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Lexicographic Optimal Homologous Chains and Applications to Point Cloud Triangulations

David Cohen-Steiner, André Lieutier, Julien Vuillamy

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1 **Lexicographic optimal homologous chains and applications**
2 **to point cloud triangulations**

3 **David Cohen-Steiner · André Lieutier · Julien**
4 **Vuillamy**

5
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7 **Abstract** This paper considers a particular case of the Optimal Homologous Chain
8 Problem (OHCP) for integer modulo 2 coefficients, where optimality is meant as a
9 minimal lexicographic order on chains induced by a total order on simplices. The
10 matrix reduction algorithm used for persistent homology is used to derive polynomial
11 algorithms solving this problem instance, whereas OHCP is NP-hard in the general
12 case. The complexity is further improved to a quasilinear algorithm by leveraging
13 a dual graph minimum cut formulation when the simplicial complex is a pseudo-
14 manifold. We then show how this particular instance of the problem is relevant, by
15 providing an application in the context of point cloud triangulation.

16 **Keywords** Simplicial homology, Point cloud triangulation, Delaunay triangulation

17 **Mathematics Subject Classification (2010)** 68U05

18 **1 Introduction**

19 **1.1 Problem statement**

20 The computation of minimal simplicial homology generators has been a wide subject
21 of interest for its numerous applications related to shape analysis, computer graphics

D. Cohen-Steiner
Université Côte d'Azur, Nice, France
Inria Sophia Antipolis - Méditerranée, Valbonne, France
E-mail: david.cohen-steiner@inria.fr

A. Lieutier
Dassault Systèmes Provence, Aix-en-Provence, France
E-mail: andre.lieutier@3ds.fr

J. Vuillamy
Université Côte d'Azur, Nice, France
Inria Sophia Antipolis - Méditerranée, Valbonne, France
Dassault Systèmes Provence, Aix-en-Provence, France
E-mail: julien.vuillamy@3ds.fr

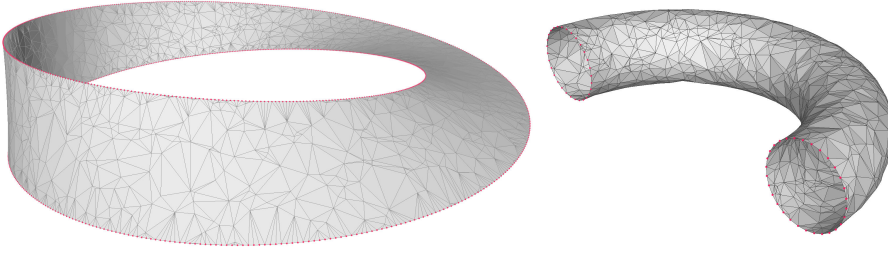


Fig. 1 Open surface triangulations under imposed boundaries (red cycles).

22 or computer-aided design. Coined in [21], we recall the Optimal Homologous Chain
 23 Problem (OHCP):

24 **Problem 1 (OHCP)** Given a d -chain A in a simplicial complex K and a set of weights
 25 given by a diagonal matrix W of appropriate dimension, find the L^1 -norm minimal
 26 chain Γ_{\min} homologous to A :

$$27 \quad \Gamma_{\min} = \min_{\Gamma, B} \|W \cdot \Gamma\|_1 \text{ such that } \Gamma = A + \partial_{d+1} B \text{ and } \Gamma \in C_d(K), B \in C_{d+1}(K)$$

28 It has been shown that OHCP is NP-hard in the general case when using coefficients in
 29 \mathbb{Z}_2 [9, 15]. However, we consider a specialization of this problem: the Lexicographic
 30 Optimal Homologous Chain Problem (Lex-OHCP). Using coefficients in \mathbb{Z}_2 , mini-
 31 mality is now meant according to a lexicographic order on chains induced by a total
 32 order on simplices. Formulated in the context of OHCP, this would require ordering
 33 the simplices using a total order and taking a weight matrix W with generic term
 34 $W_{ii} = 2^i$, where i is the rank along the total order, allowing the L^1 -norm minimization
 35 to be equivalent to a minimization along the lexicographic order.

36 1.2 Contributions

37 After providing some required definitions and notations (Section 2), we show how
 38 an algorithm based on the matrix reduction algorithm used for the computation
 39 of persistent homology [25] allows to solve this particular instance of OHCP in
 40 $O(n^3)$ worst case complexity (Section 3). Using a very similar process, we show that
 41 the problem of finding a minimal d -chain bounding a given $(d-1)$ -cycle admits
 42 a similar algorithm with the same algorithmic complexity (Section 4). Section 5
 43 then considers Lex-OHCP in the case where the simplicial complex K is a strongly
 44 connected $(d+1)$ -pseudomanifold. By formulating it as a Lexicographic Minimum
 45 Cut (LMC) dual problem, the algorithm can be improved to a quasilinear complexity:
 46 the cost of sorting the dual edges and performing a $O(E\alpha(E))$ algorithm based on
 47 disjoint-sets, where E is the number of dual edges and α is the inverse Ackermann
 48 function. Finally, Section 6 legitimizes this restriction of OHCP by characterizing
 49 the quality of lexicographic optimal homologous chains, namely in the context of
 50 point cloud triangulation. After defining a total order closely related to the Delaunay
 51 triangulation, we provide details on an open surface algorithm given a boundary as

52 well as a watertight surface reconstruction algorithm given an interior and exterior
53 information.

54 1.3 Related work

55 Several authors have studied algorithm complexities for the computation of L^1 -norm
56 optimal cycles in homology classes [9, 10, 13–15, 21–23, 27, 37]. However, to the
57 best of our knowledge, considering lexicographic-minimal chains in their homology
58 classes is a new idea. When minimal cycles are of codimension 1 in a pseudo-
59 manifold, the idea of considering the minimal cut problem on the dual graph has
60 been previously studied [35]. In particular, Chambers et al. [9] have considered graph
61 duality to derive complexity results for the computation of optimal homologous cycles
62 on 2-manifolds. Chen et al. [15] also use a reduction to a minimum cut problem
63 on a dual graph to compute minimal non-null homologous cycles on d -complexes
64 embedded in \mathbb{R}^d . Their polynomial algorithm (Theorem 5.2.3 in [15]) for computing
65 a homology class representative of minimal radius is reminiscent of our algorithm
66 for computing lexicographic minimal representatives (Algorithm 4). In a recent work
67 [22], Dey et al. consider the dual graph of pseudo-manifolds in order to obtain
68 polynomial time algorithms for computing minimal persistent cycles. Since they
69 consider arbitrary weights, they obtain the $\mathcal{O}(n^2)$ complexity of best known minimum
70 cut/maximum flow algorithms [34]. The lexicographic order introduced in our work
71 can be derived from the idea of a variational formulation of the Delaunay triangulation,
72 first introduced in [16] and further studied in [1, 17]. Finally, many methods have been
73 proposed to answer the problem of surface reconstruction in specific acquisition
74 contexts [30, 31, 33]: [32] classifies a large number of these methods according to the
75 assumptions and information used in addition to geometry. In the family of purely
76 geometric reconstruction based on a Delaunay triangulation, one early contribution
77 is the sculpting algorithm by Boissonnat [6]. The crust algorithm by Amenta et
78 al. [2, 3] and an algorithm based on natural neighbors [7] were the first algorithms
79 to guarantee a triangulation of the manifold under sampling conditions. However,
80 these general approaches usually have difficulties far from these sampling conditions,
81 in applications where point clouds are noisy or under-sampled. This difficulty can
82 be circumvented by providing additional information on the nature of the surface
83 [8, 20, 24]. Our contribution lies in this category of approaches. We provide some
84 topological information of the surface: a boundary for the open surface reconstruction
85 and interior and exterior regions for the closed surface reconstruction.

