NON-SELF-TOUCHING PATHS IN PLANE GRAPHS

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Abstract. A path in a graph G is called non-self-touching if two vertices are neighbours in the path if and only of they are neighbours in the graph. We investigate the existence of doubly infinite non-self-touching paths in infinite plane graphs.

The *matching graph* G_* of an infinite plane graph G is obtained by adding all diagonals to all faces, and it plays an important role in the theory of site percolation on G. The main result of this paper is a necessary and sufficient condition on G for the existence of a doubly infinite non-self-touching path in G_* that traverses some diagonal. This is a key step in proving, for quasi-transitive G, that the critical points of site percolation on G and G_* satisfy the strict inequality $p_c(G_*) < p_c(G)$, and it complements the earlier result of Grimmett and Li ("Percolation critical points of matching lattice pairs", `arXiv:2205.02734`), proved by different methods, concerning the case of transitive graphs. Furthermore it implies, for quasi-transitive graphs, that $p_u(G) + p_c(G) \ge 1$, with equality if and only if G is a triangulation. Here, p_u is the critical probability for the existence of a unique infinite open cluster.

1. Background and main theorem

Some basic facts are presented concerning the existence in an infinite planar graph of a certain type of doubly infinite path, namely a path π with the property that two vertices of π are neighbours if and only if they are consecutive in π. Such paths arise naturally in the theory of site percolation.

The graphs considered here are assumed to belong to the set $\mathcal{G}$ of countably infinite, locally finite, 2-connected, plane graphs, embedded in the plane $\mathbb{R}^2$ without accumulation points, and moreover such that all faces have finite diameter. A doubly infinite path $\pi = (\pi_i : -\infty < i < \infty)$ of a graph is called *non-self-touching* if it has the property that $\pi_i \sim \pi_j$ if and only if $|i - j| = 1$. The expression 'doubly infinite non-self-touching path' is abbreviated henceforth to 2∞-*nst path*.

Which graphs possess a 2∞-nst path? We do not have a complete answer to this, but certain cases are described in Section 4.2. For example, every 4-connected $G \in \mathcal{G}$

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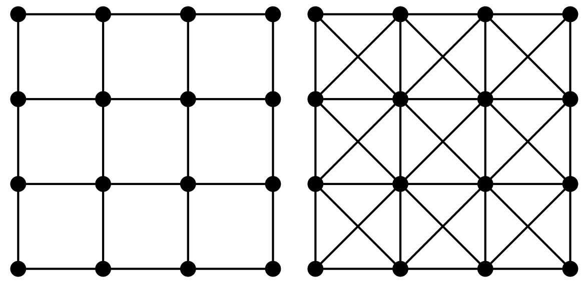

FIGURE 1.1. The square lattice $\mathbb{Z}^2$ and its matching graph.

has a 2∞-nst path, and every graph $G \in \mathcal{G}$, embedded in $\mathbb{R}^2$ in such way that its faces have uniformly bounded diameter, has a 2∞-nst path.

The *matching graph* G_* of $G \in \mathcal{G}$ is obtained from G by adding all diagonals to all non-triangular faces (see Figure 1.1). The principal purpose of this paper is to prove a property of the pair (G, G_*) of graphs. Evidently, $G_* = G$ if and only if G is a triangulation. Note that, while G is planar, its matching graph G_* is planar if and only if G is a triangulation.

The following graph property is important in the theory of site percolation (see Section 2).

Definition 1.1. *The graph $G \in \mathcal{G}$ is said to have property Π if G_* has a 2∞-nst path that includes some diagonal of G.*

No triangulation can have property Π since a triangulation has no diagonals.

We call a 3-cycle C of a connected plane graph a *separating triangle* if the bounded component of $\mathbb{R}^2 \setminus C$ contains one or more vertices. If C is a separating triangle of $G \in \mathcal{G}$, then evidently no non-self-touching path may intersect the interior of C. Thus the interiors of separating triangles may be removed without changing the property of having a 2∞-nst path. For $G \in \mathcal{G}$, we write $G_\triangle$ for the subgraph of G obtained by deleting any vertex/edge lying in the interior of any 3-cycle of G. We shall normally assume that $G_\triangle \in \mathcal{G}$, thereby eliminating the possibility that G has an infinite nested sequence of 3-cycles. A graph $G \in \mathcal{G}$ is said to be $\triangle$-*empty* if it contains no separating triangle.

We prove the straightforward fact (in Theorem 4.2(b)) that a triangulation T has a 2∞-nst path if $T_\triangle \in \mathcal{G}$. An example of a graph $G \in \mathcal{G}$ with a separating triangle but without property Π is given in Figure 1.2.

Here is the main theorem. Its application to percolation theory is outlined in Section 2.

Theorem 1.2. *Let $G \in \mathcal{G}$ be such that $G_\triangle \in \mathcal{G}$, and assume $G_\triangle$ is not a triangulation. If G_* has a 2∞-nst path, then G has property Π.*

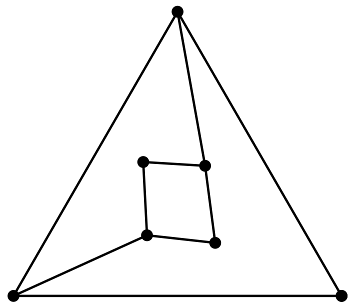

FIGURE 1.2. The graph $G \in \mathcal{G}$ is obtained from the usual triangular lattice by replacing one of more fundamental triangles with a copy of the above. The ensuing graph cannot have property Π since no 2∞-nst path may penetrate any fundamental triangle.

Here is a summary of the contents of this article. The application of Theorem 1.2 to percolation is presented in Section 2. After a section on notation, and the methodological Section 4, the principal graph-theoretic Proposition 5.1 appears in Section 5. The cycle structure of plane graphs is explored in Section 6, which ends with the proof of Theorem 1.2 (using Proposition 5.1). Sections 7 and 8 are devoted to the proof of Proposition 5.1.

The proof of Proposition 5.1 is a somewhat complicated graph-theoretic analysis of a number of possible cases. It is tempting to hope for a neater and more appetising proof of Theorem 1.2.

2. Application to site percolation

The percolation process is a prominent model for connectivity in a random medium. The model has emerged as central to the mathematical and physical theories of phase transition, and its theory is ramified and complex. Percolation comes in two flavours, bond and site, and it is site percolation that is relevant here. See [7] for an account of the standard theory of percolation.

Let $G = (V, E)$ be an infinite connected graph, and let $p \in [0, 1]$. Each vertex (or 'site') $v \in V$ is coloured *black* with probability p and *white* otherwise, different vertices receiving independent colours. We write $\mathbb{P}_p$ for the corresponding probability measure. We choose some vertex, called the *origin*, and write I for the event that the origin is the endpoint of some infinite black path. With $\theta(p) = \mathbb{P}_p(I)$, there exists a *critical probability* $p_c = p_c(G) \in [0, 1]$ such that

$$\theta(p) \begin{cases} = 0 & \text{if } p < p_c(G), \\ > 0 & \text{if } p > p_c(G). \end{cases} \tag{2.1}$$

The value of $p_c(G)$ is independent of the choice of origin.

The study of weak and strict inequalities for critical probabilities has a long history (see, for example, [13] and [15, Sect. 10]). A general method for proving strict inequalities for critical probabilities, and more generally for critical points of interacting systems, was described in [1]. One assumption for a naive application of this method is the quasi-transitivity of the underlying graph $G = (V, E)$. Recall that G is *quasi-transitive* if its automorphism group acts on V with only finitely many orbits.

Since G is a subgraph of G_*, it is elementary that $p_c(G_*) \le p_c(G)$. Strict inequality is harder to prove. The following was proved in [10].

Theorem 2.1 ([10, Thm 1.2])**.** *Let $G \in \mathcal{G}$ be quasi-transitive. Then $p_c(G_*) < p_c(G)$ if and only if G has property Π.*

Using Theorems 2.1 and 1.2, one obtains the following.

Theorem 2.2. *Let $G \in \mathcal{G}$ be quasi-transitive and $\triangle$-empty. The strict inequality $p_c(G_*) < p_c(G)$ holds if only if G is not a triangulation.*

This extends the earlier result of [10, Thm 1.4] which was restricted to transitive graphs, for which the proof is different and less complicated.

Proof of Theorem 2.2. By Theorem 1.2, it suffices to show that such G_* has a 2∞-nst path. This is included in [9, Lemma 4.3(a)], and is given explicitly in Theorem 4.2(d). □

Non-self-touching paths were introduced in [1] where they were called 'stiff paths' (see also [3, 10] and [7, p. 66]).

Suppose H is a connected, quasi-transitive graph. Let N be the number of infinite black clusters in site percolation on H. It was proved in [11, 21] that there exists $p_u(H) \in [0, 1]$ such that

$$\mathbb{P}_p(N = 1) = \begin{cases} 0 & \text{if } p < p_u(H), \\ 1 & \text{if } p > p_u(H). \end{cases}$$

Evidently, $p_c(H) \le p_u(H)$. Let $G \in \mathcal{G}$ be quasi-transitive and $\triangle$-empty. It is known that $p_u(G) + p_c(G_*) = 1$ (see [9, Thm 1.1]), and it follows by Theorem 2.2 that $p_u(G) + p_c(G) \ge 1$ with equality if and only if G is a triangulation.

3. Notation

A graph is denoted $G = (V, E)$ where V is the vertex-set and E the edge-set. Graphs considered here are mostly assumed to be countable (that is, finite or countably infinite), and simple (in that they have neither loops nor parallel edges); a possible exception to the last arises in the case of matching graphs, which may contain pairs of parallel diagonals created in abutting faces. An edge between vertices u, v is denoted $\langle u, v\rangle$; if this edge exists, we say that u and v are *adjacent* and write $u \sim v$. The edge $\langle u, v\rangle$ is said to be *incident* to its endvertices. The *degree* of a vertex is the number of its incident edges, and G is *locally finite* if all degrees are finite. Given $A, B \subseteq V$, A is said to be *adjacent* to B, written $A \sim B$, if there exist $a \in A$ and $b \in B$ such that $a \sim b$.

A *walk* in G is an alternating sequence $w = (\dots, w_0, e_0, w_1, e_1, \dots)$ where $w_i \in V$ and $e_i = \langle w_i, w_{i+1}\rangle \in E$ for all i; if G is simple, the edges e_i may be omitted from the definition. The walk w is a *path* if the w_i are distinct. The path w is *non-self-touching* if $w_i \sim w_j$ if and only if $|i - j| = 1$. A path w is called a 2∞-*nst path* if it is doubly infinite and non-self-touching; we denote by $\mathrm{NST}(G)$ the set of all 2∞-nst paths of G. The graph-distance $d_G(u, v)$ between vertices u, v is the minimal number of edges in paths from u to v; for $A, B \subseteq V$; we set $d_G(A, B) = \min\{d_G(a, b) : a \in A,\, b \in B\}$. Two walks $\pi = (\pi_i)$, $\nu = (\nu_j)$ are said to be *non-touching* if $d_G(\pi_i, \nu_j) \geq 2$ for every pair i, j. A path from u to v is called a *geodesic* if it has exactly $d_G(u, v)$ edges. We note that a finite path is non-self-touching if it is a geodesic; a similar statement holds for infinite paths.

