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Persistence-sensitive simplification of functions on surfaces in linear time

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Abstract

Persistence provides a way of grading the importance of homological features in the sublevel sets of a real-valued function. Following the definition given by Edelsbrunner, Morozov and Pascucci, an ε -simplification of a function f is a function g in which the homological noise of persistence less than ε has been removed. In this paper, we give an algorithm for constructing an ε -simplification of a function defined on a triangulated surface in linear time. Our algorithm is very simple, easy to implement and follows directly from the study of the ε -simplification of a function on a tree. We also show that the computation of persistence defined on a graph can be performed in linear time in a RAM model. This gives an overall algorithm in linear time for both computing and simplifying the homological noise of a function f on a surface.

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1 Introduction

Motivation. Much of modern science and engineering is driven by data. However, measuring nature is no easy task. Experiments are always plagued by noise. More fundamentally, physical phenomena do not exist at a single scale, and information obtained in experiments about these phenomena spans all scales at once.

Recently the theory of persistence homology [8, 19] emerged as a viable method for dealing with noise and omniscalar nature of data. Instead of forcing the user to make decisions about a fixed scale or a fixed level of noise in the data, persistence quantifies features across all different scales simultaneously. It presents the measurements in a persistence diagram [3] which records each feature as a point in the extended plane. The distance of the point to the diagonal represents the prominence, or persistence, of its feature. After examining such complete picture a user is free to decide how to view the data.

However, just knowing how much noise there is in the data, and where it occurs is not enough. Before using it in computation or visualization one usually desires to rid the data of unimportant features while keeping significant information intact. This raises the natural question of persistence-sensitive simplification.

Results and prior work. The question of simplification is tightly embedded in the history of persistence. It was considered in the first paper to introduce persistence [8] and later reinforced by the stability result [3]. Some of the first uses of persistence in the visualization community have been for simplifying various descriptors: Morse-Smale complexes [7, 2, 12] and Reeb graphs [17, 6]. We find simplification of topological descriptors convenient for visualization, but insufficient for computational analysis of the underlying data.

In this paper we follow the formalization of the simplification question proposed by Edelsbrunner, Morozov, and Pascucci [9]. Given a space $\mathbb{X}$ and a real-valued function $f : \mathbb{X} \rightarrow \mathbb{R}$ with a persistence diagram $\text{Dgm}(f)$, they call a generic function $g : \mathbb{X} \rightarrow \mathbb{R}$ a (strong) ε -simplification of f if the two functions are close, $\|f - g\|_\infty \leq \varepsilon$, and the persistence diagram $\text{Dgm}(g)$ consists only of those points in the diagram of f that are more than ε away from the diagonal. Edelsbrunner et al. [9] give a constructive proof of existence of ε -simplifications of functions on 2-manifolds, and show that the distance between the original function and its ε -simplification sometimes has to be ε . Their algorithm applies to functions defined on the vertices of the triangulated 2-manifold, and linearly interpolated elsewhere. It is technically involved, and difficult to implement since it requires potentially considerable subdivision of the domain.

In this paper we deliberately abstract ourselves from the piecewise linear function setting, and show how to simplify general filtrations of simplicial complexes without subdividing simplices. The abstraction turns out beneficial, and we obtain a simple algorithm that computes ε -simplifications in linear time. Moreover, the algorithm allows for an efficient extraction of a hierarchy of ε -simplifications, thus resolving an open question of [9]. Our discrete setup can be applied to the piecewise linear function simplification by taking the first barycentric subdivision of the domain as explained in Section 4.3. Additionally, we observe that in the RAM model, persistence of filtrations of 2-manifolds can be computed in linear time, thus giving us both an optimal computation and simplification algorithms in this model.

2 Persistence

Persistence studies evolution of classes in sequences of vector spaces. Most commonly such sequences arise as we consider the homology groups of a filtration of the space by the sublevel sets of a real-valued function defined on it. Intuitively homology is a topological invariant that keeps track of components, tunnels, voids, and their high-dimensional counterparts in a topological space; we refer the reader to Munkres [16] or Hatcher [13] for a review of homology theory.

2.1 Pairing and ε -simplifications

Let $f : \mathbb{X} \rightarrow \mathbb{R}$ be a real-valued function, and denote by $\mathbb{X}_a = f^{-1}(-\infty, a]$ its sublevel set, and by $H_p(\mathbb{X}_a)$ the p -dimensional homology group¹ of the sublevel set. For any $a < b$ inclusion of the sublevel sets $\mathbb{X}_a \subseteq \mathbb{X}_b$ induces a map between their homology groups $i_a^b : H_p(\mathbb{X}_a) \rightarrow H_p(\mathbb{X}_b)$, and we obtain a sequence

$$H_p(\mathbb{X}_{a_1}) \rightarrow H_p(\mathbb{X}_{a_2}) \rightarrow \dots \rightarrow H_p(\mathbb{X}_{a_n})$$

where a_i are those function values where p -dimensional homology of the sublevel set changes. According to persistence, a class $\lambda \in H_p(\mathbb{X}_a)$ is born in $H_p(\mathbb{X}_a)$ if λ is not in the image of the map $i_{a'}^a$ for any $a' < a$. Class λ dies in $H(\mathbb{X}_b)$ if $i_a^b(\lambda) \in \text{im } i_{a'}^b$ for some $a' < a$, but $i_a^b(\lambda) \notin \text{im } i_{a'}^b$ for any $b' < b$. In this case, we say that $H_p(\mathbb{X}_a)$ and $H_p(\mathbb{X}_b)$ are paired and we record this information by adding point (a, b) to the p -dimensional persistence diagram of the function, $\text{Dgm}_p(f)$. We add a point for every such class, and for technical reasons add every point on the diagonal with infinite multiplicity. Cohen-Steiner et al. [3] have shown that persistence diagrams are stable under small perturbations of the function.

