

## COHOMOLOGY OF THE PINWHEEL TILING

DIRK FRETTLÖH, BENJAMIN WHITEHEAD and MICHAEL F. WHITTAKER<sup>✉</sup>

(Received 26 April 2014; accepted 3 June 2014)

Communicated by J. Borwein

### Abstract

We provide a computation of the Čech cohomology of the pinwheel tiling using the Anderson–Putnam complex. A border-forcing version of the pinwheel tiling is produced that allows an explicit construction of the complex for the quotient of the continuous hull by the circle. The cohomology of the continuous hull is given using a spectral sequence argument of Barge, Diamond, Hunton and Sadun.

*2010 Mathematics subject classification:* primary 37B50; secondary 55N05.

*Keywords and phrases:* Čech cohomology, pinwheel tiling, aperiodic substitution tiling, border-forcing.

### 1. Introduction

A tiling of the plane is a collection of subsets of  $\mathbb{R}^2$ , called tiles, for which any intersection of the interiors of two distinct tiles is empty and whose union is all of  $\mathbb{R}^2$ . A tiling said to be *aperiodic* if it lacks translational periodicity. The most common method of producing aperiodic tilings is to use a substitution rule: a method for breaking each tile into smaller pieces, each of which is a scaled-down copy of one of the original tiles, and then expanding so that each tile is congruent to one of the original tiles.

One of the most enigmatic substitution tilings is the Conway–Radin pinwheel tiling, described in the seminal paper [10]. The pinwheel tiling is composed of two tile types, a 1-2- $\sqrt{5}$  right triangle and its reflection. The substitution rule  $\omega$  inflates each tile by a factor of  $\sqrt{5}$  and decomposes the inflated triangle into five isometric copies of the original triangles as follows:



This research was supported by the German Research Council (DFG) within Collaborative Research Centre 701, the Australian Mathematical Sciences Institute, and the Australian Research Council.

© 2014 Australian Mathematical Publishing Association Inc. 1446-7887/2014 \$16.00

There are two reasons why the pinwheel tiling has been so difficult to analyse. Tiles in the pinwheel appear in an infinite number of distinct orientations and the pinwheel tiling does not force its border. Heuristically, a substitution tiling is said to force its border if specified finite patches of tiles always have the same collar of tiles. Forcing the border has turned out to be essential for computing the cohomology of tilings [1, 4, 12]. One of the primary goals of this paper is to provide a version of the pinwheel tiling that forces its border, which we call the BFpinwheel tiling. To see that tiles in the pinwheel tiling appear in an infinite number of distinct orientations we observe that after two iterations of the pinwheel substitution there are two tiles that are rotated against each other by the angle  $\arctan(\frac{1}{2})$ , which is an irrational fraction of  $2\pi$  so an induction argument shows that orientations of tiles are dense in the circle.

There is a compact topological space associated with the pinwheel tiling called the continuous hull and denoted  $\Omega$ . The continuous hull is locally homeomorphic to the product of a Cantor set, a circle, and a disc [5, 9, 11, 12, 14]. The substitution rule  $\omega$  is a homeomorphism on the continuous hull [13] allowing the continuous hull to be described as an inverse limit [1]. Using the inverse limit structure allows us to compute the Čech cohomology of the continuous hull; the Čech cohomology of the inverse limit is the direct limit of the Čech cohomology of the approximants, making the cohomology quite computable. Computing the Čech cohomology groups of the continuous hull has been the focus of a significant amount of research since its introduction in [1]. Sadun's book [12] gives an excellent introduction to the cohomology of tiling spaces and provides deep insight into the meaning of the cohomology groups for tilings.

In [4], Barge *et al.* give the first computation of the Čech cohomology of the pinwheel tiling. Their computation uses Barge–Diamond collaring and a higher-dimensional analogue of the Barge–Diamond complex [3] to compute the Čech cohomology of the quotient of the continuous hull by the circle. In order to obtain the Čech cohomology of the continuous hull the obvious approach is to use the Gysin sequence to realise the continuous hull as a fibre bundle over the quotient. Unfortunately the map from the continuous hull to the quotient of the continuous hull by the circle is not an honest fibration; there are six smooth singular fibres. In the quotient space these singular fibres correspond to cone singularities, specifically at the points with  $180^\circ$  rotational symmetry. To overcome this problem the authors go back to the spectral sequence used to derive the Gysin sequence and adjust for the singular fibres. Torsion in the quotient of the continuous hull by the circle makes the spectral sequence arguments extremely subtle.

In this note we compute the cohomology of the continuous hull of the pinwheel tiling using Anderson and Putnam's original approach. The first step is to produce a border-forcing version of the pinwheel tiling, which we call the BFpinwheel. The Anderson–Putnam complex of the BFpinwheel leads to the Čech cohomology of an approximant. A direct limit computation gives the Čech cohomology of the quotient of the continuous hull of the BFpinwheel by the circle. We are able to explicitly present the generators of the Čech cohomology groups and attempt to provide all the details

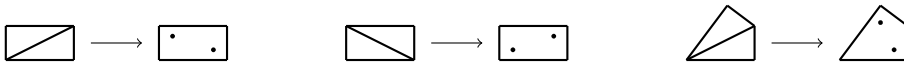
of the computation. To complete the calculation we identify the cone singularities in the BFpinwheel and apply the spectral sequence arguments in [4].

### 2. A border-forcing version of the pinwheel tiling

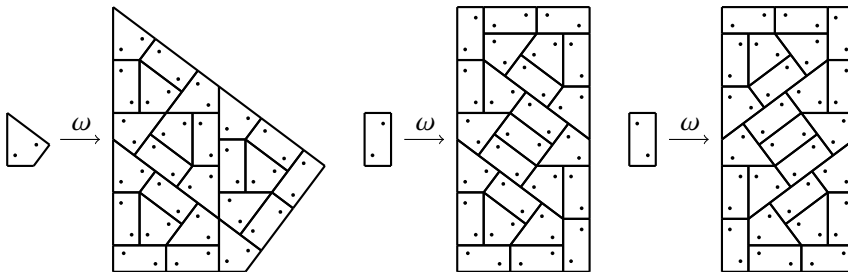
In this section we produce a version of the pinwheel tiling that forces its border. The first step is to pass to a kite-rectangle version of the pinwheel tiling and use this version to produce the BFpinwheel.

A substitution tiling is said to *force its border* if, for every proto-tile, there is a finite number of substitutions after which the pattern of tiles meeting the border of the collection of substituted tiles is the same throughout the tiling. The notion of border forcing was invented by Kellendonk in [7, page 24] (see also [12, Section 2.5]). While the Penrose tiling forces its border, the pinwheel tiling does not. In [8, page 7], Putnam and Kellendonk point out that any tiling with a finite number of local patterns can be made to force the border by relabelling the proto-tiles, one for each distinct collar of tiles that appears around any translate of a proto-tile. We use this method to produce a version of the pinwheel tiling that forces its border. The reader is invited to jump ahead to [Appendix A](#) to see the collared tiles immediately.