2 Definitions

2.1 Simplicial complexes

Consider an independent family $A = (a_0, \dots, a_d)$ of points of \mathbb{R}^N . We call a **d -simplex** σ spanned by A the set of all points:

$$x = \sum_{i=0}^d t_i a_i, \text{ where } \forall i \in \{0..d\}, t_i \geq 0 \text{ and } \sum_{i=0}^d t_i = 1$$

Any simplex spanned by a subset of A is called a **face** of σ .

A **simplicial complex** K is a collection of simplices such that every face of a simplex of K is in K and the intersection of two simplices of K is either empty or a common face.

2.2 Simplicial chains

Let K be a simplicial complex of dimension at least d . The notion of chains can be defined with coefficients in any ring but we restrict here the definition to coefficients in the field $\mathbb{Z}_2 = \mathbb{Z}/2\mathbb{Z}$. A **d -chain** A with coefficients in \mathbb{Z}_2 is a formal sum of d -simplices :

$$A = \sum_i x_i \sigma_i, \text{ with } x_i \in \mathbb{Z}_2 \text{ and } \sigma_i \in K$$

We denote $\mathbf{C}_d(K)$ the vector space over the field \mathbb{Z}_2 of d -chains in the complex K . Interpreting the coefficient $x_i \in \mathbb{Z}_2 = \{0, 1\}$ in front of simplex σ_i as indicating the existence of σ_i in the chain A , we can view the d -chain A as a set of simplices : for a d -simplex σ and a d -chain A , we write that $\sigma \in A$ if the coefficient for σ in A is 1. With this convention, the sum of two chains corresponds to the symmetric difference on their sets. In what follows, a d -simplex σ can also be interpreted as the d -chain containing only the d -simplex σ .

2.3 Boundary operator

For a d -simplex $\sigma = [a_0, \dots, a_d]$, the **boundary operator** is defined as the operator:

$$\begin{aligned} \partial_d : \mathbf{C}_d(K) &\rightarrow \mathbf{C}_{d-1}(K) \\ \partial_d \sigma &\stackrel{\text{def.}}{=} \sum_{i=0}^d [a_0, \dots, \widehat{a}_i, \dots, a_d] \end{aligned}$$

where the symbol \widehat{a}_i means the vertex a_i is deleted from the array. The kernel of the boundary operator $Z_d = \text{Ker } \partial_d$ is called the group of d -cycles and the image of the operator $B_d = \text{Im } \partial_{d+1}$ is the group of d -boundaries. We say two d -chains A and A' are **homologous** if $A - A' = \partial_{d+1} B$, for some $(d+1)$ -chain B .

2.4 Lexicographic order

We assume now a total order on the d -simplices of K , $\sigma_1 < \dots < \sigma_n$, where $n = \dim \mathcal{C}_d(K)$. From this order, we define a lexicographic total order on d -chains.

Definition 1 (Lexicographic total order) For $C_1, C_2 \in \mathcal{C}_d(K)$:

$$C_1 \sqsubseteq_{lex} C_2 \stackrel{\text{def.}}{\iff} \begin{cases} C_1 + C_2 = 0 \\ \text{or} \\ \sigma_{\max} = \max \{ \sigma \in C_1 + C_2 \} \in C_2 \end{cases}$$

This total order naturally extends to a strict total order \sqsubset_{lex} on $\mathcal{C}_d(K)$.

3 Lexicographic optimal homologous chain

3.1 Problem statement

In this section, we define a particular instance of OHCP (Problem 1), the Lexicographic Optimal Homologous Chain Problem (Lex-OHCP):

Problem 2 (Lex-OHCP) Given a simplicial complex K with a total order on the d -simplices and a d -chain $A \in \mathcal{C}_d(K)$, find the unique chain Γ_{\min} defined by :

$$\Gamma_{\min} = \min_{\sqsubseteq_{lex}} \left\{ \Gamma \in \mathcal{C}_d(K) \mid \exists B \in \mathcal{C}_{d+1}(K), \Gamma - A = \partial_{d+1} B \right\}$$

Definition 2 A d -chain $A \in \mathcal{C}_d(K)$ is said **reducible** if there is a d -chain $\Gamma \in \mathcal{C}_d(K)$ (called **reduction**) and a $(d+1)$ -chain $B \in \mathcal{C}_{d+1}(K)$ such that:

$$\Gamma \sqsubset_{lex} A \quad \text{and} \quad \Gamma - A = \partial_{d+1} B$$

If this property cannot be verified, the d -chain A is said **irreducible**. If A is reducible, we call **total reduction** of A the unique irreducible reduction of A . If A is irreducible, A is said to be its own total reduction.

Problem 2 can be reformulated as finding the total reduction of A .

3.2 Boundary matrix reduction

With $m = \dim \mathcal{C}_d(K)$ and $n = \dim \mathcal{C}_{d+1}(K)$, we now consider the m -by- n boundary matrix ∂_{d+1} with entries in \mathbb{Z}_2 . We enforce that rows of the matrix are ordered according to a given strict total order on d -simplices $\sigma_1 < \dots < \sigma_m$, where the d -simplex σ_i is the basis element corresponding to the i^{th} row of the boundary matrix. The order of columns, corresponding to an order on $(d+1)$ -simplices, is not relevant for this section and can be chosen arbitrarily.

For a matrix R , the index of the lowest (i.e. closest to the bottom) non-zero coefficient of a non-zero column R_j is denoted by $\text{low}(j)$, or sometimes $\text{low}(R_j)$ when we want to explicit the considered matrix.

143 Algorithm 1 is a slightly modified version of the boundary reduction algorithm
 144 presented in [25]. Indeed, for our purpose, we do not need the boundary matrix
 145 storing all the simplices of all dimensions and apply the algorithm to the sub-matrix
 146 $\partial_{d+1} : \mathbf{C}_{d+1}(K) \rightarrow \mathbf{C}_d(K)$. One checks easily that Algorithm 1 has $O(mn^2)$ time
 complexity. We now introduce a few lemmas useful for solving Problem 2. We allow

Algorithm 1: Reduction algorithm for the ∂_{d+1} matrix

Input: A boundary matrix ∂_{d+1}
Output: A reduced boundary matrix R
 $R = \partial_{d+1}$
for $j \leftarrow 1$ **to** n **do**
 | **while** $R_j \neq 0$ **and** $\exists j_0 < j$ with $\text{low}(j_0) = \text{low}(j)$ **do**
 | | $R_j \leftarrow R_j + R_{j_0}$
 | **end**
end

147 ourselves to consider each column R_j of the matrix R , formally an element of \mathbb{Z}_2^m , as
 148 the corresponding d -chain in the basis $(\sigma_1, \dots, \sigma_m)$.
 149

150 **Lemma 1** *A d -chain A is reducible if and only if at least one of its d -simplices is*
 151 *reducible.*

Proof If there is a reducible d -simplex $\sigma \in A$, A is reducible by the d -chain $A' = A - \sigma + \text{Red}(\sigma)$, where $\text{Red}(\sigma)$ is a reduction for σ .

