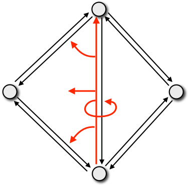
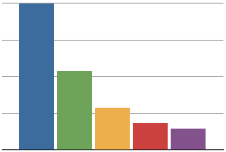
Design, Implementation, and Evaluation of the `Surface_mesh` Data Structure



```cpp
class Vertex_iterator
{
public:

    /// Default constructor
    Vertex_iterator(Vertex v=Vertex()) : hnd_(v) {}

    /// Cast to the vertex the iterator refers to
    operator Vertex() const { return hnd_; }

    /// are two iterators equal?
    bool operator==(const Vertex_iterator& rhs) const
    {
        return (hnd_==rhs.hnd_);
    }

    /// are two iterators different?
    bool operator!=(const Vertex_iterator& rhs) const
    {
        return !operator==(rhs);
    }

    /// pre-increment iterator
    Vertex_iterator& operator++()
    {
        ++hnd_.idx_;
        return *this;
    }

    /// pre-decrement iterator
    Vertex_iterator& operator--()
    {
        --hnd_.idx_;
        return *this;
    }

private:
    Vertex  hnd_;
};
```



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Outline

Introduction

Design

Implementation

Evaluation
- Memory
- Performance
- Ease of Use

Conclusions

Introduction

Mesh data structures

- Fundamental for research and development
- Time-consuming to implement

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- Strengths and weaknesses

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Existing libraries (Mesquite, CGAL, OpenMesh, ...)

- Strengths and weaknesses
- Complexity
- Performance

Introduction

Our approach:

- Systematically analyze **design** choices
- Careful and efficient **implementation**
- Comprehensive **evaluation**

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Design Goals

Compromise between

- Efficiency
- Memory
- Applicability
- Ease of use

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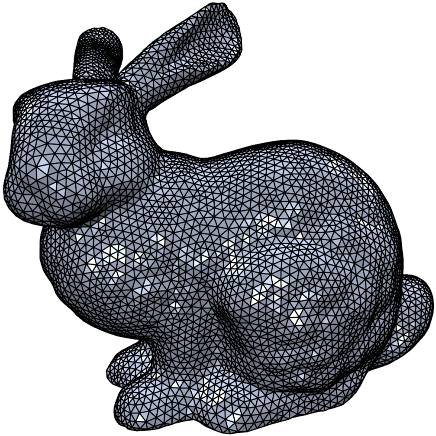
- **Ease of use**

Design Decisions

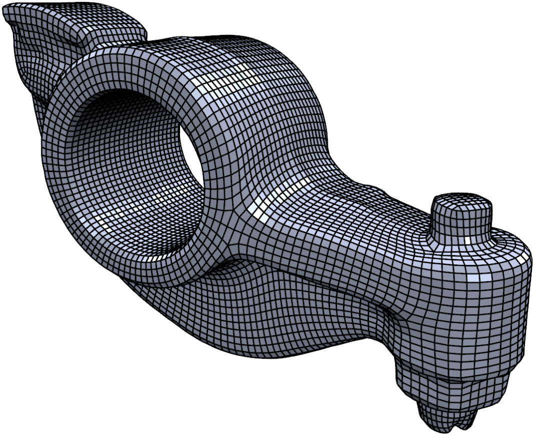
Element Types

Computer Graphics: triangle meshes



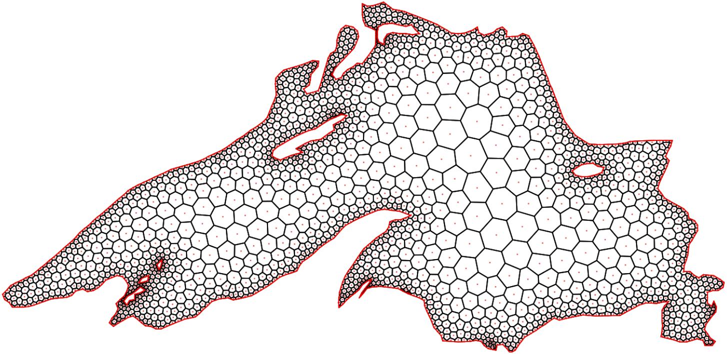
Element Types

Simulation: quad meshes



Element Types

Voronoi diagrams, Polygonal Finite Elements



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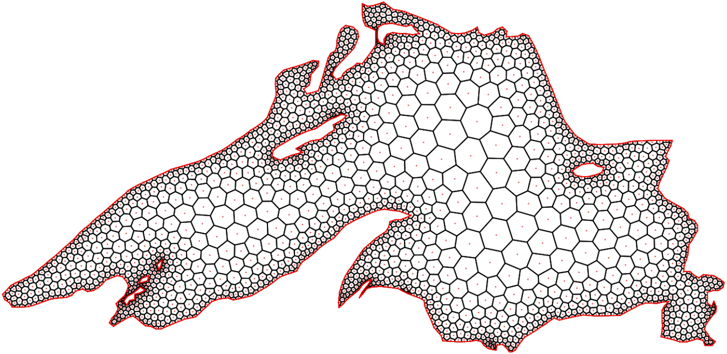


