TOPOLOGICAL CONSTRUCTIONS FOR TIGHT SURFACE GRAPHS

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Abstract. We investigate properties of sparse and tight surface graphs. In particular we derive topological inductive constructions for $(2,2)$-tight surface graphs in the case of the sphere, the plane, the twice punctured sphere and the torus. In the case of the torus we identify all 116 irreducible base graphs and provide a geometric application to configurations of circular arcs in the spirit of the Koebe-Andreev-Thurston circle packing theorem.

1. Introduction

Inductive characterisations of various families of graphs pay an important role in many parts of graph theory. A graph $G = (V, E)$ is said to be $(2,2)$-sparse if for any nonempty $V' \subset V$, we have $|E(V')| \leq 2|V'| - 2$. If, in addition, $|E| = 2|V| - 2$ we say that G is $(2,2)$-tight. Such graphs arise naturally in various parts of geometric graph theory, including framework rigidity, circle packings, and also in graph drawing.

We will derive inductive characterisations of $(2,2)$-tight graphs that are embedded without edge crossings in certain orientable surfaces of genus at most 1. Our characterisations will be base on edge contractions and are in the spirit of well known results of Barnette, Nakamoto and others ([2,16,17]) on irreducible traingulations and quadrangulations of various surfaces. It may be worth noting, for example, that a graph is a quadrangulation of the plane if and only if it is $(2,4)$-tight. There are similar characterisations of quadrangulations for various other surfaces. Thus it is clear that our results are related to, but distinct from, existing results on quadrangulations.

Since our graphs are embedded, we consider inductive characterisations based on topological edge contractions - that is to say that the contraction preserves the embedding of the graph (precise defintions given below). This is a key point, since the the well-known inductive characteristion of simple $(2,2)$-tight graphs by Nixon, Owen and Power is purely graph theoretic ([19]). To further illustrate the significance of this we give an application of our main result to a recognition problem in graph drawing. The topological nature of the inductive characterisation is crucial in this context.

Finally we note that there are similar topological inductive characterisations of Laman graphs in the literature already (see Fekete et al. and Haas et al.), which have interesting geometric applications to pseudotriangulations and auxetic structures.

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1.1. Outline of the paper and summary of main results. Section 2 and the first part of Section 3 are background material for the rest of the paper. The main contributions of the paper are as follows

- Theorem 3.4 presents an elementary but important principle concerning sparsity counts and graphs embedded in surfaces. While related results and special cases already exist in the literature, our statement and proof emphasises that this is a general principle that applies to wide range of sparsity counts and to surfaces of all genus.
- In Section 4 we analyse the quadrilateral contraction move. This operation is well known in the context of quadrangulations. Here we examine its properties with respect to $(2, 2)$-sparsity and prove some structural results about non contractible quadrilaterals in this context.
- Theorem 6.6 shows that if G is an irreducible $(2, 2)$-tight surface graph, then any $(2, 2)$-tight subgraph is also irreducible. This holds for surfaces of arbitrary genus.
- We give topological inductive characterisations of $(2, 2)$-tight graphs embedded in the sphere, plane, annulus (Theorem 5.4) and the torus (Theorem 7.6). The first two of these are relatively standard, whereas the latter two characterisations are new. In the case of Theorem 7.6 we have also identified the 116 irreducible $(2, 2)$-tight torus graphs. We do not give an explicit description of these graphs in the paper for reasons of space, but the reader is referred to [5] for details.
- Finally we present an application of our results to a recognition problem in graph drawing. Specifically we show that every $(2, 2)$-tight torus graph can be realised as the contact graph of a collection of nonoverlappingcircular arcs in the flat torus. We note that, by passing to the universal cover, this result may also be interpreted as a recognition result for contact graphs of doubly periodic collections of circular arcs in the plane.
- Conjecture 5.1 would generalise Theorem 7.6 to the set of irreducible $(2, 2)$-tight surface graphs for surfaces of arbitrary genus. This is analogous to results of Barnette, ?? and others on triangulations and quadrangulations of surfaces. As noted above and at appropriate points in the paper, many of our results are valid for a range of sparsity counts and for surfaces of arbitrary genus and these will be useful in future investigations of this conjecture.

2. Graphs, surfaces and embeddings

In this section we fix our conventions and terminology regarding topological graphs. Throughout, we use the word graph for directed multigraph. Although generally the orientation of the edges will not play an important role, the geometric application to graph drawing naturally gives rise to a directed graph so we adopt that as the basic object. Formally a graph is a quadruple (V, E, s, t) where the functions $s, t : E \to V$ encode the incidence relation between (directed) edges and vertices. All our graphs will be finite. Suppose that Σ is a compact real 2-dimensional manifold without boundary. A Σ-graph, or surface graph, is a pair (Γ, φ) where Γ is a graph and $\varphi : |\Gamma| \to \Sigma$ is a continuous embedding of the geometric realiastion of Γ in Σ. Given Σ_i-graphs (Γ_i, φ_i) for $i = 1, 2$ we say that they are isomorphic if there is a homeomorphism $h : \Sigma_1 \to \Sigma_2$ and a graph isomorphism $g : \Gamma_1 \to \Gamma_2$ such that $h \circ \varphi_1 = \varphi_2 \circ |g|$, where $|g|$ denotes the induced homeomorphism $|\Gamma_1| \to |\Gamma_2|$. By the Heffter-Edmonds-Ringel rotation principle, the surface Σ and the Σ-graph (Γ, φ) is determined up to isomorphism by data consisting of a rotation system on Γ, a partition of the set facial walks associated to the rotation system and the genus of each of the facial regions. Note that we not assume that our surface graphs are cellular. See [15] for details of this. We will be interested in determining certain classes of surface graphs up to isomorphism. The above-mentioned principle allows us to argue topologically using properties of surfaces and curves in surfaces to deduce combinatorial information and we choose to write our arguments using topological terminology based on this.

Now we clarify the meaning of some standard terms which may have ambiguous interpretations in this topological context. Let $G = (\Gamma, \varphi)$ be a Σ-graph and let $e \in E(\Gamma)$. By Γ/e we mean the graph obtained by identifying the end vertices of e and deleting (only) the edge e. Thus edge contractions can create parallel edges and/or loops. By G/e we mean the surface graph obtained by collapsing the arc corresponding to e to a single point. Clearly the underlying graph of G/e is Γ/e. A face, F, of G is a connected component of $\Sigma - \varphi(|\Gamma|)$. As is well known there is a well defined collection of closed boundary walks associated to F. We say that F is non degenerate if no vertex occurs more than once in this collection of walks. A cellular face is one that is homeomorphic to $\mathbb{R}^2$. For a cellular face F, the degree of F, denoted $|F|$, is the edge length of its unique boundary walk (which of course may differ from the number of vertices in degenerate cases). We write f_i for the number of cellular faces of degree i. Note that if Σ is connected then $f_0 = 1$ if Σ is a sphere and Γ comprises a single vertex, and $f_0 = 0$ otherwise.

Finally we note that we extend much of the standard language of graph theory concerning subgraphs, intersections and unions to surface graphs, understanding that these terms apply to the underlying graphs. Thus if $G = (\Gamma, \varphi)$ is a Σ-graph, a Σ-subgraph of G is a pair $(\Gamma', \varphi|_{\Gamma'})$ where Γ' is a subgraph of Γ and $\varphi|_{\Gamma'}$ denotes the restriction of φ to $|\Gamma'|$. If H_1, H_2 are Σ-subgraphs of G it should be clear what is meant by $H_1 \cap H_2$ and $H_1 \cup H_2$.

OLD VERSION

3. Sparsity

For a graph $\Gamma = (V, E, s, t)$ as above, define $\gamma(\Gamma) = 2|V| - |E|$. For $l \leq 2$ we say that Γ is $(2, l)$-sparse (or just sparse if l is clear from the context) if, $\gamma(\Gamma') \geq l$ for every nonempty subgraph Γ' of Γ. We say that Γ is $(2, l)$-tight if it is $(2, l)$-sparse and $\gamma(\Gamma) = l$. We will be particularly interested in $(2, 2)$-sparse graphs. Note that $(2, 2)$-tight graphs cannot have loop edges but can have parallel edges (but not triples of parallel edges).

We record some standard elementary facts for later use. The proofs are straightforward and we omit them. Suppose that Γ_1, Γ_2 are subgraphs of Γ. Then

$$\gamma(\Gamma_1 \cup \Gamma_2) = \gamma(\Gamma_1) + \gamma(\Gamma_2) - \gamma(\Gamma_1 \cap \Gamma_2) \tag{1}$$

Lemma 3.1. *Suppose that Γ is $(2, 2)$-sparse and that $\gamma(\Gamma') \leq 3$ for some subgraph Γ' of Γ. Then Γ' is connected.* □

Lemma 3.2. *Suppose that Γ_1, Γ_2 are $(2, 2)$-tight subgraphs of a $(2, 2)$-sparse graph Γ. If $\Gamma_1 \cap \Gamma_2$ is not empty then both $\Gamma_1 \cup \Gamma_2$ and $\Gamma_1 \cap \Gamma_2$ are $(2, 2)$-tight.* □

We also record a straightforward consequence of Euler's polyhedral formula.

Theorem 3.3. *If Σ is a connected boundaryless compact orientable surface of genus g and G is a cellular Σ-graph then*

$$\sum_{i \geq 0} (4 - i) f_i = 8 - 8g - 2\gamma(G) \tag{2}$$

Proof. Use the polyhedral formula and the fact that $\sum if_i = 2|E|$. $\square$

Next we will derive an elementary but but subsequently very useful principle relating the function γ, which is defined purely in terms of the underlying graph, to the embedding of the graph in the surface. We note that related results and special cases of this have appeared elsewhere (notably [8] and [3]). Here we attempt to express this principle in a more general terms: for surfaces of arbitrary genus and for a variety of sparsity counts.

In order to state the result we first need some notation. Let H is a subgraph of the Σ-graph G and suppose that F is a face of H. Let $\mathrm{int}_G(F)$ be the subgraph of G consisting of all vertices and edges of G that lie inside $\overline{F}$ (the topological closure of F in Σ). Let $\mathrm{ext}_G(F)$ denote the subgraph of G consisting of all vertices and edge of G that lie in $\Sigma - F$. Define $\partial F = \mathrm{int}_G(F) \cap \mathrm{ext}_G(F)$ and note that ∂F is the smallest subgraph of G that supports the boundary walks of F. It follows that that $G = \mathrm{int}_G(F) \cup \mathrm{ext}_G(F)$ since any edge joining $\mathrm{int}_G(F)$ to $\mathrm{ext}_G(F)$ must pass through ∂F.

Theorem 3.4. *Suppose that $l \leq 2$ and that G is a $(2, l)$-tight Σ-graph. If H is a subgraph of G and F is a face of H, then $\gamma(H \cup \mathrm{int}_G(F)) \leq \gamma(H)$.*

Proof. By (1) we have

$$\gamma(H \cup \mathrm{int}_G(F)) = \gamma(H) + \gamma(\mathrm{int}_G(F)) - \gamma(H \cap \mathrm{int}_G(F)).$$

Now, $H \cap \mathrm{int}_G(F) = \mathrm{ext}_G(F) \cap \mathrm{int}_G(F)$ and using (1) again, we see that

$$\begin{aligned}
\gamma(H \cap \mathrm{int}_G(F)) &= \gamma(\mathrm{ext}_G(F) \cap \mathrm{int}_G(F)) \\
&= \gamma(\mathrm{int}_G(F)) + \gamma(\mathrm{ext}_G(F)) - \gamma(\mathrm{ext}_G(F) \cup \mathrm{int}_G(F)) \\
&= \gamma(\mathrm{int}_G(F)) + \gamma(\mathrm{ext}_G(F)) - \gamma(G) \\
&= \gamma(\mathrm{int}_G(F)) + \gamma(\mathrm{ext}_G(F)) - l \\
&\geq \gamma(\mathrm{int}_G(F)).
\end{aligned}$$

The last inequality above follows from applying the sparsity of G to the nonempty subgraph $\mathrm{ext}_G(F)$. $\square$

Corollary 3.5. *Suppose that $l \leq 2$ and that G is a $(2, l)$-tight Σ-graph. If H is a subgraph of G and F is a face of H, then $\gamma(\mathrm{ext}_G(F)) \leq \gamma(H)$.*

Proof. Let $J_1, \cdots, J_k$ be all the faces of H that are different from F. Then $\mathrm{ext}_G(F) = H \cup \bigcup_{i=1}^{k} \mathrm{int}_G(J_i)$. Now the conclusion follows from repeated applications of Theorem 3.4. $\square$

We remark that all of the results of this section admit straightforward adaptations to the function γ_k which maps $H \mapsto k|V(H)| - |E(H)|$, for any positive integer k.

