

Irreducible Subcube Partitions

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Abstract

A *subcube partition* is a partition of the Boolean cube $\{0, 1\}^n$ into subcubes. A subcube partition is *irreducible* if the only sub-partitions whose union is a subcube are singletons and the entire partition. A subcube partition is *tight* if it “mentions” all coordinates.

We study extremal properties of tight irreducible subcube partitions: minimal size, minimal weight, maximal number of points, maximal size, and maximal minimum dimension. We also consider the existence of *homogeneous* tight irreducible subcube partitions, in which all subcubes have the same dimensions. We additionally study subcube partitions of $\{0, \dots, q-1\}^n$, and partitions of \mathbb{F}_2^n into affine subspaces, in both cases focusing on the minimal size.

Our constructions and computer experiments lead to several conjectures on the extremal values of the aforementioned properties.

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1 Introduction

A *subcube partition* is a partition of the cube $\{0, 1\}^n$ into subcubes, that is, into sets of the form

$$\{x \in \{0, 1\}^n : x_{i_1} = b_1, \dots, x_{i_d} = b_d\}.$$

Here is an example of a subcube partition of *length* $n = 3$:

$$\begin{aligned} S_3 &= \{000\}, \{111\}, \{001, 101\}, \{100, 110\}, \{010, 011\} \\ &= 000, 111, *01, 1*0, 01*. \end{aligned}$$

We will usually express our subcubes as strings in $\{0, 1, *\}^n$, in which stars stand for unconstrained coordinates.

A subcube partition is *reducible* if it has a proper subset, consisting of more than one subcube, whose union is a subcube. For example,

$$0*, 10, 11$$

is reducible since $10 \cup 11 = 1*$. In contrast, S_3 is *irreducible*.

A subcube partition is *tight* if it *mentions* all coordinates, that is, if for every $i \in [n]$, some subcube constrains x_i . Both subcube partitions above are tight, but the subcube partition $0*, 1*$ is not, since the second coordinate is not mentioned.

Peitl and Szeider [PS23] enumerated all tight irreducible subcube partitions for $n = 3, 4$, and counted the number of nonisomorphic subcube partitions with small *size* (number of subcubes) for $n = 5, 6, 7$. They ask whether there are infinitely many tight irreducible subcube partitions. In this work, we answer this question in the affirmative, giving many constructions of tight irreducible subcube partitions.

The work of Peitl and Szeider raises many natural questions, such as:

- How to determine whether a subcube partition is irreducible?
- What is the minimal size of a tight irreducible subcube partition of length n ?
(This question only makes sense if we impose tightness.)
- What is the maximal size of an irreducible subcube partition of length n ?
- Do there exist irreducible subcube partitions in which all subcubes have the same dimension?
(We call such subcube partitions *homogeneous*.)

We address these questions in Section 2. We describe an efficient algorithm for testing whether a subcube partition is irreducible in Section 2.1, and give two infinite sequences of irreducible formulas in Section 2.2.

We conjecture that the minimal size of a tight irreducible subcube partition of length n is $2n - 1$. We give a matching construction in Section 2.3, and optimize its Hamming weight in Section 2.4 (this will be useful later on).

We conjecture that the maximal size of an irreducible subcube partition of length $n \geq 5$ is $\frac{5}{8}2^n$. We give a matching construction in Section 2.6, where we also give a nontrivial upper bound. Our constructions involve 2^{n-2} points (0-dimensional subcubes) and $3 \cdot 2^{n-3}$ edges (1-dimensional subcubes). We conjecture that 2^{n-2} is the maximum number of points in an irreducible subcube partition of size n . A simple matching construction appears in Section 2.5.

We present subcube partitions in which all subcubes have linear dimension in Section 2.7. We close off the section with a discussion of homogeneous subcube partitions in Section 2.8, where we describe several constructions, and determine all lengths n and codimensions $k \leq 4$ for which there exists a tight irreducible subcube partition of length n whose subcubes have dimension $n - k$. In particular, we describe a construction due to Perezhagin [Per05] of irreducible subcube partitions of all length $n \geq 7$ in which all subcubes have dimension 1.

Section 3 studies subcube partitions of $[q]^n$ for $q \geq 3$. We show how to construct irreducible subcube partitions of $[q]^n$ from irreducible subcube partitions of $\{0, 1\}^n$ in Section 3.1, and use this to construct tight irreducible subcube partitions of length n and size $(n - 1)q(q - 1) + 1$ in Section 3.2.1; this uses the subcube partitions of Section 2.4. We conjecture that $(n - 1)q(q - 1) + 1$ is the minimum size of a tight irreducible subcube partition, and prove this for $n = 3$ in Section 3.2.2. We close by showing, in Section 3.2.3, that the minimal size of a tight *minimal cover* in this setting is $(q - 1)n + 1$.

Finally, Section 4 briefly studies the linear analog of subcube partitions, in which subcubes are replaced by affine subspaces. We show how to construct irreducible affine vector space partitions from irreducible subcube partitions in Section 4.1, and use this to construct tight irreducible affine subspace partitions of length n and size roughly $\frac{3}{2}n$ in Section 4.2. We discuss irreducible affine vector space partitions in more detail in the companion work [BFIK23].

Background

Subcube partitions appear, under various names, in theoretical computer science, as an abstraction of the salient properties of decision trees, and elsewhere. Some examples include Iwama [Iwa87, Iwa89] (as certain *independent sets of clauses*), Brandman, Orlitsky and Hennessy [BOH90] (as *nonoverlapping covers*), Berger, Felzanbaum and Fraenkel [BFF90] (as *disjoint tautologies*), Davydov and Davydova [DD98] (as *dividing formulas*), Friedgut, Kahn and Wigderson [FKW02] (as *subcube partitions*), Kullmann [Kul04] (as *unsatisfiable hitting clause-sets*), Kisielewicz [Kis20] (as realizations of *cube tiling codes*), Taranikov [Tar22] (as *coordinate partitions*). There are also *orthogonal DNFs* [CH11], also known as *disjoint DNFs* [GK13], which are systems of disjoint subcubes which do not necessarily cover the entire cube. (For the relation between decision trees and subcube partitions, see Göös, Pitassi and Watson [GPW18].)

Irreducible subcube partitions appear in a work of Kullmann and Zhao [KZ16] (as *clause-reducibility*), inspired by similar notions in the context of disjoint covering systems of residue classes [Kor84, BFF90] and motivated by applications to the study of CNFs.

Peitl and Szeider [PS23] enumerate all tight irreducible subcube partitions for $n = 3, 4$, and determine the minimal size of a regular irreducible subcube partition for $n = 5, 6, 7$. Instead of tightness, they use a different notion, *regularity*, which is equivalent to tightness for irreducible subcube partitions when $n \geq 3$. Regularity was introduced by Kullmann and Zhao [KZ13] under the name *nonsingularity*, and is defined in Section 2.3.1.

2 Subcube partitions

We start with a quick recap of the relevant definitions.

Definition 1 (Subcube partition). A *subcube partition* of length n is a partition of $\{0, 1\}^n$ into *subcubes*, which are sets of the form

$$\{x \in \{0, 1\}^n : x_{i_1} = b_1, \dots, x_{i_d} = b_d\}.$$

The parameter d is the *codimension* of the subcube, and $n - d$ is its *dimension*. A subcube of dimension 0 is called a *point*, and a subcube of dimension 1 is called an *edge*.

The *size* of a subcube partition is the number of subcubes.

We identify subcubes with words over $\{0, 1, *\}$. For example, $01*$ stands for the subcube $\{(0, 1, 0), (0, 1, 1)\}$. We index the symbols in a word w of length n by $[n] = \{1, \dots, n\}$. If $b \in \{0, 1\}$, we use \bar{b} to denote $1 - b$.

Definition 2 (Reducibility). A subcube partition F is *reducible* if there exists a subset $G \subset F$, with $1 < |G| < |F|$, such that the union of the subcubes in G is itself a subcube.

A subcube partition is *irreducible* if it is not reducible.

Definition 3 (Tightness). A subcube s *mentions* a coordinate $i \in [n]$ if $s_i \neq *$.

A subcube partition F of length n is *tight* if for every $i \in [n]$, some subcube in F mentions i .

It is coNP-complete to determine whether a given collection of subcubes covers $\{0, 1\}^n$ (this problem is just SAT in disguise). In contrast, it is easy to test whether a given collection of subcubes is a partition, as first observed by Iwama [Iwa89].

Definition 4 (Conflicting subcubes). Two subcubes s, t of the same length are said to *conflict* if there is a coordinate $i \in [n]$ such that $s_i, t_i \neq *$ and $s_i \neq t_i$.

Lemma 5. *Two subcubes are disjoint if and only if they conflict.*

Lemma 6. *A collection F of disjoint subcubes of length n is a subcube partition if and only if*

$$\sum_{s \in F} 2^{-\text{codim}(s)} = 1.$$

Similarly, it is easy to check whether a given subcube partition is tight. In contrast, checking whether a subcube partition is irreducible using the definition takes exponential time. We present an efficient algorithm for testing irreducibility in Section 2.1.

Following that, we give many examples of irreducible subcube partitions, starting with Section 2.2, which describes subcube partitions whose irreducibility can be proved using a simple parity argument. In Sections 2.3 to 2.7 we describe irreducible subcube partitions which conjecturally optimize various parameters. Section 2.8 closes with a discussion of irreducible subcube partitions in which all subcubes have the same dimension.

2.1 Testing irreducibility

In this section we give a polynomial time algorithm that checks whether a given subcube partition F is reducible, and if so, identifies a subset $G \subset F$, with $1 < |G| < |F|$, whose union is a subcube.

The idea behind the algorithm is quite simple. Suppose that F were reducible, say via the subset G . If $s, t \in G$ then $\bigcup G$ must contain the *join* $s \vee t$ of s, t , which is the smallest subcube containing both s and t , given explicitly by

$$(s \vee t)_i = \begin{cases} b & \text{if } s_i = t_i = b \in \{0, 1\}, \\ * & \text{otherwise.} \end{cases}$$

If $u \in F$ intersects $s \vee t$ (a condition we can check using Lemma 5) then G must contain u , and so $\bigcup G$ must contain $s \vee t \vee u$. Continuing in this way, we are able to recover G (or a subset of G whose union is also a subcube). The corresponding algorithm appears as Algorithm 1.

Algorithm 1 Algorithm for checking whether a subcube partition is irreducible

Input: Subcube partition $F = \{s_1, \dots, s_m\}$

```

for  $1 \leq i < j \leq m$  do
   $G \leftarrow \{s_i, s_j\}$ 
  while some  $s_k \notin G$  intersects  $\bigvee G$  do
     $G \leftarrow G \cup \{s_k\}$ 
  end while
  if  $G \neq F$  then
    return Reducible:  $\bigcup G$  is a subcube
  end if
end for
return Irreducible

```

Theorem 7. *Algorithm 1 runs in polynomial time, and its output is correct.*

Proof. We start by showing that the algorithm runs in polynomial time. The outer **for** loop runs $O(m^2)$ times, and the inner **while** loop runs at most m times. Each basic

operation can be implemented in polynomial time, and so the entire algorithm runs in polynomial time.

Suppose first that the algorithm outputs “reducible”. By construction, all subcubes in $F \setminus G$ are disjoint from $\bigvee G$. Since F is a subcube partition, this means that $\bigcup G = \bigvee G$, which is a subcube. By construction, $1 < |G| < |F|$, and so F is indeed reducible.

To complete the proof, we show that if F is reducible, then the algorithm outputs “reducible”. If F is reducible then there is a subset $H \subset F$, with $1 < |H| < |F|$, such that $\bigcup H$ is a subcube. Let $s_i, s_j \in H$, and consider the (i, j) iteration of the outer **for** loop.

We prove inductively that at each iteration of the inner **while** loop, G is contained in H . This holds by construction at the very first step. Now suppose that $G \subseteq H$ and that $s_k \notin G$ intersects $\bigvee G$. Since $G \subseteq H$, also $\bigvee G \subseteq \bigvee H$, and so s_k intersects $\bigvee H$. Since $\bigvee H = \bigcup H$ and the subcubes in F are disjoint, necessarily $s_k \in H$. Hence $G \cup \{s_k\} \subseteq H$.

When the **while** loop ends, all $s_k \notin G$ are disjoint from $\bigvee G$. Since the subcubes in F are disjoint, this means that $\bigvee G = \bigcup G$. Since $G \subseteq H$, necessarily $G \neq F$, and so the algorithm correctly declares that F is reducible. \square

2.2 Parity argument

In this section we present two constructions of infinite families of tight irreducible subcube partitions.

Theorem 8. *Let $n = 2m + 1 \geq 3$. The following subcubes comprise a tight irreducible subcube partition of size $\Theta(n^3)$:*

- The point 0^n .
- All cyclic rotations of $0^m 1 *^m$.
- For every $0 \leq i, j, k \leq m - 1$ satisfying $i + j, j + k \leq m - 1$, the subcube

$$0^i 1 *^j 0^k 1 *^{m-1-j-k} 0^j 1 *^{m-1-i-j}.$$

We found this subcube partition by starting with the subcube partition consisting of all rotations of $0^m 1 *^m$ together with all points not covered by them. This subcube partition is reducible, and we can use Algorithm 1 to merge together points into subcubes. One can show inductively that the rotations of $0^m 1 *^m$ never get merged, and so the resulting subcube partition is not trivial. It is precisely the one described in Theorem 8.

Here is the resulting partition for $n = 5$:

$$\begin{array}{cccccc} 00000 & 001** & *001* & **001 & 1**00 & 01**0 \\ & 11*1* & 1011* & 011*1 & 01011 & 1*101 \end{array}$$

Theorem 9. *Let $n \geq 1$ be odd. The following subcubes comprise a tight irreducible subcube partition of size $F_{n+1} + F_{n-1} + 1$, where F_n is the n 'th Fibonacci number:*

- The point 1^n .
- All subcubes obtained by concatenating blocks of the form $*1$ or 0 in an arbitrary way, and rotating the result arbitrarily.

This subcube partition appears in [Kis14, Section 2], where it is attributed to Lagarias and Shor [LS94]. Here is the partition for $n = 5$:

$$\begin{array}{cccccc} 00000 & *1000 & 0*100 & 00*10 & 000*1 & 1000* \\ 11111 & *1*10 & *10*1 & 0*1*1 & 1*10* & 10*1* \end{array}$$

In both cases, we will prove the irreducibility using the following lemma, suggested to us by Kisielewicz.

Definition 10 (Star pattern). The *star pattern* of a subcube $s \in \{0, 1, *\}^n$ is $P(s) := \{i \in [n] : s_i = *\}$.

Definition 11 (Parity of a subcube). The *parity* of a subcube $s \in \{0, 1, *\}^n$ is the parity of the number of 1s in s .

Lemma 12 ([Kis23]). Let F be a subcube partition. Let G be a subset of F such that $|G| > 1$ and the union of G is a subcube. Let S be an inclusion-minimal star pattern occurring in G (this means that no star pattern strictly contained in S appears in G).

Among subcubes in G whose star pattern is S , half have even parity and half have odd parity.

Proof. Let $C \subseteq \bigcup G$ consist of all points p such that $p_i = 0$ for all $i \in S$. If $|C| = 1$ then S is the star pattern of $\bigcup G$, which contradicts $|G| > 1$. Hence $|C| > 1$. Since C is a subcube, it contains an equal number of points of even parity and of odd parity.

If $s \in G$ has star pattern other than S then by inclusion-minimality, $s_i = *$ for some $i \notin S$. Therefore $s \cap C$ contains an equal number of points of even parity and of odd parity. In contrast, if $s \in G$ has star pattern S then $s \cap C$ contains a single point whose parity is the same as the parity of s . Since C has an equal number of points of either parity, the lemma immediately follows. \square

Corollary 13. Let F be a subcube partition in which there is a star pattern S occurring twice, and every other star pattern occurs at most once. If G is a subset of F whose union is a subcube and $|G| > 1$ then G contains both subcubes of F whose star pattern is S .

Proof. Let U be an inclusion-minimal star pattern in G . Lemma 12 implies that G must contain an even number of subcubes whose star pattern is U . Necessarily $U = S$, and so G contains both subcubes whose star pattern is S . \square

Corollary 13 almost immediately implies the irreducibility of the subcube partition in Theorem 9: any non-singleton subset of the subcube partition whose union is a subcube must contain both points $0^n, 1^n$, and so its union must be $\{0, 1\}^n$. The argument for Theorem 8 is only slightly longer.

We prove Theorem 8 in Section 2.2.1, and Theorem 9 in Section 2.2.2.

2.2.1 Cubic construction

In this section we prove Theorem 8.

We need to prove three things about the set of subcubes F given in the statement of the theorem: that it is a subcube partition; that it is tight; and that it is irreducible.

Subcube partition The point 0^n covers itself. All other subcubes of F contain at least one 1.

Subcubes of the second type cover *royal points*. These are points which contain a *royal* 1, which is a 1 preceded cyclically by m many 0s. Since $n < 2(m+1)$, there can be at most one royal 1, and so royal points are covered by precisely one subcube of the second type. We will soon see that they are not covered by any subcube of the third type.

We can guarantee that a subcube does not contain any royal point by adding “blocking 1s”: if each cyclic interval of length m contains a 1, then the subcube cannot contain any royal point. Each subcube of the third type is contained in the subcube $*^i 1 *^{j+k} 1 *^{m-1-k} 1 *^{m-1-i-j}$, in which the 1s are separated by $j+k, m-1-k, m-1-j \leq m-1$ many stars. Consequently, each royal point is covered by precisely one subcube of F .

It remains to handle points $x \neq 0^n$ which are not royal. Let $I+1$ be the index of the first 1 in x . Since x is not royal, $I \leq m-1$.

