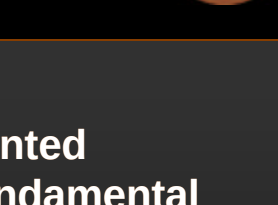
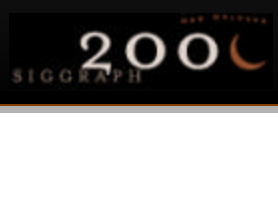
Migrating to an Object-Oriented Graphics API



Course Objective

An introduction to object-oriented graphics APIs that is more fundamental than any one specific API.



Course Presenters

- David Blythe
- Sherif Ghali
- Lutz Kettner
- Henry Sowizral

Course Audience

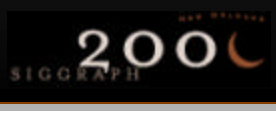
- Familiar with an OOP
- Migrating to an object-oriented API
- Building an API

Material Addressed

- Introduction to current OO APIs
- Common and different API features
- Design your own mini scene graph API

Material Not Addressed

- **Not an objective:**
  - Details sufficient for programming
  - Suggest that any one API is “better”
- **Corollary:**
  - Tutorial/reference manuals are needed
  - API selection

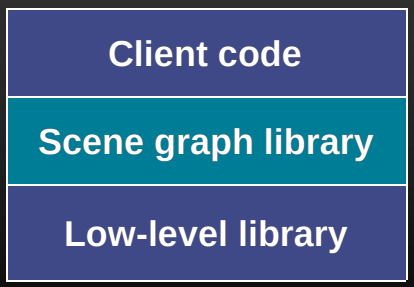


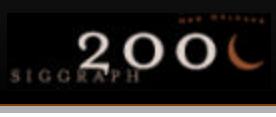
O-O vs. Scene Graph

	Non O-O	O-O
Non Scene Graph	OpenGL	C++/Java binding of OpenGL
Scene Graph	PHIGS	OpenInventor / Java3D / Fahrenheit/XSG

Application Programmer Interface

- Classes and methods defined by a library





Course Outline

- Real and Projective Geometry
- Scene Graphs
- Lighting and Visibility
- Input and User Interaction
- New Features of Scene Graph APIs

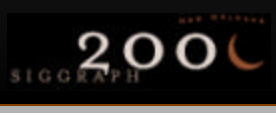
Affine and Projective Geometry

- Designing Geometry Classes (Ghali)
- Classes for Affine and Projective Geometry (Blythe)
- Geometry Class Design Issues (Sowizral)
- Robustness of Geometry Classes (Kettner)

Designing Geometry Classes

Sherif Ghali

Max Planck Institute

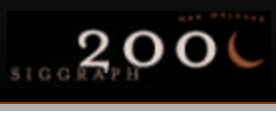


Why Talk About Geometry Classes?

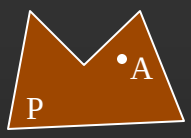
Does the design of elementary geometry classes warrant a lengthy discussion?

Issues Addressed

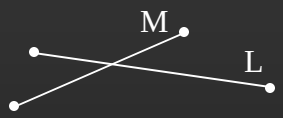
- Introduction and motivation for robustness
- Options in designing geometry classes (DB)
- A recent design of geometry classes (HS)
- A recent design of a robust library (LK)



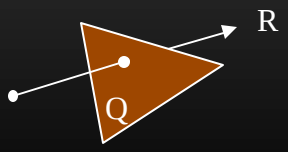
Introduction and Motivation for Robustness



Is point A inside polygon P?



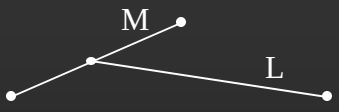
Do segments L and M intersect? where?



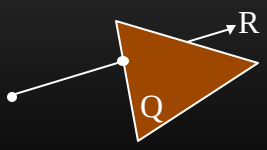
Does ray R intersect polygon Q? where?

Introduction and Motivation for Robustness

Is point A inside polygon P?

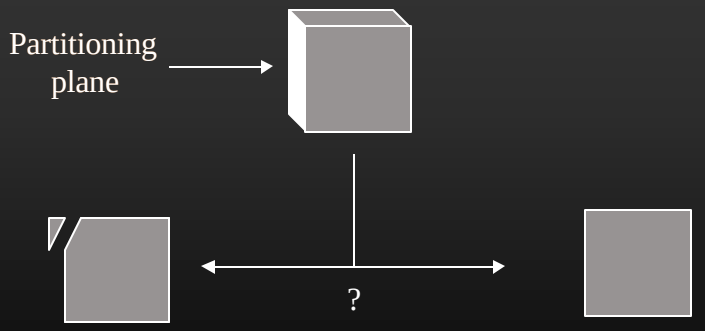


Do segments L and M intersect? where?



Does ray R intersect polygon Q? where?

Precision in 3D: Binary Space Partitioning



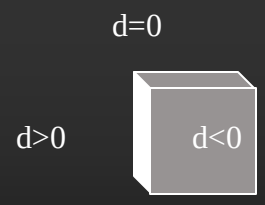
Handling Precision Problems

- Use an epsilon
- Use exact arithmetic

Handling Precision Problems

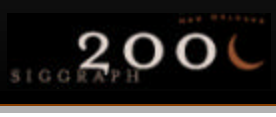
- Use an epsilon
- Use exact arithmetic

Use an Epsilon



- Introduce a line:

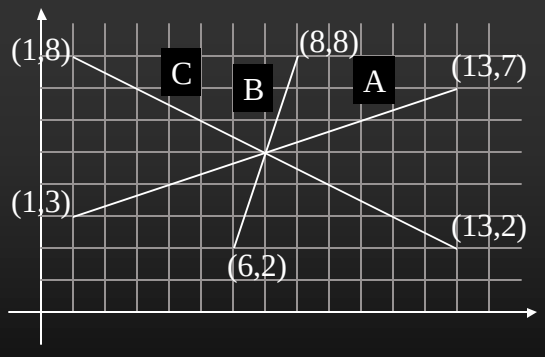
```
if ( d > - Epsilon || d < Epsilon )
        d = 0;
```



Handling Precision Problems

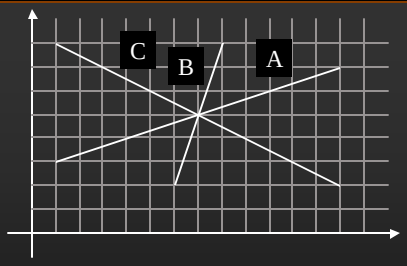
- Use an epsilon
- **Use exact arithmetic**

Segment Intersection



intersection point: (7,5)

Segment Coincidence

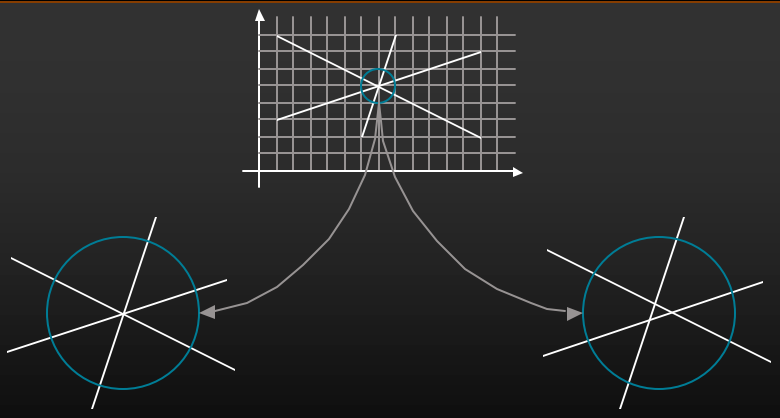


intersection point: (7,5)

point ab: intersection of A and B
point ac: intersection of A and C

Is (ab = ac) true?

Segment Coincidence

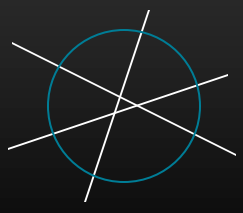


Using Floating Point Numbers

```
#include <LEDA/point.h>
#include <LEDA/segment.h>
main() {
  segment A ( point( 13, 7 ), point(   1, 3 ) );
  segment B ( point(   8, 8 ), point(   6, 2 ) );
  segment C ( point(   1, 8 ), point( 13, 2 ) );
  point ab, ac;
  A.intersection ( B, ab );
  A.intersection ( C, ac );
  std::cout << ab << std::endl << ac << std::endl;
  assert ( ab == ac );
}
```

Using Floating Point Numbers - Output

```
(7.0000000000000009,5)
(7,5)
Assertion failed: ab == ac
```

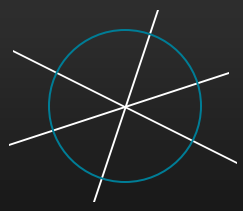


Using Rational Numbers

```
#include <LEDA/rat_point.h>
#include <LEDA/rat_segment.h>
main() {
  rat_segment A ( rat_point( 13, 7 ), rat_point(  1, 3 ) );
  rat_segment B ( rat_point(  8, 8 ), rat_point(  6, 2 ) );
  rat_segment C ( rat_point(  1, 8 ), rat_point( 13, 2 ) );
  rat_point ab, ac;
  A.intersection ( B, ab );
  A.intersection ( C, ac );
  std::cout << ab << std::endl << ac << std::endl;
  assert ( ab == ac );
}
```

Using Rational Numbers - Output

(7,5)
(7,5)



Kernel-independent Code

- **Use either**

  #define POINT point

  or

  #define POINT rat_point

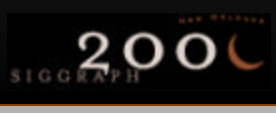
Kernel-independent Code

- **Using floating point numbers:**

  #include <LEDA/point.h>
  #include <LEDA/segment.h>
  #include <LEDA/float_kernel_names.h>

- **Using rational numbers:**

  #include <LEDA/rat_point.h>
  #include <LEDA/rat_segment.h>
  #include <LEDA/rat_kernel_names.h>



Kernel-independent Code

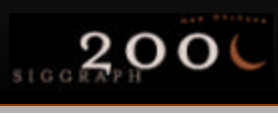
```
main() {
  SEGMENT A ( POINT( 13, 7 ), POINT(   1, 3 ) );
  SEGMENT B ( POINT(   8, 8 ), POINT(   6, 2 ) );
  SEGMENT C ( POINT(   1, 8 ), POINT( 13, 2 ) );
  POINT ab, ac;
  A.intersection ( B, ab );
  A.intersection ( C, ac );
  std::cout << ab << std::endl << ac << std::endl;
  assert ( ab == ac );
}
```

LEDA

- ***Library of Efficient Data structures and Algorithms***
  - Floating-point kernel
    - point, segment, …
  - Rational kernel
    - rat_point, rat_segment, …

Methods of Changing Kernels

- **By using aliasing**
  - LEDA
- **By using genericity**
  - CGAL



Designing Classes for Affine and Projective Geometry

David Blythe
RouteFree

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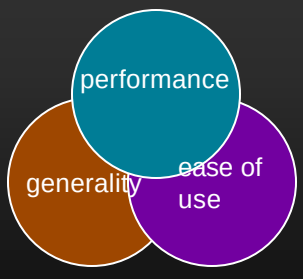
Classes for Affine and Projective Geometry

- What is your objective?



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Classes for Affine and Projective Geometry

- **Basic Classes**
  - Tuple (3 component, 4 component color)
  - Euclidean Points (2D, 3D)
  - Homogenous Points (2D, 3D)
  - Vectors (2D, 3D)
  - Normal Vectors (2D, 3D)
  - Affine Transforms (3x3 Matrix, 4x4, 4x3, …)
  - Frustum, Polytope, Ray, LineSegment

Classes for Affine and Projective Geometry

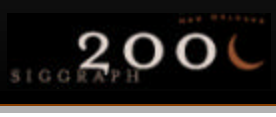
- **Type Explosions**
  - #Types X #Dimensions X #Data representation
    - e.g., integer 2D point, float 2D point, double 3D point
    - integer 3D point, float 3D point, double 3D point
  - Why all the types?
    - 2D is more convenient and saves space over 3D
    - Double precision is often necessary but takes 2x the space

Classes for Affine and Projective Geometry

- **Type Explosions**
  - Strong Typing?
    - Good for encouraging correctness
      - Don't add points $(p_1+p_2)/2$ $p_1 + (p_2-p_1)/2$
      - Treat normal vectors properly Mn $M^{-1}n$
    - Source of implementation complexity
      - Multiple methods with similar behavior
      - Limited inheritance limited reuse
      - tuple point (wrong if +/- defined on tuple)

Classes for Affine and Projective Geometry

- **Solutions**
  - Templates
    - Requires careful design (generic programming)
    - May end up forcing instantiations anyway
    - Performance limitations?
  - Limit number of types supported
    - Engineering compromise
    - Dependent on application domain



Classes for Affine and Projective Geometry

- **Implementation Tips**

```
struct Point3 {
    float v[3];
};
```

```
class Point3 {
    float x, y, z;
};
```

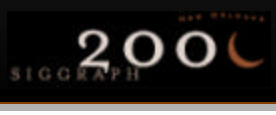
public member

obvious memory layout

generic access

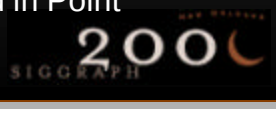
Classes for Affine and Projective Geometry

- **Compromises**
  - Compress Euclidean Point and Homogenous Point?
    - What about w?
  - Compress Normal Vector and Vector?
  - Compress Tuple and Point?
  - Allow more inheritance?



Classes for Affine and Projective Geometry

- **IRIS Performer/Open Inventor**
  - No Strong Typing
  - Everything a tuple (Vec*)
- **Java3D**
  - More strongly typed, fewer basic types
    - double vs. float vs. int
  - Inheritance model breaks typing
    - add/sub defined on Tuple, inherited in Point



Classes for Affine and Projective Geometry

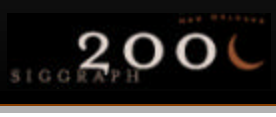
- **Naming Issues**
  - Encode
    - basic type (float, double, int, short),
    - dimensionality (2D, 3D, …)
    - intent (point, vector, …)
  - {Tuple,Point,Vector}{1,2,3,4}{l,f,d,s}
    - 3 x 4 x 4 = 48 classes

Classes for Affine and Projective Geometry

- **Operator Support**
  - Point - Point, Point*scalar
  - Point +/- Vector, Vector*scalar
  - Vector +/- Vector, cross, dot, normalize, length, length^2
  - Transform Point, Vector
  - Build Transform (Scale, Rotate, Translate, Invert)

Classes for Affine and Projective Geometry

- **Operator Explosions**
  - Allow mixtures of representations?
    - e.g., Vector3f*Matrix3d
  - Ignore homogeneous term sometimes
    - e.g., Mp, is point always translated?
  - Seldom used operators
    - tensor product, …
  - Performance tuned special cases



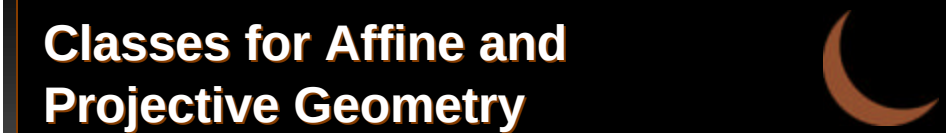
Classes for Affine and Projective Geometry

- **Row Vectors versus Column Vectors**
  - Computer graphics literature mixed (up :)
    - Foley & van Dam switched to column vectors
  - What does C/C++ 2D array map to?
  - Low-level APIs 2D arrays map to row vectors
    - OpenGL, Direct3D
  - Efficiency problems if OO-API mismatches LL-API
  - Should use column vectors (ARB_transpose_matrix)

Classes for Affine and Projective Geometry

- **Representing Rotations**
  - Matrix (3x3)
  - Axis/Angle (è,x,y,z)
  - Euler Angles (roll, pitch, yaw)
  - Quaternions

Classes for Affine and Projective Geometry



- **Bounding Volumes**
  - Bounding boxes (axis aligned)
    - Tight bounds
  - Bounding spheres
    - Low cost
  - Bounding ellipsoids
  - Oriented bounding boxes, ...
    - Compromise between box/sphere

Classes for Affine and Projective Geometry

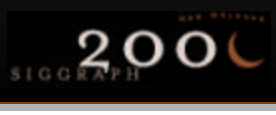
- **Bounding Volume Operations**
  - void create(Point points[]);
  - void create(Bound bounds[]);
  - void extend(Point p);
  - void extend(Bound b);
  - bool overlaps(Bound b);

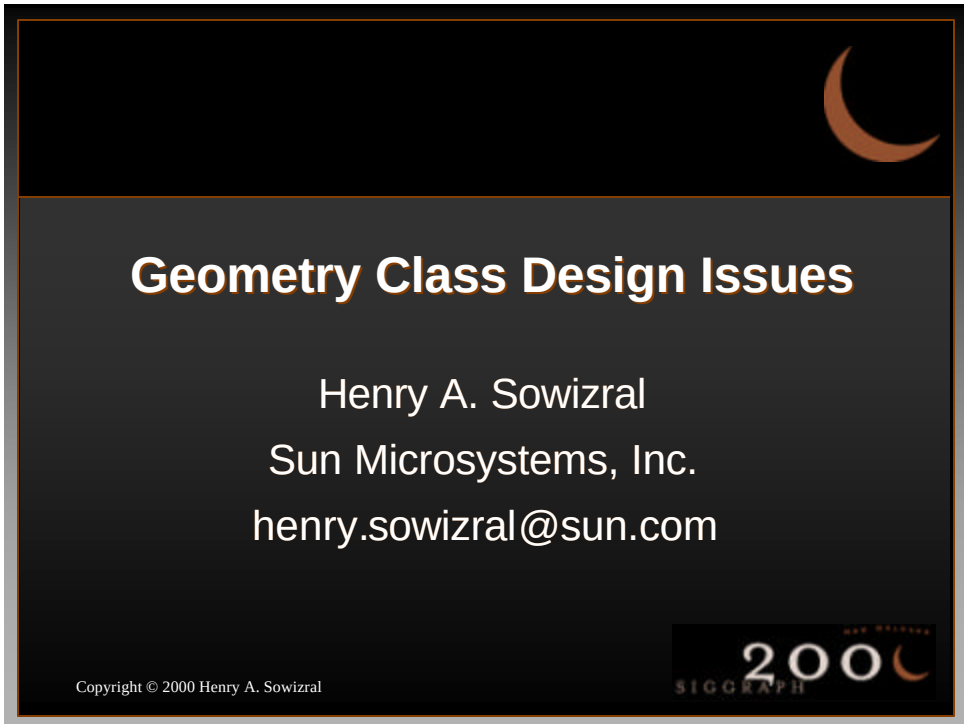
Classes for Affine and Projective Geometry

- **How Far Should Toolkit Go?**
  - Toolkit versus application framework
  - Provide comprehensive math library?
    - Larger than 4x4 matrices, SVD, linear solvers, …
  - Provide what typical 3D applications need?
    - Point, Vector, Normal, Transform, …
    - What about CAD applications, collision detection, …
  - Match the application domain

Classes for Affine and Projective Geometry

- **How Far Should A Toolkit Go?**
  - Provide a basis-set that can be extended or aliased with another library
    - Points, vectors, transforms don't contain extra state (no flags)
    - Obvious memory layout
    - Allow further derivation




Geometry Class Design Issues
Henry A. Sowizral
Sun Microsystems, Inc.
henry.sowizral@sun.com
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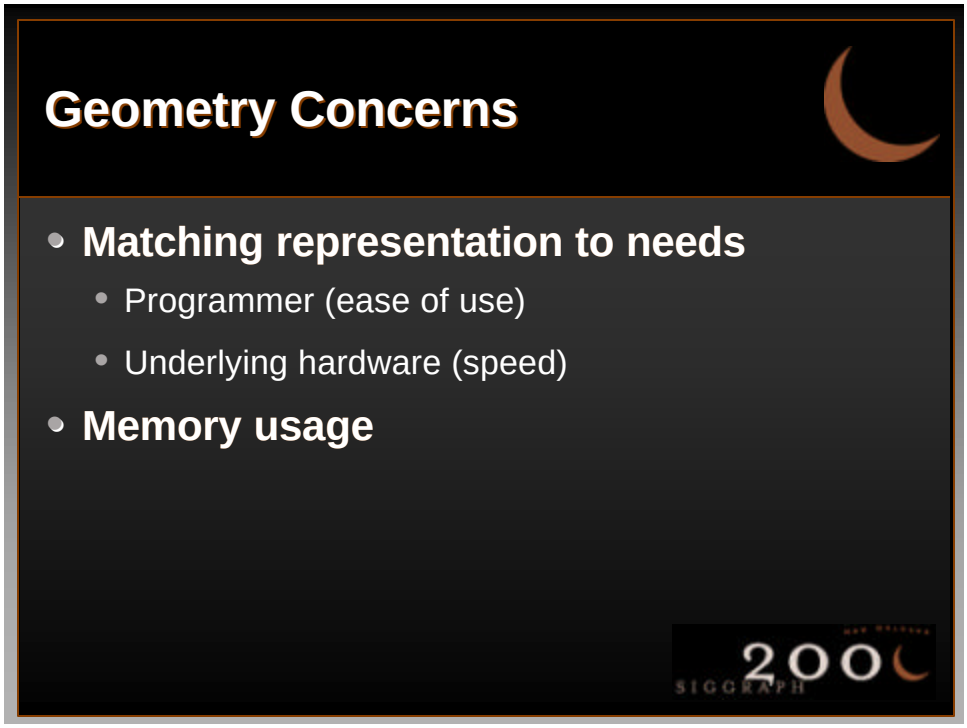
Geometry Concerns
• Matching representation to needs
• Programmer (ease of use)
• Underlying hardware (speed)
• Memory usage
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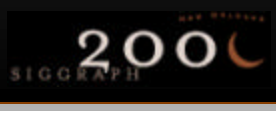
Optimization Points

- Programming
- Rendering
- Manipulating
- Modeling

Geometry Class Requirements

- **Expressiveness**
- **Representational structure**
  - Triangles
  - Analytical
- **Efficiency**
  - Memory, Disk, and Bandwidth (communication)
  - Manipulation (editing)
  - Rendering

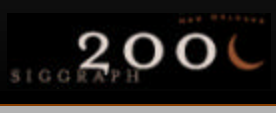


Expressiveness

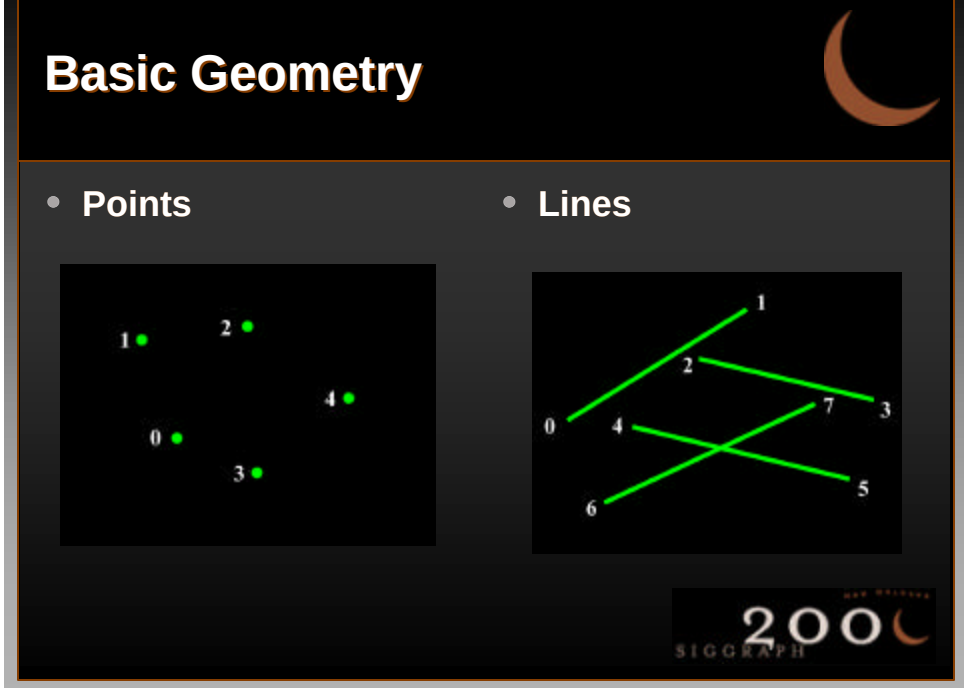
- **Rendering – tessellated object geometry**
- **Manipulation**
  - Simplification – topology and geometry
  - Editing – facet and other structural information
- **Access to non-geometric information**
  - Scene placement
  - Material properties
  - Business information

Basic Representations

- **Basic geometry**
  - Points
  - Lines
  - Triangles (Quads)
- **Stripped geometry**
  - Polylines
  - Triangle fans / Triangle strips
- **Indexed geometry**



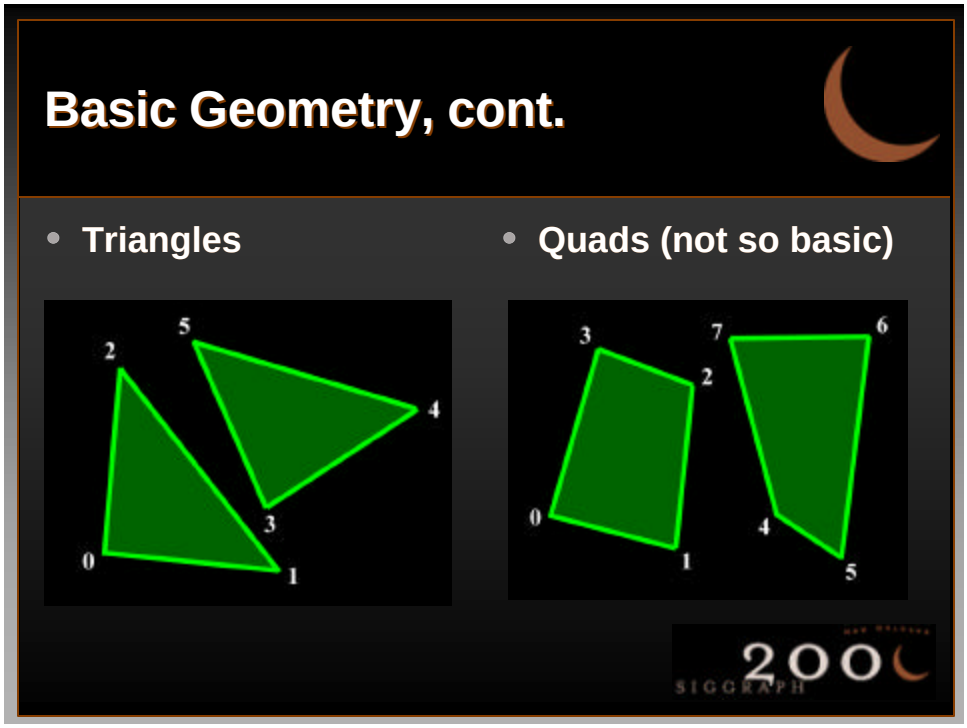
Basic Geometry



- Points

- Lines

Basic Geometry, cont.

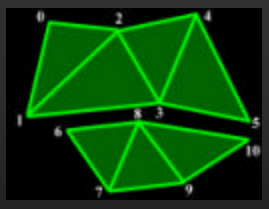


- Triangles

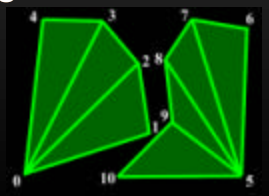
- Quads (not so basic)

Stripped Geometry

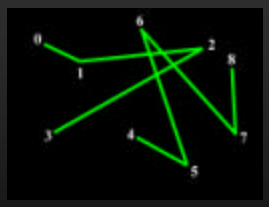
- Triangle strips



- Triangle fans



- Line strips



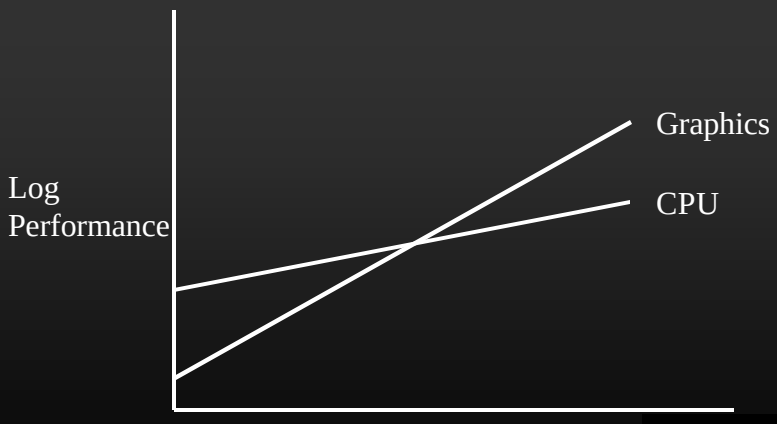
Indexed Geometry

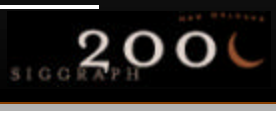
- **Vertex information**
  - Basic vertex information
  - Stored in array
  - Typically not duplicated
- **Array(s) of indices**
  - An index value references the corresponding vertex information
  - Index order specifies the order of vertex information

Analytic Representations

- **Surfaces**
  - NURBS
    - Trim curves
  - Subdivision surfaces
    - Interpolating
    - Approximating
- **Analytic surfaces**

Graphics Outpacing CPU



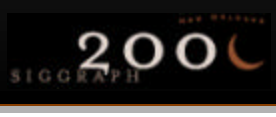


Per Vertex Information

- **Typical triangle: 24-48 bytes**
  - Lighting normals (12 bytes = 3 x 4 bytes)
  - Colors (12 | 16 bytes = 3 | 4 x 4 bytes)|
  - Coordinates (12 bytes = 3 x 4 bytes)
  - Texture coordinate(s) (k * 12 bytes = k * 3 x 4 bytes)

Speeds Too Slow

- **10 Million triangles = 240-480 Mbytes/second**
- **12-24 Million instructions just for transfer**
  - Wait states
  - Indexing
  - Any additional computation
- **Minimum bus speed**
  - 2 trips on the bus
  - 480-960 Mbytes/second on main bus
  - 240-480 on main bus
  - 240-480 on ancillary bus

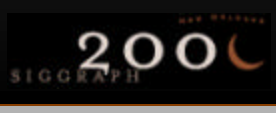


Efficiency

- **Explicit Versus Analytic Representations**
- **Pre-tessellated**
  - Known structure(s)
  - Can match to underlying hardware — very efficient
- **Non-tessellated: tessellate**
  - Each time (interactive LOD)
  - Once and cache
  - When needed and cache

Compression Techniques

- **Fewer bits per vertex, per triangle**
  - Binning: 433, etc.
- **Indexed representations**
- **Connectivity (implicit and explicit)**
- **Higher compression**
  - Binning
  - Run length encoding
  - Huffman encoding

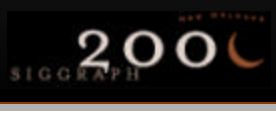


Flexibility Versus Simplicity Versus Completeness

- **What is your favorite format?**
  - Analysis of use results in best representation
- **What do you want to optimize for?**
  - Memory usage
  - Rendering speed
  - Ease in manipulation
  - Ease in modeling

Modeling Versus Rendering

- **Rendering**
- **Modeling**

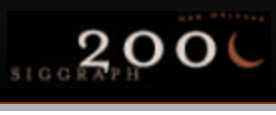


Memory Usage

- What is the nature of the contract?
- Are internal copies required?

