Integer Coordinates for Intrinsic Geometry Processing

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This paper describes a numerically robust data structure for encoding intrinsic triangulations of polyhedral surfaces. Many applications demand a correspondence between the intrinsic triangulation and the input surface, but existing data structures either rely on floating point values to encode correspondence, or do not support remeshing operations beyond basic edge flips. We instead provide an integer-based data structure that guarantees valid correspondence, even for meshes with near-degenerate elements. Our starting point is the framework of *normal coordinates* from geometric topology, which we extend to the broader set of operations needed for mesh processing (vertex insertion, edge splits, *etc.*). The resulting data structure can be used as a drop-in replacement for earlier schemes, automatically improving reliability across a wide variety of applications. As a stress test, we successfully compute an intrinsic Delaunay refinement and associated subdivision for all manifold meshes in the Thingi10k dataset. In turn, we can compute reliable and highly accurate solutions to partial differential equations even on extremely low-quality meshes.

CCS Concepts: • **Mathematics of computing** → **Mesh generation**.

Additional Key Words and Phrases: remeshing, intrinsic triangulation, Delaunay triangulation, discrete differential geometry

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1 INTRODUCTION AND RELATED WORK

Polyhedral surfaces play a central role in graphics, geometry processing, scientific computing, and computer vision, but meshes from these domains are often not directly suitable for computation. For instance, a mesh that is perfectly good for visualization may not be suitable for solving *partial differential equations (PDEs)*, which are a basic component of many modern geometric algorithms. Significant work hence focuses on algorithms that are robust to mesh quality [Zhou et al. 2016; Schneider et al. 2018; Sellán et al. 2019; Sawhney and Crane 2020; Jiang et al. 2020], including extremely robust remeshing [Hu et al. 2018, 2020]. However, current best-in-class remeshing techniques are volumetric in nature, making them less than ideal for surface problems: for instance, they do not preserve boundaries or self-intersections, and are orders of magnitude more expensive (seconds to minutes) than traditional 2D remeshing (on the order of milliseconds). More fundamentally, standard *extrinsic* approaches to remeshing based on vertex positions in $\mathbb{R}^n$ must negotiate a trade-off between mesh size, the quality of mesh elements, and geometric approximation of the input domain.

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Fig. 1. Intrinsic triangulations enable one to compute with a high-quality triangulation even on a low-quality input mesh. We introduce an integer-based intrinsic triangulation data structure that is dramatically more robust than past alternatives.

Intrinsic triangulations provide a framework for surface mesh processing with computational cost and behavior similar to ordinary 2D meshing. The basic idea is to trace out a secondary mesh along straight (*i.e.*, geodesic) paths that triangulate the same vertex set—opening up a dramatically larger space of triangulations for computation. Though intrinsic triangles may appear bent, they are fully described by just three ordinary edge lengths, since they can be unfolded into the plane without any distortion (Figure 2). Hence, algorithms designed for ordinary triangle meshes can be run on the intrinsic mesh with little to no modification. Sharp et al. [2021] provides an in-depth introduction, including a detailed discussion of practical applications.

This larger space of triangulations also makes it possible to improve element shape without introducing geometric approximation error (Figure 1). Encapsulating this machinery in a standard interface provides robustness as a subroutine: rather than make algorithms more robust one at a time, we can transform low-quality input into a high-quality intrinsic mesh, execute a “non-robust” algorithm, then read back the results in a variety of ways.

However, to make this approach truly reliable one must develop numerically robust data structures for encoding the correspondence between the input mesh T^0 and an intrinsic triangulation T^1 traced out over T^0 . The earliest example is the *overlay mesh* of Fisher et al. [2006], which explicitly tracks the *common subdivision* obtained by “slicing up” T^0 along the edges of T^1 . This approach guarantees

2 DATA STRUCTURE

Our data structure consists of a fixed input triangulation T^0 , plus a dynamic *intrinsic triangulation* T^1 sitting on top of T^0 (Section 2.1). We use V^i, E^i, F^i to denote the vertices, edges, and faces of T^i , *resp.* Initially T^0 and T^1 are identical, but subsequent local operations may add vertices to T^1 . We never remove vertices of T^0 since, in general, such vertices cannot be removed without changing the geometry of the surface. Hence, $V^1 \supseteq V^0$, and $V^\star := V^1 \setminus V^0$ gives the set of inserted vertices. For clarity, we generally use a, b, c for vertices of T^0 and i, j, k for vertices of T^1 (which may also be in T^0). We also associate four basic quantities with T^1 :

- lengths $\ell_{ij} \in \mathbb{R}_{>0}$ for each edge $ij \in E^1$ (Section 2.2),
- normal coordinates $n_{ij} \in \mathbb{Z}$ for each edge $ij \in E^1$ (Section 2.3),
- roundabouts $r_{\vec{a}j} \in \mathbb{Z}_{\geq 0}$ for each halfedge $\vec{a}j \in H^1$ rooted at a vertex $a \in V^0$ (Section 2.4), and
- barycentric coordinates q_i^0 relative to T^0 for each inserted vertex $i \in V^\star$ (Section 2.2).

Note that this scheme differs from Gillespie et al. [2021, Section 5], who always assume that $V^1 = V^0$ —and hence cannot support many of the local operations described in Section 3.

2.1 Connectivity

Formally, we consider triangulations $T = (V, E, F)$ of a fixed polyhedral surface M . By *triangulation* we mean a Δ -complex [Hatcher 2002, Section 2.1], which allows, *e.g.*, a single intrinsic triangle to “wrap around” the surface and meet along its own edge (inset, *top*). In general, the vertices of a face or edge in a Δ -complex need not be distinct, and two distinct elements can have identical vertices. For example, there can be several edges ij with the same endpoints $i, j \in V$, and we may also have $i = j$. Each edge ij is associated with two oriented halfedges $\vec{ij} \neq \vec{ji} \in H$ (inset). In practice a Δ -complex can be implemented via, *e.g.*, the *halfedge data structure* [Botsch et al. 2010, Chapter 2], or an *edge gluing map* [Sharp and Crane 2020b, Section 4.1]. We use u_σ to denote a quantity u at a vertex, edge, face, or halfedge σ ; u_i^{jk} is a quantity u at corner i of triangle ijk .