Let $I+1+m+J+1$ be the first 1 in x beyond position $I+1+m$ (so $J \geq 0$). Such a 1 exists since otherwise x starts with $0^I 1$ and ends with 0^{m-I} , and is consequently royal. For the same reason, $J \leq m-1$. Since $I+1+m+J+1 \leq n$, we see that $I+J \leq m-1$.

Let $I+1+J+K+1$ be the first 1 in x beyond position $I+1+J$ (so $K \geq 0$). Such a 1 exists as seen before. Since x is not royal, $J+K \leq m-1$. Collecting all the information, we see that x belongs to the subcube of the third type

$$0^I 1 *^J 0^K 1 *^{m-1-J-K} 0^J 1 *^{m-1-I-J}.$$

$$\begin{array}{ccc} \uparrow & & \uparrow \\ I+1+J & & I+1+m \end{array}$$

If $x \in 0^i 1 *^j 0^k 1 *^{m-1-j-k} 0^j 1 *^{m-1-i-j}$ and we follow the steps above then we find that $i = I$, $j = J$, and $k = K$. Therefore x belongs to a unique subcube of F .

Tightness This is clear, since the subcube 0^n mentions all coordinates.

Irreducibility We will use Corollary 13 in order to prove irreducibility, so we first need to understand the star patterns of the various subcubes in F .

A subcube of the second type has precisely m stars, and each subcube of the second type has a different star pattern. Furthermore, each star pattern either consists of a single interval, or of one interval starting at 1 and another interval ending at n .

A subcube of the third type has no interval of m stars, and cannot start with a star, hence its star patterns differ from those of subcubes of the second type. Given the star pattern of a subcube of the third type, we can determine i, j, k . First, we determine $i+j$ by counting the number of trailing stars, which is $m-1-i-j$. This allows us to determine j (and so i), by counting the number of stars in the first $i+1+j$ symbols.

We can now determine k by counting the number of stars in the first $i + 1 + m$ symbols, which is $m - 1 - k$.

Summarizing, if we consider only subcubes of the second and third types, then all star patterns are unique. Considering the entire subcube partition, there is one star pattern occurring twice, corresponding to the points 0^n and $0^{m-1}10^{m-1}11$, and all other star patterns occur once.

If F were reducible then there would be a subset $G \subseteq F$ such that $1 < |G| < |F|$ and the union of G is a subcube. According to Corollary 13, G must contain both points $0^n, 0^{m-1}10^{m-1}11$, and so $\bigcup G$ must contain their join $0^{m-1}*0^{m-1}*$. This implies that G must cover the point $0^{m-1}10^{m-1}00$, and so must contain the subcube $0^{m-1}1*^m0$. Similarly, it must cover the point $0^{m-1}00^{m-1}10$, and so contain the subcube $*^{m-1}0^m1*$. Since the join of the latter two subcubes is $*^n$, we conclude that $G = F$, contrary to assumption. Therefore F is irreducible.

2.2.2 Lagarias–Shor construction

In this section we prove Theorem 9.

We need to prove three things about the set of subcubes F given in the statement of the theorem: that it is a subcube partition; that it is tight; and that it is irreducible. (We leave it to the reader to prove the formula for the size of F .)

Subcube partition The point 1^n covers itself. Since n is odd, every other subcube contains 0, and so doesn't cover 1^n .

Consider now a point $x \in \{0, 1\}^n$ other than 1^n . We will convert it, in stages, to a subcube $y \in F$ which contains it.

We initialize y with x . If there is an index i such that $y_i = 1$ and $y_{i+1} \neq 1$ (treating indices cyclically) then any subcube in F which covers y must have $y_i = 1$ and so $y_{i-1} = *$. Accordingly, as long as there is an index i such that $y_{i-1} \neq *, y_i = 1, y_{i+1} \neq 1$, we set $y_{i-1} = *$.

When the process stops, every 1 is either preceded by $*$ or followed by 1. Since $x \neq 1^n$, every run of 1 in y must terminate (followed by $*$ or 0). The final 1 in each such run is not followed by 1, and so must be preceded by $*$ (implying that the run has length 1). It follows that y is, up to rotation, a concatenation of copies of $*1$ and 0, and so $y \in F$. Furthermore, the construction of y ensures that this is the only subcube in F covering x .

Tightness This is clear, since the subcube 1^n mentions all coordinates.

Irreducibility In view of using Corollary 13, we first explore the star patterns of the various subcubes in F . The main observation is that we can recover a subcube of the second type from its star pattern. Indeed, every star must be followed by 1, and every position not preceded by a star must be 0. This implies that apart from the two points $0^n, 1^n$, all other star patterns are unique.

If F were reducible then there would exist a subset $G \subset F$ with $1 < |G| < |F|$ whose union is a subcube. Corollary 13 shows that G must contain both points $0^n, 1^n$, and so their join $*^n$, contradicting the assumption $G \neq F$. Hence F is irreducible.

2.3 Minimal size

What is the minimal size of a tight irreducible subcube partition of length n ? (The question doesn't make sense without assuming tightness, since $*^n$ is always irreducible.)

When $n = 1$, there is a single tight irreducible subcube partition: $0, 1$. When $n = 2$, there are no tight irreducible subcube partitions. When $n = 3$, there is a unique tight irreducible subcube partition, up to flipping and rearranging coordinates:

$$000, *01, 1*0, 01*, 11.$$

For $n = 4, 5, 6, 7$, Peitl and Szeider [PS23] used a computer search to show that the minimal number of subcubes is 7, 9, 11, 13, respectively. This is consistent with the following conjecture.

Conjecture 14. If $n \geq 3$ then the minimal size of a tight irreducible subcube partition of length n is $2n - 1$.

Section 2.3.1 explains the best lower bound on the size, due to Kullmann and Zhao [KZ13]. Sections 2.3.2 and 2.3.3 present two constructions of an infinite family of tight irreducible subcube partitions of length n and size $2n - 1$. In Section 2.4 we present several more such constructions which will be useful in Section 3.

2.3.1 Lower bound

Before presenting the constructions of tight irreducible subcube partitions of size $2n - 1$, here is the best lower bound on the size, due to Kullmann and Zhao [KZ16]. We give an alternative proof using known results from the literature.

Theorem 15. If $n \geq 4$ then every tight irreducible subcube partition of length n has size at least $n + 3$.

Before proving the theorem, we need a simple lemma.

Definition 16 (Regularity). A subcube partition of length n is *regular* if for every $i \in [n]$ and every $b \in \{0, 1\}$ there are at least two subcubes $s \in F$ such that $s_i = b$.

This definition is due to Kullmann and Zhao [KZ13], who used the term *nonsingular*. The term *regular* appears in Peitl and Szeider [PS23].

Lemma 17 ([KZ16, Lemma 39]). If F is a tight irreducible subcube partition of length $n \geq 2$ then F is regular.

Proof. We prove the definition of regularity for $i = 1$.

For $\sigma \in \{0, 1, *\}$, let $F_\sigma = \{x : \sigma x \in F\}$. Both $F_0 \cup F_*$ and $F_1 \cup F_*$ are subcube partitions of length $n - 1$, and so $\bigcup F_0 = \bigcup F_1$. Since F is tight, F_0, F_1 are non-empty.

If $F_0 = \{x\}$ and $|F_1| > 1$ then the union of the subcubes corresponding to F_1 is the subcube $1x$, contradicting irreducibility.

If $F_0 = \{x\}$ and $|F_1| = 1$ then $F_0 = F_1 = \{x\}$ and so the union of the corresponding subcubes is $*x$. Since F is irreducible, necessarily $x = *^{n-1}$, and so $F = \{0*^{n-1}, 1*^{n-1}\}$. Since F is tight, necessarily $n = 1$, contradicting the assumption $n \geq 2$.

It follows that $|F_0| \geq 2$. Similarly $|F_1| \geq 2$. \square

We can now prove the size lower bound.

Proof of Theorem 15. Let $F = \{s_1, \dots, s_m\}$ be a tight subcube partition of length n . We can identify F with a formula Φ in *conjunctive normal form* (CNF) over variables x_1, \dots, x_n whose clauses are “ $x \notin s_i$ ” for all $i \in [m]$. For example, the subcube partition $0*, 10, 11$ corresponds to the CNF $x_1 \wedge (\bar{x}_2 \vee x_3) \wedge (\bar{x}_2 \vee \bar{x}_3)$.

Since every x belongs to some s_i , the formula Φ is unsatisfiable. It is moreover minimally unsatisfiable, meaning that if we remove any clause, then it becomes satisfiable. Indeed, if we remove the clause “ $x \notin s_i$ ”, then any point in s_i would satisfy the formula. Since F is tight, Φ mentions all n variables.

A well-known result attributed to Tarsi [AL86] states that a minimally unsatisfiable CNF mentioning n variables must contain at least $n + 1$ clauses, hence $m \geq n + 1$.

Suppose that $m = n + 1$. Davydov, Davydova, and Kleine Büning [DDKB98, Theorem 12] showed that if a minimally unsatisfiable CNF mentioning n variables contains exactly $n + 1$ clauses, then some variable appears once positively and once negatively. In particular, F is not regular, contradicting Lemma 17. Hence $m \geq n + 2$.

Suppose that $m = n + 2$. Kleine Büning [KB00, Theorem 6] showed that there is a unique regular minimally unsatisfiable CNF mentioning n variables which contains exactly $n + 2$ clauses, up to renaming and reordering variables. The collection of subcubes corresponding to this CNF consists of $0^n, 1^n$ together with all cyclic rotations of $10*^{n-2}$. When $n \geq 4$, these subcubes are not disjoint: for example, $10*^{n-2}$ and $*^210*^{n-4}$ both contain the subcube $1010*^{n-4}$. Hence $m \geq n + 3$. \square

In the following two subsections, we present two constructions of the same sequence of tight irreducible subcube partitions of length $n \geq 3$ and size $2n - 1$.

2.3.2 Merging

Our first construction is based on the following lemma, which is used to merge together two subcube partitions.

Definition 18 (Reducibility for partial subcube partitions). A subset F' of a subcube partition F of length n is *reducible* if there exists a subset $G \subseteq F'$, with $|G| > 1$, such that the union of the subcubes in G is a subcube different from $*^n$.

Lemma 19. Let F_0, F_1 be two subcube partitions of length n . Let

$$G = \{0x : x \in F_0 \setminus F_1\} \cup \{1x : x \in F_1 \setminus F_0\} \cup \{*x : x \in F_0 \cap F_1\}.$$

Then

(a) G is a subcube partition of length $n + 1$.

- (b) If $F_0 \neq F_1$ and at least one of them is tight, then G is tight.
- (c) If $F_0 \cap F_1 \neq \emptyset$ and both $F_0 \setminus F_1$ and F_1 are irreducible (or both $F_1 \setminus F_0$ and F_0 are irreducible) then G is irreducible.

Proof. The first two items follow easily from the construction (the condition $F_0 \neq F_1$ in the second item guarantees that the first coordinate is mentioned).

Now suppose that $F_0 \cap F_1 \neq \emptyset$ and both $F_0 \setminus F_1$ and F_1 are irreducible. We need to show that G is irreducible. If not, then there is a subset $H \subset G$, with $1 < |H| < |G|$, whose union is a subcube $x \neq *^n$.

If $x = 0y$ then y is a union of $|H|$ subcubes in $F_0 \setminus F_1$. Since $F_0 \setminus F_1$ is irreducible and $|H| > 1$, necessarily $y = *^n$. However, this contradicts the assumption $F_0 \cap F_1 \neq \emptyset$.

We get a similar contradiction if $x = 1y$, using the irreducibility of F_1 .

Finally, if $x = *y$ then y is a union of $|H|$ subcubes of F_0 as well as a union of $|H|$ subcubes of F_1 . Since F_1 is irreducible and $y \neq *^n$, necessarily $y \in F_1$. If $y \in F_0$ then $x \in G$, contradicting the assumption $|H| > 1$. If $y \notin F_0$ then $1y \in G$ and so y is a union of subcubes in $F_0 \setminus F_1$. Since $F_0 \setminus F_1$ is irreducible and $y \neq *^n$, necessarily $y \in F_0 \setminus F_1$, contradicting both $y \notin F_0$ and $y \in F_1$. \square

We now construct the promised sequence of tight irreducible subcube partitions.

Theorem 20. *For each $n \geq 3$ there is a tight irreducible subcube partition S_n of length n and size $2n - 1$.*

Proof. We construct the subcube partitions inductively. The starting point is

$$S_3 = \{000, *01, 1*0, 01*, 111\},$$

whose irreducibility was proved by Kullmann and Zhao [KZ16, Lemma 41], and can also be checked using Algorithm 1. The construction will maintain the invariants that $01*^{n-2} \in S_n$ and $1*^{n-1}, 00*^{n-2} \notin S_n$, and moreover $|S_n| = 2n - 1$.

Given S_n , we construct S_{n+1} by applying Lemma 19 to $F_0 = \{1*^{n-1}, 00*^{n-2}, 01*^{n-2}\}$ and $F_1 = S_n$.

Since F_0 is reducible and F_1 is irreducible, clearly $F_0 \neq F_1$, and so S_{n+1} is tight by Lemma 19.

The invariant implies that $F_0 \setminus F_1 = \{1*^{n-1}, 00*^{n-2}\}$ is irreducible. It follows that S_{n+1} is irreducible by Lemma 19.

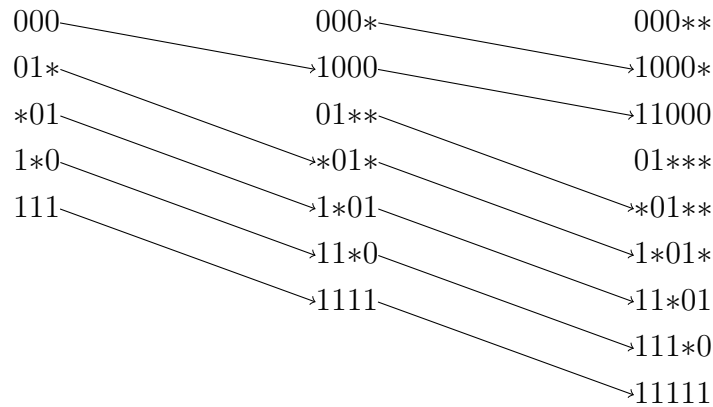
Since $1*^{n-1} \notin F_1$, it follows that $01*^{n-1} \in S_{n+1}$. Since $0*^{n-1} \notin F_0$, it follows that $00*^{n-1} \notin S_{n+1}$. Since $|F_1| > 1$, in particular $*^n \notin F_1$, and so $1*^n \notin S_{n+1}$.

Finally, the invariants imply that $F_0 \cap F_1 = \{01*^{n-2}\}$, and so

$$|S_{n+1}| = |F_0 \setminus F_1| + |F_1 \setminus F_0| + |F_0 \cap F_1| = 2 + (|F_1| - 1) + 1 = 2n + 1,$$

using $|F_1| = 2n - 1$. \square

Here are the resulting subcube partitions for $n = 3, 4, 5$:



2.3.3 Twisting

Our second construction starts with the observation

$$x00 \cup x1* = x*0 \cup x11.$$

Up to permutation and flipping of coordinates, this is the only way in which a set of points can be written as a union of two subcubes in two different ways, as we show below in Lemma 23. Following Kullmann and Zhao [KZ16, Definitions 45–46], we call such a pair of subcubes an *nfs-pair*. The *nfs-flip* of the pair on the left is the pair on the right.

Definition 21 (Nfs-pair, nfs-flip). Two subcubes s, t constitute an *nfs-pair* if they differ on exactly two positions i, j , where $(s_i, t_i) \in \{(0, 1), (1, 0)\}$ and $t_j = *$.

The *nfs-flip* of s, t is the pair of subcubes s', t' obtained by copying the coordinates except for i, j , and setting $s'_i = *$, $s'_j = s_j$, $t'_i = t_i$, $t'_j = \bar{s}_j$.

Lemma 22. *If s, t is an nfs-pair with nfs-flip s', t' then $s \cup t = s' \cup t'$.*

Nfs-pairs are the only pairs of subcubes satisfying Lemma 22 non-trivially.

Lemma 23. *Let s, t and s', t' be two pairs of disjoint subcubes such that $s \cup t = s' \cup t'$, the common value is not a subcube, and $\{s, t\} \neq \{s', t'\}$. Then either s, t or t, s is an nfs-pair, and s', t' or t', s' is its nfs-flip.*

Proof. Since s, t are disjoint, they must conflict. Without loss of generality, $s = 0p$ and $t = 1q$. If both s' and t' start with non-stars then clearly $\{s, t\} = \{s', t'\}$, and if both start with a star then $p = q$ and so $s \cup t = *p$ is a subcube. Therefore without loss of generality, $s' = *p'$ and $t' = 1q'$.

Since $0p \cup 1q = *p' \cup 1q'$, considering the points starting with 0, we see that $p' = p$. Considering the points starting with 1, we see that $q = p \cup q'$. Since p, q', q are all subcubes, it must be that p, q' are subcubes differing in a single non-star position, and q is obtained from them by changing this position to a star. Thus s, t is an nfs-pair, and s', t' is its nfs-flip. \square

The construction is based on the following simple corollary of Lemma 19.