A *cycle* of G is a finite walk of the form $w = (w_0, e_0, w_1, \dots, w_n)$ such that $w_0 = w_n$ and the sub-walk $(w_0, e_0, w_1, \dots, w_{n-1})$ is a path. Such a cycle has *length* n and is called an n-*cycle*. The set of cycles of G is denoted $\mathcal{C}(G)$.

Let $k \geq 1$. An infinite graph G is called k-*connected* if, for all $v \in V$, there exist at least k infinite paths starting from v that are pairwise vertex-disjoint (except for their common starting point v). By Menger's theorem, G is k-connected if and only if, for all $v \in V$, there exists no set $A \subseteq V \setminus \{v\}$ of cardinality strictly less that k whose removal leaves v in a finite subgraph of G. For further discussion and references, see [2, Sect. 1] and [6, 12].

A graph $G = (V, E)$ is *planar* if it may be drawn in the plane in such a way that edges cross only at vertices. An embedded planar graph is called *plane*. A point $x \in \mathbb{R}^2$ is called a *vertex accumulation point* of G if it is an accumulation point of V, and an *edge-accumulation point* if every neighbourhood of x intersects some edge not incident with x. We shall consider only plane graphs with neither vertex- nor edge-accumulation points. The number of *ends* of a graph is the supremum of the number of infinite components obtained by deletion of finite sets of vertices.

A *face* of a one-ended, plane graph $G = (V, E)$ is a connected component of $\mathbb{R}^2 \setminus G$. By [17, Thm 3], if G is 2-connected, the boundary of every face F is a cycle of G, denoted ∂F. The *size* of the face F is the number of edges in ∂F, and its (Euclidean) *diameter* is defined as

$$\mathrm{diam}(F) = \sup\{|x - y| : x, y \in F\}$$

where $|\cdot|$ denotes Euclidean distance. Let C be a cycle of G, and write $\mathrm{int}(C)$ for the (open) bounded component of $\mathbb{R}^2 \setminus C$, and $\overline{C} = C \cup \mathrm{int}(C)$. We write $\mathrm{int}(C)$ also for the subgraph of G obtained by deleting all vertices not belonging to $\mathrm{int}(C)$. A cycle C is called *facial* if it is the boundary of some face.

We denote by $\mathcal{G}$ the set of countably infinite, 2-connected, locally finite, plane graphs, embedded in the plane without vertex/edge-accumulation points, such that all faces have finite diameter (whence, in particular, such G are one-ended).

We call a 3-cycle of G a *separating triangle* if $\mathrm{int}(C)$ contains one or more vertices of G. For $G \in \mathcal{G}$, we write G_Δ for the subgraph of G obtained by deleting any vertex/edge lying in the interior of any separating triangle of G. Thus G_Δ has no separating triangle, and we say that G_Δ is $\triangle$-*empty*. We shall speak of G_Δ as being obtained from G by 'emptying the separating triangles'.

The one-ended, plane graph G is a *triangulation* if every face is bounded by a 3-cycle. Let $u, v \in V$ be such that $u \nsim v$ but there exists some face F with $u, v \in \partial F$; we may choose to add to F the further edge $\langle u, v\rangle$, and we call this a *diagonal* of G (or of G_*), denoted $\delta(u, v)$.

The *matching graph* G_* of $G \in \mathcal{G}$ is obtained from G by adding all diagonals to all non-triangular faces. See Figure 1.1, and note that G_* is not generally planar. We shall work also with the so-called 'facial graph' of G; see Section 4.3. The matching graph was introduced by Sykes and Essam [22] in the context of percolation theory.

The reasons for the assumption of 2-connectivity are as follows. Let G be 1-connected but not 2-connected. Then there exist cutpoints c such that $G \setminus \{c\}$ has one or more finite components. Such components cannot be relevant to the occurrence or not of property Π since no 2∞-nst path (of either G or G_*) may access them. Linked to this is the fact that site percolation on G possesses an infinite cluster if and only $G \setminus \{c\}$ contains such a cluster. Moreover, as remarked above, 2-connectivity is needed for the faces of G to be bounded by cycles.

Remark 3.1. *We close this section with a note about the distinction between planar and plane graphs. A planar graph H is said to have property $\mathcal{N}$ if it possesses a* 2∞*-nst path. Evidently $\mathcal{N}$ is a graph property of H which is independent of the choice of plane embedding. The situation for matching graphs is potentially more complicated since the diagonals of a plane graph depend on its facial structure and hence on its embedding. If H is* 3*-connected, its embedding is unique in the sense of the cellular-embedding theorem of* [20, p. 42]*; see also* [9, Thm 2.1]*, and thus $\mathcal{N}$ is a graph property in this case.*

The picture is more complicated if H has connectivity 2*. Assume this, and in addition* that H is quasi-transitive. *Let $G \in \mathcal{G}$ be a plane embedding of H. By the proof of Theorem 8.25 in* [18, Sect. 8.8]*, there exists a* 3*-connected plane graph G' from which G is obtained by adding certain 'dangling loops'. Since G' is* 3*-connected,* *by the cellular-embedding theorem its embedding is unique as above, so that every embedding of H gives rise to the same G'. Furthermore, one sees from the relationship between G and G' that G has $\mathcal{N}$ if and only if G' has $\mathcal{N}$. In conclusion, for 2-connected,* quasi-transitive *planar graphs, property $\mathcal{N}$ is a graph property and is independent of the choice of plane embedding. We shall see in Theorem 4.2(d) that one such embedding, and hence all such embeddings, have property $\mathcal{N}$.*

4. Three techniques

4.1. **Oxbow removal.** Paths can fail to be non-self-touching through the existence of pairs of vertices that are not neighbours in the path but are neighbours in the graph. It is useful to have a method for extracting a non-self-touching path from a path containing such vertex-pairs. The method in question was used in [10], and is termed *oxbow removal*. We shall make use of the following extract from [10, Sect. 4.1(b)].

Lemma 4.1. *Let H be a simple, plane graph embedded in $\mathbb{R}^2$. Let π be a finite (respectively, infinite) path with endpoint v. There exists a non-empty subset π' of the vertex-set of π that forms a finite (respectively, infinite) non-self-touching path of H starting at v. If π is finite, then π' may be chosen with the same endvertices as π.*

The related process of 'loop-erasure' is familiar in graph theory and probability; see, for example, [8, Sect. 2.2]. As noted in Section 3, a geodesic is non-self-touching.

Proof. Let $\pi = (v_0, v_1, v_2, \dots)$ be a path from $v = v_0$, either finite or infinite. We start at v_0 and move along π in increasing order of vertex-index. Let J be the least j such that there exists $i \in \{0, 1, \dots, j-2\}$ with $v_i \sim v_J$, and let I be the earliest such i. We delete from π the subpath $(\pi_{I+1}, \dots, \pi_{J-1})$ (which is termed an *oxbow*), thus obtaining a new path π_1 starting at v. If π is finite then π_1 has the same endvertices as π. This process is iterated until no oxbows remain. □

4.2. **Existence of 2∞-nst paths.** We present an elementary theorem concerning the existence of 2∞-nst paths. Recall the graph $G_\triangle$, obtained from G by emptying all 3-cycles; see before Theorem 1.2.

Here is some notation. A face F of $G \in \mathcal{G}$ satisfying $0 \notin \overline{F}$ is called ζ-*acute* if there exists a sector S of $\mathbb{R}^2$ with vertex 0 and angle ζ such that $F \subseteq S$.

Theorem 4.2.

(a) *Let G be an infinite, connected, plane graph such that $G_\triangle$ is 4-connected. Then G contains a 2∞-nst path.*
(b) *Every infinite, $\triangle$-empty triangulation T contains a 2∞-nst path.*

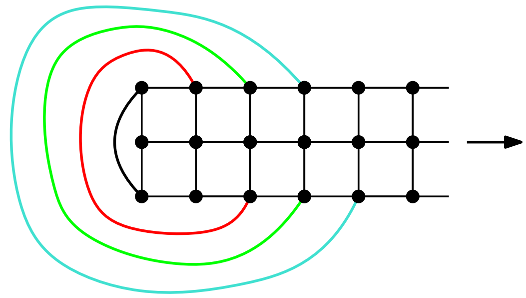

FIGURE 4.1. A 3-connected graph $G \in \mathcal{G}$ without separating triangles such that neither G nor G_* has a 2∞-nst path.

(c) *Let $G \in \mathcal{G}$. Suppose there exists $\zeta \in (0, \frac{1}{2}\pi)$ such that F is ζ-acute for all but finitely many faces F. Then G and G_* have 2∞-nst paths.*

(d) *If $G \in \mathcal{G}$ is quasi-transitive, then G and G_* have 2∞-nst paths.*

The conditions of (a) and (c) are sufficient but evidently not necessary for the existence of a 2∞-nst path. Instances of non-self-touching paths are provided by geodesics, and the existence of infinite geodesics has been explored in several articles including [4, 19, 23]. Figure 4.1 contains an illustration of a 3-connected $G \in \mathcal{G}$ such that neither G nor its matching graph has a 2∞-nst path.

Proof. (a) Let $G = (V, E)$ be as stated. By the 4-connectedness of G_Δ, for $v \in V$, there exist four infinite paths of G_Δ from v that are pairwise vertex-disjoint except for the point v. Label these π_i in a clockwise manner, and write $\pi_i^- = \pi_i \setminus \{v\}$. Then $d_{G_\Delta}(\pi_1^-, \pi_3^-) \geq 2$. For $i = 1, 3$, the path π_i^- may be reduced by oxbow removal (see Lemma 4.1) to a singly infinite non-self-touching path ν_i with the same endvertex as π_i. The path $\nu := \{v\} \cup \nu_1 \cup \nu_3$ contains the required 2∞-nst path. On adding the contents of the original triangles back into G_Δ, we see that ν is a 2∞-nst path of G.

(b) Let $T = (V, E)$ be as in the statement of the theorem. Since T is $\triangle$-empty, it is 4-connected (see, for example, [16, p. 91]), and the claim follows by part (a).

For the sake of completeness, we include a proof of the 4-connectedness of T. Suppose that T is not 4-connected. It is standard that T is 3-connected. Therefore, there exists $v \in V$ such that the maximum number of infinite paths from v that are pairwise vertex-disjoint (except at v) is exactly 3. By Menger's theorem, there exists a triple $A = \{a, b, c\}$ of vertices (with $v \neq a, b, c$) such that every infinite path from v intersects A, and A is minimal with this property. Consider the pair a, b. By the minimality of A, every component of $T \setminus A$ is adjacent to both a and b. Since T is a triangulation, we must have $\langle a, b \rangle \in E$. Similarly, $\langle b, c \rangle, \langle c, a \rangle \in E$, whence A is the vertex-set of a separating triangle.