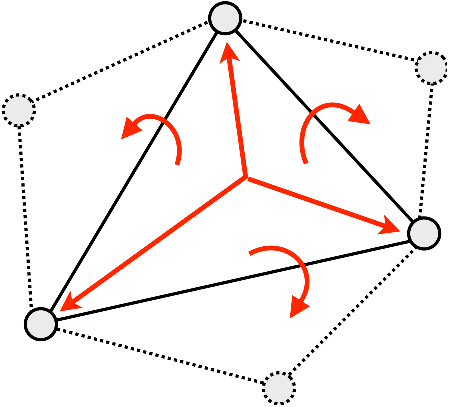
→ support arbitrary polygonal elements

Connectivity Representation

face-based vs. edge-based

Face-Based Representations

- Store faces and references to
  - Defining vertices
  - Neighboring faces



Face-Based Representations

Pros:

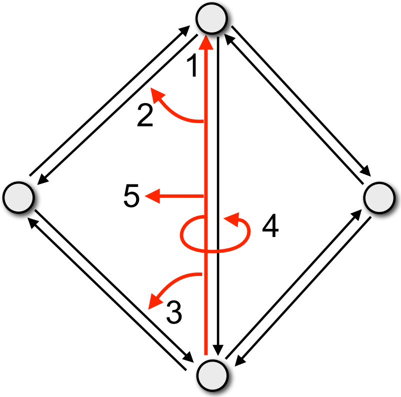
+ Simplicity
+ Memory consumption

Cons:

– Variable size data types
– One-ring traversal
– No explicit edges

Halfedge Data Structure

- Store pairs of oriented halfedges



1. Target vertex
2. Next halfedge
3. Previous halfedge
4. Opposite halfedge
5. Adjacent face

Halfedge Data Structure

Pros:

+ All entities and relations represented
+ Constant size data types
+ Efficient adjacency queries

Cons:

– Memory consumption

Halfedge Data Structure

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- \+ All entities and relations represented
- \+ Constant size data types
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→ use a halfedge data structure

Storage Scheme

List-based

+ Easy removal

– Performance
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⟶ use array-based storage

Entity References

Pointers

- \+ Direct memory access
- – Invalid upon resize
- – Memory consumption

Indices

- \+ Validity checks
- \+ Memory consumption
- – Indirect memory access

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Custom Properties

Extended entities

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class Vertex
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Vertex  vertices[N];
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⟶ use synchronized arrays

Ease of Use

Genericity

+ Customization

– Accessibility
– Documentation

Simplicity

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Ease of Use

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→ strive for simplicity

Summary

Supported element types	→	arbitrary polygons
Connectivity representation	→	halfedges
Storage scheme	→	arrays
Entity references	→	indices
Custom properties	→	synchronized arrays
Ease of use	→	simplicity

Outline

Implementation Overview

- Based on OpenMesh

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- Massively simplified
- Single class, no complicated hierarchy
- Templates reduced to a minimum

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- Based on OpenMesh
- Massively simplified
- Single class, no complicated hierarchy
- Templates reduced to a minimum
- OpenMesh: 8400 lines of code
- `Surface_mesh` : 2250 lines of code

Example: Smoothing

```
#include <Surface_mesh.h>

int main(int argc, char** argv)
{
    Surface_mesh mesh;

    mesh.read(argv[1]);

    Vertex_property<Point> points =  mesh.get_vertex_property<Point>("v:point");
    Vertex_iterator vit, vend = mesh.vertices_end();
    Vertex_around_vertex_circulator vc, vc_end;

    for (vit = mesh.vertices_begin(); vit != vend; ++vit)
    {
        Point  p(0,0,0);
        Scalar c(0);
        vc = vc_end = mesh.vertices(*vit);
        do
        {
            p += points[*vc];
            ++c;
        }
        while (++vc != vc_end);
        points[*vit] = p / c;
    }

    mesh.write(argv[2]);
}
```

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Evaluation Overview

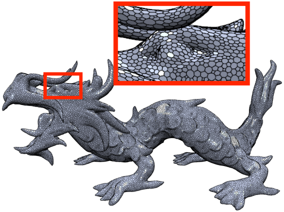
Libraries:

- Mesquite
- CGAL
- OpenMesh

Models

Imp Model
300k vertices, 600k triangles

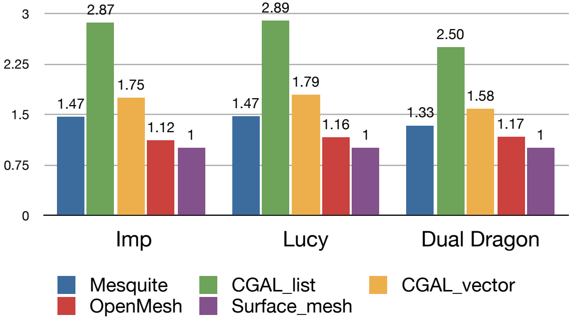
Lucy Model
10M vertices, 20M triangles



Dual Dragon Model
100k vertices, 50k polygons

Outline

Memory Consumption



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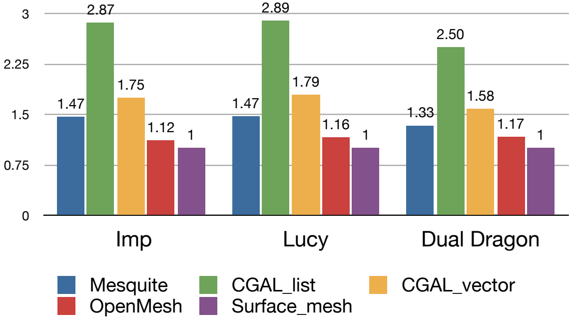

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- Variable storage
- 64-bit references
- Helper data

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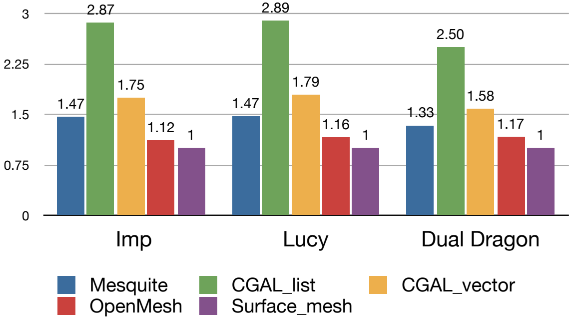

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CGAL

- 64-bit references
- List: Generally higher

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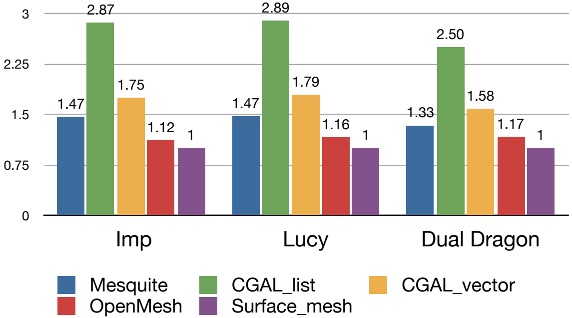

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OpenMesh

- Status information

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Benchmarks Overview

Circulator Faces around vertex, vertices around face

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Circulator	Faces around vertex, vertices around face
Barycenter	Compute barycenter of vertices

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Circulator	Faces around vertex, vertices around face
Barycenter	Compute barycenter of vertices
Normals	Compute and store face & vertex normals
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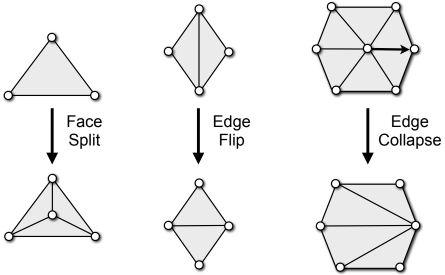
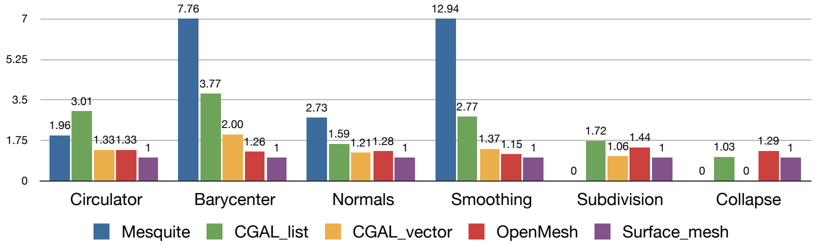
Subdivision	Face split & edge flip
Collapse	Face split & edge collapse



