

Shapes

Digital Image Synthesis

Yung-Yu Chuang

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with slides by Pat Hanrahan

Shapes



- One advantages of ray tracing is it can support various kinds of shapes as long as we can find ray-shape intersection.
- Careful abstraction of geometric shapes is a key component for a ray tracer. Ideal candidate for object-oriented design. Scan conversion may not have such a neat interface.
- All shape classes implement the same interface and the other parts of the ray tracer just use this interface without knowing the details about this shape.

Shapes



- **Primitive=Shape+Material**
- **Shape**: raw geometry properties of the primitive, implements interface such as surface area and bounding box.
- Source code in `core/shape.*` and `shapes/*`

Shapes



- pbrt provides the following shape plug-ins:
 - quadrics: sphere, cone, cylinder, disk, hyperboloid (雙曲面), paraboloid(拋物面) (surface described by quadratic polynomials in x, y, z)
 - triangle mesh
 - height field
 - NURBS
 - Loop subdivision surface
- Some possible extensions: other subdivision schemes, fractals, CSG, point-sampled geometry

Shapes



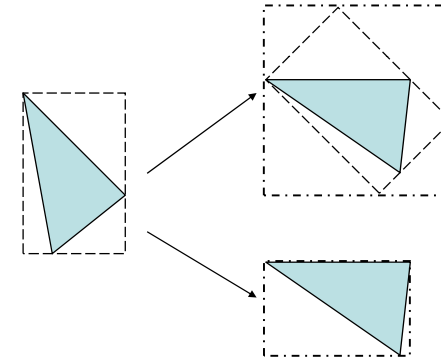
- All shapes are defined in object coordinate space

```
class Shape : public ReferenceCounted {
public:
    <Shape Interface> all are virtual functions
    const Transform ObjectToWorld, WorldToObject;
    const bool reverseOrientation,
              transformSwapsHandedness;
}
```

Shape interface: bounding



- BBox ObjectBound() *const=0; pure virtual function*
- BBox WorldBound() { *left to individual shape default implementation; can be overridden*
return ObjectToWorld(ObjectBound());
}



Shape interface: intersecting



- bool CanIntersect() *returns whether this shape can do intersection test; if not, the shape must provide*
void Refine(vector<Reference<Shape>>&refined)
examples include complex surfaces (which need to be tessellated first) or placeholders (which store geometry information in the disk)

- bool Intersect(const Ray &ray, float *tHit, **DifferentialGeometry** *dg)

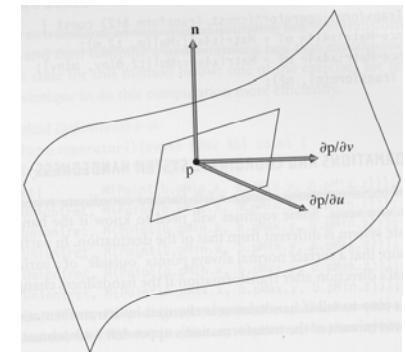
- bool IntersectP(const Ray &ray)
not pure virtual functions so that non-intersectable shapes don't need to implement them; instead, a default implementation which prints error is provided.

in world space

Differential geometry



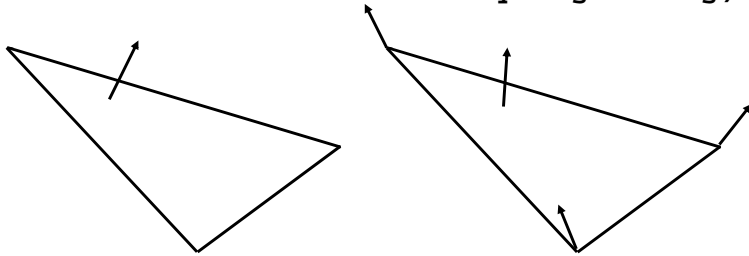
- **DifferentialGeometry**: a self-contained representation for a particular point on a surface so that all the other operations in pbrt can be executed without referring to the original shape. It contains
- Position
- Parameterization (u,v)
- Parametric derivatives (dp/du, dp/dv)
- Surface normal (derived from (dp/du)x(dp/dv))
- Derivatives of normals
- Pointer to shape



Shape interface



- float Area() *useful when using as an area light*
- void GetShadingGeometry(*for object instancing*
 const Transform &obj2world,
 const DifferentialGeometry &dg,
 DifferentialGeometry *dgShading)



- No back culling for that it doesn't save much for ray tracing and it is not physically correct

Surfaces



- Implicit: $F(x,y,z)=0$
 you can check
- Explicit: $(x(u,v),y(u,v),z(u,v))$
 you can enumerate
also called parametric

- Quadrics

$$\begin{bmatrix} x & y & z & 1 \end{bmatrix} \begin{bmatrix} A & B & C & D \\ B & E & F & G \\ C & F & H & I \\ D & G & I & J \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} = 0$$