Lemma 24. *Let F be a tight irreducible subcube partition containing an nfs-pair s, t , and let s', t' be its nfs-flip. The following subcube partition is tight and irreducible, for any $b \in \{0, 1\}$:*

$$G = \{*x : x \in F, x \neq s, t\} \cup \{bs, bt, \bar{b}s', \bar{b}t'\}.$$

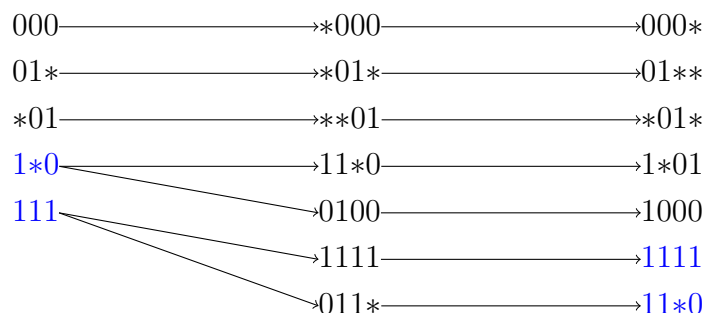
Furthermore, $|G| = |F| + 2$, and G contains the nfs-pairs bs, bt and $\bar{b}s', \bar{b}t'$.

Proof. Let F' be the formula obtained from F by replacing s, t with s', t' . We apply Lemma 19 on $F_b = F$ and $F_{\bar{b}} = F'$, obtaining the stated subcube partition G .

Since $F \neq F'$ and F is tight, G is tight.

Clearly F cannot consist only of s, t , and so $F \cap F' \neq \emptyset$. Since F and $F' \setminus F \subset F'$ are both irreducible, it follows that G is irreducible. \square

In order to obtain the sequence S_n constructed in Theorem 20 using Lemma 24, start with S_3 . Given S_n , apply the lemma with $s = 1^n$, $t = 1^{n-2}*0$, and $b = 1$, and rotate the resulting subcube partition once to the left. The result is S_{n+1} . Here is an example:



2.4 Minimal weight

In Section 3, we will consider irreducible subcube partitions over larger alphabets. As we show in Section 3.1, one of the ways to construct an irreducible subcube partition over an alphabet $\{0, \dots, q-1\}$ is to start with an irreducible subcube partition over $\{0, 1\}$, and replace each 1 in each subcube with each of $\{1, \dots, q-1\}$. The resulting number of subcubes is

$$\sum_{s \in F} (q-1)^{\#_1(s)},$$

where F is the subcube partition we start with, and $\#_1(s)$ is the number of 1s in s . This suggests looking for a tight irreducible subcube partition which minimizes the above objective function.

The concept of *majorization* allows us to optimize this objective function for all q 's at once.

Definition 25 (Weight vector). Let F be a subcube partition of length n . Its *weight vector* is the vector $w(F) = w_0, \dots, w_n$, where w_h is the number of subcubes of F of weight h , that is, with h many 1s.

The notation $w_{\geq h}$ stands for $w_h + \dots + w_n$, which is the number of subcubes with at least h many 1s.

Definition 26 (Majorization). Let a, b be two weight vectors of length $n + 1$. We say that a *majorizes* b if for every $h \leq n$, we have $a_{\geq h} \geq b_{\geq h}$.

Lemma 27. Let F, G be subcube partitions of length n . If $w(F)$ majorizes $w(G)$ then for all monotone non-decreasing functions $\phi: \{0, \dots, n\} \rightarrow \mathbb{R}$,

$$\sum_{s \in F} \phi(\#_1(s)) \geq \sum_{s \in G} \phi(\#_1(s)).$$

In particular, this holds for $\phi(h) = (q - 1)^h$ as long as $q \geq 2$.

Proof. We will show that

$$\sum_{h=0}^n w_h(F) \phi(h) \geq \sum_{h=0}^n w_h(G) \phi(h).$$

Indeed,

$$\begin{aligned} \sum_{h=0}^n w_h(F) \phi(h) &= w_{\geq 0}(F) \phi(0) + \sum_{h=1}^n w_{\geq h}(F) (\phi(h) - \phi(h-1)) \\ &\geq w_{\geq 0}(G) \phi(0) + \sum_{h=1}^n w_{\geq h}(G) (\phi(h) - \phi(h-1)) = \sum_{h=0}^n w_h(G) \phi(h). \quad \square \end{aligned}$$

Lemma 27 allows us to reformulate our goal: find the minimal weight vectors (in the sense of majorization) of the tight irreducible subcube partitions of length n . (There could be more than one minimal weight vector, since majorization is not a linear order.)

Conjecture 28. For every $n \geq 3$, the minimal weight vectors of tight irreducible subcube partitions of length n are $1, n-1, n-1, 0, \dots, 0$ and $1, n, n-3, 1, 0, \dots, 0$.

In Section 2.4.1, we show that Conjecture 14 implies the lower bound part of Conjecture 28. In Section 2.4.2 we give matching constructions.

Unconditionally, we can show that every tight irreducible subcube partition of length $n \geq 3$ must contain a subcube of weight 2.

Lemma 29. If F is a tight irreducible subcube partition of length $n \geq 3$ then F contains a subcube of weight at least 2.

Proof. Suppose that every subcube in F has weight at most 1. Let $s \in F$ be the subcube containing 1^n . If s has weight 0 then $s = *^n$, contradicting the tightness of F . If s has weight 1 then, without loss of generality, $s = 1 *^{n-1}$. The union of all other subcubes of F must be $0 *^{n-1}$, and so by irreducibility, $F = \{0 *^{n-1}, 1 *^{n-1}\}$, contradicting tightness. \square

2.4.1 Lower bound

In this section we prove the lower bound part of Conjecture 28, assuming Conjecture 14. As we explain in the proof, this amounts to ruling out the weight vector $1, n-2, 0, \dots, 0$.

Theorem 30. *Assume Conjecture 14. For every $n \geq 3$, the weight vector of any tight irreducible subcube partition of length n majorizes either $1, n-1, n-1, 0, \dots, 0$ or $1, n, n-3, 1, 0, \dots, 0$.*

Proof. Let F be a tight irreducible subcube partition of length n , and let w be its weight vector. The theorem states that (i) $w_{\geq 0} \geq 2n-1$; (ii) $w_{\geq 1} \geq 2n-2$; and either (iii) $w_{\geq 2} \geq n-1$ or (iv) $w_{\geq 2} \geq n-2$ and $w_{\geq 3} \geq 1$.

We start with the following observation: $w_h \leq \binom{n}{h}$. Indeed, every subcube s of weight h contains the point x_s obtained by switching all $*$ s to 0 s, which has weight h . Since the subcubes in F are disjoint, every $s \in F$ of weight h has a different x_s . Since there are $\binom{n}{h}$ many possible x_s , it follows that $w_h \leq \binom{n}{h}$.

The inequality $w_{\geq 0} \geq 2n-1$ is Conjecture 14. Since $w_0 \leq 1$, the inequality $w_{\geq 1} \geq 2n-2$ follows. Since $w_1 \leq n$, we deduce the inequality $w_{\geq 2} \geq n-2$. To complete the proof, we need to show that either (iii) $w_{\geq 2} \geq n-1$ or (iv) $w_{\geq 3} \geq 1$. We will show that the assumptions $w_{\geq 2} = n-2$ and $w_{\geq 3} = 0$ lead to a contradiction.

Suppose, therefore, that $w_2 = n-2$ and $w_{\geq 3} = 0$. Since $w_{\geq 0} \geq 2n-1$ and $w_0 \leq 1$, $w_1 \leq n$, this implies that $w_0 = 1$ and $w_1 = n$.

Since $w_1 = n$, for every $i \in [n]$ there is a subcube $s^{(i)} \in F$ which contains 1 in the i 'th position: $s_i^{(i)} = 1$. The point 0^n is covered by the unique subcube $s^{(0)} \in F$ of weight 0 . Since $s^{(0)}$ and $s^{(i)}$ must conflict, necessarily $s_i^{(0)} = 0$ (this is the only possible conflict), and so $s^{(0)} = 0^n$ is a point.

Since $0^n \in F$, the subcubes $s^{(i)}$ cannot be points. Indeed, if $s^{(i)}$ is a point then $s^{(i)} = 0^{i-1}10^{n-i}$, and so $s^{(0)} \cup s^{(i)} = 0^{i-1}*0^{n-i}$, contradicting irreducibility. Consequently, all points in F have even weight, contradicting Lemma 12 (applied on the star pattern \emptyset). \square

2.4.2 Construction

In this section, we prove (unconditionally) the upper bound part of Conjecture 28, by constructing tight irreducible subcube partitions of length $n \geq 3$ and weight vectors $1, n-1, n-1, 0, \dots, 0$ and $1, n, n-3, 1, 0, \dots, 0$. The constructions will use the method of Theorem 20. The same subcube partitions can also be constructed using the method of Lemma 24; we leave the details to the reader.

Theorem 31. *For each $n \geq 3$ there is a tight irreducible subcube partition A_n whose weight vector is $1, n-1, n-1, 0, \dots, 0$.*

Proof. We construct the subcube partitions inductively, starting with

$$A_3 = \{ *00, 001, 01*, 110, 1*1 \},$$

which is obtained from S_3 of Theorem 20 by flipping the third coordinate. The construction will maintain the invariants that $01*^{n-2} \in A_n$ and $1*^{n-1}, 00*^{n-2} \notin A_n$.

Given A_n , we construct A_{n+1} by applying Lemma 19 to $F_0 = A_n$ and $F_1 = \{1*^{n-1}, 00*^{n-2}, 01*^{n-2}\}$, and rotating the result G once to the left, that is, $A_{n+1} = \{xb : bx \in G\}$, where $b \in \{0, 1, *\}$ and $x \in \{0, 1, *\}^n$.

Since F_0 is irreducible and F_1 is reducible, clearly $F_0 \neq F_1$, and so A_{n+1} is tight by Lemma 19.

The invariant implies that $F_1 \setminus F_0 = \{1*^{n-1}, 00*^{n-2}\}$ is irreducible, and so A_{n+1} is irreducible by Lemma 19.

The invariant states that $01*^{n-2} \in F_0$. Since $01*^{n-2} \in F_1$ by definition, it follows that $*01*^{n-2} \in G$, and so $01*^{n-1} \in A_{n+1}$. Since A_{n+1} is irreducible, necessarily $00*^{n-1} \notin A_{n+1}$ (otherwise $00*^{n-1} \cup 01*^{n-1} = 0*^n$ would be a subcube) and $1*^n \notin A_{n+1}$ (otherwise the union of all other subcubes would be $0*^n$).

Finally, the invariants imply that $F_1 \setminus F_0 = \{1*^{n-1}, 00*^{n-2}\}$, and so compared to F_0 , the subcube partition G gains one subcube of weight 2 (namely, $11*^{n-1}$) and one subcube of weight 1 (namely, $100*^{n-2}$); all other subcubes originate from F_0 and maintain their weight. \square

Theorem 32. *For each $n \geq 3$ there is a tight irreducible subcube partition D_n whose weight vector is $1, n, n-3, 1, 0, \dots, 0$.*

Proof. The proof is very similar to that of Theorem 31. We take

$$D_3 = S_3 = \{*01, 000, 01*, 111, 1*0\}.$$

The rest of the proof is identical. \square

The subcube partition D_3 is obtained from A_3 by flipping the third coordinate, and this holds for every n , by construction. By flipping coordinates appropriately, we can also obtain other tight irreducible subcube partitions B_n, C_n whose weight vectors are $1, n-1, n-1, 0, \dots, 0$. The subcube partition B_n is obtained by flipping the first coordinate, and C_n is obtained by flipping both the first and the third coordinates. The subcube partitions B_n, C_n can also be obtained using an iterative construction as above.

Here are the subcube partitions A_5, B_5, C_5, D_5 after rotation once to the left:

0000*	0000*	0100*	0100*
01000	01001	00001	00000
0*100	0*101	0*101	0*100
0**10	0**11	0**11	0**10
1***0	1***1	1***1	1***0
10001	10000	11000	11001
*1001	*1000	*0000	*0001
**101	**100	**100	**101
***11	***10	***10	***11
A_5	B_5	C_5	D_5

Among all subcube partitions obtained from A_n by flipping coordinates, these are the only ones whose weight vector is either $1, n-1, n-1, 0, \dots, 0$ or $1, n, n-3, 1, 0, \dots, 0$.

2.5 Maximal number of points

In the following section, we tackle the problem of maximizing the number of subcubes in an irreducible subcube partition. As a warm-up, we start with the problem of maximizing the number of points (zero-dimensional subcubes) in an irreducible subcube partition.

For $n = 3, 4, 5, 6$, a computer search reveals that the maximum number of points in an irreducible subcube partition of length n is 2, 4, 8, 16. This is consistent with the following conjecture.

Conjecture 33. If $n \geq 3$ then the maximum number of points in an irreducible subcube partition of length n is 2^{n-2} .

It is easy to see that an irreducible subcube partition of length n contains at most 2^{n-1} points. Indeed, if the subcube partition contained more than 2^{n-1} points then there would be two points differing in a single coordinate. The union of these two points is an edge (a one-dimensional subcube), contradicting irreducibility.

In the rest of this section, we construct an irreducible subcube partition of length n containing 2^{n-2} many points. The construction uses the following lemma.

Lemma 34. If $F \neq \{0*^{n-1}, 1*^{n-1}\}$ is an irreducible subcube partition of length n then the following is an irreducible subcube partition of length $n+1$:

$$G = \{00t, 11t : 0t \in F\} \cup \{01t, 10t : 1t \in F\} \cup \{**t : *t \in F\}.$$

Proof. Let F' be the irreducible subcube partition obtained from F by flipping the first coordinate. The subcube partition G results from applying Lemma 19 to F and F' . According to the lemma, in order to show that G is irreducible, it suffices to show that $F \cap F' \neq \emptyset$.

If $F \cap F' = \emptyset$ then all subcubes in F start with 0 or 1. Hence the union of all subcubes in F starting with 0 is $0*^{n-1}$, and the union of all subcubes in F starting with 1 is $1*^{n-1}$. Since F is irreducible, it follows that $F = \{0*^{n-1}, 1*^{n-1}\}$, contrary to the assumption. Therefore $F \cap F' \neq \emptyset$, completing the proof. \square

Corollary 35. If $F \neq \{0*^{n-1}, 1*^{n-1}\}$ is an irreducible subcube partition of length n then for every $k \geq 1$, the following is an irreducible subcube partition of length $n+k$:

$$G = \{a_1 \dots a_k t : bt \in F, a_1, \dots, a_k, b \in \{0, 1\}, a_1 \oplus \dots \oplus a_k = b\} \cup \{**^k t : *t \in F\}.$$

Proof. Apply the lemma iteratively $k-1$ times to F , noticing that the subcube partition constructed in the lemma is never of the form $\{0*^m, 1*^m\}$. \square

In order to construct an irreducible subcube partition of length n with 2^{n-2} many points, we apply the corollary to the irreducible subcube partition S_3 from Theorem 20.

Theorem 36. *For every $n \geq 3$ there is an irreducible subcube partition of length n containing 2^{n-2} many points.*

Proof. The subcube partition $S_3 = \{000, *01, 1*0, 01*, 111\}$ is irreducible (according to Theorem 20) and contains two points. Applying Corollary 35 with $k = n - 3$, we get an irreducible subcube partition of length n in which each of the two original points gives rise to 2^{n-3} points, for a total of 2^{n-2} points. \square

Using similar ideas, we can construct an irreducible subcube partition of length n containing any even number of points between 2 and 2^{n-2} . We leave the details to the reader.

2.6 Maximal size

What is the maximal size of an irreducible subcube partition of length n ? Here are some values, based on experiments and an upper bound which we present in Section 2.6.1:

n	3	4	5	6	7	8	9
Lower bound	5	9	20	40	80	160	320
Upper bound	5	9	20	40	83	166	334

Based on these results, we make the following conjecture.

Conjecture 37. *For every $n \geq 5$, the maximal size of an irreducible subcube partition of length n is $5 \cdot 2^{n-3}$.*

We give a matching construction in Section 2.4.2. The size $5 \cdot 2^{n-3}$ is best possible, assuming Conjecture 33.

Lemma 38. *Assume Conjecture 33. For every $n \geq 3$, every irreducible subcube partition of length n has size at most $5 \cdot 2^{n-3}$.*

Proof. Let F be an irreducible subcube partition of length n . According to Conjecture 33, F contains $m \leq 2^{n-2}$ points. All other subcubes of F cover at least two points, and so the size of F is at most

$$m + \frac{2^n - m}{2} = 2^{n-1} + \frac{m}{2} \leq 2^{n-1} + 2^{n-3}. \quad \square$$

2.6.1 Upper bound

In this section, we use a result of Forcade [For73] to give an upper bound on the size of irreducible subcube partitions.

Theorem 39. *For every $n \geq 3$, the size of any irreducible subcube partition of length n is at most*

$$\frac{2n-1}{3n-1} 2^n = \left(\frac{16}{3} - \Theta\left(\frac{1}{n}\right) \right) 2^{n-3}.$$

Proof. Let F be an irreducible subcube partition of length n . Let G be a subcube partition obtained from F by subdividing each subcube of dimension larger than 1 into edges (subcubes of dimension 1) in an arbitrary way.

Since F is irreducible, no two points in G span an edge. Therefore the set of edges in G constitutes a maximal matching in the n -dimensional hypercube. Forcade [For73] proved that any maximal matching in the n -dimensional hypercube contains $m \geq \frac{n}{3n-1}2^n$ edges. Therefore

$$|F| \leq |G| = m + (2^n - 2m) = 2^n - m \leq 2^n - \frac{n}{3n-1}2^n. \quad \square$$

Forcade showed that the bound $\frac{n}{3n-1}2^n$ is asymptotically tight by giving a matching construction. Therefore this method cannot prove the conjectured upper bound $5 \cdot 2^{n-3}$.

2.6.2 Construction

In this section we construct irreducible subcube partitions of size $5 \cdot 2^{n-3}$ for all $n \geq 3$ except for $n = 4$. When $n = 4$, a computer search reveals that the maximum number of subcubes is 9, which is achieved by

$$0000, 0011, 1101, 1110, *100, *111, 0*01, 0*10, 10**.$$

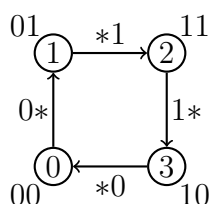
We prove this below.

