

Geometric & Graphics Programming Lab: Lecture 11

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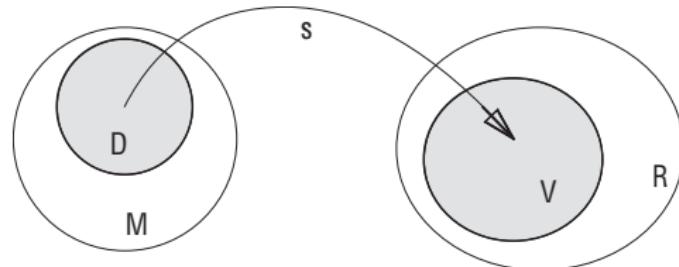
Outline: Cell complexes (LAR)

- 1 Solid Modeling
- 2 Space decompositions
- 3 Cellular complex
- 4 Simplicial mapping

Solid Modeling

Representation scheme: definition

mapping $s : M \rightarrow R$ from a space M of mathematical models to a space R of computer representations



- ① The M set contains the mathematical models of the class of solid objects the scheme aims to represent
- ② The R set contains the symbolic representations, i.e. the proper data structures, built according to a suitable grammar

A. Requicha, [Representations for Rigid Solids: Theory, Methods, and Systems](#), ACM Comput. Surv., 1980.
V. Shapiro, [Solid Modeling](#), In [Handbook of Computer Aided Geometric Design](#), 2001

Representation schemes

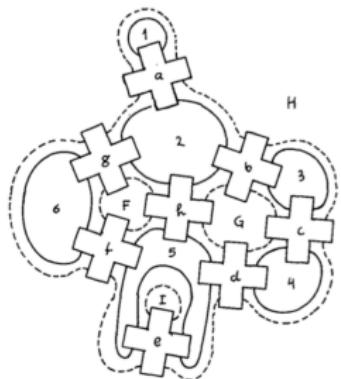
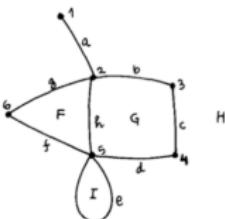
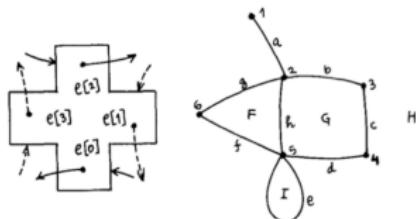
Most of such papers introduce or discuss one or more representation schemes . . .

- 1 Requicha, ACM Comput. Surv., 1980, [?]
- 2 Requicha & Voelcker, PEP TM-25, 1977, [?]
- 3 Rossignac & Requicha, Comput. Aided Des., 1991, [?]
- 4 Bowyer, SVLIS, 1994, [?]
- 5 Baumgart, Stan-CS-320, 1972, [?]
- 6 Braid, Commun. ACM, 1975, [?]
- 7 Dobkin & Laszlo, ACM SCG, 1987, [?]
- 8 Guibas & Stolfi, ACM Trans. Graph., 1985, [?]
- 9 Woo, IEEE Comp. Graph. & Appl., 1985, [?]
- 10 Yamaguchi & Kimura, Comp. Graph. & Appl., 1995, [?]
- 11 Gursoz & Choi & Prinz, Geom.Mod., 1990, [?]
- 12 S.S.Lee & K.Lee, ACM SMA, 2001, [?]
- 13 Rossignac & O'Connor, IFIP WG 5.2, 1988, [?]
- 14 Weiler, IEEE Comp. Graph. & Appl., 1985, [?]
- 15 Silva, Rochester, PEP TM-36, 1981, [?]
- 16 Shapiro, Cornell Ph.D Th., 1991, [?]
- 17 Paoluzzi et al., ACM Trans. Graph., 1993, [?]
- 18 Pratt & Anderson, ICAP, 1994, [?]
- 19 Bowyer, Djinn, 1995, [?]
- 20 Gomes et al., ACM SMA, 1999, [?]
- 21 Raghothama & Shapiro, ACM Trans. Graph., 1998, [?]
- 22 Shapiro & Vossler, ACM SMA, 1995, [?]
- 23 Hoffmann & Kim, Comput. Aided Des., 2001, [?]
- 24 Raghothama & Shapiro, ACM SMA, 1999, [?]
- 25 DiCarlo et al., IEEE TASE, 2008, [?]
- 26 Bajaj et al., CAD&A, 2006, [?]
- 27 Pascucci et al., ACM SMA, 1995, [?]
- 28 Paoluzzi et al., ACM Trans. Graph., 1995, [?]
- 29 Paoluzzi et al., Comput. Aided Des., 1989, [?]
- 30 Ala, IEEE Comput. Graph. Appl., 1992, [?]