Indexed Versus Non-indexed

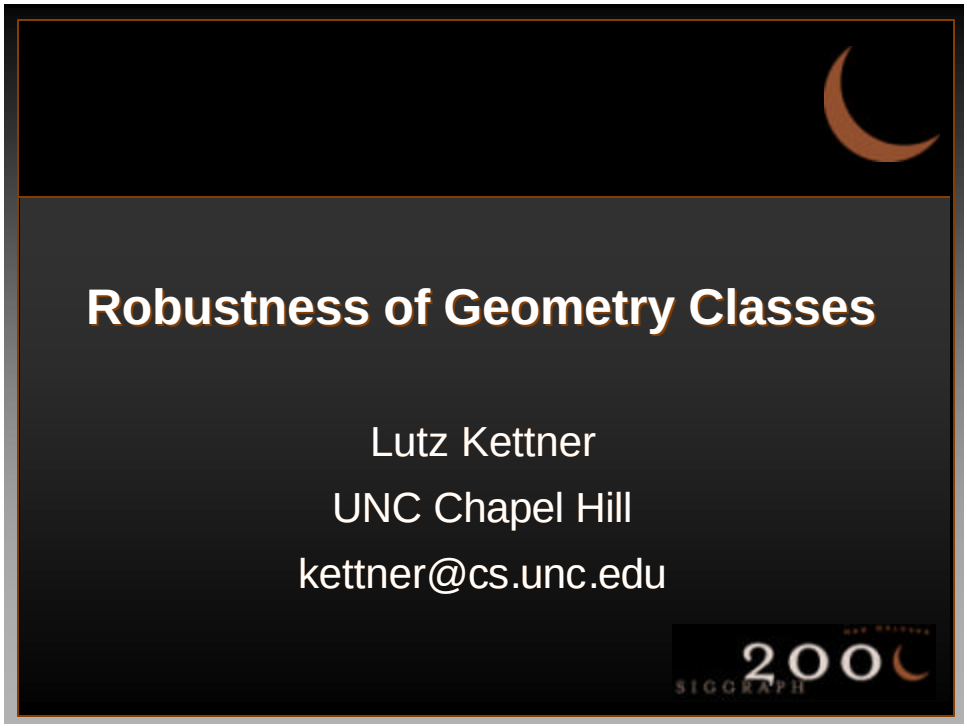
- **Memory**
  - Does it really save memory?
- **Speed**
  - Can it impact speed?

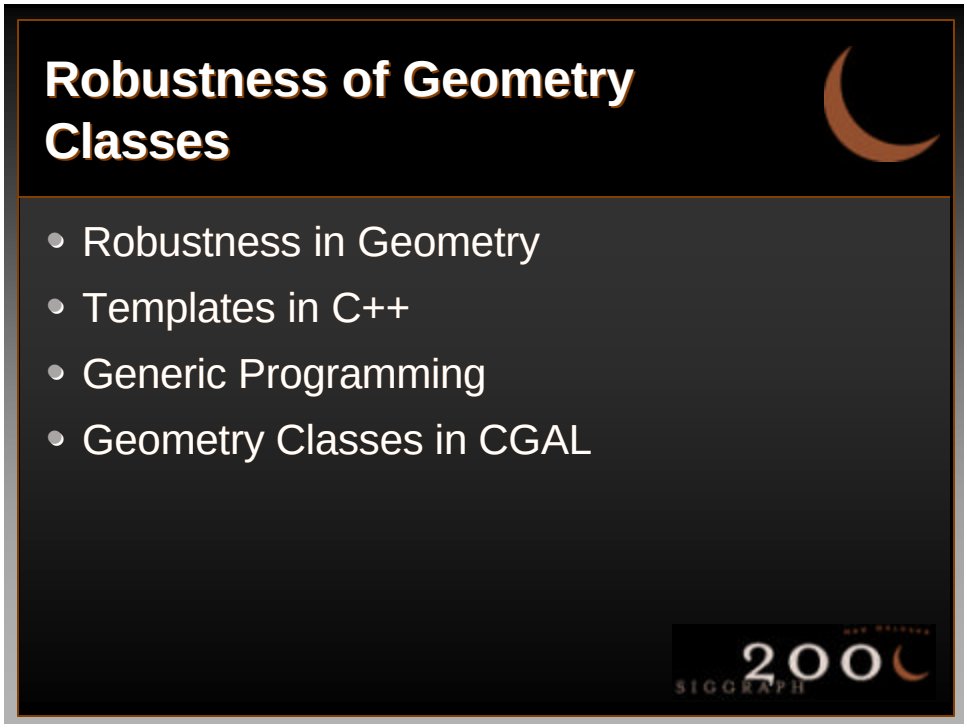


Shared Versus Non-Shared

- **Sharing is it good or bad?**
  - Under the cover costs
- **To duplicating or not to duplicate**

What About Data Staging?


Robustness of Geometry Classes
Lutz Kettner
UNC Chapel Hill
kettner@cs.unc.edu
SIGGRAPH 2000

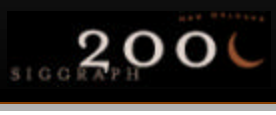

Robustness of Geometry Classes
Robustness in Geometry
Templates in C++
Generic Programming
Geometry Classes in CGAL
SIGGRAPH 2000

Robustness of Geometry Classes

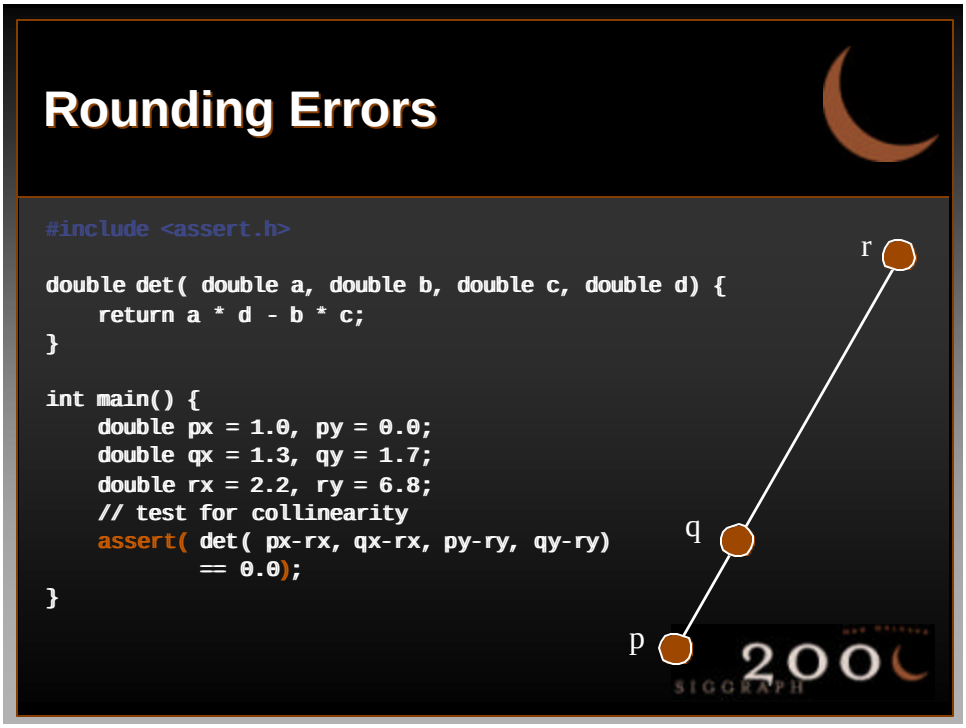
- Robustness in Geometry
- Templates in C++
- Generic Programming
- Geometry Classes in CGAL

Robustness in Geometry

- Rounding Errors
- Degeneracies



Rounding Errors

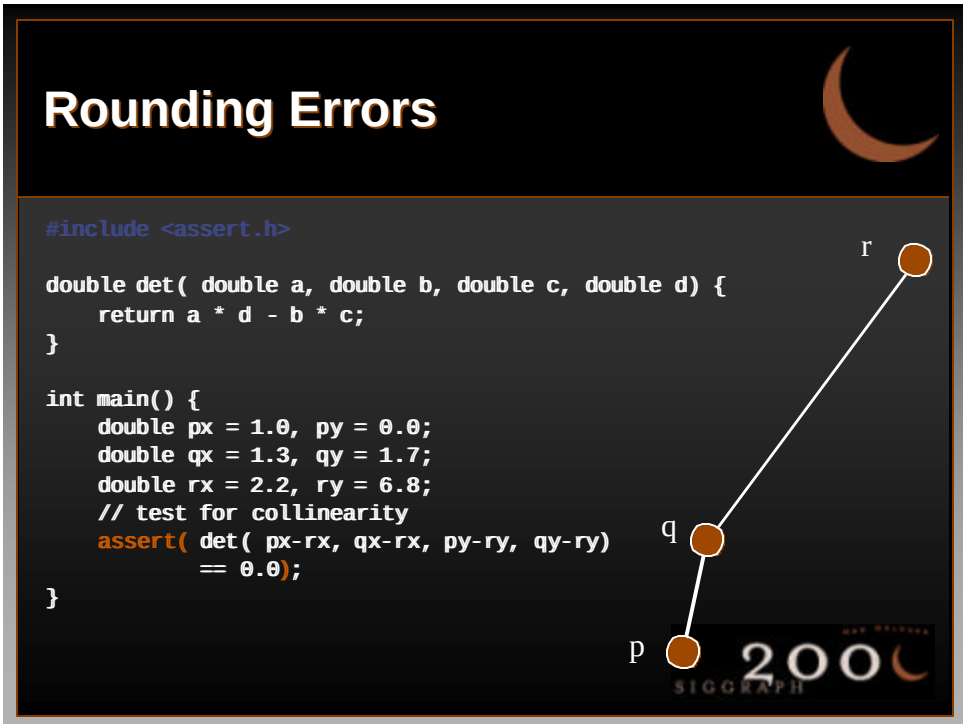


```
#include <assert.h>

double det( double a, double b, double c, double d) {
    return a * d - b * c;
}

int main() {
    double px = 1.0, py = 0.0;
    double qx = 1.3, qy = 1.7;
    double rx = 2.2, ry = 6.8;
    // test for collinearity
    assert( det( px-rx, qx-rx, py-ry, qy-ry)
            == 0.0);
}
```


Rounding Errors



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    assert( det( px-rx, qx-rx, py-ry, qy-ry)
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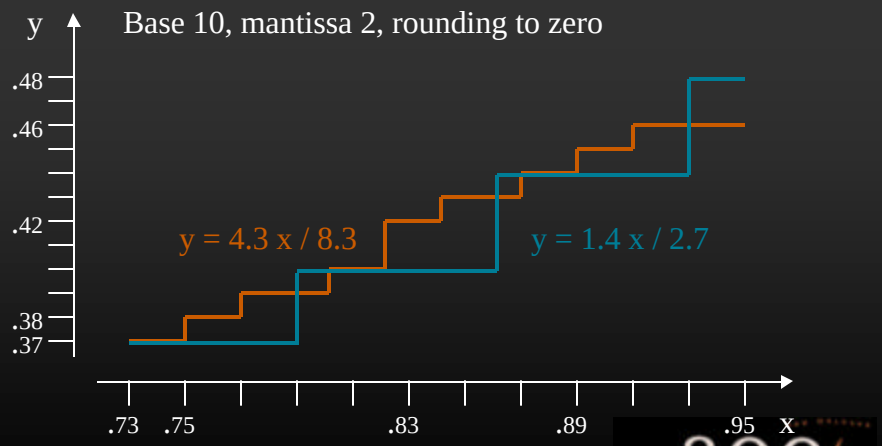
}
```

Rounding Errors (2)

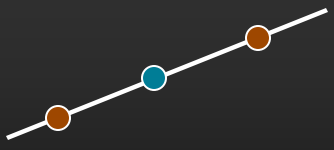


Rounding Errors (3)

- **Redesign algorithms for FP arithmetic**
  - works for some problems, no general theory
- **Exact arithmetic**
  - long integers, rationals, reals (incl. k-th roots)
- **FP filter for efficiency**
  - error bounds: static, semi-static, dynamic
- **Type of arithmetic and filter depends on the application** **Flexibility** ➡

Degeneracies

- Duplicate points (set versus sequence)
- Three points on a line

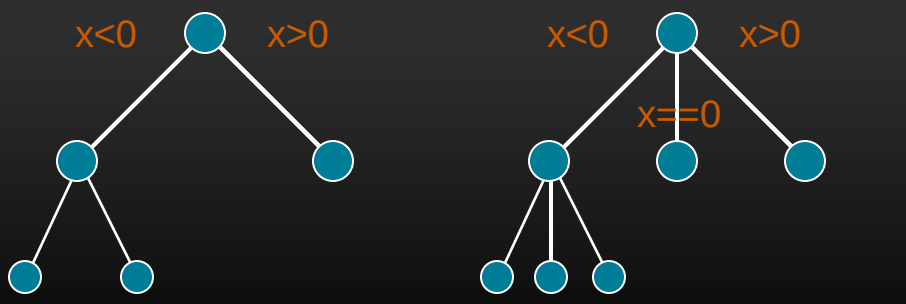


- Four points on a circle

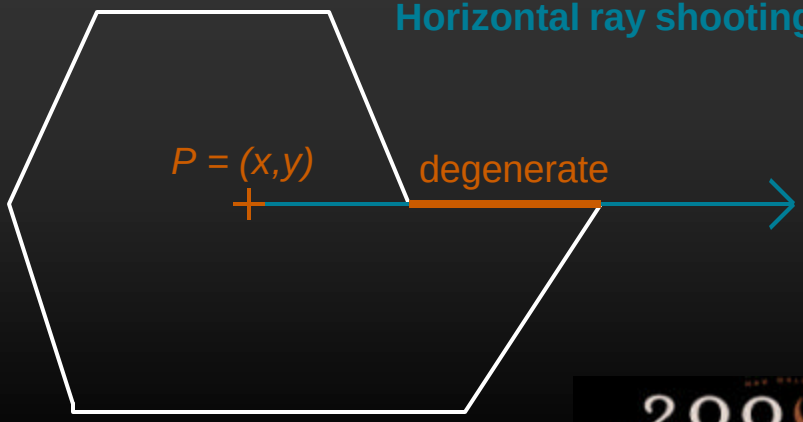
Degeneracies (2)

- Explicit handling of special cases
  - sometimes easy (segment intersection in the plane)
  - sometimes a combinatorial explosion
- Symbolic perturbation
  - exact arithmetic, validity of solution, postprocessing
- Random perturbation
  - validity check and restart for Las Vegas type

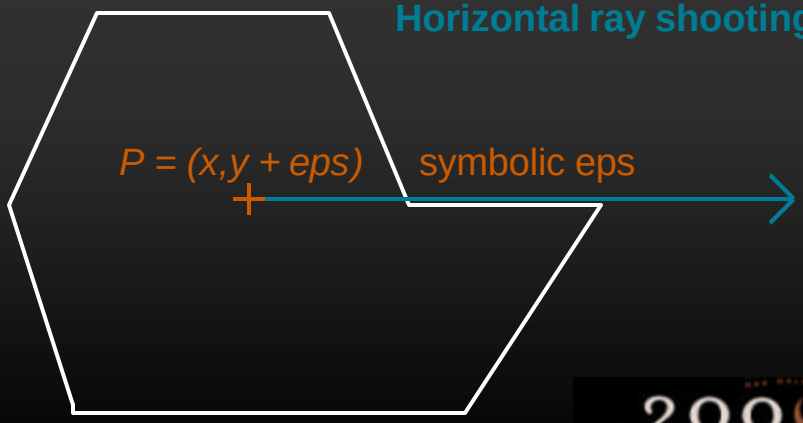
Special Case Handling



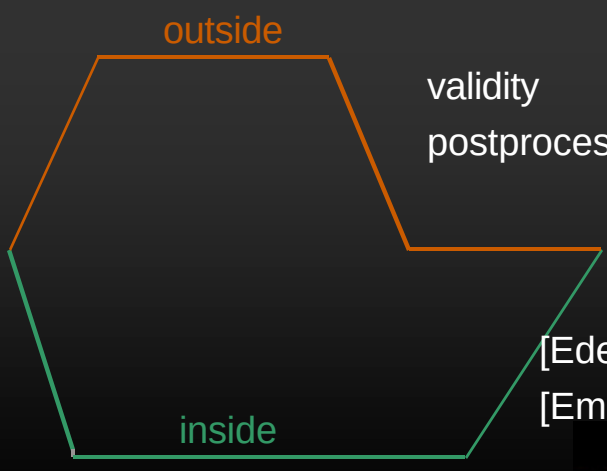
Symbolic Perturbation Point in Polygon



Symbolic Perturbation Point in Polygon



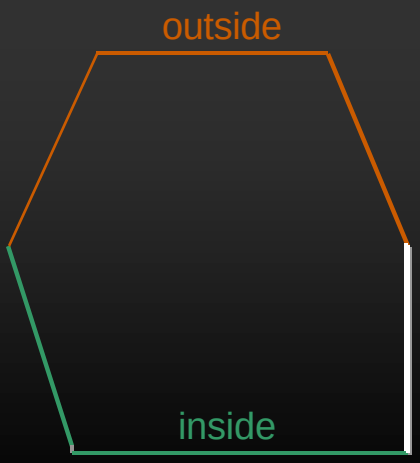
Symbolic Perturbation Point in Polygon



validity
postprocessing

[Edelsbrunner90]
[Emiris97]

Symbolic Perturbation Point in Polygon



completeness

?

P = (x + eps^2,y + eps)

Robustness of Geometry Classes

- Robustness in Geometry
- Templates in C++
- Generic Programming
- Geometry Classes in CGAL

Templates in C++

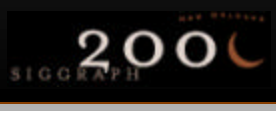
- Function Templates
- Class Templates

Function Templates

```
template <class T>
inline void swap( T& a, T& b) {
    T tmp = a; a = b; b = tmp;
}
```

```
int i = 5;
int j = 7;
swap( i, j);
```

- T is of the concept Assignable



Class Templates

```
template <class T>
class list {
    void push_back( const T& x);
    typedef  ...  iterator;
    iterator begin();
    iterator end();
};
```

```
list<int> ls;
ls.push_back(5);
```

Robustness of Geometry Classes

- Robustness in Geometry
- Templates in C++
- Generic Programming
- Geometry Classes in CGAL

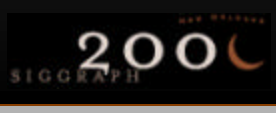
Generic Programming

- **Standard Template Library, STL**
  - Part of ISO-OSI Standard C++ Library 1998 [ISO98]
- **Generic Programming**
  - Paradigm with focus on algorithm design [Musser89]
- **Example: algorithm - iterator - container**
- **Iterator categories**
  - (input | output) < forward < bidirectional < random access

Generic Programming (2)

```
template <class InputIterator, class OutputIterator>
OutputIterator copy( InputIterator  first,
                     InputIterator  beyond,
                     OutputIterator result)
{
    while (first != beyond)
        *result++ = *first++;
    return result;
}

int a1[100];
int a2[100];
// ... initialize elements of a1.
copy( a1, a1+100, a2);
```



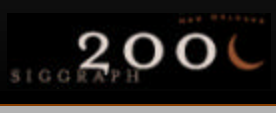
Generic Programming (2)

```
list<int> ls1;
list<int> ls2;
copy( ls1.begin(),
      ls1.end(),
      ls2.begin());
```

Generic Programming (2)

```
list<int> ls1;
list<int> ls2;
copy( ls1.begin(),
      ls1.end(),
      back_inserter(ls2));
```

```
copy( istream_iterator(cin),
      istream_iterator(),
      ostream_iterator( cout, "\n"));
```



Generic Programming Summary

- **Focus on algorithm design**
- **Templates and inline functions in C++**
  - support flexibility at compile time
  - efficiency at runtime
    - ⇨ flexibility at small scale possible

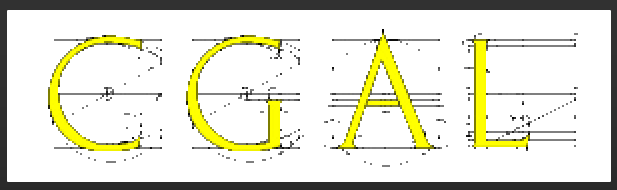
Robustness of Geometry Classes

- Robustness in Geometry
- Templates in C++
- Generic Programming
- Geometry Classes in CGAL

Geometry Classes in CGAL

- Exact Arithmetic
- Coordinate Representation
- Degeneracy Handling

Computational Geometry Algorithms Library



- **Project Goal**
  make the large body of geometric algorithms developed in the field of computational geometry available for industrial applications.
- C++ Library: Release 2.1 (Jan. 2000)

Sites Developing CGAL

Max-Planck-Institut für Informatik (Germany),
Universität des Saarlandes (Germany),
ETH Zurich (Switzerland),
Freie Universität Berlin (Germany),
INRIA Sophia-Antipolis (France),
Martin-Luther-Universität Halle-Wittenberg (Germany),
Tel Aviv University (Israel),
Utrecht University (The Netherlands).

Motivation

- Advanced algorithms and complicated data structure
- Complications with robustness
- Complications with degeneracy handling

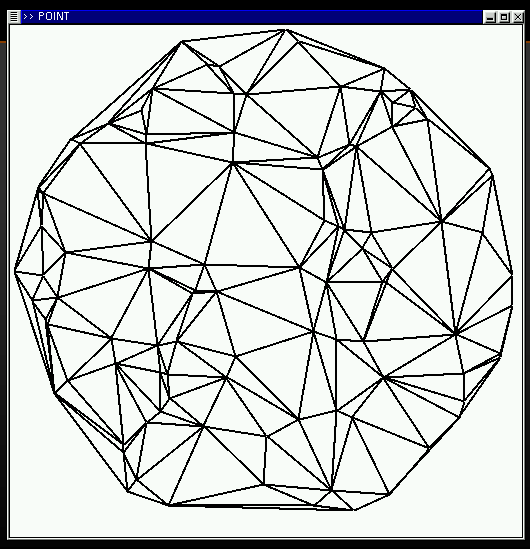
CG Impact Task Force Report 1996:
Application Challenges to Computational Geometry

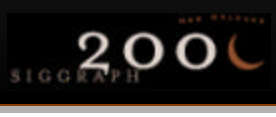
Recommendation # 1: "production and distribution of usable (and useful) geometric codes"
[CG-Report96]

Deliverables and Supported Platforms

- C++ source code (templates) (~150 KLOC)
- **OS:** IRIX 6.5, Solaris 2.6, Linux 2.x, MS Windows 95/98/NT4
- **Compiler:** SGI Mips(Pro) CC 7.3, GNU g++ 2.95, Egcs 1.1.2, MS Visual C++ 6.0
- **Supports:** STL, LEDA, GMP, GeomView, Inventor, VRML output, ...
- **Manuals:** LaTeX, for print and HTML

A First Example





Delaunay Triangulation

```
int main () {                                    // random points
    CGAL::Random                            rnd(1);
    CGAL::Random_points_in_disc_2<Point> rnd_pts( 1.0, rnd);

    Delaunay_triangulation  dt;                  // triangulation
    CGAL::copy_n( rnd_pts, 100, std::back_inserter( dt));

    leda_window* window =                        // window output
                  CGAL::create_and_display_demo_window();
    *window << dt;
    Point  p;
    *window >> p;
    delete window;
    return 0;
}
```

Structure of CGAL

Basic Library
Algorithms and data structures

Geometric Kernel
Geom. primitives, predicates, operations

Core Library
Configuration, assertions, ...

Support Library
Visualization, File I/O, Numbertypes, Generators, ...

Geometric Kernel

- Point, Vector, Direction
- Line, Ray, Segment
- Triangle
- Iso_rectangle
- Bbox
- Circle
- Affine transformation
- Order predicates
- Orientation test
- Incircle test
- Constructions
  - centerpoint
- Intersection
- Squared distance

Geometric Kernel (2)

- Exact arithmetic
- Explicit handling of degeneracies

Exact Arithmetic: Number Types

- **Builtin:** double, float, int, long, …
- **CGAL:** Filtered_exact, Interval_nt, …
- **LEDA:** leda_integer, leda_rational, leda_real
- **Gmpz:** CGAL::Gmpz
- **CLN:** cl_I, cl_RA

- **others are easy to integrate**

Coordinate Representation

- **Cartesian p = (x,y)**
  - **CGAL::Cartesian<*Field_type*>**
- **Homogeneous p = (x,y,w) = (x/w, y/w)**
  - **CGAL::Homogeneous<*Ring_type*>**
- **Geometric primitives parameterized with coordinate representation**
  - **CGAL::Point_2<CGAL::Cartesian<*Field_type*> >**

A Start: Support for k-th Roots and static expressions

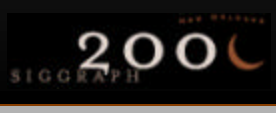
```
#include <CGAL/Cartesian.h>
#include <CGAL/Arithmetic_filter.h>
#include <CGAL/leda_real.h>
#include <CGAL/Point_2.h>

typedef CGAL::Filtered_exact<double, leda_real> NT;
typedef CGAL::Cartesian<NT>                     Rep;
typedef CGAL::Point_2<Rep>                      Point;

int main() {
    Point  p( 0.1, 0.2);
}
```

Explicit Handling of Degeneracies

- Intersection of two segments
- Voronoi diagram of points in the plane

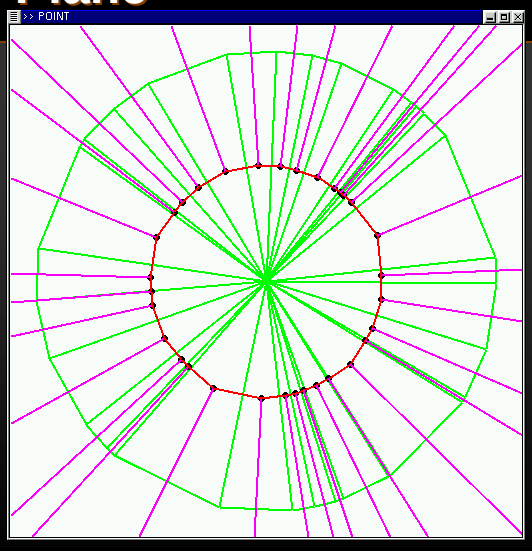


Intersection of two Segments

```
#include <CGAL/intersections.h>

int main() {
    Segment s( Point(1,1), Point(1,5));
    Segment t( Point(1,3), Point(1,8));
    CGAL::Object result = CGAL::intersection( s, t);
    Point   pt;
    Segment seg;
    if (CGAL::assign( pt, result))
        std::cout << "intsct. point = " << pt << std::endl;
    else if (CGAL::assign( seg, result))
        std::cout << "intsct. segment = " << seg << std::endl;
    else
        std::cout << "no intersection" << std::endl;
}
```

Voronoi Diagram of Points in the Plane

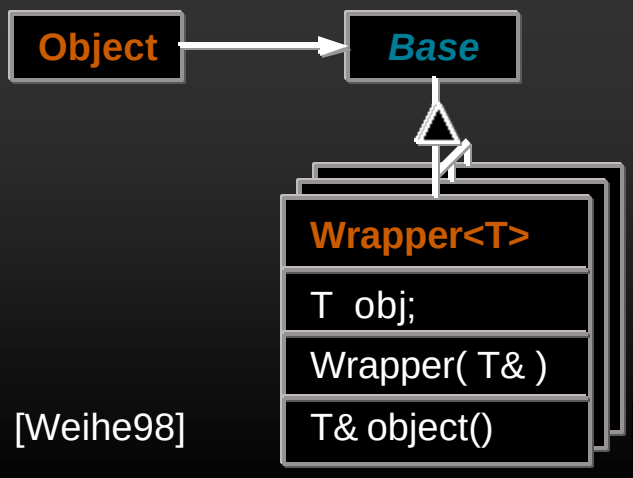


Voronoi Diagram of Points in the Plane

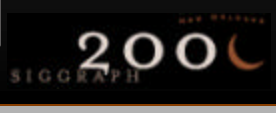
```
Delaunay_triangulation  dt;
leda_window* window; // …

