

Gröbner Bases and Syzygies of Sequences of Related Ideals

Michael Hanson Morrow
(joint work with Uwe Nagel)

University of Kentucky

May 20, 2023

Introduction

Suppose we have a sequence of related ideals I_0, I_1, I_2, \dots living in a sequence of related polynomial rings R_0, R_1, R_2, \dots (i.e. $I_n \subseteq R_n \forall n \geq 0$).

Simultaneously compute:

- 1 a finite Gröbner basis for each I_n , and
- 2 a finite Gröbner basis for the module of syzygies of each I_n .

P-Ideals

Notation: for any $n \in \mathbb{N}$ define $[n] = \{1, \dots, n\}$ and set $[0] = \emptyset$.

Fix a field K and an integer $c > 0$. Let $\mathbf{P} : \mathbf{P}_0, \mathbf{P}_1, \mathbf{P}_2, \dots$ be the sequence defined by

$$\mathbf{P}_n = K[x_{i,j} : i \in [c], j \in [n]] \quad \forall n \geq 0.$$

Example

If $c = 2$ then

$$\mathbf{P}_0 = K, \mathbf{P}_1 = K \begin{bmatrix} x_{1,1} \\ x_{2,1} \end{bmatrix}, \mathbf{P}_2 = K \begin{bmatrix} x_{1,1} & x_{1,2} \\ x_{2,1} & x_{2,2} \end{bmatrix}, \dots$$

P-Ideals

There are maps $\mathbf{P}(\varepsilon) : \mathbf{P}_m \rightarrow \mathbf{P}_n$ for each strictly increasing function $\varepsilon : [m] \rightarrow [n]$. Specifically, $\mathbf{P}(\varepsilon)$ is induced by $x_{i,j} \mapsto x_{i,\varepsilon(j)}$. We often write ε_* instead of $\mathbf{P}(\varepsilon)$.

Definition

A sequence of ideals $\mathbf{I} : \mathbf{I}_0, \mathbf{I}_1, \mathbf{I}_2, \dots$ with $\mathbf{I}_n \leq \mathbf{P}_n$ is called a **P-ideal** if $\mathbf{I}_0 = 0$ and $\varepsilon_*(\mathbf{I}_m) \subseteq \mathbf{I}_n$ for all $m \leq n$ and $\varepsilon : [m] \rightarrow [n]$.

Example

Let $c = 1$. Then the sequence $\mathbf{I}_n = \langle x_i x_j : 1 \leq i < j \leq n \rangle$ is a **P-ideal**.

Finite Generation of \mathbf{P} -Ideals

A *subset* of a \mathbf{P} -ideal \mathbf{I} is a set $G \subseteq \bigsqcup_{n \geq 0} \mathbf{I}_n$. For all $n \geq 0$ we define the n -*orbit* of G to be the set

$$\text{Orb}(G, n) = \{\varepsilon_*(g) : g \in G \cap \mathbf{I}_m, \varepsilon : [m] \rightarrow [n]\}.$$

Definition

A \mathbf{P} -ideal \mathbf{I} is *finitely generated* if there is a finite subset $G \subset \mathbf{I}$ such that $\mathbf{I}_n = \langle \text{Orb}(G, n) \rangle$ for all $n \geq 0$. In this case we write $\mathbf{I} = \langle G \rangle_{\mathbf{P}}$.

Example

The \mathbf{P} -ideal $\mathbf{I}_n = \langle x_i x_j : 1 \leq i < j \leq n \rangle$ is finitely generated by $\{x_1 x_2\}$.

Monomial Orders

A monomial in \mathbf{P} is a monomial in some \mathbf{P}_n .

Definition

A total order $<$ on the monomials of \mathbf{P} is called a *monomial order* on \mathbf{P} if for all monomials $\mu, \nu \in \mathbf{P}_m$ with $\mu < \nu$ we have

- ① $\mu < a\mu < a\nu$ for all monomials $1 \neq a \in \mathbf{P}_m$, and
- ② $\mu < \varepsilon_*(\mu) < \varepsilon_*(\nu)$ for all $\varepsilon : [m] \rightarrow [n]$ with $m < n$.

Example

Give each \mathbf{P}_n the lex order with $x_{i,j} < x_{i',j'}$ if $i < i'$ or $i = i'$ and $j < j'$. For any monomials $\mu \in \mathbf{P}_m$ and $\nu \in \mathbf{P}_n$ we declare $\mu < \nu$ if $m < n$ or $m = n$ and $\mu < \nu$ in \mathbf{P}_n .

Division with Remainder

Remark

Any monomial order $<$ on \mathbf{P} restricts to a monomial order $<_n$ on \mathbf{P}_n for all $n \geq 0$.