(c) We outline the proof, which is an adaptation of that of [10, Lemma 4.3(a)]. Suppose the condition holds, and let L_θ denote the singly infinite straight line from 0 inclined at angle θ to the x-axis X. Let S be the sector between $L_{-\zeta}$ and L_ζ, and let I_+ be the property that G has some singly infinite, non-self-touching path ν_+ lying within S. If I_+ fails to hold, there exists a family K of paths of S ($\subseteq \mathbb{R}^2$), each with endpoints in L_+ and L_-, such that (i) each $\kappa \in K$ intersects no edge of G, and (ii) the union $\bigcup K$ is unbounded in space. Since there exist only finitely many faces that intersect both X and $L_+ \cup L_-$, the statement I_+ must hold.

By a similar argument with S replaced by $-S$, G has some singly infinite, non-self-touching path ν_- lying in $-S$. Find a shortest path π connecting ν_+ and ν_-. The union $\nu_+ \cup \nu_- \cup \pi$ contains (by oxbow removal) a 2∞-nst path.

The same argument applies to the matching graph G_*.

(d) Let H be quasi-transitive, and consider its plane embeddings that belong to $\mathcal{G}$. By Remark 3.1, either all or no plane embeddings (respectively, their matching graphs) have 2∞-nst paths. Since H is quasi-transitive, it may be embedded in either the Euclidean or hyperbolic plane (denoted $\mathcal{H}$) in such a way that its edges are geodesics and its automorphisms extend to isometries of the plane (see [18, Thm 8.25 and Sect. 8.8] and [9, Thm 2.1]); let $G \in \mathcal{G}$ be such an embedding and consider for definiteness the hyperbolic case (in the model of the Poincaré disk — see [5] for an account of hyperbolic geometry). The current claim is the content of [10, Lemma 4.3(b)]. It may also be proved as follows, with slightly less recourse to hyperbolic geometry.

Since G is quasi-transitive, there are only finitely many classes of face under the action of the automorphism group of G. If two faces lie in the same class, there is an isometry of $\mathcal{H}$ that maps one to the other. Thus the hyperbolic diameters of two faces in the same class are equal. We now change from the hyperbolic metric to the Euclidean metric on the unit disk D, and apply the mapping $f : D \to \mathbb{R}^2$ given by $f(r, \theta) \mapsto (s, \theta)$ where $s = r/(1-r)$. On tracking the effects of this two-stage mapping, we find that the faces of the resulting embedding of G in $\mathbb{R}^2$ have uniformly bounded (Euclidean) diameters. Therefore, this embedding satisfies the condition of part (d) of the current theorem, and the claim follows by Remark 3.1. □

4.3. **The facial graph.** Let $G \in \mathcal{G} = (V, E)$, and let $\mathcal{Q}$ be the set of all non-triangular faces of G. We shall work with the graph $\widehat{G} = (\widehat{V}, \widehat{E})$ obtained from G by adding a new vertex within each face $F \in \mathcal{Q}$, and adding an edge from every vertex in the boundary ∂F to this central vertex. These new vertices are called *facial sites*, and the graph $\widehat{G}$ is called the *facial graph* of G. The facial site in the face F is denoted $\phi(F)$. See [10], [15, Sect. 2.3], and also Figure 4.2. If $\langle v, w \rangle$ is a diagonal of the matching graph G_*, it lies in some face F of G with four or more edges, and we write $\phi(v, w) = \phi_F(v, w) = \phi(F)$ for the corresponding facial site.

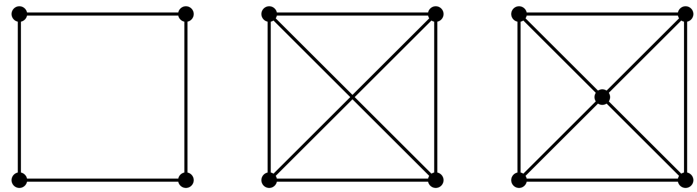

FIGURE 4.2. A square of the square lattice, its matching graph, and with its facial site added.

Of importance in this work is the graph $\widehat{G}_\Delta = (\widehat{V}_\Delta, \widehat{E}_\Delta)$, defined as the graph obtained by emptying the separating triangles of the facial graph $\widehat{G}$. We note that $\widehat{G}_\Delta = (\widehat{G})_\Delta$ but generally $\widehat{G}_\Delta \ne \widehat{(G_\Delta)}$. The reason for this distinction lies in part (c) of the following lemma. We recall the set $\mathrm{NST}(H)$ of 2∞-nst paths of a graph H.

Lemma 4.3. *Let $G = (V, E) \in \mathcal{G}$.*

(a) *Let $\nu \in \mathrm{NST}(G_*)$, and let F be a face of G. If $\nu \cap \partial F \ne \varnothing$, then the intersection is exactly one of the following: (i) a single vertex of G, (ii) a single edge of G, (iii) a single diagonal of G_*. Moreover, the graph ν is plane.*

(b) *For $\nu \in \mathrm{NST}(G_*)$, let the path $\widehat{\nu} = \sigma(\nu)$ on $\widehat{G}$ be obtained from ν by replacing a diagonal $\delta(v, w)$ in a face F by the pair $\langle v, \phi(F)\rangle, \langle \phi(F), w\rangle$ of edges. The function ϕ maps $\mathrm{NST}(G_*)$ into $\mathrm{NST}(\widehat{G})$ and is an injection. The set $\mathrm{NST}(\widehat{G})$ may be expressed as the disjoint union*

$$\mathrm{NST}(\widehat{G}) = \sigma(\mathrm{NST}(G_*)) \cup \mathrm{NST}_2(\widehat{G}), \tag{4.1}$$

where $\mathrm{NST}_2(\widehat{G})$ is the subset of $\mathrm{NST}(\widehat{G})$ containing all $\widehat{\nu}$ for which, for some face F of G, we have (i) $\phi(F) \notin \widehat{\nu}$, and (ii) the intersection $\widehat{\nu} \cap \partial F$ contains a pair of non-adjacent vertices.

(c) *Let $\mathrm{ST}(H)$ denote the set of separating triangles of a plane graph H. We have that $\mathrm{ST}(G) \subseteq \mathrm{ST}(\widehat{G})$, and moreover*

$$\mathrm{ST}(\widehat{G}) = \mathrm{ST}(G) \cup \mathrm{ST}_2(\widehat{G}), \tag{4.2}$$

where $\mathrm{ST}_2(\widehat{G})$ is the set of all non-facial 3-cycles of $\widehat{G}$ comprising two edges of the form $\langle u, \phi(F)\rangle$, $\langle v, \phi(F)\rangle$ for some face F of G and some $u, v \in V(\partial F)$ with $d_{\partial F}(u, v) \ge 2$, together with an edge $\langle u, v\rangle$ of G.

(d) *Let $\widehat{\nu}$ be a finite non-self-touching path of $\widehat{G}$. There exists a subsequence of $\widehat{\nu}$ with the same endvertices that forms a non-self-touching path ν of G_*.*

We note some further notation. Firstly, the process used in the proof of (d), to replace $\widehat{\nu}$ by ν, is termed *ϕ-removal.* Secondly, since we shall be interested in the

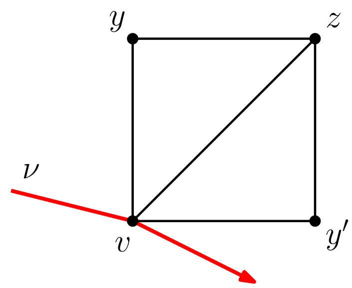

FIGURE 4.3. The 4-cycle in Proposition 5.1(b) comprises two triangles with a common edge

mapping σ, we introduce another binary relation on the vertex-set $\widehat{V}$ of $\widehat{G}$, namely:

(4.3) for $x, y \in \widehat{V}$, we write $x \mathrel{\widehat{\sim}} y$ if G has some facial cycle C such that $x, y \in \overline{C}$.

The negation of $\widehat{\sim}$ is written $\widehat{\nsim}$. For $x, y \in V$, we have $x \mathrel{\widehat{\sim}} y$ if and only if x, y are neighbours in G_*.

Proof. (a) This was proved at [10, Lemma 4.4]. Such ν cannot contain three or more vertices of any given face since that would contradict the non-self-touching property. If ν contains two such vertices, it must contain the corresponding edge. If ν were non-planar, it would contain two or more diagonals of some face.

(b) That ϕ is an injection into $\mathrm{NST}(\widehat{G})$ holds by (a) and the obvious invertibility of ϕ. Equation (4.1) holds by a consideration of 2∞-nst paths $\nu \in \mathrm{NST}(\widehat{G}_\Delta) \setminus \sigma(\mathrm{NST}(G_*))$.

(c) The inclusion holds, by definition. Let $T \in \mathrm{ST}(\widehat{G}) \setminus \mathrm{ST}(G)$. Since $T \notin \mathrm{ST}(G)$, it contains some edge of the form $\langle u, \phi(F)\rangle$. Since it is a separating 3-cycle, it contains a further edge of the form $\langle v, \phi(F)\rangle$ where $d_{\partial F}(u, v) \geq 2$. The claim of (4.2) follows.

(d) Let $\widehat{\nu}$ be as given, and view it as a directed path. If $\widehat{\nu} \in \sigma(\mathrm{NST}(G_*))$, we simply replace the facial sites in $\widehat{\nu}$ by the corresponding diagonals. Assume that $\widehat{\nu} \in \mathrm{NST}_2(\widehat{G})$, and let F be a face of G such that $\phi(F) \notin \widehat{\nu}$ and $\widehat{\nu} \cap \partial F$ contains two (or more) non-adjacent vertices. Let x (respectively, y) be the first (respectively, last) vertex of $\widehat{\nu}$ in ∂F, and note that $x \mathrel{\widehat{\sim}} y$. We delete from $\widehat{\nu}$ the subpath lying between x and y while retaining these two vertices and adding the corresponding edge (this edge lies in E if $x \sim y$ in G, and is a diagonal otherwise). This process is iterated for each such face, and the ensuing path is as required. $\square$

5. The main proposition

We present here the main proposition, which will be used twice in the proof of Theorem 1.2. The proof of the proposition is deferred to Sections 7 and 8.

