

EVERY INFINITELY EDGE-CONNECTED GRAPH CONTAINS THE FAREY GRAPH OR $T_{\aleph_0} * t$ AS A MINOR

JAN KURKOFKA

ABSTRACT. We show that every infinitely edge-connected graph contains the Farey graph or $T_{\aleph_0} * t$ as a minor. These two graphs are unique with this property up to minor-equivalence.

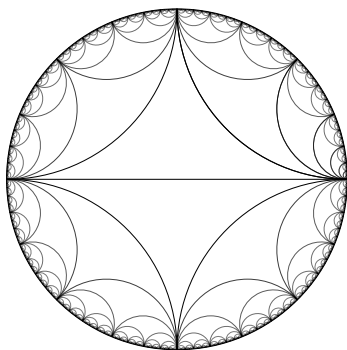


FIGURE 1. The Farey graph

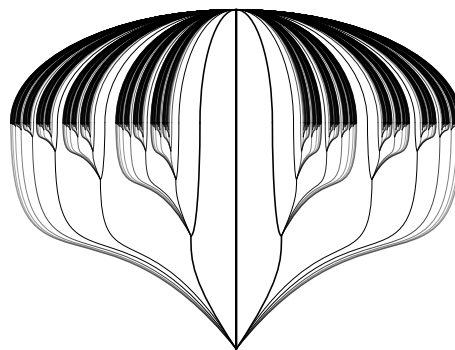


FIGURE 2. The graph $T_{\aleph_0} * t$

1. INTRODUCTION

The Farey graph, shown in Figure 1 and surveyed in [6, 13], plays a role in a number of mathematical fields ranging from group theory and number theory to geometry and dynamics [6]. Curiously, graph theory is not among these. In this paper we show that the Farey graph plays a central role in graph theory too: it is one of two infinitely edge-connected graphs that must occur as a minor in every infinitely edge-connected graph. Previously it was not known that there was any set of graphs determining infinite edge-connectivity by forming a minor-minimal list in this way, let alone a finite set.

Ramsey theory and the study of connectivity intersect in the problem of finding for any given connectivity k a small set of k -connected subgraphs that occur in every k -connected graph, and thereby characterise k -connectedness. To keep these unavoidable sets small for $k \geq 3$, the subgraph relation referred to above is usually relaxed to the graph minor relation. Here, a graph is a *minor* of a graph G if it can be obtained from a subgraph of G by contracting connected (possibly infinite) induced disjoint subgraphs [7]. We refer to [7, §9.4] or the introduction of [11] for surveys on the known results for this problem and its variations [7, 10–12, 14, 17]. Such sets of minor-minimal k -connected graphs are known only for $k \leq 4$, and only for finite graphs [17]. These results of Oporowski, Oxley and Thomas were generalised to $k > 4$ by Geelen and Joeris [10] for finite graphs, and by Gollin and Heuer [11] for infinite graphs, but with a different notion of connectivity.

2020 *Mathematics Subject Classification.* 05C63, 05C55, 05C40, 05C83, 05C10.

Key words and phrases. infinite graph; infinitely edge-connected graph; typical; unavoidable; infinite connectivity; infinite edge-connectivity; Farey graph; infinitely regular tree; $T_{\aleph_0} * t$; graph minor.

For infinite connectivity, the problem asks for a small selection of infinitely connected graphs such that every infinitely connected graph contains at least one of the selected graphs as a minor. Here, ‘infinitely connected’ can be understood in two ways. When it is understood as ‘infinitely vertex-connected’, the answer is already known: Every infinitely connected graph contains the countably infinite complete graph K^{\aleph_0} as a minor [7, §8.1]. But when ‘infinitely connected’ is understood as ‘infinitely edge-connected’ then, as we shall see, K^{\aleph_0} is not the answer, and in fact no answer has been known. Indeed it is not even clear a priori that there exists a finite set of unavoidable infinitely edge-connected minors. Any such unavoidable infinitely edge-connected minors will be countable, because in every infinitely edge-connected graph we can greedily find a countable infinitely edge-connected subgraph. But the countable graphs are not known to be well-quasi-ordered by the minor-relation. It is therefore not clear that any minor-minimal set of infinitely edge-connected graphs must be finite, nor even that such a minimal set exists.

In this paper we find a pair of infinitely edge-connected graphs that occur unavoidably as minors in any infinitely edge-connected graph, and which are unique with this property up to minor-equivalence: the Farey graph F , and the graph $T_{\aleph_0} * t$ obtained from the infinitely-branching tree T_{\aleph_0} by joining an additional vertex t to all its vertices (Figure 2).

Theorem 1. *Every infinitely edge-connected graph contains either the Farey graph or $T_{\aleph_0} * t$ as a minor.*

The uniqueness of the pair $\{F, T_{\aleph_0} * t\}$, up to minor-equivalence, follows from the fact that they are not minors of each other (Lemmas 3.1 and 3.2):

Theorem 2. *Let M be any set of infinitely edge-connected graphs such that every infinitely edge-connected graph has a minor in M and no element of M is a minor of another. Then M consists of two graphs, of which one is minor-equivalent to the Farey graph and the other is minor-equivalent to $T_{\aleph_0} * t$.*

Theorem 1 is best possible also in the sense that one cannot replace ‘minor’ with ‘topological minor’ in its wording (Theorem 3.4).

Since both the Farey graph and $T_{\aleph_0} * t$ are planar, our result implies that every infinitely edge-connected graph contains a planar infinitely edge-connected graph as a minor. Thus, in this sense, infinite edge-connectivity is an inherently planar property.

This paper is organised as follows. Section 2 formally introduces the Farey graph. In Section 3 we show that the Farey graph and $T_{\aleph_0} * t$ are not minors of each other, and deduce Theorem 2. Theorem 3.4 above is proved there as well. We outline the overall strategy of the proof of Theorem 1 in Section 4. The proof itself consists of two halves. The first half of the proof is carried out in Section 5, and the second half is carried out in Section 6. Section 7 gives an outlook, and Section 8 contains the appendix.

Acknowledgement. I am grateful to Konstantinos Stavropoulos for stimulating conversations.

2. PRELIMINARIES

We use the notation of Diestel’s book [7]. Two graphs are *minor-equivalent* if they are minors of each other. If G is any graph and $X \subseteq V(G)$ is any vertex set, then

we denote by $\partial X = \partial_G X$ the subset of X formed by the vertices in X that send an edge in G to $V(G) \setminus X$.

2.1. The Farey graph. The *Farey graph* F is the graph on $\mathbb{Q} \cup \{\infty\}$ in which two rational numbers a/b and c/d in lowest terms (allowing also $\infty = (\pm 1)/0$) form an edge if and only if $\det \begin{pmatrix} a & c \\ b & d \end{pmatrix} = \pm 1$, cf. [6]. In this paper we do not distinguish between the Farey graph and the graphs that are isomorphic to it. For our graph-theoretic proofs it will be more convenient to work with the following purely combinatorial definition of the Farey graph that is indicated in [6] and [13].

The *halved Farey graph* \check{F}_0 of order 0 is a K^2 with its sole edge coloured blue. Inductively, the *halved Farey graph* \check{F}_{n+1} of order $n+1$ is the edge-coloured graph that is obtained from \check{F}_n by adding a new vertex v_e for every blue edge e of \check{F}_n , joining each v_e precisely to the endvertices of e by two blue edges, and colouring all the edges of $\check{F}_n \subseteq \check{F}_{n+1}$ black. The *halved Farey graph* $\check{F} := \bigcup_{n \in \mathbb{N}} \check{F}_n$ is the union of all \check{F}_n without their edge-colourings, and the *Farey graph* is the union $F = G_1 \cup G_2$ of two copies G_1, G_2 of the halved Farey graph such that $G_1 \cap G_2 = \check{F}_0$.

Lemma 2.1. *The halved Farey graph and the Farey graph are minor-equivalent.*

Proof. The halved Farey graph is a subgraph of the Farey graph. Conversely, the Farey graph is a minor of the halved Farey graph: if e is a blue edge of \check{F}_1 , then the Farey graph is the contraction minor of $\check{F} - e$ whose sole non-trivial branch set is $V(\check{F}_0)$, i.e., $(\check{F} - e)/V(\check{F}_0) \cong F$. \square

We remark that the Farey graph is uniquely determined by its connectivity [15].

2.2. Separation systems and S -trees. Separation systems and S -trees are two fundamental tools in graph minor theory. In this section we briefly introduce the definitions from [7–9] that we need.