In [2], Baake *et al.* observed that, given a pinwheel tiling, one can remove every hypotenuse to get a kite-rectangle version of the pinwheel tiling, which we will call the KRpinwheel. They showed that the KRpinwheel tiling is mutually locally derivable to the original pinwheel tiling, meaning that there is a homeomorphism between the two continuous hulls and the homeomorphism can be determined locally in every tiling. The following figure shows the local bijection from the pinwheel to the KRpinwheel. The dots emphasise the decomposition, although the dots can be completely determined by local patches.



The cost of going to the KRpinwheel tiling is that we now need two of the original pinwheel substitutions in order to achieve the KRpinwheel substitution, which we also denote by  $\omega$ .



Using the KRpinwheel, we construct a border-forcing version of the pinwheel tiling, which is achieved by producing a set of collared tiles. We will call this new version the BFpinwheel tiling. A collared tile is a tile labelled by the pattern of its nearest neighbours; that is, two tiles have distinct labels if they are different tiles or if there are two different tiles sharing any edge or vertex with the tile. The BFpinwheel is constructed by considering all possible collared tiles in the KRpinwheel. Labelling the collared tiles gives 83 distinct tiles, 31 kites and 26 of each oriented rectangle. The collared tiles appear in [Appendix A](#). It is important to note that each tile is still an isometric copy of one of the KRpinwheel tiles and the labelling merely specifies the collar.

### 3. The Anderson–Putnam complex of the pinwheel tiling

In this section we compute the Čech cohomology of the quotient space  $\Omega_0 = \Omega/S^1$  for the BFpinwheel. Computing Čech cohomology for tilings with infinite rotational symmetry is the topic of [12, Ch. 4] and we direct the reader there for further information. For the pinwheel tiling, the quotient  $\Omega_0$  has been studied by several authors [4, 12, 14] and is equivalent to considering the subset of tilings in the continuous hull with the tile containing the origin of  $\mathbb{R}^2$  in a fixed standard orientation. The same holds true for the BFpinwheel, and we declare the orientations of the 83 tiles in [Appendix B](#) to be in standard orientation.

Starting with the 83 tiles, a CW complex  $\Gamma/S^1$  is defined by identifying edges and vertices in two tiles whenever they are common to both tiles in any patch of tiles appearing in a KRpinwheel tiling, and then arranging the tiles in standard orientation. It will be useful to label the 83 tiles in terms of their tile type: the 31 kite tiles are labelled  $K1, \dots, K31$ , 26 left rectangle tiles by  $L1, \dots, L26$ , and 26 right rectangle tiles by  $R1, \dots, R26$ . After identification of vertices and edges we obtain 138 edges, labelled  $e_1, \dots, e_{138}$ , and 73 vertices, labelled  $v_1, \dots, v_{73}$ . The CW complex  $\Gamma/S^1$  appears in [Appendix B](#). Note that Čech cohomology and singular cohomology agree on finite CW complexes, so we compute with singular cohomology on the approximants.

To use Anderson and Putnam’s machinery we have from [12, Section 4.4] that

$$\Omega_0 = \Omega/S^1 = \varprojlim (\Gamma/S^1 \leftarrow \Gamma/S^1 \leftarrow \Gamma/S^1 \dots)$$

with the map induced by the substitution on  $\Gamma/S^1$  (see [12, Section 4.3] for an elegant description of how the substitution induces a map on  $\Gamma/S^1$ ). Since cohomology is contravariant, inverse limits of space turn into direct limits of groups. Thus, we will compute the Čech cohomology of  $\Omega_0$  via

$$\check{H}^i(\Omega_0) = \varinjlim (H^i(\Gamma/S^1), A_i^*) \quad (3.1)$$

where  $A_i^*$  denotes the map induced by the substitution on the singular cohomology group  $H^i(\Gamma)$ .

To compute the integer cohomology of  $\Gamma/S^1$  we begin by defining the cochain complex. Let  $C^0$ ,  $C^1$  and  $C^2$  denote the functions from the vertices, edges, and tiles into the group of integers, respectively. The coboundary maps  $\delta^0 : C^0 \rightarrow C^1$  and  $\delta^1 : C^1 \rightarrow C^2$  are defined using the dual of the homology boundary maps. More precisely, we define a matrix for the homology boundary maps that gives rise to the coboundary maps in cohomology by taking the transpose of the matrix<sup>1</sup>. The cochain complex is given in the diagram below which is used to compute the cohomology groups of  $\Gamma/S^1$ :

$$\begin{array}{ccccccc} C^0 & \xrightarrow{\delta^0} & C^1 & \xrightarrow{\delta^1} & C^2 & \xrightarrow{\delta^2} & 0 \\ \mathbb{Z}^{73} & \xrightarrow{\delta^0} & \mathbb{Z}^{138} & \xrightarrow{\delta^1} & \mathbb{Z}^{83} & \xrightarrow{\delta^2} & 0. \end{array}$$

By definition, the cohomology group  $H^0(\Gamma/S^1) = \ker(\delta^0)$ . The kernel is generated by the function that assigns the value one to every vertex, and we obtain  $H^0(\Gamma/S^1) \cong \mathbb{Z}$ .

The computation of the remainder of the cohomology groups is more complicated. We have  $H^1(\Gamma/S^1) = \ker(\delta^1)/\text{Im}(\delta^0)$ . For  $1 \leq i \leq 138$ , in an abuse of notation, let  $e_i$  denote the function in  $C^1$  which assigns 1 to the edge  $e_i$  and 0 to all other edges; that is, the point mass function in  $C^1$  associated to the edge  $e_i$ . Our computations show that the group  $H^1(\Gamma/S^1)$  is generated by the class represented by the function

$$\begin{aligned} f_1 := & -e_1 + e_3 - e_7 + e_8 - e_{10} + e_{14} + e_{17} - e_{18} + e_{19} - e_{26} + e_{30} + e_{32} + e_{35} \\ & + e_{36} - e_{38} + e_{42} - e_{45} - e_{49} + e_{51} + e_{58} + e_{61} + e_{63} + e_{65} + e_{70} - e_{74} - e_{78} \\ & + e_{79} - e_{80} - e_{81} + e_{83} - e_{84} - e_{85} - e_{90} + e_{95} - e_{99} + e_{101} + e_{106} - e_{109} + e_{125}. \end{aligned} \tag{3.2}$$

Thus, we have  $H^1(\Gamma/S^1) \cong \mathbb{Z}$ .