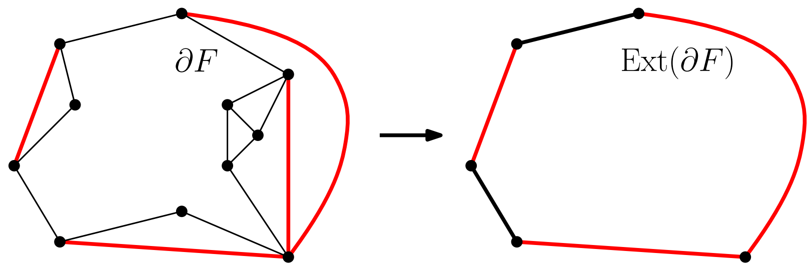

Figure 6.1. *Left*: A face F of G_Δ surrounded by the (black) cycle ∂F, and with further edges coloured red. *Right*: The exterior cycle $\mathrm{Ext}(\partial F)$ of F.

Proposition 5.1. *Let $G \in \mathcal{G}$ and suppose $G_\Delta \in \mathcal{G}$ is not a triangulation.*

(a) *Let F be a face of G_Δ with four or more edges, and let $\nu \in \mathrm{NST}(G_*)$ be a path that includes some vertex $v \in \partial F$. There exists $\overline{\nu} \in \mathrm{NST}(G_*)$ that includes some diagonal of F.*

(b) *Let Q be a 4-cycle of $\widehat{G}_\Delta$ comprising the union of two triangles with a common edge $\langle v, z\rangle$ (as in Figure 4.3), and let $\widehat{\nu} \in \sigma(\mathrm{NST}(G_*))$ be a path that includes no facial site but includes v. Either there exists $\widehat{\nu}_1 \in \sigma(\mathrm{NST}(G_*))$ that includes some facial site, or there exists $\widehat{\nu}_1 \in \sigma(\mathrm{NST}(G_*))$ that includes no facial site but includes z.*

Furthermore, the pair ν, $\overline{\nu}$ (respectively, $\widehat{\nu}$, $\widehat{\nu}_1$) differ on only finitely many edges.

6. Cycle structure of a plane graph

First, we explain how to define the so-called 'exterior cycle' of a cycle of a plane graph. This is followed by a description of a system of nested cycles surrounding a given cycle of a triangulation.

6.1. **Exterior cycles.** Let $G = (V, E)$ be a simple, plane graph, and recall the set $\mathcal{C} = \mathcal{C}(G)$ of cycles of G. For $A \in \mathcal{C}(G)$, we shall construct a new cycle $B = \mathrm{Ext}(A)$ called the *exterior cycle* of A.

Let $A \in \mathcal{C}(G)$, and let X be the set of edges of G of the form $f = \langle a, b\rangle$ with $a, b \in A$, and let Y be the subset of X containing edges that neither lie in nor intersect $\mathrm{int}(A)$. Recalling that G is embedded in the plane, an edge $f \in Y$ may appear either clockwise or anticlockwise around A. Consider the subgraph of G with edge-set X and its incident vertices, denoted as X also. Then X has an outer cycle formed of edges in Y, and we write $B = \mathrm{Ext}(A)$ for this cycle. Note that the number of edges in B is no greater than the number in A. See Figure 6.1.

Remark 6.1. *With F and $F' := \mathrm{Ext}(\partial F)$ as depicted in Figure 6.1, we may take $\phi(F') = \phi(F)$ in the facial graphs.*

Lemma 6.2. *Let $G \in \mathcal{G}$. Let F be a face of G_Δ (and hence of G also) with size 4 or more.*

(a) *The exterior cycle $\mathrm{Ext}(\partial F)$ is a cycle of G_Δ with length 4 or more.*
(b) *Let $G(F)$ (respectively, $G_\Delta(F)$) be obtained from G (respectively, G_Δ) by removing all vertices and incident edges within $\mathrm{int}(\mathrm{Ext}(\partial F))$. Then $\mathrm{NST}(G_\Delta) = \mathrm{NST}(G_\Delta(F))$.*
(c) *Let $\widehat{G}(F)_\Delta$ be obtained from the facial graph of $G(F)$ by emptying its separating triangles (that is, $\widehat{G}(F)_\Delta := (\widehat{G(F)})_\Delta$). Then $\widehat{G}(F)_\Delta = \widehat{G}_\Delta$. In particular, $\mathrm{NST}(\widehat{G}_\Delta) = \mathrm{NST}(\widehat{G}(F)_\Delta)$.*

Remark 6.3. *Let $G \in \mathcal{G}$. By Lemma 6.2(a), the exterior cycle of a 4-cycle Q of G_Δ is Q itself.*

Proof of Lemma 6.2. (a) The length l of the cycle $\mathrm{Ext}(\partial F)$ satisfies $l \geq 1$. Evidently, $l \geq 3$ since G is simple. If $l = 3$, then $\mathrm{Ext}(\partial F)$ is a 3-cycle of G_Δ whose interior intersects F, in contradiction of the definition of G_Δ.

(b) By the definition of exterior cycle, a path π of G_Δ that enters $\mathrm{int}(\mathrm{Ext}(F))$ at some vertex a leaves it at a neighbour of a (recall Figure 6.1), and is therefore not non-self-touching. Hence, $\mathrm{NST}(G_\Delta) \subseteq \mathrm{NST}(G_\Delta(F))$. Conversely, any $\nu \in \mathrm{NST}(G_\Delta(F)) \setminus \mathrm{NST}(G_\Delta)$ must have two non-consecutive vertices that are neighbours in $\mathrm{Ext}(F)$, a contradiction.

(c) The graphs G and $G(F)$ differ only on the interior of $\mathrm{Ext}(F)$. Therefore, the same holds for their facial graphs $\widehat{G}$ and $\widehat{G}(F)$. After emptying separating triangles, each of the two interiors of F in the two resulting graphs is a wheel with a hub at the facial site $\phi(F)$ and spokes to the vertices of $\mathrm{Ext}(F)$. It follows that $\widehat{G}(F)_\Delta = \widehat{G}_\Delta$ as claimed. □

6.2. **Cycle structure of a triangulation.** Let H be a plane triangulation. For $A \in \mathcal{C}(H)$, we write N_A for the set of neighbours of members of A lying in the unbounded component of $\mathbb{R}^2 \setminus A$. We think of N_A as a sequence of vertices which is ordered cyclically according to the edges between A and N_A, as one traverses A clockwise.

The following lemma and more was proved in [14, Sect. 3]. We extract the elements of interest here.

Lemma 6.4. *Let $A \in \mathcal{C}(H)$ be a cycle of the triangulation H. The set N_A contains a cycle $B \in \mathcal{C}(H)$ satisfying $A \subseteq \mathrm{int}(B)$ and $N_A \subseteq \overline{B}$.*

Proof. As noted in [16], the set N_A possesses an outer cycle, and this is the required cycle B. □

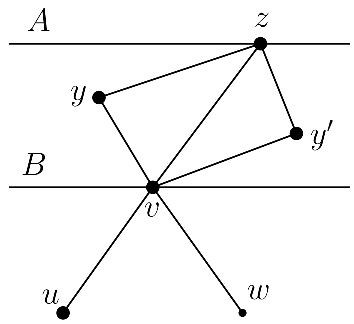

FIGURE 6.2. When $v \in \widehat{\nu} \cap B$, there exists $z \in A$ such that $v \sim z$ in $\widehat{G}_\Delta$. The edge $\langle v, z \rangle$ lies in two triangles whose union forms the quadrilateral illustrated here. Each of the vertices y, y' may lie in either A or B or neither.

There follow two lemmas that will be used in the proof of Theorem 1.2 at the end of this section.

Lemma 6.5. *Let $G \in \mathcal{G}$ and let A be a cycle of $\widehat{G}_\Delta$. Assume G_* has a 2∞-nst path ν such that $\widehat{\nu} = \sigma(\nu)$ has the following properties: (i) $\widehat{\nu}$ includes no facial site, (ii) $\widehat{\nu} \cap N_A \neq \varnothing$, and (iii) $\widehat{\nu} \cap A = \varnothing$. There exists $\overline{\nu} \in \mathrm{NST}(G_*)$ such that either (i) $\overline{\nu}$ traverses some diagonal, or (ii) $\overline{\nu}$ traverses no diagonal but satisfies $\widehat{\nu} \cap A \neq \varnothing$. Furthermore, ν and $\overline{\nu}$ differ on only finitely many edges.*

Proof of Lemma 6.5 using Proposition 5.1(b). Let $\nu \in \mathrm{NST}(G_*)$ be as given. Since $\widehat{\nu} \cap N_A \neq \varnothing$ by assumption, we have that $\widehat{\nu} \cap B \neq \varnothing$ also (where B is given in Lemma 6.4). Let v ($\in V$) be the first point in $\widehat{\nu}$ (considered as a directed path) that lies in B.

Since $B \subseteq N_A$, there exists an edge $e = \langle v, z \rangle$ of $\widehat{G}_\Delta$ with $z \in A$. The edge e lies in two 3-cycles of $\widehat{G}_\Delta$, and the union of these triangles forms a quadrilateral Q with v and z as opposite vertices. See Figure 6.2. The claim follows by Proposition 5.1(b). □

Lemma 6.6. *Let $G \in \mathcal{G}$, and let A be a cycle of G_Δ (and hence of G also) of size 4 or more. If G_* has some 2∞-nst path ν, then either (i) there exists $\overline{\nu} \in \mathrm{NST}(G_*)$ that traverses some diagonal, or (ii) there exists $\overline{\nu} \in \mathrm{NST}(G_*)$ that traverses no diagonal but includes some vertex of A. Furthermore, ν and $\overline{\nu}$ differ on only finitely many edges.*

Proof of Lemma 6.6 using Proposition 5.1(b). Let $A' = \mathrm{Ext}(A)$ be the exterior cycle of A. By iteration of Lemma 6.4, there exists a sequence $A_0, A_1, A_2, \dots$ of cycles in $\widehat{G}_\Delta$ such that $A_0 = A'$ and, for $i \geq 0$, $A_i \subseteq \mathrm{int}(A_{i+1})$ and $A_{i+1} \subseteq N_{A_i} \subseteq \overline{A_{i+1}}$. Since

$G \in \mathcal{G}$ and $A_i \subseteq \mathrm{int}(A_{i+1})$,

$$V \cap \mathrm{int}(A_i) \uparrow V \qquad \text{as } i \to \infty. \tag{6.1}$$

Let $\nu \in \mathrm{NST}(G_*)$ and $\widehat{\nu} = \sigma(\nu)$. If ν traverses some diagonal, we may take $\overline{\nu} = \nu$. Assume then that ν traverses no diagonal, so that $\widehat{\nu}$ includes no facial site.