A *separation of a set* V is an unordered pair $\{A, B\}$ such that $A \cup B = V$. The ordered pairs (A, B) and (B, A) are its *orientations*. Then the *oriented separations* of V are the orientations of its separations. The map that sends every oriented separation (A, B) to its *inverse* (B, A) is an involution that reverses the partial ordering

$$(A, B) \leq (C, D) :\Leftrightarrow A \subseteq C \text{ and } B \supseteq D$$

since $(A, B) \leq (C, D)$ is equivalent to $(D, C) \leq (B, A)$.

More generally, a *separation system* is a triple $(\vec{S}, \leq, *)$ where (\vec{S}, \leq) is a partially ordered set and $*$: $\vec{S} \rightarrow \vec{S}$ is an order-reversing involution. We refer to the elements of \vec{S} as *oriented separations*. If an oriented separation is denoted by \vec{s} , then we denote its *inverse* \vec{s}^* as \bar{s} , and vice versa. That $*$ is *order-reversing* means $\vec{r} \leq \vec{s} \Leftrightarrow \bar{r} \geq \bar{s}$ for all $\vec{r}, \vec{s} \in \vec{S}$.

A *separation* is an unordered pair of the form $\{\vec{s}, \bar{s}\}$, and then denoted by s . Its elements \vec{s} and \bar{s} are the *orientations* of s . The set of all separations $\{\vec{s}, \bar{s}\} \subseteq \vec{S}$ is denoted by S . When a separation is introduced as s without specifying its elements first, we use \vec{s} and \bar{s} (arbitrarily) to refer to these elements. Every subset $S' \subseteq S$ defines a separation system $\vec{S}' := \bigcup S' \subseteq \vec{S}$ with the ordering and involution induced by \vec{S} .

Separations of sets, and their orientations, are an instance of this abstract setup if we identify $\{A, B\}$ with $\{(A, B), (B, A)\}$. Here is another example: The set $\vec{E}(T) := \{(x, y) \mid xy \in E(T)\}$ of all *orientations* (x, y) of the edges $xy = \{x, y\}$

of a tree T forms a separation system with the involution $(x, y) \mapsto (y, x)$ and the natural partial ordering on $\vec{E}(T)$ in which $(x, y) < (u, v)$ if and only if $xy \neq uv$ and the unique $\{x, y\}$ – $\{u, v\}$ path in T is $\hat{x}yTu\hat{v} = yTu$.

In the context of a given separation system $(\vec{S}, \leq, *)$, a *star (of separations)* is a subset $\sigma \subseteq \vec{S}$ such that $\vec{r} \leq \vec{s}$ for all distinct $\vec{r}, \vec{s} \in \sigma$; see [7, Fig. 12.5.1] for an illustration.¹ If t is a node of a tree T , then the set

$$\vec{F}_t := \{ (x, t) \mid xt \in E(T) \}$$

is a star in $\vec{E}(T)$.

An *S-tree* is a pair (T, α) such that T is a tree and $\alpha: \vec{E}(T) \rightarrow \vec{S}$ propagates the ordering on $\vec{E}(T)$ and commutes with inversion: that $\alpha(\vec{e}) \leq \alpha(\vec{f})$ if $\vec{e} \leq \vec{f} \in \vec{E}(T)$ and $(\alpha(\vec{e}))^* = \alpha(\vec{e})$ for all $\vec{e} \in \vec{E}(T)$; see [7, Fig. 12.5.2] for an illustration. Thus, every node $t \in T$ is associated with a star \vec{F}_t in $\vec{E}(T)$ which α sends to a star $\alpha[\vec{F}_t]$ in \vec{S} . A tree-decomposition (T, \mathcal{V}) , for example, makes T into an *S-tree* for the set of separations it induces [7, §12.5]. For oriented edges $(x, y) \in \vec{E}(T)$ we will write $\alpha(x, y)$ instead of $\alpha((x, y))$. Note that *S-trees* are ‘closed under taking minors’ in the sense that if (T, α) is an *S-tree* and $T' \preceq T$, then $(T', \alpha \upharpoonright \vec{E}(T'))$ is again an *S-tree* when we view $E(T')$ as a subset of $E(T)$.

3. UNIQUENESS AND TOPOLOGICAL MINORS

3.1. Uniqueness. In this section we show that the pair $\{F, T_{\aleph_0} * t\}$ is unique up to minor-equivalence:

Theorem 2. *Let \mathcal{H} be any set of infinitely edge-connected graphs such that every infinitely edge-connected graph has a minor in \mathcal{H} and no element of \mathcal{H} is a minor of another. Then \mathcal{H} consists of two graphs, of which one is minor-equivalent to the Farey graph and the other is minor-equivalent to $T_{\aleph_0} * t$.*

This will follow easily from the following two lemmas:

Lemma 3.1. *The Farey graph is not a minor of $T_{\aleph_0} * t$.*

Proof. The Farey graph contains two disjoint cycles, but $T_{\aleph_0} * t$ does not. □

Lemma 3.2. *The graph $T_{\aleph_0} * t$ is not a minor of the Farey graph.*

Proof of Theorem 2. We write $\mathcal{G} = \{F, T_{\aleph_0} * t\}$ and note that neither element of \mathcal{G} is a minor of another by Lemmas 3.1 and 3.2. Every graph $H \in \mathcal{H}$ contains a graph $G \in \mathcal{G}$ as a minor (Theorem 1) which in turn contains a graph $H' \in \mathcal{H}$ as a minor, and then $H \succcurlyeq G \succcurlyeq H'$ implies $H = H'$ because no element of \mathcal{H} is a minor of another. Thus, every graph in \mathcal{H} is minor-equivalent to some graph in \mathcal{G} and, conversely, every graph in \mathcal{G} is minor-equivalent to some graph in \mathcal{H} by symmetry. Since no two graphs in \mathcal{H} or in \mathcal{G} are comparable with regard to the minor-relation, we deduce that minor-equivalence induces a bijection between \mathcal{H} and \mathcal{G} . □

Showing that $T_{\aleph_0} * t$ is not a minor of the Farey graph requires more effort, and some preparation. A *comb* is the union of a ray R (the comb’s *spine*) with infinitely many disjoint finite paths, possibly trivial, that have precisely their first vertex on R . The last vertices of those paths are the *teeth* of this comb. Given a

¹Officially, in [8] a star σ is additionally required to consist only of oriented separations \vec{s} satisfying $\vec{s} \neq \vec{s}^*$. In this paper, however, all separations considered will satisfy this condition, which is why we drop it here.

vertex set U , a *comb attached to U* is a comb with all its teeth in U , and a *star attached to U* is a subdivided infinite star with all its leaves in U . The following lemma is [7, Lemma 8.2.2], see also the series [2–5].

Lemma 3.3 (Star-comb lemma). *Let U be an infinite set of vertices in a connected graph G . Then G contains either a comb attached to U or a star attached to U .*

Proof of Lemma 3.2. Since K_{2,\aleph_0} is a subgraph of $T_{\aleph_0} * t$, it suffices to show that the Farey graph does not contain K_{2,\aleph_0} as a minor. So let us assume for a contradiction that the Farey graph contains a K_{2,\aleph_0} minor. By applying the star-comb lemma inside the branch sets of the two infinite-degree vertices of K_{2,\aleph_0} if necessary, and using that the Farey graph does not contain infinitely many independent paths between any two of its vertices, we find that our model of K_{2,\aleph_0} contains a subdivision G of one of the following two graphs G_1 and G_2 . The graph G_1 is the ladder with every rung subdivided exactly once, i.e., it is the disjoint union of two rays $R = v_1 v_2 \dots$ and $R' = v'_1 v'_2 \dots$ with infinitely many disjoint R – R' paths $v_n z_n v'_n$ ($n \in \mathbb{N}$). And the graph G_2 is obtained from G_1 by contracting R' to a single vertex that we call d .

In either case, the sole end of $G \subseteq F$ is included in a unique end ω of F . The end ω chooses, for every $n \in \mathbb{N}$, a blue edge $e_n \in F_n$ with vertex set X_n for which it lives in the component C_n of $F - X_n$ avoiding F_n . Then C_n has neighbourhood X_n , and so does the other component D_n of $F - X_n$. We remark that, by the construction of the Farey graph, for every vertex of F there is a number n such that the vertex is not contained in C_n . For all n the two vertex sets X_n and X_{n+1} together induce a triangle Δ_n in F . We write x_n for the vertex in which X_n and X_{n+1} meet, and we write Y_n for vertex set consisting of the other two vertices of the triangle Δ_n . The graph $F - \Delta_n$ has precisely three components, namely D_n and C_{n+1} and a third component with neighbourhood Y_n which we denote by H_n .

