PARTIALLY ORDERED SETS IN MACAULAY2

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Abstract. We introduce the package Posets for Macaulay2. This package provides a data structure and the necessary methods for working with partially ordered sets, also called posets. In particular, the package implements methods to enumerate many commonly studied classes of posets, perform operations on posets, and calculate various invariants associated to posets.

Introduction.

A partial order is a binary relation \( \preceq \) over a set \( P \) that is antisymmetric, reflexive, and transitive. A set \( P \) together with a partial order \( \preceq \) is called a poset, or partially ordered set.

Posets are combinatorial structures that are used in modern mathematical research, particularly in algebra. We introduce the package Posets for Macaulay2 via three distinct posets or related ideals which arise naturally in combinatorial algebra.

We first describe two posets that are generated from algebraic objects. The intersection semilattice associated to a hyperplane arrangement can be used to compute the number of unbounded and bounded real regions cut out by a hyperplane arrangement, as well as the dimensions of the homologies of the complex complement of a hyperplane arrangement.

Given a monomial ideal, the lcm-lattice of its minimal generators gives information on the structure of the free resolution of the original ideal. Specifically, two monomial ideals with isomorphic lcm-lattices have the “same” (up to relabeling) minimal free resolution, and the lcm-lattice can be used to compute, among other things, the multigraded Betti numbers \( \beta_{i,b}(R/M) = \dim_k \text{Tor}^R_{i,b}(R/M, k) \) of the monomial ideal.

In contrast to the first two examples (associating a poset to an algebraic object), we then describe an ideal that is generated from a poset. In particular, the Hibi ideal of a finite poset is a squarefree monomial ideal which has many nice algebraic properties that can be described in terms of combinatorial properties of the poset. In particular, the resolution and Betti numbers, the multiplicity, the projective dimension, and the Alexander dual are all nicely described in terms of data about the poset itself.

Intersection (semi)lattices.

A hyperplane arrangement \( \mathcal{A} \) is a finite collection of affine hyperplanes in some vector space \( V \). The dimension of a hyperplane arrangement is defined by \( \dim(\mathcal{A}) = \dim(V) \), and the rank of a hyperplane arrangement \( \text{rank}(\mathcal{A}) \) is the dimension of the span in \( V \) of the set of normals to the hyperplanes in \( \mathcal{A} \).

The intersection semilattice \( \mathcal{L}(\mathcal{A}) \) of \( \mathcal{A} \) is the set of the nonempty intersections of subsets of hyperplanes \( \bigcap_{\mathcal{H} \in \mathcal{A}'} \mathcal{H} \) for \( \mathcal{H} \in \mathcal{A}' \subseteq \mathcal{A} \), ordered by reverse inclusion. We include the empty intersection corresponding to \( \mathcal{A}' = \emptyset \), which is the minimal element in the intersection meet semilattice \( 0 \in \mathcal{L}(\mathcal{A}) \). If the intersection of all hyperplanes in \( \mathcal{A} \) is nonempty, \( \bigcap_{\mathcal{H} \in \mathcal{A}} \mathcal{H} \neq 0 \),
then the intersection meet semilattice \( \mathcal{L}(A) \) is actually a lattice. Arrangements with this property are called central arrangements.

Consider the non-central hyperplane arrangement \( A = \{H_1 = V(x + y), H_2 = V(x), H_3 = V(x - y), H_4 = V(y + 1)\} \), where \( H_i = V(\ell_i(x, y)) \subseteq \mathbb{R}^2 \) denotes the hyperplane \( H_i \) of zeros of the linear form \( \ell_i(x, y) \); see Figure 1(i). We can construct \( \mathcal{L}(A) \) in Macaulay2 as follows.

```macaulay2
i1 : needsPackage "Posets"
```

Then we can display the Hasse diagram of \( \mathcal{L}(A) \), as in Figure 1(ii).

```macaulay2
i2 : R = RR[x,y];
```

```macaulay2
i3 : A = {x + y, x, x - y, y + 1};
```

```macaulay2
i4 : LA = intersectionLattice(A, R);
```

```macaulay2
i5 : realRegions(A, R)
o5 = 10
```

```macaulay2
i6 : boundedRegions(A, R)
o6 = 2
```

A theorem of Zaslavsky [Za] provides information about the topology of the complement of hyperplane arrangements in \( \mathbb{R}^n \). Let \( \mu \) denote the Möbius function of the intersection semilattice \( \mathcal{L}(A) \). Then the number of regions that \( A \) divides \( \mathbb{R}^n \) into is

\[
r(A) = \sum_{x \in \mathcal{L}(A)} |\mu(\hat{0}, x)|.\]

Moreover, the number of these regions that are bounded is

\[
b(A) = |\mu(\mathcal{L}(A) \cup \hat{1})|,\]

where \( \mathcal{L}(A) \cup \hat{1} \) is the intersection semilattice adjoined with a maximal element.

We verify these results for the non-central hyperplane arrangement \( A \) using Macaulay2:

```macaulay2
i5 : realRegions(A, R)
o5 = 10
```

```macaulay2
i6 : boundedRegions(A, R)
o6 = 2
```

Moreover, in the case of hyperplane arrangements in \( \mathbb{C}^n \), using a theorem of Orlik and Solomon [OS], we can recover the Betti numbers (dimensions of homologies) of the complement \( M_A = \mathbb{C}^n - \cup A \) of the hyperplane arrangement using purely combinatorial data of the
intersection semilattice. In particular, $\mathcal{M}_A$ has torsion-free integral cohomology with Betti numbers given by

$$\beta_i(\mathcal{M}_A) = \dim_C\left(\mathbb{H}_i(\mathcal{M}_A)\right) = \sum_{x \in \mathcal{L}(A) \text{ dim}_C(x) = n-i} |\mu(\hat{0}, x)|,$$

where $\mu(\cdot)$ again represents the Möbius function. See [Wa] for details and generalizations of this formula.