2.2 Geometry

Edge Lengths. The intrinsic geometry of a triangulation is given by edge lengths $\ell : E \rightarrow \mathbb{R}_{>0}$ that satisfy the triangle inequality $\ell_{ki} + \ell_{ij} > \ell_{jk}$ for each triangle corner i^{jk} . Initially, $T^0 = T^1$ and both triangulations have identical edge lengths $\ell_{ij} = |f_j - f_i|$, where $f : V \rightarrow \mathbb{R}^3$ are the input vertex positions. The edge lengths of T^1 will later be modified by operations like intrinsic edge flips (Section 3.2). Even then, we can draw individual faces $ijk \in F^1$ as ordinary triangles in the plane, and obtain quantities like corner angles θ_i^{jk} via standard formulas. Finally, we use $\exp_x(u)$ to denote the exponential map at x , which gives the point reached by walking

Fig. 4. Points are encoded relative to both triangulations T^0 and T^1 . For each triangulation we store the simplex containing the point, and the barycentric coordinates within that simplex.

in the tangent direction u for a distance $|u|$ (see [Sharp et al. 2021, Section 2.4.2] for implementation details).

Barycentric Coordinates. We encode points $x \in M$ by barycentric coordinates relative to a vertex, edge, or triangle, *e.g.*, three positive values $u_i + u_j + u_k = 1$ for a triangle ijk (and for a vertex i we have a single coordinate $u_i = 1$). Importantly, for each point x we store barycentric coordinates u and v relative to both T^0 and T^1 , *resp.* (Figure 4). We use q^0 and q^1 to denote a barycentric coordinate together with its associated simplex, on either T^0 or T^1 .

2.3 Normal Coordinates

We use normal coordinates (Figure 3) to encode how two triangulations T^0, T^1 cross each other. Classically this data can be stored on either triangulation, *i.e.*, one can count the number of times each edge of T^1 is crossed by T^0 or vice versa. But to insert new vertices in T^1 we must store normal coordinates on edges of T^1 —otherwise the encoding becomes ambiguous. We hence think of each edge of T^0 as a geodesic curve crossing edges of T^1 (Figure 5, *right*).

More explicitly, the value $n_{ij} \in \mathbb{Z}$ indicates how many times each edge $ij \in E^1$ is crossed transversally by edges of E^0 ; if an edge of T^0 runs along ij , we let $n_{ij} = -1$. In this latter case, no edge of T^0 can cross ij . The value $n_{ij}^+ := \max(n_{ij}, 0)$ hence gives the number of transversal crossings; the value $n_{ij}^- := -\min(n_{ij}, 0)$ is 1 on shared edges and 0 otherwise. (Note that Gillespie et al. [2021] adopt a different convention, where $n_{ij} = 0$ for parallel edges.)

Fig. 5. The number of crossings can be encoded on either triangulation. However, storing values on the edges of T^0 does not account for vertices inserted in T^1 (*left*); we hence store normal coordinates on T^1 (*right*).

Fig. 6. The value c_i^{jk} gives the number of curves crossing corner j_i^{jk} , while e_k^{ij} gives the number of curves emanating from corner j_k^{ij} .

Using the values n_{ij}^+ we can count how many curves cross and emanate from each corner of T^1 , resp. (Figure 6):

$$c_k^{ij} := \frac{1}{2} \left(\max(0, n_{jk}^+ + n_{ki}^+ - n_{ij}^+) - e_i^{jk} - e_j^{ki} \right). \quad (1)$$

$$e_k^{ij} := \max(0, n_{ij}^+ - n_{jk}^+ - n_{ki}^+). \quad (2)$$

(For curves that do not touch vertices, the corner coordinates c are essentially dual to the normal coordinates n —see [Erickson and Nayyeri 2013, Section 2.3].)

2.4 Roundabouts

Normal coordinates allow us to trace the edges of T^0 as geodesic curves along T^1 (Section 3.1). However, they do not uniquely determine the correspondence between traced curves and logical edges $ab \in E^0$. For instance, flipping edge mk of a tetrahedron results in two distinct intrinsic edges between vertices i and j (inset). Given a curve between vertices i and j on the tetrahedron, it is not *a priori* obvious which of the two logical edges the curve corresponds to.

Gillespie et al. [2021, Section 5.2] therefore introduce *roundabouts* $r : H^1 \rightarrow \mathbb{Z}_{\geq 0}$, which for each vertex describe how the outgoing edges from both T^0 and T^1 are interleaved (inset). In particular, suppose we enumerate the halfedges of T^0 around some vertex $a \in V^0$ in counter-clockwise order, starting from zero at some arbitrary (but fixed) reference halfedge. Then for each halfedge $\vec{a}j \in H^1$, the roundabout $r_{\vec{a}j}$ gives the index of the first halfedge $ab \in H^0$ following $\vec{a}j$ (which may be $\vec{a}j$ itself). Unlike Gillespie et al. we may insert new vertices—but need only store roundabouts at shared vertices $a \in V^0$, since edges of E^0 always terminate at vertices in V^0 .

2.5 Crossings

Finally, we call a point where edges of T^0 and T^1 intersect a *crossing*. A *combinatorial crossing* $\zeta = (\vec{ij}, p)$ describes a crossing as a 0-indexed ordinal p along a halfedge $\vec{ij} \in H^1$ —i.e., which crossing, as we go from i to j . The same crossing with respect to the opposite halfedge is given by $\bar{\zeta} := (\vec{ji}, n_{ij} - p - 1)$; this reversal operation is helpful when tracing curves. A *geometric crossing* $z = (\vec{ij}, p, \vec{ab}, u, v)$ also gives the barycentric coordinates u, v along halfedges $\vec{ab} \in H^0$ and $\vec{ij} \in H^1$, resp.

Fig. 7. A curve entering triangle jik along edge ij can proceed in 3 ways: the left-most c_j^{ik} crossings go left (left), the rightmost c_i^{kj} crossings go right (right), and the remaining crossings terminate at vertex k (center).

3 ALGORITHMS

We next describe basic operations on our data structure—detailed pseudocode is given in Appendix B of the supplemental material.

3.1 Extracting Curves

Given only the normal coordinates n , we can trace out any edge of T^0 as a curve γ along T^1 , via the procedure **EXTRACTCURVE** (Algorithm 2). This procedure takes any combinatorial crossing ζ on γ , and computes the full sequence $(i, z_1, \dots, z_k, j)$ of geometric crossings plus the start and end vertices $i, j \in V^1$. (Note that this procedure generalizes Gillespie et al. [2021, Section 6].)

We proceed in two steps. First, we find the triangle strip containing γ , purely using the integers n_{ij} . Importantly, γ is guaranteed not to leave this strip since the normal coordinates account for all crossings. Hence, in the second step we can simply draw a straight line through the strip to get the geometry of γ . It is only in this second step that we use any floating point computation.