First, we consider the case that $G \subseteq F$ is a subdivision of G_1 , and we write \hat{R} and \hat{R}' for the subdivisions of R and R' in G . Then there cannot be a number N such that $x_n = x_N$ for all $n \geq N$: Indeed, for every $k \in \mathbb{N}$ there is a number $f(k) \geq k$ such that both v_k and v'_k are not contained in $C_{f(k)}$ and, as a consequence, $x_{f(k)}$ must be contained in $v_k \hat{R} \cup v'_k \hat{R}'$. Thus, every vertex of F lies in a component D_n eventually (and ω is undominated). Let N be the least number for which the first vertices of \hat{R} and \hat{R}' lie in D_N . To derive a contradiction from $G \subseteq F$, let us consider any \hat{R} – \hat{R}' path $P \subseteq G$ that lies entirely in the component C_N , and consider the maximal number n for which P avoids D_n , noting $n \geq N$. Since the two rays \hat{R} and \hat{R}' induce a bipartition of the 2-set X_{n+1} , the path P cannot meet C_{n+1} without contradicting the maximality of n . Therefore, the path P is contained entirely in $F[H_n \sqcup \Delta_n]$. Without loss of generality we have $x_n \in \hat{R}$. Then $Y_n \subseteq \hat{R}'$ follows. But now the non-empty subpath \hat{P} must be contained in H_n , contradicting that H_n has neighbourhood $Y_n \subseteq \hat{R}'$.

Second, we consider the case that $G \subseteq F$ is a subdivision of G_2 , and again we write \hat{R} for the subdivision of R in G . Since $d \in G_2$ dominates the end of G_2 , the end ω is dominated in F by d . Let N be the least number such that both d and the first vertex of \hat{R} are not contained in C_N . Then $d = x_N = x_n$ for all $n \geq N$ because d dominates ω . Thus, $Y_n \subseteq \hat{R}$ for all $n \geq N$. Now consider any d – \hat{R} path $P \subseteq G$ with $dP \subseteq C_N$ and choose n maximal with the property that the non-empty subpath \hat{P} avoids D_n , noting $n \geq N$. Then $\hat{P} \subseteq H_n$ follows because of $Y_n \subseteq \hat{R}$, contradicting that $d = x_n$ does not lie in the neighbourhood Y_n of H_n . \square

3.2. Minor versus topological minor. Theorem 1 is best possible in the sense that one cannot replace ‘minor’ with ‘topological minor’ in its wording:

Theorem 3.4. *There exists an infinitely edge-connected graph that contains neither the Farey graph nor $T_{\aleph_0} * t$ as a topological minor.*

Proof. By a recent result [16] there exists an infinitely edge-connected graph G which does not contain infinitely many edge-disjoint pairwise order-compatible paths between any two of its vertices. Here, two $u-v$ paths are *order-compatible* if they traverse their common vertices in the same order. Then the graph G does not contain a subdivision of the Farey graph or of $T_{\aleph_0} * t$ because both the Farey graph and $T_{\aleph_0} * t$ have pairs of vertices with infinitely many edge-disjoint pairwise order-compatible paths between them. \square

4. OVERALL PROOF STRATEGY

Our aim for the remainder of this paper is to show that every infinitely edge-connected graph contains either the Farey graph or $T_{\aleph_0} * t$ as a minor (Theorem 1). The proof consists of two halves. In the first half (Section 5) we show that every infinitely edge-connected graph without a $T_{\aleph_0} * t$ minor is ‘robust’ (Theorem 5.13), explained below. Then, in the second half (Section 6), we employ Theorem 5.13 to prove that every infinitely edge-connected graph without a $T_{\aleph_0} * t$ minor must contain a Farey graph minor, completing the proof of Theorem 1.

The Farey graph and $T_{\aleph_0} * t$ are both infinitely edge-connected, but in different ways. The infinite edge-connectivity of the Farey graph, on the one hand, is robust in that deleting the two endvertices of an edge always leaves only infinitely edge-connected components. The infinite edge-connectivity of $T_{\aleph_0} * t$, on the other hand, is fragile in that deleting t results in a tree. In the first half of the proof of Theorem 1 we show that every infinitely edge-connected graph without a $T_{\aleph_0} * t$ minor is essentially robust, not fragile (Theorem 5.13).

In the second half of the proof of Theorem 1 we construct a Farey graph minor in an arbitrary infinitely edge-connected $T_{\aleph_0} * t$ free graph G . By Lemma 2.1 it suffices to construct a halved Farey graph minor. Using that G is robust by Theorem 5.13, we shall essentially prove the following assertion:

For every two vertices u and v of G there exist two induced subgraphs $H_u, H_v \subseteq G$ containing u and v respectively and which satisfy the following conditions:

- (i) $X := V(H_u) \cap V(H_v)$ is finite, non-empty and connected in G ;
- (ii) both H_u/X and H_v/X are infinitely edge-connected;
- (iii) X avoids u and v ;
- (iv) uX is an edge of H_u/X and vX is an edge of H_v/X .

If we choose u and v to form an edge of G , then the three vertices u, v and X span a triangle \check{F}_1 in $(H_u \cup H_v)/X$. And since H_u/X and H_v/X are both infinitely edge-connected and robust again, we can reapply the assertion in $(H_u/X) - uX$ to u and X , and in $(H_v/X) - vX$ to v and X . By iterating this process, we obtain a halved Farey graph minor in the original graph G at the limit, and this will complete the proof of Theorem 1.

5. ROBUSTNESS

The aim of this section is to prove Theorem 5.13 which has been outlined in the previous section. Our proof proceeds in three steps. First, we provide some tools

that will help us to (i) identify infinitely edge-connected ‘parts’ of arbitrary graphs and (ii) allow us to distinguish all these ‘parts’ at once in a tree-like way. In the second step, then we employ these tools to analyse the components of $G - u - v$ for infinitely edge-connected graphs G and vertices u, v of G . In the third step, we proceed to prove Theorem 5.13.

5.1. Finitely separating spanning trees. Let G be any graph. Two vertices of G are said to be *finitely separable* in G if there is a finite set of edges of G separating them in G . If every two distinct vertices of G are finitely separable, then G itself is said to be *finitely separable*. An equivalence relation $\sim = \sim_G$ is declared on the vertex set of G by letting $x \sim y$ whenever x and y are not finitely separable. The graph \tilde{G} is defined on $V(G)/\sim$ by declaring XY an edge whenever $X \neq Y$ and there is an X – Y edge in G . Note that the graph \tilde{G} is always finitely separable. A spanning tree T of G is *finitely separating* if all its fundamental cuts are finite. By standard arguments of topological infinite graph theory, the following theorem is equivalent to Theorem 6.3 in [1]. See the appendix in Section 8 for the arguments.

Theorem 5.1. *Every connected finitely separable graph has a finitely separating spanning tree.*

Usually, we will employ Theorem 5.1 to find a finitely separating spanning tree T of \tilde{G} that we will then use to analyse the overall structure of G with regard to infinite edge-connectivity. In this context, the nodes of $T \subseteq \tilde{G}$ will also be viewed as the vertex sets of G that they formally are. When we view a node of T as a vertex set of G we will refer to it as *part* for clarity.

Every finitely separating spanning tree $T \subseteq \tilde{G}$ defines an S -tree (T, α) for the set $S = \mathcal{B}_{\aleph_0}(G)$ of all the separations of the vertex set $V(G)$ that are bipartitions induced by finite bonds of G : Let the map α send every oriented edge $(t_1, t_2) \in \vec{E}(T)$ to the ordered pair $(\bigcup V(T_1), \bigcup V(T_2))$ for the two components T_1 and T_2 of $T - t_1 t_2$ containing t_1 and t_2 respectively. Then $\alpha(t_1, t_2)$ clearly is an oriented bipartition of $V(G)$. Moreover, we have $\alpha(\vec{e}) \leq \alpha(\vec{f})$ whenever $\vec{e} \leq \vec{f} \in \vec{E}(T)$ and $(\alpha(\vec{e}))^* = \alpha(\vec{e})$ for all $\vec{e} \in \vec{E}(T)$. It remains to show that $\alpha(\vec{e})$ always stems from a finite bond of G . For this, it suffices to show that if $\{A, B\} \in \mathcal{B}_{\aleph_0}(\tilde{G})$ then $\{\bigcup A, \bigcup B\} \in \mathcal{B}_{\aleph_0}(G)$, because all the fundamental cuts of T are finite bonds. Between every two \sim -classes U and W of G there are only finitely many edges, because $u \in U$ is separated from $w \in W$ by a finite cut of G and then U and W must respect this finite cut. Hence the finitely many A – B edges in \tilde{G} give rise to only finitely many $(\bigcup A)$ – $(\bigcup B)$ edges in G , and these are all $(\bigcup A)$ – $(\bigcup B)$ edges in G . Using that G contains for all \sim -equivalent vertices x and y an x – y path avoiding the finitely many $(\bigcup A)$ – $(\bigcup B)$ edges, it is straightforward to show that both $G[\bigcup A]$ and $G[\bigcup B]$ are connected.

