

Convex cycle bases

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Abstract

Convex cycles play a role e.g. in the context of product graphs. We introduce convex cycle bases and describe a polynomial-time algorithm that recognizes whether a given graph has a convex cycle basis and provides an explicit construction in the positive case. Relations between convex cycle bases and other types of cycle bases are discussed. In particular we show that if G has a unique minimal cycle basis, this basis is convex. Furthermore, we characterize a class of graphs with convex cycle bases that includes partial cubes and hence median graphs.

Keywords: cycle basis, convex subgraph, isometric subgraph, Cartesian product, partial cubes

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1 Introduction and basics

The cycle space $\mathcal{C}(G)$ of a simple, unweighted, undirected graph $G = (V, E)$ consists of all its Eulerian subgraphs (or generalized cycles), i.e., all the subgraphs of G for which every vertex has even degree. It is convenient in this context to interpret subgraphs of G as edge sets. The generalized cycles form a vector space over $\text{GF}(2)$ with vector addition $X \oplus Y := (X \cup Y) \setminus (X \cap Y)$ and scalar multiplication $1 \cdot X = X$, $0 \cdot X = \emptyset$, for $X, Y \in \mathcal{C}(G)$. This vector space is generated by the elementary cycles of G , i.e., the connected subgraphs of G for which every vertex has degree 2. A basis \mathcal{B} of the cycle space \mathcal{C} is called a *cycle basis* of $G = (V, E)$ [9]. The dimension of the cycle space is the *cyclomatic number* $\mu(G)$ (or *first Betti number*). For a connected graph we have $\mu(G) = |E| - |V| + 1$. Notice that the cycle space of a graph is the direct sum of the cycle spaces of its 2-connected components.

Cycle bases of graphs have diverse applications in science and engineering. Examples include structural flexibility analysis [27], electrical networks [11], chemical structure storage and retrieval systems [15], scheduling problems [36], graph drawing [33], and biopolymer structures [34, 35]. Surveys and extensive references can be found in [19, 22, 28, 37].

A convexity space (V, \mathfrak{C}) [6] consists of a ground set V and a set \mathfrak{C} of subsets of V satisfying

(C1) $\emptyset \in \mathfrak{C}$, $V \in \mathfrak{C}$, and

(C2) $K', K'' \in \mathfrak{C}$ implies $K' \cap K'' \in \mathfrak{C}$.

For a simple, undirected graph G with vertex set V , every set \mathfrak{P} of paths on G defines a convexity space $(V, \mathfrak{C}(\mathfrak{P}))$ in the following way: A set of vertices K is \mathfrak{P} -convex, $K \in \mathfrak{C}(\mathfrak{P})$, if and only if, for every path $P \in \mathfrak{P}$ with both end vertices in K , all vertices of P are contained in K . This construction is discussed in detail in [14]. Several special types of paths \mathfrak{P} have been studied in this context, most prominently the set of all paths [5], the set of all triangle paths [8], the set of all induced paths [13], and the set of all shortest paths [39].

We will be concerned here only with the latter definition of convexity, usually known as geodesic convexity, see Section 2 for a formal definition. Geodesically convex cycles play an important role in the theory of Cartesian graphs products and their isometric subgraphs. The absence of convex cycles longer than 4, for example, characterizes semi-median graphs [3]. Such long convex cycles furthermore play a role e.g. in Euler-type inequalities for partial cubes [31].

It appears natural, hence, to investigate whether there is a connection between the cycle space and the (geodesic) convexity space of a graph $G = (V, E)$. Note that the cycle space is defined on the edge set, while the convexity space is defined on the vertex set. Intuitively, this connection is made possible by the fact that induced elementary cycles in G are characterized by either their vertex sets or their edge sets.

Definition 1.1. A *convex cycle basis* of a graph G is a cycle basis that consists of convex elementary cycles.

We briefly consider a generalized definition of convex cycle bases relaxing the requirement for elementary basis cycles in the final section.

Cycle bases with special properties have been investigated in much detail in the literature. Examples include minimum cycle bases [2, 17, 19, 29, 44], (strictly) fundamental

cycle bases [20, 32, 38], or (quasi) robust cycle bases [26, 40]. Here, we consider *convex* cycle bases. We show that convex cycle bases are not related to other types of cycle bases, we introduce a polynomial-time algorithm to compute a convex cycle basis for an arbitrary input graph, and we construct a class of graphs with convex cycles bases by means of Cartesian products that in particular includes partial cubes.

2 Geodetic convexity and characterization of convex cycles

For a graph G we denote the vertex set and edge set of G by $V(G)$ and $E(G)$, respectively. Similarly, we write $\mathcal{C}(G)$ for the cycle space of G . An edge that joins vertices x and y is denoted by the unordered pair $\{x, y\}$. The lengths $|P|$ and $|C|$ of a path P and a cycle C in G , respectively, is the number of their edges. For simplicity, we will refer to a path with end vertices u and v as uv -path. The distance $\text{dist}_G(u, v)$ between two vertices u and v of G is the length of a shortest uv -path. It is well known that this distance forms a metric on V . The set of all shortest uv -paths will be denoted by $\mathbb{P}_G[u, v]$. The cardinality of this set, i.e., the number of shortest uv -paths, will be denoted by $S_{uv} = |\mathbb{P}_G[u, v]|$. A modification of Dijkstra's algorithm computing both the distance matrix of G and the matrix S is given in the appendix.

A subgraph H of G is *isometric* if $\text{dist}_H(u, v) = \text{dist}_G(u, v)$ holds for all $u, v \in V(H)$. We say that H is a (*geodetically*) *convex* subgraph of G if for all $u, v \in V(H)$, all shortest uv -paths $P \in \mathbb{P}_G[u, v]$ are contained in H . In the following, convex will always mean geodetically convex. The empty subgraph will be considered as convex. The intersection of convex subgraphs of G is again a convex subgraph of G [42].

Since H is an isometric subgraph of G if and only if H contains at least one $P \in \mathbb{P}_G[u, v]$ for every pair $u, v \in V(H)$, we see that convex implies isometric. Furthermore, if H is an isometric subgraph of G , it is in particular an induced subgraph of G . Finally, the connectedness of G implies that all its isometric subgraphs are connected.

Our first result characterizes elementary convex cycles.