For algorithmic purposes one replaces space $\mathbb{X}$ with its triangulation K , and function f with a filtration of the simplices in K . Namely, we take an ordering $\mathcal{F} = \sigma_1, \sigma_2, \dots, \sigma_m$ of simplices of K , and denote by $K_i = \bigcup_{j=1}^i \sigma_j$ the union of simplices up to σ_i . For all K_i to be subcomplexes, a face σ of a simplex τ must precede it in the filtration, which we denote $\sigma <_{\mathcal{F}} \tau$. We will use sometimes equivalently the terminology σ older than τ in $\mathcal{F}$ or σ lower than τ in $\mathcal{F}$ to designate $\sigma <_{\mathcal{F}} \tau$. A filtration $\mathcal{F}$ is *compatible* with the function $f : K \rightarrow \mathbb{R}$ if $f(\sigma) \leq f(\tau)$ whenever $\sigma <_{\mathcal{F}} \tau$. Equivalently, we will also say that $\mathcal{F}$ is an f -filtration.

The way in which we obtain a filtration depends on the function we study. One example common in practice is a piecewise linear function $f : |K| \rightarrow \mathbb{R}$ defined on the vertices of a triangulation K and linearly interpolated on the interior of the simplices. If we assign to each simplex the maximum value the function attains on it, we get a piecewise constant approximation $\bar{f} : K \rightarrow \mathbb{R}$ of $f : |K| \rightarrow \mathbb{R}$ with $\bar{f}(\sigma) = \max_{x \in \sigma} f(x)$. Sorting the simplices by their $\bar{f}$ -value and breaking the ties by dimension and arbitrarily in each dimension, we get a total order on the simplices which gives an $\bar{f}$ -filtration.

The sequence of simplices implies a filtration of subcomplexes built-up simplex by simplex, $\emptyset = K_0 \subseteq K_1 \subseteq K_2 \subseteq \dots \subseteq K_m = K$. Applying the homology functor, the inclusions induce maps between homology groups, and we obtain a sequence

$$H(K_1) \rightarrow H(K_2) \rightarrow \dots \rightarrow H(K_m).$$

Applying the definition of persistence to this sequence we have a homology class born with the addition of simplex $\sigma = \sigma_i$ that dies with addition of simplex $\tau = \sigma_j$. We call σ positive and τ

¹In this paper we implicitly assume that homology groups are computed with coefficients in $\mathbb{Z}/2\mathbb{Z}$, but other coefficient fields may be used as long as the machine model can handle basic operations in this field.

negative, and say that the two simplices are paired. Assuming we have a f -filtration, the *persistence* of (σ, τ) is $f(\tau) - f(\sigma)$. For example, for the case of 0-dimensional homology, an edge is negative if it merges two components. From the oldest vertices of each component, we pick the youngest one, and say that it is paired with the negative edge. Some positive simplices remain unpaired because the classes they create never die, we call such simplices *essential*. The number of essential p -simplices is equal to the rank of the p -dimensional homology group of K . Edelsbrunner, Letscher, and Zomorodian [8] gave an algorithm to compute the pairing of simplices in the filtration of a simplicial complex. In particular, they show how to compute the dimension 0 persistence diagram in $O(m\alpha(m))$, where α is the inverse Ackermann function.

In this paper, we consider a function $f : K \rightarrow \mathbb{R}$ defined on a triangulation K and suppose sublevel sets of f are subcomplexes. In other words, we assume that K has a f -filtration. We want to simplify f in a way that removes its less persistent features. For this, we investigate the concept of ε -simplification introduced in [9] that we slightly adapt to our purpose. First, we need the following definition:

Definition 1. *A persistence pair is local if its simplices are consecutive in the filtration.*

It is not too difficult to prove [15] that two consecutive simplices in a filtration are (locally) paired if and only if the first simplex is a face of the second. The reason for considering local pairs is that adding a local pair to a subcomplex does not change its homotopy type.

Definition 2 (ε -simplification). *A dimension p ε -simplification of a function $f : K \rightarrow \mathbb{R}$ is a function $g : K \rightarrow \mathbb{R}$ such that:*

1. $\|f - g\|_\infty \leq \varepsilon$,
2. *all persistence diagrams of g are the same as those of f except for $\text{Dgm}_p(g)$ which is the same as $\text{Dgm}_p(f)$ but with all off-diagonal points at L_1 -distance at most ε from the diagonal removed,*
3. *K has a g -filtration such that all pairs of dimension $(p, p+1)$ with persistence 0 are local.*

A function which is a dimension p ε -simplification of f for all p is called an ε -simplification of f . In Section 4.3, we will explain how to adapt our framework to the simplification of piecewise linear functions.

2.2 Computing the persistence of a filtered graph in linear time

Having defined persistence for simplicial complexes, we now turn our attention to the computation of persistence for connected graphs. For this, consider a filtration of a connected graph $G = (V, E)$. Computing the persistence of this filtration amounts (1) to distinguish positive from negative edges and (2) to pair the negative edges with the (positive) vertices. As noticed in [1] for the special case of height functions over terrain meshes, (1) and (2) can be implemented using the union-find data-structure, keeping track of the oldest vertex in each component. In particular, G can be interpreted as a union graph [1] with edge weights corresponding to the filtration ordering. From Kruskal's algorithm [18], we know that the set of negative edges of G 's filtration corresponds to the minimum spanning tree of this union graph. To obtain a linear time algorithm we use a two step algorithm:

1. We compute the minimum spanning tree T of G with filtration ordering for the edges.

2. We compute the persistence pairing in T using T itself as a batched (or off-line) union tree.

The first step can be implemented with the Fredman and Willard [10] linear time algorithm for the minimum spanning tree problem.² The model of computation is a Random Access Machine with fixed word size, allowing usual arithmetic operations and bitwise Boolean operations in constant time per word. The word size is also assumed to be large enough to hold the various parameters of the problem (when the filtration is deduced from a function on $V \cup E$, each function value should fit into a single machine word). We refer to this model simply as a RAM. The second step can be implemented in the same model of computation with the algorithm by Gabow and Tarjan [11] for union trees, see Appendix A for details. In conclusion,

Theorem 3. *The persistent homology of a connected graph with m edges can be computed in $O(m)$ -time on a RAM.*

Notice that when the filtration of G is implicitly given by a function on $V \cup E$, the filtration order of the edges in T can be obtained in linear time with Radix sort. In any case, using a decision tree model will add at most a logarithmic factor for the whole procedure.