Our construction is based on the work of Perezhogin [Per05], brought to our attention by Tarannikov [Tar23].¹ The construction is inductive, increasing the length by 2 at each step. Consequently, we will need two base cases, for $n = 3$ and for $n = 6$. The same inductive construction will also be used in Section 2.8 to construct subcube partitions consisting only of edges for all $n \geq 4$ except for $n = 5$.

We start with the inductive step. The construction uses a mapping from \mathbb{Z}_4 to $\{0, 1\}^2$:

$$\begin{array}{cccc} 0 & 1 & 2 & 3 \\ \hline 00 & 01 & 11 & 10 \end{array}$$

From a geometric perspective, we enumerate vertices of a two-dimensional face clockwise:



¹The construction on page 55 in [Per05] contains several minor errors. Tarannikov pointed out to us that the definition of the $M_{\sigma_i \sigma_j}^{n+2}$ there should read

$$\begin{aligned} M_{00}^{n+2} &= (M_{00}^n(00) \cup M_{01}^n(01) \cup M_{11}^n(11) \cup M_{10}^n(10) \cup \mathbf{v}_1^{00} \cup \mathbf{v}_2^{00} \cup \mathbf{v}_3^{00} \cup \mathbf{v}_4^{00}) \setminus (\mathbf{e}_1(00) \cup \mathbf{e}_2(01) \cup \mathbf{e}_3(11) \cup \mathbf{e}_4(10)), \\ M_{01}^{n+2} &= (M_{00}^n(01) \cup M_{01}^n(11) \cup M_{11}^n(10) \cup M_{10}^n(00) \cup \mathbf{v}_1^{01} \cup \mathbf{v}_2^{10} \cup \mathbf{v}_3^{01} \cup \mathbf{v}_4^{10}) \setminus (\mathbf{e}_1(01) \cup \mathbf{e}_2(11) \cup \mathbf{e}_3(10) \cup \mathbf{e}_4(00)), \\ M_{11}^{n+2} &= (M_{00}^n(11) \cup M_{01}^n(10) \cup M_{11}^n(00) \cup M_{10}^n(01) \cup \mathbf{v}_1^{11} \cup \mathbf{v}_2^{11} \cup \mathbf{v}_3^{11} \cup \mathbf{v}_4^{11}) \setminus (\mathbf{e}_1(11) \cup \mathbf{e}_2(10) \cup \mathbf{e}_3(00) \cup \mathbf{e}_4(01)), \\ M_{10}^{n+2} &= (M_{00}^n(10) \cup M_{01}^n(00) \cup M_{11}^n(01) \cup M_{10}^n(11) \cup \mathbf{v}_1^{10} \cup \mathbf{v}_2^{01} \cup \mathbf{v}_3^{10} \cup \mathbf{v}_4^{01}) \setminus (\mathbf{e}_1(10) \cup \mathbf{e}_2(00) \cup \mathbf{e}_3(01) \cup \mathbf{e}_4(11)). \end{aligned}$$

We denote this mapping, known as the *Gray map*, by $\alpha \mapsto \llbracket \alpha \rrbracket$. We use the same notation to associate two adjacent elements of \mathbb{Z}_4 with the corresponding edge, e.g. $\llbracket 1, 2 \rrbracket = *1$.

Let \mathbb{W}_4 consist of all subsets of \mathbb{Z}_4 which are either singletons or pairs of adjacent elements. The function $\phi \mapsto \llbracket \phi \rrbracket$ maps \mathbb{W}_4 into $\{0, 1, *\}^2 \setminus \{**\}$. Given $\phi \in \mathbb{W}_4$ and $\alpha \in \mathbb{Z}_4$, we define $\phi + \alpha$ in the obvious way. For example, $\{1\} + 2 = \{3\}$ and $\{1, 2\} + 2 = \{3, 0\} = \{0, 3\}$.

The construction will apply to subcube partitions which satisfy the following *complementation property*.

Definition 40 (Complementation property). A subcube partition F of length $n \geq 2$ satisfies the *complementation property* if the following properties hold:

- (a) No subcube in F ends with $**$.
- (b) If $s\llbracket \phi \rrbracket \in F$, where $\phi \in \mathbb{W}_4$, then $s\llbracket \phi + 2 \rrbracket \notin F$.

(Note that $\llbracket \alpha + 2 \rrbracket$ is obtained from $\llbracket \alpha \rrbracket$ by complementing both symbols, leaving stars untouched.)

The construction is given by the following lemma.

Lemma 41. Let F be an irreducible subcube partition of length $n \geq 2$ containing $0^{n-2}\llbracket 0, 1 \rrbracket$ and satisfying the complementation property. Define

$$F' = \{s\llbracket \phi - \alpha \rrbracket \llbracket \alpha \rrbracket : s\llbracket \phi \rrbracket \in F, \alpha \in \mathbb{Z}_4, s\llbracket \alpha \rrbracket \neq 0^{n-2}\llbracket 0, 1 \rrbracket\} \\ \cup \{0^{n-2}\llbracket -\alpha \rrbracket \llbracket \alpha, \alpha + 1 \rrbracket : \alpha \in \mathbb{Z}_4\}.$$

Then F' is a tight irreducible subcube partition of length $n + 2$ containing $0^n\llbracket 0, 1 \rrbracket$ and satisfying the complementation property. Moreover, for every d , if F contains m subcubes of dimension d then F' contains $4m$ subcubes of dimension d .

Proof. We can write F' as follows:

$$F' = \underbrace{\{s\llbracket \phi - \alpha \rrbracket \llbracket \alpha \rrbracket : s\llbracket \phi \rrbracket \in F\}}_{F''} \setminus \underbrace{\{0^{n-2}\llbracket \alpha, \alpha + 1 \rrbracket \llbracket -\alpha \rrbracket\}}_{\text{removed edges}} \cup \underbrace{\{0^{n-2}\llbracket -\alpha \rrbracket \llbracket \alpha, \alpha + 1 \rrbracket\}}_{\text{added edges}},$$

where α ranges over \mathbb{Z}_4 . We use the terms “removed edges” and “added edges” below to refer to the sets in the expression above.

Most of the properties (apart from irreducibility) are easy to verify:

Subcube partition The removed edges and the added edges cover the same set of points, namely

$$\{0^{n-2}\llbracket \alpha \rrbracket \llbracket \beta \rrbracket : \alpha + \beta \in \{0, 1\}\},$$

and so F' is a subcube partition.

Tightness The added edges $0^{n-2}\llbracket 0 \rrbracket \llbracket 0, 1 \rrbracket$ and $0^{n-2}\llbracket 3 \rrbracket \llbracket 1, 2 \rrbracket$ together mention all coordinates.

Contains $0^n\llbracket 0, 1 \rrbracket$ This is one of the added edges.

Complementation property By construction, no subcube in F' ends with $**$. It remains to show that if $t\llbracket \psi \rrbracket \in F'$ then $t\llbracket \psi + 2 \rrbracket \notin F'$. If ψ is a pair then $t\llbracket \psi \rrbracket$ is one of the added edges, and each of these has a different t .

If $\psi = \{\alpha\}$ is a singleton then $t\llbracket \psi \rrbracket = s\llbracket \phi - \alpha \rrbracket\llbracket \alpha \rrbracket$ for some $s\llbracket \phi \rrbracket \in F$. If F' also contains $t\llbracket \psi + 2 \rrbracket = s\llbracket \phi - \alpha \rrbracket\llbracket \alpha + 2 \rrbracket$ then $s\llbracket \phi + 2 \rrbracket \in F$, contradicting the assumption that F satisfies the complementation property.

Subcube counts Since $\llbracket \phi + \alpha \rrbracket$ has the same number of stars as $\llbracket \phi \rrbracket$ and $\llbracket \alpha \rrbracket$ has no stars, each subcube in F gives rise to four subcubes of the same dimension in F'' . Getting from F'' to F' involved adding and removing four edges, hence the claim about subcube counts.

Irreducibility The main part of the proof is proving the irreducibility of F' . Let G' be a non-empty set whose union is a subcube. We need to show that either $|G'| = 1$ or $G' = F'$.

For every $\alpha \in \mathbb{Z}_4$, define

$$\begin{aligned} G_\alpha &= \{s\llbracket \phi \rrbracket : s\llbracket \phi - \alpha \rrbracket\llbracket \alpha \rrbracket \in G'\}, \\ H_\alpha &= \{s\llbracket \phi - \alpha \rrbracket : s\llbracket \phi - \alpha \rrbracket\llbracket \alpha \rrbracket \in G'\}, \\ P_\alpha &= \{t \in \{0, 1\}^n : t\llbracket \alpha \rrbracket \in \bigcup G'\}. \end{aligned}$$

By construction, $G_\alpha \subseteq F \setminus \{0^{n-2}\llbracket 0, 1 \rrbracket\}$.

We consider several cases, according to which added edges (if any) belong to G' .

No added edges Suppose first that G' contains no added edge. In this case,

$$G' = \bigcup_{\alpha} \{t\llbracket \alpha \rrbracket : t \in H_\alpha\}.$$

This implies that $\bigcup H_\alpha$, and so $\bigcup G_\alpha$, are subcubes of F for each α . By irreducibility of F , each G_α is either empty or a singleton.

If there is a single non-empty H_α then G' is a singleton, and we are done. Suppose therefore that at least two H_β are non-empty. If $H_\alpha, H_{\alpha+2}$ are non-empty then since $\llbracket \alpha \rrbracket \vee \llbracket \alpha + 2 \rrbracket = **$, in fact H_β is non-empty for all β . Therefore we can assume that $H_\alpha, H_{\alpha+1}$ are non-empty for some α .

Suppose $H_\alpha = \{s\llbracket \phi - \alpha \rrbracket\}$, where $s\llbracket \phi \rrbracket \in F$. Since $\bigcup G'$ is a subcube, we have $\bigcup H_\alpha = \bigcup H_{\alpha+1}$. Recalling that $H_{\alpha+1}$ is a singleton, this shows that $s\llbracket \phi - \alpha \rrbracket \in H_{\alpha+1}$, and so $s\llbracket \phi + 1 \rrbracket \in F$. Thus $s\llbracket \phi \rrbracket, s\llbracket \phi + 1 \rrbracket \in F$.

If $\phi = \{\alpha\}$ then $s\llbracket \alpha \rrbracket \cup s\llbracket \alpha + 1 \rrbracket = s\llbracket \alpha, \alpha + 1 \rrbracket$, contradicting the irreducibility of F . If $\phi = \{\alpha, \alpha + 1\}$, then $s\llbracket \phi \rrbracket \cap s\llbracket \phi + 1 \rrbracket = s\llbracket \alpha + 1 \rrbracket$, contradicting the assumption that F is a partition. Therefore this case cannot happen.

Single added edge Suppose that G' contains a single added edge, $0^{n-2}[-\alpha][\alpha, \alpha + 1]$. Then

$$\begin{aligned} P_\alpha &= \bigcup H_\alpha \cup \{0^{n-2}[-\alpha]\}, \\ \bigcup G_\alpha &= \{s[\beta + \alpha] : s[\beta] \in P_\alpha, s[\beta] \neq 0^{n-2}[-\alpha]\} \\ &= \{s[\beta + \alpha] : s[\beta] \in P_\alpha\} \setminus \{0^{n-2}[0]\}, \\ P_{\alpha+1} &= \bigcup H_{\alpha+1} \cup \{0^{n-2}[-\alpha]\}, \\ \bigcup G_{\alpha+1} &= \{s[\beta + \alpha + 1] : s[\beta] \in P_{\alpha+1}, s[\beta] \neq 0^{n-2}[-\alpha]\} \\ &= \{s[\beta + \alpha + 1] : s[\beta] \in P_{\alpha+1}\} \setminus \{0^{n-2}[1]\}. \end{aligned}$$

Since $\bigcup G'$ is a subcube, we have $P_\alpha = P_{\alpha+1}$, and the common value is a subcube containing $0^{n-2}[-\alpha]$. We claim that this subcube must be of the form $r[-\alpha]$. This is because of the following:

- Since $0^{n-2}[0, 1] \in F$, in particular $0^{n-2}[1] \notin F$, and so $0^{n-2}[1 - \alpha] \notin P_\alpha$.
- By assumption G' doesn't contain the added edge $0^{n-2}[-\alpha - 1][\alpha + 1, \alpha + 2]$, and so $0^{n-2}[-\alpha - 1] \notin P_{\alpha+1} = P_\alpha$.
- Since $[-\alpha] \vee [2 - \alpha] = **$, also $0^{n-2}[2 - \alpha] \notin P_\alpha$ (otherwise P_α would contain $0^{n-2}**$ since P_α is a subcube).

Notice now that

$$\bigcup (G_\alpha \cup G_{\alpha+1} \cup 0^{n-2}[0, 1]) = \{s[\beta + \alpha], s[\beta + \alpha + 1] : s[\beta] \in P_\alpha\} = r[0, 1].$$

The irreducibility of F implies that $r[0, 1] = 0^{n-2}[0, 1]$. Therefore either $\bigcup G' = 0^{n-2}[-\alpha][\alpha, \alpha + 1]$ or $\bigcup G' = 0^{n-2}[-\alpha]**$. In the former case, G' is a singleton consisting just of a single added edge, and so it remains to rule out the latter case.

If $\bigcup G' = 0^{n-2}[-\alpha]**$ then in particular $0^{n-2}[-\alpha][\alpha + 2, \alpha + 3] \subseteq \bigcup G'$, and so $\bigcup H_{\alpha+2} = 0^{n-2}[-\alpha]$ and $\bigcup H_{\alpha+3} = 0^{n-2}[-\alpha]$. This implies that $\bigcup G_{\alpha+2} = 0^{n-2}[2]$ and $\bigcup G_{\alpha+3} = 0^{n-2}[3]$, and so both $0^{n-2}[2], 0^{n-2}[3] \in F$. However, this contradicts the irreducibility of F , since $0^{n-2}[2] \cup 0^{n-2}[3] = 0^{n-2}[2, 3]$ is a subcube.

Exactly two adjacent added edges Suppose next that G' contains precisely two added edges, whose indices differ by 1, say the edge $0^{n-2}[-\alpha][\alpha, \alpha + 1]$ and the edge $0^{n-2}[-\alpha - 1][\alpha + 1, \alpha + 2]$. Therefore

$$P_{\alpha+1} = \bigcup H_{\alpha+1} \cup \{0^{n-2}[-\alpha - 1, -\alpha]\},$$

which implies that

$$\bigcup G_{\alpha+1} = \{s[\beta + \alpha + 1] : s[\beta] \in P_{\alpha+1}\} \setminus \{0^{n-2}[0, 1]\}.$$

Since $\bigcup G'$ is a subcube, also $P_{\alpha+1}$ is a subcube, and so $\bigcup(G_{\alpha+1} \cup 0^{n-2}\llbracket 0, 1 \rrbracket)$ is a subcube. The irreducibility of F implies that $G_{\alpha+1} = \emptyset$, and so $P_{\alpha+1} = 0^{n-2}\llbracket -\alpha - 1, -\alpha \rrbracket$.

The join of the two added edges is $0^{n-2}\llbracket -\alpha - 1, -\alpha \rrbracket **$, and this shows that all P_β are equal. In particular, since $P_\alpha = \bigcup H_\alpha \cup \{0^{n-2}\llbracket -\alpha \rrbracket\}$, we have $H_\alpha = \{0^{n-2}\llbracket -\alpha - 1 \rrbracket\}$ and so $G_\alpha = \{0^{n-2}\llbracket 3 \rrbracket\}$. Similarly, $P_{\alpha+2} = \bigcup H_{\alpha+2} \cup \{0^{n-2}\llbracket -\alpha - 1 \rrbracket\}$ and so $H_{\alpha+2} = \{0^{n-2}\llbracket -\alpha \rrbracket\}$, implying that $G_{\alpha+2} = \{0^{n-2}\llbracket 2 \rrbracket\}$. However, then $0^{n-2}\llbracket 2 \rrbracket, 0^{n-2}\llbracket 3 \rrbracket \in F$, which contradicts the irreducibility of F since $0^{n-2}\llbracket 2 \rrbracket \cup 0^{n-2}\llbracket 3 \rrbracket = 0^{n-2}\llbracket 2, 3 \rrbracket$ is a subcube.

Two non-adjacent added edges In the remaining case, the set G' contains two non-adjacent edges, say $0^{n-2}\llbracket -\alpha \rrbracket \llbracket \alpha, \alpha + 1 \rrbracket$ and $0^{n-2}\llbracket -\alpha - 2 \rrbracket \llbracket \alpha + 2, \alpha + 3 \rrbracket$. The join of these two edges is $0^{n-2}****$, and so $\bigcup G'$ is a subcube ending with $****$. In particular, G' must contain all added edges.

Let G'' be obtained from G' by replacing the added edges with the removed edges. Since the added edges and the removed edges span the same points, $\bigcup G''$ is still a subcube. Consider

$$G''_0 = \{s\llbracket \phi \rrbracket : s\llbracket \phi \rrbracket \llbracket 0 \rrbracket \in G''\} \subseteq F.$$

Since $\bigcup G''_0$ is a subcube, the irreducibility of F implies that either G''_0 is a singleton or $\bigcup G''_0 = \{0, 1\}^n$. In the latter case, clearly $\bigcup G' = \{0, 1\}^{n+2}$, and so $G' = F'$. In the former case, since the removed edge $0^{n-2}\llbracket 0, 1 \rrbracket$ belongs to G''_0 by construction, we see that $G''_0 = \{0^{n-2}\llbracket 0, 1 \rrbracket\}$. However, since $\bigcup G''$ is a subcube ending with $****$, we see that $\bigcup G''_0$ should be a subcube ending with $**$ rather than with $\llbracket 0, 1 \rrbracket$. So this case cannot happen. \square

We can now construct the desired subcube partitions.