A subroutine **TRACEFROM** (Algorithm 1) starts at a given combinatorial crossing $\zeta = (\vec{ij}, p)$ and iteratively computes the next combinatorial crossing until it reaches a vertex. Figure 7 shows how the next crossing can be determined purely from integer data. Note that the orientation of $\vec{ij}$ determines the tracing direction.

EXTRACTCURVE calls **TRACEFROM** once in each direction, and combines the two resulting crossing sequences. Using the roundabouts, it identifies the sequence with an edge of T^0 . Finally, it unfolds the corresponding triangle strip into the plane, where a straight line through the two endpoints is intersected with each interior edge to obtain the geometric crossings (Figure 8).

Note that one can also use **EXTRACTCURVE** to convert a single combinatorial crossing into a geometric crossing: just run the same procedure, but return only the crossing of interest. We will refer to this procedure as **EXTRACTGEOMETRICCROSSING**.

Fig. 8. We trace a curve γ by first unfolding a triangle strip in the plane, then intersecting a straight line with each interior edge. Since normal coordinates encode all crossings, this line is guaranteed to be contained in the strip.

Fig. 9. An edge flip replaces an edge with its opposite diagonal (left). A flip cannot be performed if it would yield an isolated (degree-0) vertex, or if the two triangles containing the edge form a nonconvex quadrilateral (right).

3.2 Edge Flip

An intrinsic edge flip reconnects a triangle pair along the opposite diagonal (Figure 9, left). Unlike an ordinary (extrinsic) edge flip, the new diagonal is a geodesic curve rather than a straight line segment in space. An edge is flippable if and only if (i) both endpoints have degree at least one after the flip, and (ii) the two triangles containing the edge form a convex quadrilateral (Figure 9, right). Here we detail how to update integer coordinates for an edge flip—note that our treatment differs only slightly from [Gillespie et al. 2021, Equation 15], which does not account for inserted vertices.

Mesh Update. After updating the connectivity of T^1 , we obtain the new length ℓ_{lk} by laying out the triangles ijk, jil in the plane and measuring the distance from k to l .

Normal Coordinates & Roundabouts. The new normal coordinate n_{kl} does not depend on the geometry of T^1 , and is given by

$$n_{kl} = c_l^{jk} + c_k^{ij} + \frac{1}{2} |c_j^{il} - c_j^{ki}| + \frac{1}{2} |c_i^{lj} - c_i^{jk}| - \frac{1}{2} e_l^{ji} - \frac{1}{2} e_k^{ij} + e_i^{lj} + e_i^{jk} + e_j^{il} + e_j^{ki} + n_{ij}^- \quad (3)$$

We update each roundabout from its previous neighbor, e.g.,

$$r_{kl} = \text{mod} \left(r_{ki} + e_k^{il} + n_{ki}^-, \deg_0(k) \right), \quad (4)$$

where $\deg_0(k)$ is the degree of vertex k in triangulation T^0 . The quantity e_k^{il} increments the roundabout index once for each edge strictly between $\vec{ki}$ and $\vec{kl}$, and n_{ki}^- adds one if there is also an edge lying along $\vec{ki}$. Recall from Section 2.4 that we maintain these values only for halfedges emanating from vertices $a \in V^0$.

3.3 Face Split

Given a point $x \in M$ expressed as barycentric coordinates v relative to a face $ijk \in F^1$, the procedure **SPLITFACE** (Algorithms 5 and 6) inserts a new vertex $m \in V^1$, and computes the barycentric encoding $q_m^0 = (u, abc)$ of x relative to T^0 .

SPLITFACE is the first of several new operations introduced in this paper, which manipulate vertices rather than just flipping edges. (Schaefer et al. [2002, Section 5.4] describe a face split operation in the topological setting, but do not provide the ability to insert a point at a particular geometric location, which is essential in our setting of Euclidean polyhedra.)

Mesh Update. We first insert m into T^1 at x , splitting ijk into three new triangles. The new edge lengths can be computed directly in barycentric coordinates—in particular, any tangent vector w expressed in barycentric coordinates has length

$$\|w\|^2 = -\ell_{ij}^2 w_i w_j - \ell_{jk}^2 w_j w_k - \ell_{ki}^2 w_k w_i \quad (5)$$

(see [Schindler and Chen 2012, Section 3.2] or [Sharp et al. 2021, Sections 2.3.2 and 2.3.7]). We can hence compute $\ell_{im} = \|v - (1, 0, 0)\|$, and similarly for ℓ_{jm}, ℓ_{km} .

Normal Coordinates & Roundabouts. Unlike edge flips, where the new normal coordinates depend solely on the old ones, normal coordinates resulting from a vertex insertion depend on the particular geometric region R containing the inserted point m (see inset). We hence compute geometric crossings for all curves passing through face ijk , then determine the region R via line-side tests (implemented via a simple cross product). If m is extremely close to a region boundary we may pick the wrong region (due to floating-point error), but will still produce valid connectivity for a nearly identical vertex location. Moreover, barycentric coordinates v arising from, say, Delaunay refinement (Section 4.2) will not be exact anyway. New roundabouts emanating from vertices in $\{i, j, k\} \cap V^0$ are set via Equation 4.

Position on T^0 . The geometric crossings at R 's corners provide barycentric coordinates u and v relative to T^0 and T^1 resp. Hence, to get q_m^0 we simply express x as a linear combination of the corners' v -coordinates, then take the same linear combination of the corners' u -coordinates (see Appendix A for details).

3.4 Edge Split

Similarly, given a point $x \in M$ expressed as barycentric coordinates v relative to a halfedge $\vec{ij} \in H^1$, procedure **SPLITEDGE** (Algorithm 7) inserts a new vertex $m \in V^1$, and updates all associated quantities.

If $n_{ij} \geq 0$ (i.e. no curve runs along $\vec{ij}$), we simply perform a face split followed by an edge flip (Figure 10, top). However, if $n_{ij} < 0$ (which is common in practice—e.g. Section 4.2), we perform an explicit edge split to insert the new vertex along the coincident curve (Figure 10, bottom). After such an edge split a single edge $ab \in E^0$ may correspond to a sequence of geodesic segments meeting at intermediate vertices $i \in V^*$. But since each segment terminates at vertices, one can still encode these curves via normal coordinates.

Mesh Update. We insert a new vertex m along $\vec{ij}$ and triangulate any adjacent faces, computing the new edge lengths via Equation 5.

