Reconfiguring Triangulations with Edge Flips and Point Moves*

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Abstract. We examine reconfigurations between triangulations and near-triangulations of point sets, and give new bounds on the number of *point moves* and *edge flips* sufficient for any reconfiguration. We show that with $O(n \log n)$ edge flips and point moves, we can transform any geometric near-triangulation on n points to any other geometric near-triangulation on n possibly different points. This improves the previously known bound of $O(n^2)$ edge flips and point moves. We then show that with a slightly more general point move, we can further reduce the complexity to $O(n)$ point moves and edge flips.

1 Introduction

An *edge flip* is a graph operation that is defined on triangulations and near-triangulations[3]. An edge flip on a triangulation is simply the deletion of an edge, followed by the insertion of another edge such that the resulting graph remains a triangulation. The definition of an edge flip gives rise to several natural questions: Does there always exist a sequence of flips that transforms or reconfigures a given triangulation to any other triangulation? Are there bounds on the lengths of such sequences if they exist? Can these sequences be computed? These questions have been studied in the literature in many different settings [7, 11, 19, 10, 2, 16, 3, 15, 18, 14, 4, 17, 5, 20, 6, 9, 8]. In particular, Wagner [19] proved that given any two n-vertex triangulations G_1 and G_2, there always exists a finite sequence of edge flips that reconfigures G_1 into a graph isomorphic to G_2. Subsequently, Komuro [10] showed that in fact $O(n)$ edge flips suffice. Recently, Bose et al.[2] showed that $O(\log n)$ simultaneous edge flips suffice and are sometimes necessary. This setting of the problem is referred to as the combinatorial setting since the triangulations are only embedded combinatorially, i.e. only the cyclic order of edges around each vertex is defined.

In the geometric setting, the graphs are embedded in the plane with edges represented by straight line segments. Pairs of edges can only intersect at their

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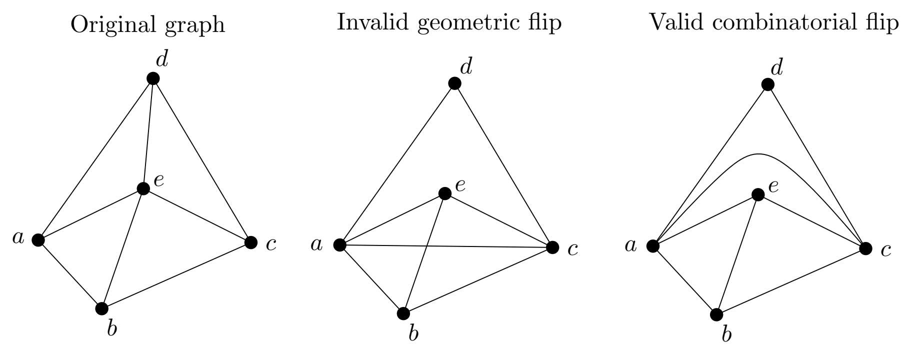
[3] A near-triangulation is a plane graph where every face except possibly the outer face is a triangle.

endpoints. Edge flips are still valid operations in this setting, except that now the edge that is added must be a line segment and this line segment cannot properly intersect any of the existing edges of the graph. This additional restriction implies that there are valid edge flips in the combinatorial setting that are no longer valid in the geometric setting, as can be seen in Figure 1.



Delete edge de and add edge ac. This is a valid combinatorial edge flip since the graph is still planar but it is an invalid geometric edge flip since the edges ac and be intersect properly.

Fig. 1. Valid combinatorial edge flip but invalid geometric edge flip.

Lawson [12] showed that given any two geometric near-triangulations N_1 and N_2 embedded on the same n points in the plane, there always exists a finite sequence of edge flips that transforms the edge set of N_1 to the edge set of N_2. Hurtado, Noy and Urrutia [9] showed that $O(n^2)$ flips are always sufficient and that $\Omega(n^2)$ flips are sometimes necessary.

Note that there is a discrepancy between the combinatorial and the geometric settings. In the combinatorial setting, Wagner [19] showed that *every* triangulation on n vertices can be reached from every other triangulation via edge flips. In the geometric setting, Lawson [12] showed that only the near-triangulations that are defined on the *specified point set* can be attained via edge flips. For example, in the point set shown in Figure 2, no planar K_4 (complete graph on 4 vertices) can be drawn on the given point set without introducing a crossing. In fact, in the geometric setting, given a set of points in convex position, the only plane graphs that can be drawn without crossings are outer-planar.