We conclude this section by making some straightforward observations about the subgraphs $\mathrm{int}_G(F)$ and $\mathrm{ext}_F(G)$ that will be useful in the sequel. Any face of $\mathrm{int}_G(F)$ that is contained in F is also a face of G. On the other hand, there are one or more faces of $\mathrm{int}_G(F)$ which are contained in $\Sigma - \overline{F}$. We call such a face an external face of $\mathrm{int}_G(F)$. Such an external face need not be a face of G. Note that if F has a unique boundary walk that is a simple cycle, then $\mathrm{int}_G(F)$ has just one external face. In general it may have more than one external face. Observe that $\mathrm{ext}_G(F)$ has one exceptional face, namely F, such that all other faces of $\mathrm{ext}_G(F)$ are also faces of G.

4. Inductive operations on surface graphs

In this section we will focus on topological inductive operations on graphs that are natural in the context of $(2, l)$-tight graphs. We consider three types contractions associated to cellular faces of degree 2, 3 and 4, respectively called digons, triangles and quadrilaterals hereafter. In each case the contraction decreases the number of vertices by one and the number of edges by two. We investigate necessary and sufficient conditions for these moves to preserve the property of being $(2, 2)$-tight. We pay particular attention to degenerate cases as these play an important role later.

4.1. **Digon and triangle contractions.** Let G be a Σ-graph and suppose that D is a digon of G with boundary walk v_1, e_1, v_2, e_2, v_1 such that $v_1 \neq v_2$ and $e_1 \neq e_2$. Let $G_D = (G/e_1) - e_2$. Observe that $(G/e_1) - e_2$ is canonically isomorphic to $(G/e_2) - e_1$, so G_D depends only on the digon and not the particular choice of labelling of the edges. We remark that, for a connected surface Σ, while a digon in a $(2, 2)$-sparse Σ-graph necessarily has distinct vertices, it may have degenerate boundary, but only in the case that the graph is a single (non loop) edge and Σ is a sphere.

The proof of the following is straightforward and we omit it.

Lemma 4.1. *G is $(2, l)$-sparse if and only if G_D is $(2, l)$-sparse*

Now suppose that T is a triangle in G with boundary walk $v_1, e_1, v_2, e_2, v_3, e_3, v_1$ such that $v_1 \neq v_2$ and $e_1 \neq e_2$. Let $G_{T,e_1} = (G/e_1) - e_2$. Again we omit the proof of the following lemma as it is a strightforward consequence of the definitions.

Lemma 4.2. *Suppose that G is $(2, l)$-sparse and that G_{T,e_1} is not $(2, l)$-sparse. Then there is a subgraph H of G that contains e_1 but not v_3 such that $\gamma(H) = l$*

We refer to the graph H whose existence is asserted in Lemma 4.2 as a blocker for the contraction G_{T,e_1}.

We note that a triangle in a $(2, 2)$-sparse surface graph necessarily has a non degenerate boundary walk, since any degeneracy would entail a (forbidden) loop edge. Thus, in this case there are three possible contractions (one for each of the edges) associated to any such face.

Lemma 4.3. *Suppose that G is a $(2, 2)$-sparse Σ-graph and that T is a triangle with edges e_1, e_2, e_3. Then at least two of the Σ-graphs $G_{T,e_1}, G_{T,e_2}, G_{T,e_3}$ are $(2, 2)$-sparse.*

Proof. Suppose that there are blockers H_1, respectively H_2, for G_{T,e_1} respectively G_{T,e_2}. Then $v_1, v_3 \in H_1 \cup H_2$. However $v_3 \notin H_1$ and $v_1 \notin H_2$ so $e_3 \notin H_1 \cup H_2$. However $v_2 \in H_1 \cap H_2$ so by Lemma 3.2, $H_1 \cup H_2$ is $(2, 2)$-tight. This contradicts the sparsity of G. □

4.2. **Quadrilateral contractions.** In the case of quadrilaterals we consider a somewhat different contraction move. In this case the analysis is a little more complicated and we include the details.

Suppose that Q is a quadrilateral of G with possibly degenerate boundary walk $v_1, e_1, v_2, e_2, v_3, e_3, v_4, e_4, v_1$. Suppose that $v_1 \neq v_3$ and $e_1 \neq e_3$. Let d be a new edge that joins v_1 and v_3 and is embedded as a diagonal of the quadrilateral Q. Define G_{Q,v_1,v_3} to be $(G \cup \{d\})/d - \{e_1, e_3\}$. Clearly the underlying graph of G_{Q,v_1,v_3} is obtained from Γ by identifying the vertices v_1 and v_3 and then deleting e_1 and e_3. Thus $\gamma(G) = \gamma(G_{Q,v_1,v_3})$. However this quadrilateral contraction move does not necessarily preserve $(2, l)$-sparsity.

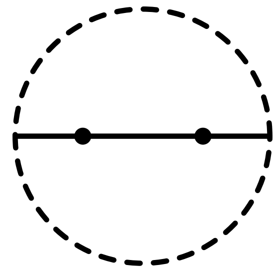

FIGURE 1. A $(2,2)$-tight projective plane graph. Here we are using the representation of the projective plane as a disc with antipodal boundary points identified. This surface graph has a single quadrilateral face, with a degenerate boundary walk.

Lemma 4.4. *Suppose that G is $(2,l)$-sparse but G_{Q,v_1,v_3} is not $(2,l)$-sparse. Then at least one of the following statements is true.*

1. *There is some subgraph H of G such that $v_1, v_3 \in H$, exactly one of v_2, v_4 is in H and $\gamma(H) = l$. (H is called a type 1 blocker.)*
2. *There is some subgraph K of G such that $v_1, v_3 \in K$, $v_2, v_4 \notin K$ and $\gamma(K) = l + 1$. (K is called a type 2 blocker.)*

Proof. Let K be a maximal subgraph of G_{Q,v_1,v_3} satisfying $\gamma(K) \leq l - 1$. Let z be the vertex of G_{Q,v_1,v_3} corresponding to v_1 and v_3. Clearly $z \in K$, otherwise K would also be a subgraph of G. Let H be the maximal subgraph of G satisfying $(H \cup \{d\})/d - \{e_1, e_3\} = K$. It is clear that H is an induced subgraph, since K is an induced subgraph. If $\{v_2, v_4\} \subset H$, then $\gamma(H) = \gamma(K) \leq l - 1$ which contradicts the sparsity of G. So at most one of v_2, v_4 belongs to H. Also, it is clear that $l \leq \gamma(H) \leq \gamma(K) + 2 \leq l - 1$. So $\gamma(H) = l$ or $l + 1$. If $\gamma(H) = l$ and one of $v_2, v_4 \in H$ then (1) is true. If $\gamma(H) = l$ and neither of v_2, v_4 is in H, then let $H' = H \cup \{v_2\} \cup \{e_1, e_2\}$. Now observe that $e_1 \neq e_2$ since $v_1 \neq v_3$. Thus $\gamma(H') = \gamma(H) = l$ and, again, (1) is true. Finally if $\gamma(H) = l + 1$. Then $\gamma(H) = \gamma(K) + 2$ and since H is a induced graph, it follows that neither of v_2, v_4 belongs to H. Thus (2) is true in this case. $\square$

In the special case that $l = 2$, various degeneracies are forbidden. Now suppose that G is a $(2,2)$-sparse Σ-graph and that Q is a quadrilateral face of G with boundary walk $v_1, e_1, v_2, e_2, v_3, e_3, v_4, e_4, v_1$. $e_5 = e_1$.

Lemma 4.5. *For $i = 1, 2, 3$, $v_i \neq v_{i+1}$, and $v_1 \neq v_4$.*

Proof. Loop edges are forbidden in a $(2,2)$-sparse graph. $\square$

Lemma 4.6. *Suppose that Σ is orientable and that G is $(2,2)$-tight. Then $e_i \neq e_j$ for $1 \leq i < j \leq 4$.*

Proof. We observe that since Σ is orientable, a repeated edge in ∂Q implies the existence either of a vertex of degree one or of a loop edge. Both of these are forbidden in a $(2,2)$-tight graph. $\square$

Lemma 4.7. *Suppose that Σ is orientable, G is $(2,2)$-tight and that $v_1 = v_3$. Then $v_2 \neq v_4$. Furthermore G_{Q,v_2,v_4} is also $(2,2)$-tight.*

Proof. Suppose that $v_2 = v_4$. By Lemma 4.5 and the sparsity of G, ∂Q has exactly two vertices and two edges. This contradicts Lemma 4.6. Thus $v_2 \neq v_4$.

Now suppose that G_{Q,v_2,v_4} is not $(2,2)$-tight. By Lemma 4.4 there is a blocker for this contraction. Since $v_1 = v_3$ by assumption, the blocker must be a type 2 blocker. Thus we have a subgraph K such that $\gamma(K) = 3$, $v_2, v_4 \in K$ and $v_1 \notin K$. However, by Lemma 4.6 there are at least four edges joining v_1 to K, contradicting the sparsity of G. □

See Figure 1 for an example of $(2,2)$-tight projective plane graph whose only face is a quadrilateral with repeated edges in the boundary walk. This example shows that orientability is a necessary hypothesis in the statements of Lemmas 4.6 and 4.7.

Lemma 4.8. *Suppose that Σ is orientable, G is $(2,2)$-tight and Q is a quadrilateral face of G such neither G_{Q,v_1,v_3} nor G_{Q,v_2,v_4} is $(2,2)$-sparse. Then Q has a non degenerate boundary. Furthermore, if H_1 and H_2 are blockers for G_{Q,v_1,v_3} respectively G_{Q,v_2,v_4}, then both H_1 and H_2 are type 2 blockers and $H_1 \cap H_2 = \emptyset$.*

Proof. The non degeneracy of the boundary walk of Q follows immediately from Lemmas 4.5, 4.6 and 4.7.

Now suppose that one of the blockers, say H_1, is of type 1 and suppose that $v_2 \notin H_1$. Then $v_4 \in H_1 \cap H_2$. So $\gamma(H_1 \cup H_2) = \gamma(H_1) + \gamma(H_2) - \gamma(H_1 \cap H_2) \leq 2 + \gamma(H_2) - 2 = \gamma(H_2)$. Now if H_2 is also type 1 then $\gamma(H_1 \cup H_2) = 2$. However $v_1, v_2, v_3 \in H_1 \cup H_2$ but $H_1 \cup H_2$ does not contain one of e_1, e_2 which contradicts the sparsity of G. Similarly if H_2 is type 2, then $\gamma(H_1 \cup H_2) \leq 3$, but $H_1 \cup H_2$ does not contain either of e_1, e_2, again contradicting the sparsity of G.

So both H_1 and H_2 are type 2 blockers. Moreover $v_1, v_2, v_3, v_4 \in H_1 \cup H_2$ but $e_1, e_2, e_3, e_4 \notin H_1 \cup H_2$. Now

$$\begin{aligned} 2 &\leq \gamma(H_1 \cup H_2 \cup \{e_1, e_2, e_3, e_4\}) \\ &= \gamma(H_1) + \gamma(H_2) - \gamma(H_1 \cap H_2) - 4 \\ &= 2 - \gamma(H_1 \cap H_2) \end{aligned}$$

So $\gamma(H_1 \cap H_2) \leq 0$ which implies that $H_1 \cap H_2 = \emptyset$. □

4.3. **Simple loops in surfaces.** Now we briefly digress to review some necessary terminology and facts from low dimensional topology. Proofs of all of the assertions below can found in (or at least easily deduced from) many sources (for example [7]). A loop in a surface Σ is a continuous function $\alpha : S^1 \to \Sigma$. We say that α is simple if it is injective. We say that α is non separating if $\Sigma - \alpha(S^1)$ has the same number of connected components as Σ. Given simple loops α, β in Σ, recall that the geometric intersection number is defined by

$$i(\alpha, \beta) = \min |\alpha'(S^1) \cap \beta'(S^1)|$$

where α', respectively β', varies over all simple loops that are homotopic to α, respectively β. If $i(\alpha, \beta) \neq 0$ then both α and β are essential: that is to say they are not null homotopic. If $i(\alpha, \beta) = 1$ then both α and β are non separating in Σ. In the special case that Σ is the torus, if $i(\alpha, \beta) = 0$ and $i(\beta, \delta) = 0$ then $i(\alpha, \delta) = 0$.

Given a simple loop α in a surface Σ we say that $\Sigma - \alpha(S^1)$ is the surface obtained by cutting along α. Given a surface Σ with boundary we can cap a boundary component by gluing a copy of a closed disc to the surface along the given boundary component.

If Σ is an orientable surface of genus g and α is a non separating simple loop in Σ then we form Σ^α by removing a tubular neighbourhood of α and then capping the two resulting new boundary components. Clearly Σ^α is an orientable surface of genus $g-1$.