Theorem 42. *For every $n \geq 3$ other than $n = 4$ there is a tight irreducible subcube partition of length n and size $5 \cdot 2^{n-3}$.*

Proof. Using Lemma 41, it suffices to construct tight irreducible subcube partitions of lengths $n \in \{3, 6\}$ containing $0^{n-1}*$ and satisfying the complementation property in the lemma.

For $n = 3$, we can take

$$100, *10, 1*1, 00*, 011.$$

For $n = 6$, we can take

$$\begin{aligned} abcdef : a \oplus b &= c \oplus f = \overline{d \oplus e} \\ *aba\bar{b}\bar{a} \\ a*\bar{a}b\bar{a}b \\ ab*\bar{b}\bar{a}b \\ ab\bar{a}*ab \\ abab*\bar{b} \\ ababa* \end{aligned}$$

Here a, b, c, d, e, f range over $\{0, 1\}$. \square

We close this section by showing that $n = 4$ is indeed exceptional. We first need the following lemma, which will also be useful in Section 2.8.

Lemma 43. *Let F be an irreducible subcube partition of length 4. The set of points in F is either empty or one of the following, up to permutation and flipping of coordinates:*

0000	0000
1110	1110
	1101
	0011

Proof. Suppose that F contains a point, say $0000 \in F$. According to Lemma 12, F must contain a point of odd parity. Due to irreducibility, this point needs to have weight 3, say $1110 \in F$.

If $|F| > 2$ then according to Lemma 12, F contains another point of odd parity, which due to irreducibility needs to have weight 3, say $1101 \in F$. According to Lemma 12, F needs to contain another point of even parity, which due to irreducibility cannot be one of $1100, 1010, 0110, 1001, 0101, 1111$. Therefore $0011 \in F$.

Due to irreducibility, $1011, 0111 \notin F$, and so Lemma 12 shows that in this case F contains precisely the following points: $0000, 1110, 1101, 0011$. \square

We can now show that Theorem 42 cannot hold for $n = 4$.

Lemma 44. *There is no irreducible subcube partition of length 4 and size 10.*

Proof. Let F be an irreducible subcube partition of length 4 and size 10. According to Lemma 43, F contains at most 4 points, and so has to consist of 4 points and 6 edges. Moreover, without loss of generality the points in F are $0000, 1110, 1101, 0011$.

Let F_i consist of all subcubes $s \in F$ with $s_i = *$. Note that F_i is non-empty, since otherwise the union of subcubes $s \in F$ with $s_i = 0$ is $*^{i-1}0*^{4-i}$, contradicting irreducibility.

There are exactly two points in F belonging to $*^{i-1}0*^{4-i}$. Each edge outside of F_i contains an even number of such points, and each edge in F_i contains one such point. Therefore $|F_i|$ is even, and so $|F_i| \geq 2$. This implies that $|F_1| + |F_2| + |F_3| + |F_4| \geq 8$, contradicting the fact that F contains only 6 edges. \square

This lemma also follows from the computation of Peitl and Szeider [PS23, Table 1].

2.7 Maximal minimum dimension

All irreducible subcube partitions we have exhibited so far contain points. Is this necessary? More generally, given n , what is the maximal d such that there exists a tight irreducible subcube partition in which every subcube has dimension at least d ? (The question doesn't make sense without assuming tightness, since $*^n$ is always irreducible.)

The constructions we give below suggest the following conjecture.

Definition 45 (Minimum dimension). For a subcube partition F , let $\delta(F)$ denote the minimum dimension of a subcube of F .

Also, let $\delta_*(F)$ denote the minimum dimension of a subcube of F ending with a star (if such a subcube exists), and let $\delta_b(F)$ denote the minimum dimension of a subcube of F not ending with a star (if such a subcube exists).

Conjecture 46. Every tight irreducible subcube partition F of length n satisfies $\delta(F) \leq n/2 - o(n)$.

One can similarly ask for the maximum value of $\Delta(F)$, which is the minimum codimension of a subcube of F , over all irreducible subcube partitions of length n . The results in Section 2.6 shows that when $n \geq 3$ the maximal value is $\Delta(F) = n - 1$ (the case $n = 4$ is covered in Section 2.8).

In the remainder of this section, we give a construction matching Conjecture 46. The construction is based on the following lemma.

Lemma 47. Let F be a subcube partition of length n . Define

$$G = \{t** : t* \in F\} \cup \{0tb*, 1tb* : b \in \{0, 1\}, tb \in F\}.$$

Then

- (a) G is a subcube partition of length $n + 2$.
- (b) If F is tight then G is tight.
- (c) If F is irreducible and contains a subcube ending with a star then G is irreducible and contains a subcube ending with a star.
- (d) We have $\delta_*(G) = \min(\delta_*(F) + 2, \delta_b(F) + 1)$ and $\delta_b(G) = \delta_b(F) + 1$, and so $\delta(G) \geq \delta(F) + 1$. Moreover, if $\delta(F) = \delta_b(F)$ then $\delta(G) = \delta_*(G) = \delta_b(G) = \delta(F) + 1$.

Proof. Let $F_0 = \{tc* : tc \in F\}$ and $F_1 = \{t*c : tc \in F\}$, where $c \in \{0, 1, *\}$ in both cases. Applying Lemma 19 to F_0, F_1 , we obtain the subcube partition G .

Suppose that F is tight. For every $i \in \{1, \dots, n - 1\}$, some subcube of F mentions coordinate i . The corresponding subcube or subcubes of G mention coordinate $i + 1$. Some subcube of F mentions coordinate n . The corresponding subcubes of G mention the remaining coordinates $1, n + 1, n + 2$.

Suppose that F is irreducible and contains a subcube $s \in F$ ending with a star. The irreducibility of F directly implies the irreducibility of F_0 and F_1 . Since $s* \in F_0 \cap F_1$, Lemma 19 implies that G is irreducible. Furthermore, $*s* \in G$ is a subcube ending with a star.

The remaining claims are easy to verify directly once we notice that the dimension of a subcube is the number of star coordinates. \square

We apply the construction on three specific tight irreducible subcube partitions (one only for $n = 4$) in order to obtain the following result, which gives the best constructions we are aware of.

Theorem 48. For every odd $n \geq 3$ there is a tight irreducible subcube partition F of length n with $\delta(F) = \frac{n-3}{2}$.

For $n = 4$ there is a tight irreducible subcube partition F of length n with $\delta(F) = \frac{n-4}{2}$.

For every even $n \geq 6$ there is a tight irreducible subcube partition F of length n with $\delta(F) = \frac{n-2}{2}$.

Proof. The first part follows from applying Lemma 47 to the tight irreducible subcube partition S_3 of Theorem 20. The second part follows from taking the tight irreducible subcube partition S_4 of the same theorem. The third part follows from applying Lemma 47 to the following tight irreducible subcube partition, whose irreducibility can be checked using Algorithm 1:

0*0*1*	00**0*	001*1*	010*0*	0110**
1**0*1	10***0	10*1*1	11*0*0	1101**
				*111**

□

2.8 Homogeneous subcube partitions

So far we have considered various parameters of irreducible subcube partitions, attempting to optimize them. The final question we consider concerns subcube partitions in which all subcubes have the same codimension.

Definition 49 (Homogeneity). An (n, k) -homogeneous subcube partition is a tight subcube partition of length n in which all subcubes have codimension k .

In this section, we explore the following question: for which n, k does there exist an irreducible (n, k) -homogeneous subcube partition?

Here is a table with some experimental results:

	$n = 4$	$n = 5$	$n = 6$	$n = 7$	$n = 8$	$n = 9$
$k = 3$	✓	×	×	×	×	×
$k = 4$		×	✓	×	×	×
$k = 5$			✓	✓	✓	✓
$k = 6$				✓	✓	✓
$k = 7$					✓	✓
$k = 8$						✓

In Section 2.8.1 we prove several elementary results: an irreducible $(n, 1)$ -homogeneous subcube partition exists only for $n = 1$; no irreducible $(n, 2)$ -homogeneous partition exists; and for $k \geq 3$, if an irreducible (n, k) -homogeneous subcube partition exists then $k + 1 \leq n \leq 2^k - 3$. In Section 2.8.2 we show that the weight distribution of an (n, k) -homogeneous subcube partition is binomial.

In Section 2.8.3, we describe a construction of Perezhagin [Per05], which gives irreducible $(n, n - 1)$ -homogeneous subcube partitions for all $n \geq 4$ other than $n = 5$. We also show that no irreducible $(5, 4)$ -homogeneous subcube partition exists, and that an irreducible $(6, 4)$ -homogeneous subcube partition does exist.

In Section 2.8.4, we show how the irreducible subcube partitions constructed in Section 2.8.3 give rise to even more irreducible subcube partitions, using a simple inductive construction.

Finally, in Section 2.8.5 we show that an irreducible $(n, 3)$ -homogeneous partition exists only for $n = 4$, and in Section 2.8.6 we show that an irreducible $(n, 4)$ -homogeneous partition exists only for $n = 6$ (with the help of a computer).

2.8.1 Elementary bounds

We start with the following general bound.

Lemma 50. *Suppose that $n \geq 4$ and $k \geq 2$. If there exists an irreducible (n, k) -homogeneous subcube partition then $k + 1 \leq n \leq 2^k - 3$.*

Proof. Let F be an irreducible (n, k) -homogeneous subcube partition. Clearly $n \geq k$. If $n = k$ then all subcubes in F are points, and so F is not irreducible. Hence $n \geq k + 1$. Since F has size 2^k , the upper bound $n \leq 2^k - 3$ follows from Theorem 15. \square

The following corollary of Lemma 12 will be useful. The corollary itself, and its applications below, were suggested to us by Kisielewicz [Kis23].

Corollary 51. *Let F be a homogeneous subcube partition, and let S be a star pattern occurring in F . Among subcubes in F whose star pattern is S , half have even parity and half have odd parity.*

Proof. Since F is homogeneous, all star patterns in F are inclusion-minimal, and so the corollary follows immediately from Lemma 12 (applied with $G = F$). \square

We now determine when an irreducible (n, k) -homogeneous subcube partition exists for $k = 1$ and $k = 2$.

Lemma 52. *If F is an irreducible $(n, 1)$ -homogeneous subcube partition then $n = 1$ and $F = \{0, 1\}$.*

Proof. The two subcubes in F contain a single non-star position, which must be identical. Since F is tight, necessarily $n = 1$, and so $F = \{0, 1\}$. \square

Lemma 53. *There are no irreducible $(n, 2)$ -homogeneous subcube partitions, for any n .*

Proof. Let F be an $(n, 2)$ -homogeneous subcube partition. Suppose, without loss of generality, that $00*^{n-2} \in F$. Corollary 51 implies that F must contain a subcube with the same star pattern and odd parity, without loss of generality $01*^{n-2}$. Since $00*^{n-2} \cup 01*^{n-2} = 0*^{n-1}$ is a subcube, F is reducible. \square

Here is an alternative proof, suggested by the reviewer. As in the proof of Lemma 50, we have $n \geq k + 1 = 3$. On the other hand, the result of Tarsi mentioned in the proof of Theorem 15 implies that $n \leq 2^k - 1 = 3$. Hence $n = 3$, and this case can be ruled out by hand (and also follows from [KZ16, Lemma 41]).

2.8.2 Weight distribution

In this section we prove the following surprising property, which involves the concept of weight vector defined in Section 2.4.

Lemma 54. *The weight vector of any (n, k) -homogeneous subcube partition is*

$$\binom{k}{0}, \binom{k}{1}, \dots, \binom{k}{k}, 0, \dots, 0.$$

Proof. Let F be an (n, k) -homogeneous subcube partition, and let w be its weight vector. Considering the number of points of weight ℓ which are covered, for each $\ell \in \{0, \dots, k\}$ we have

$$\sum_{r=0}^{\ell} \binom{n-k}{\ell-r} w_r = \binom{n}{\ell}.$$

This is a triangular system of equations, and so it has a unique solution. In other words, all (n, k) -homogeneous subcube partitions (if any) have the same weight vector.

The argument above applies even if we don't assume that F is tight. Therefore all (n, k) -homogeneous subcube partitions have the same weight vector as the subcube partition $\{x^{*n-k} : x \in \{0, 1\}^k\}$, whose weight vector is the one in the statement of the lemma. \square

2.8.3 Special perfect matchings

Perezhogin [Per05] defines a *special perfect matching* to be a perfect matching in the hypercube graph which is irreducible (in our terminology). If the hypercube has dimension n , then this is the same as an irreducible $(n, n-1)$ -homogeneous subcube partition. He constructs a special perfect matching for all $n \geq 4$ other than $n = 5$, and shows that no special perfect matching exists when $n = 5$. In this section, we give an exposition of his work.

We start with the construction.

Theorem 55. *For every $n \geq 4$ other than $n = 5$ there exists an irreducible $(n, n-1)$ -homogeneous subcube partition.*

Proof. Using Lemma 41, it suffices to construct irreducible $(n, n-1)$ -homogeneous subcube partitions of lengths $n \in \{4, 7\}$ containing $0^{n-1}*$ and satisfying the complementation property in the lemma.

For $n = 4$, we can take

$$0*10, 01*1, 000*, 1*01, 10*0, 111*, *100, *011.$$

For $n = 7$, we can take the subcube partition obtained by applying Lemma 19 with F_0 being the subcube partition constructed in Theorem 42 for $n = 6$, and with F_1 being obtained from F_0 by flipping the first two coordinates. \square

The following result shows that Theorem 55 cannot be extended to $n = 5$.

Lemma 56. *There is no irreducible $(5, 4)$ -homogeneous subcube partition.*

Proof. Suppose that F is an irreducible $(5, 4)$ -homogeneous subcube partition. Every subcube in F contains a single $*$. For $i \in \{1, \dots, 5\}$, let $F_i \subset F$ consist of those subcubes $s \in F$ with $s_i = *$. According to Lemma 12, $|F_i|$ is even. If $|F_i| = 0$ then the union of all subcubes $s \in F$ with $s_i = 0$ is the subcube $*^{i-1}0*^{5-i}$, contradicting irreducibility, and so $|F_i| > 0$.

The proof of Lemma 43 implies that for each $i \in \{1, \dots, 5\}$, either $|F_i| = 2$ or $|F_i| = 4$. Moreover, if $|F_i| = 4$ then each coordinate in F_i is *balanced* (0 appears the same number of times as 1), whereas if $|F_i| = 2$ then exactly one coordinate is unbalanced. In the entire formula, each coordinate is balanced, since the union of subcubes with $s_i = 0$ is the same as the union of subcubes with $s_i = 1$, and each subcube contains exactly two points.

Without loss of generality, $|F_1| \leq \dots \leq |F_5|$. Since $|F_1| + \dots + |F_5| = 16$, it follows that $|F_1| = |F_2| = 2$ and $|F_3| = |F_4| = |F_5| = 4$. Recall that each of F_1 and F_2 contains exactly one unbalanced coordinates. Since all coordinates in F_3, F_4, F_5, F are balanced, F_1 and F_2 have the same unbalanced coordinate. In particular, the second coordinate in F_1 and the first coordinate in F_2 are balanced.

Let $F_1 = \{*0x_0, *1x_1\}$ and $F_2 = \{0*y_0, 1*y_1\}$. For $\alpha, \beta \in \{0, 1\}$, we have $\{s : \alpha\beta s \in F_1 \cup F_2\} = \{x_\alpha, y_\beta\}$. The set $\{s : \alpha\beta s \in F_3 \cup F_4 \cup F_5\}$ consists of three edges, each covering a point of even parity and a point of odd parity. Therefore x_α and y_β have opposite parity.

Suppose that x_α and y_β differ in a single bit, say $x_\alpha = 000$ and $y_\beta = 001$. The set $\{s : \alpha\beta s \in F_3 \cup F_4 \cup F_5\}$ must be a matching of the remaining points. There are only four possibilities:

$$\begin{array}{l} 01*, 10*, 11* \\ 01*, 1*0, 1*1 \\ *10, *01, *11 \\ *10, 0*1, 1*1 \end{array}$$

In each of them, F is reducible. Therefore y_β must be the negation of x_α . However, this implies that $x_0 = x_1$, contradicting irreducibility. \square

In contrast, there does exist an irreducible $(6, 4)$ -homogeneous subcube partition.

Lemma 57. *There exists an irreducible $(6, 4)$ -homogeneous subcube partition.*

Proof. Here is such a subcube partition:

$$\begin{array}{l} 0000**, 001**1, 01*01*, 01**00, 0*01*1, 0**110, *010*0, *0*100, \\ 1101**, 111**0, 10*11*, 10**01, 1*00*0, 1**011, *111*1, *1*001. \end{array} \quad \square$$

Computer search reveals that up to permutation and flipping of coordinates, the irreducible $(6, 4)$ -homogeneous subcube partition is unique.

2.8.4 More infinite families

In this section we show how any irreducible homogeneous subcube partition gives rise to an infinite family.

Lemma 58. *Let $k \geq 2$. If there exists an irreducible (n, k) -homogeneous subcube partition then there exists an irreducible $(3n, 2k)$ -homogeneous subcube partition.*

Proof. Let F be an irreducible (n, k) -homogeneous subcube partition. We start by observing that for each coordinate i , there must be some subcube $s \in F$ with $s_i = *$. Otherwise, the union of the subcubes $s \in F$ with $s_i = 0$ will be $*^{i-1}0*^{n-i}$, which contradicts irreducibility.

Repeat the following operation n times to F : apply Lemma 47, and rotate the result twice to the right (equivalently, replace $t* \in F$ with $***t$ and $tb \in F$ with $b*0t, *b1t$, where $b \neq *$). The observation in the preceding paragraph ensures that the resulting subcube partition G is tight and irreducible. By construction, G has length $n + 2n = 3n$ and codimension $k + k = 2k$. \square

Applying this to the results of Section 2.8.3, we obtain the following infinite families.