Sphere



- A sphere of radius r at the origin
- Implicit: $x^2+y^2+z^2-r^2=0$
- Parametric: $f(\theta, \phi)$

$$x=r\sin\theta\cos\phi$$

$$y=r\sin\theta\sin\phi$$

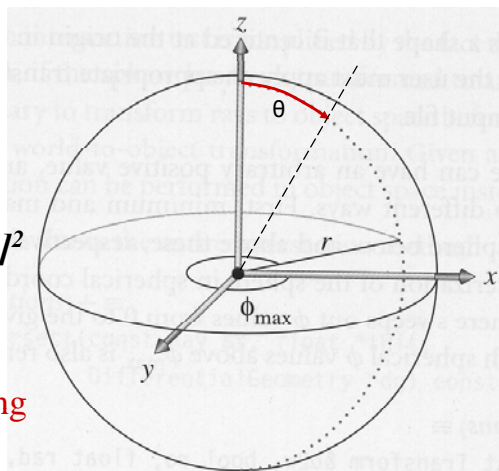
$$z=r\cos\theta$$

mapping $f(u,v)$ over $[0,1]^2$

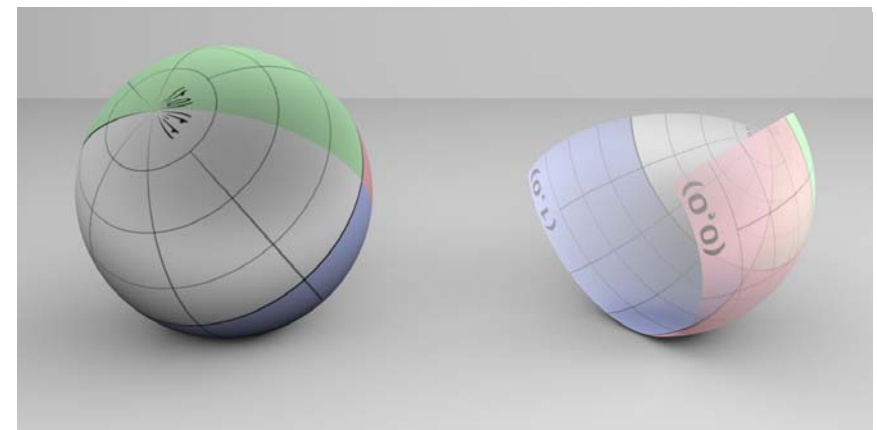
$$\phi = u\phi_{\max}$$

$$\theta = \theta_{\min} + v(\theta_{\max} - \theta_{\min})$$

useful for texture mapping



Sphere



Sphere (construction)



```
class Sphere: public Shape {
.....
private:
    float radius;
    float phiMax;
    float zmin, zmax;    thetas are derived from z
    float thetaMin, thetaMax;
}
Sphere(const Transform &o2w, bool ro,
        float rad, float zmin, float zmax,
        float phiMax);
```

- Bounding box for sphere, only z clipping

Intersection (algebraic solution)



- Perform in object space, `worldToObject(r, &ray)`
- Assume that ray is normalized for a while

$$x^2 + y^2 + z^2 = r^2$$

$$(o_x + td_x)^2 + (o_y + td_y)^2 + (o_z + td_z)^2 = r^2$$

$$At^2 + Bt + C = 0$$

Step 1

$$A = d_x^2 + d_y^2 + d_z^2$$

$$B = 2(d_x o_x + d_y o_y + d_z o_z)$$

$$C = o_x^2 + o_y^2 + o_z^2 - r^2$$

Algebraic solution



$$t_0 = \frac{-B - \sqrt{B^2 - 4AC}}{2A} \quad t_1 = \frac{-B + \sqrt{B^2 - 4AC}}{2A}$$

Step 2

If $(B^2 - 4AC < 0)$ then the ray misses the sphere

Step 3

Calculate t_0 and test if $t_0 < 0$ (actually `mint`, `maxt`)

Step 4

Calculate t_1 and test if $t_1 < 0$

check the real source code in sphere.cpp

Quadric (in pbrt.h)



```
inline bool Quadratic(float A, float B, float C,
                     float *t0, float *t1) {
    // Find quadratic discriminant
    float discrim = B * B - 4.f * A * C;
    if (discrim < 0.) return false;
    float rootDiscrim = sqrtf(discrim);
    // Compute quadratic _t_ values
    float q;
    if (B < 0) q = -.5f * (B - rootDiscrim);
    else      q = -.5f * (B + rootDiscrim);
    *t0 = q / A;
    *t1 = C / q;
    if (*t0 > *t1) swap(*t0, *t1);
    return true;
}
```

Why?