It is this discrepancy that sparked the work of Abellanas et al. [1]. In order to resolve this discrepancy, they introduced a geometric operation called a *point move*. A point move on a geometric triangulation is simply the modification of the coordinates of one vertex such that after the modification the graph remains a geometric triangulation. That is, the move is valid provided that after moving the vertex to a new position, no edge crossings are introduced (see Figure 3). As

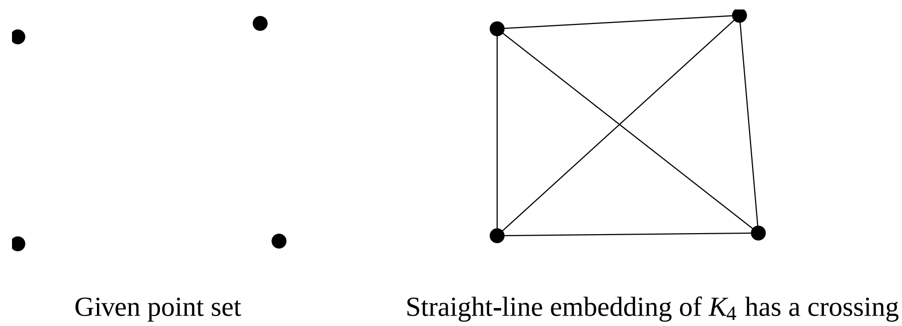


Fig. 2. Discrepancy between combinatorial and geometric setting.

can be seen in Figure 2, point moves are required in order to be able to move from *any* geometric triangulation to any other.

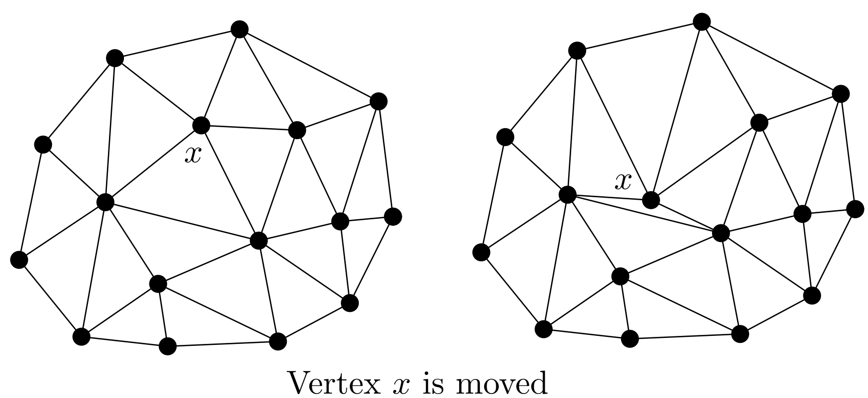


Fig. 3. Illustration of a valid point move.

Abellanas et al. [1] showed that with $O(n^2)$ edge flips and $O(n)$ point moves, any geometric triangulation on n points can be transformed to any other geometric triangulation on n possibly different points. This result can be viewed as the "geometric equivalent" to Wagner's [19] result since it is not restricted to remaining on the same point set as is the case with Lawson's result [12].

The question which initiated our investigation is whether or not $O(n^2)$ edge flips are necessary in the result by Abellanas et al. [1]. When restricted to edge flips, Hurtado, Noy and Urrutia [9] showed that $\Omega(n^2)$ flips are sometimes necessary to transform one triangulation on a given point set to another one on the same point set. However, are $\Omega(n^2)$ edge flips required if one is also allowed to use point moves? In this paper, we show that point moves are quite powerful and allow one to break the quadratic lower bound. We show that with $O(n \log n)$

edge flips and point moves, we can transform any geometric near-triangulation on n points to any other geometric near-triangulation on n possibly different points. Next, we show that if we restrict our attention to geometric near-triangulations defined on a fixed point set of size n, i.e. the setting studied in [12], the problem is just as difficult even in the presence of point moves. Specifically, we show that if there exists an algorithm that can allow one to transform any near-triangulation on an n-point set to any other near-triangulation on the same point set using $O(n)$ point moves and edge flips, then this algorithm can be used to solve the more general problem of transforming any near-triangulation on one point set to any other near-triangulation on a possibly different point set with $O(n)$ point moves and edge flips. Finally, we show that with a slightly more general point move, we can remove the extra log factor from our main result.