The *part* of a star $\{(A_i, B_i) \mid i \in I\}$ of separations of a given set is the intersection $\bigcap_{i \in I} B_i$. If (T, α) is a $\mathcal{B}_{\aleph_0}(G)$ -tree that is defined by a finitely separating spanning tree T of \tilde{G} , then for every node $t \in T$ the part of the star $\alpha[\vec{F}_t] \subseteq \mathcal{B}_{\aleph_0}(G)$ associated with t is equal to the part $t \subseteq V(G)$. And the parts $t \subseteq V(G)$ in turn are precisely the \sim -classes of G . Thus, in this sense, by Theorem 5.1 every connected graph admits a tree structure that displays all its \sim -classes.

Parts of infinite stars in $\mathcal{B}_{\aleph_0}(G)$ can be made connected for a reasonable price:

Lemma 5.2. *Suppose that G is a connected graph, that $\sigma = \{(A_i, B_i) \mid i \in I\}$ is an infinite star in $\mathcal{B}_{\aleph_0}(G)$ and that $i_* \in I$ is given. Then there is an infinite subset*

$J \subseteq I$ containing i_* such that the part of the infinite substar $\{(A_j, B_j) \mid j \in J\} \subseteq \sigma$ is connected in G .

Proof. For each $i \in I$ we write F_i for the finite bond $E(A_i, B_i)$ of G .

Inductively, we construct an ascending sequence $T_0 \subseteq T_1 \subseteq \dots$ of finite trees in G together with a sequence of distinct indices i_0, i_1, \dots in $I \setminus \{i_*\}$ such that, for all $n \in \mathbb{N}$ and $J_n := \{i_*\} \sqcup \{i_0, \dots, i_{n-1}\}$, the tree T_n is a subgraph of $G_n := G[\bigcap_{j \in J_n} B_j]$ containing all ∂B_j with $j \in J_n$. Then the tree $T := \bigcup_{n \in \mathbb{N}} T_n$ will ensure that $G_\infty := G[\bigcap_{j \in J} B_j]$ is connected for $J := \bigcup_{n \in \mathbb{N}} J_n$. (For whenever a path in G connecting two given vertices in G_∞ uses vertices that are not in G_∞ , then the path crosses one of the bonds F_j , and the number of bonds crossed can be decreased by replacing path segments with detours in $T \supseteq \partial B_j$ because $T \subseteq G_\infty$. Therefore, choosing a path that crosses as few bonds F_j as possible will suffice to find a path that lies entirely in G_∞ .)

To start the construction, let T_0 be any finite tree in $G[B_{i_*}]$ that contains ∂B_{i_*} . At step $n+1$ of the construction, suppose that we have already constructed T_n and J_n . As T_n is finite, we find an index $i_n \in I \setminus J_n$ for which A_{i_n} avoids T_n , ensuring $T_n \subseteq G_{n+1}$. To ensure that T_n can be extended in G_{n+1} to a finite tree T_{n+1} that contains ∂B_{i_n} , it suffices to show that G_{n+1} is connected. Given any two vertices in G_{n+1} , consider any path between them in $G[B_{i_n}]$, chosen to cross as few of the finite bonds F_j with $j \in J_n$ as possible. Then the path avoids all these F_j , for otherwise the number of bonds crossed could be decreased by replacing path segments with detours in $T_n \supseteq \bigcup_{j \in J_n} \partial B_j$. Therefore, G_{n+1} is connected. \square

5.2. Analysing the components. Now we analyse the components of $G - u - v$ for infinitely edge-connected graphs G and vertices u, v of G . The main results here are the two Lemmas 5.3 and 5.8. Here is the first main lemma:

Lemma 5.3. *Suppose that G is an infinitely edge-connected graph, that u, v are two distinct vertices of G , and that C is a component of $G - u - v$. If \tilde{C} has a finitely separating spanning tree that contains a subdivision of the infinite binary tree, then $G[C + u + v]$ contains $T_{\aleph_0} * t$ as a minor.*

Proof. Consider any finitely separating spanning tree of \tilde{C} that contains a subdivision of the infinite binary tree. Then this spanning tree also contains T_{\aleph_0} as a contraction minor which gives rise to a $\mathcal{B}_{\aleph_0}(C)$ -tree (T, α) . Next, we fix any root $r \in T$, and for every edge $e \in T$ we fix \vec{e} as its orientation pointing away from the root r (the orientation $\vec{e} = (x, y)$ of $e = \{x, y\}$ satisfying $x \in rTy$). Let $O := \{\vec{e} \mid e \in E(T)\}$. Since G is infinitely edge-connected, O is equal to the union $O_u \cup O_v$ where $\vec{e} \in O_w$ (for $w = u, v$) if and only if w sends an edge in G to B for $\alpha(\vec{e}) = (A, B)$. Now O_u is cofinal² in $O \subseteq \vec{E}(T)$ or there is an oriented edge $\vec{e} \in O$ with O_v cofinal in $[\vec{e}]_O := \{\vec{f} \in O \mid \vec{e} \leq \vec{f}\}$. In either case, there is $\vec{e} \in O$ with O_u or O_v cofinal in $[\vec{e}]_O$. Without loss of generality O_u is cofinal in $[\vec{e}]_O$ for some $\vec{e} \in O$. By replacing T with one of its subtrees and restricting α accordingly, we may even assume that O_u is cofinal in O . In fact, then $O_u = O$ follows as O_u is down-closed in O . We will use this to show $T_{\aleph_0} * t \preceq G[C + u]$.

For this, we enumerate the vertices of T_{\aleph_0} as x_0, x_1, \dots such that every x_n is neighbour to some earlier x^k ($k < n$). Inductively, we construct a sequence

²A subset X of a poset $P = (P, \leq)$ is *cofinal* in P , and \leq , if for every $x \in X$ there is a $p \in P$ with $p \geq x$.

W_0, W_1, \dots of disjoint connected vertex sets $W_n \subseteq V(C)$, a sequence w_0, w_1, \dots of vertices $w_n \in W_n$, and a sequence t_0, t_1, \dots of distinct nodes $t_n \in T$ such that, for all $n \in \mathbb{N}$:

- (i) $uw_n \in G$;
- (ii) C contains a $W_i - W_j$ edge ($i, j \leq n$) whenever $x_i x_j \in T_{\aleph_0}$;
- (iii) w_n is contained in the part of the star $\alpha[\vec{F}_{t_n}]$;
- (iv) for all $k \leq n$ there are infinitely many oriented edges $\vec{e} \in O \cap (\vec{F}_{t_k})^*$ such that, for $\alpha(\vec{e}) = (B, A)$, the vertex set W_k contains $\partial_C B$ while A is avoided by all W_i with $i \leq n$.

Once the construction is completed, the sets W_n and $\{u\}$ will give rise to a model of $T_{\aleph_0} * t$ in $G[C + u]$ by (i) and (ii).

At the construction start, we choose any neighbour w_0 of u in C (which exists as $O_u = O$ and T is infinite), guaranteeing (i). Then t_0 is defined by (iii). Applying Lemma 5.2 in C to the infinite star $\alpha[\vec{F}_{t_0}]$ yields an infinite substar whose connected part $W_0 \subseteq V(C)$ contains w_0 and satisfies both (ii) and (iv) trivially.

At step $n > 0$ of the construction, consider the $k < n$ for which $x_k x_n$ is an edge of T_{\aleph_0} , and pick an edge $\vec{e} \in O \cap (\vec{F}_{t_k})^*$ that (iv) provides for $k \leq n-1$. If we write $\alpha(\vec{e}) = (B, A)$, then the vertex set W_k contains $\partial_C B$ while A is avoided by all W_i with $i \leq n-1$. Using $O_u = O$ we find a neighbour w_n of u in A giving (i), and w_n defines t_n by (iii). Then we apply Lemma 5.2 in C to the infinite star

$$\{(A_i, B_i) \mid i \in I\} := \alpha[(\vec{F}_{t_n} \setminus O) \cup \{\vec{e}\}]$$

where we take $i_* \in I$ to be the index of the separation $\alpha(\vec{e})$. This yields an infinite substar whose connected part $W_n \subseteq V(C)$ contains w_n and satisfies (ii) because W_n contains $\partial_C A$ while W_k contains $\partial_C B$. Using the infinite substar and the choice of \vec{e} it is straightforward to verify (iv) for all $k \leq n$. \square

Our second main lemma, Lemma 5.8, requires some preparation.

Definition 5.4 (Arrow). Suppose that u and v are two distinct vertices.

An *arrow from u to v* is a graph G that arises from the two vertices u and v by disjointly adding an infinitely edge-connected graph H , adding a $u-H$ edge uh , and adding infinitely many $v-(H-h)$ edges. Then H is the arrow's *payload*, u is its *nock* and v is its *head*.