2.3 Persistence on d -manifolds via duality

Let K be a complex representing a d -manifold. We can define its dual block-complex K^* (which is a cell complex for $d \leq 3$) [16]. We associate to each simplex $\sigma \in K$ of dimension p a block $\sigma^* \in K^*$ of dimension $d - p$ inverting the adjacency relation (*i.e.* a block τ^* is a face of σ^* in the dual if and only if σ is a face of τ in the original complex). A filtration $\mathcal{F}$ of K induces a filtration $\mathcal{F}^*$ of K^* using the reverse of the ordering of $\mathcal{F}$.

Theorem 4. *The persistence pairs of dimension $(p, p+1)$ in $\mathcal{F}^*$ correspond to the pairs of dimension $(d - 1 - p, d - p)$ in $\mathcal{F}$.*

This result can be deduced by applying the symmetry theorem of [4] to the first barycentric subdivision of the complex (which is the same as the first barycentric subdivision of the dual complex). Appendix B presents a simpler proof which is sufficient for our needs.

In this paper, we focus on the simplification of the 0-dimensional persistence diagram of a filtered graph. By duality, this directly gives a way to simplify the 1-dimensional persistence diagram of a filtered 2-manifold, and more generally the $(d - 1)$ -dimensional diagram of a filtered d -manifold.

3 ε -Simplification on trees

In this section, we state and prove a key result concerning trees.

Theorem 5. *Given a tree T with n vertices, a function $f : T \rightarrow \mathbb{R}$ and a positive constant ε , there exists an ε -simplification $g : T \rightarrow \mathbb{R}$. Moreover, assuming the persistence pairs in a f -filtration of T are given, the computation of g can be performed in $O(n)$ time using $O(n)$ storage.*

In Section 3.1, we give an algorithm for computing an ε -simplification g of f . Section 3.2 states all technical lemmas required by the proof of the correctness. Throughout this section, $\mathcal{F}$ designates a f -filtration of T and we assume persistence pairs in $\mathcal{F}$ are given. To simplify the presentation, we assume f is generic, *i.e.* injective on the set of vertices. If f is non-generic, we first apply a symbolic perturbation to it.

²If the genus of the graph G is fixed, Mareš [14] gives a linear time algorithm in the pointer machine model.