Delaunay_triangulation::Edge_iterator e = dt.edges_begin();
while ( e != dt.edges_end()) {
    CGAL::Object o = dt.dual(e);
    Delaunay_triangulation::Segment seg;
    Delaunay_triangulation::Ray     ray;
    if (CGAL::assign( seg, o))
        *window << CGAL::RED << seg;
    else if (CGAL::assign( ray, o))
        *window << CGAL::VIOLET << ray;
    ++e;
}
```

Implementing CGAL::Object

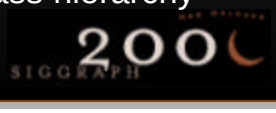


[Weihe98]



Summary Part I

- **Exact arithmetic**
- **Templates to select arithmetic**
  - tradeoff between efficiency and correctness
  - tradeoff between efficiency and required arithmetic
- **Explicit degeneracy handling**
  - Polymorphic return type
  - Local design solution, **NO** global class hierarchy



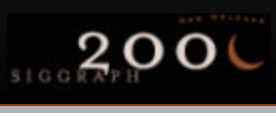
Introduction to Scene Graphs

- Scene Graph Motivation (Ghali)
- Introduction to Scene Graphs (Blythe)
- Building Scene Graphs (Sowizral)
- Shapes and Transformations in CGAL (Kettner)

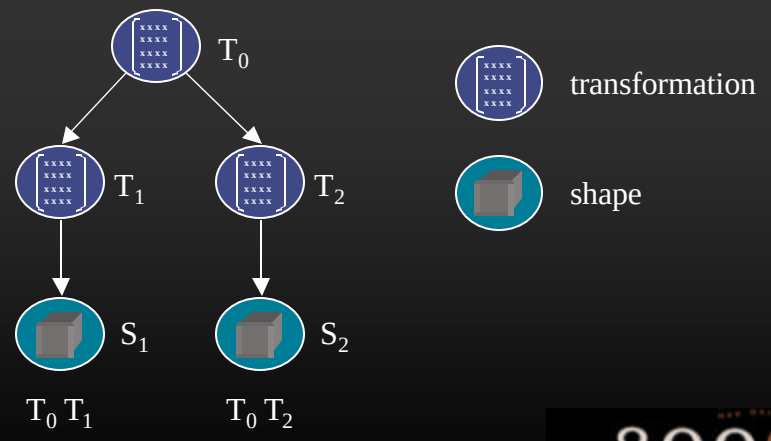
Scene Graph Motivation

Sherif Ghali

Max Planck Institute



Organizing Scenes Hierarchically



Creating Scene Hierarchy

- **Creating hierarchy procedurally**
  - Sequence of commands
  - Commands repeatedly executed
- **Creating hierarchy using objects**
  - Set up data structures
  - Render by parsing data structures

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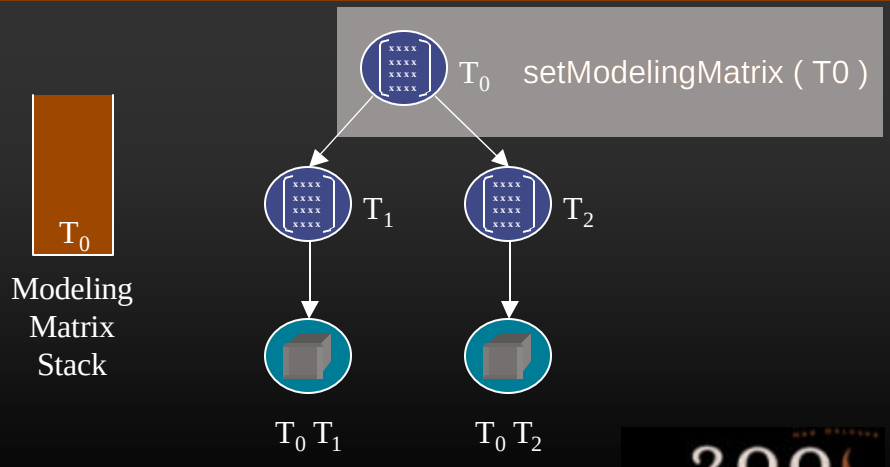
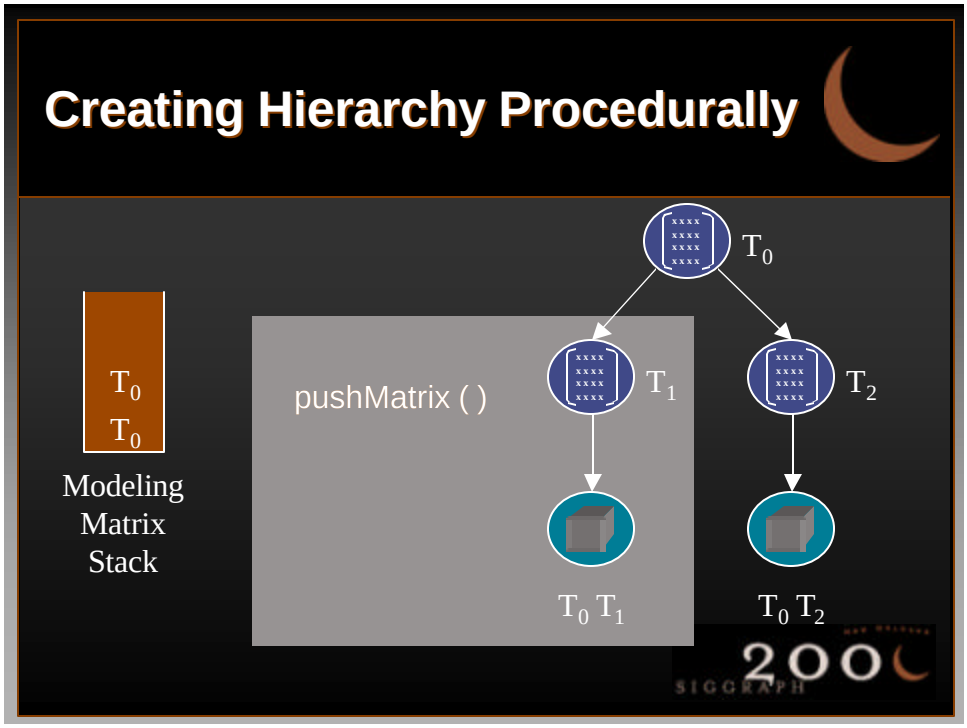
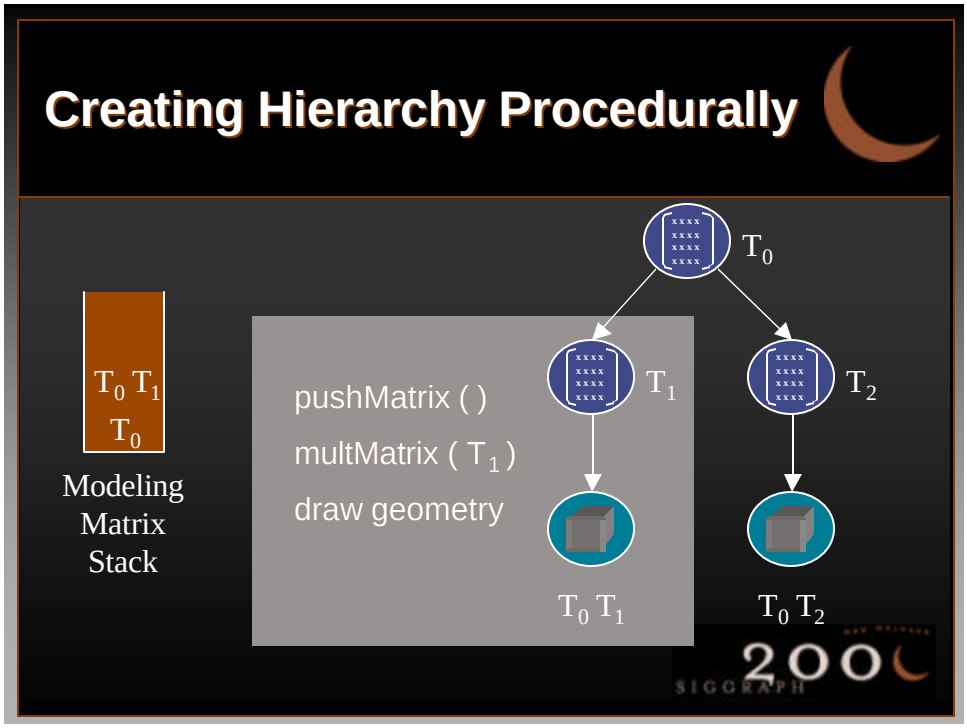
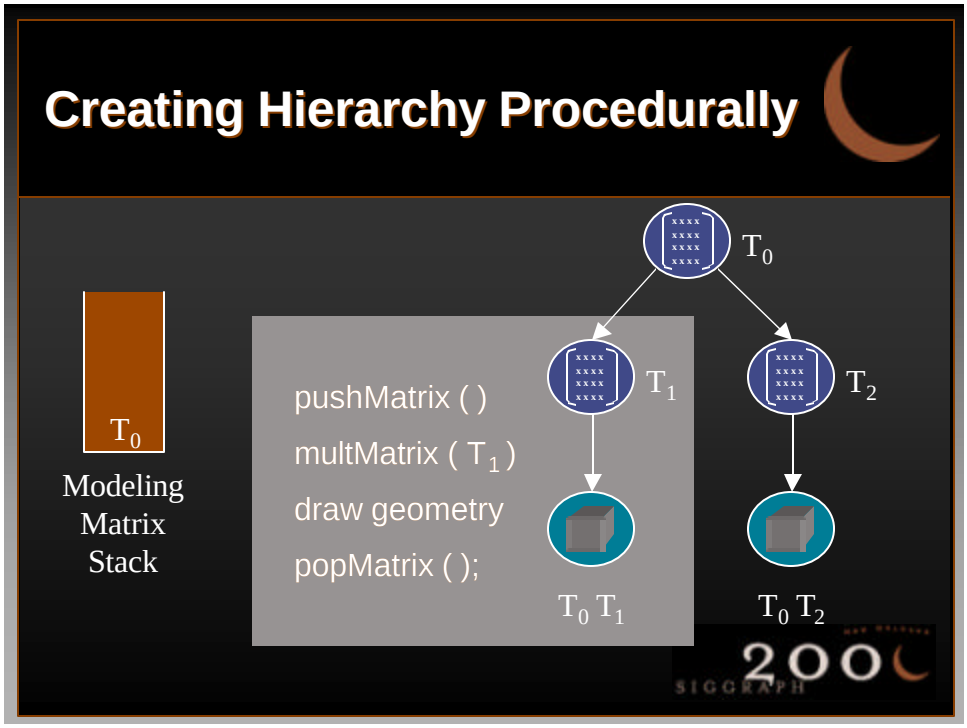
Creating Hierarchy Procedurally




Creating Hierarchy Procedurally
T0
T0
Modeling
Matrix
Stack
pushMatrix ( )
T0
T1
T2
T0 T1
T0 T2


Creating Hierarchy Procedurally
T0 T1
T0
Modeling
Matrix
Stack
pushMatrix ( )
multMatrix (T1)
draw geometry
T0
T1
T2
T0 T1
T0 T2


Creating Hierarchy Procedurally
T0
Modeling Matrix Stack
pushMatrix ( )
multMatrix (T1)
draw geometry
popMatrix ( );
T0
T1
T2
T0 T1
T0 T2
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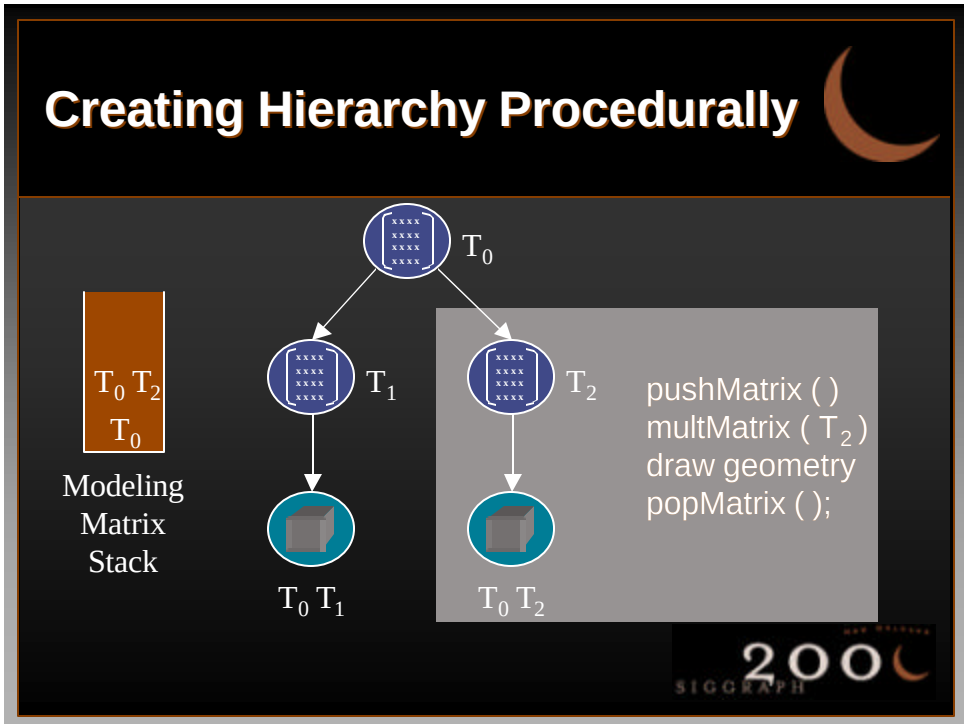
Creating Hierarchy Procedurally
T0 T2
T0
Modeling Matrix Stack
T0
T1
T2
T0 T1
T0 T2
pushMatrix ( )
multMatrix (T2)
draw geometry
popMatrix ( );
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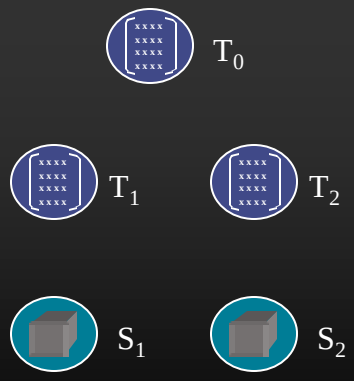
Creating Scene Hierarchy

- Creating hierarchy procedurally
  - Sequence of commands
  - Commands repeatedly executed
- Creating hierarchy using objects
  - Set up data structures
  - Render by parsing data structures

Creating Hierarchy Using Objects

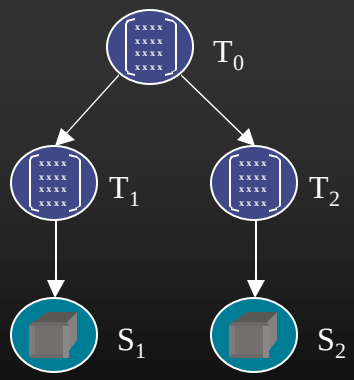
- Create transformation objects T_0, T_1, T_2
- Create two geometry objects
- Assemble in a suitable data structure

Nodes of the Graph



Nodes = {T_0 , T_1 , T_2 , S_1 , S_2}

Edges of the Graph

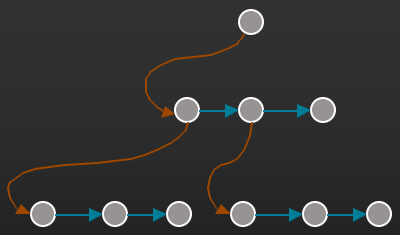


Nodes = {T_0 , T_1 , T_2 , S_1 , S_2}
Edges = {(T0,T1), (T1, C_1),
(T0,T2), (T2, C_2)}

Edges are (almost!) not needed

A Binary Tree Implementation

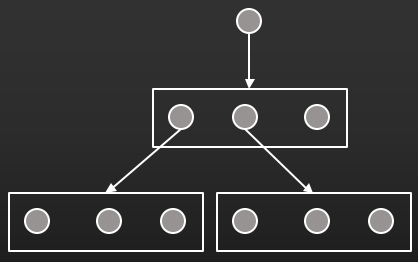
```
class Node {
  Content* c;
  Node* left;
  Node* right;
  …
};
```



- **Inefficient access to children**

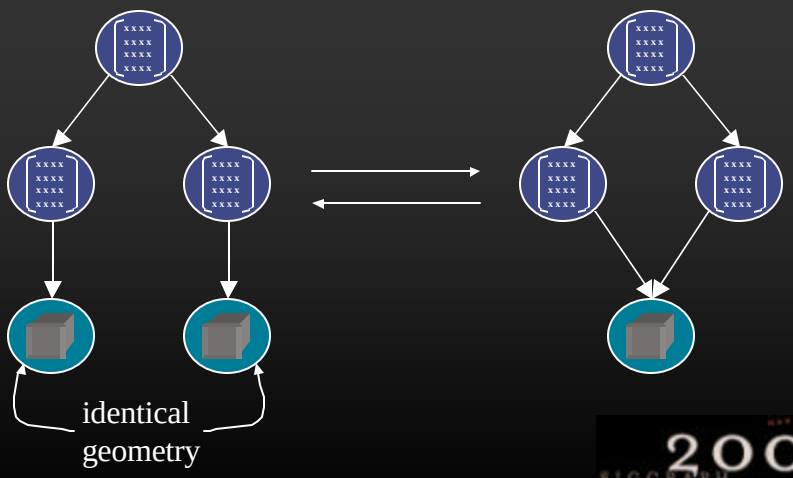
An N-ary Tree Implementation

```
class Node {
  Content* c;
  vector<Node*> children;
  …
};
```



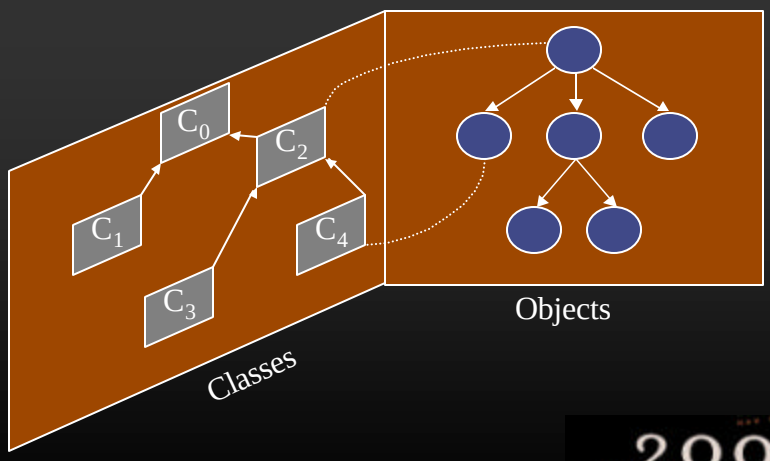
- **Number of children**
- **Child deletion**

Directed Acyclic Graphs

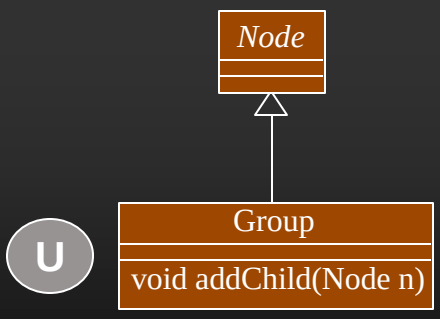


Choice of a Node Class Hierarchy

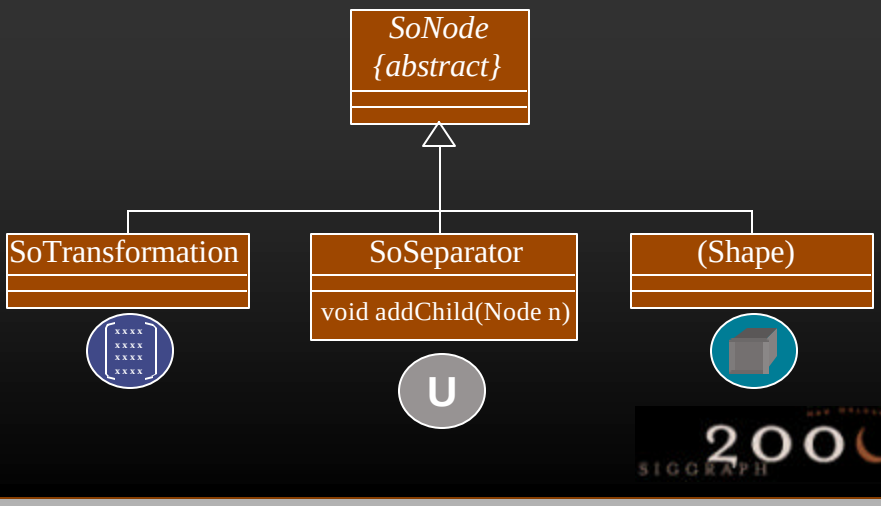
Object Hierarchy and Class Hierarchy



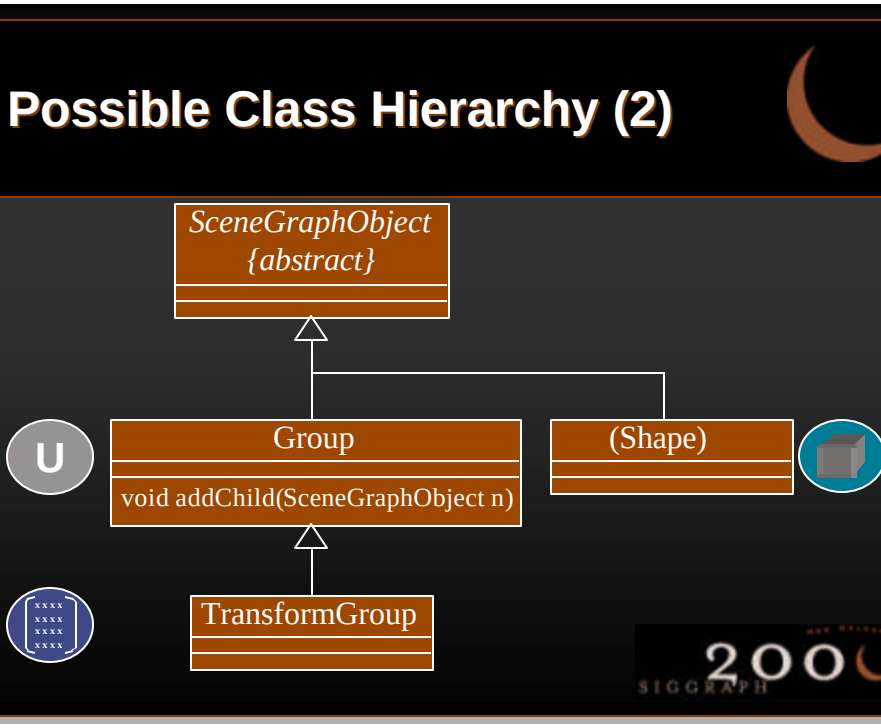
Class Hierarchy



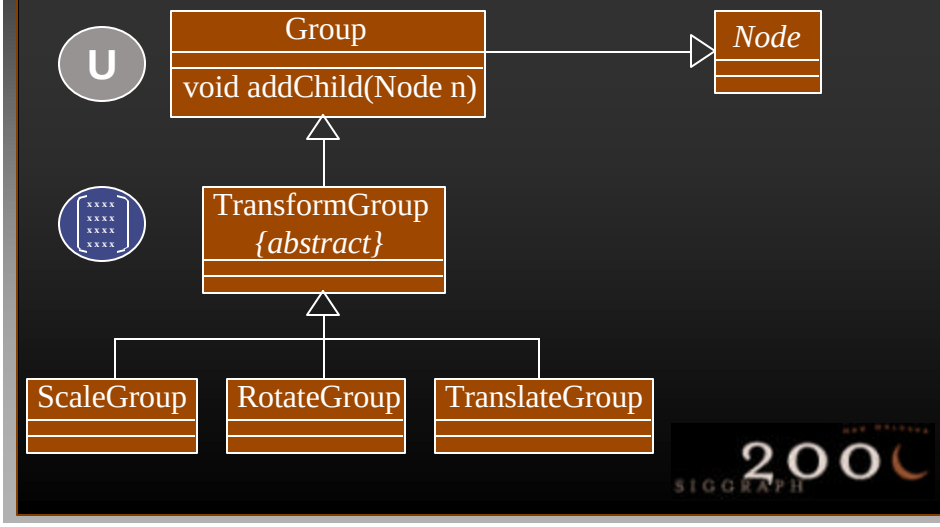
Possible Class Hierarchy (1)



Possible Class Hierarchy (2)



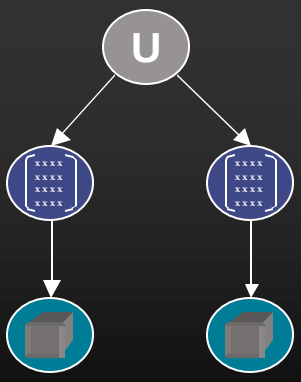
Children of Transform Groups



Code Example

```
Group* root = new Group;
TranslateGroup* tgrp1 =
    new TranslateGroup(Vector3d(1,0,0));
TranslateGroup* tgrp2 =
    new TranslateGroup(Vector3d(-1,0,0));
Shape* cube = new Shape("cube.vpl");
Shape* cone = new Shape("cone.vpl");