An *arrow barrage from u to v* is a countably infinite union $\bigcup_{n \in \mathbb{N}} A_n$ of arrows A_n from u to v such that A_n and A_m do not meet in any vertices other than u and v for all $n \neq m$. Then u and v are the *nock* and *head* of the arrow barrage.

When we say that some graph contains an arrow (barrage) minor *from x to y* for two vertices x and y , we mean that the graph contains an arrow (barrage) minor such that the branch set corresponding to the arrow (barrage)'s nock contains x while the branch set corresponding to the arrow (barrage)'s head contains y .

The next definition captures the concept of recursive pruning that Diestel describes in his book [7] as follows:

Definition 5.5 (Recursive pruning). Let T be any tree, equipped with a root and the corresponding tree-order on its vertices. We recursively label the vertices of T by ordinals, as follows. Given an ordinal α , assume that we have decided for every $\beta < \alpha$ which of the vertices of T to label β , and let T_α be the subgraph of T induced by the vertices that are still unlabelled. Assign label α to every vertex t of

T_α whose up-closure $[t]_{T_\alpha} = [t]_T \cap T_\alpha$ in T_α is a chain. The recursion terminates at the first α not used to label any vertex; for this α we put $T_\alpha =: T^*$. We call T *recursively prunable* if every vertex of T gets labelled in this way, i.e., if $T^* = \emptyset$.

Proposition 5.6 ([7, Proposition 8.5.1]). *A rooted tree is recursively prunable if and only if it contains no subdivision of the infinite binary tree.*

The next lemma is an observation that we will use often:

Lemma 5.7. *Suppose that G is an infinitely edge-connected graph, that u, v are two distinct vertices of G , and that C is a component of $G - u - v$. If T is a finitely separating spanning tree of \tilde{C} and $t \in T$ has finite degree in T , then $C[t]$ is infinitely edge-connected and either u or v sends infinitely many edges in G to the part $t \subseteq V(C)$.*

Proof. As t has finite degree in T , the finite fundamental cuts of the edges of T incident with t together give rise to a finite cut of C with the part t as one of its sides. Thus, in the graph G every vertex in the part t can send only finitely many edges to $C - t$, at most one edge to each of u and v , and some edges to the rest of the part t . As every vertex of the infinitely edge-connected graph G has infinite degree, it follows that the part t must be infinite. And since no two vertices in t are finitely separable in C while t is separated from the rest of C by a single finite cut, it follows that $C[t]$ is infinitely edge-connected. Finally, at least one of u and v sends infinitely many edges to the part t , because otherwise t is separated from the rest of G by a finite cut, contradicting that G is infinitely edge-connected. \square

Here is the second main lemma of this section:

Lemma 5.8. *Suppose that G is an infinitely edge-connected graph, that u, v are two distinct vertices of G , and that C is a component of $G - u - v$ such that u sends at least one edge to C . If \tilde{C} has a recursively prunable finitely separating rooted spanning tree T such that u sends no edges to parts $t \in T$ that are finite-degree nodes of T , then $G[C + u + v]$ contains an arrow barrage minor from u to v .*

Proof. Given T , we let $X \subseteq V(T)$ consist of the 0-labelled nodes of T that are minimal in the tree-order. Then the nodes in X form a maximal antichain in the tree-order, giving $T = \lfloor X \rfloor \cup \lceil X \rceil$, as T is recursively prunable. Note that all the nodes in $\lfloor X \rfloor$ have degree at most two in T . We claim that X must be infinite. Indeed, if X is finite, then so is $\lceil X \rceil$, and in particular T is locally finite. But then u may send no edges to C by assumption, contradicting our other assumption that u does send an edge to C . Therefore, X must be infinite.

Recall that the finitely separating spanning tree $T \subseteq \tilde{C}$ gives rise to a $\mathcal{B}_{\aleph_0}(C)$ -tree (T, α) . For every $x \in X$ let us write $(A_x, B_x) := \alpha(x, p_x)$ for the predecessor p_x of x in T . As u sends some edges to C , but none to the parts in $\lfloor X \rfloor$, there is a neighbour w of u in the part $\bigcap_{x \in X} B_x$ of the star $\sigma := \{(A_x, B_x) \mid x \in X\}$. By Lemma 5.2 we find an infinite subset $Y \subseteq X$ such that the part of the infinite substar $\sigma' := \{(A_y, B_y) \mid y \in Y\} \subseteq \sigma$ is connected. Note that w is contained in the part of σ' because the part of σ is included in the part of σ' . We now find an arrow barrage minor from u to v in $G[C + u + v]$ as follows. For the branch set of the neck we take the part of σ' plus the vertex u . For the branch set of the head we take $\{v\}$. The payloads we let be modelled by the subgraphs $C[y]$, one for every $y \in Y$ (here, each $C[y]$ is infinitely edge-connected and sends infinitely many edges in G to v by Lemma 5.7 and $Y \subseteq X$). \square

5.3. Football minors. We are almost ready now to prove Theorem 5.13. But first, we prove an intermediate proposition, which requires the following lemma and definition:

Lemma 5.9. *If G is an infinitely edge-connected graph and G' is obtained from G by contracting disjoint finite vertex sets that are possibly disconnected, then G' is infinitely edge-connected as well.*

Proof. To show that G' is infinitely edge-connected, consider any two distinct vertices x and y of G' , and choose vertices $\tilde{x} \in x$ and $\tilde{y} \in y$ of G . Now, in the infinitely edge-connected graph G we choose infinitely many pairwise edge-disjoint \tilde{x} – \tilde{y} paths P_0, P_1, \dots as follows. To get started, choose P_0 arbitrarily. At step $n > 0$, consider all the branch sets that are met by some P_k with $k < n$, and let X_n be their union. Then X_n is finite, and we let P_n be an \tilde{x} – \tilde{y} path in G that avoids all the finitely many edges of G running inside X_n .

Now every \tilde{x} – \tilde{y} path $P_n \subseteq G$ gives rise to some x – y path $P'_n \subseteq G'$ satisfying $E(P'_n) \subseteq E(P_n)$ by a slight abuse of notation. We claim that the paths P'_0, P'_1, \dots are all edge-disjoint. For this, consider any two paths P'_n and P'_m with $n < m$, and let e be any edge of P'_n . Then e , viewed as an edge of G , runs between two branch sets that P_n meets because it uses e . Hence these two branch sets are both included in X_m , and so P_m does not use any of the edges running between them. In particular, P'_m does not use e . \square

Definition 5.10 (Football, Muscle). Suppose that u and v are two distinct vertices.

A *football* with *endvertices* u and v is an infinitely edge-connected graph G containing u and v such that $G - u - v$ is again infinitely edge-connected.

When we say that some graph contains a football minor *connecting* two vertices x and y we mean that the graph contains a football minor with some endvertices u and v such that the branch set corresponding to u contains x and the branch set corresponding to v contains y (or vice versa).

A *muscle* with *endvertices* u and v is a graph G that is obtained from the vertices u and v by disjointly adding an infinitely edge-connected graph H and adding one u – H edge ux and one v – H edge vy such that $x \neq y$.

A *muscle barrage* with *endvertices* u and v is a countably infinite union $\bigcup_{n \in \mathbb{N}} G_n$ of muscles G_n with endvertices u and v such that G_n and G_m do not meet in any vertices other than u and v for all $n \neq m$.

Muscle (barrage) minors *connecting* two vertices are defined like for footballs.

Proposition 5.11. *Suppose that G is an infinitely edge-connected graph, that u, v are two distinct vertices of G , and that C is a component of $G - u - v$ to which both u and v do send some edges. Then at least one of the following assertions holds:*

- (i) $G[C + u + v]$ contains a $T_{\aleph_0} * t$ minor;
- (ii) $G[C + u + v]$ contains a football minor connecting u and v ;
- (iii) $G[C + u + v]$ contains an arrow barrage minor either from u to v or from v to u ; in particular, $G[C + u + v]$ contains a muscle barrage minor connecting u and v .

Proof. We may assume that both u and v send infinitely many edges to C . Indeed, if—say— u sends only finitely many edges to C , then consider the infinitely edge-connected graph $G' := G[C + v]$ and let u' be one of the neighbours of u in C . If there is a component C' of $G' - u' - v$ to which both u' and v send infinitely many

edges, then we may replace G, u, v, C with G', u', v, C' . Hence we may assume that there are infinitely many components C'_0, C'_1, \dots of $G' - u' - v$ such that, without loss of generality, u' sends only finitely many but at least one edge to each C'_n while v sends infinitely many edges to each C'_n .

