



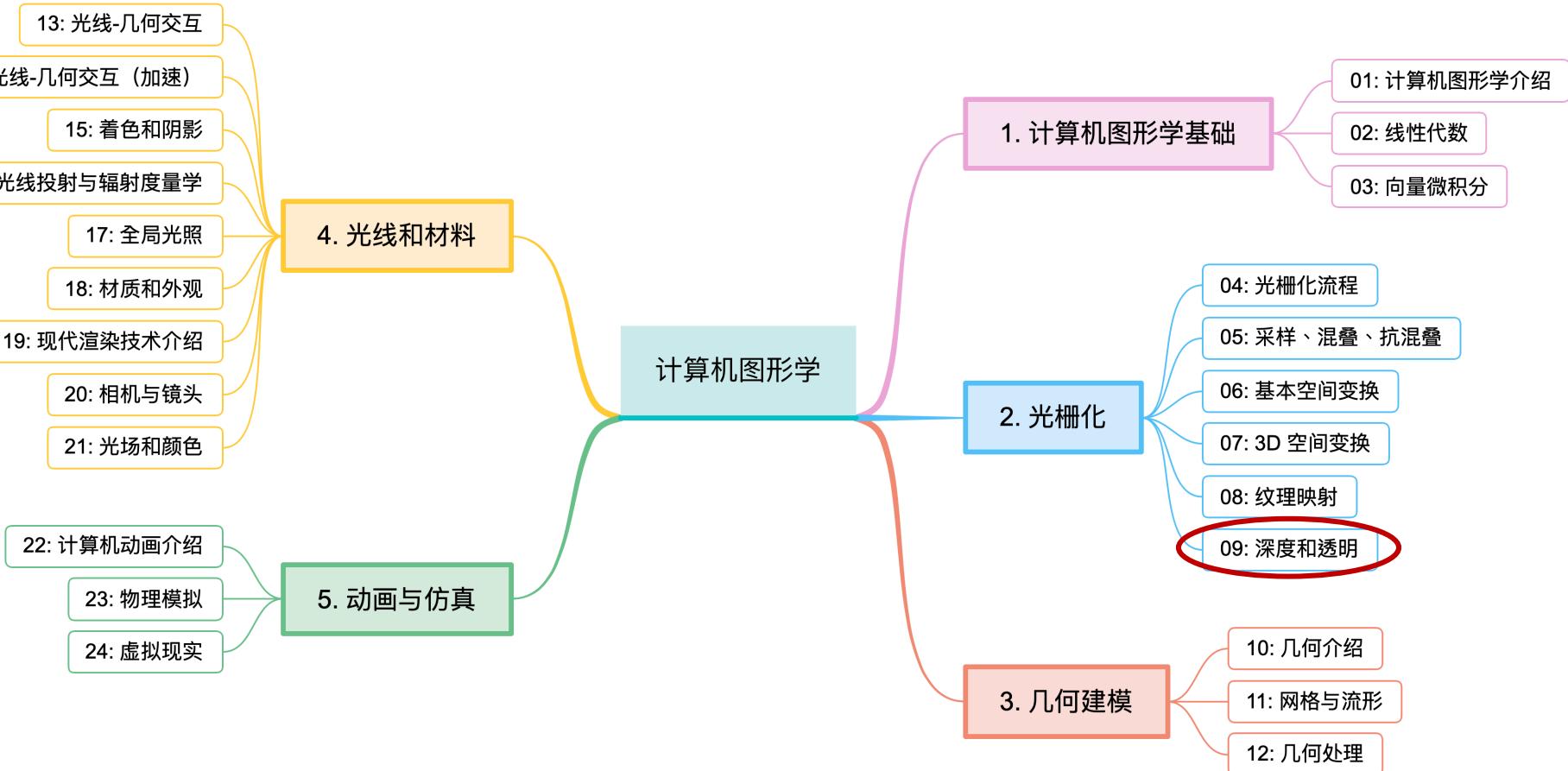
Lecture 09: 深度和透明度

SSE315: 计算机图形学
Computer Graphics

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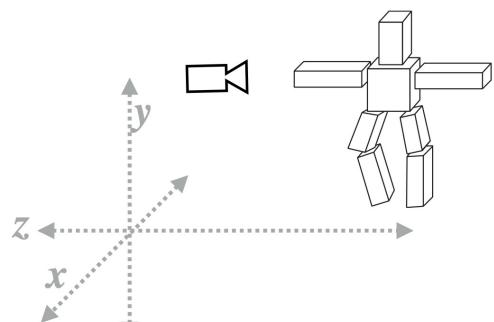
Today: 总结光栅话流程!

回顾我们的目标

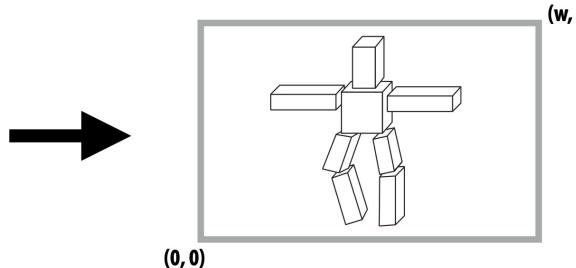
- 从一些输入 (INPUTS) 开始 (基本都是点和三角形)
 - 可能有一些其他属性 (比如颜色, 纹理)
- 应用一系列的变换: 流程的不同阶段 (STAGES)
- 生成输出 (OUTPUTS), 即最终图片



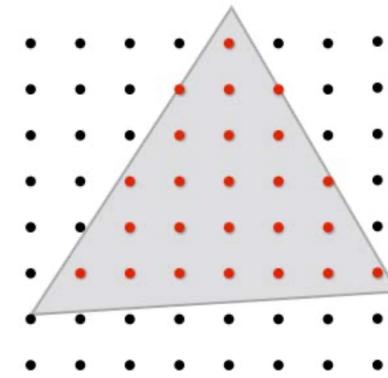
What we know how to do so far...



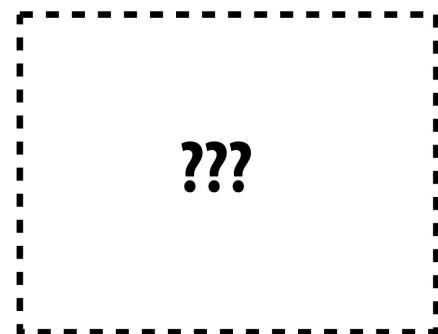
**position objects in the world
(3D transformations)**



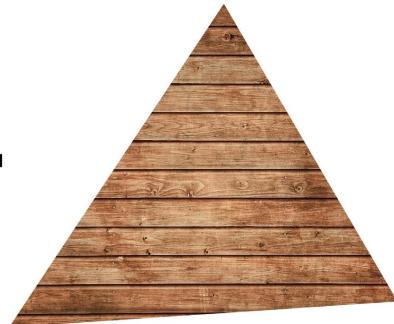
**project objects onto the screen
(perspective projection)**



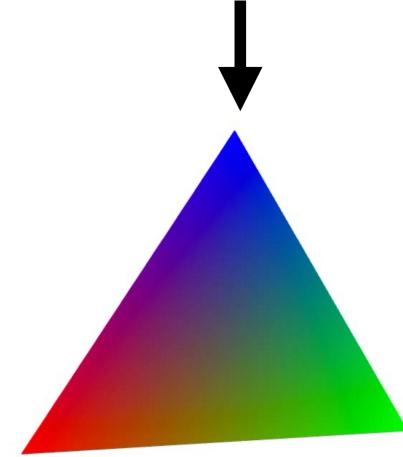
**sample triangle coverage
(rasterization)**



**put samples into frame buffer
(depth & alpha)**



**sample texture maps
(filtering, mipmapping)**

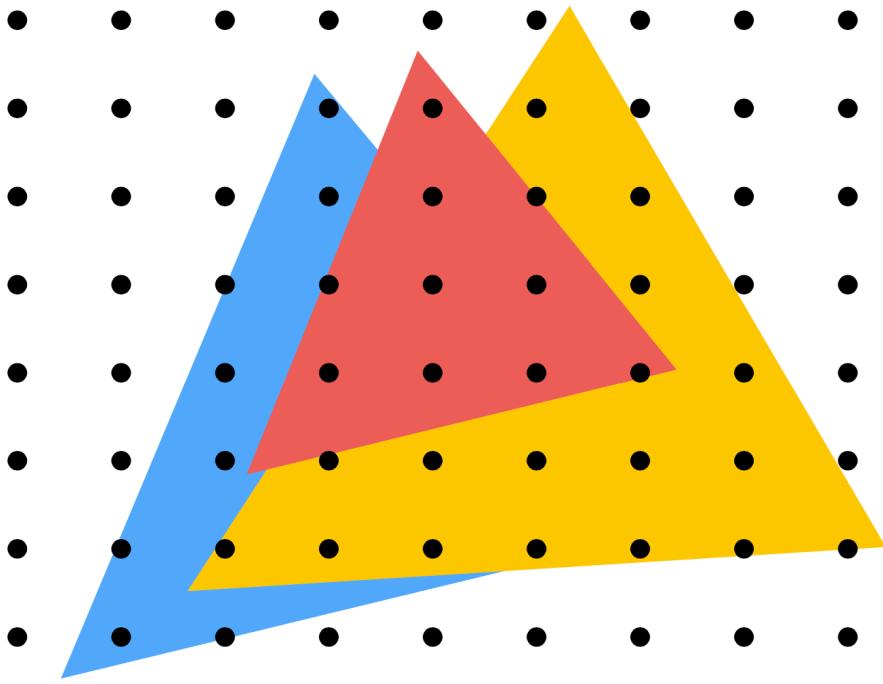


**interpolate vertex attributes
(barycentric coordinates)**

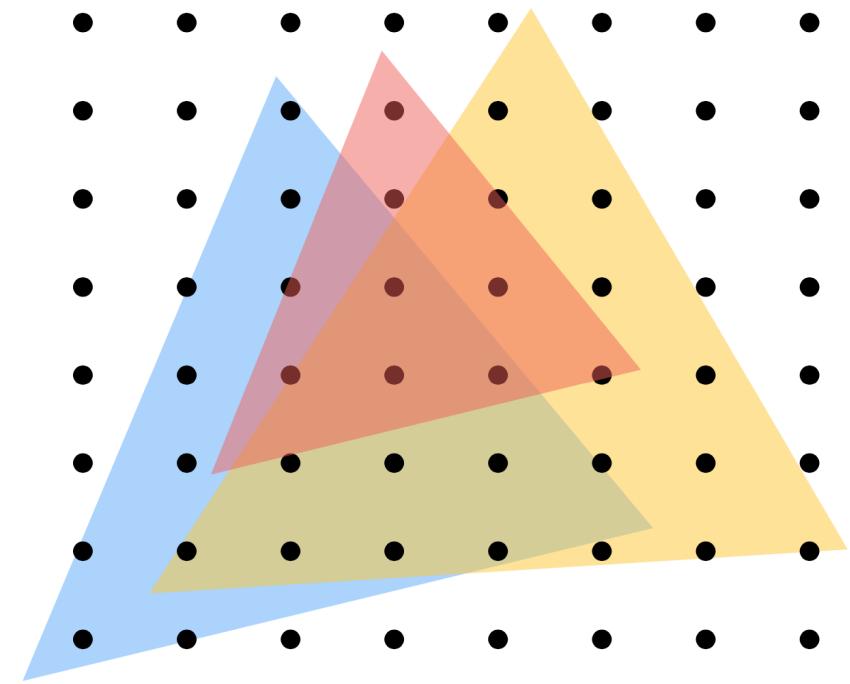
遮挡
Occlusion

遮挡

口在每个采样点上，哪个三角形可见？



Opaque Triangles

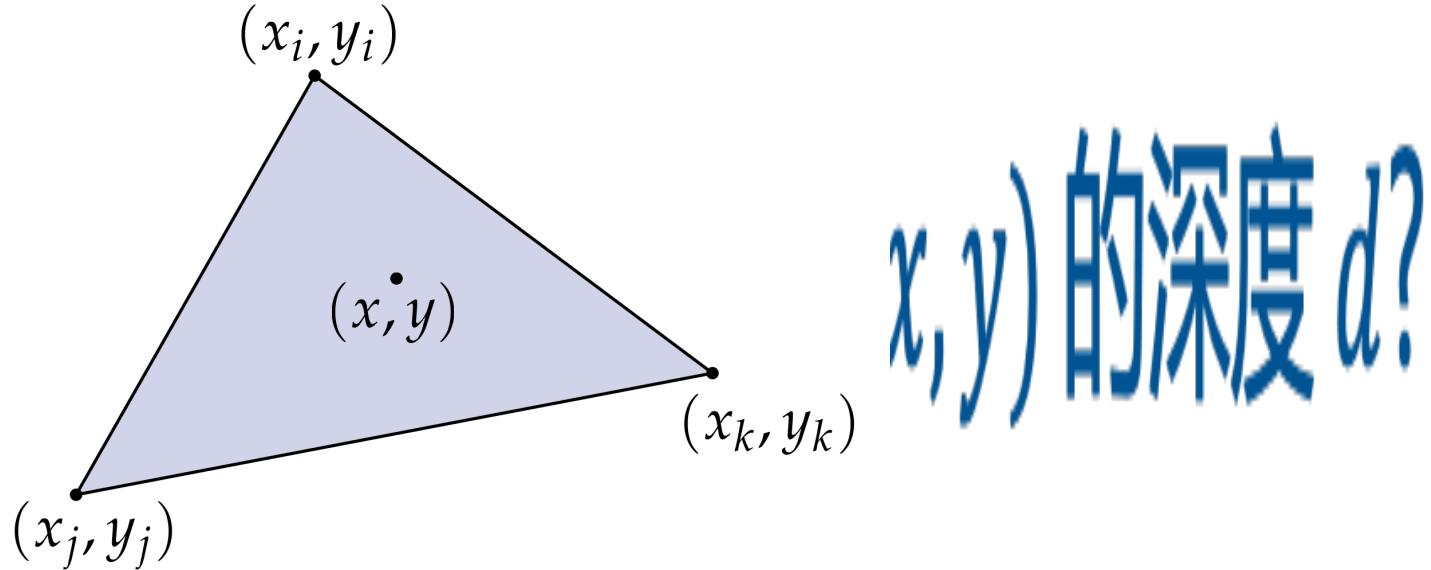


50% transparent triangles

采样深度 Depth

□假设我们有如下三角形：

- 每个顶点的 2D 投影坐标为 (x_i, y_i)
- 每个顶点的深度 (点到观察者的距离) 为 d_i

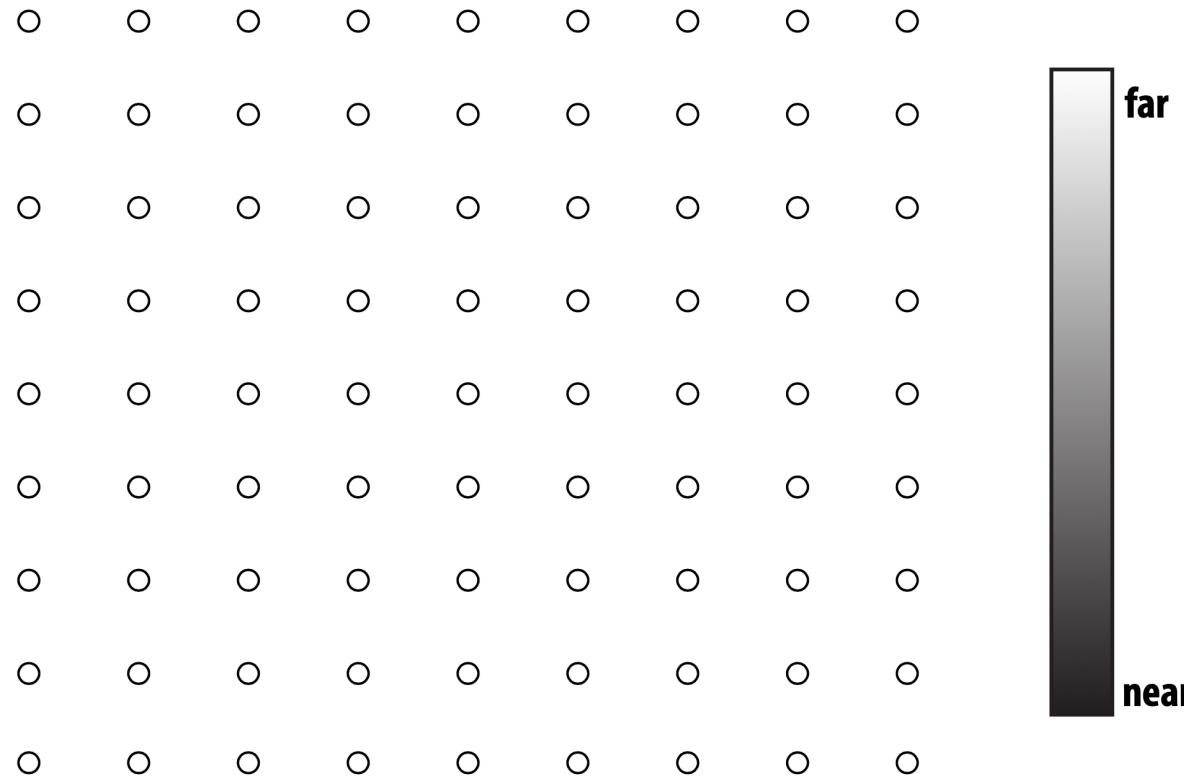


Q: 如何计算任意给定点 (x, y) 的深度 d ?

