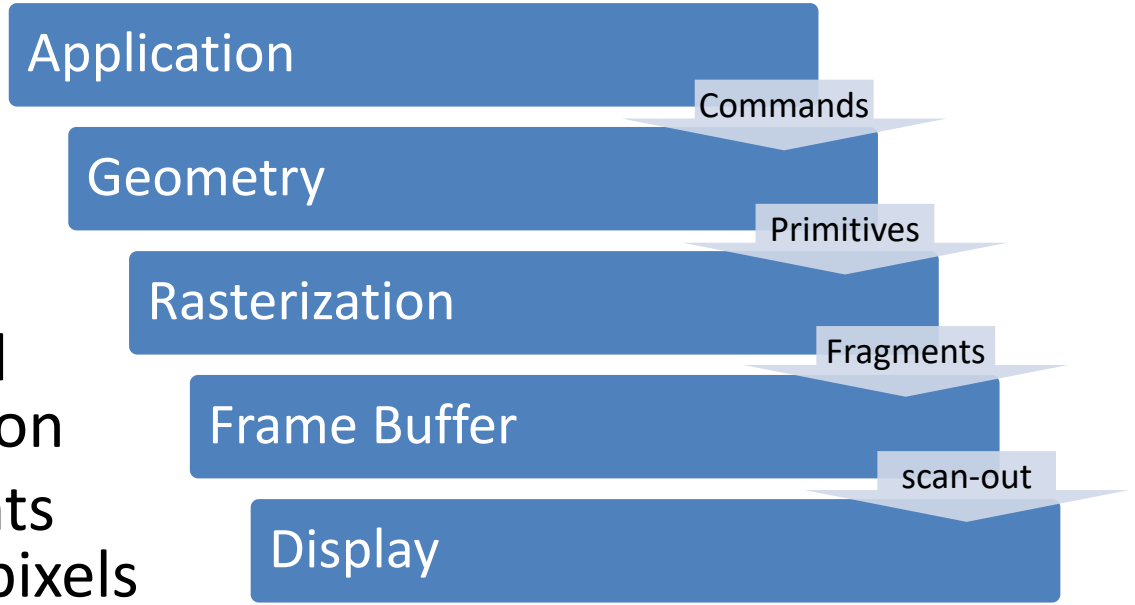
# The Graphics Pipeline

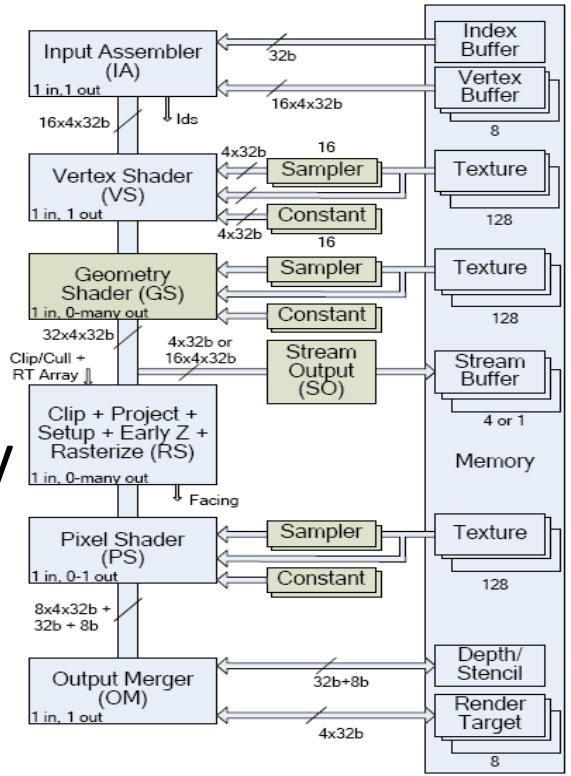
- High-level view:




- "Fragment":
  - Sample produced during rasterization
  - Multiple fragments are *merged* into pixels

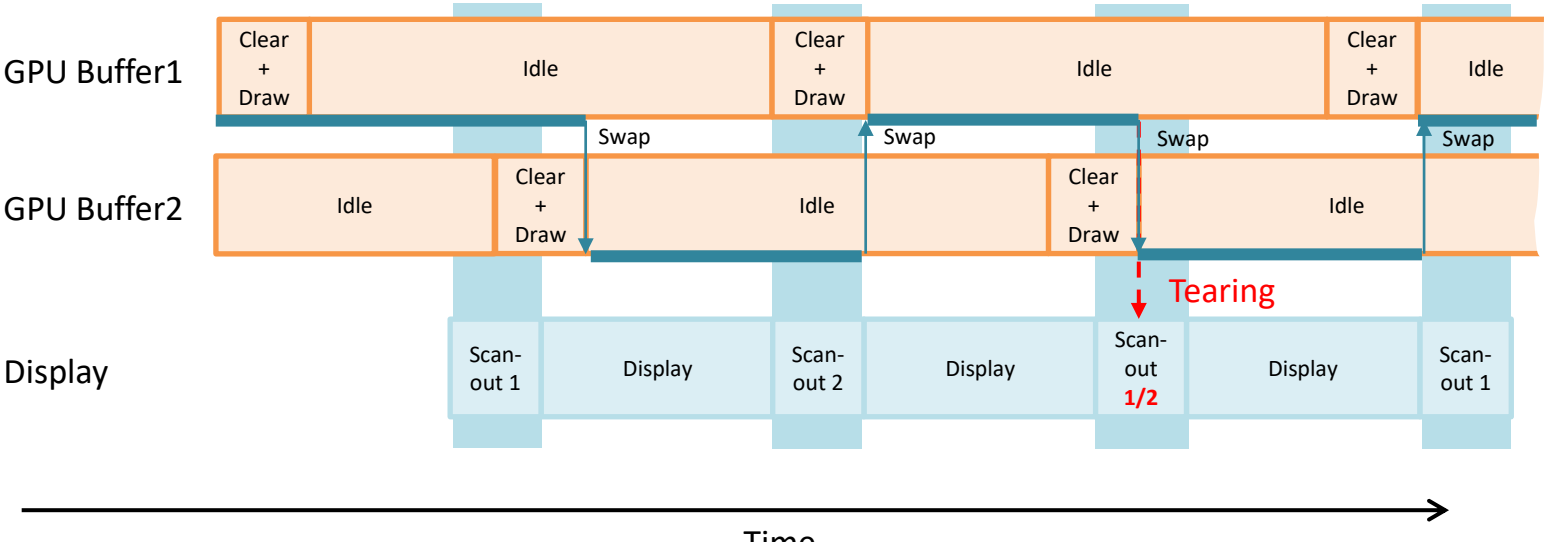
# Geometry Shader

- Between vertex and pixel shader
- Can generate primitives dynamically
- Procedural geometry
  - E.g., growing plants
- Geometry shader can write to memory
  - Called „stream output“
  - Enables multi-pass for geometry



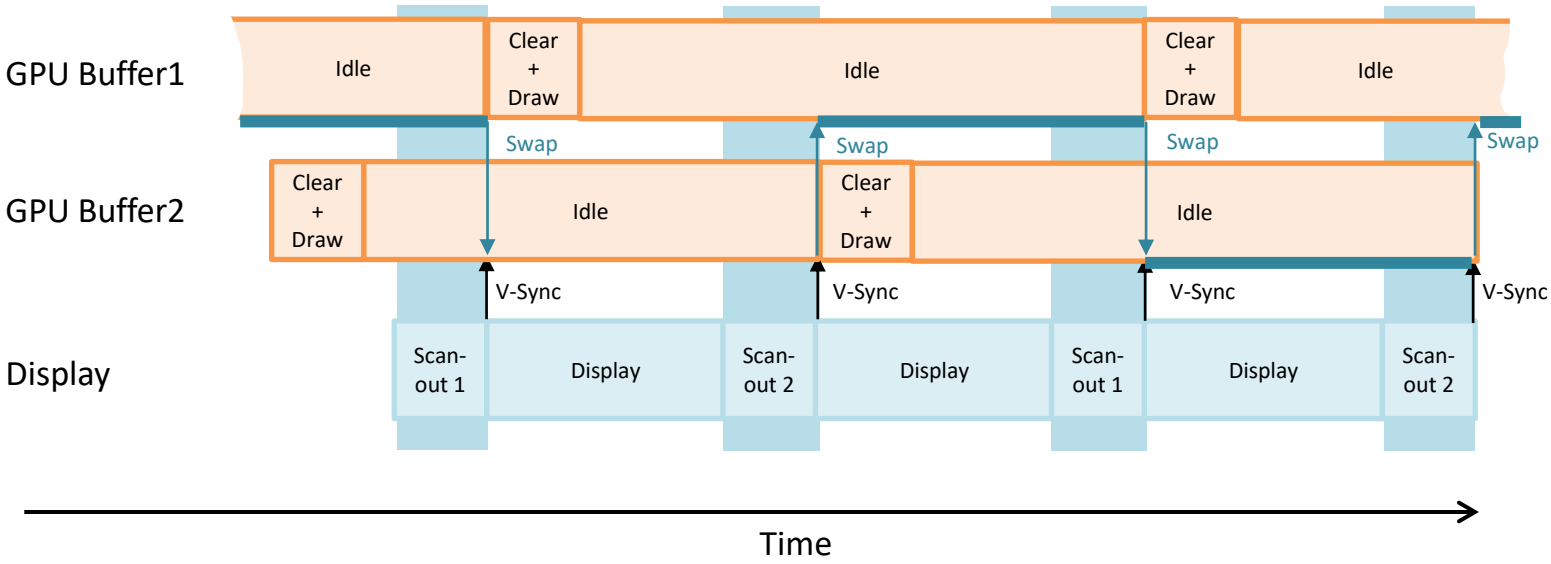
# Double Buffering without V-Sync

- Front buffer used for scan-out GPU→display
- SwapBuffers() changes front and back buffer
- No flickering, but tearing artefacts



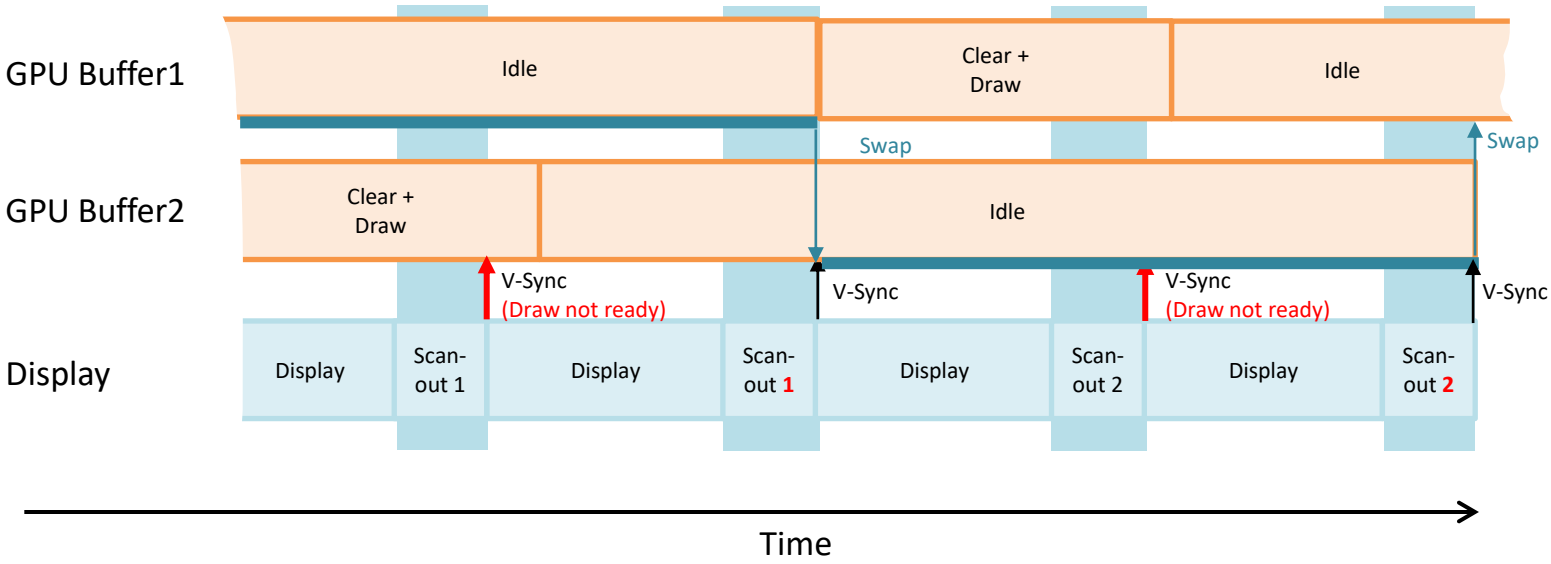
# Double Buffering with V-Sync, Fast

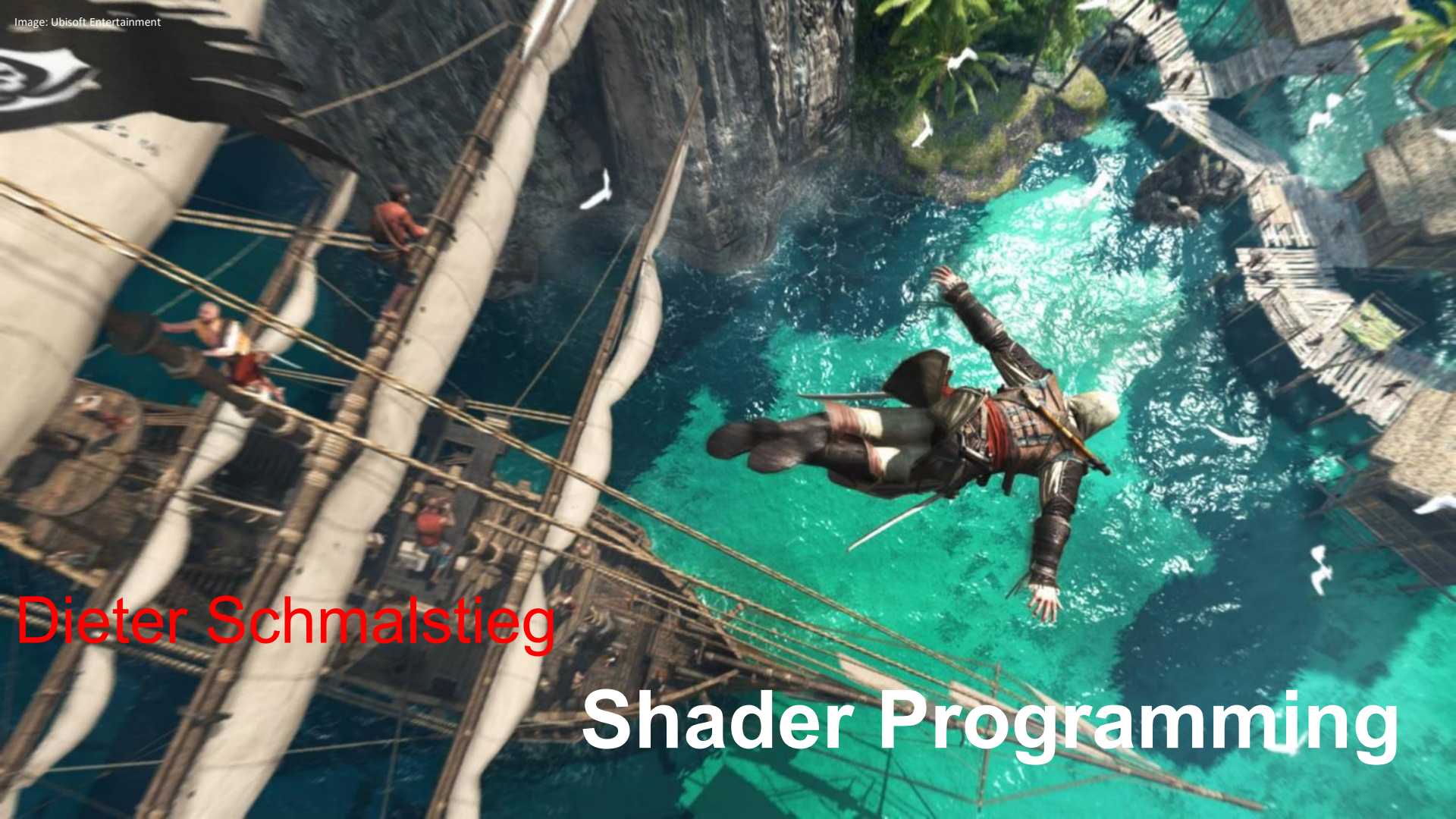
- V-Sync means the display is done with frame scan-out from GPU
- When rendering is **fast**, the frame rate is limited by display rate
- Additional latency of max. one frame time



# Double Buffering with V-Sync, Slow

- When rendering is **slow**, frame rates can only be integer fractions of display rate
- Display rate 60Hz → frame rates 60, 30, 20, 15, … (but not 59) possible
- Adaptive V-Sync (NVIDIA) turns off V-Sync automatically if rendering is slow






Dieter Schmalstieg

# Shader Programming

# Traditional API

- **Graphics context**: the system object in a traditional API
  - OpenGL, DirectX11 and below
  - Represents a virtual GPU
  - One process can have multiple contexts
  - Multiple contexts can share resources
- **Current context** for a given process
  - One to one mapping
    - Maximum of one current context per thread
    - Current context only assigned to one thread at the same time
  - All OpenGL operations work on current context

# Modern API

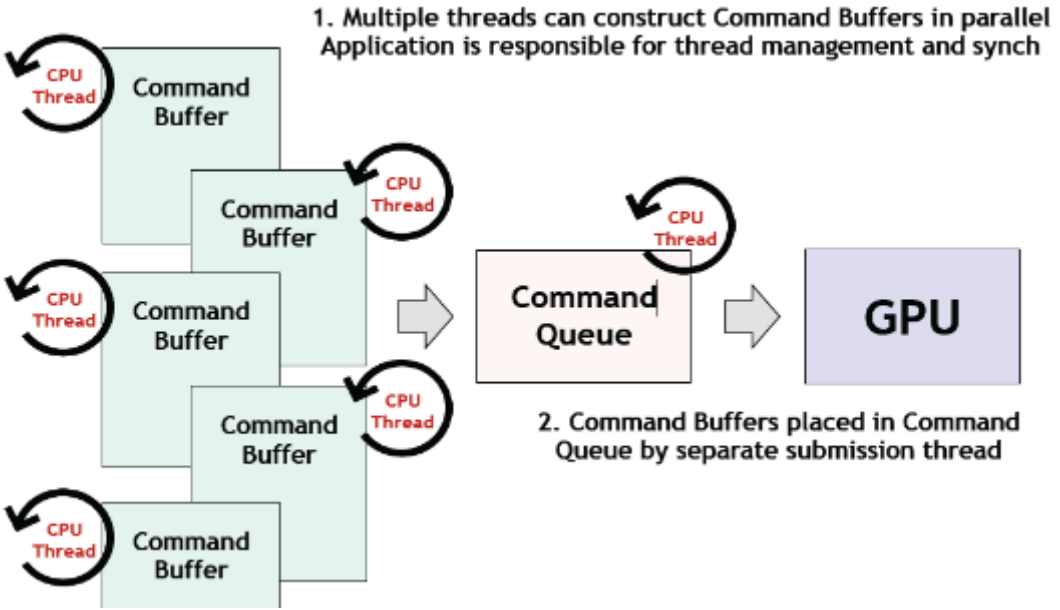
- DirectX 12, Vulkan (=OpenGL successor)
- Designed for modern GPU types (including mobile)
- Make (CPU driver side of) pipeline more programmable
- CPU multi-threading possible (at your own risk)
- Split rendering context into command buffers and queues
- Make pipeline state (and render passes) explicit
- Low overhead
- Fine-grained control (minimal program 1K lines of code)

# Command Buffers

- Commands collected in command buffers
  - Optimize and validate command buffers during building, not during submission
  - Yields *immutable*, re-useable pipeline state configurations
  - Selected pipeline state variables can be declared *mutable*
- Command buffer submitted to *queue* for execution
- Build *many* command buffers from *many* threads
  - When the buffers are ready, one can submit them all at once
- Each command buffer just *switches* to its favorite pipeline
- Can use *synchronization* primitives across command buffers
  - Event, barrier, semaphore, fence

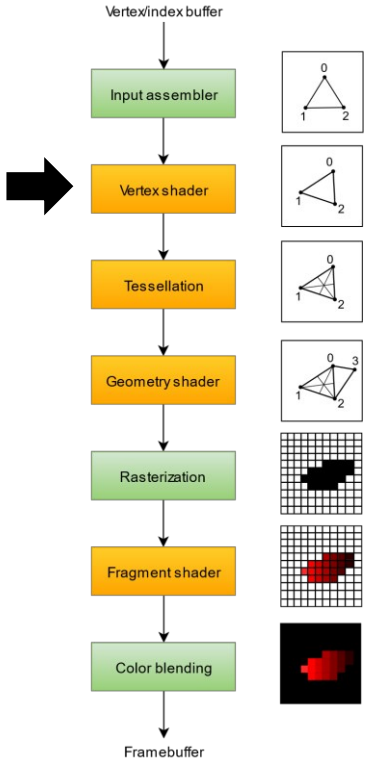
# Queues

- Queues replace traditional contexts
- Insert command buffer into queue to schedule it



# Vertex Shader

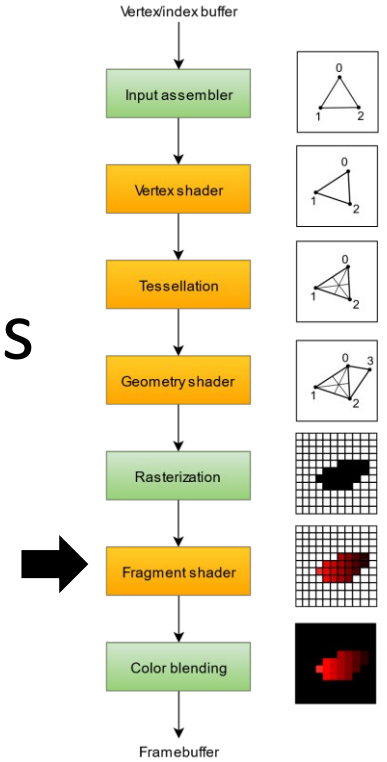
- Processes each vertex
- Input: vertex attributes
- Output: vertex attributes
- Mandatory output: gl_Position




Blinn-Phong Vertex Shader

# Fragment Shader

- Processes each fragment
- Input: interpolated vertex attributes
- Output: fragment color



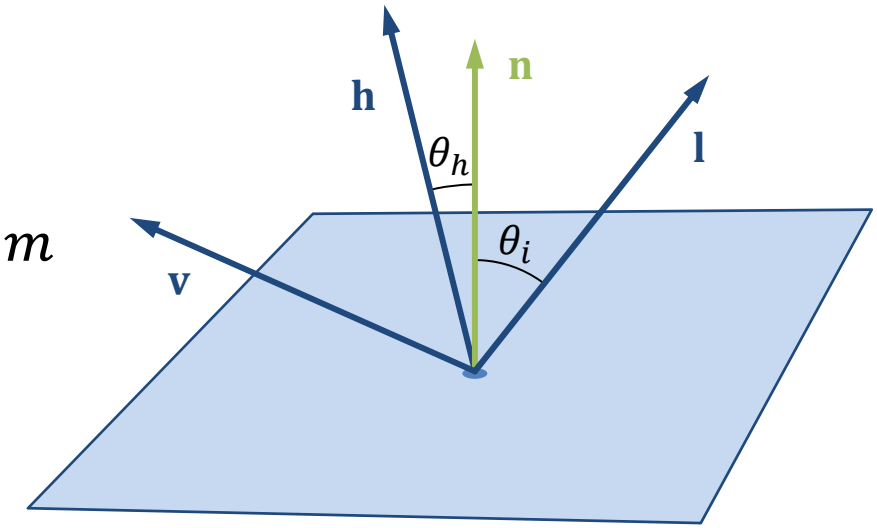

Phong, Blinn-Phong Fragment Shader


Image source: Epic Games
Shading Models

Es berechnet die Beleuchtung auf einer Oberfläche anhand der Intensität des einfallenden Lichts, der Materialeigenschaften (z.B. Farbe und Oberflächenbeschaffenheit) und der Richtung des beobachtenden Auges.

# Blinn-Phong Model

- Approximates energy conservation
- $f_r = \frac{\mathbf{c}_d}{\pi} + \frac{m+8}{8\pi}\mathbf{c}_s(\cos\theta_h)^m$
  - $\mathbf{c}_d$ Diffuse color
  - $\mathbf{c}_s$ Specular color
  - $m$ Specular power




$$\mathbf{h} = \frac{\mathbf{v}+\mathbf{l}}{\|\mathbf{v}+\mathbf{l}\|}$$

All vectors assumed to be normalized!



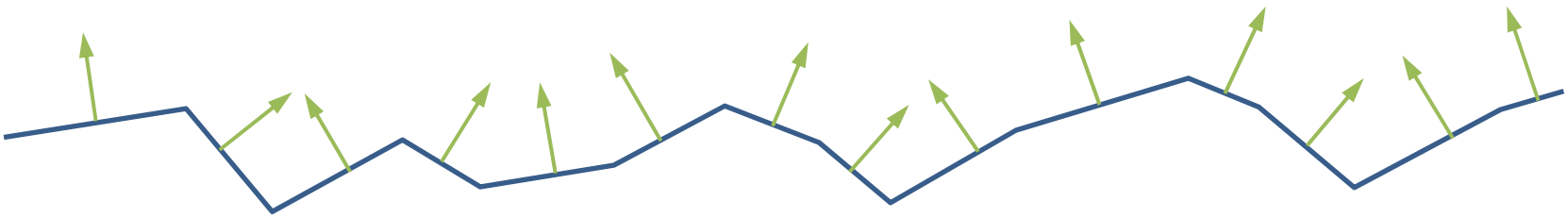
Der Half-Vector ist ein vereinfachter Schätzwert für die Richtung des spiegelnden Lichts, der berechnet wird, indem man die Richtung des einfallenden Lichts und die Richtung des beobachtenden Auges miteinander verbindet. Dieser Half-Vector wird verwendet, um die Reflexionen auf der Oberfläche zu berechnen, anstatt den exakten Glanzwinkel zu berechnen, wie es beim Phong-Modell der Fall ist.

# Fresnel Laws

- What happens at boundary between two media
  - Phase speed of light different in each medium
- Part of the light wave is directly *specularly* reflected
- Part of the light wave is transmitted
  - We assume the material is not transparent
  - The transmitted part becomes the *diffuse* reflection
- What is the exact ratio?
  - *Augustin-Jean Fresnel knows.*

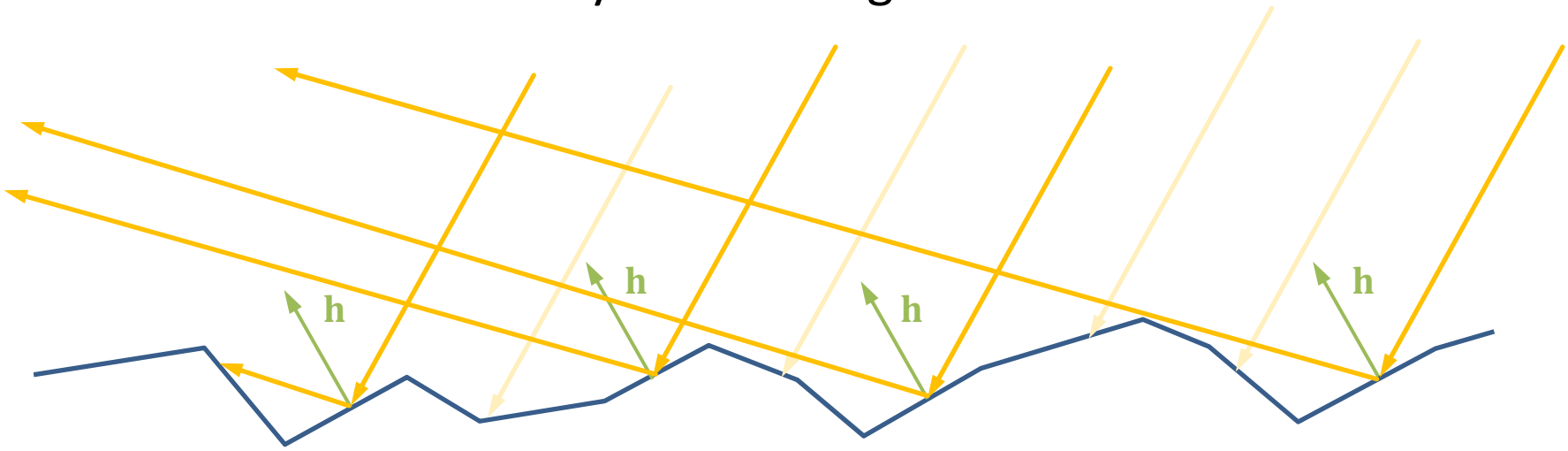
# Microfacets

- Surface assumed to be made up of tiny mirrors
  - Lots of tiny mirrors
- Need to model the distribution of mirrors



# Half-Vector

- Only mirrors oriented halfway between light and view direction reflect light into camera
- Direction **h** … halfway between light and view direction



# Microfacet Distribution

- Fraction of microfacets oriented in direction $\mathbf{h}$
- Example: Beckmann Distribution

$$D(\mathbf{n}, \mathbf{h}, m) = \frac{1}{4m^2(\mathbf{n} \cdot \mathbf{h})^4} \exp\left(\frac{(\mathbf{n} \cdot \mathbf{h})^2 - 1}{m^2(\mathbf{n} \cdot \mathbf{h})^2}\right)$$

$m$ Root mean squared slope of microfacets (corresponds to roughness)

[Beckmann, Spizzichino 1963]

# Geometric Attenuation

- Accounts for shadowing
  - Light blocked from reaching microfacet by other microfacets
- Accounts for masking
  - Reflected light blocked from reaching camera by other microfacets
  - Example: Torrance-Sparrow model

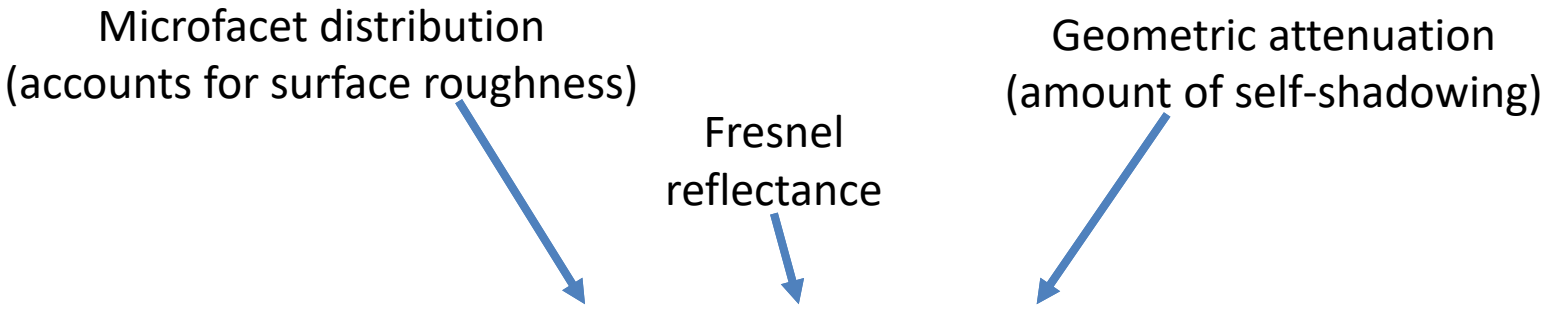
$$G(\mathbf{l},\mathbf{v}) = \min\left(1, \frac{2\cos\theta_h \cos\theta_o}{\cos\alpha_h}, \frac{2\cos\theta_h \cos\theta_i}{\cos\alpha_h}\right)$$

$\cos\theta_h = h \cdot n$
$\cos\theta_o = v \cdot n$
$\cos\alpha_h = v \cdot h$

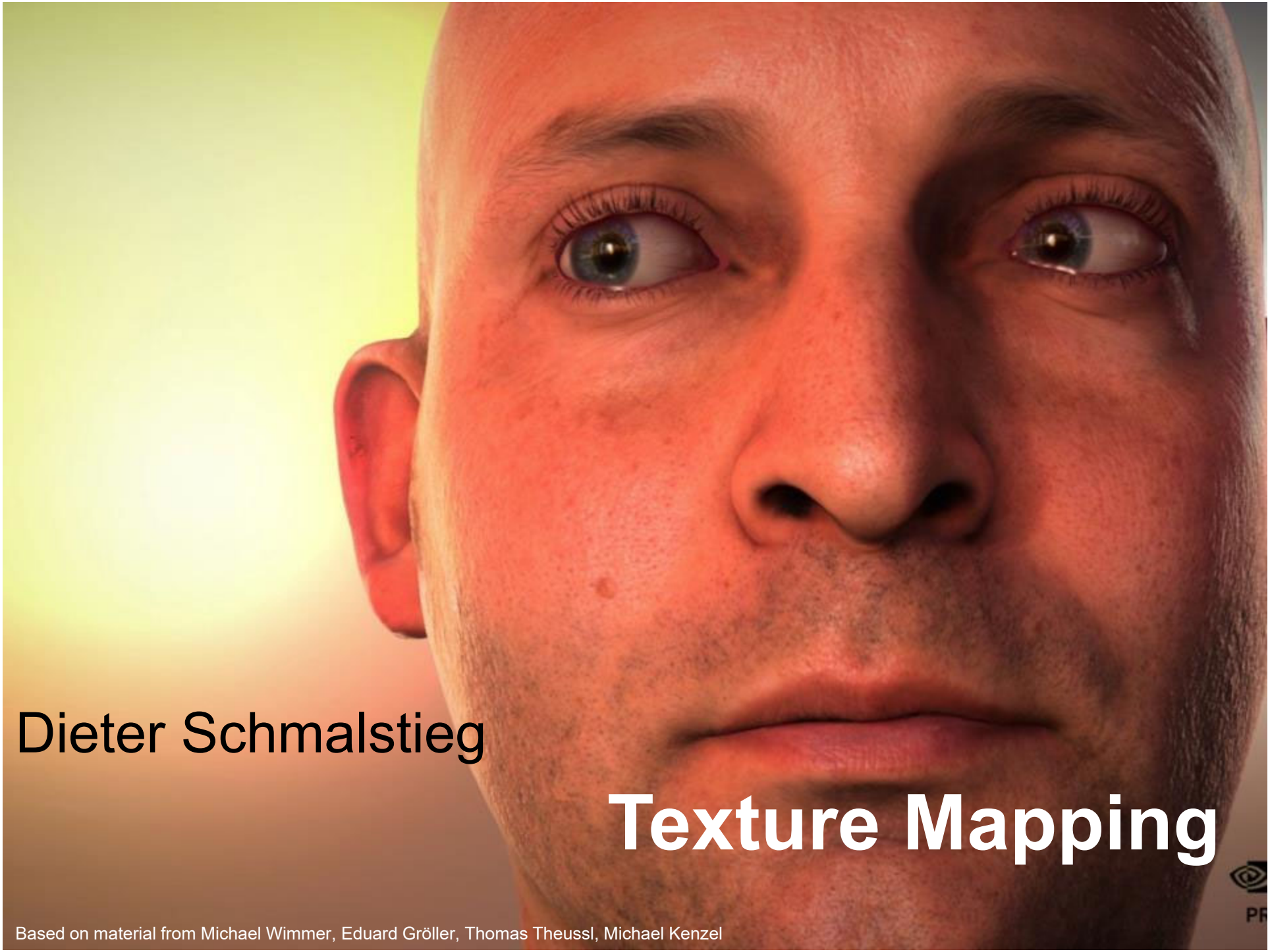
[Torrance, Sparrow 1967]

