

Sum Complexes—a New Family of Hypertrees

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Abstract A k -dimensional hypertree X is a k -dimensional complex on n vertices with a full $(k - 1)$ -dimensional skeleton and $\binom{n-1}{k}$ facets such that $H_k(X; \mathbb{Q}) = 0$. Here we introduce the following family of simplicial complexes. Let n, k be integers with $k + 1$ and n relatively prime, and let A be a $(k + 1)$ -element subset of the cyclic group \mathbb{Z}_n . The *sum complex* X_A is the pure k -dimensional complex on the vertex set \mathbb{Z}_n whose facets are $\sigma \subset \mathbb{Z}_n$ such that $|\sigma| = k + 1$ and $\sum_{x \in \sigma} x \in A$. It is shown that if n is prime, then the complex X_A is a k -hypertree for every choice of A . On the other hand, for n prime, X_A is k -collapsible iff A is an arithmetic progression in \mathbb{Z}_n .

Keywords Hypertrees · Homology · Fourier transform

1 Introduction

What is the high-dimensional analogue of a tree? Several approaches to this question can be found in the literature. Here we follow the lead of Kalai [1]. We start with some standard notation. All simplicial complexes we consider X have n vertices, and we always identify the vertex set of X with the cyclic group \mathbb{Z}_n . The number of i -dimensional faces of X is denoted by $f_i(X)$. We denote by Δ_{n-1} the $(n - 1)$ -

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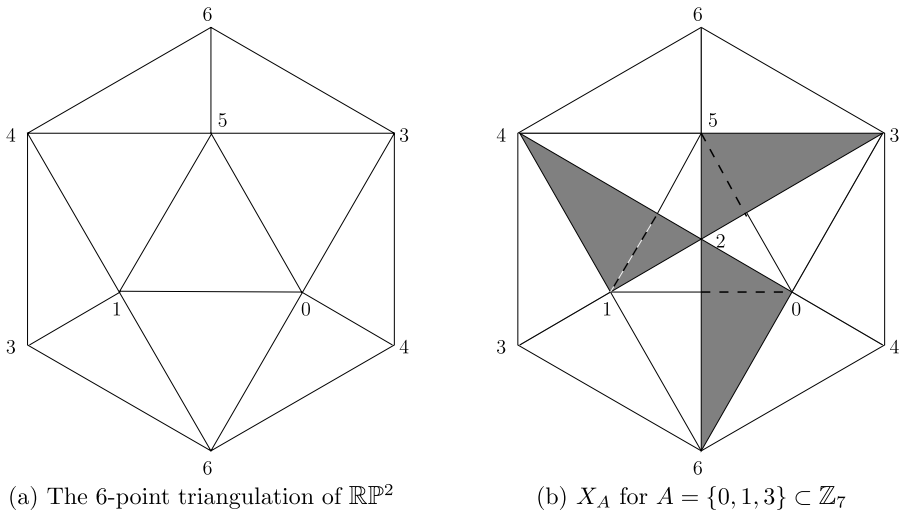


Fig. 1

simplex on the vertex set \mathbb{Z}_n and by $\Delta_{n-1}^{(i)}$ the i -dimensional skeleton of Δ_{n-1} . A k -hypertree is a simplicial complex $\Delta_{n-1}^{(k-1)} \subset X \subset \Delta_{n-1}^{(k)}$ such that $f_k(X) = \binom{n-1}{k}$ and with a vanishing k th rational homology $H_k(X; \mathbb{Q}) = 0$. Throughout the paper we assume that $k + 1$ is coprime to n . For $a \in \mathbb{Z}_n$, let X_a be the following collection of subsets of \mathbb{Z}_n :

$$X_a = \left\{ \sigma \subset \mathbb{Z}_n : |\sigma| = k + 1, \sum_{x \in \sigma} x = a \right\}.$$

For a subset $A \subset \mathbb{Z}_n$ of cardinality $k + 1$, define the *Sum Complex* X_A by

$$X_A = \Delta_{n-1}^{(k-1)} \cup \left(\bigcup_{a \in A} X_a \right).$$

Example Let $n = 7, k = 2$, and $A = \{0, 1, 3\} \subset \mathbb{Z}_7$. The two-dimensional complex X_A (Fig. 1b) is obtained from the standard 6-point triangulation of the real projective plane $\mathbb{R}P^2$ on the vertices $\{0, 1, 3, 4, 5, 6\}$ (Fig. 1a) by replacing the face $\{0, 1, 5\}$ with the three faces $\{0, 1, 2\}, \{0, 2, 5\}$, and $\{1, 2, 5\}$ and adding the faces $\{2, 3, 5\}, \{0, 2, 6\}$, and $\{1, 2, 4\}$. X_A is clearly homotopy equivalent to $\mathbb{R}P^2$.

In this paper we are concerned with topological and combinatorial properties of X_A . Let \mathbb{F} be a field, and let $h_i(X_A; \mathbb{F}) = \dim_{\mathbb{F}} H_i(X_A; \mathbb{F})$. Since $X_A \supset \Delta_{n-1}^{(k-1)}$, it follows that $h_0(X_A; \mathbb{F}) = 1$ and $h_i(X_A; \mathbb{F}) = 0$ for $1 \leq i \leq k - 2$. Since $k + 1$ is coprime to n , it follows that for any $y \in \mathbb{Z}_n$, the number of $\sigma \subset \mathbb{Z}_n$ of cardinality $k + 1$ that satisfy $\sum_{x \in \sigma} x = y$ is $\frac{1}{n} \binom{n}{k+1}$. Therefore $f_k(X_A) = \frac{k+1}{n} \binom{n}{k+1} = \binom{n-1}{k}$. The Euler–Poincaré relation $\sum_{i \geq 0} (-1)^i f_i(X_A) = \sum_{i \geq 0} (-1)^i h_i(X_A; \mathbb{F})$ then implies that $h_{k-1}(X_A; \mathbb{F}) = h_k(X_A; \mathbb{F})$. In the sequel we assume that the characteristic of \mathbb{F} does not divide n .