A: 使用重心坐标进行插值 (与三角形其他线性变化的属性一样, 如颜色)

深度缓冲 Depth-buffer (Z-buffer)

对于每个样本，深度缓冲存储到目前为止看到的最近三角形的深度

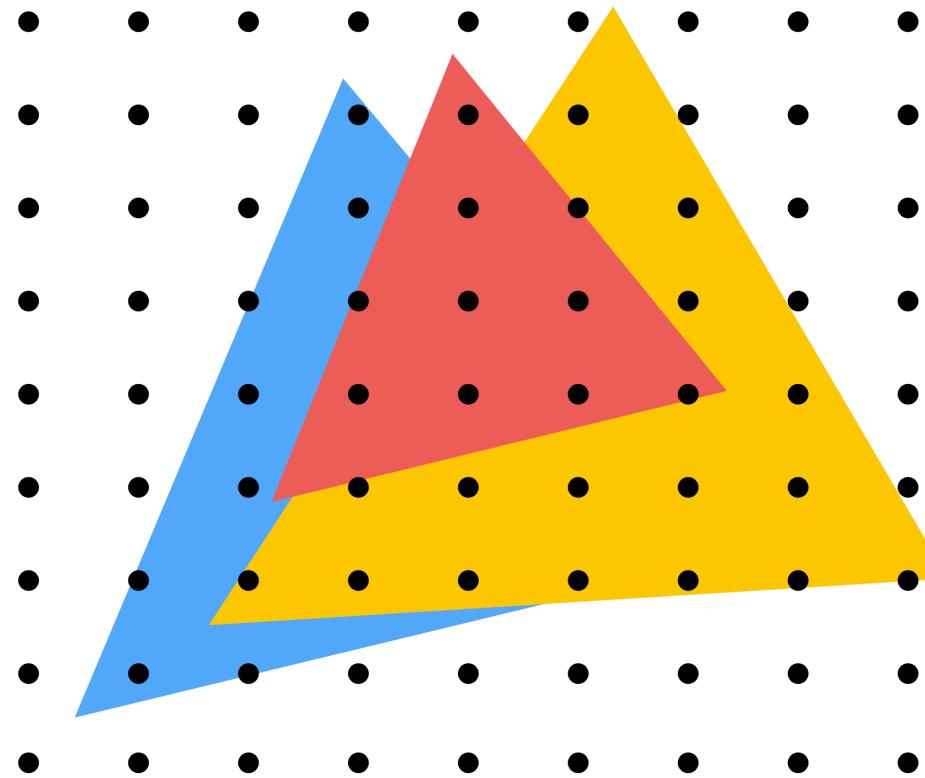


将所有深度缓冲值初始化为“无穷大”（最大值）

深度缓冲示例

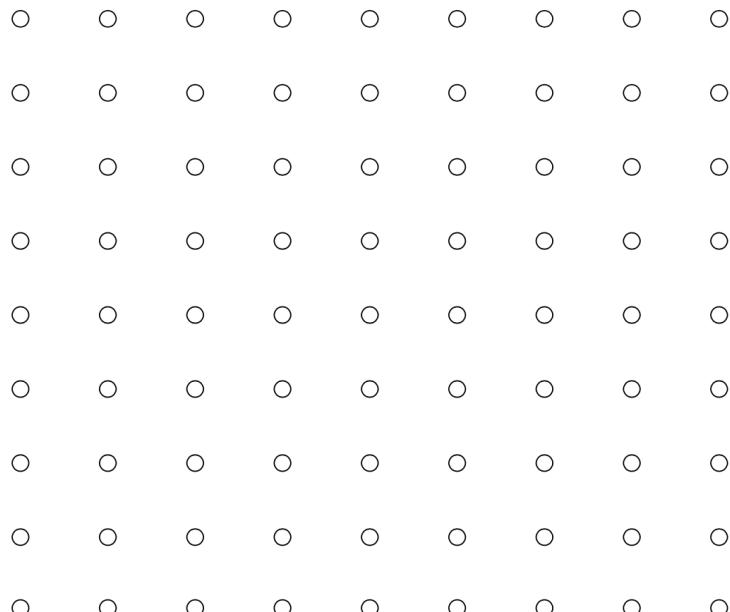


示例：渲染三个不透明三角形



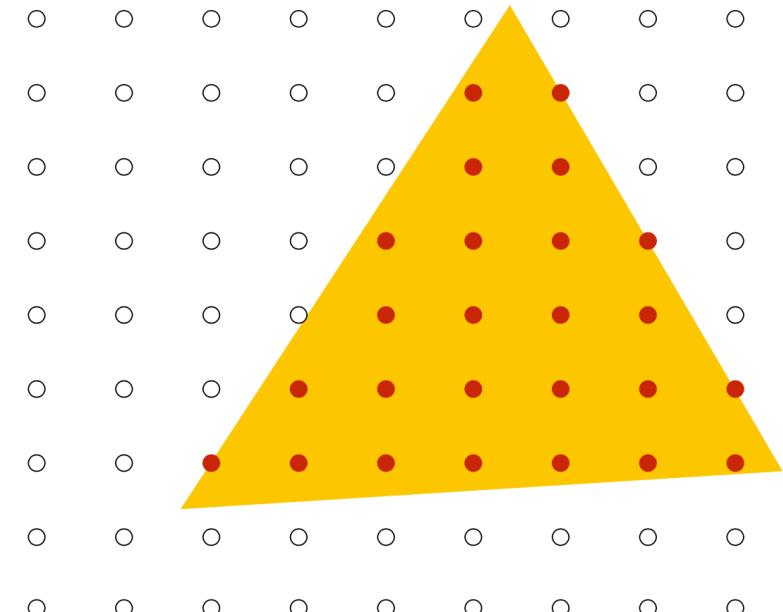
使用深度缓冲 (z-buffer) 进行遮挡

Processing yellow triangle:
depth = 0.5



Color buffer contents

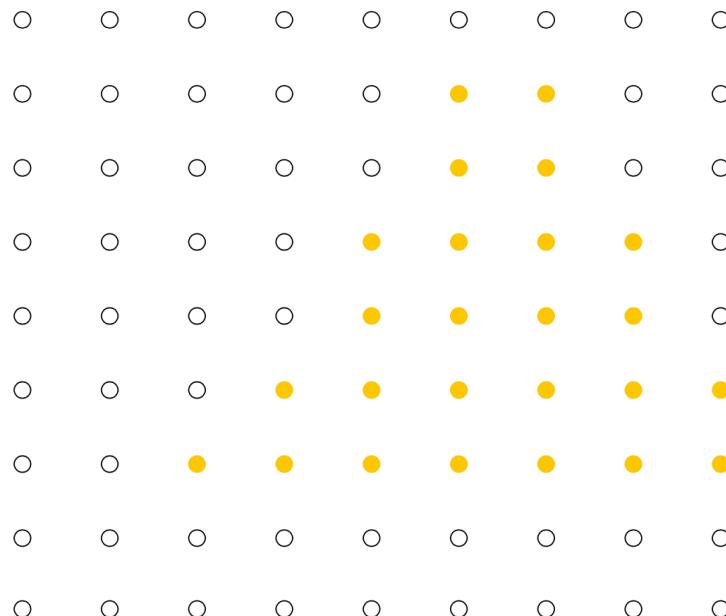
near  far
● — sample passed depth test



Depth buffer contents

使用深度缓冲 (z-buffer) 进行遮挡

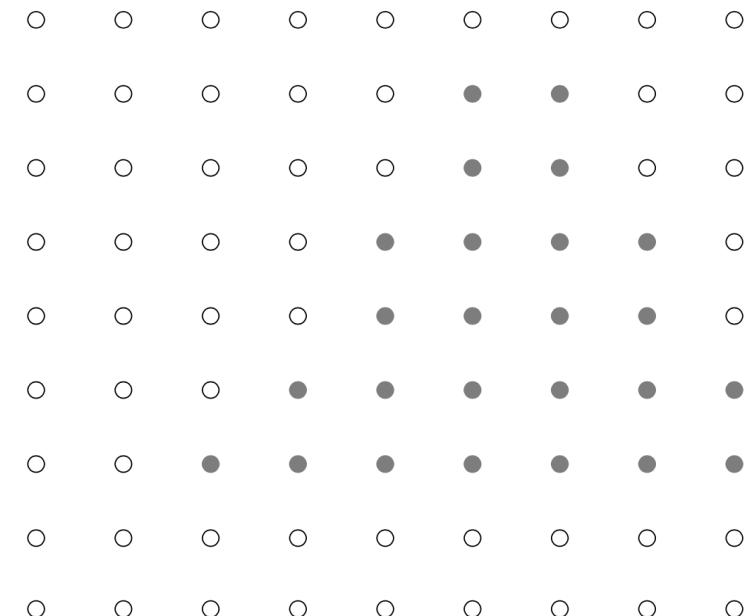
After processing yellow triangle:



Color buffer contents

near  far

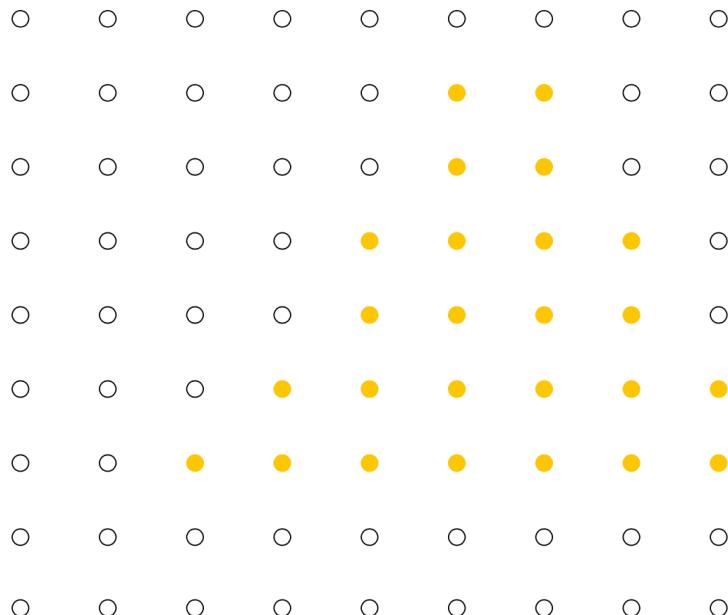
● — sample passed depth test



Depth buffer contents

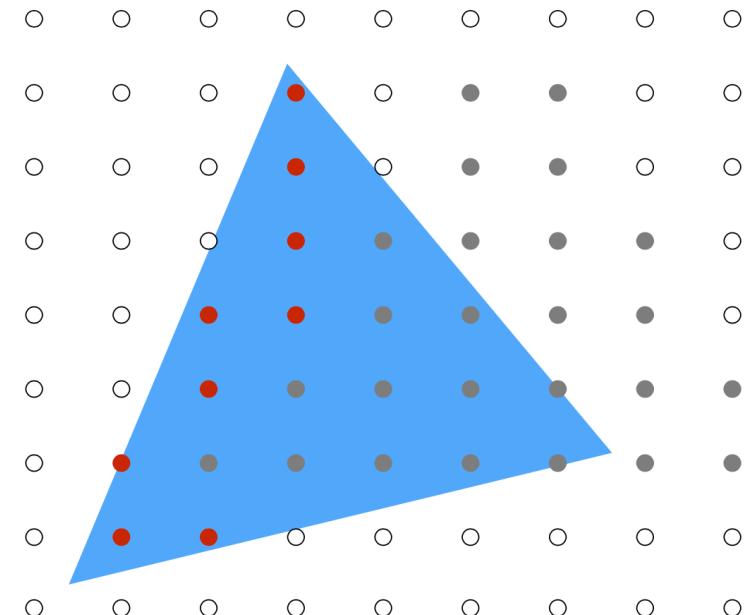
使用深度缓冲 (z-buffer) 进行遮挡

Processing blue triangle:
depth = 0.75



Color buffer contents

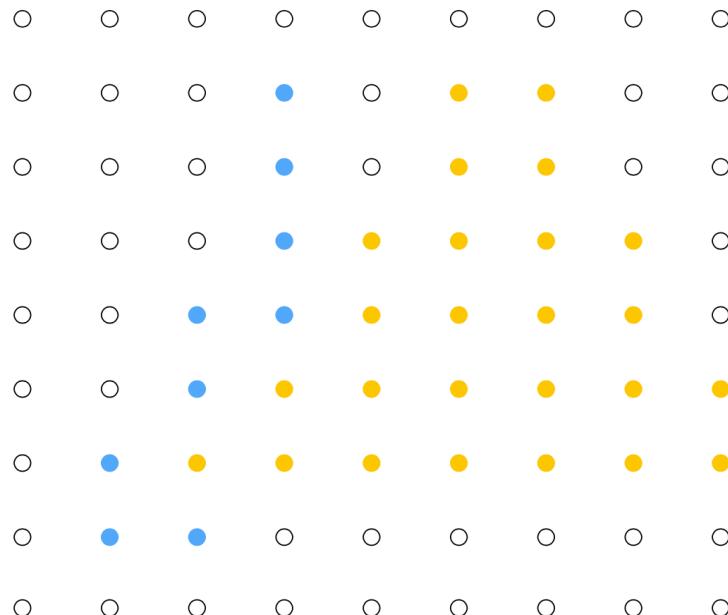
near — sample passed depth test



Depth buffer contents

使用深度缓冲 (z-buffer) 进行遮挡

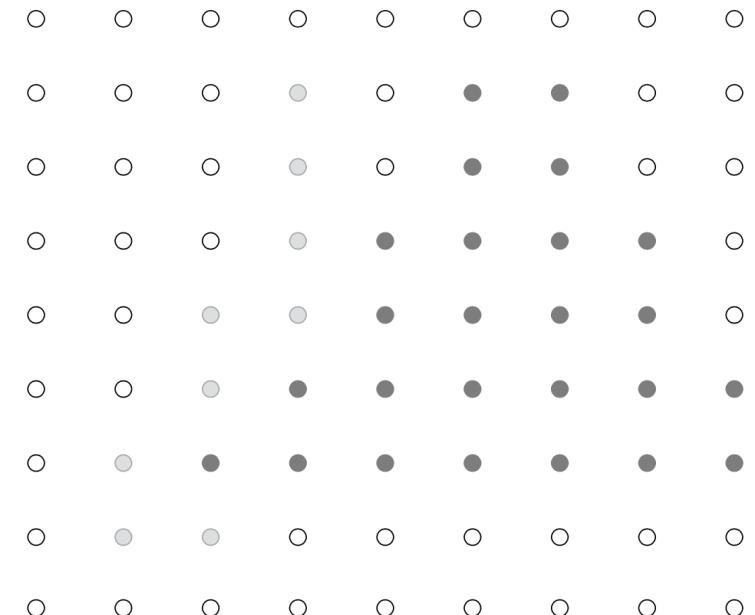
After processing blue triangle:



Color buffer contents

near far

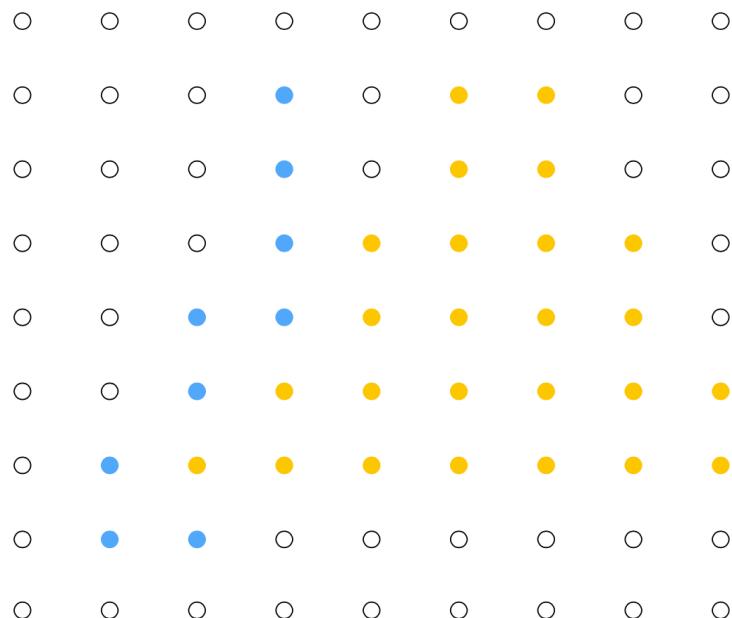
● — sample passed depth test



Depth buffer contents

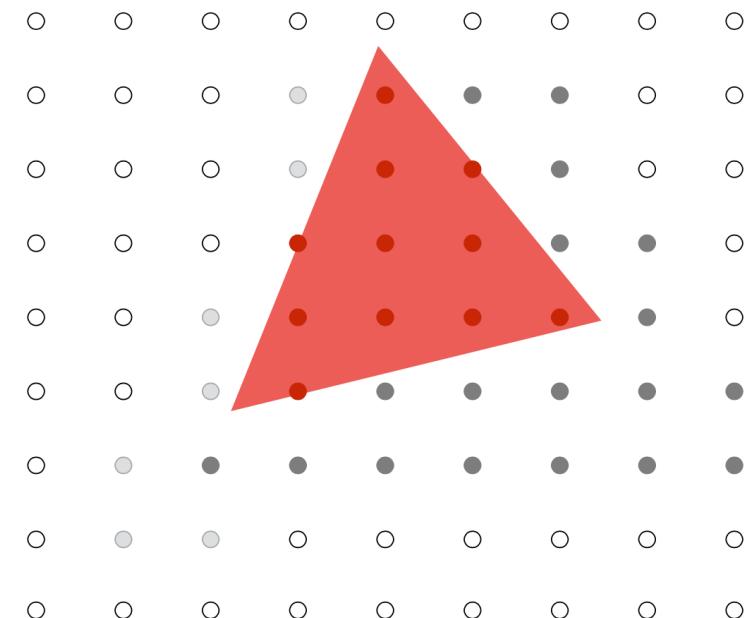
使用深度缓冲 (z-buffer) 进行遮挡

Processing red triangle:
depth = 0.25



Color buffer contents

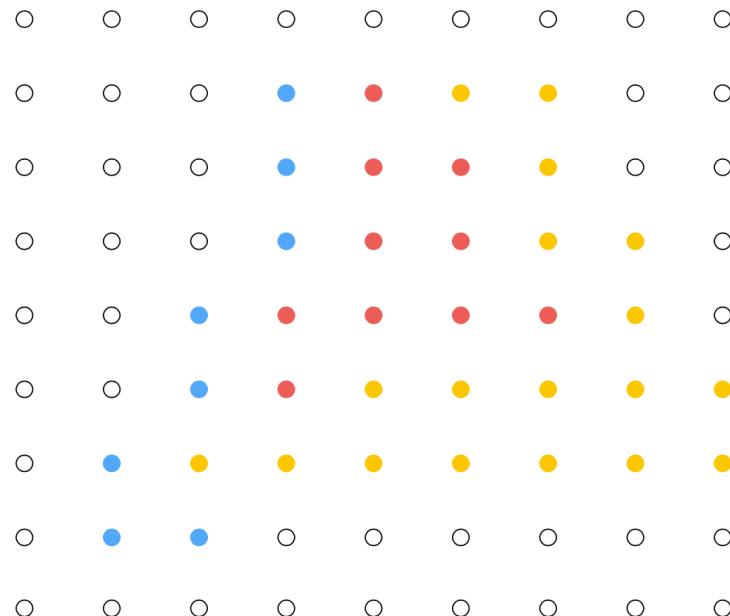
near far
● — sample passed depth test



Depth buffer contents

使用深度缓冲 (z-buffer) 进行遮挡

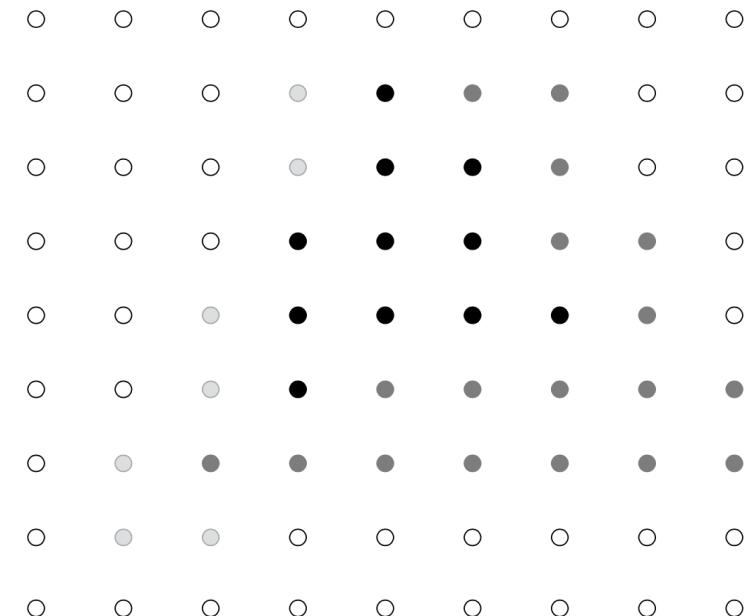
After processing red triangle:



Color buffer contents

near far

● — sample passed depth test



Depth buffer contents

Does the order matter?

使用深度缓冲进行遮挡

```
bool pass_depth_test(d1, d2)
{
    return d1 < d2;
}
```

```
draw_sample(x, y, d, c) //new depth d & color c at (x,y)
{
    if( pass_depth_test( d, zbuffer[x][y] ))
    {
        // triangle is closest object seen so far at this
        // sample point. Update depth and color buffers.
        zbuffer[x][y] = d;    // update zbuffer
        color[x][y] = c;     // update color buffer
    }
    // otherwise, we've seen something closer already;
    // don't update color or depth
}
```

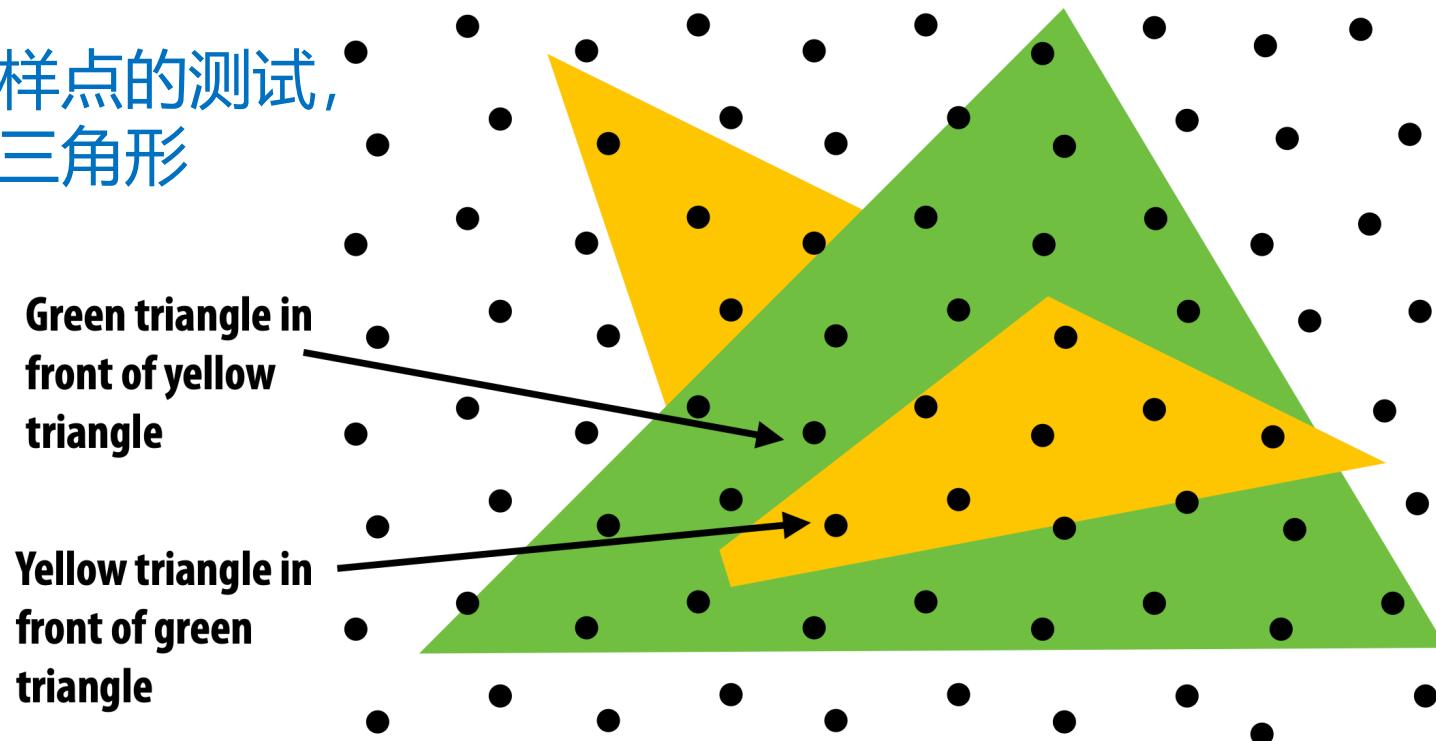
深度与交叉

□ Q：深度缓冲算法能处理相互穿插的三角形吗？

□ 遮挡测试基于给定采样点的三角形深度

□ 三角形的相对深度在不同的采样点可能不同

基于采样点的测试，
而不是三角形

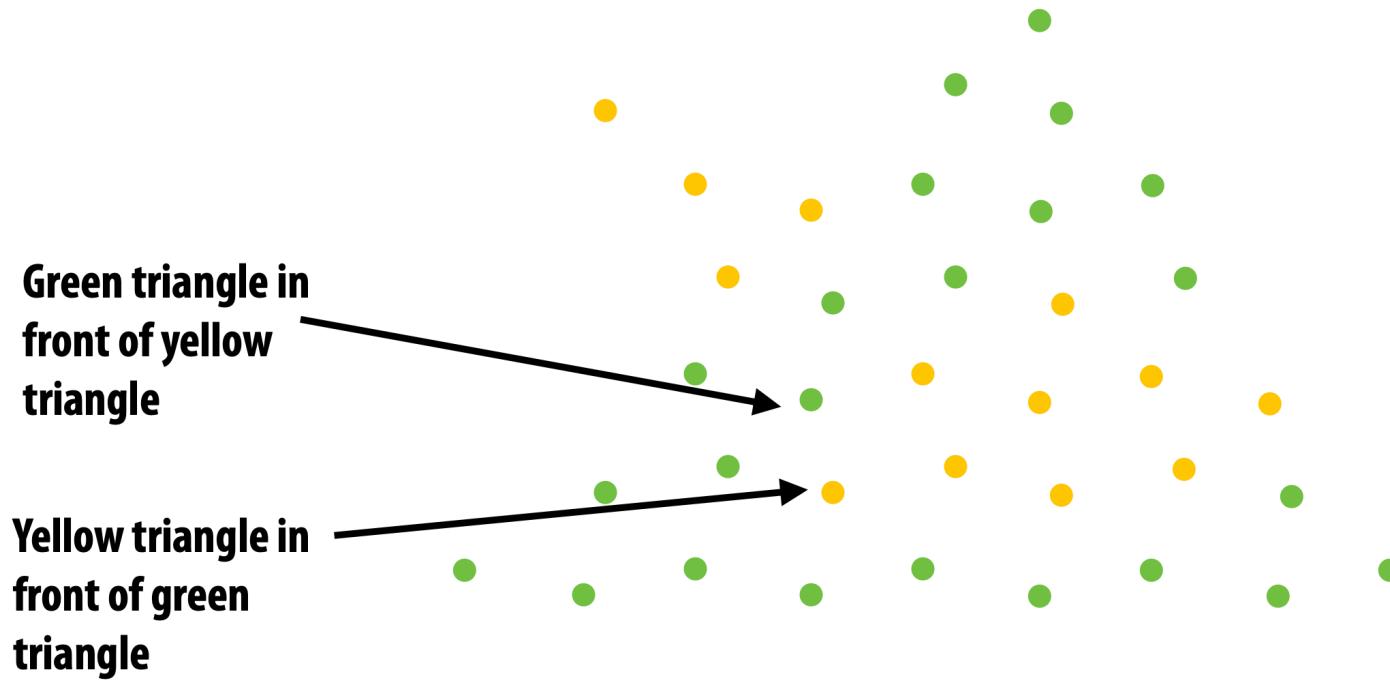


交叉 Intersection

□Q：深度缓冲算法能处理相互穿插的三角形吗？

□遮挡测试基于给定采样点的三角形深度

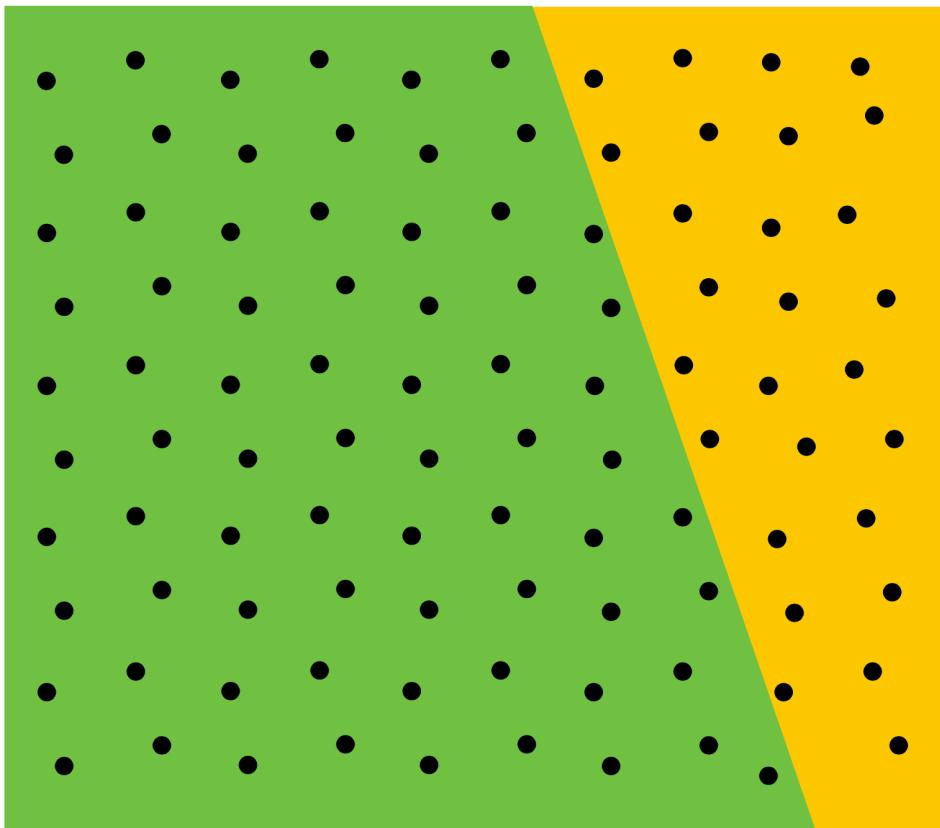
□三角形的相对深度在不同的采样点可能不同



深度与超采样

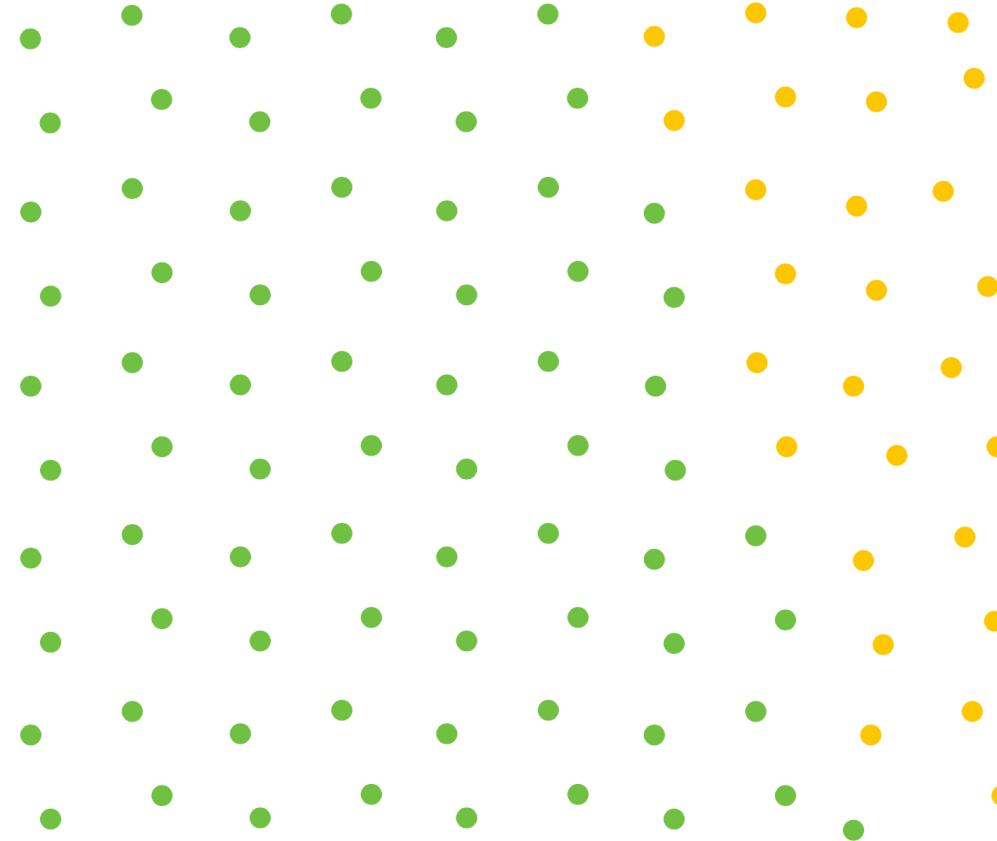
□Q: 深度缓冲能配合超采样 (supersampling) 一起工作吗?