and much more . . .

Representation scheme: Quad-Edge data structure

(Guibas & Stolfi, ACM Transactions on Graphics, 1985)



- (a) Edge record showing Next links.
- (b) A subdivision of the sphere.
- (c) Data structure for the subdivision

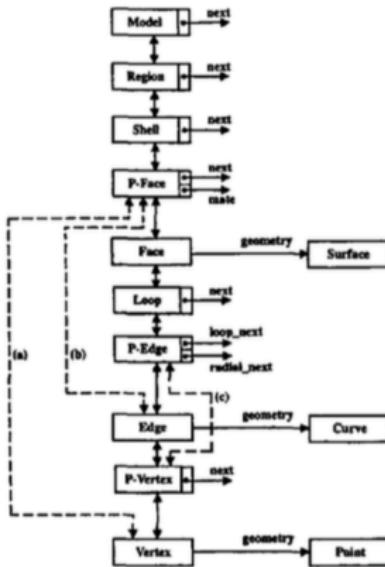
Primitives for the Manipulation
of General Subdivisions and
the Computation of Voronoi
Diagrams

largely used in computational
geometry algorithms and in
geometric libraries

Representation scheme: Partial-Entity data structure

(Sang Hun Lee & Kunwoo Lee, ACM Solid Modeling, 2001)