The computation of  $H^2(\Gamma/S^1) = \ker(\delta^2)/\text{Im}(\delta^1)$  is more involved. Let  $t_1, \dots, t_{83}$  denote the point mass functions in  $C^2$  associated to the corresponding tile in  $K1, \dots, K31, L1, \dots, L26, R1, \dots, R26$  in order. For example,  $t_{12}$  assigns the value 1 to tile  $K12$  and 0 to all other tiles. Similarly,  $t_{56}$  is the point mass function associated with tile  $L25$ . Our computations show that the group  $H^2(\Gamma/S^1)$  is generated by classes represented by the 19 functions  $g_j \in C^2$  described below in (3.3). For  $j = 1, \dots, 19$ , denote the entries of the vectors in **Appendix C** by  $y_{ij}$  for  $i = 1, \dots, 83$  and let

$$g_j = \sum_{i=1}^{83} y_{ij}t_i \quad j \in \{1, \dots, 19\}. \tag{3.3}$$

The classes of  $H^2(\Gamma/S^1)$  are represented by  $g_j + \text{Im}(\delta^1)$ .

We obtain  $H^2(\Gamma/S^1) \cong \mathbb{Z}^{18} \oplus \mathbb{Z}_2$ , where the generator of  $\mathbb{Z}_2$  is represented by the function  $g_{19}$ . More specifically, the generator of  $\mathbb{Z}_2$  is  $t_{59} - 2t_{64} + \text{Im}(\delta^1)$  where  $t_{59}$  and  $t_{64}$  are the point mass functions associated with tiles  $R2$  and  $R7$  respectively.

<sup>1</sup>The substitution and boundary matrices are available upon request.

We have proved the following proposition.

**PROPOSITION 3.1.** *Let  $\Gamma/S^1$  be the Anderson–Putnam complex of the KRpinwheel tiling described in Appendix B. The integer cohomology groups are given by*

$$\begin{aligned} H^0(\Gamma/S^1) &\cong \mathbb{Z}, \\ H^1(\Gamma/S^1) &\cong \mathbb{Z}, \\ H^2(\Gamma/S^1) &\cong \mathbb{Z}^{18} \oplus \mathbb{Z}_2. \end{aligned}$$

The next step is to compute the Čech cohomology of  $\Omega_0$  using the inverse limit construction in Equation (3.1). We state the main result of this section.

**THEOREM 3.2** (cf. [4, Section 7]). *Let  $\Omega_0$  be the quotient  $\Omega/S^1$  for the KRpinwheel tiling. The Čech cohomology groups of  $\Omega_0$  are given by*

$$\begin{aligned} \check{H}^0(\Omega_0) &\cong \mathbb{Z}, \\ \check{H}^1(\Omega_0) &\cong \mathbb{Z}, \\ \check{H}^2(\Omega_0) &\cong \mathbb{Z}[\frac{1}{25}] \oplus \mathbb{Z}[\frac{1}{3}]^2 \oplus \mathbb{Z}^5 \oplus \mathbb{Z}_2. \end{aligned}$$

We will prove Theorem 3.2 using a sequence of lemmas.

**LEMMA 3.3.** *Let  $\Omega_0$  be the quotient  $\Omega/S^1$  for the KRpinwheel tiling. Then  $\check{H}^0(\Omega_0) \cong \mathbb{Z}$ .*

**PROOF.** The induced matrix  $A_0^*$  is the identity on the generator of  $H^0(\Gamma/S^1)$ . Therefore,

$$\check{H}^0(\Omega_0) = \varinjlim (H^0(\Gamma/S^1), A_0^*) \cong \varinjlim (\mathbb{Z}, id) \cong \mathbb{Z}. \quad \square$$

**LEMMA 3.4.** *Let  $\Omega_0$  be the quotient  $\Omega/S^1$  for the KRpinwheel tiling. Then  $\check{H}^1(\Omega_0) \cong \mathbb{Z}$ .*

**PROOF.** The induced matrix  $A_1^*$  is the identity map on the generator  $f_1 + \text{Im } \delta^0$  of  $H^1(\Gamma/S^1)$ , where  $f_1$  is described in (3.2). Therefore,

$$\check{H}^1(\Omega_0) = \varinjlim (H^1(\Gamma/S^1), A_1^*) \cong \varinjlim (\mathbb{Z}, id) \cong \mathbb{Z}. \quad \square$$

The group  $\check{H}^2(\Omega_0)$  is the most difficult to compute.

**LEMMA 3.5.** *Let  $\Omega_0$  be the quotient  $\Omega/S^1$  for the KRpinwheel tiling. Then  $\check{H}^2(\Omega_0) \cong \mathbb{Z}[\frac{1}{25}] \oplus \mathbb{Z}[\frac{1}{3}]^2 \oplus \mathbb{Z}^5 \oplus \mathbb{Z}_2$ .*

**PROOF.** We have  $H^2(\Gamma/S^1) \cong \mathbb{Z}^{18} \oplus \mathbb{Z}_2$ . We write  $A_2^* : H^2(\Gamma/S^1) \rightarrow H^2(\Gamma/S^1)$  as a matrix with respect to the 19 generators  $g_i$  of  $H^2(\Gamma/S^1)$  introduced in (3.3):

$$A_2^* = \begin{pmatrix} 25 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 612 & 25 & -150 & 0 & 0 & 0 & 110 & 0 & -110 & 0 & 0 & -110 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 102 & 50 & 250 & 0 & 0 & 0 & 110 & 0 & -110 & 0 & 0 & -110 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 567 & 100 & 1050 & 275 & -275 & 825 & 110 & 0 & -110 & 0 & 0 & -110 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 382 & -50 & 300 & 0 & 550 & -2200 & 110 & 0 & -110 & 0 & 0 & -110 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 216 & 25 & -150 & 0 & 0 & 0 & -220 & 0 & 220 & 0 & 0 & 220 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

where the last coordinate is the generator of  $\mathbb{Z}_2$ . We compute the direct limit

$$\check{H}^2(\Omega_0) = \varinjlim (H^2(\Gamma), A_2^*).$$





Using the generating set for  $A_2^*H^2(\Gamma/S^1)$  above, we have  $H^2(\Gamma/S^1)/\ker(A_2^*) \cong A_2^*H^2(\Gamma/S^1) \cong \mathbb{Z}^8 \oplus \mathbb{Z}_2$ . Observe that the homomorphism  $B$  is the identity on the fourth, fifth and sixth coordinates of  $\mathbb{Z}^8$  and on  $\mathbb{Z}_2$ . Thus,  $\check{H}^2(\Omega_0)$  is the direct sum of  $\mathbb{Z}^3 \oplus \mathbb{Z}_2$  and  $\varinjlim(\mathbb{Z}^5, M)$  where

$$M := \begin{pmatrix} 25 & 0 & 0 & 0 & 0 \\ 0 & 3 & 0 & 0 & 0 \\ 0 & 0 & 3 & 0 & 0 \\ 15\,300 & 75 & -450 & 1 & 0 \\ 5400 & 75 & -450 & 0 & 1 \end{pmatrix}.$$