2 Results

In the remainder of the paper, we assume that all triangulations and near-triangulations are geometric. We assume that the n vertices of any given triangulation are in general position. It is not difficult to see that $O(n)$ point moves can reconfigure a triangulation to this form. We begin with a few of the basic building blocks that will allow us to prove the main theorems.

Lemma 1. **[2]** *A reconfiguration between two triangulations of the same point set that is in convex position can be done with $O(n)$ edge flips.*

Lemma 2. **[9]** *Let v_1, v_2 and v_3 be three consecutive vertices on the outer face of a near-triangulation T_1. Let C be the path from v_1 to v_3 on the convex hull of all vertices but v_2. A near-triangulation T_2 containing all edges of C may be constructed from T_1 with t edge flips, where t is the number of edges initially intersecting C in T_1.*

Lemma 3. *Given a near-triangulation T, any vertex $p \in T$ with degree $d > 3$ that is inside the convex hull of the vertices of T can have its degree reduced to 3 with $d - 3$ edge flips.*

Proof. Let P be the polygon that is the union of all triangles incident to p. P is a star-shaped polygon and p is in the kernel. By Meister's *two-ears theorem* [13], if P has more than three vertices, then it has at least two disjoint ears[4]. At most one of them can contain p. Therefore p and one of the ears form a convex quadrilateral. We may flip the edge from p to the tip of the ear, effectively cutting the ear from P and reducing the number of vertices of P by one (see Figure 4). This process may be continued until P is reduced to a triangle that contains p as desired. ☐

[4] A triangle, defined by three consecutive vertices of a polygon, is an ear if it is empty and the vertices form a convex angle. The second vertex is the *tip* of the ear.

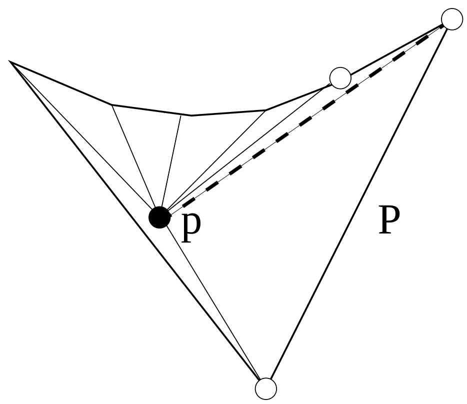


Fig. 4. Polygon P is visible from vertex p, which is inside one of the two ears of P. The empty ear is labeled with white vertices. The edge that may be flipped is dashed.

Lemma 4. *Given a near-triangulation T, any vertex $p \in T$ with degree 3 that is inside the convex hull of the vertices of T can be moved to a new position in the triangulation along a straight path crossing t edges, using at most $2t$ edge flips and $2t+1$ point moves, assuming the path does not cross through any vertices.*

Proof. Suppose that p is joined by edges to vertices v_1, v_2 and v_3. Without loss of generality, let edge v_2v_3 intersect the path that p must follow, and let this path continue into triangle $v_2v_3v_4$, as shown in Figure 5.

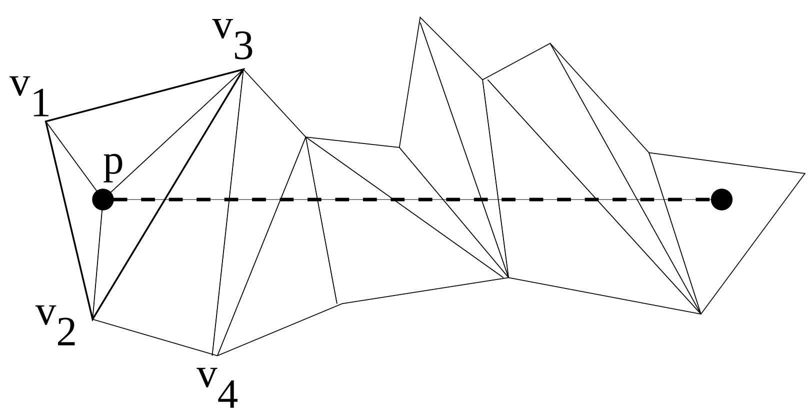


Fig. 5. A vertex p and a straight path that it must move along (dashed). p can pass through any edge with two edge flips.