Definition

Let $f \in \mathbf{P}_n$ and let $G \subseteq \mathbf{P}$. A *remainder of f modulo G* (with respect to $<$) is defined to be a remainder of f modulo $\text{Orb}(G, n)$ (with respect to $<_n$).

Remainders of f modulo G can be computed in finite time [CLO].

Gröbner Bases

Given a monomial order $<$ on \mathbf{P} one defines $\text{lm}(f) \in \mathbf{P}_n$, $\text{lt}(f) \in \mathbf{P}_n$ and $\text{lc}(f) \in K$ for any $f \in \mathbf{P}_n$.

Definition

Fix a monomial order $<$ on \mathbf{P} and let \mathbf{I} be a \mathbf{P} -ideal. A subset $G \subseteq \mathbf{I}$ is called a *Gröbner basis* for \mathbf{I} (with respect to $<$) if

$$\langle \text{lm}(\mathbf{I}) \rangle_{\mathbf{P}} = \langle \text{lm}(G) \rangle_{\mathbf{P}}$$

where $\text{lm}(\mathbf{I}) = \{\text{lm}(f) : f \in \mathbf{I}\}$ and $\text{lm}(G) = \{\text{lm}(g) : g \in G\}$.

Remark

A set $G \subseteq \mathbf{I}$ forms a Gröbner basis for \mathbf{I} if and only if $\text{Orb}(G, n)$ forms a Gröbner basis for \mathbf{I}_n with respect to $<_n$ for all $n \geq 0$.

S-Polynomials and Critical Pairs

Definition

The *S-polynomial* of $f, g \in \mathbf{P}_n$ is the combination

$$S(f, g) = \frac{\text{lcm}(\text{lm}(f), \text{lm}(g))}{\text{lt}(f)} f - \frac{\text{lcm}(\text{lm}(f), \text{lm}(g))}{\text{lt}(g)} g.$$

Definition

Let $B \subseteq \mathbf{P}$ and let $m \geq 0$. A tuple

$$(\sigma_*(f), \tau_*(g)) \in \text{Orb}(B, m) \times \text{Orb}(B, m)$$

is called a *critical pair* if $m = |\text{im}(\sigma) \cup \text{im}(\tau)|$. The set of all critical pairs of B is denoted $\mathcal{C}(B)$.

Important: the set $\mathcal{C}(B)$ is finite if B is finite.

Buchberger's Criterion

Theorem (M, Nagel)

A generating set G of a \mathbf{P} -ideal \mathbf{I} forms a Gröbner basis for \mathbf{I} if and only if each $S(f, g)$ with $(f, g) \in \mathcal{C}(G)$ has a remainder of zero modulo G .

Key idea: any S-polynomial $S(\sigma_*(f), \tau_*(g))$ can be written as $\rho_*(S(\bar{\sigma}_*(f), \bar{\tau}_*(g)))$ where $(\bar{\sigma}_*(f), \bar{\tau}_*(g))$ is a critical pair.

Buchberger's Algorithm

Let $<$ be a monomial order on \mathbf{P} and let $G \subset \mathbf{P}$ be a finite set.

- 1 Are there $(f, g) \in \mathcal{C}(G)$ such that $S(f, g)$ has a nonzero remainder modulo G ?
- 2 If so, append the remainder to G and repeat.
- 3 Terminates by a Noetherianity argument (see [MN23]).
- 4 Computes a finite Gröbner basis for $\langle G \rangle_{\mathbf{P}}$.

Gröbner Basis Example

Let $c = 2$ and let $B = \{x_{2,1}^2 + x_{1,1} \in \mathbf{P}_1, x_{2,2} + x_{1,2}x_{1,1} \in \mathbf{P}_2\}$. Using Macaulay2, we can compute a Gröbner basis for $\langle B \rangle_{\mathbf{P}}$. It consists of the elements

$$x_{2,1}^2 + x_{1,1} \in \mathbf{P}_1$$

$$x_{2,2} + x_{1,2}x_{1,1} \in \mathbf{P}_2$$

$$x_{1,2}^2x_{1,1}^2 + x_{1,2} \in \mathbf{P}_2$$

$$x_{1,3}^2 + x_{1,3}x_{1,1} \in \mathbf{P}_3$$

$$x_{1,3}x_{1,2} - x_{1,3}x_{1,1} \in \mathbf{P}_3$$

$$x_{1,3}x_{1,1}^3 + x_{1,3} \in \mathbf{P}_3$$

What is a Syzygy?

Example

Let $c = 1$ and consider the elements $x_1 \in \mathbf{P}_1$ and $x_2x_3 \in \mathbf{P}_3$. We have a relation

$$x_2\varepsilon_*(x_1) - x_2x_3 = x_2x_3 - x_2x_3 = 0 \in \mathbf{P}_3$$

where $\varepsilon : [1] \rightarrow [3]$ is the map given by $1 \mapsto 3$. Such a relation is an example of a syzygy on the elements x_1 and x_2x_3 .