Lemma 2.1. *Let C be an elementary cycle of G .*

If $|C|$ is odd, then C is convex if and only if for every edge $e = \{x, y\}$ in C there is a unique vertex z in C such that $\text{dist}_G(x, z) = \text{dist}_G(y, z) = (|C| - 1)/2$ and $S_{xz} = S_{yz} = 1$.

If $|C|$ is even, then C is convex if and only if for every edge $e = \{x, y\}$ in C there is a unique edge $h = \{u, v\}$ in C such that (i) $\text{dist}_G(x, u) = \text{dist}_G(y, v) = |C|/2 - 1$, (ii) $\text{dist}_G(x, v) = \text{dist}_G(y, u) = |C|/2$, (iii) $S_{xu} = S_{yv} = 1$, and (iv) $S_{xv} = S_{yu} = 2$.

Proof. Suppose C is convex. Consider two vertices p and q in C with $\text{dist}_G(p, q) < |C|/2$. If C is convex, then the unique shortest path between p and q must run along C , so that $S_{pq} = 1$. Clearly, this condition characterizes convex cycles provided C is odd.

The situation is more complicated for even cycles. Let us first suppose that C is convex and fix an arbitrary edge $\{x, y\}$. In an even elementary cycle there is a unique edge $h = \{u, v\}$ satisfying (i) $\text{dist}_C(x, u) = \text{dist}_C(y, v) = |C|/2 - 1$, (ii) $\text{dist}_C(x, v) = \text{dist}_C(y, u) = |C|/2$. Isometry of C implies that properties (i) and (ii) are satisfied. The argument of the preceding paragraph shows that (iii) holds. For x , the only point in C at distance $|C|/2$ is v . Thus there are two paths P' and P'' in C of length $\text{dist}_G(x, v) = |C|/2$. By the convexity of C , these paths are contained in C (so that $C = P' \cup P''$) and must be the only shortest paths connecting x and v ; hence consequently $S_{xv} = 2$. An analogous argument shows that $S_{yu} = 2$.

In order to prove the converse, consider an even elementary cycle C satisfying (i) through (iv). Again we fix an arbitrary edge $\{x, y\}$ of C . Since C is even, there is a unique antipodal point v of x and a unique antipodal point u of y with $\text{dist}_C(x, v) = \text{dist}_C(y, u) = |C|/2$. We claim that $\{u, v\}$ is the required edge. If this were not the case, then there would be some other edge with both endpoints closer to x along C than v that satisfies condition (ii). This is impossible, however, since for such a vertex v' we would have $|C|/2 = \text{dist}_G(x, v') \leq \text{dist}_C(x, v') < \text{dist}_C(x, v) = |C|/2$. We easily check that $\text{dist}_C(x, u) = |C|/2 - 1$ and $\text{dist}_C(y, v) = |C|/2 - 1$. By property (i), therefore, the paths from x to u and from y to v along C are shortest paths in G . Furthermore, the two paths from x to v along C via either u or y are also shortest paths in G by property (ii). Thus $\text{dist}_C(x, q) = \text{dist}_G(x, q)$ for all vertices q in C . Repeating this argument for all x in C shows that C is isometric. By property (iii), the shortest path from x to u is unique. Since all sub-paths of shortest paths are again shortest path, this is also true for all vertices q in C along the shortest path from x to u . The same is true for all q in C along the unique shortest path from v to y . By property (iv), finally, there are exactly two shortest paths from x to v . We have already seen that two of these run along either half of the cycle C . The same is true for the two paths connecting y with u . Thus all shortest path connecting a vertex q in C with either x or y are contained in C . Repeating the argument for all edges $\{x, y\}$ in C shows that C is convex. \square

A direct consequence of Lemma 2.1 is that a cycle C in G can be efficiently tested for convexity provided both the distance matrix and the matrix S containing the number of shortest paths have been pre-computed: it suffices to verify, in constant time, the conditions of the lemma for each antipodal pair of edges or pair of edge and vertex, respectively. The test thus requires $\mathcal{O}(|C|)$ time provided that C is given as ordered list of its vertices.

As a simple corollary of Lemma 2.1 we have

Corollary 2.2. *Let C be an elementary convex cycle of G . Then, for every $e = \{x, y\} \in C$ there is a vertex z in C such that $C = P' \cup P'' \cup \{x, y\}$, $P' \in \mathbb{P}_G[x, z]$, and $P'' \in \mathbb{P}_G[y, z]$.*

A closely related, but much weaker, condition appears in the theory of minimal cycles bases [22]:

Definition 2.3. A cycle C is *edge-short* if it contains an edge $e = \{x, y\}$ and a vertex z such that $C = C_{xy,z} := \{x, y\} \cup P_{xz} \cup P_{yz}$ where P_{xz} and P_{yz} are shortest paths.

Corollary 2.4. *If C is an elementary convex cycle of G then it is edge-short.*

3 Convex cycle bases

Corollary 2.2 sets the stage for enumerating all elementary convex cycles in a graph. The following result establishes an upper bound and provides a polynomial time algorithm for this purpose.

Theorem 3.1. *Any graph $G = (V, E)$ contains at most $|E||V|$ elementary convex cycles. These can be constructed and listed in $\mathcal{O}(|E||V|^2)$ time.*

Proof. Every pair of an edge $e = \{x, y\}$ and a vertex z specifies at most one elementary convex cycle in the following way: If $\text{dist}_G(x, z) = \text{dist}_G(y, z)$ and $S_{xz} = S_{yz} = 1$ we set $C_{ez} := P_{xz} \cup P_{yz} \cup \{x, y\}$. If $\text{dist}_G(x, z) = \text{dist}_G(y, z) + 1$, $S_{xz} = 2$ and $S_{yz} = 1$, then

we choose a neighbor u of z such that $\text{dist}_G(x, u) = \text{dist}_G(y, z)$, $S_{ux} = 1$ and $S_{uy} = 2$, and set $C_{ez} := P_{xu} \cup \{u, z\} \cup P_{yz} \cup \{x, y\}$. Note that the choice of u is unique if C is convex. The selection of these $|E| |V|$ candidates thus requires $\mathcal{O}(|E| |V|^2)$ time.