root->addChild(tgrp1);
root->addChild(tgrp2);
tgrp1->addChild(cube);
```



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```
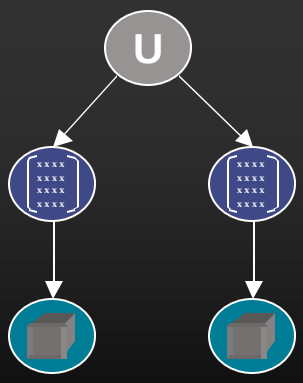
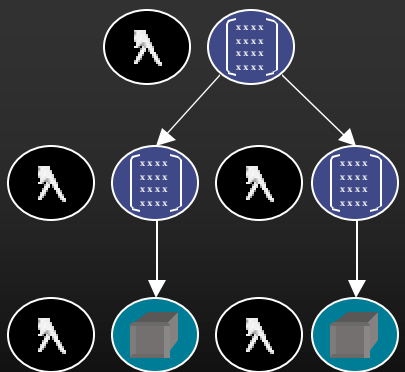



Traversing a Scene Graph

Visitor



Render Visitors

- **Transformation node**
  - update transformation matrix
- **Shape node**
  - draw

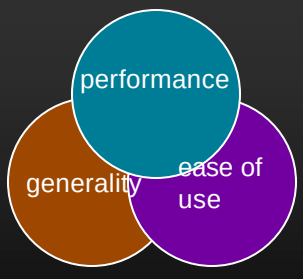
Introduction To Scene Graphs

David Blythe
RouteFree

SIGGRAPH 2000

Scene Graphs

- What is your objective?



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Scene Graphs

- **Graph Representation**
  - What do edges mean?
  - Inherit state along edges
    - group all red object instances together
    - group logical entities together
      - parts of a car
  - Capture intent with the structure

Scene Graphs

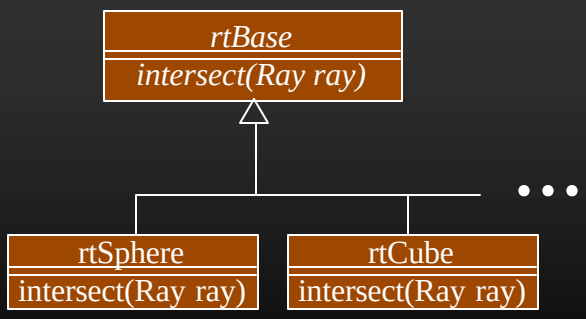
- **Inheritance - Overloaded Term**
  - Behavior inheritance (subclassing)
    - Benefit of OO design
  - Implementation inheritance
    - Perhaps provided by implementation language
    - *Not essential* for a good API design
  - Implied inheritance
    - Designed into the API

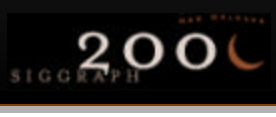
Scene Graphs

- **Inheritance - Example**
  - Ray tracer scene objects
    - sphere, cube, NURBS surface, triangle mesh
  - Each object type supports a rayIntersect method
    - Inherit behavior (methods) from base class
  - Implementation of rayIntersect method *not* inherited
  - Object instances arranged in a spatial data structure
    - inherit spatial information from graph

Scene Graphs

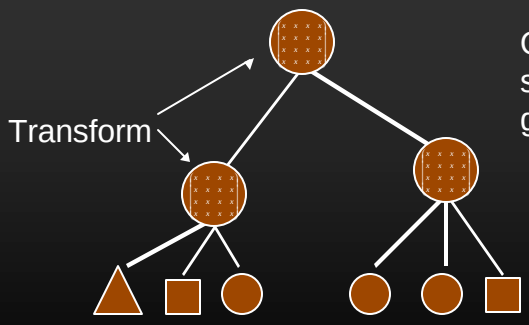
- **Ray Tracer Type Hierarchy**





Scene Graphs

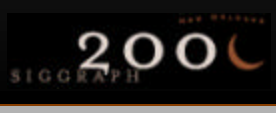
- **Ray Tracer Scene**



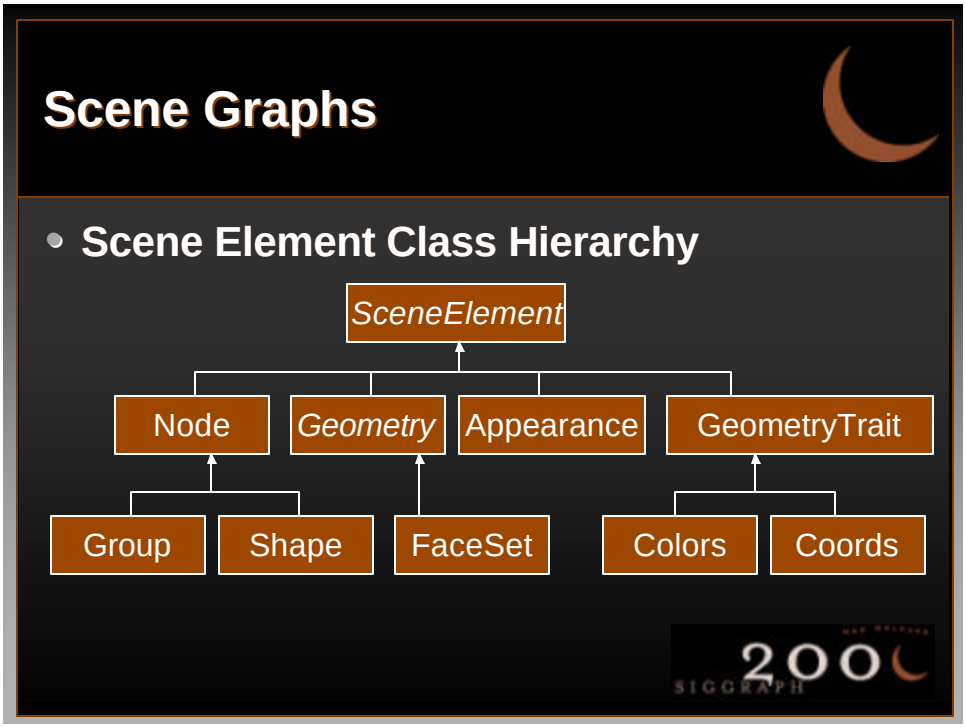
Object instances inherit spatial information through graph edges

Scene Graphs

- **Scene Elements**
  - Interior Nodes
    - Have children that inherit state
      - transform, lights, fog, color, …
  - Leaf nodes
    - Terminal
      - geometry, text
  - Attributes
    - Additional sharable state (textures)

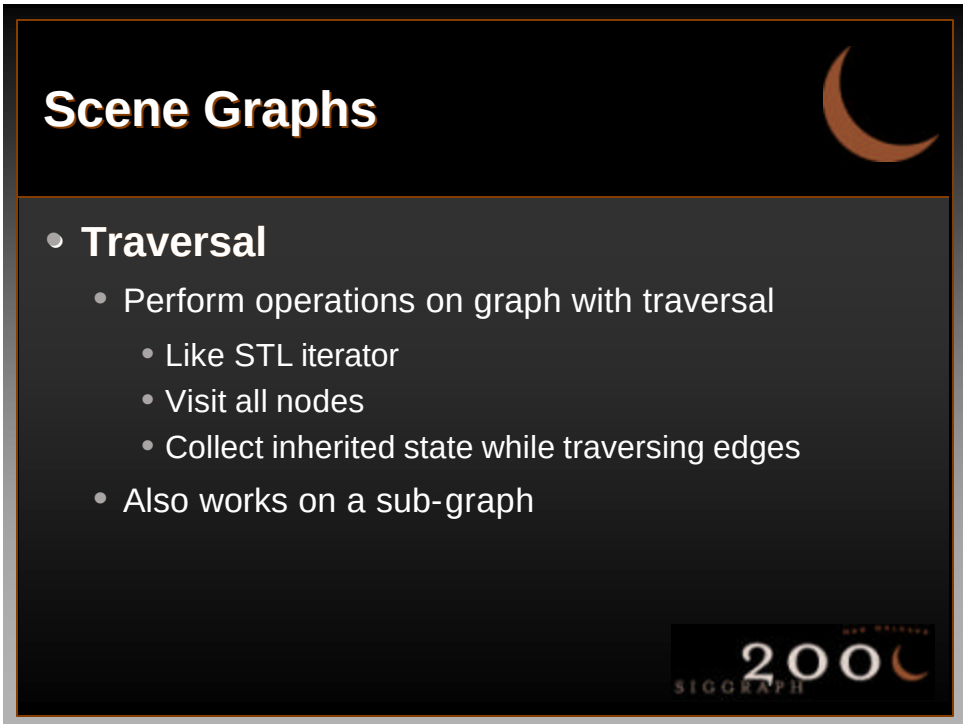


Scene Graphs



- **Scene Element Class Hierarchy**

Scene Graphs



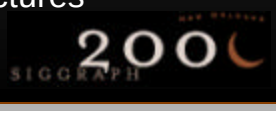
- **Traversal**
  - Perform operations on graph with traversal
    - Like STL iterator
    - Visit all nodes
    - Collect inherited state while traversing edges
  - Also works on a sub-graph

Scene Graphs

- **Traversal**
  - Typical operations
    - Render
    - Search (pick, find by name)
    - View-frustum cull
    - Tessellate
    - Preprocess (optimize)

Scene Graphs

- **Graph Organization**
  - Tree structure best
    - No cycles for simple traversal
    - Implied depth-first traversal (not essential)
    - Includes lists, single node, etc as degenerate trees
  - If allow multiple references (instancing)
    - Directed acyclic graph (DAG)
  - Difficult to represent cell/portal structures



Scene Graphs

- **State Inheritance**
  - General (left to right, top to bottom, all state)
    - Open Inventor
    - Need Separator node to break inheritance
    - Need to visit all children to determine final state
  - Top to bottom only
    - IRIS Performer, Java3D, …
    - State can be determined by traversing path to node

Scene Graphs

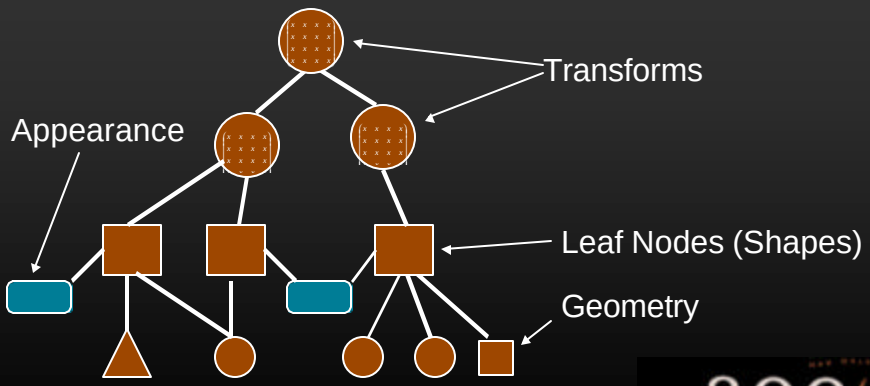
- **What State To Inherit?**
  - Affects graph organization
    - Affects query performance
    - Red objects together?
    - Parts of a car together?
    - Spatially close objects together?
  - What are the most frequent operations?

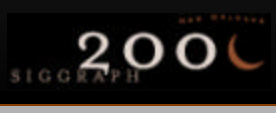
Scene Graphs

- **Limited State Inheritance**
  - Transform hierarchy
    - IRIS Performer, Java3D, …
    - Allows for efficient spatial queries
      - View-frustum culling
      - Ray-pick
      - Intersection testing
  - Allow secondary inheritance of other attributes
    - Traversal mask?
    - Environment (lights, fog, …)

Scene Graphs

- **Limited State Inheritance**



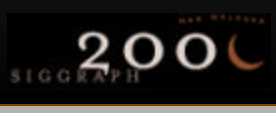


Scene Graphs

- **Limited State Inheritance**
  - Use to encourage a particular organization
  - Be careful of secondary inheritances
    - Will encourage other organizations
      - e.g., objects sharing the same light
  - Attach other state at leaves of graph

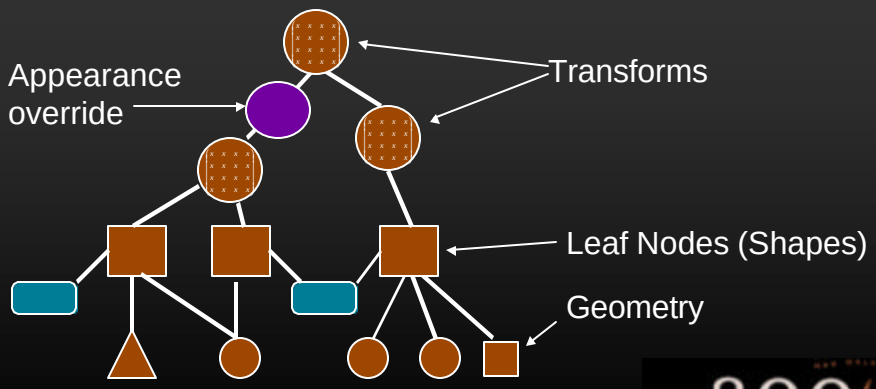
Scene Graphs

- **Appearance Overrides**
  - One attempt to solve the “highlighting” problem
    - After picking an object, want to display it differently
    - Don’t want to explicitly edit and restore its appearance
  - Use override node in the scene graph to override appearance of children
  - Only works if graph organization matches model organization



Scene Graphs

- **Appearance Overrides**



Scene Graphs

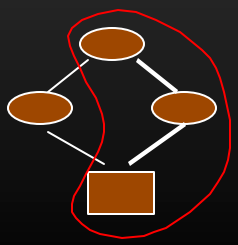
- **Multiple Referencing (Instancing)**
  - Convenient for representing multiple instances of an object
    - rivet in a large assembly
  - Save memory
  - Need life-time management
    - is the object still in use
    - garbage collection, reference counts

Scene Graphs

- **Multiple Referencing**
  - Changes trees into DAGs
  - Instance of an object represented by its *path*
  - Difficult to attach instance specific properties
    - e.g., caching transform at leaf node

Scene Graphs

- **Paths**
  - Node in DAG may have multiple paths to it
  - Record path when remembering specific instances
    - Use path to retrieve inherited properties



path

Scene Graphs

- **Paths**
  - Treat path like a mini-scene
  - Run traversals on path (render, search, etc)

Scene Graphs

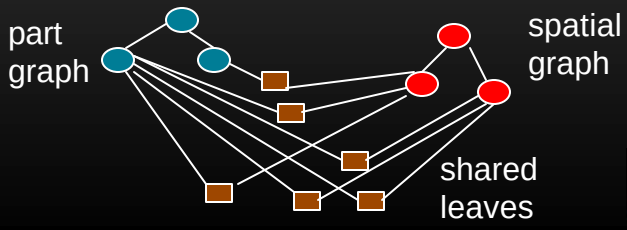
- **Other organizations**
  - Logical structure (part, assembly, etc.)
    - Used by modeling applications
  - Topology structure, e.g., boundary
    - surfaces, faces, edges, vertices
    - Useful for CAD applications
  - Behaviors, e.g., engine graph
  - Environment graph (fog, lights, etc.)

Scene Graphs

- **Multiple Graphs (Multi-graphs)**
  - Applications may need to organize the data in more than one way
  - May reuse same instances of leaf data
    - geometry, appearance descriptions
  - New collections of interior nodes
  - Need to keep them all in sync
    - node additions, deletes

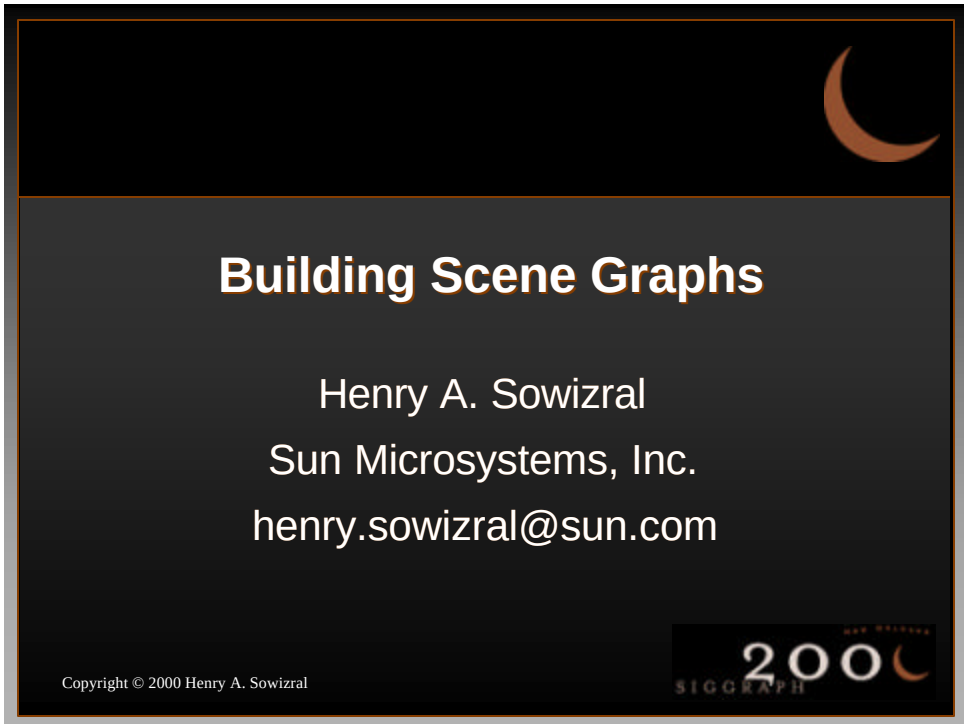
Scene Graphs

- **Multi-graphs**
  - Use same traversal mechanism to operate on all graph types (including paths)
  - Use a notification/dependency tracking scheme to synchronize graphs



Scene Graphs

- Scene Graphs Are Not Just for Rendering


Building Scene Graphs
Henry A. Sowizral
Sun Microsystems, Inc.
henry.sowizral@sun.com
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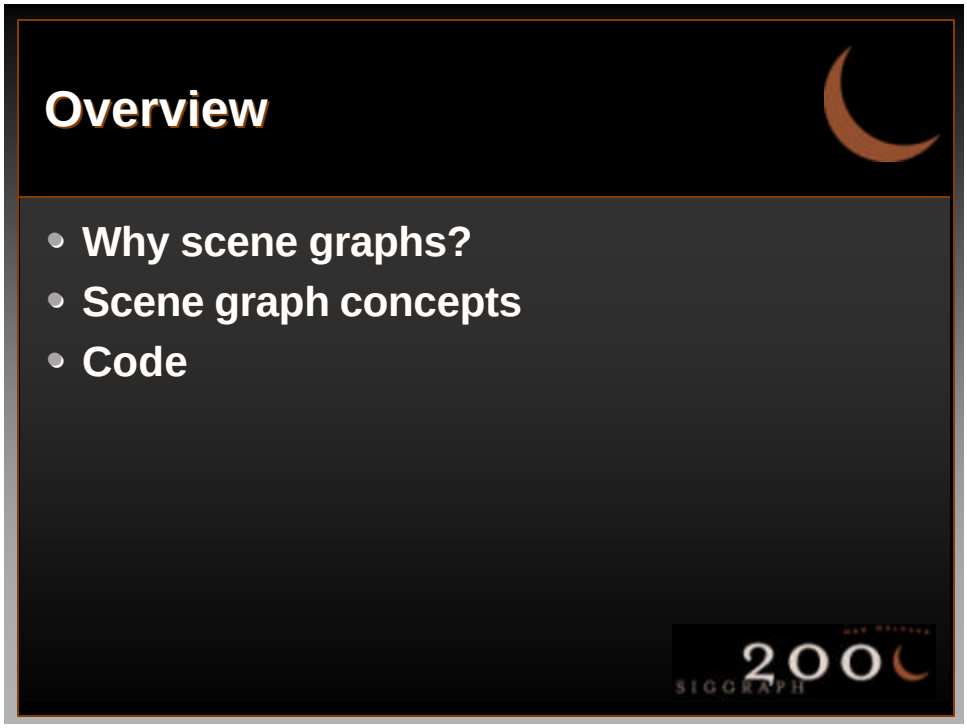
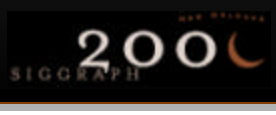

Overview
Why scene graphs?
Scene graph concepts
Code
SIGGRAPH 2000

Programming At A Higher Level

- Raise the programming “floor”
- Thinking objects
  … not vertices
- Thinking content
  … not rendering process
- Descriptive

Scene Graph Structure

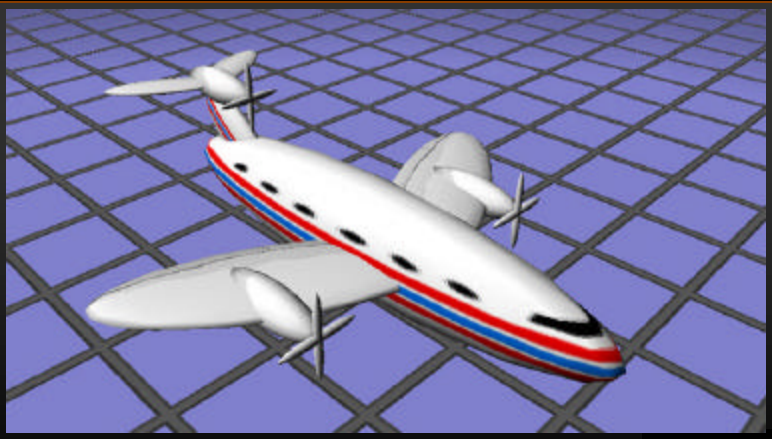
- Purpose
  - Display
  - Manipulation
  - Animation
  - Interaction

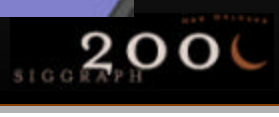


Building A Scene Graph

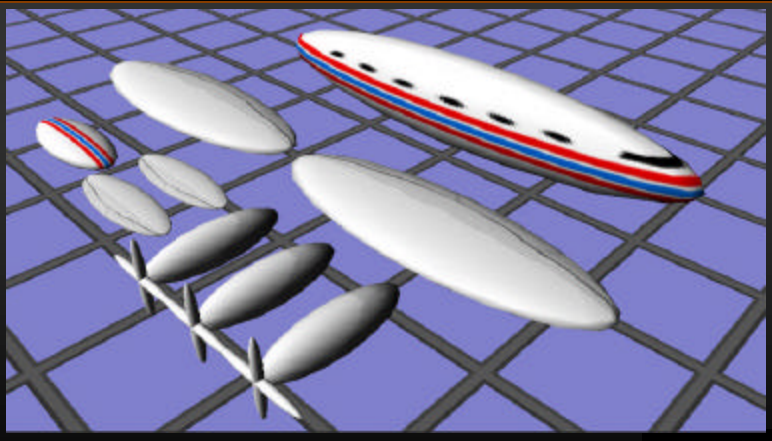
- **A scene graph is a “tree”**
  - A hierarchy containing scene data
  - Parents: group children and other parents
  - Children: shapes, lights, sounds, *etc.*

Scene Graph Example

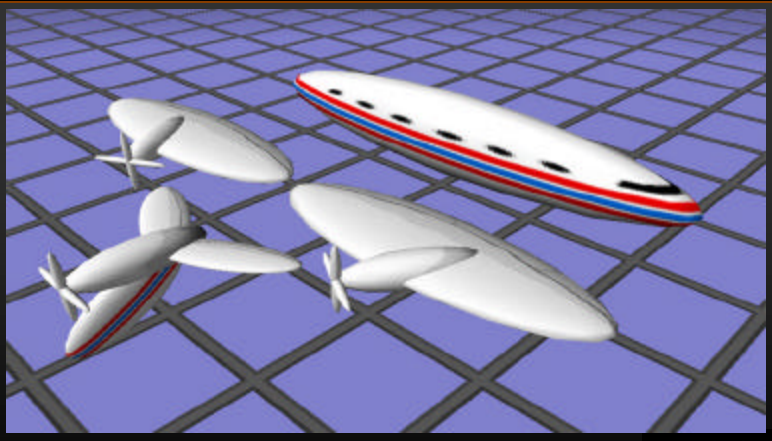




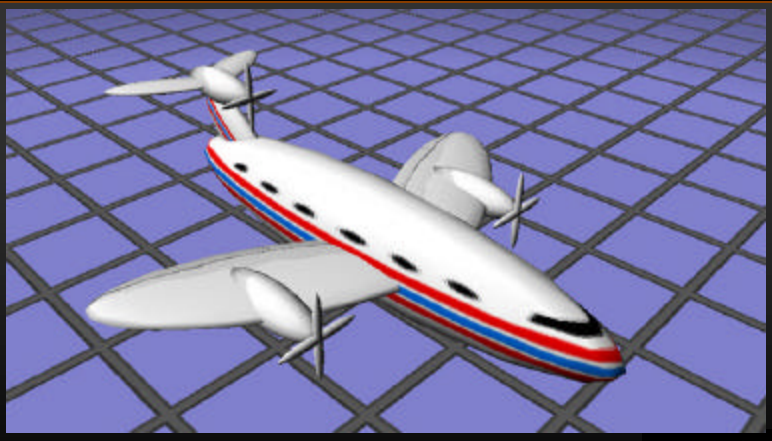
Scene Graph Items



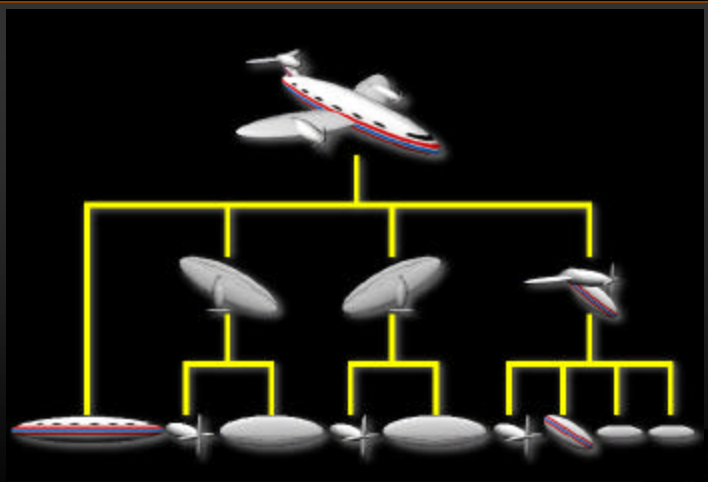
Scene Graph Groupings



Scene Graph Final View



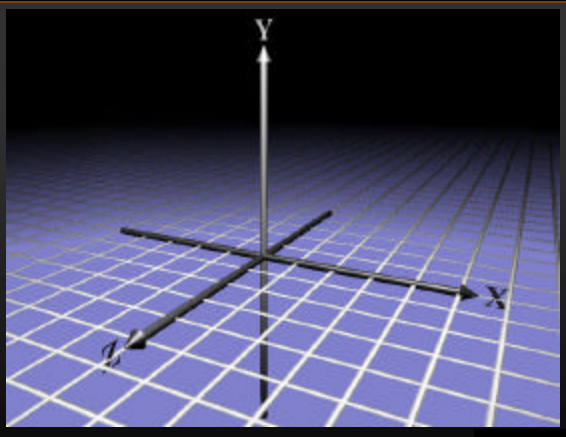
The Scene Graph

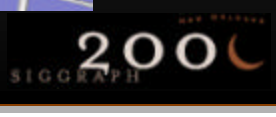


Items In A Scene Graph

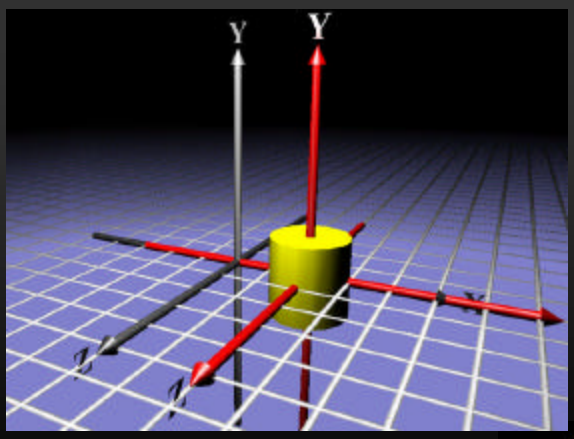
- Geometry
- Lights
- Sounds
- Environmental (fog, background)
- Behaviors
- Bounds
- ViewPlatforms — places the user can be

Coordinate systems

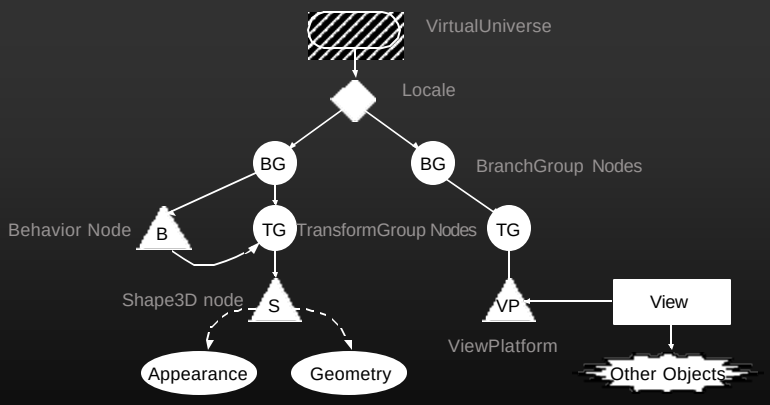




Placement



Scene Graph Components



Building Nodes

- **Build nodes by instancing Java 3D classes**

```
Shape3D myShape1
        = new Shape3D(myGeom1, myAppear1);
Shape3D myShape2 = new Shape3D(myGeom2);
```

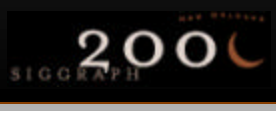
- **Invoking methods to modify nodes**