- Cancellation error: devastating loss of precision when small numbers are computed from large numbers by addition or subtraction.

```
double x1 = 10.000000000000004;  
double x2 = 10.000000000000000;  
double y1 = 10.000000000000004;  
double y2 = 10.000000000000000;  
double z = (y1 - y2) / (x1 - x2); // 11.5
```

$$t_0 = \frac{q}{A} \quad q = \begin{cases} -\frac{1}{2}(B - \sqrt{B^2 - 4AC}) & \text{if } B < 0 \\ -\frac{1}{2}(B + \sqrt{B^2 - 4AC}) & \text{otherwise} \end{cases}$$
$$t_1 = \frac{C}{q}$$

Range checking

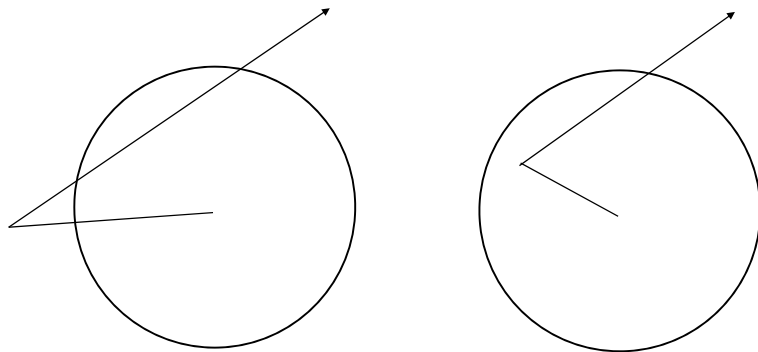


```
if (t0 > ray.maxt || t1 < ray.mint) return false;  
float thit = t0;  
if (t0 < ray.mint) {  
    thit = t1;  
    if (thit > ray.maxt) return false;  
}  
...  
phit = ray(thit);  
phi = atan2f(phit.y, phit.x);  
if (phi < 0.) phi += 2.f*M_PI;  
// Test sphere intersection against clipping  
parameters  
if (phit.z < zmin || phit.z > zmax || phi > phiMax)  
{  
    ... // see if we should check another hit point  
}
```

Geometric solution



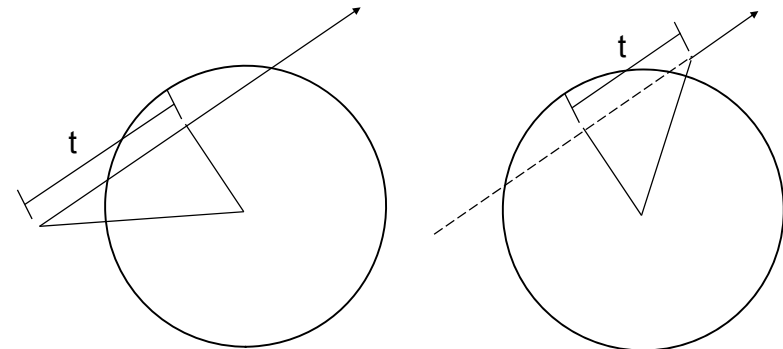
1. Origin inside? $o_x^2 + o_y^2 + o_z^2 > r^2$



Geometric solution



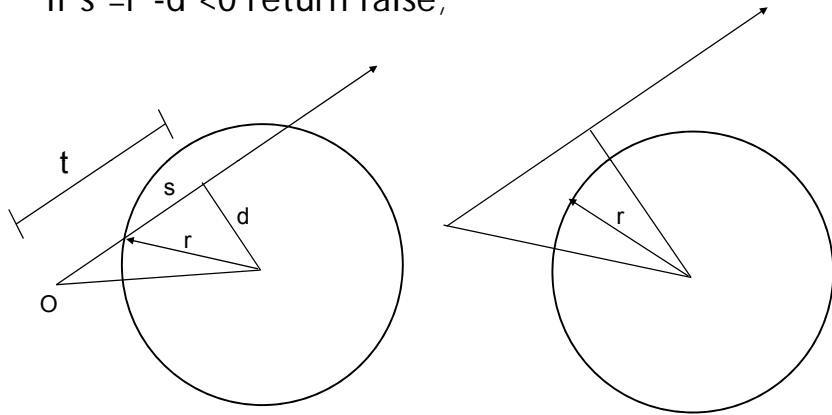
2. find the closest point, $t = -O \cdot D$ **D is normalized**
if $t < 0$ and O outside return false



Geometric solution



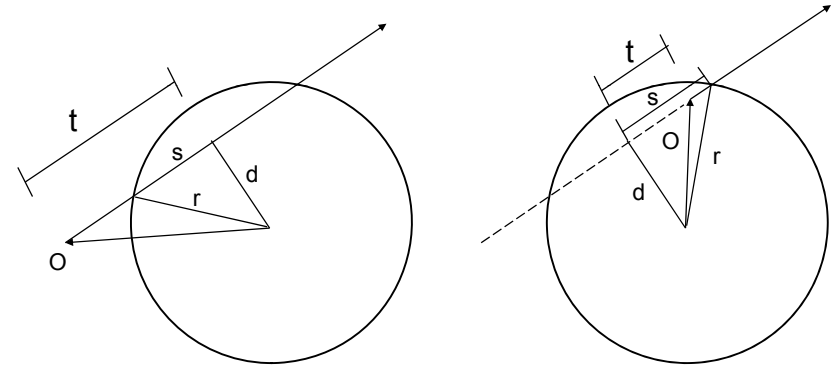
3. find the distance to the origin, $d^2 = O^2 - t^2$
if $s^2 = r^2 - d^2 < 0$ return false;