3.1 Algorithm

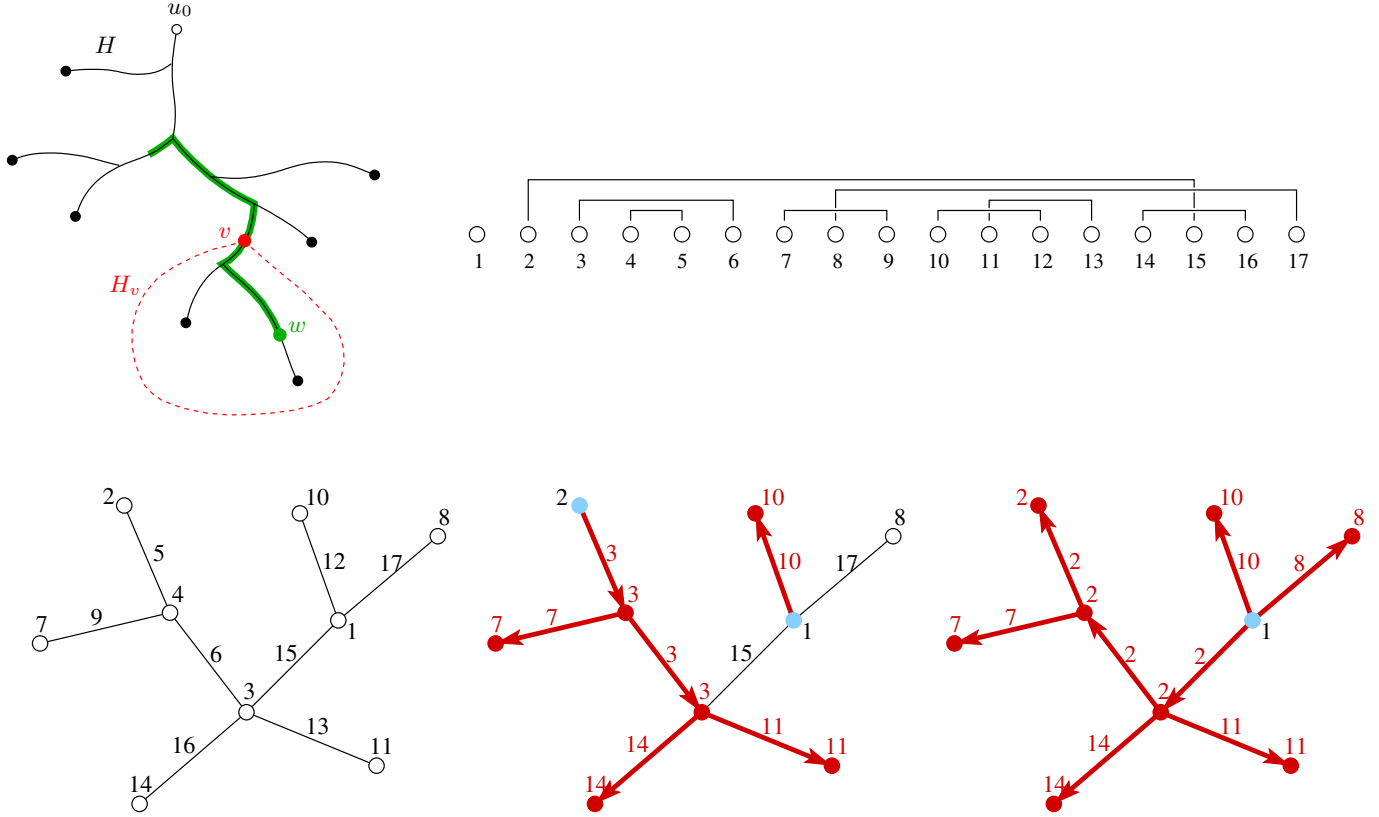


Figure 1: Top left: the connecting path starting at $w = \min_{\mathcal{F}} H_v$ passes through v . Top right: filtration of the tree on the bottom left. Oriented edges are locally paired with their head. Bottom middle: ε -simplification for $\varepsilon = 3$. The forest is composed of 2 trees, rooted at the blue vertices. Bottom right: $(+\infty)$ -simplification.

3.1.1 Special case: $\varepsilon = +\infty$

In a f -filtration $\mathcal{F}$ of a tree T , all vertices are positive and all edges are negative. The vertex v_0 with smallest f -value creates an essential connected component and is the only vertex which is unpaired. In particular, the persistence diagram of f has a unique point with infinite persistence, namely the point $(f(v_0), +\infty)$. Suppose all vertices in $\mathcal{F}$ are locally paired but v_0 . We observe that every edge must be paired with its endpoint of largest f -value. Let us orient the edges in T from their endpoint of smallest f -value to their endpoint of largest f -value as in Figure 1 (right). The previous observation shows that every vertex but v_0 has in-degree 1. The vertex v_0 has in-degree 0. In particular, f is increasing on the vertices going down the tree from v_0 .

If the pairs are not already local, an $(+\infty)$ -simplification g of f can be constructed as follows. We define the vertex v_0 with smallest f -value as the root of T and let T_v be the subtree of T rooted at vertex v (see Figure 1). We set $g(v_0) = f(v_0)$. For all vertices $v \neq v_0$ we set $g(v) = \min f(T_v)$. Note that g is indeed increasing on the vertices going from the root to the leaves. The reason for

choosing this function g will become clear shortly. The function g can be computed in linear time for all vertices by recursively removing the leaves of T after initializing g to f : if v is a leaf and w is its neighbor, simply set $g(w) = \min(g(w), g(v))$. Once the g -values at vertices have been determined as described above, we set $g(ab) = \max\{g(a), g(b)\}$ for all vertices ab in T .

To prove that g is an $(+\infty)$ -simplification, we construct a filtration $\mathcal{G}$ compatible with g with the property that all persistence pairs are local and the persistence diagram of g shares with $\text{Dgm}(f)$ the same point with infinite persistence, $(f(v_0), +\infty)$. For this, we rank simplices in such a way that every edge follows immediately its endpoint of highest rank.

3.1.2 General case

All lemmas used in this section are stated and proved in Section 3.2.

To construct an ε -simplification g of f , we first initialize g to f and mark simplices that belong to pairs of persistence less than ε . We will prove in the next section that the set of marked simplices has the structure of a forest, in which each tree H has a missing vertex u_0 . We use this missing vertex u_0 as the root of the tree $\bar{H} = H \cup \{u_0\}$ and apply to $\bar{H}$ the simplification described above. Specifically, writing H_v for the subtree of H rooted at v , we set $g(v) = \min f(H_v)$ for all vertices v in H and $g(ab) = \max\{g(a), g(b)\}$ for all edges ab in H . By processing the forest componentwise, this gives a linear time algorithm for computing an ε -simplification g of f . Remark the data-structure is reduced to T and has linear size.

We now establish the correctness of our algorithm, delaying the proof of technical lemmas to the next section. For this, we use the fact that the root u_0 of each tree $\bar{H}$ has a value smaller than any simplex in H (Lemma 8). Similar to the case $\varepsilon = +\infty$, this allows us to construct a filtration $\mathcal{G}$ compatible with g with the property that all marked simplices are locally paired and have zero persistence. Specifically, we initialize $\mathcal{G}$ to $\mathcal{F}$. Note that the set of simplices in H which are assigned the same g -value $f(w)$ forms a subpath of the path from w to u_0 . This is a direct consequence of the fact that $H_v \subseteq H_w$ iff w is an ancestor of v in the tree $\bar{H}$ rooted at u_0 . We move all simplices on this subpath next to w in $\mathcal{G}$ and reorder them in such a way that they are locally paired in $\mathcal{G}$. We will prove in Lemma 11 that the pairing of non-marked simplices is the same in $\mathcal{F}$ and $\mathcal{G}$, implying that the persistence diagram of g is the same as the one of f but with all off-diagonal points at L_1 -distance at most ε from the diagonal removed. To complete the proof, we will also establish that $\|f - g\| \leq \varepsilon$ in Lemma 10.

3.2 Technical lemmas

We write $[\sigma, \tau]_{\mathcal{F}}$ for the sequence of simplices between σ and τ in filtration $\mathcal{F}$. We say that a set of persistence pairs $\mathcal{P}$ is *closed under inclusion* if whenever $(\sigma, \tau) \in \mathcal{P}$ and (σ', τ') is a persistence pair with $[\sigma', \tau']_{\mathcal{F}} \subseteq [\sigma, \tau]_{\mathcal{F}}$, then $(\sigma', \tau') \in \mathcal{P}$. In particular, the set of pairs with persistence less than ε is closed under inclusion. Given a set of persistence pairs $\mathcal{P}$ closed under inclusion, we first study the way simplices in $\mathcal{P}$ are arranged in the tree T .