□A: 可以, 每个超采样点有一个深度的采样



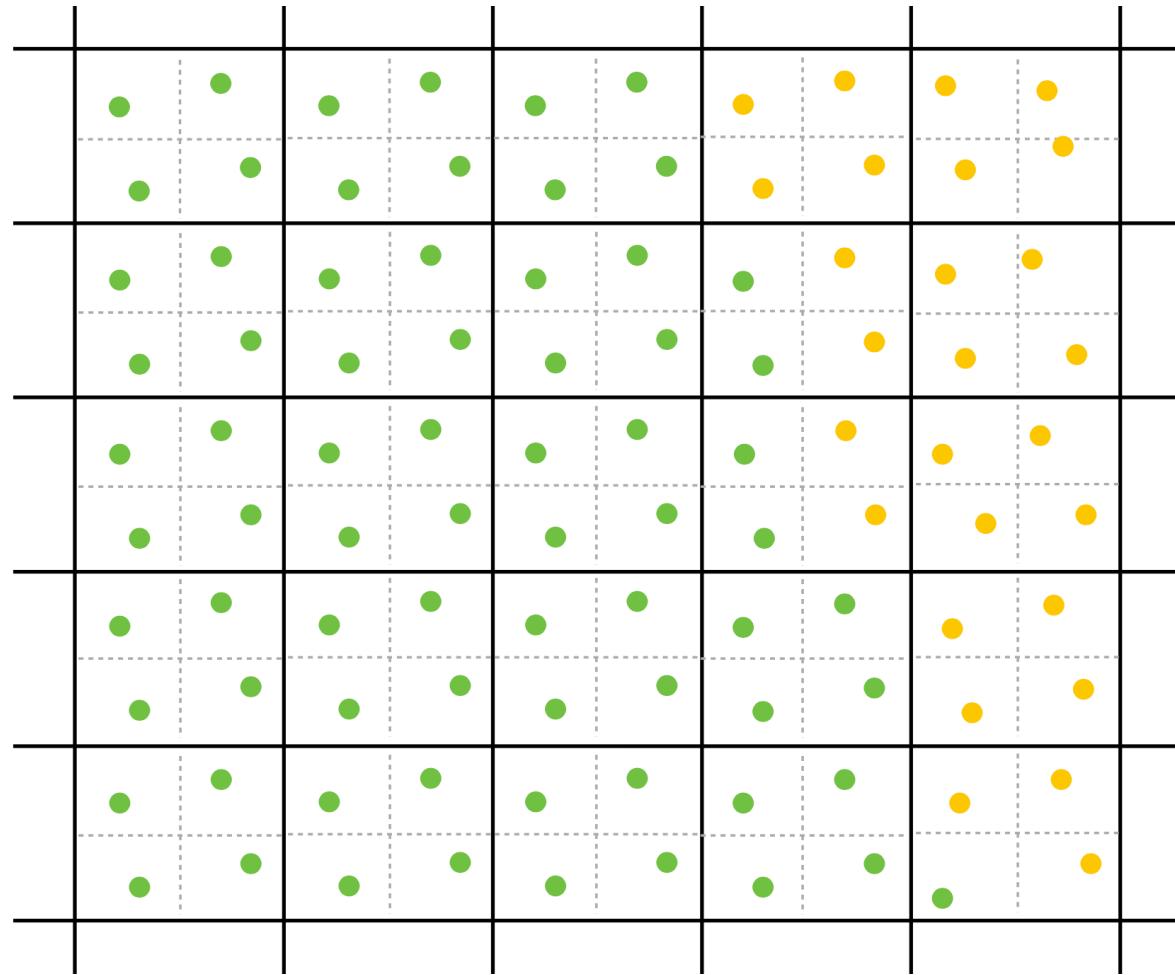
(Here: green triangle occludes yellow triangle)

深度与超采样

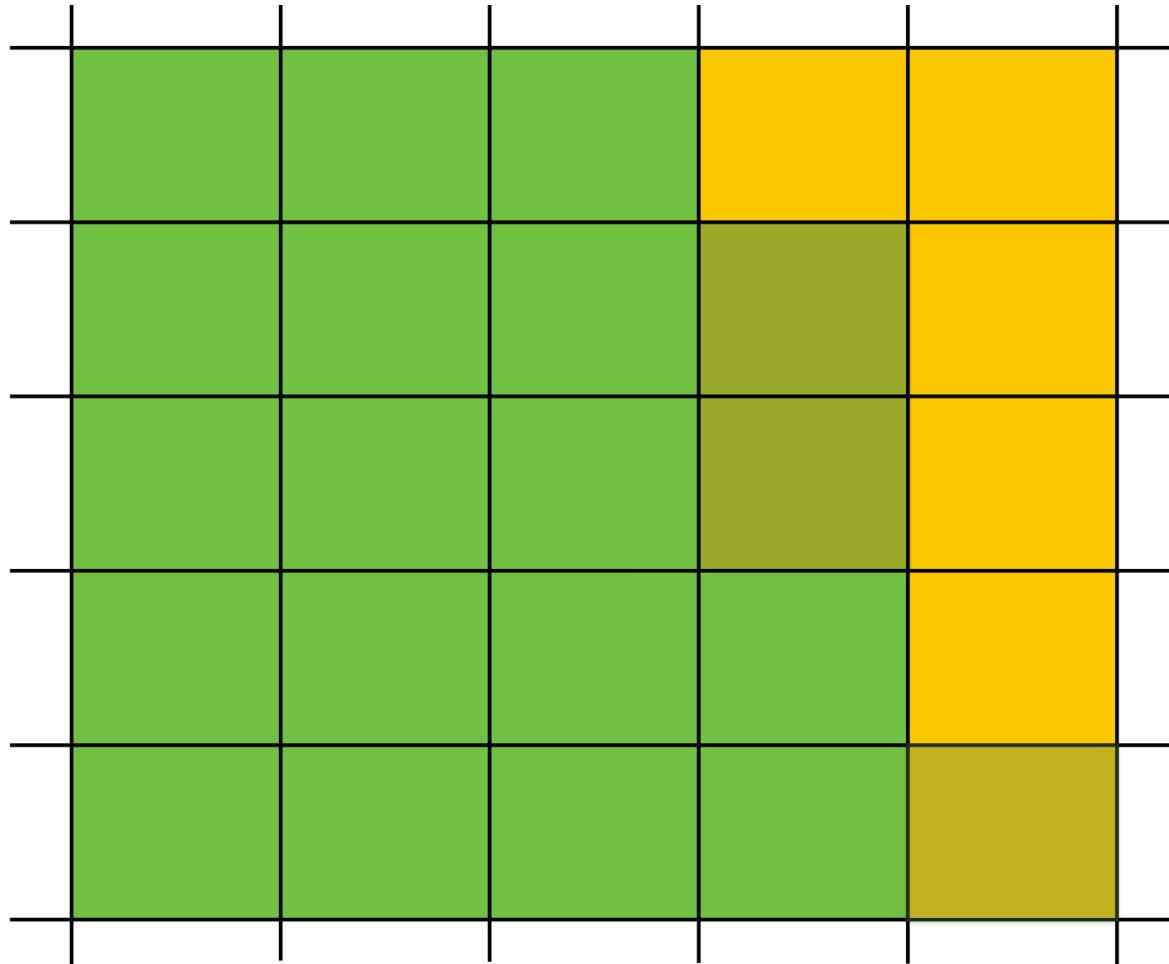


Color of super samples after rasterizing w/ depth buffer

深度与超采样



深度与超采样



Note anti-aliasing of edge due to filtering of green and yellow samples

小结：使用深度缓冲的遮挡

□ 每个超样本存储一个深度值，而不是每个像素存储一个！

□ 每个样本具有恒定的额外存储空间 (RGB + Depth)

- 因此，深度缓冲所需的空间恒定
- 不依赖于重叠图形基元的数量 (仅存储一个深度值)！

□ 每个样本具有恒定的深度测试时间

- 如果 “通过” 深度测试，读取-修改-写入深度缓冲区
- 如果 “失败”，只需读取

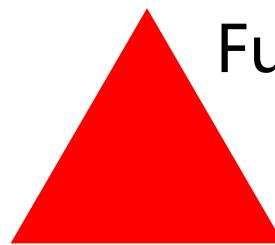
□ 不特定于三角形：只要求可以在屏幕采样点评估表面深度

对于半透明的表面呢？

合成 Compositing

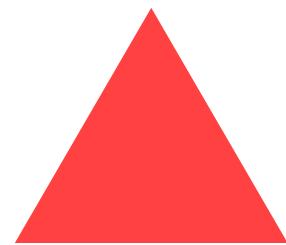
将不透明度 opacity 表示为 alpha

□ $\alpha, 0 \leq \alpha \leq 1$ 表示对象的不透明度

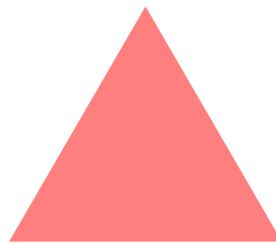


Fully opaque

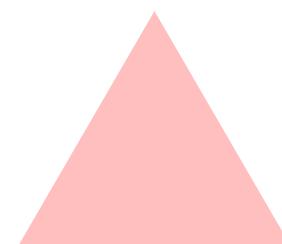
$$\alpha = 1$$



$$\alpha = 0.75$$



$$\alpha = 0.5$$

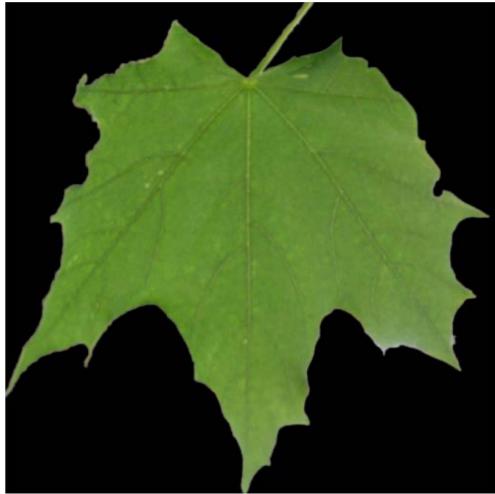


$$\alpha = 0.25$$

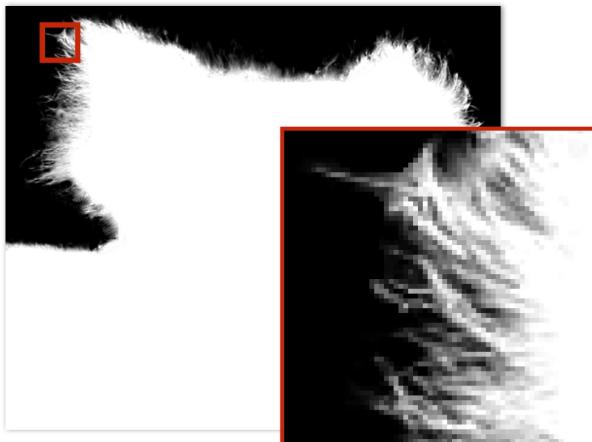
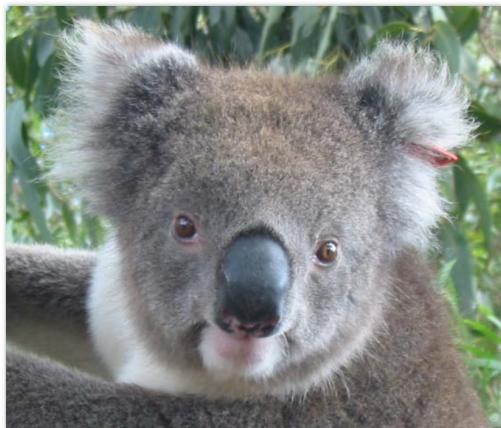
$\alpha = 0$
Fully transparent

图像的 alpha 通道

color channels



α channel



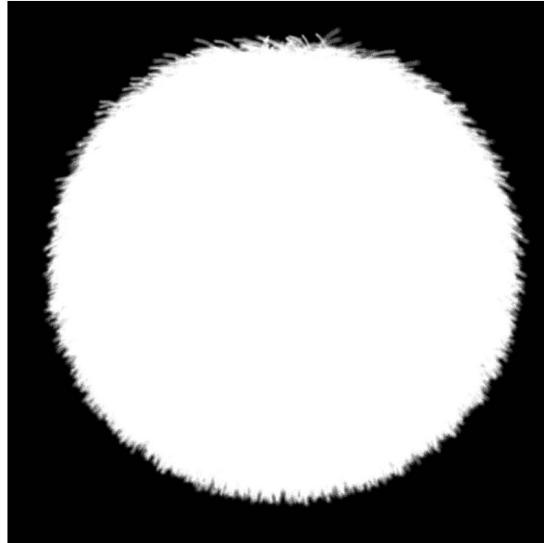
Key idea: 我们可以利用图像的 alpha 通道将一张图片叠在另一张图片上以合成新的图片

边缘晕影 Fringing

口不正确地处理颜色/alpha 值会导致边缘晕影



foreground color



foreground alpha



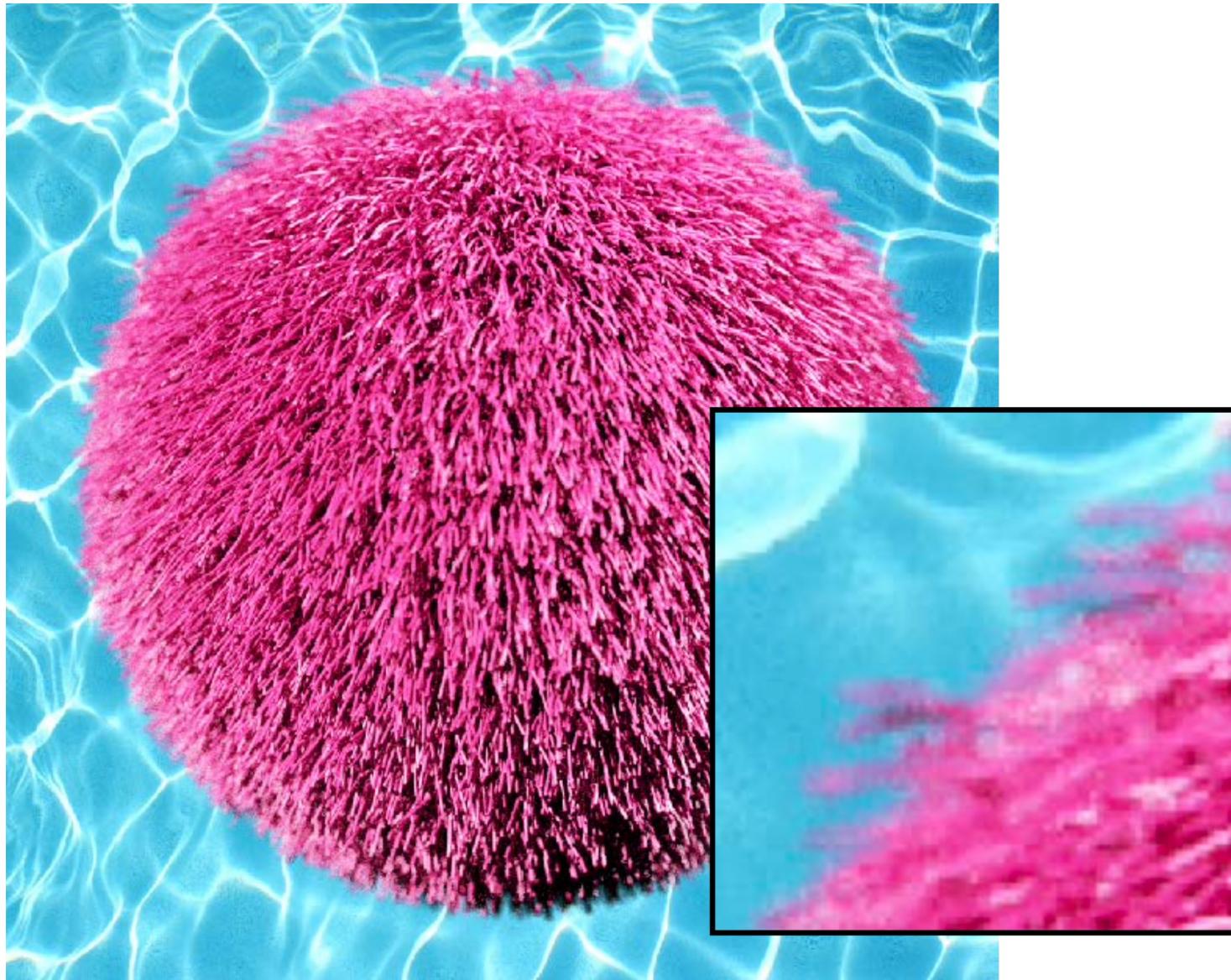
background color

fringing

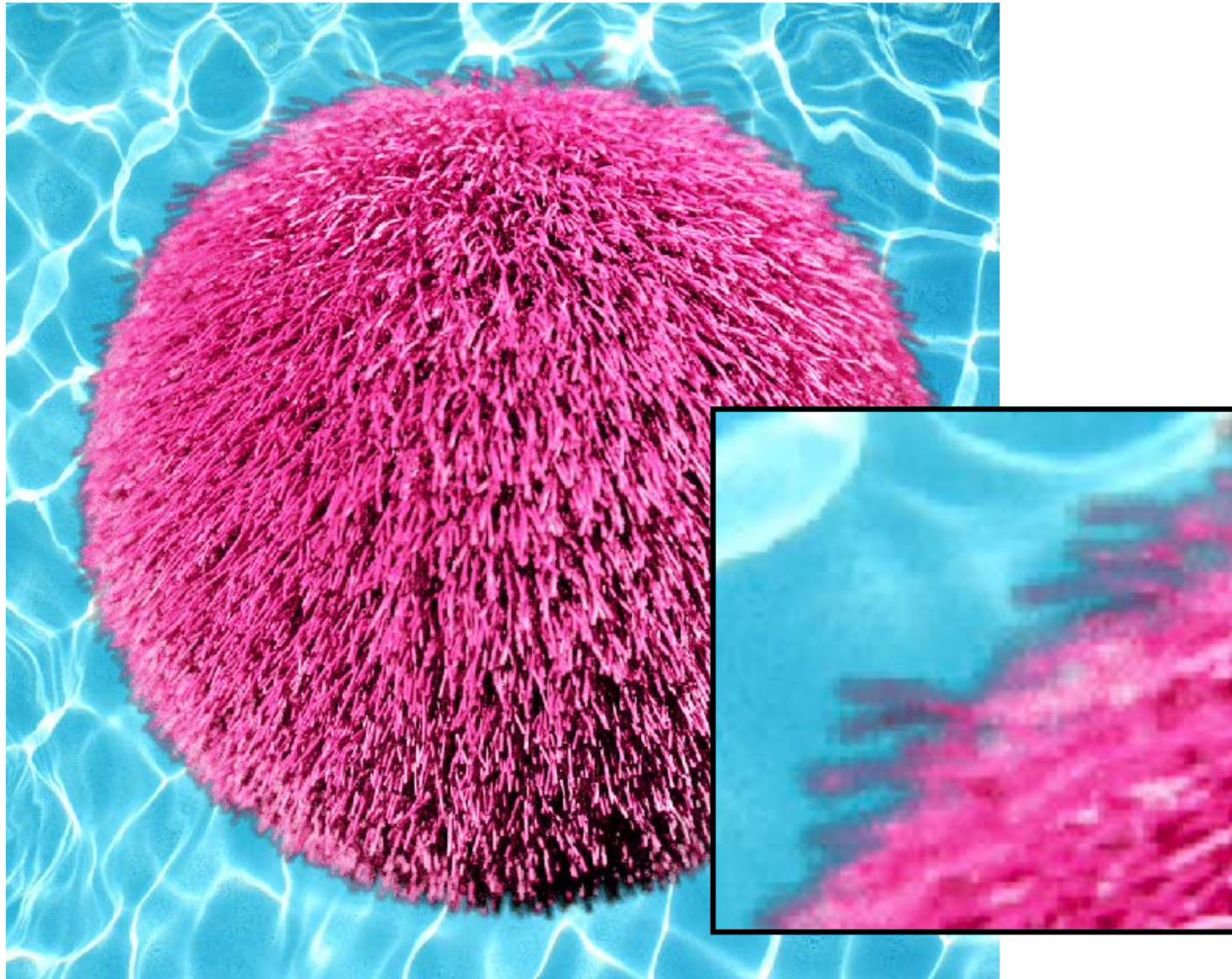


no fringing

No fringing

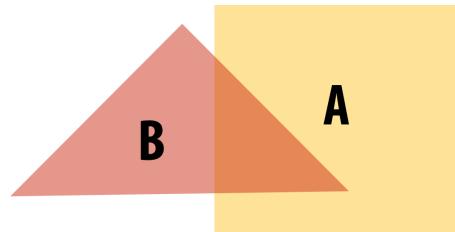


Fringing 为什么会出现?