By (6.1), there exists I such that $\widehat{\nu} \cap A_I \neq \varnothing$, and we pick $I = I(\widehat{\nu})$ minimal with this property. If $I = 0$, there is nothing to prove since $A_0 = A'$ and $A' \subseteq A$. Assume then that $I \geq 1$, and let $v \in \widehat{\nu} \cap A_I$; since $\widehat{\nu}$ includes no facial site, we have $v \in V$. By Lemma 6.5, there exists $\nu' \in \mathrm{NST}(G_*)$ such that either (i) ν' traverses some diagonal, or (ii) ν' traverses no diagonal but $\widehat{\nu}' := \sigma(\nu')$ satisfies $\widehat{\nu}' \cap A_{I-1} \neq \varnothing$. If (i) above holds, the proof is complete. Otherwise, $\widehat{\nu}'$ satisfies $I(\widehat{\nu}') \leq I - 1$.

We continue by iteration. At each stage we may obtain some $\overline{\nu} \in \mathrm{NST}(G_*)$ that traverses no diagonal. If this occurs at no stage of the iteration, we obtain finally some $\nu'' \in \mathrm{NST}(G_*)$ that traverses no diagonal, and such that $\widehat{\nu}'' = \sigma(\nu'')$ satisfies $I(\widehat{\nu}'') = 0$ and $\widehat{\nu}'' \cap A' \neq \varnothing$. The claim follows since $A' \subseteq A$. □

Proof of Theorem 1.2 using Proposition 5.1. Let $G \in \mathcal{G}$ be such that $G_\Delta \in \mathcal{G}$ is not a triangulation, and let F be a face of G_Δ of size 4 or more. Let $\nu \in \mathrm{NST}(G_*)$. If ν traverses some diagonal then the proof is complete, so we may assume that ν traverses no diagonal. By Lemma 6.6, there exists $\nu_1 \in \mathrm{NST}(G_*)$ that traverses no diagonal but intersects ∂F. We apply Proposition 5.1(a) to complete the proof. □

7. Proof of Proposition 5.1(a)

We begin with an outline. Let G be as in the statement. Since G_Δ is not a triangulation, it has some face F of size 4 or more (note that F is also a face of G). Let ν and v be as in the statement of part (a). We shall explain how to make local changes to ν to obtain a 2∞-nst path $\overline{\nu}$ of G_* that agrees with ν except on finitely many edges, and that contains some diagonal of ∂F. This will be done in the universe of non-self-touching paths on the facial graph $\widehat{G}_\Delta = (\widehat{V}_\Delta, \widehat{E}_\Delta)$. Let $\widehat{\nu} = \sigma(\nu)$ be the 2∞-nst path of $\widehat{G}_\Delta$ corresponding to ν (see Lemma 4.3(b)). We shall make local changes to $\widehat{\nu}$ to obtain a 2∞-nst path $\widehat{\nu}_1 \in \sigma(\mathrm{NST}(G_*))$ that includes the facial site $\phi(F)$. The path $\overline{\nu} = \sigma^{-1}(\widehat{\nu}_1) \in \mathrm{NST}(G_*)$ has the required property. There are a number of steps in the pursuit of this strategy, as follows.

Let $G = (V, E)$, v, F be as above, and let $\nu = (\dots, \nu_{-1}, \nu_0, \nu_1, \dots) \in \mathrm{NST}(G_*)$ with $\nu_0 = v$; it is sometimes convenient to think of ν as a *directed* path. We may assume that

$$\nu \text{ contains no diagonal of } F, \tag{7.1}$$

since otherwise there is nothing to prove. Therefore, by Lemma 4.3(a),

$$\nu \cap \partial F \text{ comprises either a single vertex of } V \text{ or a single edge of } E. \tag{7.2}$$

Rather than working with the face F, we shall work with its exterior cycle $F' := \mathrm{Ext}(\partial F)$. Recall from Lemma 6.2 that $\widehat{G}(F)_\Delta = \widehat{G}_\Delta$. By Remark 6.1, we may take $\phi(F') = \phi(F)$. Let $\widehat{\nu} = \sigma(\nu) \in \mathrm{NST}(\widehat{G}_\Delta)$. By (7.1) and (7.2),

$$\widehat{\nu} \text{ does not contain the facial site } \phi(F'), \tag{7.3}$$

$$\widehat{\nu} \cap \partial F' \text{ comprises either a single vertex of } V \text{ or a single edge of } E. \tag{7.4}$$

In the various steps and figures that follow, we write

$$u = \nu_{-1}, \quad v = \nu_0, \quad w = \nu_1.$$

Represent the triple u, v, w in the plane graph $\widehat{G}_\Delta$ as in Figure 7.1, so that F' lies 'above' the triple (F' is depicted in the figure with its facial site and incident edges removed). Let $f_i = \langle v, y_i \rangle$, $i = 1, 2, \dots, r$, be the edges of $\widehat{G}_\Delta$ incident to v in the sector obtained by rotating $\langle u, v \rangle$ clockwise about v until it coincides with $\langle w, v \rangle$; the f_i are listed in clockwise order. Since $\widehat{G}_\Delta$ is simple, the y_i are distinct.

For a (directed) path π and a vertex $x \in \pi$, let $\pi(x-)$ (respectively, $\pi(x+)$) be the subpath of π prior to and including x (respectively, after and including x).

There are two cases to consider depending on which case of (7.4) holds (see Sections 7.1 and 7.2). If $\widehat{\nu} \cap \partial F'$ is a singleton v (as in Figure 7.1), we denote by y_N and y_{N+1} the two neighbours of v lying in $\partial F'$ (in particular, we have $y_N \neq y_{N+1}$). If $\widehat{\nu} \cap \partial F'$ is an edge, we may take that edge to be $\langle v, w \rangle$, and we denote by y_N the vertex of $\partial F'$ other than w that is incident to v (as in Figure 7.8); in this case we have $N = r$.

Lemma 7.1.

(a) *Let $s_0 = u$, $s_{r+1} = w$, and $s_i = y_i$ for $i = 1, 2, \dots, r$. If $s_i \sim s_j$ then $|i-j| = 1$. Conversely, $s_0 \sim s_1 \sim \cdots \sim s_N$ and $s_{N+1} \sim \cdots \sim s_{r+1}$, where N is such that y_N and y_{N+1} are the two neighbours of v lying in $\partial F'$.*

(b) *If $y_i \in \partial F'$, then $i \in \{N, N+1\}$.*

(c) *No y_i lies in $\widehat{\nu}(u-) \cup \widehat{\nu}(w+)$.*

Proof. (a) Suppose $s_i \sim s_j$ where $j \geq i + 2$. Then (v, s_i, s_j) forms a 3-cycle T of the triangulation $\widehat{G}_\Delta$ whose interior intersects the edge $\langle v, s_{i+1} \rangle$. This is a contradiction since $\widehat{G}_\Delta$ is $\triangle$-empty. The partial converse holds as stated since $\widehat{G}_\Delta$ is a triangulation.

(b) This holds by the definition of the exterior cycle $F' = \mathrm{Ext}(F)$.

(c) This follows from the fact that ν is non-self-touching in G_*. □

For $i = 1, 2, \dots, r$, denote the neighbours of y_i other than possibly $u, v, y_{i-1}, y_{i+1}, w$ as $z_{i,1}, z_{i,2}, \dots, z_{i,\delta_i}$, listed in clockwise order of the planar embedding. More precisely, we list the edges exiting y_i (other than any edges to $u, v, y_{i-1}, y_{i+1}, w$) according to clockwise order, and we denote the other endvertex of the jth such edge as $z_{i,j}$. Note

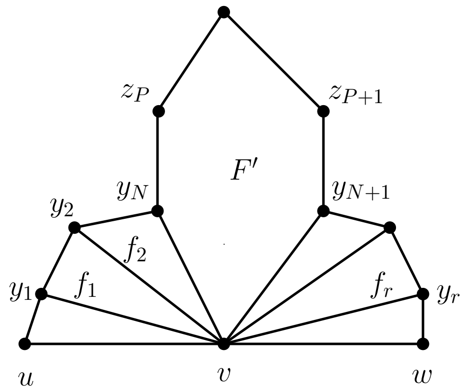

FIGURE 7.1. The path $\widehat{\nu}$ passes through a vertex v that lies in the boundary of a 6-face F'. This is an illustration of the case when neither $\langle u, v\rangle$ nor $\langle v, w\rangle$ lie in $\partial F'$.

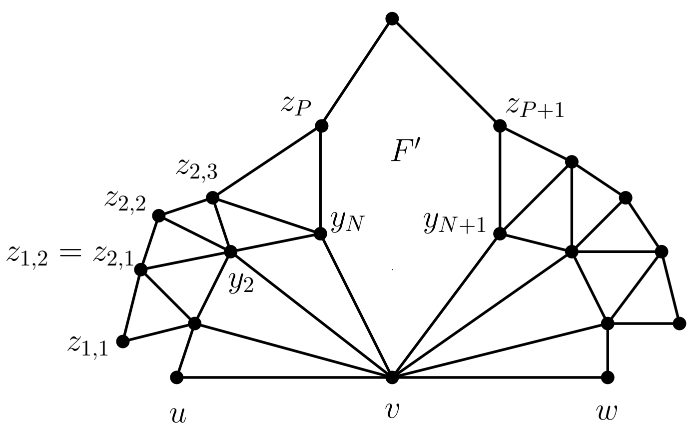

FIGURE 7.2. An illustration of the vertices $z_{i,j}$. Note that $z_{i,\delta_i} = z_{i+1,1}$ for $i \neq N$, as in (7.7), and that any two consecutive $z_{i,j}$ (other than (z_P, z_{P+1})) close a triangle, as in (7.6). This illustration is a simplification — see Figure 7.3.

that, while the $z_{i,1}, z_{i,2}, \ldots, z_{i,\delta_i}$ are distinct for given i (since $\widehat{G}_\Delta$ is simple), there may generally exist values of $i \neq j$ and $1 \leq a \leq \delta_i$, $1 \leq b \leq \delta_j$ with $z_{i,a} = z_{j,b}$.

