will discuss in detail the graded structures of \(^*E(R/P)\) as an \(R\)-module and as a \(\mathcal{D}\)-module. The underlying idea is that, there does not exist a canonical choice of grading on \(^*E(R/P)\) when it is considered as a graded \(R\)-module; however, there is a canonical grading when it is considered as a graded \(\mathcal{D}\)-module.

**Remark 6.1.** \([^*E(R/P)\) as a graded \(R\)-module] Since \(P \neq m\), there is at least one \(x_i\) that is not contained in \(P\). Hence the multiplication by \(x_i\) induces an automorphism on \(^*E(R/P)\), and consequently we have a degree-preserving isomorphism

\[ ^*E(R/P)(-1) \xrightarrow{x_i} ^*E(R/P)\]
We have a graded injective resolution of $R$.

Proof. Where each $d$ for each integer $m$ in the category of graded $R$-modules. In other words, we have

\[ *E(R/P) \cong *E(R/P)(m) \]

for all integers $i$ and $j$.

In some sense, this tells us that $*E(R/P)$ does not have a canonical grading when considered merely as a graded $R$-module.

However, as we will see, $*E(R/P)$ is equipped with a natural Eulerian graded $\mathcal{D}$-module structure, and from this point of view there is indeed a unique natural grading on $*E(R/P)$. The $\mathcal{D}$-module structure on $*E(R/P)$ is obtained via considering $H^P_{ht}(R)_{(P)}$ where $(-)_{(P)}$ denotes homogeneous localization with respect to $P$ (i.e., inverting all homogeneous elements not in $P$), which has a natural grading as follows.

Remark 6.2 (Grading on $H^P_{ht}(R)_{(P)}$). Choose a set of homogeneous generators $f_1, \ldots, f_t$ of $P$ and consider the Čech complex

\[ C^\bullet(P) : 0 \to R \to \bigoplus_i R_{f_i} \to \cdots \to \bigoplus_{i_1 < i_2 < \cdots < i_j} R_{f_{i_1} \cdots f_{i_j}} \to \cdots \to R_{f_1 \cdots f_t} \to 0. \]

Then, since each module has a natural grading and each differential is degree-preserving, $H^h(C^\bullet(P))$ also has a natural grading ($h = \text{ht } P$), hence so is $H^h(C^\bullet(P))_{(P)}$. We will identify $H^P_{ht}(R)_{(P)}$ with $H^h(C^\bullet(P))_{(P)}$ with its natural grading.

Proposition 6.3. $*E(R/P) \cong H^P_{ht}(R)_{(P)}$ in the category of graded $R$-modules.

Proof. We have a graded injective resolution of $R$ (or a $*$-injective resolution of $R$, cf. [2, Chapter 13])

\[ 0 \to R \to *E(R)(d_0) \to \cdots \to \bigoplus_{\text{ht } Q=s} *E(R/Q)(d_Q) \to \cdots \to *E(R/m)(d_m) \to 0, \]

where each $d_Q$ is an integer depending on $Q$. Notice that when $Q \neq m$, $*E(R/Q)(i) \cong *E(R/Q)(j)$ for all integers $i$ and $j$ by Remark 6.1. So the above resolution can be written as

\[ 0 \to R \to *E(R) \to \cdots \to \bigoplus_{\text{ht } Q=s} *E(R/Q) \to \cdots \to *E(R/m)(d_m) \to 0 \]

Let $h = \text{ht } P$. Then $H^P_{ht}(R)_{(P)}$ is the homogeneous localization of the $h$th homology of (5.4.2) when we apply $\Gamma_P(\cdot)$. But when we apply $\Gamma_{P}(\cdot)$, (5.4.2) becomes

\[ 0 \to 0 \to \cdots \to *E(R/P) \to \Gamma_P\left( \bigoplus_{\text{ht } Q=h+1} *E(R/Q) \right) \to \cdots \to \Gamma_P(*E(R/m)(d_m)) \to 0 \]

and when we do homogeneous localization at $P$ to (5.4.3), we get

\[ 0 \to \cdots \to 0 \to *E(R/P) \to 0 \to \cdots \to 0. \]

So the $h$th homology is exactly $*E(R/P)$ (and when $P = m$, we get $H^P_m(R) \cong *E(R/m)(d_m)$, so actually $d_m = n$). This finishes the proof. □
Remark 6.4 ($\mathcal{D}$-module structure on $^*E(R/P)$). Since $H^h_\mathcal{P}(R)_{(P)}$ has a natural graded $\mathcal{D}$-module structure, it follows from Proposition 6.3 that $^*E(R/P)$ also has a natural graded $\mathcal{D}$-module structure.

Since $^*E(R/P)$ is a graded $\mathcal{D}$-module, it is natural to ask the following question.

Question 6.5. Let $P$ be a homogeneous prime ideal in $R$. Is there a natural grading on $^*E(R/P)$ making it Eulerian graded?

Remark 6.6. $H^\text{ht}_\mathcal{P} P(R)_{(P)}$ is always Eulerian graded by Theorem 5.3, Propositions 3.5, and 4.1. From Remark 2.5(1), we know that, in the category of graded $\mathcal{D}$-modules, $^*E(R/P)(\ell)$ is Eulerian graded for exactly one $\ell$, we will identify this “canonical” $\ell$.

Contrary to the case when we consider $^*E(R/P)$ as a graded $R$-module, we can see that in the category of graded $\mathcal{D}$-modules we have

$$^*E(R/P)(i) \cong ^*E(R/P)(j)$$

if and only if $i = j$.