By Theorem 5.1, all \tilde{C}'_n have finitely separating spanning trees. If one \tilde{C}'_n has a finitely separating spanning tree that contains a subdivision of the infinite binary tree, then Lemma 5.3 provides a $T_{\aleph_0} * t$ minor witnessing (i). Otherwise, by Proposition 5.6, every \tilde{C}'_n has a rooted finitely separating spanning tree T_n that is recursively prunable. Then we pick for every n a finite-degree node $t_n \in T_n$, and we let P_n be a path in C'_n that links a neighbour of u' to the subgraph $C'_n[t_n]$ such that P_n has only its endvertex x_n in $C'_n[t_n]$. Now we obtain an arrow barrage minor in $G[C + u + v]$ from u to v that is sought in (iii), as follows. For the branch set of the arrow barrage's nock we take $\{u, u'\} \cup \bigcup_{n \in \mathbb{N}} V(P_n \dot{x}_n)$. The arrows' payloads we let be modelled by the infinitely edge-connected subgraphs $C'_n[t_n]$ (see Lemma 5.7). And for the branch set of the arrow barrage's head we take $\{v\}$ (that v sends infinitely many edges to each part t_n is ensured by Lemma 5.7 and the assumption that u' sends only finitely many edges to each C'_n).

Therefore, we may assume that both u and v send infinitely many edges to C . By Theorem 5.1 we may let T be a finitely separating spanning tree of C , rooted arbitrarily. We make the following two observations.

If T contains a subdivision of the infinite binary tree, then Lemma 5.3 yields a $T_{\aleph_0} * t$ minor giving (i).

If T has finite-degree nodes t_u and t_v (possibly $t_u = t_v$) such that u sends infinitely many edges to the part $t_u \subseteq V(C)$ in G and v sends infinitely many edges to the part $t_v \subseteq V(C)$ in G , then we deduce (ii), as follows. By Lemma 5.7 both $C[t_u]$ and $C[t_v]$ are infinitely edge-connected. If $t_u = t_v$, then $G[t_u + u] \cup G[t_v + v]$ is a football subgraph connecting u and v . Otherwise t_u and t_v are distinct. Then we let P be any t_u - t_v path in C , and $(G[t_u + u] \cup G[t_v + v] \cup P)/V(P)$ is a football minor connecting u and v .

By these two observations and Proposition 5.6, we may assume that T is recursively prunable and that, without loss of generality, whenever $t \in T$ has finite degree then v does send infinitely many edges to the part $t \subseteq V(C)$ in G while u may send only finitely many edges to it.

If u sends edges in G to infinitely many parts $t \in T$ that have finite degree in T , then we find an arrow barrage minor from u to v giving (iii), because v sends infinitely many edges to all of the infinitely edge-connected subgraphs $C[t]$ (cf. Lemma 5.7) by our assumption above. Otherwise u sends, in total, only finitely many edges in G to the parts $t \in T$ that have finite degree in T . Since u sends infinitely many edges in G to C , this means that we may assume without loss of generality that u sends no edges to the parts $t \in T$ that have finite degree in T . Then Lemma 5.8 yields an arrow barrage minor from u to v giving (iii). \square

Now we have all we need to prove the main result of the section, Theorem 5.13. In its proof, we will face the construction of a minor in countably many steps. The following notation and lemma will help us to keep the technical side of this construction to the minimum.

Suppose that G and H are two graphs with H a minor of G . Then there are a vertex set $U \subseteq V(G)$ and a surjection $f: U \rightarrow V(H)$ such that the preimages $f^{-1}(x) \subseteq U$ form the branch sets of a model of H in G . A *minor-map* $\varphi: G \succcurlyeq H$

formally is such a pair (U, f) . Given $\varphi = (U, f)$ we address U as $V(\varphi)$ and we write $\varphi = f$ by abuse of notation. Usually, we will abbreviate ‘minor-map’ as ‘map’. If we are given two maps $\varphi: G \succcurlyeq H$ and $\varphi': H \succcurlyeq H'$, then these give rise to another map $\psi: G \succcurlyeq H'$ by letting $V(\psi) := \varphi^{-1}(\varphi'^{-1}(V(H')))$ and $\psi := \varphi' \circ (\varphi \upharpoonright V(\psi))$. On the notational side we write $\varphi' \diamond \varphi = \psi$.

Lemma 5.12. *If G_0, G_1, \dots and $H_0 \subseteq H_1 \subseteq \dots$ are sequences of graphs $H_n \subseteq G_n$ with maps $\varphi_n: G_n \succcurlyeq G_{n+1}$ that restrict to the identity on H_n , then $G_0 \succcurlyeq \bigcup_{n \in \mathbb{N}} H_n$.*

Proof. Recursively, each map $\varphi_n: G_n \succcurlyeq G_{n+1}$ gives rise to a map $\hat{\varphi}_n: G_0 \succcurlyeq G_{n+1}$ via $\hat{\varphi}_0 := \varphi_0$ and $\hat{\varphi}_{n+1} := \varphi_{n+1} \diamond \hat{\varphi}_n$. For every $n \in \mathbb{N}$ we write $V_x^n = \hat{\varphi}_n^{-1}(x)$ for all vertices $x \in H_{n+1}$. For every vertex $x \in H := \bigcup_{n \in \mathbb{N}} H_n$ we denote by $N(x)$ the least number n with $x \in H_n$. As the maps φ_n restrict to the identity on H_n , for every vertex $x \in H$ the vertex sets V_x^n form an ascending sequence $V_x^{N(x)} \subseteq V_x^{N(x)+1} \subseteq \dots$ whose overall union we denote by V_x . We claim that the vertex sets V_x form the branch sets of an H minor in G_0 .

Indeed, every branch set V_x is non-empty and connected in G_0 because all V_x^n are. If xy is an edge of H , then G_0 contains a $V_x^n - V_y^n$ edge as soon as $xy \in H_n$, and this edge is a $V_x - V_y$ edge due to the inclusions $V_x^n \subseteq V_x$ and $V_y^n \subseteq V_y$. It remains to show that V_x and V_y are disjoint for distinct vertices $x, y \in H$. This follows at once from the vertex sets V_x^n and V_y^n being disjoint for all n and the definition of V_x and V_y as ascending unions of these vertex sets. \square

Finally, we prove the main result of the section:

Theorem 5.13. *Suppose that G is any infinitely edge-connected graph, that u, v are two distinct vertices of G , and that C is a component of $G - u - v$ to which both u and v do send some edges. Then at least one of the following assertions holds:*

- (i) $G[C + u + v]$ contains a $T_{\aleph_0} * t$ minor;
- (ii) $G[C + u + v]$ contains a football minor connecting u and v .

Proof. Assume for a contradiction that both (i) and (ii) fail. We will use Proposition 5.11 to find the following graph H as a minor in $G' := G[C + u + v]$. Let T_u be an \aleph_0 -regular tree with root r_u , and let T_v be a copy of T_u that is disjoint from T_u . We write r_v for the root of T_v . The graph H is obtained from the disjoint union of the two trees T_u and T_v by adding the perfect matching between their vertex sets that joins every vertex of T_u to its copy in T_v . For every number $n \in \mathbb{N}$ we write H_n for the subgraph of H that is induced by the first n levels of T_u together with the first n levels of T_v . Thus, $H = \bigcup_{n \in \mathbb{N}} H_n$. Finding an H minor in G' completes the proof, because H/T_u is isomorphic to $T_{\aleph_0} * t$.

A *foresighted* H_n is a graph that is obtained from H_n by adding for every edge $xy \in H_n$ that runs between the two n th levels of T_u and T_v a muscle barrage B_{xy} having endvertices x and y such that B_{xy} contains no vertices from H_n other than x and y , and all muscle barrages added are pairwise disjoint.

By Lemma 5.12 it suffices to find a sequence $G' \succcurlyeq \hat{H}_0 \succcurlyeq \hat{H}_1 \succcurlyeq \dots$ of graphs \hat{H}_n that are foresighted H_n with maps $\varphi_n: \hat{H}_n \succcurlyeq \hat{H}_{n+1}$ that restrict to the identity on $H_n \subseteq \hat{H}_n$ in order to find an H minor in $\hat{H}_0 \preccurlyeq G'$. To get started, we apply Proposition 5.11 to G, u, v, C to obtain in G' a muscle barrage minor connecting u and v . By turning one of the muscles into an edge we obtain $\hat{H}_0 \preccurlyeq G'$.

At step $n > 0$, consider the muscle barrages B_{xy} that turn H_n into \hat{H}_n . For every muscle M_{xy}^k of each of these muscle barrages $B_{xy} = \bigcup_{k \in \mathbb{N}} M_{xy}^k$ we apply

Proposition 5.11 in $M := M_{xy}^k - x - y$ to the neighbours x' and y' of x and y in M_{xy}^k and some component of $M - x' - y'$ to which both x' and y' send some edges to find a muscle barrage minor connecting x' and y' . By turning one muscle of each new barrage into an edge, we find $\varphi_n: \hat{H}_n \succ \hat{H}_{n+1}$. \square

6. PROOF OF THE MAIN RESULT

In this section we employ the main result of the previous section (Theorem 5.13) to prove the main result of this paper (Theorem 1).