We suppose A to be reducible. Let $\Gamma \sqsubseteq_{\text{lex}} A$ be a reduction for A and B the $(d+1)$ -chain such that $\Gamma - A = \partial B$. We denote $\sigma_{\max} = \max \{\sigma \in A - \Gamma\}$. Note that σ_{\max} is homologous to $\Gamma - A + \sigma_{\max}$. The chain $\Gamma - A + \sigma_{\max}$ only contains simplices smaller than σ_{\max} , by definition of the lexicographic order (Definition 1). We have thus shown that if A is reducible, it contains at least one simplex that is reducible. \square

152 **Lemma 2** *After matrix reduction (Algorithm 1), a non-zero column $R_j \neq 0$ can be*
 153 *described as*

$$R_j = \sigma_{\text{low}(j)} + \Gamma, \text{ where } \Gamma \text{ is a reduction for } \sigma_{\text{low}(j)}.$$

Proof As all matrix operations performed on R by the reduction algorithm consist of sums of columns of ∂_{d+1} , each non-zero column R_j of R is in the image of ∂_{d+1} . Therefore, there exists a $(d+1)$ -chain B such that $R_j = \sigma_{\text{low}(j)} + \Gamma = \partial_{d+1} B$, which, is equivalent in \mathbb{Z}_2 to $\Gamma - \sigma_{\text{low}(j)} = \partial_{d+1} B$. By definition of the low of a column, we also have immediately: $\Gamma \sqsubseteq_{\text{lex}} \sigma_{\text{low}(j)}$. For each non-zero column, the largest simplex is therefore reducible by the other d -simplices of the column. \square

155 **Lemma 3** *After matrix reduction (Algorithm 1), there is a one-to-one correspondence*
 156 *between the reducible d -simplices and non-zero columns of R :*

$$\sigma_i \in \mathbf{C}_d(K) \text{ is reducible} \iff \exists j \in \{1..n\}, R_j \neq 0 \text{ and } \text{low}(j) = i$$

157

158 *Proof* Lemma 2 shows immediately that the simplex corresponding to the lowest
 159 index of a non-zero column is reducible. Suppose now that a d -simplex $\tilde{\sigma}$ is reducible
 160 and let $\tilde{\Gamma}$ be a reduction of it: $\tilde{\sigma} + \tilde{\Gamma} = \partial_{d+1}B$ and $\tilde{\Gamma} \sqsubset_{lex} \tilde{\sigma}$. Algorithm 1 realizes
 161 the matrix factorization $R = \partial_{d+1} \cdot V$, where matrix V is invertible [25]. It follows
 162 that $\text{Im } R = \text{Im } \partial_{d+1}$. Therefore, non-zero columns of R span $\text{Im } \partial_{d+1}$ and since
 163 $\tilde{\sigma} + \tilde{\Gamma} = \partial_{d+1}B \in \text{Im } \partial_{d+1}$, there is a family $(R_j)_{j \in J} = (\sigma_{\text{low}(j)}, \Gamma_j)_{j \in J}$ of columns of
 164 R such that :

$$165 \quad \tilde{\sigma} + \tilde{\Gamma} = \sum_{j \in J} \sigma_{\text{low}(j)} + \Gamma_j$$

166 Every $\sigma_{\text{low}(j)}$ represents the largest simplex of a column, and Γ_j a reduction chain for
 167 $\sigma_{\text{low}(j)}$. As observed in section VII.1 of [25], one can check that the low indexes in R
 168 are unique after the reduction algorithm. Therefore, there is a $j_{\text{max}} \in J$ such that for
 169 all j in $J \setminus \{j_{\text{max}}\}$, $\text{low}(j) < \text{low}(j_{\text{max}})$, which implies:

$$170 \quad \sigma_{j_{\text{max}}} = \max \left\{ \sigma \in \sum_{j \in J} \sigma_{\text{low}(j)} + \Gamma_j \right\} = \max \left\{ \sigma \in \tilde{\sigma} + \tilde{\Gamma} \right\} = \tilde{\sigma}$$

We have shown that for the reducible simplex $\tilde{\sigma}$, there is a non-zero column $R_{j_{\text{max}}}$
 with $\tilde{\sigma} = \sigma_{\text{low}(j_{\text{max}})}$ as its largest simplex. \square

171 3.3 Total reduction algorithm

172 Combining the three previous lemmas give the intuition on how to construct the total
 173 reduction solving Problem 2: Lemma 1 allows to consider each simplex individually,
 174 Lemma 3 characterizes the reducible nature of a simplex using the reduced boundary
 175 matrix and Lemma 2 describes a column of the reduction boundary matrix as a simplex
 176 and its reduction. We now present Algorithm 2, referred to as the **total reduction**
 177 **algorithm**. For a d -chain Γ , $\Gamma[i] \in \mathbb{Z}_2$ denotes the coefficient of the i^{th} simplex in
 the chain Γ .

Algorithm 2: Total reduction algorithm

Inputs: A d -chain Γ , the reduced boundary matrix R
Output: The total reduction of Γ
for $i \leftarrow m$ **to** 1 **do**
 | **if** $\Gamma[i] \neq 0$ **and** $\exists j \in \{1..n\}$ with $\text{low}(j) = i$ in R **then**
 | | $\Gamma \leftarrow \Gamma + R_j$
 | **end**
end

178

179 **Proposition 1** Algorithm 2 finds the total reduction of a given d -chain in $O(m^2)$ time
 180 complexity.

181 *Proof* In Algorithm 2, let Γ_{i-1} be the value of the variable Γ after iteration i . Since
 182 the iteration counter i decreases from m to 1, the input and output of the algorithm are

183 respectively Γ_m and Γ_0 . At each iteration, Γ_{i-1} are either equal to Γ_i or $\Gamma_i + R_j$. Since
 184 $R_j \in \text{Im } \partial_{d+1}$, Γ_{i-1} is in both cases homologous to Γ_i . Therefore, Γ_0 is homologous to
 185 Γ_m . We are left to show that Γ_0 is irreducible. From Lemma 1, it is enough to check
 186 that it does not contain any reducible simplex.

187 Let σ_i be a reducible simplex and let us show that $\sigma_i \notin \Gamma_0$. Two possibilities may
 188 occur:

- 189 – if $\sigma_i \in \Gamma_i$, then $\Gamma_{i-1} = \Gamma_i + R_j$. Since $\text{low}(j) = i$, we have $\sigma_i \in R_j$ and therefore
 190 $\sigma_i \notin \Gamma_{i-1}$.
- 191 – if $\sigma_i \notin \Gamma_i$, then $\Gamma_{i-1} = \Gamma_i$ and again $\sigma_i \notin \Gamma_{i-1}$.

192 Furthermore, from iterations $i - 1$ to 1, the added columns R_j contain only simplices
 193 smaller than σ_i and therefore $\sigma_i \notin \Gamma_{i-1} \Rightarrow \sigma_i \notin \Gamma_0$.