Syzygies of \mathbf{P} -ideals have been studied in the context of free resolutions and complexes in [FN21] and [FN22].

How do we compute them?

P-Modules

Definition

A sequence $\mathbf{M} : \mathbf{M}_0, \mathbf{M}_1, \mathbf{M}_2, \dots$ of modules is a **P-module** if

- ① each \mathbf{M}_n is a \mathbf{P}_n -module,
- ② there is a K -linear map $\mathbf{M}(\varepsilon) : \mathbf{M}_m \rightarrow \mathbf{M}_n$ for all strictly increasing $\varepsilon : [m] \rightarrow [n]$, and
- ③ for all $a \in \mathbf{P}_m$ the diagram

$$\begin{array}{ccc}
 \mathbf{M}_m & \xrightarrow{\mathbf{M}(\varepsilon)} & \mathbf{M}_n \\
 a \cdot \downarrow & & \downarrow \mathbf{P}(\varepsilon)(a) \cdot \\
 \mathbf{M}_m & \xrightarrow{\mathbf{M}(\varepsilon)} & \mathbf{M}_n
 \end{array}$$

commutes, where the vertical maps are multiplication by the indicated element.

P-Modules

Definition

Let \mathbf{M} be a \mathbf{P} -module. A \mathbf{P} -submodule of \mathbf{M} is a sequence of modules $\mathbf{N} : \mathbf{N}_0, \mathbf{N}_1, \mathbf{N}_2, \dots$ such that each \mathbf{N}_n is a \mathbf{P}_n -submodule of \mathbf{M}_n and $\mathbf{M}(\varepsilon)(\mathbf{N}_m) \subseteq \mathbf{N}_n$ for all $\varepsilon : [m] \rightarrow [n]$.

Example

The \mathbf{P} -ideals are precisely the \mathbf{P} -submodules of \mathbf{P} .

P-Linear Maps

Definition

Let \mathbf{M} and \mathbf{N} be \mathbf{P} -modules. A \mathbf{P} -linear map $\varphi : \mathbf{M} \rightarrow \mathbf{N}$ is a collection of \mathbf{P}_n -linear maps $\varphi_n : \mathbf{M}_n \rightarrow \mathbf{N}_n$ such that the diagram

$$\begin{array}{ccc} \mathbf{M}_m & \xrightarrow{\varphi_m} & \mathbf{N}_m \\ \downarrow \mathbf{M}(\varepsilon) & & \downarrow \mathbf{N}(\varepsilon) \\ \mathbf{M}_n & \xrightarrow{\varphi_n} & \mathbf{N}_n \end{array}$$

commutes for all $\varepsilon : [m] \rightarrow [n]$.

Definition

The *kernel* of a \mathbf{P} -linear map $\varphi : \mathbf{M} \rightarrow \mathbf{N}$ is the \mathbf{P} -submodule of \mathbf{M} given by $\ker(\varphi)_n = \ker(\varphi_n)$ for all $n \geq 0$.

Free \mathbf{P} -Modules

Definition

Fix integers $d_1, \dots, d_s \geq 0$ and define the sequence $\mathbf{F} : \mathbf{F}_0, \mathbf{F}_1, \mathbf{F}_2$ via

$$\mathbf{F}_n = \bigoplus_{\substack{1 \leq i \leq s \\ \pi: [d_i] \rightarrow [n]}} \mathbf{P}_n e_{\pi, i}$$

with maps $\mathbf{F}(\varepsilon) : \mathbf{F}_m \rightarrow \mathbf{F}_n$ induced by $e_{\pi, i} \mapsto e_{\varepsilon \circ \pi, i}$. We call \mathbf{F} a *free \mathbf{P} -module with basis $\{e_{\text{id}_{[d_i]}, i}\}$* .

Example

Let \mathbf{F} have basis $\{e_{\text{id}_{[2]}}\}$. Then \mathbf{F}_n is a free \mathbf{P}_n -module of rank $\binom{n}{2}$ for all $n \geq 0$.

Remark

Any $\varphi : \mathbf{F} \rightarrow \mathbf{M}$ is determined by where the $e_{\text{id}_{[d_i]}, i}$ are sent.

P-Module Concepts

The following concepts for \mathbf{P} -ideals generalize to \mathbf{P} -modules:

- Finite generation
- Monomial orders
- Division with remainder
- S-polynomials
- Gröbner bases

Computing Syzygies

Let $B = \{b_1, \dots, b_s\} \subset \mathbf{P}$ be a Gröbner basis with $b_i \in \mathbf{P}_{d_i}$ and let \mathbf{F} be a free \mathbf{P} -module with basis $\{e_{\text{id}_{[d_i]}, i}\}$.