Compact Non-Manifold Boundary Representation Based on Partial Topological Entities



```

class Entity {
    int _id;
    Attribute *_attribute;
};

class Model : public Entity {
    Model *_next; // next model
    Region *_region; // list of regions
};

class Region : public Entity {
    Region *_next; // link field of the region list of a model
    Model *_model; // parent model
    Shell *_shell; // peripheral shell
};

class Shell : public Entity {
    Shell *_next; // next void shell
    Region *_region; // parent region
    Pface *_pface; // partial face
};

class Pface : public Entity { // partial face (p-face) class
    Pface *_next; // next p-face
    Shell *_shell; // parent shell
    Entity *_child; // child entity: a face, an edge, or a vertex
    Orient *_orient; // orientation flag w.r.t. the face normal
    Pface *_mate; // mate p-face
};

class Face : public Entity {
    Pface *_pface; // one of two incident p-faces
    Loop *_loop; // peripheral loop
    Surface *_geometry; // surface
};

class Loop : public Entity { // next hole loop
    Loop *_next; // next hole loop
    Face *_face; // parent face
    Pedge *_pedge; // a p-edge in a loop
};

class Pedge : public Entity { // partial edge (p-edge) class
    Loop *_loop; // parent loop
    Entity *_child; // child entity: an edge or a p-vertex
    Orient *_orient; // orientation flag w.r.t. the edge direction
    Pvertex *_pvertex; // start p-vertex
    Pedge *_looped_prev; // previous p-edge in the loop cycle
    Pedge *_looped_next; // next p-edge in the loop cycle
    Pedge *_radial_prev; // previous p-edge in the radial cycle
    Pedge *_radial_next; // next p-edge in the radial cycle
};

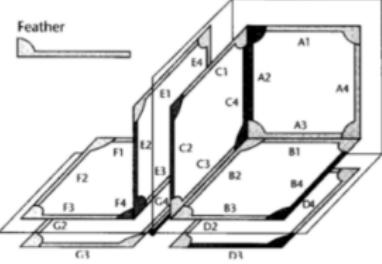
class Pvertex : public Entity { // partial vertex (p-vertex) class
    Pvertex *_next; // another p-vertex associated with _vertex
    Entity *_parent; // parent entity: an edge or a p-edge
    Vertex *_vertex; // mother vertex
};

class Vertex : public Entity { // parent entity: a p-vertex or a p-face
    Entity *_parent; // parent entity: a p-vertex or a p-face
    Point *_geometry; // position
};

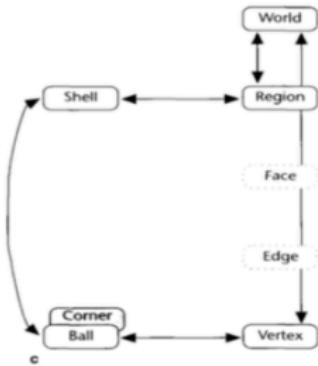
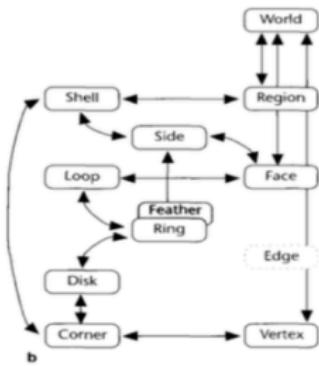
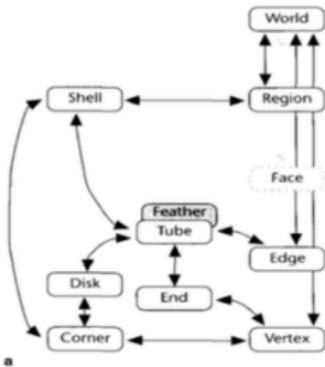
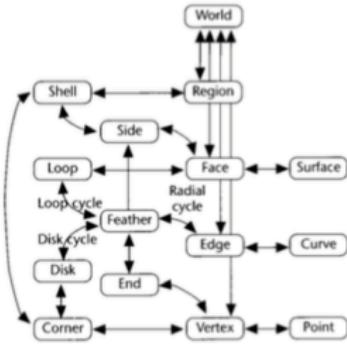
```

Representation scheme: Coupling Entities data structure

(Yamaguchi & Kimura, IEEE Computer Graphics and Applications, 1995)



Fan	$B4 \& D3$	$:D3 = FM(B4), B4 = FM(D3)$
Blade	$C2 \& E2$	$:E2 = BM(C2), C2 = BM(E2)$
Wedge	$A2 \& C4$	$:C4 = WM(A2), A2 = WM(C4)$
Loop cycle	$A1 \gg A2 \gg A3 \gg A4$	$:A2 = CCL(A1), A3 = CCL(A2)$
	$A4 \gg A3 \gg A2 \gg A1$	$:A1 = CL(A2), A2 = CL(A3)$
Radial cycle	$D2 \gg C3 \gg F4$	$:C3 = CCR(D2), F4 = CCR(C3)$
	$F4 \gg C3 \gg D2$	$:D2 = CR(C3), C3 = CR(F4)$
Disk cycle	$A3 \gg C4 \gg B2$	$:C4 = CCD(A3), B2 = CCD(C4)$
	$B2 \gg C4 \gg A3$	$:A3 = CD(C4), C4 = CD(B2)$



Space decompositions

Join of pointsets

The **join** of two sets $P, Q \subset \mathbb{E}^n$ is the convex hull of their points:

$$PQ = \text{join}(P, Q) := \{\gamma p + \lambda q, \ p \in P, \ q \in Q\}$$
$$\gamma, \lambda \in \mathbb{R}, \ \gamma, \lambda \geq 0, \ \gamma + \lambda = 1$$

The join operation is **associative** and **commutative**.