Normal Coordinates & Roundabouts. When $n_{ij} < 0$ the new normal coordinates depend only on the old ones: we set n_{mj} and n_{mi} equal to n_{ij} , and set

$$n_{mk} = \max(n_{ki}, n_{jk}, 0). \quad (6)$$

Note that if $n_{ij} < 0$, edge mk crosses all curves contained in face ijk (since they may only emanate from i or j , or cross k). The number of such curves is precisely $\max(n_{ki}, n_{jk}, 0)$.

Fig. 10. Generally, one can split edge ij by performing a face split on a neighboring face followed by an edge flip (top). However, if ij carries a curve, this strategy will cause the inserted vertex to miss the curve (bottom). We hence provide a different edge split procedure for this case in Section 3.4.

As with face splits, roundabouts on any new halfedges emanating from original vertices can be set from their neighbors (Equation 4).

Position on T^0 . Since, i and j necessarily have known locations q_i^0, q_j^0 resp. along some edge in $ab \in E^0$, we can simply interpolate by v to obtain the position q_m^0 of x along ab .

3.5 Vertex Removal

Generally, a vertex of the original triangulation cannot be removed without distorting the intrinsic metric: any curvature at that vertex would be lost. However, inserted vertices $i \in V^*$ have no curvature, and can hence be removed safely. In fact this operation is necessary for Delaunay refinement of domains with boundary (Section 4.2).

The basic strategy behind REMOVEVERTEX (Algorithm 8) is to flip edges incident on the vertex to be removed until it has degree three, then delete the three edges incident on the vertex as well as the vertex itself. No other data needs to be updated, since the edges of the resulting triangle already appear in the triangulation. Theorem D.1 proves the correctness of this procedure for simplicial complexes. A nearly identical procedure can be used to remove an inserted boundary vertex. Schaefer et al. [2002, Section 5.4] also suggest a similar flipping procedure, but do so in the topological setting where the necessary edge flips are always valid—they do not consider the convexity condition (Section 3.2).

3.6 Moving Inserted Vertices

Using the previous operations, we can define a procedure for moving around inserted vertices. Specifically, given a tangent vector v at an inserted vertex i , we can move i along v in the following way:

- First, compute the new location $x = \exp_i(v)$.
- Insert x using SPLITFACE.
- Remove i using REMOVEVERTEX.

We insert x first since the removal procedure could flip edges incident on the triangle containing x , invalidating its barycentric

Fig. 11. We extract the connectivity of common subdivision within each triangle using its normal coordinates.

coordinates. Note that Sharp *et al.* propose an alternative strategy for local vertex displacement [Sharp et al. 2019a, Section 3.3.3].

3.7 Common Subdivision

As noted previously, the *common subdivision*² S of T^0 and T^1 is the polygon mesh obtained by “slicing up” the underlying surface along the edges of both T^0 and T^1 . The vertices of S are hence a superset of V^0 and V^1 , and every edge or face of T^0 and T^1 can be expressed as union of edges or faces of S (resp.). Moreover, the faces of S are always planar and convex. Most importantly in our setting, any piecewise-linear function on T^0 or T^1 can be represented exactly as a piecewise-linear function on S .

The common subdivision thus serves as an essential “bridge” between an intrinsic triangulation and the original extrinsic domain: it provides the minimal piecewise linear basis on which both intrinsic data at vertices and extrinsic vertex positions can simultaneously be interpolated. S can then be used to pull back functions from the abstract intrinsic setting to an ordinary mesh sitting in space.

Note however that even if T^0 and T^1 have nice elements, S is not in general a high-quality mesh, and may not itself be suitable for, e.g., solving PDEs. Rather, it plays a complementary role in the geometry processing pipeline, enabling (for instance) transfer of data between triangulations (Section 4.3), or visualization of data downstream via standard rendering tools.

We compute the common subdivision by cutting T^1 along the edges of T^0 . First we extract the connectivity of S , using only the normal coordinates n_{ij} . Then we recover the intersection geometry, allowing us to interpolate data stored at the vertices of T^0 or T^1 to S —most commonly, vertex positions on T^0 along with any solution data on T^1 . This procedure was previously described by Sharp et al. [2019a, Section 3.4.2]; we recap it here for completeness, and to give a convenient description using our integer coordinates. Note that one can construct pathological cases in which there are quadratically many intersections between T^0 and T^1 (or worse—consider a triangulation with many *Dehn twists*, as pictured in [Sharp et al. 2019a, Figure 4]). However, we do not observe such extreme behavior in practice (see Section 7).

²Also known as the *supermesh* in the FEM literature, e.g. Farrell et al. [2009, Section 2].

Connectivity. We subdivide T^1 independently in each face ijk (Figure 11). There are two cases to consider. In case 1, when no curves emanate from any corner, we simply connect the first c_i^{jk} crossings along edge ij to the first c_i^{jk} crossings along ik (in order), and likewise for corners j and k . In case 2 curves emanate from some corner; without loss of generality, let this corner be k so that the number of emanating curves is $e_k^{ij} > 0$. We walk from i to j , connecting the first c_i^{jk} crossings to those along ik , the next e_k^{ij} crossings to vertex k , and the remaining c_j^{ki} crossings to those along edge kj . Note that curves running along edges ($n_{ij} < 0$) require no special treatment.

Intersection Geometry. Next, we associate each vertex i of the common subdivision with a point in T^0 and a point in T^1 , encoded in barycentric coordinates (Section 2.2). Using these values, one can linearly interpolate data from T^0 or T^1 to the vertices of S . Again, there are just two cases: each vertex i in S is either a vertex of T^1 or the intersection of an edge of T^0 with an edge of T^1 . In the first case, the position on T^1 is given by i itself, and the position q_i^0 on T^0 was computed when i was inserted. In the second case, we compute the desired barycentric coordinates using `EXTRACTCURVE`.

3.8 Visualization

To produce figures depicting intrinsic triangulations (e.g. Figure 12), we compute the common subdivision (Section 3.7) and draw the edges of the input mesh with a black wireframe, while coloring the intrinsic triangles in arbitrarily-chosen colors. In figures displaying functions defined on intrinsic triangulations (e.g. Figure 15), we interpolate the solutions along the common subdivision for rendering.

3.9 Robust Implementation

Our integer coordinates are guaranteed to encode a triangulation sitting atop T^1 . The geometric accuracy of this triangulation, of course, depends on floating point arithmetic, which can become inaccurate in near-degenerate configurations. *Exact predicates* have been applied with great success to similar problems [Devillers and Pion 2003]. Unfortunately they do not directly apply to intrinsic triangulations, as the predicates that we evaluate are not fixed functions of the input data; an intrinsic edge length can depend upon arbitrarily many input edge lengths. Hence, we focus on fast and robust implementations using ordinary floating point arithmetic.