Observe that using an auxiliary array allows to compute the correspondence
 $\text{low}(j) \rightarrow i$ in time $\mathcal{O}(1)$. The column addition nested inside the loop lead to a $\mathcal{O}(m^2)$
 time complexity for Algorithm 2. \square

194 It follows that Problem 2 can be solved in $\mathcal{O}(mn^2)$ time complexity, by applying
 195 successively Algorithms 1 and 2, or in $\mathcal{O}(N^3)$ complexity if N is the size of the
 196 simplicial complex.

197 4 Lexicographic-minimal chain under imposed boundary

198 4.1 Problem statement

199 This section will study a variant of Lex-OHCP (Problem 3) in order to solve the
 200 subsequent problem of finding a minimal d -chain bounding a given $(d - 1)$ -cycle
 201 (Problem 4).

202 **Problem 3** Given a simplicial complex K with a total order on the d -simplices and a
 203 d -chain $\Gamma_0 \in \mathcal{C}_d(K)$, find :

$$204 \quad \Gamma_{\min} = \min_{\sqsubseteq_{lex}} \left\{ \Gamma \in \mathcal{C}_d(K) \mid \partial_d \Gamma = \partial_d \Gamma_0 \right\}$$

205 **Problem 4** Given a simplicial complex K with a total order on the d -simplices and a
 206 $(d - 1)$ -cycle A , check if A is a boundary:

$$207 \quad B_A \stackrel{\text{def.}}{=} \left\{ \Gamma \in \mathcal{C}_d(K) \mid \partial_d \Gamma = A \right\} \neq \emptyset$$

208 If it is the case, find the minimal d -chain Γ bounded by A :

$$209 \quad \Gamma_{min} = \min_{\sqsubseteq_{lex}} B_A$$

210 In Problem 4, finding a representative Γ_0 in the set $B_A \neq \emptyset$ such that $\partial_d \Gamma_0 = A$ is
 211 sufficient: we are then taken back to Problem 3 to find the minimal d -chain Γ_{\min} such
 212 that $\partial_d \Gamma_{\min} = \partial_d \Gamma_0 = A$.

Algorithm 3: Total reduction variant

Inputs: A d -chain Γ and V^{Ker}
Output: The minimal chain with the same boundary as Γ

```

for  $i \leftarrow m$  to 1 do
  if  $\Gamma[i] \neq 0$  and  $\exists j \in \{1..n^{\text{Ker}}\}$  with  $\text{low}(j) = i$  in  $V^{\text{Ker}}$  then
     $\Gamma \leftarrow \Gamma + V_j^{\text{Ker}}$ 
  end
end

```

241 *Proof* The proof is similar to the one of Proposition 1.

242 In Algorithm 3, we denote by Γ_{i-1} the value of variable Γ after iteration i . Since
 243 iteration counter i is decreasing from m to 1, the input and output of the algorithm are
 244 respectively Γ_m and Γ_0 . Since $V_j^{\text{Ker}} \in \text{Ker } \partial_d$, at each iteration $\partial\Gamma_{i-1} = \partial\Gamma_i$ therefore
 245 $\partial\Gamma_0 = \partial\Gamma_m$. We are left to show the algorithm's result is the minimal solution.

246 Suppose there is Γ^* such that $\partial_d\Gamma^* = \partial\Gamma$ and $\Gamma^* \sqsubset_{lex} \Gamma_0$. Let's consider the
 247 difference $\Gamma_0 - \Gamma^*$, and its largest element index $\text{low}(\Gamma_0 - \Gamma^*) = i$, with $\sigma_i \in \Gamma_0$
 248 and $\sigma_i \notin \Gamma^*$ by Definition 1 of the lexicographic order. As $\Gamma_0 - \Gamma^* \in \text{Ker } \partial_d \setminus \{0\}$,
 249 there has to be a column V_j^{Ker} in V^{Ker} where $\text{low}(V_j^{\text{Ker}}) = i$, from Lemma 4. Two
 250 possibilities may occur at iteration i :

- 251 – if $\sigma_i \in \Gamma_i$, then $\Gamma_{i-1} = \Gamma_i + V_j^{\text{Ker}}$. Since $i = \text{low}(j)$, we have $\sigma_i \in V_j^{\text{Ker}}$ and
 252 therefore $\sigma_i \notin \Gamma_{i-1}$.
- 253 – if $\sigma_i \notin \Gamma_i$, then $\Gamma_{i-1} = \Gamma_i$ and again $\sigma_i \notin \Gamma_{i-1}$.

However, from iterations $i-1$ to 1, the added columns V_j^{Ker} contains only simplices with
 indices smaller than i and therefore we obtain $\sigma_i \notin \Gamma_{i-1} \Rightarrow \sigma_i \notin \Gamma_0$, a contradiction
 to the definition of σ_i as the largest element of $\Gamma^* - \Gamma_0$. \square

254 4.4 Finding a representative of \mathbf{B}_A

255 As previously mentioned, solving Problem 4 requires deciding if the set B_A is empty
 256 and in case it is not empty, finding an element of the set B_A . Algorithm 3 can then be
 257 used to minimize this element under imposed boundary. In the following algorithm,
 258 $m = \dim C_{d-1}(K)$ and $n = \dim C_d(K)$.

259 **Proposition 3** *Algorithm 4 decides if the set B_A is non-empty, and in that case, finds*
 260 *a representative Γ_0 such that $\partial\Gamma_0 = A$ in $O(m^2)$ time complexity.*

261 *Proof* We start by two trivial observations from the definition of a reduction. First, A
 262 is a boundary if and only if its total reduction is the null chain. Second, if a non-null
 263 chain is a boundary, then its greatest simplex is reducible.

264 If, at iteration i , $A_0[i] \neq 0$, then σ_i is the greatest simplex in A_0 . In the case R has
 265 no column R_j such that $\text{low}(j) = i$, σ_i is not reducible by Lemma 3 and therefore A_0
 266 is not a boundary. Since A and A_0 differ by a boundary (added columns of R), A is
 267 not a boundary either. This means the set B_A is empty.

268 The main difference with the previous chain reduction is we keep track of the column

Algorithm 4: Finding a representative

Inputs: A $(d - 1)$ -chain A , a boundary matrix R reduced by V
Output: A d -chain Γ_0 bounded by A if A is a boundary.
 $\Gamma_0 \leftarrow \emptyset$
 $A_0 \leftarrow A$
for $i \leftarrow m$ **to** 1 **do**
 if $A_0[i] \neq 0$ **then**
 if $\exists j \in \{1..n\}$ with $\text{low}(j) = i$ **in** R **then**
 $A_0 \leftarrow A_0 + R_j$
 $\Gamma_0 \leftarrow \Gamma_0 + V_j$
 else
 The set B_A is empty.
 end
 end
end

269 operations in Γ_0 . If the total reduction of A is null, we have found a linear combination
270 $(R_j)_{j \in J}$ such that $A = \sum_{j \in J} R_j$. We have also computed Γ_0 as the sum of the
271 corresponding columns in V : $\Gamma_0 = \sum_{j \in J} V_j$. As $R = \partial_d \cdot V$, we can now verify:

$$272 \quad \partial_d \Gamma_0 = \partial_d \left(\sum_{j \in J} V_j \right) = \sum_{j \in J} R_j = A$$

□

273 **5 Efficient algorithm for codimension 1 (dual graph)**

274 In this section we focus on Problem 5, a specialization of Problem 2, namely when K
275 is a subcomplex of a $(d + 1)$ -pseudomanifold.