Join of pointsets: examples

```

pts = [[0,0],[.5,0],[0,.5],[.5,.5],
       [1,.5],[1.5,.5],[1.5,1],[.25,1]]      # coords
P = AA(MK)(pts)                          # 0-polyhedra
S = AA(JOIN)([P[0:4],P[4:7],P[7]])      # array of d-polyhedra
H = JOIN(S)                             # 2-polyhedron

```

```

VIEW(STRUCT(AA(SKELETON(1))(S)))
VIEW(H)

```

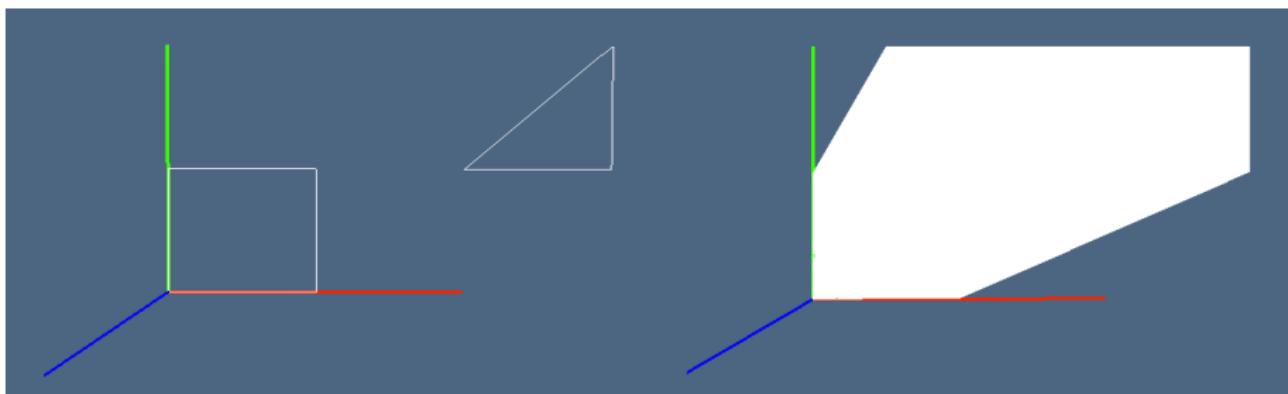


Figure 1: (a) 1-skeleton of pointsets in S ; (b) convex hull H of pointset P

Simplex

A **simplex** $\sigma \subset \mathbb{E}^n$ of order d , or d -simplex, is the **join** of $d + 1$ **affinely independent points**, called **vertices**.

The $n + 1$ points p_0, \dots, p_n are **affinely independent** when the n vectors $p_1 - p_0, \dots, p_n - p_0$ are **linearly independent**.

A **d -simplex** can be seen as a **d -dimensional triangle**: 0-simplex is a **point**, 1-simplex is a **segment**, 2-simplex is a **triangle**, 3-simplex is a **tetrahedron**, and so on.

Simplex: examples

```
s0,s1,s2,s3 = [SIMPLEX(d) for d in range(4)]      # array of standard d-simplices
VIEW(s1); VIEW(s2); VIEW(s3);

points = [[1,1,1],[0,1,1],[1,0,0],[1,1,0]]        # coords of 4 points
tetra = JOIN(AA(MK)(points))                         # 3-simplex
VIEW(tetra)
```

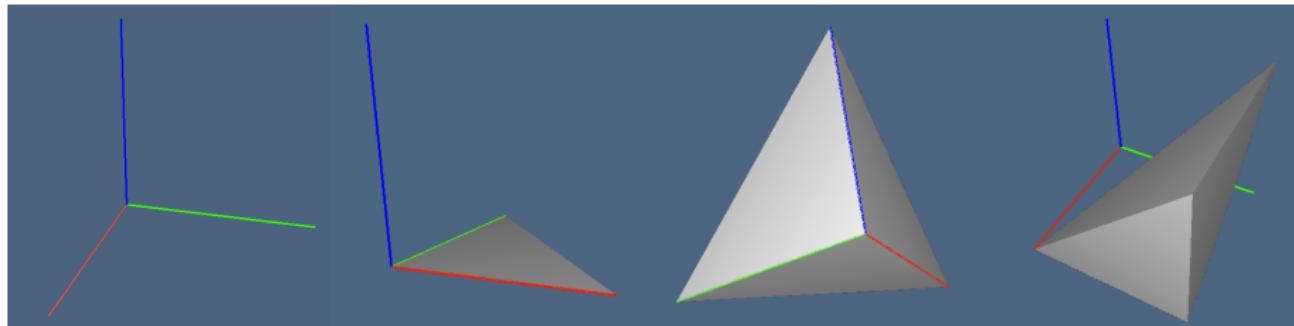


Figure 2: (a,b,c) 1-, 2-, and 3-standard simplex; (d) 3-simplex defined by 4 points