One essential tool for manipulating intrinsic triangulations on near-degenerate input meshes is *intrinsic mollification*, introduced by Sharp and Crane [2020b]. Mollification provably ameliorates near-degenerate meshes by adding a small value δ to every edge length, ensuring that every triangle satisfies the triangle inequality with slack at least ϵ . This operation only changes the geometry if some triangle is within ϵ of being degenerate, and even then changes the geometry by a negligible amount. Intrinsic mollification works particularly well with our data structure compared to past approaches: the signpost data structure of Sharp et al. [2019a] relies on tracing edges along the surface, which becomes *less* accurate when mollification is applied. Integer coordinates have no such problem. In our experiments we mollify with $\epsilon = 10^{-5}h$, where h is the mean edge length, and find that it resolves almost all numerical difficulties.

Even after mollification, it is still beneficial to use care when working with floating point. For example, there are well-conditioned triangles on which the Delaunay condition (Equation 8, discussed in the next section) is difficult to evaluate; in practice, we only enforce Equation 8 up to some ϵ tolerance. As a further example, when computing new normal coordinates in `SPLITFACE`, one could lay out the face in the plane, and independently count intersections along the new edges. However, this can produce invalid normal coordinates in floating point. We apply a more nuanced policy (see Appendix B) which always yields valid normal coordinates.

3.10 Other Operations

Normal coordinates also enable a wide variety of other operations not detailed here. For instance, Schaefer et al. [2002, Section 5] provide algorithms for counting connected components, checking if crossings are part of the same curve, checking if curves are isotopic, and computing the oriented intersection number. Erickson and Nayyeri [2013] provide an asymptotically-fast algorithm for tracing normal curves across a surface. Finally, Dynnikov [2020, Proposition 13] provides an algorithm for computing how many times curves represented by normal coordinates intersect.

4 RETRIANGULATION AND TRANSFER

Retriangulation. On top of the basic operations from Section 3, one can start to build up the same kind of fundamental building blocks as in extrinsic geometry processing. In this section we focus on *intrinsic Delaunay refinement*, which is a critical tool guaranteeing that a high-quality triangulation can always be built on top of any (e.g., low-quality) input mesh. In particular, we give a new proof about guaranteed quality for surfaces without boundary, and extend the algorithm to surfaces with boundary (without proof).

Transfer. Given a function on a high-quality intrinsic Delaunay mesh, there are then several ways to transfer this function back to an ordinary (extrinsic) mesh. One is to simply copy values at shared vertices, but this approach is often less than satisfactory since the intrinsic and extrinsic basis functions can look quite different. Another is to interpolate it over the common subdivision—made far more robust by our data structure. In this section, we also describe a third, alternative route that finds the best representation of an intrinsic function in a basis on the original mesh (Section 4.3), again made possible by robust extraction of the common subdivision.

4.1 Intrinsic Delaunay Triangulations

One key application of intrinsic triangulations is the computation of *intrinsic Delaunay triangulations* (Figure 12, top). A triangulation is said to be Delaunay if the sum of angles opposite every edge is at most π , i.e. for every $ij \in E$ we have

$$\theta_k^{ij} + \theta_l^{ji} \leq \pi. \quad (7)$$

Delaunay triangulations have a number of beneficial properties. One consequence of Equation 7 is that edges of a Delaunay triangulation must have nonnegative *cotan weights*:

$$\cot \theta_k^{ij} + \cot \theta_l^{ji} \geq 0. \quad (8)$$

Fig. 12. Using our integer-based data structure, we can not only improve near-degenerate meshes by generating *intrinsic Delaunay triangulations* (top), but can also extract the common subdivision after computing a high-quality *intrinsic Delaunay refinement* (bottom).

In fact, Equation 8 is equivalent to Equation 7 above, and provides a convenient formula for checking the Delaunay property in an intrinsic triangulation. Moreover, Equation 8 ensures that the finite element Laplacian L satisfies the *maximum principle*, guaranteeing that discrete harmonic functions do not have local extrema in the interior of the domain [Bobenko and Springborn 2007, Proposition 19]. Similarly Equation 8 also ensures that discrete harmonic vector fields are “flip-free” [Sharp et al. 2019b, Section 5.4]. Furthermore, the local Delaunay condition implies the *empty circumcircle property*: each triangle’s geodesic circumdisk contains no vertices, illustrated in Figure 13, *left* [Bobenko and Springborn 2007, Proposition 10].

The Delaunay triangulation can be computed via a simple greedy algorithm: flip any non-Delaunay edge until all edges satisfy Equation 7 [Bobenko and Springborn 2007, Propositions 11 and 12].

4.2 Intrinsic Delaunay Refinement

Delaunay refinement inserts vertices in order to produce a Delaunay mesh whose triangles all satisfy a minimum angle bound (Figure 12, *bottom*). Here we modify *Chew’s second algorithm* to perform intrinsic Delaunay refinement [Chew 1993; Shewchuk 1997]. This problem has been extensively studied in the plane, but an intrinsic (*i.e.* geodesic) scheme was only recently proposed by Sharp et al. [2019a, Section 4.2]. However, they did not handle meshes with

Fig. 13. Triangles in Delaunay meshes have empty circumdisks, and thus well-defined circumcenters (*left*). When necessary, we locate a triangle’s circumcenter by walking outwards from its barycenter (*right*).

boundary—here we resolve the essential difficulties of the boundary case, and show how refinement can be implemented using our integer-based data structure.

In the plane, the basic algorithm is to greedily pick any triangle which violates the minimum angle bound, insert a vertex at its circumcenter, then flip to Delaunay. This process continues until all triangles satisfy the angle bound. If a triangle’s circumcenter is outside the domain, then the boundary edge ij separating the triangle from its circumcenter is split at its midpoint; subsequently, all interior vertices within at least a distance of $\ell_{ij}/2$ are removed—though removing additional interior vertices causes no issues (Appendix C.1). One can prove that this process succeeds for minimum angle bounds up to 25.65 degrees on planar domains with boundary angles at least 60° [Shewchuk 1997, Section 3.4.2]. More advanced versions of this procedure can achieve better angle bounds, *e.g.* [Rand 2011], but here we restrict our attention to the basic algorithm for simplicity.