In order to efficiently retrieve each candidate cycle in $\mathcal{O}(|C|)$ time given $\{x, y\}$ and z we need to know the predecessor π_{su} of u on the shortest path from s to u . Note that this information is needed only if $S_{su} = 1$. The modified Dijkstra algorithm in the Appendix computes this array without changing the asymptotic complexity of the shortest path algorithm. Since each candidate cycle can then be checked for convexity in $\mathcal{O}(|C|)$ time, the total effort to extract all elementary convex cycles is in $\mathcal{O}(|E| |V|^2)$. \square

This algorithm outlined in the proof of Theorem 3.1 can be regarded as a variant of Vismara’s construction of prototypes of candidates for relevant cycles [44]. The fact that the number of elementary convex cycles in G is bounded by $|V| |E|$ immediately implies that a convex cycle basis can also be found in polynomial time:

Corollary 3.2. *For each graph $G = (V, E)$ it can be decided whether G has a convex cycle basis, and if so, a convex cycle bases can be constructed, in $\mathcal{O}(|E|^2 |V| \mu(G)^2)$ time.*

Proof. Since the cycles of a graph form a matroid, the canonical greedy algorithm can be applied to find a maximum set of linearly independent elementary convex cycles, see e.g. [21]. G has a convex cycle basis if and only if this set has size $\mu(G) = |E| - |V| + 1$. For each of the at most $|V| |E|$ candidate cycles, this requires a test of linear independence with a partial basis that is not larger than $\mu(G) = |E| - |V| + 1$, i.e., $\mathcal{O}(|E|)$. Applying Gaussian elimination for this purpose, the total effort is bounded by $\mathcal{O}(|E| |V|^2) + \mathcal{O}(|E|^2 |V| \mu(G)^2) = \mathcal{O}(|E|^2 |V| \mu(G)^2)$ time. \square

There are graphs that do not have a convex cycle basis. The complete bipartite graph $K_{2,3}$ is the simplest counter example (see Fig. 1). None of its three cycles (all have length 4) is convex.

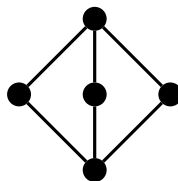


Figure 1: None of the cycles in $K_{2,3}$ is convex.

4 Relation of convex cycle bases to other types of cycle bases

Although we have an efficient algorithm to test whether a graph has a convex cycle basis, it will be interesting to characterize the class of graphs that admit convex cycle bases. However, we first investigate the relation between convex cycle bases and other types of cycle bases.

A procedure analogous to Corollary 3.2 was introduced in [22] for the purpose of retrieving minimal cycle bases from a candidate set of edge-short cycles. One would expect, therefore, that convex cycle bases and minimal cycles bases are closely related.

Convex cycle bases of a graph need not have the same length. Consider the graph that is obtained from the cube Q_3 where one edge is contracted. Then the four quadrangles and two triangles are convex and five of these form a convex cycle basis. Thus convex bases contain either exactly one or two triangles and thus may have different lengths.

The length $\ell(\mathcal{B})$ of a cycle basis \mathcal{B} is the sum of the lengths of its generalized cycles: $\ell(\mathcal{B}) = \sum_{C \in \mathcal{B}} |C|$. A *minimum cycle basis* \mathcal{M} is a cycle basis with minimum length. The generalized cycles in \mathcal{M} are chord-less cycles (see [22]). Hence, we may consider elementary cycles instead of generalized cycles in the remaining part of this section. For the sake of completeness we note that a minimum cycle basis is a cycle basis in which the longest cycle has the minimum possible length [10].

The set \mathcal{R} of *relevant cycles* of a graph is the union of its minimum cycle bases [41, 44]. In analogy to convex cycle bases one may want to consider *isometric cycle bases*, i.e., cycle bases consisting of isometric cycles.

Lemma 4.1. *All relevant cycles of a graph are isometric. Thus every minimal cycle basis is an isometric cycle basis.*

Proof. We start from Lemma 2 of [44]: If P is a subpath of a relevant cycle C such that $|P| \leq \frac{1}{2}|C|$, then P is a shortest path. It follows that every relevant cycle is isometric, and hence every minimal cycle basis of G consists of elementary isometric cycles. \square

Theorem 4.2. *If G has a uniquely defined minimal cycle basis, then this minimal cycle basis is convex.*

Proof. Assume that G has a unique minimal cycle basis \mathcal{B} . By Lemma 4.1 the cycles of \mathcal{B} are necessarily isometric. Now suppose that $C \in \mathcal{B}$ is not convex. Then there exist two vertices $u, v \in C$ and (at least) three edge disjoint uv -paths P, P' and P'' such that $|P| \geq |P'| = |P''|$ and $C = P \cup P'$. Hence there are two cycles $C_1 = P \cup P''$ and $C_2 = P' \cup P''$ with $|C| = |C_1| \geq |C_2|$. By construction C, C_1 , and C_2 are linearly dependent and thus one of C_1 or C_2 cannot be represented as sum of cycles in $\mathcal{B} \setminus \{C\}$. Hence we get a new cycle basis $\mathcal{B}' = (\mathcal{B} \setminus \{C\}) \cup \{C'\}$ where C' is either C_1 or C_2 . In either case we find $\ell(\mathcal{B}') \leq \ell(\mathcal{B})$ a contradiction to our assumption that \mathcal{B} is the unique minimal cycle basis. \square

As a consequence, we can conclude that Halin graphs that are not necklaces [43] and outerplanar graphs [35] have a convex cycle basis.

The converse of Theorem 4.2 is not true, however, as Figure 2 shows. This graph has a convex cycle basis but its minimal cycle basis is not uniquely defined. Even worse, none of its minimal cycle bases is convex.

A cycle basis $\mathcal{B} = \{C_1, \dots, C_{\mu(G)}\}$ of G is called *fundamental* [20, 46] if there is an ordering π such that for $2 \leq k \leq \mu(G)$:

$$C_{\pi(k)} \setminus \left(\bigcup_{j=1}^{k-1} C_{\pi(j)} \right) \neq \emptyset. \tag{4.1}$$

Fundamental cycle bases are obtained from ear decomposition, suggesting that there could be a relation between convex and fundamental cycles bases. Champetier’s graph [4], however, has a cycle basis consisting entirely of triangles, which obviously is convex. On the other hand, this basis is not fundamental [1]. Conversely, fundamental cycle bases need not be convex, as shown, e.g., by the planar basis of $K_{2,3}$.