Clearly p can be moved anywhere within triangle $v_1v_2v_3$ without the need of any edge flips. Then it can be moved along its path, as close to edge v_2v_3 as necessary, so that the quadrilateral $pv_2v_3v_4$ becomes convex. This allows edge v_2v_3 to be flipped into edge pv_4. Now p may continue along its path. As soon as it enters $v_2v_3v_4$, edge pv_1 may be flipped into v_2v_3. Now, with two edge flips and two point moves, p has crossed through the first edge intersecting its path, and still has degree 3. By the same argument, p may traverse its entire path with two edge flips and two point moves for each intersecting edge. One additional point move is required in the last triangle. Note that only three edges in the original and final triangulations will be different. □

Lemmata 3 and 4 imply the following result:

Lemma 5. *Given a near-triangulation T, any vertex in the interior of the convex hull of the vertices of T with degree d can be moved to a new position in the triangulation along a path crossing t edges, using $O(d+t)$ edge flips and point moves.*

Lemma 6. *An edge can be constructed between a convex hull vertex and any other vertex in a triangulation using $O(n)$ edge flips, with the aid of one moving point that is moved $O(n)$ times.*

Proof. Let v_1 be the hull vertex. First suppose that the second vertex is an interior point. Then it will play the role of the moving point, and we will label it p. We can move p directly towards v_1, until it is located within a triangle that has v_1 as a vertex. Now v_1 and p must be joined with an edge. Next we move p back along the same line to its original position, always maintaining edge v_1p. To do this, we consider the set of triangles that intersect p's path, as in lemma 4. Vertex p can always enter a triangle intersecting the path back to its original location. The difference is that once it has crossed an intersecting edge, we do not restore the edge. This means that p will accumulate edge degree. An issue that needs to be taken care of is that of maintaining a triangulation when p is about to lose visibility to another vertex. This occurs when one of its incident edges is about to overlap with another edge in the triangulation, as shown in Figure 6.

Suppose that edge pv_3 is about to overlap with edge v_3v_4. v_3 and v_4 cannot be on opposite sides of the remaining path that p must traverse, otherwise v_3v_4 may be flipped. Vertex p must share an edge with v_4 in this configuration. Vertices p and v_3 are also part of another triangle, along with some vertex v^* which may be anywhere on the path from v_1 to v_3. These two triangles must form a convex quadrilateral $pv^*v_3v_4$, otherwise p would have already lost visibility to v^*. Thus pv_3 may be flipped into v_4v^*, which means that v_3 is removed from the polygon that intersects p's path. The result is that when p reaches its original position, it leaves a *fan*[5] behind it, which includes edge v_1p. Overall one edge flip is used when p enters a new triangle, and at most one flip is used for every edge that attaches to p.

If both vertices of the edge that we wish to construct are on the hull, then we can take any point p within the hull and move it close to v_1 and onto the

[5] A fan is a star-shaped polygon with a vertex as its kernel.

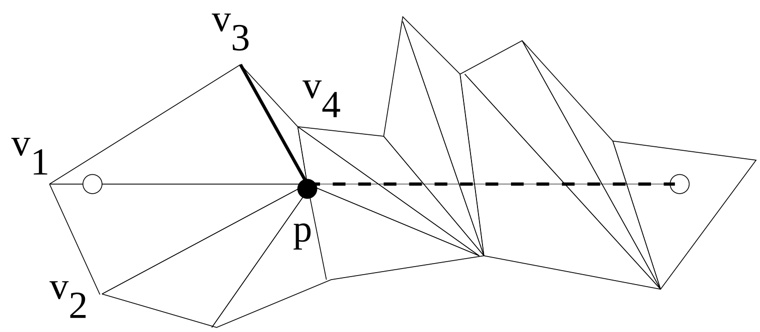


Fig. 6. Maintaining a triangulation while extending edge v_1p: p has moved from a position close to v_1 (shown white), and still has to traverse the dashed segment to its original position. Edge pv_3 causes a problem if p is to continue.

segment between the two hull vertices. p can then move along this segment to the second hull vertex until it is connected to both. At this moment, p may be perturbed so that the three vertices form a triangle. This triangle might contain other edges incident to p. Lemma 2 implies that these edges may be removed so that the desired edge can be constructed with $O(n)$ edge flips. □

2.1 Triangulations

With the basic building blocks in place, we now prove one of our main results.

Theorem 1. *With $O(n \log n)$ edge flips and point moves, we can transform any geometric triangulation on n points to any other geometric triangulation on n possibly different points.*

Proof. We transform one triangulation to another via a canonical configuration. As shown in Figure 7, the interior vertices form a *backbone* (i.e. their induced subgraph is a path). The top of the backbone is joined to the topmost hull vertex v_1, and all interior vertices are joined to the other two hull vertices, v_L and v_R.