Corollary 59. *For every $t \geq 0$ and every $n \geq 4$ other than $n = 5$ there exists an irreducible $(3^t \cdot n, 2^t \cdot (n - 1))$ -homogeneous subcube partition.*

For every $t \geq 0$ there exists an irreducible $(3^t \cdot 6, 2^t \cdot 4)$ -homogeneous subcube partition.

2.8.5 Codimension 3

Theorem 55 shows that an irreducible $(4, 3)$ -homogeneous subcube partition exists. In this section, we show that an irreducible $(n, 3)$ -homogeneous subcube partition exists only for $n = 4$, and that it is unique up to permutation and flipping of coordinates.

Theorem 60. *If there exists an irreducible $(n, 3)$ -homogeneous subcube partition then $n = 4$. Moreover, the irreducible $(4, 3)$ -homogeneous subcube partition is unique up to permutation and flipping of coordinates.*

Proof. Let F be an irreducible $(n, 3)$ -homogeneous subcube partition. We start by proving the following claims:

- (i) If $s \in F$ then $\bar{s} \in F$, where \bar{s} is obtained by flipping all bits in s .
- (ii) If $s \in F$ then s and \bar{s} are the only subcubes in F of the star pattern $P(s)$.
- (iii) Every two subcubes in F have at least two non-star coordinates in common.

Suppose that $s \in F$, without loss of generality $s = 000*^{n-3}$. Corollary 51 implies that F contains another subcube having the same star pattern but with opposite parity. Since F is irreducible, this cannot be one of $100*^{n-3}, 010*^{n-3}, 001*^{n-3}$, and so $111*^{n-3} \in F$, proving Item i. Irreducibility implies that no other subcube with the same star pattern can belong to F , proving Item ii. Any other subcube in F must conflict with both $000*^{n-3}$

and $111*^{n-3}$, hence must mention at least two coordinates among the first three, proving Item iii.

Suppose now without loss of generality that $000*^{n-3} \in F$. According to Item i, also $111*^{n-3} \in F$. According to Item ii, these are the only two subcubes with this star pattern. Hence F must contain a subcube s with a different star pattern. According to Item iii, the subcube s must mention at least two coordinates out of $\{1, 2, 3\}$. Since s must conflict with both $000*^{n-3}$ and $111*^{n-3}$, without loss of generality $s = 01*0*^{n-4} \in F$. According to Item i, also $10*1*^{n-4} \in F$, and according to Item ii, these are the only subcubes in F with this star pattern.

According to Item iii, every other subcube t in F must mention two coordinates out of $\{1, 2, 3\}$ and two coordinates out of $\{1, 2, 4\}$. If t mentions coordinates 1, 2 (and a third coordinate not in $\{3, 4\}$) then t cannot possibly conflict with all of $000*^{n-3}$, $111*^{n-3}$, $01*0*^{n-4}$, $10*1*^{n-4}$, and so t must mention either $\{1, 3, 4\}$ or $\{2, 3, 4\}$. Since F is tight, we deduce that $n = 4$.

According to Item ii, F contains precisely two subcubes mentioning $\{1, 3, 4\}$ and precisely two subcubes mentioning $\{2, 3, 4\}$. Moreover, in each pair, one of the subcubes is the negation of the other, according to Item i. The subcube of the form $0*ab$ must be $0*11$ in order to conflict with $000*$ and $01*0$, and so $0*11, 1*00 \in F$. Similarly, the subcube of the form $*0ab$ must be $*010$ in order to conflict with $000*$ and $10*0$, and so $*010, *101 \in F$. Since F contains eight subcubes, this completes the description of F , and so F is unique up to permutation and flipping of coordinates. \square

2.8.6 Codimension 4

Lemma 57 shows that an irreducible $(6, 4)$ -homogeneous subcube partition exists. Using techniques similar to the preceding section, in this section we show that an irreducible $(n, 4)$ -homogeneous subcube partition exists only for $n = 6$.

Theorem 61. *If there exists an irreducible $(n, 4)$ -homogeneous subcube partition then $n = 6$.*

Since the proof is a bit long, we break it into three parts, starting with the following lemma.

Lemma 62. *If F is an irreducible $(n, 4)$ -homogeneous subcube partition and $s, t \in F$ are two different subcubes, then s, t have at least two non-star coordinates in common.*

Proof. Let F be an irreducible $(n, 4)$ -homogeneous subcube partition. We start with the following observations:

- (i) If $u \in F$ then F contains another subcube with the same star pattern differing in exactly three coordinates.
- (ii) For every coordinate i , there is some $v \in F$ with $v_i = *$.

Let $u \in F$, say $u = 0000*^{n-4}$. According to Corollary 51, F must contain another subcube with the same star pattern and opposite parity. Since F is irreducible, this cannot be one of $1000*^{n-4}, 0100*^{n-4}, 0010*^{n-4}, 0001*^{n-4}$, implying Item i.

If all $v \in F$ satisfy $v_i \in \{0, 1\}$ then the union of all subcubes with $v_i = 0$ is the subcube $*^{i-1}0*^{n-i}$, hence $*^{i-1}0*^{n-i} \in F$ by irreducibility; but then F is not $(n, 4)$ -homogeneous. This proves Item ii.

Suppose, for the sake of contradiction, that F contains two subcubes s, t which share fewer than two non-star coordinates. Since s, t conflict, they have exactly one non-star coordinate in common. Without loss of generality, $s = 0000*^{n-4}$ and $t = ***1000*^{n-7}$. Applying Item i, F must contain one of $0111*^{n-4}, 1011*^{n-4}, 1101*^{n-4}, 1110*^{n-4}$. The only one of these which conflicts with t is $1110*^{n-4}$. Applying Item i to t , we similarly get that $***1111*^{n-7} \in F$. Thus F contains the following subcubes:

$$\begin{aligned} &0000*** *^{n-7} \\ &1110*** *^{n-7} \\ &***1000 *^{n-7} \\ &***1111 *^{n-7} \end{aligned}$$

According to Item ii with $i = 4$, the subcube partition F must contain a subcube v with $v_4 = *$. In order to conflict with the first two subcubes above, v must contain a 0 and a 1 in coordinates 1, 2, 3. In order to conflict with the latter two subcubes, it must contain a 0 and a 1 in coordinates 5, 6, 7. Without loss of generality, v is the following subcube:

$$01**01* *^{n-7}$$

Applying Item i to v , one of the following subcubes belongs to F :

$$\begin{aligned} &00**10* *^{n-7} \\ &11**10* *^{n-7} \\ &10**00* *^{n-7} \\ &10**11* *^{n-7} \end{aligned}$$

However, the i 'th subcube in this list fails to conflict with the i 'th subcube in the previous list, and we reach the desired contradiction. \square

We use Lemma 62 together with the following lemma to bound n .

Lemma 63. *Let F be an irreducible (n, k) -homogeneous subcube partition, where $n \geq 2$. Each coordinate is mentioned in at least six subcubes of F .*

Proof. We will show that the first coordinate is mentioned at least six times. For $\sigma \in \{0, 1, *\}$, let $F_\sigma = \{x : \sigma x \in F\}$. Since $F_0 \cup F_*$ and $F_1 \cup F_*$ are both subcube partitions, $\bigcup F_0 = \bigcup F_1$, and so $|F_0| = |F_1|$.

Lemma 17 shows that $|F_0| \geq 2$. If $|F_0| = 2$ then let $F_0 = \{s, t\}$ and $F_1 = \{s', t'\}$. Notice that $s \cup t = s' \cup t'$ and the union is not a subcube, since otherwise F would contain

$0s, 0t$ whose union is a subcube, contradicting irreducibility. Lemma 23 shows that either $\{s, t\} = \{s', t'\}$ or s, t are an nfs-pair (in some order). In the former case, F contains $0s, 1s$, contradicting irreducibility. The latter case is impossible by homogeneity, since the two subcubes in an nfs-pair have different dimensions. \square

We can now prove the theorem.

Proof of Theorem 61. Let F be an irreducible $(n, 4)$ -homogeneous subcube partition. Suppose without loss of generality that $0000*^{n-4} \in F$. According to Lemma 62, every other subcube in F mentions at most two coordinates beyond the first four, and so at most $2 \cdot 15/6 = 5$ of these are mentioned at least six times. Lemma 63 implies that $n \leq 4 + 5 = 9$.

We can slightly improve on this, as follows. Let $u^{(1)}, u^{(2)}, u^{(3)}, u^{(4)}$ be the subcubes containing the points $10000^{n-4}, 01000^{n-4}, 00100^{n-4}, 00010^{n-4}$, respectively. Each of these subcubes must be different. Indeed, if for example $u^{(1)} = u^{(2)}$ then $u^{(1)} \supseteq 10000^{n-4} \vee 01000^{n-4} = **000^{n-4}$, which intersects with $0000*^{n-4}$.

Any two of $u^{(1)}, u^{(2)}, u^{(3)}, u^{(4)}$ must conflict, and so for distinct $i, j \in \{1, \dots, 4\}$, either $u_j^{(i)} = 0$ or $u_i^{(j)} = 0$. This means that together, $u^{(1)}, u^{(2)}, u^{(3)}, u^{(4)}$ contain at least $\binom{4}{2} = 6$ zeroes among the first four coordinates. Therefore one of $u^{(1)}, u^{(2)}, u^{(3)}, u^{(4)}$ must contain at least $\lceil 6/4 \rceil = 2$ zeroes among the first two coordinates, and so mentions at most one coordinate beyond the first four.

This means that strictly fewer than $2 \cdot 15/6 = 5$ coordinates are mentioned at least six times, and so $n \leq 4 + 4 = 8$.

Recalling that $n \geq 5$ due to Lemma 50, we complete the proof of the theorem by checking with a computer that no irreducible $(n, 4)$ -homogeneous subcube partitions exist for $n = 5, 7, 8$. (The case $n = 5$ was also worked out by hand in Lemma 56.) \square

3 Nonbinary subcube partitions

So far we have considered subcube partitions of the hypercube $\{0, 1\}^n$. In this section, we study subcube partitions of $\{0, \dots, q-1\}^n$ for arbitrary $q \geq 2$.

Definition 64 (Subcube partition). A *subcube partition* of $\{0, \dots, q-1\}^n$ (or: a subcube partition *over* $\{0, \dots, q-1\}$ of length n) is a partition of $\{0, \dots, q-1\}^n$ into *subcubes*, which are sets of the form

$$\{x \in \{0, \dots, q-1\}^n : x_{i_1} = b_1, \dots, x_{i_d} = b_d\}.$$

We identify subcubes with words over $\{0, \dots, q-1, *\}$. The definitions of the following concepts are identical to the binary case: dimension and codimension of a subcube, point, edge, size (Definition 1); reducible subcube partition (Definition 2); tight subcube partition (Definition 3); conflicting subcubes (Definition 4).

Given a collection F of subcubes of $\{0, \dots, q-1\}^n$, we can determine whether they form a subcube partition using the criterion of Lemma 6, replacing 2 with q . Determining

whether a subcube partition of $\{0, \dots, q-1\}^n$ is tight is easy using the definition, and we can determine irreducibility using Algorithm 1.

We start our exploration of subcube partitions over $\{0, \dots, q-1\}$ in Section 3.1, where we show how to convert an irreducible subcube partition of $\{0, 1\}^n$ into an irreducible subcube partition of $\{0, \dots, q-1\}^n$.

We then study the minimal size of tight irreducible subcube partitions over $\{0, \dots, q-1\}$ in Section 3.2.

3.1 Expansion

In this section we show how to convert a subcube partition of $\{0, 1\}^n$ into a subcube partition of $\{0, \dots, q-1\}^n$ in a way which preserves tightness and irreducibility.

Lemma 65. *Let F be a subcube partition of $\{0, 1\}^n$, let $q \geq 2$, and let $\phi_1, \dots, \phi_n: \{0, \dots, q-1\} \rightarrow \{0, 1\}$ be surjective functions.*

*Extend the definitions of ϕ_1, \dots, ϕ_n to $\{0, \dots, q-1, *\}$ by defining $\phi_i(*) = *$. Define a function $\phi: \{0, \dots, q-1, *\}^n \rightarrow \{0, 1, *\}^n$ as follows: $\phi(\sigma_1 \dots \sigma_n) = \phi_1(\sigma_1) \dots \phi_n(\sigma_n)$. Let*

$$G = \{s \in \{0, \dots, q-1, *\}^n : \phi(s) \in F\}.$$

Then

(a) *G is a subcube partition of $\{0, \dots, q-1\}^n$.*

(b) *If F is tight then so is G .*

(c) *If F is irreducible then so is G .*

Proof. We start by showing that G is a subcube partition. Notice first that the subcubes in G are disjoint. Indeed, suppose that $s, s' \in G$ are distinct. If $\phi(s) = \phi(s')$ then s, s' must disagree on a non-star position, and so conflict. If $\phi(s) \neq \phi(s')$ then $\phi(s), \phi(s')$ conflict at some position i , and s, s' conflict at the same position.

In order to show that the subcubes in G cover all of $\{0, \dots, q-1\}^n$, let $x \in \{0, \dots, q-1\}^n$. Since F is a subcube partition, $\phi(x)$ is covered by some subcube $t \in F$. Define a subcube s as follows: if $t_i = *$ then $s_i = *$, and otherwise $s_i = x_i$. Then $\phi(s) = t$ and so $s \in G$, and s covers x by definition.

Now suppose that F is tight. Then for every $i \in [n]$ there is a subcube $t \in F$ mentioning i . Since ϕ is surjective, we can find a subcube s mentioning i such that $\phi(s) = t$. Hence $s \in G$, and so G also contains a subcube mentioning i . Hence G is tight.

Finally, suppose that F is irreducible. If G is reducible then there is a subset $H \subset G$, with $1 < |H| < |G|$, whose union is a subcube r . We claim that the union of $\phi(H) = \{\phi(s) : s \in H\}$ is the subcube $\phi(r)$.

Indeed, on the one hand, any $s \in H$ satisfies $s \subseteq r$ and so $\phi(s) \subseteq \phi(r)$, hence $\bigcup \phi(H) \subseteq \phi(r)$. On the other hand, let $x \in \phi(r)$ be an arbitrary point. Define a point $y \in \{0, \dots, q-1\}^n$ as follows: if $r_i = *$ then y_i is an arbitrary element of $\phi_i^{-1}(x_i)$, and

otherwise $y_i = r_i$; in the latter case, $\phi_i(y_i) = \phi_i(r_i) = x_i$. By construction, $y \in r$, and so y is covered by some $s \in H$. Since $\phi(y) = x$, it follows that $\phi(s)$ covers x .

Since F is irreducible, either $|\phi(H)| = 1$ or $|\phi(H)| = |F|$. In the latter case, $\phi(r) = *^n$ and so $r = *^n$, implying that $H = G$, contrary to assumption. In the former case, $\phi(s) = \phi(r)$ for all $s \in H$. Choose two distinct subcubes $s, s' \in H$. Let $i \in [n]$ be a coordinate at which s, s' conflict. Since $r \supseteq s \vee s'$ we have $r_i = *$, and so $\phi(r)_i = *$. On the other hand, $s_i, s'_i \neq *$, contradicting $\phi(s) = \phi(s') = \phi(r)$. \square

3.2 Minimal size

Section 2.3 studies the minimal size of a tight irreducible subcube partition of $\{0, 1\}^n$. In this section we extend this study to tight irreducible subcube partitions of $\{0, \dots, q-1\}^n$, asking: what is the minimal size of a tight irreducible subcube partition of $\{0, \dots, q-1\}^n$?

Applying Lemma 65 to the tight irreducible subcube partitions constructed in Theorem 31, we obtain a tight irreducible subcube partition of size $(n-1)q(q-1) + 1$. We conjecture that this is optimal.

Conjecture 66. If $n \geq 3$ then for all $q \geq 2$, the minimal size of a tight irreducible subcube partition of $\{0, \dots, q-1\}^n$ is $(n-1)q(q-1) + 1$.

We formally describe the matching construction in Section 3.2.1, where we also show that this is the minimal size that can be achieved by a direct application of Lemma 65, assuming Conjecture 14.

We prove Conjecture 66 for $n = 3$ in Section 3.2.2, where we also show that no tight irreducible subcube partition exists for $n = 2$. We have also verified the conjecture using a computer for $n = 4$ and $q \leq 6$, as well as for $n = 5$ and $q = 3$.

We close the section by proving a modest lower bound of $(q-1)n + 1$ on the size of a tight subcube partition of $\{0, \dots, q-1\}^n$, using the technique of Tarsi [AL86]. The lower bound applies more generally to tight minimal subcube covers, where it is sharp.

3.2.1 Construction

In this section we show how to construct tight irreducible subcube partitions of $\{0, \dots, q-1\}^n$ of size $(n-1)q(q-1) + 1$ using Lemma 65, and explain why this is the minimal possible size when using the lemma, assuming Conjecture 14. We start with the construction.

Theorem 67. For each $n \geq 3$ and $q \geq 2$ there exists a tight irreducible subcube partition of $\{0, \dots, q-1\}^n$ of size $(n-1)q(q-1) + 1$.

Proof. Theorem 31 constructs a tight irreducible subcube partition of $\{0, 1\}^n$ whose weight vector is $1, n-1, n-1, 0, \dots, 0$. Applying Lemma 65 with the mappings ϕ_i given by $\phi_i(0) = 0$ and $\phi_i(1) = \dots = \phi_i(q-1) = 1$ for all $i \in [n]$, we obtain a tight irreducible subcube partition of size

$$1 \cdot (q-1)^0 + (n-1) \cdot (q-1)^1 + (n-1) \cdot (q-1)^2 = (n-1)q(q-1) + 1. \quad \square$$

We now show that this construction is the optimal way of applying Lemma 65, assuming Conjecture 14.