Suppose that G is a Σ-graph and let F be a face of G. Further suppose that α is a non separating loop in Σ such that $\alpha(S^1) \subset F$. By cutting and capping Σ along α we can form a Σ^α-graph, denoted G^α which has the same underlying graph as G. Observe that all faces of G^α except the one(s) corresponding to F are also faces of G.

Finally in this digression, some terminology. If $G = (\Gamma, \varphi)$ is a Σ-graph and α is a loop in Σ, we say that α is contained in G if $\alpha(S^1) \subset \varphi(|\Gamma|)$.

Now we return to the situation of Lemma 4.8. Suppose that Q is a quadrilateral in G as in the statement of that lemma. We say that the quadrilateral Q is blocked. By Lemma 3.1 the blocker H_1 is connected so it is possible to find a simple walk from v_1 to v_3 in H_1. By concatenating the geometric realisation of this walk with the diagonal of Q joining v_3 and v_1 we obtain a simple loop in Σ, which we denote by α_1. Note that we can choose different parameterisations of this loop, but this ambiguity will make no difference in our context. Similarly we construct another simple loop, denoted α_2, by concatenating a walk in H_2 with the diagonal of Q that joins v_4 and v_2. Now since $H_1 \cap H_2$ is empty by Lemma 4.8, we can choose these loops so that they intersect transversely at exactly one point (where the diagonals meet). Thus these loops have geometric intersection number equal to one. In particular, we note that both α_1 and α_2 must be non separating loops in Σ. These loops will play an important role in the following sections.

5. Irreducible surface graphs

Let G be a $(2,2)$-tight Σ-graph. In light of Lemmas 4.1 and 4.3 we say that G is irreducible if it has no digons, no triangles and if, for every quadrilateral face of G, both of the possible contractions result in graphs that are not $(2,2)$-sparse.

For each of the contractions described in Section 4 there are the corresponding vertex splitting moves. More precisely, if $G' = G_D$, respectively $G' = G_{T,e}$, respectively $G' = G_{Q,u,v}$ for some digon D, respectively triangle T and edge $e \in \partial T$, respectively quadrilateral Q and vertices $u, v \in \partial Q$, then we say that G is obtained from G' by a digon, respectively triangle, respectively quadrilateral split. Thus every $(2,2)$-tight Σ-graph can be constructed from some irreducible by applying a sequence of digon/triangle/quadrilateral splits. Our goal is to identify, for various surfaces, the set of irreducibles.

Conjecture 5.1. *If Σ is a surface with finite genus and finitely many boundary components and punctures, then there are finitely many distinct isomorphism classes of irreducible $(2,2)$-tight Σ-graphs.*

We will address some special cases of Conjecture 5.1 in this and later sections. Let $\mathbb{S}$ be the 2-sphere.

Theorem 5.2. *If G is a $(2,2)$-tight $\mathbb{S}$-graph with at least two vertices then G has at least two faces of degree at most 3. In particular, any $(2,2)$-tight $\mathbb{S}$-graph can be constructed from a single vertex by a sequence of digon and/or triangle splits.*

Proof. By Lemma 3.1, G is connected and therefore cellular. Since G has at least two vertices, $f_0 = 0$. Also $f_1 = 0$ by sparsity, so by Theorem 3.3, we see that $2f_2 + f_3 \geq 4$. $\square$

The case of plane graphs is similarly straightforward.

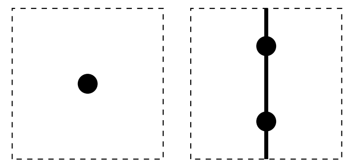

FIGURE 2. The two non cellular irreducible torus graphs. Here and in subsequent diagrams we use the standard representation of the torus as a square with opposite edges identified appropriately. Note that by cutting the torus along a non separating loop these graphs can also be viewed as graphs in the twice punctured sphere.

Corollary 5.3. *If G is a $(2,2)$-tight $\mathbb{R}^2$-graph with at least two vertices then G has at least one cellular face of degree at most 3. In particular, any $(2,2)$-tight $\mathbb{R}^2$-graph can be constructed from a single vertex by a sequence of digon and/or triangle splits.*

Proof. Cap (i.e fill in the puncture of) the non cellular face of G and then apply Theorem 5.2. $\square$

Let $\mathbb{A}$ be the twice punctured sphere $\mathbb{R}^2 - \{(0,0)\}$. There are two obvious examples of irreducible $(2,2)$-tight $\mathbb{A}$-graphs, with one vertex and two vertices respectively: see Figure 2.

Theorem 5.4. *If G is an irreducible $(2,2)$-tight $\mathbb{A}$-graph, then G is isomorphic to one of the $\mathbb{A}$-graphs shown in Figure 2.*

Proof. There are two cases to consider. First suppose that G does not separate the two punctures of $\mathbb{A}$. Then there is a unique non cellular face of G. By capping this face (i.e. filling in the two punctures) we create a cellular $(2,2)$-tight $\mathbb{S}$-graph $\tilde{G}$. As in the proof of Theorem 5.2, we see that either this graph has a single vertex or it has at least two faces that are digons or triangles. In the latter case, one of these faces must also be a face of G and so, in this case, if G has at least two vertices then it is not irreducible.

Now suppose that G does separate the punctures of $\mathbb{A}$. Clearly G has exactly two non cellular faces. By capping these two faces, we create a $(2,2)$-tight $\mathbb{S}$-graph $\tilde{G}$. This graph satisfies $2f_2 + f_3 = 4 + f_5 + 2f_6 + \cdots$ and since all but two of the faces of $\tilde{G}$ are also faces of the irreducible G, it follows that the two exceptional faces of $\tilde{G}$ are digons and all other faces are quadrilateral faces of G. Thus it suffices to show that there cannot be any quadrilateral faces in G.

For a contradiction, suppose that Q is a quadrilateral. Since G is irreducible, both possible contractions of Q are blocked and we infer the existence of simple loops α_1 and α_2 as described at the end of Section 4. Recall that these loops intersect transversely at exactly one point and thus α_1 is non separating in $\mathbb{A}$. However the Jordan Curve Theorem tells us that that any simple loop in $\mathbb{A}$ must be separating. $\square$

We note that, for any positive integer n, it is straightforward to construct an $\mathbb{A}$-graph that has no digons or triangles, but has n quadrilateral faces. So, in contrast to the cases of the sphere or plane, we do require the quadrilateral contraction move in order to have finitely many irreducible $(2,2)$-tight $\mathbb{A}$-graphs.

6. Subgraphs of irreducibles

Throughout this section, let Σ be an orientable boundaryless surface and let $G = (\Gamma, \varphi)$ be an irreducible $(2,2)$-tight Σ-graph. The goal of this section is to show that any $(2,2)$-tight subgraph of G is also irreducible.

Let $H = (\Lambda, \varphi|_{|\Lambda|})$ be a subgraph of G. We say that H is inessential if there is some embedded open disc $U \subset \Sigma$ such that $\varphi(|\Lambda|) \subset U$. If there is no such disc U then H essential.

We observe that if F is a cellular face of G that has a non degenerate boundary walk, then ∂F is inessential: let U be an open disc neighbourhood of the embedded closed disc $\overline{F}$. We also note that if H is inessential and is connected then it has at most one non cellular face F. Moreover if we cut and cap along a maximal non separating set of loops in F we obtain an $\mathbb{S}$-graph which, in this section, we will denote by $\hat{H}$.

Let K_1 be the graph with one vertex and no edges. Let K_2 be the complete graph on two vertices. For $n \geq 2$ let C_n be the n-cycle graph (in particular C_2 has exactly two parallel edges).

Lemma 6.1. *Suppose that H is a subgraph of G whose underlying graph is isomorphic to either C_2 or C_3. Then H is essential.*

Proof. Suppose that the underlying graph of H is isomorphic to C_2. The other case is similar. Suppose that H is inessential. Let U be an open disc that contains $\varphi(\Lambda)$. Clearly there is a digon face D of H that is contained in U. Now let K be the $\mathbb{S}$-graph obtained by cutting and capping the external face of $\mathrm{int}_G(D)$. By Theorem 3.4, $\gamma(K) = 2$ and by Theorem 3.3, K has at least two faces of degree at most 3. One of these faces is also a face of G contradicting the irreducibility of G. $\square$

Lemma 6.2. *Suppose that H is an inessential subgraph of G and that $\gamma(H) = 2$. Then the underlying graph of H is K_1.*

Proof. Suppose that H has at least two vertices. Then by Theorem 3.3, $\hat{H}$ has at least two faces of degree at most 3. If one of these is a triangle or a digon with non degenerate boundary then the underlying graph of H contains a copy of C_2 or C_3 which contradicts Lemma 6.1. Therefore $\hat{H}$ must have two digon faces both of which have degenerate boundaries. However, as pointed out in Section 4.1, no $\mathbb{S}$-graph can have more than one degenerate digon. $\square$

Lemma 6.3. *Suppose that H is an inessential subgraph of G and that $\gamma(H) = 3$. Then the underlying graph of H is K_2.*

Proof. By Theorem 3.3, $\hat{H}$ satisfies $2f_2 + f_3 = 2 + f_5 + 2f_6 + \cdots$. As in the proof of Lemma 6.2 we see that $\hat{H}$ cannot have a triangle or a digon with non degenerate boundary. So the only possibility is that $\hat{H}$ has a digon face with degenerate boundary. As pointed out in Section 4.1,, there is only one $\mathbb{S}$-graph with a degenerate digon face and its underlying graph is indeed K_2. $\square$

The case of a subgraph isomorphic to C_4 is a little more involved.

Lemma 6.4. *Suppose that H is an inessential subgraph of G whose underlying graph is isomorphic to C_4. Then H is the boundary of some quadrilateral face of G.*

Proof. Suppose that U is an embedded disc containing $\varphi(|\Lambda|)$ and let R be the face of H that is contained in U. First observe that $\gamma(H) = 4$, so by Theorem 3.4, $\gamma(\mathrm{int}_G(R)) \leq 4$. Now, by Lemma 6.1, $\mathrm{int}_G(R)$ has no digons or triangles and it follows easily from Theorem 3.3 that

$\gamma(\mathrm{int}_G(R)) = 4$ and that all the cellular faces of $\mathrm{int}_G(R)$ are quadrilaterals: that is to say that $\mathrm{int}_G(R)$ is in fact a quadrangulation of $\overline{R}$.

Now, let Q (with boundary vertices v_1, v_2, v_3, v_4) be a quadrilateral face of $\mathrm{int}_G(R)$ that is contained in R. Since G is irreducible, we have blockers H_1 and H_2 for the two possible contractions of Q, as described in Lemma 4.8. Also we have simple loops α_1 and α_2 as described in Section 4. These loops intersect transversely at one point in Q. If w_1, w_2, w_3, w_3 are the vertices of ∂R in cyclic order, it follows that one of the loops, say α_1, contains w_1 and w_2 and that α_2 contains w_2 and w_4. Thus α_2 divides R into disjoint open subsets R_1 and R_3 (see Figure 3) where $w_1, v_1 \in \overline{R_1}$ and $w_3, v_3 \in \overline{R_3}$. Now we can decompose the blocker H_1 as $K_e \cup K_1 \cup K_3$, where $K_e = \mathrm{ext}_G(R) \cap H_1$, K_1 is the part of H_1 contained in $\overline{R}_1$ and K_3 is the part of H_1 contained in $\overline{R}_3$. It is clear that $K_e \cap K_1 = \{w_1\}$ and $K_e \cap K_3 = \{w_3\}$. Therefore, by (1),

$$3 = \gamma(H_1) = \gamma(K_e) + \gamma(K_1) + \gamma(K_3) - 4.$$

Using the sparsity of G it follows that at least one of $\gamma(K_1)$ or $\gamma(K_3)$ is equal to 2. Now K_1 and K_3 are both inessential subgraphs of G since $\overline{R}_1$ and $\overline{R}_3$ are both embedded closed discs in Σ. It follows from Lemma 6.2 that at least one of K_1 or K_3 is a single vertex. So either $v_1 = w_1$ or $v_3 = w_3$. We have shown that at least one of v_1 or v_3 actually lies in the boundary of R. Similarly at least one of v_2 or v_4 lies in the boundary of R.

Thus we have shown that if Q is any quadrilateral face of G contained in R then ∂Q and ∂R share at least one edge. Now it is an elementary exercise to show that in any quadrangulation of R that has this property, either there are no quadrilaterals properly contained in R, or some quadrilateral has a boundary vertex with degree 2. Clearly, by Lemma 4.8, no quadrilateral face of the irreducible graph G can have a boundary vertex of degree 2. It follows that there are no quadrilateral faces of G that are properly contained in R and so R is itself a face of G. $\square$

We say that a subgraph $H = (\Lambda, \varphi|_{|\Lambda|})$ of G is annular if it is essential and $\varphi(|\Lambda|)$ is contained in some embedded open annulus of Σ. Let $\mathfrak{B}$ be the graph $(\{u, v, w\}, \{e, f, g, h\}, s, t)$, where $s(e) = s(f) = s(g) = s(h) = u$, $t(e) = t(f) = v$ and $t(g) = t(h) = w$.