Let ω be a fixed primitive n th root of unity in the algebraic closure $\overline{\mathbb{F}}$. For $x \in \mathbb{Z}_n$, let $e(x) = \omega^x$. The $n \times n$ Fourier matrix M over $\overline{\mathbb{F}}$ is given by $M(u, v) = e(-uv)$ for $u, v \in \mathbb{Z}_n$. For a subset $B \subset \mathbb{Z}_n$ of cardinality $k + 1$, let $M_{A,B}$ denote the $(k + 1) \times (k + 1)$ submatrix of M determined by A and B . Let $\mathcal{B}_{n,k}$ denote the family of all $(k + 1)$ -element subsets of \mathbb{Z}_n that contain 0.

Theorem 1.1

$$h_{k-1}(X_A; \mathbb{F}) = h_k(X_A; \mathbb{F}) = \frac{1}{k + 1} \sum_{B \in \mathcal{B}_{n,k}} \dim \ker M_{A,B}. \tag{1}$$

The Fourier transform matrix $M = (M_{uv})$ of \mathbb{Z}_n over $\overline{\mathbb{Q}} \subset \mathbb{C}$ is given by $M_{uv} = \exp(-2\pi i uv/n)$. A classical result of Chebotarëv (see, e.g., [3]) asserts that if n is prime, then any square submatrix of M is nonsingular. Theorem 1.1 therefore implies the following:

Corollary 1.2 *If n is prime, then X_A is a k -hypertree.*

If A is an arithmetic progression in \mathbb{Z}_n , then $M_{A,B}$ is a Vandermonde matrix for all $B \in \mathcal{B}_{n,k}$. Hence, by Theorem 1.1, X_A is \mathbb{F} -acyclic for any \mathbb{F} whose characteristic is coprime to n . More is in fact true. Let σ be a face of dimension at most $k - 1$ of a simplicial complex X which is contained in a *unique* maximal face τ of X , and let $[\sigma, \tau] = \{\eta : \sigma \subset \eta \subset \tau\}$. The operation $X \rightarrow Y = X - [\sigma, \tau]$ is called an *elementary k -collapse*. X is *k -collapsible* if there exists a sequence of elementary k -collapses

$$X = X_1 \rightarrow X_2 \rightarrow \dots \rightarrow X_m = \{\emptyset\}.$$

Note that if $\Delta_{n-1}^{(k-1)} \subset X \subset \Delta_{n-1}^{(k)}$ is k -collapsible and $f_k(X) = \binom{n-1}{k}$, then X is \mathbb{Z} -acyclic.

Theorem 1.3 *Let n be a prime, and let A be a subset of \mathbb{Z}_n of cardinality $k + 1$. Then X_A is k -collapsible iff A is an arithmetic progression in \mathbb{Z}_n .*

Theorems 1.1 and 1.3 are proved in Sects. 2 and 3. In Sect. 4 we compute the homology of X_A for $A = \{0, 1, 3\}$. We conclude in Sect. 5 with some remarks concerning possible extensions and open problems.

2 Homology of X_A

We first recall some topological terminology (see, e.g., [2]). Let X be a finite simplicial complex on the vertex set V . For a set S and a field \mathbb{K} , let $\mathcal{L}(S, \mathbb{K})$ denote the \mathbb{K} -linear space of all \mathbb{K} -valued functions on S . The space $C^m(X; \mathbb{K})$ of \mathbb{K} -valued m -cochains of X consists of all functions $\phi \in \mathcal{L}(V^{m+1}, \mathbb{K})$ such that $\phi(v_0, \dots, v_m) = \text{sgn}(\pi)\phi(v_{\pi(0)}, \dots, v_{\pi(m)})$ for any permutation π on $\{0, \dots, m\}$ and such that $\phi(v_0, \dots, v_m) = 0$ if $\{v_0, \dots, v_m\}$ is not an m -dimensional simplex of X .

(In particular, $\phi(v_0, \dots, v_m) = 0$ if $v_i = v_j$ for some $i \neq j$.) The coboundary operator $d_m : C^m(X; \mathbb{K}) \rightarrow C^{m+1}(X; \mathbb{K})$ is given by

$$d_m \phi(v_0, \dots, v_{m+1}) = \sum_{i=0}^{m+1} (-1)^i \phi(v_0, \dots, \hat{v}_i, \dots, v_{m+1}).$$

Let $Z^m(X; \mathbb{K}) = \ker d_m$ denote the space of m -cocycles of X over \mathbb{K} , and let $B^m(X; \mathbb{K}) = \text{Im } d_{m-1}$ denote the space of m -coboundaries of X over \mathbb{K} . The m -dimensional cohomology space of X with coefficients in \mathbb{K} is

$$H^m(X; \mathbb{K}) = \frac{Z^m(X; \mathbb{K})}{B^m(X; \mathbb{K})}.$$

Let $h^m(X, \mathbb{K}) = \dim_{\mathbb{K}} H^m(X; \mathbb{K})$. Then $h^m(X, \mathbb{K}) = h^m(X, \mathbb{F}) = h_m(X; \mathbb{F})$ for any algebraic extension \mathbb{K} of \mathbb{F} . In order to establish Theorem 1.1, we may therefore assume that \mathbb{F} already contains a primitive n th root of unity ω .

The Fourier transform of a function $\phi \in \mathcal{L}(\mathbb{Z}_n^k; \mathbb{F})$ is the function $\mathcal{F}(\phi) = \widehat{\phi} \in \mathcal{L}(\mathbb{Z}_n^k; \mathbb{F})$ given by

$$\widehat{\phi}(u_1, \dots, u_k) = \sum_{(x_1, \dots, x_k) \in \mathbb{Z}_n^k} \phi(x_1, \dots, x_k) e\left(-\sum_{j=1}^k u_j x_j\right).$$

The Fourier transform is an automorphism of $\mathcal{L}(\mathbb{Z}_n^k; \mathbb{F})$.

The proof of Theorem 1.1 involves computing the image of $H^{k-1}(X; \mathbb{F})$ under the Fourier transform. We first consider the Fourier image of the $(k - 1)$ -coboundaries.