# Cook-Torrance Model

Popular shading model which is putting all these components together




$$f_r(\mathbf{l},\mathbf{v}) = \frac{D(\mathbf{h})F(\mathbf{l},\mathbf{v})G(\mathbf{l},\mathbf{v})}{4(\mathbf{n}\cdot\mathbf{v})(\mathbf{n}\cdot\mathbf{l})}$$



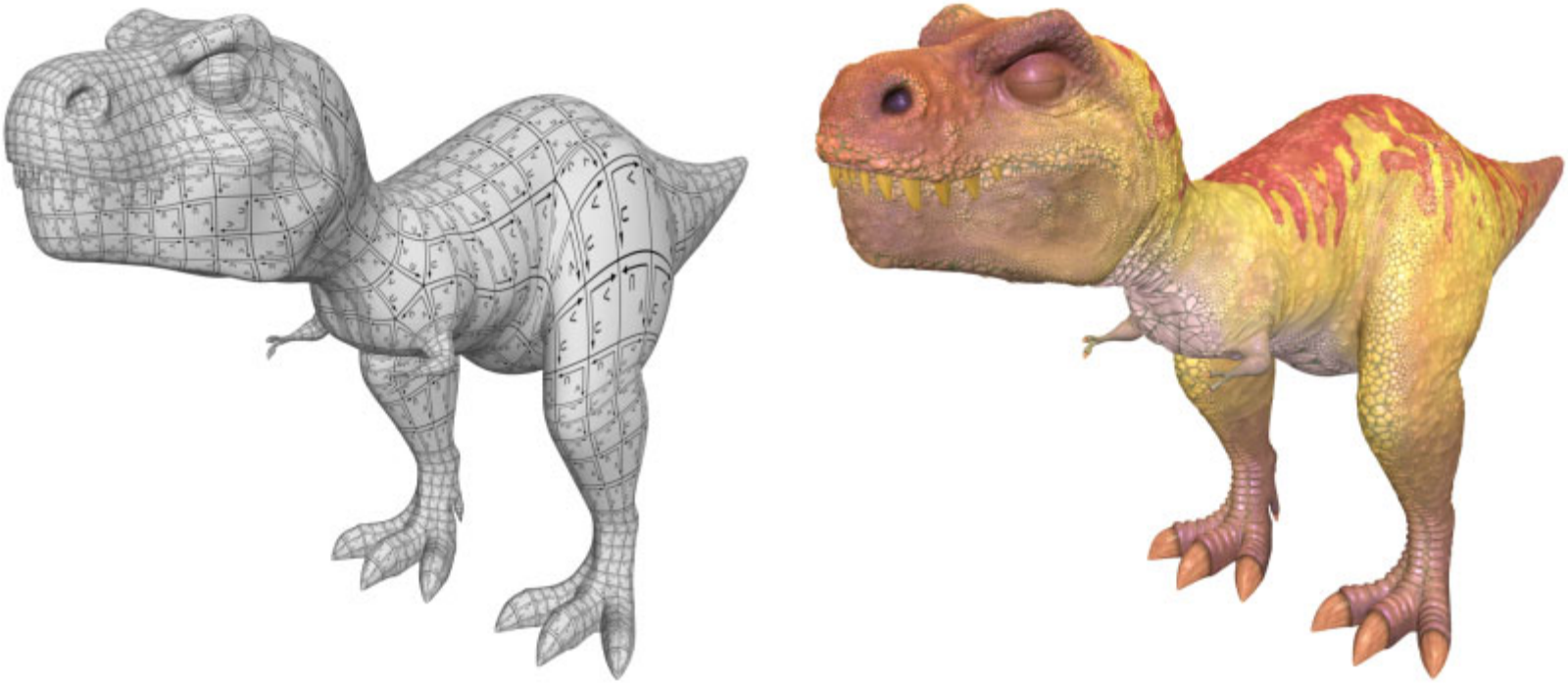
Dieter Schmalstieg

# Texture Mapping

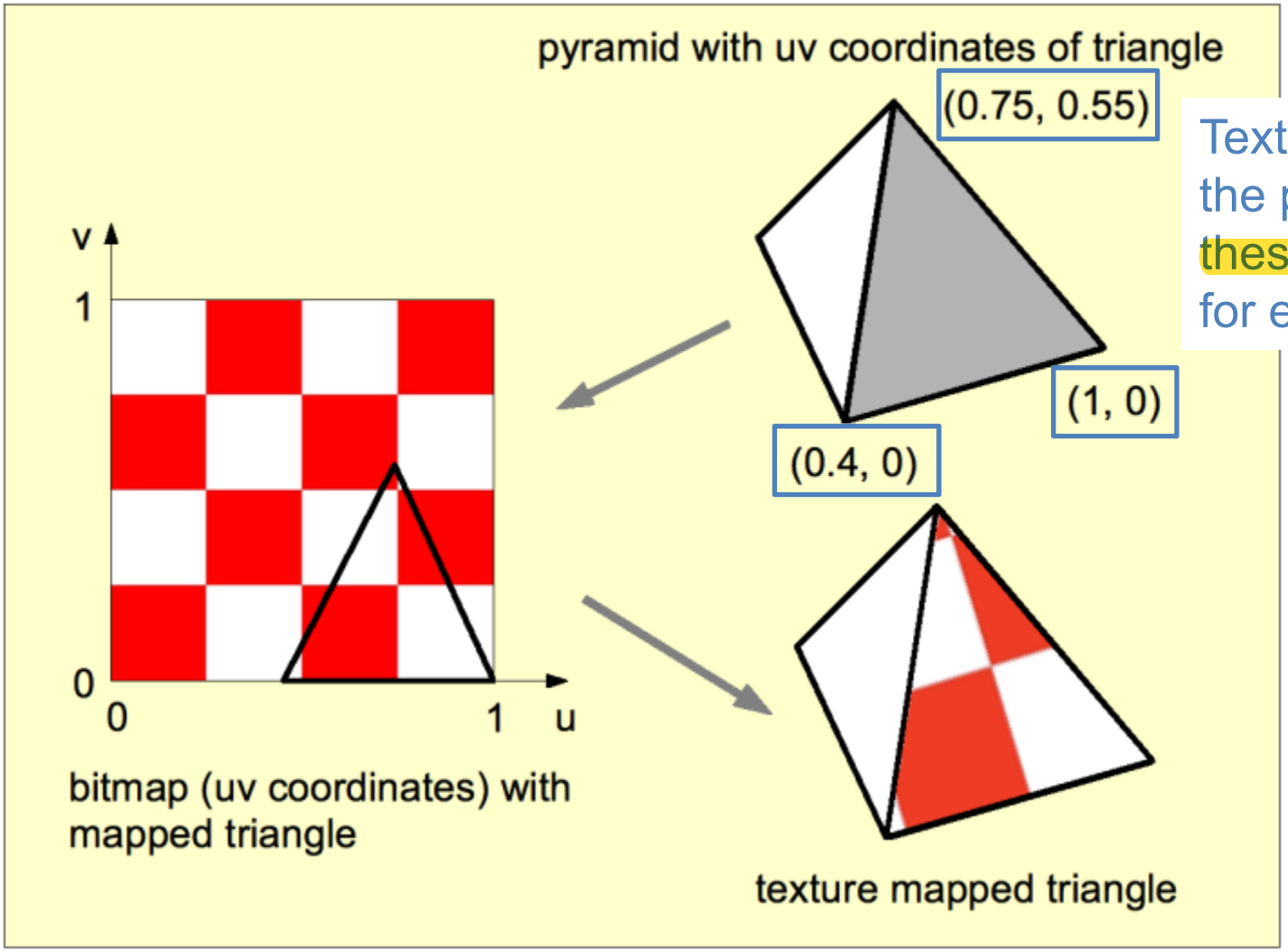
Based on material from Michael Wimmer, Eduard Gröller, Thomas Theussl, Michael Kenzel

# Why Texturing?

- Enhance visual appearance of plain surfaces and objects by applying fine structured details



# Texture Coordinates




Texture mapping is the process of finding these (u,v) coordinates for each vertex!

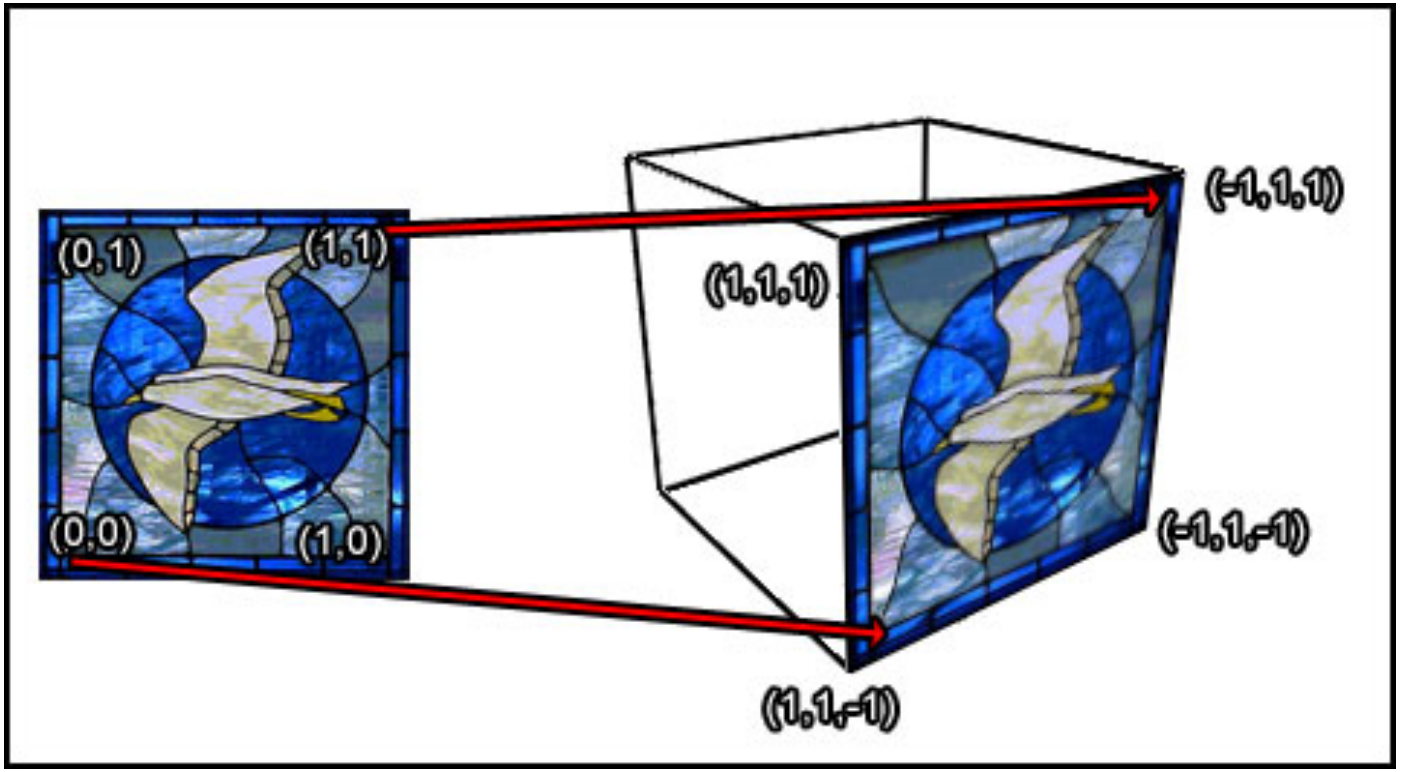
Das Texture Mapping mit (u,v) Koordinaten nutzt ein zweidimensionales Texturkoordinatensystem, auch bekannt als "UV-Mapping". Jeder Punkt auf der zu texturierenden Fläche des 3D-Modells wird mit einem entsprechenden Punkt auf der Textur verbunden, indem ihm ein Paar von u,v-Koordinaten zugeordnet wird. Diese Koordinaten beschreiben die Position des Punktes auf der Textur und werden verwendet, um die Farbwerte für den Punkt auf der Fläche zu berechnen.

Die (u,v) Koordinaten sind normalisiert und bewegen sich im Bereich von 0 bis 1 auf der Textur. Dies ermöglicht es, die Textur wiederholt auf die Fläche zu projizieren oder Teile der Textur zu skalieren oder zu verschieben.

Hierfür gibt es verschiedene Mapping-Methoden, wie z.B. planare, cylindrische oder sphärische Projektion

# Parametrization

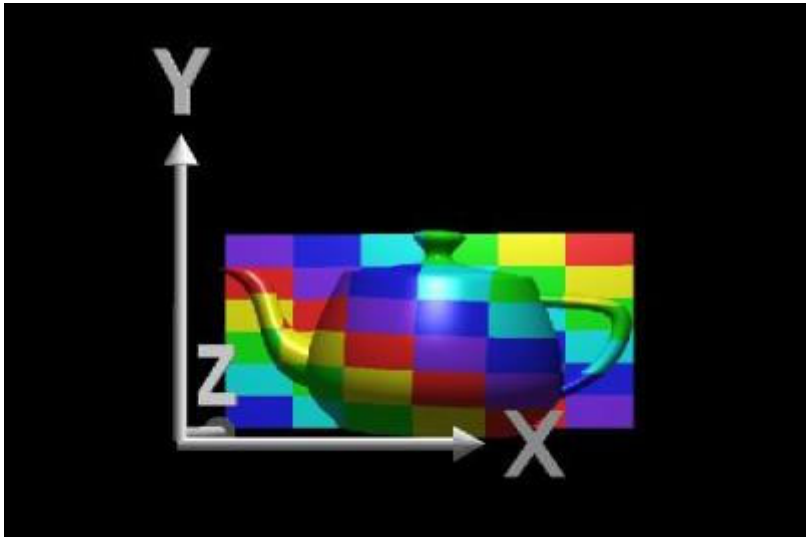
- How to do the mapping?

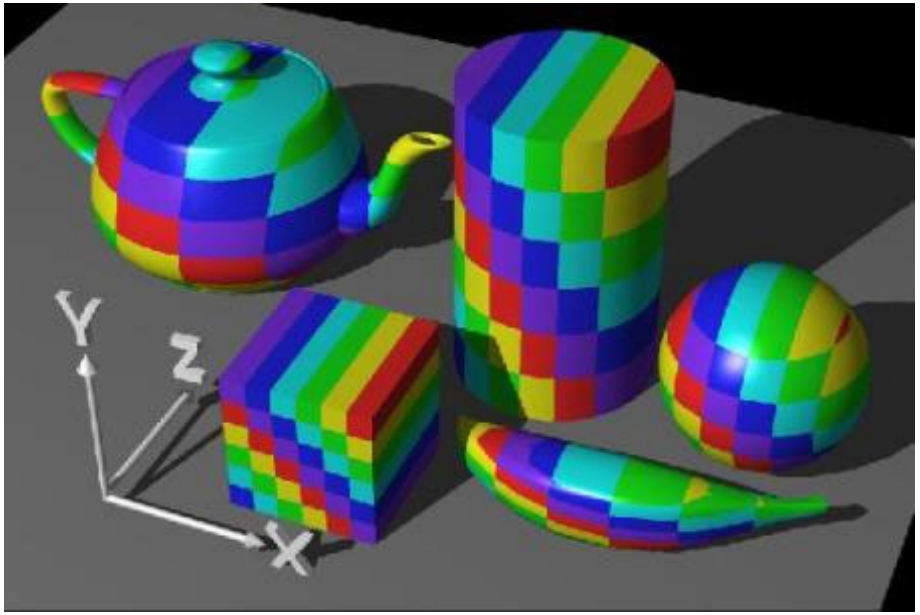



- Usually objects are not that simple

# Parametrization: Planar

- Planar mapping: dump one of the coordinates

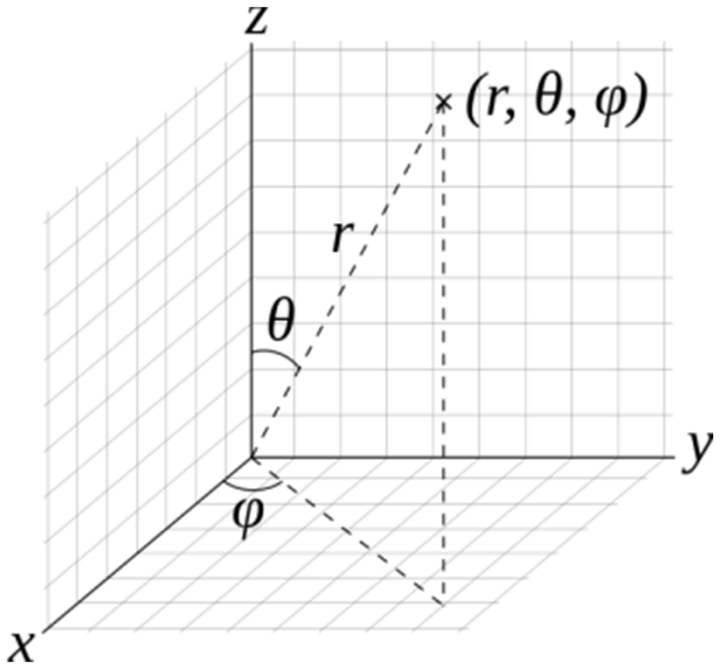



Only looks good from the front!

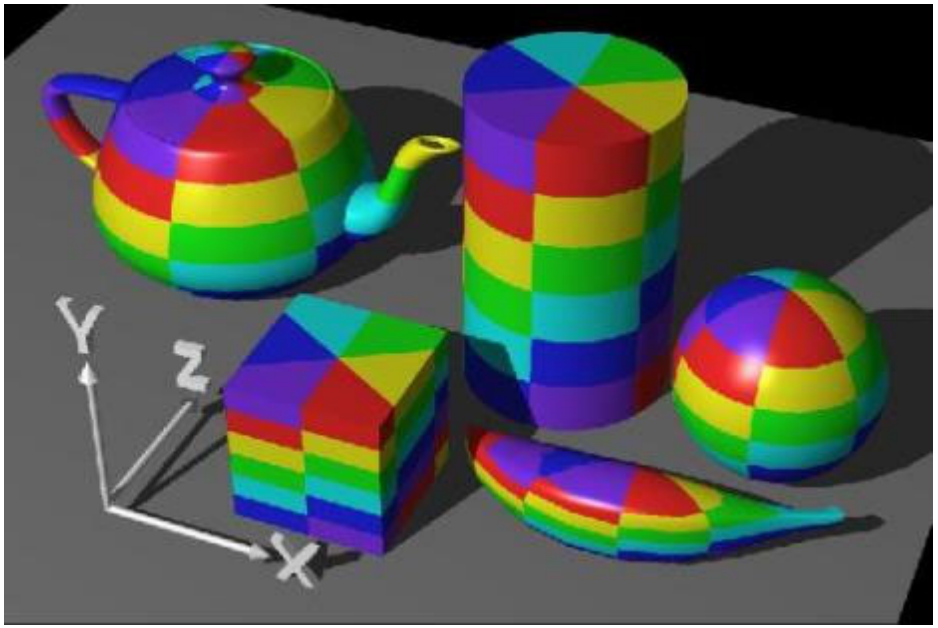
# Parametrization: Cylindrical

- Cylindrical and spherical mapping: compute angles between vertex and object center
- Compare to polar/spherical coordinate systems

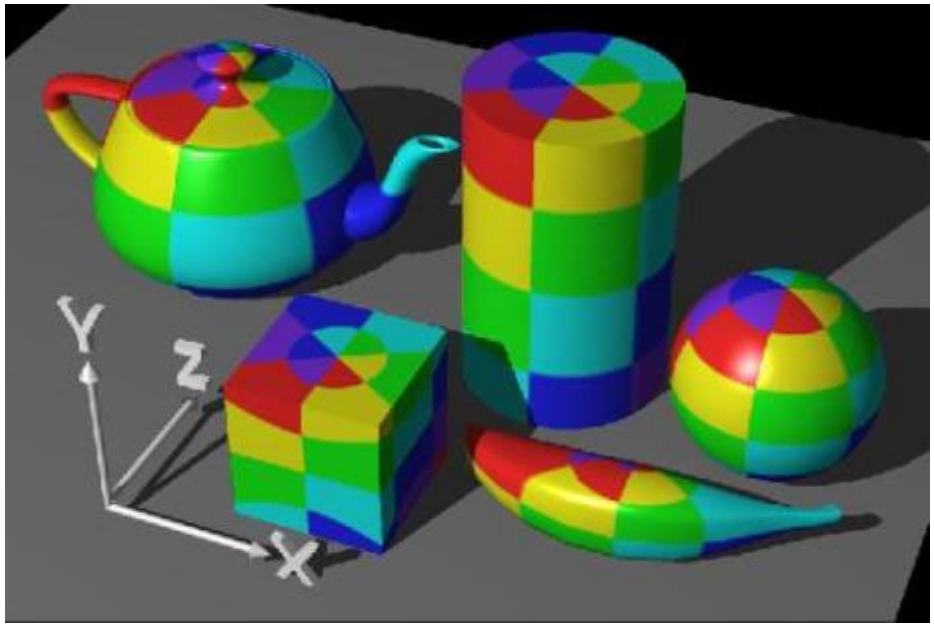


# Parametrization: Polar

- Cylindrical and spherical mapping



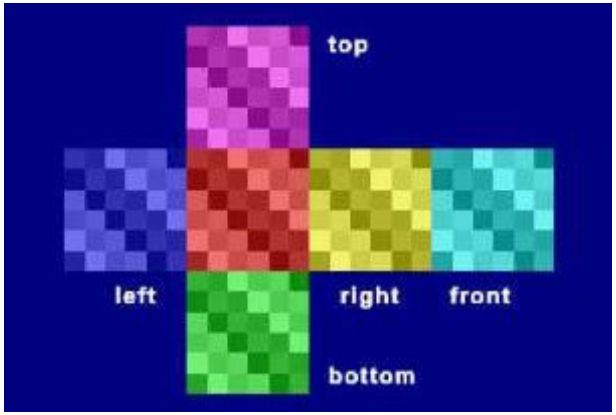

Cylindrical

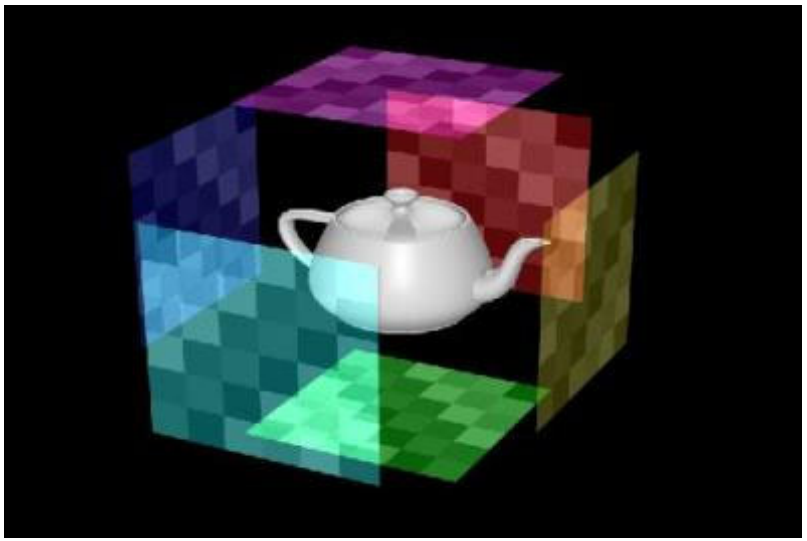


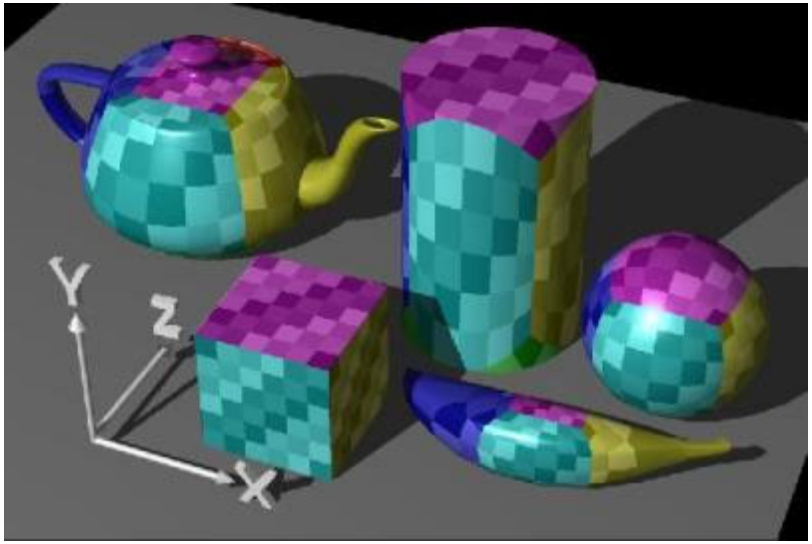

Spherical

# Parametrization: Box

- Box mapping: used mainly for environment mapping (see later)



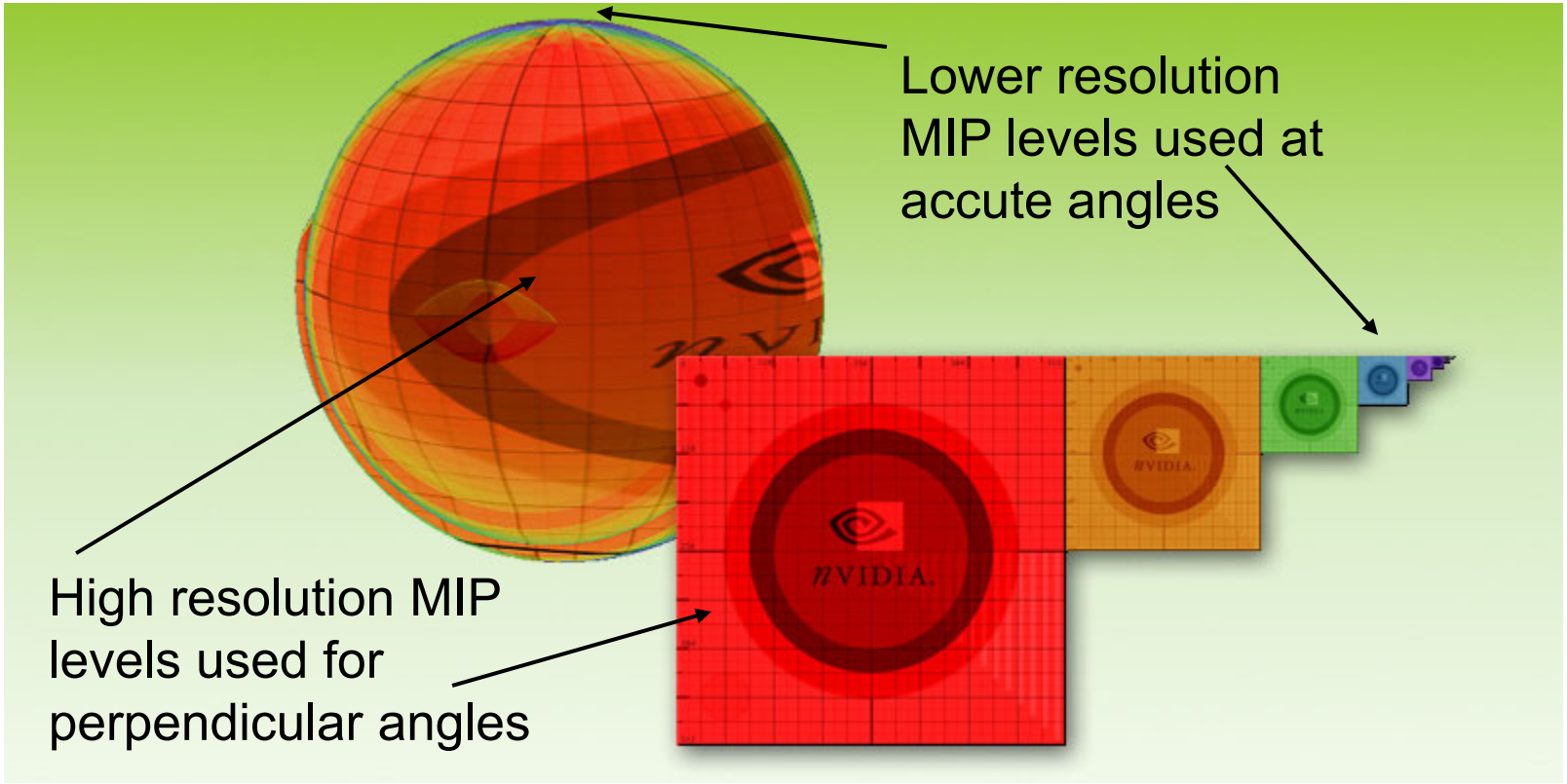


# Mip Mapping

**downsampling** $\Rightarrow$ much in a small area
= “multum in parvo” (mip)

- Texture is precalculated for different sizes
- Heavily used in real-time graphics
- Texture is reduced by factors of two
  - Simple
  - Memory efficient
- The last image is only one texel

# Mip Mapping Example

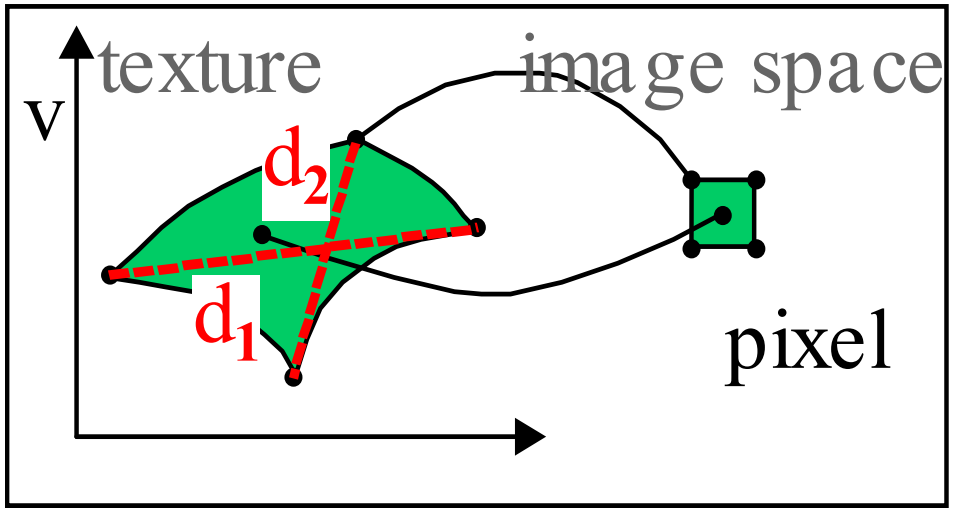



Mip Maps are reduce bandwidth requirements of distant textures and minimize scintillating pixels

# Mip Mapping Algorithm

$$D := ld(max(|d_1|, |d_2|))$$

D ... Level of Detail (Welche Texture auf der Pyramide)
d … Distanz zwischen Pixeleckpunkten im Texture Space
Berechnet die Größe des Pixels im Verhältnis zur Textur




Passende Miplevel herausfinden durch Abrunden des Ergebnisses

$$T_0 := \text{value from table } D_0 = \text{trunc } (D)$$
$$T_1 := \text{value from table } D_1 = D_0+1$$

D0 und D1 sind Indizes für die verschiedenen Mip-Map-Stufen und .

T0, T1 Texel auf den verschiedenen level?

- $T_0$, $T_1$ obtained with bilinear interpolation
- How to combine $T_0$, $T_1$?