Theorem 68. *Assume that Conjecture 14 holds for some $n \geq 3$. Let F be a tight irreducible subcube partition of $\{0, 1\}^n$. Let G be a subcube partition obtained by an application of Lemma 65 on F , for some $q \geq 2$. Then G has size at least $(n - 1)q(q - 1) + 1$.*

Proof. Let $g(z_1, \dots, z_n)$ be the size of G when Lemma 65 is applied with functions $\phi_1, \dots, \phi_n: \{0, \dots, q - 1\} \rightarrow \{0, 1\}$ such that $|\phi_i^{-1}(0)| = z_i$ for all $i \in [n]$. The function g is multilinear, and so its minimal value over $\{1, \dots, q - 1\}^n$ is attained at some $z \in \{1, q - 1\}^n$. Define a subcube partition F' by flipping all coordinates i such that $z_i = q - 1$. Then

$$|G| \geq g(z) = \sum_{s \in F'} (q - 1)^{\#_1(s)}.$$

Since F' is tight and irreducible, a combination of Theorem 30 and Lemma 27 shows that

$$|G| \geq \min(1 + (n - 1)(q - 1) + (n - 1)(q - 1)^2, 1 + n(q - 1) + (n - 3)(q - 1)^2 + (q - 1)^3).$$

If we subtract the first sum from the second then we obtain

$$(q - 1)^3 - 2(q - 1)^2 + (q - 1) = (q - 2)^2(q - 1) \geq 0,$$

and so the minimum equals the first sum. \square

3.2.2 Short length

In this section we characterize all tight irreducible subcube partitions of $\{0, \dots, q - 1\}^n$ for $q \geq 2$ and $n \leq 3$.

It is easy to see that the unique tight irreducible subcube partition of $\{0, \dots, q - 1\}^1$ is $\{0, \dots, q - 1\}$. In contrast, there is no tight irreducible subcube partition of $\{0, \dots, q - 1\}^2$.

Lemma 69. *There are no tight irreducible subcube partitions of $\{0, \dots, q - 1\}^2$ for any $q \geq 2$.*

Proof. Let F be a tight subcube partition of $\{0, \dots, q - 1\}^2$. If all subcubes in F are points then F is clearly reducible. Otherwise, without loss of generality $0* \in F$. For every $a \in \{1, \dots, q - 1\}$, let $F_a \subset F$ consist of all subcubes of F starting with a . Since F is tight, $F_a \neq \{a*\}$ for some a . Since $\bigcup F_a = a*$, it follows that F is reducible. \square

Kullmann and Zhao [KZ16, Lemma 41] showed that there is a unique tight irreducible subcube partition of $\{0, 1\}^3$, up to flipping coordinates. An analogous result holds for all $q \geq 2$.

Lemma 70. *Every tight irreducible subcube partition of $\{0, \dots, q - 1\}^3$, for any $q \geq 2$, can be obtained from $S_3 = \{000, 01*, 1*0, *01, 111\}$ by Lemma 65.*

Proof. Let G be a tight irreducible subcube partition of $\{0, \dots, q-1\}^3$. Since G is tight, $*** \notin G$. Furthermore, no subcube in G contains two stars. Indeed, suppose that $0** \in G$. Then for all $a \in \{1, \dots, q-1\}$, the subcubes in G starting with a together cover $a**$. Since G is irreducible, we see that $G = \{a** : a \in \{0, \dots, q-1\}\}$, contradicting tightness.

Let $A(\cdot?*)$ denote the projection of all subcubes of G of the form $??*$ to the first coordinate, and define other A -sets analogously.

If $A(\cdot?*) = \emptyset$ then no subcube of G ends with $*$. Therefore the subcubes ending with $b \in \{0, 1, 2\}$ cover all of $**b$. Since G is irreducible, $**b \in G$, which is impossible. Therefore $A(\cdot?*) \neq \emptyset$.

We claim that $A(\cdot?*)$ and $A(*?*)$ are disjoint. Indeed, if $a \in A(\cdot?*) \cap A(*?*)$, then $ab*, a*c \in G$ for some $b, c \in \{0, 1, 2\}$, which is impossible since these subcubes intersect.

We claim that if $a \in A(\cdot?*)$ and $b \in A(*?*)$ then $ab* \in G$. Indeed, suppose that $ab', a'b* \in G$ but $ab* \notin G$. Consider a point $abc \in \{0, \dots, q-1\}^3$. This point cannot be covered by $a*c$ since this subcube does not conflict with $ab'*$, and cannot be covered by $*bc$ since this subcube does not conflict with $a'b*$. Therefore $abc \in G$. Since this holds for all c and $\bigcup_c abc = ab*$, we get a contradiction with the irreducibility of G .

It follows that G is composed of points and edges, where the edges are

$$\begin{aligned} & \{ab* : a \in A(\cdot?*), b \in A(*?*)\} \\ & \cup \{a*c : a \in A(\cdot?*), c \in A(*?*)\} \\ & \cup \{*bc : b \in A(*?*), c \in A(*?*)\}. \end{aligned}$$

We claim that $A(\cdot?*) \cup A(*?*) = \{0, \dots, q-1\}$, and so these two sets partition $\{0, \dots, q-1\}$. Indeed, suppose that a is contained in neither set. Let $b \in A(\cdot?*)$, so that $b \notin A(*?*)$. By construction, points of the form abc are not covered by any of the edges of G , hence all of them belong to G . Since $\bigcup_c abc = ab*$, this contradicts the irreducibility of G .

It follows that G can be obtained by applying Lemma 65 to S_3 with the mappings

$$\phi_1(a) = 1 \leftrightarrow a \in A(*?), \quad \phi_2(b) = 1 \leftrightarrow b \in A(?*), \quad \phi_3(c) = 1 \leftrightarrow c \in A(*?).$$

Indeed, the edges of G are

$$\begin{aligned} & \{ab* : \phi_1(a) = 0, \phi_2(b) = 1\} \\ & \cup \{a*c : \phi_1(a) = 1, \phi_3(c) = 0\} \\ & \cup \{*bc : \phi_2(b) = 0, \phi_3(c) = 1\}, \end{aligned}$$

and these cover all points $abc \in \{0, \dots, q-1\}^3$ other than the ones satisfying $\phi_1(a) = \phi_2(b) = \phi_3(c)$. \square

Corollary 71. *Conjecture 66 holds for $n = 3$ and all $q \geq 2$.*

Proof. Let G be a tight irreducible subcube partition of $\{0, \dots, q-1\}^3$, where $q \geq 2$. According to the lemma, it can be obtained by applying Lemma 65. The result now follows from Theorem 68, since it is known that all tight irreducible subcube partitions of $\{0, 1\}^3$ have size 5. \square

When $n \geq 4$, not all tight irreducible subcube partitions are obtained via Lemma 65. Here is an example:

0000, 0002, 0020, 0022, 0101, 0102, 0111, 0122, 0200, 0201, 0211, 0220, 1010, 1011, 1020, 1021, 1102, 1110, 1120, 1122, 1201, 1202, 1211, 1212, 2011, 2012, 2021, 2022, 2110, 2111, 2200, 2212, 2220, 2222, 2100, 2101, 01*0, 02*2, 0*21, 10*2, 11*1, 1*00, 20*0, 22*1, 2*02, 001*, 122*, 212*, *001, *112, *210.

This is a tight irreducible subcube partition of $\{0, 1, 2\}^4$. The underlined subcubes show that it cannot be obtained by applying Lemma 65, since both 001, 122, 212 and 001, 112, 210 are not product sets.

3.2.3 Lower bound

Theorem 15 gives our best lower bound on the size of a tight irreducible subcube partition of $\{0, 1\}^n$, slightly improving on the “trivial” lower bound of $n + 1$ which follows from the well-known lemma of Tarsi [AL86] on minimally unsatisfiable CNFs.

Tarsi’s lemma applies more generally to subcube covers.

Definition 72 (Subcube cover). A *subcube cover* of $\{0, \dots, q - 1\}^n$ is a collection of subcubes whose union is $\{0, \dots, q - 1\}^n$.

A subcube cover is *minimal* if no proper subset of it is a subcube cover.

In this language, Tarsi’s lemma states that a tight minimal subcube cover of $\{0, 1\}^n$ has size at least $n + 1$. This bound is achieved, for example, by the subcube partition

$$\{0^i 1 *^{n-i-1} : 0 \leq i \leq n - 1\} \cup \{0^n\}.$$

The analogous subcube partition for arbitrary $q \geq 2$ is

$$\{0^i b *^{n-i-1} : 0 \leq i \leq n - 1, 1 \leq b \leq q - 1\} \cup \{0^n\},$$

which has size $(q - 1)n + 1$.

In this section, we generalize Tarsi’s lemma to the setting of matroids. A special case of our generalization shows that every tight minimal subcube cover of $\{0, \dots, q - 1\}^n$ (and so every tight subcube partition of $\{0, \dots, q - 1\}^n$) has size at least $(q - 1)n + 1$, proving the optimality of the above construction.

There are several proofs of Tarsi’s lemma [AL86, CS88, ML97, DDKB98, Kul00, BET01]. We generalize the well-known proof using Hall’s theorem.

Definition 73 (Cover). Let M be a matroid. A collection F of subsets of the ground set of M is an M -*cover* if no basis of M intersects all sets in F . An M -cover is *minimal* if no proper subset is an M -cover.

Theorem 74 (Generalized Tarsi’s lemma). *Let M be a matroid with rank function r . Every minimal M -cover F satisfies*

$$|F| > r\left(\bigcup F\right).$$

The statement might look opaque, so before proving the theorem, we first show how it can be used to derive the lower bound $(q-1)n+1$.

Theorem 75. *Every tight minimal subcube cover of $\{0, \dots, q-1\}^n$, where $n \geq 1$ and $q \geq 2$, has size at least $(q-1)n+1$.*

Proof. Let $H(n, q)$ be the matroid over the ground set $[n] \times \{0, \dots, q-1\}$ in which a set is independent if for every $i \in [n]$, it doesn't contain all elements of the form $(i, ?)$. A basis of $H(n, q)$ is any set of the form $B(a_1, \dots, a_n) := \{(i, j) : i \in [n], j \in [q], j \neq a_i\}$, where $a_1, \dots, a_n \in \{0, \dots, q-1\}$.

Let F be a tight minimal subcube cover of $\{0, \dots, q-1\}^n$. We can represent every subcube in $s \in F$ as the following subset of the ground set of $H(n, q)$:

$$\phi(s) = \{(i, s_i) : i \in [n], s_i \neq *\}.$$

Let $\phi(F) = \{\phi(s) : s \in F\}$. We claim that $\phi(F)$ is an $H(n, q)$ -cover. Indeed, let $B(a_1, \dots, a_n)$ be any basis of $H(n, q)$. Since F is a subcube cover, the point $a_1 \dots a_n$ is covered by some subcube s . If $(i, s_i) \in \phi(s)$ then $s_i = a_i$, and so $\phi(s)$ is disjoint from $B(a_1, \dots, a_n)$.

A similar argument shows that $\phi(F)$ is a minimal $H(n, q)$ -cover. Indeed, any proper subset of $\phi(F)$ has the form $\phi(G)$ for some proper subset $G \subset F$. Since F is a minimal subcube cover, some point $a_1 \dots a_n$ is not covered by G . The corresponding basis $B(a_1, \dots, a_n)$ intersects all sets in $\phi(G)$. Indeed, if $\phi(s) \in \phi(G)$ then s doesn't cover a , and so $s_i \neq a_i, *$ for some $i \in [n]$. Consequently, $\phi(s)$ contains $(i, s_i) \in B(a_1, \dots, a_n)$.

Since $\phi(F)$ is a minimal $H(n, q)$ -cover, Theorem 74 shows that $|F| = |\phi(F)|$ exceeds the rank of $\bigcup \phi(s)$. We will show that $\bigcup \phi(s) = [n] \times \{0, \dots, q-1\}$, a set whose rank is $(q-1)n$, completing the proof.

Let $i \in [n]$. Since F is tight, some subcube $s \in F$ mentions i . Since F is minimal, there exists a point $x \in \{0, \dots, q-1\}^n$ which is only covered by s . In particular, no subcube of F contains $x^{i \rightarrow *}$, the subcube obtained from x by changing the i 'th coordinate to a star. This implies that for every $b \in \{0, \dots, q-1\}$, every subcube of F containing $x^{i \rightarrow b}$ must contain b in its i 'th coordinate. Therefore $\bigcup \phi(F)$ contains all elements of the form (i, b) , for any $b \in \{0, \dots, q-1\}$, as promised. \square

The proof of Theorem 74 uses a generalization of Hall's theorem to matroids.

Proposition 76 (Hall–Rado [Rad67, Wel71]). *Let M be a matroid with rank function r , and let F be a collection (multiset) of subsets of the ground set of M .*

If each subset $G \subseteq F$ satisfies $|G| \leq r(\bigcup G)$ then we can choose an element e_s from each set $s \in F$ such that the elements e_s are distinct, and $\{e_s : s \in F\}$ is an independent set of M .

We can now prove Theorem 74.

Proof of Theorem 74. Let F be a minimal M -cover, and suppose that $|F| \leq r(\bigcup F)$. We will show that this assumption leads to a contradiction.

If every subset $G \subseteq F$ satisfies $|G| \leq r(\bigcup G)$ then Proposition 76 shows that F intersects the independent set $\{e_s : s \in F\}$. Since every independent set can be completed to a basis, this contradicts the assumption that F is an M -cover.

We conclude that some subset $G \subset F$ satisfies $|G| > r(\bigcup G)$. Among all such subsets, choose one which is inclusion-maximal. By assumption, $G \neq F$, and so by minimality, G is not an M -cover, say the basis B intersects all sets in G .

Let $M' = M / \bigcup G$ be the contraction of M by $\bigcup G$. The ground set of M' is the ground set of M with $\bigcup G$ removed, and its rank function is $r'(S') = r(S' \cup \bigcup G) - r(\bigcup G)$.

Let $F' = \{S \setminus \bigcup G : S \in F \setminus G\}$. Suppose that H' is a non-empty subset of F' , say $H' = \{S \setminus \bigcup G : S \in H\}$. Since G is inclusion-maximal,

$$\begin{aligned} r'(H') &= r\left(\bigcup H' \cup \bigcup G\right) - r\left(\bigcup G\right) = r\left(\bigcup (H \cup G)\right) - r\left(\bigcup G\right) \\ &> |H \cup G| - |G| = |H| = |H'|. \end{aligned}$$

Applying Proposition 76, we obtain a basis B' of F' which intersects all sets in F' , and so all sets in $F \setminus G$.

The set $B \cap \bigcup G$ is an independent subset of $\bigcup G$. Complete it to a basis B_G of $M|_{\bigcup G}$. Since B' is a basis of M' , $B' \cup B_G$ is a basis of M . By construction, B intersects all subsets in F , contradicting the assumption that F is an M -cover. \square

4 Affine vector space partitions

Section 2 considers partitions of $\{0, 1\}^n$ into subcubes. In this section, we consider partitions of $\{0, 1\}^n$ into affine subspaces. The companion work [BFIK23] considers the more general case of partitions of \mathbb{F}_q^n into affine subspaces.

Definition 77 (Affine vector space partition). An *affine vector space partition* of length n is a partition of $\{0, 1\}^n$ into *affine subspaces*, that is, sets of the form $x + V$, where $x \in \{0, 1\}^n$ and V is a subspace of $\{0, 1\}^n$ (identified with \mathbb{F}_2^n). The *size* of an affine vector space partition is the number of affine subspaces.

The *linear part* of an affine subspace $U = x + V$ is the subspace V . The *dimension* of an affine subspace is the dimension of its linear part, and codimension is defined analogously.

The notion of reducibility is defined just as in Definition 2 and Definition 18, replacing *subcube* with *affine subspace*.

Definition 78 (Reducibility). A collection F of disjoint affine subspaces of $\{0, 1\}^n$ is *reducible* if there exists a subset $G \subseteq F$, with $|G| > 1$, whose union is an affine subspace of $\{0, 1\}^n$ other than $\{0, 1\}^n$. If no such G exists then F is *irreducible*.

The definition of tightness is perhaps less obvious. A subcube partition of length n is not tight if it arises from a subcube partition of length $n - 1$ via an embedding of

$\{0, 1\}^{n-1}$ inside $\{0, 1\}^n$. If this is the case, then there is a direction i which is “ignored” by all subcubes, in the sense that $s_i = *$. This definition generalizes to our setting, where an affine subspace $x + V$ “ignores” a direction $y \in \{0, 1\}^n \setminus \{0^n\}$ if $y \in V$. The same definition was proposed by Agievich [Agi08], under the name *primitivity*, and was dubbed *A-primitivity* by Tarannikov [Tar22].

Definition 79 (Tightness). An affine vector space partition F of length n is *tight* if the intersection of the linear parts of all affine subspaces in F is $\{0^n\}$.

We can determine whether two affine subspaces intersect by solving linear equations. Using this, we can determine whether a collection of affine subspaces forms an affine vector space partition as in Lemma 6, by checking that

$$\sum_s 2^{-\text{codim}(s)} = 1.$$

We can check tightness using the definition, and irreducibility using Algorithm 1, suitably generalized. For this we need to be able to compute the join of two affine subspaces, which is the minimal affine subspace containing their union.

Lemma 80. *The minimal affine subspace containing $a + V$ and $b + W$ is $a + \text{span}(V, W, b - a)$.*

We leave the straightforward proof to the reader.

We commence the study of affine vector space partitions in Section 4.1, where we show how to convert an irreducible subcube partition to an irreducible affine vector space partition. We use this technique in Section 4.2 to construct tight irreducible affine vector space partitions of length n and size $\frac{3}{2}n - O(1)$. In the same section we also prove a lower bound of $n + 1$ on the size of a tight irreducible affine vector space partition of length n .