There are two difficulties in adapting this algorithm to the intrinsic setting: locating circumcenters and computing (geodesic) distances. As mentioned earlier, intrinsic Delaunay triangulations obey the empty circumcircle property; hence each triangle has an intrinsically-flat circumdisk with a well-defined center (Figure 13, *left*). So long as this center corresponds to a point on the surface, it can be found by walking from the triangle’s barycenter (Figure 13, *right*). In practice, we compute triangle ijk ’s circumcenter in homogeneous (*i.e.*, unnormalized) barycentric coordinates $\hat{v}_i$ via the following formula [Schindler and Chen 2012, Section 2.3]:

$$\hat{v}_i := \ell_{jk}^2 (\ell_{ij}^2 + \ell_{ki}^2 - \ell_{jk}^2), \quad (9)$$

and then normalize to obtain barycentric coordinates

$$v_i := \frac{\hat{v}_i}{\hat{v}_i + \hat{v}_j + \hat{v}_k}. \quad (10)$$

To locate the circumcenter on the surface, we then evaluate the exponential map (Section 2.2) starting at the barycenter $w_i = w_j = w_k = 1/3$, along the vector $v - w$. If we hit a boundary edge ij while tracing out this path, then the circumcenter is not contained in the surface, so we split ij at its midpoint and flip to Delaunay. We must then remove all inserted interior vertices within a geodesic ball of radius $\ell_{ij}/2$ centered at the inserted point. Computing geodesic distance on a surface mesh is nontrivial, but Xia [2013, Corollary 1] shows that on a Delaunay triangulation any vertex inside a geodesic ball of radius r will also be inside the Dijkstra ball of radius $2r$ (*i.e.*

Fig. 14. Accuracy is improved by transferring PDE solutions back to an original triangulation as the L^2 -nearest solution, evaluated via the common subdivision. Here we generate random low-quality meshes of the unit square by random edge splits (left), and plot the error in the solution of a Poisson equation compared to analytic ground truth, always represented in the basis of the original triangulation (right). Each data point is the average error over 100 trials. As expected, solving on the intrinsic Delaunay triangulation dramatically increases accuracy, but further improvements are gained by choosing the solution on the original mesh which is L^2 -nearest to the intrinsic solution, rather than naively copying vertex values.

points whose distance along the edge graph are at most $2r$). We hence remove all interior inserted vertices within a Dijkstra distance of ℓ_{ij} . While Xia considers only the planar setting, their proof (which is based on triangle strips) applies without modification to intrinsic Delaunay triangulations of surfaces.

Observe also that, as in the planar case, Delaunay refinement only ever removes *previously-inserted* vertices. Hence, as promised in Section 2, the original extrinsic vertex set V^0 is still preserved.

On meshes with narrow cone vertices or boundary angles, it may be impossible to find any triangulation satisfying a given angle bound. In such cases, we do not insert circumcenters of intrinsic triangles which are incident on exactly one narrow vertex, or are entirely contained in a triangle of T^0 which is incident a narrow vertex, and ignore such triangles when computing the minimum corner angle of the output mesh. Although the final output may violate the angle bound, such triangles appear only near narrow vertices. In analogy with the planar case, we set 60° as the minimum allowed angle sum (see inset); in practice the vast majority of meshes obey this constraint at all vertices (97.2% of Thingi10k), and even on those which do not we obtain high-quality triangulations.

4.3 Attribute Transfer

Intrinsic triangulations can drastically improve the quality of solutions to PDEs on low-quality meshes, as will be explored in Section 5. In practice, however, one often needs to represent the solution on the input mesh. Past approaches have simply “copied back” the solution values at vertices of the original mesh, but this strategy is ad-hoc and suboptimal. A more principled approach is to choose the function on the original mesh which is closest to the intrinsic solution. This strategy has been widely explored in the FEM literature

(e.g. Jiao and Heath [2004]) in the context of extrinsic triangulations. With our reliable common subdivision we can now apply this technique in the intrinsic setting. Here, we restrict treatment to piecewise-linear bases and L^2 distance for simplicity, though the same strategy could easily be applied to other basis functions and notions of distance.

Precisely, given a function f on the intrinsic triangulation, we seek $\hat{f}$ on the original mesh that minimizes the squared L^2 distance

$$\|f - \hat{f}\|_{L^2}^2 := \int_M |f(x) - \hat{f}(x)|^2 dx. \quad (11)$$

Here, f and $\hat{f}$ are functions represented in finite-dimensional bases with nodal values at the vertices of the intrinsic triangulation and the original mesh *resp.* In traditional finite elements, this integral commonly arises over a *single* triangulation, in which case it can be evaluated via the Galerkin mass matrix M as

$$\|f - \hat{f}\|_{L^2}^2 = (f - \hat{f})^T M (f - \hat{f}), \quad (12)$$

where M is constructed as in [Strang and Fix 2008, Chapter 10, (32)]. However, in the intrinsic setting f and $\hat{f}$ are encoded over *different* triangulations; they are members of different function spaces. The key observation is that the common subdivision S (Section 3.7) provides exactly the structure needed to evaluate $\|f - \hat{f}\|_{L^2}^2$, as both functions are linear on each triangle of S . In fact, we have

$$\|f - \hat{f}\|_{L^2}^2 = (P_1 f - P_0 \hat{f})^T M_S (P_1 f - P_0 \hat{f}), \quad (13)$$

where now M_S is the Galerkin mass matrix of the common subdivision, and P_0, P_1 are interpolation matrices which map piecewise-linear functions on original and intrinsic triangulations to piecewise-linear functions on S , *resp.* In particular, P_0 is a $|V^0| \times |V^S|$ matrix, where each row corresponds to a vertex of S , and has that vertex’s barycentric coordinates on T^0 as entries. P_1 is defined likewise for T^1 . We then find the function $\hat{f}$ which minimizes Equation 13 as the solution to the following positive-definite linear system:

$$M_0 \hat{f} = P_0^T M_S P_1 f. \quad (14)$$

Here M_0 is the Galerkin mass matrix of T^0 , and can be prefactored if desired to efficiently transfer many functions:

We can leverage this formulation to transfer functions from any intrinsic triangulation back to the original mesh. In Figure 14, we show how this transfer indeed improves the accuracy of PDE solutions as measured on the original low-quality mesh. This machinery is enabled because our integer coordinates efficiently and robustly compute the common subdivision. More broadly, this paradigm opens the door to a wide variety of future finite-element formulations involving intrinsic triangulations.