Consider the set of connected components in the subcomplex defined by the first i simplices in filtration $\mathcal{F}$. Each connected component in this subcomplex has a unique unpaired vertex, which is the oldest in its component. The persistence pair (v, e) in $\mathcal{F}$ is characterized by the fact that adding e to the filtration $\mathcal{F}$ merges two components C_v and C_w such that $v = \min_{\mathcal{F}} C_v$ and $w = \min_{\mathcal{F}} C_w$ for some vertex w which precedes v in the filtration, $v >_{\mathcal{F}} w$. Let $p(v, e)$ be the half-open path in

the tree T connecting v to e . Clearly,

$$p(v, e) \subseteq C_v \cup \{e\} \subseteq [v, e]_{\mathcal{F}}. \quad (1)$$

Lemma 6. *Any simplex $\sigma \in p(v, e)$ is paired with some simplex $\tau \in [v, e]_{\mathcal{F}}$. In particular, $[\sigma, \tau]_{\mathcal{F}} \subseteq [v, e]_{\mathcal{F}}$.*

Proof. Let $\sigma \in p(v, e)$. We may assume $\sigma \neq v, e$. By Equation (1), σ belongs to C_v . Suppose σ is a vertex. Since v is the only simplex unpaired in C_v , this implies that when e is added to the filtration, σ must already be paired with an edge $e(\sigma)$ preceding e in the filtration, $e(\sigma) <_{\mathcal{F}} e$. Suppose now that σ is an edge and denote $v(\sigma)$ its paired vertex. As $\sigma \in C_v$, the two components it joins when σ is added must be included in C_v , hence $v(\sigma) \in C_v$ and $v(\sigma) >_{\mathcal{F}} v$. $\square$

Let us denote by $\{\mathcal{P}\}$ the set of simplices in the pairs of $\mathcal{P}$.

Lemma 7. *Consider a connected component H of $\{\mathcal{P}\}$ in T . Any simplex in H is paired with a simplex in H .*

Proof. Let (v, e) be a pair in $\mathcal{P}$. Since $\mathcal{P}$ is closed by inclusion, Lemma 6 shows that $p(v, e) \subseteq \{\mathcal{P}\}$. It follows that e and v belong to a same component of $\{\mathcal{P}\}$ in T . $\square$

Let $\bar{H}$ be the closure of a component H of $\{\mathcal{P}\}$ in T . It follows from Lemma 7 that each component H of $\{\mathcal{P}\}$ is a subtree of T which contains the same number of vertices and edges. Therefore, $\bar{H} \setminus H$ must be reduced to a single vertex which we call the root of H . Note that H may share its root with other subtrees.

Lemma 8. *The root of H is lower in $\mathcal{F}$ than any simplex in H .*

Proof. Let u_0 be the root of H . We show that the hypothesis $u_0 >_{\mathcal{F}} \min_{\mathcal{F}} H$ leads to a contradiction. For all simplices w in H lower than u_0 , we consider the highest edge on the path connecting w to u_0 and let e be the lowest of such edges. We claim that e must be paired with a vertex $v \in H$ lower than u_0 . Indeed, when e is added in the filtration, e connects two components: one of whom contains u_0 and possibly vertices of H higher than u_0 , while the other component contains at least one vertex of H lower than u_0 . Since e is paired in H , the claim follows. Let $e(u_0)$ be paired with u_0 . Since $\mathcal{P}$ is closed by inclusion, we must have $e(u_0) >_{\mathcal{F}} e$. But this contradicts that $e(u_0)$ is paired with u_0 since the component below $e(u_0)$ that contains u_0 also contains v (they are connected by a path below e) which is lower than u_0 by the above hypothesis. $\square$

We now define connecting paths which will turn out to be useful to bound the difference between f and the function g computed by the algorithm in Section 3.1.2. Given a persistence pair (v, e) , we let $\text{Closure}_{\mathcal{F}}(v, e)$ be the set of persistence pairs obtained by taking the closure of (v, e) under inclusion in $\mathcal{F}$. Applying what we just saw, $\text{Closure}_{\mathcal{F}}(v, e)$ is a forest in which each tree has a missing vertex. This missing vertex is designated as the root of the associated tree.

Definition 9. *The connecting path of (v, e) is the half-open path connecting v to the root of the tree containing v in $\{\text{Closure}_{\mathcal{F}}(v, e)\}$.*

Lemma 10. *The function g computed by the algorithm in Section 3.1.2 satisfies $\|f - g\| \leq \varepsilon$.*

Proof. Let $\{\mathcal{P}\}$ be the set of pairs with persistence less than ε . For all simplices σ in $\{\mathcal{P}\}$, we let H be the connected component of $\{\mathcal{P}\}$ containing σ and designate as the root of H its missing vertex $u_0 = \bar{H} \setminus H$. If σ is a vertex, we let H_σ be the subtree of H rooted at σ . If σ is an edge, we let H_σ be the subtree of H rooted at the endpoint of σ furthest away from the root of H . We have $g(\sigma) = \min f(H_\sigma)$. Consider the vertex w such that $w = \min_{\mathcal{F}} H_\sigma$, i.e. $g(\sigma) = f(w)$ and let us prove that $f(w) \leq f(\sigma) \leq f(e(w))$ where $e(w)$ is the edge paired with w in $\mathcal{F}$. By definition, the connecting path of $(w, e(w))$ is contained in $\text{Closure}_{\mathcal{F}}(w, e(w)) \subseteq \mathcal{P}$ and therefore is contained in H . It starts from w and ends at a vertex whose f -value is smaller than the f -value of w while staying inside H . On the other hand w is the simplex of H_σ with smallest f -value. This shows that the connecting path of $(w, e(w))$ must go outside H_σ and in particular must pass through σ (see Figure 1). Thus, σ belongs to the connecting path of $(w, e(w))$ which is contained in $[w, e(w)]_{\mathcal{F}}$. It follows that $f(w) \leq f(\sigma) \leq f(e(w))$ and since $(w, e(w))$ has persistence less than ε , $|f(\sigma) - g(\sigma)| \leq \varepsilon$. $\square$

Let $\mathcal{G}$ be the filtration constructed in Section 3.1.2 and let $\{\mathcal{P}\}$ be the set of pairs with persistence less than ε . Some key properties are that $<_{\mathcal{F}}$ and $<_{\mathcal{G}}$ agree on $K \setminus \{\mathcal{P}\}$, simplices of $\{\mathcal{P}\}$ can only be lowered from $\mathcal{F}$ to $\mathcal{G}$ and $\mathcal{P}$ is composed only of local pairs in $\mathcal{G}$.