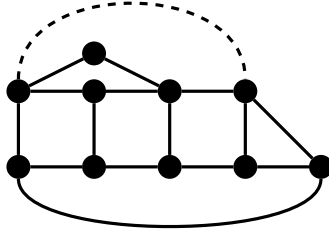


Figure 2: The cyclomatic number of the graph is 7. All minimal cycle bases consist of the two triangles, all quadrangles that do not contain the upper dashed edge and two of the three quadrangles that contain the upper dashed edge (which also includes the outer cycle). However, two of these three quadrangles that contain the upper dashed edge are not convex. Hence none of the minimal cycle bases is a convex cycle basis.

On the other hand there is a unique convex cycle basis that consists of all triangles, all quadrangles that do not contain the upper dashed edge, the outer quadrangle and the cycle of length 5 at the bottom.

5 Convexity in subgraphs and intersections

This section contains some auxiliary results which we will need for our investigation of isometric subgraphs in Section 6 below.

Lemma 5.1. *Let M be an isometric (convex) subgraph of G and $F \subseteq M$ be a subgraph of M . Then F is isometric (convex) in M if and only if it is isometric (convex) in G .*

Proof. If F is an isometric subgraph of G , then for each pair of vertices $u, v \in V(F)$, F contains a shortest uv -path. Since $F \subseteq M$, this path is also a shortest uv -path in M and hence F is isometric in M . If F is a convex subgraph of G , then it contains all shortest uv -paths which are also shortest paths in M and thus F is convex in M .

Now assume that F is not isometric in G . Then there exist two distinct vertices $u, v \in V(F) \subseteq V(M)$ such that there are shortest uv -paths P in G with $|P| < \text{dist}_F(u, v)$. At least one of these paths must be contained in M since M is an isometric subgraph of G . Thus F cannot be an isometric subgraph of M , either. If F is not convex in G then there exist two distinct vertices $u, v \in V(F) \subseteq V(M)$ such that there is at least one shortest uv -path P which is not contained in F . Since M is convex, P must be contained in M and thus F cannot be convex in M , either. □

Lemma 5.2. *Let M be an isometric subgraph of G and F be a convex subgraph of G . Then $F \cap M$ is convex in M .*

Proof. For each pair of vertices $x, y \in V(F) \cap V(M)$, F contains all shortest xy -path in G . Since M is an isometric subgraph of G it must contain at least one of these and thus the proposition follows. □

Lemma 5.3. *Assume that G has a convex cycle basis. Let M be a convex subgraph of G that has a convex cycle basis \mathcal{B}_M . Then \mathcal{B}_M can be extended to a convex cycle basis \mathcal{B}_G of G .*

Proof. By Lemma 5.1 the cycles in \mathcal{B}_M are convex subgraphs of G . By assumption there exists a convex cycle basis \mathcal{B}'_G of G . By the *Austauschsatz* we can replace appropriate cycles in \mathcal{B}'_G by the cycles in \mathcal{B}_M . Thus we obtain a convex cycle basis \mathcal{B}_G of G which such that $\mathcal{B}_M \subseteq \mathcal{B}_G$ as claimed. \square

Figure 3 shows that the converse of this lemma is not true in general: a convex subgraph of a graph that has a convex cycle basis need not necessarily have a convex cycle basis.

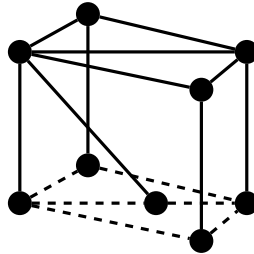


Figure 3: The cyclomatic number of this graph is $|E| - |V| + 1 = 16 - 9 + 1 = 8$. The three triangles and the five quadrangles that do not entirely consist of dashed edges form a convex cycle basis. The subgraph that consists of the dashed edges is convex but does not have a convex cycle basis (see Fig. 1).

6 Isometric subgraphs of Cartesian products

In this section, we will be concerned with the Cartesian product $G \square H$ and its isometric and convex subgraphs. The Cartesian product has vertex set $V(G \square H) = V(G) \times V(H)$; two vertices (x_G, x_H) and (y_G, y_H) are adjacent in $G \square H$ if $\{x_G, y_G\} \in E(G)$ and $x_H = y_H$, or $\{x_H, y_H\} \in E(H)$ and $x_G = y_G$. For detailed information about product graphs we refer the interested reader to [18, 24].

For the Cartesian product $G \square H$ the subgraph G^v induced by all vertices (x, v) with $x \in V(G)$ and a fixed vertex $v \in V(H)$ is called a *layer* of G (or G -layer) in $G \square H$. The projection $\pi_G: G \square H \rightarrow G$ is the usual weak homomorphism defined as $(x, y) \in V(G \square H) \mapsto x \in V(G)$. Note that edges in G -layers are mapped into edges in G and edges in H -layers are mapped into vertices in G .

There is a close relationship between (geodesic) convexity and Cartesian products, see [7] for a general result. The fundamental result for this purpose is the distance lemma.

Proposition 6.1 (Distance Lemma, [23]). *Let $x = (x_G, x_H)$ and $y = (y_G, y_H)$ be arbitrary vertices of the Cartesian product $G \square H$. Then*

$$\text{dist}_{G \square H}(x, y) = \text{dist}_G(x_G, y_G) + \text{dist}_H(x_H, y_H) .$$

Moreover, if P is a shortest xy -path in $G \square H$, then $\pi_G(P)$ is a shortest $x_G y_G$ -path in G .

It seems natural that convexity properties of products also hold for layers and projections.

Lemma 6.2 ([24]). *The layers G^v and H^w are convex subgraphs of the Cartesian product $G \square H$. Moreover, if F is an isometric (convex) subgraph of $G \square H$, then for all $v \in V(H)$*

and $w \in V(G)$ the following holds: $F \cap G^v$ and $F \cap H^w$ are isometric (convex) subgraphs of F , G^v and H^w , respectively.

Corollary 6.3. *Let M be an isometric subgraph of $G \square H$. If (x_G, x_H) and (y_G, y_H) are two vertices in M with $x_G = y_G$, then there exists a shortest $x_H y_H$ -path in $M \cap H^{x_G}$. Moreover, all shortest $(x_G, x_H)(y_G, y_H)$ -paths in M are contained in H^{x_G} .*

Another consequence of the distance lemma is the following auxiliary result.