276 5.1 Problem statement

277 Recall that a d -dimensional simplicial complex is said **pure** if it is of dimension d
278 and any simplex has at least one coface of dimension d .

279 **Definition 3** A d -**pseudomanifold** is a pure d -dimensional simplicial complex for
280 which each $(d - 1)$ -face has exactly two d -dimensional cofaces.

281 **Definition 4** The **dual graph** of a d -pseudomanifold \mathcal{M} is the graph whose vertices
282 are in one-to-one correspondence with the d -simplices of \mathcal{M} and whose edges are in
283 one-to-one correspondence with $(d - 1)$ -simplices of \mathcal{M} : an edge e connects two
284 vertices v_1 and v_2 of the graph if and only if e corresponds to the $(d - 1)$ -face with
285 cofaces corresponding to v_1 and v_2 .

286 **Definition 5** A **strongly connected** d -pseudomanifold is a d -pseudomanifold whose
287 dual graph is connected.

288 Given a strongly connected $(d + 1)$ -pseudomanifold \mathcal{M} and $\tau_1 \neq \tau_2$ two $(d + 1)$ -
 289 simplices of \mathcal{M} , we consider a special case of Problem 2 where $K = \mathcal{M} \setminus \{\tau_1, \tau_2\}$ and
 290 $A = \partial\tau_1$:

291 **Problem 5** Given a strongly connected $(d + 1)$ -pseudomanifold \mathcal{M} with a total order
 292 on the d -simplices and two distinct $(d + 1)$ -simplices (τ_1, τ_2) of \mathcal{M} , find:

$$293 \quad \Gamma_{\min} = \min_{\sqsubseteq_{lex}} \left\{ \Gamma \in \mathbf{C}_d(\mathcal{M}) \mid \exists B \in \mathbf{C}_{d+1}(\mathcal{M} \setminus \{\tau_1, \tau_2\}), \Gamma - \partial\tau_1 = \partial B \right\}$$

294 **Definition 6** Seeing a graph G as a 1-dimensional simplicial complex, we define
 295 the **coboundary operator** $\partial^0 : \mathbf{C}_0(G) \rightarrow \mathbf{C}_1(G)$ as the linear operator defined by
 296 the transpose of the matrix of the boundary operator $\partial_1 : \mathbf{C}_1(G) \rightarrow \mathbf{C}_0(G)$ in the
 297 canonical basis of simplices.¹

298 For a given graph $G = (\mathcal{V}, \mathcal{E})$, \mathcal{V} and \mathcal{E} respectively denote its vertex and edge sets.
 299 For a d -chain $\alpha \in \mathbf{C}_d(\mathcal{M})$ and a $(d + 1)$ -chain $\beta \in \mathbf{C}_{d+1}(\mathcal{M})$, $\tilde{\alpha}$ and $\tilde{\beta}$ denote their
 300 respective dual 1-chain and dual 0-chain in the dual graph $G(\mathcal{M})$ of \mathcal{M} . We easily
 301 see that:

302 *Remark 1* For a set of vertices $\mathcal{V}_0 \subset \mathcal{V}$, $\partial^0\mathcal{V}_0$ is exactly the set of edges in $G = (\mathcal{V}, \mathcal{E})$
 303 that connect vertices in \mathcal{V}_0 with vertices in $\mathcal{V} \setminus \mathcal{V}_0$.

304 *Remark 2* Let \mathcal{M} be a $(d + 1)$ -pseudomanifold. If $\alpha \in \mathbf{C}_d(\mathcal{M})$ and $\beta \in \mathbf{C}_{d+1}(\mathcal{M})$,
 305 then $\tilde{\alpha} = \partial^0\tilde{\beta} \iff \alpha = \partial_{d+1}\beta$.

306 5.2 Codimension 1 and Lexicographic Min Cut (LMC)

307 The order on d -simplices of a $(d + 1)$ -pseudomanifold \mathcal{M} naturally defines a corre-
 308 sponding order on the edges of the dual graph: $\tau_1 < \tau_2 \iff \tilde{\tau}_1 < \tilde{\tau}_2$. This order
 309 extends similarly to a lexicographic order \sqsubseteq_{lex} on sets of edges (or, equivalently,
 310 1-chains) in the graph.

311 In what follows, we say a set of edges $\tilde{\Gamma}$ **disconnects** $\tilde{\tau}_1$ and $\tilde{\tau}_2$ in the graph $(\mathcal{V}, \mathcal{E})$
 312 if $\tilde{\tau}_1$ and $\tilde{\tau}_2$ are not in the same connected component of the graph $(\mathcal{V}, \mathcal{E} \setminus \tilde{\Gamma})$.

313 Given a graph with weighted edges and two vertices, the min-cut/max-flow prob-
 314 lem [26, 34] consists in finding the minimum cut (i.e. set of edges) disconnecting the
 315 two vertices, where minimum is meant as minimal sum of weights of cut edges. We
 316 consider a similar problem where the minimum is meant in term of a lexicographic
 317 order: the Lexicographic Min Cut (LMC).

318 **Problem 6 (LMC)** Given a connected graph $G = (\mathcal{V}, \mathcal{E})$ with a total order on \mathcal{E} and
 319 two vertices $\tilde{\tau}_1, \tilde{\tau}_2 \in \mathcal{V}$, find the set $\tilde{\Gamma}_{\text{LMC}} \subset \mathcal{E}$ minimal for the lexicographic order
 320 \sqsubseteq_{lex} , that disconnects $\tilde{\tau}_1$ and $\tilde{\tau}_2$ in G .

¹ In order to avoid to introduce non essential formal definitions, the coboundary operator is defined over chains since, for finite simplicial complexes, the canonical inner product defines a natural bijection between chains and cochains.

321 **Proposition 4** Γ_{\min} is solution of Problem 5 if and only if its dual 1-chain $\tilde{\Gamma}_{\min}$ is
 322 solution of Problem 6 on the dual graph $G(\mathcal{M})$ of \mathcal{M} where $\tilde{\tau}_1$ and $\tilde{\tau}_2$ are respective
 323 dual vertices of τ_1 and τ_2 .