```
myShape2.setAppearance( newAppear2);
```

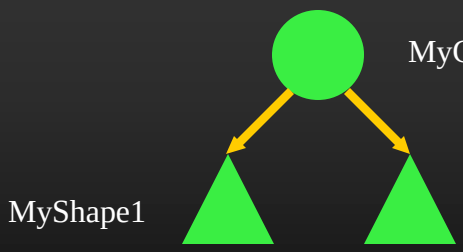
Building The Graph

- **Building a group of nodes**

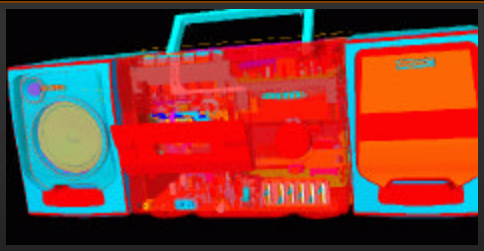
```
BranchGroup myGroup = new BranchGroup();
myGroup.addChild(myShape1);
myGroup.addChild(myShape2);
```

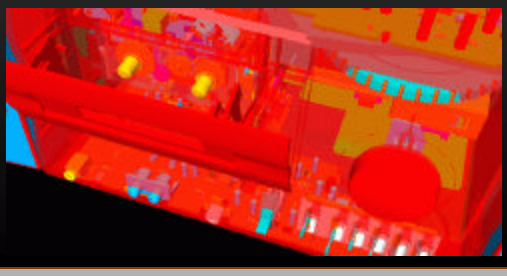


The Constructed Scene Graph



Scene Graphs May Be Large





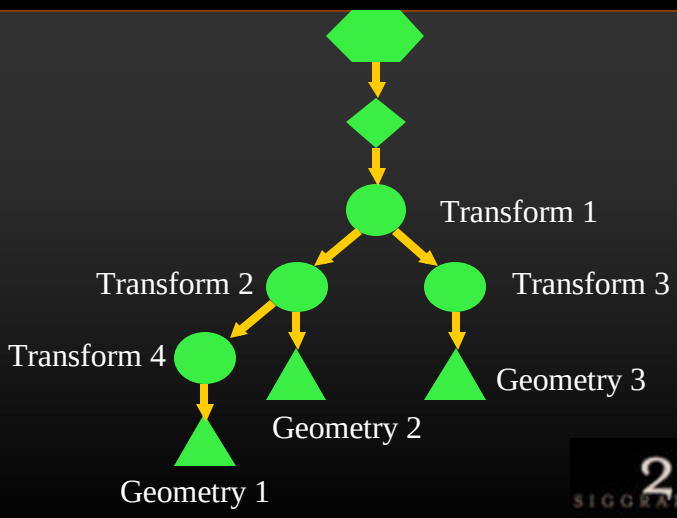
Hints for Designing Scene Graphs

- Always draw the scene graph
- Structure for the task at hand

What About Encapsulation?

- Subclassing Branch Group
  - Have it construct the requisite additional objects
  - Provide accessor and manipulator methods on the subclassed object

A Scene Graph



Transform classes

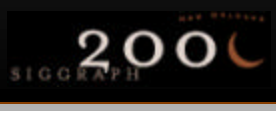
- Places the geometry
- Is it part of the geometry?
- Speed
  - Internal classification

Drawing Modes

- Immediate --- no need for scene graph
- Retained --- a scene graph (or display lists)
- Compiled-retained --- optimized scene graphs

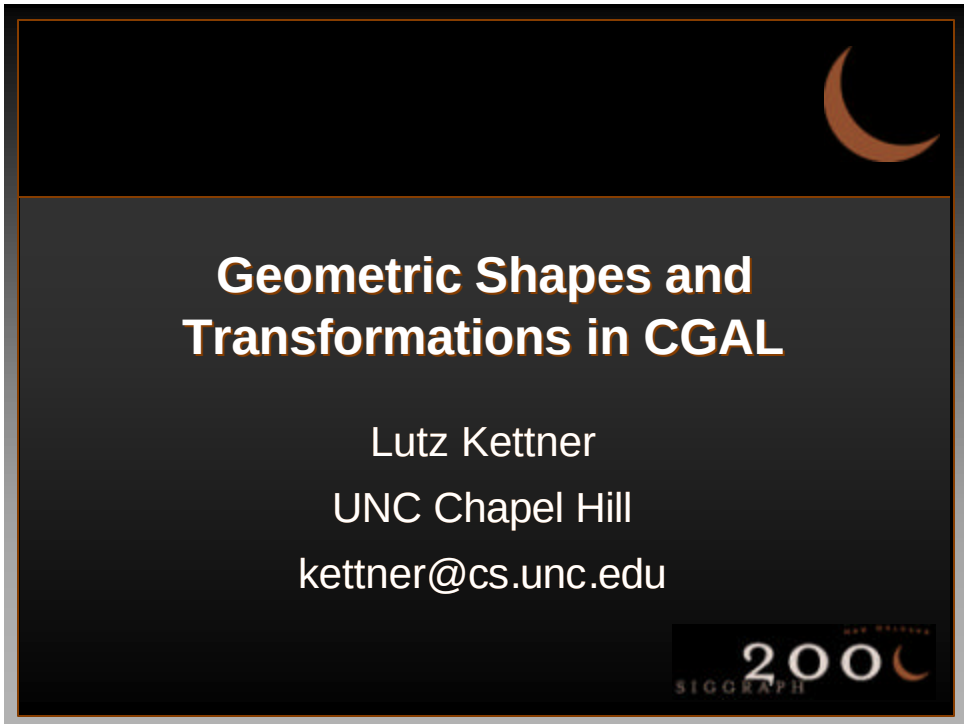
Scene Graph Compilation

- Knowledge of use (or hints (or assumptions))
- Tree flattening
- Attribute batching
- Tension
  - Combining geometries
  - Breaking geometries into multiple pieces



Drawing The Scene Graph

- Traversal of scene graphs
- Ancillary Structures


Geometric Shapes and
Transformations in CGAL
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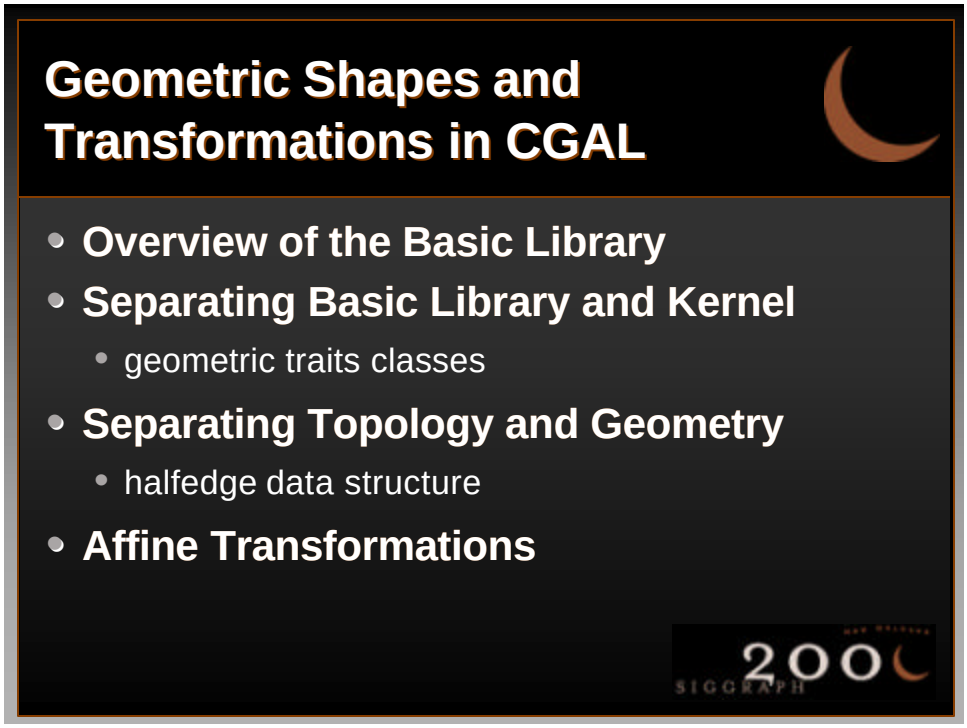
SIGGRAPH 2000

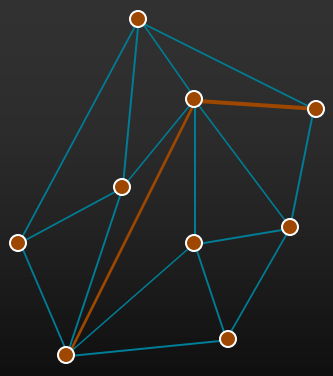

Geometric Shapes and
Transformations in CGAL
Overview of the Basic Library
Separating Basic Library and Kernel
geometric traits classes
Separating Topology and Geometry
halfedge data structure
Affine Transformations
SIGGRAPH 2000

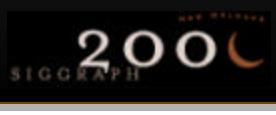
Geometric Shapes and Transformations in CGAL

- **Overview of the Basic Library**
- **Separating Basic Library and Kernel**
  - geometric traits classes
- **Separating Topology and Geometry**
  - halfedge data structure
- **Affine Transformations**

Basic Library: Triangulation

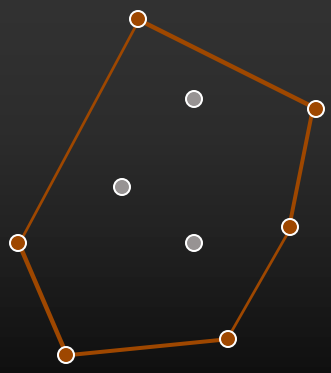
- **Triangle-based data-structure**
  - compact, fast, but point location is slow
- **Delaunay/Voronoi**
- **Constrained Delaunay**
  - => terrain triangulations
- **Regular triangulations**
- **Tetrahedrization in 3D**





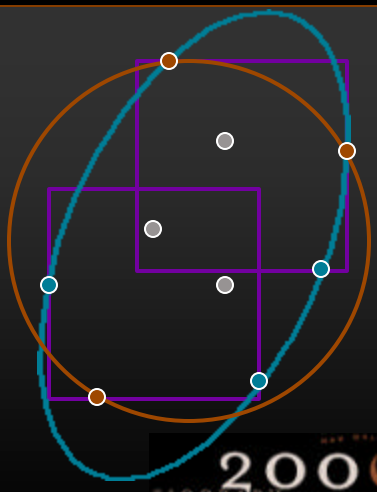
Basic Library: Convex Hull

- 5 different algorithms for 2D
- Randomized incremental algorithm for 3D



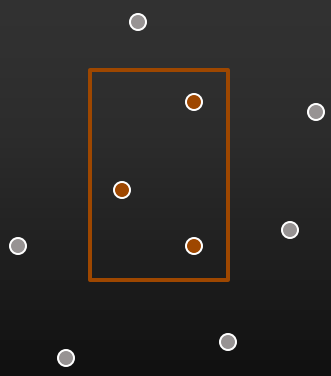
Basic Library: Geometric Optimization

- Smallest enclosing circle and ellipse in 2D
- Smallest enclosing sphere in dD
- Rectangular p center, 2 <= p <= 4



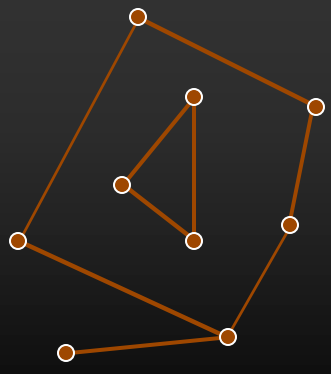
Basic Library: Search Structures

- Range-, segment-, KD-tree
- Arbitrary dimension
- Mixed segment-range-trees
- Static
- Window query, enclosing query

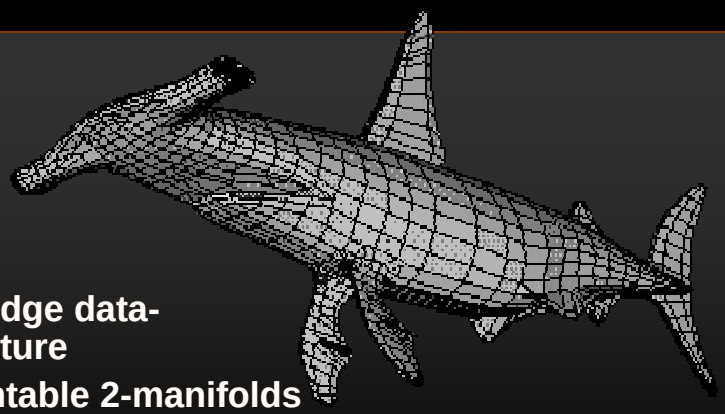


Basic Library: Planar Map

- Halfedge data-structure
- Efficient point location, fully dynamic
- Arrangements

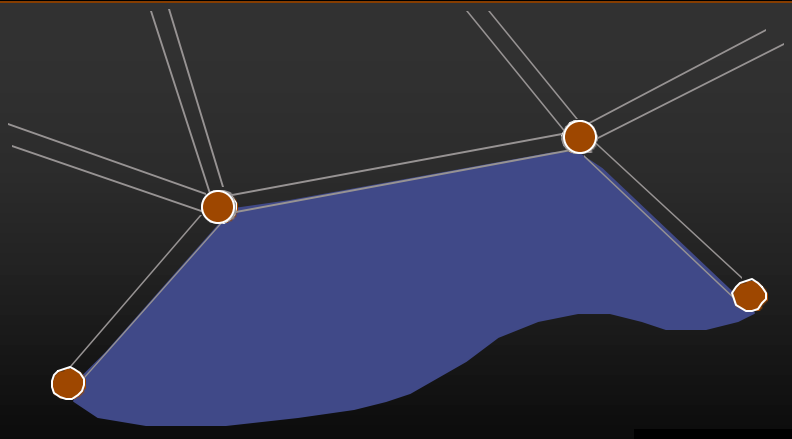


Basic Library: Polyhedral Surface

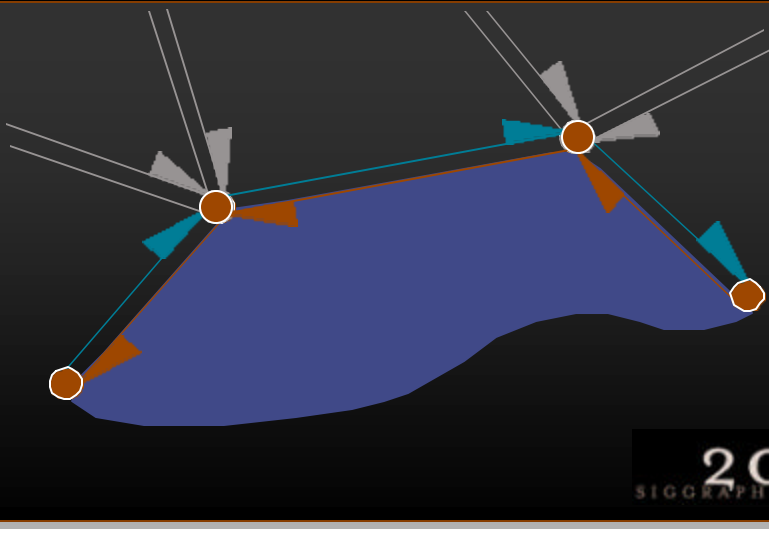


- Halfedge data-structure
- Orientable 2-manifolds with boundary

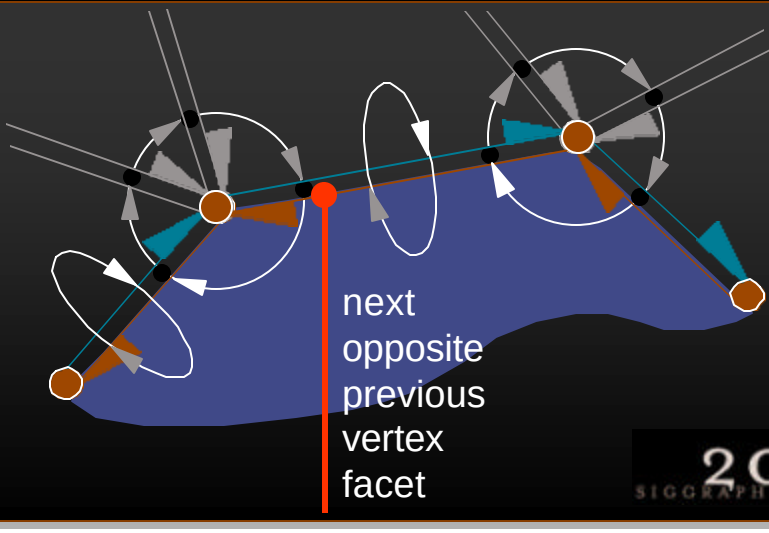
Halfedge data-structure



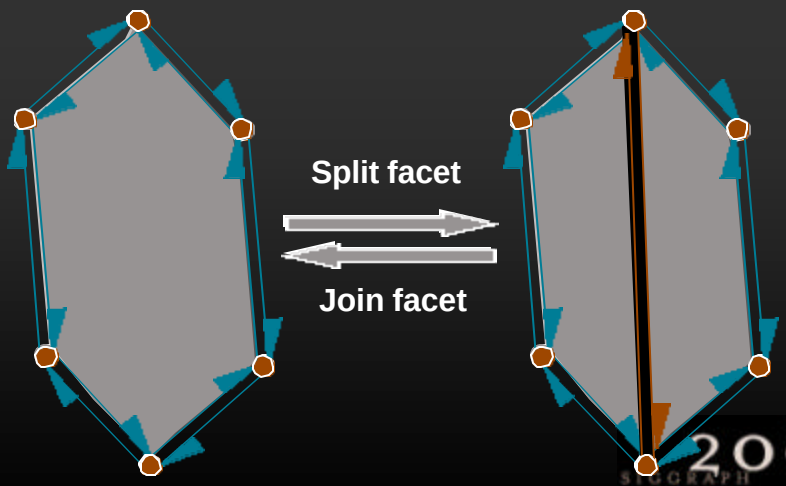
Halfedge data-structure



Halfedge data-structure



Euler Operator



Geometric Shapes and Transformations in CGAL

- Overview of the Basic Library
- **Separating Basic Library and Kernel**
  - geometric traits classes
- **Separating Topology and Geometry**
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- **Affine Transformations**

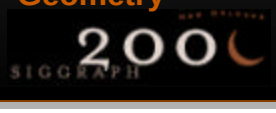
Separating Basic Library and Geometric Kernel

Convex_hull
Point_2
leftturn(p,q,r)

Combinatorics

CGAL Geometric Kernel
CGAL::Point_2<…>
CGAL::leftturn(p,q,r)

Geometry



Separating Basic Library and Geometric Kernel

Convex_hull
Point_2
leftturn(p,q,r)

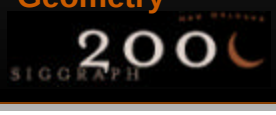
Combinatorics

Convex_hull_traits
Point_2 --> CGAL::Point_2
leftturn(p,q,r) --> CGAL::leftturn(p,q,r)

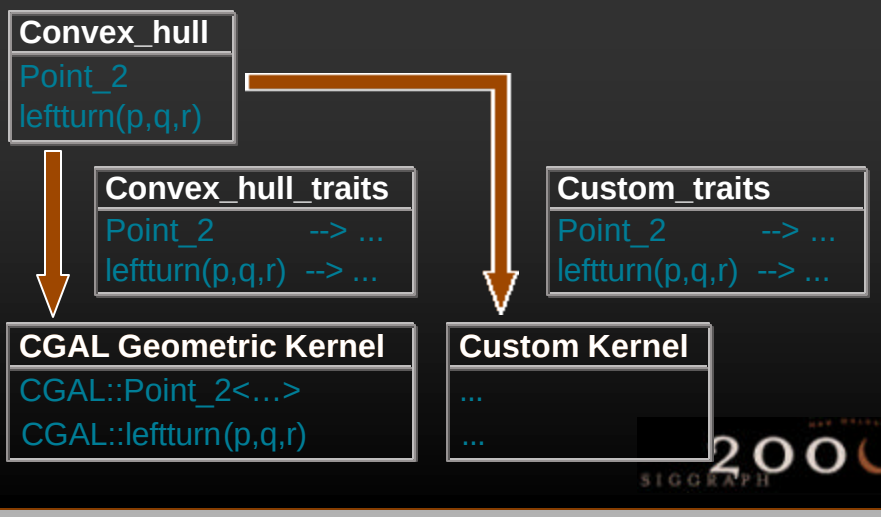
Type Mapping

CGAL Geometric Kernel
CGAL::Point_2<…>
CGAL::leftturn(p,q,r)

Geometry



Separating Basic Library and Geometric Kernel



Function Objects (Functor)

```
template <class Iterator>
void sort( Iterator first, Iterator beyond);
```

Function Objects (Functor)

```
template <class Iterator, class Comp>
void sort( Iterator first, Iterator beyond, Comp cmp);
```

Function Objects (Functor)

```
template <class Iterator, class Comp>
void sort( Iterator first, Iterator beyond, Comp cmp);

bool compare( string s, string t) { return strcmp(s,t) < 0; }
```

```
vector<string> v;
sort( v.begin(), v.end(), compare );
```

Function Objects (Functor)

```
template <class Iterator, class Comp>
void sort( Iterator first, Iterator beyond, Comp cmp);

struct Compare {
    bool operator()( string s, string t) {
        return strcmp(s,t) < 0;
    }
};
```

```
vector<string> v;
sort( v.begin(), v.end(), Compare());
```

Function Objects (Functor) (2)

```
struct Compare2 {
    int* counter;
    Compare2( int* p) : counter(p) {}
    bool operator()( string s, string t) {
        ++ *counter;
        return strcmp(s,t) < 0;
    }
};
```

```
int count = 0;
sort( v.begin(), v.end(), Compare2( &count));
```

Function Objects (Functor) (3)

Composing functors

```
int main( int argc, char** argv) {
    if ( argc != 2)
        throw( "usage: remove_if_divides integer\n");
    remove_copy_if( istream_iterator<int>(cin),
                    istream_iterator<int>(),
                    ostream_iterator<int>(cout, "\n"),
                    not1( bind2nd( modulus<int>(),
                                   atoi( argv[1]))));
    return 0;
}
```

Currying in C++ ! All at Compile Time !

An Example: CGAL Convex Hull with LEDA Kernel

```
int main() {
    std::list<Point>  pts;  // ...
    std::list<Point>  ch;
    CGAL::ch_graham_andrew( pts.begin(), pts.end(),
                            std::back_inserter(ch),
                            Traits());
    // ...
}
```

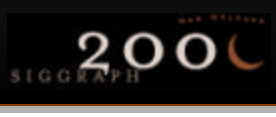
An Example: CGAL Convex Hull with LEDA Kernel (2)

```
typedef leda_rat_point   Pt;

struct  My_Less_xy {
    bool operator()( const Pt& p, const Pt& q) {
        return (p.xcoord() <  q.xcoord()) || (
                (p.xcoord() == q.xcoord()) &&
                (p.ycoord() < q.ycoord()));
    }
};
struct  My_Leftturn {
    bool operator()( const Pt& p, const Pt& q, const Pt& r) {
        return left_turn( p, q, r); // leda_left_turn
    }
};
```

An Example: CGAL Convex Hull with LEDA Kernel (3)

```
struct Traits {
    typedef Pt          Point_2;
    typedef My_Less_xy  Less_xy;
    typedef My_Leftturn Leftturn;

    Less_xy  get_less_xy_object()  const { return Less_xy(); }
    Leftturn get_leftturn_object() const { return Leftturn();
  }
};
```

Member functions required for functors with state



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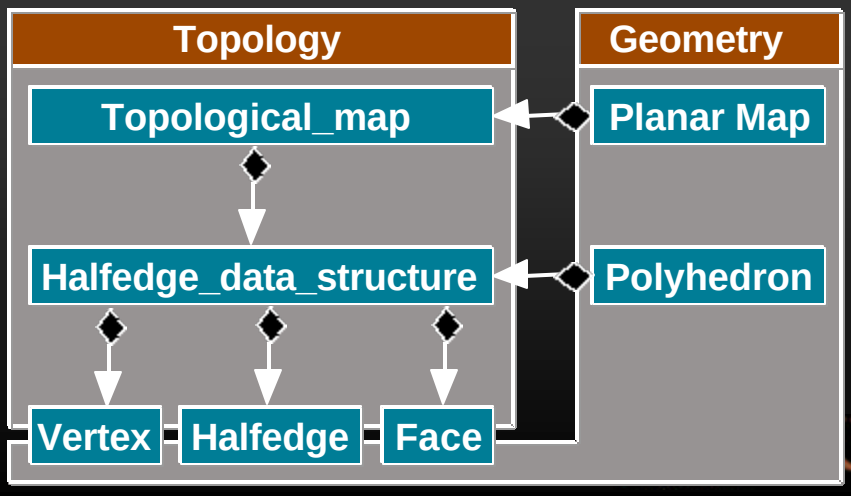
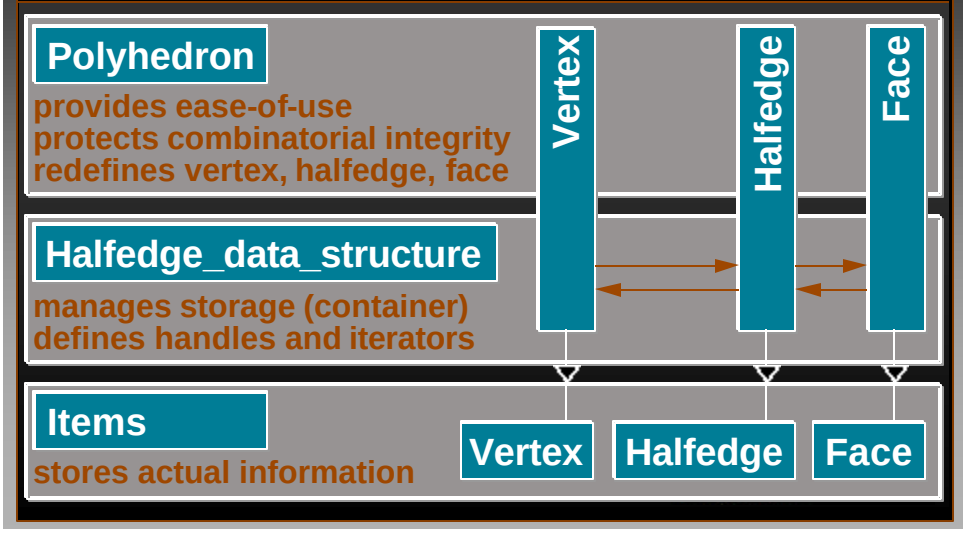
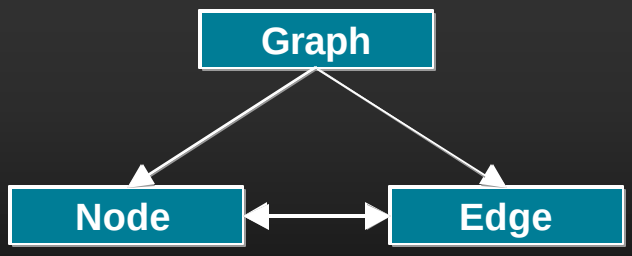
Separating Topology from Geometry



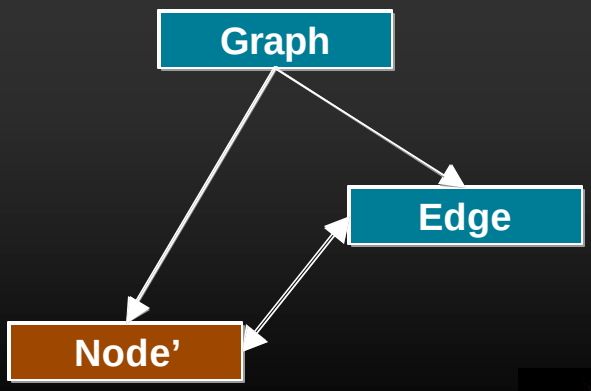
Separating Topology from Geometry (2)



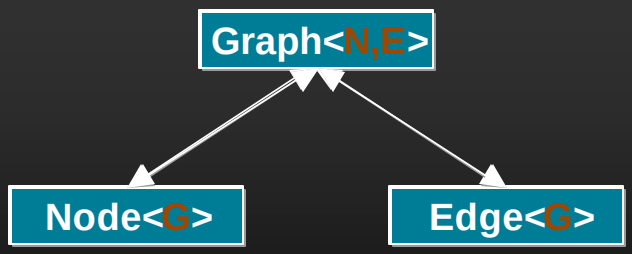
Cyclic Type Dependencies with Templates



Cyclic Type Dependencies with Templates



Cyclic Type Dependencies with Templates



Cyclic Type Dependencies with Templates (2)

```
template <class Graph>
struct Node {
    typedef typename Graph::Edge Edge;
    Edge* edge;
    // .... maybe some more edges ....
};

template <class Graph>
struct Edge {
    typedef typename Graph::Node Node;
    Node* node;
};
```

Cyclic Type Dependencies with Templates (3)

```
template <class Graph>
struct Node {
    typedef typename Graph::Edge Edge;
    Edge* edge;
    // .... maybe some more edges ....
};

template < template <class G> class T_Node,
           template <class G> class T_Edge>
struct Graph {
    typedef Graph< T_Node, T_Edge>      Self;
    typedef T_Node<Self>                Node;
    typedef T_Edge<Self>                Edge;
};
```

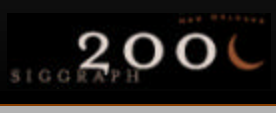
Cyclic Type Dependencies with Templates (4)

```
int main() {
    typedef Graph< Node, Edge> G;
    G::Node node;
    G::Edge edge;
    node.edge = &edge;
    edge.node = &node;
}
```

Cyclic Type Dependencies with Templates (5)

```
template <class Graph>
struct Colored_node : public Node<Graph> {
    int color;
};

int main() {
    typedef Graph< Colored_node, Edge> G;
    G::Node node;
    G::Edge edge;
    node.edge = &edge;
    edge.node = &node;
    node.color = 3;
}
```



Example: Declaration of Default Polyhedron

```
#include <CGAL/Cartesian.h>
#include <CGAL/Polyhedron_default_traits_3.h>
#include <CGAL/Polyhedron_3.h>

typedef CGAL::Cartesian<double>                 Rep;
typedef CGAL::Polyhedron_default_traits_3<Rep>  Traits;
typedef CGAL::Polyhedron_3<Traits>              Polyhedron;

int main() {
    Polyhedron P;
    Polyhedron::Halfedge_handle h = P.make_tetrahedron();
    assert( P.is_tetrahedron( h));
    return 0;
}
```

Geometric Shapes and Transformations in CGAL

- Overview of the Basic Library
- Separating Basic Library and Kernel
  - geometric traits classes
- Separating Topology and Geometry
  - halfedge data structure
- **Affine Transformations**

Affine Transformations

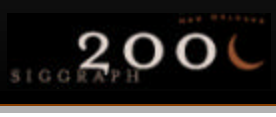
- Transforms points, vectors, and hyperplanes (covectors)
- Functor (STL)