The eigenvectors of  $M$  are  $(2, 0, 0, 1275, 450)$ ,  $(0, 6, 1, 0, 0)$  and  $(0, 2, 0, 75, 75)$  with eigenvalues 25, 3 and 3, respectively. The quotient of  $\mathbb{Z}^5$  by the corresponding eigenspaces is isomorphic to  $\mathbb{Z}^2$  and the quotient is generated by the classes of  $(0, 0, 0, 1, 0)$  and  $(0, 0, 0, 0, 1)$ . We have the short exact sequence

$$0 \rightarrow \mathbb{Z}^3 \rightarrow \mathbb{Z}^5 \rightarrow \mathbb{Z}^2 \rightarrow 0, \tag{3.4}$$

where  $\mathbb{Z}^3$  is the direct sum of the eigenspaces with eigenvalues 25, 3 and 3. Since  $(0, 0, 0, 1, 0)$  and  $(0, 0, 0, 0, 1)$  are eigenvectors of  $M$  both with eigenvalue 1,  $M$  is the identity map on the quotient  $\mathbb{Z}^2$ . Taking direct limits of (3.4) gives the short exact sequence

$$0 \rightarrow \mathbb{Z}[\frac{1}{25}] \oplus \mathbb{Z}[\frac{1}{3}]^2 \rightarrow \varinjlim(\mathbb{Z}^5, M) \rightarrow \mathbb{Z}^2 \rightarrow 0.$$

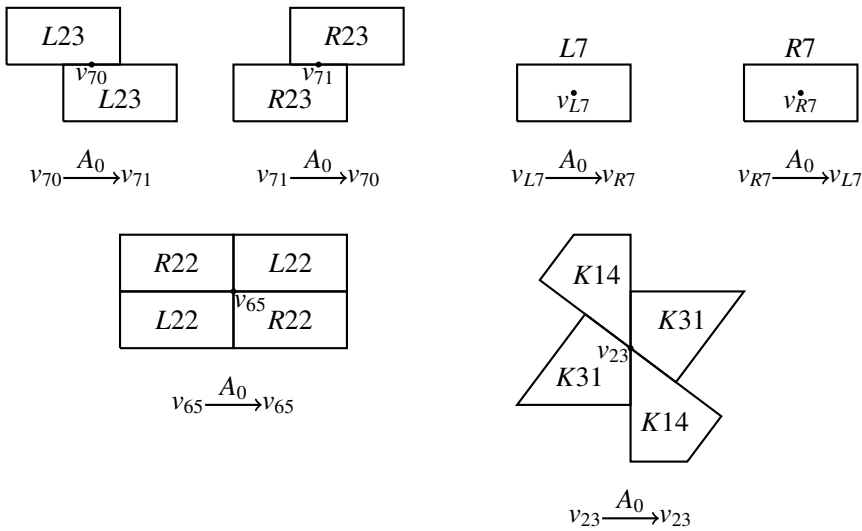
Since the quotient is free the sequence splits, and we have  $\varinjlim(\mathbb{Z}^5, M) = \mathbb{Z}[\frac{1}{25}] \oplus \mathbb{Z}[\frac{1}{3}]^2 \oplus \mathbb{Z}^2$ . Hence

$$\check{H}^2(\Omega_0) = \varinjlim(\mathbb{Z}^5, M) \oplus \mathbb{Z}^3 \oplus \mathbb{Z}_2 \cong \mathbb{Z}[\frac{1}{25}] \oplus \mathbb{Z}[\frac{1}{3}]^2 \oplus \mathbb{Z}^5 \oplus \mathbb{Z}_2. \quad \square$$

### 4. Čech cohomology of the pinwheel tiling

Beginning with the integer Čech cohomology of  $\Omega_0$ , the integer Čech cohomology of  $\Omega$  was computed in [4, Section 7]. There are two steps in the computation: the first is to identify cone singularities, and the second is to use a spectral sequence argument coming from the definition of the Gysin sequence. The second part of Barge *et al.*'s computation was extremely difficult, and we briefly outline the steps in the calculation. Using the results of [4, Section 7], we give the integer Čech cohomology of the pinwheel tiling.

We begin by identifying the cone singularities. In the pinwheel tiling, cone singularities correspond to pinwheel tilings with  $180^\circ$  symmetry. Rotational symmetry is preserved under substitution, so we can identify cone singularities by finding periodic points under the substitution of  $180^\circ$  symmetric patches of collared tiles. From Appendix A we find the following patches with  $180^\circ$  symmetry and vertices at the centre of rotation that are periodic under the substitution:



Placing the vertex of rotation at the origin of  $\mathbb{R}^2$  and substituting an infinite number of times leads to a tiling of the plane with  $180^\circ$  symmetry [12, Theorem 1.4]. Therefore, there are six cone singularities. We note that there are four additional patches with  $180^\circ$  symmetry (using tiles L3, L26, R3, and R26); however, the vertex at the centre of rotation is not periodic under the substitution, so they do not contribute to the number of cone singularities.

We now briefly outline the spectral sequence argument in [4, Section 7] used to compute  $\check{H}^*(\Omega)$ . The Gysin sequence [6, page 177] is used to compute the cohomology of an  $S^1$ -fibre bundle over the base space from the cohomology of the base space. Unfortunately, due to the presence of cone singularities, the map  $\Omega \rightarrow \Omega_0$  is not quite a fibration. However, the spectral sequence used to prove the Gysin sequence can be adjusted to account for these cone singularities. In [4], the authors show that the generators of the cone singularities account for five linearly independent torsion elements contributing a  $\mathbb{Z}_2^5$  term to  $\check{H}^2(\Omega)$ . The relevant results of [4] are summarised in the following theorem.

