THE TOPOLOGY AND GEOMETRY
OF UNITS AND ZERO-DIVISORS: ORIGAMI

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ABSTRACT. We define a product structure \( \Pi \), its corresponding 2-dimensional cell complexes \( X_\Pi \) and \( Y_\Pi \), associate to them the universal groups \( G_\Pi \) and \( \bar{G}_\Pi \), and a pair \((a_\Pi, b_\Pi)\) of elements in the group algebra \( \mathbb{Z}_2 \bar{G}_\Pi \) or in the group ring \( R \bar{G}_\Pi \) for any ring \( R \) with unity. We give lists of sufficient combinatorial conditions on a product structure \( \Pi \) implying that \( G_\Pi \) and \( \bar{G}_\Pi \) are torsion-free and that the associated \( a_\Pi \) and \( b_\Pi \) are nontrivial units or zero-divisors. The proofs use graphs and geometry of cell complexes in a substantial way. These results allow using computer-based search to look for counterexamples to the Kaplansky unit and zero-divisor conjectures.

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1. Introduction.

The Kaplansky conjectures are several purely algebraic questions that have been open for a long time. In 1956-1957 Kaplansky presented a list of several questions about group algebras $FG$, where $F$ is a field and $G$ is a group (see [27], [28]). In this paper we will concentrate on two of those conjectures.

- The unit conjecture. For any torsion-free group $G$ and any $a, b \in FG$, does $ab = 1$ imply that $a$ and $b$ are trivial units, meaning that $a$ is a multiple of one element in $G$ and $b$ is a multiple of an element in $G$?

- The zero-divisor conjecture. For any torsion-free group $G$ and any $a, b \in FG$, does $ab = 0$ imply that $a$ and $b$ are trivial zero-divisors, meaning that $a = 0$ or $b = 0$?

The unit conjecture has actually been known since 1940, when Higman stated it as a question in his article [26]. One counterexample to the unit conjecture is currently known, recently found by Gardam [22].

To study the Kaplansky conjectures, we propose a conceptual shift: instead of looking for nontrivial units or zero-divisors over a particular group $G$, we propose directing the effort to constructing multiple groups that would admit such units and zero-divisors. In section 2.1 we define product structures and product substructures. Those are abstract concepts—originally unrelated to any group—that reflect the structure of a desired unit or a zero-divisor. Next, sections 3.1, 3.2, 3.4 introduce topology into the picture: for any product structure or substructure $\Pi$ we associate particular 2-dimensional complexes $X_{\Pi}$, $Y_{\Pi}$, $\bar{X}_{\Pi}$, $\bar{Y}_{\Pi}$. These complexes lead to the full universal group $\bar{G}_{\Pi} := \pi_1(\bar{X}_{\Pi})$. We show in sections 3.5 and 3.6 how, given a product structure $\Pi$, one can associate specific units or zero-divisors $a_{\Pi}$ and $b_{\Pi}$ in the group rings $\mathbb{Z}_2\bar{G}_{\Pi}$ and $R\bar{G}_{\Pi}$, where $R$ is any ring with unity.

While trying to construct counterexamples to the unit conjecture and to the zero-divisor conjecture, the main difficulty is to guarantee that the group $\bar{G}_{\Pi}$ is torsion-free and that the associated units and zero-divisors are nontrivial. We address these two challenges by using geometry of cell complexes: it is shown in sections 4.5 and 6.3 that a product structure $\Pi$ is nondegenerate and the group $\bar{G}_{\Pi}$ is torsion-free if the corresponding complex $Y_{\Pi}$ admits a metric structure of curvature $\leq 0$. Then, as described in section 3.9 nondegeneracy implies the nontriviality of the associated units and zero-divisors.

Further, in section 7.1 we provide several purely combinatorial conditions on a product structure or substructure $\Pi$ that guarantee the existence of such a metric structure on $Y_{\Pi}$. This allows for a unified computer search to look for counterexamples to the two Kaplansky conjectures. We finish with a general program on how to look for units and zero-divisors, in section 7.2.

This article combines five areas of mathematics: using topology and geometry, algebraic problems are translated into combinatorial questions about graphs that can be verified by computational means. It is the author’s hope and belief that a computer search should be able to find examples satisfying the combinatorial conditions of section 7.1 and therefore provide multiple examples of groups with nontrivial units and zero-divisors, or that this general approach can be modified to enable finding counterexamples computationally. A negative computational result would also be of interest from a geometric viewpoint: if one
checks computationally that for a given size \((m, n)\) there are no product structures satisfying the combinatorial conditions, this shows that no 2-complexes \(Y_{11}\) or \(\bar{Y}_{11}\) of this particular size \((m, n)\) admit certain polyhedral metric structures of curvature \(\leq 0\).

The partition illustrated in Fig. 2 below is a result of the ongoing computational project in collaboration with Manisha Garg and Haizi Yu. The project is devoted to designing various algorithms and performing searches to look for product structures satisfying the combinatorial conditions described in section 7.1 below, and therefore, for counterexamples to the unit and zero-divisor conjectures. The methods and results of the computation will be published in a subsequent article.

Another outcome of this project is the author’s ongoing joint activity with students at the University of Illinois to develop and keep improving the “ColorTaiko!” computer game, based on the taikos (= product graphs) defined in section 2.6 below. A player will draw pairs of edges in a bipartite graph, consecutively. The game will color the edges at each step and check whether certain combinatorial conditions are satisfied (as in section 7.1). The goal is to progress as much as possible towards creating a full partition of the edges in the complete bipartite graph. The goal of writing the game is to popularize Kaplansky conjectures to the general public and to engage students in research. Eventually, the “ColorTaiko!” game will be available to the public on the author’s website and elsewhere.

Full disclosure: the research presented in this article is expressly not supported by the National Science Foundation. The author’s proposal to write this article, to perform computational search for counterexamples to the Kaplansky conjectures and to develop the “ColorTaiko!” computer game was declined in February 2024 by the Topology program at the NSF. The reviewers and the panel did not count “the research itself” as “broader impact” contrary to the policies and procedures guide, stated – in spite of the existing Gardam counterexample to the unit conjecture – that “it would be helpful if the PI provided more context as to why they believe these conjectures to be false”, that “the panel found the proposed research to be innovative, but speculative and would have liked to see more evidence that counterexamples would be found using this approach”, that “some panelists had additional concerns that the outcomes would have minimal impact beyond the scope of the proposed problems”, and that “the proposal would have been stronger if had more clearly addressed the potential societal outcomes that would result from the activities described”.

2. Combinatorial notions describing units and zero-divisors

2.1. Product structures and product substructures. Let \(\mathcal{G}(A, B)\) denote the complete bipartite graph on two finite sets \(A\) and \(B\). The numbers \(m\) and \(n\) will always denote the cardinalities of \(A\) and \(B\), respectively. We will identify the edges in \(\mathcal{G}(A, B)\), which we will call the vertical edges, with the elements of the cartesian product \((a, b) \in A \times B\). A product structure is a triple \(\Pi = (A, B, P)\) in which

- \(A = \{a_1, \ldots, a_m\}\) and \(B = \{b_1, \ldots, b_n\}\) are finite sets,
- \(P\) is a partition of the set of edges in \(\mathcal{G}(A, B)\), that is, of the set \(A \times B\), such that any two distinct edges \((a, b), (a', b') \in A \times B\) belonging to a cell of the partition \(P\) have no
common vertices, i.e.,
\[ \forall C \in P \ (a, b), (a', b') \in C \quad ((a, b) \neq (a', b') \Rightarrow (a \neq a' \text{ and } b \neq b')) . \]

A product substructure is a triple \( \Pi = (A, B, P) \) in which

- \( A = \{a_1, \ldots, a_m\} \) and \( B = \{b_1, \ldots, b_n\} \) are finite sets,
- \( P \) is a subpartition of the set \( A \times B \), i.e., a family of subsets in \( A \times B \) such that

\[
\forall C_1, C_2 \in P \quad (C_1 \neq C_2 \Rightarrow C_1 \cap C_2 = \emptyset),
\]

\[
\forall C \in P \ (a, b), (a', b') \in C \quad ((a, b) \neq (a', b') \Rightarrow (a \neq a' \text{ and } b \neq b')) .
\]

Clearly, each product structure is a product substructure. The pair \((m, n)\) will be called the size of \( \Pi \).

Let \( P \) be a partition or a subpartition. \( P \) will be called even if each cell in \( P \) has exactly two elements. We will call such cells 2-cells. \( P \) will be called odd if it has exactly one cell having one element (1-cell) and all other cells are 2-cells.

For the purpose of studying zero-divisors in group algebras of the form \( \mathbb{Z}_2 G \), Schweitzer [32] considered partitions of the set \( \{(i, j) \mid i \in \{1, \ldots, n\}, j \in \{1, \ldots, m\}\} \) into pairs, and he defined the related matched rectangles as a means of illustrating such partitions. Our product structure notion is similar in spirit, but is more general since it applies both to zero-divisors and to units, and we additionally require that the two edges in each 2-cell have no common vertices. The corresponding notion of \( \text{taiko} \) (the product graph) that we introduce in section 2.6 is a different way to illustrate units and zero-divisors; it is suitable for illuminating both the combinatorial and topological/geometric nature of our approach.

2.2. Signatures. A signature on a product structure \( (A, B, P) \) is a function \( \sigma : A \sqcup B \to \{1, -1\} \) such that for each 2-cell \( \{(a_i, b_j), (a'_i, b'_j)\} \) of the partition \( P \), \( \sigma(a_i) \sigma(b_j) = -\sigma(a'_i) \sigma(b'_j) \).

Here one should think of \( \{1, -1\} \) as being a subset of \( R \), where \( R \) is any ring with unity 1. A product structure with signature is a quadruple \( \Pi^\pm = (A, B, P, \sigma) \) such that \( (A, B, P) \) is a product structure and \( \sigma \) is a signature on \( (A, B, P) \).

2.3. Group rings. As the name suggests, a product structure is a tool describing the structure of products in group rings. \( \mathbb{Z}_2 \) will denote the field of order 2. Given any group \( G \), each pair of elements in the group algebra \( \mathbb{Z}_2 G \),
\[
a = \sum_{i=1}^{m} a_i, \quad b = \sum_{j=1}^{n} b_j, \quad a_i, b_j \in G \subseteq \mathbb{Z}_2 G,
\]

naturally leads to the product structure \( \{(a_1, \ldots, a_m), (b_1, \ldots, b_n), P\} \), where \( P \) is the partition of \( \{a_1, \ldots, a_m\} \times \{b_1, \ldots, b_n\} \) into the equivalence classes under the equivalence relation
\[
(a_i, b_j) \sim (a'_i, b'_j) \iff a_i b_j = a'_i b'_j .
\]

If, in addition, \( ab = 1 \) or \( ab = 0 \), then this partition \( P \) admits a refinement \( P' \) that is odd or even, respectively. Conversely, we will see in sections 3.5 and 3.6 below how certain product structures lead to groups \( \tilde{G}_{11} \) and to certain associated elements \( a_{11} \) and \( b_{11} \) in group rings \( \mathbb{Z}_2 \tilde{G}_{11} \) or \( \mathbb{R} \tilde{G}_{11} \). These elements are units if \( mn \) is odd and zero-divisors if \( mn \) is even.
The important and difficult questions are: when is the group $\Gamma$ torsion-free and when are $a_{11}$ and $b_{11}$ nontrivial? These properties are necessary to guarantee that a given product structure $\Pi$ indeed leads to a counterexample to the unit or zero-divisor conjectures. We will address these questions in theorems 10 and 23 below, by topological and geometric means. First, let us present a convenient way of illustrating product structures.