Lemma 11. *The pairing of simplices not in $\{\mathcal{P}\}$ is the same in $\mathcal{F}$ and $\mathcal{G}$.*

A proof is provided in Appendix C.

4 Applications

4.1 ε -Simplification of the 0-dimensional diagram of a complex

The goal of this section is to prove that in a complex, we can simplify the dimension 0 persistent homology using our algorithm without affecting or being affected by higher dimensions. The following lemma is easily verified:

Lemma 12. *The pairing of the dimension p persistent homology depends only on the relative order of the positive p -simplices and the relative order of the negative $(p+1)$ -simplices.*

Let $\mathcal{F}$ be a filtration of a connected simplicial complex K . The vertices and negative edges of $\mathcal{F}$ form a tree. The simplification algorithm of Section 3 only lowers the value of the simplices of this tree. The positive edges of $\mathcal{F}$ thus remain positive after the simplification. Indeed, when a positive edge appears in $\mathcal{F}$, its extremities are already in the same connected component, and this remains true if we only add vertices and edges before this edge. The negative edges therefore also remain negative (their number does not depend on $\mathcal{F}$). The tree of negative edges thus remains the same during the algorithm. Using Lemma 12, this proves that our algorithm is not affected by the presence of positive edges and higher dimensional simplices. It also proves that persistent homology of dimension 1 or higher is not affected by our algorithm.

4.2 ε -Simplification on surfaces

As stated in the title of this paper, our goal is to simplify a function on a surface. That is, our main interest is in a complex whose underlying space is a 2-manifold.

Section 4.1 proves that we can find an ε -simplification of the dimension 0 persistent homology of a function on such a complex without affecting the dimension 1 persistence.

By Theorem 4, the persistence pairs of dimension $(1, 2)$ are simply the persistence pairs of dimension $(0, 1)$ of a dual graph. We can therefore apply the algorithm of Section 3 in the dual. Besides, it is straightforward to see that the last paragraph of Section 4.1 also applies for this dual simplification, *i.e.* that since the dual simplification only moves positive edges and negative triangles higher, simplices do not change sign and the algorithm does not affect and is not affected by simplices that are neither positive edges nor negative triangles. We therefore obtain an ε -simplification of the dimension 1 persistence without affecting the dimension 0 persistence.

The set of simplices whose value can be changed by the dimension 0 simplification and the dimension 1 simplification are disjoint (they don't have the same dimension and sign). Since each simplification changes the value of a simplex by at most ε , cumulating the two simplifications also changes the value of each simplex by at most ε . We thus have the following theorem:

Theorem 13. *Given a function f on a triangulated 2-manifold K , there exists an ε -simplification g of f . Moreover, given the persistence pairing of a f -filtration of K , we can compute an ε -simplification g and the g -filtration in linear time.*

In conjunction with Theorem 3, this gives:

Corollary 14. *In the special case of the RAM model, given only a function f , an ε -simplification of f can be computed in linear time.*

If the underlying space of K is a d -manifold with $d > 2$, the algorithm presented for 2-manifolds can be adapted to compute a function g that is ε -close to f and has simplified persistence diagrams of dimension 0 and $d - 1$. The intermediate persistence diagrams are not affected. This is very similar to a classical result in Morse theory where, after canceling handles (by inverting the gradient between two critical points), a connected d -manifold has only one critical point of dimension 0 and one critical point of dimension d left. Our result is a combinatorial and hierarchical (we can do partial simplification) version with bounds on the modification of the function.

4.3 Simplification of piecewise linear functions

The preceding Theorem 13 may be used to simplify piecewise linear functions. For this, we consider a piecewise linear function $f : |K| \rightarrow \mathbb{R}$ and its discrete version $\bar{f} : K \rightarrow \mathbb{R}$ as in section 2.1. We know that f and $\bar{f}$ have the same persistence diagrams [15]. Following the preceding theorem we compute an ε -simplification $\bar{g} : K \rightarrow \mathbb{R}$ of $\bar{f}$. We then define a piecewise linear function $\text{Sd } g : |K| \rightarrow \mathbb{R}$ on the underlying barycentric subdivision of K . If $\hat{\sigma}$ is the barycenter of the simplex $\sigma \in K$, we set $\text{Sd } g(\hat{\sigma}) = \bar{g}(\sigma)$ and extend $\text{Sd } g$ linearly. It can be shown [15] that $\bar{g}$ and $\text{Sd } g$ have the same persistence diagram. We need to bound $\|f - \text{Sd } g\|_\infty$. Consider a simplex σ of K of dimension 0, 1 or 2. The maximal difference between f and $\text{Sd } g$ over $|\sigma|$ is attained at one of the vertices of the barycentric subdivision $\text{Sd } \sigma$ of σ . For every vertex v of σ we have $|f(v) - \text{Sd } g(v)| = |\bar{f}(v) - \bar{g}(v)| \leq \varepsilon$ by definition of $\bar{g}$. It thus suffices to bound $|f - \text{Sd } g|$ over the vertices of the form $\hat{\tau}$, for τ a face of σ . We have

$$|f(\hat{\tau}) - \text{Sd } g(\hat{\tau})| = |f(\hat{\tau}) - \bar{g}(\tau)| \leq |f(\hat{\tau}) - \bar{f}(\tau)| + |\bar{f}(\tau) - \bar{g}(\tau)| \leq |f(\hat{\tau}) - \max_{|\tau|} f| + \varepsilon$$