Posets will compute the ranks of elements in a poset, where the ranks in the intersection lattice $\mathcal{L}_A$ are determined by the codimension of elements. Combining the outputs of our rank function with the Möbius function allows us to calculate $\beta_0(\mathcal{M}_A) = 1$, $\beta_1(\mathcal{M}_A) = 4$, and $\beta_2(\mathcal{M}_A) = 5$.

**LCM-lattices.**

Let $R = K[x_1, \ldots, x_t]$ be the polynomial ring in $t$ variables over the field $K$, where the degree of $x_i$ is the standard basis vector $e_i \in \mathbb{Z}^t$. Let $M = (m_1, \ldots, m_n)$ be a monomial ideal in $R$, then we define the lcm-lattice of $M$, denoted $L_M$, as the set of all least common multiples of subsets of the generators of $M$ partially ordered by divisibility. It is easy to see that $L_M$ will always be a finite atomic lattice. While lcm-lattices are nicely structured, they can be difficult to compute by hand especially for large examples or for ideals where $L_M$ is not ranked.

Consider the ideal $M = (a^3b^2c, a^3b^2d, a^2cd, abc^2d, b^2c^2d)$ in $R = k[a, b, c, d]$. Then we can construct $L_M$ in Macaulay2 as follows. See Figure 2 for the Hasse diagram of $L_M$, as generated by the texPoset method.

**Lcm-lattices, which were introduced by Gasharov, Peeva, and Welker [GPW], have become an important tool used in studying free resolutions of monomial ideals. There have been a number of results that use the lcm-lattice to give constructive methods for finding free resolutions for monomial ideals, for some examples see , [Cl], [PV], and [Ve].**
These computations can all be done using Posets together with the package Simplicial-Complexes, by S. Popescu, G. Smith, and M. Stillman. In particular, we can show that \( \beta_{i, a^{3}b^{2}c^{2}d} = 0 \) for all \( i \) with the following calculation.

\[
i_{13} : D_{1} = \text{orderComplex(openInterval(LM, 1_R, a^{2}b^{2}c^{2}d))};
i_{14} : \text{prune HH(D1)}
\]

\[
o_{14} = \begin{array}{c}
-1 : 0 \\
0 : 0 \\
1 : 0
\end{array}
\]

These computations can all be done using Posets together with the package Simplicial-Complexes, by S. Popescu, G. Smith, and M. Stillman. In particular, we can show that \( \beta_{1, a^{3}b^{2}c^{2}d} = 0 \) for all \( i \) with the following calculation.

\[
i_{13} : D_{1} = \text{orderComplex(openInterval(LM, 1_R, a^{2}b^{2}c^{2}d))};
i_{14} : \text{prune HH(D1)}
\]

\[
o_{14} = \begin{array}{c}
-1 : 0 \\
0 : 0 \\
1 : 0
\end{array}
\]

Similarly, we can show that \( \beta_{1, a^{3}b^{2}c^{2}d} = 2 \).

\[
i_{15} : D_{2} = \text{orderComplex(openInterval(L, 1_R, a^{3}b^{2}c^{2}d))};
i_{16} : \text{prune HH(D2)}
\]

\[
o_{16} = \begin{array}{c}
-1 : 0 \\
2
\end{array}
\]

\[
o_{16} : \text{GradedModule}
\]

**Hibi ideals.**

Let \( P = \{p_1, \ldots, p_n\} \) be a finite poset with partial order \( \preceq \), and let \( K \) be a field. The *Hibi ideal*, introduced by Herzog and Hibi [HH], of \( P \) over \( K \) is the squarefree ideal \( H_P \) in \( R = K[x_1, \ldots, x_n, y_1, \ldots, y_n] \) generated by the monomials

\[ u_I := \prod_{p_i \in I} x_i \prod_{p_i \not\in I} y_i, \]

where \( I \) is an order ideal of \( P \), i.e., for every \( i \in I \) and \( p \in P \), if \( p \preceq i \), then \( p \in I \). Nota bene: The Hibi ideal is the ideal of the monomial generators of the Hibi ring, a toric ring first described by Hibi [Hi].

\[
i_{17} : P = \text{divisorPoset 12};
i_{18} : H_P = \text{hibiIdeal P};
i_{19} : H_p\_\ast
\]

\[
o_{19} = \{x x x x x x , x x x x x y , x x x x y y , x x x y y y , x x y y y y , x y y y y y ,
\]

\[
\text{Figure 2. The lcm-lattice for } M = (a^{3}b^{2}c, a^{3}b^{2}d, a^{2}cd, abc^{2}d, b^{2}c^{2}d)\]
Herzog and Hibi [HH] proved that every power of $H_P$ has a linear resolution, and the $i^{th}$ Betti number $\beta_i(R/H_P)$ is the number of intervals of the distributive lattice $\mathcal{L}(P)$ of $P$ isomorphic to the rank $i$ boolean lattice. Using Exercise 3.47 in Stanley’s book [St], we can recover this by looking instead at the number of elements of $\mathcal{L}(P)$ that cover exactly $i$ elements.

Moreover, Herzog and Hibi [HH] proved that the projective dimension of $H_P$ is the Dilworth number of $H_P$, i.e., the maximum length of an antichain of $H_P$.

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