**Product structure example 1:**

\[
\{(a_4, b_5), (a_5, b_5)\}, \{(a_6, b_4), (a_7, b_3)\}, \{(a_1, b_1), (a_2, b_9)\}, \{(a_6, b_5), (a_7, b_4)\}, \\
\{(a_1, b_2), (a_2, b_1)\}, \{(a_5, b_6), (a_7, b_5)\}, \{(a_1, b_3), (a_3, b_1)\}, \{(a_4, b_9), (a_5, b_8)\}, \\
\{(a_6, b_7), (a_7, b_6)\}, \{(a_1, b_4), (a_2, b_3)\}, \{(a_3, b_2), (a_4, b_1)\}, \{(a_6, b_8), (a_7, b_7)\}, \\
\{(a_1, b_5), (a_2, b_4)\}, \{(a_4, b_2), (a_7, b_8)\}, \{(a_3, b_6), (a_5, b_4)\}, \{(a_4, b_3), (a_5, b_9)\}, \\
\{(a_1, b_7), (a_2, b_6)\}, \{(a_3, b_5), (a_4, b_4)\}, \{(a_5, b_1), (a_6, b_9)\}, \{(a_1, b_8), (a_2, b_7)\}, \\
\{(a_4, b_5), (a_5, b_2)\}, \{(a_6, b_1), (a_7, b_9)\}, \{(a_2, b_2), (a_3, b_9)\}, \{(a_5, b_7), (a_6, b_6)\}, \\
\{(a_2, b_5), (a_3, b_3)\}, \{(a_2, b_8), (a_3, b_6)\}, \{(a_6, b_2), (a_7, b_1)\}, \{(a_3, b_7), (a_4, b_6)\}, \\
\{(a_5, b_3), (a_7, b_2)\}, \{(a_3, b_8), (a_4, b_7)\}, \{(a_5, b_4), (a_6, b_3)\}.
\]

**Figure 1.** Size $(m, n) = (7, 9)$. Taiko (the product graph). The 1-cell of the partition is $\{(a_1, b_9)\}$. The 31 2-cells of the partition are split into 6 colors. There are no folds. Some patterns repeat.

**Product structure example 2:**

\[
\{(a_1, b_1), (a_2, b_2)\}, \{(a_1, b_2), (a_2, b_3)\}, \{(a_2, b_1), (a_3, b_3)\}, \{(a_4, b_1), (a_1, b_3)\}, \\
\{(a_3, b_1), (a_5, b_4)\}, \{(a_3, b_2), (a_4, b_4)\}, \{(a_1, b_4), (a_6, b_5)\}, \{(a_2, b_4), (a_7, b_3)\}, \\
\{(a_3, b_4), (a_6, b_3)\}, \{(a_3, b_5), (a_4, b_2)\}, \{(a_4, b_3), (a_7, b_5)\}, \{(a_5, b_1), (a_1, b_5)\}, \\
\{(a_5, b_2), (a_7, b_4)\}, \{(a_5, b_3), (a_8, b_5)\}, \{(a_8, b_1), (a_2, b_5)\}, \{(a_8, b_4), (a_4, b_5)\}, \\
\{(a_5, b_5), (a_7, b_2)\}, \{(a_6, b_1), (a_8, b_2)\}, \{(a_6, b_2), (a_8, b_3)\}, \{(a_7, b_1), (a_6, b_4)\}. 
\]
2.4. **Horizontal edges.** Given a product structure or substructure \( \Pi \), by the horizontal edges of \( \Pi \) we will mean the elements of the sets below; they come from the 2-cells in the partition \( P \).

\[
\begin{align*}
\tilde{E}_A &:= \{ \{a,a'\} \in \tilde{E}_A \mid \exists b, b' \in B \ \{ (a,b),(a',b') \} \in P \}, \\
\tilde{E}_B &:= \{ \{b,b'\} \in \tilde{E}_B \mid \exists a, a' \in A \ \{ (a,b),(a',b') \} \in P \}, \\
\tilde{E}_{AB} &:= \tilde{E}_A \sqcup \tilde{E}_B, \\
E_A &:= \{ (a,a') \in E_A \mid \exists b, b' \in B \ \{ (a,b),(a',b') \} \in P \}, \\
E_B &:= \{ (b,b') \in E_B \mid \exists a, a' \in A \ \{ (a,b),(a',b') \} \in P \}, \\
E_{AB} &:= E_A \sqcup E_B.
\end{align*}
\]

An orientation on \( \Pi \) is a function \( O : \tilde{E}_{AB} \to E_{AB} \) such that

- for each \( \{a,a'\} \in \tilde{E}_A \), \( O(\{a,a'\}) = (a,a') \) or \( O(\{a,a'\}) = (a',a) \),
- for each \( \{b,b'\} \in \tilde{E}_B \), \( O(\{b,b'\}) = (b,b') \) or \( O(\{b,b'\}) = (b',b) \), and
- for each 2-cell \( \{(a,b),(a',b')\} \in P \),
  \[
  (O(\{a,a'\}) = (a,a') \) and \( O(\{b,b'\}) = (b,b') \) or
  \[
  (O(\{a,a'\}) = (a',a) \) and \( O(\{b,b'\}) = (b',b) \).
  \]

We will say that a product substructure \( \Pi \) is **orientable**, or that \( \Pi \) satisfies the orientation condition, if there exists an orientation on \( \Pi \).

2.5. **Bottom graph** \( L_A \), **top graph** \( L_B \). Given a subproduct structure \( \Pi = (A,B,P) \) in which \( P \) is either even or odd, the **bottom graph** \( L_A \) is the unoriented graph whose vertex set is \( A \)
and the set of edges is $\mathcal{E}_{1A}$ (the bottom horizontal edges). The top graph $L_B$ is the unoriented graph whose vertex set is $B$ and the set of edges is $\mathcal{E}_{1B}$ (the top horizontal edges). Denote $L_{AB} := L_A \sqcup L_B$.

If, in addition, the subproduct structure $\Pi$ admits an orientation $O : \tilde{\mathcal{E}}_\Pi \to \mathcal{E}_{AB}$, then the bottom graph $L_A$ can be viewed as an oriented graph whose vertex set is $A$ and the set of edges is $O(\mathcal{E}_{1A})$. Similarly, the top graph $L_B$ can be viewed as an oriented graph whose vertex set is $B$ and the set of edges is $O(\mathcal{E}_{1B})$. This turns $L_{AB}$ into an oriented graph whose set of edges is $O(\mathcal{E}_{\Pi})$.

2.6. Taiko, the product graph. Suppose a subproduct structure $\Pi = (A, B, P)$ is given whose subpartition $P$ is either even or odd. The taiko for $\Pi$, or the product graph for $\Pi$, is the picture illustrating $\Pi$ by placing $A$ on the bottom, $B$ on the top, drawing a vertical edge $(a, b) \in A \times B$ whenever there exists a 2-cell in $P$ containing $(a, b)$, and adding all the horizontal edges from the set $\tilde{\mathcal{E}}_\Pi$.

Furthermore, colors are used in taikos to indicate those horizontal edges that simultaneously occur in 2-cells of the partition $P$. More precisely, a color of horizontal edges is an equivalence class of unoriented horizontal edges, where the equivalence relation $\sim$ is the one generated by the relation $\sim'$: for two horizontal edges $\{a, a'\}$ and $\{b, b'\}$ we write $\{a, a'\} \sim' \{b, b'\}$ if there is a 2-cell in the partition $P$ of the form $\{(a, b), (a', b')\}$ or $\{(a, b'), (a', b)\}$. With this definition, the 2-cells in $\tilde{\mathcal{E}}_\Pi$ naturally inherit the same colors as their horizontal edges have, that is, there is a consistent coloring of 2-cells and horizontal edges. If there exists an orientation on $\tilde{\mathcal{E}}_\Pi$, we indicate it by placing an arrow on each unoriented horizontal edge as in Figures 1 and 2.

Figure 1 illustrates a particular Bass unit over a particular finite cyclic group (which clearly does have torsion). The size of the unit is $(m, n) = (7, 9)$ and the partition coming from that unit was further subdivided to make it odd. Figure 2 illustrates a particular product structure obtained by a computer search.

3. The topology of units and zero-divisors: cell complexes and origami.

For each product structure $\Pi$ we define 2-dimensional cell complexes $X_{\Pi}$, $Y_{\Pi}$, $\tilde{X}_{\Pi}$, $\tilde{Y}_{\Pi}$ by an origami-like construction, by putting together several pieces of paper and folding them in a certain way.

3.1. The complex $X_{\Pi}$. To each product structure $\Pi = (A, B, P)$, where $A = \{a_1, \ldots, a_m\}$ and $B = \{b_1, \ldots, b_n\}$, we associate a cell complex $X_{\Pi}$ as follows. First consider the oriented graph with three vertices $x_A$, $x_1$, $x_B$, and two sets of oriented edges:

- the set of edges labeled by $a_1, \ldots, a_m$, each going from $x_A$ to $x_1$,
- the set of edges labeled by $b_1, \ldots, b_n$, each going from $x_1$ to $x_B$.

The 2-dimensional cell complex $X_{\Pi}$ is defined by attaching, for each 2-cell $\{(a_i, b_j), (a_i', b_j')\}$, one square along the loop $a_i b_j b_j^{-1} a_i^{-1}$ in the graph (see Fig. 3). (In this way, the “2-cells” of the partition $P$ exactly correspond to the “2-cells” in the cell complex $X_{\Pi}$.) $G_{\Pi}$ will denote the
fundamental group of $X_{\Pi}$ with basepoint $x_1$. $G_{\Pi}$ will be called the universal group associated with the product structure $\Pi$.

3.2. The complex $Y_{\Pi}$. The next complex, $Y_{\Pi}$, is obtained from $X_{\Pi}$ by performing 2-foldings (or origami) as follows. First, for each 2-cell $\{(a_i, b_j), (a_i', b_{j'})\}$ in the partition $P$ draw an edge $e_{jj'}^{ii''}$ going from $x_1$ to $x_1$ within the corresponding 2-cell in $X_{\Pi}$, as illustrated in Fig 3. Such $e_{jj'}^{ii''}$ will be called the middle edges. The same edge $e_{jj'}^{ii''}$ considered with the opposite orientation will be denoted $(e_{jj'}^{ii''})^{-1}$. Next, whenever there are two 2-cells in the partition $P$ of the form $\{(a_i, b_j), (a_i', b_{j'})\}$ and $\{(a_i', b_{j''}), (a_i, b_{j'''})\}$,

- identify the interiors of the two bottom triangles labeled $a_i^{-1}a_i'(e_{ii''}^{jj'})^{\varepsilon_1}$ and $a_i^{-1}a_i'(e_{ii''}^{jj''})^{\varepsilon_2}$, where $\varepsilon_1, \varepsilon_2 \in \{1, -1\}$,
- identify the edges $e_{ii''}^{jj'}$ and $e_{ii''}^{jj''}$ if they have the same orientation in the sense that $\varepsilon_1 = \varepsilon_2$, and
- identify the edge $e_{ii''}^{jj'}$ with the edge opposite to $e_{ii''}^{jj''}$ if $e_{ii''}^{jj'}$ and $e_{ii''}^{jj''}$ have opposite orientations, that is, if $\varepsilon_1 = -\varepsilon_2$.

Similarly, whenever there are two 2-cells in the partition $P$ of the form $\{(a_i, b_j), (a_i', b_{j'})\}$ and $\{(a_i', b_{j''}), (a_i, b_{j'''})\}$, identify the two top triangles labeled $b_jb_{j''}^{-1}(e_{ii''}^{jj'})^{\varepsilon_1}$ and $b_jb_{j''}^{-1}(e_{ii''}^{jj''})^{\varepsilon_2}$. Keep performing such identifications for as long as possible. We let $Y_{\Pi}$ be the 2-complex obtained at the end of this process.