We list the labels $z_{i,j}$ in lexicographic order (that is, $z_{a,b} < z_{c,d}$ if either $a < c$, or $a = c$ and $b < d$) as $z_1 < z_2 < \cdots < z_s$; this is a total order of the *label-set* but not necessarily of the underlying *vertex-set* since a given vertex may occur multiple times (if two labelled vertices z_a, z_b satisfy $z_a = z_b$ when viewed as vertices, we say that each label is an *image* of the other). If $a < b$ we speak of z_a as preceding, or

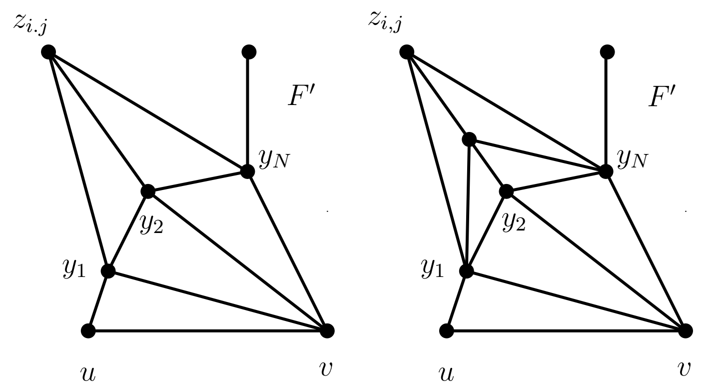

FIGURE 7.3. On the left, there is a vertex $z_{i,j}$ connected to each of $y_1, y_2, \dots, y_N$. On the right, the relationship of this vertex to y_2 is more complicated.

being to the *left* of z_b (and z_b succeeding, or being to the *right* of z_a). For $1 \le i \le r$, let

$$S_i = (z_{i,j} : j = 1, 2, \dots, \delta_i), \text{ viewed as an ordered subsequence of } Z. \tag{7.5}$$

Since $\widehat{G}_\Delta = (\widehat{V}_\Delta, \widehat{E}_\Delta)$ is a triangulation,

$$\langle z_{i,j}, z_{i,j+1} \rangle \in \widehat{E}_\Delta, \qquad j = 1, 2, \dots, \delta_i - 1, \ 1 \le i \le r, \tag{7.6}$$

and moreover

$$z_{i,\delta_i} = z_{i+1,1} \qquad 1 \le i < r, \ i \ne N, \tag{7.7}$$

whenever the relevant pair of vertices is defined.

As in Figure 7.2, let y_N, y_{N+1} be the two neighbours of v in $\partial F'$, and z_P, z_{P+1} their further neighbours in $\partial F'$ (if F' is a quadrilateral, we have $z_P = z_{P+1}$). It can be the case that $z_i \in \partial F'$ for some $i \notin \{P, P+1\}$.

See Figures 7.2 and 7.3 for illustrations of the $z_{i,j}$. By (7.6)–(7.7),

$$\pi_u = (u, z_1, z_2, \dots, z_P) \text{ and } \pi_w = (z_{P+1}, \dots, z_s, w) \text{ are walks of } \widehat{G}_\Delta. \tag{7.8}$$

Note that π_u and π_w may contain cycles and oxbows, and may intersect one another.

In making changes to the path $\widehat{\nu}$, it is useful to first record which vertices lie in either $\widehat{\nu}(u-)$ or $\widehat{\nu}(w+)$, or in neither. We label each vertex $x \in V$ by

$$\begin{cases} U & \text{if } x \in \widehat{\nu}(u-), \\ W & \text{if } x \in \widehat{\nu}(w+), \\ Q & \text{if } x \notin \widehat{\nu}(u-) \cup \widehat{\nu}(w+). \end{cases}$$

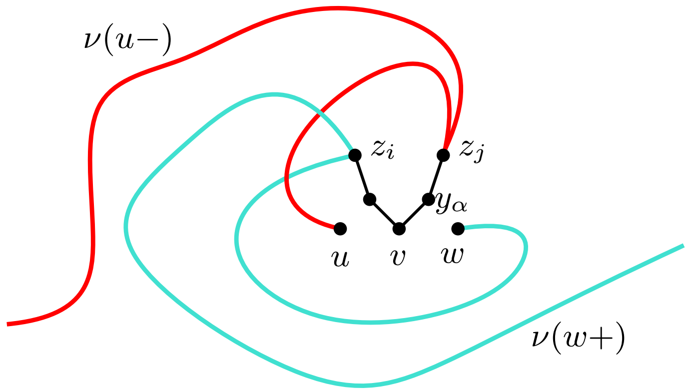

FIGURE 7.4. If $z_i \in \widehat{\nu}(w+)$ and $z_j \in \widehat{\nu}(u-)$ where $i < j$, then the pair $\widehat{\nu}(u-)$, $\widehat{\nu}(w+)$ fails to be non-touching, and is indeed intersecting.

Write N_L be the number of z_i with label L. Since $\nu \in \mathrm{NST}(G_*)$, by (7.1)

$$\text{every } x \in \partial F' \text{ satisfying } x \neq v, w \text{ is labelled } Q. \tag{7.9}$$

According to (7.2) there are two cases, which we consider in order.

7.1. **Case I: Suppose $\partial F'$ contains neither of the edges $\langle u, v\rangle$, $\langle v, w\rangle$.** This case is illustrated in Figure 7.1. Here is a technical lemma.

Lemma 7.2. *Suppose $N_U \geq 1$ and let $z_\rho = z_{\alpha,\beta}$ be the rightmost z_i with label U. Let $\widehat{\nu}''_\rho(u-)$ be the subpath of $\widehat{\nu}(u-)$ from z_ρ to u, and $\widehat{\nu}'_\rho(u-)$ that obtained from $\widehat{\nu}(u-)$ by deleting $\widehat{\nu}''_\rho(u-)$ while retaining its endpoint z_ρ.*

(a) *The path $\widehat{\nu}''_\rho(u-)$ moves around v in an anticlockwise direction in the sense that the directed cycle D obtained by traversing $\widehat{\nu}''_\rho(u-)$ from z_ρ to u, followed by the edges $\langle u, v\rangle$, $\langle v, y_\alpha\rangle, \langle y_\alpha, z_\rho\rangle$, has winding number -1. Furthermore, $\overline{D} \cap \widehat{\nu}(w+) = \varnothing$.*

(b) *For $1 \leq i \leq \rho - 1$, z_i is labelled either Q or U.*

(c) *For $1 \leq i \leq \rho - 1$, z_i has no $\widehat{G}_\Delta$-neighbour lying in $\widehat{\nu}'_\rho(u-)$, apart possibly from z_ρ or one of its images. Moreover, for all $x \in \widehat{\nu}'_\rho(u-) \setminus \{z_\rho\}$, we have that $z_i \,\widehat{\not\sim}\, x$.*

(d) *For $1 \leq i \leq \rho$, z_i has no $\widehat{G}_\Delta$-neighbour lying in $\widehat{\nu}(w+)$. Moreover, for all $x \in \widehat{\nu}(w+)$, we have that $z_i \,\widehat{\not\sim}\, x$.*

Proof. (a) If the given cycle has winding number 1, then $\widehat{\nu}''_\rho(u-)$ intersects $\widehat{\nu}(w+)$ in contradiction of the definition of $\widehat{\nu}$. See Figure 7.4. The final claim holds since $v, y_N \notin \widehat{\nu}(w+)$.

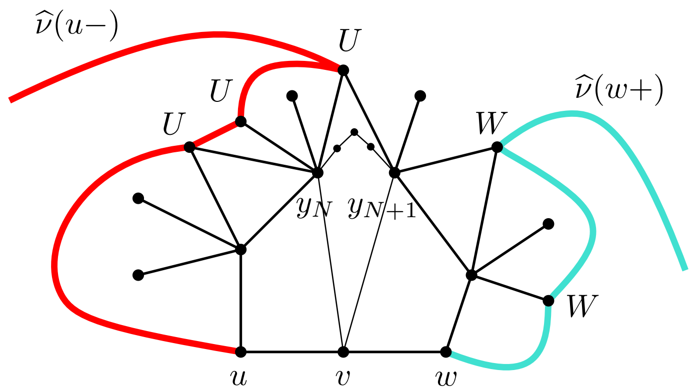

FIGURE 7.5. The path $\widehat\nu(u-)$ intersects the z_a at the rightmost z_ρ and then progresses anticlockwise to u. Similarly $\widehat\nu(w+)$ hits at the leftmost vertex z_λ and progresses clockwise to w.

(b) Let $1 \le i \le \rho-1$. If $z_i \in \widehat\nu(w+)$, then (as illustrated in Figure 7.4), $\widehat\nu(u-)$ and $\widehat\nu(w+)$ must intersect (when viewed as arcs in $\mathbb{R}^2$). This contradicts the planarity of $\widehat\nu$. Therefore, such z_i is labelled either Q or U.

(c) Let $1 \le i \le \rho - 1$ and suppose z_i has a $\widehat G_\Delta$-neighbour x (with x a different vertex from z_ρ) belonging to $\widehat\nu'_\rho(u-)$. By a consideration of the cycle D of Lemma 7.2(a), we have that $d_{\widehat G_\Delta}(x, \widehat\nu''_\rho(u-)) \le 1$, which (as above) contradicts the fact that $\widehat\nu(u-)$ is non-self-touching in $\widehat G_\Delta$. The second statement holds similarly, since $\nu \in \mathrm{NST}(G_*)$.

(d) This is similar to (c) above. □

Similar conclusions hold with U replaced by W, and z_ρ replaced by the leftmost z_λ in $\widehat\nu(w+)$. See Figure 7.5 for an illustration of Lemma 7.2(b) and some of its consequences. In its approach towards u (from infinity) $\widehat\nu(u-)$ passes through the rightmost z_ρ. It may subsequently visit one or more z_i with $i < \rho$, but it must do this in decreasing order of suffix. Similarly, $\widehat\nu(w+)$ passes through the leftmost z_λ and may subsequently visit one or more z_i with $i > \lambda$ in clockwise order of suffix. That $\lambda > \rho$ (when these suffices are defined) holds by Lemma 7.2(b).

Let $z_\rho = z_{a,b}$ be the rightmost z_i labelled U (with $\rho = 0$ and $z_0 := u$ if $N_U = 0$). Similarly, let $z_\lambda = z_{c,d}$ be the leftmost z_i labelled W (with $\lambda = r + 1$ and $z_{r+1} := w$ if $N_W = 0$). By the non-self-touching property of ν (see also (7.9)), we have

$$z_\rho \mathrel{\widehat{\not\sim}} z_\lambda,\ \ z_\rho, z_\lambda \notin \partial F'. \tag{7.10}$$

For the special case when $\rho = 0$ and $\lambda = r + 1$, we use here the fact that v is not a facial site.

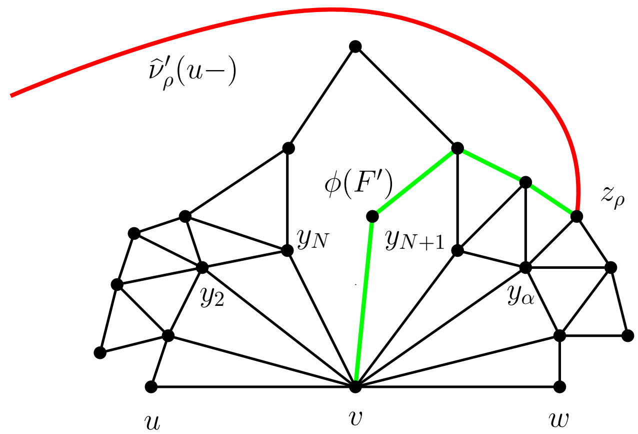

FIGURE 7.6. An illustration of $\widehat{\nu}_1$ when the rightmost z_i labelled U is to the right of z_{P+1}.