Lemma 6.5. *Suppose that H is a subgraph of G whose underlying graph is isomorphic to $\mathfrak{B}$. Then H is not annular.*

Proof. Suppose, seeking a contradiction, that H is annular. Let U be an open annulus containing $\varphi(|\Lambda|)$ and let R be the face of H that is contained in U. Observe that $\gamma(H) = 2$, so by Theorem 3.4, $\gamma(\mathrm{int}_G(R)) = 2$. Let K be the $\mathbb{S}$-graph obtained by cutting and capping the external faces of $\mathrm{int}_G(R)$ (there could be more than one in this case). Now K is a $(2,2)$-tight $\mathbb{S}$-graph with two digon faces. Since all other faces of K are also faces of the irreducible G, it follows easily from Theorem 3.3 that all other faces of K are quadrilaterals. Thus, all faces of G that are contained in R are in fact quadrilaterals.

Now we can argue, using a straightforward modification of the argument from the proof of Lemma 6.4, that any quadrilateral face of G that is contained in R must in fact share a boundary edge with R. Again, following the proof of Lemma 6.4 it follows that R itself must be a face of G. However this contradicts Lemma 4.8 where we showed that any quadrilateral face of an irreducible has a non degenerate boundary. $\square$

Now the main result of this section: a tight subgraph of an irreducible is also irreducible.

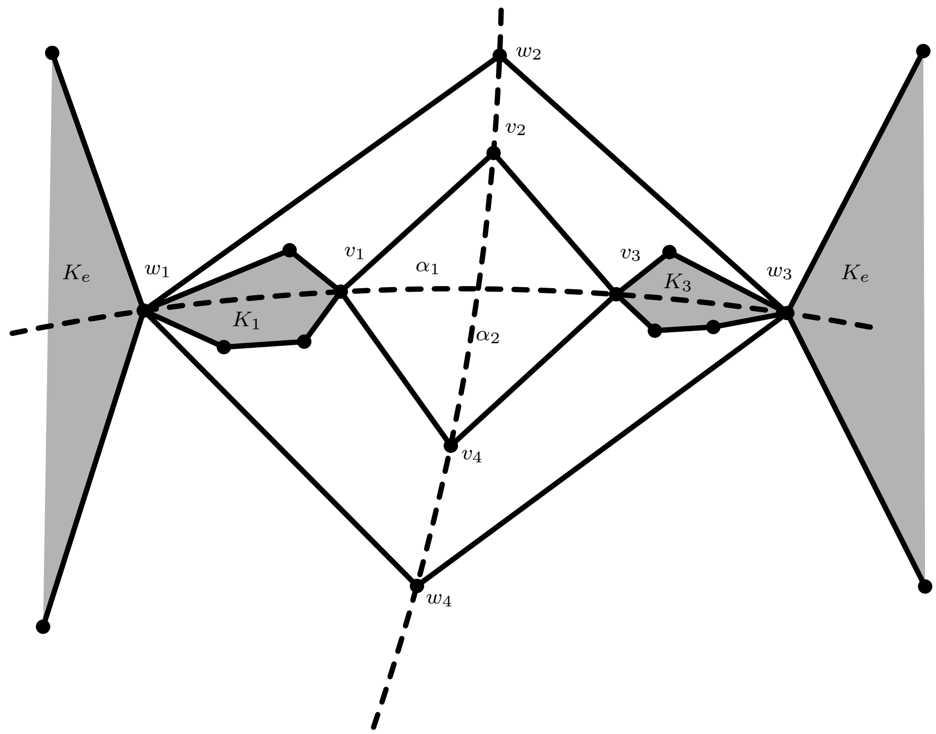

FIGURE 3. From the proof of Lemma 6.4: the shaded region represents the blocker for the contraction G_{Q,v_1,v_3}.

Theorem 6.6. *Suppose that $G = (\Gamma, \varphi)$ is an irreducible $(2,2)$-tight Σ-graph and Λ is a $(2,2)$-tight subgraph of Γ. Then $H = (\Lambda, \varphi|_{|\Lambda|})$ is an irreducible Σ-graph.*

Proof. We see that H cannot have any triangle or digon, since the boundary of such a face would contradict Lemma 6.1. Now suppose that Q is a quadrilateral face of H. It is not clear, a priori, that the boundary of Q is non degenerate, so we must prove that before proceeding.

Applying Lemma 4.6 to H, we see that there are no repeated edges in the boundary of Q. Thus the only possibility for a degenerate boundary is that one vertex is repeated and that ∂Q has underlying graph isomorphic to $\mathfrak{B}$. If ∂Q is inessential then, since $\mathfrak{B}$ contains a copy of C_2, this contradicts Lemma 6.1. On the other hand, if ∂Q is inessential then it must be annular and this contradicts Lemma 6.5. Thus we see that in fact Q must have a non degenerate boundary.

By Lemma 6.4 this means that Q is also a face of G and so there are blockers H_1, H_2 as described by Lemma 4.8. Now consider the Σ-graph $K = H_1 \cup H_2 \cup \partial Q$. This is $(2,2)$-tight, so, by Lemma 3.2, $K \cap H$ is also $(2,2)$-tight. Now, $K \cap H = (H_1 \cap H) \cup (H_2 \cap H) \cup \partial Q$. Using (1), $H_1 \cap H_2 = \emptyset$, $H_1 \cap H \cap \partial Q = \{v_1, v_3\}$ and $H_2 \cap H \cap \partial Q = \{v_2, v_4\}$, we have

$$\begin{aligned} 2 &= \gamma(K \cap H) \\ &= \gamma(\partial Q) + \gamma(H_1 \cap H) + \gamma(H_2 \cap H) - \gamma(H_1 \cap H \cap \partial Q) - \gamma(H_2 \cap H \cap \partial Q) \\ &= 4 + \gamma(H_1 \cap H) + \gamma(H_2 \cap H) - 4 - 4. \end{aligned}$$

Thus $\gamma(H_1 \cap H) + \gamma(H_2 \cap H) = 6$. If $\gamma(H_1 \cap H) = 2$ then $(H_1 \cap H) \cup \{v_2\} \cup \{e_1, e_2\}$ would be a type 1 blocker for the contraction G_{Q,v_1,v_3}, contradicting Lemma 4.8. So $\gamma(H_1 \cap H) \geq 3$ and similarly $\gamma(H_2 \cap H) \geq 3$. It follows that $\gamma(H_1 \cap H) = \gamma(H_2 \cap H) = 3$ and that $H_1 \cap H$ and $H_2 \cap H$ are blockers for the contractions H_{Q,v_1,v_3} and H_{Q,v_1,v_3} respectively. Thus both possible contractions of Q are blocked in H as required. □

For example, suppose that Γ is the simple $(2, 2)$-tight graph obtained by adding a vertex of degree two to K_4. Is it possible to embed Γ into the torus to create an irreducible torus graph? There are several possible embeddings to consider, however we can significantly narrow the search space by observing that since K_4 is tight, by Theorem 6.6, any irreducible embedding of Γ must extend an irreducible embedding of K_4. Now, it is not hard to see that there is only one irreducible embedding of K_4 in the torus, up to isomorphism. Moreover, one readily checks that there is no way to add the remaining vertex of Γ to this embedding without creating a face of degree at most 4. Thus there is no irreducible embedding of Γ in the torus.

7. Irreducible torus graphs

Let $\mathbb{T} = S^1 \times S^1$ be the torus. Throughout this section let $G = (\Gamma, \varphi)$ be an irreducible $(2, 2)$-tight $\mathbb{T}$-graph. Our goal in this section is to show that there are only finitely many isomorphism classes of such graphs by establishing an upper bound for the number of vertices of G.

In the case that G is not cellular we will see that we can essentially reduce the problem to the sphere or the annulus. If G is cellular then using Theorem 3.3 and $f_2 = f_3 = 0$ we see that G satisfies $f_5 + 2f_6 + 3f_7 + 4f_8 = 4$ and $f_i = 0$ for $i \geq 9$. Since $|V| = 2 + \sum_{i \geq 2} f_i$, the problem reduces to establishing a bound for the number of quadrilateral faces that an irreducible $\mathbb{T}$-graph can have.

First we deal with the non cellular case.

Lemma 7.1. *Suppose that G is not cellular. Then Γ is either isomorphic to K_1 or to C_2. Furthermore, in the latter case, G is annular.*

Proof. Since Γ is connected it is clear G has a single non cellular face. By cutting along a non separating loop in this face we obtain an $\mathbb{A}$-graph $\hat{G}$. Observe that any face of $\hat{G}$ that is not also a face of G is non cellular. It follows that $\hat{G}$ is an irreducible $\mathbb{A}$-graph. Now the conclusion follows from Theorem 5.4. □

For the remainder of the section, assume that G is cellular. Let Q be a quadrilateral face of G with boundary walk $v_1, e_1, v_2, e_2, v_3, e_3, v_4, e_4, v_1$. As described in Section 4 we have blockers H_1 and H_2 and simple loops α_1 and α_2 that intersect transversely at one point.

Lemma 7.2. *At least one of H_1 or H_2 is an inessential subgraph of G.*

Proof. Suppose that both are essential. Then there are non separating simple loops β_1 contained in H_1 and β_2 contained in H_2. Now $H_1 \cap H_2 = \emptyset$, so $i(\beta_1, \beta_2) = 0$. However, it is also clear that $i(\alpha_1, \beta_2) = i(\alpha_2, \beta_1) = 0$. As pointed out in Section 4.3 this implies that $i(\alpha_1, \alpha_2) = 0$, contradicting the fact that these curves intersect transversely at one point. □

For the remainder of the section, suppose that H_1 is an inessential blocker. By Lemma 6.3, the graph of H_1 is K_2. Furthermore we will assume that H_2 is a maximal blocker with respect to inclusion and let J be the face of H_2, that contains v_1, v_3. See Figure 4 for an illustration of these assumptions in the case where H_2 is an essential blocker.

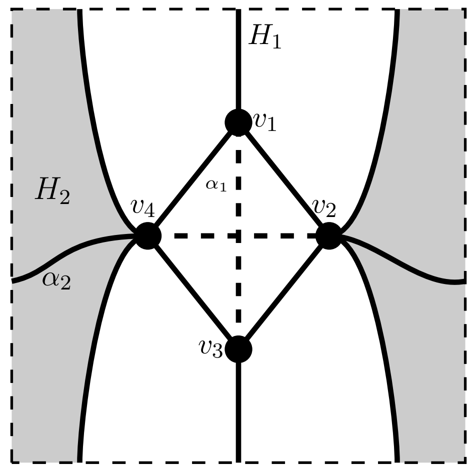

FIGURE 4. A quadrilateral face with an essential blocker. The shaded region represents the essential blocker H_2.

Lemma 7.3. *Any face of H_2 that is not J is also a face of G.*

Proof. Suppose that $F \neq J$ is a face of H_2. Then $\gamma(H_2 \cup \mathrm{int}_G(F)) \leq \gamma(H_2) = 3$, by Theorem 3.4. Also $v_1, v_3 \notin \mathrm{int}_G(F)$, since $F \neq J$. If follows that $H_2 \cup \mathrm{int}_G(F)$ is a blocker for G_{Q,v_2,v_4} and so by the maximality of H_2, $\mathrm{int}_G(F) \subset H_2$ as required. $\square$

Next we want to examine the structure of H_2. It turns out that there are exactly ten distinct possibilities. If H_2 is inessential then, by Lemma 6.3 it has graph K_2 (Figure 5). On the other hand, if H_2 is essential we have the following.

Lemma 7.4. *Suppose that H_2 is essential. Then it is isomorphic to one of the nine torus graphs shown in Figures 6 and 7.*

Proof. Since $\gamma(H_2) = 3$, it is connected by Lemma 3.1. Let K be the $\mathbb{S}$-graph obtained by cutting and capping H_2 along a non separating loop in J. Clearly K has two exceptional faces J^+ and J^- such that all other faces of K are faces of G (using Lemma 7.3). Now, since J^+ and J^- are the only faces of K that could have degree less than 4, Theorem 3.3 implies that K satisfies

$$2f_2 + f_3 = 2 + f_5 + 2f_6 \tag{3}$$

and $f_i = 0$ for $i \geq 7$. There are two cases to consider.

(a) There is no quadrilateral face of G in H_2. There are various subcases:

(1) $|J^+| = |J^-| = 2$. Then, from Equation 3 we get $f_5 + 2f_6 = 2$. So either $f_5 = 0$ and $f_6 = 1$ and we have the example shown in Figure 6 (a), or, $f_5 = 2$ and $f_6 = 0$ and we have one of the examples shown in Figure 6 (b) or (c).