Simplicial complex

Any subset of $s + 1$ vertices ($0 \leq s \leq d$) of a d -simplex σ defines an s -simplex, which is called **s -face** of σ .

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A **simplicial complex** is a set of simplices Σ , verifying the following conditions:

- ① if $\sigma \in \Sigma$, then any s -face of σ belongs to Σ ;
- ② if $\sigma, \tau \in \Sigma$, then $\sigma \cap \tau \in \Sigma$.

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- ① if $\sigma \in \Sigma$, then any s -face of σ belongs to Σ ;
- ② if $\sigma, \tau \in \Sigma$, then $\sigma \cap \tau \in \Sigma$.

Geometric carrier $|\Sigma|$ is the pointset union of simplices in Σ .

Simplicial complex: examples

```

from larlib import *
V,CV = larSimplexGrid1([5,5,5])
FV = larSimplexFacets(CV)
EV = larSimplexFacets(FV)
VIEW(EXPLODE(1.5,1.5,1.5)(MKPOLS((V,CV))))
VIEW(EXPLODE(1.5,1.5,1.5)(MKPOLS((V,FV))))
VIEW(EXPLODE(1.5,1.5,1.5)(MKPOLS((V,EV))))


BV = [FV[t] for t in boundaryCells(CV,FV)]
VIEW(EXPLODE(1.5,1.5,1.5)(MKPOLS((V,BV))))      # boundary 2-simplices

```

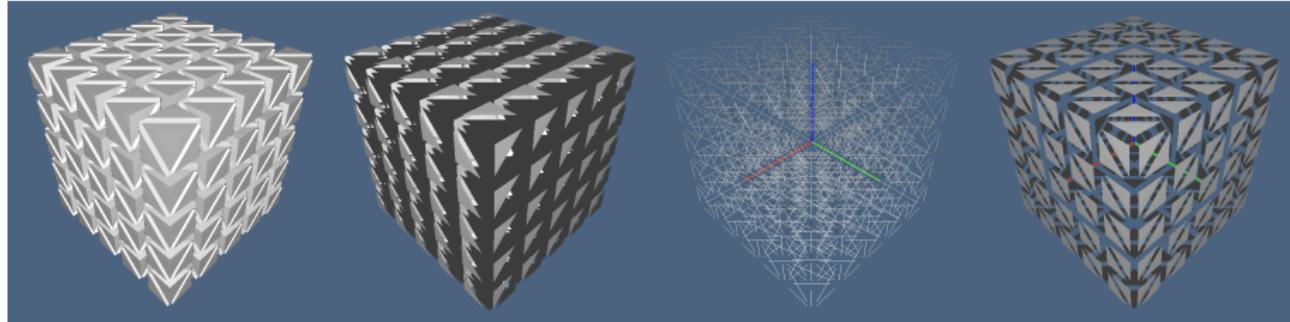


Figure 3: (a) 3-complex; (b) 2-subcomplex; (c) 1-subcomplex; (d) 2-boundary.