Lemma 6.4. *Let P be a shortest xy -path in $G \square H$. Then $\pi_G(P)$ is a path with $|\pi_G(P)| = \text{dist}_G(x_G, y_G) = \sum_{v \in H} |P \cap G^v|$, where the last term is the total number of edges of P in G -layers. The result holds analogously for $\pi_H(P)$.*

Proof. If (w, x_H) and (w, y_H) are two distinct points of P , then by Corollary 6.3 all shortest $x_H y_H$ -paths are contained in layer H^w . Consequently, there cannot be two distinct edges e_1 and e_2 in G with $\pi_G(e_1) = \pi_G(e_2)$ that belong to P since otherwise P also must contain two shortest paths in different H -layers that connect corresponding vertices of these edges, that is, P would contain a cycle. Hence all vertices of $\pi_G(P)$ have degree 2 except its end vertices which have degree 1 (or 0 in the case where $\pi_G(P)$ is a single vertex). Thus $\pi_G(P)$ is path of length $|\pi_G(P)| = \text{dist}_G(x_G, y_G) = \sum_{v \in H} |P \cap G^v|$, as claimed. \square

Lemma 6.5. *For every isometric (convex) subgraph F of $G \square H$, $\pi_G(F)$ is an isometric (convex) subgraph of G .*

Proof. Let $x = (x_G, x_H)$ and $y = (y_G, y_H)$ be two vertices in F . If F is isometric in $G \square H$, then there exists a shortest xy -path P in F . By the distance lemma, $\pi_G(P)$ is a shortest $x_G y_G$ -path in G and contained in $\pi_G(F)$. Thus $\pi_G(F)$ is an isometric subgraph of G . Now if $\pi_G(F)$ is not convex in G , then there exists a shortest $x_G y_G$ -path P_G in G that is not contained in $\pi_G(F)$. Let P_H be a shortest $x_H y_H$ -path in H . Then $P = P_G \square \{x_H\} \cup P_H \square \{y_H\}$ is a shortest xy -path as its length is $|P| = \text{dist}_G(x_G, y_G) + \text{dist}_H(x_H, y_H) = \text{dist}_{G \square H}(x, y)$. However, by construction P cannot be contained in F and hence F is not convex in $G \square H$. Consequently, if F is convex in $G \square H$, then $\pi_G(F)$ is convex in G , as claimed. \square

On the other hand convexity and isometry properties of factors are also propagated to their Cartesian product. The following result is well-known and holds for more general notions of convexity.

Lemma 6.6 ([7]). *If F and M are convex subgraphs of G and H , respectively, then $F \square M$ is a convex subgraph of $G \square H$.*

The last lemma also holds for isometric subgraphs.

Lemma 6.7. *If F and M are isometric subgraphs of G and H , respectively, then $F \square M$ is an isometric subgraph of $G \square H$.*

Proof. Immediate corollary of the distance lemma. \square

We now want to extend convex cycle bases of two graphs G and H to a cycle basis of their Cartesian product $G \square H$. Let T_G and T_H denote spanning trees of G and H , respectively. Let

$$\mathcal{B}_{\square} = \{e \square f : e \in E(G), f \in T_H\} \cup \{e \square f : e \in T_G, f \in E(H)\}. \quad (6.1)$$

Then for fixed vertices $v \in V(H)$ and $w \in V(G)$ and respective cycle basis \mathcal{B}_G and \mathcal{B}_H

$$\{C^v : C \in \mathcal{B}_G\} \cup \{C^w : C \in \mathcal{B}_H\} \cup \mathcal{B}_\square \tag{6.2}$$

is a cycle basis of $G \square H$ [25].

Theorem 6.8. *Let G and H be two graphs that have convex cycle bases \mathcal{B}_G and \mathcal{B}_H , respectively. Then their Cartesian product $G \square H$ has a convex cycle basis that can be constructed using Eq. (6.2).*

Proof. Notice that all quadrangles in \mathcal{B}_\square are convex subgraphs in $G \square H$. By Lemma 5.1 C^v is a convex cycle in $G \square H$. Thus we get a convex cycle basis of $G \square H$ by means of basis (6.2) when both \mathcal{B}_G and \mathcal{B}_H are convex cycle basis. \square

Remark 6.9. An analogous statement for the strong product (see [18]) is not true, as the strong product of an elementary cycle and an edge K_2 shows.

We have seen in Figure 3 that a convex subgraph of a graph that has a convex cycle basis does not necessarily have a convex cycle basis. However, a more restrictive property appears to propagate under the formation of Cartesian products: we consider the class of graphs for which every convex subgraph has a convex cycles basis.

Theorem 6.10. *Let G be a graph that has a convex cycle basis. Then every isometric subgraph M of $G \square K_2$ with $\pi_G(M) = G$ has a convex cycle basis.*

For the proof of this theorem we need some intermediate results.

Lemma 6.11. *Let C be an isometric elementary cycle in $G \square H$. Then one of the following holds:*

- (1) $\pi_G(C) \cong K_1$, i.e., a single vertex, or
- (2) $\pi_G(C) \cong K_2$, i.e., a single edge, or
- (3) $\pi_G(C)$ is an isometric elementary cycle in G .

Proof. Notice that $\pi_G(C) = \bigcup_{v \in V(H)} \pi_G(C \cap G^v)$. Let $x = (x_G, x_H)$ and $y = (y_G, y_H)$ be two vertices in C with $x_G = y_G$ and $x_H \neq y_H$. Analogously to the proof of Lemma 6.4 no vertex v in $\pi_G(C)$ can have degree greater than 2. Now if $C \subseteq H^w$ for some $w \in V(G)$, then $\pi_G(C) = \{w\} \cong K_1$, i.e., case (1). If there is a vertex x where $\pi_G(x)$ has degree 1, then there exist two distinct vertices $u, v \in V(H)$ such that $\pi_G(C \cap G^u)$ and $\pi_G(C \cap G^v)$ have a common edge e . However, this only can happen if $\pi_G(C) = \{e\} \cong K_2$, i.e., for case (2). Otherwise, there would be two vertices y' and y'' in C so that $\pi_G(y') = \pi_G(y'')$ is adjacent to $\pi_G(x)$ with vertex degree larger than 1 in the projection, contradicting isometry of C . If we have neither case (1) nor case (2), then all vertices of $\pi_G(C)$ have degree 2 and hence $\pi_G(C)$ is an elementary cycle which is isometric in G by Lemma 6.5, i.e., case (3). \square

Now let C be an elementary cycle in G and M be an isometric subgraph of $G \square K_2$. Let $\mathcal{Z}(C, M)$ denote the set of elementary cycles $C' \subseteq M$ that are convex in M and satisfy $\pi_G(C') = C$. We set $\mathcal{Z}(C, M) = \emptyset$ if no such cycle exists.