324 *Proof* Problem 5 can be equivalently formulated as:

$$325 \quad \Gamma_{\min} = \min_{\sqsubseteq_{lex}} \left\{ \partial_{d+1}(\tau_1 + B) \mid B \in \mathcal{C}_{d+1}(\mathcal{M} \setminus \{\tau_1, \tau_2\}) \right\} \quad (1)$$

326 Using Observation 2, we see that Γ_{\min} is the minimum in Equation (1) if and only if
 327 its dual 1-chain $\tilde{\Gamma}_{\min}$ satisfies:

$$328 \quad \tilde{\Gamma}_{\min} = \min_{\sqsubseteq_{lex}} \left\{ \partial^0(\tilde{\tau}_1 + \tilde{B}) \mid \tilde{B} \subset \mathcal{V} \setminus \{\tilde{\tau}_1, \tilde{\tau}_2\} \right\} \quad (2)$$

329 Denoting $\tilde{\Gamma}_{\text{LMC}}$ the minimum of Problem 6, we need to show that $\tilde{\Gamma}_{\text{LMC}} = \tilde{\Gamma}_{\min}$.
 330 As $\tilde{\Gamma}_{\text{LMC}}$ disconnects $\tilde{\tau}_1$ and $\tilde{\tau}_2$ in $G = (\mathcal{V}, \mathcal{E})$, $\tilde{\tau}_2$ is not in the connected component of
 331 $\tilde{\tau}_1$ in $(\mathcal{V}, \mathcal{E} \setminus \tilde{\Gamma}_{\text{LMC}})$. We define \tilde{B} as the connected component of $\tilde{\tau}_1$ in $(\mathcal{V}, \mathcal{E} \setminus \tilde{\Gamma}_{\text{LMC}})$
 332 minus $\tilde{\tau}_1$. We have that $\tilde{B} \subset \mathcal{V} \setminus \{\tilde{\tau}_1, \tilde{\tau}_2\}$. Consider an edge $e \in \partial^0(\tilde{\tau}_1 + \tilde{B})$. From
 333 Observation 1, e connects a vertex $v_a \in \{\tilde{\tau}_1\} \cup \tilde{B}$ with a vertex $v_b \notin \{\tilde{\tau}_1\} \cup \tilde{B}$. From
 334 the definition of \tilde{B} , $\tilde{\Gamma}_{\text{LMC}}$ disconnects v_a and v_b in G , which in turn implies $e \in \tilde{\Gamma}_{\text{LMC}}$.
 335 We have therefore shown that $\partial^0(\tilde{\tau}_1 + \tilde{B}) \subset \tilde{\Gamma}_{\text{LMC}}$. Using Equation (2), we get:

$$336 \quad \tilde{\Gamma}_{\min} \sqsubseteq_{lex} \partial^0(\tilde{\tau}_1 + \tilde{B}) \sqsubseteq_{lex} \tilde{\Gamma}_{\text{LMC}} \quad (3)$$

Now we claim that if there is a $\tilde{C} \subset \mathcal{V} \setminus \{\tilde{\tau}_1, \tilde{\tau}_2\}$ with $\tilde{\Gamma} = \partial^0(\tilde{\tau}_1 + \tilde{C})$, then $\tilde{\Gamma}$
 disconnects $\tilde{\tau}_1$ and $\tilde{\tau}_2$ in $(\mathcal{V}, \mathcal{E})$. Consider a path in G from $\tilde{\tau}_1$ to $\tilde{\tau}_2$. Let v_a be the last
 vertex of the path that belongs to $\{\tilde{\tau}_1\} \cup \tilde{C}$ and v_b the next vertex on the path (which
 exists since $\tilde{\tau}_2$ is not in $\{\tilde{\tau}_1\} \cup \tilde{C}$). From Observation 1, we see that the edge (v_a, v_b)
 must belong to $\tilde{\Gamma} = \partial^0(\tilde{\tau}_1 + \tilde{C})$. We have shown that any path in G connecting $\tilde{\tau}_1$ and
 $\tilde{\tau}_2$ has to contain an edge in $\tilde{\Gamma}$ and the claim is proved.

In particular, the minimum $\tilde{\Gamma}_{\min}$ disconnects $\tilde{\tau}_1$ and $\tilde{\tau}_2$ in $(\mathcal{V}, \mathcal{E})$. As $\tilde{\Gamma}_{\text{LMC}}$ denotes
 the minimum of Problem 6, $\tilde{\Gamma}_{\text{LMC}} \sqsubseteq_{lex} \tilde{\Gamma}_{\min}$ which, together with Equation (3), gives
 us $\tilde{\Gamma}_{\text{LMC}} = \tilde{\Gamma}_{\min}$. We have therefore shown the minimum defined by Equation (2)
 coincides with the minimum defined in Problem 6. \square

337 5.3 Algorithm for Lexicographic Min Cut

338 In light of the new problem equivalency, we will study an algorithm solving Problem
 339 6. As we will only consider the dual graph for this section, we leave behind the dual
 340 chain notation: vertices $\tilde{\tau}_1$ and $\tilde{\tau}_2$ are replaced by α_1 and α_2 , and the solution to the
 341 problem is simply noted Γ_{LMC} . The following lemma exposes a constructive property
 342 of the solution on subgraphs.

343 **Lemma 5** Consider Γ_{LMC} solution of Problem 6 for the graph $G = (\mathcal{V}, \mathcal{E})$ and
 344 $\alpha_1, \alpha_2 \in \mathcal{V}$. Let e_0 be an edge in $\mathcal{V} \times \mathcal{V}$ such that $e_0 < \min\{e \in \mathcal{E}\}$. Then:

345 – The solution for $(\mathcal{V}, \mathcal{E} \cup \{e_0\})$ is either Γ_{LMC} or $\Gamma_{\text{LMC}} \cup \{e_0\}$.

346 – $\Gamma_{\text{LMC}} \cup \{e_0\}$ is solution for $(\mathcal{V}, \mathcal{E} \cup \{e_0\})$ if and only if α_1 and α_2 are connected
 347 in $(\mathcal{V}, \mathcal{E} \cup \{e_0\} \setminus \Gamma_{\text{LMC}})$.

348 *Proof* Let's call Γ'_{LMC} the solution for $(\mathcal{V}, \mathcal{E} \cup \{e_0\})$. Since $\Gamma'_{\text{LMC}} \cap \mathcal{E}$ disconnects
 349 α_1 and α_2 in $(\mathcal{V}, \mathcal{E})$, one has $\Gamma_{\text{LMC}} \sqsubseteq_{\text{lex}} \Gamma'_{\text{LMC}}$. Since $\Gamma_{\text{LMC}} \cup \{e_0\}$ disconnects
 350 α_1 and α_2 in $(\mathcal{V}, \mathcal{E} \cup \{e_0\})$, we also have $\Gamma'_{\text{LMC}} \sqsubseteq_{\text{lex}} \Gamma_{\text{LMC}} \cup \{e_0\}$. Therefore,
 351 $\Gamma_{\text{LMC}} \sqsubseteq_{\text{lex}} \Gamma'_{\text{LMC}} \sqsubseteq_{\text{lex}} \Gamma_{\text{LMC}} \cup \{e_0\}$.