Simplicial complex: examples

(see Disk Point Picking)

```

from larlib import *; from random import random as rand
points = [[2*PI*rand(),rand()] for k in range(1000)]
V = [[SQRT(r)*COS(alpha),SQRT(r)*SIN(alpha)] for alpha,r in points]
cells = [[k+1] for k,v in enumerate(V)]
VIEW(MKPOL([V,cells,None])))

from scipy.spatial import Delaunay
FV = Delaunay(array(V)).vertices
VIEW(EXPLODE(1.2,1.2,1)(MKPOLS((V,FV))))
VIEW(SKELETON(1)(STRUCT(MKPOLS((V,FV)))))

```

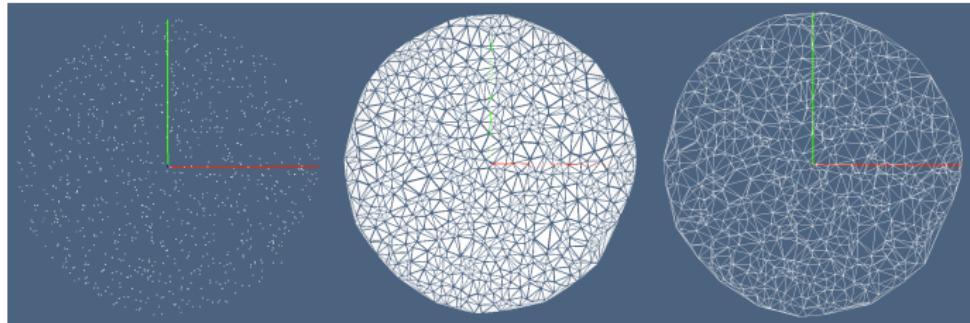


Figure 4: (a) Points; (b) Delaunay triangulation; (c) 1-skeleton.

Simplicial complex: examples

(see Disk Point Picking)

```
from larlib import *; from random import random as rand
points = [[2*rand()-1,2*rand()-1,2*rand()-1] for k in range(30000)]
V = [p for p in points if VECTNORM(p) <= 1]
VIEW(STRUCT(MKPOLS((V,AA(LIST)(range(len(V)))))))
```

```
from scipy.spatial import Delaunay
CV = Delaunay(array(V)).vertices
def test(tetra): return AND([v[-1] < 0 for v in tetra])
CV = [cell for cell in CV if test([V[v] for v in cell]) ]
VIEW(STRUCT(MKPOLS((V,CV))))
```

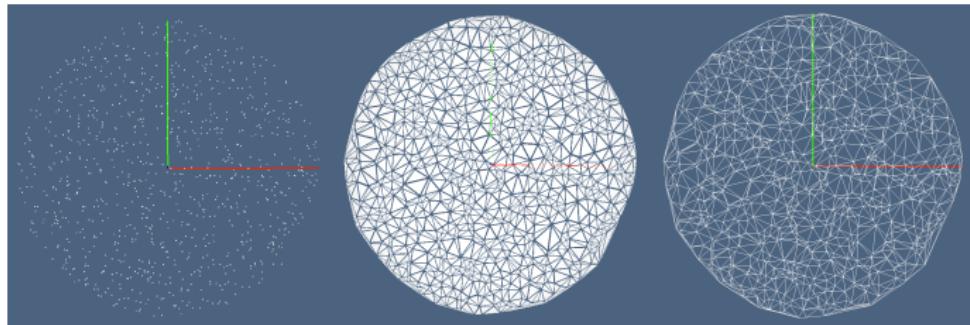


Figure 5: (a) Points; (b) Delaunay triangulation; (c) 1-skeleton.

Cellular complex

Politopal, simplicial, cuboidal complexes

Cellular complexes characterised by different types of cells:

- ① In polytopal complexes cells are polytopes, i.e. bounded convex sets;
- ② In simplicial complexes cells are simplices, i.e. d -polyedra with $d + 1$ facets ($(d - 1)$ -faces) and $d + 1$ vertices.
- ③ In cuboidal complexes cells are cuboids, (in general, sets homeomorphic to) Cartesian products of intervals, i.e. d -polyedra with $2d$ facets and $2d$ vertices.

Numbers of vertices and facets

A d -simplex, or d -dimensional simplex, has $d + 1$ extremal points called **vertices** and $d + 1$ facets.

- a **point** (0-simplex) has $0 + 1 = 1$ vertices and 1 facet (\emptyset);
- an **edge** (1-simplex) has $1 + 1 = 2$ vertices and 2 facets;
- a **triangle** (2-simplex) has $2 + 1 = 3$ vertices and 3 facets;
- a **tetrahedron** (3-simplex) has $3 + 1 = 4$ vertices and 4 facets, etc.