Bilinear Interpolation wird verwendet, um die Textur des Pixels auf der Grundlage dieser Mip-Map-Stufen zu berechnen

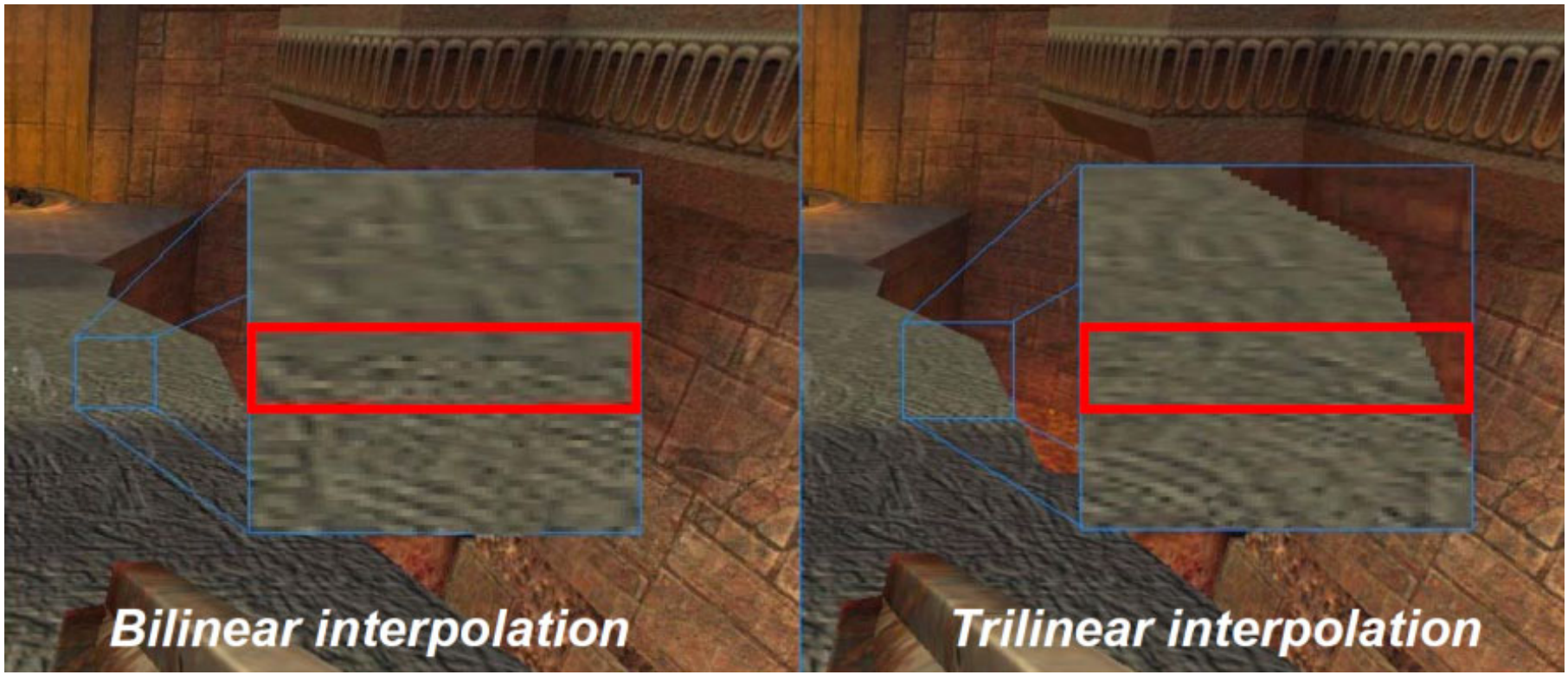
# Bilinear vs Trilinear

- **Bilinear** := $(D_1\text{-}D>0.5)\ ?\ T_1 : T_0$
- **Trilinear** := $(D_1\text{-}D)\cdot T_0 + (D\text{-}D_0)\cdot T_1 =$

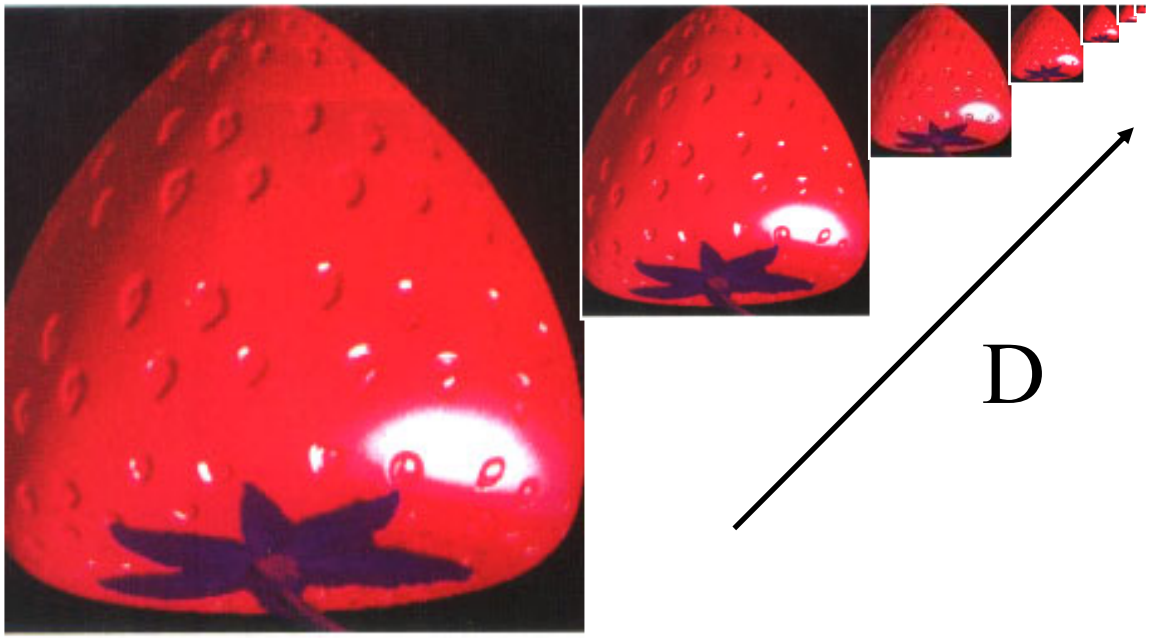
  $= (D_1\text{-}D)\cdot(T_0\text{-}T_1) + T_1$

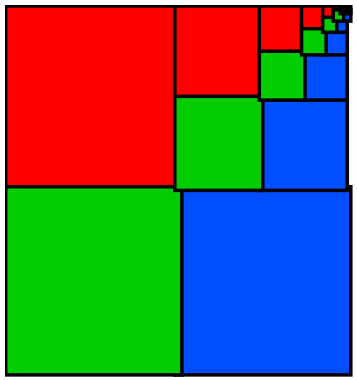
Bilinear:
4 benachbarte Pixel auf gleicher Ebene Interpoliert

Trilinear:
8 benachbarte Pixel auf 2 Ebenen interpoliert



# Mip Mapping Memory Layout

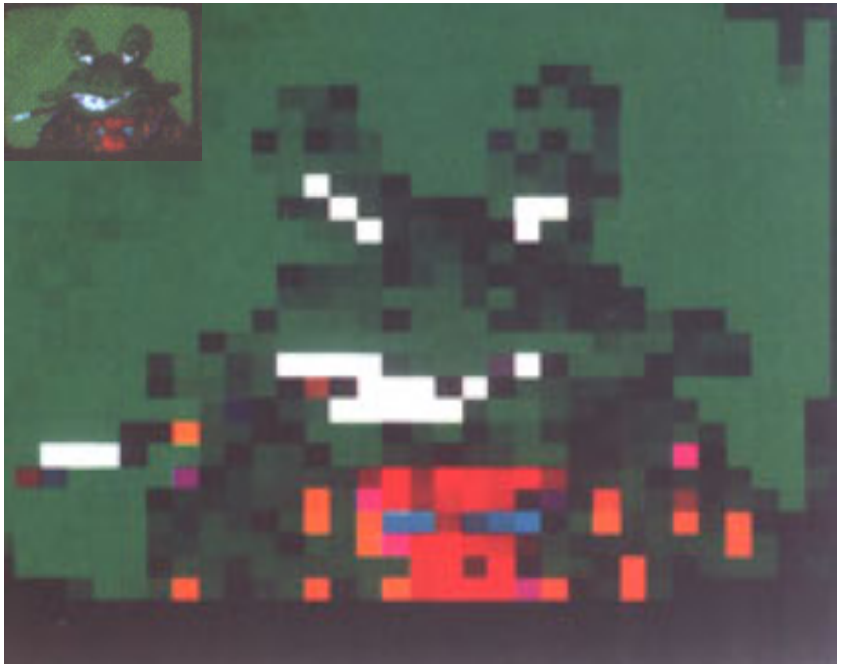


Memory overhead is just 33%
when channels are packed this way

# Mip Mapping Upsampling

- When the texture resolution is too small: Upsampling of the mip level with highest res.
- „Magnification“



# Multipass Rendering

- Basic GPU lighting model is
  - Local
  - Limited in complexity
- Many effects possible with multiple passes
  - Environment maps
  - Shadow maps
  - Reflections, mirrors
  - Transparency

Multipass rendering ist eine Technik in der Computergrafik, bei der ein 3D-Szenenbild in mehreren Schritten oder "Passes" berechnet wird. Jeder Pass fokussiert sich auf einen bestimmten Aspekt des Bildes und die Ergebnisse werden zusammengeführt, um das endgültige Bild zu erstellen.

# Multipass Rendering: How?

Two main methods

- Render to auxiliary buffers (Zwischenspeicher), use result as texture
  - E.g.: environment maps, shadow maps
  - Requires FBO support
- Redraw scene using fragment operations
  - E.g.: reflections, mirrors, light mapping
  - Uses framebuffer blending
  - Uses depth, stencil, alpha, … tests
- Can mix both techniques

# Multipass via Render to Texture

Auxiliary buffer method = *render to texture* (RTT)

1. Frame buffer with color attachment is bound
2. Scene (or subset) is rendered, possibly using a custom shader program
3. Frame buffer is unbound
   Color attachment is bound as texture
4. Scene is rendered to the back buffer,
   Rendered texture can be used either by fixed function pipeline or a custom shader

1. Framebuffer erstellen der einen Farbanhang als Renderziel hat

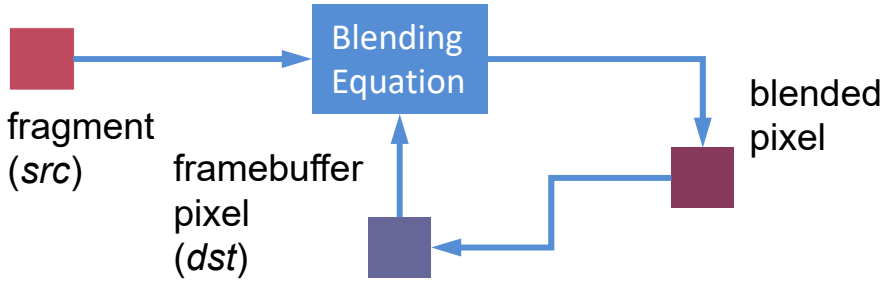
2. Scene wird in Texture gerendert

3. Nach dem Rendern wird der Framebuffer entbunden und der Farbanhang wird als Textur gebunden, um sie in weiteren Schritten verwenden zu können.

4. Die Szene wird schließlich auf dem Back-Buffer gerendert, wobei die gerenderte Textur entweder vom festen Funktionspfad oder einem benutzerdefinierten Shader verwendet wird, um das endgültige Render-Ergebnis zu erzeugen.

# Blending

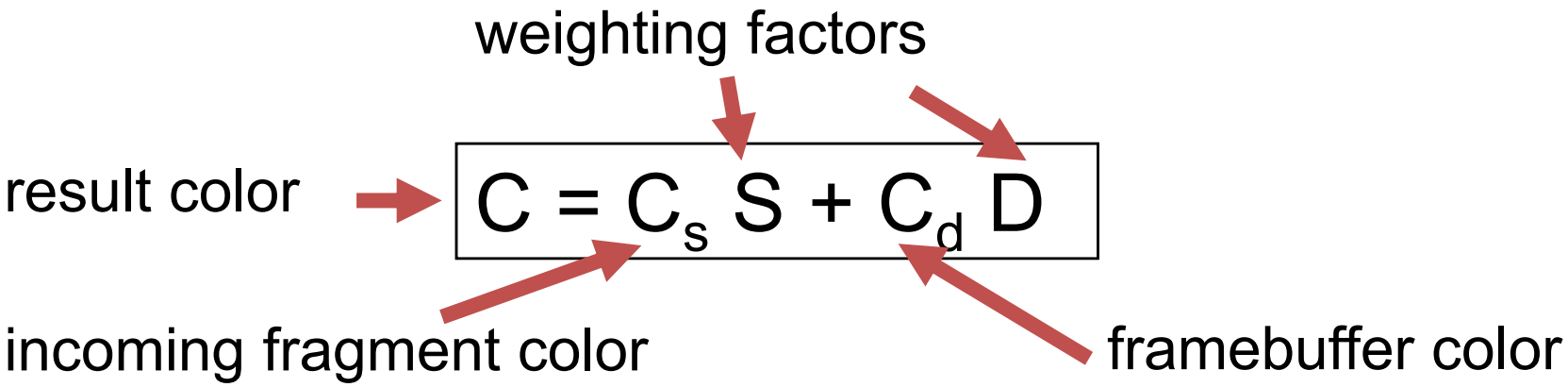
- So far, every new pixel simply overwrote existing framebuffer




- Blending combines new pixels with what is already in the framebuffer
- Blending does not always require alpha buffer

# Multipass – Framebuffer Blending

- Select a blend equation
- Hardware supports a finite number of equations
- Most common is linear blending




Prüfungsfrage!

# Blending Source and Destination

- Weights can be defined arbitrarily
- Alpha/color weights can be defined separately
- Choices of weight
  - *One*, *zero*, *dst color*, *src color*, *alpha*, 1 - *src color*…
- Example: transparency blending (window)

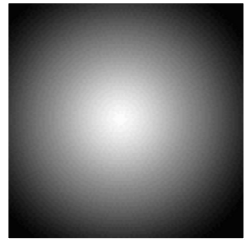
$$C = C_s \cdot \alpha + C_d \cdot (1- \alpha)$$

# Alpha Buffer Transparancy Buffer

- Measure of opacity to
  - Simulate translucent objects (glass, water, etc.)
  - Composite images
  - Antialiasing
- Do not forget to enable blending first!
- Beware
  - Usage of alpha requires depth-sorting of objects
  - Z-Buffer not helpful for partially transparent pixels

# Light Mapping

×



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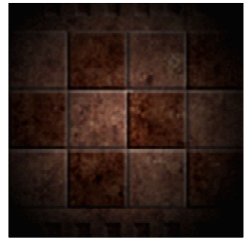


- Used in most first-person shooters
- Precalculate (*bake*) diffuse lighting on static objects
  - Only low resolution necessary
  - Diffuse lighting is view independent!
- Advantages
  - No runtime lighting necessary (good for older cards)
  - More accurate than vertex lighting (no need to tesselate for highlights)
  - Can take global effects (shadows, radiosity) into account

# Light Mapping Procedure

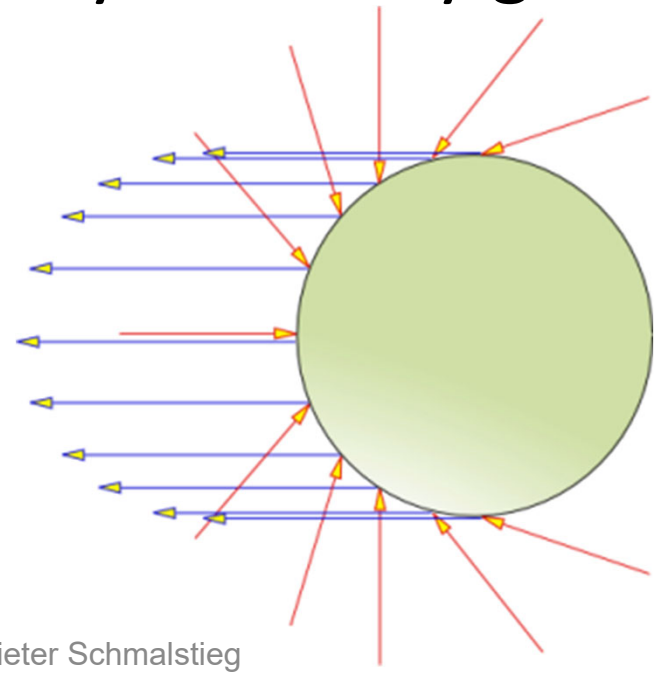
- Map generation
  - Use single map for group of coplanar polys
  - Map back to worldspace to calculate lighting
- Map application
  - Premultiply textures by light maps
    - Large textures, no dynamics
  - Multitexturing at runtime
    - Fast, flexible

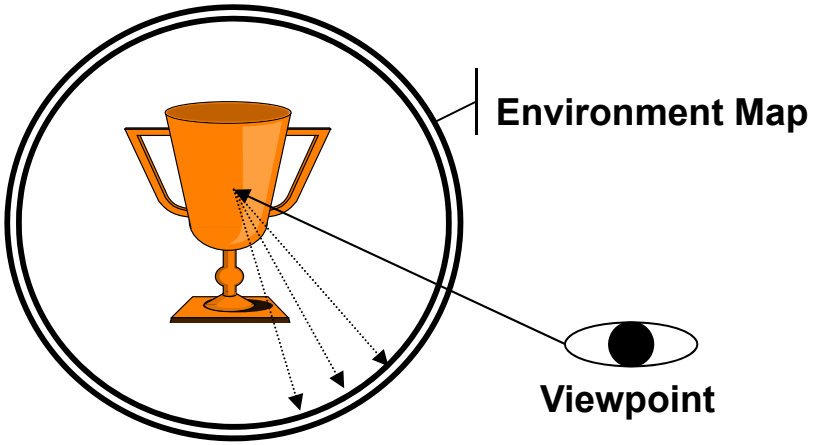
# Environment Mapping

- Idea: use texture to create reflections
- Uses texture coordinate generation, multitexturing, RTT, …

# Environment Mapping Indexing

- Assumption: index envmap via orientation →
  - Reflecting object shrunk to a single point
  - Or: environment infinitely far away
- Eye not very good at discovering the fake

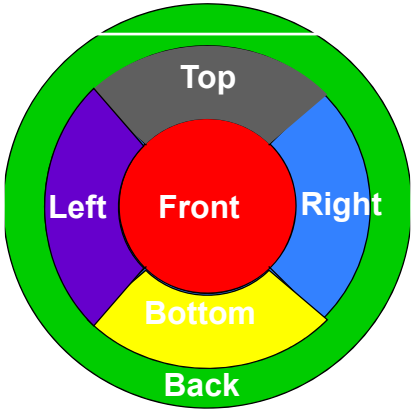




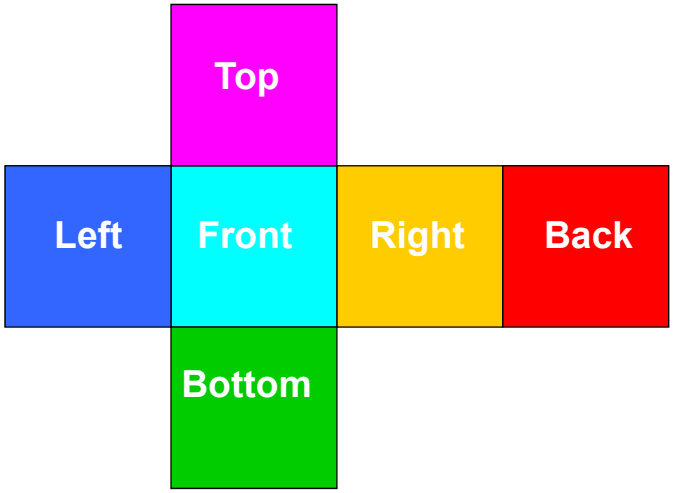
# Environment Mapping Types

- Typical mappings:
  Each maps all directions to a 2D texture

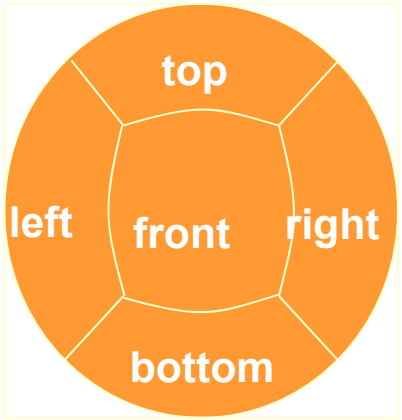
Sphere




Cube

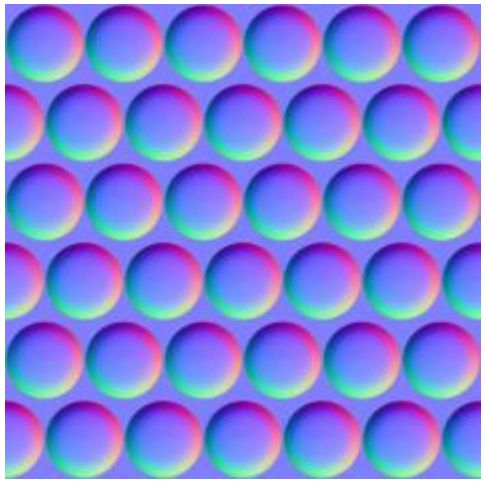



Dual paraboloid



# Bump Mapping

- Per-pixel normals are a prerequisite for BM
- Simulating rough surfaces by calculating per-pixel illumination
- Replace geometry with (faster) texture



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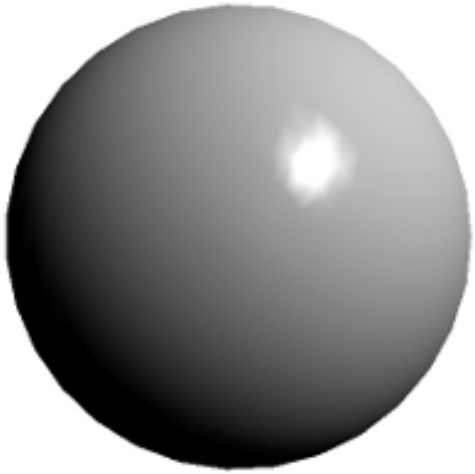

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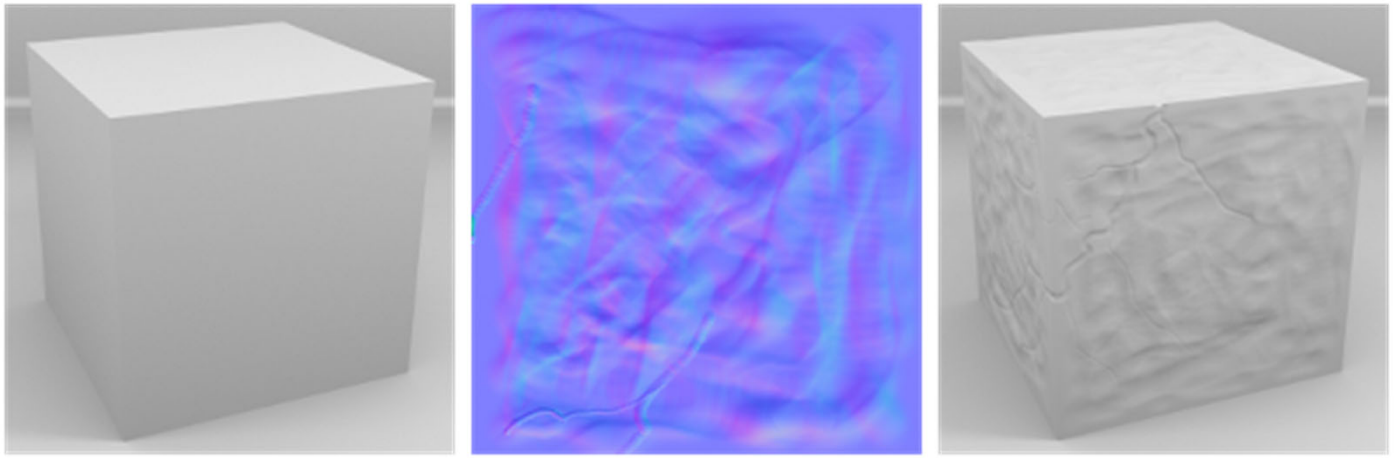
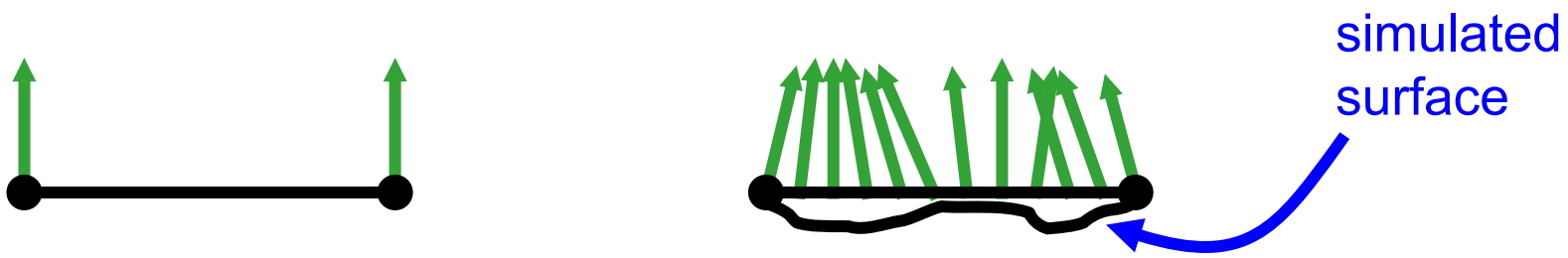
# Bump Mapping Examples



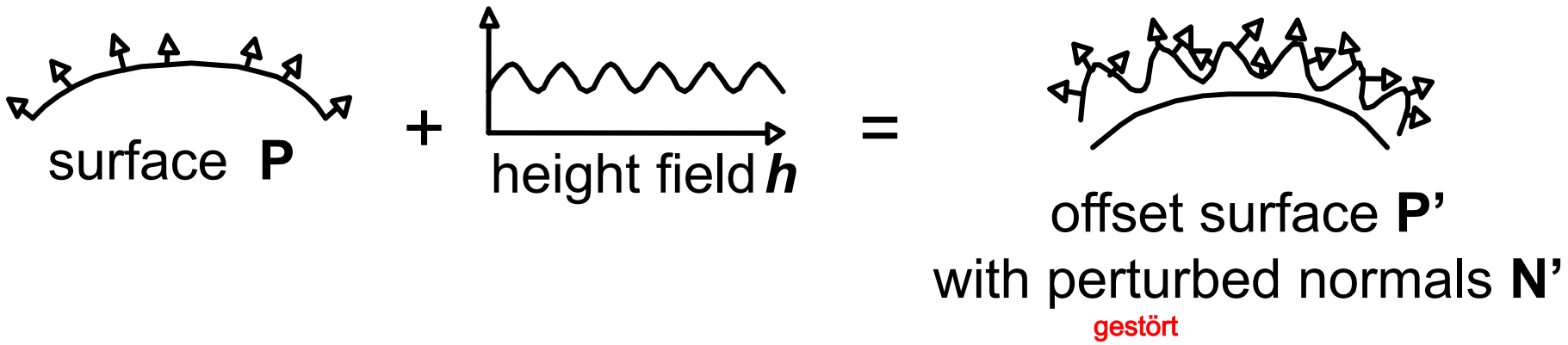
# Bump Mapping Basics

- Original idea from ray tracing [Blinn 1978]
- Simulate surface features with illumination only
- Instead of interpolating normals, take them from a map



# Bump Mapping Basics

- Assume a (u,v)-parameterization
  - Points **P** on the surface given as **P**(u,v)
- Surface **P** is modified by 2D height field h



# Mathematics of Bump Mapping

- Displaced surface:

$$\mathbf{p}'(u,v) = \mathbf{p}(u,v) + h(u,v)\mathbf{n}(u,v)$$

- Partial derivatives:

$$\frac{\partial \mathbf{p}'}{\partial u} = \frac{\partial \mathbf{p}}{\partial u} + \frac{\partial h}{\partial u} \cdot \mathbf{n} + h \cdot \underbrace{\frac{\partial \mathbf{n}}{\partial u}}$$

$$\frac{\partial \mathbf{p}'}{\partial v} = \frac{\partial \mathbf{p}}{\partial v} + \frac{\partial h}{\partial v} \cdot \mathbf{n} + h \cdot \underbrace{\frac{\partial \mathbf{n}}{\partial v}}$$

$= 0$ for locally flat base surface

- Perturbed normal:

$$\mathbf{n}'(u,v) = \frac{\partial \mathbf{p}'}{\partial u} \times \frac{\partial \mathbf{p}'}{\partial v}$$

after some computation…

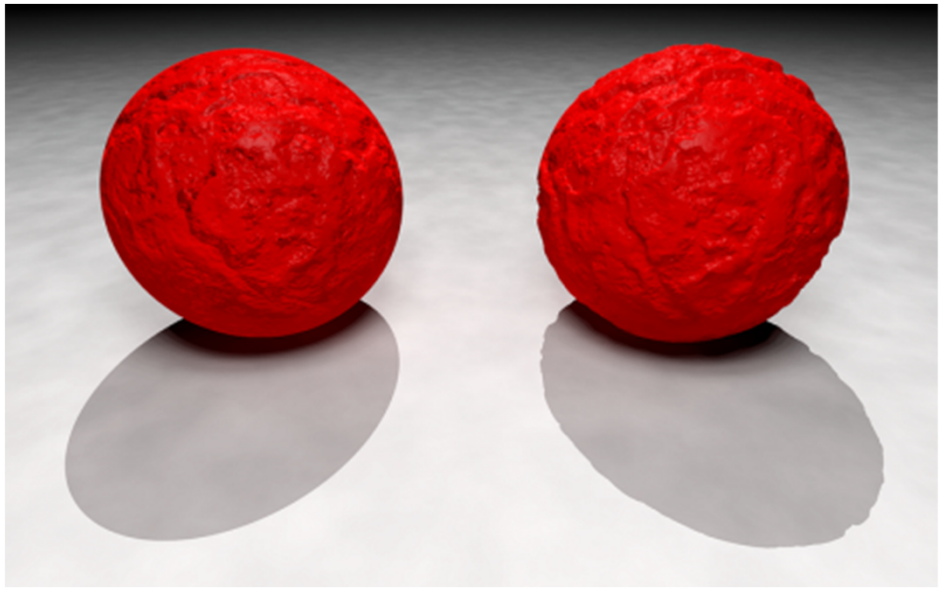
$$\Rightarrow \mathbf{n}' = \mathbf{n} + \frac{\partial h}{\partial u} \cdot \left(\mathbf{n} \times \frac{\partial \mathbf{p}}{\partial v}\right) - \frac{\partial h}{\partial v} \cdot \left(\mathbf{n} \times \frac{\partial \mathbf{p}}{\partial u}\right)$$

# Bump Mapping Representations

- Height fields
  - Must approximate derivatives during rendering
  - Simple case: emboss bump mapping
- Offset maps
  - Encode orthogonal offsets from unperturbed normal
  - e.g.: $\left(\frac{\partial h}{\partial u}, \frac{\partial h}{\partial v}\right)$, or whole vector, …
  - Require renormalization
  - Enable bump environment mapping
  - Calculate using finite differencing on height field
- Normal (perturbation/rotation) maps
  - Encode direction vectors (in whatever space)
  - No normalization required
  - Standard method

# Bump Mapping Issues

- Artifacts
  - Shadows
  - Silhouettes edgy
  - No parallax



Bump mapped Real geometry

- Effectiveness
  - No effect if neither light nor object moves
  - In this case, use light maps
  - Exception: specular highlights


Image: Arrowhead Game Studios
Deferred Shading

# Overview

- Motivation: why not conventional shading?
  - Shader permutation problem
  - Combinatorial explosion
- Deferred shading method
- G-Buffers
- Other post-processing effects
- Advantages/disadvantages

# Conventional Forward Rendering

- After rasterization
- Shading calculations in fixed function pipeline or fragment shader
- Complexity = O(Light sources * Objects)

# Overdraw

- Complex scenes, large virtual environments → overdraw
- Overdraw → redundant calculations
- Why shade a pixel, if it gets overdrawn in final image?
- Idea: perform shading at the end of rendering
  → we need only one shading operation per pixel

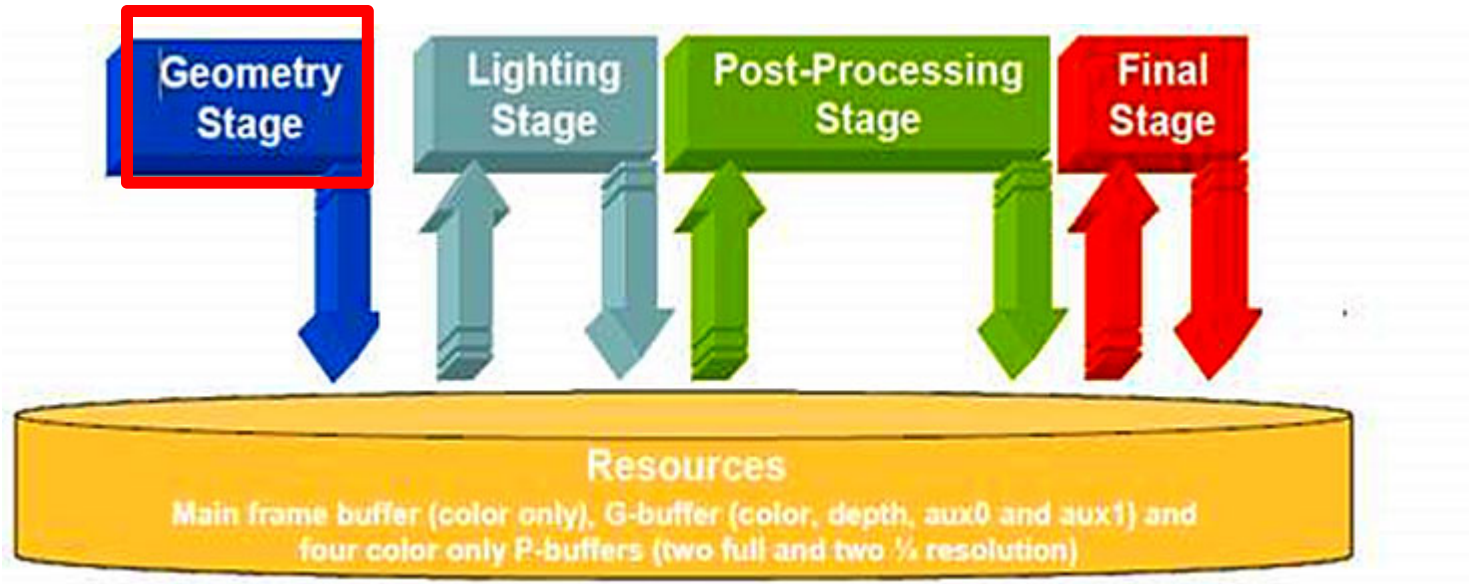
Intermediate:

Final:

# Basic Deferred Rendering

Split rendering pipeline in two separate stages

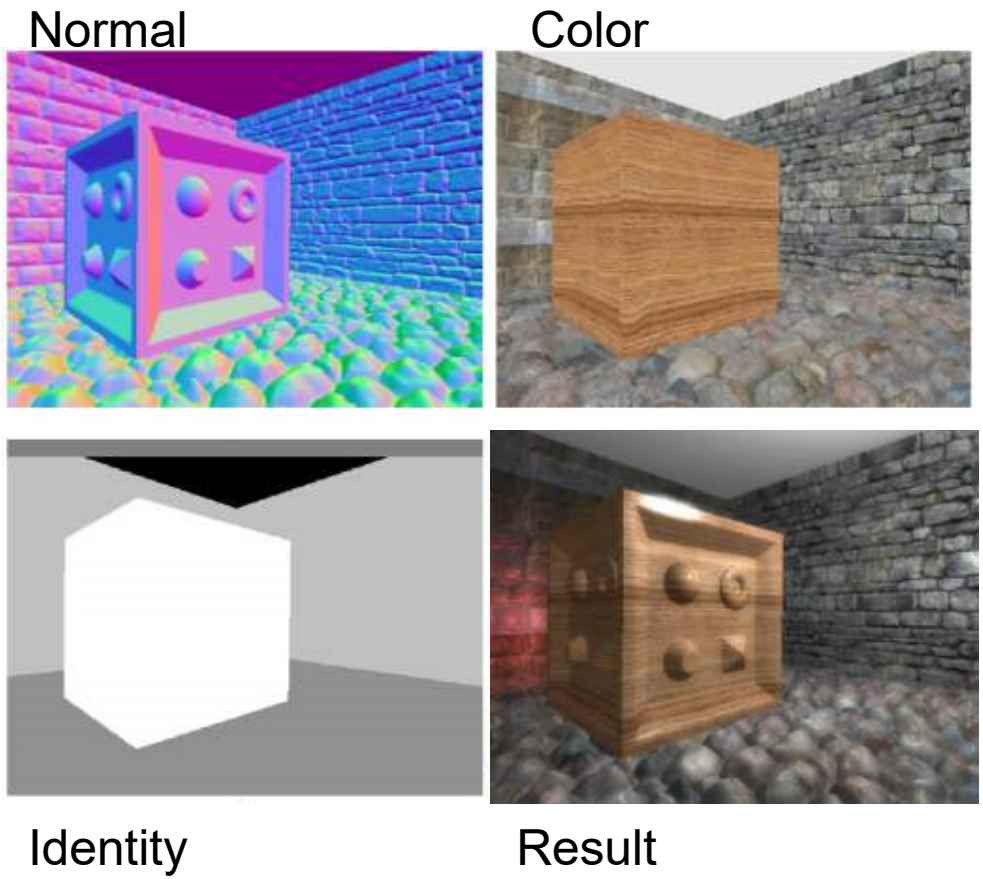
1. Geometry transformation and rasterization



# Types of G-Buffers

G-Buffers store per pixel:

- Color
- Depth
- Normal vector
- Position
- Object identity
- etc.