Lemma 6.12. *Let M be an isometric subgraph of $G \square K_2$ and let $C \in G$ be a convex elementary cycle with $C \subseteq \pi_G(M)$. Then $\mathcal{Z}(C, M)$ is non-empty.*

Proof. First notice that $C \square K_2$ is a convex subgraph of $G \square K_2$ by Lemma 6.6. $M' = M \cap (C \square K_2)$ is isometric in $C \square K_2$ by Lemma 5.1 and convex in M by Lemma 5.2. Let M^1 and M^2 denote the respective intersections of M' with the two K_2 -layers of $C \square K_2$. If $M^1 \cong C$ (or $M^2 \cong C$) then M^1 (M^2) is a convex elementary cycle in $C \square K_2$ by Lemma 6.2, and thus also in M' by Lemma 5.2. Otherwise, both M^1 and M^2 are paths of length $|M^i| \leq \frac{1}{2}|C|$ for $i = 1, 2$, since M' is isometric. As $\pi_C(M') = C$, $\pi_C(M^1) \cup \pi_C(M^2) = C$. Consequently, as M' is isometric, M' is an elementary cycle that is trivially convex in M' . In all cases $\mathcal{Z}(C, M')$ is non-empty. Since Lemma 5.1 implies that $\mathcal{Z}(C, M') \subseteq \mathcal{Z}(C, M)$, the proposition follows. \square

Remark 6.13. The arguments in the proof of Lemma 6.12 together with the distance lemma also show that the elements of $\mathcal{Z}(C, M)$ form the set of all shortest cycles C' in M with the property $\pi_C(C') = C$.

Proof of Theorem 6.10. Let \mathcal{B}_G be a convex cycles basis of G . Let \mathcal{B}_\square be as in (6.1) and define $\mathcal{B}_\mathcal{Z}$ be a set of cycles that contains exactly one cycle $C' \in \mathcal{Z}(C, M)$ for each $C \in \mathcal{B}_G$. By Lemma 6.12 all these sets $\mathcal{Z}(C, M)$ are non-empty. Clearly, the cycles in $\mathcal{B}_\square \cup \mathcal{B}_\mathcal{Z}$ are linearly independent and thus form a cycle basis of $G \square K_2$. Now let \mathcal{B}_M be the set of all cycles in $\mathcal{B}_\square \cup \mathcal{B}_\mathcal{Z}$ that are contained in M . By construction all cycles in \mathcal{B}_M are convex subgraphs of M and $\mathcal{B}_\mathcal{Z} \subseteq \mathcal{B}_M$. Thus it remains to show that $|\mathcal{B}_M| = \mu(M)$. Let \tilde{m}_G and \tilde{m}_{K_2} denote the numbers of edges in $(G \square K_2) \setminus M$ that lie in G -layers and K_2 -layers, respectively. Let \tilde{n} be the number of vertices in $(G \square K_2) \setminus M$. Since $\pi_G(M) = G$ and M is an isometric subgraph of $G \square K_2$ we find that $\tilde{m}_{K_2} = \tilde{n}$. Thus $\mu(M) = (|E(G \square K_2)| - \tilde{m}_G - \tilde{m}_{K_2}) - (|V(G \square K_2)| - \tilde{n}) + 1 = |E(G \square K_2)| - |V(G \square K_2)| + 1 - \tilde{m}_G = \mu(G \square K_2) - \tilde{m}_G$. On the other hand, there are exactly \tilde{m}_G cycles in \mathcal{B}_\square that are not contained in M and hence $|\mathcal{B}_M| = \mu(G \square K_2) - \tilde{m}_G = \mu(M)$, i.e., \mathcal{B}_M is a cycle basis of M . This finishes the proof of the theorem. \square

We easily can generalize Theorem 6.10 to arbitrary isometric subgraphs of $G \square K_2$.

Theorem 6.14. *Let G be a graph such that every isometric subgraph has a convex cycle basis. Then every isometric subgraph of $G \square K_2$ also has a convex cycle basis.*

Proof. Let H be an isometric subgraph of $G \square K_2$. By Lemma 6.5, $G' = \pi_G(H)$ is an isometric embedding into G and thus has a convex cycle basis by our assumptions. Hence by Theorem 6.10 every isometric subgraph M of $G' \square K_2 \subseteq G \square K_2$ has a convex cycle basis. \square

Theorem 6.14 has quite strong implications. A d -dimensional *hypercube* is the d -fold product of K_2 by itself, $Q_d = \square_{i=1}^d K_2$. *Partial cubes* are isometric subgraphs of Q_d and form a very rich graph class that contains hypercubes, trees, median graphs, tope graphs of oriented matroids, benzenoid graphs, tiled partial cubes, netlike partial cubes, and flip graphs of point sets that have no empty pentagons; see [30, 31] and references therein. As K_2 has a convex cycle basis (namely \emptyset) we immediately obtain the following results by a recursive application of Theorem 6.14.

Theorem 6.15. *Partial cubes have a convex cycle basis.*

Theorem 6.16. *Let G be a graph such that every isometric subgraph has a convex cycle basis and let Q be any partial cube. Then every isometric subgraph of $G \square Q$ has a convex cycle basis.*

Proof. Let G be as claimed. Theorem 6.14 implies that every isometric subgraph of $G \square K_2 \square \dots \square K_2 = G \square Q_n$ has a convex cycle basis. Lemma 6.7 implies that $G \square Q$ is an isometric subgraph of $G \square Q_n$. Moreover, Lemma 5.1 implies that every isometric subgraph of $G \square Q$ is an isometric subgraph of $G \square Q_n$ and thus, has a convex cycles basis. \square

Figure 4 shows that the class covered by Theorem 6.16 is much larger than the class of partial cubes. Recall that partial cubes are characterized by the so-called *Djoković-Winkler-Relation* Θ : Two edges $e = \{u, v\}$ and $f = \{x, y\}$ are in relation Θ , $(ef) \in \Theta$, if $\text{dist}(u, x) + \text{dist}(v, y) \neq \text{dist}(u, y) + \text{dist}(v, x)$. A graph is a partial cube if and only if it is bipartite and the relation Θ is an equivalence relation [47].