(2) $|J^+| = 2$ and $|J^-| = 3$. Then we have $f_5 = 1$. There is one possibility: Figure 6 (d).

(3) $|J^+| = |J^-| = 3$. In this case, Equation 3 implies that J^+ and J^- are the only faces of K. So we have the example shown in Figure 6 (e).

(4) $|J^+| = 2$ and $|J^-| = 4$. In this case, Equation 3 implies that J^+ and J^- are the only faces of K and we have the example shown in Figure 6 (f).

(b) There is some quadrilateral face of G in H_2. This case requires a little more effort as we must first establish that there is no more than one such face. Let $G' = \partial Q \cup H_1 \cup H_2$. Clearly G' is $(2,2)$-tight and so by Theorem 6.6 it is also irreducible.

Suppose that R is a quadrilateral face of G, with boundary vertices w_1, w_2, w_3, w_4, that is contained in H_2 (and so is also a face of G'). By Lemma 7.2 we know that there is a blocker for one of the contractions of R in G' whose graph is K_2. Without loss of generality assume that a blocker L_1 for the contraction G'_{R,w_1,w_3} has graph K_2. Now we claim that $L_1 \subset H_2$. If not then it is clear that L_1 must intersect H_1. Since the vertices of L_1 are both in H_2 this contradicts $H_1 \cap H_2 = \emptyset$, thus establishing our claim.

Now consider a maximal blocker, L_2, for the contraction G'_{R,w_2,w_4}. We have

$$\begin{aligned} 3 &= \gamma(L_2) \\ &= \gamma(L_2 \cap (\partial Q \cup H_1)) + \gamma(L_2 \cap H_2) - \gamma(L_2 \cap (\partial Q \cup H_1) \cap H_2) \\ &= \gamma(L_2 \cap (\partial Q \cup H_1)) + \gamma(L_2 \cap H_2) - \gamma(L_2 \cap \{v_2, v_4\}) \end{aligned}$$

Now it is clear that $\{v_2, v_4\} \subset L_2$ since L_2 is connected, so we have

$$\gamma(L_2 \cap H_2) = 7 - \gamma(L_2 \cap (\partial Q \cup H_1)) \tag{4}$$

Furthermore, it is also clear that L_1 separates v_2 from v_4 in H_2, so $L_2 \cap H_2$ has at least two components. Also $L_2 \cap (\partial Q \cup H_1)$ is a subgraph of $\partial Q \cup H_1$ that contains the vertices v_2, v_4. It follows easily that $\gamma(L_2 \cap (\partial Q \cup H_1)) \geq 3$ with equality only if $L_2 \cap (\partial Q \cup H_1) = \partial Q \cup H_1$. Therefore the only way that (4) can be satisfied is that $\partial Q \cup H_1 \subset L_2$ and $L_2 \cap H_2$ has exactly two components $X_2 \ni v_2$ and $X_4 \ni v_4$ such that $\gamma(X_2) = \gamma(X_4) = 2$. In particular it follows from Theorem 6.6 and Lemma 7.1 that the underlying graph of X_2, and also of X_4, is isomorphic to K_1 or C_2. Now since L_1 also separates w_2 and w_4 in H_1 we can, without loss of generality, assume that $v_2, w_2 \in X_2$ and $v_4, w_4 \in X_4$.

Let Z_2, respectively Z_4, be the maximal $(2,2)$-tight subgraph of H_2 that contains v_2, respectively v_4. By Lemma 3.2 we see that $X_2 \subset Z_2$ and $X_4 \subset Z_4$. Furthermore we see that since Z_2 and Z_4 are both disjoint from α_1, they are either annular or inessential. By Lemma 7.1, Z_2 has graph K_1 (inessential case) or C_2 (annular case). Similar comments apply to Z_4. Now the argument in the paragraph above shows that every quadrilateral face of H_2 has a boundary vertex in Z_2 and a diagonally opposite vertex in Z_4. It follows easily that there is at most one such quadrilateral face in H_2.

Now we can argue as in case (a) but with the proviso that there is exactly one quadrilateral face, R, of H_2 that is also a face of G. We observe that there is a cycle of length 3 in H_2 (formed by two edges of ∂R and the inessential blocker for R) and so also in K. It is not hard to see that it follows that K must have at least two faces of odd degree: at least one on either 'side' of the cycle of length 3. We find the following subcases.

(1) $|J^+| = |J^-| = 2$. From Equation (3) we have $f_5 + 2f_6 = 2$. Since K has some face of odd degree we can rule out the possibility $f_5 = 0, f_6 = 1$. Therefore $f_5 = 2$ and $f_6 = 0$. There is only one possibility for H_2: Figure 7 (a).
(2) $|J^+| = 2$ and $|J^-| = 3$. Then, as in case (a) we have $f_5 = 1$ and there is one possibility: Figure 7 (b).
(3) $|J^+| = |J^-| = 3$. In this case, Equation 3 implies that R, J^+ and J^- are the only faces of K: Figure 7 (c).

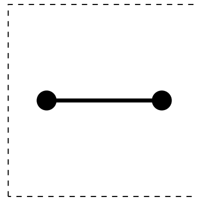

Figure 5. The unique inessential blocker

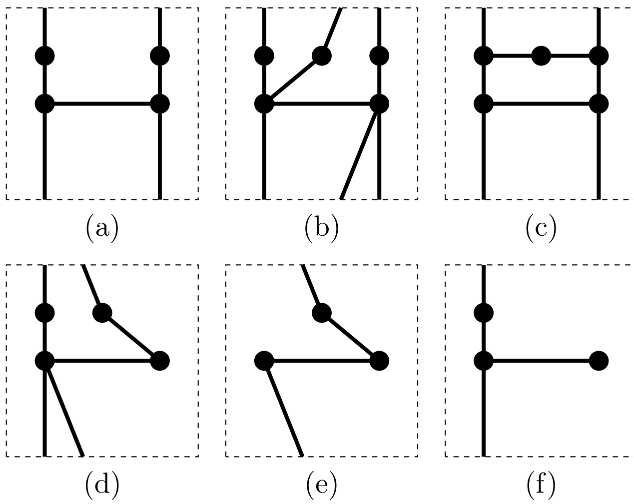

Figure 6. Essential blockers with no quadrilateral face

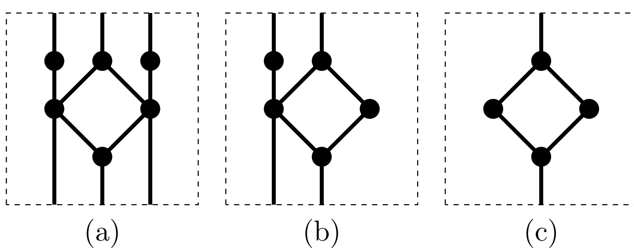

Figure 7. Essential blockers with a quadrilateral face

(4) $|J^+| = 4$ and $|J^-| = 2$. Since K must have at least two faces of odd degree, Theorem 3.3 would imply that there is a triangle or digon in K that is also a face of G, contradicting its irreducibility. Thus this subcase cannot arise.

□

It remains to rule out the possibility of a quadrilateral face that is neither Q nor a face of H_2. In fact we can prove something a little more general than that.

Lemma 7.5. *K be a $(2,2)$-tight subgraph of G and suppose that F is a cellular face of K. There is no quadrilateral face of G properly contained within F.*

Proof. Suppose that R, with vertices w_1, w_2, w_3, w_4, is a quadrilateral face of G properly contained within F and let B_1 and B_2 be blockers for contractions of R in G. If $B_1 \subset F$, then since F is cellular, B_1 would separate w_2 from w_4 which contradicts $B_1 \cap B_2 = \emptyset$. Therefore B_1 is not contained in F or equivalently, since B_1 is connected, $B_1 \cap K \neq \emptyset$. Similarly $B_2 \cap K \neq \emptyset$.

Now, let $M = \partial R \cup B_1 \cup B_2$ and observe that M is $(2,2)$-tight and therefore, by Lemma 3.2, $M \cap K$ is also $(2,2)$-tight. Now it is clear that $M \cap K = (B_1 \cap K) \cup (B_2 \cap K) \cup E(\partial R \cap K)$. Therefore

$$2 = \gamma(M \cap K) = \gamma(B_1 \cap K) + \gamma(B_2 \cap K) - |E(\partial R \cap K)| \tag{5}$$

Now, we observe that $|E(\partial R \cap K)| \in \{0, 1, 2, 4\}$ since K is an induced subgraph of G. If $|E(\partial R \cap K)| = 4$ then clearly R must be a face of K which contradicts our assumption that R is properly contained within F. On the other hand if $|E(\partial R \cap K)| \leq 1$, then (5) yields $\gamma(B_1 \cap K) + \gamma(B_2 \cap K) \leq 3$ which contradicts the fact that both $B_1 \cap K$ and $B_2 \cap K$ are nonempty. Finally if $|E(\partial R \cap K)| = 2$ then it is clear that K contains exactly three of the vertices w_1, w_2, w_3, w_4. However in this case (5) implies that $\gamma(B_1 \cap K) = \gamma(B_2 \cap K) = 2$. It follows that K contains at most one of the vertices w_1, w_3, otherwise $(B_1 \cap K) \cup \{w_2\}$ would span a type 1 blocker for G_{R,w_1,w_3}, contradicting Lemma 4.8. Similarly K contains at most one of the vertices w_2, w_4. Thus K contains at most two of the vertices w_1, w_2, w_3, w_4 yielding the required contradiction. □

Finally we have our main theorem about torus graphs.

Theorem 7.6. *Suppose that G is an irreducible $(2,2)$-tight $\mathbb{T}$-graph. Then G has at most two quadrilateral faces.*

Proof. Suppose, as above, that Q is a quadrilateral face of G, with maximal blockers H_1 and H_2. Also assume that H_1 is inessential. We have seen that there is at most one other quadrilateral face of G contained among faces of H_2. Now let $K = \partial Q \cup H_1 \cup H_2$. Clearly K is a $(2,2)$-tight subgraph of G. Now we consider the faces of K that are not also faces of G. If H_2 is also inessential then there is at most one such face and this face is cellular of degree 8. If H_2 is essential then there at most two such faces and each such face is cellular and has degree at least 5. So by Lemma 7.5, there is no quadrilateral face of G that is not also a face of K. □

Corollary 7.7. *There are finitely many distinct isomorphism classes of irreducible $(2,2)$-tight torus graphs. In particular any such irreducible torus graph has at most eight vertices.*

Proof. We may as well assume that G is cellular, since in the non cellular case we know that G has at most two vertices. Since $\gamma(G) = 2$ we have $|V| = 1 + \frac{1}{4}\sum i f_i$, so we must maximise $\sum i f_i$. Since G is irreducible, $f_i = 0$ for $i = 0, 1, 2, 3$ and $f_4 \leq 2$. From Theorem 3.3 we have $f_5 + 2f_6 + 3f_7 + 4f_8 = 4$ and $f_i = 0$ for $i \geq 9$. Clearly the maximum value for $\sum i f_i$ is attained by having $f_4 = 2$, $f_5 = 4$ and $f_i = 0$ for $i \neq 4, 5$. In that case $|V| = 8$. Now there are finitely many isomorphism classes of $(2,2)$-tight graphs with at most eight vertices. Moreover, for each such graph, there are finitely many isomorphism classes of torus graphs with that underlying graph. □

7.1. **Identifying irreducibles.** Given Corollary 7.7, a naive algorithm to find all the irreducibles mentioned therein would be

(1) Find all $(2,2)$-tight graphs with at most 8 vertices.

(2) For each such graph, find all isomorphism classes of torus embeddings.
(3) Eliminate all embeddings that are not irreducible.

It is impractical to carry out this procedure without the assistance of a computer as step (1) will already yield many thousands of distinct graphs, each of which could have many different torus embeddings.

However, since we have a lot of structural information about irreducibles, we can narrow the search space significantly. For example, it is clear from the proof of Corollary 7.7 that any irreducible with 8 vertices must have 2 quadrilateral faces, 4 faces of degree 5 and no other faces. Moreover, we know that each quadrilateral face has one essential blocker and one other blocker which must be one of the 10 graphs described in Section 7. It is not too difficult to deduce that any 8 vertex irreducible must be isomorphic to one of the examples shown in Figure 19.

Similarly for torus graphs with at most 4 vertices there are relatively few possibilities for the underlying graph: 13 in total. Now, using Lemmas 6.1, 6.4 and 6.5 we can easily deduce that an irreducible with at most 4 vertices is isomorphic to one of the examples shown in Figures 14 or 15. For the cases of 5, 6 and 7 vertices the naive this approach yields a relatively manageable problem in computational grpah theory. We have used the computer algebra system SageMath [22] to automate much of the search process in these cases. The interested reader can find full details of the search algorithm and its implementation at [5].

