NBC Complexes of Convex Geometries

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Brylawski's Decomposition of NBC Complexes of Abstract Convex Geometries and Their Associated Algebras

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We introduce a notion of a *broken circuit* and an *NBC complex* for an (abstract) convex geometry. Based on these definitions, we shall show the analogues of the Whitney-Rota's formula and Brylawski's decomposition theorem for broken circuit complexes on matroids for convex geometries. We also present an Orlik-Solomon type algebra on a convex geometry, and show the NBC generating theorem. This note is on the same line as the studies in [10, 11, 12].

Keywords: broken circuit, characteristic polynomial, NBC basis theorem

1 Closure Systems, Matroids, and Convex Geometries

A collection $K \subseteq 2^E$ of subsets of a finite set E is a *closure system* if

(1) $E \in K$,

(2) $X, Y \in K \Longrightarrow X \cap Y \in K$.

An element of K is called a *closed set*. A closure system determines a closure operator

$$\sigma(A) = \bigcap_{X \in K, A \subseteq X} X \qquad (A \subseteq E). \tag{1.1}$$

An element in $\cap\{X : X \in K\} = \sigma(\emptyset)$ is a *loop*, and K is *loop-free* if it has no loops.

A map $Ex : 2^E \to 2^E$ defined by $Ex(A) = \{e \in A : e \notin \sigma(A \setminus e)\}$ $(A \subseteq E)$ is an *extreme function*. We say that an element in $Ex(A)$ is an *extreme element* of A, and we call an extreme element of the entire set E a *coloop*. A subset $A \subseteq E$ is an *independent set* if $Ex(A) = A$. A set which is not independent is *dependent*, and a minimal dependent set is called a *circuit*. It is easy to see that any subset of an independent set is independent.

When a closure operator satisfies the Steinitz-McLane exchange property below,

$$\text{if } x, y \notin \sigma(A) \text{ and } y \in \sigma(A \cup x), \text{ then } x \in \sigma(A \cup y) \qquad (x, y \in E,\ A \subseteq E), \tag{1.2}$$

then the corresponding closure system is the set of flats (closed sets) of a matroid M on E, and vice versa. The notions of an independent set and a circuit introduced above as a closure system agree with the ordinary definitions of matroid theory.

Let M be a matroid on E, and suppose we have a linear order ω on E. When C is a circuit of M and e is the minimum element in C with respect to ω, we call $C \setminus e$ a *broken circuit*.

A subset of E is *nbc-independent* if it contains no broken circuits of M. Evidently an nbc-independent set is an independent set of M. The collection of nbc-independent sets forms a simplicial complex $NBC(M, \omega)$, which is called a *broken circuit complex* of M (with respect to ω).

When the closure operator satisfies the anti-exchange property below

$$\text{if } x, y \notin \sigma(A) \text{ and } y \in \sigma(A \cup x), \text{ then } x \notin \sigma(A \cup y) \qquad (x, y \in E,\ A \subseteq E), \tag{1.3}$$

the closure system K is called an *(abstract) convex geometry*. Convex geometries arise from various combinatorial objects such as affine point configurations, chordal graphs, posets, semi-lattices, searches on a rooted graph, and so on. (See [4, 9].)

Since a convex geometry itself is a closure system, we have the corresponding definitions of an independent set and a circuit for a convex geometry. In a circuit of a convex geometry there exists uniquely an element that is not extreme. (In a circuit of a matroid there is no element that is extreme.) That is, a circuit C of a convex geometry contains a unique element e such that $Ex(C) = C \setminus e$. We say that e is the *root* of C, and $X = C \setminus e$ is a *broken circuit* with respect to the root e. And (X, e) is a *rooted circuit*. Let us call a set *nbc-independent* if it contains no broken circuit. The collection of nbc-independent sets forms a simplicial complex, which is the *NBC complex* of K denoted by $NBC(K)$.