As $e_0 < \min\{e \in \mathcal{E}\}$, there is no set in $\mathcal{E} \cup \{e_0\}$ strictly between Γ_{LMC} and $\Gamma_{\text{LMC}} \cup \{e_0\}$ for the lexicographic order. It follows that Γ'_{LMC} is either equal to Γ_{LMC} or $\Gamma_{\text{LMC}} \cup \{e_0\}$. The choice for Γ'_{LMC} is therefore ruled by the property that it should disconnect α_1 and α_2 : if α_1 and α_2 are connected in $(\mathcal{V}, \mathcal{E} \cup \{e_0\} \setminus \Gamma_{\text{LMC}})$, Γ_{LMC} does not disconnect α_1 and α_2 in $(\mathcal{V}, \mathcal{E} \cup \{e_0\})$ and $\Gamma_{\text{LMC}} \cup \{e_0\}$ has to be the solution for $(\mathcal{V}, \mathcal{E} \cup \{e_0\})$. On the other hand, if α_1 and α_2 are not connected in $(\mathcal{V}, \mathcal{E} \cup \{e_0\} \setminus \Gamma_{\text{LMC}})$, then both Γ_{LMC} and $\Gamma_{\text{LMC}} \cup \{e_0\}$ disconnect α_1 and α_2 in $(\mathcal{V}, \mathcal{E} \cup \{e_0\})$, but as $\Gamma_{\text{LMC}} \sqsubset_{\text{lex}} \Gamma_{\text{LMC}} \cup \{e_0\}$, $\Gamma_{\text{LMC}} \cup \{e_0\}$ is not the solution for $(\mathcal{V}, \mathcal{E} \cup \{e_0\})$. \square

352 Building an algorithm from Lemma 5 suggests a data structure able to check
 353 if vertices α_1 and α_2 are connected in the graph: the disjoint-set data structure,
 354 introduced for finding connected components [28], does exactly that. In this structure,
 355 each set of elements has a different root value, called representative. Calling the
 356 operation **MakeSet** on an element creates a new set containing this element. The
 357 **FindSet** operation, given an element of a set, returns the representative of the set. For
 358 all elements of the same set, **FindSet** will of course return the same representative.
 359 Finally, the structure allows merging two sets, by using the **UnionSet** operation. After
 360 this operation, elements of both sets will have the same representative.

361 We now describe Algorithm 5. The algorithm expects a set of edges sorted in
 362 decreasing order according to the lexicographic order.

Algorithm 5: Lexicographic Min Cut

Inputs: $G = (\mathcal{V}, \mathcal{E})$ and $\alpha_1, \alpha_2 \in \mathcal{V}$, with $\mathcal{E} = \{e_i, i = 1, \dots, n\}$ in decreasing order

Output: Γ_{LMC}

$\Gamma_{\text{LMC}} \leftarrow \emptyset$

for $v \in \mathcal{V}$ **do**

 | **MakeSet**(v)

end

for $e \in \mathcal{E}$ in decreasing order **do**

 | $e = (v_1, v_2) \in \mathcal{V} \times \mathcal{V}$

 | $r_1 \leftarrow \mathbf{FindSet}(v_1), r_2 \leftarrow \mathbf{FindSet}(v_2)$

 | $c_1 \leftarrow \mathbf{FindSet}(\alpha_1), c_2 \leftarrow \mathbf{FindSet}(\alpha_2)$

 | **if** $\{r_1, r_2\} = \{c_1, c_2\}$ **then**

 | $\Gamma_{\text{LMC}} \leftarrow \Gamma_{\text{LMC}} \cup e$

 | **else**

 | **UnionSet**(r_1, r_2)

 | **end**

end

363 **Proposition 5** *Algorithm 5 computes the solution of Problem 6 for a given graph*
 364 *$(\mathcal{V}, \mathcal{E})$ and two vertices $\alpha_1, \alpha_2 \in \mathcal{V}$. Assuming the input set of edges \mathcal{E} are sorted,*
 365 *the algorithm has $O(n\alpha(n))$ time complexity, where n is the cardinal of \mathcal{E} and α the*
 366 *inverse Ackermann function.*

367 *Proof* We denote by e_i the i^{th} edge along the decreasing order and Γ_{LMC}^i the value
 368 of the variable Γ_{LMC} of the algorithm after iteration i . The algorithm works by
 369 incrementally adding edges in decreasing order and tracking the growing connected
 370 components of the set associated with α_1 and α_2 in $(\mathcal{V}, \{e \in \mathcal{E}, e \geq e_i\} \setminus \Gamma_{\text{LMC}}^i)$, for
 371 $i = 1, \dots, n$.

372 At the beginning, no edges are inserted, and $\Gamma_{\text{LMC}}^0 = \emptyset$ is indeed solution for
 373 (\mathcal{V}, \emptyset) . With Lemma 5, we are guaranteed at each iteration i to find the solution for
 374 $(\mathcal{V}, \{e \in \mathcal{E}, e \geq e_i\})$ by only adding to $\Gamma_{\text{LMC}}^{i-1}$ the current edge e_i if α_1 and α_2 are
 375 connected in $\{e \in \mathcal{E}, e \geq e_i\} \setminus \Gamma_{\text{LMC}}^{i-1}$, which is done in the if-statement. If the edge is
 376 not added, we update the connectivity of the graph $(\mathcal{V}, \{e \in \mathcal{E}, e \geq e_i\} \setminus \Gamma_{\text{LMC}}^i)$ by
 377 merging the two sets represented by r_1 and r_2 . After each iteration, Γ_{LMC}^i is solution
 378 for $(\mathcal{V}, \{e \in \mathcal{E}, e \geq e_i\})$ and when all edges are processed, Γ_{LMC}^n is solution for
 379 $(\mathcal{V}, \mathcal{E})$.

The complexity of the **MakeSet**, **FindSet** and **UnionSet** operations have been shown to be respectively $O(1)$, $O(\alpha(v))$ and $O(\alpha(v))$, where $\alpha(v)$ is the inverse Ackermann function on the cardinal of the vertex set [36]. Assuming sorted edges as input of the algorithm – which is performed in $O(n \ln(n))$, the algorithm runs in $O(n\alpha(n))$ time complexity. \square

380 The similarity of Algorithm 5 with Kruskal’s algorithm for minimum spanning-
 381 tree suggests an even better theoretical time complexity, by using Chazelle’s algorithm
 382 [12] for minimum spanning-tree, running in $O(n\alpha(n))$ complexity without requiring
 383 sorted edges.

384 6 Application to point cloud triangulation

385 In all that precedes, the order on simplices was not specified and one can wonder if
 386 choosing such an ordering makes the specialization of OHCP too restrictive for it to
 387 be useful. In this section, we give a concrete example where this restriction makes
 388 sense and provides a simple and elegant application to the problem of point cloud
 389 triangulation. Whereas all that preceded dealt with an abstract simplicial complex,
 390 we now consider a bijection between vertices and a set of points in Euclidean space,
 391 allowing to compute geometric quantities on simplices.

392 6.1 Simplicial ordering

393 Recent works have studied a characterization of the 2D Delaunay triangulation as a
 394 lexicographic minimum over 2-chains. Denote by $R_{\text{B}}(\sigma)$ the radius of the smallest
 395 enclosing ball and $R_{\text{C}}(\sigma)$ the radius of the circumcircle of a 2-simplex σ . For an

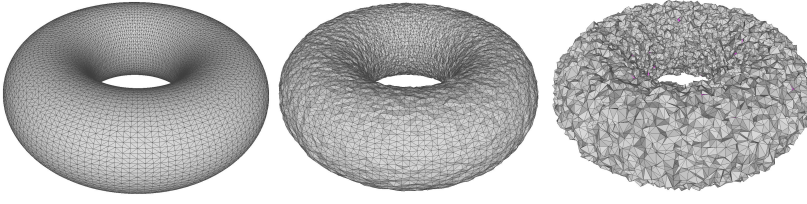


Fig. 2 Watertight reconstructions under different perturbations. Under small perturbations (first two images from the left), the reconstruction is a triangulation of the sampled manifold. A few non-manifold configurations appear however under larger perturbations (Rightmost image).