**THEOREM 4.1** (Barge, Diamond, Hunton and Sadun [4, Section 7 and Theorem 12]). *Suppose that  $\Omega$  is the continuous hull of the pinwheel tiling and  $\Omega_0 = \Omega/S^1$ . Given  $\check{H}^*(\Omega_0)$  and the cone singularities corresponding to tilings with  $180^\circ$ -rotational symmetry. The integer Čech cohomology groups are given by*

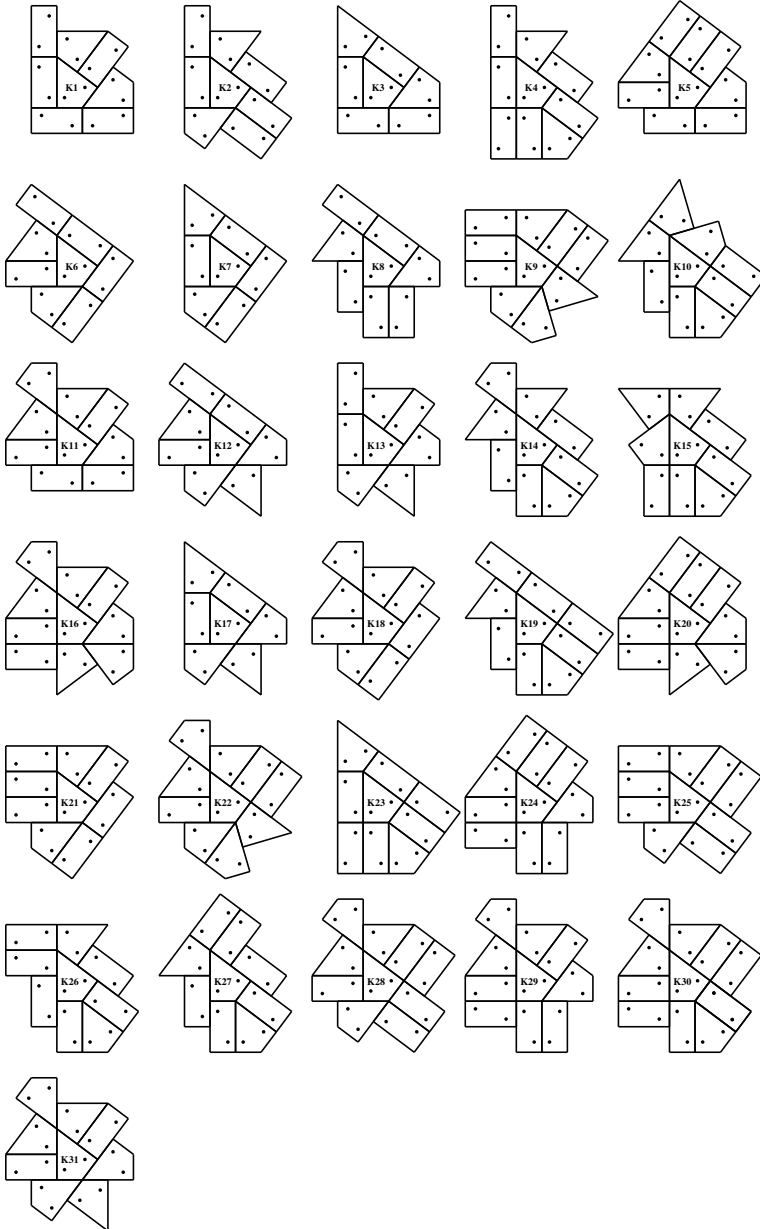
$$\begin{aligned} \check{H}^0(\Omega) &= \check{H}^0(\Omega_0) = \mathbb{Z}, \\ \check{H}^1(\Omega) &= \check{H}^0(\Omega_0) \oplus \check{H}^1(\Omega_0) = \mathbb{Z} \oplus \mathbb{Z}, \\ \check{H}^2(\Omega) &= E_{1,1}^\infty \oplus E_{2,0}^\infty = \mathbb{Z}[\frac{1}{25}] \oplus \mathbb{Z}[\frac{1}{3}]^2 \oplus \mathbb{Z}^6 \oplus \mathbb{Z}_2^5, \\ \check{H}^3(\Omega) &= \check{H}^2(\Omega_0) = \mathbb{Z}[\frac{1}{25}] \oplus \mathbb{Z}[\frac{1}{3}]^2 \oplus \mathbb{Z}^5 \oplus \mathbb{Z}_2, \end{aligned}$$

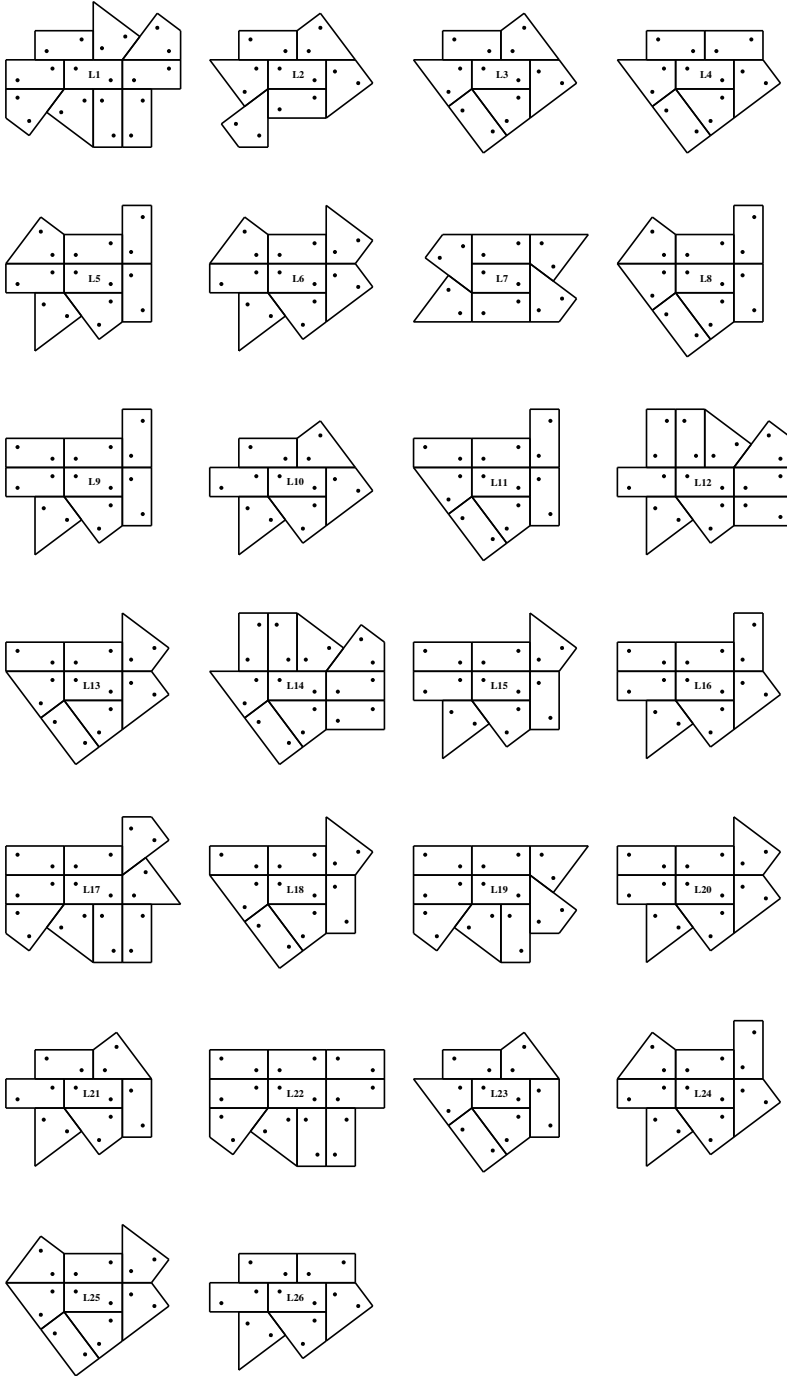
where the terms  $E_{1,1}^\infty = \mathbb{Z} \oplus \mathbb{Z}_2^5$  and  $E_{2,0}^\infty = \mathbb{Z}[\frac{1}{25}] \oplus \mathbb{Z}[\frac{1}{3}]^2 \oplus \mathbb{Z}^5$  come from the spectral sequence  $E^\infty$  which adjusts for the cone singularities and the torsion in  $\check{H}^2(\Omega_0)$ .