Let $\varphi : \mathbf{F} \rightarrow \mathbf{P}$ be the map induced by $e_{\text{id}_{[d_i]}, i} \mapsto b_i$. We wish to compute a finite Gröbner basis for the syzygy module of $\langle B \rangle_{\mathbf{P}}$, i.e. $\text{Syz}(B) := \ker(\varphi)$.

Computing Syzygies

Definition

For any $i, j \in [s]$, $\sigma : [d_i] \rightarrow [m]$ and $\tau : [d_j] \rightarrow [m]$ with $m \geq \max(d_i, d_j)$ we can use the division algorithm to write

$$S(\sigma_*(b_i), \tau_*(b_j)) = \sum_{\ell} a_{i,j,\ell}^{\sigma,\tau} \mathbf{P}(\pi_{i,j,\ell}^{\sigma,\tau})(b_{k_{i,j,\ell}^{\sigma,\tau}})$$

for some $a_{i,j,\ell}^{\sigma,\tau} \in \mathbf{P}_m$ and $\mathbf{P}(\pi_{i,j,\ell}^{\sigma,\tau})(b_{k_{i,j,\ell}^{\sigma,\tau}}) \in \text{Orb}(B, m)$. Define

$$s_{i,j}^{\sigma,\tau} = m_{i,j}^{\sigma,\tau} e_{\sigma,i} - m_{i,j}^{\tau,\sigma} e_{\tau,j} - \sum_{\ell} a_{i,j,\ell}^{\sigma,\tau} e_{\pi_{i,j,\ell}^{\sigma,\tau}, k_{i,j,\ell}^{\sigma,\tau}} \in \mathbf{F}_m$$

where

$$m_{i,j}^{\sigma,\tau} = \frac{\text{lcm}(\sigma_*(\text{lm}(b_i)), \tau_*(\text{lm}(b_j)))}{\sigma_*(\text{lm}(b_i))} \in \mathbf{P}_m.$$

Computing Syzygies: Schreyer's Theorem

Theorem (M, Nagel)

There exists a monomial order on \mathbf{F} with respect to which the $s_{i,j}^{\sigma,\tau}$ with $(\sigma_(b_i), \tau_*(b_j)) \in \mathcal{C}(B)$ form a finite Gröbner basis for $\text{Syz}(B)$.*

For the classical version of this theorem, see [E95, Chapter 15].

Remark

If G forms a Gröbner basis for $\text{Syz}(B)$ then $\text{Orb}(G, n)$ forms a Gröbner basis for $\text{Syz}(B)_n$ for all $n \geq 0$.

Syzygy Example

Let \mathbf{F} be the free \mathbf{P} -module with basis $\{e_{\text{id}_{[2]}}\}$ and let $B = \{x_{1,1}x_{2,2} - x_{1,2}x_{2,1} \in \mathbf{P}_2\}$ so that $(\langle B \rangle_{\mathbf{P}})_n$ is the ideal of \mathbf{P}_n generated by the 2×2 minors of the matrix

$$\begin{bmatrix} x_{1,1} & x_{1,2} & \cdots & x_{1,n} \\ x_{2,1} & x_{2,2} & \cdots & x_{2,n} \end{bmatrix}.$$

Using Macaulay2 we compute a Gröbner basis for $\text{Syz}(B)$:

$$\begin{aligned} x_{1,2}e_{13} - x_{1,1}e_{23} - x_{1,3}e_{12} &\in \mathbf{F}_3 \\ -x_{2,3}e_{12} + x_{2,2}e_{13} - x_{2,1}e_{23} &\in \mathbf{F}_3. \end{aligned}$$

Note: $e_{ij} \rightsquigarrow e_{\pi}$ where $\pi : [2] \rightarrow [3]$ is given by $1 \mapsto i$ and $2 \mapsto j$.

References

- [CLO] D. Cox, J. Little, D. O'Shea, *Ideals, Varieties, and Algorithms*, Springer (2006).
- [E95] D. Eisenbud, *Commutative algebra with a view toward algebraic geometry*, Springer (1995).
- [FN21] N. Fieldsteel, U. Nagel, *Minimal and cellular free resolutions over polynomial OI -algebras*, Preprint, arXiv:2105.08603, 2021.
- [FN22] N. Fieldsteel, U. Nagel, *Buchsbaum-Eisenbud complexes of OI -modules*, Preprint, arXiv:2206.12960, 2022.
- [NR19] U. Nagel, T. Römer, *FI - and OI -modules with varying coefficients*, J. Algebra **535** (2019), 286-322.
- [MN23] M. Morrow, U. Nagel, *Computing Gröbner Bases and Free Resolutions of OI -Modules*, Preprint, arXiv:2303.06725, 2023.