We briefly outline the relevant data structures and algorithms here.

7.2. **Data structures.** In order to carry out our computer assisted search we needed to implement two key data structures, one to model graphs (the native SageMath `Graph` class is not particularly well adapted to our purposes), and one to model surface graphs.

7.2.1. *Graphs.* A dart (or half-edge) of a graph $\Gamma = (V, E, s, t)$ is a pair $(e, \mathfrak{r})$ where $e \in E$ and $\mathfrak{r} \in \{s, t\}$. Let D be the set of darts of Γ and observe that there is a partition $\mathcal{V}$ of D defined by $P_v = \{(e, \mathfrak{r}) \in D : \mathfrak{r}(e) = v\}$. There is another partition $\mathcal{E}$ of D defined by $Q_e = \{(e, s), (e, t)\}$. Using this construction one readily sees that there is a correspondence between graphs and triples $(X, \mathcal{P}, \mathcal{Q})$ where X is a set, $\mathcal{P}$ is a partition of X and Q is a partition of X each of whose parts has two elements. We use this observation to implement a class in SageMath that accurately models our notion of graph. We have subclassed the native SageMath `Graph` class in order to take advantage of the built in graph theoretic functionality in SageMath. We have also implemented methods modelling various standard graph theoretic operations including vertex splitting and edge contractions. We adapted the built-in SageMath graph isomorphism checker to work with our subclass.

We also need to check $(2, 2)$-sparsity for our graphs and for this purpose we created a very basic implementation of the pebble game algorithm of Lee and Streinu ([14]).

7.2.2. *Surface graphs.* Let S_k be the group of permutations of the set $\{1, \cdots, k\}$. An oriented rotation system is a pair (σ, τ) where σ is some element of S_{2n} and τ is a fixed point free involution in S_{2n}. By a theorem of Edmonds ([6]) there is a correspondence between isomorphism classes of oriented rotation systems and isomorphism classes of cellular surface graphs whose underlying surface is orientable. For a contemporary exposition of this theory see [15].

Oriented rotation systems provide a convenient data structure for carrying out computations with surface graphs. In particular it is straightforward to compute boundary walks of faces, the genus and components of the underlying surface etc. Furthermore it is straightforward to implement the topological edge contraction and deletion operations discussed in Section 4, as well as other standard operations such as adding a new vertex within a specified face and adding a new edge that subdivides a face in a specified way. We have implemented this data structure in SageMath along with methods corresponding to the invariants and operations mentioned above.

7.3. **The search algorithm.** In order to search for irreducibles, we make use of Theorem 6.6 in a relatively straightforward way. Observe that if a $(2,2)$-tight graph has a vertex of degree 2 then deleting this vertex yields a smaller $(2,2)$-tight graph. If we know all possible irreducible torus embeddings of this smaller graph then we need only work out all possible ways to add back in the deleted vertex 'topologically'. That is to say we must add the vertex within a face together with edges to the required neighbours that must lie in the boundary of the face. This is substantially more efficient than searching among all possible embeddings of the original graph. On the other hand if the graph has minimum degree 3 then we carry out a brute force search among all possible rotation systems whose underlying graph is the given one. A slightly more formal description of this idea is given in Algorithm 1.

Algorithm 1 An inductive algorithm for finding all irreducibles with n vertices

Input: lists $\mathcal{G}_{n-1}$, respectively $\mathcal{G}_n$, of all $(2,2)$-tight graphs with $n-1$, respectively n vertices, a list $\mathcal{I}_{n-1}$ of all the irreducible torus graphs with $n-1$ vertices and a mapping $f_{n-1}: \mathcal{I}_{n-1} \to \mathcal{G}_{n-1}$ that maps each irreducible to its underlying graph.

Output: A list $\mathcal{I}_n$ of all the irreducible torus graphs with n vertices together with a mapping $f_n: \mathcal{I}_n \to \mathcal{G}_n$.

for $\Gamma \in \mathcal{G}_n$ **do**

    if Γ has a vertex of degree 2 **then**

        Let Θ be the graph obtained by deleting the vertex of degree 2

        for $G \in f_{n-1}^{-1}(\Theta)$ **do**

            Identify any face whose boundary contains both neighbours of the deleted vertex. See if a new vertex can be added within the face and adjacent to the two neighbours without creating any face of degree 2, 3 or 4. Add all resulting rotation systems to the list $\mathcal{I}_n$, check to see if any new entry is isomorphic to any existing one and remove the new one if it is. Update the mapping f_n mapping all the new entries in $\mathcal{I}_n$ to the appropriate Henneberg extension of Θ in $\mathcal{G}_n$.

        end for

    else

        Label the darts of Γ, $1, \cdots, 2n$ and identify the partitions $\mathcal{V}$, respectively $\mathcal{E}$ corresponding to the vertices, respectively edges. Let τ be the involution whose cycle partition is $\mathcal{E}$.

        for each $\sigma \in S_{2n}$ whose cycle partition is $\mathcal{V}$ **do**

            Check that the rotation system (σ, τ) corresponds to an irreducible torus graph. Check to see if it is isomorphic to any existing entry in $\mathcal{I}_n$. If not then add to $\mathcal{I}_n$ and update f_n appropriately.

        end for

    end if

end for

7.4. **Computational results.** Using a SageMath implementation of Algorithm 1 we have found the complete list of irreducible torus graphs: there are 116 in total. See [5] for the SageMath code together with data files describing the rotation systems corresponding to each of cellular irreducible torus graphs and corresponding diagrams.

8. Application: contacts of circular arcs

In this section we describe an application to the study of contact graphs. The foundational result in this area is the well known Koebe-Andreev-Thurston Circle Packing Theorem ([12]) which says that every plane simple graph can be realised as the contact graph of some arrangement of circles with non overlapping interiors in the Euclidean plane. Following this theorem, contact graphs arising in many other geometric contexts have been investigated. We consider contact graphs arising from certain families of curves in surfaces of constant curvature. We begin by giving a model for a general class of contact problems and then specialise to a case of particular interest.

Let $\alpha : [0,1] \to \Sigma$ be a curve. We say that α is non selfoverlapping if it is injective on the open interval $(0,1)$. Now suppose that $\alpha, \beta : [0,1] \to \Sigma$ are distinct curves in Σ. We say that α and β are non overlapping if $\alpha((0,1)) \cap \beta((0,1)) = \emptyset$. Let $\mathcal{C}$ be a collection of curves in Σ having the following properties

- Every $\alpha \in \mathcal{C}$ is non selfoverlapping.
- For every distinct $\alpha, \beta \in \mathcal{C}$, α and β are non overlapping.

We want to construct a combinatorial object that describes the contact properties of such a collection. In order to do this we impose some further non degeneracy conditions on $\mathcal{C}$ as follows.

- $\alpha(0) \neq \alpha(1)$ for every $\alpha \in \mathcal{C}$
- For every distinct $\alpha, \beta \in \mathcal{C}$, $\{\alpha(0), \alpha(1)\} \cap \{\beta(0), \beta(1)\}$ is empty.

In other words, we allow the end of one curve to touch another curve (or to touch itself), but the point that it touches cannot be an endpoint of that curve. We say that $\mathcal{C}$ is a non degenerate collection of non overlapping curves. Note that if a collection fails the non degeneracy conditions, it can typically be made degenerate by an arbitrarily small perturbation. A contact of $\mathcal{C}$ is a quadruple (α, β, x, y) where $\alpha, \beta \in \mathcal{C}$, $x \in \{0,1\}$ and $\alpha(x) = \beta(y)$.

Now we can define a graph $\Gamma_{\mathcal{C}}$ as follows. The vertex set is $\mathcal{C}$ and the edge set is $\mathcal{T}$, the set of contacts of $\mathcal{C}$. We define the required incidence functions by $s(\alpha, \beta, x, y) = \alpha$ and $t(\alpha, \beta, x, y) = \alpha$. Finally we can construct an embedding $|\Gamma_{\mathcal{C}}| \to \Sigma$. For $\beta \in \mathcal{C}$, suppose that $t^{-1}(\beta) = \{(\alpha_1, \beta, x_1, y_1), \cdots, (\alpha_k, \beta, x_k, y_k)\}$. Let J_β be a nonempty closed subinterval of $[0,1]$ with the following properties.

(1) $\{y_1, \cdots, y_k\} \subset J_\alpha$.
(2) $0 \in J_\beta$ if and only there is no contact $(\beta, \gamma, 0, y)$ in $\mathcal{T}$.
(3) $1 \in J_\beta$ if and only there is no contact $(\beta, \gamma, 1, y)$ in $\mathcal{T}$.

In other words J_β is a subinterval that covers all the 'points of contact' in β together with any endpoints of β that do not touch a curve. Now we observe that $\beta : J_\beta \to \Sigma$ is a homeomorphism onto its image. So it follows from the Jordan-Schoenflies Theorem that $\Sigma/\beta(J_\beta)$ is homeomorphic to Σ. Furthermore, since $\beta(J_\beta) \cap \delta(J_\delta) = \emptyset$ for $\beta \neq \delta$ it follows that Σ is homeomorphic to $\Sigma/\sim$ where $\sim$ is the equivalence relation that collapses each $\beta(J_\beta)$ to a point, for all $\beta \in \mathcal{C}$. Using this homeomorphism we construct an embedding by mapping each vertex of $\Gamma_{\mathcal{C}}$ (i.e. element of $\mathcal{C}$) to the corresponding point of $\Sigma/\sim$. Since an edge of

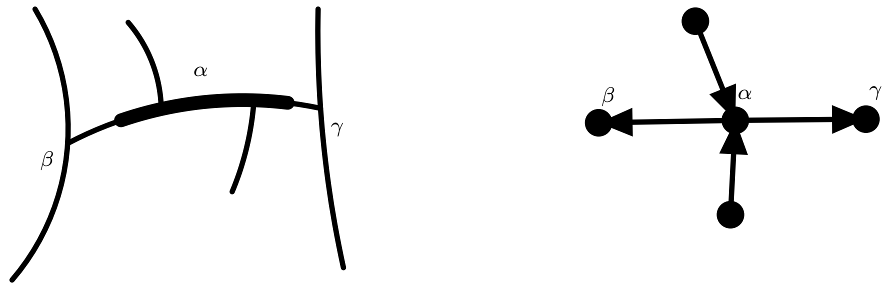

Figure 8. The construction of the contact graph associated to a collection of curves. On the left we have a collection of curves. The bold section of α represents $\alpha(J_\alpha)$. On the right is the corresponding graph with edge orientations as indicated.

$\Gamma_{\mathcal{C}}$ is a contact (α, β, x, y), we can construct the corresponding edge embedding by using the restriction of α to the component of $[0,1] - J_\alpha$ that contains x: see Figure 8.

We are interested in the recognition problem for contact graphs: can we find necessary and/or sufficient conditions for a surface graph to be the contact graph of a collection of curves? Typically we are looking for conditions for which there are efficient algorithmic checks. As noted in the introduction, there are efficient algorithms for checking whether or not a given graph is $(2, l)$-sparse. See [14] and [10] for details.

Hliněný ([11]) has shown that a plane graph admits a representation by contacts of curves if and only if it is $(2, 0)$-sparse. This result easily generalises to other surfaces. We include the statement to provide some context for our later result.

Lemma 8.1. *Let G be a Σ-graph. Then $G \cong G_{\mathcal{C}}$ for some $\mathcal{C}$ as above if and only if G is $(2, 0)$-sparse.* □

It is worth noting here that the definition of the contact graph used in [11] and elsewhere is different to the one we have given above. In the literature the contact graph is typically defined as the intersection graph of the collection of curves. This definition works well in the plane. However for non simply connected surfaces we propose that it is more natural to define the contact graph as above.

Now we suppose that Σ is also equipped with a metric of constant curvature. In this context we can distinguish many interesting subclasses of non selfoverlapping curves. For example, a circular arc is a curve of constant curvature and a line segment is a locally geodesic curve. For collections of such curves the representability question can depend on the embedding of the graph and not just the graph itself (in contrast to Lemma 8.1). For example, if Π is the graph consisting of two vertices joined by two parallel edges, then Π cannot be represented by a collection of line segments in the flat plane. However, if Π is embedded as a non separating cycle in the torus, then it is easy to construct a representation of the resulting surface graph as a collection of line segments in the flat torus.

Given a Σ-graph G and a non degenerate non overlapping collection of circular arcs C such that $G \cong G_{\mathcal{C}}$ we say that $\mathcal{C}$ is a CCA representation of $\mathcal{C}$ (abbreviating Contacts of Circular Arcs). See Figure 9 for an example in the torus. Alam et al. ([1]) have shown that any $(2, 2)$-sparse plane graph has a CCA representation in the flat plane. We prove an analogous result for the flat torus.