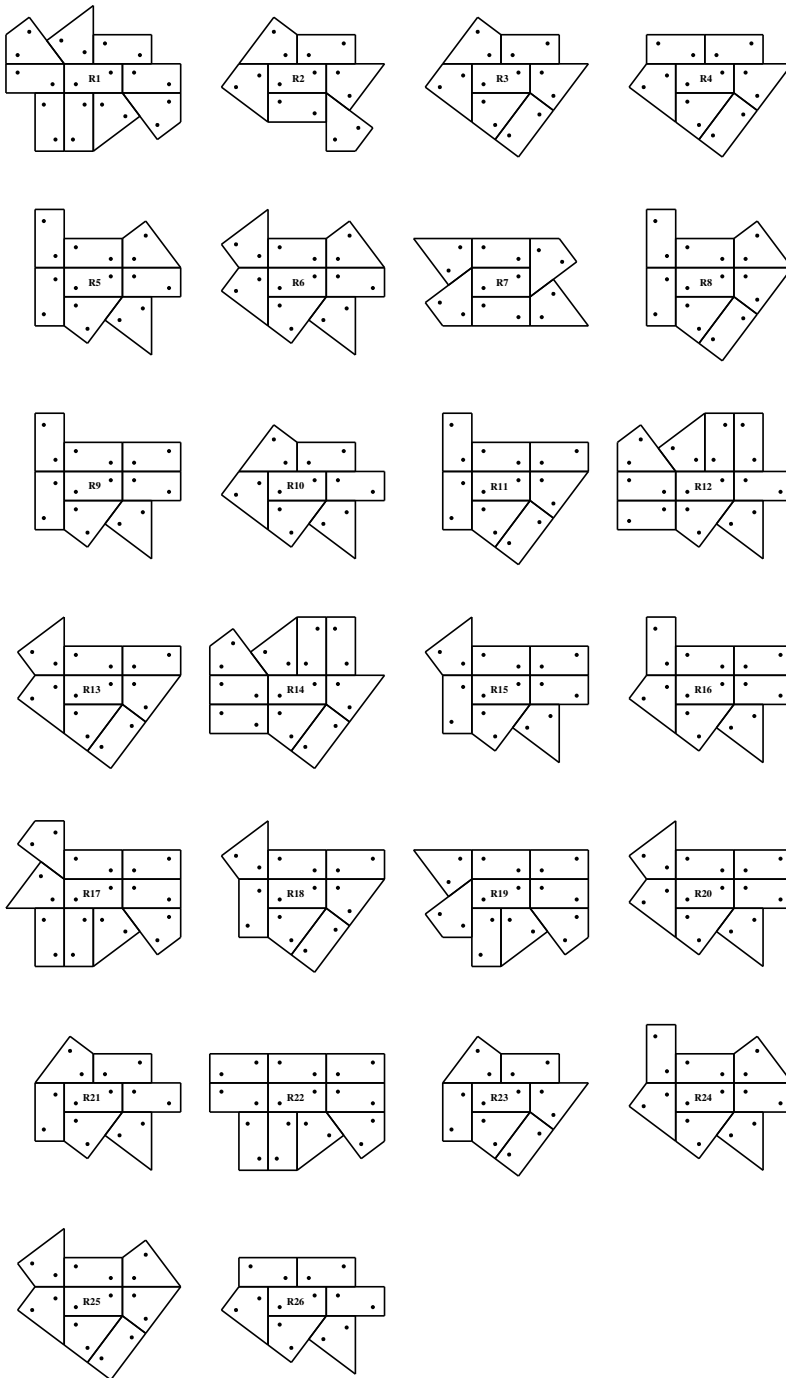
### Acknowledgements

We would like to thank Michael Baake, Lorenzo Sadun, and Aidan Sims for several helpful suggestions. We are especially grateful to Lorenzo for expanding on the constructions in [4] and providing insightful feedback on an early version of the paper.