It can be checked that the links of the vertices $x_A$ and $x_B$ in $Y_{\Pi}$ are isomorphic to $L_A$ and $L_B$ – the bottom and top horizontal subgraphs of the taiko, respectively. For this reason $L_A$ and $L_B$ can also be called the bottom link and the top link, respectively.
3.3. **Middle links and patterns.** Let $\Pi$ be an orientable product structure or substructure. The middle link of $X_{\Pi}$ is the link of the middle vertex $x_1$ in $X_{\Pi}$. It can be seen from Fig. 3 that it has a natural structure of a bipartite graph on the vertex set $A \sqcup B$, and is isomorphic to the subgraph of the taiko formed by all its vertices and vertical edges $(a_i, b_j)$. For this reason, the taiko for $\Pi$ can also be called the X-taiko for $\Pi$.

By the middle link of $\Pi$, denoted $L_1$, we will mean the middle link of the complex $Y_{\Pi}$, that is, the link of the middle vertex $x_1$ in $Y_{\Pi}$. Since $Y_{\Pi}$ is obtained from $X_{\Pi}$ by 2-foldings, then $L_1$ can be obtained from the middle link of $X_{\Pi}$ by adding the midpoint to each vertical edge, therefore subdividing it in half (which corresponds to drawing the horizontal edge $e_{ij}$ in each 2-cell of $X_{\Pi}$), and then folding certain pairs of half-edges into one half-edge in accordance with the 2-foldings in $X_{\Pi}$. After all foldings, the additional vertices coming from the midpoints will one-to-one correspond to the ends of all horizontal edges in $Y_{\Pi}$. That is, these additional vertices can be labeled by pairs $(c, d)$, where $c$ is an equivalence class of horizontal edges in the taiko (or, equivalently, a horizontal edge in $Y_{\Pi}$) and $d \in \{in, out\}$.

The Y-taiko for $\Pi$ is the colored graph obtained from the X-taiko for $\Pi$ by performing these same operations – dividing in half and folding – on its vertical edges. In this way, the middle part of the X-taiko (the middle link of $X_{\Pi}$) is replaced with $L_1$, while the bottom graph $L_A$ and the top graph $L_B$ stay unchanged. This means that the Y-taiko for $\Pi$ illustrates the three links of the complex $Y_{\Pi}$: the bottom link $L_A$, the middle link $L_1$, and the top link $L_B$ (see Fig. 4 and 5).

A simplified version of the middle link, denoted $L_1^{sim}$, also might be useful for illustration. It is defined as the graph whose vertices are the pairs $(c, d)$ as above and the edges are the patterns occurring in $L_A$ and $L_B$ (see Fig. 6).
Figure 4. $(m, n) = (7, 9)$. The $Y$-taiko corresponding to the $X$-taiko in Fig. 1. Crosses (arrow tails) represent out and dots (arrow tips) represent in.

Figure 5. $(m, n) = (8, 5)$. The $Y$-taiko corresponding to the $X$-taiko in Fig. 2.
3.4. The complexes $X_{\Pi}$ and $Y_{\Pi}$. The complex $X_{\Pi}$ is obtained from $X_{\Pi}$ by identifying the three vertices $x_A$, $x_1$ and $x_B$ into one vertex $\bar{x}_0$. The complex $Y_{\Pi}$ is defined similarly: starting with the complex $Y_{\Pi}$, identify the vertices $x_A$, $x_1$ and $x_B$ into one vertex $\bar{y}_0$. The fundamental group of $\bar{X}_{\Pi}$ will be denoted $\bar{G}_{\Pi}$ and will be called the full universal group of the product structure $\Pi$. In this quotient, the edges $a_i$ and $b_j$ become loops, so they represent elements of $\bar{G}_{\Pi}$, which we will also denote $a_i$ and $b_j$, respectively.

$\bar{X}_{\Pi}$ can be equivalently described as the presentation complex of the presentation

$$\langle a_1, \ldots, a_m, b_1, \ldots, b_n \mid a_i^{-1}a_i'b_jb_j^{-1} \text{ for } \{(a_i, b_j), (a_i', b_j')\} \in P \rangle.$$ 

By the van Kampen theorem, the group given by the above presentation is isomorphic to $\bar{G}_{\Pi}$.

This presentation and its corresponding group seem to be folklore, having occurred in multiple places in the literature and on the internet; see, for example, [34], [21], [32].

3.5. Associated units and zero-divisors over $\mathbb{Z}_2$. Let $\Pi = (A, B, P)$ be a product structure in which the partition $P$ is either odd or even. Let $\bar{a}_i$ and $\bar{b}_j$ denote the elements of $\bar{G}_{\Pi} \cong \pi_1(\bar{X})$ represented by the edge-loops labeled $a_i$ and $b_j$, respectively.

Assume that $mn$ is odd and $P$ is odd. After relabeling we can assume that $\{(a_1, b_1)\}$ is the unique 1-cell in the partition $P$. Denote

$$a_{\Pi} := \bar{b}_1^{-1}\bar{a}_1^{-1} \sum_{i=1}^{m} \bar{a}_i = \sum_{i=1}^{m} \bar{b}_1^{-1}\bar{a}_1^{-1}\bar{a}_i \in \mathbb{Z}_2\bar{G}_{\Pi}, \quad b_{\Pi} := \sum_{j=1}^{n} \bar{b}_j \in \mathbb{Z}_2\bar{G}_{\Pi}.$$ 

For each 2-cell $\{(a_i, b_j), (a_i', b_j')\}$ in the partition $P$, the edge-loops in $\bar{X}_{\Pi}$ labeled $a_i b_j$ and $a_{i'} b_{j'}$ are homotopic because the loop $a_i b_j b_{j'}^{-1} a_{i'}^{-1}$ bounds a (topological) 2-cell. This means that $\bar{a}_i \bar{b}_j = \bar{a}_i' \bar{b}_{j'}$ for each 2-cell $\{(a_i, b_j), (a_{i'}, b_{j'})\} \in P$, therefore, $\bar{a}_i \bar{b}_j + \bar{a}_{i'} \bar{b}_{j'} = 0 \in \mathbb{Z}_2\bar{G}_{\Pi}$. 

\textbf{Figure 6.} The simplified middle links corresponding to the X-taikos in Fig. 1 and Fig. 2, respectively. Lime edges are patterns occurring once. Apricot edges are patterns occurring at least twice.
Then
\[
a_{II}b_{II} = \bar{b}_{1}^{-1} \bar{a}_{1}^{-1} \sum_{i=1}^{m} \bar{a}_{i} \sum_{j=1}^{n} \bar{b}_{j}
\]
\[
= \bar{b}_{1}^{-1} \bar{a}_{1}^{-1} \left( \bar{a}_{1} \bar{b}_{1} + \sum_{\{(a_{i}, b_{j}), (a_{i}, b_{j'})\} \in P} (\bar{a}_{i} \bar{b}_{j} + \bar{a}_{i} \bar{b}_{j'}) \right) = \bar{b}_{1}^{-1} \bar{a}_{1}^{-1} \bar{a}_{1} \bar{b}_{1} = 1 \in \mathbb{Z}_{2}G_{II},
\]
i.e., \(a_{II}\) and \(b_{II}\) are units. They will be called the units in \(\mathbb{Z}_{2}G_{II}\) associated with \(\Pi\).

If \(mn\) is even and \(P\) even, denote
\[
a_{II} := \sum_{i=1}^{m} \bar{a}_{i} \in \mathbb{Z}_{2}G_{II}, \quad b_{II} := \sum_{j=1}^{n} \bar{b}_{j} \in \mathbb{Z}_{2}G_{II}.
\]
Since \(P\) is an even partition,
\[
a_{II}b_{II} = \sum_{i=1}^{m} \sum_{j=1}^{n} \bar{a}_{i} \bar{b}_{j} = \sum_{\{(a_{i}, b_{j}), (a_{i}, b_{j'})\} \in P} (\bar{a}_{i} \bar{b}_{j} + \bar{a}_{i} \bar{b}_{j'}) = 0 \in \mathbb{Z}_{2}G_{II},
\]
i.e. \(a_{II}\) and \(b_{II}\) are zero-divisors. They will be called the zero-divisors in \(\mathbb{Z}_{2}G_{II}\) associated with the product structure \(\Pi\).

Lemma 1. If a product structure \(\Pi\) is nondegenerate and \(P\) is either odd or even, then \(|\text{supp}(a_{II})| = m\) and \(|\text{supp}(b_{II})| = n\).

Proof. Assume that \(mn\) is odd and \(P\) is odd. If \(\Pi\) is nondegenerate, then the elements \(\bar{b}_{1}^{-1}, \bar{b}_{1}^{-1} \bar{a}_{1}^{-1} \bar{a}_{2}, \ldots, \bar{b}_{1}^{-1} \bar{a}_{1}^{-1} \bar{a}_{n} \in G_{II}\) are pairwise distinct and the elements \(\bar{b}_{1}, \ldots, \bar{b}_{n} \in G_{II}\) are pairwise distinct. This implies that the supports of \(a_{II}\) and \(b_{II}\) are the sets
\[
\text{supp}(a_{II}) = \{\bar{b}_{1}^{-1}, \bar{b}_{1}^{-1} \bar{a}_{1}^{-1} \bar{a}_{2}, \ldots, \bar{b}_{1}^{-1} \bar{a}_{1}^{-1} \bar{a}_{n}\}, \quad \text{supp}(b_{II}) = \{\bar{b}_{1}, \ldots, \bar{b}_{n}\}
\]
and \(|\text{supp}(a_{II})| = m, |\text{supp}(b_{II})| = n\).

Now assume that \(mn\) is even and \(P\) is even. If \(\Pi\) is nondegenerate, then the elements \(\bar{a}_{1}, \ldots, \bar{a}_{m} \in G_{II}\) are pairwise distinct and the elements \(\bar{b}_{1}, \ldots, \bar{b}_{n} \in G_{II}\) are pairwise distinct. This implies that the supports of \(a_{II}\) and \(b_{II}\) are the sets
\[
\text{supp}(a_{II}) = \{\bar{a}_{1}, \ldots, \bar{a}_{m}\}, \quad \text{supp}(b_{II}) = \{\bar{b}_{1}, \ldots, \bar{b}_{n}\}
\]
and \(|\text{supp}(a_{II})| = m, |\text{supp}(b_{II})| = n\). \(\square\)

3.6. Associated units and zero-divisors over any ring with unity. If \(\Pi^{\sigma} = (A, B, P, \sigma)\) is a product structure with signature in which \(P\) is either odd or even, then we can produce associated units and zero-divisors in the algebra \(RG_{II}\) over any ring \(R\) with unity, as follows.
First let \( \Pi := (A, B, P) \) and, as before, let \( \hat{G}_\Pi \) be the corresponding full universal group. If \( mn \) is odd and \( P \) is odd, we can assume that \( \{(a_1, b_1)\} \) is the unique 1-cell in \( P \) and let

\[
a_{\Pi} := \bar{b}_1^{-1}\bar{a}_1^{-1} \sum_{i=1}^{m} \sigma(a_i)\bar{a}_i = \sum_{i=1}^{m} \sigma(a_i)(\bar{b}_1^{-1}\bar{a}_1^{-1}\bar{a}_i) \in R\hat{G}_\Pi,
\]

\[
b_{\Pi} := \sum_{j=1}^{n} \sigma(b_j)\bar{b}_j \in R\hat{G}_\Pi,
\]

then

\[
a_{\Pi}b_{\Pi} = \bar{b}_1^{-1}\bar{a}_1^{-1} \sum_{i=1}^{m} \sum_{j=1}^{n} (\sigma(a_i)\sigma(b_j))(\bar{a}_i\bar{b}_j)
\]

\[
= \bar{b}_1^{-1}\bar{a}_1^{-1}\left( \bar{a}_1\bar{b}_1 + \sum_{\{(a_i, b_j)\}} \left((\sigma(a_i)\sigma(b_j))(\bar{a}_i\bar{b}_j) + (\sigma(a_{\bar{i}})\sigma(b_{\bar{j}}))\bar{a}_{\bar{i}}\bar{b}_{\bar{j}}) \right) \right)
\]

\[
= \bar{b}_1^{-1}\bar{a}_1^{-1}\left( \bar{a}_1\bar{b}_1 + \sum_{\{(a_i, b_j)\}} (\sigma(a_i)\sigma(b_j))(\bar{a}_i\bar{b}_j - \bar{a}_{\bar{i}}\bar{b}_{\bar{j}}) \right)
\]

\[
= \bar{b}_1^{-1}\bar{a}_1^{-1}\bar{a}_1\bar{b}_1 = 1 \in R\hat{G}_\Pi,
\]

i.e., \( a_{\Pi} \) and \( b_{\Pi} \) are units in \( R\hat{G}_\Pi \), which we will call the units over \( R \) associated with \( \Pi^\sigma \).