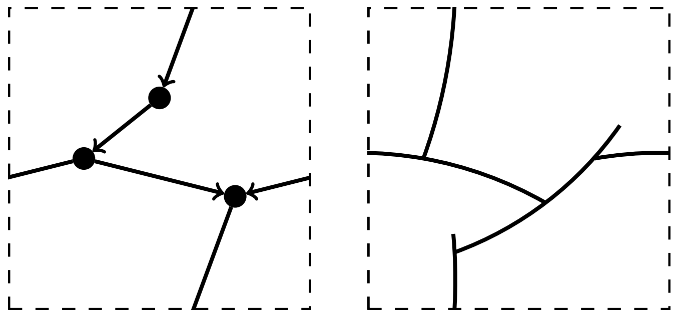

FIGURE 9. A torus graph and a corresponding CCA representation in the flat torus. The orientation of the graph edges is the orientation induced by the CCA representation.

First we need a lemma to show that every sparse surface graph can be obtained by deleting only edges from a tight surface graph.

Lemma 8.2. *Suppose that Σ is a connected surface, $l \leq 2$ and G is a $(2,l)$-sparse Σ-graph. There is some $(2,2)$-tight Σ-graph H such that $V(H) = V(G)$ and G is a subgraph of H.*

Proof. Clearly it suffices to show that if $\gamma(G) \geq l+1$ then we can add an edge e within some face of G so that $G \cup \{e\}$ is $(2,l)$-sparse.

Now if G has no tight subgraph then we can add any edge without violating the sparsity count. So we assume that G has some nonempty tight subgraph. Let L be a maximal tight subgraph of G. If L spans all vertices of G then $L = G$ and G is already tight, so we assume that L is not spanning in G. Since Σ is connected there is some face F of G whose boundary contains vertices $u \in L$ and $v \notin L$. Let e be a new edge that joins u and v through a path in F. We claim that $G \cup \{e\}$ is $(2,l)$-sparse. If not then there must be some tight subgraph K of G such that $u, v \in K$. But $K \cap L$ is nonempty, so by Lemma 3.2, $K \cup L$ is $(2,l)$-tight. This contradicts the maximality of L. □

Theorem 8.3. *Every $(2,2)$-sparse torus graph admits a CCA representation in the flat torus.*

Proof. First observe that edge deletion is CCA representable: just shorten one of the arcs slightly. So by Lemma 8.2 it suffices to prove the theorem for $(2,2)$-tight torus graphs. To that end we must show that

(a) each irreducible $(2,2)$-tight torus graph has a CCA representation.
(b) if $G \to G'$ is a digon, triangle or quadrilateral contraction move and G' has a CCA representation, then G also has a CCA representation. In other words the relevant vertex splitting moves are CCA representable.

For (a) it is possible to give an explicit CCA representation for each of the 116 irreducibles listed in Appendix A. We will not describe those here but below we shall explain a simple method to make these constructions easily. Full details are given in [23].

For (b), see Figure 10 for an illustration of the CCA representation of the quadrilateral split. It is easily seen that any quadrilateral split is similarly CCA representable. The digon and triangle vertex splits are also representable and indeed have already been dealt with in the plane context in [1]. We observe that the constructions described there work equally well for torus graphs. □

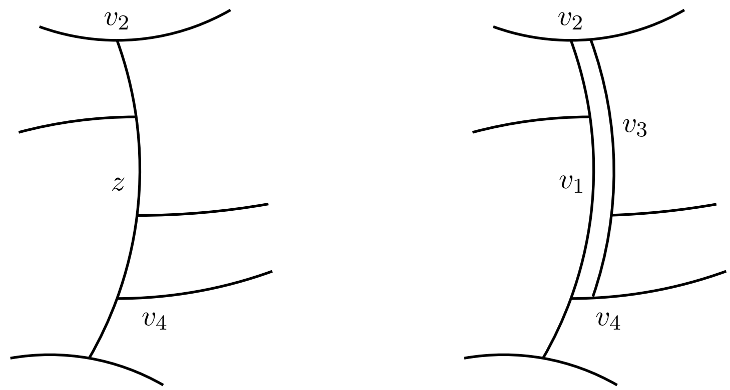

FIGURE 10. A CCA representation of a quadrilateral splitting move. The contact graph of the configuration on the left is a quadrilateral contraction of the contact graph of the configuration on the right.

In order to construct the CCA representations of the irreducibles mentioned in the proof we can make use of topological Henneberg moves. We remind the reader that a Henneberg vertex addition move is the operation of adding a new vertex to a graph and two edges from that vertex to the existing graph. Note that we allow the two new edges to be parallel. Moreover in the context of surface graphs we insist that the new vertex is placed in some face of the existing graph and the two edges are incident with vertices in the boundary of that face. We refer to such an operation as a topological Henneberg move. Clearly a Henneberg move is the inverse operation to divalent vertex deletion. It is well known (and elementary) that divalent vertex deletions preserve $(2, l)$-sparseness for all l. On the other hand Henneberg moves preserve $(2, l)$-sparseness for $l \leq 2$, and for $l = 3$ if we also insist that the new edges are not parallel.

It turns out that there are just 12 irreducibles that have no vertices of degree 2. In Figure 12 we given diagrams of each of these torus graphs and in Figure 13 we give sample CCA representations of each of these in the flat torus. We observe that each of the 116 irreducible graphs can be constructed by a sequence topological Henneberg moves from one of the torus graphs in Figure 12: indeed one easily sees that at most five Henneberg moves are required.

It remains to show that the required topological Henneberg moves are CCA representable. A CCA representation of a topological Henneberg move is illustrated in Figure 11. In general of course, topological Henneberg moves can fail to be CCA representable given a fixed representation of the initial graph. It is easy to construct an CCA representation of a graph that has a highly nonconvex region and so may not admit the required circular arc to realise a topological Henneberg move. However, it is readily verified that given the CCA representations in Figure 13, it is possible to represent all the necessary Henneberg moves that are required to construct CCA representations of the full set of 116 irreducible graphs. See [23] for complete details of this.

Finally we observe that allowing divalent vertex additions we have the following inductive construction for $(2, 2)$-tight torus graphs.

Theorem 8.4. *If G is a $(2, 2)$-tight torus graph then G can be constructed from one of the torus graphs in Figure 12 by a sequence of moves each of which is is either a digon split, triangle split, quadrilateral split or a divalent vertex addition.* □

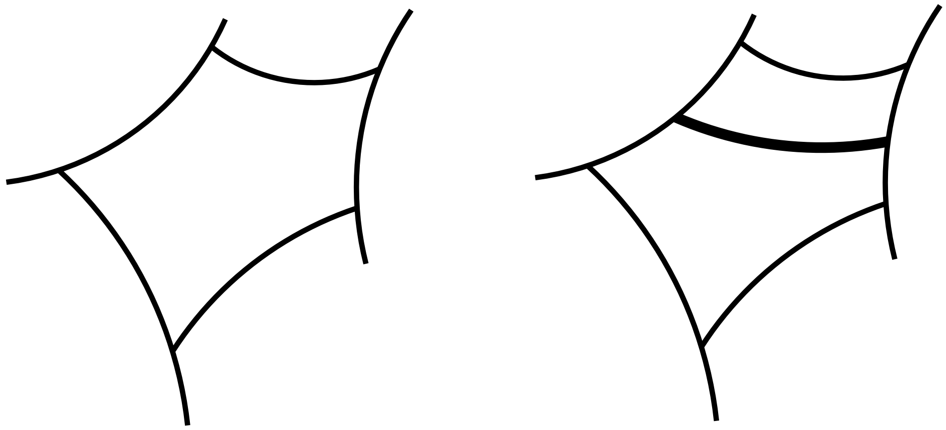

FIGURE 11. A CCA representation of a topological Henneberg move. The bold arc on the right represents the new vertex, that touches two of the initial arcs.

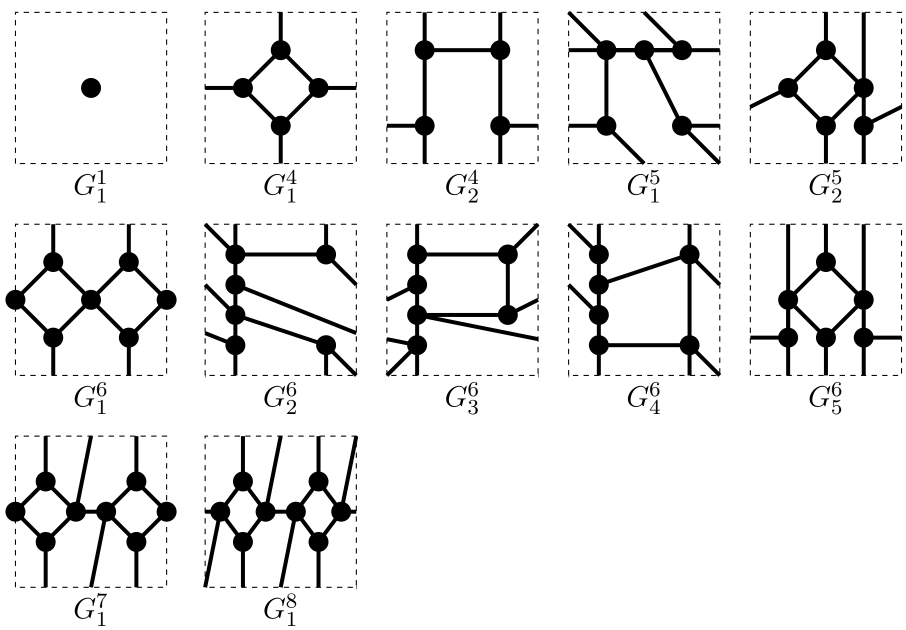

FIGURE 12. The irreducibles that have no vertex of degree 2.

APPENDIX A. IRREDUCIBLE TORUS GRAPHS

Up to isomorphism there are 116 distinct irreducible $(2, 2)$-tight torus graphs. We describe them all in this section, grouped according to the number of vertices. Our descriptions will consist of a diagram of a representative of each class. Each diagram is a standard representation of a torus as a rectangle with the usual side identifications.

For graphs with at most three vertices (Figure 14) the situation is straightforward. There are four $(2, 2)$-tight graphs and each has a unique irreducible embedding in the torus.

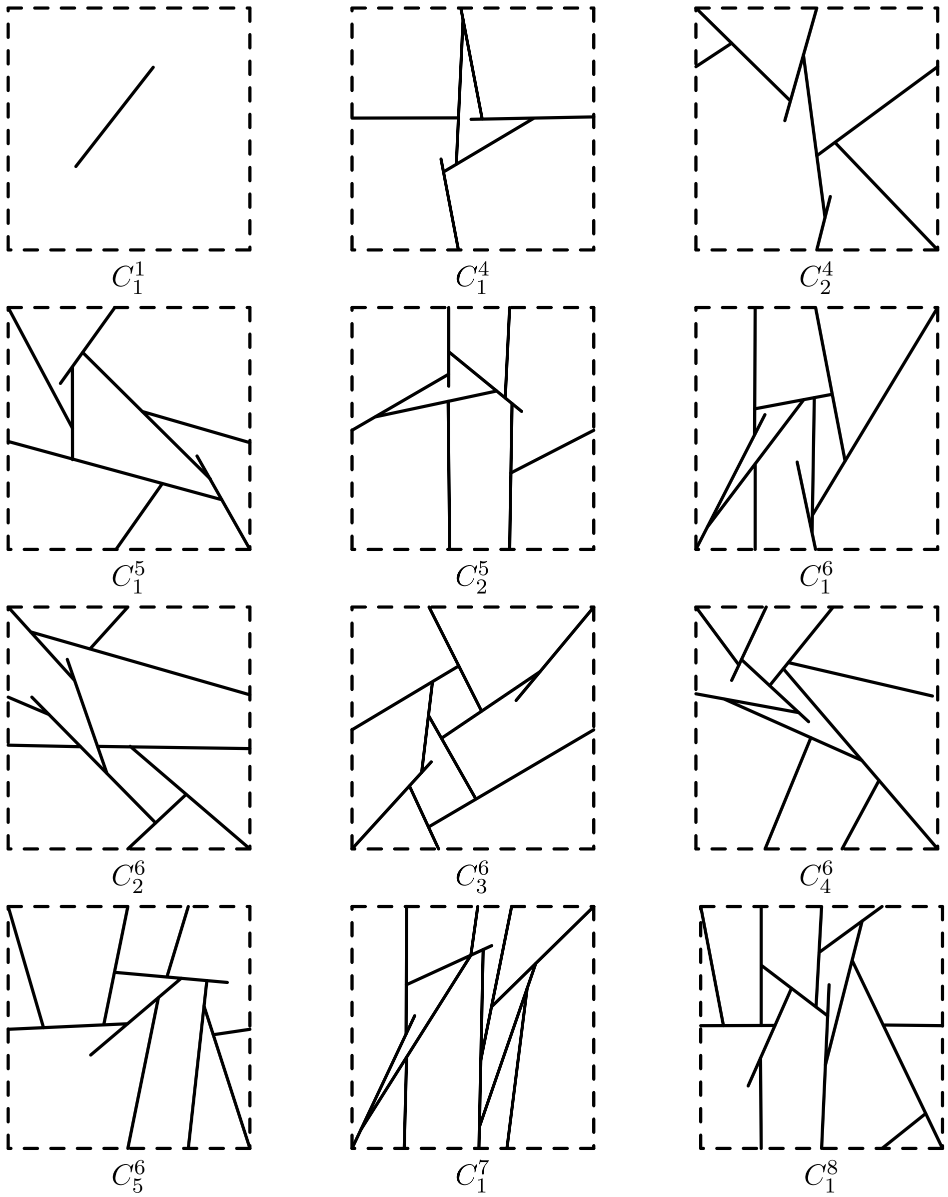

FIGURE 13. CCA representations of the 12 irreducible torus graphs with no vertices of degree two: C^i_j is a CCA representation of G^i_j from Figure 12.