Geometric solution



4. calculate intersection distance, if (origin outside) then t-s else t+s



Sphere



- Have to test sphere intersection against clipping parameters
- Fill in information for **DifferentialGeometry**
 - Position
 - Parameterization (u,v)
 - Parametric derivatives
 - Surface normal
 - Derivatives of normals
 - Pointer to shape

Partial sphere



$$u = \phi / \phi_{max}$$

$$v = (\theta - \theta_{min}) / (\theta_{max} - \theta_{min})$$

- Partial derivatives (pp103 of textbook)

$$\frac{\partial p}{\partial u} = (-\phi_{max} y, \phi_{max} x, 0)$$

$$\frac{\partial p}{\partial v} = (\theta_{max} - \theta_{min})(z \cos \phi, z \sin \phi, -r \sin \theta)$$

- Area (pp107)

$$A = \phi_{max} r (z_{max} - z_{min})$$

Cylinder

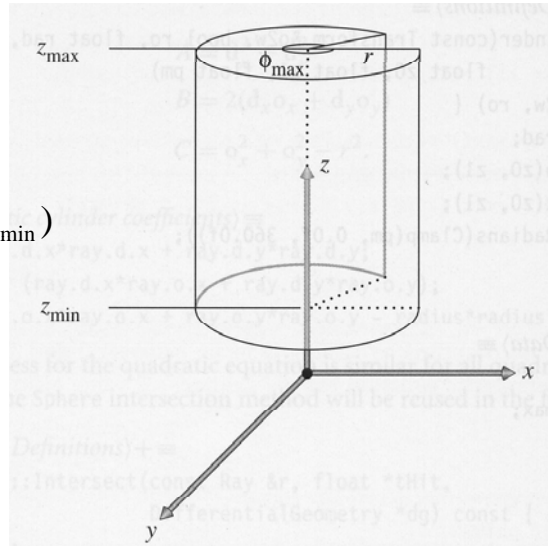


$$\phi = u\phi_{\max}$$

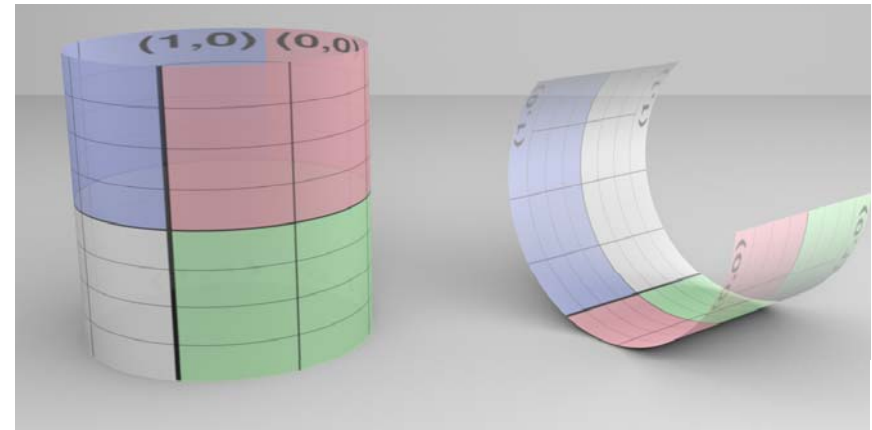
$$x = r \cos \phi$$

$$y = r \sin \phi$$

$$z = z_{\min} + v(z_{\max} - z_{\min})$$



Cylinder



Cylinder (intersection)