```
std::transform( P.points_begin(), P.points_end(),
                P.points_begin(), A);
```

- Smart pointers with reference counting
- Polymorph
  - specialized representations for: translation, rotation, uniform scale

Summary Part II

- Templates, C++, and concepts from generic programming (iterators, functors)
  - provide expressiveness
  - provide flexibility at compile time
  - provide efficiency at runtime
- Shapes beyond IndexedFaceSet
  - e.g., for subdivision surfaces, mesh compr., etc.
- Example code on the CD-Rom



Acknowledgements

Thanks to all my friends and colleagues in CGAL!
Thanks to my advisors Emo Welzl and Jean-Daniel Boissonnat.

Support from the ESPRIT IV LTR Projects No. 21957 (CGAL) and 28155 (GALIA), and by the Swiss Federal Office for Education and Science (CGAL and GALIA) is acknowledged.

Internet Addresses

[SGI-STL]

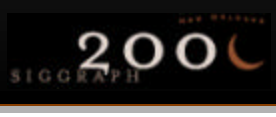
SGI: Standard Template Library Programmer's Guide:
http://www.sgi.com/Technology/STL/

[CGAL]

Computational Geometry Algorithms Library:
http://www.cgal.org

[LEDA]

Library of Efficient Data Types and Algorithms:
http://www.mpi-sb.mpg.de/LEDA/



Internet Addresses

[CG]

Directory of Computational Geometry Software:
http://www.geom.umn.edu/software/cglist/

[GMP]

The GNU Multiple Precision Arithmetic Library:
http://www.gnu.org/software/gmp

[CLN]

Class Library for Numbers:
http://clisp.cons.org/~haible/packages-cln.html

References

[Austern98]

Mathew H. Austern. *Generic Programming and the STL: Using and Extending the C++ Standard Template Library*. Addison-Wesley, 1998.

[CG-Report96]

CG Impact Task Force Report. *Application Challenges to Computational Geometry*. Technical Report, TR-521-96, Princeton University, 1996. http://www.cs.princeton.edu/~chazelle/taskforce/CGreport.ps.Z

[Edelsbrunner90]

Herbert Edelsbrunner and Ernst P. Mücke. *Simulation of Simplicity: a Technique to Cope with Degenerate Cases in Geometric Algorithms*. ACM Trans. Graph., 9(1): 66--104, 1990.

References

[Emiris97]

Ioannis Emiris, John F. Canny, and Raimund Seidel. *Efficient Perturbations for Handling Geometric Degeneracies*. Algorithmica, 19(1--2): 219--242, September 1997.

[Fabri99]

Andreas Fabri, Geert-Jan Giezeman, Lutz Kettner, Stefan Schirra, and Sven Schönherr. *On the Design of CGAL, the Computational Geometry Algorithms Library*. Software -- Practice and Experience, submitted 1999, to appear. (also available as technical report)

[ISO98]

International Standard ISO/IEC 14882: *Programming languages -- C++*. American National Standards Institute, 11 West 42nd Street, New York 10036, 1998.

References

[Kettner98]

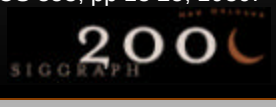
Lutz Kettner. *Designing a Data Structure for Polyhedral Surfaces*. In: Proc. of the 14th ACM Symp. on Computational Geometry, Minneapolis, Minnesota, pp. 146-154, June 1998.

[Kettner99]

Lutz Kettner. *Using Generic Programming for Designing a Data Structure for Polyhedral Surfaces*. Computational Geometry - Theory and Applications 13, pp. 65-90, 1999.

[Musser89]

David R. Musser and Alexander A. Stepanov. *Generic Programming*. 1st Intl. Joint Conf. of ISSAC-88 and AAEC-6, Springer LNCS 358, pp 13-25, 1989.



References

[Schirra99]

Stefan Schirra. *Robustness Issues*. In: Handbook of Computational Geometry, Jörg-Rüdiger Sack and Jorge Urrutia (Eds.), Elsevier Science Publishers B.V. North-Holland, 1999.

[Stepanov95]

Alexander Stepanov and Meng Lee. *The Standard Template Library*. http://www.cs.rpi.edu/~musser/doc.ps, 1995.

[Stroustrup97]

Bjarne Stroustrup. *The C++ Programming Language*. 3rd edition, Addison-Wesley, 1997.

[Weihe98]

Karsten Weihe. *Using Templates to Improve C++ Design*. C++ Report 10(2), pp 14-21, 1998.

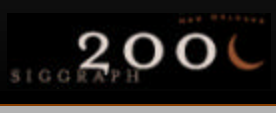
Lighting and Visibility

- Camera and Light Objects (Ghali)
- Performing Visibility Computation (Blythe)
- Separating the Physical and the Virtual Worlds (Sowizral)

Camera and Light Objects

Sherif Ghali

Max Planck Institute



The Camera

- **Non scene-graph issues**
  - Specifying the camera
- **Scene-graph issues**
  - Relation of camera object to the scene graph?
  - Transformations affecting the camera?

The Camera

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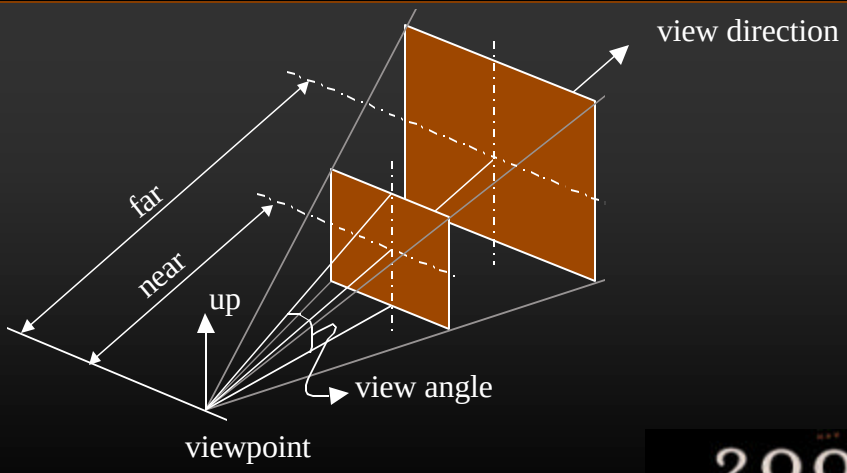
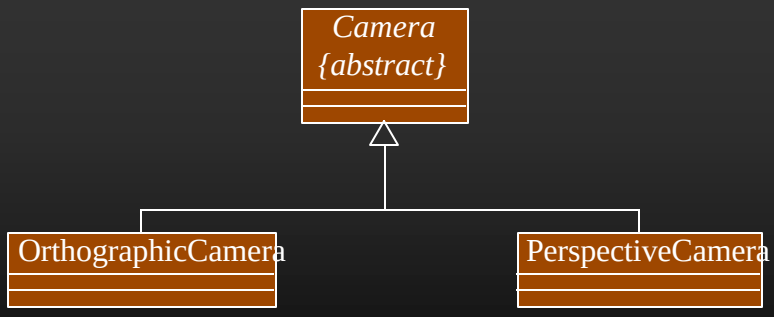
Non-Scene Graph Issue: Specifying the Camera



Camera Object: Single Class

Camera
viewpoint: Point3d viewDirection: Direction3d upDirection: Direction3d near, far, angle: double

Camera Object: Orthographic and Perspective Classes



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The Camera

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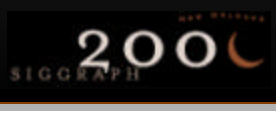
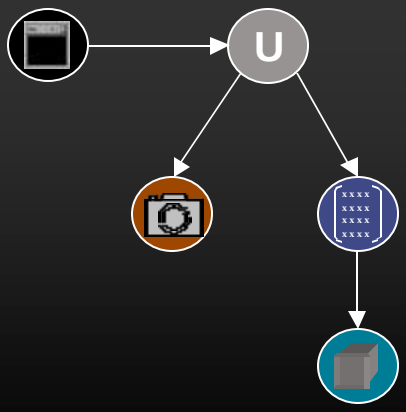
  - Transformations affecting the camera

Is the Camera a Node in the Scene Graph?

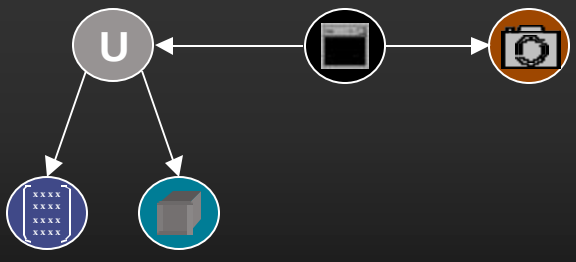
1. **User is immersed in the virtual world**
   - Camera is a node in the scene graph
2. **User is looking (through a window) at the virtual world**
   - Camera is not a node in the scene graph



Option 1: Camera Is Part of the Scene Graph



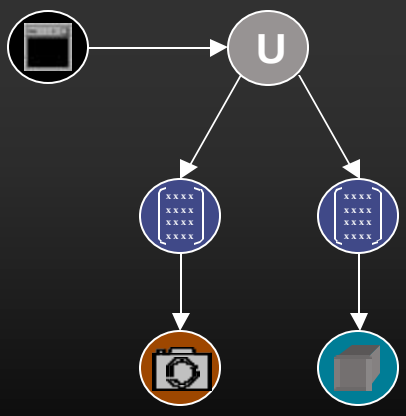
Option 2: Camera Is Not Part of the Scene Graph



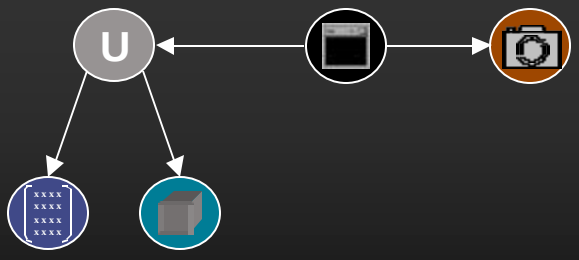
The Camera

- Non scene-graph issues
  - Specifying the camera
- Scene-graph issues
  - Relation of camera object to the scene graph
  - Transformations affecting the camera

Transformations Affecting the Camera



Transformations Affecting the Camera



Light Sources

- **Non scene-graph issues**
  - Specifying the light source
- **Scene-graph issues**
  - Subset of scene graph illuminated
  - Transformations affecting the light

Light Sources

- **Non scene-graph issues**
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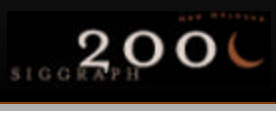
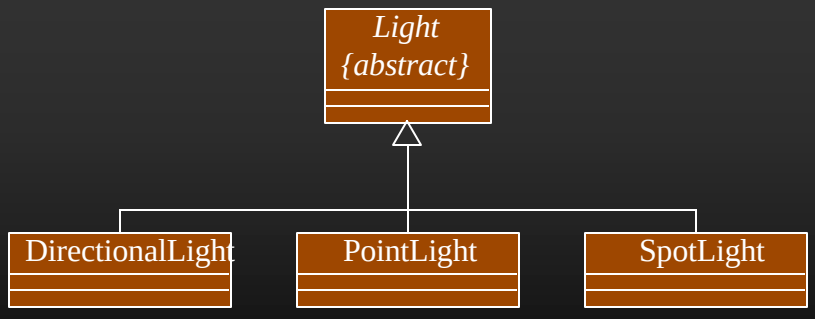
Non Scene-Graph Issue: Specifying the Light

- **Light type:**
  - Directional light:
    - Light at infinity
  - Point light:
    - Light at proximity
  - Spot light:
    - Specific direction and spread angle
- **Light intensity**
- **Light color**



Light Classes



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  - Specifying the light source
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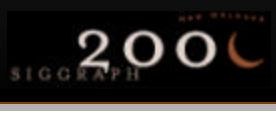
Subset of Scene Graph Illuminated

1. Light illuminates nodes traversed after it:
   1. Scene Graph parsed sequentially
   2. Scene Graph parsed hierarchically
2. Light illuminates a region of influence



Subset of Scene Graph Illuminated

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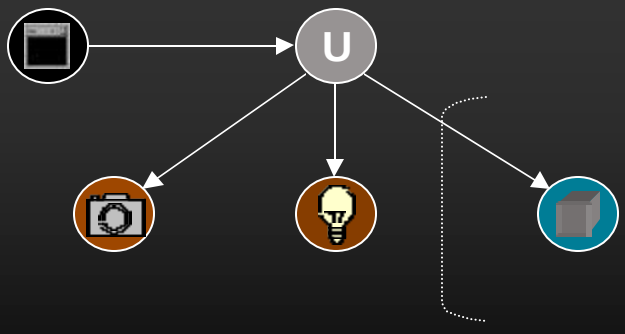
   2. Scene Graph parsed hierarchically
2. Light illuminates a region of influence

Light Illuminates Geometry Traversed After It



Subset of Scene Graph Illuminated

1. Light illuminates nodes traversed after it:
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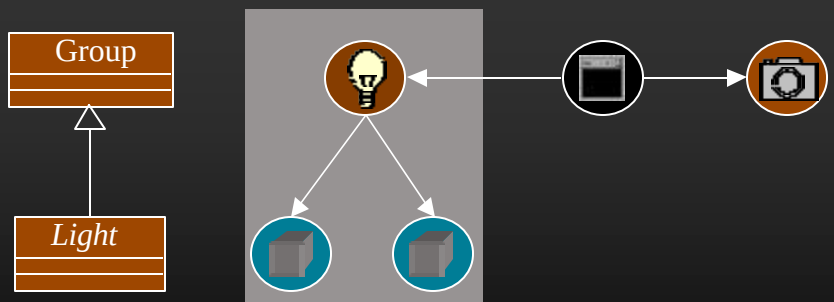
   2. Scene Graph parsed hierarchically
2. Light illuminates a region of influence

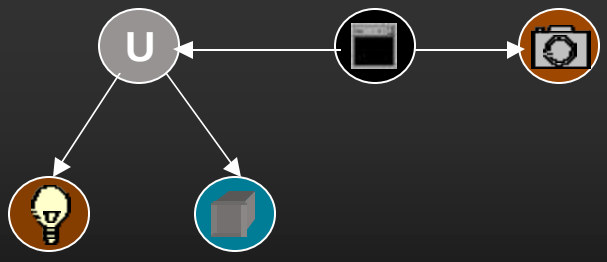
Light Illuminates Descendant Geometry



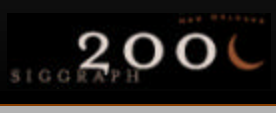
Subset of Scene Graph Illuminated

1. Light illuminates nodes traversed after it:
   1. Scene Graph parsed sequentially
   2. Scene Graph parsed hierarchically
2. **Light illuminates a region of influence**

Light Illuminates a Region of Influence



Light
setInfluencingBounds(BoundingBox bb)



Light Sources

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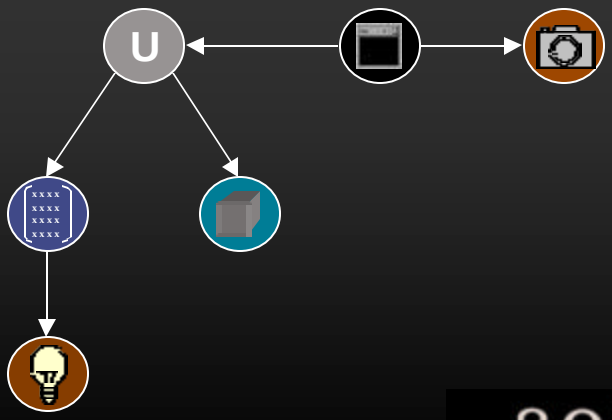
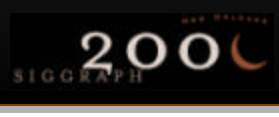
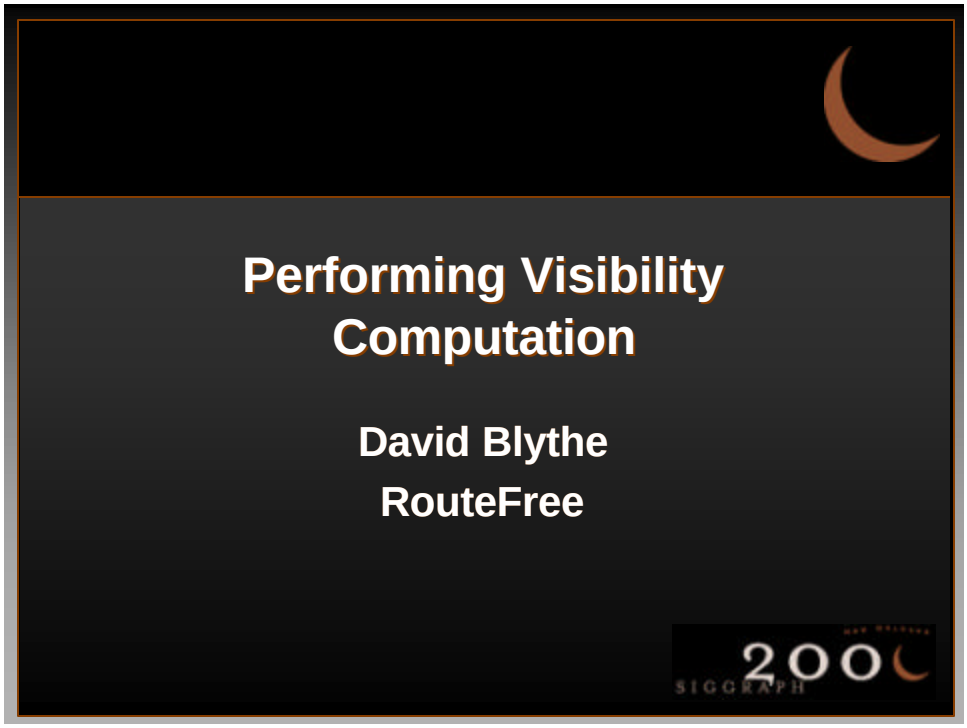
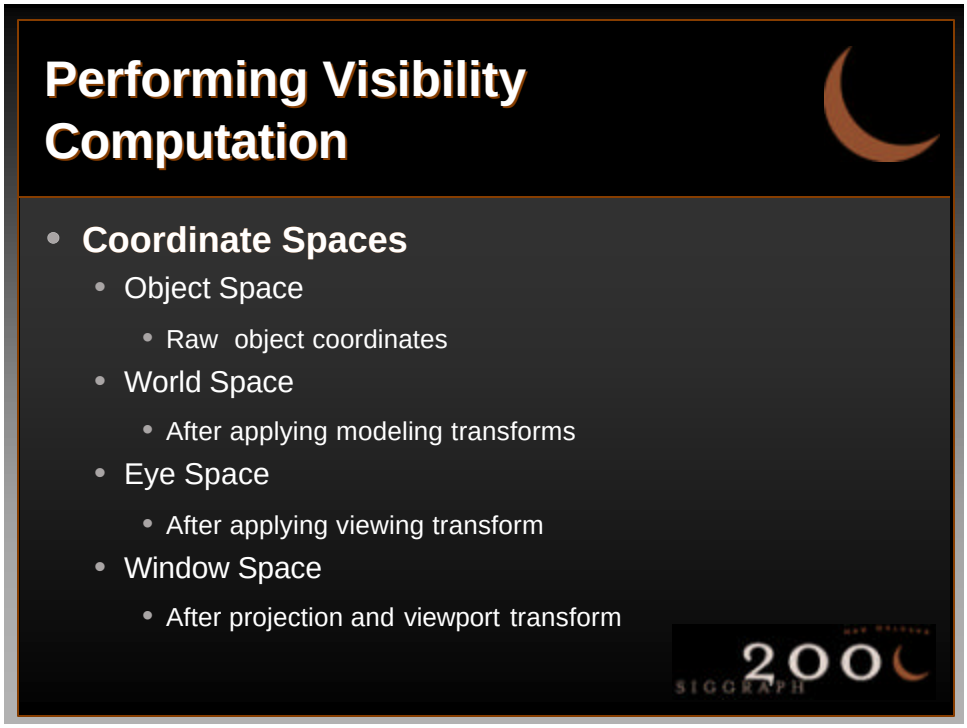
Transformations Affecting Light





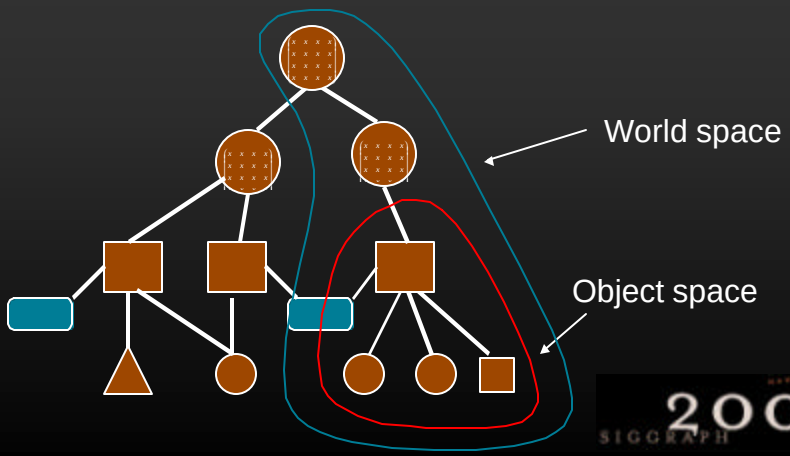

Performing Visibility Computation
David Blythe
RouteFree
SIGGRAPH 2000


Performing Visibility Computation
Coordinate Spaces
Object Space
Raw object coordinates
World Space
After applying modeling transforms
Eye Space
After applying viewing transform
Window Space
After projection and viewport transform
SIGGRAPH 2000

Performing Visibility Computation

- **Coordinate Spaces**
  - Some low-level APIs combine modeling and viewing transforms into one
    - OpenGL
  - Scene graph APIs separate modeling transforms and viewing transform

Performing Visibility Computation



Performing Visibility Computation

- **Coordinate Spaces**
  - Various computations occur in different spaces
  - Lighting eye space
  - Occlusion culling window space
  - LOD resolution world space
  - Frustum culling world space?
  - Terrain following, collision detection, …?

Performing Visibility Computation

- **The Camera Abstraction**
  - Typically includes both viewing and projection transforms
  - Position and orientation
  - Projection type (Perspective, Parallel)
  - Depth of Field
  - Mapping to the display surface (viewport)

Performing Visibility Computation

- **Camera in the Scene Graph**
  - Allows tethering the camera to scene objects
  - Need to locate camera before rendering
  - Multi-surface rendering complicates things
    - Multiple cameras in the scene graph?

Performing Visibility Computation

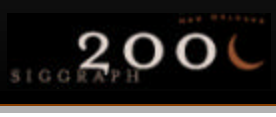
- **Camera in the Scene Graph**
  - Can solve the tethering problem with a proxy in the graph
    - Still need to locate proxies before rendering
    - Need to accumulate transform along the path to the proxy
    - pre-traversal

Performing Visibility Computation

- **Specifying Parameters**
  - Keep projection and viewing transforms separate
  - Use camera for rendering and view-frustum culling
  - Projection
    - Use frustum as canonical representation
      - frustum (left, right, bottom, top, near, far, perspective)
      - Easy to convert to plane equations for culling

Performing Visibility Computation

- **Specifying Frustum**
  - Additional projection convenience functions
    - Perspective(fovy, aspect, near, far)
    - Ortho(left, right, bottom, top, near, far)
    - Frustum(left, right, bottom, top, near, far)

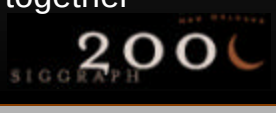


Performing Visibility Computation

- **Specifying Viewing Transform**
  - Use 4x4 matrix as canonical representation
  - Convenience functions for generating matrix
    - LookAt(eye_point, reference_point, up_vector)

Performing Visibility Computation

- **Specifying Viewport Mapping**
  - Viewport(x, y, width, height)
  - May need to set scissor as well
    - If rendering to a portion of a window
  - Dependency between display surface, viewport, and projection
  - Want to observe aspect ratio
  - Useful to tie all camera parameters together

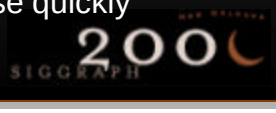


Performing Visibility Computation

- **Multiple Cameras**
  - Multiple channels on the same accelerator
  - Multiple accelerators
  - Tiled displays
    - Curved or domed
    - Flat
  - Single eye point, multiple cameras
    - Link with offsets

Performing Visibility Computation

- **View-Frustum Culling**
  - Quickly eliminate irrelevant objects (not-visible)
    - Spend less time drawing
  - Test individual objects
    - Use bounding volumes as proxy geometry
  - Use spatial organization and hierarchical bounding volumes
    - Eliminate large sections of data base quickly

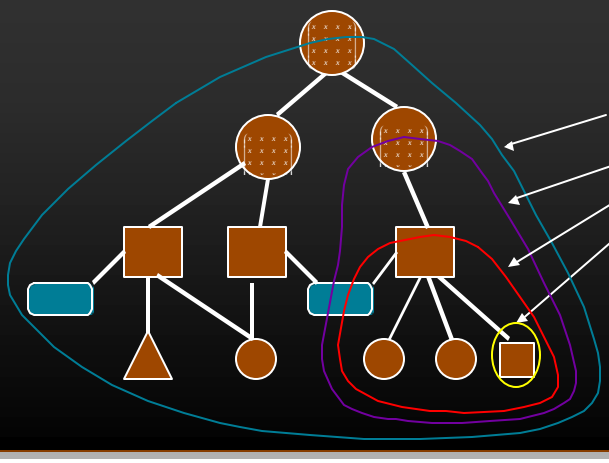


Performing Visibility Computations

- **View-Frustum Culling**
  - What space are bounding volumes stored in?
  - Instancing use hierarchical model spaces
  - Incorporate viewing transform during cull operation

Performing Visibility Computation

- **View-Frustum culling**

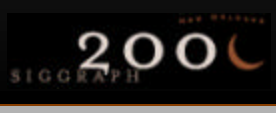


Performing Visibility Computation

- **Multiple Cameras**
  - Non-tiled displays
  - Top, front, side views (CAD)
  - Orthographic and perspective views
  - Wire-frame and Solid views
  - Non-simple relationship between cameras

Performing Visibility Computation

- **View-Frustum Culling \w Multiple Cameras**
  - Tiled displays
    - Perform one cull operation for entire visible scene
  - Unrelated cameras
    - e.g., front view + rear view mirror
    - Perform multiple cull operations



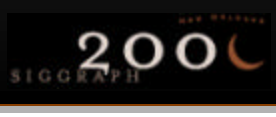
Performing Visibility Computation

- **Spatial Queries**
  - Other uses for hierarchical bounding volumes
    - Intersection operations
      - Simple collision detection
      - Terrain following
  - Factoring to two pass operations
    - Rather than replicating culling code in other tasks
    - Cull first, save result, operate on result

Performing Visibility Computation

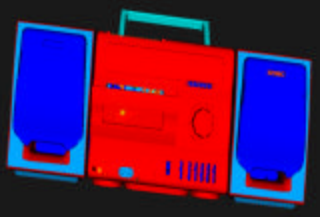
- **Generalize Frustum Culling**
  - Use polytope rather than frustum
  - Collection of half-spaces (plane equations)
  - e.g., Cylinder -> faceted cylinder

  - More computationally expensive, but tighter culls



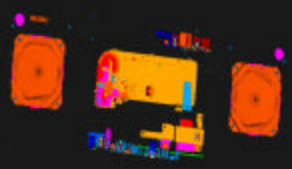
Performing Visibility Computation

- **Occlusion Culling**



Model courtesy SDRC

Visible Geometry



Occluded Geometry

Performing Visibility Computation

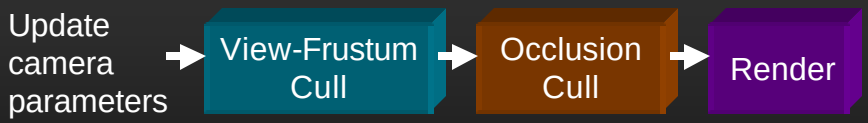
- **Occlusion Culling**
  - Don’t render occluded objects
  - Find list of occluders
    - Good occluder has a large window space extent
    - Transform bounding volume to window space
    - Remember occluders from frame to frame
    - Where to save occluder list?
      - – Instancing need paths to occluder geometry

Performing Visibility Computation

- **Occlusion Culling**
  - Test other objects (PVOs) against occluders
    - Compare depth values and window coverage
      - Is object contained within occluder
    - Use real projection of occluders (not BVs)
    - Use projected bounding volumes of PVOs
    - Use software scan converter or hardware support
      - e.g., Occlusion maps

Performing Visibility Computation

- **Visibility Pipeline**



Separating The Physical and Virtual Worlds

Henry A. Sowizral

Sun Microsystems, Inc.

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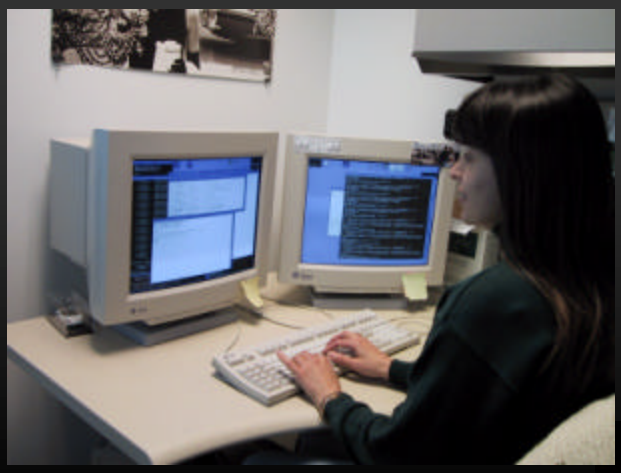
Copyright © 2000 Henry A. Sowizral

Camera-based Model

- **Camera-in-the-scene**
- **The program controls the camera's**
  - Position
  - Orientation
  - Aspect ratio
  - Field-of-view (FOV)
- **The camera's image maps onto a canvas**

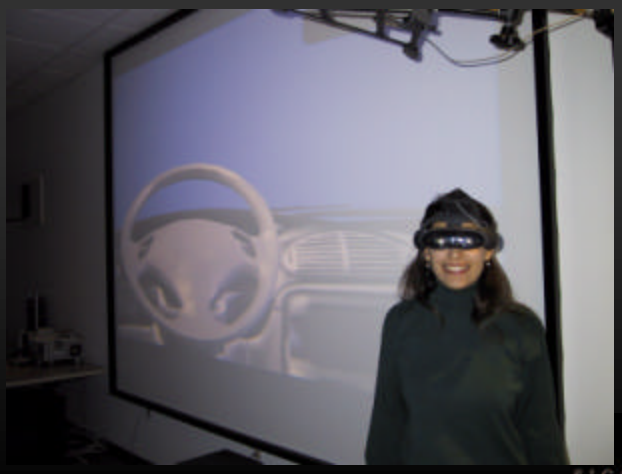
Works Well For Monitors



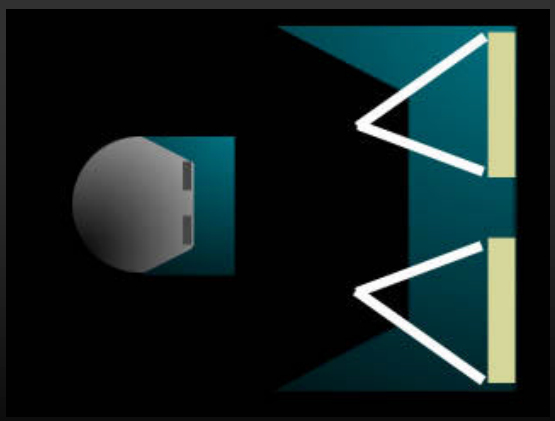
Too much control

- **FOV**
  - Fixed: physical constraints
  - Changing: function of head position
- **Aspect ratio**
  - Determined by physical screens

Head-Mounted Displays

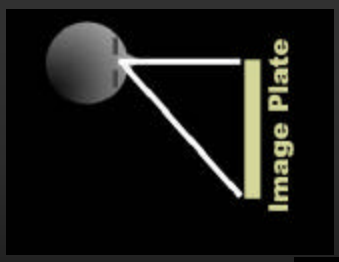


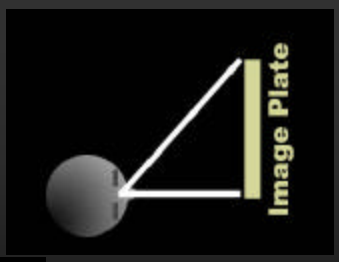
Head-mounted FOV

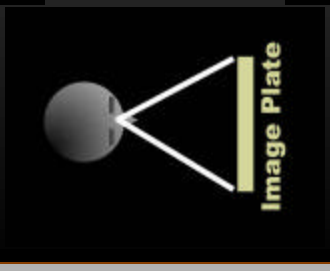


Head-tracked Monitor

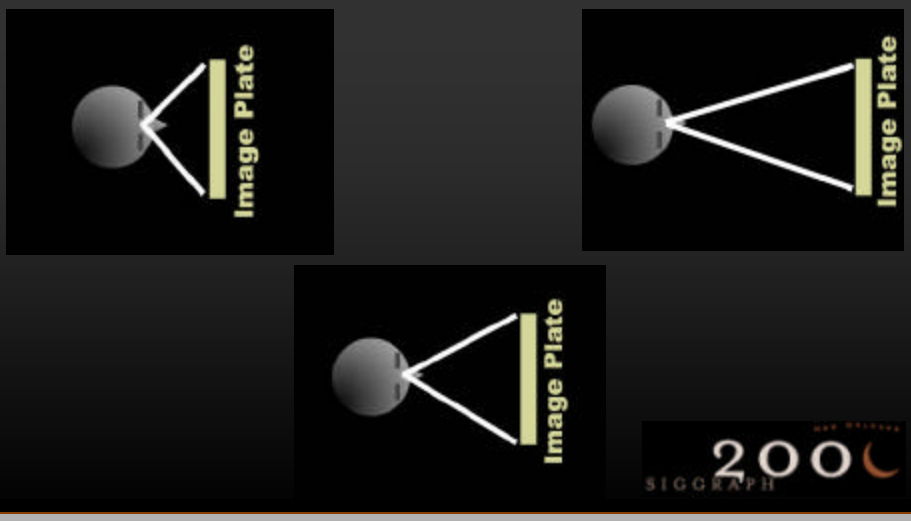
Moving Left, Moving Right







Moving Closer, Moving Further

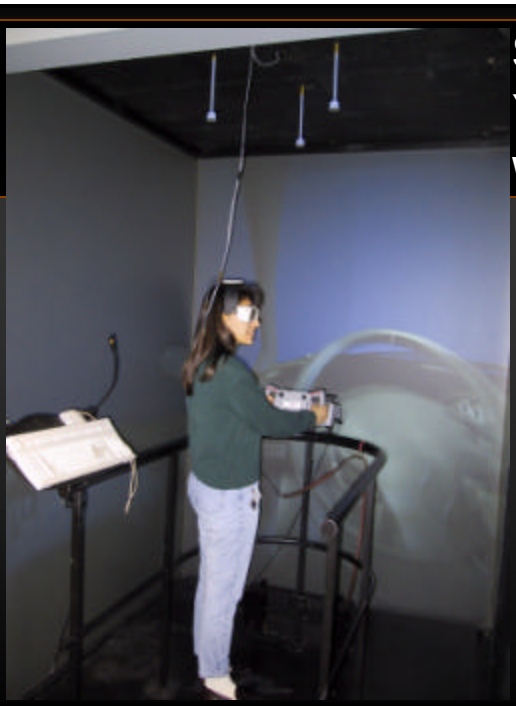


Too Little Control

- **Multiple displays**
  - Coplanar (tessellated wall)
  - Non-coplanar (portal: cave-like environment)
- **Head position**

One Screen Just Isn't Enough

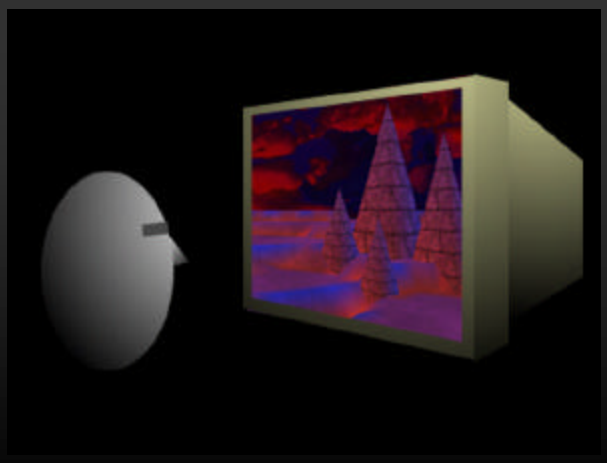
Surrounding Yourself With Data

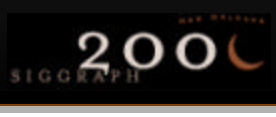


A New View Model

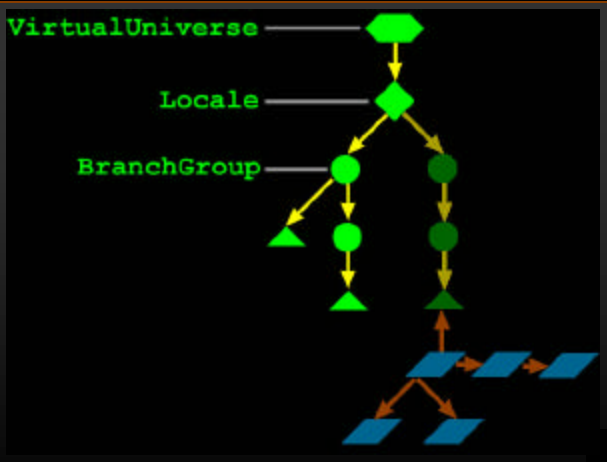
- **Not a camera-based model**
  - ViewPlatform metaphor accommodates head-tracking
- **Easily change display environments**
  - Scene graph independent
  - Without rewriting code

A User And A Monitor

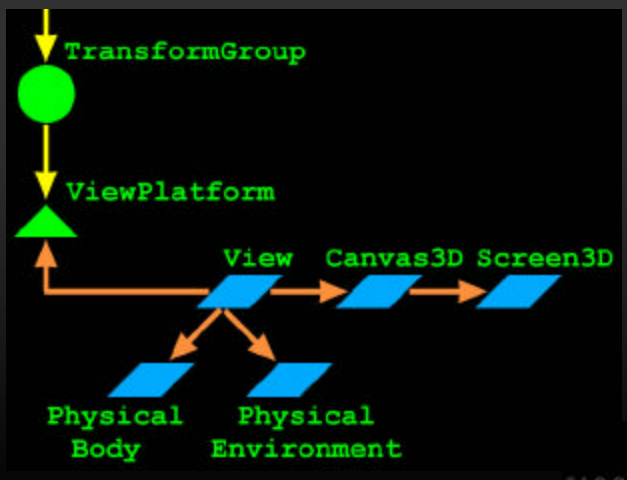




A Scene Graph



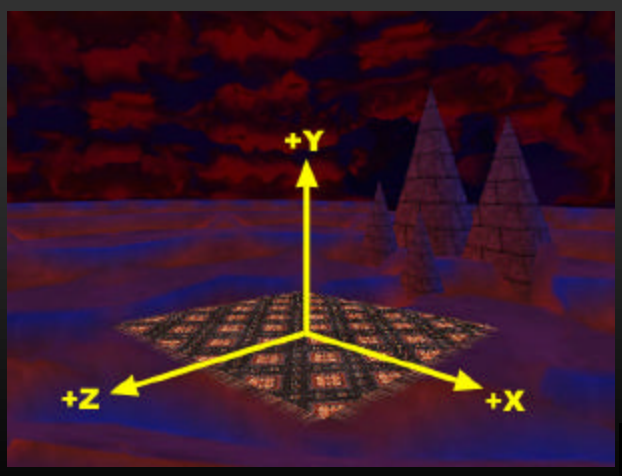
ViewBranch

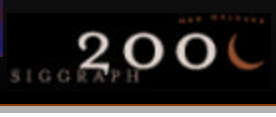


Separating the Physical from the Virtual

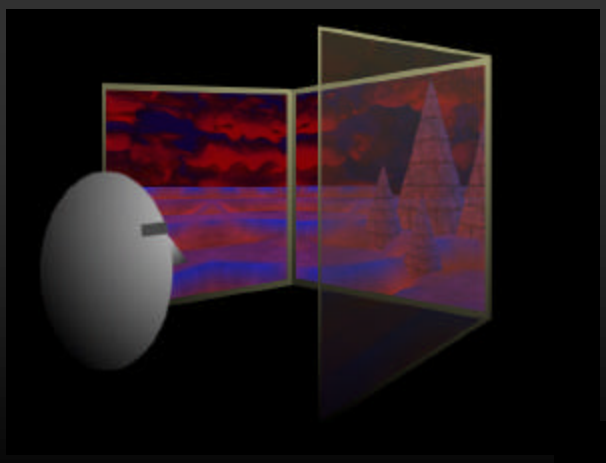
- **Virtual World**
  - ViewPlatform
  - Position and orientation
  - Navigable
- **Physical World**
  - Location of screens
  - Location of tracker

In The Virtual World: The ViewPlatform, A Magic Carpet

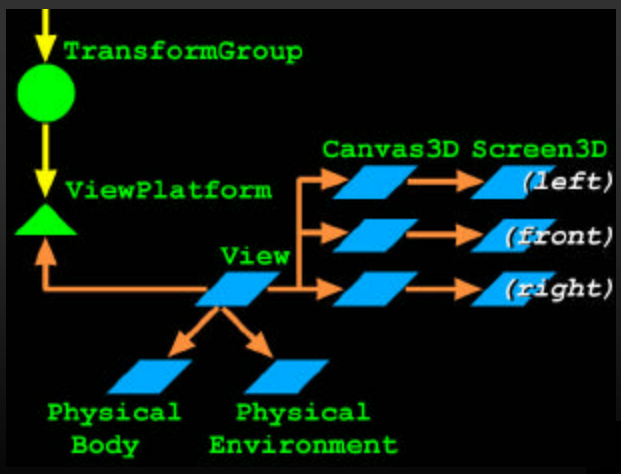




In The Physical World: The Screens, User, And Tracker



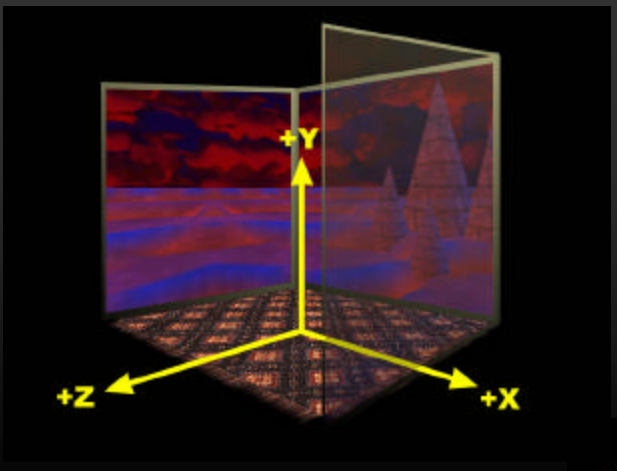
A Portal's ViewBranch



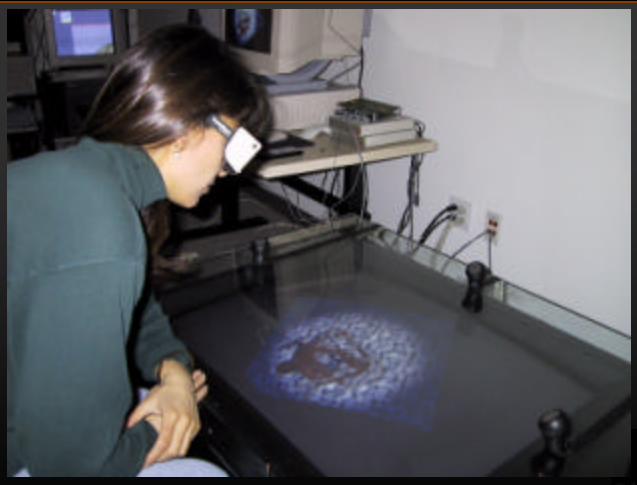
Coexistence

- **Physical world**
  - User's location and orientation
  - Screen location and orientation
  - Speakers, etc.
- **Virtual world**
  - Abstract location and orientation
- **One-to-one and onto mapping**

Relating The Two: Coexistence



Manipulating Your Data



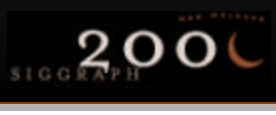
Input and User Interaction

- Scene Graph Inputs (Ghali)
- Input File Formats (Blythe)
- User Interaction (Sowizral)

Scene Graph Inputs

Sherif Ghali

Max Planck Institute

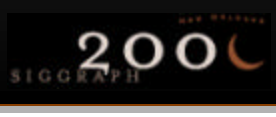


Off-line Storage

- Adopt a file format?
- Adopt a minimalistic file format?
- Save compiled graph?
- Save human-readable file?

Information Saved

- Geometry
  - Vertex and polygon lists
- Geometry and Materials
  - Subset of VRML / OpenInventor
- Geometry, Materials, and Hierarchy
  - VRML / OpenInventor



Information Saved

- **Geometry**
  - Vertex and polygon lists
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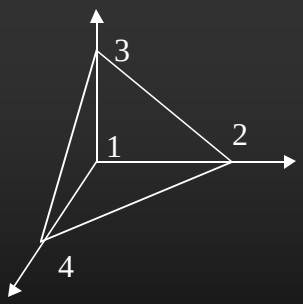
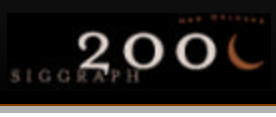
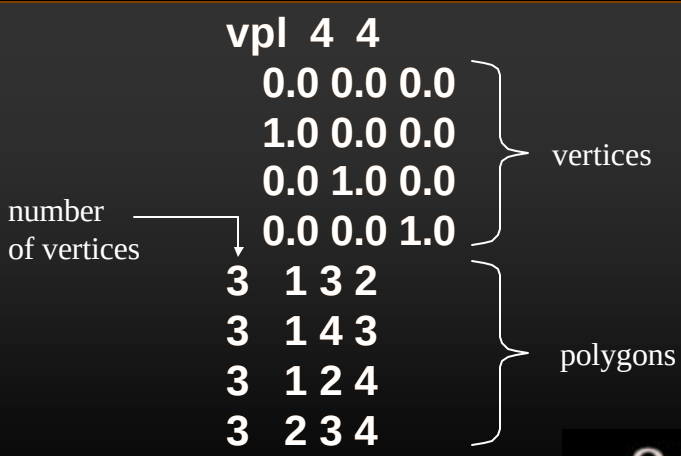
  - Subset of VRML / OpenInventor
- **Geometry, Materials, and Hierarchy**
  - VRML / OpenInventor

A Minimalistic File Format





A Minimalistic File Format



A Minimalistic File Format

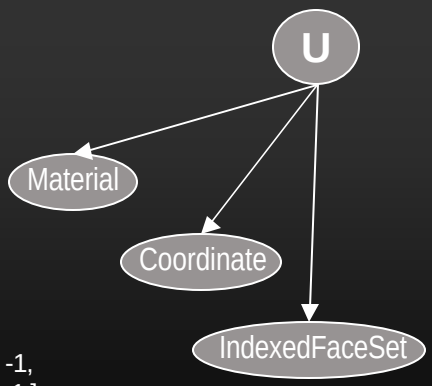
- **Advantages**
  - Automatic generation is easy
  - Human readable
  - Compact
- **Disadvantages**
  - No material information

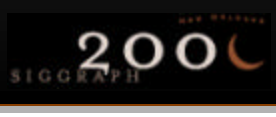
Information Saved

- Geometry
  - Vertex and polygon lists
- **Geometry and Materials**
  - Subset of VRML / OpenInventor
- Geometry, Materials, and Hierarchy
  - VRML / OpenInventor

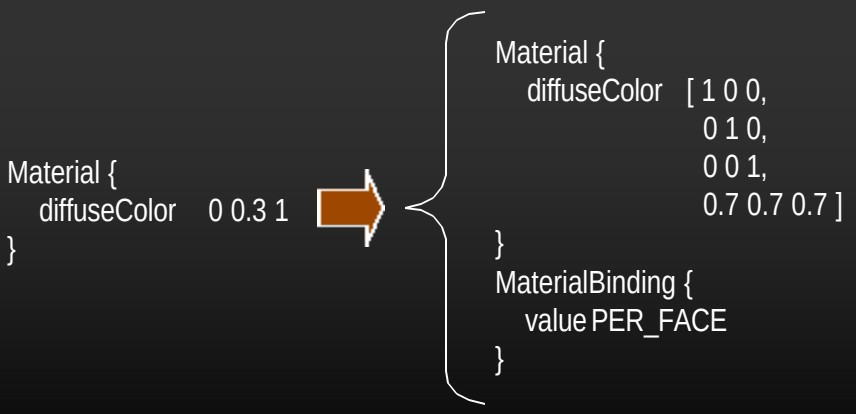
Geometry and Materials