But $|f(\hat{\tau}) - \max_{|\tau|} f|$ can be made as small as we wish by placing $\hat{\tau}$ in the interior of $|\tau|$ sufficiently close to the vertex that maximizes f over $|\tau|$. This only gives a bound of the form $\varepsilon + \eta$ for any

$\eta > 0$, but can be reduced to ε if we assume that f is generic, i.e. injective on the set of vertices. Indeed, it can be shown in this case that the function at the vertices of K needs only be changed by $\varepsilon' < \varepsilon$ to obtain an ε -simplification of $\bar{f}$, leaving room for an ε -simplification of f .³ To conclude,

Theorem 15. *Given a piecewise linear generic function f on a triangulated 2-manifold $|K|$ with m edges, there exists an ε -simplification of f that can be computed in $O(m)$ time on a RAM machine, or in $O(m \log m)$ time if we are dealing with real function values on a real-RAM.*

5 Optimal filtrations and counterexamples

As ε -simplifications can always be performed on surfaces, a natural question is to extend the process to higher dimensional triangulated manifolds. We show that, in some restricted sense of optimal simplification, this is not always possible already for 3-manifolds and general complexes of dimension 2. In the following we only consider filtrations where simplices are added one at a time. We assume the reader familiar with some basics of algebraic topology and refer to the textbook by A. Hatcher [13] for the various definitions.

Definition 16. *A filtration is said optimal if all its non-essential simplices are locally paired. In other words, an optimal simplification is an ε -simplification with $\varepsilon = +\infty$.*

Let K be a simplicial complex. If σ and τ are two simplices of K such that σ is a face of τ but is not a face of any other simplex in K , then we say that K *collapses* to $K - \{\sigma, \tau\}$. Furthermore, K is said *collapsible* if it can be reduced to a vertex by a sequence collapses. It can be proved that a collapsible complex is simply connected, i.e. has a trivial fundamental group. The following lemma is easy.

Lemma 17. *Let $\sigma_1, \sigma_2, \dots, \sigma_m$ be the ordering of the simplices of a filtration of K . If (σ_i, σ_{i+1}) is a local pair, then K_{i+1} collapses to K_{i-1} , where K_j denotes the subcomplex of K spanned by the j first simplices.*

Claim 18. *A triangulated Poincaré homology 3-sphere has no optimal filtration.*

Proof. Let $\mathcal{K}$ be a filtration of a triangulated homology 3-sphere K . Since a homology sphere has the homology of a sphere, $\mathcal{K}$ has precisely two essential simplices: a vertex σ and a tetrahedron τ . Clearly, from Section 2.1, σ must be the first simplex in the filtration. Also, since the 3-cycle space of a proper subcomplex of a connected 3-manifold is trivial, the only positive – hence essential – tetrahedron must be the last simplex in $\mathcal{K}$. If $\mathcal{K}$ was optimal, then by the preceding Lemma, $K - \tau$ would be collapsible, hence simply connected. Since the fundamental group of K only depends on its 2-skeleton, K would also be simply connected. A contradiction. $\square$

In fact, 2-complexes may already lack an optimal filtration. This will be the case for non-collapsible contractible complexes, as is easily shown with the same type of arguments as above. In particular,

Claim 19. *A triangulated dunce cap or Bing’s house with two rooms has no optimal filtration.*

³Using our subdivision method and taking $\varepsilon = 0$ will actually modify f , though f is an obvious 0-simplification of itself. We can easily remedy to this problem by a simple merging procedure of vertices with equal value.

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A Computing persistence on a tree in linear time

This computation is based on the algorithm by Gabow and Tarjan [11] for union trees. We first pick an arbitrary vertex as the root of the tree T and orient in linear time the edges of T away from this root. Thus, each non-root vertex v has a unique parent $p(v)$. We next perform a sequence of Union operations corresponding to the edges of T and maintain a pointer to the oldest vertex in each component. If $e = (p(v), v)$ is a tree edge, Gabow and Tarjan define a $Union(v, p(v))$ operation that only uses v as a parameter and is referred to as $Link(v)$. This leads to the following implementation of the second step, where we assume that each vertex (representative of a set) has a field *oldest* pointing to the oldest vertex in its component. Here, $Find(v)$ returns as usual the representative of the component of v .

```

for each edge  $e = (p(v), v)$  of  $T$  taken in filtration order
   $pvSet \leftarrow Find(p(v))$ ; // It results from [11] that  $v = Find(v)$  at this point.
  if  $v.oldest$  is younger than  $pvSet.oldest$  then
    output  $(v.oldest, e)$  as a persistence pair;
  else
    output  $(pvSet.oldest, e)$  as a persistence pair;
     $pvSet.oldest \leftarrow v.oldest$ ;
  endif
   $Link(v)$ ; // The representative of the set  $p(v)$  becomes the
             // representative for the union of the sets of  $v$  and  $p(v)$ .
endfor

```

Putting $n = |V|$, this algorithm performs an intermixed sequence of $2n - 2$ Find and Link operations, which takes $O(n)$ time according to [11].

B Proof of Theorem 4

Let D be the adjacency matrix of K with the rows and columns in the order given by the filtration $\mathcal{F}$. A result in [5] shows that the pairing function $r_D(i, j)$ defined by 1 if the simplices of index i and j are paired and 0 otherwise can be expressed as

$$r_D(i, j) = \text{rank} D_i^j - \text{rank} D_{i+1}^j + \text{rank} D_{i+1}^{j-1} - \text{rank} D_i^{j-1},$$

where D_i^j is the lower left minor of D obtained by deleting the first $i - 1$ rows and the last $n - j$ columns (the simplices are indexed by $1 \dots n$ here).

The adjacency matrix D^* associated to $\mathcal{F}^*$ is the transpose of D with respect to the non-standard diagonal: exchanging faces and cofaces means transposing D , while changing the filtration order means reversing the order of rows, and reversing the order of columns.