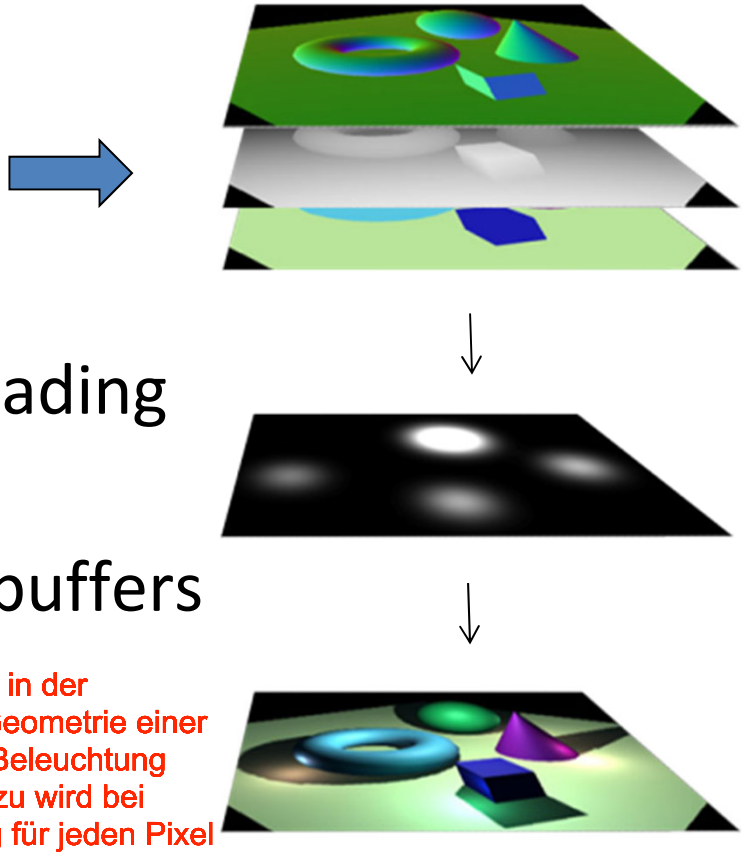


# Deferred Rendering Overview

- DR is a framework supporting various effects
  - Screen-space ambient occlusion
  - Non photo-realistic rendering
  - High-dynamic range rendering
  - Deferred shading
  - …
- Implemented as a post-processing effect
- Most important sub-type: deferred shading

# Deferred Shading

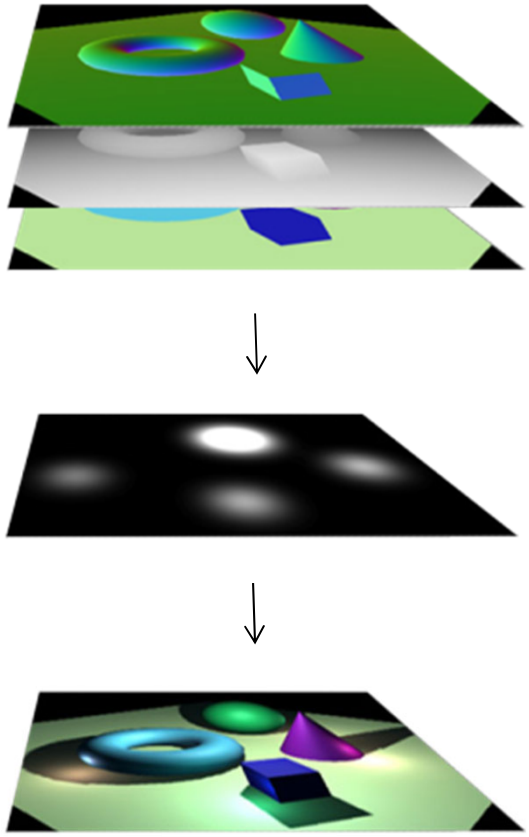
- Geometry stage as usual
  1. Geometry transformations
  2. Rasterization
  3. Material, texturing, but no shading
- Instead of shading,
  store intermediate results in G-buffers
  - Diffuse color
  - Depth
  - Position
  - Normal vectors



Deferred Shading ist eine Technik in der Computergrafik, bei der erst die Geometrie einer Szene berechnet wird, bevor die Beleuchtung berechnet wird. Im Gegensatz dazu wird bei Forward Shading die Beleuchtung für jeden Pixel einzeln berechnet, während die Geometrie berechnet wird. Deferred Shading ermöglicht es, dass man mehrere Lichtquellen und deren Wechselwirkungen mit Oberflächen gleichzeitig berechnen kann, was zu realistischeren Ergebnissen führt. Es ist jedoch auch rechenintensiver als Forward Shading.

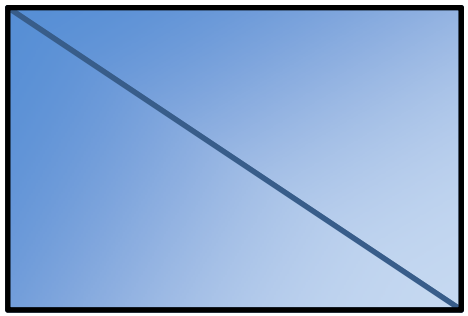
# Actual Shading Stage

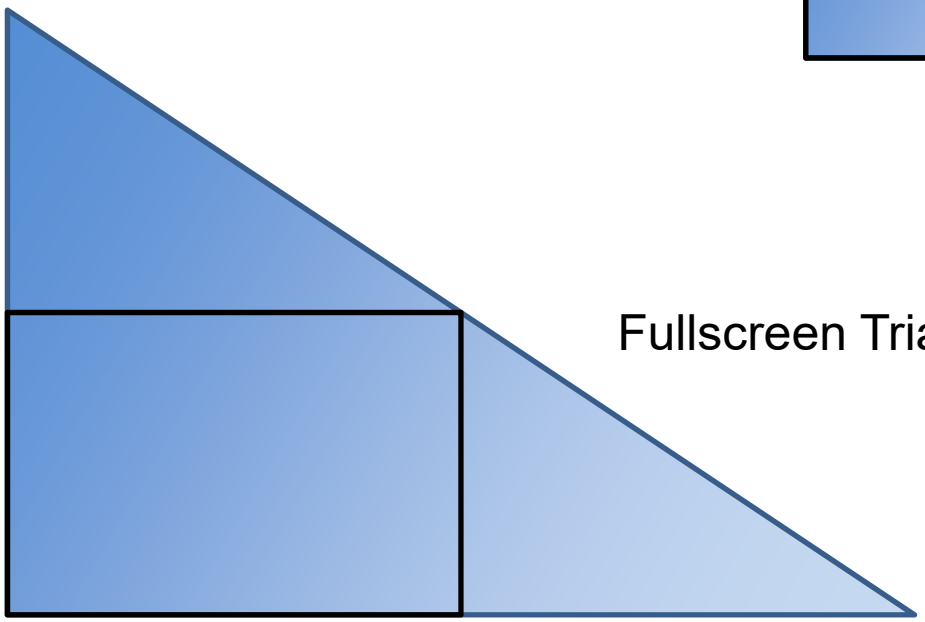
- Render screen-sized quad
- Fragment shader reads G-Buffers
- Perform shading and postprocessing
- Store result in framebuffer



# Screen-filling Primitives

Fullscreen Quad





Fullscreen Triangle

# Deferred Rendering Advantages

- Render geometry only once
- Perform complex shading and post-processing per pixel
- Complexity O(Light sources + Objects) instead of O(Lights*Objects)
- Independent of geometry and depth complexity
- Time for shading can be predicted well
  → good for games

# Deferred Rendering Disadvantages

- Requires more memory and frequent read/write operations
- Advanced effects (transparency, ghostings) require per-pixel sorting
- Cannot use hardware anti-aliasing

- Forward shading may be faster, if
  - Low number of light sources
  - Low depth complexity
  - No need for post-processing effects

Dieter Schmalstieg

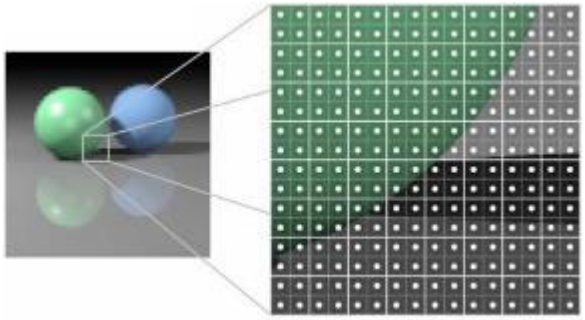
# Image-Space Special Effects

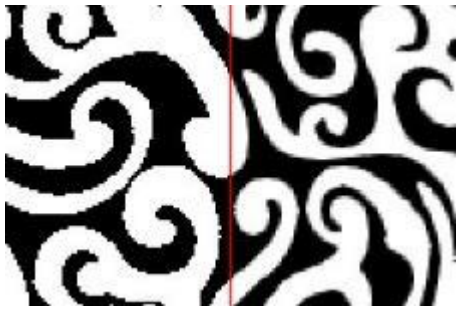
Based on material by Daniel Wagner, Michael Kenzel, Thomas Neff

# Anti-aliasing in Real-Time Graphics

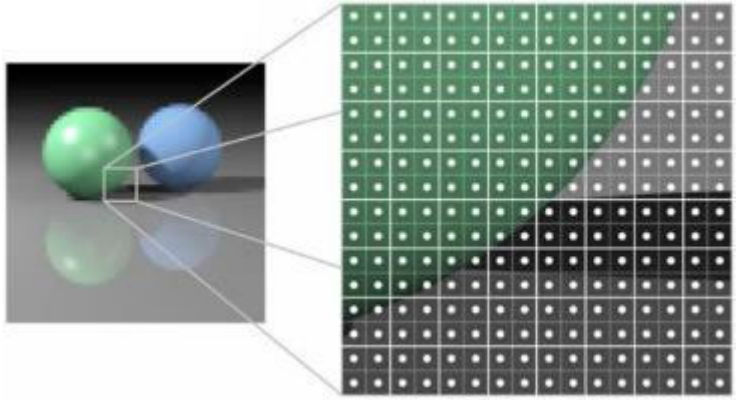
Anti-aliasing can mainly be categorized in

- Better sampling (SSAA, MSAA, TAA)
  - Take more samples during rasterization
- Better filtering (MLAA, TAA)
  - After rasterization as a post process
  - Often incorporates temporal and/or spatial information for filtering





# Supersampled Anti-Aliasing (SSAA)



- Multiple samples per pixel
- Accumulated via reconstruction filter
- Equivalent to rendering in higher resolution, then downsampling
- Most accurate antialiasing method
- Helps with all forms of spatial aliasing
- But very expensive, since load increases across whole pipeline

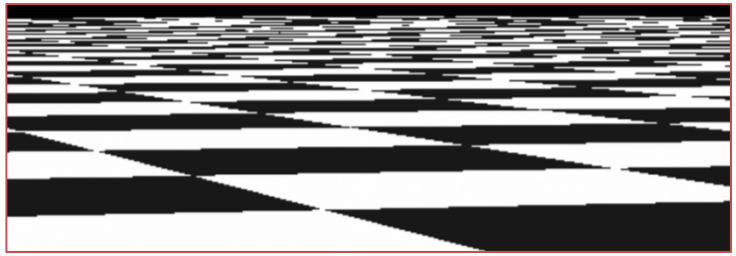
SSAA bekämpft Kantenbildung, indem es das Bild mit einer höheren Auflösung als die tatsächliche Anzeigeauflösung berechnet. Beispielsweise kann ein Bild mit einer Auflösung von 1920x1080 mit SSAA mit einer Auflösung von 3840x2160 berechnet werden. Dies erzeugt ein hochaufgelöstes Bild mit glatteren Kanten und einer höheren Detailgenauigkeit.

Nach der Berechnung wird das hochaufgelöste Bild dann auf die tatsächliche Anzeigeauflösung herunter skaliert. Dies erzeugt ein endgültiges Bild mit glatteren Kanten und einer höheren Qualität.

# SSAA Algorithm

- Allocate all screen-sized textures and buffers with *N* x resolution
- Render as usual (at higher resolution)
- For display, downsample final color texture to target resolution using  fullscreen shader
- Box filter, Lanczos filter, Gaussian…
- Display final image in target resolution

Dieser Filter nutzt eine Art von gewichteter Mittelwertberechnung, um die Farben und Pixelwerte der hochaufgelösten Bilder auf die tatsächliche Anzeigeauflösung herunterzuskalieren.



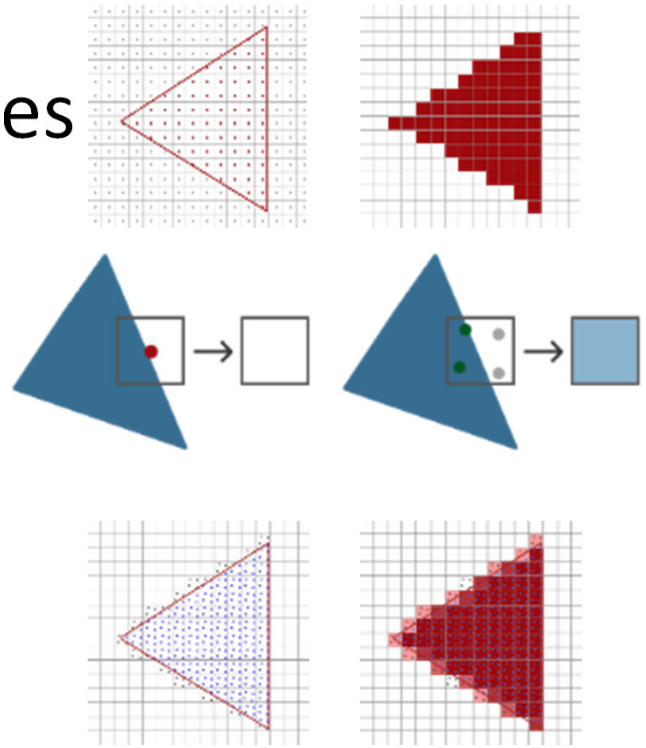
1 sample per pixel

256 samples per pixel

# Multisampling (MSAA)

Jaggies sind sichtbare Stufen, Ecken oder Kanten in einem gerenderten Bild, die aufgrund der begrenzten Auflösung des Bildschirms und der Unfähigkeit des Computers, glatte Linien zu zeichnen, entstehen.

- Most aliasing effects related to “jaggies”
  - Depth and coverage aliasing
- MSAA places additional subsamples
  - Fragment shader is only invoked once per pixel
  - Output color is blended based on number of covered samples
- Hardware support in graphics API



Pixel wird in mehrere Subpixel unterteilt und Farb und Tiefeninformation wird für jedes Farbpixel gespeichert. Danach werden diese „Samples“ kombiniert (blend) um den Endgültigen Wert für den Pixel zu bestimmen.

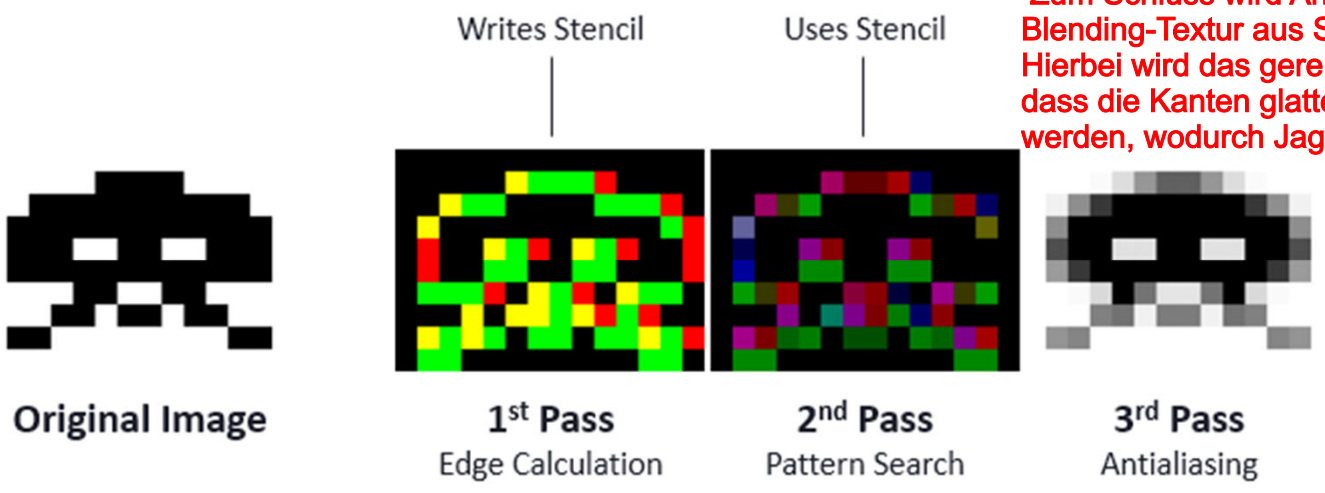
MLAA (Morphological Anti-Aliasing) ist eine Technik zur Reduzierung von Jaggies in Computergrafiken. MLAA verwendet morphologische Verfahren, um Kanten in einem Bild zu erkennen und dann eine glattere Darstellung dieser Kanten zu erreichen.

# Morphological Anti-Aliasing (MLAA)

1. Edge detection in input image e.g. Sobel, La Place
2. Compute blending texture based on distance to line end/crossing and line shape
3. Anti-Aliasing using blending map from step 2

"Blending-Textur" berechnet, die auf Basis der Entfernung zu den Endpunkten oder Übergängen der Kanten und der Form der Kanten berechnet wird.

Zum Schluss wird Anti-Aliasing auf Basis der Blending-Textur aus Schritt 2 durchgeführt. Hierbei wird das gerenderte Bild so angepasst, dass die Kanten glatter und feiner dargestellt werden, wodurch Jaggies reduziert werden.



# SSAA vs. MSAA vs. MLAA

- SSAA
  - Spatial anti-aliasing for everything (textures, edges, shading)
  - Very expensive, therefore hardly used for real-time rendering
- MSAA
  - Resolves aliasing for edges only (not for textures and shading)
  - Too expensive with deferred rendering, alpha aliasing causes issues
  - Current gold standard for VR
  - Not applicable to deferred rendering engines
- MLAA
  - Blurs mostly along edges, resolving edge-aliasing only
  - Very cheap post-process even for weaker systems
  - Can look overly blurred
  - Can cause issues with fine details such as text, requires fine-tuning
  - Not temporally stable → flickering
  - Preferred solution for deferred rendering engines

# Temporal Accumulation

Prüfungsfrage

- Idea: combine multiple samples taken at different times
- Past samples are stored in a buffer
- Examples
  - Motion blur
  - Temporal anti-aliasing

# Temporal Anti-Aliasing (TAA)

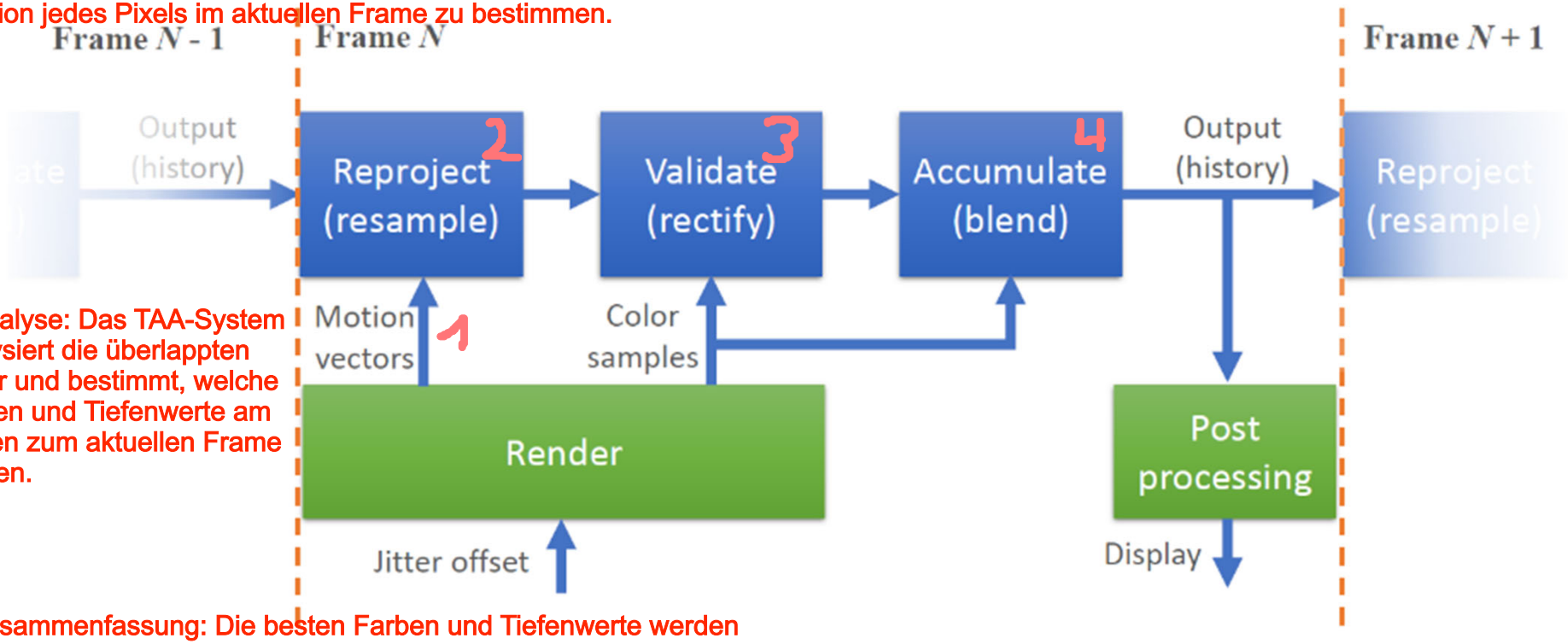
- Idea: Blend previous frames' **jittered shading result** with successive frames
  - Stochastic/subpixel supersampling
  - Works for **geometric and shading aliasing**
- Current gold standard for game engines
  - Works with any rendering architecture
- Requires more involved modifications to the renderer compared to other AA solutions

Die Schritte von TAA sind folgendermaßen:

1. Motion-Vektor-Erkennung: Das TAA-System erkennt die Bewegungen von Objekten im Bild, indem es Motion-Vektoren berechnet. Diese Vektoren beschreiben die Bewegung jedes Pixels im Vergleich zum vorherigen Frame. (TAA:Jittering wird hier verwendet)

# Temporal Anti-Aliasing (TAA)

2. Überlagerung: Das TAA-System überlappt das aktuelle Frame mit dem vorherigen Frame, indem es die Motion-Vektoren verwendet, um die Position jedes Pixels im aktuellen Frame zu bestimmen.




3. Analyse: Das TAA-System analysiert die überlappten Bilder und bestimmt, welche Farben und Tiefenwerte am besten zum aktuellen Frame passen.

4. Zusammenfassung: Die besten Farben und Tiefenwerte werden verwendet, um das endgültige Bild zu erstellen, das auf dem Bildschirm angezeigt wird.

*Yang, L., Liu, S. and Salvi, M. (2020), A Survey of Temporal Antialiasing Techniques. Computer Graphics Forum, 39: 607-621. https://doi.org/10.1111/cgf.14018*

Jittering is an AA method typically used for static scenes which works by very subtly moving (or shaking) world geometry in (viewspace?), by using an array of evenly distributed noise values (Halton [2, 3] sequence).

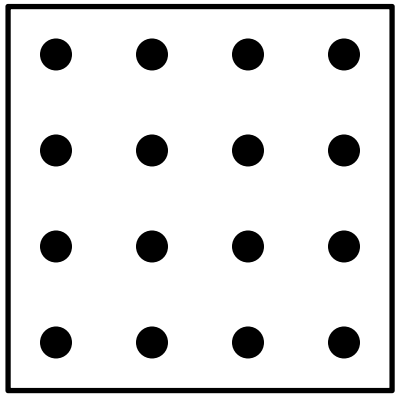
# TAA: Jittering

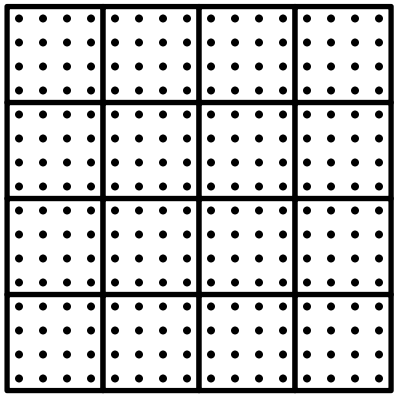
- To generate sampling locations for temporal supersampling, we **jitter the projection matrix**

```
ProjMatrix[2][0] += ( SampleX * 2.0f – 1.0f ) / ViewRect.Width();
ProjMatrix[2][1] += ( SampleY * 2.0f – 1.0f ) / ViewRect.Height();
```

Jittering is done via a vertex shader by manipulating the projection matrix.

Regular grid

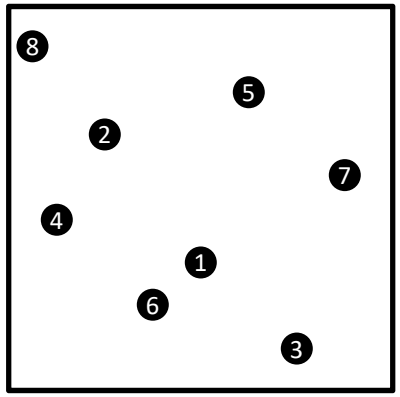


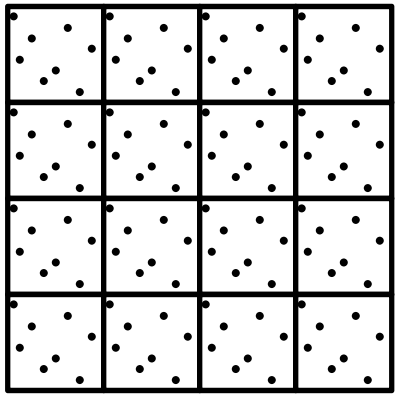


# TAA: Jittering Sequence

- For fast convergence, each subsequence should be evenly distributed in the pixel domain
- **Halton(2, 3)** is a good candidate (used in UE4)

Halton(2,3)



Durch die Verwendung einer geeigneten Jittering-Sequenz, wie der Halton(2, 3)-Sequenz, kann sichergestellt werden, dass die Projektionsmatrix gleichmäßig verändert wird und so eine schnelle Konvergenz erreicht wird.

Der History Buffer ist ein wichtiger Teil bei der Implementierung von Temporal Anti-Aliasing (TAA). Es dient als Speicher für vergangene Bilder und wird verwendet, um das aktuelle und vorhergehende Bild miteinander zu verbinden. Dazu wird eine aktuelle Bildmarke (in der Regel eine Bool-Variable) verwendet, die bestimmt, welches History Buffer aktiv gezeichnet und welches geleert wird. Diese Marke wird jedes Frame zwischen zwei Zuständen umgeschaltet, um die Rolle der Puffer jedes Frame zu wechseln.

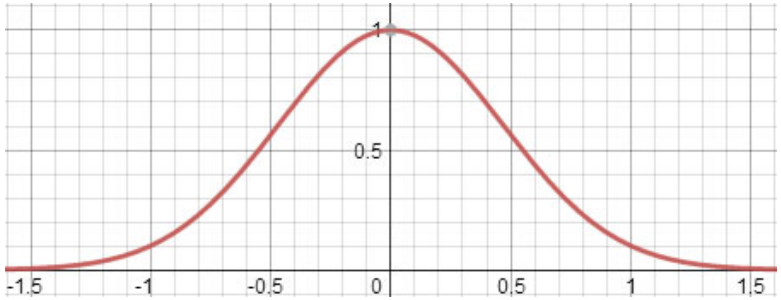
# TAA: History Buffering

- Simple moving average is not feasible
  - Would require N times storage for N samples
- Exponential moving average
  - Nearly "infinite" number of samples with fixed storage
  - When $\alpha$ is small, approaches a simple moving average
  - $\alpha$ = 0.1 is common
- This can simply be stored in a screen-sized buffer!

$$s_t = \alpha x_t + (1 - \alpha) s_{t-1}$$

TAA Reconstruction bezieht sich auf den Prozess, bei dem bei der Implementierung von Temporal Anti-Aliasing (TAA) das resultierende Bild nach der Überlagerung der aktuellen und vergangenen Bilder wiederhergestellt wird.

# TAA: Reconstruction




$$W(x) = e^{-2.29x^2}$$

- Simple approach
  - Average all subpixels inside pixel rectangle (Box filter)
  - However, box filter not stable under motion

Ein einfacher Ansatz ist, alle Subpixel innerhalb eines Pixelrechtecks (Box Filter) zu berechnen. Diese Methode ist jedoch bei Bewegungen nicht stabil.

- Alternative approach: Gaussian
  - UE4 uses a Gaussian fit to Blackman-Harris 3.3
  - Since every pixel shares the same jitter, filter weights are precomputed and passed as shader uniforms

Hierbei wird ein Gauss-Fit auf Blackman-Harris 3.3 verwendet, da jedes Pixel die gleichen Verzerrungen teilt. Die Filtergewichte werden vorab berechnet und als Shader-Uniformen übergeben.

# TAA: Dynamic Scenes

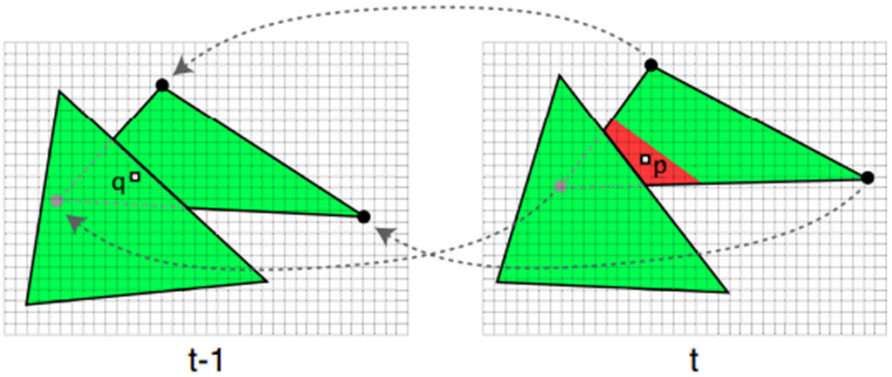
- So far, we discussed jittering, averaging and reconstruction
- What happens if the sample location changes between frames?
  - Animated objects, moving camera…
- For a given pixel, **we need to locate its previous location in the history buffer**
  - **Reprojection**

TAA Reprojection bezieht sich auf den Prozess, bei dem die Bewegung eines Pixel zwischen zwei aufeinanderfolgenden Frames berechnet wird, um seinen Standort im Vorherigen Frame zu bestimmen.