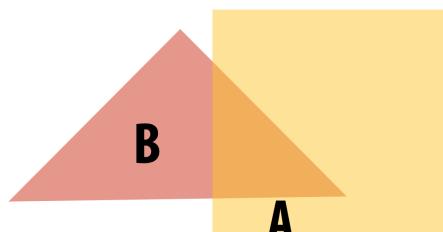


Over 算子 Operator

口将透明度为 α_A 的照片 A 与透明度为 α_B 的照片 B 混合



B over A



A over B

Notice: “over” is not commutative

$$A \text{ over } B \neq B \text{ over } A$$



Koala



NYC



Koala over NYC

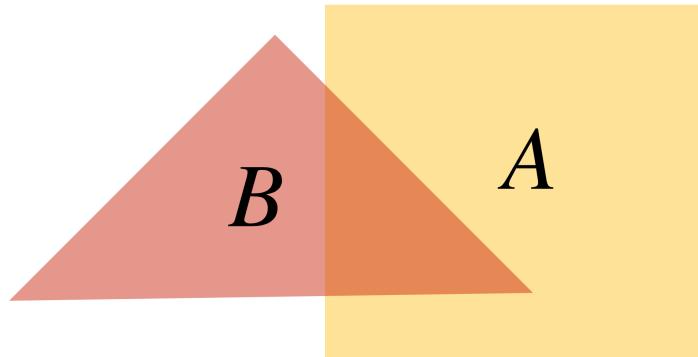
Over 算子：非预乘 α (non-premultiplied α)

□ 将透明度为 α_A 的照片 A 与透明度为 α_B 的照片 B 混合

□ 第一次尝试

$$A = (A_r, A_g, A_b)$$

$$B = (B_r, B_g, B_b)$$



□ 混合颜色

B 允许 A 通过的部分

$B \text{ over } A$

$$C = \alpha_B B + (1 - \alpha_B) \alpha_A A$$

半透明 B 的颜色

半透明 A 的颜色

□ 混合 alpha 值 $\alpha_C = \alpha_B + (1 - \alpha_B)\alpha_A$

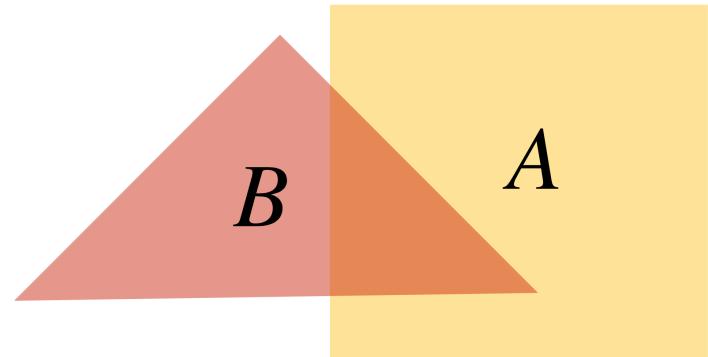
Over 算子：预乘 α (premultiplied α)

口预乘 α : 先将颜色乘以 α , 再进行混合

$$A' = (\alpha_A A_r, \alpha_A A_g, \alpha_A A_b, \alpha_A)$$

$$B' = (\alpha_B B_r, \alpha_B B_g, \alpha_B B_b, \alpha_B)$$

$$C' = B' + (1 - \alpha_B)A'$$



注意到预乘 α 混合 α 的方式与其混合 RGB 的方式一样 (非预乘则以不同的方式混合 α 和 RGB) B over A

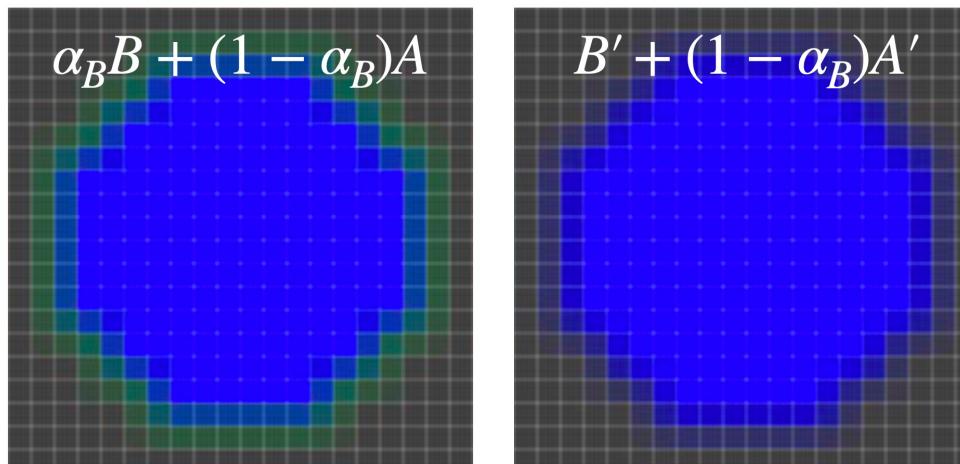
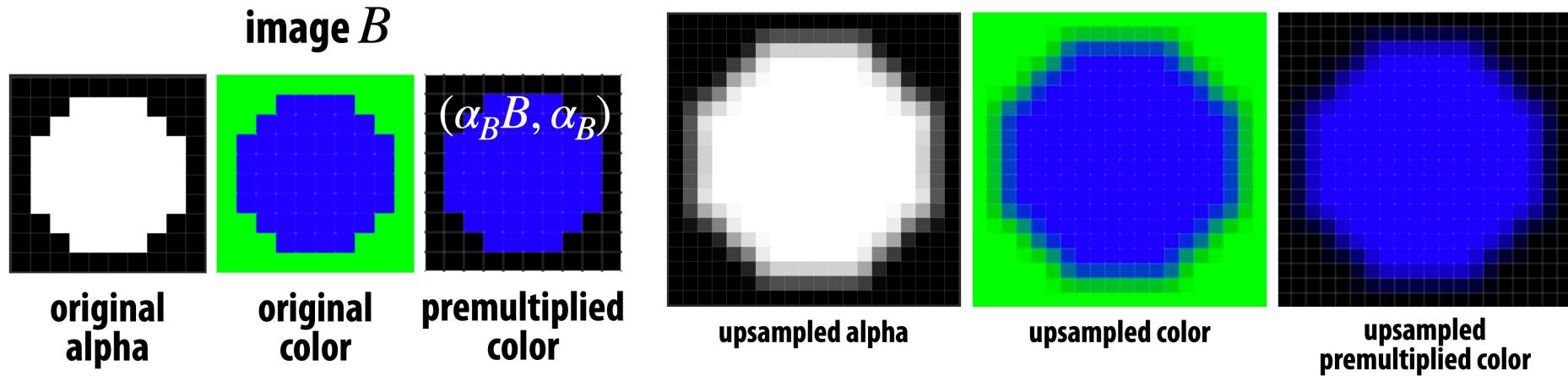
口以 “Un-premultiply” 的方式得到最后的颜色 (除以 α_C)

$$(C_r, C_g, C_b, \alpha_C) \Rightarrow (C_r/\alpha_C, C_g/\alpha_C, C_b/\alpha_C)$$

Q: Does this division remind you of anything?

使用或不使用预乘 α 进行混合

口采样一张具有 α 通道的照片，再将其与一个背景混合



new background A
 $(\alpha_A = 1)$

B over A
non-premultiplied

B over A
premultiplied

Q: Why do we get the “green fringe” when we don't premultiply?

一个使用非预乘 α 的相似问题

考虑下采样 (downsampling) 一个透明度为 α 的纹理

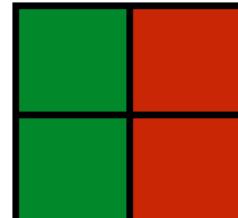


desired downsampled result

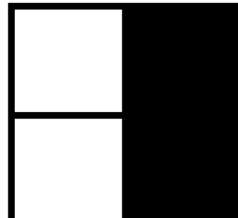


MIP Map

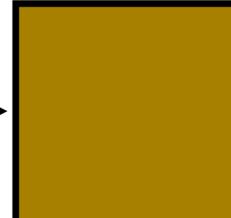
Leaf
edge



input color



input α



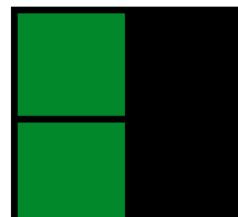
filtered color



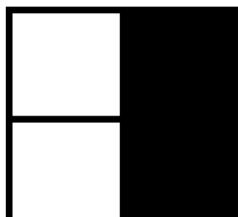
filtered α



composited over white



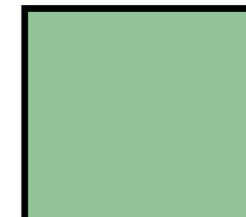
premultiplied
color
 α



filtered color



filtered α



composited over white

更多问题：重复使用 over 操作

口将透明度分别为 $\alpha_A, \alpha_B, \alpha_C$ 的照片 A, B, C 进行混合

口预乘 α 在混合操作下是闭合 (closed) 的，非预乘 α 不是

口例子，将 50% 的红色与 50% 的红色混合
(其中 红色=(1, 0, 0), $\alpha = 0.5$)

non-premultiplied

color

$$.5(1,0,0) + (1-.5).5(1,0,0)$$



$$(0.75,0,0)$$

too dark!

alpha

$$.5 + (1-.5).5 = .75$$

premultiplied

color

$$(.5,0,0,.5)+(1-.5)(.5,0,0,.5)$$



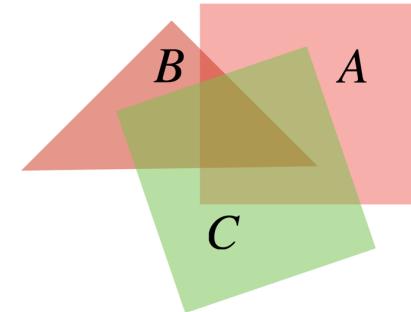
$$(0.75,0,0.75)$$



$$\text{bright red } (1,0,0)$$

alpha

$$\alpha = 0.75$$



C over B over A

若不对非预乘 α 的结果进行调整，将越来越黑，预乘 α 的结果仍是合法的预乘形式 (closed)，因此能正常趋近于红色

更多问题：重复使用 over 操作

□再次混合 50% 的红色

non-premultiplied

color

$$.5(1,0,0) + (1-.5).5(1,0,0)$$



$$(0.75,0,0)$$

too dark!

alpha

$$.5 + (1-.5).5 = .75$$

premultiplied

color

$$(.5,0,0,.5)+(1-.5)(.5,0,0,.5)$$



$$(.75,0,0.75)$$



$$\text{bright red } (1,0,0)$$

alpha

$$\alpha = 0.75$$

$$.75(.75, 0, 0) + (1 - .75).5(1, 0, 0)$$

$$(.75, 0, 0, .75) + (1 - .75)(.5, 0, 0, .5)$$

$$color = (0.6875, 0, 0)$$

$$(0.875, 0, 0, 0.875)$$

$$\alpha = .75 + (1 - .75).5 = 0.875$$

$$color = (1, 0, 0)$$

$$\alpha = 0.875$$

“物体原本颜色是亮红色 (1, 0, 0)” 这个关键信息丢失了，导致错误累积

预乘 α 的优点

- 口合成操作对所有通道 (颜色及 α) 一视同仁
- 口与非预乘表示相比, over 运算的算术运算更少
- 口在合成操作中是闭合的 (重复 over 运算的结果是合法的)
- 口是使用 α 通道过滤 (上采样/下采样) 图像更好的表示
- 口无缝衔接光栅化流程 (齐次坐标)

绘制半透明图形基元的策略

假设所有基元都是半透明的，并且颜色值已经预乘了 α ，下面是光栅化图像的策略：

```
over(c1, c2)
{
    return c1.rgb + (1-c1.a) * c2.rgb;
}
```

```
update_color_buffer( x, y, sample_color, sample_depth )
{
    if (pass_depth_test(sample_depth, zbuffer[x][y])
    {
        // (how) should we update depth buffer here??
        color[x][y] = over(sample_color, color[x][y]);
    }
}
```

Q：上述操作的隐含假设是什么？

A：三角形必须按从后往前的顺序进行渲染！

Putting it all together

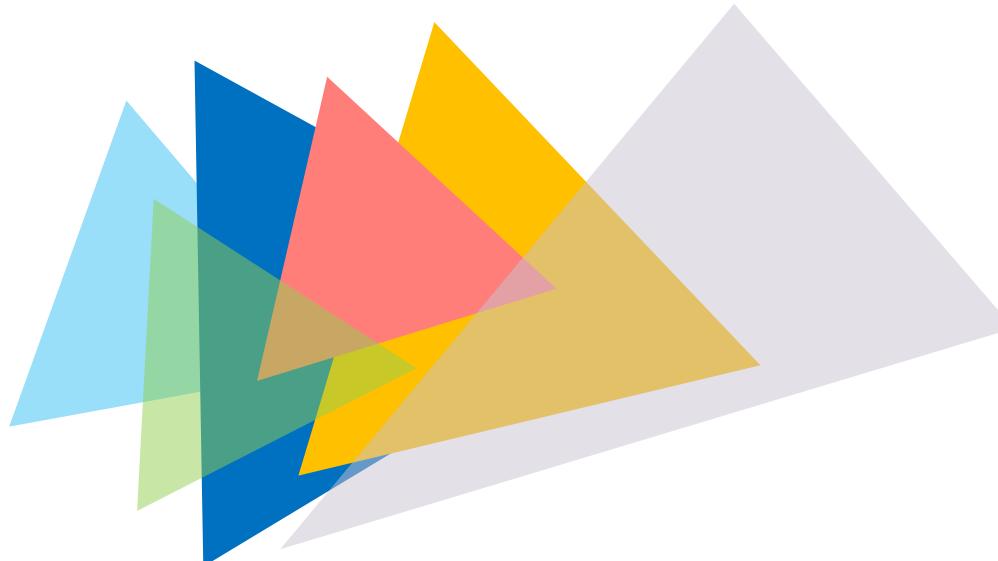
□如果我们同时有不透明和透明的三角形呢？

□第一步

- 使用深度缓冲遮挡渲染不透明的基元（按任何顺序）
- 若通过深度测试，三角形将覆盖采样处颜色缓冲区中的值

□第二步：

- 禁用深度缓冲更新，按**从后往前**的顺序渲染半透明基元
- 若通过深度测试，三角形将基于样本缓冲区中的颜色合成

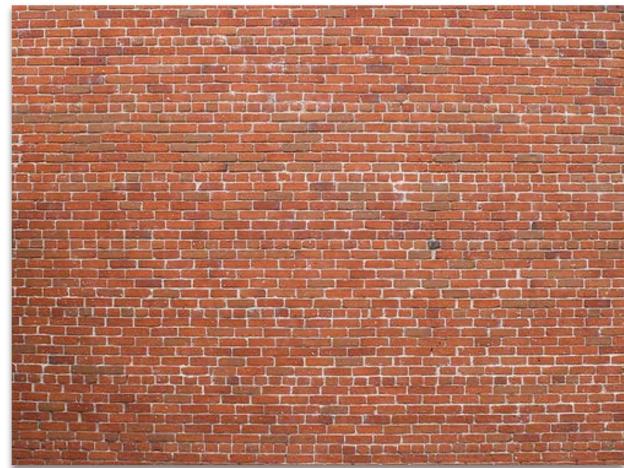


点到点的光栅化流程 End-to-end rasterization pipeline

目标：将输入变成图像

Inputs:

```
positions = {           texcoords = {  
    v0x, v0y, v0z,       v0u, v0v,  
    v1x, v1y, v1x,       v1u, v1v,  
    v2x, v2y, v2z,       v2u, v2v,  
    v3x, v3y, v3x,       v3u, v3v,  
    v4x, v4y, v4z,       v4u, v4v,  
    v5x, v5y, v5x       v5u, v5v  
};                      };
```