```
#Inventor V2.1 ascii
Separator {
    Material {
            diffuseColor        0 0.3 1
    }
    Coordinate3 {
            point       [ 0 0 0,
                          1 0 0,
                          0 1 0,
                          0 0 1 ]
    }
    IndexedFaceSet {
            coordIndex  [ 0, 2, 1, -1, 0, 3, 2, -1,
                          0, 1, 3, -1, 1, 2, 3, -1 ]
    }
}
```

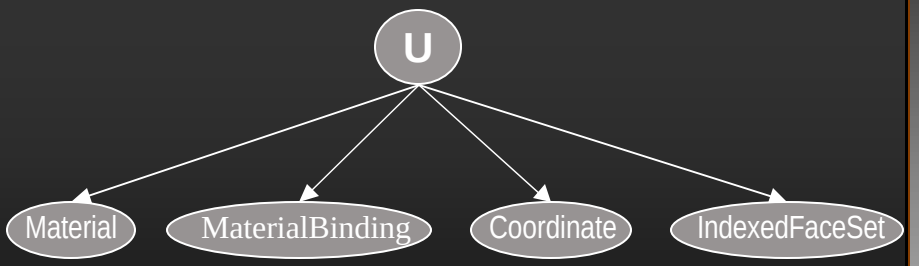




Geometry and Materials



Geometry and Materials

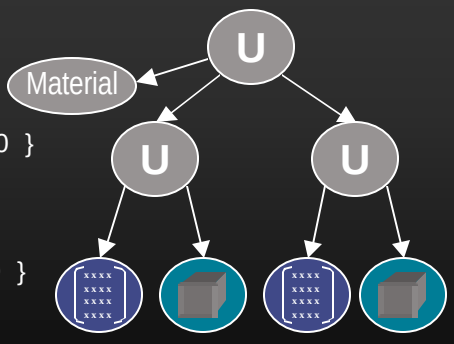


Information Saved

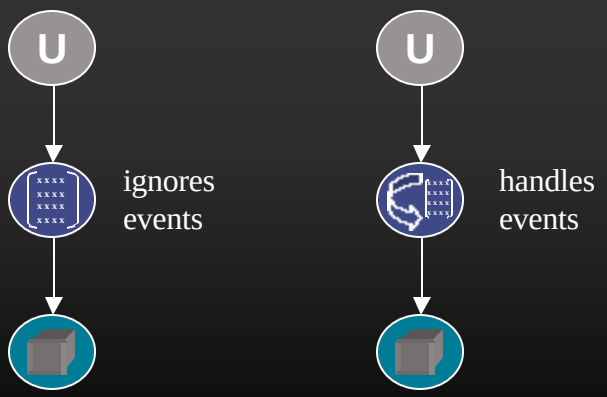
- **Geometry**
  - Vertex and polygon lists
- **Geometry and Materials**
  - Subset of VRML / OpenInventor
- **Geometry, Materials, and Hierarchy**
  - VRML / OpenInventor

Geometry, Materials, and Hierarchy

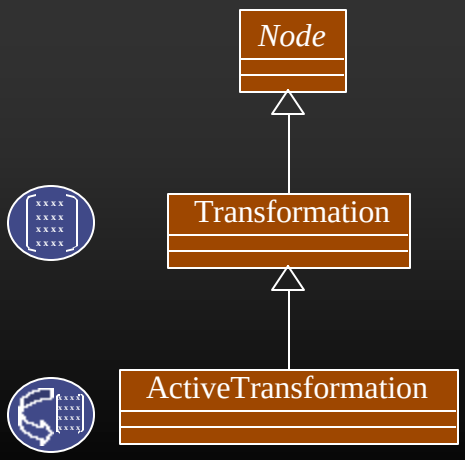
```
#Inventor V2.1 ascii

Separator {
    Material {  diffuseColor  1 0 0  }
    Separator {
            Translation {  translation  0 -1 0  }
            Cylinder { }
    }
    Separator {
            Translation {  translation  0 1 0  }
            Cone { }
    }
}
```



Event Handling



Event-Handling Transformation Node



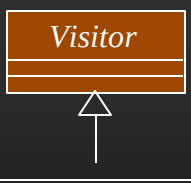
Visitors

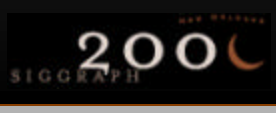
- Visitors traverse scene graph
- Render Visitors

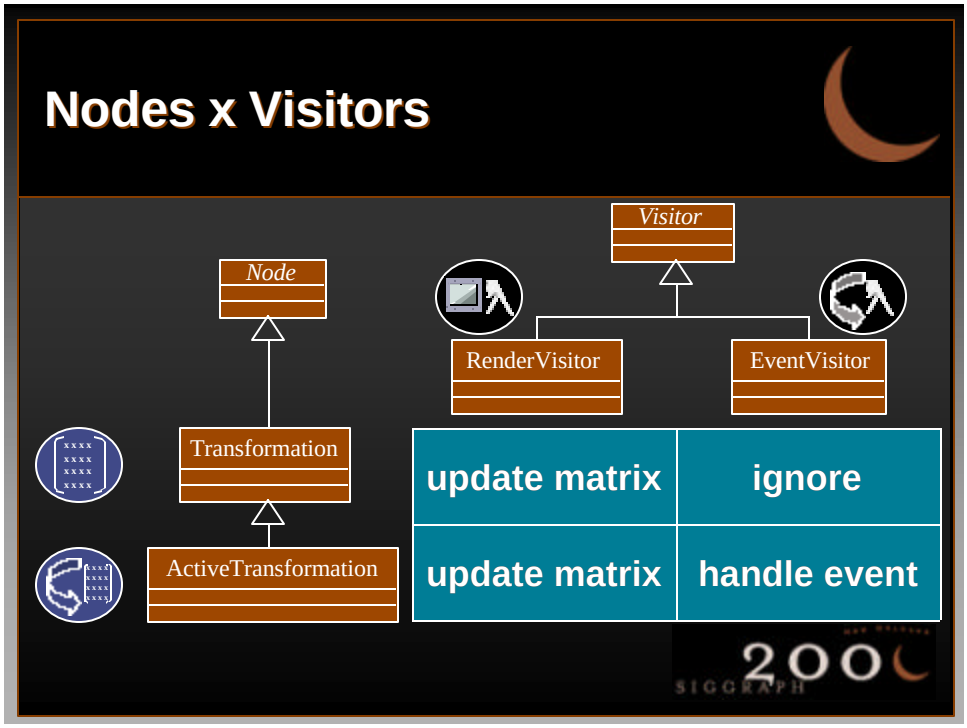
  - activate draw methods
- Event Visitors

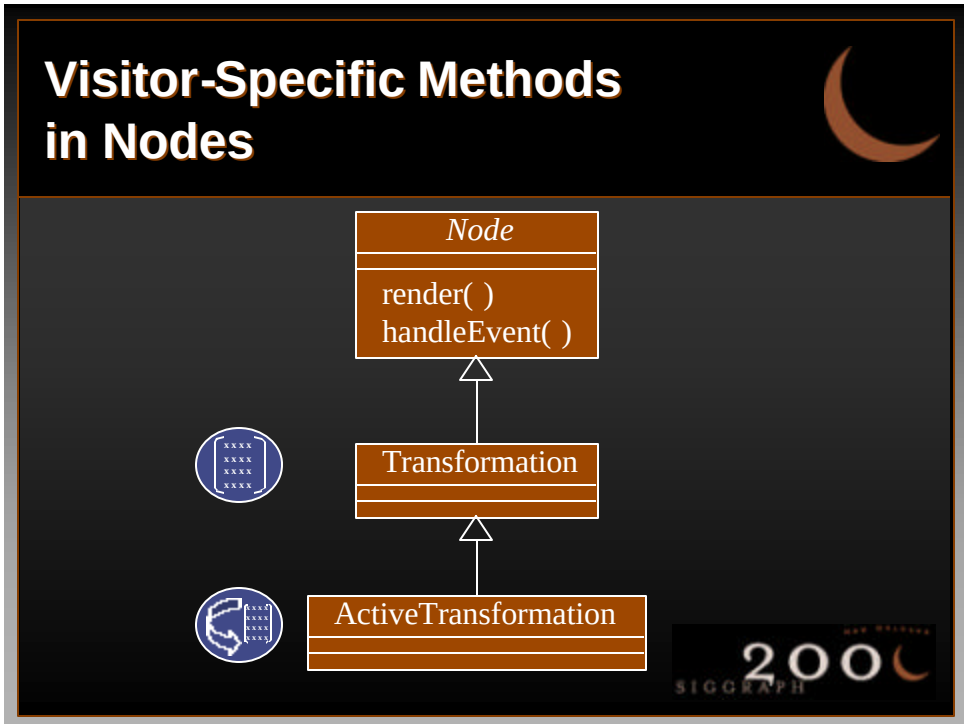
  - activate handleEvent methods
  - propose events to nodes

Visitor Classes

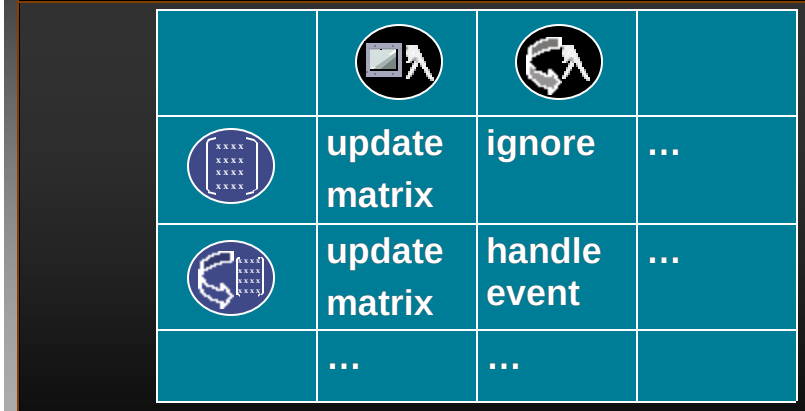





Nodes x Visitors
Visitor
Node
RenderVisitor
EventVisitor
Transformation
ActiveTransformation
update matrix
ignore
update matrix
handle event
SIGGRAPH 2000


Visitor-Specific Methods in Nodes
Node
render( )
handleEvent( )
Transformation
ActiveTransformation
SIGGRAPH 2000

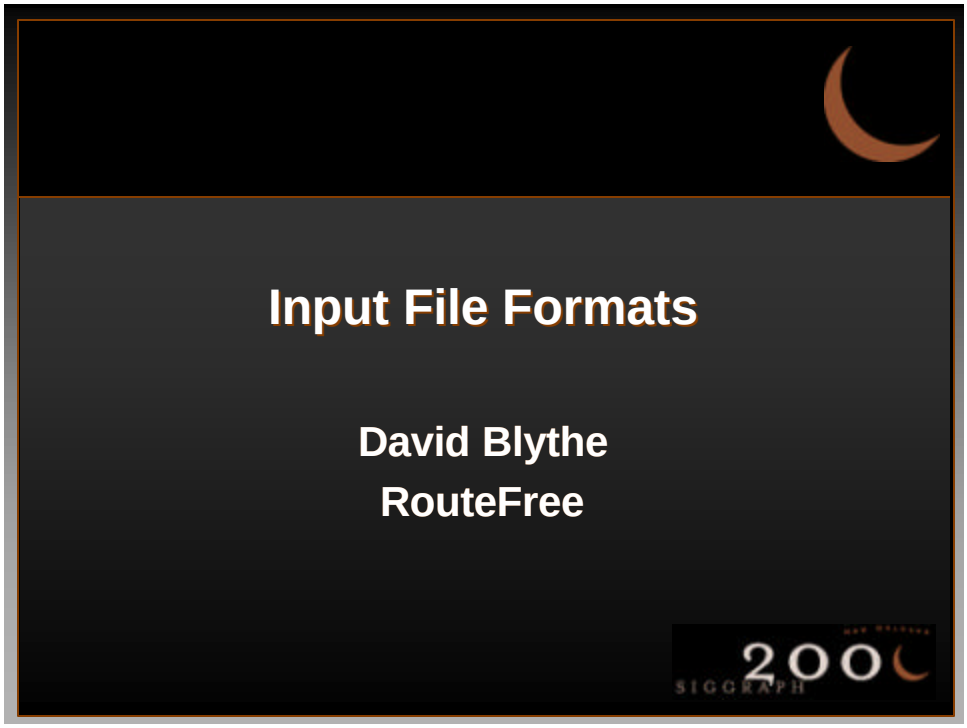
Adding Nodes / Visitors



	update matrix	ignore	…
	update matrix	handle event	…
	…	…	

Code Example

```
main(int argc, char **argv)
{
  DirectionalLight   *lum = new DirectionalLight(Point3d(3,4,5));
  ActiveTransformGroup  *active = new ActiveTransformGroup;
  Shape  *cube = new Shape("cube.vpl");

  lum->addChild(active);
  active->addChild(cube);

  Camera cam (Point3d(0,3,3), Point3d(0,0,0), Vector3d(0,1,0));

  window = new Window(argc, argv, lum, cam);
  window->mainLoop();
  return 0;
}
```



Input File Formats

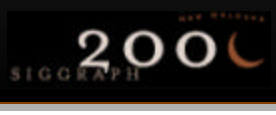
- **Data Driven Applications**
  - Viewing applications are data independent
  - Use input files to driver viewer
    - static scenes provide simple scene data
    - dynamic scenes need to encapsulate behavior
      - Inventor/VRML engines, behaviors, ..
  - The *database* is the application

Input File Formats

- **Uses**
  - Restore/Restart
  - Application Interchange
  - Import/Export
  - Prototyping/Debugging
  - Run-time “Paging”

Input File Formats

- **Restore/Restart**
  - Save current state of application
    - e.g., authoring application
  - Serialization of objects
    - Serialization built into objects?
  - Typically involves more than scene data



Input File Formats

- **Application Interchange**
  - Share data between different applications
  - Complicated if applications use different APIs
    - Pick an interchange format (VRML?, STEP)
  - If applications use the same API
    - Native file format
      - e.g., Inventor File format

Input File Formats

- **Import/Export**
  - Viewers/authoring tools read multiple input formats
    - VRML, OBJ, 3DStudio, Maya, …
  - Authoring programs export multiple formats for other applications
  - Lossy process
    - Toolkit objects don't capture all information in file
    - File format can't capture object semantics

Input File Formats

- **Import/Export**
  - Use offline translator?
    - E.g., Performer has pfconv
  - If translator uses the same API code base, should integrate as a reader module
  - Simple reader class hierarchy
    - Find correct reader using filename extension - or -
    - Magic numbers

Input File Formats

- **Reader Class Hierarchy**

```
class Reader {
   virtual Node* loadFile(const char* filename) = 0;
};

class VrmlReader : public Reader {
   Node* loadFile(const char* filename);
};

class ObjReader : public Reader {
   Node* loadFile(const char* filename);
}
```

Input File Formats

- **Prototyping/Debugging**
  - Very readable, easy to enter
  - ASCII preferred
  - Ideally represent all attributes of Toolkit objects
    - Data types
    - Behavior
    - Native format best match

Input File Formats

- **Example - VRML Format**

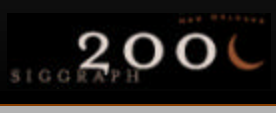
```
Transform {
   translate 0 0 3
   children [
      Shape {
         geometry Sphere
         appearance Appearance {
            material Material { diffuseColor 0 0 1 }
         }
      }
   ]
}
```

Input File Formats

- **Paging**
  - Database too large to fit in memory
  - Segment a database
    - spatial organization
    - tiling?
  - High performance read and write
    - binary representation
      - (pointers, endianness)

Input File Formats

- **Paging**
  - Organize data for I/O
    - separate arrays from objects
    - read directly into objects
      - avoid copying memory
  - Format may change when object definitions change
    - IRIS Performer
    - Not good as an interchange format

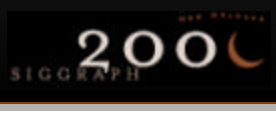


Input File Formats

- **Paging**
  - Need a way to trigger paging operations from scene
  - ‘External Reference’ node refers to file storage
  - Trigger file read when traverse external reference
  - May want to page out parts of scene when not in view
    - Throw away if scene is immutable
    - Save changes if not

Input File Formats

- **Instancing**
  - Multiple references to an object definition
  - Preserve using a DEF/USE table (hash table)
  - Allow use before definition?
    - Need to patch on definition



Input File Formats

- **Machine Dependencies**
  - What if a certain feature isn't supported?
    - Multi-texture, cube maps?
    - Convert to a different abstraction
  - Author on one platform/Use on another
  - Use more generic terms
    - NICEST, FATEST
    - Map definitions to specific platform

Input File Formats

- **Machine Dependencies**
  - Create more generic abstractions
    - Bump map rather than multi-texture config
    - Environment map rather than cube map
    - Using hint to bias mappings

Input File Formats

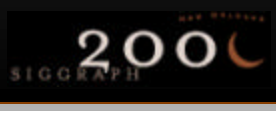
- **Extensibility**
  - New object types added to system
    - Add new definitions to file format
  - Dynamically loaded object types
    - May need file format hook to load file reader extensions

Input File Formats

- **Extension Example**