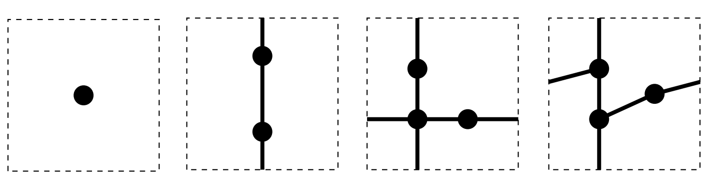

FIGURE 14. Irreducible torus graphs with at most three vertices

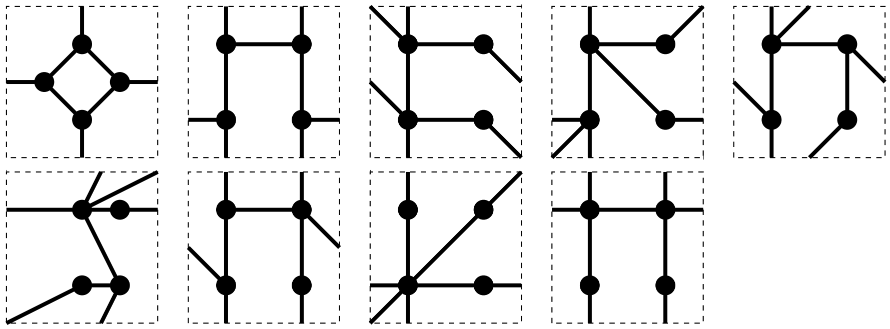

FIGURE 15. Irreducible torus graphs with four vertices

Among the graphs with four vertices (Figure 15) we see the first instance of a irreducible torus graph with a quadrilateral face. Also we have a pair of non isomorphic irreducibles that have the same underlying graph.

Given that there are 23 irreducibles with five vertices and 47 with six, one might expect even larger numbers for the cases of seven or eight vertices. However irreducibles with seven, respectively eight, vertices must contain at least one, respectively two, quadrilateral faces. This follows easily from Theorem 3.3. The presence of these quadrilateral faces enforces a lot of additional structure, hence the relatively small number of examples in these cases.

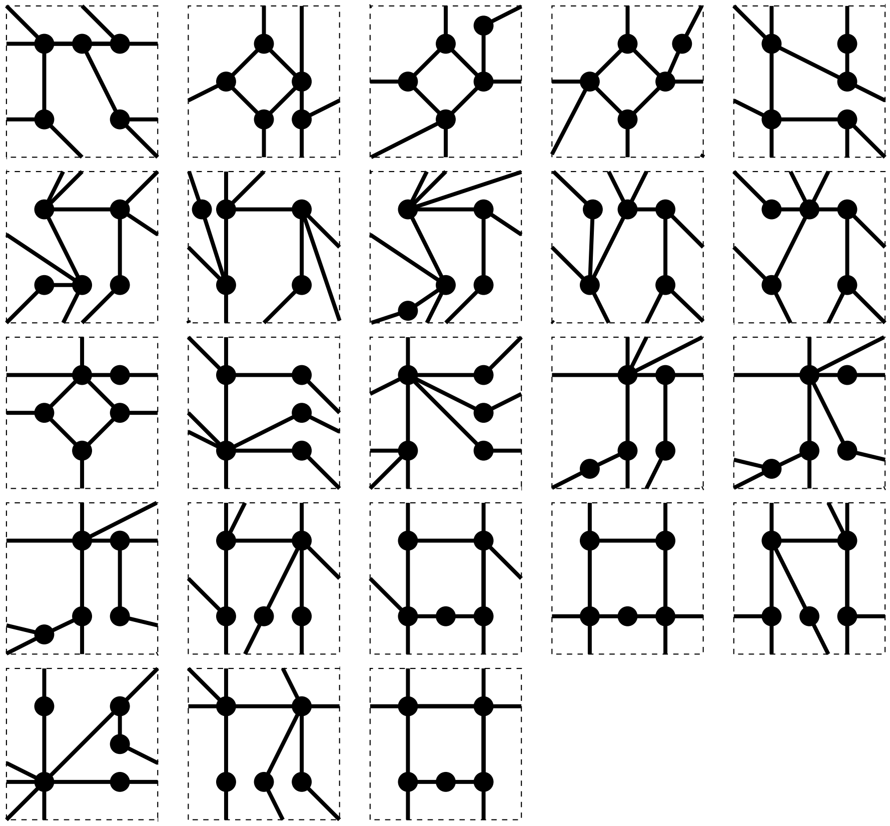

FIGURE 16. Irreducible torus graphs with five vertices

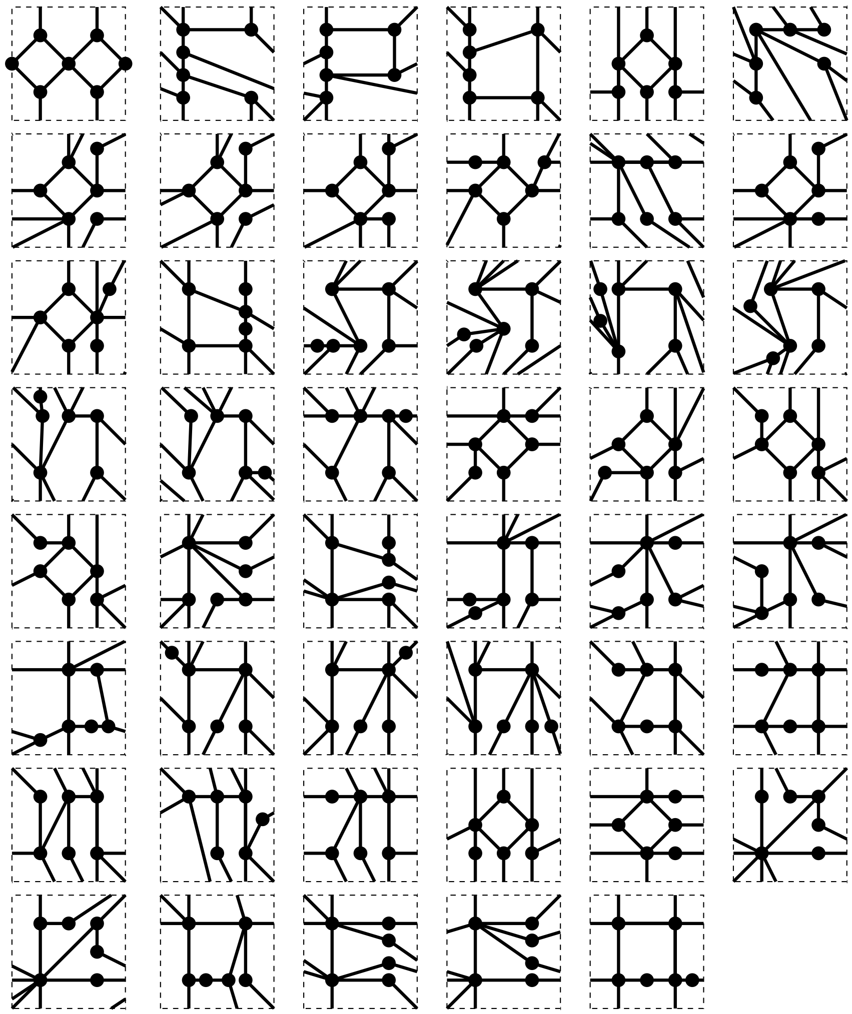

FIGURE 17. Irreducible torus graphs with six vertices

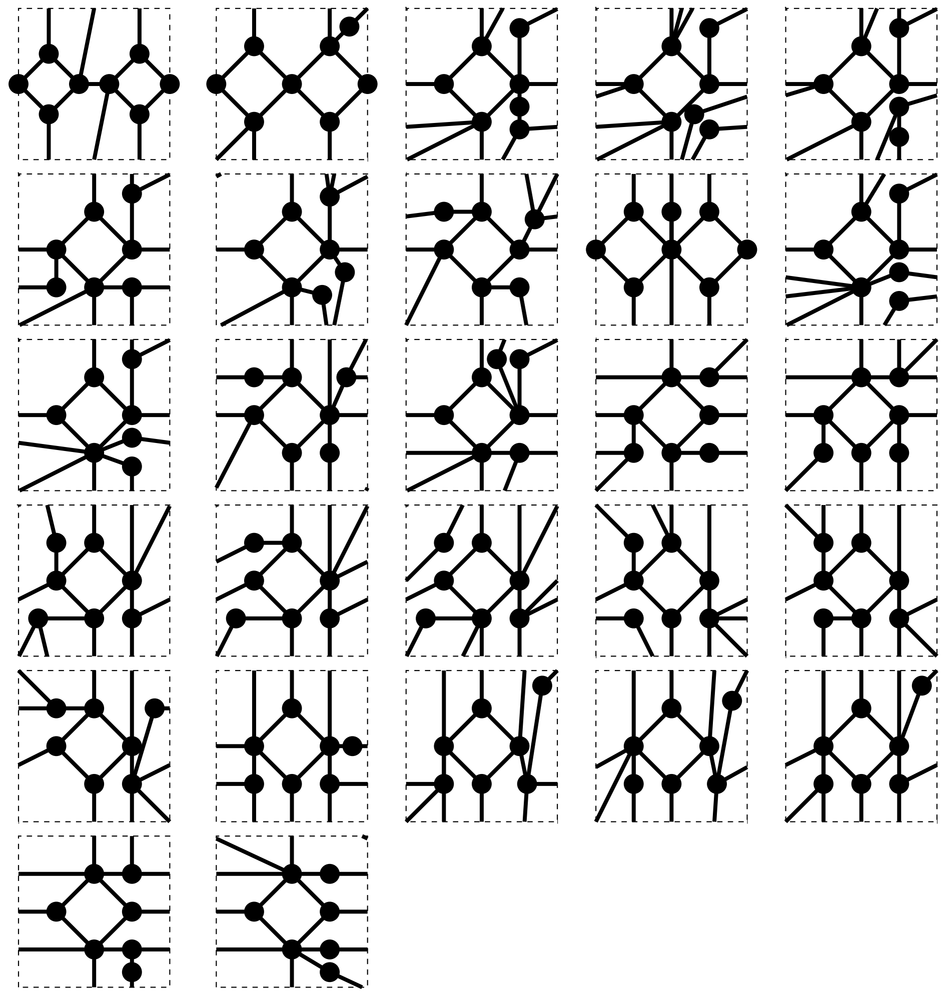

FIGURE 18. Irreducible torus graphs with seven vertices

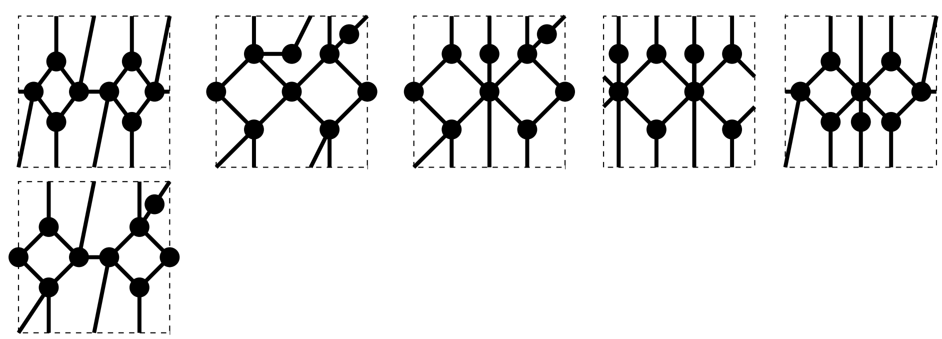

FIGURE 19. Irreducible torus graphs with eight vertices

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