The canonical configuration is constructed in a divide-and-conquer manner. We perform a radial sweep from v_1, to find the median vertex interior to the convex hull, v_M. After constructing edge v_1v_M we move v_M directly away from v_1 towards the base v_Lv_R, maintaining v_1v_M until triangle $v_Mv_Lv_R$ contains no interior points. By Lemma 6, we use $O(n)$ operations to accomplish this. Now, we transform $v_1v_Mv_L$ and $v_1v_Mv_R$ into backbone configurations by induction since they are smaller instances of the same problem. The resulting configuration is shown in Figure 8.

We now show that the two sides may be merged using $O(n)$ operations. As shown in Figure 9a, we first move the lowest vertex of a backbone into a position that is close to the base and is along the extension of edge v_1v_M. This requires one edge flip. The vertices on the left/right backbones are processed in ascending order, and are always moved just above the previous processed vertex,

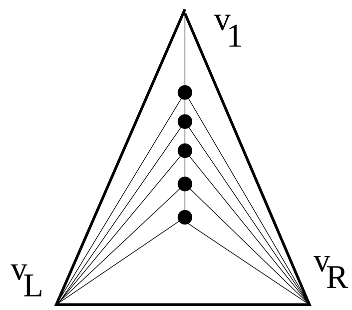


Fig. 7. The canonical configuration used for triangulations.

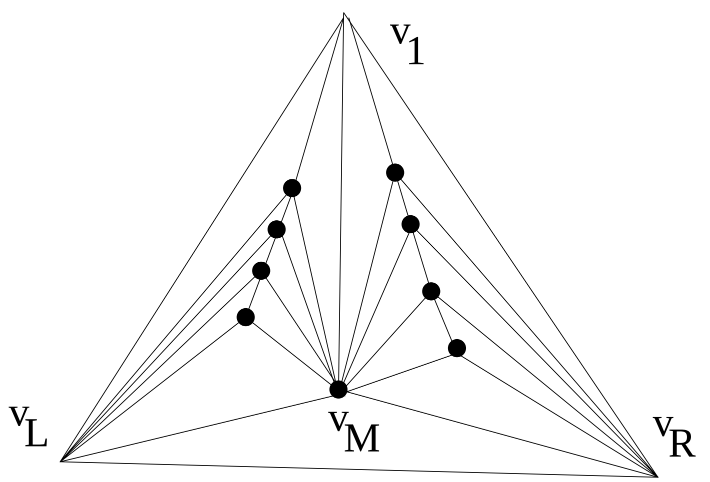


Fig. 8. The configuration of a triangulation prior to merging the backbones on each side of the median vertex v_M.

as shown in Figure 9b. Each vertex will require two point moves and one edge flip. Thus $v_1 v_L v_R$ is reconfigured into canonical form, and by a simple recurrence the number of edge flips and point moves used is $O(n \log n)$. It is trivial to move a canonical triangulation to specific coordinates using n point moves. Thus the transformation between any two triangulations may be completed. □

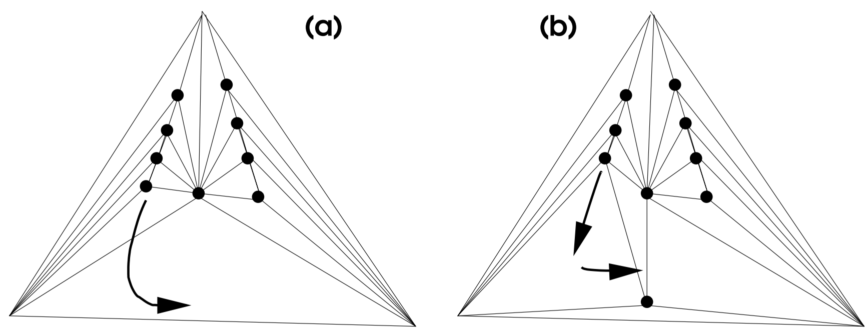


Fig. 9. Merging two backbones into one.

2.2 Near-triangulations

If the initial graph is a near-triangulation, we assume that the outer face is a convex polygon. Since the outer face is not a triangle, Theorem 1 does not directly apply. Some care must be taken to handle a non-triangular outer face. We outline the details below.