Lemma 6.1. *If A and B are two infinite vertex sets in a graph G that does not contain a subdivision of K^{\aleph_0} , then there are vertices $a \in A$ and $b \in B$ plus a finite vertex set $S \subseteq V(G) \setminus \{a, b\}$ such that S separates a and b in $G - ab$.*

Proof. The absence of such an S for a pair $a \neq b$ means that, inductively, we can find infinitely many independent a - b paths in G . So if there is no S for every pair $a \neq b$, then inductively we find a TK_{\aleph_0, \aleph_0} in G , and $TK_{\aleph_0} \subseteq TK_{\aleph_0, \aleph_0}$ (contradiction). \square

Lemma 6.2. *Suppose that G is a football with endvertices u and v . If G does not contain a subdivision of K^{\aleph_0} , then G contains an infinitely edge-connected graph H as a minor with branch sets V_h ($h \in H$) such that u and v are contained in distinct branch sets V_x and V_y , respectively, and there is a finite vertex set $S \subseteq V(H) \setminus \{x, y\}$ separating x and y in H .*

Proof. Write C for the infinitely edge-connected graph $G - u - v$. We apply Lemma 6.1 in C to the infinite neighbourhoods $N(u)$ and $N(v)$ of u and v in G to obtain vertices $a \in N(u)$ and $b \in N(v)$ plus a finite vertex set $S \subseteq V(C) \setminus \{a, b\}$ that separates a and b in $C - ab$. Then H can be obtained from the infinitely edge-connected graph $G - ab$ as follows. We discard all the edges that are incident with u or v , except for the two edges ua and vb each of which we contract. Then H is infinitely edge-connected because it is isomorphic to the infinitely edge-connected graph $C - ab$. And the way we treated the edges at u and v ensures that S separates the two vertices $\{u, a\}$ and $\{v, b\}$ in H as desired. \square

Lemma 6.3. *Suppose that G is an infinitely edge-connected graph and that u, v are two distinct vertices of G that are separated in G by some finite vertex set $S \subseteq V(G) \setminus \{u, v\}$. Then there exist induced subgraphs $H_u, H_v \subseteq G$ containing u and v respectively, such that the following assertions hold:*

- (i) $X := V(H_u) \cap V(H_v)$ is finite, non-empty and connected in G ;
- (ii) both H_u/X and H_v/X are infinitely edge-connected;
- (iii) X avoids u and v ;
- (iv) uX is an edge of H_u/X and vX is an edge of H_v/X .

Proof. Given G, u, v, S let us write C_u and C_v for the distinct components of $G - S$ that contain u and v respectively. For both $w \in \{u, v\}$ we abbreviate $\sim_{G[C_w \cup S]}$ as \sim_w . As G is infinitely edge-connected, we infer that every \sim_w -class meets S . In particular, there are only finitely many \sim_w -classes in total, which means that each of the non-singleton classes induces an infinitely edge-connected subgraph of G . Let us write K_u and K_v for the infinitely edge-connected subgraphs induced by the classes containing u and v respectively, i.e., $K_u := G[[u]_{\sim_u}]$ and $K_v := G[[v]_{\sim_v}]$. To find H_u and H_v , we distinguish two cases.

In the first case, K_u and K_v are disjoint. For both $w \in \{u, v\}$, the finite partition of $V(C_w) \cup S$ induced by \sim_w has only finitely many cross-edges. Since G is infinitely edge-connected, this means that we can find a $(K_u \cap S)-(K_v \cap S)$ path P in G avoiding all these finitely many edges. Then P , as it may not use these edges, is a K_u-K_v path with endvertices in S . We let P_w be a $w-P$ path in K_w for both $w \in \{u, v\}$. Letting $H_u := G[K_u \cup P \cup \dot{v}P_v]$ and $H_v := G[K_v \cup P \cup \dot{u}P_u]$ completes this case with $X = V(P_u \cup P \cup P_v) \setminus \{u, v\}$ because the graph H_w/X contains the spanning subgraph $K_w/V(\dot{w}P_w)$, and $K_w/V(\dot{w}P_w)$ is infinitely edge-connected by Lemma 5.9 and because K_w is infinitely edge-connected.

In the second case, K_u and K_v meet in a vertex $s \in S$. We write D_u for the component of $K_u - u$ containing s . In D_u we pick a finite tree T that contains the finite intersection $V(D_u) \cap V(K_v) \subseteq S$ and contains a neighbour of u . Then T contains s but neither u nor v . We let P_v be any $v-s$ path in K_v . Letting $H_u := G[D_u \cup \dot{v}P_v + u]$ and $H_v := G[K_v \cup T]$ completes this case with $X = V(T \cup \dot{v}P_v)$: On the one hand, the graph H_u/X is infinitely edge-connected because it contains the spanning subgraph $G[D_u + u]/V(T)$ which is infinitely edge-connected by Lemma 5.9 and the fact that $G[D_u + u]$ is an infinitely edge-connected subgraph of K_u . On the other hand, the graph H_v/X contains the spanning subgraph K_v/Y for $Y := (V(K_v) \cap V(D_u)) \cup V(\dot{v}P_v)$, and K_v/Y is infinitely edge-connected by Lemma 5.9 and because K_v is infinitely edge-connected. \square

Definition 6.4 (Plows). Suppose that u and v are two distinct vertices. A *half-plow* with *endvertices* u and v is an infinitely edge-connected graph containing the edge uv . A *plow* with *endvertices* u and v and *head* h is a union of two half-plows with end-vertices u, h and h, v that do not meet in any vertex other than h . Plow minors *connecting* some two vertices are defined like for footballs and muscles.

Theorem 6.5. *If G is an infinitely edge-connected graph and u, v are two distinct vertices of G , then at least one of the following two assertions holds:*

- (i) G contains a $T_{\aleph_0} * t$ minor;
- (ii) G contains a plow minor connecting u and v .

Proof. Let G, u, v be given, we show $\neg(\text{i}) \rightarrow (\text{ii})$. For this, suppose that G does not contain a $T_{\aleph_0} * t$ minor. By Theorem 5.13 and Lemma 6.2 we may assume that there is a finite vertex set $S \subseteq V(G) \setminus \{u, v\}$ that separates u and v in G . Then applying Lemma 6.3 provides induced subgraphs $H_u, H_v \subseteq G$ containing u and v respectively, such that the following assertions hold:

- $X := V(H_u) \cap V(H_v)$ is finite, non-empty and connected in G ;
- both H_u/X and H_v/X are infinitely edge-connected;
- X avoids u and v ;
- uX is an edge of H_u/X and vX is an edge of H_v/X .

Then $(H_u \cup H_v)/X$ is a plow minor connecting u and v . \square

Theorem 1. *Every infinitely edge-connected graph contains either the Farey graph or $T_{\aleph_0} * t$ as a minor.*

Proof. If G contains $T_{\aleph_0} * t$ as a minor, then we are done. So let us suppose that G does not contain a $T_{\aleph_0} * t$ minor. Our task then is to find a Farey graph minor in G . By Lemma 2.1 it suffices to find a halved Farey graph minor.

Call a graph a *foresighted* halved Farey graph of order $n \in \mathbb{N}$ if it is the union of \check{F}_n with infinitely edge-connected graphs A_{xy} , one for every blue edge $xy \in \check{F}_n$, such that:

- (i) each A_{xy} meets \check{F}_n precisely in x and y but $xy \notin A_{xy}$;
- (ii) every two distinct A_e and $A_{e'}$ meet precisely in the intersection $e \cap e'$ of their corresponding edges (viewed as vertex sets).

By Lemma 5.12 it suffices to find a sequence H_0, H_1, \dots of foresighted halved Farey graphs of orders $0, 1, \dots$ with maps $\varphi_n: H_n \succcurlyeq H_{n+1}$ that restrict to the identity on $\check{F}_n \subseteq H_n$ to yield a halved Farey graph minor in $G =: H_0$.

To get started, pick any edge e of G , and note that $G = H_0$ is a foresighted halved Farey graph of order 0 when we rename e to the edge of which $\check{F}_0 = K^2$ consists. At step $n+1$, suppose that we have already constructed $H_n \supseteq \check{F}_n$, and consider the infinitely edge-connected graphs A_{xy} that were added to \check{F}_n to form H_n . Theorem 6.5 yields in each A_{xy} a plow minor with head h_{xy} that connects x and y . These plow-minors combine with \check{F}_n and with each other to give a map $\varphi_n: H_n \succcurlyeq H_{n+1} \supseteq \check{F}_{n+1}$ that sends the branch set of every head h_{xy} to the vertex $v_{xy} \in \check{F}_{n+1} - \check{F}_n$ that arises from the blue edge $xy \in \check{F}_n$ in the recursive definition of \check{F}_{n+1} . \square

7. OUTLOOK

Here are two open problems that came to my mind.