$$x^2 + y^2 = r^2$$

$$(o_x + td_x)^2 + (o_y + td_y)^2 = r^2$$

$$At^2 + Bt + C = 0$$

$$A = d_x^2 + d_y^2$$

$$B = 2(d_x o_x + d_y o_y)$$

$$C = o_x^2 + o_y^2 - r^2$$

Disk

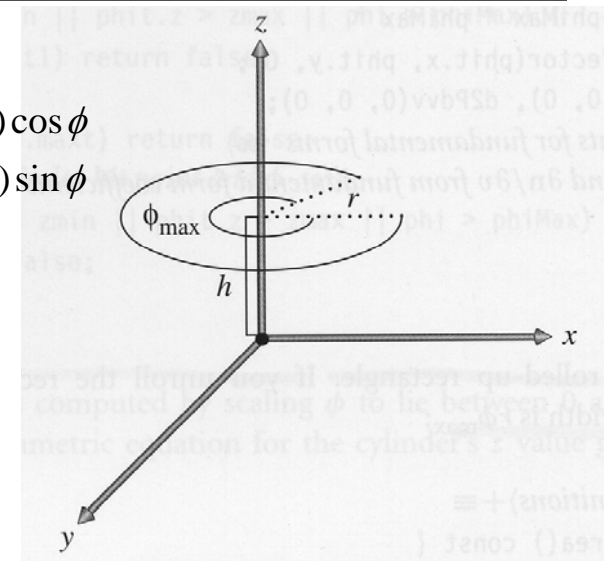


$$\phi = u\phi_{\max}$$

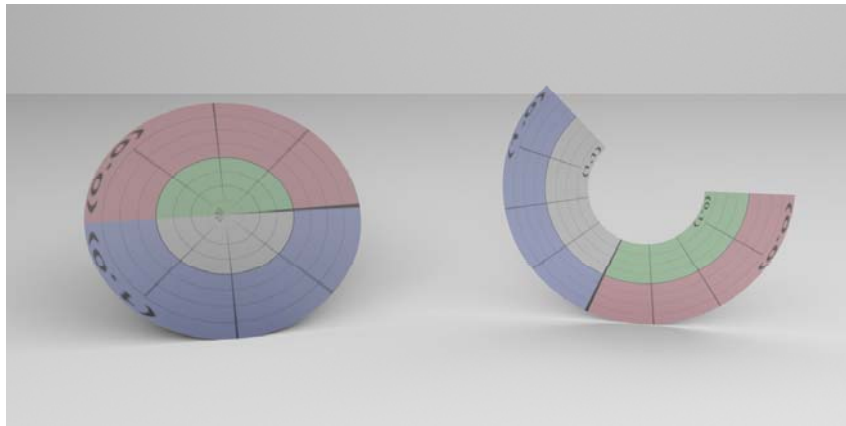
$$x = ((1-v)r_i + vr) \cos \phi$$

$$y = ((1-v)r_i + vr) \sin \phi$$

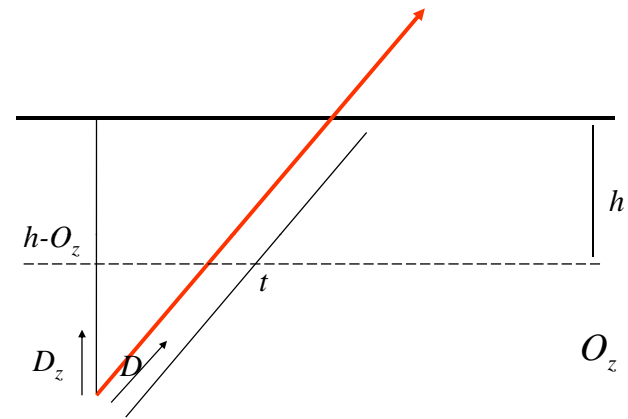
$$z = h$$



Disk



Disk (intersection)



$$O_z + tD_z = h$$

$$t = \frac{h - O_z}{D_z}$$

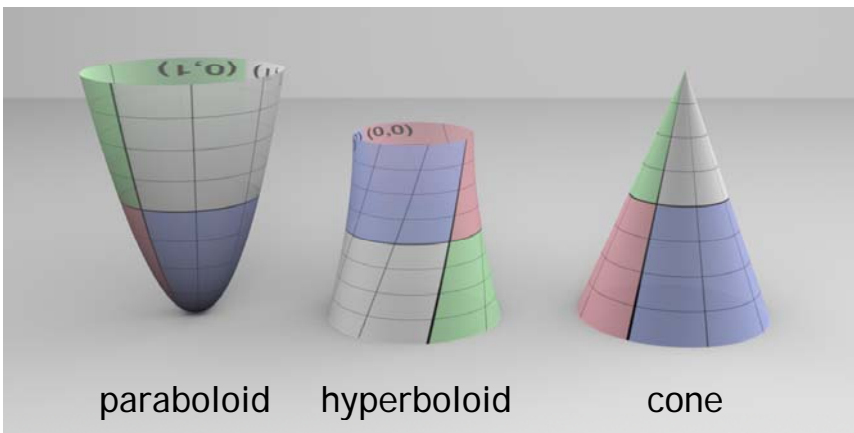
Other quadrics



$$\frac{hx^2}{r^2} + \frac{hy^2}{r^2} - z = 0$$

$$x^2 + y^2 - z^2 = -1$$

$$\left(\frac{hx}{r}\right)^2 + \left(\frac{hy}{r}\right)^2 - (z-h)^2 = 0$$



Triangle mesh



The most commonly used shape. In pbrt, it can be supplied by users or tessellated from other shapes.