396 acute triangle σ , $R_B(\sigma) = R_C(\sigma)$. Based on [18, 19], we define the total order on
 397 2-simplices:

$$398 \quad \sigma_1 \leq \sigma_2 \iff \begin{cases} R_B(\sigma_1) < R_B(\sigma_2) \\ \text{or} \\ R_B(\sigma_1) = R_B(\sigma_2) \quad \text{and} \quad R_C(\sigma_1) \geq R_C(\sigma_2) \end{cases} \quad (4)$$

399 Under generic condition on the position of points, we can show this order is total. In
 400 what follows, the lexicographic order \sqsubseteq_{lex} is induced by this order on simplices. The
 401 following proposition from [19] shows a strong link between the simplex ordering
 402 and the 2D Delaunay triangulation.

403 **Proposition 6 (Proposition 7.9 in [19])** *Let $\mathbf{P} = \{P_1, \dots, P_N\} \subset \mathbb{R}^2$ with $N \geq 3$ be*
 404 *in general position and let $K_{\mathbf{P}}$ be any 2-dimensional complex containing the Delaunay*
 405 *triangulation of \mathbf{P} . Denote by $\beta_{\mathbf{P}} \in C_1(K_{\mathbf{P}})$ the 1-chain made of edges belonging to*
 406 *the boundary of convex hull $\mathcal{CH}(\mathbf{P})$. If $\Gamma_{\min} = \min_{\sqsubseteq_{lex}} \{\Gamma \in C_2(K_{\mathbf{P}}), \partial\Gamma = \beta_{\mathbf{P}}\}$, the*
 407 *simplicial complex $|\Gamma_{\min}|$ support of Γ_{\min} is the Delaunay triangulation of \mathbf{P} .*

408 As the 2D Delaunay triangulation has some well-known optimality properties, such
 409 as maximizing the minimal angle, we can hope that using the same order to minimize
 410 2-chains in dimension 3 will keep some of those properties. In fact, it has been shown
 411 that for a Čech or Vietoris-Rips complex, under strict conditions linking the point set
 412 sampling, the parameter of the complex and the reach of the underlying manifold of
 413 Euclidean space, the minimal lexicographic chain using the described simplex order
 414 is a triangulation of the sampled manifold [18]. Experimental results (Figure 2) show
 415 that this property remains true relatively far from these theoretical conditions.

416 6.2 Open surface triangulation

417 Given a point cloud sampling an open surface and a 1-cycle sampling the boundary of
 418 the surface, we generate a Čech complex of the point cloud using the Phat library [5].
 419 The parameter of the complex should be sufficient to capture the homotopy type
 420 of the surface to reconstruct and should contain the provided boundary cycle. After
 421 constructing the 2-boundary matrix, we apply the boundary reduction algorithm,
 422 slightly modified to store the transformation matrix V (Section 4.2). We then apply

423 Algorithm 4 to find out if a 2-chain bounded by the cycle exists in the current Čech
 424 complex. In this case, we get a chain bounded by the provided cycle and apply
 425 Algorithm 3 to minimize the chain under imposed boundary. Otherwise, we might
 426 have to increase the Čech parameter to capture the homotopy type of the surface to
 427 reconstruct [4, 11]. Figure 1 shows results of this method.

428 6.3 Closed surface triangulation

429 Using Algorithm 5 requires a strongly connected 3-pseudomanifold: we therefore use
 430 a 3D Delaunay triangulation, for its efficiency and non-parametric nature, using the
 431 CGAL library [29], and complete it into a topological 3-sphere by connecting, for any
 432 triangle on the convex hull of the Delaunay triangulation, its dual edge to an "infinite"
 433 dual vertex.

434 Experimentally, sorting triangles does not require exact predicates: the R_B and
 435 R_C quantities can simply be calculated in fixed precision. The quasilinear complexity
 436 of Algorithm 5 makes it competitive in large point cloud applications. Outliers are
 437 naturally ignored and, being parameter free, the algorithm adapts to non uniform point
 438 densities, as seen in the closeup of Figure 4.

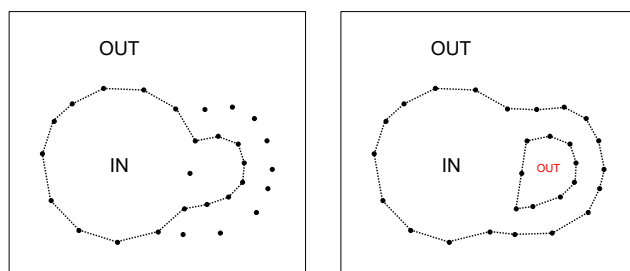


Fig. 3 Providing additional topological information can improve the result of the reconstruction. Here, the lexicographic order on 1-chains is induced by edge length comparison.

439 The choice of α_1 and α_2 defines the location of the closed separating surface and
 440 are chosen interactively. Although we could devise an algorithm where these inputs
 441 are not required – the algorithm would simply merge regions until only two connected
 442 components remain – this would only work for uniform and non-noisy point clouds
 443 but not make for a robust algorithm. On the contrary, adding multiple interior and
 444 exterior regions can guide the algorithm by providing better topological constraints,
 445 as depicted in Figure 3.

446 Algorithm 5 requires to be slightly modified to take as input multiple α_1, α_2 : after
 447 creating all sets with MakeSet, we need to combine all α_1 sets together, and all α_2
 448 sets together. The algorithm remains unchanged for the rest.

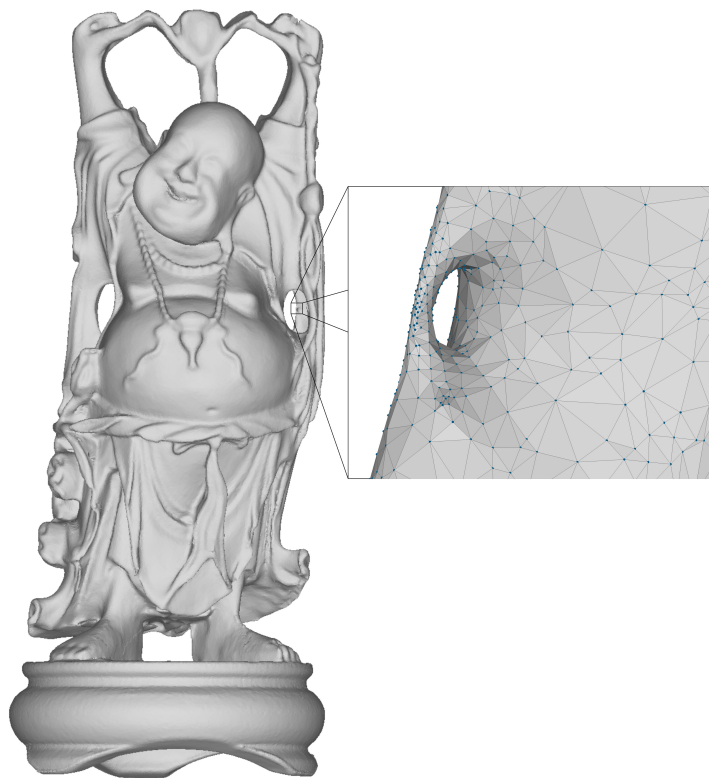


Fig. 4 Closed surface triangulation of 440K points in 7.33 seconds. Beside the point cloud, the only user input is one inner tetrahedron. The closeup shows that small features are correctly recovered.

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