If \( mn \) is even and \( P \) is even, let

\[
a_{\Pi} := \sum_{i=1}^{m} \sigma(a_i)\bar{a}_i \in R\hat{G}_\Pi, \quad b_{\Pi} := \sum_{i=1}^{m} \sigma(b_j)\bar{b}_j \in R\hat{G}_\Pi,
\]

then

\[
a_{\Pi}b_{\Pi} = \sum_{i=1}^{m} \sum_{j=1}^{n} (\sigma(a_i)\sigma(b_j))(\bar{a}_i\bar{b}_j)
\]

\[
= \sum_{\{(a_i, b_j)\}} \left((\sigma(a_i)\sigma(b_j))\bar{a}_i\bar{b}_j + (\sigma(a_{\bar{i}})\sigma(b_{\bar{j}}))\bar{a}_{\bar{i}}\bar{b}_{\bar{j}}) \right)
\]

\[
= \sum_{\{(a_i, b_j)\}} (\sigma(a_i)\sigma(b_j))(\bar{a}_i\bar{b}_j - \bar{a}_{\bar{i}}\bar{b}_{\bar{j}}) = 0 \in R\hat{G}_\Pi,
\]

i.e., \( a_{\Pi} \) and \( b_{\Pi} \) are zero-divisors in \( R\hat{G}_\Pi \), which we will call the zero-divisors over \( R \) associated with \( \Pi^\sigma \). The proof of the following lemma is similar to the proof of Lemma \( \Pi \).

**Lemma 2.** If a product structure with signature \( \Pi^\sigma \) is nondegenerate, then \( |\text{supp}(a_{\Pi})| = m \) and \( |\text{supp}(b_{\Pi})| = n \).
3.7. The fundamental groups of $X_{II}$, $Y_{II}$, $X_{III}$, $Y_{III}$. We have the following diagrams for the four complexes and their fundamental groups

\[
\begin{array}{ccc}
X_{II} & \xrightarrow{q_{II}} & Y_{II} \\
\downarrow q_x & & \downarrow q_Y \\
X_{III} & \xrightarrow{q_{III}} & Y_{III}
\end{array}
\]

\[
\begin{array}{ccc}
G_{II} = \pi_1(X_{II}) & \xrightarrow{q_{II_1}} & \pi_1(Y_{II}) \\
\downarrow q_{X_1} & & \downarrow q_{Y_1} \\
G_{III} = \pi_1(X_{III}) & \xrightarrow{q_{III_1}} & \pi_1(Y_{III})
\end{array}
\]

(1)

where $q_x$, $q_y$, $q_{III}$, $q_{III_1}$ are the canonical quotient maps. The maps $q_x$, $q_y$, $q_{III}$ are given by the definitions of the corresponding complexes, and $q_{III_1}$ is defined by performing the 2-foldings on the complex $X_{III}$ in parallel to the 2-foldings on $X_{II}$ in the definition of $Y_{II}$. The homomorphisms $q_{X_1}$, $q_{Y_1}$, $q_{III_1}$, $q_{III_1}$ are the corresponding induced homomorphisms.

Lemma 3. The following properties hold for each product structure $\Pi$.

(a) The diagrams in (1) are commutative.
(b) The full universal group $G_{II} = \pi_1(X_{II})$ is isomorphic to the free product $G_{II} \ast F_2$, where $F_2$ is the free group of rank 2. With the identification $\tilde{G}_{II} \cong G_{II} \ast F_2$, the homomorphism $q_{X_1} : G_{II} \to \tilde{G}_{II}$ induced by the quotient map $q_x : X_{II} \to X_{III}$ is the same as the standard inclusion $G_{III} \hookrightarrow G_{II} \ast F_2$ onto the factor $G_{II}$. In particular, $q_{X_1}$ is injective.
(c) The group $\pi_1(Y_{II})$ is isomorphic to the free product $\pi_1(Y_{II}) \ast F_2$. With the identification $\pi_1(Y_{II}) \cong \pi_1(Y_{II}) \ast F_2$, the homomorphism $q_{Y_1} : \pi_1(Y_{II}) \to \pi_1(Y_{III})$ induced by the quotient map $q_y : Y_{II} \to Y_{III}$ is the same as the standard inclusion $\pi_1(Y_{III}) \hookrightarrow \pi_1(Y_{II}) \ast F_2$ onto the factor $\pi_1(Y_{II})$. In particular, $q_{Y_1}$ is injective.

Proof: (a) The left diagram commutes because the 2-foldings in $X_{II}$ and in $X_{III}$ do not affect their vertices. The right diagram commutes because it is induced by the left one.

(b) $X_{III}$ is obtained from $X_{II}$ by identifying three vertices $x_A$, $x_1$, and $x_B$ into one. This operation can be split into two steps: first attach two edges connecting $x_A$ to $x_1$ and $x_1$ to $x_B$, respectively, then collapse these edges to a point. The second step is a homotopy equivalence, and, since $X_{II}$ is path-connected, the result of the first step is homotopy equivalent to the wedge sum of $X_{II}$ with two circles, $X_{II} \vee S^1 \vee S^1$. Then by the van Kampen theorem,

$$G_{III} = \pi_1(X_{III}) \cong \pi_1(X_{II} \vee S^1 \vee S^1) \cong \pi_1(X_{II}) \ast F_2 = G_{II} \ast F_2.$$

The proof of (c) is similar. \hfill \Box

3.8. When $\pi_1(Y_{II}) \cong \pi_1(X_{II})$ and $\pi_1(Y_{III}) \cong \pi_1(X_{III})$. In general, the 2-foldings used to obtain $Y_{II}$ and $Y_{III}$ do not necessarily preserve the homotopy type, but we now show that they do preserve the fundamental group if $\Pi$ is orientable as defined in section 2.4.

Lemma 4. If $\Pi$ is orientable, then $\pi_1(Y_{II}) \cong \pi_1(X_{II}) = G_{II}$ and $\pi_1(Y_{III}) \cong \pi_1(X_{III}) = G_{III}$, and the homomorphisms $q_{II_1}$ and $q_{III_1}$ in diagram (1) are isomorphisms.

Proof: $Y_{II}$ is obtained from $X_{II}$ by performing 2-foldings. Since $\Pi$ is orientable, there is a consistent orientation of the middle edges, hence at each step a 2-folding is of one of the following two types:
The edges drawn on the bottom represent some middle edges (or their images after gluing). The two vertices of each middle edge actually coincide in $X_{\Pi}$; we draw them distinct in the picture to illustrate the 2-foldings clearly.

The 2-folding of type 1, pictured on the left, is a homotopy equivalence, so it does not change the fundamental group. The 2-folding of type 2, pictured on the right, can be equivalently described as follows. The two triangles share all their three sides, so that their union $V$ is homeomorphic to the 2-sphere. First attach a closed 3-disk $D^3$ to $V$ by identifying its boundary with $V$ by a homeomorphism. Attaching a 3-ball is not a homotopy equivalence, but it preserves the fundamental group, by the Van Kampen theorem, because both $D^3$ and the image of its boundary $S^2$ are simply connected. Then collapse the attached 3-disk so that the two triangles are identified. This operation is a homotopy equivalence, so we have an isomorphism $\pi_1(Y_{\Pi}) \cong \pi_1(X_{\Pi}) = G_{\Pi}$.

To prove the existence of an isomorphism $\pi_1(\bar{Y}_{\Pi}) \cong \pi_1(\bar{X}_{\Pi}) = \bar{G}_{\Pi}$, perform the same 2-foldings on $\bar{X}_{\Pi}$ to obtain $\bar{Y}_{\Pi}$. The same argument applies. \qed

If $\Pi$ is not orientable, after performing 2-foldings some middle edge $e$ in the above figure will eventually be identified with its inverse; this amounts to folding $e$ in half. Since each such edge $e$ is actually a loop, it might represent a nontrivial element in the fundamental group, and folding it in half makes it nullhomotopic in the quotient, therefore potentially changing the fundamental group.

3.9. Nondegeneracy and nontriviality. For any product substructure $\Pi$, the elements in $A = \{a_1, \ldots, a_m\}$ and in $B = \{b_1, \ldots, b_n\}$ one-to-one correspond to the edges in $X_{\Pi}$, also labeled $a_1, \ldots, a_m$ and $b_1, \ldots, b_n$. These edges become loops in the complex $X_{\Pi}$, so they represent some elements of the full universal group $G_{\Pi} = \pi_1(X_{\Pi})$, which we denote $a_1, \ldots, a_m$ and $b_1, \ldots, b_n$, respectively. A product structure or substructure $\Pi$ is called nondegenerate if $a_i \neq a_i'$ for $i \neq i'$ and $b_j \neq b_j'$ for $j \neq j'$. We will use the same definition of nondegeneracy for product structures with signature. The following equivalent description of nondegeneracy follows from Lemma 3.

**Lemma 5.** A product structure or substructure $\Pi$ is nondegenerate if and only if

- for each pair $(a_i, a_i')$ with $i \neq i'$, the loop in $X_{\Pi}$ at $x_1$ with label $a_i^{-1}a_i'$ represents a non-trivial element in the universal group $G_{\Pi} = \pi_1(X_{\Pi})$, and
- for each pair $(b_j, b_j')$ with $j \neq j'$, the loop in $X_{\Pi}$ at $x_1$ with label $b_jb_j'^{-1}$ represents a non-trivial element in $G_{\Pi}$. 


The support of an element \( a = \sum_{g \in G} r_g g \) in a group ring \( RG \) is the set
\[
\text{supp}(a) = \{ g \mid r_g \neq 0 \}.
\]
A unit \( a \) in a group ring \( RG \) is nontrivial if \( a \) is not an \( R \)-multiple of a single element in \( G \), that is, if \( |\text{supp}(a)| \geq 2 \). A zero-divisor \( a \) in a group ring \( RG \) is nontrivial if \( a \neq 0 \), that is, if \( |\text{supp}(a)| \geq 1 \).

Lemma 6. If a product structure \( \Pi \) is nondegenerate, \( \Pi \) is of size \( (m, n) \), \( m \geq 2 \) and \( n \geq 2 \), then the associated units or zero-divisors \( a_{\Pi}, b_{\Pi} \in \mathbb{Z}_2 \tilde{G}_{\Pi} \) are nontrivial. If a product structure with signature \( \Pi^\sigma \) is nondegenerate, \( \Pi^\sigma \) is of size \( (m, n) \), \( m \geq 2 \) and \( n \geq 2 \), then the associated units or zero-divisors \( a_{\Pi^\sigma}, b_{\Pi^\sigma} \in RG_{\Pi^\sigma} \) are nontrivial.