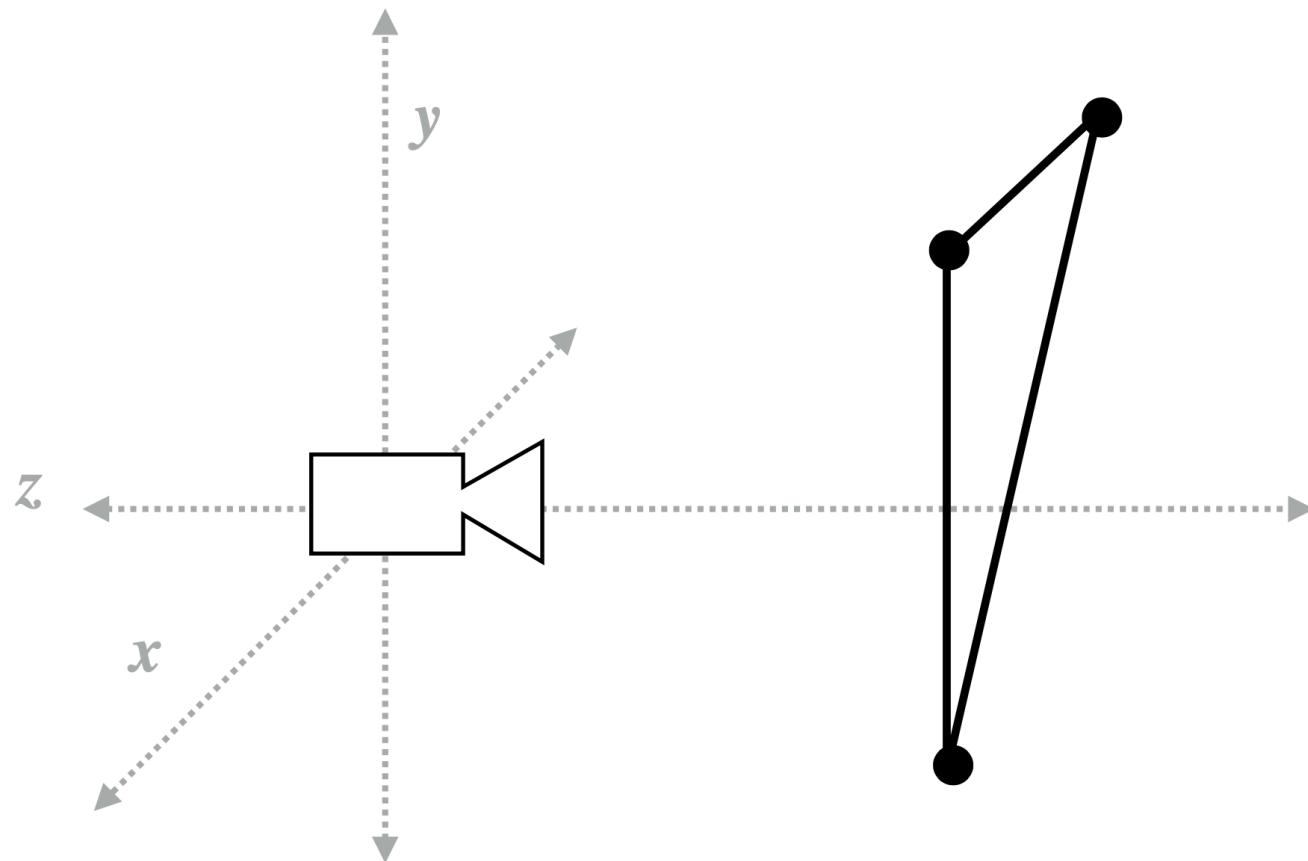
texture map

- 将物体转换到相机坐标： $T \in \mathbb{R}^{4 \times 4}$
- 透视投影转换： $P \in \mathbb{R}^{4 \times 4}$
- 显示器大小： $(W \times H)$

目前为止，我们已经有了制作图像所需的所有工具
让我们复习一下！

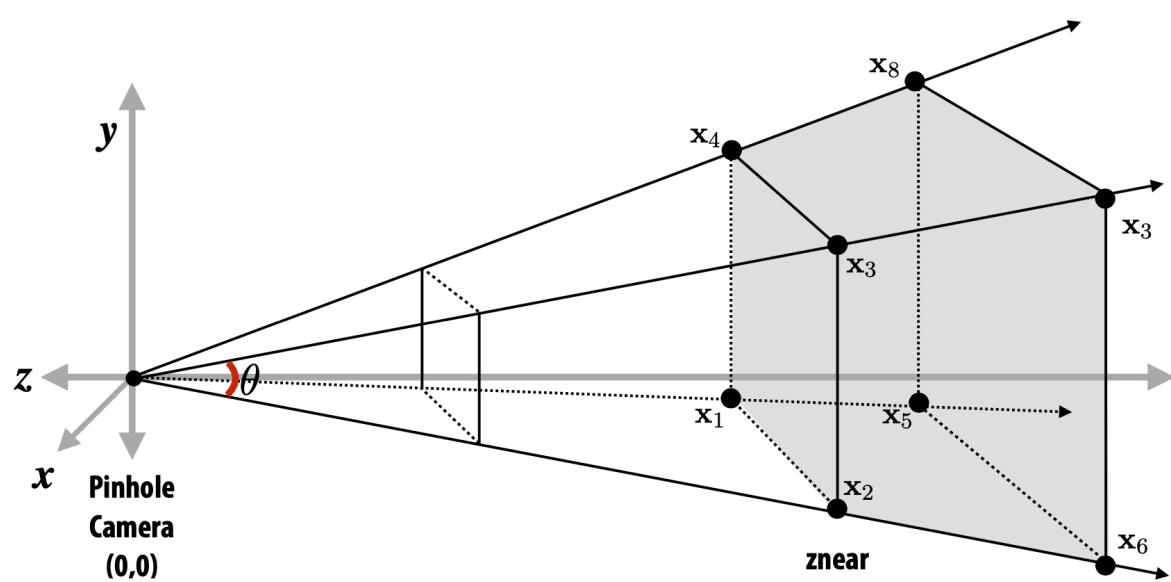
Step: 1

□ 将三角形的顶点转换到相机坐标系中

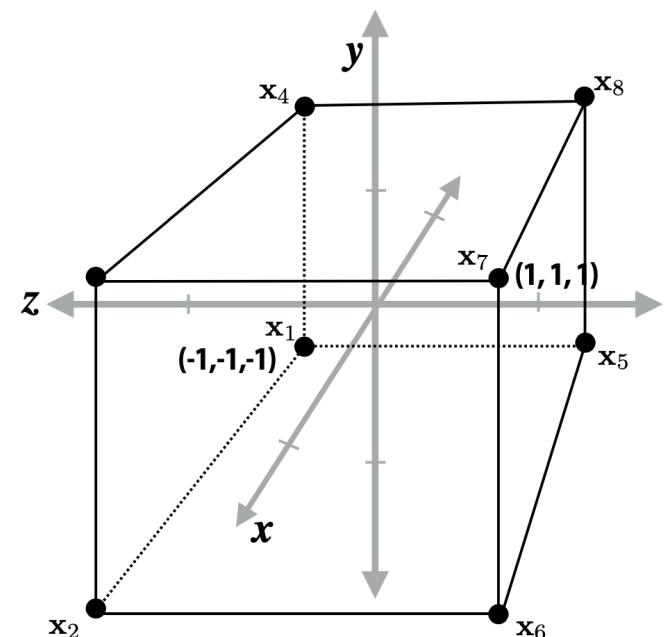


Step: 2

应用透视投影转换将三角形顶点转换到归一化的坐标空间



Camera-space positions: 3D



Normalized space positions

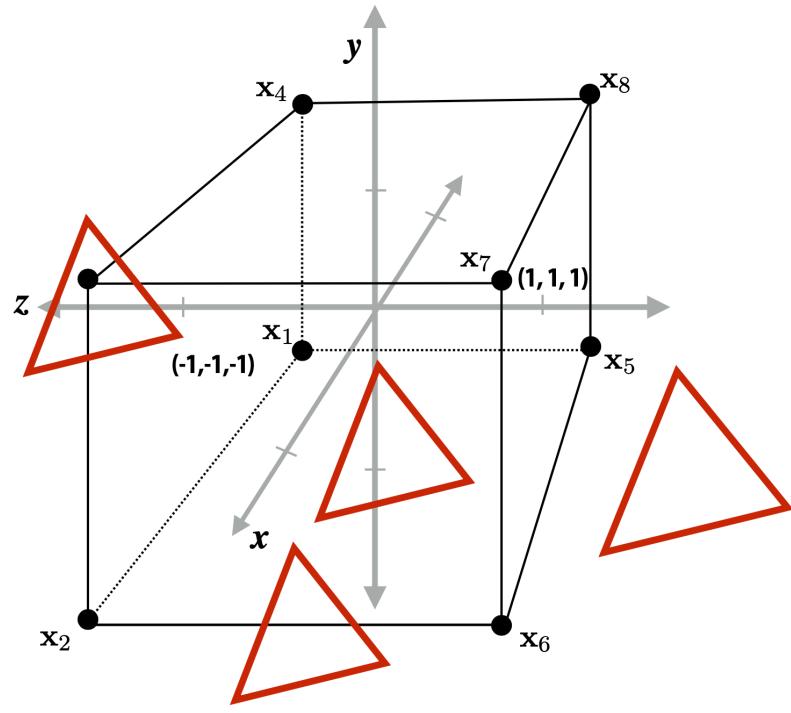
Step 3: 裁剪 Clipping

□丢弃完全位于单位立方体之外的三角形（剔除 culling）

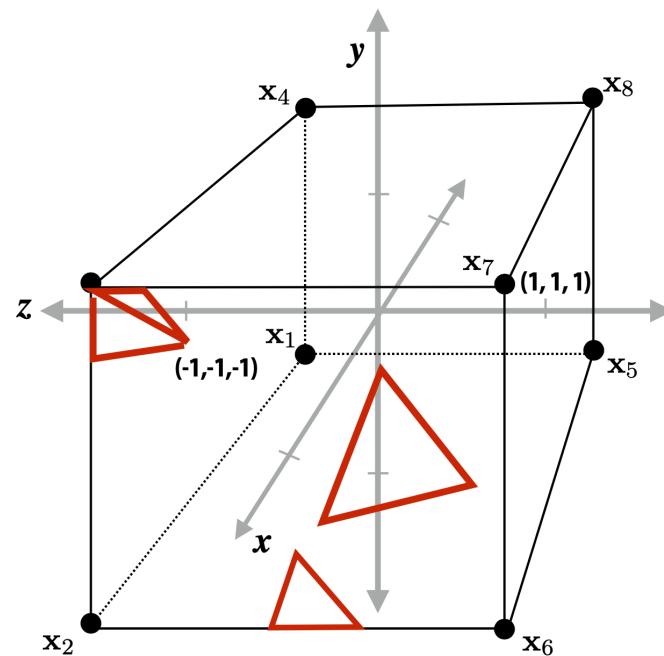
- 它们不在屏幕上，不用再处理了

□剪裁超出单位立方体的三角形

- 可能会生成新的三角形



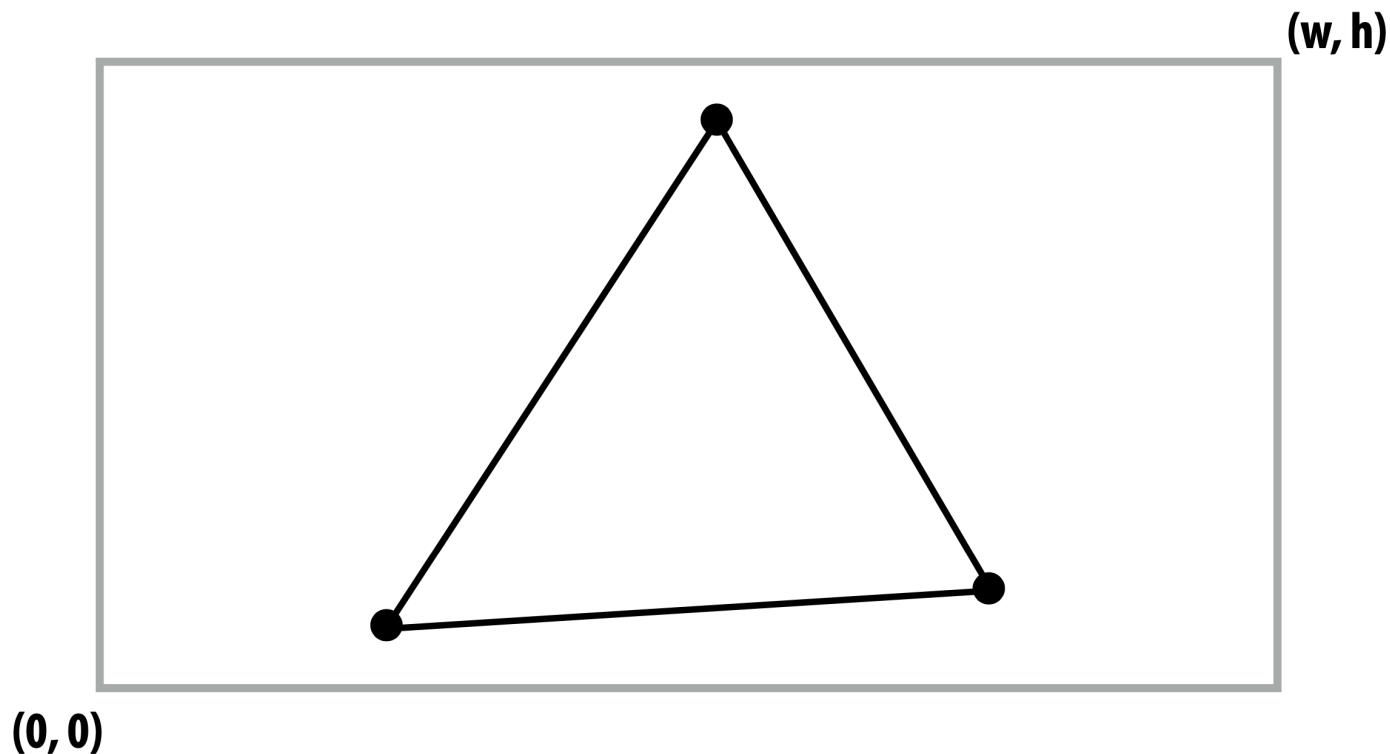
Triangles before clipping



Triangles after clipping

Step 4: 转换到屏幕坐标

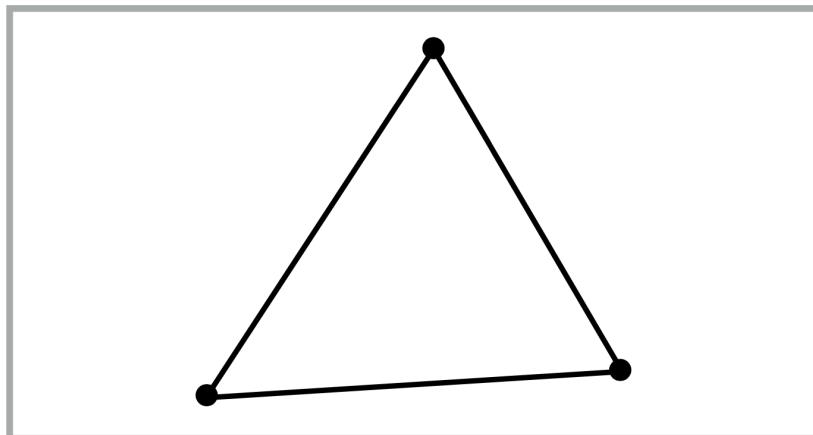
执行齐次分割，将顶点 (x, y) 位置从归一化坐标转换为屏幕坐标（屏幕大小为 $W \times H$ ）