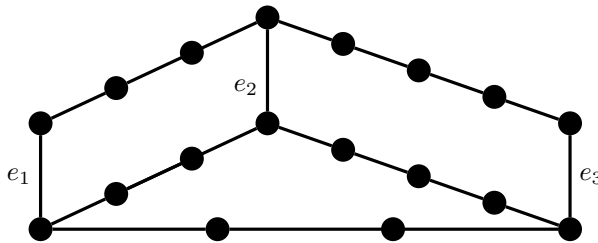


Figure 4: Observe that $(e_1e_2) \in \Theta$ and $(e_2e_3) \in \Theta$, but $(e_1e_3) \notin \Theta$. Thus Θ is not an equivalence relation. Therefore, this bipartite graph is not a partial cube. However, it has a convex cycle basis consisting of the three planar faces.

It seems natural that Theorem 6.16 should remain true also for a more general type of Cartesian products. We state this as

Conjecture 6.17. *Let G_1 and G_2 be graphs such that each of their isometric subgraphs have convex cycle bases. Then every isometric subgraph of $G_1 \square G_2$ has a convex cycle basis.*

A further step towards a proof of this conjecture is given by the following special case:

Theorem 6.18. *Let G be a graph such that every isometric subgraph has a convex cycle basis and let C_n be an elementary cycle. Then every isometric subgraph of $G \square C_n$ has a convex cycle basis.*

Notice that this theorem is an immediate corollary of Theorem 6.16 if n is even since cycles of even length are partial cubes [30, 45]. The proof of the general case is present after Lemma 6.19 below. For this purpose we first have to introduce a graph operation for the case when C is a cycle of odd length. So assume that $C = C_{2k-1}$ for some integer $k \geq 2$. First fix three vertices $u, v, w \in V(C)$ with $\{u, v\}, \{v, w\} \in E(C_{2k-1})$. Create a new cycle $C' \cong C_{2k}$ by splitting vertex v , that is, replace v by two vertices v' and v'' and the edges $\{u, v\}, \{v, w\}$ by three edges $\{u, v'\}, \{v', v''\}, \{v'', w\}$.

This splitting operation can be generalized to subgraphs F of $G \square C$. In essence, we replace $F \cap G^v$ by $(F \cap G^v) \square K_2$. In more detail, we introduce the graph operations Υ and its converse Υ^* as follows: For a fixed vertex $v \in C$, and any subgraph

$F \subseteq G \square C$, we obtain the subgraph $\Upsilon(F) \subseteq G \square C'$ by splitting all vertices $(x, v) \in F$ with $x \in G$ in the following way: Replace vertex (x, v) by (x, v') and (x, v'') , and replace the edges $\{(x, u), (x, v)\}$, $\{(x, v), (x, w)\}$, and $\{(x, v), (y, v)\}$, when present, by the corresponding edges $\{(x, u), (x, v')\}$, $\{(x, v'), (x, v'')\}$, $\{(x, v''), (x, w)\}$, $\{(x, v'), (y, v')\}$ and $\{(x, v''), (y, v'')\}$. Conversely, for a subgraph $F' \subseteq B \square C'$ we obtain the subgraph $\Upsilon^*(F') \subseteq G \square C$ by contracting all edges $\{(x, v'), (x, v'')\} \in E(G \square C')$ and remove possible double edges. This construction in particular has the property that $\Upsilon(G \square C) = G \square C'$ and $\Upsilon^*(G \square C') = G \square C$.

Lemma 6.19. *Let $C = C_{2k-1}$ be an elementary cycle of odd length $2k - 1$. If P is a shortest xy -path in $G \square C$, then $\Upsilon(P)$ contains a shortest $x'y'$ -path P' in $G \square C'$ where x' and y' are vertices in $\Upsilon(x)$ and $\Upsilon(y)$, resp.*

Proof. Let $x = (x_G, x_C)$ and $y = (y_G, y_C)$ be two vertices in $G \square C$ and let $x' = (x'_G, x'_{C'})$ and $y' = (y'_G, y'_{C'})$ be two vertices in $\Upsilon(x)$ and $\Upsilon(y)$, resp. Let P' be a shortest $x'y'$ -path in $\Upsilon(P)$. We have to show that P' is also a shortest $x'y'$ -path in $G \square C'$. Observe that Lemma 6.4 implies that $|\pi_G(P)| = |\pi_G(P')|$ and $|\pi_C(P)| = |\pi_{C'}(P')| - \delta(P')$ where $\delta(P') = 1$ if $\pi_{C'}(P')$ contains edge $\{v', v''\}$ and $\delta(P') = 0$ otherwise. Moreover, $\text{dist}_C(x_C, y_C) \leq k - 1$ and $\text{dist}_{C'}(x'_{C'}, y'_{C'}) \leq k$. Now suppose that P' is not a shortest $x'y'$ -path in $G \square C'$. Then there exists a $x'y'$ -path P'' that is strictly shorter than P' , that is, $|\pi_{C'}(P'')| < |\pi_{C'}(P')| \leq k$. As P is a shortest xy -path we have $|\pi_C(\Upsilon^*(P''))| = |\pi_C(\Upsilon^*(P'))| = |\pi_C(P)| \leq k - 1$. Again $|\pi_C(\Upsilon^*(P''))| = |\pi_{C'}(P'')| - \delta(P'')$. Consequently $\pi_{C'}(P'')$ must contain edge $\{v', v''\}$ while $\pi_{C'}(P')$ must not. Therefore $\pi_{C'}(P'') \cap \pi_{C'}(P') \cong C'$. However $|\pi_{C'}(P'')| + |\pi_{C'}(P')| < k + k = 2k = |C'|$, a contradiction. This completes the proof. \square