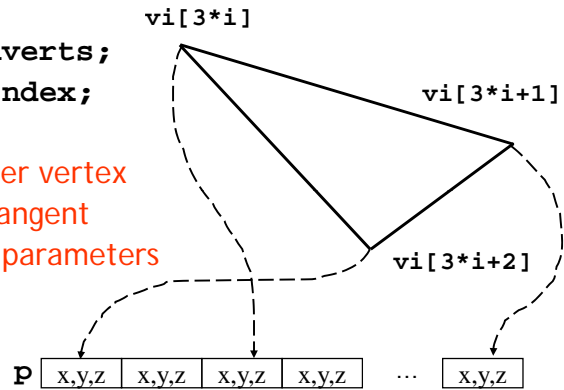
Some ray tracers only support triangle meshes.



Triangle mesh



```
class TriangleMesh : public Shape {
...
    int ntris, nverts;
    int *vertexIndex;
    Point *p;
    Normal *n; per vertex
    Vector *s; tangent
    float *uvs; parameters
}
```



Note that p is stored in world space to save transformations. n and s are in object space.

Triangle mesh



Pbrt calls Refine() when it encounters a shape that is not intersectable. (usually, refine is called in acceleration structure creation)

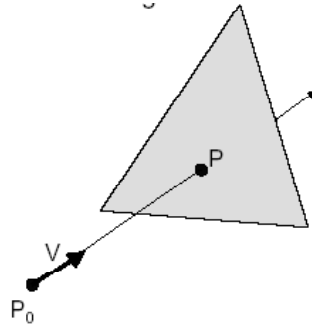
```
Void TriangleMesh::Refine(vector<Reference<Shape>>
                        &refined)
{
    for (int i = 0; i < ntris; ++i)
        refined.push_back(new Triangle(ObjectToWorld,
        reverseOrientation, (TriangleMesh *)this, i));
}
```

Refine breaks a triangle mesh into a list of **Triangles**.
Triangle only stores a pointer to mesh and an index.

Ray triangle intersection



1. Intersect ray with plane
2. Check if point is inside triangle



Ray plane intersection



$$\text{Ray: } P = P_0 + tV$$

$$\text{Plane: } P \cdot N + d = 0$$

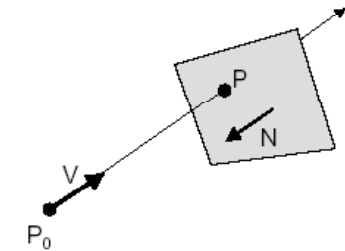
Algebraic Method

Substituting for P , we get:

$$(P_0 + tV) \cdot N + d = 0$$

Solution:

$$t = \frac{-(P_0 \cdot N + d)}{(V \cdot N)}$$



$$P = P_0 + tV$$

Ray triangle intersection I



Algebraic Method

For each side of triangle:

$$V_1 = T_1 - P_0$$

$$V_2 = T_2 - P_0$$

$$N_1 = V_1 \times V_2$$

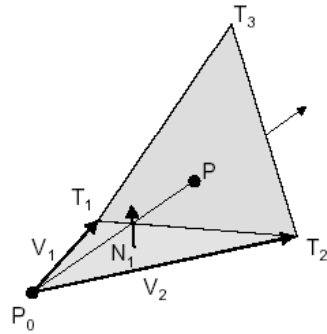
Normalize N_1

$$d_1 = -P_0 \cdot N_1$$

$$\text{if } ((P \cdot N_1 + d_1) < 0)$$

return FALSE

end



Ray triangle intersection II



Parametric Method

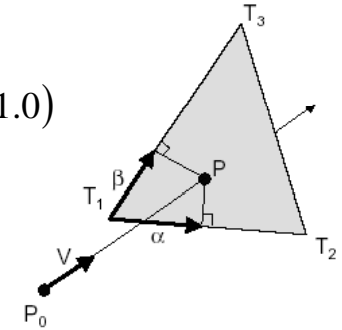
Compute α, β :

$$P = \alpha(T_2 - T_1) + \beta(T_3 - T_1)$$

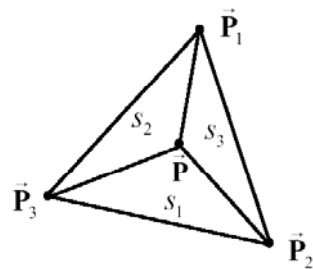
if $(0.0 \leq \alpha \leq 1.0)$ and $(0.0 \leq \beta \leq 1.0)$