Theorem 2. *With $O(n \log n)$ edge flips and point moves, we can transform any geometric near-triangulation on n points to any other geometric near-triangulation on n possibly different points.*

Proof. As in the case with triangulations, we transform one near-triangulation to another via a canonical configuration. In the primary canonical configuration, shown in Figure 10, one chosen hull vertex (v_1) is joined by chords to all other hull vertices. Thus v_1 is in the kernel of a convex fan. Every triangle incident to a hull edge, except for one, is empty. All interior vertices, located in the non-empty triangle T, are in the canonical configuration of a triangulation. Once this configuration is achieved, all vertices can easily be placed at specific coordinates, so that the transformation between two-near triangulations can be completed. This will be described further on.

We first construct all edges of the top-level fan configuration, leaving interior vertices in their original positions. Then within each triangle of the fan, we rearrange the interior vertices into a canonical triangulation. Finally, we merge

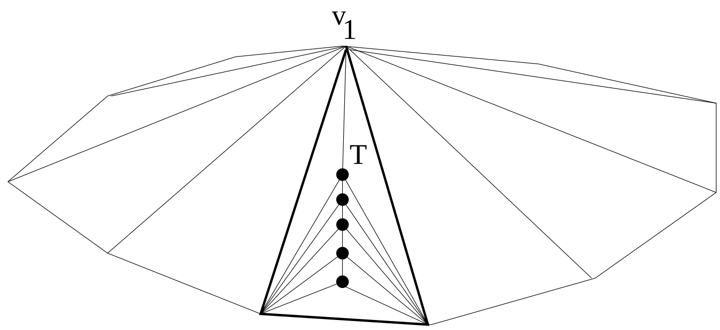


Fig. 10. The primary canonical configuration used for near-triangulations.

all triangles of the fan, so that all interior points move to a single triangle and are in canonical form.

To construct the fan chords, we always divide the problem into two roughly equal parts. We begin by constructing two chords as follows: perform a radial sweep from v_1 to successive hull vertices v_i $\{2 \leq i \leq n-1\}$, always keeping fewer than $\frac{n}{3}$ vertices in the swept region. Let v_j be the last hull vertex for which this holds. Construct chords $v_1 v_j$ and $v_1 v_{j+1}$. The unswept region not including triangle $v_1 v_j v_{j+1}$ contains fewer than $\frac{2n}{3}$ vertices. The swept region contains fewer than $\frac{n}{3}$ vertices. Triangle $v_1 v_j v_{j+1}$ may contain an arbitrary number of vertices, but this is not a sub-problem (we will not look at this region again during the construction of the fan). Now we can continue a new sweep on each side of $v_1 v_j v_{j+1}$. Construction of the two chords could take $O(n)$ edge flips and point moves, as described in Lemma 6. However the even split of the sub-problems ensures that the total number of operations is $O(n \log n)$.

Each fan triangle $v_1 v_i v_{i+1}$, containing k_i interior points, can be reconfigured into a backbone structure with $O(k_i \log k_i)$ operations, by Theorem 1. Thus the total number of edge flips and point moves used to reconfigure all triangles of the fan into backbone structures is $O(n \log n)$.

Now we are left only with the task of merging the fan triangles so that only one of them will contain all interior points. To do this, we pair up consecutive triangles, merge them, and continue recursively: We can add k_i interior points of a canonical triangulation to an adjacent canonical triangulation using $O(k_i)$ edge flips and point moves. The k_i points are processed in descending order and are always added to the top of the adjacent triangulation, as shown in Figure 11.

Thus we obtain one triangle in canonical form next to an empty triangle. It is just as easy to merge two canonical triangles separated by an empty triangle. If we ever encounter two or more adjacent empty fan triangles, we may use Lemma 1 to reconfigure them so that they will not affect the fan-merging process (see Fig 12).

By the above arguments, once we select the triangle that is to finally contain all of the interior points (the median triangle is a good choice), we can iteratively

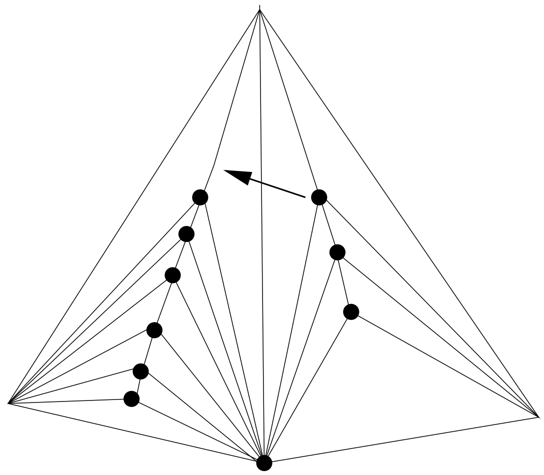


Fig. 11. Merging two adjacent fan triangles.