# TAA: Reprojection

- The history for the current pixel may be at a different location, or might not exist at all
- The geometry is transformed twice, using
  - 1.) the current frame's transformation matrices
  - 2.) the previous frame's transformation matrices
- The resulting offsets are stored into a **motion vector texture**
- Using this texture, we can look up the previous location in the history buffer

Dies geschieht, indem die Geometrie des Objekts mit den Transformationen aus dem aktuellen Frame und dem vorherigen Frame transformiert wird. Die Resultierenden Verschiebungen werden in einem Motion-Vector-Textur gespeichert, aus denen man den vorherigen Standort im History-Buffer abrufen kann.




Diego Nehab, Pedro V. Sander, Jason Lawrence, Natalya Tatarchuk, and John R. Isidoro. 2007. Accelerating real-time shading with reverse reprojection caching. https://dl.acm.org/doi/10.5555/1280094.1280098

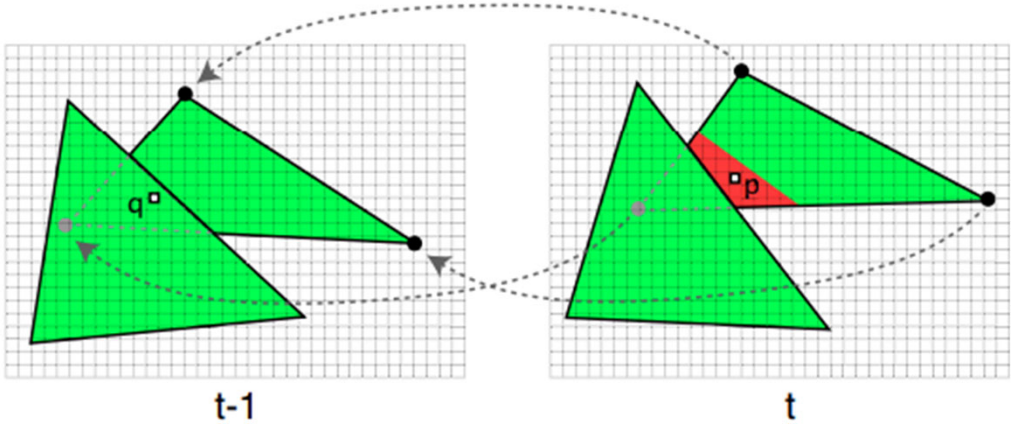
TAA History Rejection ist ein Teil des Temporal Anti-Aliasing (TAA), bei dem es darum geht, die Geschichte des letzten Frames für den aktuellen Pixel zu verwerfen, wenn sie ungültig ist.

# TAA: History Rejection

- When reprojecting, the history might be invalid
  - Occlusion/Disocclusion events
  - Shading changes (lights turning on/off…)
- Use **geometry data** (depth, normal, object ID, motion vector) or **color variance** to detect history confidence
- When history is invalid, simply clear the history buffer (set $\alpha$ to 1)

Dies kann aufgrund von Veränderungen im Sichtfeld (z.B. Verdeckungen, Verdeckungen), Änderungen im Beleuchtungszustand oder Variationen im Farbwert festgestellt werden.

Hierfür werden Geometriedaten (Tiefe, Normalen, Objekt-ID, Bewegungsvektor) oder Farbvariationen verwendet. Wenn die Geschichte ungültig ist, wird einfach der History-Buffer gelöscht (auf 1 gesetzt).

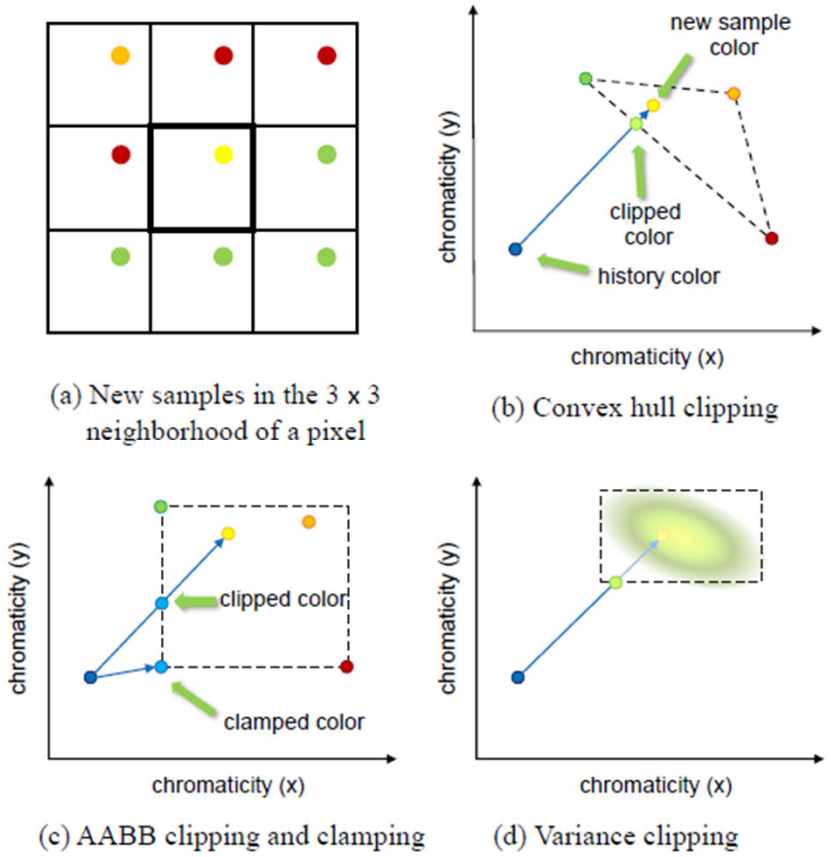


TAA History Rectification ist ein Ansatz, um das Temporal Anti-Aliasing (TAA) zu verbessern, indem die bestehende Geschichte an die neuen Samples angepasst wird.

# TAA: History Rectification

- Instead of rejecting history, we can make data more consistent with the new samples
  - Clip existing history to neighborhood of new sample
  - Further reduces temporal artifacts

Dies geschieht, indem bestehende Geschichte auf das Nachbarschaftsgebiet des neuen Samples beschränkt wird. Dadurch werden temporale Artefakte weiter reduziert. Die Rektifikation wird durchgeführt, indem die bestehenden Geschichten mit den neuen Samples verglichen und angepasst werden.




(a) New samples in the 3 x 3 neighborhood of a pixel

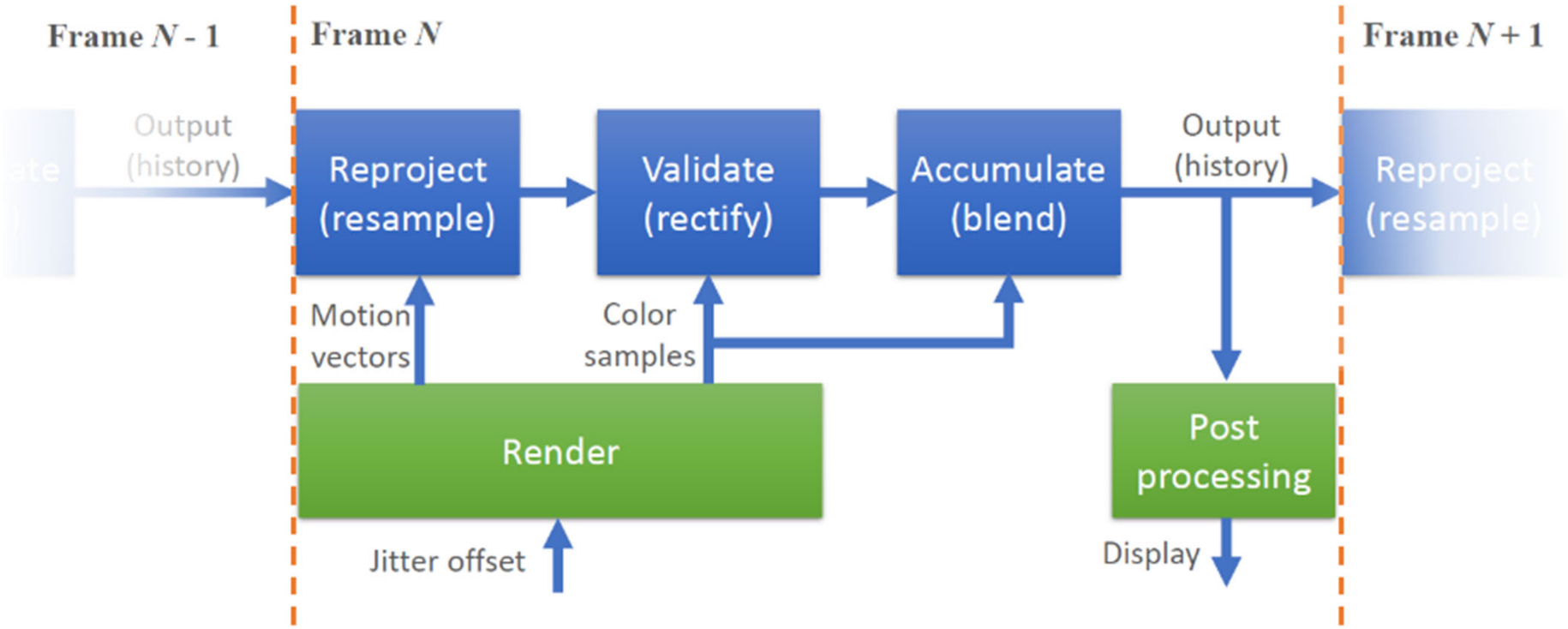
(b) Convex hull clipping

(c) AABB clipping and clamping

(d) Variance clipping

*Yang, L., Liu, S. and Salvi, M. (2020), A Survey of Temporal Antialiasing Techniques. Computer Graphics Forum, 39: 607-621. https://doi.org/10.1111/cgf.14018*

# TAA: Review




*Yang, L., Liu, S. and Salvi, M. (2020), A Survey of Temporal Antialiasing Techniques. Computer Graphics Forum, 39: 607-621. https://doi.org/10.1111/cgf.14018*

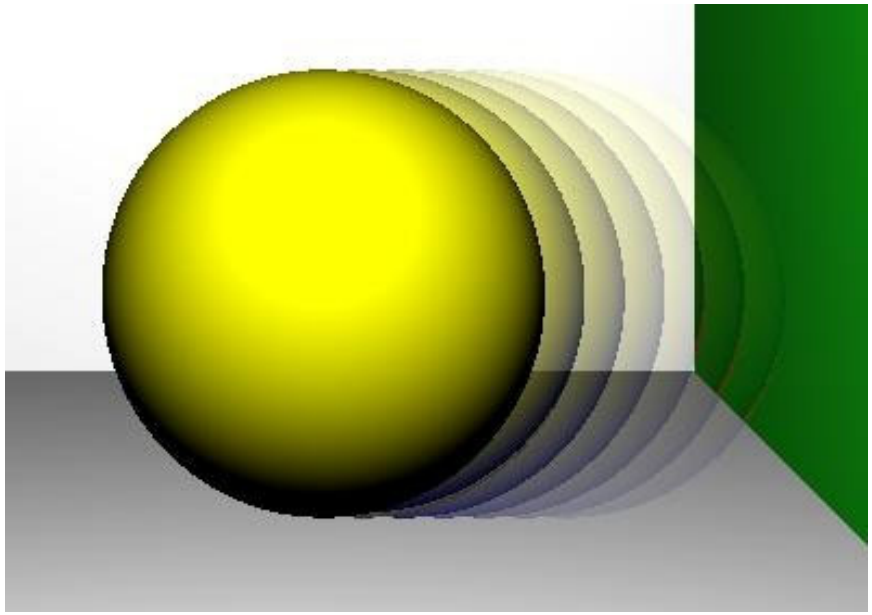
# Motion Blur

- Fast moving objects appear blurry
- Property of the human eye and cameras
- Cameras: too long exposure
- Humans: moving the eye causes blur
- Advantages:
  - Looks good/realistic
  - Can cover performance problems

# Continuous vs Discrete

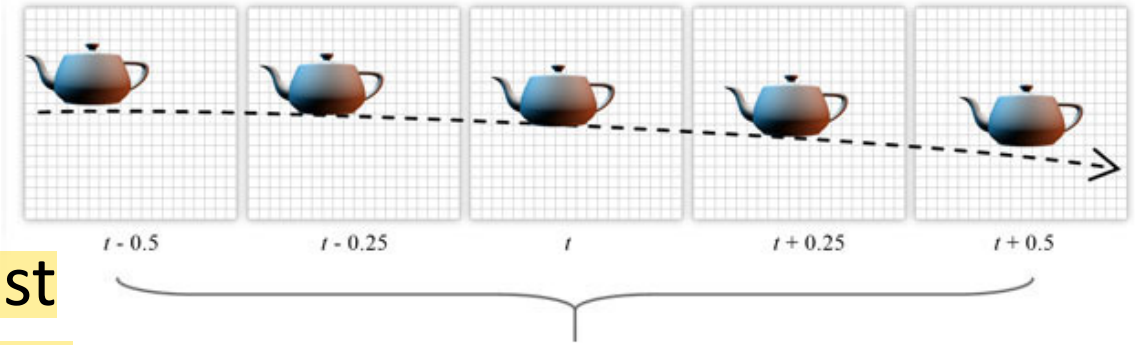
Is a continuous effect

Correct, continuous MB

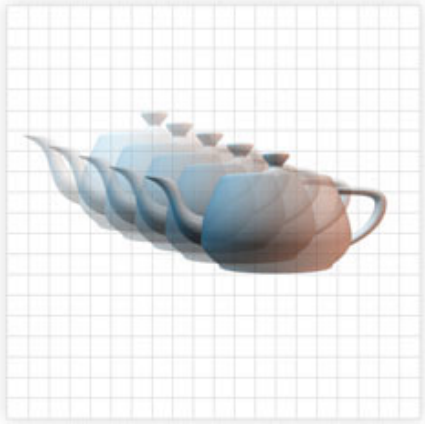


Approximated, discrete MB

# Discrete Methods




- Simplest method
  - Render object at past positions with varying transparency
  - Object needs to be rendered multiple times

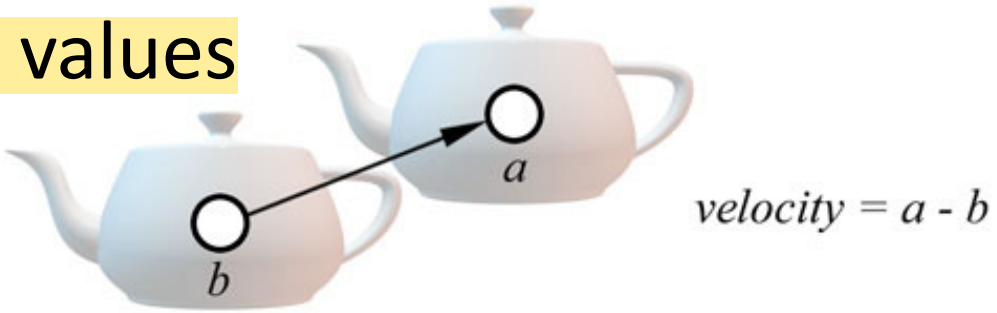


- Image Space Motion Blur
  - Render object to buffer
  - Copy buffer with varying transparency
  - More efficient

# Continuous Motion Blur

For each pixel:

- Compute how pixel moves over time
- Current and previous model-view projection matrix form *velocity buffer*
- Sample line along that direction
- Accumulate color values



# Particle Systems: Introduction

- Modeling of objects changing over time
  - Flowing
  - Billowing
  - Spattering
  - Expanding

- Typically many small objects
  - Rendering with billboards
- State-less vs. state-full particles

# Applications

- Modeling of natural phenomena:
  - Rain, snow, clouds
  - Explosions, fireworks, smoke, fire
  - Sprays, waterfalls

https://youtu.be/H_lco7TSUIY

https://youtu.be/UnZMp17lqy4

https://youtu.be/RpiDGqjhOX8

# Procedure

- All particles of a system use the same update method (share the same properties)
- The particle system handles
  - Initializing
  - Updating
  - Randomness
  - Rendering

# Particle System Parameters

- Particle parameters change over time:
  - Location, Speed, lifetime
- Particles “die” after some time
- Particle shapes
  - points, spheres, boxes, arbitrary models
  - Size and shape may vary over time

```
struct particle
{
  float t;           // life time
  float v;           // speed
  float x, y, z;     // coordinates
  float xd, yd, zd; // direction
  float alpha;       // fade alpha
};
```

# Particle Physics

- Motion may be controlled by external forces
  - E.g., gravity, collision
- Particles can interfere with other particles
- Causes a more entropic movement, e.g., sprays of liquids

# Things to Consider

- Requires fast physics and collision detection
- Correct modeling not important
- Memory consumption important
- Rendering speed important

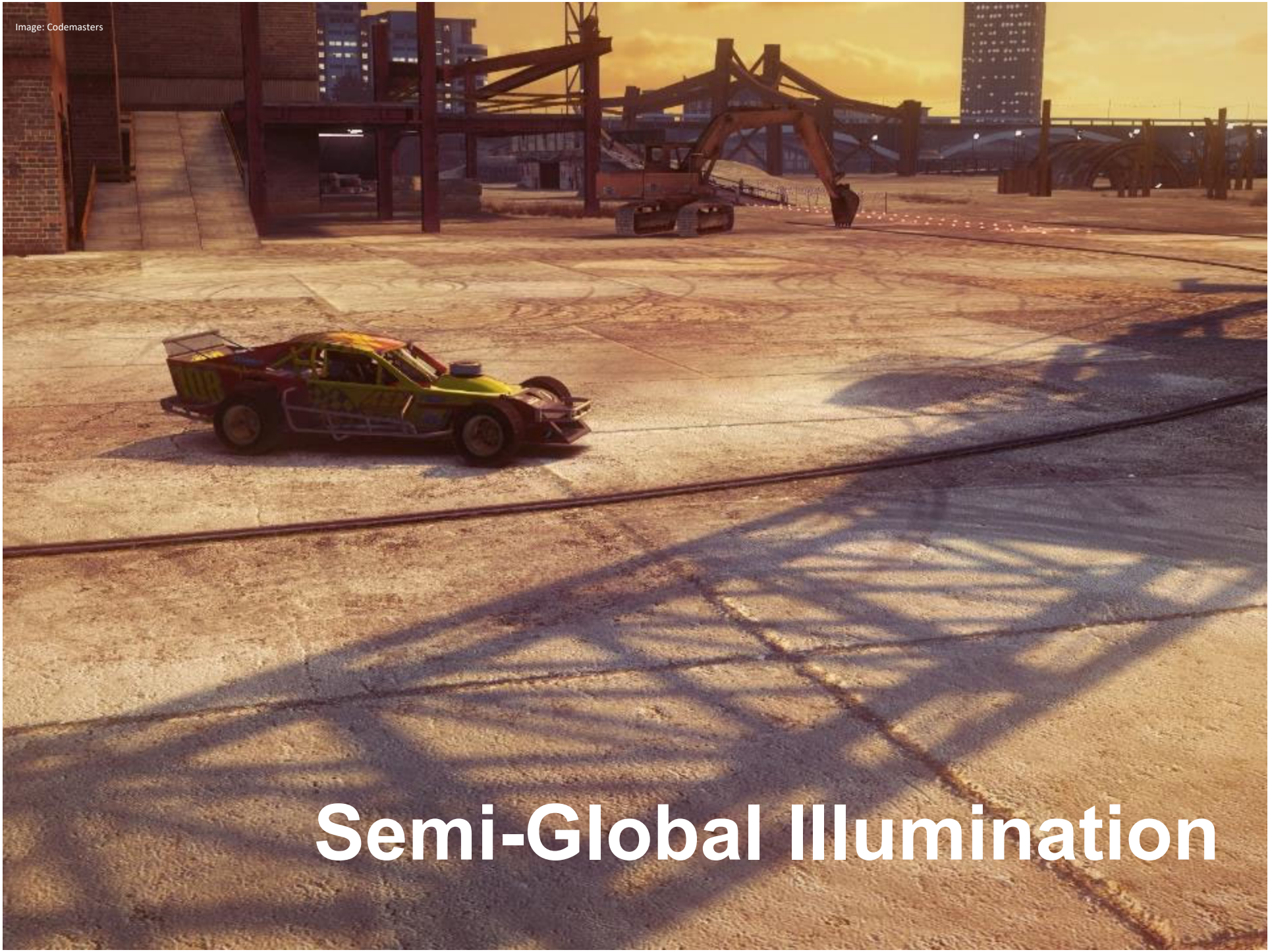
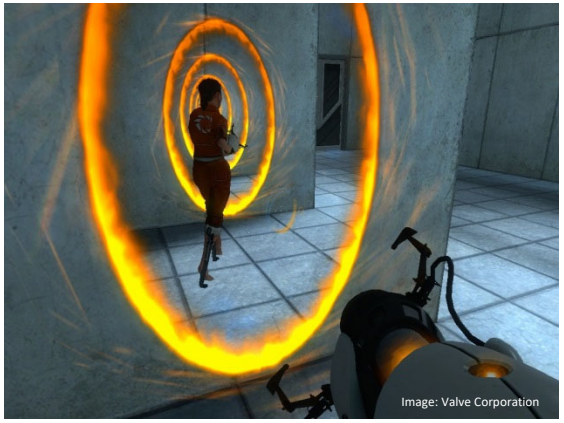


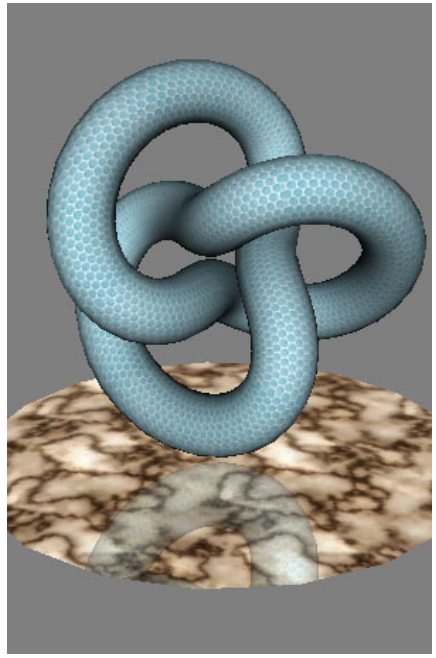
Image: Codemasters
Semi-Global Illumination

# Stencil Buffer

- Allows to mask parts of the framebuffer
- 1 Bit Stencil Buffer ($\in \{0,1\}$) e.g. for masks on or off
- 8 Bit Stencil Buffer (256 states)
- Applications
  - Reflections
  - CSG (constructive solid geometry)
  - Shadow volumes
- Today:
  - Most applications do stenciling in shader code
  - Hardware stencil still very fast – example: Portal



# Stencil Buffer Reflections

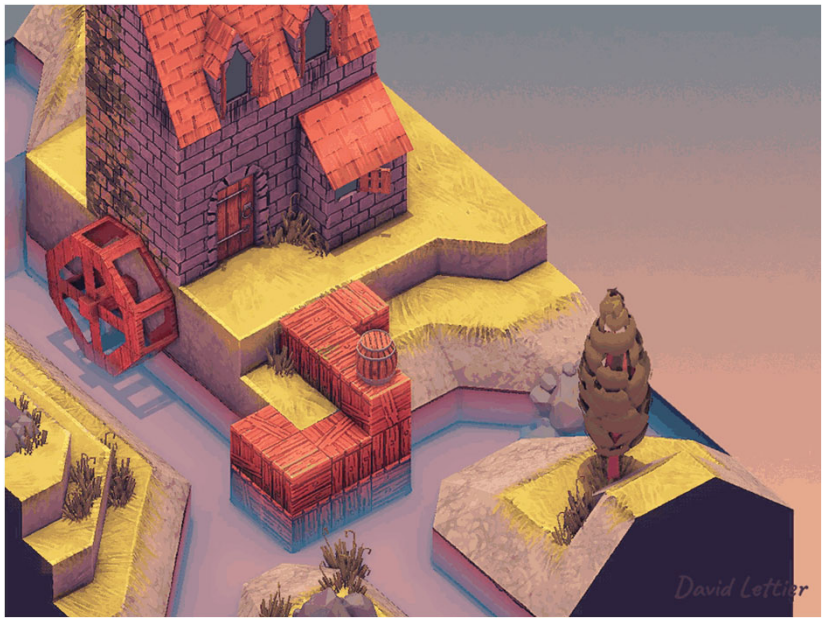


- Reset stencil buffer
  - Clear stencil buffer to zero
- Render mirror into stencil buffer
  - Enable stencil test
  - Set stencil operation to always write (on stencil-fail, depth-fail, depth-pass)
- Render mirrored object only in mirror
  - Set stencil operation to write if stencil bit set
- Render object normally

# Screen Space Reflections (SSR)

mimic ray tracing in the depth buffer

- Fully dynamic raytraced reflections are very expensive (even with RTX)
- Idea:
  - Reflect view ray across normal
  - Find depth buffer intersection in screen space
- Result: cheap dynamic approximation of reflections

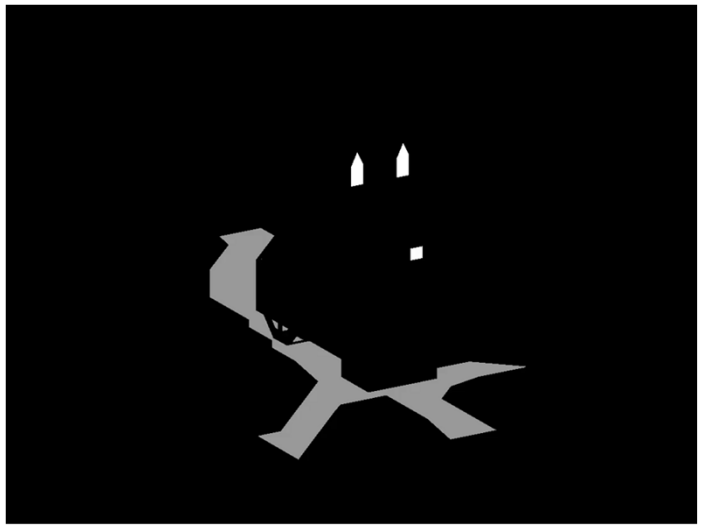



https://lettier.github.io/3d-game-shaders-for-beginners/screen-space-reflection.html

Screen Space Reflections (SSR) sind eine Technik in der Computergrafik, die es ermöglicht, Spiegelungen auf Oberflächen in Echtzeit darzustellen. SSR berechnet die Reflexionen auf der Grundlage der Informationen, die auf dem Bildschirm sichtbar sind, anstatt die Reflexionen in der 3D-Szene selbst zu berechnen. Dies ermöglicht es, die Reflexionen schnell und effizient zu berechnen, aber es hat auch einige Einschränkungen, wie z.B. begrenzte Genauigkeit und die Unfähigkeit, Reflexionen von Objekten darzustellen, die nicht im Sichtfeld des Kameras sind.

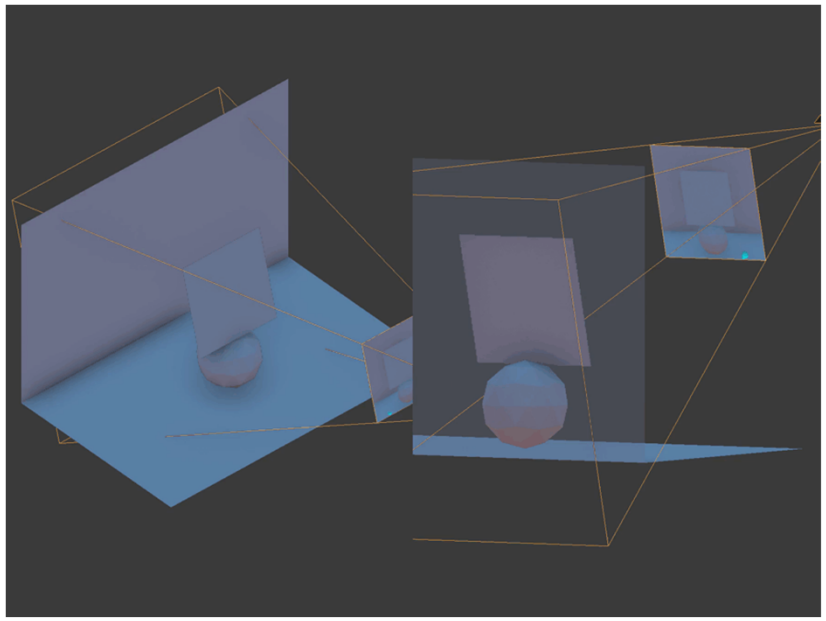
# SSR: Reflection Map

- Compute a reflection map
  - Controls amount of reflection per fragment in screen space, depending on material
- Black pixels do not show SSR
- White pixels show full SSR



# SSR: View Ray

- For each non-zero pixel in reflection map, reflect view ray across surface normal
- Along reflection vector
  - Choose a point
  - Project it
  - Compute reflection vector in screen space

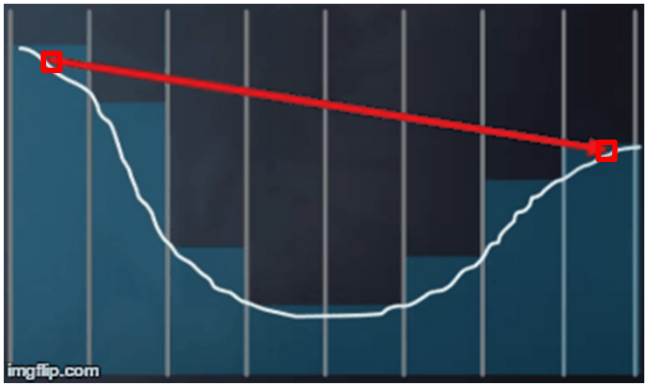


https://lettier.github.io/3d-game-shaders-for-beginners/screen-space-reflection.html

Ray werden verwendet um das nächste Objekt im Depth Buffer zu finden wo rauf reflektiert wird

# SSR: Ray Marching

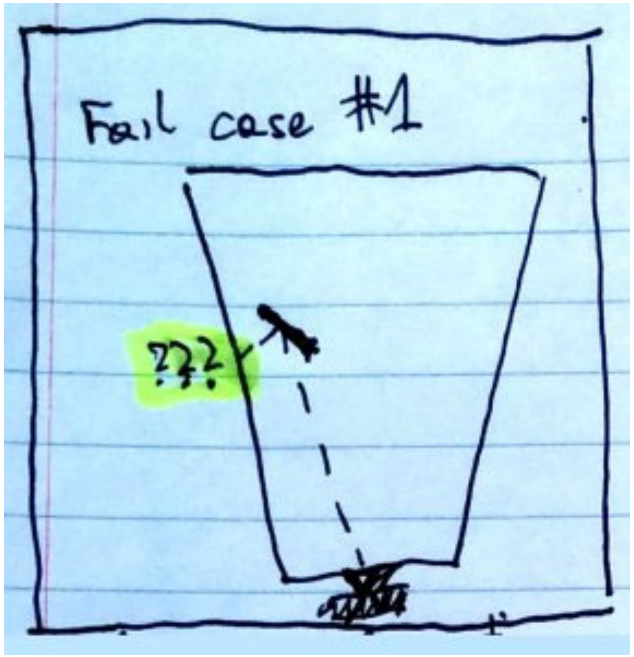
- From initial screen space position, **ray march** towards reflected screen space position
- If ray **intersects depth buffer**, we found our reflection point




https://sakibsaikia.github.io/graphics/2016/12/26/Screen-Space-Reflection-in-Killing-Floor-2.html

# SSR: Limitations 1

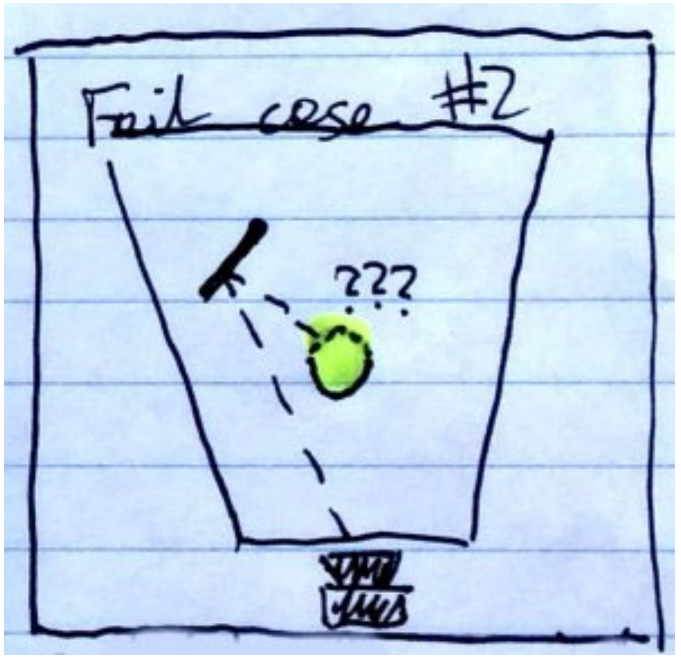
- Viewer facing reflections
- Reflections outside viewport




https://bartwronski.com/2014/01/25/the-future-of-screenspace-reflections/

# SSR: Limitations 2

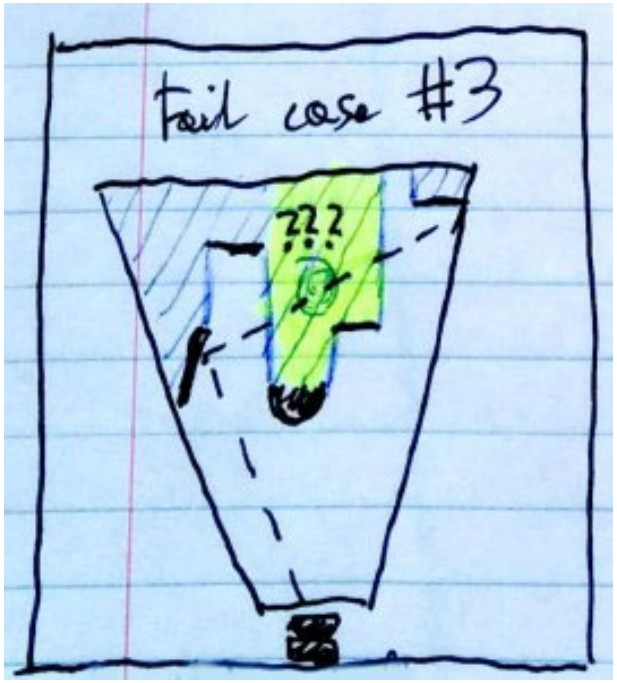
- Reflections of back faces




https://bartwronski.com/2014/01/25/the-future-of-screenspace-reflections/

# SSR: Limitations 3

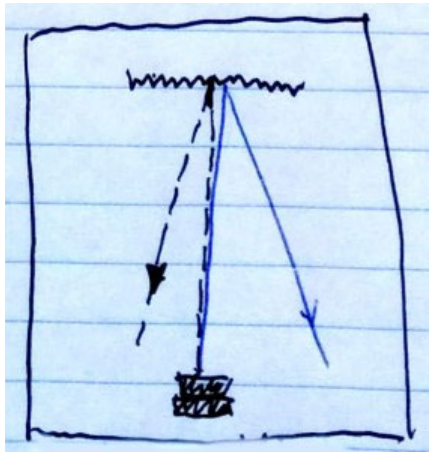
- Depth complexity

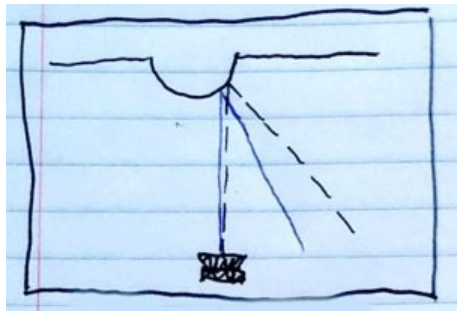



https://bartwronski.com/2014/01/25/the-future-of-screenspace-reflections/

# SSR: Limitations 4

- Flickering
- Holes
- Temporal artifacts





https://bartwronski.com/2014/01/25/the-future-of-screenspace-reflections/

# SSR: Further Improvements

- Blend with cubemaps or baked reflections
- Use temporal filtering to smoothen results
  - TAA is often exploited for this
- Use spatial filtering or blurring for rough surfaces
- Limit ray range in world space
  - For efficiency
  - To prevent far-away objects from flickering

# Transparency

- Transparency blending is order dependent
- Blending must be back to front
- Need to sort scene elements by depth

# Methods for Sorting Fragments

- Explicit depth sorting
  - Writed sorted order into draw buffer
- Depth peeling
  - Multi-pass rendering, once per *depth layer*
- Deep frame buffer
  - Write per-pixel linked lists
- Weighted blended order-independent rendering
  - Use depth as implicit weight (heuristic)

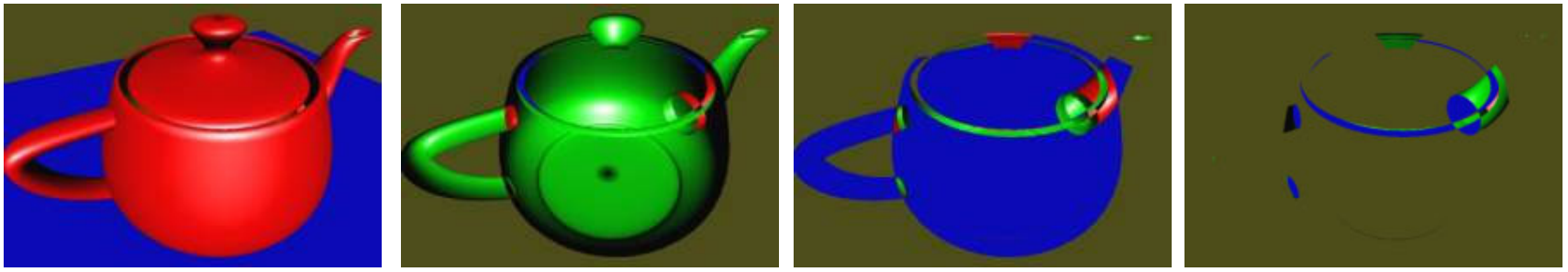
Depth Peeling ist eine Technik in der Computer-Grafik, die verwendet wird, um transparente Objekte in einer 3D-Szene korrekt darzustellen. Normalerweise kann die herkömmliche Methode zur Darstellung von Transparenz, das alpha blending, Probleme bei der Darstellung von Überlappungen von transparenten Objekten verursachen.
Depth Peeling löst dieses Problem, indem es mehrere Schichten von Pixeln separat rendert und dann zusammenfügt. Jede Schicht enthält nur die Pixel, die an der aktuellen Front (also an der Stelle mit dem geringsten Tiefenwert) sichtbar sind. Die Front wird durch den Vergleich des Tiefenwertes jedes Pixels mit den bereits gerenderten Schichten bestimmt.