and $(\alpha + \beta \leq 1.0)$

then P is inside triangle



Ray triangle intersection III



$$s_1 = \text{area}(\Delta PP_2P_3)$$

$$s_2 = \text{area}(\Delta PP_3P_1)$$

$$s_3 = \text{area}(\Delta PP_1P_2)$$

Barycentric coordinates

$$\vec{P} = s_1\vec{P}_1 + s_2\vec{P}_2 + s_3\vec{P}_3$$

Inside criteria

$$0 \leq s_1 \leq 1$$

$$0 \leq s_2 \leq 1$$

$$0 \leq s_3 \leq 1$$

$$s_1 + s_2 + s_3 = 1$$

Fast minimum storage intersection



*a point on
the ray*

*a point inside
the triangle*

$$O + tD = (1 - u - v)V_0 + uV_1 + vV_2$$

$$u, v \geq 0 \text{ and } u + v \leq 1$$

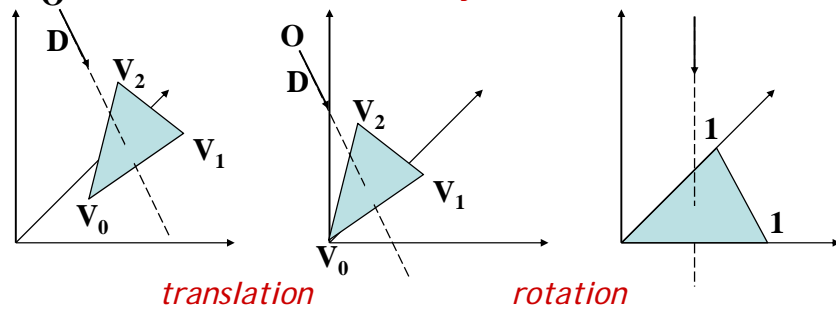
$$\begin{bmatrix} -D & V_1 - V_0 & V_2 - V_0 \end{bmatrix} \begin{bmatrix} t \\ u \\ v \end{bmatrix} = O - V_0$$

Fast minimum storage intersection



$$\begin{bmatrix} -D & V_1 - V_0 & V_2 - V_0 \end{bmatrix} \begin{bmatrix} t \\ u \\ v \end{bmatrix} = O - V_0$$

Geometric interpretation: what is O's coordinate under the new coordinate system?



Fast minimum storage intersection



$$\begin{bmatrix} -D & V_1 - V_0 & V_2 - V_0 \end{bmatrix} \begin{bmatrix} t \\ u \\ v \end{bmatrix} = O - V_0$$

$$E_1 = V_1 - V_0 \quad E_2 = V_2 - V_0 \quad T = O - V_0$$

$$\begin{bmatrix} -D & E_1 & E_2 \end{bmatrix} \begin{bmatrix} t \\ u \\ v \end{bmatrix} = T$$

Fast minimum storage intersection



- Cramer's rule

$$\begin{bmatrix} -D & E_1 & E_2 \end{bmatrix} \begin{bmatrix} t \\ u \\ v \end{bmatrix} = T$$

$$\begin{bmatrix} t \\ u \\ v \end{bmatrix} = \frac{1}{\begin{vmatrix} -D, E_1, E_2 \end{vmatrix}} \begin{bmatrix} |T, E_1, E_2| \\ |-D, T, E_2| \\ |-D, E_1, T| \end{bmatrix}$$

$$|A, B, C| = -(A \times C) \cdot B = -(C \times B) \cdot A$$

Fast minimum storage intersection



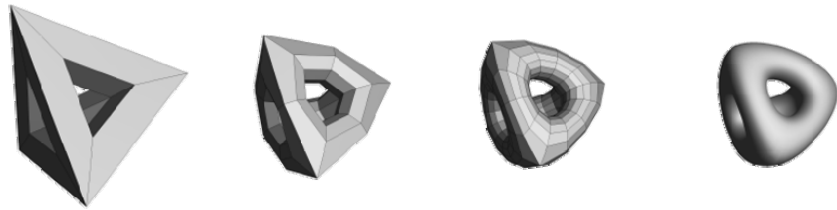
$$\begin{bmatrix} t \\ u \\ v \end{bmatrix} = \frac{1}{\begin{vmatrix} -D, E_1, E_2 \end{vmatrix}} \begin{bmatrix} |T, E_1, E_2| \\ |-D, T, E_2| \\ |-D, E_1, T| \end{bmatrix}$$

$$Q = T \times E_1 \quad P = D \times E_2$$

$$\begin{bmatrix} t \\ u \\ v \end{bmatrix} = \frac{1}{P \cdot E_1} \begin{bmatrix} Q \cdot E_2 \\ P \cdot T \\ Q \cdot D \end{bmatrix}$$