Claim 2.1

$$\mathcal{F}(B^{k-1}(X_A; \mathbb{F})) = \{g \in C^{k-1}(X_A; \mathbb{F}) : \text{support}(g) \subset \mathbb{Z}_n^k - (\mathbb{Z}_n - \{0\})^k\}.$$

Proof Let $\psi \in C^{k-2}(X_A; \mathbb{F})$. Then

$$\begin{aligned} & \widehat{d_{k-2}\psi}(u_1, \dots, u_k) \\ &= \sum_{(x_1, \dots, x_k) \in \mathbb{Z}_n^k} d_{k-2}\psi(x_1, \dots, x_k) e\left(-\sum_{j=1}^k u_j x_j\right) \\ &= \sum_{(x_1, \dots, x_k) \in \mathbb{Z}_n^k} \left(\sum_{i=1}^k (-1)^{i+1} \psi(x_1, \dots, \hat{x}_i, \dots, x_k)\right) e\left(-\sum_{j=1}^k u_j x_j\right) \\ &= \sum_{i=1}^k (-1)^{i+1} \sum_{x_i} e(-u_i x_i) \sum_{x_1, \dots, \hat{x}_i, \dots, x_k} \psi(x_1, \dots, \hat{x}_i, \dots, x_k) e\left(-\sum_{j \neq i} u_j x_j\right) \\ &= n \sum_{i=1}^k (-1)^{i+1} \delta(0, u_i) \sum_{x_1, \dots, \hat{x}_i, \dots, x_k} \psi(x_1, \dots, \hat{x}_i, \dots, x_k) e\left(-\sum_{j \neq i} u_j x_j\right), \end{aligned}$$

where $\delta(0, u_i) = 1$ if $u_i = 0$ and is zero otherwise. Therefore,

$$\mathcal{F}(B^{k-1}(X_A; \mathbb{F})) \subset \{g \in C^{k-1}(X_A; \mathbb{F}) : \text{support}(g) \subset \mathbb{Z}_n^k - (\mathbb{Z}_n - \{0\})^k\}.$$

Equality follows since both spaces have dimension $\binom{n-1}{k-1}$ over \mathbb{F} . □

We next study the Fourier image of the $(k - 1)$ -cocycles of X_A . Fix a $\phi \in C^{k-1}(X_A; \mathbb{F})$. For $a \in \mathbb{Z}_n$, define the function $f_a \in \mathcal{L}(\mathbb{Z}_n^k; \mathbb{F})$ by

$$\begin{aligned} f_a(x_1, \dots, x_k) &= d_{k-1}\phi\left(a - \sum_{i=1}^k x_i, x_1, \dots, x_k\right) \\ &= \phi(x_1, \dots, x_k) + \sum_{i=1}^k (-1)^i \phi\left(a - \sum_{j=1}^k x_j, x_1, \dots, \hat{x}_i, \dots, x_k\right). \end{aligned}$$

Let T be the automorphism of \mathbb{Z}_n^k given by

$$T(u_1, \dots, u_k) = (u_2 - u_1, \dots, u_k - u_1, -u_1).$$

Then $T^{k+1} = I$ and, for $1 \leq i \leq k$,

$$T^i(u_1, \dots, u_k) = (u_{i+1} - u_i, \dots, u_k - u_i, -u_i, u_1 - u_i, \dots, u_{i-1} - u_i).$$

Claim 2.2 *Let $u = (u_1, \dots, u_k) \in \mathbb{Z}_n^k$. Then*

$$\widehat{f}_a(u) = \widehat{\phi}(u) + \sum_{i=1}^k (-1)^{ki} e(-u_i a) \widehat{\phi}(T^i u). \tag{2}$$

Proof For $1 \leq i \leq k$, let $\psi_i \in \mathcal{L}(\mathbb{Z}_n^k, \mathbb{F})$ be given by

$$\psi_i(x_1, \dots, x_k) = \phi\left(a - \sum_{j=1}^k x_j, x_1, \dots, \hat{x}_i, \dots, x_k\right).$$

Then

$$\widehat{\psi}_i(u) = \sum_{(x_1, \dots, x_k) \in \mathbb{Z}_n^k} \phi\left(a - \sum_{j=1}^k x_j, x_1, \dots, \hat{x}_i, \dots, x_k\right) e\left(-\sum_{j=1}^k u_j x_j\right).$$

Substituting

$$y_j = \begin{cases} a - \sum_{\ell=1}^k x_\ell, & j = 1, \\ x_{j-1}, & 2 \leq j \leq i, \\ x_j, & i + 1 \leq j \leq k, \end{cases}$$

it follows that

$$\sum_{j=1}^k u_j x_j = (a - y_1)u_i + \sum_{j=2}^i (u_{j-1} - u_i)y_j + \sum_{j=i+1}^k (u_j - u_i)y_j.$$

Therefore,

$$\begin{aligned} \widehat{\psi}_i(u) &= e(-u_i a) \\ &\times \sum_{y=(y_1, \dots, y_k) \in \mathbb{Z}_n^k} \phi(y) e\left(u_i y_1 - \sum_{j=2}^i (u_{j-1} - u_i)y_j - \sum_{j=i+1}^k (u_j - u_i)y_j\right) \\ &= e(-u_i a) \widehat{\phi}(-u_i, u_1 - u_i, \dots, u_{i-1} - u_i, u_{i+1} - u_i, \dots, u_k - u_i) \\ &= e(-u_i a) (-1)^{i(k-i)} \widehat{\phi}(T^i u). \end{aligned} \tag{3}$$

Now (2) follows from (3) since $f_a = \phi + \sum_{i=1}^k (-1)^i \psi_i$. □

For $u \in \mathbb{Z}_n^k$, let $E_u = \{T^i u : 0 \leq i \leq k\}$, and let

$$L_u = \bigcap_{a \in A} \left\{ g \in \mathcal{L}(E_u, \mathbb{F}) : g(u) + \sum_{i=1}^k (-1)^{ki} e(-u_i a) g(T^i u) = 0 \right\}. \tag{4}$$