# Depth Peeling

Dieser Prozess wird mehrere Male wiederholt, bis alle transparenten Pixel in der Szene gerendert wurden. Am Ende werden alle Schichten zusammengefügt, um ein korrekt dargestelltes Bild der transparenten Objekte in der Szene zu erhalten.

Interactive order independent transparency [Everitt'01]

- Multiple passes
  - First pass - find the front-most depth/color
  - Each successive pass - finds the depth/color for the next nearest fragment on a per-pixel basis
- Compare previous layer and current layer



# Rendering Depth Peeling

- Render the scene *n* times
- Save the results in texture using render-to-texture/FBO
- Each pass forms a layer
- Starting from the second pass, use a shader for comparison with previous layer
- Compose *n* layers

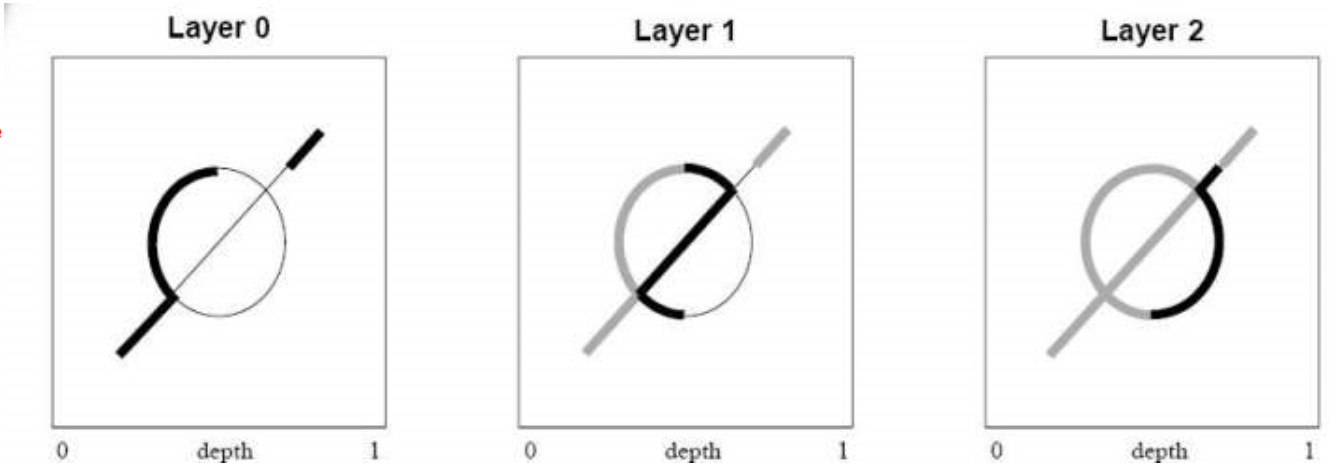
Die Szene wird n-mal gerendert, wobei jeder Durchlauf eine eigene Schicht bildet.

Jede Schicht wird in einer Textur gespeichert

Jeder Durchlauf bildet eine eigene Schicht, die später zusammengefügt wird, um das endgültige Bild zu erhalten.

Ab dem zweiten Durchlauf wird ein Shader verwendet, um jedes Pixel mit der vorherigen Schicht zu vergleichen. Hierbei wird bestimmt, ob das Pixel sichtbar ist oder nicht, basierend auf seinem Tiefenwert.

Am Ende werden alle n Schichten zusammengefügt, um das endgültige Bild zu erhalten.



Dual Depth Peeling ist eine Optimierung des Depth Peeling Rendering-Verfahrens, bei dem die Anzahl der benötigten Render-Durchläufe reduziert wird. Hierbei werden gleichzeitig die Vorder- und Rückseiten transparenten Objekte in einem einzigen Durchlauf gerendert.

# Dual Depth Peeling

- Peel front and back in one pass

Vorder- und Rückseiten transparenten Objekte werden gleichzeitig in einem einzigen Durchlauf gerendert.

- Keep track of min/max depth in two textures

Es werden gleichzeitig die minimale und maximale Tiefe in zwei Texturen verfolgt.

- Compare current depth with min/max values
  - If < min write to front layer
  - If > max write to back layer

Der aktuelle Tiefenwert wird mit den Minimal- und Maximalwerten verglichen.

Wenn der Tiefenwert kleiner als der Minimalwert ist, wird das Pixel in die Vordergrundschicht geschrieben sonst in das Hintergrundbild.

- Use previous front/back layer depth values in current pass

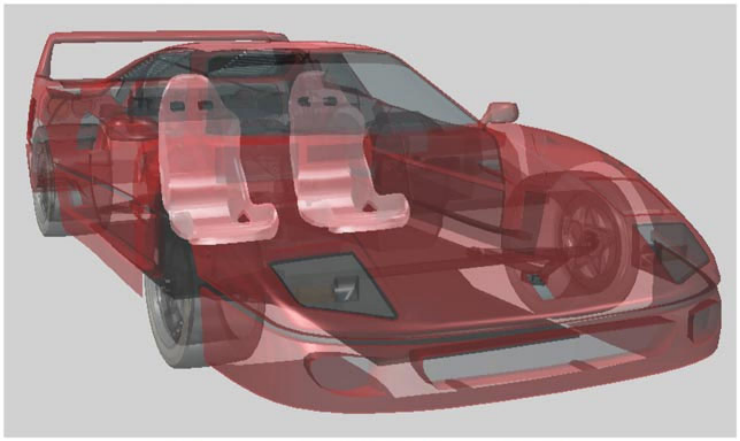
Die Tiefenwerte der Vorder- und Rückseitenschichten des vorherigen Durchlaufs werden im aktuellen Durchlauf verwendet.

- Decreases number of passes from $n$ to $n/2+1$

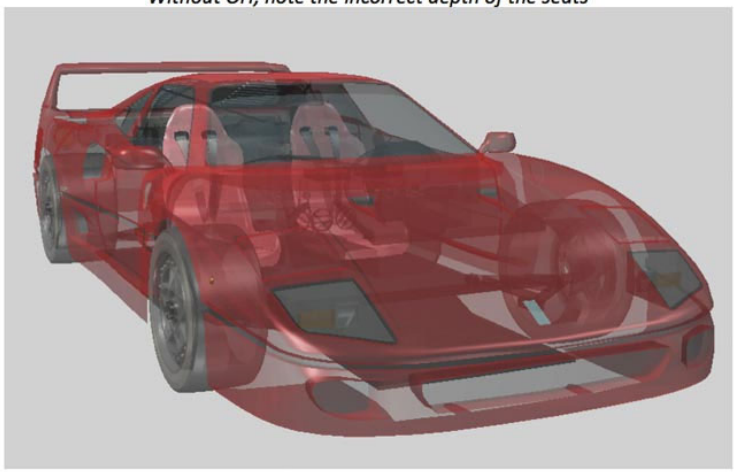
Die Anzahl der benötigten Durchläufe wird von n auf n/2+1 reduziert, was eine bessere Leistung und eine höhere Effizienz bei der Darstellung von transparenten Objekten ermöglicht.

# Deep Framebuffer

- Depth peeling creates too much geometry overhead
  - O(triangles*overdraw)
- Use pixel operations instead
  - Write every fragment to a per-pixel linked list
- Sort and blend the lists
- Historically called *accumulation buffer* (*A-buffer*)



*Without OIT, note the incorrect depth of the seats*



*With OIT applied*

Sie speichert die Informationen über die Transparenz für jeden Pixel auf dem Bildschirm in einer verknüpften Liste. Jeder Eintrag in der Liste enthält Informationen über das transparente Polygon, das für diesen Pixel sichtbar ist, sowie die Farbinformationen für diesen Pixel.

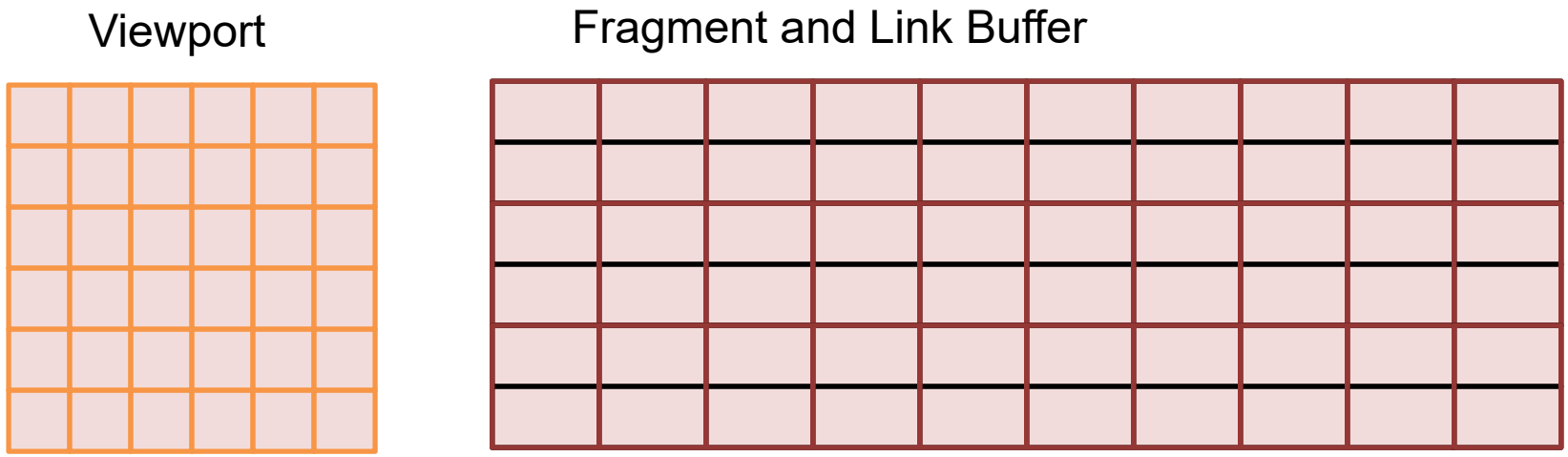
# Per-Pixel Linked Lists

- Algorithm
  - Render scene and generate linked list per pixel
  - Sort list and compose fragments
- Requires read/write buffer
- Need two additional buffers
  - Fragment and link buffer
  - Start offset buffer

Beim Rendern von transparenten Polygonen wird zunächst die Tiefeninformationen der Sichtbare Polygone berechnet. Dann werden die Einträge in der PPLL aktualisiert, indem die Einträge für die unsichtbaren Polygone entfernt und neue Einträge für die sichtbaren Polygone hinzugefügt werden. Schließlich werden die Farbinformationen für jeden Pixel aus der PPLL berechnet.

# Fragment and Link Buffer

- Contains all fragment data produced during rasterization
- Must be large enough to store all fragments



# Start Offset Buffer

- Contains the offset of the last fragment written at every pixel location
- Screen-sized: `(width * height * sizeof(UINT32))`
- Initialized to magic value
  - Magic value indicates end of list (no more fragments stored)

| | | | | | |
|---|---|---|---|---|---|
| -1 | -1 | -1 | -1 | -1 | -1 |
| -1 | -1 | -1 | -1 | -1 | -1 |
| -1 | -1 | -1 | -1 | -1 | -1 |
| -1 | -1 | -1 | -1 | -1 | -1 |
| -1 | -1 | -1 | -1 | -1 | -1 |
| -1 | -1 | -1 | -1 | -1 | -1 |

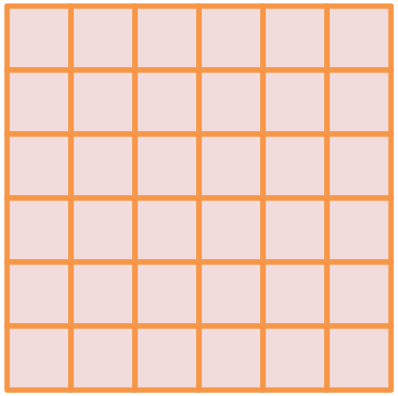
Start Offset Buffer

# Linked List Creation 1

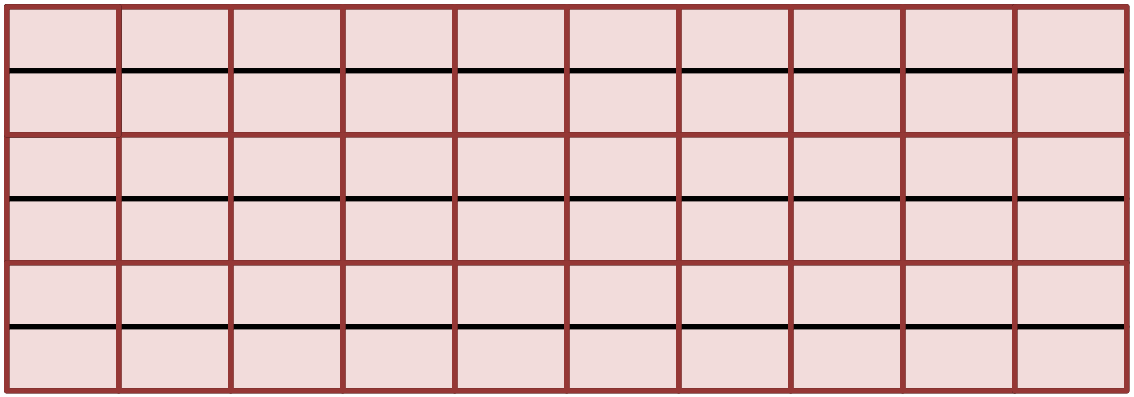
Start Offset Buffer

| | | | | | |
|---|---|---|---|---|---|
| -1 | -1 | -1 | -1 | -1 | -1 |
| -1 | -1 | -1 | -1 | -1 | -1 |
| -1 | -1 | -1 | -1 | -1 | -1 |
| -1 | -1 | -1 | -1 | -1 | -1 |
| -1 | -1 | -1 | -1 | -1 | -1 |
| -1 | -1 | -1 | -1 | -1 | -1 |

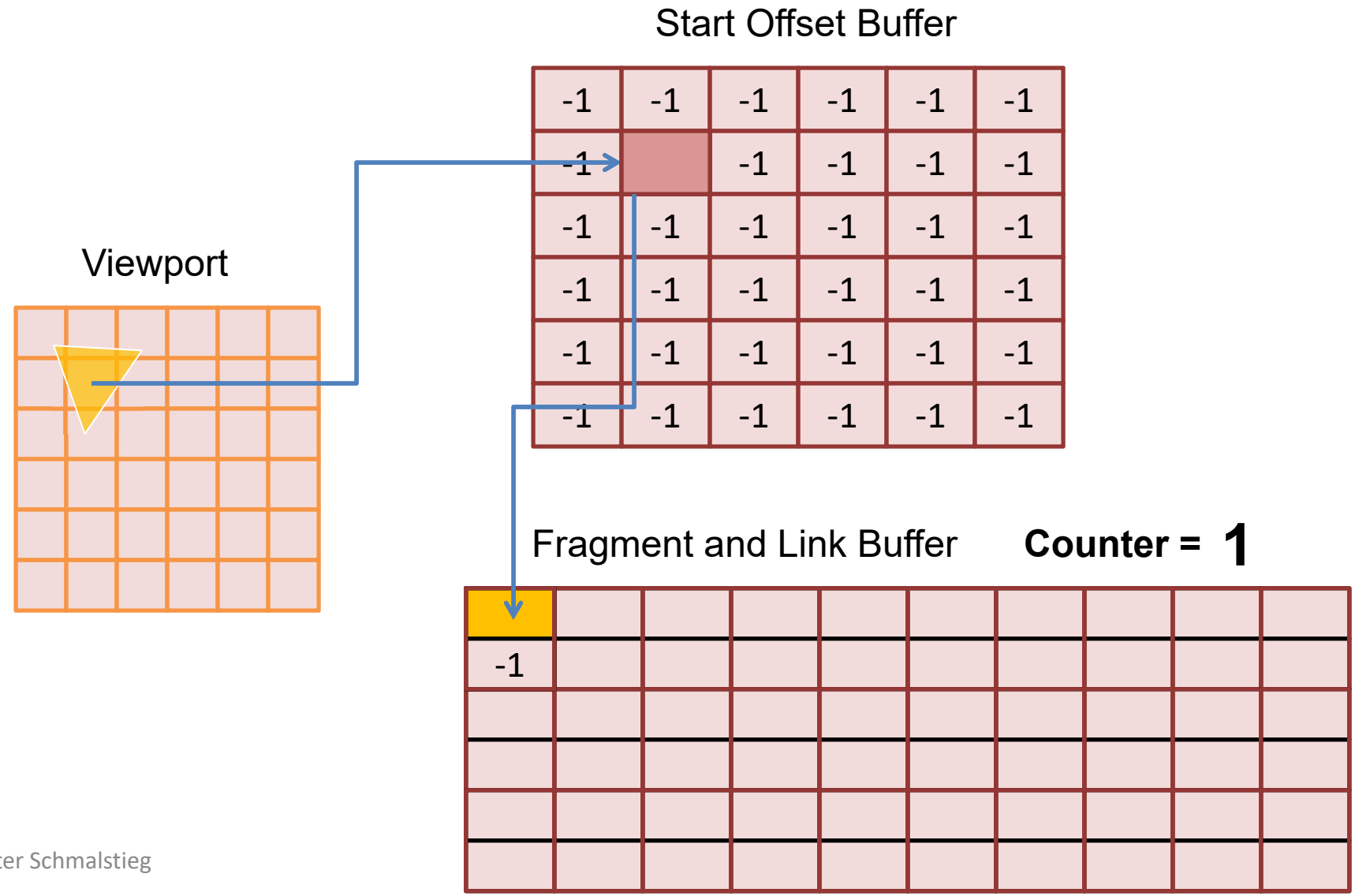
Viewport



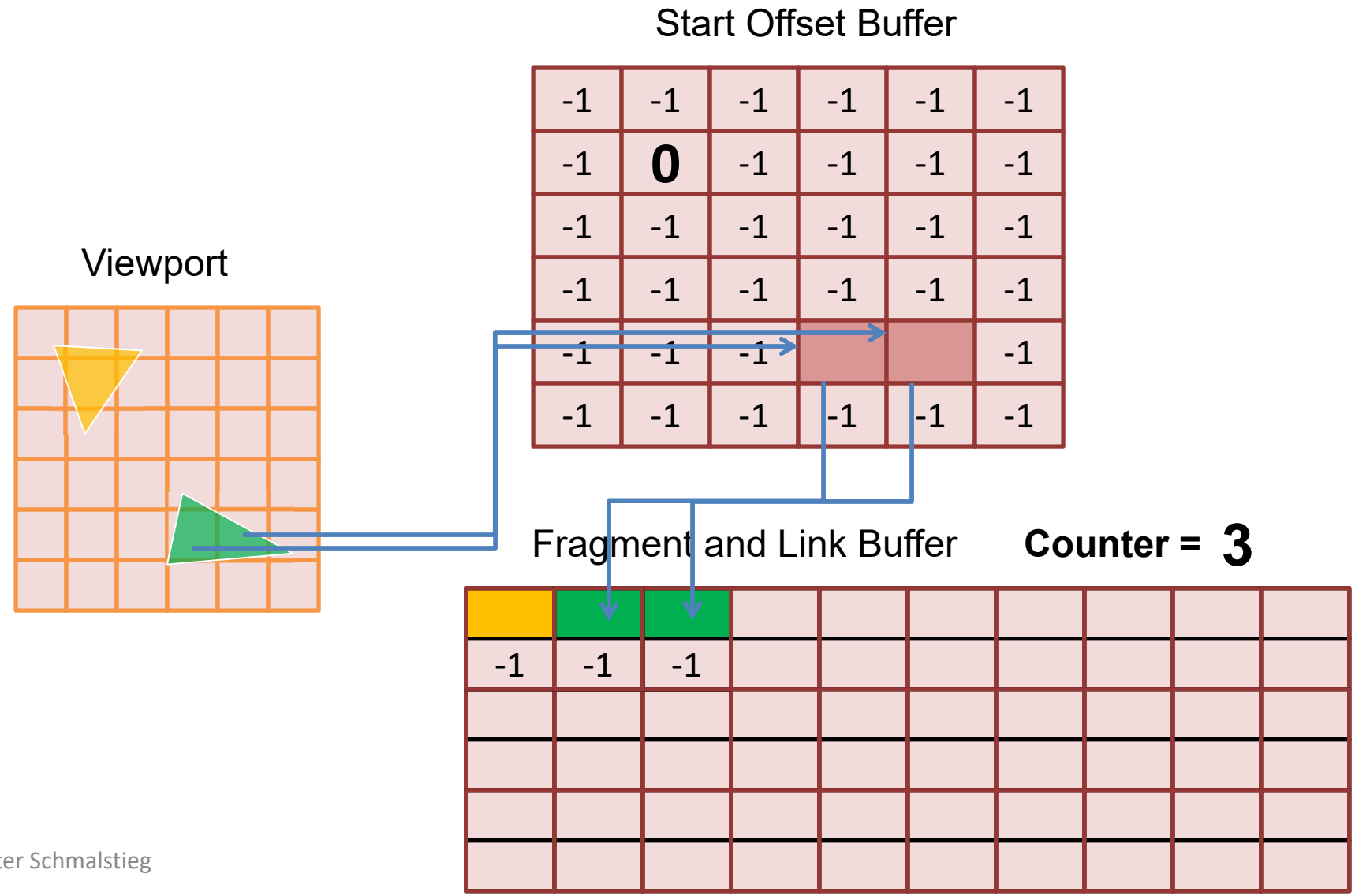
Fragment and Link Buffer **Counter = 1**



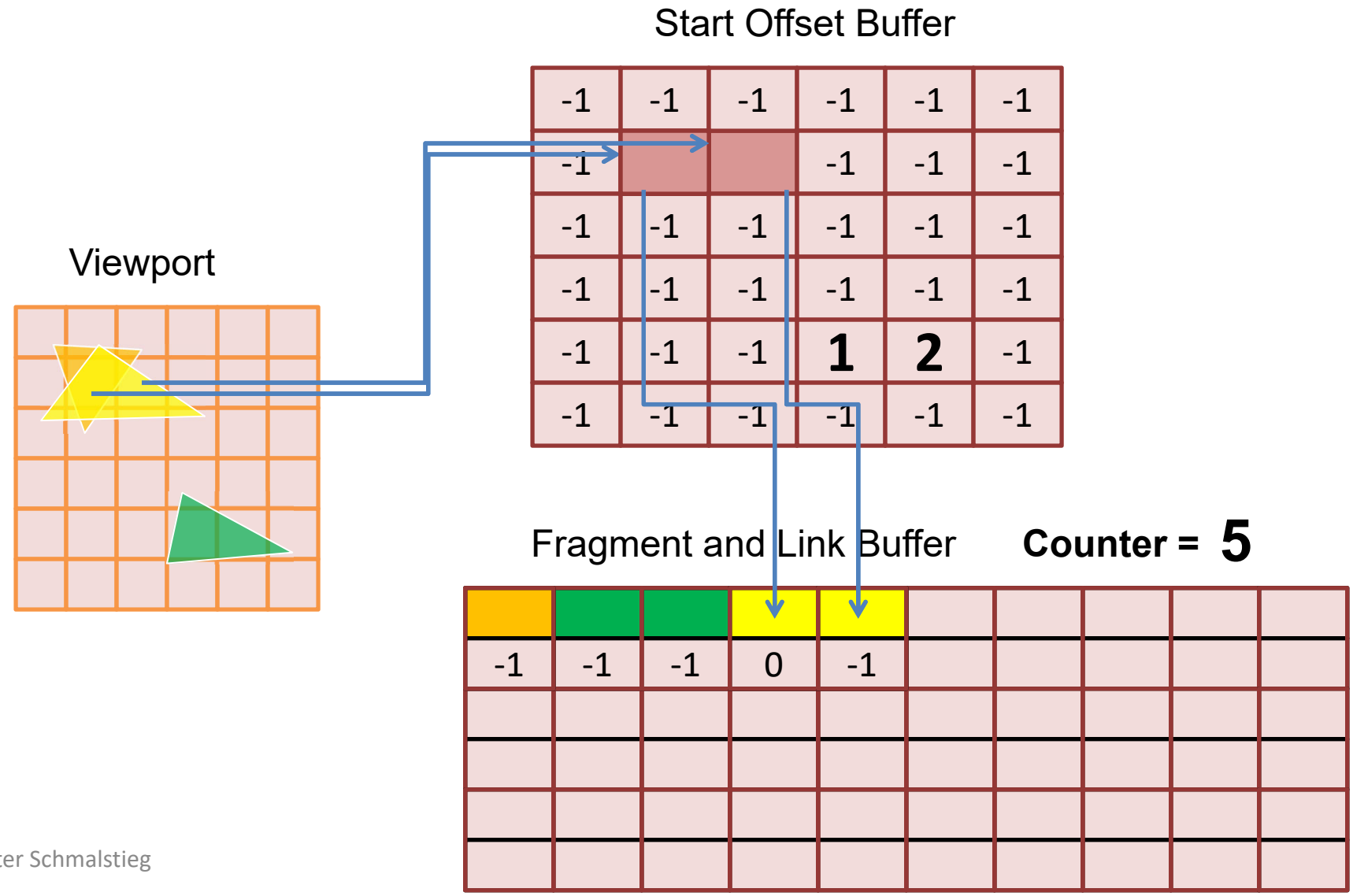
# Linked List Creation 2



# Linked List Creation 3



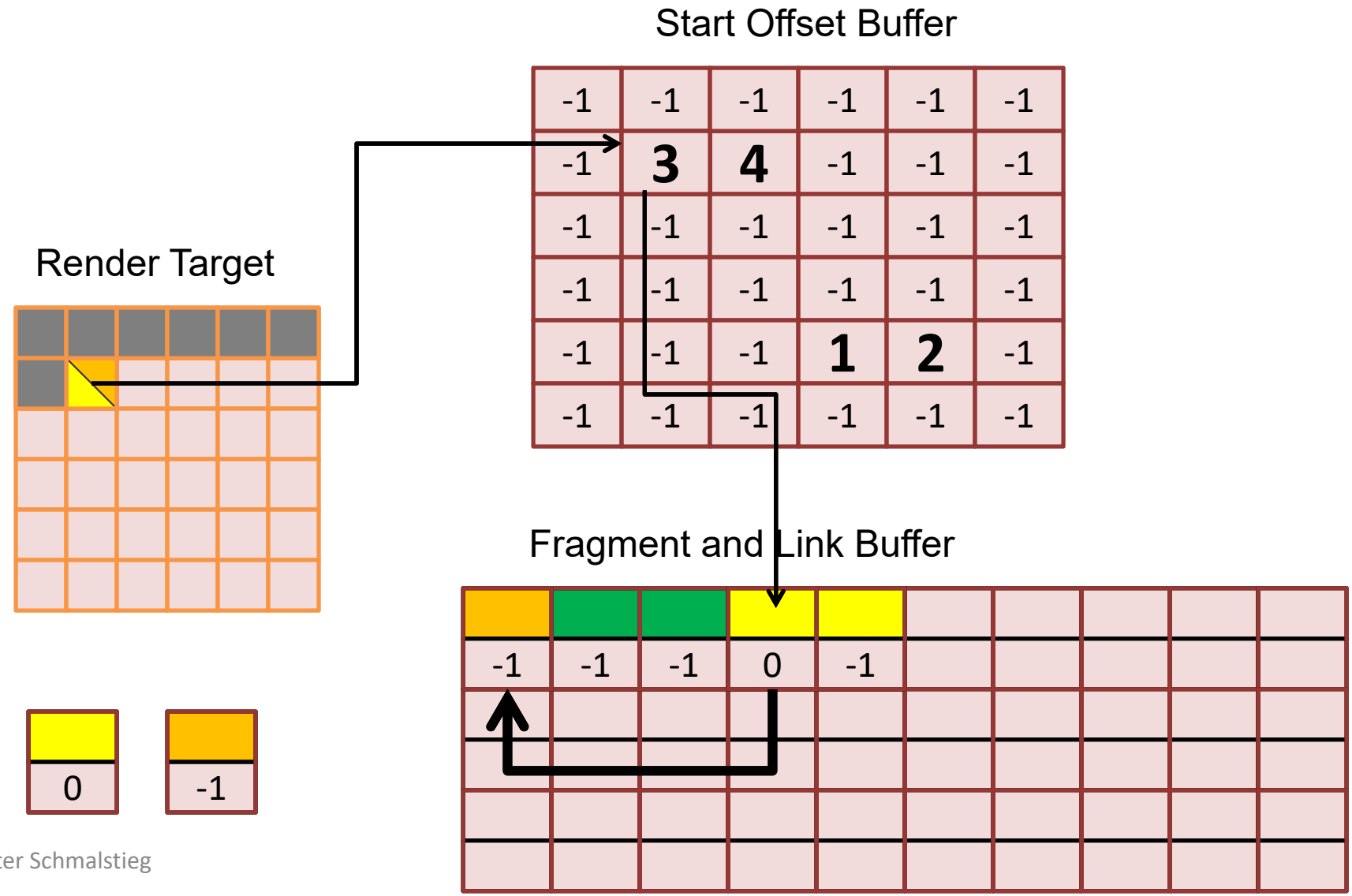
# Linked List Creation 4



# Linked List Traversal

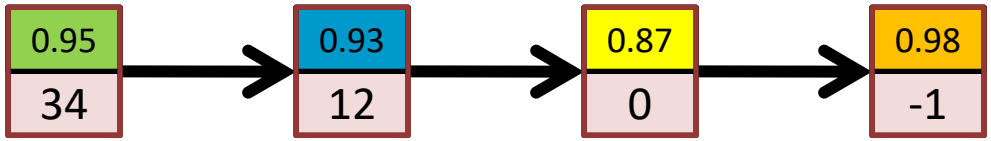
- Render a fullscreen quad (or compute shader)
- For each pixel
  - Parse the linked list
  - Retrieve fragments for this screen position
- Process list of fragments (Sort and Blend)