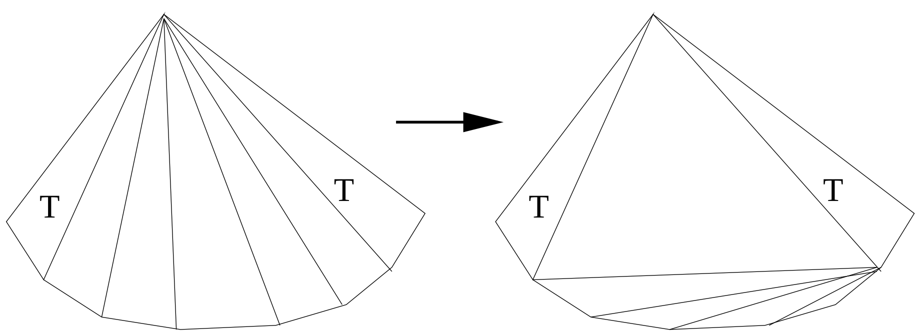


Fig. 12. Handling multiple adjacent empty fan triangles. Triangles marked (T) contain triangulations.

merge its neighboring triangles onto it using a total of $O(n)$ edge flips and point moves.

Finally we are left with a single triangle containing all interior points in canonical form. On either side, we may have an arbitrary triangulation (resulting from handling multiple adjacent empty fan triangles), but the vertices will be in convex position. By Lemma 1 they may be moved to our desired configuration using $O(n)$ edge flips.

We must still show that this primary canonical configuration can be moved to specific coordinates. This can be done with $O(n)$ point moves: First we move all vertices onto the bounding rectangle, by processing each of the hull paths between extreme vertices X_{max}, X_{min}, Y_{max} and Y_{min} separately. Let the path from X_{min} to Y_{max} contain vertices $X_{min} = v_1, \ldots, v_k = Y_{max}$. Vertex v_2 can be moved directly away from v_3 until edge v_1v_2 becomes vertical, as shown in Figure 13a. Similarly, vertices $v_3, \ldots, v_{k-1}$ may be moved to this vertical line through X_{min}. By performing similar motions for the other paths, we obtain a configuration as the one in Figure 13b. In each case one point move suffices, except for the hull vertices belonging to the triangle that contains the interior points. To move these two vertices, we have to displace the interior points, but one point move per interior point suffices.

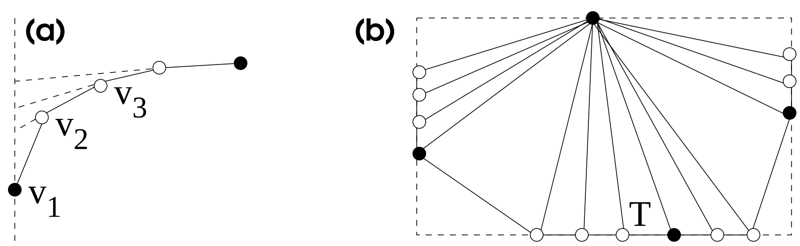


Fig. 13. (a) Moving a vertex onto the bounding rectangle. (b) All hull vertices on the bounding rectangle.

Now it is trivial to move all hull vertices except for Y_{max} along the edges of the bounding rectangle so that they reach the bottom edge. This allows the top vertex to move to any chosen coordinate above the bottom edge. All remaining vertices may be shifted horizontally to any position. Finally, by moving them again along the boundary of their new bounding rectangle, they can be positioned on the two vertical sides, which now allows them to be moved to any position vertically. Thus the reconfiguration may be achieved within the bounding box of the source and target triangulations. □

2.3 Remarks

If two triangulations have the same point set, the problem is no easier than the general problem. Suppose that there exists an algorithm that can transform a triangulation T_1 on a given n-point set to a triangulation T_2 on the same point set using $F_n = o(n \log n)$ edge flips and point moves. Then this algorithm can be used to transform a triangulation on one point set to any other triangulation on a possibly different point set with $F_n + O(n)$ edge flips and point moves. This argument is summarized in Fig 14. Let Fig 14(a) be the input triangulation. With F_n flips and moves, move to the triangulation in Fig 14(b) where every interior vertex is adjacent to the lower left vertex v_ℓ of the outer face.