Let $\phi \in Z^{k-1}(X_A; \mathbb{F})$. Then, for all $a \in A$ and $(x_1, \dots, x_k) \in \mathbb{Z}_n^k$,

$$f_a(x_1, \dots, x_k) = d_{k-1} \phi\left(a - \sum_{i=1}^k x_i, x_1, \dots, x_k\right) = 0.$$

Equation (2) then implies that, for all $a \in A$ and $u \in \mathbb{Z}_n^k$,

$$\widehat{\phi}(u) + \sum_{i=1}^k (-1)^{ki} e(-u_i a) \widehat{\phi}(T^i u) = 0.$$

Writing $\widehat{\phi}|_{E_u}$ for the restriction of $\widehat{\phi}$ to E_u , we obtain the following:

Corollary 2.3 *Let $\phi \in C^{k-1}(X_A; \mathbb{F})$. Then $\phi \in Z^{k-1}(X_A; \mathbb{F})$ iff $\widehat{\phi}|_{E_u} \in L_u$ for all $u \in \mathbb{Z}_n^k$.* □

Let the symmetric group S_k act on \mathbb{Z}_n^k by

$$\sigma((u_1, \dots, u_k)) = (u_{\sigma^{-1}(1)}, \dots, u_{\sigma^{-1}(k)}),$$

and let $G_{n,k}$ denote the subgroup of $\text{Aut}(\mathbb{Z}_n^k)$ generated by T and S_k . The subset

$$D_{n,k} = \{(u_1, \dots, u_k) \in (\mathbb{Z}_n - \{0\})^k : u_i \neq u_j \text{ for } i \neq j\}$$

is clearly invariant under $G_{n,k}$.

Claim 2.4

- (i) Let $\sigma \in S_k$ and $1 \leq i \leq k$. Then $\eta = T^i \sigma T^{-\sigma^{-1}(i)} \in S_k$ and $\text{sgn}(\eta) = (-1)^{k(i+\sigma^{-1}(i))} \text{sgn}(\sigma)$.
- (ii) Any element of $G_{n,k}$ can be written uniquely as σT^i where $\sigma \in S_k$ and $0 \leq i \leq k$. $G_{n,k}$ acts freely on $D_{n,k}$.
- (iii) $L_u = L_{T^j u}$ for all $u \in D_{n,k}$ and $0 \leq j \leq k$.

Proof

- (i) For $1 \leq \ell \leq k$, let $\tau_\ell \in S_k$ be given by

$$\tau_\ell(i) = \begin{cases} k - \ell + 1 + i, & 1 \leq i \leq \ell - 1, \\ k - \ell + 1, & i = \ell, \\ i - \ell, & \ell + 1 \leq i \leq k. \end{cases}$$

It can be checked that

$$\eta = T^i \sigma T^{-\sigma^{-1}(i)} = \tau_{k-i+1}^{-1} \sigma \tau_{k-\sigma^{-1}(i)+1}.$$

Noting that $\text{sgn}(\tau_\ell) = (-1)^{k\ell+1}$, it thus follows that

$$\text{sgn}(\eta) = \text{sgn}(\sigma) \text{sgn}(\tau_{k-i+1}) \text{sgn}(\tau_{k-\sigma^{-1}(i)+1}) = (-1)^{k(i+\sigma^{-1}(i))} \text{sgn}(\sigma).$$

- (ii) It follows from (i) that

$$G_{n,k} = \{ \sigma T^i : \sigma \in S_k, 0 \leq i \leq k \}.$$

Let $u = (u_1, \dots, u_k) \in D_{n,k}$, and let $v = (v_1, \dots, v_k) = \sigma T^i u$. If $i \neq 0$, then

$$\sum_{j=1}^k v_j = \sum_{j=1}^k u_j - (k+1)u_i \neq \sum_{j=1}^k u_j,$$

and therefore $\sigma T^i u \neq u$. It follows that $G_{n,k}$ acts freely on $D_{n,k}$ and that the representation of an element of $G_{n,k}$ as σT^i is unique.

- (iii) Let $g \in L_u$ and $a \in A$. Then

$$\begin{aligned} &g(T^j u) + \sum_{i=1}^k (-1)^{ik} e(-(T^j u)_i a) g(T^{i+j} u) \\ &= g(T^j u) + \sum_{i=1}^{k-j} (-1)^{ik} e(-(u_{i+j} - u_j) a) g(T^{i+j} u) \\ &\quad + (-1)^{(k-j+1)k} e(u_j a) g(u) \end{aligned}$$

$$\begin{aligned}
 &+ \sum_{i=k-j+2}^k (-1)^{ik} e^{-(u_{i-k+j-1} - u_j)a} g(T^{i+j}u) \\
 &= (-1)^{jk} e^{(u_j a)} \left(g(u) + \sum_{i=1}^k (-1)^{ik} e^{-u_i a} g(T^i u) \right) = 0. \tag{5}
 \end{aligned}$$

Hence $g \in L_{T^j u}$. □

Proof of Theorem 1.1: Let $R \subset D_{n,k}$ be a fixed set of representatives of the orbits of $G_{n,k}$ on $D_{n,k}$. Then $|R| = \frac{|D_{n,k}|}{|G_{n,k}|} = \frac{1}{k+1} \binom{n-1}{k}$. Consider the mapping

$$\Theta : Z^{k-1}(X_A; \mathbb{F}) \rightarrow \bigoplus_{u \in R} L_u$$

given by

$$\Theta(\phi) = (\widehat{\phi}|_{E_u} : u \in R).$$

□

Claim 2.5

$$\ker \Theta = B^{k-1}(X_A; \mathbb{F}).$$

Proof

$$\begin{aligned}
 \ker \Theta &= \{ \phi \in Z^{k-1}(X_A; \mathbb{F}) : \widehat{\phi}|_{E_u} = 0 \text{ for all } u \in R \} \\
 &= \{ \phi \in Z^{k-1}(X_A; \mathbb{F}) : \widehat{\phi}(u) = 0 \text{ for all } u \in D_{n,k} \} = B^{k-1}(X_A; \mathbb{F})
 \end{aligned}$$

by Claim 2.1. □

Claim 2.6 Θ is surjective.