Step 5: 三角形预处理

在光栅化三角形之前，可以预先计算一系列将被反复用到的函数，比如：

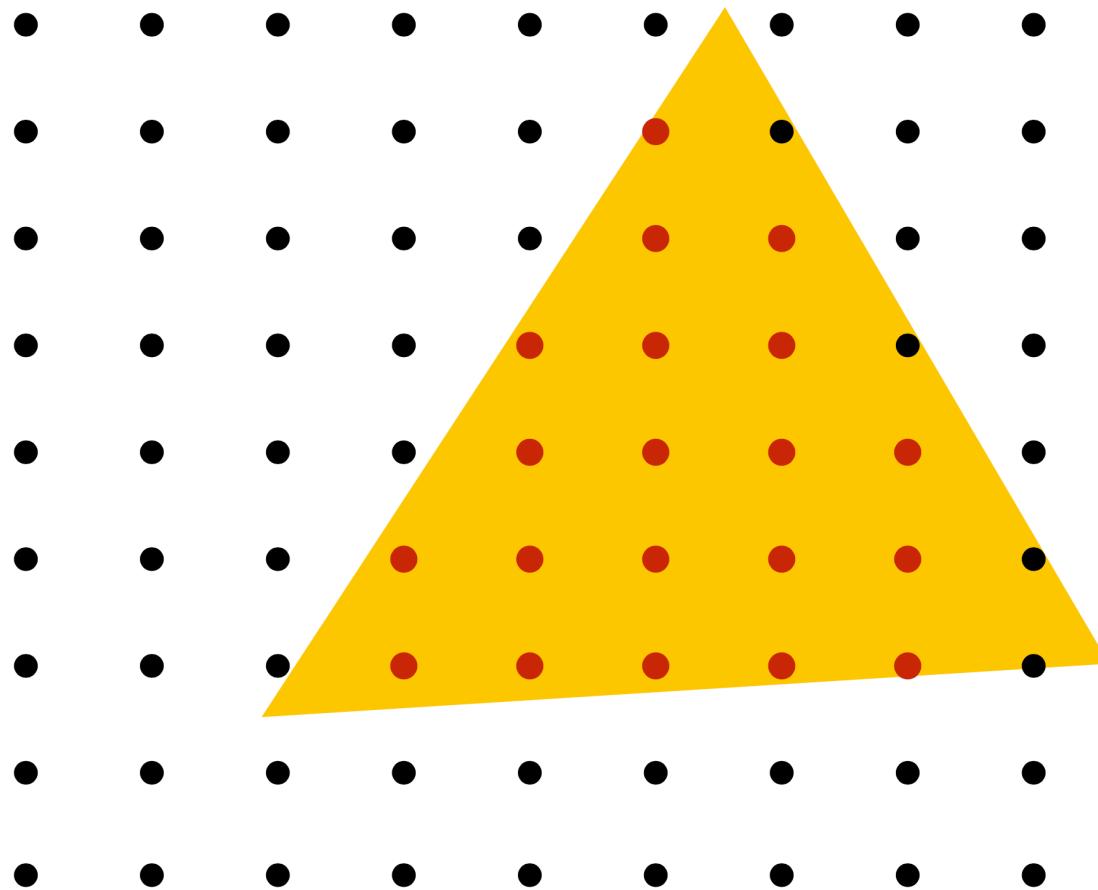
- 三角形边的公式
- 三角形属性的公式
- ...



| | |
|---------------------|-----------|
| $E_{01}(x, y)$ | $U(x, y)$ |
| $E_{12}(x, y)$ | $V(x, y)$ |
| $E_{20}(x, y)$ | |
| $\frac{1}{w}(x, y)$ | |
| $Z(x, y)$ | |

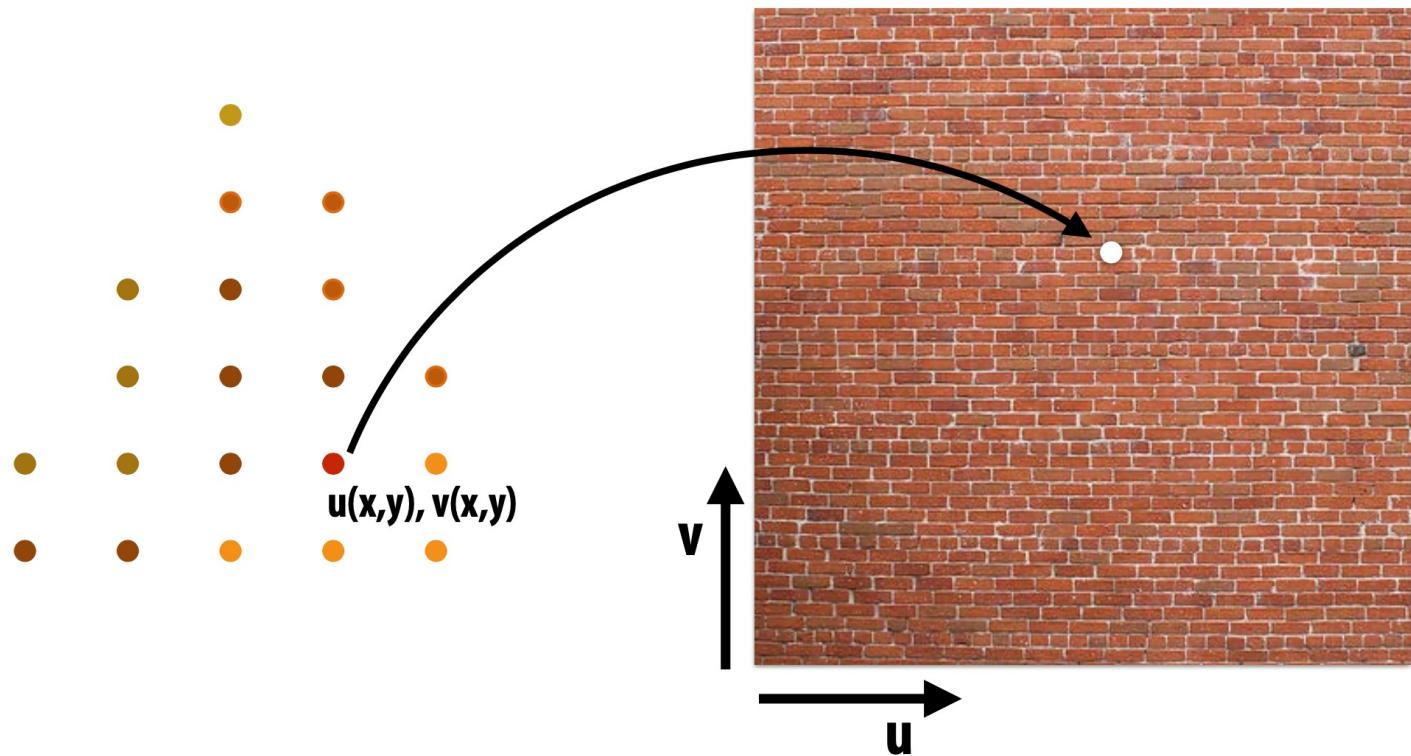
Step 6: 采样覆盖

□ 在所有覆盖的样本评估属性



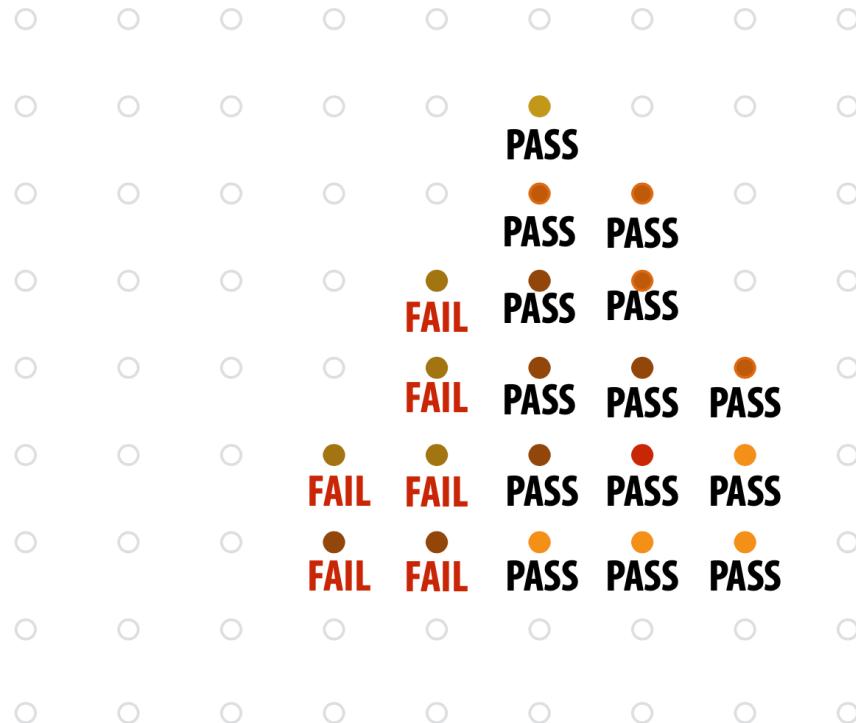
Step 6: 在样本点计算三角形的颜色

口比如，采样纹理映射

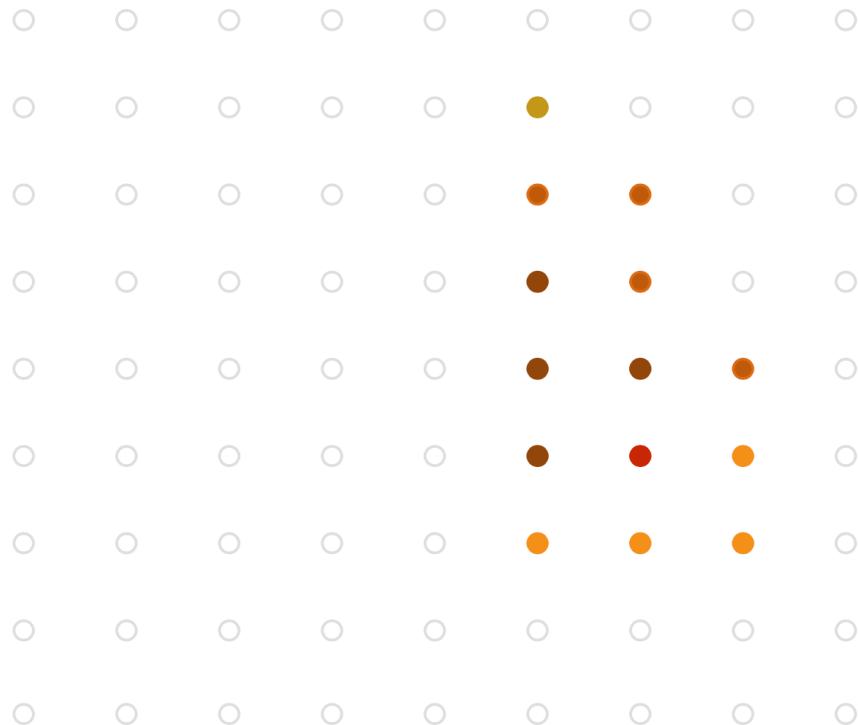


Step 7: 进行深度测试 (if enabled)

同时更新覆盖样本的深度值 (如有必要)



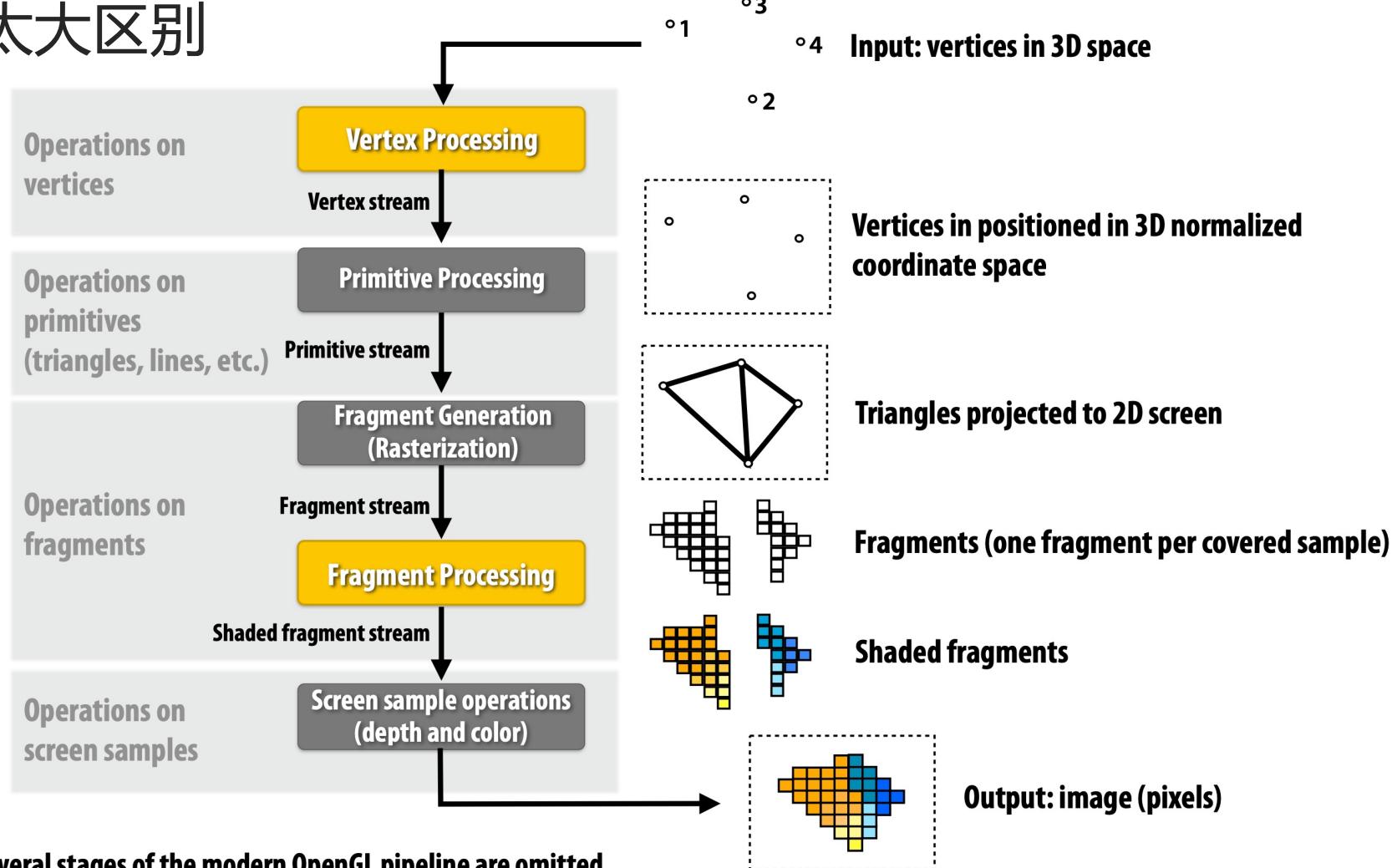
Step 8: 更新颜色缓存* (若通过深度测试)



*可能使用 over 操作来处理透明度

OpenGL/Direct3D graphics pipeline

口我们的光栅化流程与现代API/图形硬件中的实际流程没有太大区别



目标：渲染超高复杂度的 3D 场景

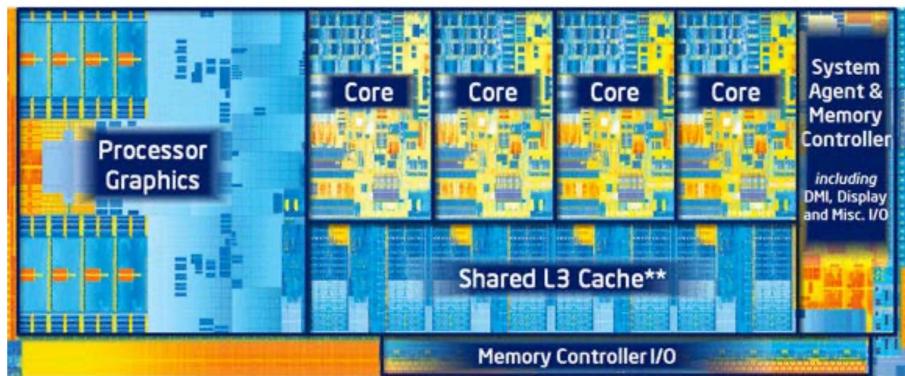
- 一个场景中可能包含百万个三角形
- 复杂的顶点和片段着色计算
- 高分辨率屏幕输出 (~10万像素+超采样), 30-120帧/秒



Unreal Engine Kite Demo (Epic Games 2015)