It follows that $r_{D^*}(n + 1 - j, n + 1 - i) = r_D(i, j)$ ⁴. This means that the persistence pairing is preserved by duality. In particular, if (σ, τ) is a pair in the primal, (τ^*, σ^*) is a pair in the dual, and if σ creates an essential cycle in the primal σ^* also creates an essential cycle in the dual. The dual of a negative simplex is positive, and the dual of a positive simplex is negative if it is paired and positive if it creates an essential cycle.

C Proof of Lemma 11

Consider a $(0, 1)$ -pair (v, e) of $\mathcal{F}$ not in $\mathcal{P}$. As above, we denote C_v and C_w the two components merged by e when it is added in $\mathcal{F}$. Let C'_v and C'_w be the two components merged by e in $\mathcal{G}$. Since reducing only lowers

⁴Note that i and j are indices in the filtration, so the simplex of index i in the primal is the same as the simplex of index $n + 1 - i$ in the dual.

simplices of $\{\mathcal{P}\}$, C_v and C_w can only grow in $\mathcal{G}$, i.e $C_v \subseteq C'_v$ and $C_w \subseteq C'_w$. Suppose for the purpose of contradiction that e is not paired with v in $\mathcal{G}$, and that v is the lowest vertex of $\mathcal{F} \setminus \{\mathcal{P}\}$ whose pairing is different in $\mathcal{G}$. Then the lowest vertex u of C'_v in $\mathcal{G}$ is not v . If $u \in C_v$, $u \in \{\mathcal{P}\}$ (its value changed). Since the simplices of $\{\mathcal{P}\}$ are paired with vertices of $\{\mathcal{P}\}$ in $\mathcal{G}$ (they form local pairs), e cannot be paired with u , so it must be paired with the lowest vertex w' of C'_w which is at least as low as w and then lower than v . For the same reason as before, $w' \notin \{\mathcal{P}\}$. w' is then a vertex of $\mathcal{F} \setminus \{\mathcal{P}\}$ whose pairing is different in $\mathcal{G}$ and is lower than v which contradicts our hypothesis. Assuming now that $u \in C'_v \setminus C_v$, the path from v to u must contain an edge of C'_v whose f -value is larger than the f -value of e in $\mathcal{F}$ (otherwise that path would already be in C_v). Consider the edge η on this path with largest f -value. This edge must be an edge of $\{\mathcal{P}\}$. It merges in $\mathcal{F}$ two components, one contains w and the other one contains u . So η must be paired in $\mathcal{F}$ with a vertex ν lower than u or w . But this implies $[v, e]_{\mathcal{F}} \subseteq [\nu, \eta]_{\mathcal{F}}$ and contradicts that $\mathcal{P}$ is closed by inclusion.

D Application to the topological simplification of terrains

We wrote an implementation of our algorithms using the python language. It is specialized to the topological simplification of terrains. The terrain is a triangulated 2D grid whose simplices are assigned a height value in $[0, 1]$. The terrain is made manifold by gluing dummy triangles from the boundary of the terrain to a dummy vertex, thus forming a topological 2-sphere. The dummy simplices are assigned height greater than one. In practice, this is not ideal, as the many dummy triangles and edges tend to interfere with the pairing of the actual terrain's simplices; it would be preferable to use a single dummy 2-dimensional face whose boundary spans the whole terrain boundary edges. Such a dummy face would become the only positive (and un-paired) 2-simplex, and would therefore not interfere with the pairing of the actual simplices. Figure 2 shows two simplifications of the height function of a terrain. Additional views of the same terrain, including 3D views, can be found at the following URL: <http://www-sop.inria.fr/members/Samuel.Hornus/simplif/>.

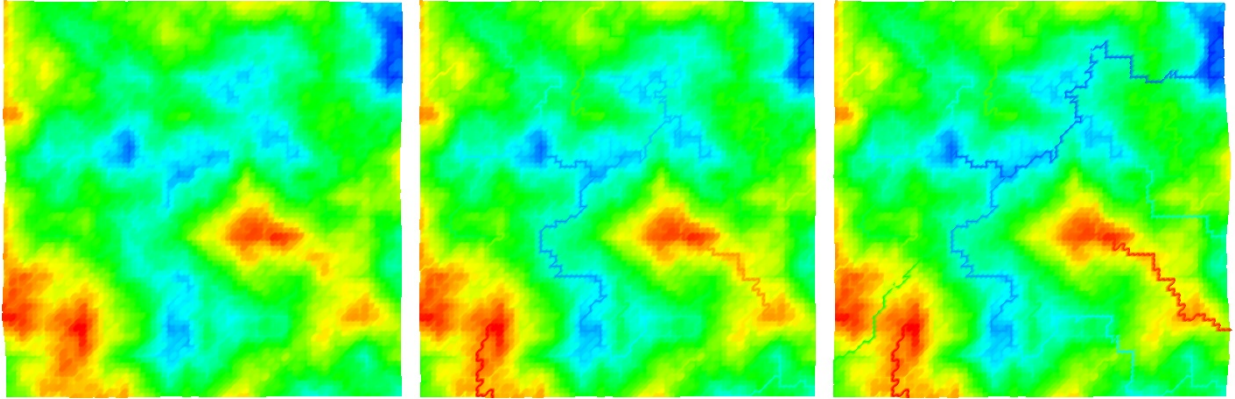


Figure 2: (This is a color figure) *Left*: a 80x80 terrain. Heights range from blue (low = 0.0), through cyan, green, yellow to red (high = 1.0). *Middle*: A 0.2-simplification of the height function has been computed. *Right*: A 1-simplification of the height function has been computed. The terrain has 38396 simplices. The computation of the spanning tree took 1.32 seconds. Each computation of the persistence pairs took roughly 2.37 seconds. Each simplification step took roughly 0.41 seconds. Timings were measured on a Core 2 duo 2.6 GHz processor.