Proof Let $(g_u : u \in R) \in \bigoplus_{u \in R} L_u$. Define $g \in C^{k-1}(X_A; \mathbb{F})$ by

$$g(v) = \begin{cases} 0, & v \notin D_{n,k}, \\ \text{sgn}(\sigma) g_u(T^j u), & v = \sigma T^j u, \text{ where } u \in R. \end{cases}$$

Clearly $\Theta(\mathcal{F}^{-1}(g)) = (g_u : u \in R)$. To show that $\mathcal{F}^{-1}(g) \in Z^{k-1}(X_A; \mathbb{F})$, it suffices by Corollary 2.3 to check that $g \in L_v$ for all $v \in \mathbb{Z}_n^k$. If $v \notin D_{n,k}$, then $g|_{E_v} = 0$. Suppose then that $v = \sigma T^j u \in D_{n,k}$, where $u \in R$ and $0 \leq j \leq k$. Combining Claim 2.4(i) and (5), it follows that

$$\begin{aligned}
 &g(v) + \sum_{i=1}^k (-1)^{ik} e^{-v_i a} g(T^i v) \\
 &= g(\sigma T^j u) + \sum_{i=1}^k (-1)^{ik} e^{-(\sigma T^j u)_i a} g(T^i \sigma T^j u)
 \end{aligned}$$

$$\begin{aligned}
 &= \operatorname{sgn}(\sigma)g_u(T^j u) \\
 &\quad + \sum_{i=1}^k (-1)^{ik} e(-(T^j u)_{\sigma^{-1}(i)} a) (-1)^{k(i+\sigma^{-1}(i))} \operatorname{sgn}(\sigma)g_u(T^{\sigma^{-1}(i)+j} u) \\
 &= \operatorname{sgn}(\sigma) \left(g_u(T^j u) + \sum_{i=1}^k (-1)^{ik} e(-(T^j u)_i a) g_u(T^{i+j} u) \right) \\
 &= (-1)^{jk} \operatorname{sgn}(\sigma) e(u_j a) \left(g_u(u) + \sum_{i=1}^k (-1)^{ik} e(-u_i a) g_u(T^i u) \right) = 0. \quad \square
 \end{aligned}$$

Claims 2.5 and 2.6 imply that

$$H^{k-1}(X_A, \mathbb{F}) \cong \bigoplus_{u \in R} L_u. \tag{6}$$

For $u = (u_1, \dots, u_k) \in D_{n,k}$, let $B_u = \{0, u_1, \dots, u_k\}$. Then $\dim L_u = \dim \ker M_{A, B_u}$. Combining (6) with Claim 2.4(iii), it thus follows that

$$\begin{aligned}
 h^{k-1}(X_A; \mathbb{F}) &= \sum_{u \in R} \dim L_u \\
 &= \frac{1}{k+1} \sum_{u \in R} \sum_{j=0}^k \dim L_{T^j u} = \frac{1}{k+1} \sum_{B \in \mathcal{B}_{n,k}} \dim \ker M_{A, B}. \quad \square
 \end{aligned}$$

3 When is X_A Collapsible?

In this section we prove Theorem 1.3, so that in this section n is prime. We find it convenient to maintain the vertices in a face sorted according to the order induced from \mathbb{N} and also refer to subsets of \mathbb{F}_n as sorted vectors and not only as sets.

3.1 Equivalence

Let $\phi : \mathbb{F}_n \rightarrow \mathbb{F}_n$ be the linear map $\phi(x) = \alpha x + \beta$. It is clear that the image of X_a under ϕ is X_t where $t = \alpha a + (k + 1)\beta$. We say that the complexes X_{a_0, \dots, a_k} and X_{b_0, \dots, b_k} are *equivalent* iff there exist a permutation π on $\{b_0, \dots, b_k\}$ and α, β such that $\pi(b_i) = \alpha a_i + (k + 1)\beta$ for every $0 \leq i \leq k$. Equivalent complexes are clearly isomorphic.

It is an easy observation that a_0, \dots, a_k is an arithmetic progression iff X_{a_0, \dots, a_k} is equivalent to the complex $X_{0, \dots, k}$. We show that $X = X_{0, \dots, k}$ is collapsible, whence X_{a_0, \dots, a_k} is collapsible for a_0, \dots, a_k an arithmetic progression.

3.2 Proof of Sufficiency

To show that X is collapsible, we introduce an order \prec_R by which we remove the k -faces from X . We first need some preliminary definitions. With every k -face $u \in X$,

we associate a vector $h(u)$ of dimension $\lceil \frac{k}{2} \rceil$. The i th coordinate in h counts how many integers in the interval $[u_i, u_{k-i}]$ do not belong to $\{u_i, \dots, u_{k-i}\}$. Namely, the i th coordinate of $h(u)$ is

$$h_i(u) := u_{k-i} - u_i - (k - 2i).$$

Clearly $h_i(u)$ is nonincreasing in i . For every two k -faces $u, v \in X$, we say that $u <_L v$ if $h(u)$ is lexicographically smaller than $h(v)$. When $h(u) = h(v)$, we say that $u \equiv_L v$. It should be clear that h is invariant under set reversal, i.e., $x \rightarrow n - x$. It is also invariant under shifts that “do not overflow” in the obvious sense, but we will not use this fact. If $u \not\equiv_L v$ for some $u, v \in X$, we denote by $\delta_L(u, v)$ the first index for which $h(u)$ and $h(v)$ differ. Thus if $u <_L v$ and $\delta_L(u, v) = i$, then $h_j(u) = h_j(v)$ for all $j < i$ and $h_i(u) < h_i(v)$.

For $i, j \in \mathbb{F}_n$, it is convenient to define $\rho(i, j)$ as $i - j$ if $i > j$ and as $j - i$ otherwise. This is extended as usual to $\rho(i, A) = \min\{\rho(i, a) \mid a \in A\}$ and $\rho(A, B) = \min\{\rho(a, b) \mid a \in A, b \in B\}$.