Problem 7.1. *Can Theorem 1 be strengthened to always find one of the two minors with finite branch sets?*

Seymour and Thomas [20], together with Robertson [18, 19], have characterised the graphs without K^κ or T_κ minors in terms of tree-decompositions and, alternatively, in terms of various other structures. Can their list be extended to include the Farey graph? Tree-decompositions might not be the right complementary structures for infinitely edge-connected substructures, but there might be other structures (e.g. $\mathcal{B}_{\aleph_0}(G)$ -trees):

Problem 7.2. *Characterise the graphs without a Farey graph minor in terms of tree-decompositions or in terms of other structures.*

8. APPENDIX

The following lemma proves that Theorem 6.3 in [1] is equivalent to Theorem 5.1. The lemma and its proof are formulated in the terminology of [1]. In particular, \tilde{G} denotes the topological space considered in [1], not the quotient graph that we considered in the previous sections.

Lemma 8.1. *Let G be any finitely separable connected graph. Then the following assertions are equivalent:*

- (i) G has a spanning tree whose closure in \tilde{G} contains no circle;
- (ii) G has a finitely separating spanning tree.

Proof. (ii) \rightarrow (i) Every finite cut $F = E(V_1, V_2)$ of G gives rise to a clopen bipartition $\overline{G[V_1]} \oplus \overline{G[V_2]}$ of the space $\tilde{G} - \check{F}$, just like in the jumping arc lemma [7, 8.6.3]. Now suppose for a contradiction that $T \subseteq G$ is a finitely separating spanning tree and that $C \subseteq \bar{T}$ is a circle. Then C contains an edge $e \in T$ as Bruhn and Diestel remark in [1, §2]. But the fundamental cut F_e of e with respect to T is finite, and

hence its induced clopen bipartition topologically separates the endpoints of the arc $C - \dot{e}$ in $\tilde{G} - \dot{F}$, a contradiction.

(i)→(ii) Given any spanning tree $T \subseteq G$ whose closure in \tilde{G} contains no circle, let us assume for a contradiction that some fundamental cut F_e of T is infinite.

We claim that

- (1) no ray in T is dominated in G , and that
- (2) no two disjoint rays in T are equivalent in G .

Indeed, if T contains a ray that is dominated in G by a vertex v , then that ray is a tail of ray $R \subseteq T$ that starts in v , so $\overline{R} \subseteq \overline{T}$ is a circle contradicting the choice of T . And if T contains two disjoint equivalent rays, then there is a double ray $D \subseteq T$ that contains both rays, and neither of the two rays is dominated by (1). Thus, $\overline{D} \subseteq \overline{T}$ is a circle contradicting the choice of T .

To complete the proof, we consider the two components T_1 and T_2 of $T - e$.

If some infinitely many edges in F_e meet in the same vertex v with $v \in T_1$, say, then applying the star-comb lemma in T_2 to their other endvertices must yield a comb since G is finitely separable. But then the spine of that comb is dominated by v , contradicting (1).

Otherwise we find an infinite independent edge set $M \subseteq F_e$. Applying the star-comb lemma in T_1 to the endvertices of the edges in M yields either a star or a comb, and by replacing M with an infinite subset we may assume without loss of generality that every edge in M has an endvertex that is either a leaf of the star or a tooth of the comb. But now applying the star-comb lemma in T_2 to the endvertices of the edges in M yields a contradiction, as follows. On the one hand we cannot get a star, because this would contradict either that G is finitely separable or (1). On the other hand we cannot get a comb, because this would contradict either (1) or (2). \square

REFERENCES

- [1] H. Bruhn and R. Diestel, *Duality in infinite graphs*, Comb., Probab. & Comput. **15** (2006), 75–90, DOI [10.1017/S0963548305007261](https://doi.org/10.1017/S0963548305007261). MR2195576 ↑[5.1](#), [8](#), [8](#)
- [2] C. Bürger and J. Kurkofka, *Duality theorems for stars and combs I: Arbitrary stars and combs* (2020), available at [arXiv:2004.00594](https://arxiv.org/abs/2004.00594). Submitted. ↑[3.1](#)
- [3] ———, *Duality theorems for stars and combs II: Dominating stars and dominated combs* (2020), available at [arXiv:2004.00593](https://arxiv.org/abs/2004.00593). Submitted. ↑[3.1](#)
- [4] ———, *Duality theorems for stars and combs III: Undominated combs* (2020), available at [arXiv:2004.00592](https://arxiv.org/abs/2004.00592). Submitted. ↑[3.1](#)
- [5] ———, *Duality theorems for stars and combs IV: Undominating stars* (2020), available at [arXiv:2004.00591](https://arxiv.org/abs/2004.00591). Submitted. ↑[3.1](#)
- [6] M. Clay and D. Margalit, *Office Hours with a Geometric Group Theorist*, Princeton University Press, 2017. MR3645425 ↑[1](#), [2.1](#)
- [7] R. Diestel, *Graph Theory*, 5th, Springer, 2016. ↑[1](#), [2](#), [2.2](#), [3.1](#), [5.2](#), [5.6](#), [8](#)
- [8] ———, *Abstract Separation Systems*, Order **35** (2018), no. 1, 157–170, DOI [10.1007/s11083-017-9424-5](https://doi.org/10.1007/s11083-017-9424-5), available at [arXiv:1406.3797v6](https://arxiv.org/abs/1406.3797v6). MR3774512 ↑[2.2](#), [1](#)
- [9] ———, *Tree Sets*, Order **35** (2018), no. 1, 171–192, DOI [10.1007/s11083-017-9425-4](https://doi.org/10.1007/s11083-017-9425-4), available at [arXiv:arXiv:1512.03781v3](https://arxiv.org/abs/1512.03781v3). ↑[2.2](#)
- [10] J. Geelen and B. Joeris, *A generalization of the Grid Theorem* (2016), available at [arXiv:1609.09098](https://arxiv.org/abs/1609.09098). Submitted. ↑[1](#)
- [11] J.P. Gollin and K. Heuer, *Characterising k -connected sets in infinite graphs* (2018), available at [arXiv:1811.06411](https://arxiv.org/abs/1811.06411). Submitted. ↑[1](#)
- [12] R. Halin, *Simplicial decompositions of infinite graphs*, Advances in Graph Theory, Annals of Discrete Mathematics, 1978, DOI [10.1016/S0167-5060\(08\)70500-4](https://doi.org/10.1016/S0167-5060(08)70500-4). MR0499113 ↑[1](#)
- [13] A. Hatcher, *Topology of numbers*, Book in preparation (2017). Available [online](#). ↑[1](#), [2.1](#)

- [14] B. Joeris, *Connectivity, tree-decompositions and unavoidable-minors*, University of Waterloo, 2015. [↑1](#)
- [15] J. Kurkofka, *The Farey graph is uniquely determined by its connectivity* (2020), available at [arXiv:2006.12472](#). Submitted. [↑2.1](#)
- [16] ———, *Ubiquity and the Farey graph* (2019), available at [arXiv:1912.02147](#). Submitted. [↑3.2](#)
- [17] B. Oporowski and J. Oxley and R. Thomas, *Typical Subgraphs of 3- and 4-connected Graphs*, J. Combin. Theory (Series B) **57** (1993), no. 2, 239–257, DOI [10.1006/jctb.1993.1019](#). MR1207490 [↑1](#)
- [18] N. Robertson and P.D. Seymour and R. Thomas, *Excluding infinite minors*, Disc. Math. **95** (1991), no. 1, 303–319, DOI [10.1016/0012-365X\(91\)90343-Z](#). MR1141945 [↑7](#)
- [19] ———, *Excluding subdivisions of infinite cliques*, Trans. Amer. Math. Soc. **332** (1992), 211–223, DOI [10.1090/S0002-9947-1992-1079057-3](#). MR1079057 [↑7](#)
- [20] P.D. Seymour and R. Thomas, *Excluding infinite trees*, Trans. Amer. Math. Soc. **335** (1993), 597–630, DOI [10.1090/S0002-9947-1993-1079058-6](#). MR1079058 [↑7](#)

UNIVERSITY OF HAMBURG, DEPARTMENT OF MATHEMATICS, BUNDESSTRASSE 55 (GEOMATIKUM),
20146 HAMBURG, GERMANY

Email address: jan.kurkofka@uni-hamburg.de