(A). *Suppose* $\rho \geq P+1$. Let $\alpha = \max\{i \geq N+1 : z_\rho \in S_\alpha\}$, say $z_\rho = z_{\alpha,\beta}$ (recall the set S_α from (7.5)). We add to $\widehat{\nu}'_\rho(u-)$ the set of vertices

$$W := \{z_{a,b} : N+1 \leq a \leq \alpha - 1,\ 1 \leq b \leq \delta_a\} \cup \{z_{\alpha,j} : 1 \leq j \leq \beta - 1\},$$

viewed as an ordered sequence of vertices from z_ρ to z_{P+1}. It can be that some $z \in W$ with $z \neq z_{P+1}$ satisfies $z \in \partial F'$. If that holds, we find such z with greatest suffix and remove all elements of W with lesser suffix than z. Note, in this case, that $z \notin \{y_N, v, y_{N+1}, z_{P+1}\}$. See Figure 7.6.

This yields a doubly infinite path $\widehat{\nu}_1 = (\widehat{\nu}'_\rho(u-), W', \phi(F'), v, \widehat{\nu}(w-))$ of $\widehat{G}_\Delta$ where W' is obtained from W by ϕ-removal and oxbow removal. We claim that $\widehat{\nu}_1 \in \sigma(\mathrm{NST}(G_*))$. To check this, it suffices to verify that there exist no $x \in (\widehat{\nu}'_\rho(u-), W')$ and $y \in \widehat{\nu}(w+)$ such that $x \mathrel{\widehat{\sim}} y$. This follows from Lemma 7.2(d) and a consideration based on whether or not y_α is a facial site.

Since $\widehat{\nu}_1$ includes the facial site $\phi(F')$, there exists $\overline{\nu} = \sigma^{-1}(\widehat{\nu}_1) \in \mathrm{NST}(G_*)$ that traverses a diagonal of F', as required.

(B). *Suppose* $\lambda \leq P$. This is similar to Case (A).

(C). *Suppose either* $\rho = P$ *or* $\lambda = P+1$. Assume $\rho = P$; the other case is similar. By (7.10), we may add $\phi(F')$ to $\widehat{\nu}'_\rho(u-) \cup \{v\} \cup \widehat{\nu}(w+)$ to obtain the required 2∞-nst path $\widehat{\nu}_1$, and hence $\overline{\nu} = \sigma^{-1}(\widehat{\nu}_1)$ as before.

(D). *Suppose* $\rho < P$ *and* $\lambda > P+1$. Write $z_\rho = z_{\alpha,\beta}$ and $z_\lambda = z_{\gamma,\delta}$ (with $\alpha = 1$ if $\rho = 0$, and $\gamma = r$ if $\lambda = r+1$). There are two cases, depending on whether or not

(7.11)
$$\exists\ i,\ j \text{ with } \rho < i < P < P+1 < j < \lambda \text{ such that } z_i = z_j = \phi(J) \text{ for some } J.$$

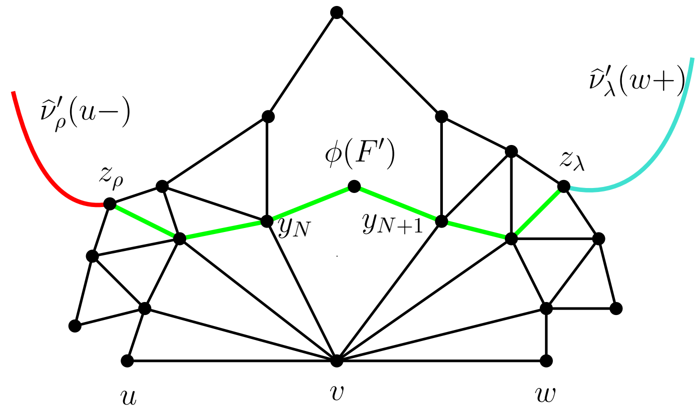

FIGURE 7.7. An illustration of $\widehat{\nu}_1$ when the rightmost U lies to the left and the leftmost W lies to the right.

1. Assume (7.11) does not hold. There is no pair y_k, y_l with $\alpha < k \le N$, $N+1 \le l < \gamma$ that lie in the same facial cycle of $\widehat{G}_\Delta$. In this case we remove $\widehat{\nu}''_\rho(u-)$ and $\widehat{\nu}''_\lambda(w+)$ and add the vertices $y_\alpha, y_{\alpha+1}, \dots, y_N$, $\phi(F')$, and $y_{N+1}, y_{N+2}, \dots, y_\gamma$. The resulting set of vertices contains (after ϕ-removal and oxbow removal) a 2∞-nst path $\widehat{\nu}_1 \in \sigma(\mathrm{NST}(G_*))$ that includes the facial site $\phi(F')$. The required 2∞-nst path of G_* is $\overline{\nu} := \sigma^{-1}(\widehat{\nu}_1)$. See Figure 7.7.
2. Assume that (7.11) holds and pick i least and then j greatest. Write z for the common vertex $z_i = z_j$ where $z = \phi(J)$ for some face J of G_Δ. It cannot be that both $\widehat{\nu}(u-) \cap \partial J \ne \varnothing$ and $\widehat{\nu}(w+) \cap \partial J \ne \varnothing$, since that contradicts $\nu \in \mathrm{NST}(G_*)$; assume then that $\widehat{\nu}(w+) \cap \partial J = \varnothing$.
   (i) Suppose there exists $x \in \widehat{\nu}(u-) \cap \partial J$. By the planarity of $\widehat{\nu}$, it must be that $x \in \widehat{\nu}'_\rho(u-)$, and we pick such x earliest with this property. We consider the walk
   $$(\widehat{\nu}(x-), z_i, z_{i+1} \dots, z_P, \phi(F'), v, \widehat{\nu}(w+)).$$
   After ϕ-removal and oxbow removal, this becomes a 2∞-nst path $\widehat{\nu}_1$ of $\widehat{G}_\Delta$ lying in $\sigma(\mathrm{NST}(G_*))$. The required 2∞-nst path of G_* is $\overline{\nu} := \sigma^{-1}(\widehat{\nu}_1)$. See Figure 7.8.
   (ii) Suppose that $\widehat{\nu}(u-) \cap \partial J = \varnothing$. We apply the argument of the above case to the walk $(\widehat{\nu}'_\rho(u-), z_{\rho+1}, z_{\rho+2}, \dots, z_P, \phi(F'), v, \widehat{\nu}(w+))$.

7.2. **Case II: Suppose $\partial F'$ contains $\langle v, w\rangle$ but not $\langle u, v\rangle$.** The argument is similar to that of Section 7.1, and we sketch it. Let $y_1, y_2, \dots, y_N$ be the vertices adjacent to v above the triple u, v, w, as illustrated in Figure 7.9. Let the $z_{i,j}$ be as in the last section, and let $(z_i : 1 \le i \le P)$, z_ρ, and z_λ be given as before.

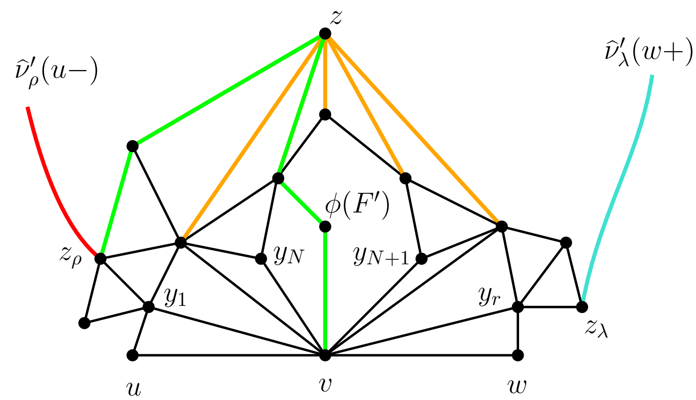

FIGURE 7.8. An illustration of $\widehat{\nu}_1$ in case 2(ii). The vertex z is a facial site in the face J, and is joined to ∂J by the orange edges. The additional path from z_ρ to v is marked in green, and it makes use of the facial site $\phi(F')$.

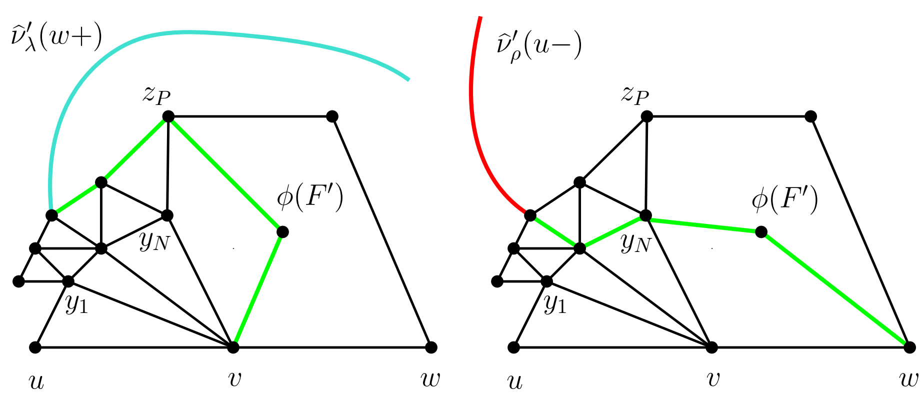

FIGURE 7.9. Illustrations of the constructions in Section 7.2. *Left*: When $\lambda \le P$, the path $\widehat{\nu}'_\lambda(w+)$ followed by certain vertices as marked results in a 2∞-nst path including the facial site $\phi(F')$. *Right*: When $\lambda \ge P+1$, the path $\widehat{\nu}'_\rho(u-)$ followed by certain vertices as marked forms a 2∞-nst path including $\phi(F')$.

(E). *Suppose some $z_{i,j}$ is labelled W.* We proceed as in (A), (B) above. Find the leftmost such vertex, say z_λ. We delete $\widehat{\nu}''_\lambda(w+)$ from $\widehat{\nu}$ and add the $z_{i,j}$ that lie between z_λ and z_P. This results (after ϕ-removal and oxbow removal) in a 2∞-nst path $\widehat{\nu}_1 \in \sigma(\mathrm{NST}(G_*))$ that includes the ordered sequence $(z_P, \phi(F'), \widehat{\nu}(u-))$.