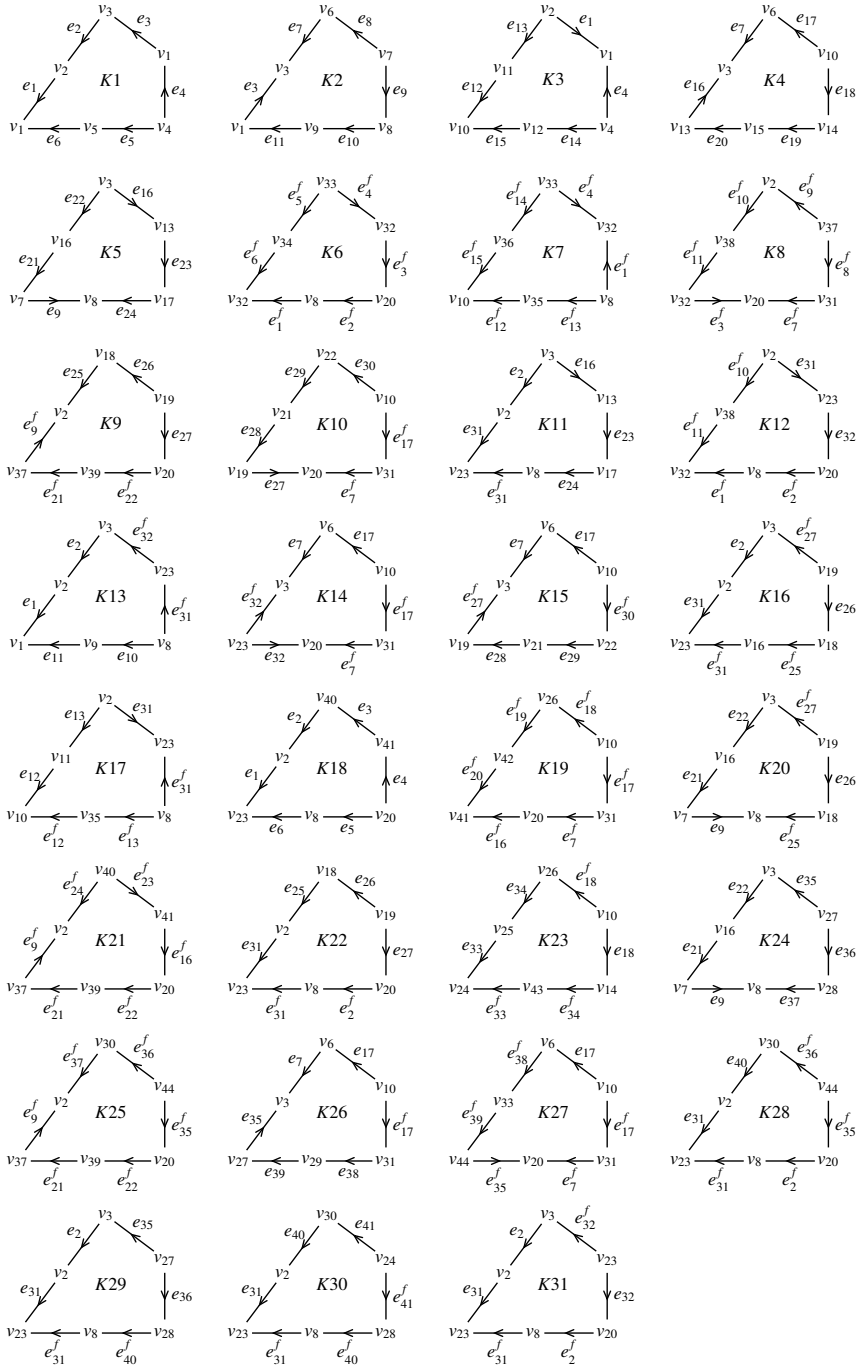
### Appendix A. The collared tiles

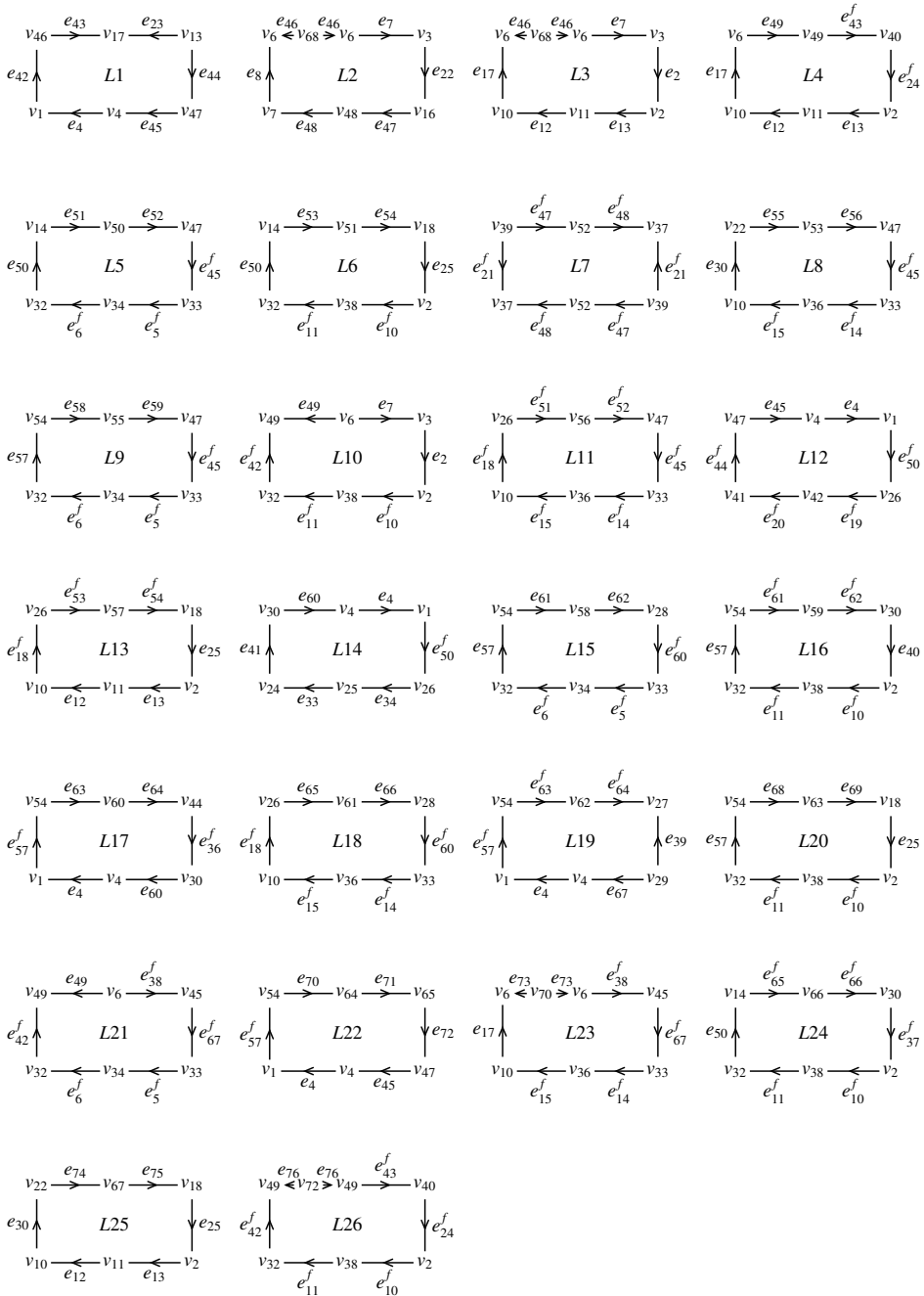


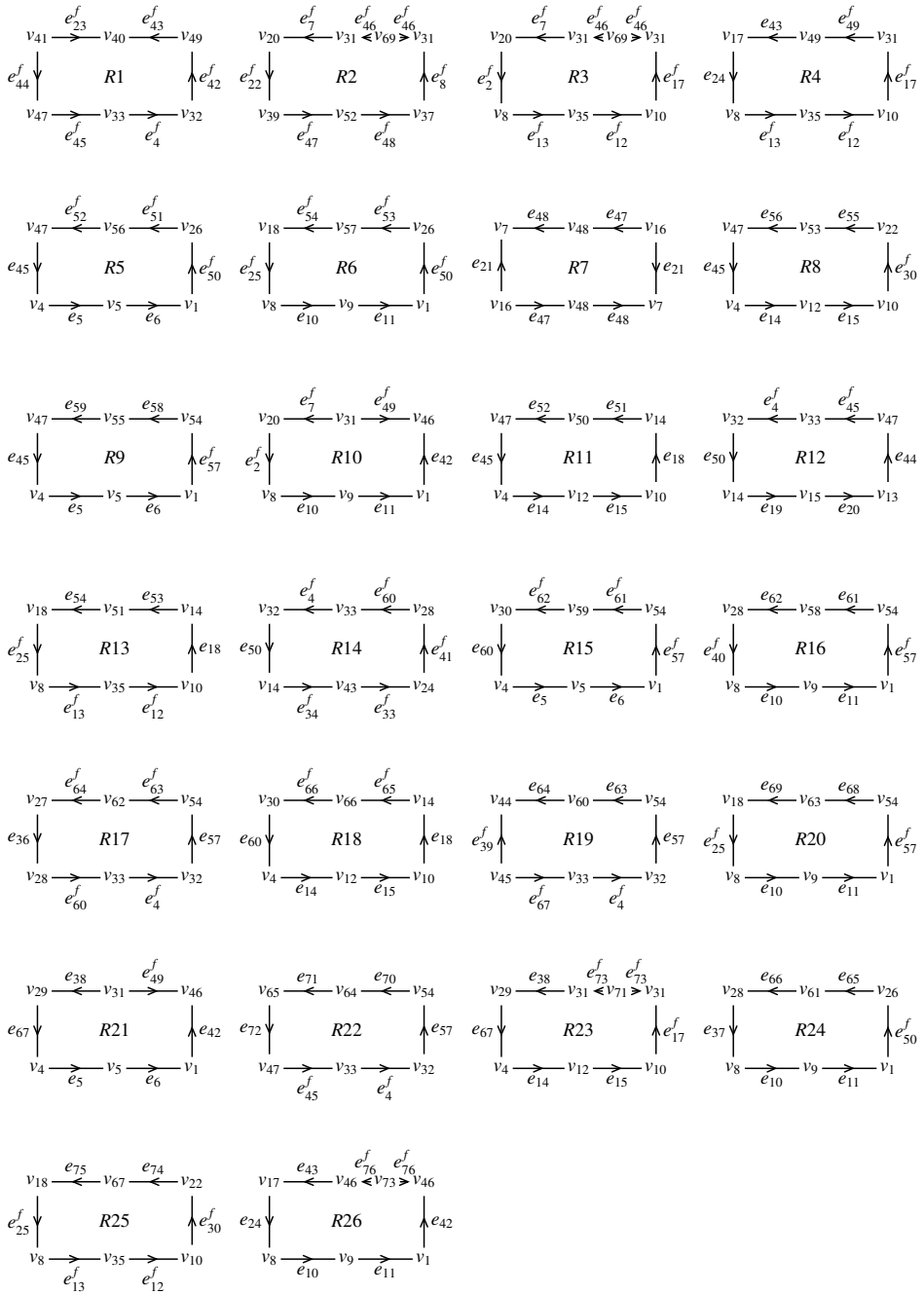




Appendix B. The labelled tiles











## References

- [1] J. Anderson and I. F. Putnam, ‘Topological invariants for substitution tilings and their  $C^*$ -algebras’, *Ergod. Th. & Dynam. Sys.* **18** (1998), 509–537.
- [2] M. Baake, D. Frettlöh and U. Grimm, ‘A radial analogue of Poisson’s summation formula with application to powder diffraction and pinwheel patterns’, *J. Geom. Phys.* **57** (2007), 1331–1343.
- [3] M. Barge and B. Diamond, ‘Cohomology in one-dimensional substitution tiling spaces’, *Proc. Amer. Math. Soc.* **136** (2008), 2183–2191.
- [4] M. Barge, B. Diamond, J. Hunton and L. Sadun, ‘Cohomology of substitution tiling spaces’, *Ergod. Th. & Dynam. Sys.* **30** (2010), 1607–1627.
- [5] R. Benedetti and J. M. Gambaudo, ‘On the dynamics of  $G$ -solenoids: application to Delone sets’, *Ergod. Th. & Dynam. Sys.* **23** (2003), 673–691.
- [6] R. Bott and L. W. Tu, *Differential Forms in Algebraic Topology*, Graduate Texts in Mathematics (Springer, New York, 1982).
- [7] J. Kellendonk, ‘Noncommutative geometry of tilings and gap labelling’, *Rev. Math. Phys.* **7** (1995), 1133–1180.