Proof of Theorem 6.18. Let C be an odd cycle. Thus C' is even and hence a partial cube. Lemma 6.19 implies that $\Upsilon(M)$ is an isometric subgraph of $G \square C'$ if M is an isometric subgraph in $G \square C$. In this case, $\Upsilon(M)$ has a convex cycle basis \mathcal{B}' . Now consider a convex cycle $D' \in \mathcal{B}'$. Lemma 6.11 implies that $\Upsilon^*(D')$ is either an elementary cycle or $\Upsilon^*(D')$ is a single edge in layer G^v . The latter happens if and only if D' contains edges $\{(x, v'), (x, v'')\}$ and $\{(y, v'), (y, v'')\}$. In this case D' must be a convex quadrangle. There are $|E(M \cap G^v)|$ quadrangles of this type, and they form an linearly independent set \mathcal{Q} of convex cycles. Thus we can assume, w.l.o.g., that they all are contained in \mathcal{B}' . Lemma 6.19 implies that $\Upsilon^*(D')$ is a convex subgraph of M . Thus let

$$\mathcal{B} := \{ \Upsilon^*(D') \mid D' \in \mathcal{B}' \text{ and } \Upsilon^*(D') \text{ is an elementary cycle} \} .$$

The cycles in \mathcal{B} are linearly independent: Consider any linear combination $\sum_i \lambda_i \Upsilon^*(D'_i) = 0$. It follows that there is a corresponding linear combination $\sum_i \lambda_i D'_i = \sum_j \xi_j Q_j$, where $Q_j \in \mathcal{Q}$ is a quadrangle that is contracted to 0 by Υ^* . Since \mathcal{B}' is linearly independent by assumption, all ξ_j and λ_i must be 0, however.

It remains to show that $|\mathcal{B}| = \mu(M)$. Observe that $\Upsilon(M)$ contains the subgraph induced by vertices (x, v') and (x, v'') if $(v, x) \in V(M)$ for some $x \in G$. Otherwise $\Upsilon(M)$ contains none of these two vertices. Thus we find for the cyclomatic number $\mu(M) = \mu(\Upsilon(M)) - |E(M \cap G^v)|$. On the other hand $|\mathcal{B}| = |\mathcal{B}'| - |E(M \cap G^v)| = \mu(\Upsilon(M)) - |E(M \cap G^v)| = \mu(M)$. This completes the proof. \square

7 Convex Eulerian graphs that are not cycles

Convex cycles need not be elementary, even though they are necessarily connected when G is connected. Furthermore, the elementary cycles whose union forms convex Eulerian subgraph need not be convex themselves. An example is the $K_{2,4}$, which can be decomposed into two elementary but not convex squares. In fact, the sum of convex cycles typically is not convex:

Lemma 7.1. *Let C_1 and C_2 be two convex cycles in G . If $C_1 \oplus C_2$ is 2-connected, then $C_1 \oplus C_2$ is not convex.*

Proof. If $C_1 \oplus C_2$ is 2-connected, then it contains at least two distinct vertices $u, v \in V(C_1) \cap V(C_2)$. Since $C_1 \cap C_2$ is also convex, it contains the set of all shortest uv -path which cannot be empty as $u \neq v$. Consequently, $C_1 \oplus C_2 = (C_1 \cup C_2) \setminus (C_1 \cap C_2)$ cannot contain any of these shortest path and is thus not convex. \square

If $C_1 \oplus C_2$ is convex for two convex cycles C_1 and C_2 , then $C_1 \oplus C_2 = C_1 \cup C_2$ and connected (but not 2-connected). Thus $V(C_1) \cap V(C_2)$ consists of a single vertex. Notice, however, that even then $C_1 \oplus C_2$ need not be convex.

One may ask, therefore, whether the cycle space of a graph that does not have a convex cycle basis nevertheless may have a basis consisting of convex Eulerian subgraphs. The example in Figure 5 shows that this is indeed possible.

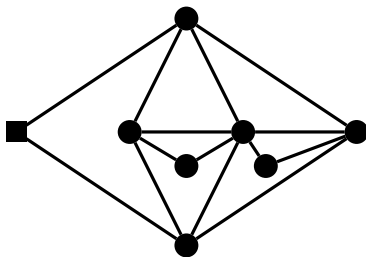


Figure 5: The 6 triangles and the whole graph are all convex cycles and form a cycle basis. However, there is no convex cycle basis according to Definition 1.1: none of the elementary cycle that pass through the square node is convex.

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Appendix A: Modified Dijkstra Algorithm

A shortest path algorithm that keeps track of the multiplicity of shortest paths and keeps some backtracing information is required as a pre-processing step in the computation of convex cycle bases. We use a modified version of Dijkstra’s approach [12]. Let $\ell(x, y)$ denote the length of the edge $\{x, y\}$ in G , $d_{xy} = \text{dist}_G(x, y)$ is the length and S_{xy} is the number of shortest paths in between x and y , π_{sx} is the predecessor of x along the *unique* shortest path from s to x , and $\pi_{sx} = \emptyset$ otherwise. Q denotes a priority queue sorted by d_{sx} for fixed s .

Input: $G = (V, E, \ell)$ /* an edge-weighted graph */

Output: Matrices $[S_{xy}]$, $[d_{xy}]$, and $[\pi_{xy}]$.

- 1: **for all** $s \in V$ **do**
- 2: /* Modified Dijkstra algorithm */
- 3: **for all** $v \in V$ **do**
- 4: $d_{sv} = \infty$; $S_{sv} = 0$; $\pi_{sv} = \emptyset$
- 5: $d_{ss} = 0$; $S_{ss} = 1$; $\pi_{ss} = s$
- 6: $Q \leftarrow V$;
- 7: **while** ($Q \neq \emptyset$) **do**
- 8: $u :=$ vertex with smallest d_{su} .
- 9: **if** ($d_{su} = \infty$) **then**
- 10: break /* G not connected */
- 11: remove u from Q
- 12: **for all** neighbors $v \in Q \cap N(u)$ of u **do**
- 13: $t := d_{su} + \ell(u, v)$
- 14: **if** ($d_{sv} = t$) **then**
- 15: $S_{sv} := S_{sv} + 1$; $\pi_{s,v} = \emptyset$ /* more than one shortest path */
- 16: **if** ($d_{sv} > t$) **then**

17: $d_{sv} := t; S_{sv} := 1; \pi_{sv} = u$

The algorithm runs in $\mathcal{O}(|V|(|E| + |V| \log |V|))$ when the min-priority queue Q is implemented by means of a Fibonacci heap [16]. The modifications do not change the asymptotic complexity of the algorithm.