4.1 Compression

Every subcube partition of length n can be viewed as an affine vector space partition of length n . Furthermore, if the subcube partition is tight, then so is the affine vector space partition. However, irreducibility is not maintained in this conversion. For example,

$$000, 111, 01*, 1*0, *01$$

is irreducible as a subcube partition but reducible as an affine vector space partition, since $000 \cup 111$ is an affine subspace, which we can represent by aaa . If we merge these two points, we get the tight irreducible affine vector space partition

$$aaa, 01*, 1*0, *01.$$

In this section we generalize this process of merging for arbitrary irreducible subcube partitions, using the concept of *star pattern* introduced in Definition 10: the star pattern of a subcube $s \in \{0, 1, *\}^n$ is $P(s) := \{i \in [n] : s_i = *\}$.

Lemma 81. *Let F be an irreducible subcube partition. For $S \subseteq [n]$, let F_S consist of all subcubes in F whose star pattern is S . For each $S \subseteq [n]$, choose a partition of F_S in which the union of each part is an affine subspace, and let G_S be the corresponding collection of affine subspaces. (If $F_S = \emptyset$, take $G_S = \emptyset$.)*

If all G_S are irreducible then $G = \bigcup_S G_S$ is also irreducible.

Proof. If G is reducible then there exists a subset $G' \subset G$, with $|G'| > 1$, whose union is an affine subspace U other than $\{0, 1\}^n$. Each affine subspace in G' is a union of subcubes of F . Let F' be the collection of all such subcubes, so that $\bigcup F' = U$.

If F' contains a subcube s with $s_i = *$ then according to Lemma 80, the linear part of U contains $0^{i-1}10^{n-i}$. This motivates defining S as the set of coordinates $i \in [n]$ such that $s_i = *$ for some $s \in F'$. Note that $S \neq [n]$, since otherwise $U = \{0, 1\}^n$.

Let $U|_{\bar{S}}$ be the projection of U into the coordinates outside of S , so that

$$U = \{x \in \{0, 1\}^n : x|_{\bar{S}} \in U|_{\bar{S}}\}.$$

Let $y \in U|_{\bar{S}}$. Every $x \in \{0, 1\}^n$ such that $x|_{\bar{S}} = y$ is covered by some subcube $s \in F'$. The definition of S implies that $s_i = y_i$ for all $i \in \bar{S}$. Consequently the union of all subcubes $s \in F'$ such that $s|_{\bar{S}} = y$ is the subcube $s_y := \{x \in \{0, 1\}^n : x|_{\bar{S}} = y\}$. Since F is irreducible, $s_y \in F$ and so $s_y \in F'$. Since $s_y \in F_S$, it follows that $F' \subseteq F_S$, and so $G' \subseteq G_S$. This contradicts the irreducibility of G' . \square

In general, F being tight doesn't guarantee that G is tight. For example, applying Lemma 81 to the tight subcube partition

$$*000, *111, 001*, 0*01, 01*0, 110*, 1*10, 10*1$$

results in the non-tight affine vector space partition

$$*aaa, aa\bar{a}*, a*a\bar{a}, a\bar{a}*a,$$

in which all linear parts contain the non-zero vector 1111.

The following lemma is a simplification of Lemma 81 which also includes a criterion for tightness.

Lemma 82. *Let F be an irreducible subcube partition. For $S \subseteq [n]$, let F_S consist of all subcubes in F whose star pattern is S .*

Suppose that whenever F_S is non-empty, the union of all subcubes in F_S is an affine subspace g_S (this is always the case when $|F_S| \leq 2$). Then $G = \{g_S : F_S \neq \emptyset\}$ is an irreducible affine vector space partition.

Furthermore, G is tight if

$$\bigcap_{S: F_S \neq \emptyset} P\left(\bigvee_{F_S} F_S\right) = \emptyset, \quad (1)$$

where the join is taken in the sense of subcubes.

Proof. The irreducibility of G follows directly from Lemma 81. Indeed, if for every non-empty F_S we take the partition consisting of a single part then the affine vector space partition G in this lemma coincides with that in Lemma 81. Moreover, if $F_S = \{a\}$ then a is itself an affine subspace, and if $F_S = \{a, b\}$ then $a \cup b$ is the affine subspace obtained from a by adding the following vector to the linear part: $v_i = 1$ if $a_i \neq b_i$ and $v_i = 0$ otherwise.

We proceed to show that if Equation (1) holds then G is tight. Let $S \subseteq [n]$ be such that F_S is non-empty. If $i \notin P(\bigvee F_S)$ then all $x \in g_S$ have the same value of x_i , and so $y_i = 0$ for all y in the linear part of g_S . Therefore if $y_i = 1$ for some y in the linear part of g_S then $i \in P(\bigvee F_S)$. Equation (1) thus guarantees that the only vector in the intersection of the linear parts of all g_S is the zero vector, and so G is tight. \square

4.2 Minimal size

In Section 2.3 we conjectured that the minimal size of a tight irreducible subcube partition of length n is $2n - 1$. Using a computer, we have determined the minimal size of a tight irreducible affine vector space partition of length n for small n [BFIK23]:

n	3	4	5	6	7
scp	5	7	9	11	13
avsp	4	6	7	8	10

The first row is the minimal size of a tight irreducible subcube partition of length n , and the second row is the minimal size of a tight irreducible affine vector space partition of length n .

The constructions presented later in this section suggest the following conjecture.

Conjecture 83. The minimal size of a tight irreducible affine vector space partition is $\frac{3}{2}n - o(n)$.

We give a matching construction in Section 4.2.2. The best lower bound we are aware of is $n + 1$, which we prove in Section 4.2.1 using an argument similar to the proof of Theorem 74.

4.2.1 Lower bound

In this section, we adapt the proof of Theorem 74 to the setting of affine vector space partitions.

Theorem 84. *Every tight affine vector space partition of length $n \geq 1$ has size at least $n + 1$.*

As in Theorem 75, the lower bound holds more generally for every tight minimal affine vector space cover, a concept we do not define formally.

Proof. Let M be the matroid over $\{0, 1\}^n$ in which a subset is independent if it is linearly independent, and let r be its rank function.

Suppose that F a tight irreducible affine vector space partition of length $n \geq 1$, and let $\mathbf{F} = \{V^\perp : x + V \in F\}$ (which we consider as a multiset).

We claim that $r(\mathbf{F}) = n$. Indeed, since F is tight,

$$\text{span}(\{V^\perp : x + V \in F\}) = \left(\bigcap \{V : x + V \in F\} \right)^\perp = \{0^n\}^\perp = \{0, 1\}^n,$$

and so $r(\mathbf{F}) = n$.

Suppose that every $\mathbf{G} \subseteq \mathbf{F}$ satisfies $|\mathbf{G}| \leq r(\bigcup \mathbf{G})$. According to Proposition 76, we can choose an element $y_{x+V} \in V^\perp$ for each $x + V \in F$ such that the elements y_{x+V} form an independent set. In particular, we can find an element $z \in \{0, 1\}^n$ such that $\langle z, y_{x+V} \rangle \neq \langle x, y_{x+V} \rangle$ for all $x + V \in F$. By construction, $z \notin x + V$ for all $x + V \in F$, contradicting the assumption that F is an affine vector space partition.

It follows that there exists some subset $\mathbf{G} \subseteq \mathbf{F}$ satisfying $|\mathbf{G}| > r(\bigcup \mathbf{G})$. Among all such subsets, choose one which is inclusion-maximal. If $\mathbf{G} = \mathbf{F}$ then we are done, so suppose that $\mathbf{G} \neq \mathbf{F}$. Since \mathbf{F} is an affine vector space partition, there is a point z_0 which is not covered by any subspace in \mathbf{G} .

Let $M' = M/\text{span}(\mathbf{G})$, and let r' be its rank function. Let $\mathbf{F}' = \{V^\perp \setminus \text{span}(\mathbf{G}) : V^\perp \in \mathbf{F} \setminus \mathbf{G}\}$. If $\mathbf{G}' \subseteq \mathbf{F}'$ then

$$r'(\mathbf{G}') = r(\mathbf{G}' \cup \text{span}(\mathbf{G})) - r(\text{span}(\mathbf{G})) = r(\mathbf{G}' \cup \mathbf{G}) - r(\mathbf{G}) > |\mathbf{G}' \cup \mathbf{G}| - |\mathbf{G}| = |\mathbf{G}'|,$$

using the inclusion-maximality of \mathbf{G}' . Hence Proposition 76 allows us to choose $y'_{x+V} \in V^\perp \setminus \text{span}(\mathbf{G})$ for all $x + V \in F \setminus G$ such that these vectors are independent in M' , which means that no linear combination of them lies in $\text{span}(\mathbf{G})$ (and in particular, they are linearly independent).

Let z be a point such that $\langle z, y'_{x+V} \rangle \neq \langle x, y'_{x+V} \rangle$ for all $x + V \in F \setminus G$ and $\langle z, y \rangle = \langle z_0, y \rangle$ for all $y \in \text{span}(\mathbf{G})$. By construction, z is not covered by any of the subspaces of $F \setminus G$. It is also not contained in any $x + V \in G$, since $x + V = \{w : \langle w, y \rangle = \langle x, y \rangle \text{ for all } y \in V^\perp\}$ and $\langle z, y \rangle = \langle z_0, y \rangle$ for all $y \in V^\perp$ (recalling that z_0 is not covered by G). This contradicts the assumption that F is an affine vector space partition. \square

It is tempting to conjecture a common generalization of Theorem 75 and Theorem 84, namely that a tight affine vector space partition of \mathbb{F}_q^n has size at least $(q - 1)n + 1$. Unlike Theorem 75 and Theorem 84, this cannot be true for tight minimal affine vector space covers for $q \geq 4$ (hence, the proof above cannot generalize): we can construct tight minimal affine vector space covers of size $(q - 1)(n - 3) + \frac{3}{2}(q + 1) - 1$ for q odd, and we can construct tight minimal affine vector space covers of size $(q - 1)(n - 3) + q + q/p$ for $q = p^h$, where p is a prime. These constructions derive from the two examples of minimal blocking sets in a projective plane described in [BB86]. We leave the details for elsewhere.

4.2.2 Construction

In this section, we construct tight irreducible affine vector space partitions of length n and size $\frac{3}{2}n - O(1)$ for all $n \geq 3$, using Lemma 82. To construct the underlying subcube

partitions, we use an inductive approach in the style of the constructions in Sections 2.3 and 2.4.

Lemma 85. *Let F, H be irreducible subcube partitions of length $n \geq 2$ satisfying the following conditions, where F_S consists of all subcubes in F whose star pattern in S :*

- (i) $\{s \in F : s_1 = *\} = \{s \in H : s_1 = *\}$.
- (ii) $|F_S|, |H_S| \leq 2$ for all S .
- (iii) Equation (1) holds for H .

Let $m = m(H)$ be the number of star patterns S such that H_S is non-empty, and let $m' = m'(H)$ be the number of those star patterns where $1 \notin S$ (that is, the first coordinate is not a star).

For every $k \geq 0$ there exists a tight irreducible affine vector space partition of length $n + 2k$ and size $m + km'$.

Proof. For $N \geq 0$, let $F *^N = \{s *^N : s \in F\}$, and define $*^N F$ similarly.

Let $F^* = \{s \in \{0, 1\}^{n-1} : *s \in F\}$. If F^* is empty then the union of the subcubes starting with $b \in \{0, 1\}$ is $b *^{n-1}$. Since F is irreducible, $F = \{0 *^{n-1}, 1 *^{n-1}\}$. However, this contradicts Equation (1), using $n \geq 2$. Therefore F^* is non-empty.

We will construct an infinite sequence of subcube partitions $F^{(k)}$ such that the following hold:

- (i) $F^{(k)}$ is an irreducible subcube partition of length $n + 2k$.
- (ii) $F^* *^{2k+1} \subseteq F^{(k)}$.
- (iii) Subcubes in $F^* *^{2k+1}$ have different star patterns from subcubes in $F^{(k)} \setminus F^* *^{2k+1}$.
- (iv) $|F_S^{(k)}| \leq 2$ for all S .
- (v) $m(F^{(k)}) = m + km'$.
- (vi) Equation (1) holds for $F^{(k)}$.

The result then follows by applying Lemma 82 to $F^{(k)}$.

The starting point is $F^{(0)} = \{sa : as \in H, |a| = 1, |s| = n - 1\}$. By assumption, $F^{(0)}$ is irreducible and $F^* * = H^* *$. By construction, $F^* * \subseteq F^{(0)}$, and all subcubes in $F^{(0)} \setminus F^* *$ end with a non-star. The remaining properties are by assumption.

Given $F^{(k)}$, we construct $F^{(k+1)}$ as follows. Apply Lemma 19 with $F_0 = *F^{(k)}$ and $F_1 = F^* *^{2k+1}$ to obtain a subcube partition $G^{(k)}$. We define $F^{(k+1)} = \{tab : abt \in G^{(k)}, |a| = |b| = 1, |t| = n + 2k\}$. Since $F^* *^{2k+1} \subseteq F^{(k)}$, we can explicitly write

$$F^{(k+1)} = \{t** : t \in F^* *^{2k+1}\} \cup \{t0* : t \in F^{(k)} \setminus F^* *^{2k+1}\} \cup \{t1b : bt \in F^* *^{2k+1}, b \neq *\}.$$

We now verify the properties of $F^{(k+1)}$ one by one:

- (i) By the induction hypothesis, $F^* *^{2k+1} \subseteq F^{(k)}$, and so $*F^* *^{2k+1} \subseteq *F^{(k)}$. Since F^* is non-empty, $F_0 \cap F_1 = *F^* *^{2k+1}$ is non-empty. Therefore Lemma 19 shows that $G^{(k)}$ is irreducible, and it follows that $F^{(k+1)}$ is irreducible.
- (ii) The formula for $F^{(k+1)}$ immediately implies that $F^* *^{2k+3} \subseteq F^{(k+1)}$.
- (iii) The formula for $F^{(k+1)}$ shows that all $s \in F^{(k+1)} \setminus F^* *^{2k+3}$ satisfy $s_{n+2k+1} \neq *$, and so have different star patterns from any subcube in $F^* *^{2k+3}$.
- (iv) The subcubes in each of the three sets in the formula for $F^{(k+1)}$ have different star patterns. Since $|F_S^*| \leq 2$ for all S and $|F_S^{(k)}| \leq 2$ for all S , it follows that $|F_S^{(k+1)}| \leq 2$ for all S .
- (v) Denote the three parts in the formula for $F^{(k+1)}$ by A, B, C . Clearly $m(A) = m(F^*)$. Since the star patterns of the subcubes in $F^* *^{2k+1}$ are different from the star patterns of the subcubes in $F^{(k)} \setminus F^* *^{2k+1}$, we have $m(B) = m(F^{(k)}) - m(F^*)$. Finally, $m(C) = m'$. We conclude that $m(F^{(k+1)}) = m(F^{(k)}) + m' = m + (k+1)m'$.
- (vi) Since the star patterns of the subcubes in $F^* *^{2k+1}$ are different from the star patterns of the subcubes in $F^{(k)} \setminus F^* *^{2k+1}$, the induction hypothesis implies that the intersection of $P(\bigvee F_S)$ for all star patterns S appearing in $A \cup B$ is contained in $\{n+2k+1, n+2k+2\}$.

Equation (1) for F implies that some $s \in F$ satisfies $s_1 \neq *$, and so C is non-empty. All star patterns of subcubes in S do not contain $n+2k+1$ or $n+2k+2$, and so Equation (1) holds for $F^{(k+1)}$. \square

Using this lemma, we construct tight irreducible affine vector space partitions of length n and size $\frac{3}{2}n - O(1)$ for all $n \geq 3$. Our construction matches the optimal values in the table appearing in the beginning of the section.

Theorem 86. *For all odd $n \geq 3$ there is a tight irreducible affine vector space partition of length n and size $\frac{3}{2}n - \frac{1}{2}$.*

There is a tight irreducible affine vector space partition of length 4 and size 6.

For all even $n \geq 6$ there is a tight irreducible affine vector space partition of length n and size $\frac{3}{2}n - 1$.

Proof. Consider the following subcube partitions:

$$\begin{aligned} S_3 &= \{ *01, 000, 111, 1*0, 01* \}, \\ S_4 &= \{ *01*, 1000, 1111, 11*0, 1*01, 000*, 01** \}, \\ T_6 &= \{ *0110*, *1101*, *001*1, *010*0, *00**0, *0*0*1, \\ &\quad **111*, 011*0*, 110*1*, 010***, 11**0* \}. \end{aligned}$$

Using Algorithm 1, one can check that they are irreducible. One checks directly that the prerequisites of Lemma 85 hold in all cases (with $H = F$).

Since $m(S_3) = 4$ and $m'(S_3) = 3$, Lemma 85 with $F = H = S_3$ constructs tight irreducible affine subspace partitions of length $3 + 2k$ and size $4 + 3k = \frac{3}{2}(3 + 2k) - \frac{1}{2}$.

Applying Lemma 82 directly to S_4 , we obtain a tight irreducible affine subspace partition of length 4 and size 6.

Since $m(T_6) = 8$ and $m'(T_6) = 3$, Lemma 85 with $F = H = T_6$ constructs tight irreducible affine subspace partitions of length $6 + 2k$ and size $8 + 3k = \frac{3}{2}(6 + 2k) - 1$. \square

Applying Lemma 85 with $F = S_3^*$ and $H = S_4$ constructs tight irreducible affine subspace partitions of length $4 + 2k$ and size $6 + 3k = \frac{3}{2}(4 + 2k)$, which is slightly worse than what we get using $F = H = T_6$.

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