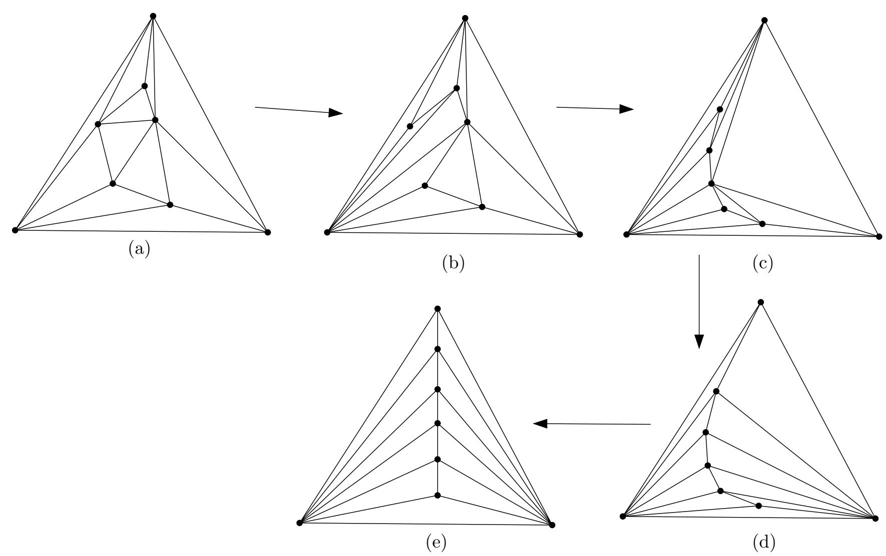


Fig. 14. Problem on fixed point set is not easier.

Now consider the triangulated polygon, P, that consists of edges not adjacent to v_ℓ. Notice that if we perform a radial sweep from v_ℓ, the boundary of P is monotonic. At least two of the triangles in P are disjoint ears, which means there must exist an ear tip that is an interior vertex and is also joined to v_ℓ by an edge in the original triangulation. We may move this point directly towards v_ℓ and cut the ear from P. This still leaves a monotone polygon P'. By continuously locating such ears, and moving them to a predefined convex position, we can obtain the configuration illustrated in Figure 14c. The monotonicity of P (and its descendants) and the convexity of the final configuration of interior points guarantee that no edge crossings will occur. This process requires a linear number of point moves.

Next, by Lemma 1, we can use $O(n)$ edge flips to obtain the triangulation where the lower right vertex of the outer face is adjacent to every vertex, as illustrated in Figure 14d. From here, it is trivial to move to the canonical configuration.

We conclude with the following:

Theorem 3. *If an algorithm exists that can reconfigure between any two geometric triangulations of the same point set with $o(n \log n)$ edge flips and point moves, then we can also transform any geometric triangulation on n points to any other geometric triangulation on n different points with $o(n \log n)$ flips and moves.*

It is tempting to try to find a fast algorithm that will construct a monotone path, as illustrated in the transition from Figure 14a to Figure 14b. Consider the polygon that is the union of all triangles incident to the lower left vertex of Figure 14b. By continuously cutting ears of this polygon, we may get to a triangulation that is *similar* to that of Figure 14a, using $O(n)$ edge flips. The similarity is that all neighbors of the lower left vertex will be in convex position. However, we have little control over the resulting positions of the remaining edges if we use only $O(n)$ operations. It is possible to create triangulations for which the reversal of this ear-cutting technique is not possible. In fact, Figure 14c serves as an example, if we add a few more vertices inside the large triangle. In this figure none of the edges directly visible from the lower left vertex can be flipped, so there is no obvious way to achieve a monotone path by using operations only in the neighborhood of v_ℓ.

We finally consider the following more powerful point move as an alternative to the point move studied so far. In this more powerful point move, we can delete an interior vertex of degree three (and all its incident edges), and create a new vertex of degree three inside another triangle of the triangulation. With this type of move we can reconfigure triangulations using $O(n)$ operations. We simply select a triangle incident to a hull edge and create a backbone inside. This is done by continuously selecting a vertex of constant degree from outside the triangle, reducing its degree to three, and moving it to the lower end of the backbone.

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