Note that to determine a broken circuit for a matroid it is required to assume a linear order on the underlying set, while there is no need to suppose such an order when we define a broken circuit for a convex geometry.

2 Whitney-Rota's Formula and Its Analogue

2.1 Matroid

The NBC complexes of matroids appear in the Whitney-Rota's formula. Let $\mathcal{L}(M)$ be the lattice consisting of the closed sets (flats) of M. The characteristic polynomial $p(M; \lambda)$ of M is defined by

$$p(\lambda; M) = \sum_{X \in \mathcal{L}(M)} \mu(\sigma(\emptyset), X)\lambda^{r(E)-r(X)}. \tag{2.1}$$

Then the Whitney-Rota's formula for matroids is described as

Theorem 2.1 (Rota [14]) For an arbitrary linear order ω on E, we have

$$p(\lambda; M) = \sum_{X \in NBC(M,\omega)} (-1)^{|X|}\lambda^{r(E)-r(X)}. \tag{2.2}$$

2.2 Convex Geometry

Let K be a loop-free convex geometry on a finite set E. The characteristic function of K is

$$p(\lambda; K) = \sum_{X \in K} \mu_K(\emptyset, X)\lambda^{|E|-|X|} \tag{2.3}$$

where μ_K is the Möbius function of the lattice K. A set which is both closed and independent is a *free set*. The collection of the free sets constitutes a simplicial complex, called a free complex [3]. A free complex plays an important role in the counting formula of the interior points of an affine point configuration proved by Klain [8], and Edelman and Reiner [5]. A free complex of a convex geometry can be revealed to be equal to its NBC complex. That is,

Theorem 2.2 A subset of E is a free set if and only if it is nbc-independent. Equivalently, the free complex of a convex geometry coincides with its NBC complex.

Edelman [3] explicitly determined the values of μ_K as:

Lemma 2.1 (Edelman [3]) For a closed set $X \in K$,

$$\mu_K(\emptyset, X) = \begin{cases} (-1)^{|X|} & \text{if } X \text{ is free,} \\ 0 & \text{otherwise.} \end{cases} \tag{2.4}$$

Theorem 2.2 and Lemma 2.1 immediately give rise to the Whitney-Rota's formula for convex geometry:

Theorem 2.3 For a convex geometry K and the characteristic polynomial (2.3), it holds that

$$p(\lambda; K) = \sum_{X \in NBC(K)} (-1)^{|X|} \lambda^{|E|-|X|}. \tag{2.5}$$

3 Brylawskifs Decomposition and Its Analogue

3.1 Matroid

Brylawski [2] showed a direct-sum decomposition theorem of NBC complex of a matroid below.

Theorem 3.1 (Brylawski [2]) Let (M, ω) be an ordered matroid, and x be the maximum element with respect to ω. Then

$$NBC(M, \omega) = NBC(M \setminus x, \omega) \uplus (NBC(M/x, \omega) * x) \tag{3.1}$$

where $NBC(M/x, \omega) * x = \{A \cup x \ : \ A \in NBC(M/x, \omega)\}$

3.2 Convex Geometry

Let K be a convex geometry on E. For a coloop e, $K \setminus e = \{X : X \in K, e \notin X\}$ is a convex geometry on $E \setminus e$, which is a *deletion* of e from K. For any element $e \in E$, $K/e = \{X \setminus e : X \in K, e \in X\}$ is a convex geometry on $E \setminus e$, which is a *contraction* of e from K. We have Brylawski's decomposition theorem for convex geometries as