Graphics pipeline implementation: GPUs

口用于执行图形计算的专用处理器



integrated GPU: part of modern CPU die

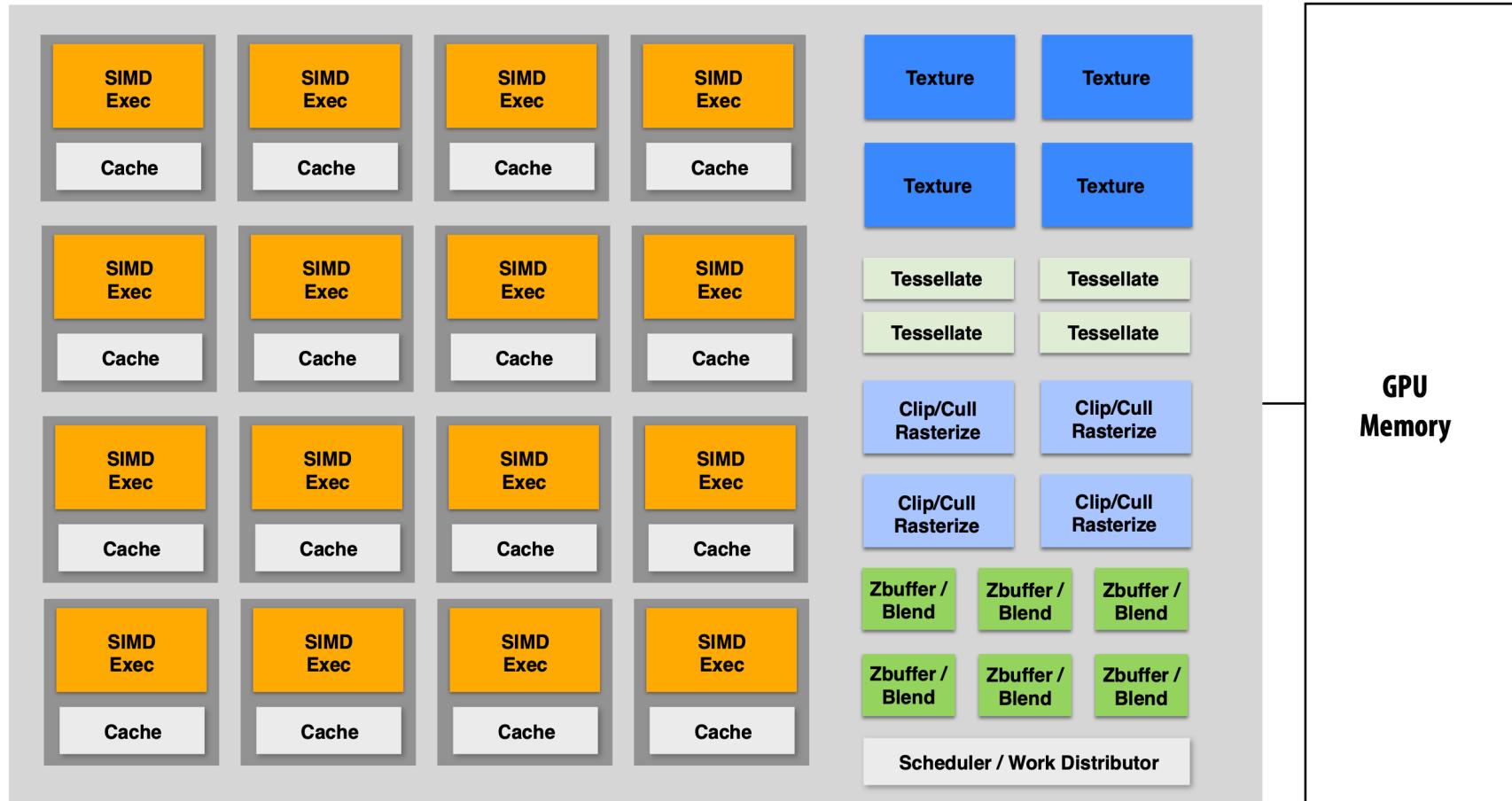
smartphone GPU (integrated)



GPU: 异构多核处理器

Modern GPUs offer ~35 TFLOPs of performance for generic vertex/fragment programs (“compute”)

still enormous amount of *fixed-function* compute over here

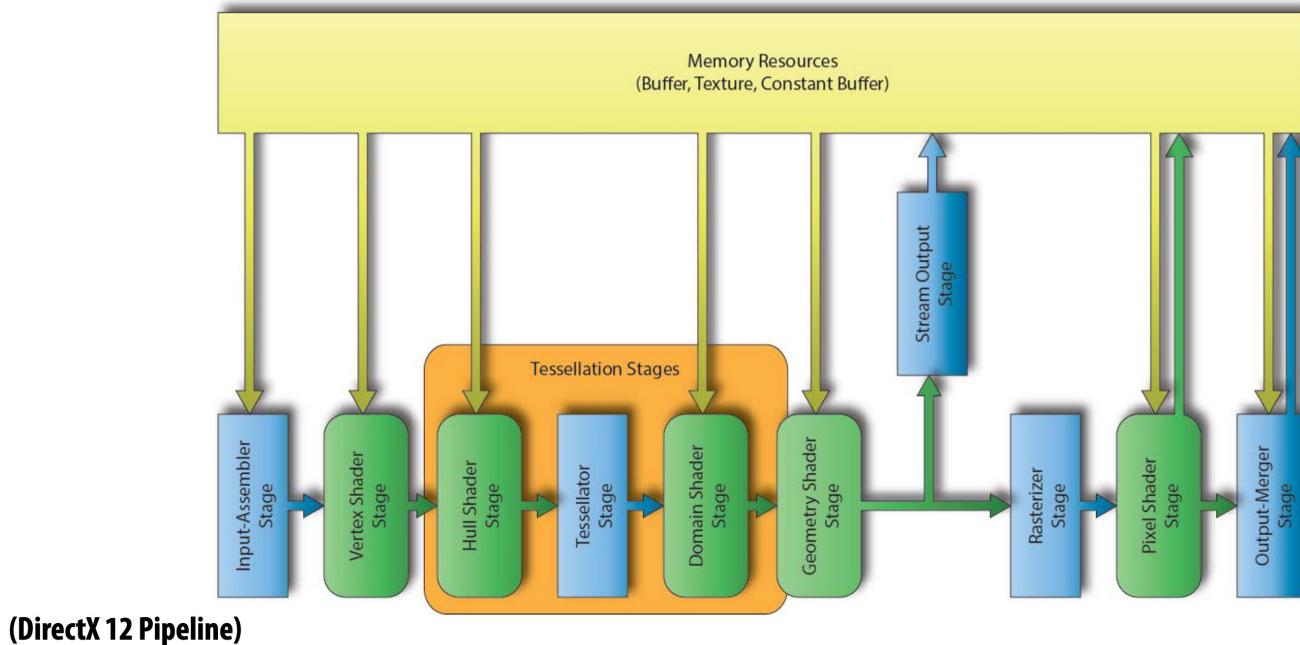


This part (mostly) not used by CUDA/OpenCL; raw graphics horsepower still greater than compute!

现代光栅化流程

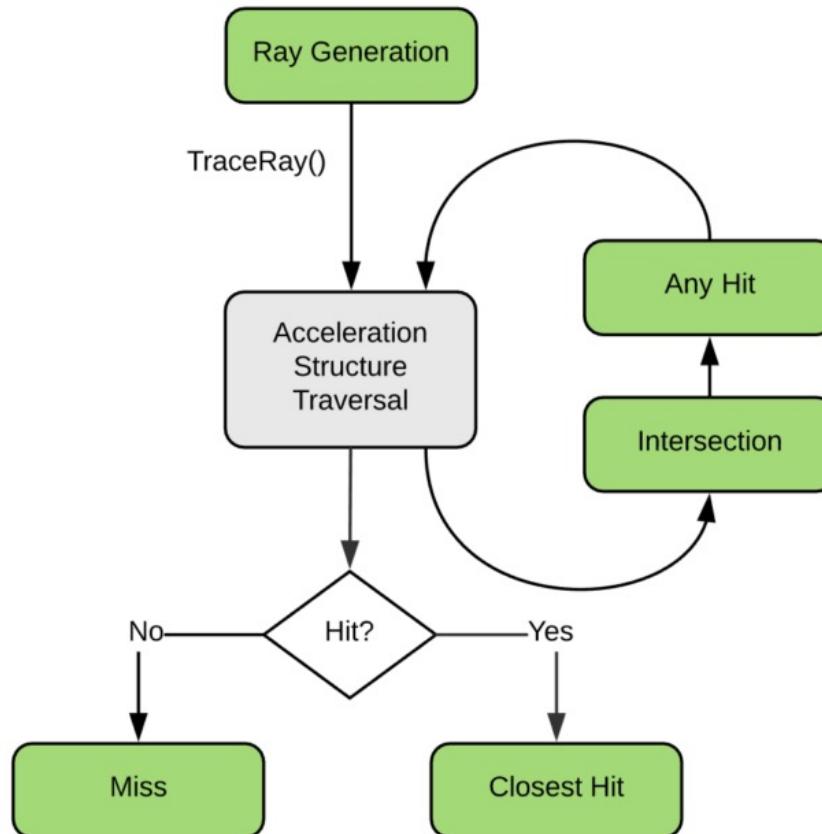
口趋向于更通用（但仍然高度并行！）的计算：

- 使阶段可编程
 - 替换固定的顶点，片段处理函数
 - 添加几何体，镶嵌着色器
 - 通用“计算”着色器
- 更灵活的阶段调度

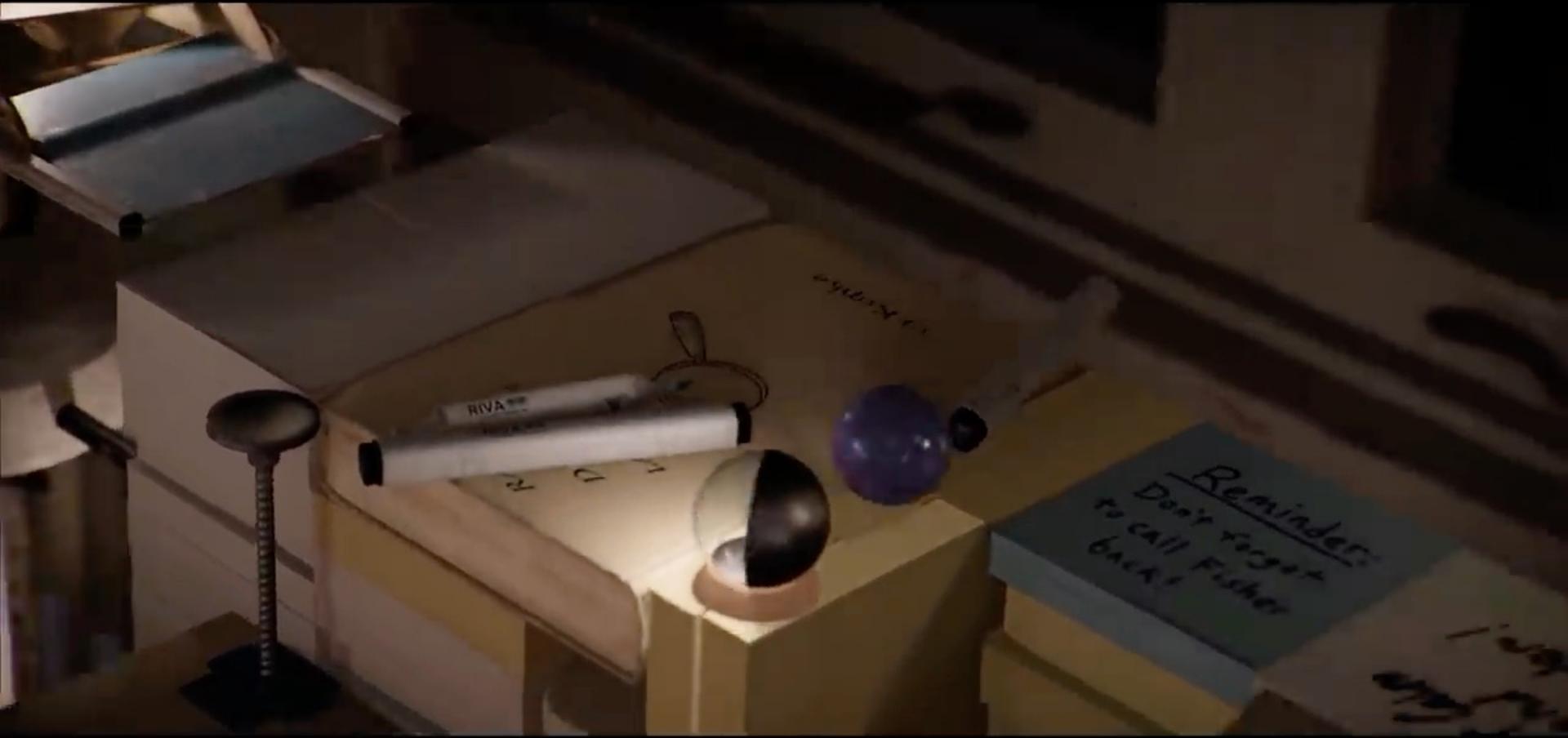


图形流程中的光线跟踪 (ray tracing)

口最近：光线跟踪的特定流程 (NVIDIA RTX)



GPU Ray Tracing Demo (Marbles at night)



我们还要知道什么才能生成这样的图像？

□ 几何形状 (Geometry)

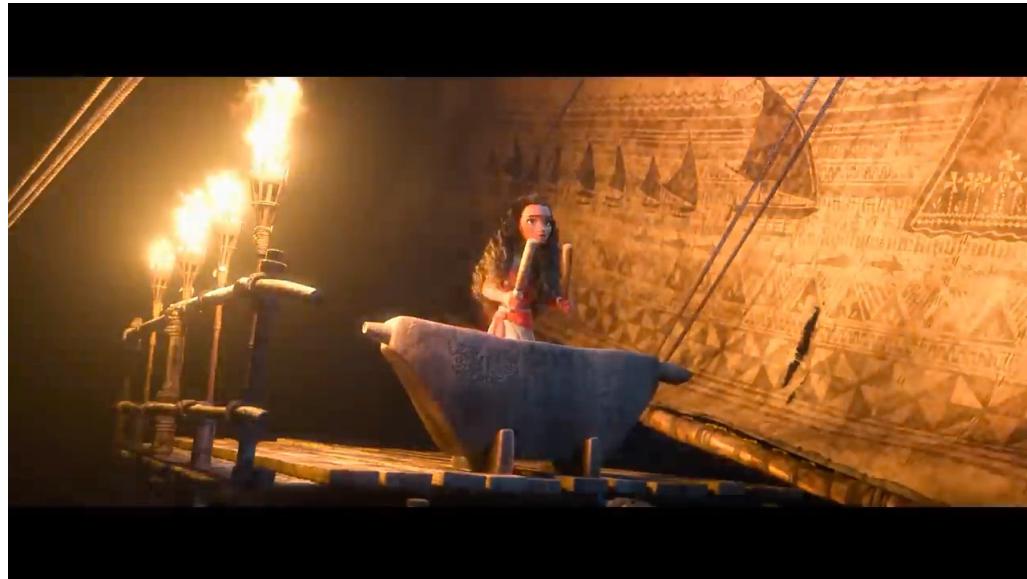
- 我们如何描述复杂的形状 (到目前为止只有三角形...)

□ 渲染 (Rendering)

- 光是如何与材料相互作用产生颜色的？

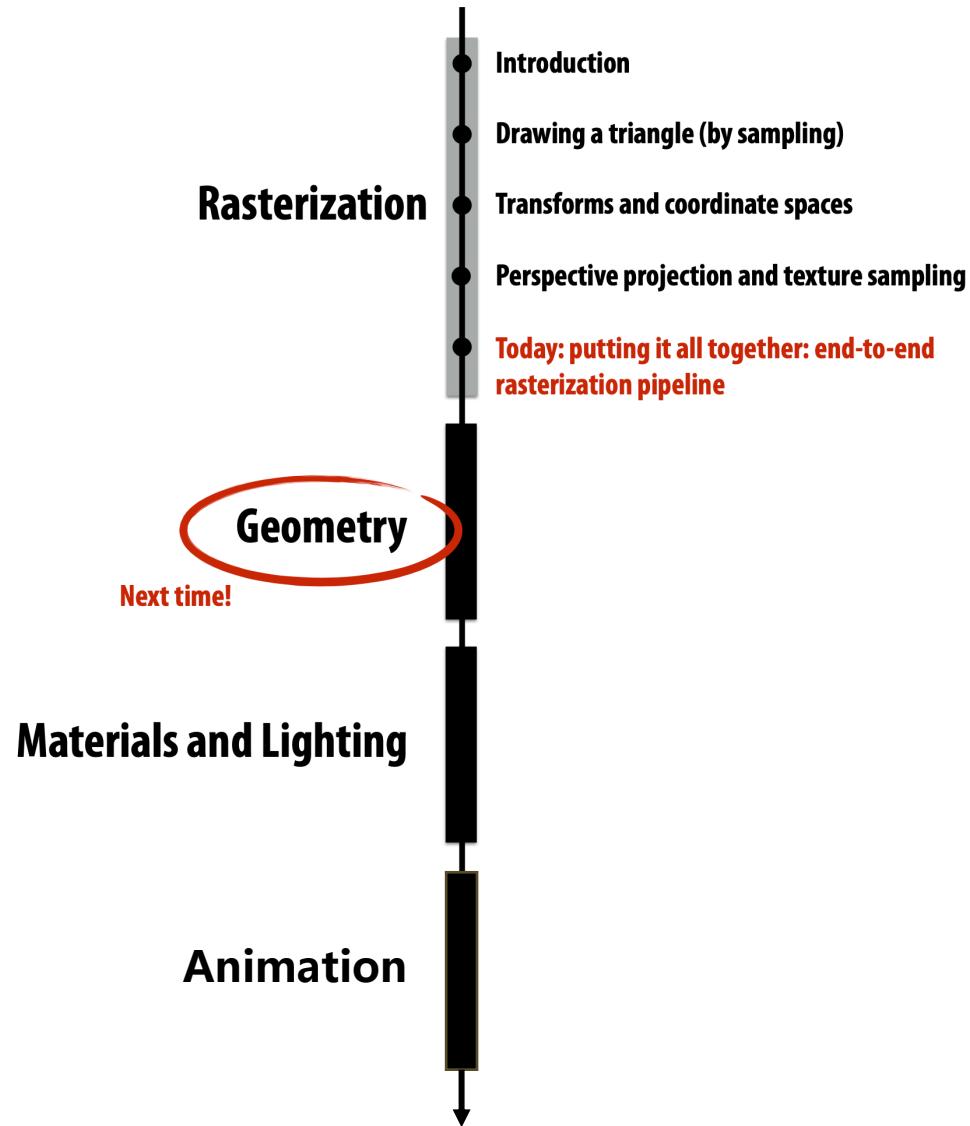
□ 动画 (Animation)

- 我们如何描述事物的运动方式？



迪士尼“摩阿娜”

Course roadmap





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谢谢

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