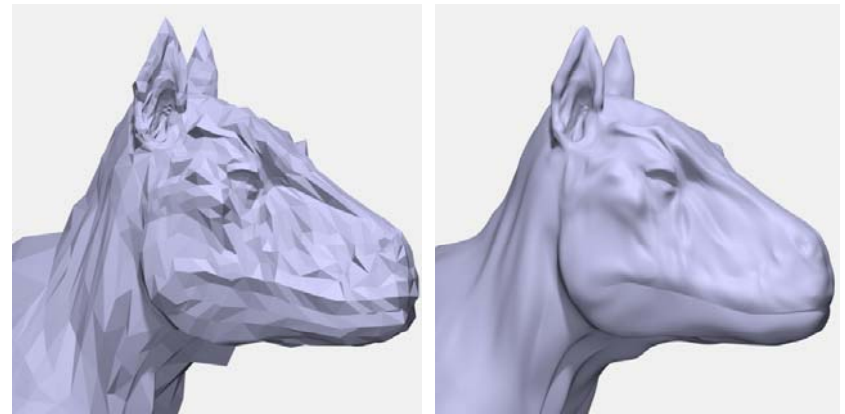
*1 division
27 multiplies
17 adds*

Subdivision surfaces

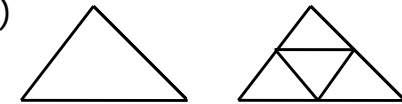


<http://www.subdivision.org/demos/demos.html>

Subdivision surfaces



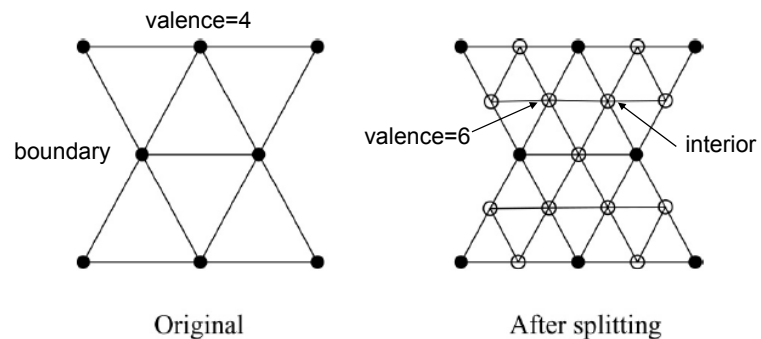
- Catmull-Clark (1978)



Loop Subdivision Scheme



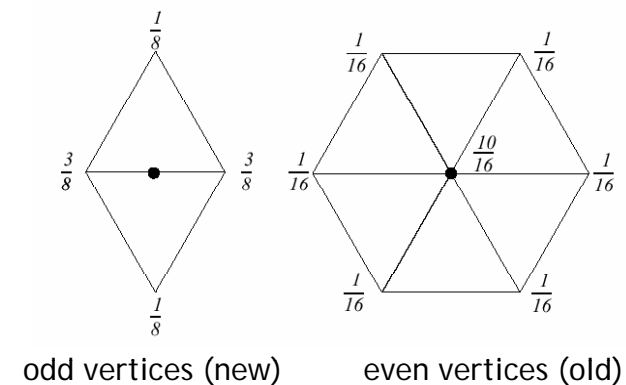
- Refine each triangle into 4 triangles by splitting each edge and connecting new vertices



Loop Subdivision Scheme



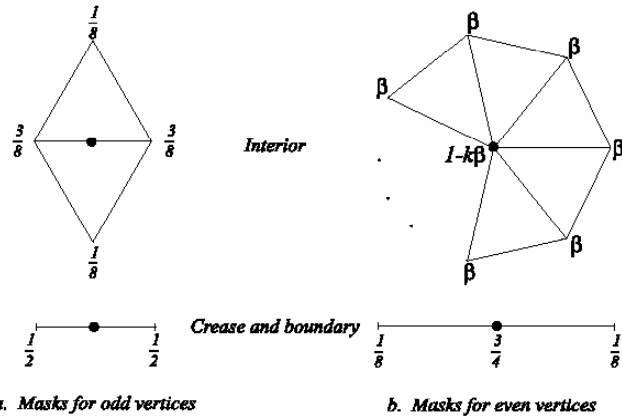
- Where to place new vertices?
 - Choose locations for new vertices as weighted average of original vertices in local neighborhood



Loop Subdivision Scheme



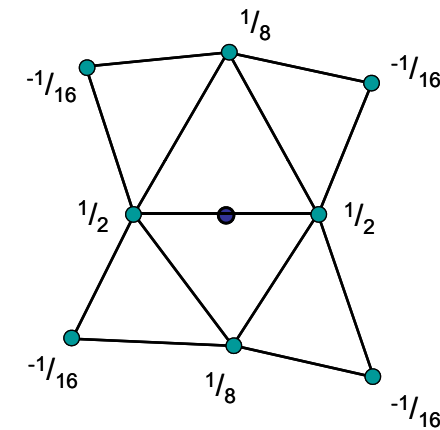
- Where to place new vertices? $\beta = \frac{1}{n}(5/8 - (\frac{3}{8} + \frac{1}{4} \cos \frac{2\pi}{n})^2)$
 - Rules for *extraordinary vertices* and *boundaries*:



Butterfly subdivision



- Interpolating subdivision: larger neighborhood



Advantages of subdivision surfaces



- Smooth surface
- Existing polygon modeling can be retargeted
- Well-suited to describing objects with complex topology
- Easy to control localized shape
- Level of details
- [Demo](#)

Geri's game