(Otherwise we would have $^*E(R/P)(\ell) \cong ^*E(R/P)(\ell + j - i)$ for every $\ell$, and hence there would be more than one choice of $\ell$ such that $^*E(R/P)(\ell)$ is Eulerian.)

We wish to find the natural grading on $^*E(R/P)$ that makes it Eulerian, and we need the following lemma (which may be well-known to experts).

Lemma 6.7. We have a canonical degree-preserving isomorphism ($h = \text{ht } P$)

$$\text{Ext}^h_R(R/P, R) \cong \text{Hom}_R(R/P, H^h_\mathcal{P}(R)).$$

Proof. $H^h_\mathcal{P}(R)$ is the $h$th homology of (5.4.2) when we apply $\Gamma_\mathcal{P}(-, \cdot)$, which is the $h$th homology of (5.4.3), which is the kernel of $^*E(R/P) \to \Gamma_\mathcal{P}(\oplus_{Q=ht} h^*E(R/Q))$. Since $\text{Hom}_R(R/P, \cdot)$ is left exact, we know that $\text{Hom}_R(R/P, H^h_\mathcal{P}(R))$ is isomorphic to the kernel of

$$^*E(R/P) \to \text{Hom}_R(R/P, \Gamma_\mathcal{P}(\oplus_{Q=ht} h^*E(R/Q)))$$

$$\cong \text{Hom}_R(R/P, (\oplus_{Q=ht} h^*E(R/Q))).$$

But this is exactly the $h$th homology of (5.4.2) when we apply $\text{Hom}_R(R/P, \cdot)$, which by definition is $\text{Ext}^h_R(R/P, R)$. And we want to emphasize here that the isomorphism obtained does not depend on the grading on $^*E(R/P)$ as long as $^*E(R/P)$ is equipped with the same grading when we calculate $\text{Ext}^h_R(R/P, R)$ and $\text{Hom}_R(R/P, H^h_\mathcal{P}(R))$ as above. \qed

Definition 6.8. For a $d$-dimensional graded $K$-algebra $S$ with irrelevant maximal ideal $m$, the $a$-invariant of $S$ is defined to be

$$a(S) = \max\{t \in \mathbb{Z} | H^d_m(S)_t \neq 0\}.$$

Proposition 6.9. We have $\min\{t | (\text{Ann}_{H^h_\mathcal{P} P(R)} P)_t \neq 0\} = -a(R/P) - n$. Hence we have a degree-preserving inclusion

$$R/P \hookrightarrow H^\text{ht}_\mathcal{P} P(R)(-a(R/P) - n) \hookrightarrow H^\text{ht}_\mathcal{P} P(R)_{(P)}(-a(R/P) - n).$$

Proof. Let $h = \text{ht } P$ and let $s = \min\{t | (\text{Ann}_{H^h_\mathcal{P} P(R)} P)_t \neq 0\}$. By lemma 6.7, we know

$$\text{Ext}^h_R(R/P, R) \cong \text{Hom}_R(R/P, H^h_\mathcal{P}(R)) \cong \text{Ann}_{H^h_\mathcal{P}(R)} P,$$
so we know
\[ s = \min \{ t | (\text{Ext}_R^h(R/P, R)_t \neq 0) \} = \min \{ t | (\text{Ext}_R^h(R/P, R(-n))_t \neq 0) - n \} \]
by graded local duality
\[ \min \{ t | (\text{Ext}_R^h(R/P, R(-n))_t \neq 0) \} = -\max \{ t \in \mathbb{Z} | H_m^n_{\text{ht}}(R/P)_t \neq 0 \} = -a(R/P). \]
Hence we get \( s = -a(R/P) - n \). The second statement follows from the first one by sending \( \overline{t} \) in \( R/P \) to any element in \( \text{Ann}_{H_m^n_{\text{ht}}} r(R)P \) of degree \(-a(R/P) - n \). \( \square \)

Remark 6.10. From what we have discussed so far, we can see that \( H^{\text{ht}}_{P} R/\sigma(P) \) is a graded injective module (or *-injective module) and there is a degree-preserving inclusion \( R/P \hookrightarrow H^{\text{ht}}_{P} R/\sigma(P)(-a(R/P) - n) \), always sending \( \overline{t} \) in \( R/P \) to the lowest degree element in \( \text{Ann}_{H^{\text{ht}}_{P} R/\sigma(R)}P \). Therefore we propose a “canonical” grading on \( *E(R/P) \) to the effect that \( *E(R/P) \) can be identified with \( H^{\text{ht}}_{P} R/\sigma(P)(-a(R/P) - n) \) (where the grading on \( H^{\text{ht}}_{P} R/\sigma(P) \) is obtained via Čech complex).

We end with the following proposition.

Proposition 6.11 (Compare with Theorem 13.2.10 and Lemma 13.3.3 in [2]). Given the grading on \( *E(R/P) \) as proposed in Remark 6.10, we have that

1. \( *E(R/P)(\ell) \) is Eulerian if and only if \( \ell = a(R/P) + n \);
2. the minimal graded injective resolution (or *-injective resolution) of \( R \) can be written as
\[ 0 \to R \to *E(R) \to \cdots \to \bigoplus_{\text{ht} P = j} *E(R/P)(a(R/P) + n) \to \cdots \to *E(R/m)(n) \to 0. \]

Proof. (1). This is clear by our grading on \( *E(R/P) \) and the fact that there is a unique grading on \( H^{\text{ht}}_{P} R/\sigma(P) \) that makes it Eulerian.

(2). This follows immediately from the calculation of \( H^{\text{ht}}_{P} R/\sigma(P) \) using the minimal *-injective resolution of \( R \) (note that \( a(R) = -n \) and \( a(R/m) = 0 \)). \( \square \)

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