The fact that Fig. 1 comes from a known nontrivial unit implies that it represents a non-degenerate product structure. For Fig. 2 nondegeneracy is not immediately apparent, and generally there is no known way to verify nondegeneracy.

Generally, deciding whether two elements in a group \( G \) given by a presentation are equal is equivalent to the word problem introduced by Max Dehn in 1911 [20]. Novikov [29], [30], [31] and Boone [12], [13], [14] independently proved that the word problem is unsolvable, in general, for finitely presented groups. Since there are many types of product structures, it is reasonable to expect that the question whether a given product structure \( \Pi \) is nondegenerate should be hard or impossible to decide algorithmically in general. This is where geometry helps: we will show that a product structure \( \Pi \) is nondegenerate if the complex \( Y_{\Pi} \) admits a metric of negative curvature. Further, we will list specific combinatorial conditions guaranteeing that \( Y_{\Pi} \) admits a metric of negative curvature. This makes it possible to utilize computer search to look for nontrivial units and zero divisors.

4. Geometry of metric spaces

One benefit of working with riemannian manifolds is that one can define and use a notion of sectional curvature. There is an extensive bibliography of articles and books generalizing this notion to more general metric spaces, particularly, to simplicial complexes and cell complexes. In this section we summarize known results that allow, under certain assumptions, to put a nice metric structure on a given cell complex.

4.1. Length spaces, geodesic spaces. A length space is a metric space \( X \) in which the distance between every pair of points \( x, y \in X \) is equal to the infimum of the lengths of rectifiable curves joining them. A geodesic, or a geodesic path, in a metric space \( X \) is an isometric embedding of an interval into \( X \). A geodesic metric space is a metric space in which each pair of points can be connected by a geodesic. The length metric on a metric space is defined as the infimum of the lengths of rectifiable curves; we refer to [16, I.3.2, I3.3, pp. 32-33] for details.

4.2. \( \text{CAT}(\kappa)-\text{spaces and spaces of curvature} \leq \kappa \). In 1948 Busemann [18] introduced a notion of a nonpositively curved space using upper bounds on the middle lines of geodesic triangles. In 1951 Aleksandrov [2] §1.3, p. 8 and §4, p. 19] gave a general definition of spaces of curvature bounded above. Aleksandrov’s earlier works also discussed notions of curvature for metric spaces, in particular the notion of curvature bounded below; see [11, 6].
Given a real number $\kappa$, a $\text{CAT}(\kappa)$-space is a geodesic metric space in which each geodesic triangle is at least as thin as its comparison triangle in the standard (simply connected) space of curvature $\kappa$; see [16, II.1.1, pp. 158-159] for precise definitions. A comparison triangle is a triangle with the same side lengths as those of the original triangle, and for $\kappa > 0$ we impose the condition only on the triangles of perimeter $< 2\pi/\sqrt{\kappa}$. For $\kappa = 0$ the standard space is the euclidean plane, for $\kappa = -1$ it is the hyperbolic plane, and for $\kappa = 1$ it is the unit 2-dimensional sphere. This in particular implies that if $\kappa \leq 0$, for each pair of points $x$ and $y$ in a $\text{CAT}(\kappa)$-space, the geodesic joining $x$ to $y$ is unique.

A metric space is said to be of curvature $\leq \kappa$ if it is locally a $\text{CAT}(\kappa)$-space; see [16, p. 159]. A space of curvature $\leq 0$ is also called a nonpositively curved space.

4.3. The Cartan-Hadamard theorem. This theorem relates spaces of curvature $\leq \kappa$ to $\text{CAT}(\kappa)$-spaces. The original statement of the theorem was proved by Hadamard [24] in the case of surfaces and by Cartan [19] for arbitrary riemannian manifolds of nonpositive curvature. This is an example of a local-to-global result, i.e., deducing properties of the universal covering from the local structure of a space. The following theorem is a generalization of the original Cartan-Hadamard theorem from manifolds to metric spaces. It is a variation of the theorem stated by Gromov [23, p.119], a detailed proof of which was given by Ballmann in the locally compact case [7] and by Alexander-Bishop [5] under the additional assumption that $\tilde{X}$ is a geodesic metric space.

**Theorem 7** (The Cartan-Hadamard theorem [24], [19], [23, p.119], [7], [5], [16, II.4.1, p.193]). Let $X$ be a complete connected metric space.

1. If the metric on $X$ is locally convex, then the induced length metric on the universal cover $\tilde{X}$ is (globally) convex. (In particular, there is a unique geodesic segment joining each pair of points in $\tilde{X}$ and geodesic segments vary continuously with their endpoints.)
2. If $X$ is of curvature $\leq \kappa$, where $\kappa \leq 0$, then $\tilde{X}$ (with the induced length metric) is a $\text{CAT}(\kappa)$-space.

4.4. Fixed points. Certain notions of center for a given subset $Y \subseteq X$ were considered by Cartan [19] for any simply connected manifold $M$ of nonpositive curvature. He used this notion to prove the existence of a fixed point for the action of any compact group of isometries of $M$. Bruhat and Tits [17] proved a similar theorem for group actions on euclidean buildings.

We now quote similar theorems in the more general case of $\text{CAT}(\kappa)$ spaces. Define the radius of a subset $Y$ in a metric space $X$ to be the infimum of the positive numbers $r$ such that $Y \subseteq B(x, r)$ for some $x \in X$.

**Theorem 8** ([16 II.2.7, p. 179]). Let $X$ be a complete $\text{CAT}(\kappa)$ space and $Y \subseteq X$ be a bounded subset. If $\kappa > 0$, assume additionally that the radius of $Y$ is $< \pi/(2\sqrt{\kappa})$. Then there exists a unique point $c_Y \in X$, called the center of $Y$, such that $Y \subseteq B(c_Y, r_Y)$.

The following general theorem is sometimes called the Cartan fixed-point theorem or the Bruhat-Tits fixed-point theorem.
Theorem 9 ([16] II.2.8, p. 179). If \( X \) is a complete \( \text{CAT}(0) \) space and \( \Gamma \) is a finite group of isometries of \( X \) or, more generally, a group of isometries with a bounded orbit, then the fixed-point set of \( \Gamma \) is a non-empty convex subset of \( X \).

4.5. Nonpositive curvature implies “torsion-free”. For any complete, path-connected, non-positively curved metric space \( X \), consider the action of its fundamental group \( \pi_1(X) \) on the universal covering \( \tilde{X} \) (see, for example, [25] Ch. 1, Prop. 1.39, p. 71]). The action is defined by representing each \( g \in \pi_1(\tilde{X}) \) by a loop \( f \), lifting \( f \) to a path \( \tilde{f} \) in \( \tilde{X} \), and defining the unique deck transformation that sends \( \tilde{f}(0) \) to \( \tilde{f}(1) \). If an element \( g \in \pi_1(X) \) fixes a point in \( \tilde{X} \), then \( \tilde{f} \) is a loop, hence it is nullhomotopic, then so is \( f \), so \( g \) is trivial. In other words, the \( \pi_1(X) \)-action on \( \tilde{X} \) is free. By the Cartan-Hadamard theorem (Theorem 7), \( \tilde{X} \) is a \( \text{CAT}(0) \) space. If there were a nontrivial element \( g \in \pi_1(X) \) of finite order, then by Theorem 9, \( g \) must have a fixed point in \( \tilde{X} \), which is a contradiction. This proves the following.

Theorem 10 ([16] II.4.13, p. 201]). Let \( X \) be a complete, path-connected, nonpositively curved metric space. Then the group \( \pi_1(X) \) is torsion-free.


The main idea to define a metric on the cone is to use the three laws of cosines: one for curvature \( \kappa = 0 \) (in the euclidean plane), one for constant negative curvature \( \kappa < 0 \) (in a rescaled hyperbolic plane), and one for constant positive curvature \( \kappa > 0 \) (in a rescaled 2-sphere). Specifically,

\[
\begin{align*}
\text{for } \kappa = 0: & \quad c^2 = a^2 + b^2 - 2ab \cos \gamma, \\
\text{for } \kappa < 0: & \quad \cosh(\sqrt{-\kappa}c) = \cosh(\sqrt{-\kappa}a) \cosh(\sqrt{-\kappa}b) \\
& \quad - \sinh(\sqrt{-\kappa}a) \sinh(\sqrt{-\kappa}b) \cos \gamma, \\
\text{for } \kappa > 0: & \quad \cos(\sqrt{\kappa}c) = \cos(\sqrt{\kappa}a) \cos(\sqrt{\kappa}b) + \sin(\sqrt{\kappa}a) \sin(\sqrt{\kappa}b) \cos \gamma.
\end{align*}
\]

Let \((Y, d_Y)\) be a metric space and \( \kappa \) be a real number. The \( \kappa \)-cone over \( Y \) is the metric space \((C_\kappa Y, d)\) defined as follows. First denote

\[
I_\kappa := \begin{cases} [0, \infty) & \text{if } \kappa \leq 0, \\ [0, \pi/(2\sqrt{\kappa})] & \text{if } \kappa > 0. \end{cases}
\]

Let \( C_\kappa Y \) be the quotient of the set \( I_\kappa \times Y \) by the equivalence relation

\[
(t, y) \sim (t', y') \iff t = t' = 0 \text{ or } (t = t' \text{ and } y = y').
\]

Denote the equivalence class of \((t, y)\), i.e., the point in the cone corresponding to \((t, y)\) by \( ty \). Depending on \( \kappa \), the distance between two points \( ty \) and \( t'y' \) in the cone \( C_\kappa Y \) is defined by solving for \( c \) in the corresponding law of cosines for \( a := t, b := t', \) and \( \gamma := \)
min\{d_Y(y,y'), \pi \}. Specifically,

for \( \kappa = 0 \):
\[
d(ty, t'y') := \sqrt{t^2 + t'^2 - 2tt' \cos(\min\{\pi, d_Y(y,y')\})},
\]

for \( \kappa < 0 \):
\[
d(ty, t'y') := \cosh^{-1}\left( \left[ \cosh(\sqrt{-\kappa}a) \cosh(\sqrt{-\kappa}b) - \sinh(\sqrt{-\kappa}a) \sinh(\sqrt{-\kappa}b) \cos(\min\{\pi, d_Y(y,y')\}) \right] / \sqrt{-\kappa} \right),
\]

for \( \kappa > 0 \):
\[
d(ty, t'y') := \arccos\left( \left[ \cos(\sqrt{\kappa}a) \cos(\sqrt{\kappa}b) + \sin(\sqrt{\kappa}a) \sin(\sqrt{\kappa}b) \cos(\min\{\pi, d_Y(y,y')\}) \right] / \sqrt{\kappa} \right).
\]

The proof of the following theorem due to Berestovskii can be found in [10], [9], [4], [3], [16, II.3.14, pp. 188-190].

**Theorem 11** (Berestovskii). Let \( Y \) be a metric space. The \( \kappa \)-cone \( X = \mathbb{C}_\kappa Y \) over \( Y \) is a CAT(\( \kappa \))-space if and only if \( Y \) is a CAT(1)-space.

4.7. **Local and global isometric embeddings.** The following theorem is another example of a local-to-global property.