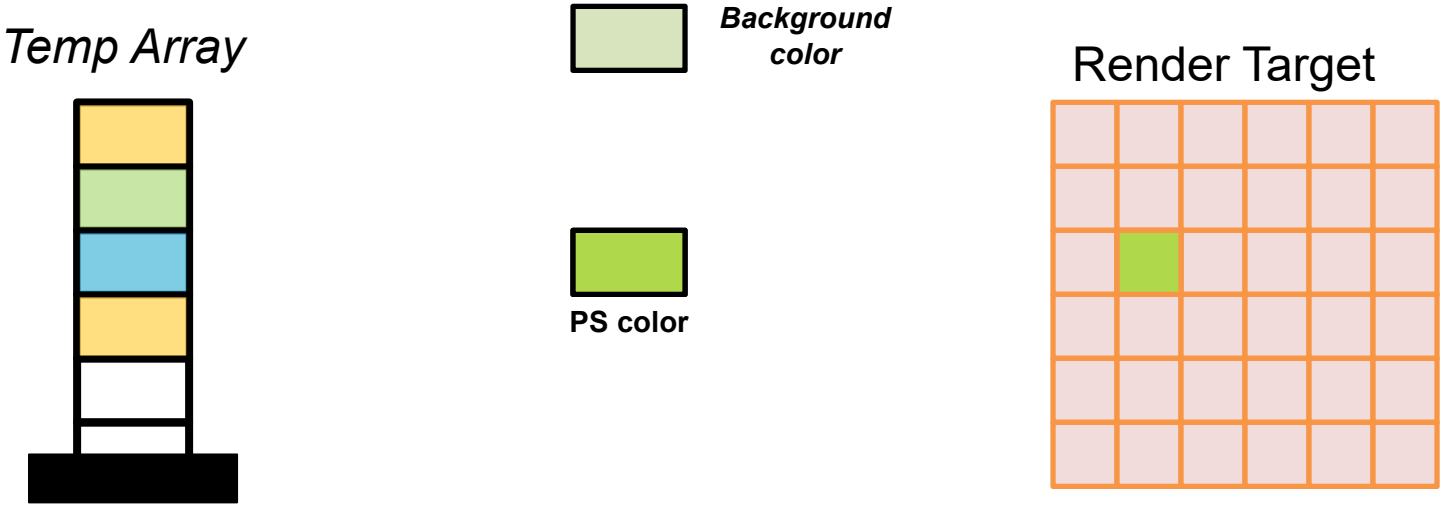
# Rendering from Linked List



# Sorting and Blending

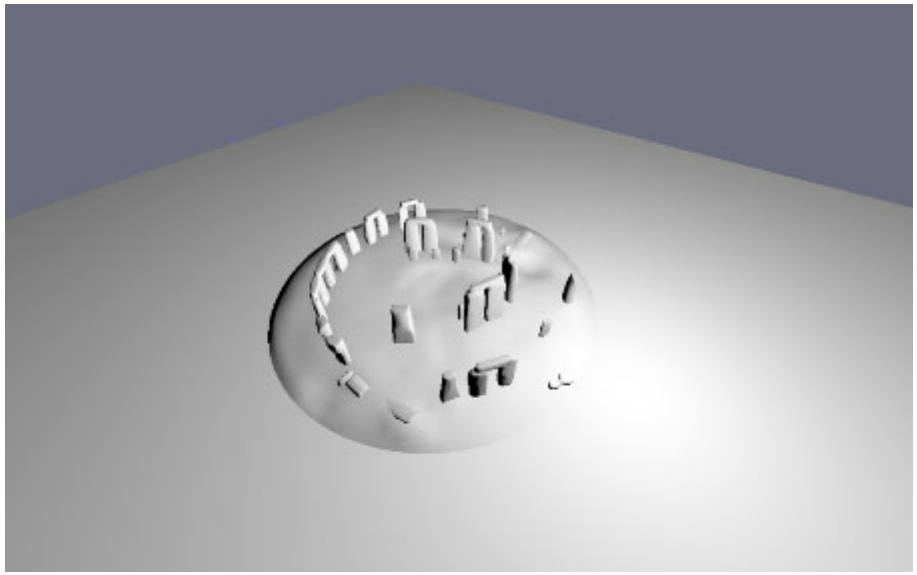
- Blend fragments back to front in PS
- Must sort by depth value in temp.array

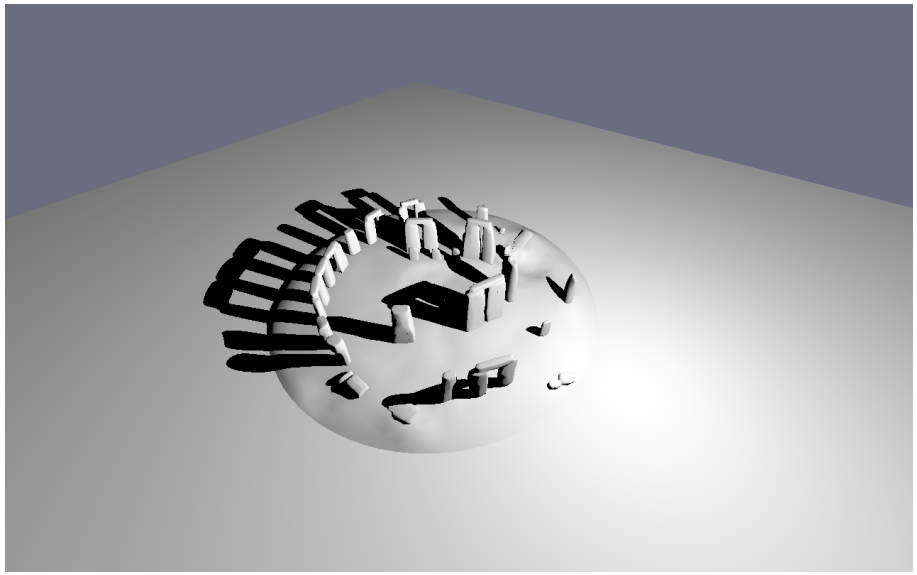


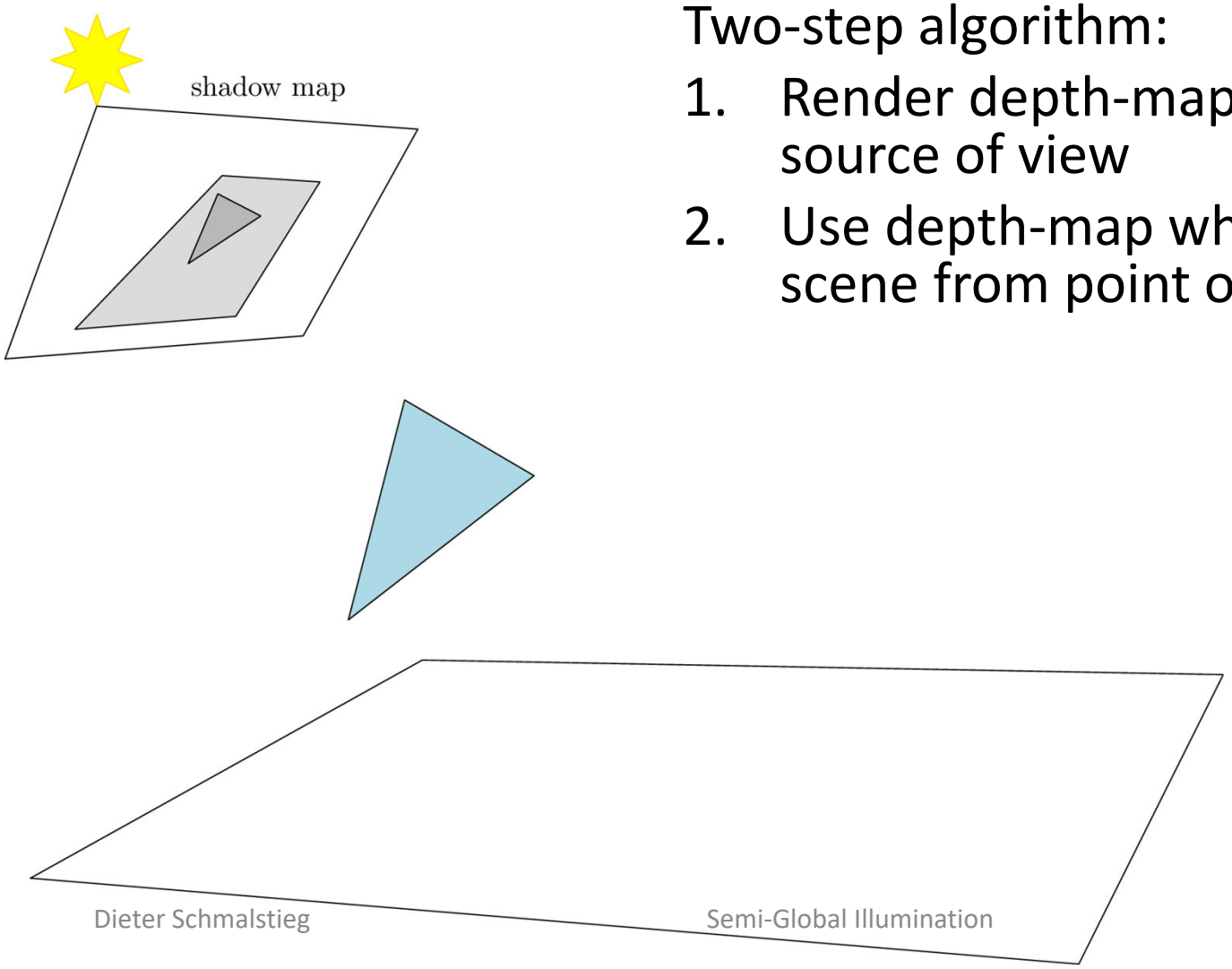
# Shadows

- Light blocked by other objects
- Important visual cue
  - Relative location
  - Position of light





# Shadow Mapping Algorithm 1

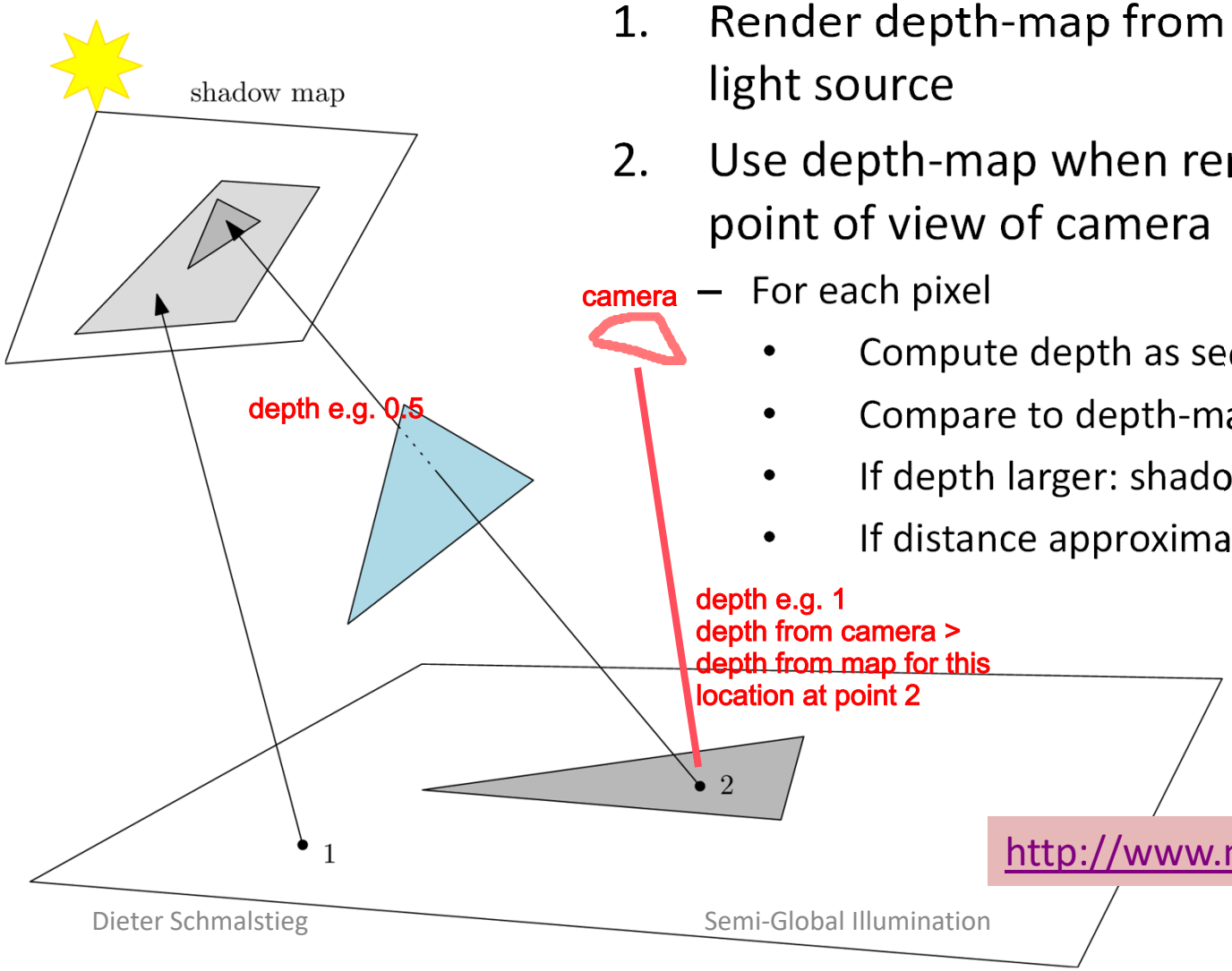



Two-step algorithm:

1. Render depth-map from point light source of view
2. Use depth-map when rendering scene from point of view of camera

Point is illuminated = point is visible from the light source

# Shadow Mapping Algorithm 2



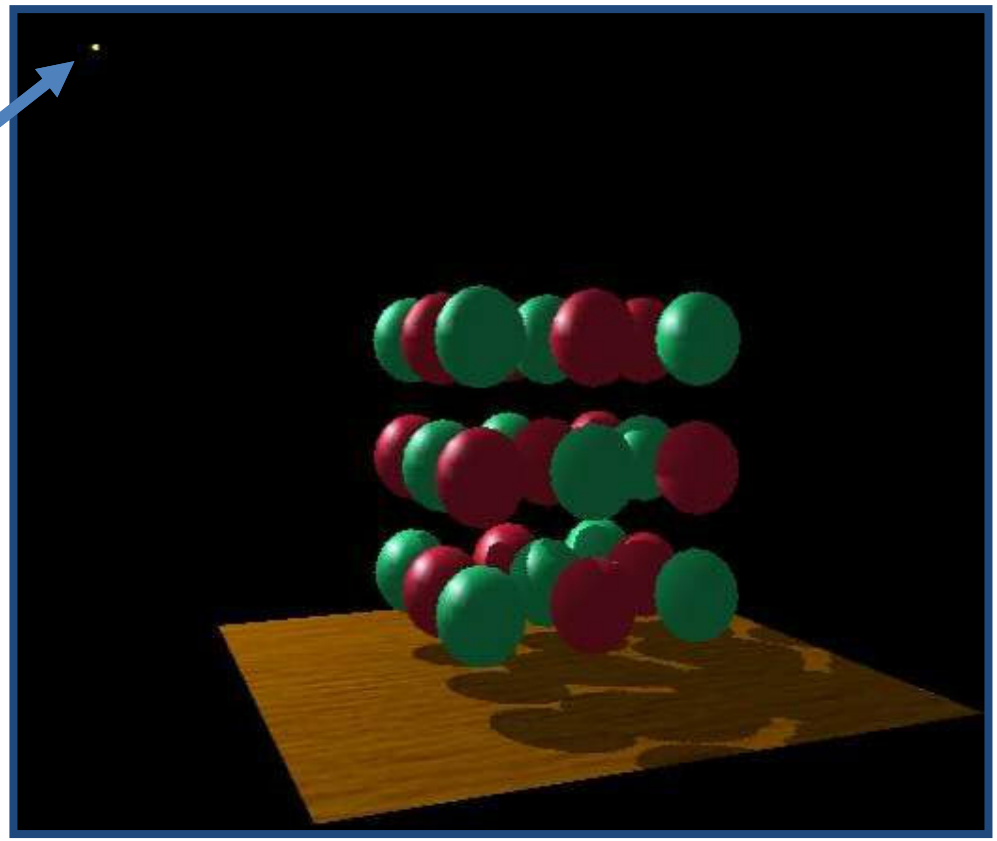

1. Render depth-map from point of view of the light source
2. Use depth-map when rendering scene from point of view of camera
   - For each pixel
     - Compute depth as seen from light source
     - Compare to depth-map
     - If depth larger: shadow
     - If distance approximately equal: light

http://www.nutty.ca/webgl/shadows/

# Shadow Mapping - Point Light

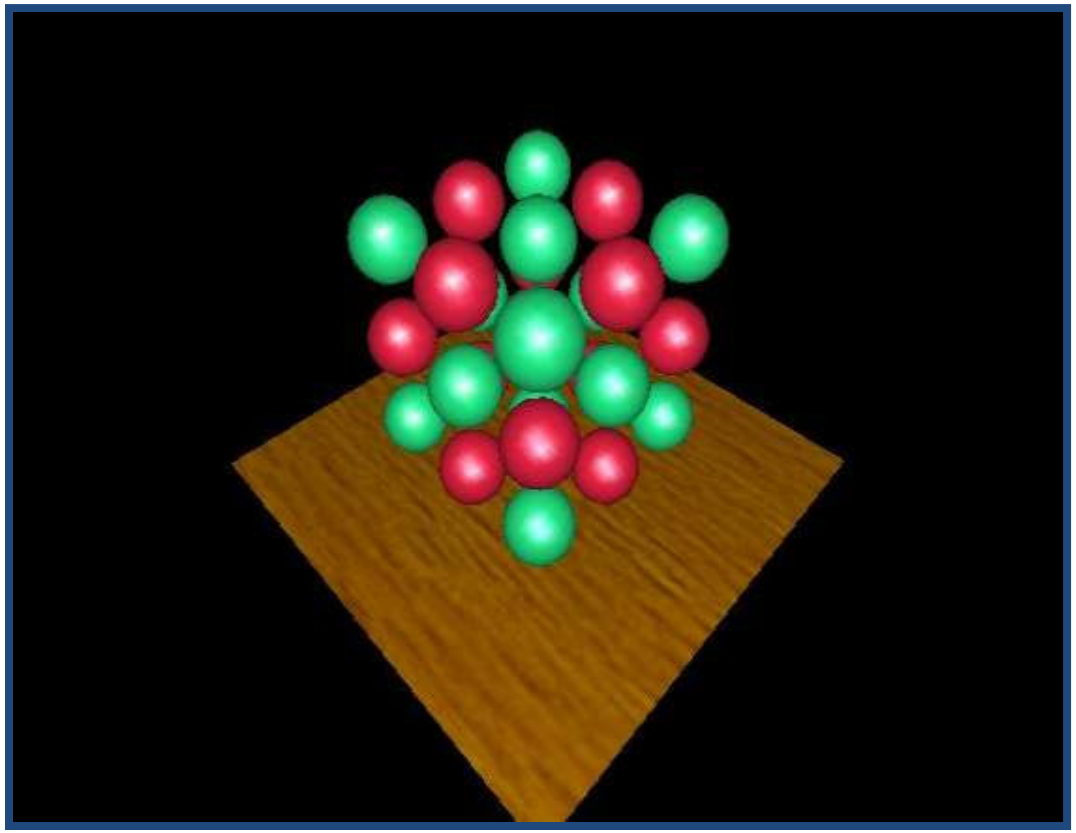
Beispiel des oben beschriebenen Hurensalgorithmus

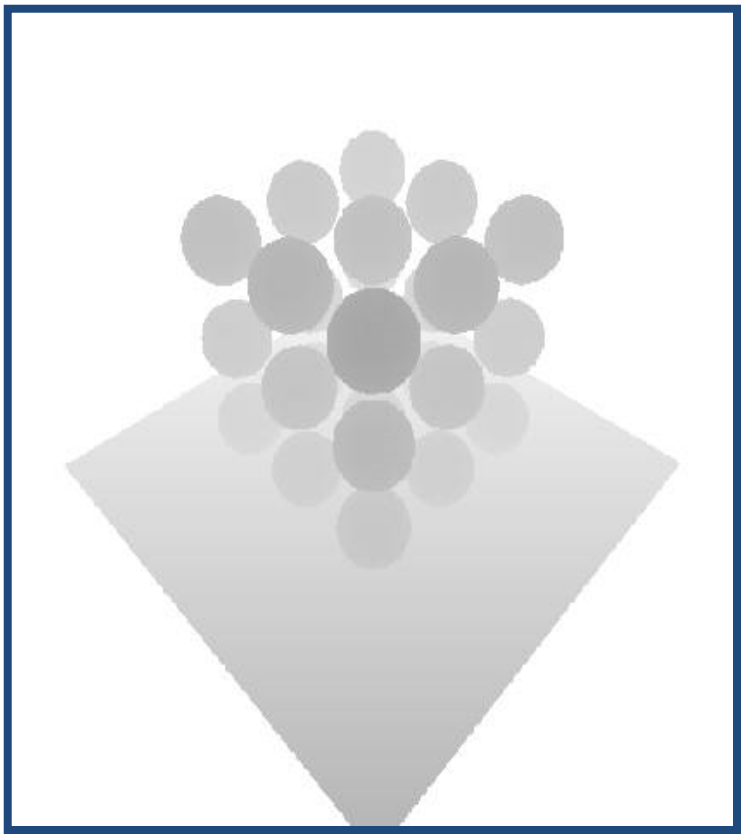
Our point light source



# Shadow Map as Depth Map

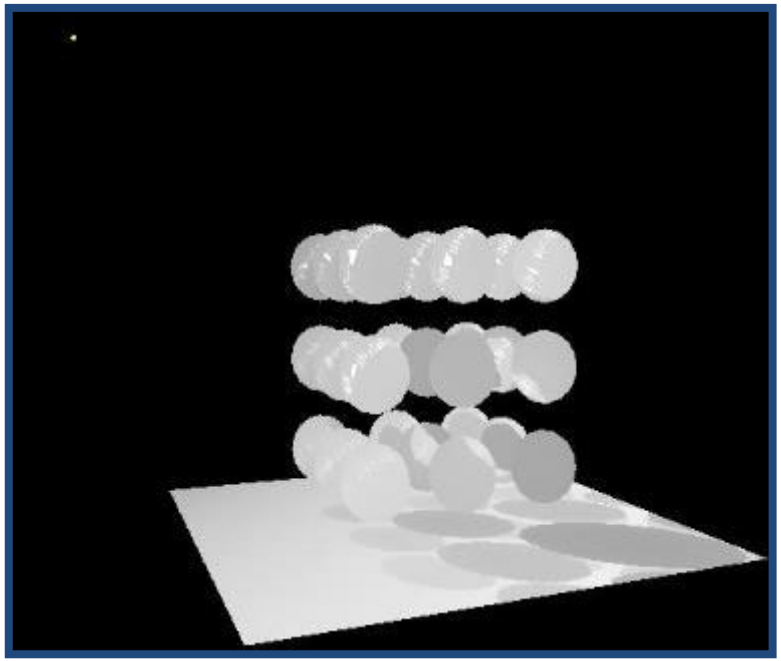
- Rendering the Depth-Map

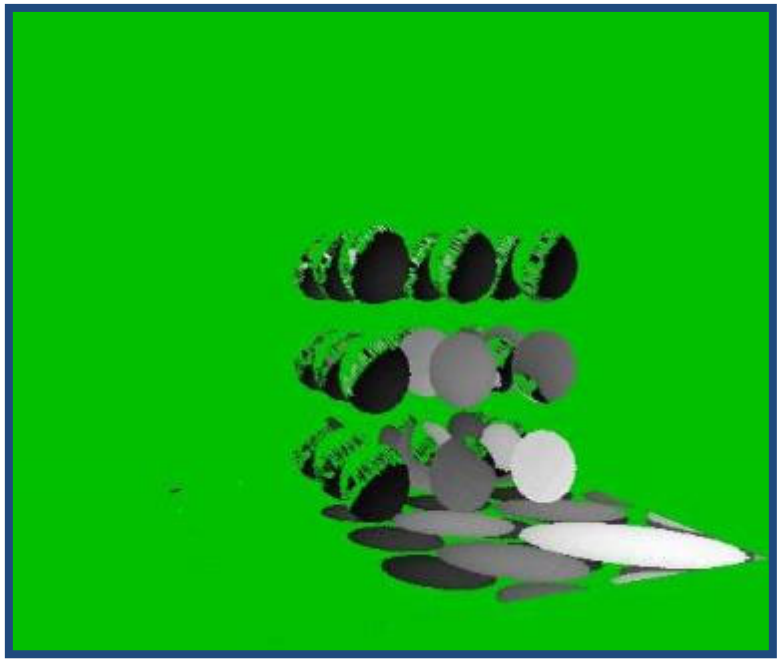




# Shadow Mapping - Depth Test

- Green: depth approximately equal
- Non-green: shadow





Shadow volumes sind 3D-Formen, die die Schattenbereiche einer Szene definieren, wenn eine Lichtquelle vorhanden ist. Sie werden verwendet, um Schatten von flachen und sich gegenseitig überlappenden Objekten zu berechnen.

# Shadow Volumes

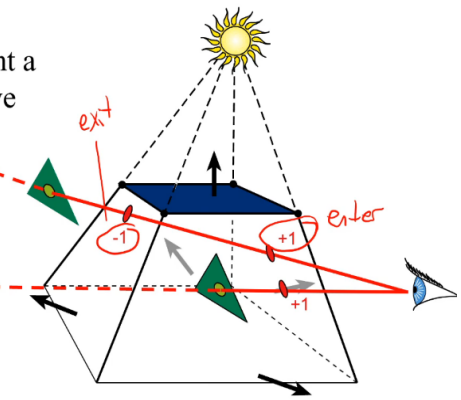
[Frank Crow, 1977]

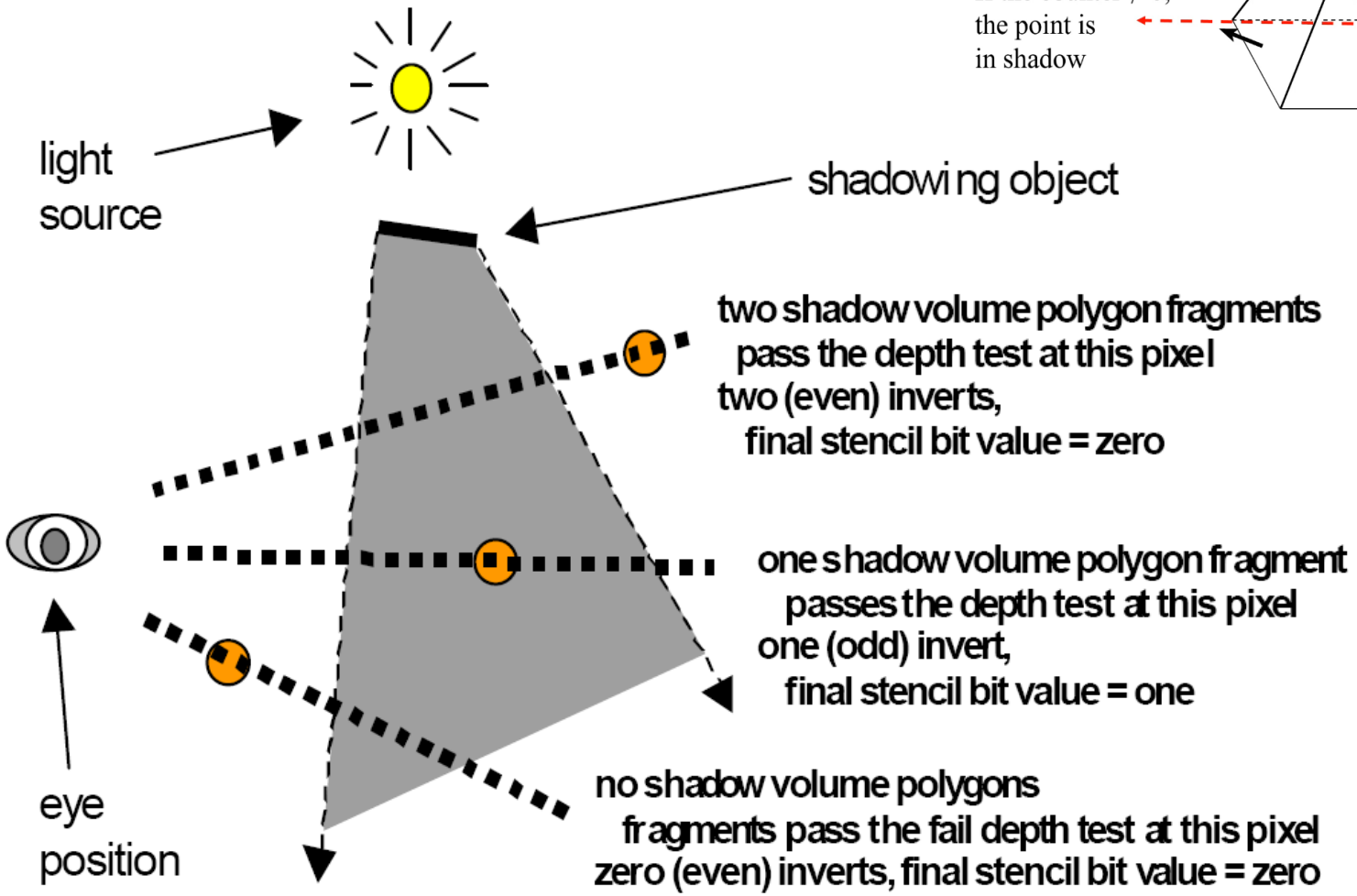
- Complex, but can be implemented efficiently using stencil buffer
- No aliasing
- Method
  - Intersect view rays with shadow volume
  - Count number of intersections, until receiver is hit

# Shadow Volur

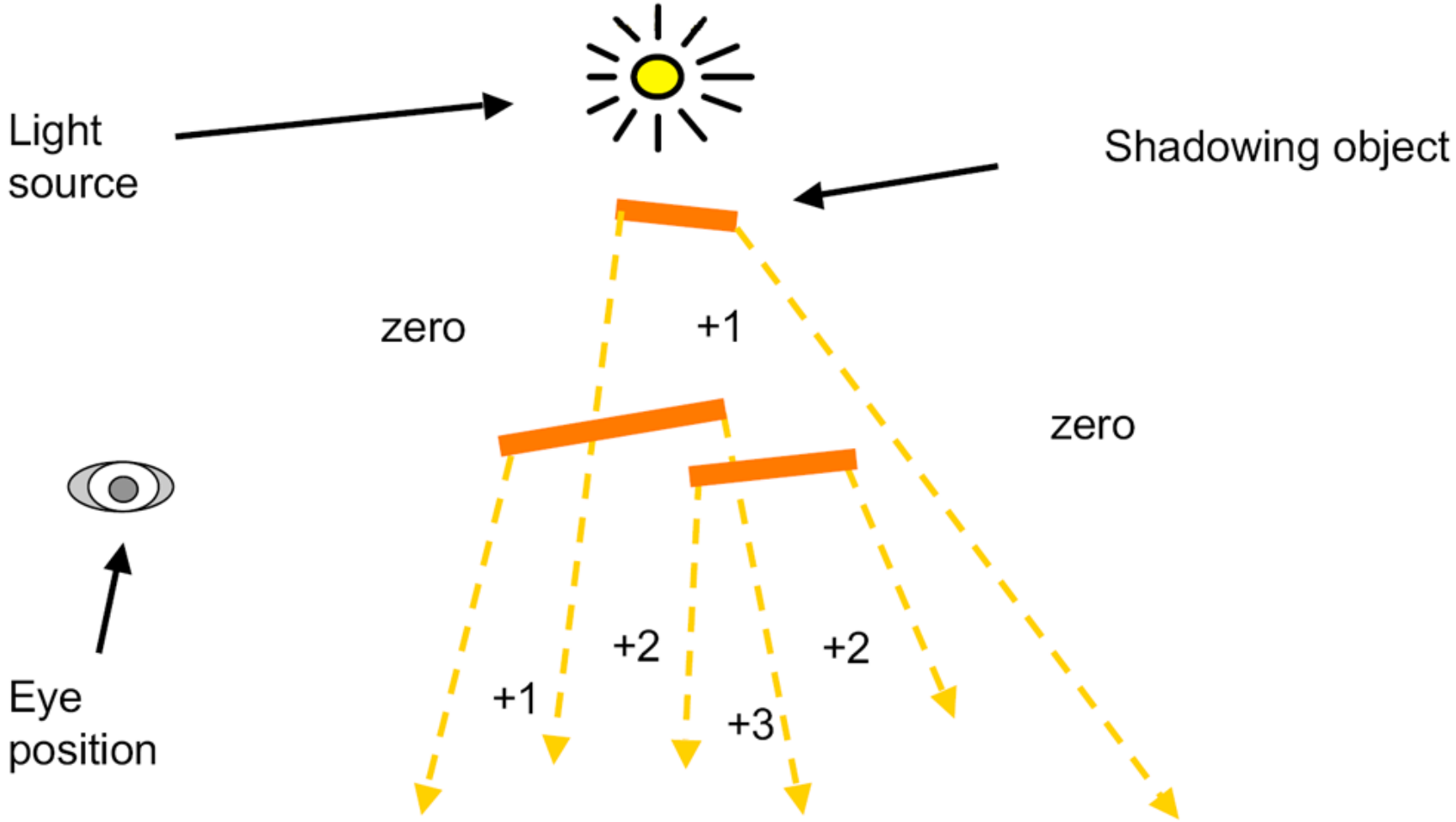
## Better Shadow Volumes

- Shoot a ray from the eye to the visible point
- Increment/decrement a counter each time we intersect a shadow volume polygon
- If the counter ≠ 0, the point is in shadow



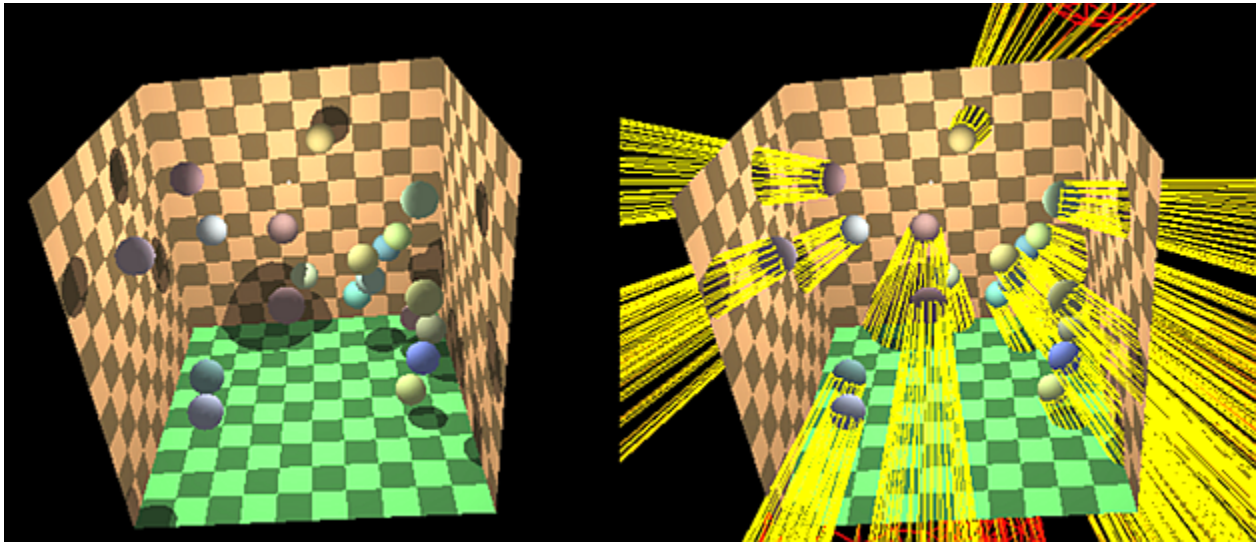



# Counting Scheme



# Shadow Volume Problems

- Camera inside shadow volume
  - Treat as special case or use “depth-fail” method
- Shadow volume intersects near-plane
  - Solution: render “front-caps”
- Objects must be manifold
- High amount of overdraw
- Fill-rate bound

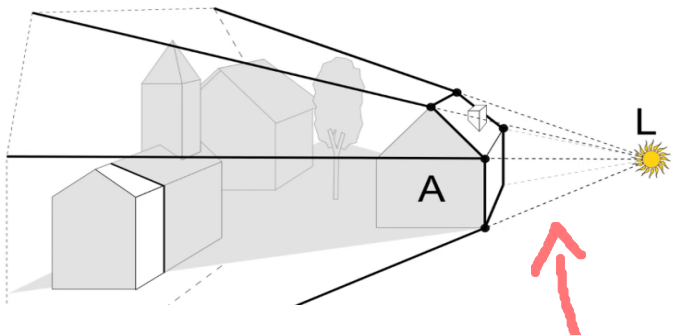


# Shadow Volume Geometry

- Closed polyhedron with 3 sets of polygons
  - Light cap
    - Object polygons facing the light
  - Dark cap
    - Object polygons facing away from the light
    - Projected to infinity (with *w*=0)
  - Sides
    - Actual extruded object edges
    - Which edges?