If $u \in X_i$ and $v \in X_j$, we say that $u <_I v$ if i is closer than j to $\{0, k\}$, i.e., if $\rho(i, \{0, k\}) < \rho(j, \{0, k\})$. We say that $u \equiv_I v$ when $\rho(i, \{0, k\}) = \rho(j, \{0, k\})$, namely, $i = j$ or $i = k - j$. Letting $i' = \rho(i, \{0, k\})$, it is clear that $u <_I v$ iff $i' < j'$. If $u \not\equiv_I v$, we denote $\delta_I(u, v) = \min\{i', j'\} = \rho(\{i, j\}, \{0, k\})$.

We are now ready to define the relation $<_R$. This is done in terms of the relations $<_L$ and $<_I$. To begin, $u \equiv_R v$ iff $u \equiv_L v$ and $u \equiv_I v$. If $u \leq_L v$ and $u \leq_I v$ and at least one inequality is proper, then $u <_R v$. Finally, when $u <_L v$ and $u >_I v$, the order $<_R$ is determined according to the smaller of $\delta_I(u, v), \delta_L(u, v)$. Namely, if $\delta_I(u, v) < \delta_L(u, v)$, then $u >_R v$, and if $\delta_I(u, v) \geq \delta_L(u, v)$, then $u <_R v$.

To sum up, for $u, v \in X$:

1. if $u \equiv_I v$ and $u \equiv_L v$, then $u \equiv_R v$
2. if $u \equiv_I v$ and $u <_L v$, then $u <_R v$
3. if $u <_I v$, then $u <_R v$ unless
 - (a) $u >_L v$ and
 - (b) $\delta_L(u, v) \leq \delta_I(u, v)$
 in which case $u >_R v$

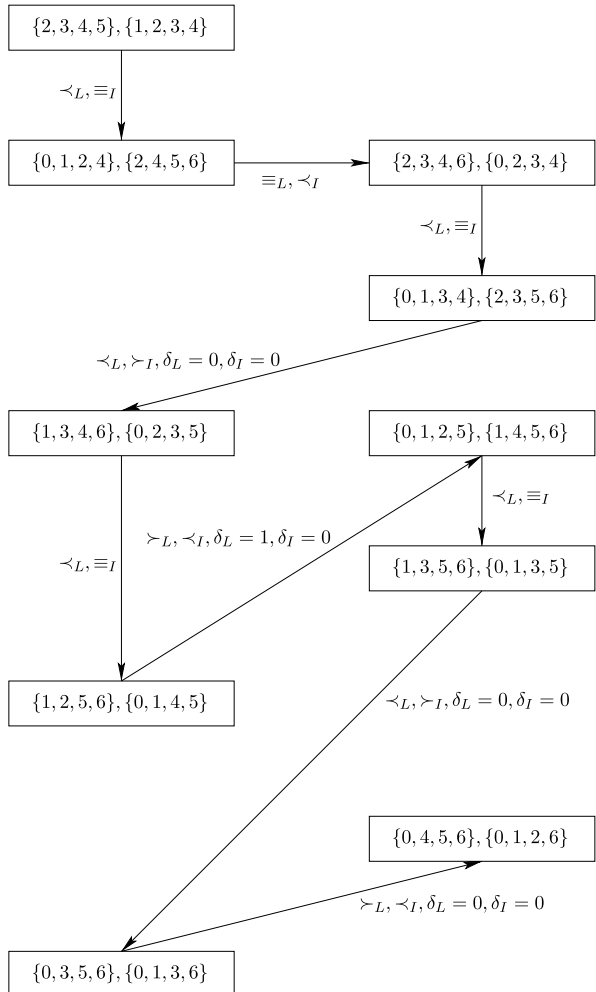
To clarify this definitions a little bit more, we present an example from the complex $X_{0,1,2,3}$ over \mathbb{F}_7 . Let $u = \{0, 1, 2, 5\}$ and $v = \{1, 2, 5, 6\}$. The set u has two missing integers between 0 and 5 and no missing integers between 1 and 2; hence $h(u) = h(\{0, 1, 2, 5\}) = (2, 0)$. Similarly $h(v) = h(\{1, 2, 5, 6\}) = (2, 2)$. Also, $u <_L v$ because $(2, 0)$ is lexicographically smaller than $(2, 2)$. Furthermore, $\delta_L(u, v) = 1$ because the first coordinate the vectors differ is the second coordinate (and we start indexing coordinates from zero). Now $u \in X_1$ since $0 + 1 + 2 + 5 \equiv 1 \pmod 7$. Similarly $v \in X_0$. We next calculate that $1' = 1 = \rho(1, \{0, 7\})$ and $0' = 0$. Hence $v <_I u$ because $0' < 1'$, and $\delta_I(u, v) = \min\{0, 1\} = 0$. To recap, $u <_L v$ and $v <_I u$, so we turn to compare $0 = \delta_I(u, v) < \delta_L(u, v) = 1$; it follows that in this case the order R is determined by I , and hence $\{0, 1, 2, 5\} = u >_R v = \{1, 2, 5, 6\}$. A full description of the order R on $X_{0,1,2,3}$ over \mathbb{F}_7 is shown in Figs. 2 and 3.

A few words are in order about Fig. 2. The rows are sorted by the lexicographic order of $h(\cdot)$. The columns on the right include all facets of X sorted by value of i' .

$\delta_L(x, y)$	$h(x)$	$i' = 0$	$i' = 1$
0	(0, 0)	{2, 3, 4, 5}, {1, 2, 3, 4}	
1	(1, 0)	{0, 1, 2, 4}, {2, 4, 5, 6}	{2, 3, 4, 6}, {0, 2, 3, 4}
0	(1, 1)		{0, 1, 3, 4}, {2, 3, 5, 6}
1	(2, 0)	{1, 3, 4, 6}, {0, 2, 3, 5}	{0, 1, 2, 5}, {1, 4, 5, 6}
1	(2, 1)		{1, 3, 5, 6}, {0, 1, 3, 5}
0	(2, 2)	{1, 2, 5, 6}, {0, 1, 4, 5}	
1	(3, 0)		{0, 4, 5, 6}, {0, 1, 2, 6}
1	(3, 1)	{0, 3, 5, 6}, {0, 1, 3, 6}	

Fig. 2 $X_{0,1,2,3}$ parameters over \mathbb{F}_7

Fig. 3 The order of collapse determined by \prec_R



Note that for each value of h and each i' , there are two facets that attain this pair of values. The leftmost column gives the value of $\delta_L(x, y)$ for every two consecutive lines in the table.