**Theorem 13** ([16, Prop. 4.14, p. 201]). Let \( X \) and \( Y \) be complete connected metric spaces. Suppose that \( X \) is non-positively curved and that \( Y \) is locally a length space. If there is a map \( f : X \to Y \) that is locally an isometric embedding, then \( Y \) is non-positively curved and:

1. For every \( y_0 \in Y \), the homomorphism \( f_* : \pi_1(Y,y_0) \to \pi_1(X,f(x_0)) \) induced by \( f \) is injective.
2. Consider the universal coverings \( \tilde{X} \) and \( \tilde{Y} \) with their induced length metrics. Every continuous lift \( \tilde{f} : \tilde{X} \to \tilde{Y} \) of \( f \) is an isometric embedding.
5. Geometry of cell complexes

5.1. $M_\kappa$-simplicial and $M_\kappa$-polyhedral complexes. For $\kappa \in (0, \infty)$, $M_\kappa$ denotes the standard (simply connected) $n$-dimensional space of constant curvature $\kappa$. For example, $M_0^n$ is the $n$-dimensional euclidean space, $M_{-1}$ is the $n$-dimensional hyperbolic space, and $M_1^n$ is the $n$-dimensional sphere of radius $1$. An $n$-dimensional $M_\kappa$-simplex is the convex hull of $n+1$ points in $M_\kappa$ in general position; in the case $\kappa = 1$ we additionally require that those points lie in some ball of radius $< \pi/2$ (i.e., in some open hemisphere) in the sphere $M_1^n$.

An $M_\kappa$-simplicial complex is built out of a family of $M_\kappa$-simplices by identifying certain faces of those simplices by isometries; we refer to [16] I.7.2.p.98 for the precise definition. It is required that the map of each simplex to the quotient space is injective. A convex $M_\kappa$-cell is the convex hull of finitely many points in the standard space $M_\kappa^n$. An $M_\kappa$-polyhedral complex is built similarly from a family of convex $M_\kappa$-cells by gluing certain faces of those cells; we refer to [16] I.7.37, p.114 for the precise definition. The map from each cell $C$ to the quotient is required to be injective only on the interior of the face; it is allowed, for example, to glue together some faces of $C$.

Let $K$ be an $M_\kappa$-polyhedral complex. Each cell $C$ in $K$ comes with the metric $d_C$ induced from its inclusion into $M_\kappa^n$. The intrinsic pseudometric $d$ on $K$ is defined using piecewise geodesic paths: for $x, y \in K$,

$$d(x, y) := \inf_c l(c),$$

where $c : [a, b] \to K$ is a path from $x$ to $y$ that is subdivided as a concatenation of geodesic pieces $c_i$ so that the image of each $c_i$ lies in some cell $C_i$ of $K$, $l(c_i)$ is the length of $c_i$ with respect to the original metric on $C_i$, and $l(c) := \sum_{i=1}^k l(c_i)$. Equivalently, instead of piecewise geodesic paths one can use strings of points. Also, the quotient pseudometric can be defined using particular finite sequences of points. See [16] I.7.4 and I.5.19, p.65, [16] I.7.4 and I.7.5, p.99 and [16] I.7.38, p.114 for the equality of all these metrics.

One can easily switch between simplicial and polyhedral $M_\kappa$-complexes because each simplicial $M_\kappa$-complex is a polyhedral $M_\kappa$-complex, and each polyhedral $M_\kappa$-complex can be subdivided to become a simplicial $M_\kappa$-complex with the same metric; see [16] Proposition I.7.49, p.118.

For an $M_\kappa$-polyhedral complex $K$, Shapes($K$) denotes the set of all isometry classes of the $M_\kappa$-cells in $K$.

**Theorem 14** (Bridson [15], [16] I.7.19, p.105 and I.7.50, p.118). Let $K$ be a connected $M_\kappa$-simplicial or $M_\kappa$-polyhedral complex. If Shapes($K$) is finite, then $K$ is a complete geodesic metric space.

5.2. Links. Given a vertex $x$ in $K$, the link of $x$, denoted $\text{Lk}(x, K)$, is the set of all directions at $x$ in $K$; see [16] I.7.15, p.103. Informally, one can think of the directions at $x$ as all the unit tangent vectors at $x$ that “point inside” the (closed) cells containing $x$. For each $n$-cell $C$ in $K$ containing $x$, we can view $\text{Lk}(x, C)$ as a $(n-1)$-cell in $\text{Lk}(x, K)$. Furthermore, using angles between directions, $\text{Lk}(x, C)$ can be identified with an $(n-1)$-simplex lying inside
the \((n - 1)\)-dimensional sphere, that is, of \(M_1^{n-1}\). In this way, the structure of \(M_\kappa\)-polyhedral complex on \(K\) induces a structure of an \(M_1\)-polyhedral complex on each link \(\text{Lk}(x, K)\).

5.3. **Local geometry of \(M_\kappa\)-polyhedral complexes.** For an \(M_\kappa\)-simplicial complex \(X\) and \(x \in K\), define

\[
\varepsilon(x) := \inf\{\varepsilon(x, S) \mid S \subseteq K \text{ is a simplex containing } x\},
\]

where

\[
\varepsilon(x, S) := \inf\{d_S(x, T) \mid T \text{ is a face of } S \text{ and } x \notin T\}.
\]

Here \(d_S\) is the original metric on the metric simplex \(S\), the one coming from its inclusion into \(M_\kappa\). More generally, if \(K\) is an \(M_\kappa\)-polyhedral complex and \(x \in K\), \(\varepsilon(x)\) can be defined similarly as the distance from \(x\) to the closure of its star \(\text{st}(x)\) minus \(\text{st}(x)\), where the distance is measured in terms of the original metric on each cell in \(K\); see [16] I.7.38, p. 114 for details. If the set \(\text{Shapes}(K)\) is finite, then \(\varepsilon(x) > 0\).

**Theorem 15 ([16] I.7.16, pp. 103-105]).** Let \(K\) be an \(M_\kappa\)-simplicial complex and let \(x \in K\). If \(\varepsilon(x) > 0\), then \(B(x, \varepsilon(x)/2)\) is naturally isometric to the open ball of radius \(\varepsilon(x)/2\) about the cone point in \(C_\kappa(\text{Lk}(x, K))\).

**Lemma 16 ([16] I.7.56, p. 120]).** Let \(K\) be an \(M_\kappa\)-polyhedral complex with \(\text{Shapes}(K)\) finite. If the points \(x\) and \(y\) lie in in the same open cell in \(K\), then for sufficiently small \(\varepsilon > 0\) there exists an isometry from \(B(x, \varepsilon)\) to \(B(y, \varepsilon)\) that restricts to an isometry from \(B(x, \varepsilon) \cap C\) to \(B(y, \varepsilon) \cap C\) for every closed cell \(C\) containing \(x\).

**Lemma 17.** Let \(K\) be an \(M_\kappa\)-polyhedral complex with \(\text{Shapes}(K)\) finite. For any edge (=1-cell) \(e\) in \(K\), the canonical map \(c_e : e \to K\) is locally an isometric embedding.

**Proof.** The 1-cell \(e\) is topologically a closed interval, though the canonical map in general might identify its endpoints, so \(c_e\) it is not necessarily injective. Let \(v\) be a vertex in \(K\) corresponding to an endpoint of \(e\). By Theorem 15, some neighborhood \(V\) of \(v\) in \(K\) is isometric to some neighborhood of the cone point in the \(x\)-cone \(C_\kappa(\text{Lk}(v, K))\). Furthermore, following the proof of that theorem one can see that this isometry is consistent with the cellular structures of \(V\) and of the link \(\text{Lk}(v, K)\) (both induced from \(K\)). In particular, each vertex in the link \(\text{Lk}(v, K)\) corresponds to an edge in the cone \(C_\kappa(\text{Lk}(v, K))\), and that edge is mapped to an edge in \(V\) isometrically. By Lemma 12, the canonical embedding \(I_x : C_\kappa(\text{Lk}(v, K)) \to K\) is an isometry. This implies that if \(a\) is an endpoint of the edge \(e\), then there exists a neighborhood of \(a\) in \(e\) such that the restriction of the canonical map \(c_e\) to this neighborhood is an isometric embedding.

Now take \(a\) to be any point in the interior of \(e\) in \(K\), and let \(b\) be a point in the interior of \(e\) in \(K\) that is mapped into \(V\) by \(c_e\). Since some neighborhood of \(b\) in \(e\) is mapped isometrically into \(K\), then by Lemma 16, some neighborhood of \(a\) in \(e\) is also mapped isometrically. This proves that \(c_e\) is locally an isometric embedding. \(\square\)
5.4. Complexes of curvature $\leq \kappa$. The following link condition was introduced by Gromov [23]. An $M_\kappa$-polyhedral complex $K$ with $\text{Shapes}(X)$ finite is said to satisfy the link condition if for every vertex $v \in K$ the link complex $\text{Lk}(v, K)$ is a $\text{CAT}(1)$ space. The following result was first stated by Gromov [23, p. 120], proved by Ballmann [7] in the locally compact case and by Bridson [15] in the general case.

**Theorem 18** ([16, section II.5.5, p. 207]). Let $X$ be an $M_\kappa$-polyhedral cell complex such that $\text{Shapes}(X)$ is finite. The curvature of $X$ is $\leq \kappa$ if and only if $X$ satisfies the link condition.

An injective loop in a graph $\mathcal{G}$ can be defined as an injective continuous function from a circle to $\mathcal{G}$. A simple closed curve in $\mathcal{G}$ can be defined as a continuous function $[0,1] \to \mathcal{G}$, which is injective except the two endpoints 0 and 1 are mapped to the same point in $\mathcal{G}$. These two notions determine each other, and can be used interchangeably in what follows. It is not hard to see that that a metric graph $\mathcal{G}$ is a $\text{CAT}(1)$-space if an only if it has metric girth $\geq 2\pi$, i.e., every injective loop in $\mathcal{G}$ is of length $\geq 2\pi$. This implies the following lemma.

**Lemma 19** ([16, section II.5.6, p. 207]). A 2-dimensional $M_\kappa$-complex $K$ satisfies the link condition if and only if for each vertex $v$ in $K$ every injective loop in $\text{Lk}(v, K)$ has length at least $2\pi$.

The proof of the following theorem is obtained by combining Theorem 18 and Lemma 19.

**Theorem 20.** Let $X$ be a 2-dimensional piecewise euclidean cell complex. $X$ is non-positively curved if and only if at each vertex $v \in X$, each injective loop in the link of $v$ is of length at least $2\pi$.

6. THE GEOMETRY OF UNITS AND ZERO-DIVISORS

6.1. Metric structures on $Y_{\Pi}$. For each $\alpha \in (0, \pi)$, let $\Delta_\alpha$ be the isosceles triangle in the euclidean plane with base of length 1 and the angles $(\alpha, \beta, \beta)$, then necessarily $\beta = (\pi - \alpha)/2$. The three special cases for $\alpha = \pi/3$, $\pi/2$, $2\pi/3$ are drawn below.