(F). *Suppose no $z_{i,j}$ is labelled W.* We proceed as in (D) above. Find the rightmost $z_{i,j}$ labelled U, say $z_\rho = z_{\alpha,\beta}$ (with $\rho = 0$ if no such vertex exists). We delete $\widehat{\nu}''_\rho(u-)$

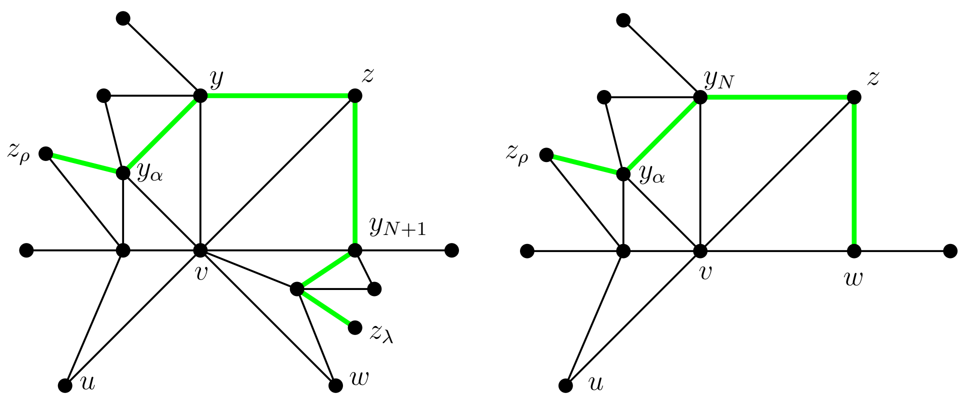

FIGURE 7.10. Illustrations of the constructions in Sections 8.1 and 8.2, respectively.

and v from $\widehat{\nu}$ and add $y_\alpha, y_{\alpha+1} \dots, y_N$ to obtain a 2∞-nst path $\widehat{\nu}_1 \in \mathrm{NST}(G_*))$ that includes the ordered triple $(y_N, \phi(F'), w)$.

8. Proof of Proposition 5.1(b)

For consistency with Section 7, we use the letter F rather than Q. Let F be a 4-cycle in $\widehat{G}_\Delta$ as in Figure 6.2, and note some vertices of F may be facial sites. Let $\widehat{\nu} \in \sigma(\mathrm{NST}(G_*))$ be such that $v \in \widehat{\nu} \cap \partial F$. If $\widehat{\nu}$ includes some facial site, there is nothing more to prove, and so we may assume henceforth that

$$\widehat{\nu} \text{ includes no facial site.} \tag{8.1}$$

In particular, $u, v, w \in V$.

We may assume that $z \notin \widehat{\nu}$, since otherwise there is nothing to prove. In place of (7.1) we have (in the notation of Figure 6.2) that $\widehat{\nu} \cap \overline{F}$ is one of (i) the single vertex v, (ii) the single edge $\langle v, y' \rangle$, (iii) the single edge $\langle v, y \rangle$, (iv) the two edges $\langle v, y' \rangle$, $\langle v, y \rangle$. Case (iii) is handled as case (ii), and we proceed with cases (i), (ii), (iv) next.

8.1. **(i) Assume that $\widehat{\nu} \cap \partial F = \{v\}$,** and temporarily remove the diagonal from F to obtain a 4-face also denoted F.

We follow the constructions in the proof of Section 7.1. With the exception of case (D) of that section, we may take $\widehat{\nu}_1$ as given there (with the facial site $\phi(F')$ removed, so that the new path traverses the diagonal of F). Either $\widehat{\nu}_1$ includes some facial site or it does not, and in either case the claim follows.

We next consider case (D) with the diagonal reinstated in F, and see Figure 7.10. Vertices $z_\rho = z_{\alpha,\beta}$ and $z_\lambda = z_{\gamma,\delta}$ are as before. Since ν is non-self-touching and traverses no diagonal,

$$\widehat{\nu}'_\rho(u-) \mathrel{\widehat{\nsim}} \widehat{\nu}'_\lambda(w+). \tag{8.2}$$

1. If $z \mathrel{\widehat{\nsim}} \widehat{\nu}'_\rho(u-) \cup \widehat{\nu}'_\lambda(w+)$, we consider the walk

   $$w = (\widehat{\nu}'_\rho(u-), y_\alpha, y_{\alpha+1}, \dots, y_N(=y), z, y_{N+1}(=y'), y_{N+2}, \dots, y_\gamma, \widehat{\nu}'_\lambda(w+)).$$

   It may that $y_i \mathrel{\widehat{\sim}} y_j$ for some $\alpha < i \le N$ and $N+1 \le j < \gamma$. This is treated as in case (D) of Section 7.1 (see (7.11)), which results (after ρ-removal and oxbow removal) in some $\widehat{\nu}_1 \in \sigma(\mathrm{NST}(G_*))$ including z. Either $\widehat{\nu}_1$ includes some facial site or it does not, and in either case the claim is shown.
2. Assume $z \mathrel{\widehat{\sim}} \widehat{\nu}'_\rho(u-)$ but $z \mathrel{\widehat{\nsim}} \widehat{\nu}'_\lambda(w+)$. Find the earliest $x \in \widehat{\nu}'_\rho(u-)$ satisfying $x \mathrel{\widehat{\sim}} z$ (noting that $x \in V$); truncate $\widehat{\nu}'_\rho(u-)$ at x to the subpath $\widehat{\nu}'(x-)$, and add the vertices $z, y_{N+1}, y_{N+2}, \dots, y_\gamma$ to $\widehat{\nu}'_\lambda(w-)$. Let J be the face such that $z, x \in \overline{J}$; if $z \ne \phi(J)$ and $z \nsim x$ in G, we add $\phi(J)$ also. After ρ-removal and oxbow removal, one obtains the required $\widehat{\nu}_1$. It needs be checked that

   $$\widehat{\nu}'(x-) \mathrel{\widehat{\nsim}} \{y_{N+1}, y_{N+2}, \dots, y_\gamma\}, \tag{8.3}$$

   and this holds in a similar manner to that of case (A) of Section 7.1. A similar argument holds with u and w interchanged.
3. Assume $z \mathrel{\widehat{\sim}} \widehat{\nu}'_\rho(u-)$ and $z \mathrel{\widehat{\sim}} \widehat{\nu}'_\lambda(w+)$. By (8.2), $z \in V$. Find the earliest $x \in \widehat{\nu}'_\rho(u-)$ satisfying $x \mathrel{\widehat{\sim}} z$, and the latest $y \in \widehat{\nu}'_\lambda(w+)$ satisfying $y \mathrel{\widehat{\sim}} z$; truncate the two paths at x and y respectively, and add the vertex z and any required facial site. The outcome is the required $\widehat{\nu}_1$.

8.2. **(ii) Assume that $\widehat{\nu} \cap \partial F$ is the edge $\langle v, w\rangle$,** where $w = y'$, and consider cases (E), (F) of Section 7.2. In (E) above, we may take $\widehat{\nu}_1$ to be as defined there. Consider the second case (F) as illustrated in Figure 7.10. We follow Section 8.1 above but with minor differences as follows.

1. If $z \mathrel{\widehat{\nsim}} \widehat{\nu}'_\rho(u-) \cup \widehat{\nu}(w+) \setminus \{w\}$, we add to $\widehat{\nu}'_\rho(u-) \cup \widehat{\nu}(w+)$ the vertex sequence $y_\alpha, y_{\alpha+1}, \dots, y_N(=y), z$. If

   $$\{y_\alpha, y_{\alpha+1}, \dots, y_N\} \mathrel{\widehat{\nsim}} \widehat{\nu}(w+), \tag{8.4}$$

   the resulting path $\widehat{\nu}_1$ (after ϕ-removal and oxbow removal) is as required. If (8.4) fails, we find the earliest I such that $\alpha \le I \le N$ and $y_I \mathrel{\widehat{\sim}} \widehat{\nu}(w+)$ and the latest $x \in \widehat{\nu}(w-)$ such that $y_I \mathrel{\widehat{\sim}} x$. Note that $y_I, x \in V$, so that they lie in some common cycle J. Now apply ϕ-removal and oxbow removal to the walk $(\widehat{\nu}_\rho(u-), y_\alpha, \dots, y_I, \phi(J), \widehat{\nu}(x-))$ to obtain $\widehat{\nu}_1 \in \sigma(\mathrm{NST}(G_*))$ that traverses a diagonal.
2. Assume $z \mathrel{\widehat{\sim}} \widehat{\nu}'_\rho(u-)$ but $z \mathrel{\widehat{\nsim}} \widehat{\nu}(w+) \setminus \{w\}$. Find the earliest $x \in \widehat{\nu}'_\rho(u-)$ satisfying $x \mathrel{\widehat{\sim}} z$ (noting that $x \in V$); truncate $\widehat{\nu}'_\rho(u-)$ at x, and add z to

$\widehat{\nu}(w+)$ (and also the facial site $\phi(J)$ if needed, as explained above), to obtain the required $\widehat{\nu}_1$. We argue similarly with u and w interchanged.

3. Assume $z \mathrel{\widehat{\sim}} \widehat{\nu}'_\rho(u-)$ and $z \mathrel{\widehat{\sim}} \widehat{\nu}(w+) \setminus \{w\}$. Find the earliest $x \in \widehat{\nu}'_\rho(u-)$ satisfying $x \mathrel{\widehat{\sim}} z$, and the latest $y \in \widehat{\nu}(w-)$ satisfying $y \mathrel{\widehat{\sim}} z$; truncate the two paths at x and y respectively, and add the vertex z (possibly with facial sites as needed). The outcome is the required $\widehat{\nu}_1$.

8.3. **(iv) Assume that $\widehat{\nu} \cap \partial F$ comprises the two edges $\langle v, w\rangle$, $\langle v, y\rangle$,** so that $u = y$ and $w = y'$. The idea is to replace v by z, and we proceed as above.

1. If $z \mathrel{\widehat{\nsim}} (\widehat{\nu}'(u-) \setminus \{u\}) \cup (\widehat{\nu}'(w+) \setminus \{w\})$, we remove v from $\widehat{\nu}$ and add z to $\widehat{\nu}'(u-) \cup \widehat{\nu}(w+)$.
2. Assume $z \mathrel{\widehat{\sim}} (\widehat{\nu}'(u-) \setminus \{u\})$ but $z \mathrel{\widehat{\nsim}} (\widehat{\nu}'(w+) \setminus \{w\})$. Find the earliest $x \in \widehat{\nu}'(u-)$ satisfying $x \mathrel{\widehat{\sim}} z$ (noting that $x \in V$); truncate $\widehat{\nu}'(u-)$ at x, and add z to $\widehat{\nu}(w+)$ (and also the facial site $\phi(J)$ if needed, as explained above), to obtain the required $\widehat{\nu}_1$. We argue similarly with u and w interchanged.
3. Assume $z \mathrel{\widehat{\sim}} (\widehat{\nu}'(u-) \setminus \{u\})$ and $z \mathrel{\widehat{\sim}} (\widehat{\nu}'(w+) \setminus \{w\})$. Find the earliest $x \in \widehat{\nu}'(u-)$ satisfying $x \mathrel{\widehat{\sim}} z$, and the latest $y \in \widehat{\nu}'(w-)$ satisfying $y \mathrel{\widehat{\sim}} z$; truncate the two paths at x and y respectively, and add the vertex z (possibly with facial sites as needed). The outcome is the required $\widehat{\nu}_1$.

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