```
Transform {
   translate 0 0 3
   children [
      Shape {
         geometry Foo { }
         appearance Appearance {
            material Material { diffuseColor 0 0 1 }
         }
      }
   ]
}
```

New data type



Input File Formats

- **Extension Example**
  - Reader encounters unknown type Foo
  - Reader searches registry for module to handle Foo
  - Reader loads module and jumps to Foo handler
  - Maybe add tag to file format to preload extensions

Input File Formats

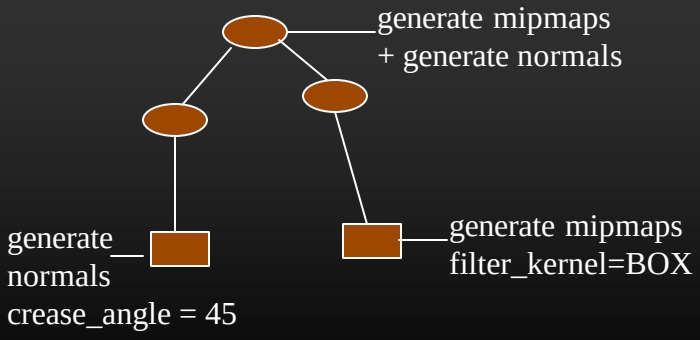
- **How much processing to do in reader?**
  - Generate normals
  - Tessellate geometry
  - Generate mipmap textures
  - If reader does work, may need to pass hints to reader to control processing
  - Harder to do code reuse between readers

Input File Formats

- **Post-Reader Processing**
  - Have reader mark scene for additional processing
  - Run “fix-up” traversals after reader completes
  - Move work out of readers into a central place
    - Allow more control
    - Integrate with other optimization processing
      - e.g., re-strip geometry, generate LODs, etc.
  - Need a way for reader to tag the scene

Input File Formats

- **Tagging with attributes**

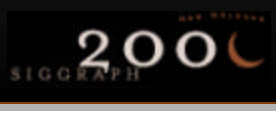


Input File Formats

- **Built-in Serialization**
  - File I/O defined as part of object definition
  - Only works for native format
    - Need another way to export to other formats
  - Problematic with paging
    - all object data may not be grouped together

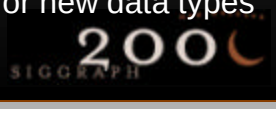
Input File Formats

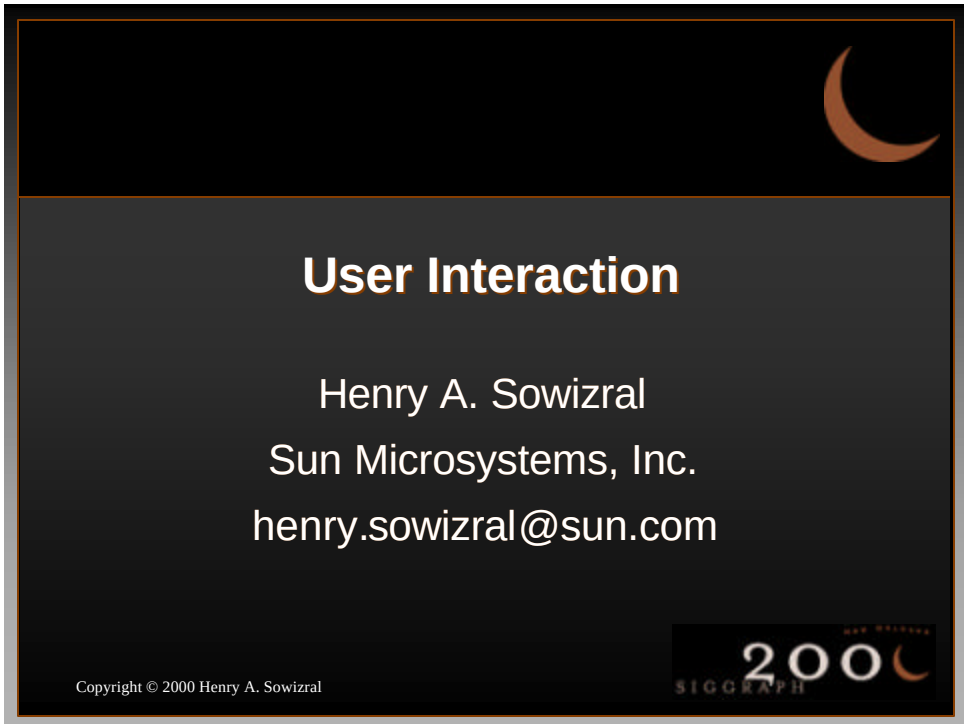
- **Adding Behaviors to File Format**
  - Holy grail of file formats
  - database is the application
  - Analogue in the database world is “stored procedures”
  - Store processing with the data



Input File Formats

- **Adding Behaviors to File Format**
  - Add serializable form of behavior data types
  - Add behavior object connectivity
    - e.g., Open Inventor engines + routes
    - Routes effectively form another graph (engine graph)
  - May need to dynamically load code to implement behavior
    - Similar to problem of loading code for new data types




User Interaction
Henry A. Sowizral
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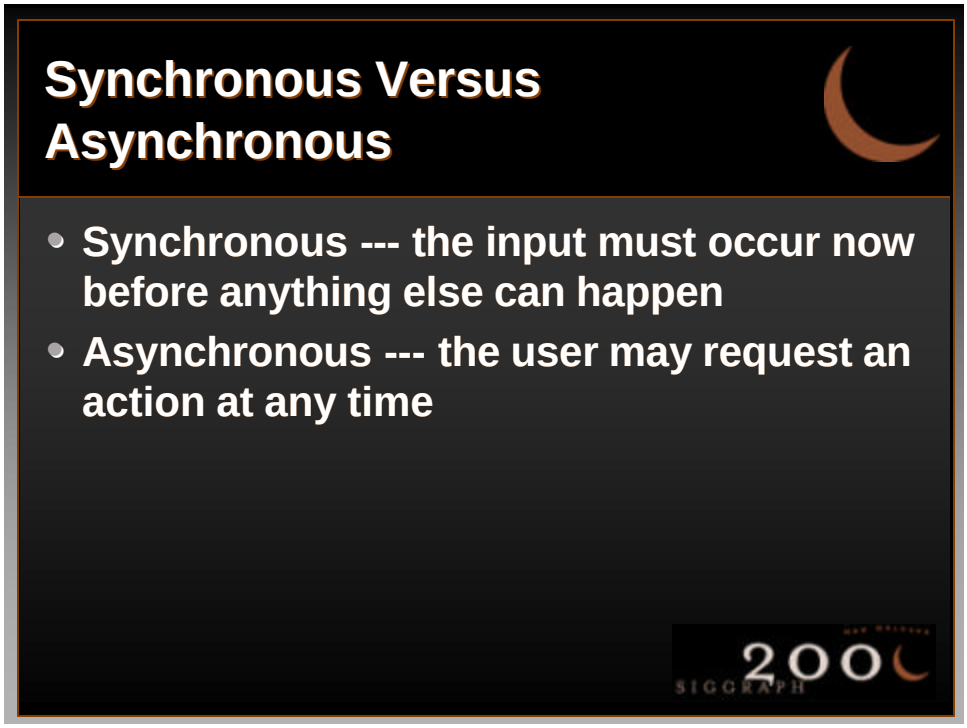
Synchronous Versus Asynchronous
Synchronous --- the input must occur now before anything else can happen
Asynchronous --- the user may request an action at any time
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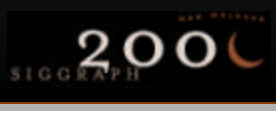
Events As Drivers

- Keyboard presses
- Position sensor motion
- Timers expiring
- Collision occurance

Model, View, Controller

- Model ~ Data
- View ~ An on-screen representation
- Controller ~ An method for changing aspects of the model through the view

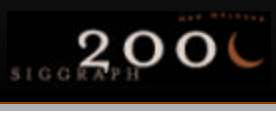


Coupling

- Tight coupling between Controller - View
- Controller has a representation within the View
- Manipulation closely tied to the controller

Input Device Interface

- An abstraction of an input device
  - A 6DOF value
  - Any number of multi-position buttons

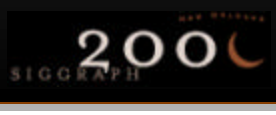


Query Mechanism

- Scene graph query mechanism
- Independent of device

Picking

- The pick process
  - PickShape defines the query
  - A “controller” behavior uses the query to search for an answer
- How do you define the PickShape?
  - The mouse
  - Gloved hands

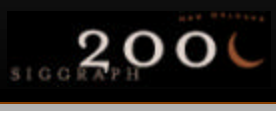


Collision detection

- **Generate an event when two geometries collide**
  - Behavior driven
  - Sensor driven

Output

- **There is more to output than graphics**
- **Sound!**



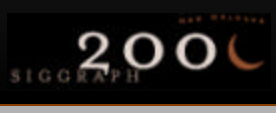
The Future of Scene Graph APIs

- Scene Graph Shadow Generation (Ghali)
- Multiprocessing and Extensibility (Blythe)
- The Future of Scene Graph APIs (Sowizral)

Scene Graph Shadow Generation

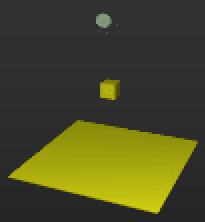
Sherif Ghali

Max Planck Institute



Active vs. Passive Light Sources

- **Passive light source:**
  - Shadow-responsibility lies on client



- **Active light source:**
  - Client is relieved from shadow generation

Responsibility for Shadows

Client	client code
	shadow generation
Scene Graph API	interface to low-level API

Client	client code
Scene Graph API	shadow generation
	interface to low-level API

Shadow Generation

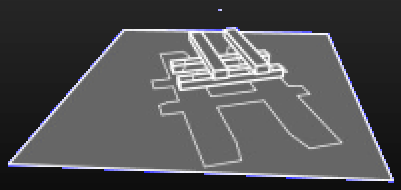
- Raster light sources
- Object-space light sources
- Fake shadows

Raster Light Sources

- First pass: raster shadow map computation
- Moving objects, camera, light source
- Handling curved objects
- Shadow aliasing

Object-Space Light Sources - Geometry Modification

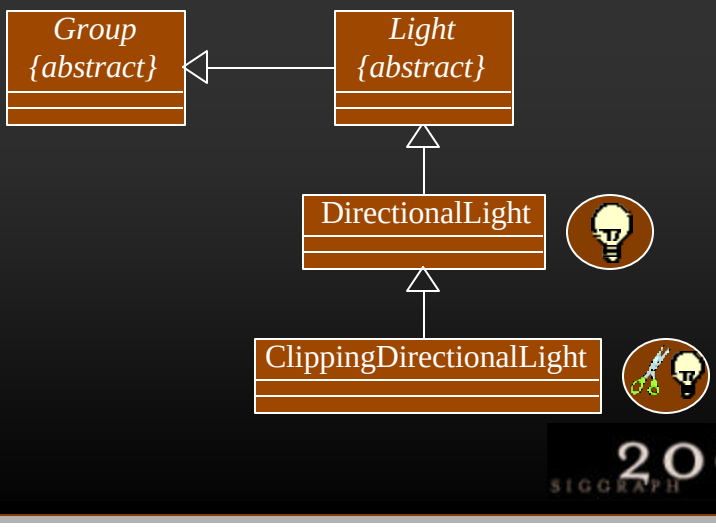
- Object-space visibility
- One pass to update geometry
- Moving objects or light difficult to handle
- True shadow boundaries



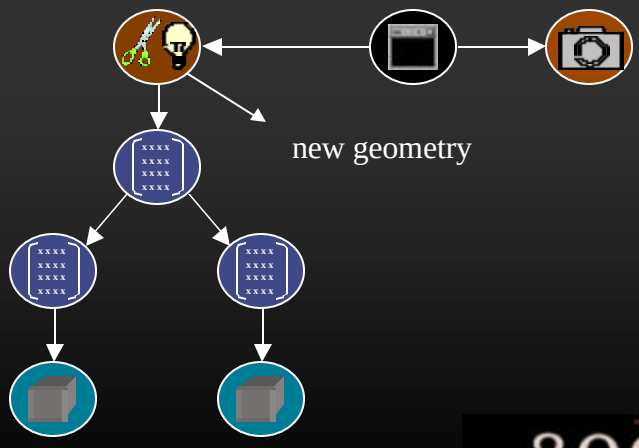
Fake Shadows

- No extra visibility pass
- Geometry is duplicated
- Usually single ground plane

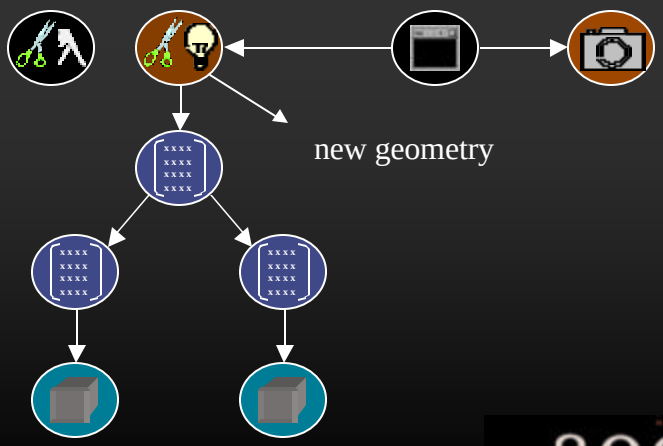
Clipping Active-Light Classes



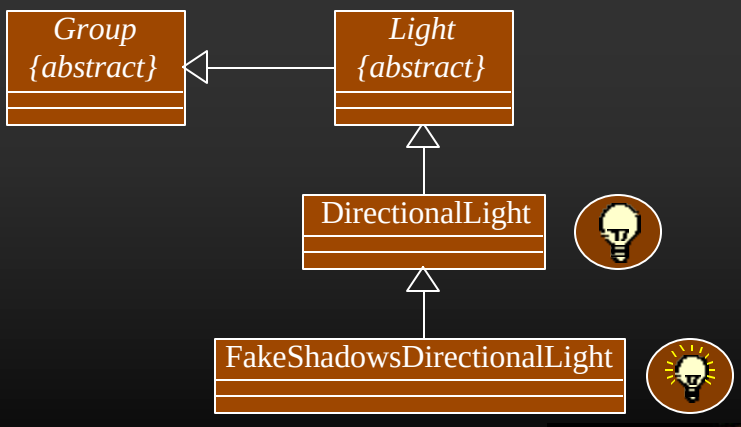
Clipping Light Sources

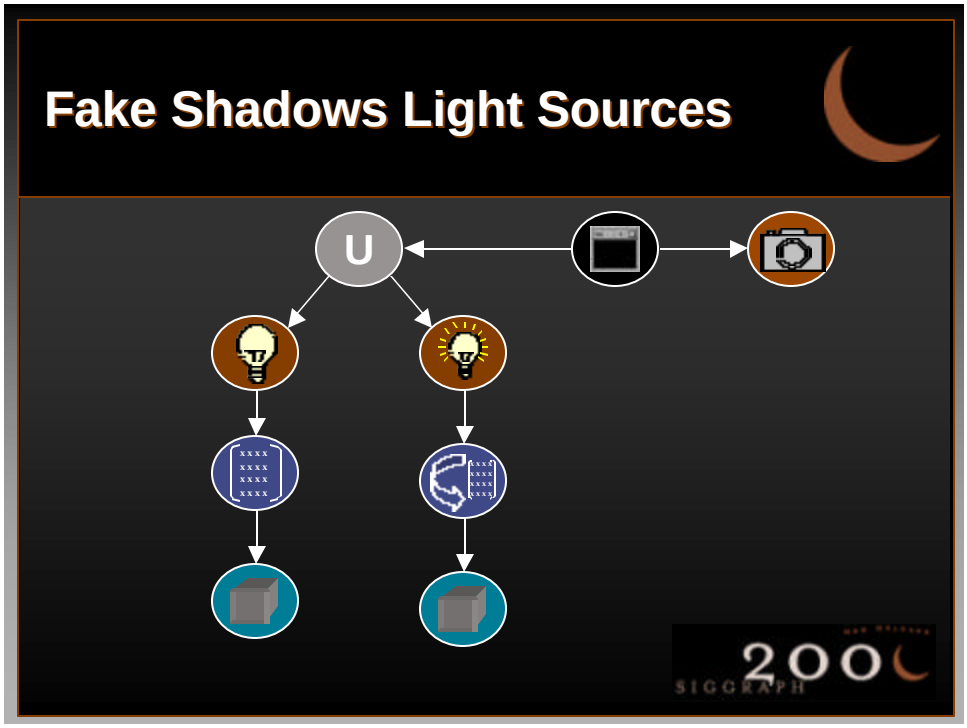


Compiling New Geometry



Fake Shadows Active-Light Classes




Fake Shadows Light Sources
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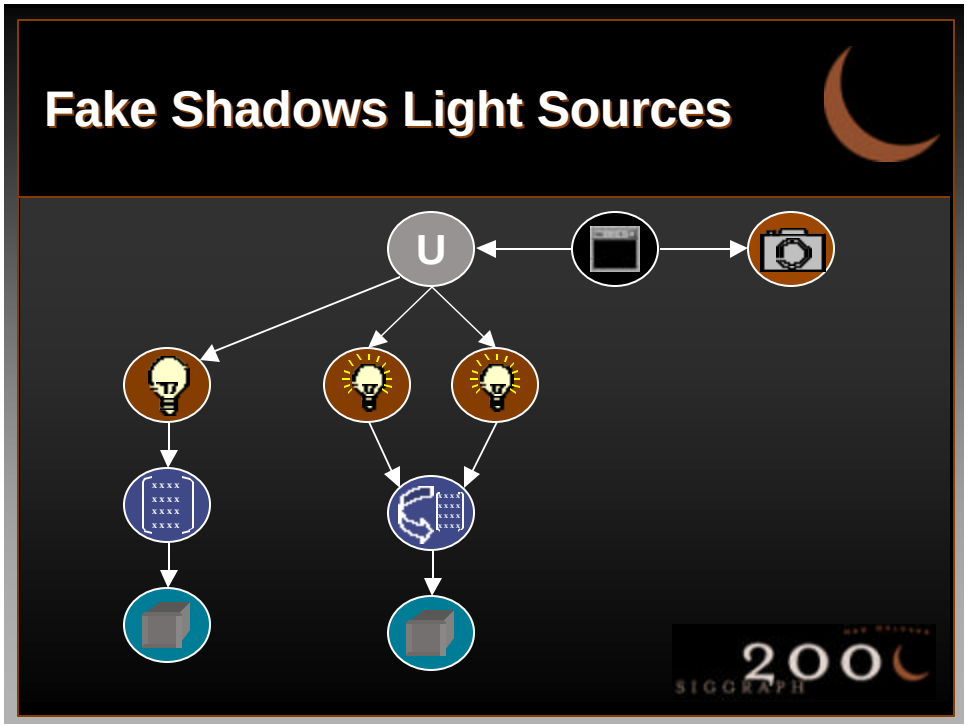
Fake Shadows Light Sources
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Multi-processing and Extensibility

David Blythe
RouteFree

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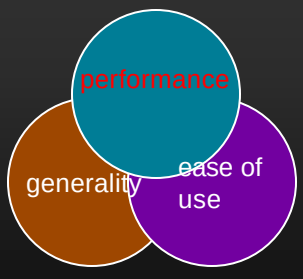
Multi-processing/Multi-threading

- What is your objective?



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Multi-processing/Multi-threading

- **Motivation**
  - Improve performance
    - increase scene complexity
    - decrease frame time
  - Utilize other processors in multi-processor configurations
    - 2-way systems becoming common

Multi-processing/Multi-threading

- **Processing Tasks**
  - Event processing
  - Behavior processing
  - LOD resolution
  - Collision detection
  - View-frustum culling
  - Sort to minimize state changes
  - Render audio
  - Render to display surfaces
  - Occlusion culling

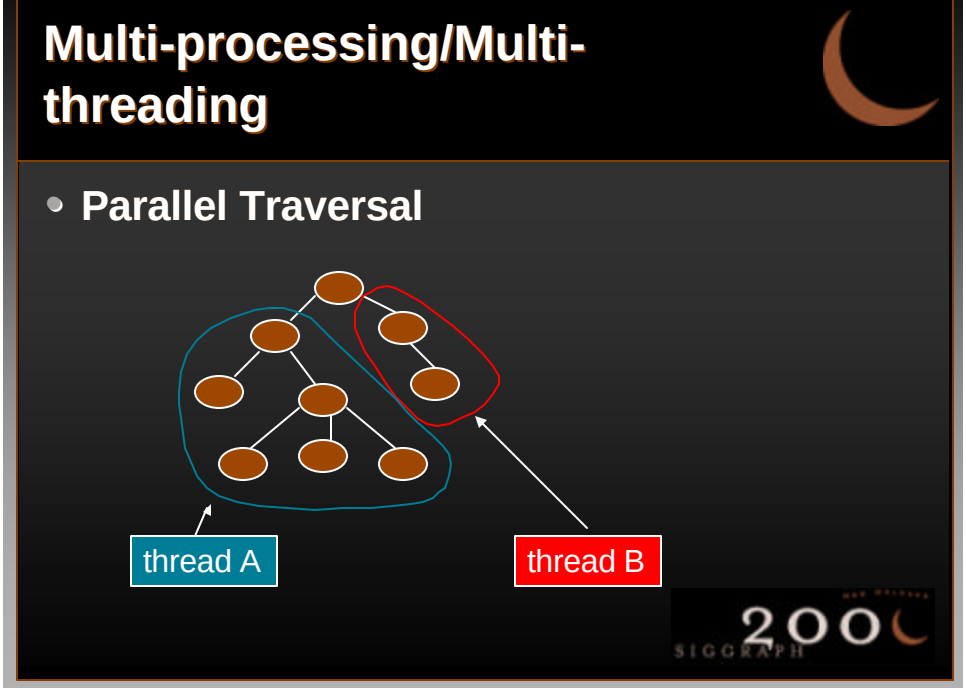
Multi-processing/Multi-threading

- **Approaches**
  - Parallel Traversal
    - Process parts of scene in parallel
    - VisKit
  - Pipelined Traversal
    - Perform different tasks on whole scene using thread per task
    - Performer, Fahrenheit/XSG, Java3D
  - Leave up to application :(

Multi-processing/Multi-threading

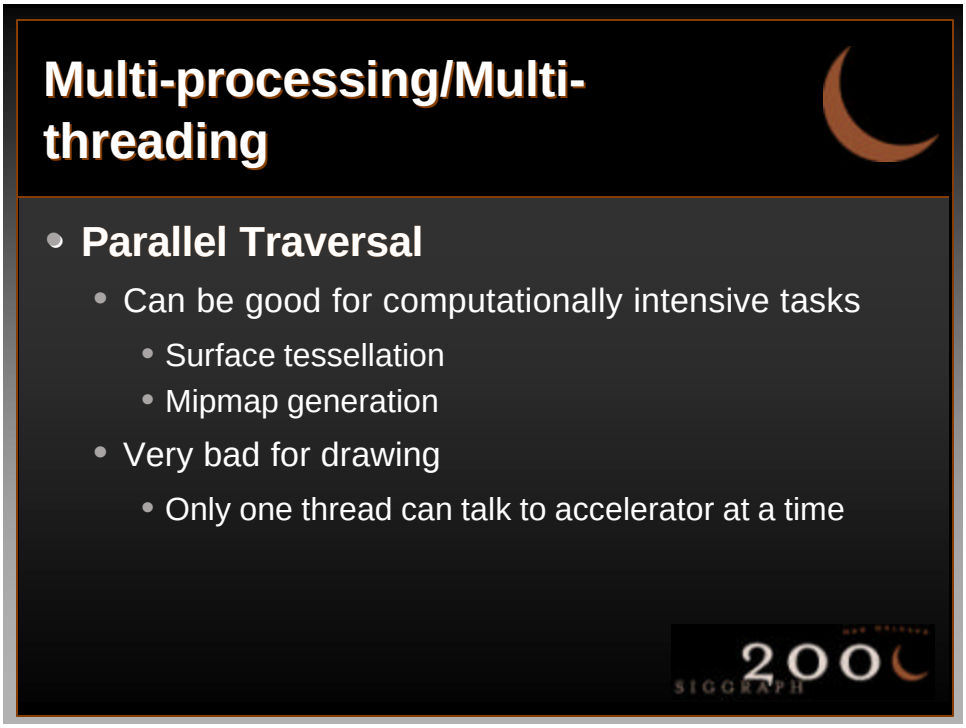
- **Parallel Traversal**
  - Perform multiple tasks at each node during traversal
  - Break scene up into chunks and assign to threads
  - Load balancing complicated
    - Early culling makes it difficult to predict load
  - May involve locking if not careful
    - Locking == bottlenecks

Multi-processing/Multi-threading



- **Parallel Traversal**

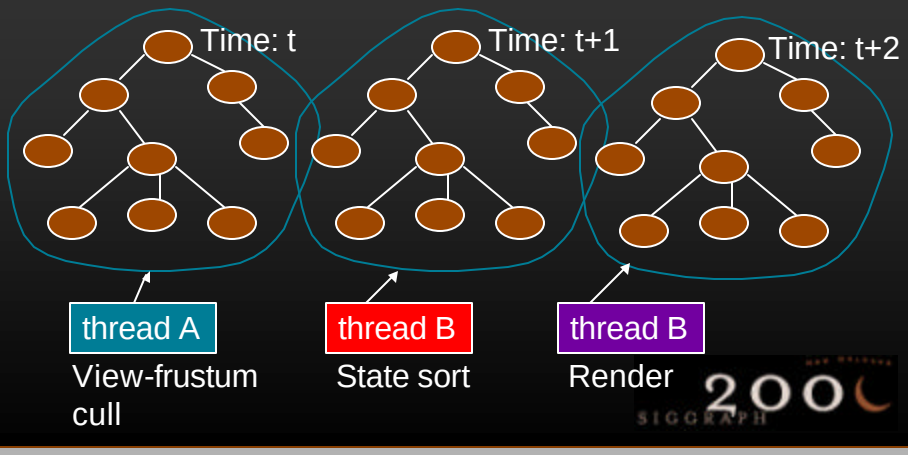
Multi-processing/Multi-threading



- **Parallel Traversal**
  - Can be good for computationally intensive tasks
    - Surface tessellation
    - Mipmap generation
  - Very bad for drawing
    - Only one thread can talk to accelerator at a time

Multi-processing/Multi-threading

- **Pipelined Traversal**



Multi-processing/Multi-threading

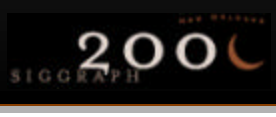
- **Pipelined Traversal**
  - Use a thread per task
  - Problem if threads write to nodes
    - Locking == bottlenecks
    - Use multiple logical copies of data
    - Phased-pipeline to allows overlapped processing
    - Application computation
    - Cull/LOD Resolution
    - Render

Multi-processing/Multi-threading

- **Pipelined Traversal**
  - Allow multiple read-only tasks to occur in parallel
  - True read-only tasks may be hard to identify

Multi-processing/Multi-threading

- **Multi-buffering**
  - Provide illusion of a copy of node data(buffer) for each thread
  - Use copy-on-write for efficiency
    - Node starts off with a single copy
    - Create a copy per thread on first write
    - Don’t consolidate copies
  - Use special processing to synchronize state of buffers



Multi-processing/Multi-threading

- **Update Processing**
  - Synchronize an *upstream* buffer with a *downstream* one
  - Log all changes to a buffer
    - Don’t need to copy data, just a reference to data
  - Play log against downstream buffer
    - Update downstream buffer using references to upstream buffer

Multi-processing/Multi-threading

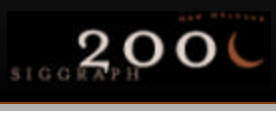
- **Serendipity**
  - Log can be used for other things
  - Integrate with event processing to implement
    - Sensors/Auditors
  - Transmit log over network to synchronize distributed databases
    - Need actual data, not just reference

Multi-processing/Multi-threading

- **Shared Address Space or Not**
  - Older APIs assume fork model
    - Use shared arenas to hold scene data
    - Process-private state easy
  - New APIs use multi-threading with shared address space
    - Pthreads, Java threads
    - Entire address space shared
    - Thread-private state challenging

Multi-processing/Multi-threading

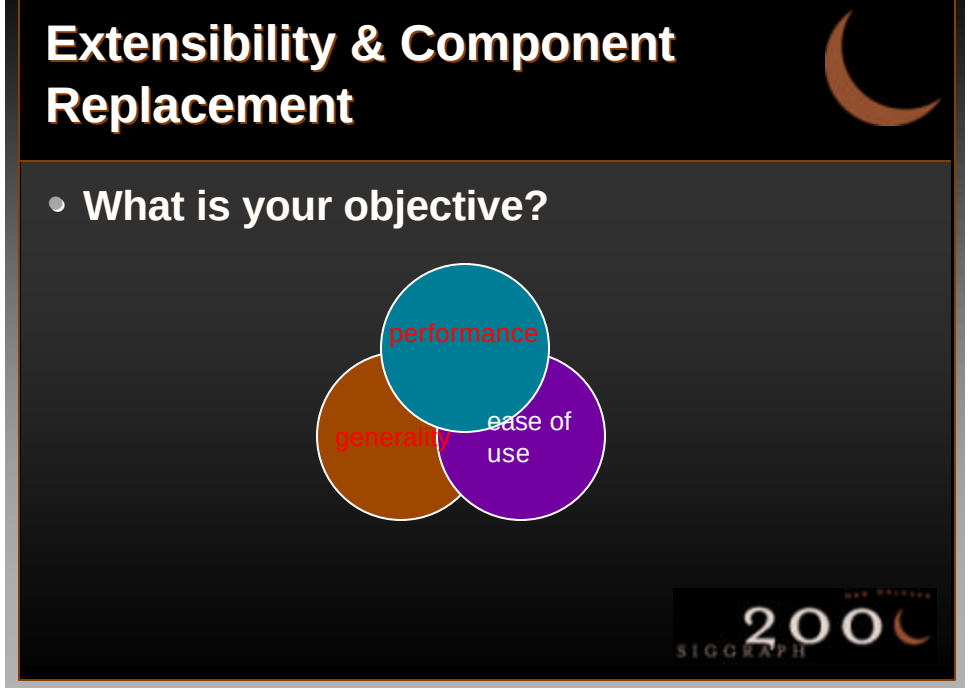
- **Shared Address Space or Not**
  - Need per-thread state for
    - Multi-buffering
    - Error processing



Multi-processing/Multi-threading

- **Hybrids**
  - Pipeline + Parallel Traversal
    - Within one pipe-line stage perform parallel traversal
    - Good for computationally intensive tasks
      - Load balancing simpler

Extensibility & Component Replacement



- What is your objective?

Extensibility & Component Replacement

- **Motivation**
  - Designers can't foresee all necessary functionality
  - Add new types of traversal tasks
    - Collision detection
    - Occlusion culling
  - Add new scene abstractions
    - Advanced shading
    - Surfaces
    - Progressive meshes

Extensibility & Component Replacement

- **Motivation**
  - May want to customize a component
    - Add additional data to a node
    - Perform additional processing during a traversal

Extensibility & Component Replacement

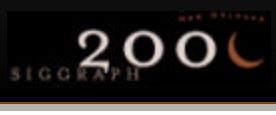
- **Cheesy^{tm} Extensibility**
  - Add “user-data” pointers to nodes
    - Store additional application-specific data at node
  - Add traversal callbacks to nodes
    - Perform application-specific processing at each node visit
  - Hard to share with other developers
  - Extensions embedded in the application

Extensibility & Component Replacement

- **Open Source It!**
  - Customize to your hearts content
  - Can change anything
  - Very difficult to share
    - Multiple incompatible customizations
  - Very difficult to maintain correctness
    - May make random changes to semantics

Extensibility & Component Replacement

- **Binary Compatibility**
  - Extensibility + Compatibility challenging
  - Extra hard with C++
    - private mixed with public
    - use discipline - or -
    - solvable using methodology like COM
  - Easier in Java
  - Still need to watch out for semantic changes



Extensibility & Component Replacement

- **Fahrenheit Approach**
  - Kernel facilities with extensibility model
    - Multi-buffering, error handling, node, traversal
  - All built-ins above kernel use extension services
    - Everything is an extension
  - Uses COM-hybrid for binary compatibility
    - Break some rules to improve performance
    - Extenders deal with

Extensibility & Component Replacement

- **Fahrenheit Approach**
  - Everything a component
    - Interface and implementation kept separate
    - Packaged in dynamic libraries
    - Advertised in a database
  - Components loaded on demand
  - Components **must** obey rules

Extensibility & Component Replacement

- **Fahrenheit Approach**
  - Add new nodes, traversals, other components
  - Replace implementations of components with alternatives
    - e.g., different culling algorithms
    - different tessellation algorithms
  - Create different pipelines
  - Easy to share components with other developers

Extensibility & Component Replacement

- **Hard Problems**
  - Fragile base classes
    - Resist temptation to customize base classes
      - Re-implement all subclasses
    - Left with user-data, RFields
  - Performance cost for encapsulation
    - Virtual function calls
    - No inlines

Extensibility & Component Replacement

- **Hard Problems**
  - Large semantic changes require large amounts of re-implementation
    - Change organization from spatial to something else
    - Change from depth-first traversal to priority order
  - Component replacement can compromise security
    - Digital signatures on core components, etc

Scene Graph API Futures

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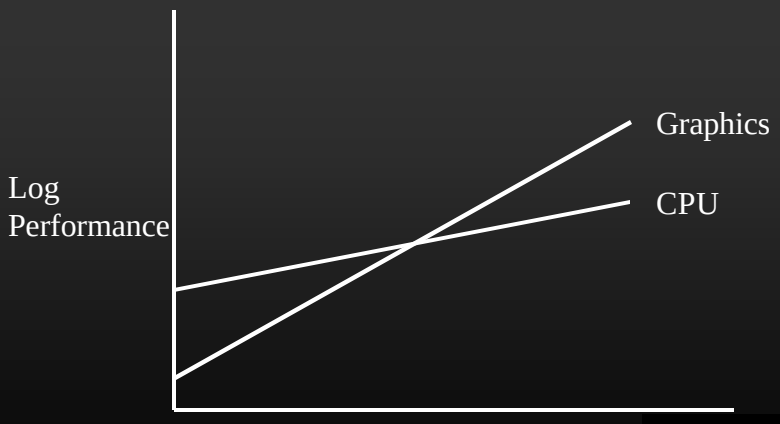
Graphics Outpacing CPU



The Hardware Gaps

- CPU versus graphics
- Bus versus graphics
- Memory versus graphics

Historic Trends

- Back to the Past
- Display lists
  - Vector displays
  - Raster displays
- Equilibrium

The Software Gap

- Hardware evolving faster than software
- Time-to-market dominates

3D Software Development

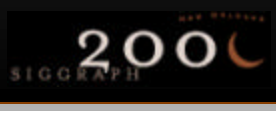
- **Newer graphics hardware brings features and complexity**
  - Most developers ignore HW-specific features
  - Over 95% of SGI Performer apps are built with Perfly, the included demo app
- **Developers struggling with:**
  - Texture mapping, anti-aliasing, multi-pass textures, fog, bump mapping, . . .
  - They will face parallelism, texture streaming, asynchronous culling, morphing, multi-channel, multi-pipeline configurations, . . .
- **Rising development complexity**
  - ~8 years ago: Castle Wolfenstein, 6 months to develop, $100K, no tools
  - ~4 years ago: Doom, 12 months, $300-$500K, OpenGL
  - ~2 years ago: Quake, 18 months, > $1M, OpenGL, Glide
  - In ~2 years: 24-36 months development time, > $10M, scene graph APIs
- **Hardware development cycles are accelerating!**

All Future Graphics Programs Will Use Scene Graphs

- This is true today: but mainly custom
- Time-to-market dominates
- Scene graphs:
  - specialized versus generic

Problems With Generalized Scene Graph

- Memory usage
- Speed of hardware evolution



Missing Features

- Support for modeling
- Complex illuminations
- Complex material interactions

Issue: Composition of Worlds

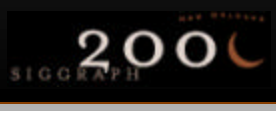
- Locality of structure and reference
- Encapsulation

Stability and Lifecycle of a Graphics API

- Functionality
- Extensibility

Functionality

- Keeping pace with hardware
- Hardware trends
  - Speed: 100Mtris/sec
  - Surfacing
  - Multi-textures nee programmable shaders



Extensibility

- **Traversal with pre-, in-, and post-order visit**
  - Integration and use of low level API
  - Low-level API specific
- **Registration**

What To Do?

- **Plan for a variety of**
  - Display environments
  - Interaction modalities
- **Plan for multiple**
  - Processors
  - Platforms
- **Plan for change**