5 APPLICATIONS

The applications of intrinsic triangulations to robust geometry processing have been extensively explored in past work, including parameterization, surface embedding, distance computation, spectral filtering, surface editing, *etc.* [Fisher et al. 2006; Bobenko and Izestiev 2008; Sun et al. 2015; Sharp et al. 2019a; Sharp and Crane 2020b,a; Fumero et al. 2020; Gillespie et al. 2021]. The particular importance of our new data structure is not that it enables new applications on the intrinsic mesh—in fact, to merely execute most

Fig. 15. Running PDE-based algorithms such as the heat method on poor triangulations (*left*) can lead to inaccurate solutions. Flipping to intrinsic Delaunay (*center*) and performing Delaunay refinement (*right*) can drastically improve the results.

methods, one needs only the basic intrinsic connectivity and edge lengths. Rather, the point is that we can now provide a valuable guarantee of robustness—namely that the connectivity of the common subdivision is always properly recovered—and hence we can exactly represent intrinsic solutions on the extrinsic surface (Section 6 provides experimental evaluation on a large dataset). In turn, data computed on a high-quality mesh can reliably be used for downstream tasks (texture mapping, deformation, *etc.*) in the original context. In this section we explore this approach using several established algorithms.

5.1 PDE-Based Geometry Processing

PDE-based methods abound in geometry processing, as they are generally simple to implement and benefit from decades of research into numerical solvers. Many such methods depend only on intrinsic data, and are hence a natural application of intrinsic Delaunay triangulations and refinements. For low-quality input meshes, simply running standard algorithms on an intrinsic triangulation (instead of the original mesh) yields solutions of dramatically higher quality.

In Figures 15 and 16, we show several representative examples of this paradigm: fast geodesic distance computation [Crane et al. 2017], local parameterization via the logarithmic map [Sharp et al. 2019b], and smooth vector fields [Knöppel et al. 2013]. Unfortunately, the high-quality intrinsic solution is not a piecewise-linear function on the original triangulation—and hence cannot be used immediately downstream. Here the common subdivision comes to the rescue: it allows one to represent the intrinsic solution exactly on an ordinary (extrinsic) mesh, for visualization, deformation, or other purposes. Alternatively, we can transfer the solution back to the original basis *à la* Section 4.3, again taking advantage of the common subdivision. Importantly, unlike past schemes, our integer encoding guarantees that this subdivision can be correctly recovered.

Fig. 16. Here we compute a local parameterization (the *logarithmic map*, *top*), and a smooth vector field (*bottom*) using the connection Laplacian. Both procedures yield inaccurate results on near-degenerate inputs (*left*)—intrinsic Delaunay triangulations (*center*) and intrinsic Delaunay refinements (*right*) greatly improve solution quality. Whether our solution is a scalar function or vector field, we can visualize it on the common refinement.

Fig. 17. We construct geodesic paths by flipping edges in a normal coordinate intrinsic triangulation, as in [Sharp and Crane 2020a]. Normal coordinates guarantee a valid path, even on degenerate inputs (*left*). This unlocks advanced applications of geodesics in normal coordinates with the same guarantees, such as geodesic loops and Bézier curves (*right*).

Table 1. The success rate of our method and past approaches for building high-quality intrinsic triangulations in the Thingi10k dataset. For each we construct a Delaunay triangulation, either on the original vertex set or with Delaunay refinement to a 25° minimum angle bound, and attempt to recover the connectivity of the common subdivision. The explicit overlay method does not support refinement.

Method	Intrinsic Delaunay Triangulation	Intrinsic Delaunay Refinement
Explicit Overlay	100 %	-
Signpost Tracing	96.0 %	69.1 %
Integer Coordinates	100 %	100 %

5.2 Flip-Based Geodesic Paths

The previous sections have demonstrated the value of intrinsic triangulations as a high-quality basis for discretizing functions on surfaces; more broadly, these triangulations also provide simple and robust solutions to other tasks across geometry processing. As an example, the recent FLIPOUT procedure of Sharp and Crane [2020a] computes exact geodesic paths on surfaces via a simple intrinsic edge flipping strategy, introducing the geodesic as a path of edges in the triangulation. This method is easily implemented in our integer representation in terms of the mesh operations in Section 3, and the resulting geodesic paths may then be recovered with the EXTRACTEDGE subroutine. Computing geodesics with our robust integer coordinates is particularly appealing, because geodesic algorithms are notoriously difficult to implement robustly [Sharp and Crane 2020a, Section 5.3]. Even the method of Sharp *et al.* uses the signpost data structure, which may fail to reconstruct a connected path along the surface for degenerate inputs. In contrast, implementing FLIPOUT in our integer coordinate representation extends the benefits of our approach to this task, including a guarantee of valid connectivity in the output (Figure 17, *left*). It also enables higher-level tasks involving geodesic paths to be safely run on low-quality input, such as constructing geodesic loops on surfaces, and even geodesic Bézier curves, using a de Casteljau-style scheme due to Morera *et al.* [2008] as shown in Figure 17, *right*. Experimentally, we repeat the benchmark of Sharp and Crane [2020a, Section 5.1] and validate that our integer scheme successfully generates a connected polyline along the surface across $\sim 62,000$ trials on the Thingi10k dataset.

6 EVALUATION

We implemented all algorithms in C++; since basic vertex-face adjacency list cannot represent a general Δ -complex (Section 2.1), we use a halfedge data structure for triangle meshes. Timings are measured on a single core of an Intel i9-9980XE with 32 GB of RAM. An implementation is provided at <https://github.com/MarkGillespie/intrinsic-triangulations-demo>.

Performance. Generally our data structure is quite fast, computing Delaunay refinements for complex meshes in seconds. For example, computing the Delaunay refinement Figure 15 takes 0.2s, and the Delaunay refinement in Figure 16 (*top*) takes 0.6s. Because we lazily recover intersection geometry from our integer coordinates when

Fig. 18. Past methods extracted edges by tracing “signposts” along the mesh, which may fail in the presence of degenerate triangles. In contrast, our integer coordinates always yield a topologically-valid common subdivision, even on extremely poor quality inputs.

inserting vertices, routines such as Delaunay refinement which perform many insertions may become moderately expensive on large near-degenerate inputs. For instance we take 4 minutes to perform Delaunay refinement on 719791 (Figure 19, *top*) whereas signposts take only 1.5 minutes, but on such meshes signposts generally fail to compute a valid common subdivision. Section 7 discusses hybrid routines which may give the best of both worlds.

6.1 Robustness

We validate robustness by successfully computing Delaunay triangulations, refinements, and their common subdivisions on all manifold meshes in Thingi10k [Zhou and Jacobson 2016]. In particular, we used *MeshLab* to convert each mesh to the PLY file format [Cignoni *et al.* 2008], resulting in 7696 valid manifold meshes. We begin by mollifying each mesh to a tolerance of 10^{-5} (Section 3.9). For each model we compute the intrinsic Delaunay triangulation (Section 4.1) with a tolerance of 10^{-5} , as well as an intrinsic Delaunay refinement (Section 4.2) with a 25° angle bound. We verify that the algorithms terminate with the expected conditions. Additionally, we successfully extract an explicit mesh of the common subdivision in both cases, except for 1 model in the case of refinement whose common subdivision contains around 30 million vertices (Figure 19, *top*).