We now turn to show that X can indeed be collapsed in the order $<_R$. That is, for every $x \in X$, it is possible to apply an elementary collapse step to x if all the $<_R$ -predecessors of x have already been collapsed. In order to show this, we need to point out a free $(k - 1)$ -face that is contained in x . What we will show is that for $x \in X_a$, the face $\hat{x} := x \setminus \{x_a\}$ is free. (Note that since $x \in X = X_{0,\dots,k}$, there indeed must exist some $a \in \{0, \dots, k\}$ such that $x \in X_a$.) It may be helpful to mention that a plays a double role here. It is an index in the vector x as well as the sum of the elements of x . Being free means that all the k -faces containing \hat{x} precede x in the order $<_R$. A k -face that contains \hat{x} has the form $y^{(b)} := \hat{x} \cup \{x_a + (b - a)\}$ with $0 \leq b \leq k$ and $b \neq a$. Clearly, $y^{(b)}$ is a k -face in X iff $x_a + (b - a) \notin \hat{x}$. Also, in this case $y^{(b)} \in X_b$, as we assume below.

The proof that $y^{(b)} <_R x$ has two cases:

1. We first consider the case where $y^{(b)} \succeq_I x$. Since $y^{(b)} \in X_b$ and $x \in X_a$, the meaning of $y^{(b)} \succeq_I x$ is that $b' \geq a'$. Therefore $\delta_I(y^{(b)}, x)$, which is the smaller of a' and b' , equals a' . This means that b lies between a and $k - a$ (whether a or $k - a$ is bigger is immaterial here).
 - Consequently, $x_a + (b - a)$ is in the interval $[x_{a'}, x_{k-a'}]$. It follows that the first and last $a' - 1$ elements of x and $y^{(b)}$ are identical. In particular, $h_i(y^{(b)}) = h_i(x)$ for $i < a'$.
 - We recall that $y^{(b)}$ is created by removing x_a from x and replacing it by the term $x_a + (b - a)$. Thus the interval $[y_{a'}^{(b)}, y_{k-a'}^{(b)}]$ is shorter than $[x_{a'}, x_{k-a'}]$. It follows that the first coordinate where $h(y^{(b)})$ and $h(x)$ differ is the a' th coordinate, where $h_{a'}(y^{(b)}) < h_{a'}(x)$. Consequently, $y^{(b)} <_L x$ and $a' = \delta_L(y^{(b)}, x)$.
 - If $y^{(b)} \equiv_I x$, then we are done, because we already know that $y^{(b)} <_L x$. By the definition of $<_R$, this yields the desired conclusion $y^{(b)} <_R x$.
 - If $y^{(b)} \succ_I x$, then from the previous points we conclude that $a' = \delta_L(y^{(b)}, x) = \delta_I(y^{(b)}, x)$. To sum up, $y^{(b)} <_L x$ and $\delta_L(y^{(b)}, x) = \delta_I(y^{(b)}, x)$, which yields by definition, $y^{(b)} <_R x$, as claimed.
2. Now consider the case $y^{(b)} <_I x$. This means that $b' < a'$. Therefore $b' = \delta_I(y^{(b)}, x)$. Consequently, b does not lie between a and $k - a$.
 - It follows that $x_a + (b - a) \in [x_{b'}, x_{k-b'}]$. Consequently, the first and last $b' + 1$ elements of x and $y^{(b)}$ are identical. In particular, $h_i(y^{(b)}) = h_i(x)$ for $i \leq b'$. Thus $\delta_L(y^{(b)}, x) > b'$.
 - If $y^{(b)} \leq_L x$, then $y^{(b)} <_R x$, and we are done.
 - If $y^{(b)} \succ_L x$, then from the previous points we conclude that $b' = \delta_I(y^{(b)}, x) < \delta_L(y^{(b)}, x)$. Hence $y^{(b)} \succ_I x$ and $\delta_I(y^{(b)}, x) < \delta_L(y^{(b)}, x)$. Again, by definition, $y^{(b)} <_R x$, as claimed.

This completes the proof that $X_{0,\dots,k}$ is collapsible and hence that $X = X_{a_0,\dots,a_k}$ is collapsible whenever a_0, \dots, a_k is an arithmetic progression.

3.3 Proof of Necessity

We now turn to show that if a_0, \dots, a_k is not arithmetic, then X_{a_0, \dots, a_k} is not collapsible. In fact we show that in this case exactly $k + 1$ elementary collapse steps can be carried out.

For $X \subseteq \mathbb{F}_n$, we denote as usual by $X + a$ the a -shift of X , namely, the set $\{x + a \mid x \in X\}$. We start with the following simple observation.

Observation 3.1 *Let n be a prime. A subset $X \subsetneq \mathbb{F}_n$ is an arithmetic progression iff there is an element l for which $|(X + l) \setminus X| = 1$.*

When is the $(k - 1)$ -face x_1, \dots, x_k a free face? This is the case iff, for each $k \geq i \geq 1$, the element $x_i + \sum_{j=1}^k x_j$ belongs to the set $\{a_0, \dots, a_k\}$. If $x_i + \sum x_j = a_l$, this means that x_1, \dots, x_k cannot be extended to a k -face in X_{a_l} . This translates into a linear system of equations in x_1, \dots, x_k whose matrix has 2's along the main diagonal and 1's elsewhere. Such a matrix is nonsingular, so the solution is unique. Also, all the k terms $x_i + \sum x_j$ are distinct, so the only choice we have in constructing this linear system is which of the $k + 1$ elements in $\{a_0, \dots, a_k\}$ to omit. There are $k + 1$ such choices which yield $k + 1$ distinct collapse steps that can be carried out.