Theorem 3.2 For a coloop $x \in E$ of a convex geometry K, we have

$$NBC(K) = NBC(K \setminus x) \uplus (NBC(K/x) * x) \tag{3.2}$$

4 Orlik-Solomon Algebra and Its Analogues

4.1 Matroid

An NBC complex is known to provide a linear basis of the Orlik-Solomon algebra, which we shall describe below. Suppose $E = \{e_1, \ldots, e_n\}$. Taking $e_1, \ldots, e_n$ as generators, we denote a graded external algebra over the free module $\oplus_{e \in E} \mathbb{Z}e$ by $\bigwedge E = \oplus_{i \in \mathbb{N}} \bigwedge^i E$. A linear map $\partial : \bigwedge E \longrightarrow \bigwedge E$ is defined by

(1) $\partial_0 : \mathbb{Z} \longrightarrow (0)$, (2) $\partial_1 : \bigwedge^1 E \longrightarrow \mathbb{Z}$ where $\partial(e) = 1 \quad (e \in E)$,

(3) for $k = 2, \ldots, n$:

$$\partial_k : \bigwedge^k E \longrightarrow \bigwedge^{k-1} E, \qquad \partial_k(e_{i_1} \wedge \ldots \wedge e_{i_k}) = \sum_{j=1}^{k} (-1)^{j-1} e_{i_1} \wedge \ldots \wedge \widehat{e_{i_j}} \wedge \ldots \wedge e_{i_k}$$

Although it is a little abuse of terminology, for the sake of simplicity, we associate a term $e_X = x_1 \wedge \cdots \wedge x_t$ in $\bigwedge E$ with each subset $X = \{x_1, \ldots, x_t\} \subseteq E$.

Suppose $I(M)$ to be an ideal generated by $\{\partial(e_C) : C \text{ is a circuit of } M \text{ with } |C| \geqslant 2\} \cup \{e : e \text{ is a loop od } M\}$. Then the *Orlik-Solomon algebra* of M is defined as

$$OS(M) = \left(\bigwedge E\right) / I(M). \tag{4.1}$$

Theorem 4.1 (NBC basis theorem for the Orlik-Solomon algebra [1], [13]) Let M be a matroid on E, and ω be an arbitrary linear order on the underlying set. Then $\{e_X : X \in NBC(M, \omega)\}$ is a linear basis of module $OS(M)$.

4.2 Convex Geoemtry

Suppose K to be a loop-free convex geometry on $E = \{e_1, \ldots, e_n\}$. The graded external algebra $\bigwedge E = \oplus_{i=0}^{n} \bigwedge^i E$ and a linear map $\partial : \bigwedge E \longrightarrow \bigwedge E$ are defined in the same way as before. And let $I(K)$ be the ideal in $\bigwedge E$ generated by $\{\partial(e_C) : C \text{ is a circuit of } K\}$, and let us define an *Orlik-Solomon type algebra of a convex geometry* K by

$$OS(K) = \left(\bigwedge E\right) / I(K). \tag{4.2}$$

It can be shown that $\{e_X : X \in NBC(K)\}$ is a linear generating set of $OS(K)$. That is, although the NBC basis theorem (Theorem 4.1) does not hold for $OS(K)$, we have a weaker form, the NBC generating theorem, below.

Theorem 4.2 An arbitrary element in $OS(K)$ can be represented as a linear combination of the terms in $\{e_X : X \in NBC(K)\}$.

There is an alternative definition of an Orlik-Solomon type algebra so that the NBC basis theorem would be satisfied. Let $J(K)$ be the ideal generated by $\{e_X : X \text{ is a broken circuit of } K\}$, and let us define an algebra

$$A(K) = \left(\bigwedge E\right) / J(K) \tag{4.3}$$

By definition $\{e_X : X \in NBC(K)\}$ is necessarily a linear basis of module $A(K)$.

Hence the decomposition of Theorem 3.2 readily implies the short exact split sequence theorem for $A(K)$.

Theorem 4.3 For a coloop x of a convex geometry K,

$$0 \rightarrow A(K \setminus x) \xrightarrow{i_x} A(K) \xrightarrow{p_x} A(K/x) \rightarrow 0 \tag{4.4}$$

is an exact short split sequence.

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