- [8] J. Kellendonk and I. F. Putnam, ‘Tilings,  $C^*$ -algebras, and K-theory’, in: *Directions in Mathematical Quasicrystals*, CRM Monograph Series, 13 (eds. M. Baake and R. V. Moody) (American Mathematical Society, Providence, RI, 2000), 177–206.
- [9] N. Ormes, C. Radin and L. Sadun, ‘A homeomorphism invariant for substitution tiling spaces’, *Geom. Dedicata* **90** (2002), 153–182.
- [10] C. Radin, ‘The pinwheel tilings of the plane’, *Ann. of Math. (2)* **139** (1994), 661–702.
- [11] L. Sadun, ‘Tiling spaces are inverse limits’, *J. Math. Phys.* **44** (2003), 5410–5414.
- [12] L. Sadun, *Topology of Tiling Spaces*, University Lecture Series, 46 (American Mathematical Society, Providence, RI, 2008).
- [13] B. Solomyak, ‘Dynamics of self-similar tilings’, *Ergod. Th. & Dynam. Sys.* **17** (1997), 695–738.
- [14] M. Whittaker, ‘ $C^*$ -algebras of tilings with infinite rotational symmetry’, *J. Operator Theory* **64** (2010), 299–319.

DIRK FRETTLÖH, Faculty of Technology,  
 Universität Bielefeld, Postfach 100131, 33501 Bielefeld, Germany  
 e-mail: [dirk.frettlöh@math.uni-bielefeld.de](mailto:dirk.frettlöh@math.uni-bielefeld.de)

BENJAMIN WHITEHEAD, School of Mathematics and Applied Statistics,  
 University of Wollongong, NSW 2522, Australia  
 e-mail: [bw219@uowmail.edu.au](mailto:bw219@uowmail.edu.au)

MICHAEL F. WHITTAKER, School of Mathematics and Applied Statistics,  
 University of Wollongong, NSW 2522, Australia  
 e-mail: [mfwhtaker@gmail.com](mailto:mfwhtaker@gmail.com)