Numbers of vertices and facets

A *d*-simplex, or *d*-dimensional simplex, has $d + 1$ extremal points called **vertices** and $d + 1$ facets.

- a **point** (0 -simplex) has $0 + 1 = 1$ vertices and 1 facet (\emptyset);
- an **edge** (1 -simplex) has $1 + 1 = 2$ vertices and 2 facets;
- a **triangle** (2 -simplex) has $2 + 1 = 3$ vertices and 3 facets;
- a **tetrahedron** (3 -simplex) has $3 + 1 = 4$ vertices and 4 facets, etc.

A *d*-cuboid has conversely 2^d vertices and $2d$ facets:

- a **point** (0 -cuboid) has $2^0 = 1$ vertices and 0 facets;
- an **edge** (1 -cuboid) has $2^1 = 2$ vertices and 2 facets;
- a **quadrilateral** (2 -cuboid) has $2^2 = 4$ vertices and 4 facets;
- a **hexahedron** (3 -cuboids) has $2^3 = 8$ vertices and 8 facets, etc.

Cellular complex: properties

- Support $|K|$ of a cellular complex K is the union of points of its cells
- A triangulation of a polytope P is a simplicial complex K whose support is $|K| = P$
 - For example, a triangulation of a polygon is a subdivision in triangles
- Simplices and cuboids are polytopes.
- A polytope is always triangulable;
 - For example, a quadrilateral can be divided in two triangles, and a cube in either 5 or 6 tetrahedra without adding new vertices

Simplicial mapping

Simplicial mapping: definition

Definition

A **simplicial map** is a map between simplicial complexes with the property that the images of the vertices of a simplex always span a simplex.

Remarks

Simplicial maps are determined by their effects on vertices
for a precise definition of **Simplicial Map** look at [Wolfram MathWorld](#)

MAP operator in plasm

Map operator

`MAP(fun)(domain)`

Semantics

- ① **domain** (HPC value) is decomposed into a **simplicial complex**
- ② **fun** (a simplicial function) is applied to the **domain vertices**
- ③ the **mapped domain** is returned

MAP examples: 1-sphere (S^1) and 2-disk (D^2)

```

def sphere1(p): return [COS(p[0]), SIN(p[0])] # point function
def domain(n): return INTERVALS(2*PI)(n)          # generator of domain decomp
VIEW( MAP(sphere1)(domain(32)) )                  # geometric value (HPC type)

def disk2D(p):                                     # point function
    u,v = p
    return [v*COS(u), v*SIN(u)]                   # coordinate functions
domain2D = PROD([INTERVALS(2*PI)(32), INTERVALS(1)(3)]) # 2D domain decompos
VIEW( MAP(disk2D)(domain2D) )
VIEW( SKELETON(1)(MAP(disk2D)(domain2D)) )

```

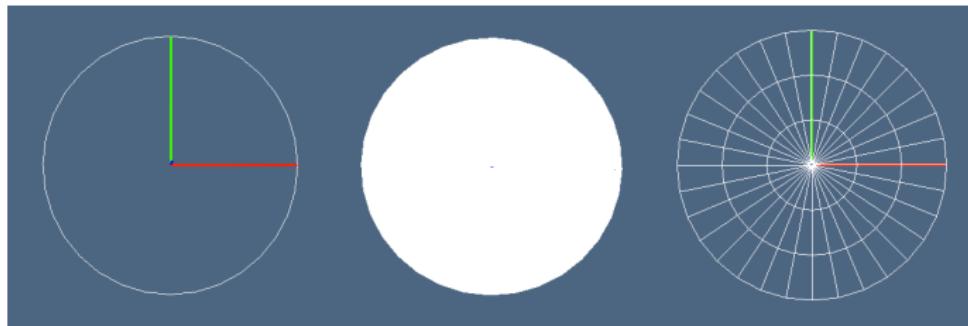


Figure 6: (a) sphere S^1 (b) disk D^2 ; (c) 1-skeleton.