We compare against the explicit overlay representation of Fisher *et al.* [2006] and the signpost representation of Sharp *et al.* [2019a] (Table 1). The overlay representation similarly offers a guarantee of valid connectivity, but does not provide a constant-time edge flip operation (like normal coordinates do). More importantly it does not support operations beyond edge flips and thus cannot perform Delaunay refinement. Signposts support a wide range of operations, but may not successfully recover the common subdivision on degenerate inputs (Figure 18). The statistic reported here differs from the result in Sharp *et al.* [2019a], because no preprocessing of meshes is performed. For refinement Sharp *et al.* [2019a] do not treat the boundary case, so we evaluate only on models without boundary.

7 LIMITATIONS AND FUTURE WORK

Limitations. The common subdivisions that we compute after Delaunay refinement can be quite large: on the difficult Thingi10k

Fig. 19. We fail to compute an explicit mesh of the common subdivision following Delaunay refinement on one Thingy10k model (top). Its common subdivision would contain 34 million vertices and our program runs out of memory. We succeed on a nearly identical model (bottom), whose common subdivision contains merely 27 million vertices.

dataset, the mean increase in $|V|$ is 20x, and the 95th percentile increase is 45x. We emphasize again that the common subdivision is not generally a high-quality mesh anyway: one should perform numerical computations on the intrinsic triangulation instead. The intrinsic mesh has much higher element quality and is generally much smaller with a mean increase in $|V|$ of 3.7x and 95th percentile increase of 7.8x. However, for applications that rely on the common subdivision (e.g. Section 4.3), it would still be beneficial to explore strategies for simplifying S .

A related issue is that Delaunay refinement sometimes generates meshes with many small triangles. One can prove that Delaunay refinement in the plane produces *well-graded* meshes, meaning essentially that it only places small triangles in regions with small features, and our Delaunay refinement on surfaces seems to behave similarly. Nonetheless, on poorly-conditioned input meshes, Delaunay refinement can insert many small triangles. This can cause problems for diffusion-based algorithms (e.g. the logarithmic map computation in Figure 16), which use the mean edge length to determine a suitable diffusion time. We found that computing the diffusion time on the original mesh and then performing diffusion on the intrinsic triangulation produced the best results.

More broadly, we inherit the usual tradeoffs of the intrinsic paradigm. There is no clear application to some extrinsic problems (such as bending energies), and algorithms applied in the intrinsic setting must be adapted to take edge lengths as input (though this translation is generally straightforward). As with past work on intrinsic

triangulations, our data structure always exactly preserves the input geometry. This imposes a strong restriction that $V^0 \subseteq V^1$ in general position, and furthermore precludes any mesh repair-style operations that might fix spurious holes or handles in the input. Relaxing these assumptions is an important area of ongoing work.

Hybrid Data Structures. At this point, there are several intrinsic triangulation data structures, but no single one is perfect:

- Overlay (explicit) provides exact connectivity; flipping can be slow; no vertex insertion.
- Signposts (implicit) provide inexact connectivity; flipping and vertex insertion are both fast.
- Integer coordinates (implicit) provide exact connectivity; flipping is fast; vertex insertion can be slow.

We conjecture that a good way to get the best of all worlds would be to use a hybrid signpost + integer coordinate data structure. This is fully implicit, avoiding the quadratic costs that may arise when explicitly tracking edge crossings. Nonetheless, flipping and insertion remain fast, and connectivity is exact, if one accepts the inserted locations.

Even further in the implicit direction, storing edge lengths is an “optimization” in our data structure. One could *just* store the normal coordinates and original triangulation, recovering edge length whenever necessary via a layout operation. This is appealing, since it is truly an integer-only representation for intrinsic triangulations.

General geodesic curves. It would also be natural to use this machinery as a representation for general geodesic curves on surfaces, which commonly arise in geometry processing tasks such as cutting, segmentation, etc..

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A INSERTED VERTEX POSITIONS ON T^0

In Section 3.3, we identify a region R containing an inserted point x . Each corner of R is either a vertex of T^1 or a crossing between an edge of T^0 and an edge of T^1 . In the former case, q^0 provides the corner’s position on T^0 , and in the latter case `EXTRACTGEOMETRICCROSSING` provides the corner’s position on T^0 . The face $abc \in F^0$ containing R —and hence the inserted point x —is then identified as the unique face of T^0 containing all of these corners.

Then we recover barycentric coordinates u for x within face abc by solving a small linear system. In principle one could use any 3 corners of R to determine the desired barycentric coordinates, but we make use of all corners of R for numerical stability.

Precisely, let $3 \leq \rho \leq 6$ denote the number of corners of R . Let the m^{th} corner of R have barycentric coordinates $u_a^{(m)}, u_b^{(m)}, u_c^{(m)}$ on $abc \in F^0$ and barycentric coordinates $v_i^{(m)}, v_j^{(m)}, v_k^{(m)}$ on $ijk \in F^1$, all of which are known. We also know the barycentric coordinates v_i for x in ijk . We then want to solve for the corresponding u_a on abc . We proceed in two steps: first, we express v as a linear combination ξ of the $v^{(m)}$. Then, we apply this same linear combination to the $u^{(m)}$ to obtain u . Concretely, we first solve for the minimum-norm solution of the underdetermined system

$$\begin{pmatrix} v_i^{(0)} & v_j^{(0)} & v_k^{(0)} \\ v_i^{(1)} & v_j^{(1)} & v_k^{(1)} \\ \vdots & \vdots & \vdots \\ v_i^{(\rho)} & v_j^{(\rho)} & v_k^{(\rho)} \end{pmatrix} \begin{pmatrix} \xi_0 \\ \xi_1 \\ \vdots \\ \xi_\rho \end{pmatrix} = \begin{pmatrix} v_i \\ v_j \\ v_k \end{pmatrix}, \quad (15)$$

and then set

$$u_a := \sum_m u_a^{(m)} \xi_m, \quad u_b := \sum_m u_b^{(m)} \xi_m, \quad u_c := \sum_m u_c^{(m)} \xi_m. \quad (16)$$

Note that while one often seeks a nonnegative ξ , any solution will suffice here: we only use ξ to interpolate in Equation 16.