Now we turn the cell complex $Y_{\Pi}$ defined in section 3.2 into a metric space: first identify each of its 2-cells with the isosceles euclidean triangle $\Delta_\alpha$, so that the corners with angle $\alpha$ are either on the top or on the bottom. Put the intrinsic pseudometric on $Y_{\Pi}$ as defined in (2). $Y_{\Pi}$ is not a simplicial complex because some vertices of its triangles are identified, but it is an $M_0$-polyhedral complex. Furthermore, it becomes an $M_0$-simplicial complex after taking the first barycentric subdivision.
6.2. Multiplicity. The angles $\alpha$ and $\beta$ are uniquely determined by each other. Specifically, for $\alpha \in (0, \pi)$, $\beta = \tilde{\beta}(\alpha) := (\pi - \alpha)/2$, and the function $\tilde{\beta}$ is a decreasing bijection $(0, \pi) \rightarrow (0, \pi/2)$. We will be interested in an explicit description of the set

$$Q := \{(i, j) \in \mathbb{Z} \times \mathbb{Z} \mid \exists \alpha \in (0, \pi) \quad ai \geq 2\pi\text{ and } 2\tilde{\beta}(\alpha) j \geq 2\pi\}.$$ 

To address this question, for $\alpha \in (0, \pi)$, define the $\alpha$-multiplicity function $\hat{\mu} : (0, \pi) \rightarrow \mathbb{Z}$ and the $\beta$-multiplicity function $\bar{\mu} : (0, \pi) \rightarrow \mathbb{Z}$ by the formulas

$$\hat{\mu}(\alpha) := \min\{k \in \mathbb{Z} \mid \alpha k \geq 2\pi\} = \left\lceil \frac{2\pi}{\alpha} \right\rceil,$$

$$\bar{\mu}(\alpha) := \min\{k \in \mathbb{Z} \mid 2\tilde{\beta}(\alpha) \cdot k \geq 2\pi\} = \left\lceil \frac{2\pi}{(\pi - \alpha)} \right\rceil,$$

respectively. Observe that $\hat{\mu}$ is nonstrictly decreasing and $\bar{\mu}$ is nonstrictly increasing. The nonempty sets of the form $\hat{\mu}^{-1}(i)$ for integers $i$ form a partition of $(0, \pi)$. Similarly, the nonempty sets of the form $\bar{\mu}^{-1}(j)$ for integers $j$ form a partition of $(0, \pi)$. The canonical common refinement of these two partitions consists of all nonempty sets of the form $A_{ij} := \hat{\mu}^{-1}(i) \cap \bar{\mu}^{-1}(j)$. Call a pair of integers $(i', j')$ minimal if $A_{i'j'} \neq \emptyset$ but $A_{i'-1,j'} = \emptyset$ and $A_{i',j'-1} = \emptyset$. To find all minimal pairs, we plot the solutions of the equations $2\pi/\alpha = i$ and $2\pi/(\pi - \alpha) = j$:

$$\hat{\alpha}_i := 2\pi / i, \quad \bar{\alpha}_j := \pi - 2\pi / j.$$

The cells of the two partitions of $(0, \pi)$ are as follows:

$$\hat{\mu}^{-1}(i) = [\hat{\alpha}_i, \hat{\alpha}_{i-1}] \text{ for } i = \ldots, 5, 4, 3,$$

$$\bar{\mu}^{-1}(j) = (\bar{\alpha}_{j-1}, \bar{\alpha}_j] \text{ for } j = 3, 4, 5, \ldots$$

The following lemma is proved by tracing the above plot of points.

**Lemma 21.** For any pair $(i, j)$ such that $A_{ij} \neq \emptyset$ there exists a minimal pair $(i', j')$ such that $i' \leq i$ and $j' \leq j$. The full list of minimal pairs $(i', j')$ and their corresponding cells are as follows:

$$(i', j') = (6, 3), (4, 4), (3, 6);$$

$$A_{6,3} = [\hat{\alpha}_6, \bar{\alpha}_3] = \left\{\pi/3\right\}, \quad A_{4,4} = [\hat{\alpha}_4, \bar{\alpha}_4] = \left\{\pi/2\right\}, \quad A_{3,6} = [\hat{\alpha}_3, \bar{\alpha}_6] = \left\{2\pi/3\right\}.$$ 

Now we can give an explicit description of the set $Q$. The notation $(i_1, j_1) \leq (i_2, j_2)$ or $(i_2, j_2) \geq (i_1, j_1)$ will mean “$i_1 \leq i_2$ and $j_1 \leq j_2$”.

**Lemma 22.**

$$Q = \{(i, j) \in \mathbb{Z} \times \mathbb{Z} \mid \exists (i', j') \in \mathbb{Z} \times \mathbb{Z} \quad (i', j') \text{ is minimal and } (i', j') \leq (i, j)\}$$

$$= \{(i, j) \in \mathbb{Z} \times \mathbb{Z} \mid (i, j) \geq (6, 3) \text{ or } (i, j) \geq (4, 4) \text{ or } (i, j) \geq (3, 6)\}.$$
Proof.

\[(i, j) \in Q \iff \exists \alpha \in (0, \pi) \quad \alpha i \geq 2\pi \quad \text{and} \quad 2\hat{\mu}(\alpha) j \geq 2\pi \]
\[\iff \exists \alpha \in (0, \pi) \quad \hat{\mu}(\alpha) \leq i \quad \text{and} \quad \bar{\mu}(\alpha) \leq j \]
\[\iff \exists (i', j') \in \mathbb{Z} \times \mathbb{Z} \quad \left( (i', j') \leq (i, j) \right) \]
\[\quad \text{and} \quad \exists \alpha \in (0, \pi) \quad \hat{\mu}(\alpha) \leq i' \quad \text{and} \quad \bar{\mu}(\alpha) \leq j' \]
\[\quad \text{and} \quad \neg \exists \alpha \in (0, \pi) \quad \hat{\mu}(\alpha) \leq i' - 1 \quad \text{and} \quad \bar{\mu}(\alpha) \leq j' \]
\[\quad \text{and} \quad \neg \exists \alpha \in (0, \pi) \quad \hat{\mu}(\alpha) \leq i' \quad \text{and} \quad \bar{\mu}(\alpha) \leq j' - 1 \]
\[\iff \exists (i', j') \in \mathbb{Z} \times \mathbb{Z} \quad \left( (i', j') \leq (i, j) \right) \]
\[\quad \text{and} \quad \exists \alpha \in (0, \pi) \quad i' - 1 < \hat{\mu}(\alpha) \quad \text{or} \quad j' < \bar{\mu}(\alpha) \]
\[\quad \text{and} \quad \exists \alpha \in (0, \pi) \quad i' < \hat{\mu}(\alpha) \quad \text{or} \quad j' - 1 < \bar{\mu}(\alpha) \]
\[\iff \exists (i', j') \in \mathbb{Z} \times \mathbb{Z} \quad \left( (i', j') \leq (i, j) \right) \quad \text{and} \quad \hat{\mu}^{-1}(i') \cap \bar{\mu}^{-1}(j') \neq \emptyset \]
\[\quad \text{and} \quad \neg (\exists \alpha \in (0, \pi) \quad \hat{\mu}(\alpha) \leq i' - 1 \quad \text{and} \quad \bar{\mu}(\alpha) \leq j') \]
\[\quad \text{and} \quad \neg (\exists \alpha \in (0, \pi) \quad \hat{\mu}(\alpha) \leq i' \quad \text{and} \quad \bar{\mu}(\alpha) \leq j' - 1) \]
\[\iff \exists (i', j') \in \mathbb{Z} \times \mathbb{Z} \quad \left( (i', j') \leq (i, j) \right) \quad \text{and} \quad \hat{\mu}^{-1}(i') \cap \bar{\mu}^{-1}(j') \neq \emptyset \]
\[\quad \text{and} \quad \left[ \bigcup_{i'' \leq i' - 1} \hat{\mu}^{-1}(i'') \right] \cap \left[ \bigcup_{j'' \leq j'} \bar{\mu}^{-1}(j'') \right] = \emptyset \]
\[\quad \text{and} \quad \left[ \bigcup_{i'' \leq i'} \hat{\mu}^{-1}(i'') \right] \cap \left[ \bigcup_{j'' \leq j' - 1} \bar{\mu}^{-1}(j'') \right] = \emptyset \]
(because \(\hat{\mu}\) is decreasing and \(\bar{\mu}\) is increasing)
\[\iff \exists (i', j') \in \mathbb{Z} \times \mathbb{Z} \quad \left( (i', j') \leq (i, j) \right) \quad \text{and} \quad \hat{\mu}^{-1}(i') \cap \bar{\mu}^{-1}(j') \neq \emptyset \]
\[\quad \text{and} \quad \hat{\mu}^{-1}(i' - 1) \cap \bar{\mu}^{-1}(j') = \emptyset \quad \text{and} \quad \hat{\mu}^{-1}(i') \cap \bar{\mu}^{-1}(j' - 1) = \emptyset \]
\[
\Leftrightarrow \exists (i', j') \in \mathbb{Z} \times \mathbb{Z} \quad ( (i', j') \leq (i, j) \text{ and } A_{i'; j'} \neq \emptyset \text{ and } A_{i'-1, j'} = \emptyset \text{ and } A_{i', j'-1} = \emptyset ) \\
\Leftrightarrow \exists (i', j') \in \mathbb{Z} \times \mathbb{Z} \quad ( (i', j') \leq (i, j) \text{ and } (i', j') \text{ is minimal}).
\]

The second equality in the lemma follows from Lemma 21.

6.3. **Nonpositive curvature implies nondegeneracy.**

**Theorem 23.** Given an orientable product structure or substructure \( \Pi \), equip \( Y_{\Pi} \) is with the structure of an \( M_0 \)-polyhedral complex by making one choice of the angle \( a \) uniformly for all triangles in \( Y_{\Pi} \). If \( Y_{\Pi} \) has curvature \( \leq 0 \), then \( \Pi \) is nondegenerate.

**Proof.** Suppose that \( \Pi \) is degenerate, so that there is a pair of distinct elements \( a, a' \in A \) and the corresponding distinct pair of edges in \( X_{\Pi} \) labeled \( a \) and \( a' \) such that the loop in \( X_{\Pi} \) at \( x_1 \) with label \( a_1^{-1}a \) represents the identity element in the universal group \( G_{\Pi} = \pi_1(X_{\Pi}) \). By Lemma 3, the edge-loop in \( \tilde{Y}_{\Pi} \) with label \( a_1^{-1}a' \) is nullhomotopic in \( X_{\Pi} \). Since the product structure is orientable, by Lemma 4 the quotient map \( X_{\Pi} \to Y_{\Pi} \) induces an isomorphism on the fundamental groups, so we have similar two edges \( a \) and \( a' \) and a nullhomotopy of the loop \( a_1^{-1}a' \) in the complex \( Y_{\Pi} \). Lifting the edges \( a \) and \( a' \) to edges \( \tilde{a} \) and \( \tilde{a}' \) in the universal covering \( \tilde{Y}_{\Pi} \) starting at the same point, we obtain the path labeled \( \tilde{a}^{-1}\tilde{a}' \). Since the nullhomotopy of the loop \( a_1^{-1}a' \) can also be lifted to \( \tilde{Y}_{\Pi} \), we see that the path \( \tilde{a}^{-1}\tilde{a}' \) is also a loop in \( \tilde{Y}_{\Pi} \).

Since \( Y_{\Pi} \) has nonpositive curvature, the Cartan-Hadamard theorem (Theorem 7) implies that \( \tilde{Y}_{\Pi} \) is a CAT(0)-space with respect to the induced metric. Lemma 17 says that the inclusion maps of the edges \( a \) and \( a' \) into \( Y_{\Pi} \) are local isometric embeddings. Since the interval is simply connected, Theorem 13 says that the edges labeled \( \tilde{a} \) and \( \tilde{a}' \) are embedded into \( \tilde{Y}_{\Pi} \) isometrically, so they provide two geodesic path with the same endpoints. Since geodesics are unique in \( \tilde{Y}_{\Pi} \) by Theorem 7, we deduce that \( \tilde{a} = \tilde{a}' \), hence \( a = a' \) in \( Y_{\Pi} \). This gives a contradiction with the assumptions. \( \square \)

7. **Necessary and sufficient combinatorial conditions on product structures**

We will now see how certain combinatorial conditions on a product structure \( \Pi \), and its corresponding taiko, relate to geometric structures on the complex \( Y_{\Pi} \).