We now explicitly describe the $k + 1$ collapse steps that can be carried out. Each of these collapsible faces has the form $x^{(t)} := \{a_0 + l_t, \dots, a_k + l_t\} \in X_{a_t}$ for some l_0, \dots, l_k .

The condition $x^{(t)} \in X_{a_t}$ determines l_t via $l_t = \frac{a_t - \sum_{i=0}^k a_i}{k+1}$. We claim that the face $y := x^{(t)} \setminus \{a_t + l_t\}$ is free. The sum of y 's elements is $-l_t$, so that for every $i \neq t$, we need to add the term $\{a_i + l_t\}$ to y in order to attain the sum a_i . This is, however, impossible since $\{a_i + l_t\}$ is an element of y .

We turn to show that after these first $k + 1$ collapse steps are carried out, there remain no free $(k - 1)$ -faces in X . In order for a $(k - 1)$ -face y to be free following the above collapses, y has to be contained in exactly one of these $k + 1$ collapsed faces. Since $\{a_0, \dots, a_k\}$ is not an arithmetic progression, by Observation 3.1, the intersection of any two of the $x^{(t)}$ contains at most $k - 1$ elements. In particular there is no $(k - 1)$ -face that they both contain. Thus we have to consider only $(k - 1)$ -faces y which are contained in one of the $x^{(t)}$ and exactly one more k -face.

It follows that y must be of the form $x^{(t)} \setminus \{a_j + l_t\}$ for some j and t . The sum of y 's elements is $a_t - a_j - l_t$. If y is contained as well in a k -face $z \in X_{a_i}$, then necessarily $z_i = z = y \cup \{a_i - a_t + a_j + l_t\}$. We are assuming that y becomes free with the collapse of $x^{(t)}$, so there must be exactly one index i for which z_i is a legal k -face different from $x^{(t)}$. It follows that $x^{(t)}$ and $x^{(t)} + (a_j - a_t)$ must have k elements in common. Again by Observation 3.1 this means that the elements in $x^{(t)}$ form an arithmetic progression, a contradiction. The proof of Theorem 1.3 is now complete.

4 Example: Homology of $X_{\{0,1,3\}}$

For a prime p and an integer n indivisible by p , let $U_{p,n}$ be the group of n th roots of unity in $\overline{\mathbb{F}_p}$.

Proposition 4.1 *Let $k = 2$, $A = \{0, 1, 3\}$. Let p be a prime and suppose that n is coprime to $3p$. Then*

$$h_1(X_A; \mathbb{F}_p) = \frac{1}{3} |\{ \{u, v\} \subset U_{p,n} - \{1\} : u \neq v \text{ and } 1 + u + v = 0 \}|.$$

Proof Let $B = \{0, k, \ell\}$ with $0 < k < \ell < n$, and let $u = \omega^{-k}$, $v = \omega^{-\ell}$. Then

$$\begin{aligned} \det M_{A,B} &= \det \begin{bmatrix} 1 & 1 & 1 \\ 1 & u & v \\ 1 & u^3 & v^3 \end{bmatrix} \\ &= uv^3 - vu^3 + u^3 - u - v^3 + v = (u - 1)(v - 1)(v - u)(u + v + 1). \end{aligned}$$

It follows that

$$\text{rk } M_{A,B} = \begin{cases} 2, & 1 + u + v = 0, \\ 3, & \text{otherwise.} \end{cases}$$

Thus the Proposition follows directly from Theorem 1. □

Corollary 4.2 *Let $k = 2$ and $A = \{0, 1, 3\}$. Let p be a prime and suppose that $n = p^m - 1$ is coprime to 3. Then*

$$h_1(X_A; \mathbb{F}_p) = \begin{cases} \frac{n-1}{6}, & p = 2, \\ \frac{n-2}{6}, & p = 3, \\ \frac{n-4}{6}, & p > 3. \end{cases}$$

Proof Clearly $\mathbb{F}_{p^m}^* = U_{p,n}$. Therefore, by Proposition 4.1,

$$h_1(X_A; \mathbb{F}_p) = \frac{1}{6} |\{u \in \mathbb{F}_{p^m}^* - \{1\} : -(1 + u) \notin \{0, 1, u\}\}|.$$

The Corollary now follows since

$$\{u \in \mathbb{F}_{p^m}^* - \{1\} : -(1 + u) \notin \{0, 1, u\}\} = \begin{cases} \mathbb{F}_{2^m}^* - \{1\}, & p = 2, \\ \mathbb{F}_{3^m}^* - \{\pm 1\}, & p = 3, \\ \mathbb{F}_{p^m}^* - \{\pm 1, -2, -\frac{1}{2}\}, & p > 3. \end{cases} \quad \square$$

5 Concluding Remarks

Theorem 1.1 provides an explicit description of the homology of the sum complex X_A over fields of characteristic coprime to n . In particular, it follows via Chebotarëv’s Theorem that if n is prime, then X_A is \mathbb{Q} -acyclic, i.e., X_A is a k -hypertree. When A is an arithmetic progression, X_A was shown to be k -collapsible and in particular \mathbb{Z} -acyclic. One natural question is whether there exist other A ’s for which

X_A is \mathbb{Z} -acyclic. Kalai's k -dimensional Cayley's formula [1] suggests that most k -hypertrees are not \mathbb{Z} -acyclic. Likewise we conjecture that X_A is not \mathbb{Z} -acyclic for most $(k + 1)$ -subsets $A \subset \mathbb{Z}_n$. One possible approach to the question of \mathbb{F}_p -acyclicity of X_A for primes $p \nmid n$ is via the following reduction. Let $S_{\mathbb{F}}(A)$ be the \mathbb{F} -linear space of polynomials in $\mathbb{F}[x]$ spanned by the monomials $\{x^a : a \in A\}$. Theorem 1.1 then implies that X_A is \mathbb{F}_p -acyclic iff $\deg \gcd(f(x), x^n - 1) \leq k$ for all $0 \neq f(x) \in S_{\mathbb{F}_p}(A)$.

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