Results: Imp Model



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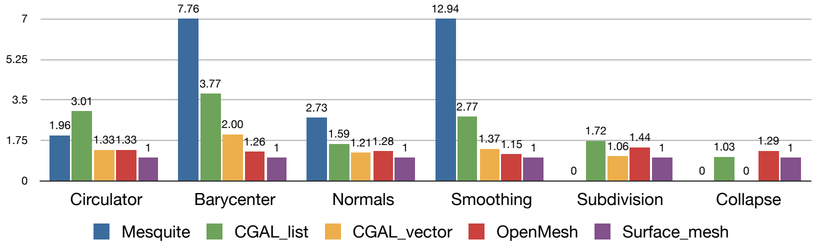

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- Virtual functions
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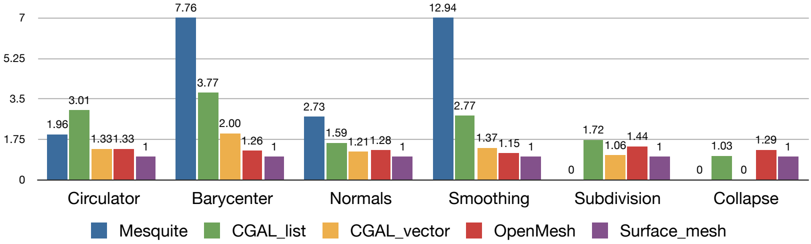

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CGAL

- Extended entities
- List: Memory layout
- Vector: No removal

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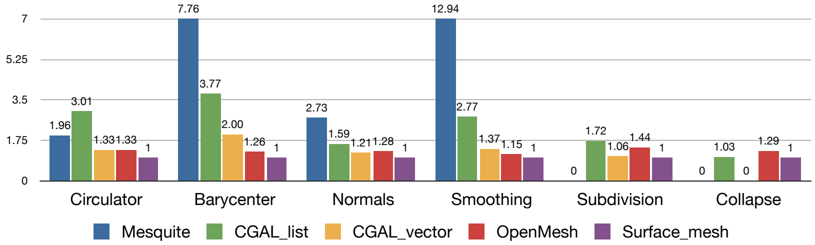

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OpenMesh

- Circulators
- Properties

Outline

Simplicity & Properties

Working with a custom edge property in `Surface_mesh`

```
Surface_mesh mesh;

// allocate property storing a point per edge
Edge_property<Point> edge_points
  = mesh.add_edge_property<Point>("property-name");

// access the edge property like an array
Edge e;
edge_points[e] = Point(x,y,z);

// remove property and free memory
mesh.remove_edge_property(edge_points);
```

Simplicity & Properties

Just declaring a custom edge property in CGAL

```
typedef CGAL::Simple_cartesian<double>  Kernel;
typedef Kernel::Point_3                 Point_3;

template <class Refs> struct My_halfedge
  : public CGAL::HalfedgeDS_halfedge_base<Refs>
{
    Point_3 halfedge_point;
};

class Items : public CGAL::Polyhedron_items_3
{
public:
    template <class Refs, class Traits>
    struct Halfedge_wrapper
    {
        typedef My_halfedge<Refs> Halfedge;
    };
};

typedef CGAL::Polyhedron_3<Kernel, Items>  Mesh;
```

User Feedback

- SGP 2011 graduate course on geometric modeling
- 18 participants, varying experience
- Q: Is `Surface_mesh` easy to use and understand?

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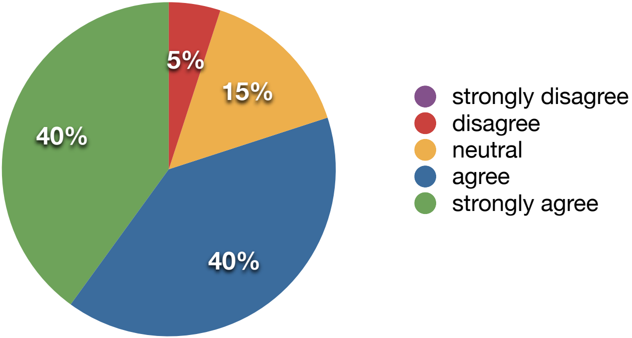

User Feedback: Comments

“It is easy to use for users that have experience with CGAL or OpenMesh. It is nice to have a template-free structure.”

“Much easier than OpenMesh.”

“I thought the data structure was quite easy to understand even though I have never worked with a real mesh data structure before.”

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- Highly efficient
- Low memory consumption

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Our implementation of `Surface_mesh` :

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Other libraries:

- Much more functionality beyond a pure data structure

Limitations & Future Work

Limitations:

- Single `Surface_mesh` declaration in one application
- Two-manifold surface meshes only

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Future work:

- Volumetric meshes

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Future work:

- Volumetric meshes
- Include more libraries (VCGLib, LR, yours?)
- Establish standard set of benchmarks

→ `http://graphics.uni-bielefeld.de`

Thanks

... for your attention.