7.1. **Conditions on product structures.** Consider the following conditions on a product structure \( \Pi \):

- **Orientation.** This condition was defined in section 2.4 there exists an orientation \( O : E_{AB} \to E_{AB} \) on \( \Pi \). Each of the conditions below will be defined under the assumption that orientation holds.
- **No-fold.** A fold in a taiko is a pair of horizontal edges that are incident to the same vertex \( v \in A \cap B \), have the same color and the same direction at \( v \), meaning that they are either both incoming towards \( v \) or both outgoing from \( v \). (This is related to the notion of folds introduced by Stallings [33].) The no-fold condition says that at each vertex \( v \) in the taiko for \( \Pi \), there is no fold at any vertex in the taiko.
• No-pattern. A pattern in a taiko is an unordered pair of colors of horizontal edges together with their orientations, that occur incident at a common vertex $v$ in $L_{AB} = L_A \sqcup L_B$. That is, a pattern is a pair of the form $\{(c_1, d_1), (c_2, d_2)\}$, where $c_1$ and $c_2$ are colors and $d_1, d_2 \in \{\text{in}, \text{out}\}$. The no-pattern condition says that a given product structure has no repeating patterns. That is, each pattern occurs at most once in $L_{AB}$.

• girth$(p, q)$. The girth of a graph $G$, denoted girth$(G)$, is the length of the shortest nonconstant injective loop in $G$, where each edge is considered to be of length 1. The half-girth of a graph $G$, denoted half-girth$(G)$, is, naturally, $\text{girth}(G)/2$. The condition girth$(p, q)$ says that $\text{girth}(L_{AB}) \geq p$ and half-girth$(L_1) \geq q$.

• girth$(6, 3)$, $\text{girth}(4, 4)$, and $\text{girth}(3, 6)$. Also called the triple girth condition, it is defined to be the disjunction “girth$(6, 3)$ or girth$(4, 4)$ or girth$(3, 6)$”.

• metric-girth$(2\pi)$. This condition is a metric version of girth$(p, q)$. The metric girth of a metric graph $G$, denoted metric-girth$(G)$, is the length of the shortest nonconstant injective loop in $G$, with respect to the given metric on $G$. The metric-girth$(2\pi)$ condition says that there exists a metric on $Y_\Pi$ that makes it an $M_0$-complex such that metric-girth$(L_{AB}) \geq 2\pi$ and metric-girth$(L_1) \geq 2\pi$.

These conditions can be verified – algorithmically, in finite time – for any given product structure $\Pi$, and for its corresponding taiko. All these conditions, for example, the existence of orientation and the absence of folds, can be checked by a human visually from Fig. 1 and Fig. 2, which is one benefit of drawing taikos in the first place.

**Lemma 24.** Let $\Pi$ be an orientable product structure or substructure. Then, the half-girth of the middle link $L_1$ is an integer.

**Proof.** Let $C$ be the set of colors, that is, equivalence classes of horizontal edges in the taiko for $\Pi$. Then $C$ is a bijective copy of the set of middle edges in $Y_\Pi$. The set of vertices of the middle link can be naturally identified with the set $A \sqcup (C \times \{\text{in}, \text{out}\}) \sqcup B$, and the three parts of this union can be viewed as three levels: bottom, middle, and top. The edges in the middle link can only go between the bottom and the middle, or between the middle and the top. This implies that any simple loop (that is, an nonconstant, injective loop) in $L_1$ traverses an even number of edges. Therefore, half-girth$(L_1)$ is an integer.

**Lemma 25.** Let $\Pi$ be an orientable product structure or substructure. Then, the following statements are equivalent.

- There is a fold in the taiko for $\Pi$.
- There are double edges in the middle link $L_1$, i.e., there is a pair of distinct edges $L_1$ incident to the same pair of vertices in $L_1$.
- half-girth$(L_1) \leq 1$.

By negation, the following statements are equivalent.

- The no-fold condition holds.
- There are no double edges in the middle link $L_1$.
- half-girth$(L_1) > 1$ (or, equivalently, $\geq 2$).

Also, the following statements are equivalent.
• The conditions no-fold and no-pattern hold.
• half-girth($L_1$) > 2 (or, equivalently, $\geq 3$).

Proof. The proof is an exercise using the definition of $Y_{\Pi}$ and the following illustrations.

\[
\begin{align*}
&\text{a fold} \quad x_A \text{ or } x_B \\
&x_1 \quad x_1
\end{align*}
\]

\[
\begin{align*}
&\text{a repeating pattern} \\
&x_A \text{ or } x_B \\
&x_1 \quad x_1
\end{align*}
\]

\[\square\]

Lemma 26 (Necessary conditions for curvature $\leq 0$). Let $\Pi$ be an orientable product structure or substructure. Put the metric on the 2-complex $Y_{\Pi}$ corresponding to an angle $\alpha$ as in section 6.1 and suppose that this metric is of curvature $\leq 0$.

(a) If $\alpha = \pi/3$, then no-fold, no-pattern, girth($6, 3$) hold.
(b) If $\alpha = \pi/4$, then no-fold, no-pattern, girth($4, 4$) hold.
(c) If $\alpha = 2\pi/3$, then no-fold, no-pattern, girth($3, 6$) hold.

Since we are mostly interested in sufficient conditions for nonpositive curvature, we leave the proof of this lemma as an exercise: first show that the curvature $\leq 0$ assumption implies the link condition for $Y_{\Pi}$, which in turn implies each of the conditions listed in the lemma.

In Figure 1 and Figure 2, nondegeneracy of the product structure and being torsion-free for the full universal group $\bar{G}_{\Pi}$ are not immediately apparent, and generally there should be no easy way to verify them. Unless, that is, a given product structure satisfies some favorable sufficient conditions.

Theorem 27 (Sufficient conditions for counterexamples to Kaplansky conjectures). For the conjunctions

(1) orientation and girth($6, 3$),
(1') orientation, no-fold, no-pattern, and girth($L_{AB}$) $\geq 6$,
(2) orientation and girth($6, 3$)($4, 4$)($3, 6$),
(2') orientation, no-fold and girth($6, 3$)($4, 4$)($3, 6$),
(3) orientation and metric-girth($2\pi$),
(3') orientation, no-fold and metric-girth($2\pi$),

the following implications hold: (1) $\iff$ (1'), (2) $\iff$ (2'), (3) $\iff$ (3'), (1) $\implies$ (2) $\implies$ (3).

If a product structure $\Pi$ of size $(m, n)$ satisfies at least one of the conjunctions (1), (1'), (2), (2'), (3), (3'), then $\Pi$ is non-degenerate and both universal groups $G_{\Pi}$ and $\bar{G}_{\Pi}$ are torsion-free. In particular, if $m \geq 2$ and $n \geq 2$, then the associated elements $a_{\Pi}$ and $b_{\Pi}$ in $\mathbb{Z}_2\bar{G}_{\Pi}$ give a counterexample to the unit conjecture when $mn$ is odd, and a counterexample to the zero-divisor conjecture when $mn$
is even. If, in addition, the product structure admits a signature, then the associated elements $a_{11}$ and $b_{11}$ in $\overline{R}_{11}$ give such counterexamples over any ring $R$ with unity.

Proof. The implications $(2) \iff (2')$, $(3) \iff (3')$ and $(1) \implies (2)$ are obvious.

The equivalence $(1) \iff (1')$ follows from Lemma 25, “no-fold and no-pattern” is equivalent to half-girth$(L_1) \geq 3$.

To prove $(2) \implies (2')$, suppose that $(2)$ holds but $(2')$ does not. Then there is a fold in the taiko, then by Lemma 25 half-girth$(L_1) \leq 1$, which contradicts the condition $\text{girth}(6, 3)(4, 4)(3, 6)$ in $(2)$. This shows the equivalence $(2) \iff (2')$.

The equivalence $(3) \iff (3')$ is proved similarly: if there is a fold, then by Lemma 25 there are double edges in $L_1$ and two such edges form an simple loop of length $\leq 2\beta < 2\pi$, which contradicts condition metric-girth$(2\pi)$ in $(3)$.

To prove $(2) \implies (3)$, first assume that $\text{girth}(6, 3)$ is satisfied. Put the metric structure on $Y_{11}$ corresponding to $\alpha = \pi/3$ as in section 6.1. Since any simple loop in $L_{AB}$ has at least 6 edges, then its metric length is at least $6\alpha = 2\pi/3$. Similarly, since half-girth$(L_1) \geq 3$, then any simple loop in $L_1$ has at least 6 edges, so its metric length is at least $6\beta = 3(\pi - \alpha)/2 = 2\pi$. This proves that $Y_{11}$ is an $M_0$-complex of nonpositive curvature. The cases $\text{girth}(4, 4)$ and $\text{girth}(3, 6)$ are handled similarly.

To show that any one of the conjunctions $(1)$, $(1')$, $(2)$, $(2')$, $(3)$, $(3')$ implies the existence of units and zero-divisors, it suffices to prove this for the conjunction $(3)$ only. Assume that $(3)$ holds, this implies that the link condition holds for $Y_{11}$, so by Theorem 18 $Y_{11}$ is nonpositively curved. By Theorem 10 the universal group $G_{11} = \pi_1(Y_{11})$ is torsion-free, then by Theorem 10 the full universal group $\overline{G}_{11} = \pi_1(\overline{Y}_{11})$ is torsion-free as well. (Another way of proving this is to observe that the metric structure of nonpositive curvature on $Y_{11}$ induces a metric structure of nonpositive curvature on its quotient $\overline{Y}_{11}$, then to apply Theorem 10 to $\overline{Y}_{11}$.)

By Theorem 23 $\Pi$ is nondegenerate. If $m \geq 2$ and $n \geq 2$, then by lemmas 1 and 2, the associated units or zero-divisors are nondegenerate.

Remark 1. As one can see from Theorem 27, the no-fold condition can be removed from $(2')$ and $(3')$, but it is helpful for computation: if no-fold is satisfied, then there are no double edges in the middle link $L_1$, which means that the edges in the middle link can be coded simply as ordered pairs of vertices in $L_1$. Among the six conjunctions, the conjunctions $(1')$, $(2')$ and $(3')$ are the most suitable ones for utilizing computer search.

Remark 2. Consider all metric structures on $Y_{11}$ given by all choices of angles $\alpha$, as in section 6.1. For each pair $(i, j)$ in the set $Q$ defined in section 6.2 there exists $\alpha \in (0, \pi)$ such that $\text{girth}(i, j)$ implies metric-girth$(2\pi)$, that is, the link condition. Lemma 22 then implies that the triple girth condition $\text{girth}(6, 3)(4, 4)(3, 6)$ is the weakest possible condition on girth one can hope for to look for product structures whose complex $Y_{11}$ satisfies the link condition (for some choice of $a$). That is, the triple girth condition maximizes the chances of finding complexes $Y_{11}$ of this type, and their associated units and zero-divisors.

7.2. The program. To look for counterexamples to the Kaplansky unit and zero-divisor conjectures, follow these steps.
For each size \((m, n)\), search for product structures of size \((m, n)\) satisfying at least one conjunction in Theorem 27.

If such product structures are found, list and classify such product structures and their associated units or zero-divisors \((a_{11}, b_{11})\).

If not found for a given size \((m, n)\), conclude that for the metric structures on complexes \(Y_{11}\) associated with any product structures of size \((m, n)\) and any choices of \(\alpha\) are not of curvature \(\leq 0\).

Modify the construction of the complex \(Y_{11}\) and the conditions in a way that they still imply that the full universal group \(\tilde{G}_{11}\) is torsion-free and the product structure \(\Pi\) is nondegenerate.

Repeat.

REFERENCES


THE TOPOLOGY AND GEOMETRY OF UNITS AND ZERO-DIVISORS: ORIGAMI


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