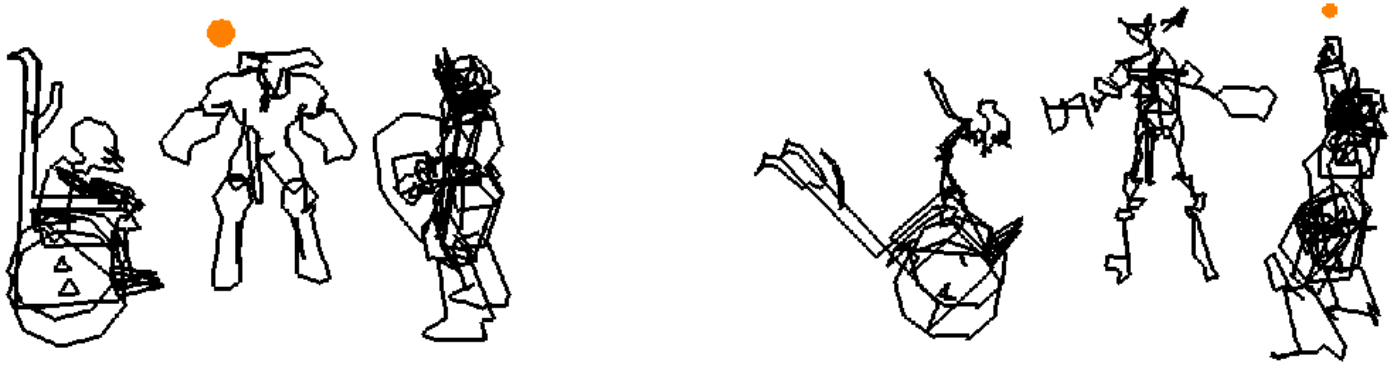
Optimizing Shadow Volumes

- Use silhouette edges only (edge where a back-facing & front-facing polygon meet)

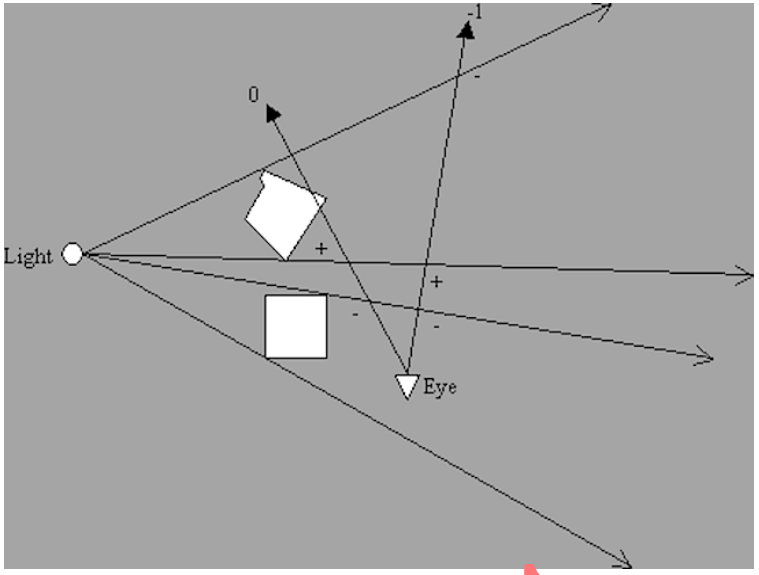


# Silhouette Detection

- Classify polygons into frontfaces and backfaces
- Edge shared by front + back face is on silhouette
- Extrude silhouette edges away from light source
  - In vertex shader
- If necessary: add front-cap and back-cap



# Stencil Shadow Volumes Algorithm




- Fill depth-buffer with scene
- Disable depth writes
- Render front-faces of stencil volumes with stencil increment on depth test pass
- Counts shadows in front of objects
- Render back-faces of stencil volumes with stencil decrement on depth test pass
- All lit surfaces have stencil value of 0
- Incorrect if the camera is inside a shadow volume!

Ambient Occlusion ist eine Technik, die in der Computergrafik verwendet wird, um Schatten und Tiefe in 3D-Modellen zu berechnen und zu simulieren. Die Berechnung von Ambient Occlusion findet pro Vertex (pro Eckpunkt) statt.

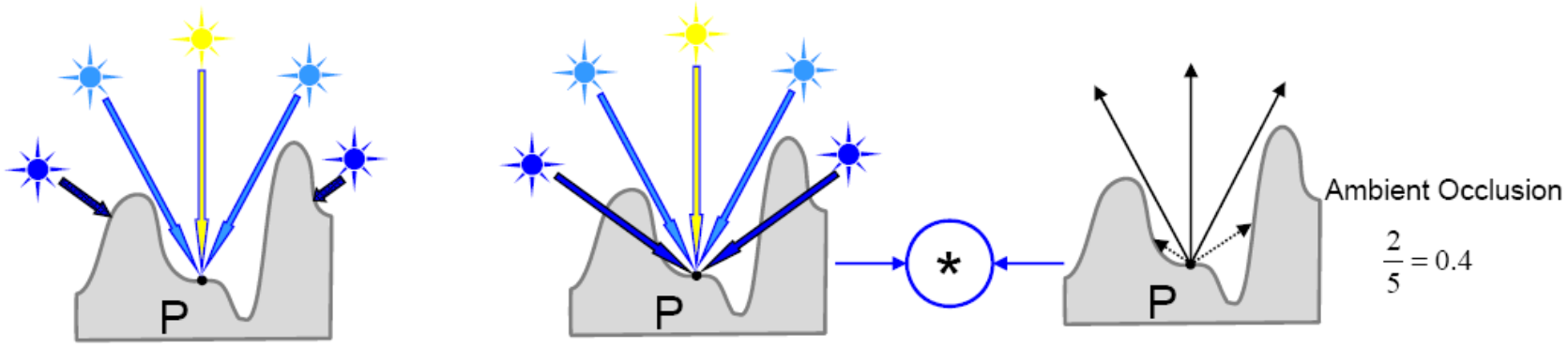
# Ambient Occlusion

Die resultierende Information besteht aus einem Durchschnittswert für die Sichtbarkeit (VAO). Dieser Wert wird dann verwendet, um das übliche Beleuchtungsmodell zu gewichten und die Helligkeit des Modells zu beeinflussen.

- Compute (per vertex)
  - Mean visibility $V_{AO} = 1 - AO$
  - Bent normal vector pointing into direction of average visibility
  - Used for advanced lighting instead of surface normal
- Weigh ordinary shading using mean visibility

Zusätzlich wird auch ein gebogener Normalvektor berechnet, der in Richtung der durchschnittlichen Sichtbarkeit zeigt. Dieser Vektor kann für eine fortgeschrittenere Beleuchtung verwendet werden, anstelle des Oberflächennormalvektors.

$$I = (1 - AO)(k_a I_a + k_d I_d \max(\mathbf{n} \cdot \mathbf{l}, 0))$$



Mean Visibility (durchschnittliche Sichtbarkeit) ist ein Konzept, das in Verbindung mit Ambient Occlusion in der Computergrafik verwendet wird. Es bezieht sich auf den Prozentsatz an Licht, der an einem bestimmten Punkt in einer Szene ankommt.

# Mean Visibility

Vorabberechnung durch Raycasting,

- Pre-computation = raycasting to find self-occlusions
- For each vertex
  - Cast *n* rays into the half sphere oriented by the normal
  - Count blocked rays *m*
  - Mean visibility $V_{AO} = 1 - m/n$

Für jeden Vertex werden n Strahlen in eine halbkugelförmige Richtung geworfen, die von dem Normalvektor ausgerichtet ist. Die Anzahl der geblockten Strahlen (m) wird gezählt und die durchschnittliche Sichtbarkeit (VAO) wird berechnet, indem man 1 von (m/n) subtrahiert.

- Account for Lambert's law
  - Apply cosine distribution around normal vector

Zusätzlich wird auch Lamberts Gesetz berücksichtigt, indem eine Kosinus-Verteilung um den Normalvektor angewendet wird.

- To account for other nearby objects
  - Use ordinary raycasting with maximal distance

Um die Auswirkungen anderer nahegelegener Objekte zu berücksichtigen, wird ein gewöhnliches Raycasting mit einer maximalen Distanz verwendet.

- Problem: raycasting from every point is expensive

Das Problem bei dieser Methode ist, dass Raycasting von jedem Punkt aus sehr rechenintensiv ist.

# Ambient Occlusion

(a) Gouraud shading

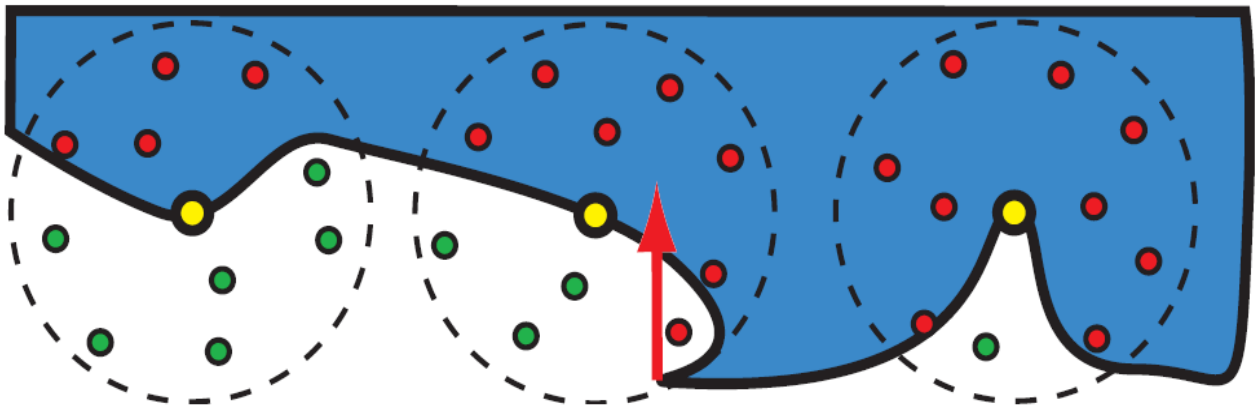
(b) Ambient Occlusion

(c) Ground truth

https://www.youtube.com/watch?v=9Fe1nYnvmiA

# Screen Space Ambient Occlusion

- Z-buffer = approximation of surrounding
- Compute ambient occlusion from neighboring pixels
- Use random sampling of z-buffer
  - $V_{AO}$ = Ratio occluded/unoccluded samples
  - $L_{in}$ = incoming radiance
  - $\omega_i$ = incoming (=light source) direction
  - $\theta_i$ = angle to normal



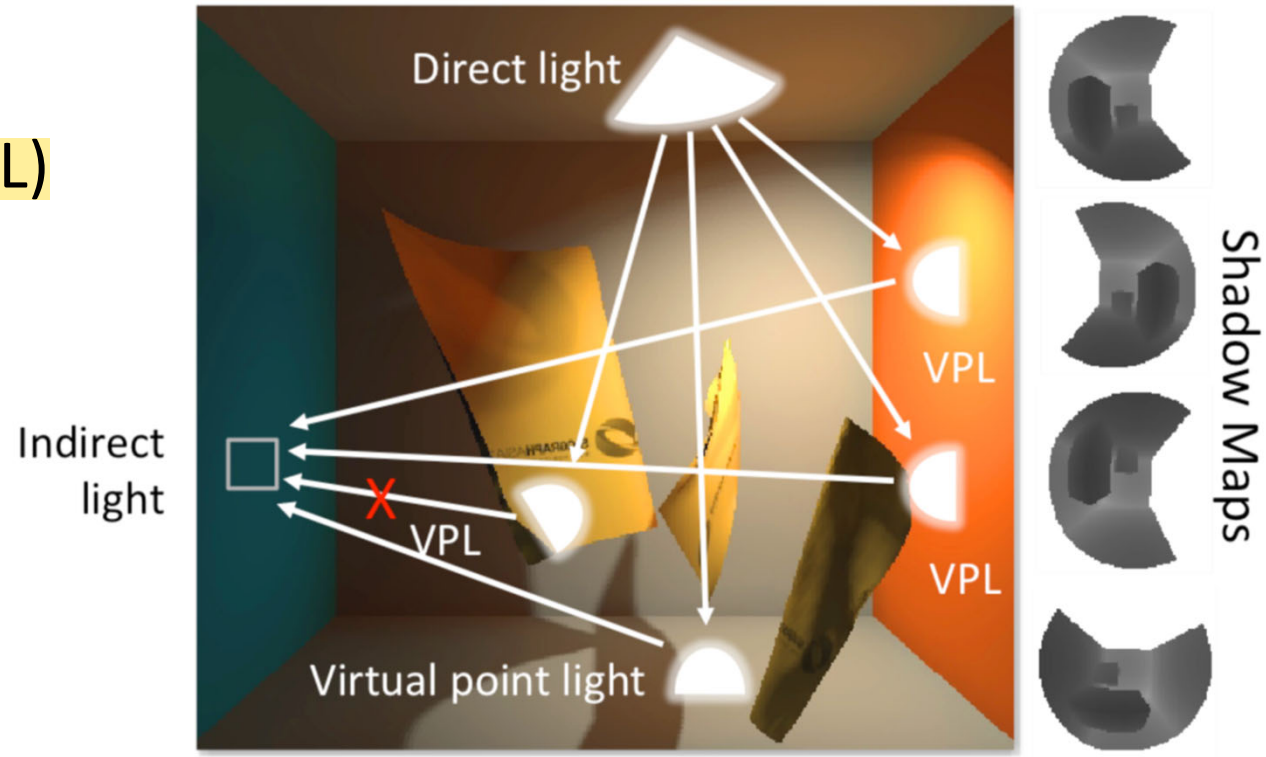
# Questions?

# Real-Time Global Illumination

Based on material by Carsten Dachsbacher, Jan Kautz, Michael Kenzel

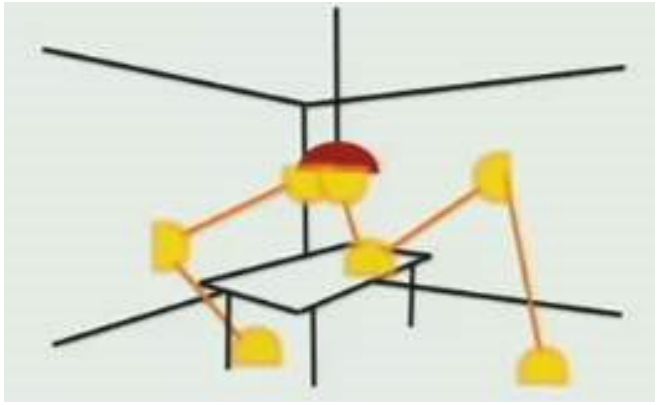
# Instant Radiosity

- Idea: model the light bounces as light sources
- Virtual point lights (VPL)
- Convert indirect into direct light transport



# Virtual Point Light Sources

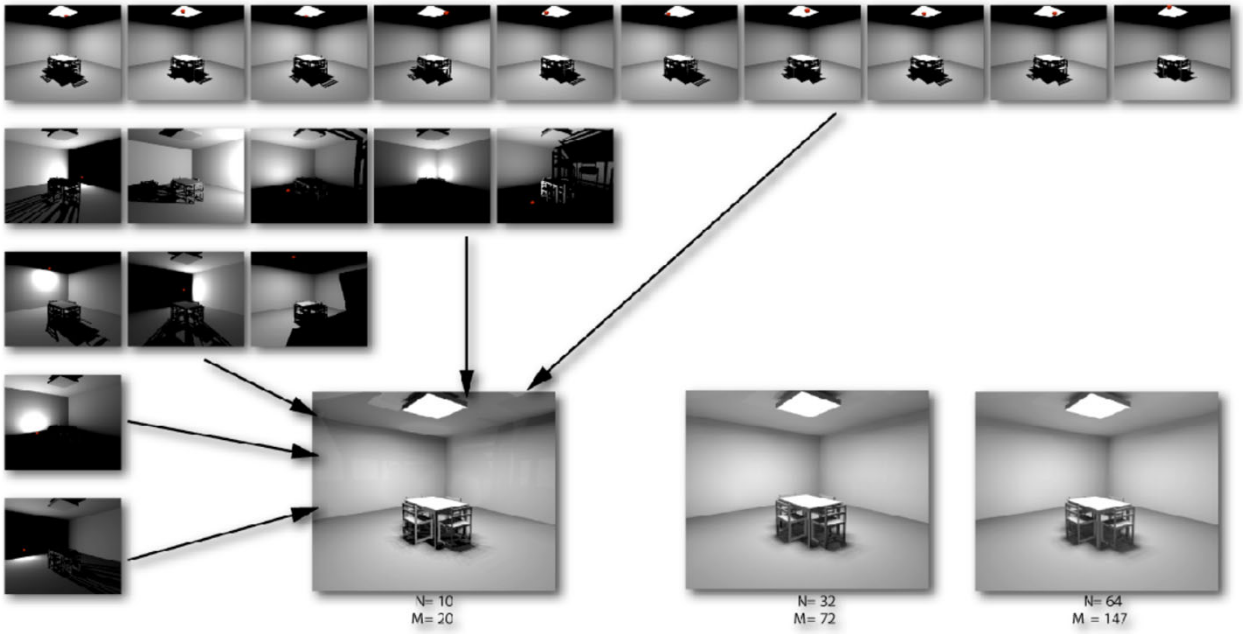
- Pass 1: VPL generation
  - Shoot photons from light source
  - Follow them through scene
  - At each hit point: create VPL
  - Russian roulette to end path
  - One shadow map for each VPL



- Pass 2: Deferred rendering
  - Render considering all the VPL and their shadow maps

# VPL Distribution

- VPLs are distributed according to
  - $\rho^{i}$ = av. Reflectance, *i* = bounce



PRT berechnet und speichert Lichtenergie und Farbwert für jeden Punkt in der Szene und die Art und Weise, wie Licht zwischen den Punkten übertragen wird. Diese Informationen werden dann verwendet, um die Beleuchtung und Schatten in der Szene in Echtzeit zu berechnen.

# Precomputed Radiance Transfer

- Realistic, interactive illumination of complex scenes
  - Complex materials
  - Dynamically changing lighting environment
  - General light sources
  - Shadows, interreflections, translucency
- Do not want to use real-time ray tracing

# Method

**Light sources** and **light transport** are independent

1. Step: Precompute light transport
   - E. g., with ray tracing
   - Offline, slow and costly
   - Store compressed representation
     - Light sources as an environment map
     - Light transport function for each surface point
2. Step: evaluate scene illumination
   - During rendering, in real-time

1 Schritt: Vorabberechnung von Lichtübertragung: Hier wird die Lichtübertragung in der Szene mit einer Technik wie Raytracing berechnet. Dies geschieht offline, ist jedoch langsam und kostspielig. Das Ergebnis dieser Berechnungen wird in einer komprimierten Darstellung gespeichert. Diese Darstellung beinhaltet die Lichtquellen als Umgebungskarte und eine Lichtübertragungsfunktion für jeden Punkt auf der Oberfläche.

2 Schritt: Bewertung der Szenenbeleuchtung: Während des Renderings werden die gespeicherten Informationen verwendet, um die Beleuchtung in Echtzeit zu berechnen. Da die Berechnungen bereits vorab durchgeführt wurden, ist die Bewertung der Szenenbeleuchtung schnell und effizient, und es müssen keine langsamen Berechnungen während des Renderings mehr durchgeführt werden.



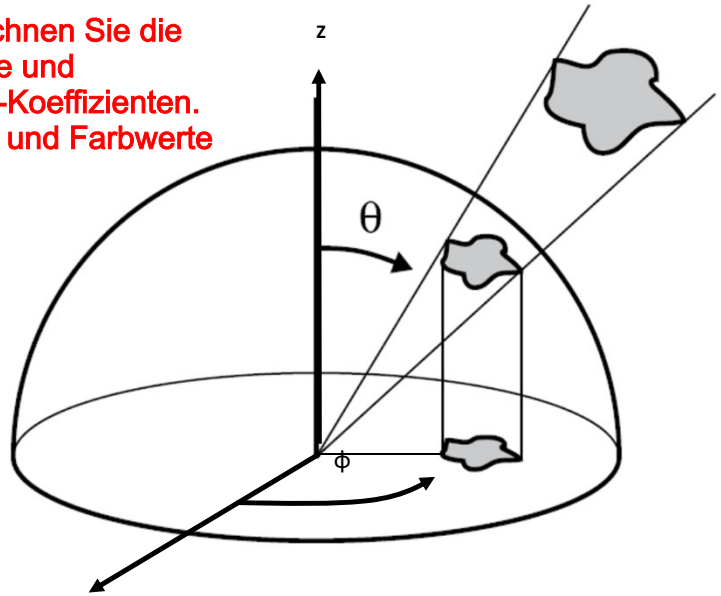
Zusammenfassend kann man sagen, dass PRT die Lichtquellen und Lichtübertragung voneinander unabhängig berechnet, um eine schnelle und effiziente Berechnung der Beleuchtung in einer 3D-Szene zu ermöglichen.

Spherical Harmonics (SH) spielen eine wichtige Rolle bei der Implementierung von Precomputed Radiance Transfer (PRT). SH sind mathematische Funktionen, die verwendet werden, um die Umgebungsbeleuchtung in einer 3D-Szene zu modellieren.

# Spherical Harmonics

## Base functions for representing functions with a spherical domain

Während der Vorabberechnung von PRT berechnen Sie die Beleuchtung für jeden Punkt auf der Oberfläche und speichern diese Informationen in Form von SH-Koeffizienten. Diese Koeffizienten repräsentieren die Energie und Farbwerte der Beleuchtung für jeden Punkt in der Szene.



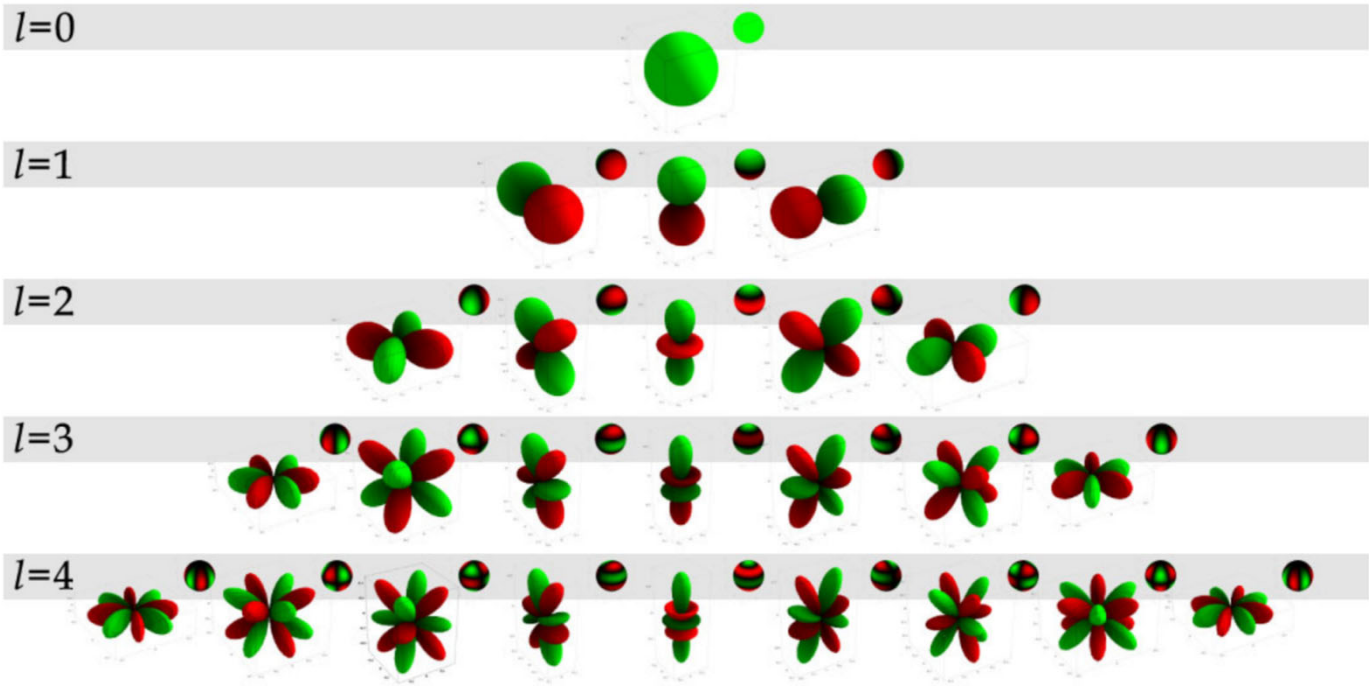

$$(\sin\theta\cos\varphi \quad \sin\theta\sin\varphi \quad \cos\theta) \mapsto (x \quad y \quad z)$$



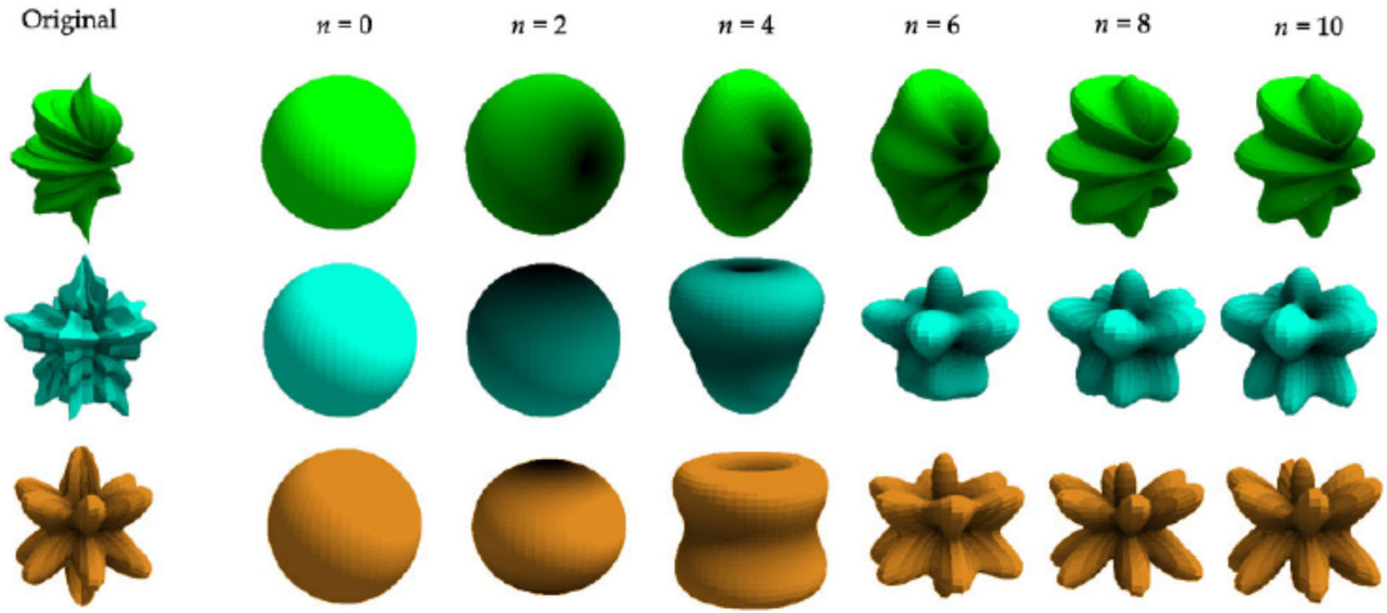
Während des Renderings können die berechneten SH-Koeffizienten verwendet werden, um die Beleuchtung in Echtzeit zu berechnen. Sie können auch verwendet werden, um Schatten und interne Reflektionen zu berechnen, indem Sie die Lichtübertragung zwischen den Punkten in der Szene modellieren.

# Spherical Harmonics Bands

SH ... Basis functions for representing an arbitrary spherical function as a linear weighted sum



# Examples for SH-Reconstruction



Spherical Harmonic (SH) Representation for Light Transfer ist eine Technik, bei der die visuelle Informationen, die bei der Berechnung von Ambient Occlusion (AO) gewonnen werden, in Form von SH-Koeffizienten gespeichert werden.

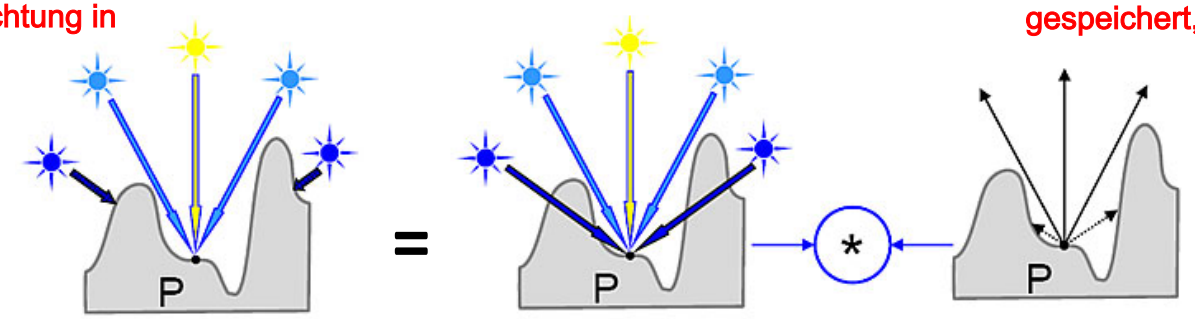
# SH Representation for Light Transfer

- Directional visibility, computed as for AO
- But stored per-point as SH coefficients (vertex texture)

Diese SH-Koeffizienten repräsentieren die Informationen über die Beleuchtung und Schattierung, die auf einer Oberfläche eintreffen, und werden während des Renderings verwendet, um die Beleuchtung in Echtzeit zu berechnen.

$$I_{dir}(\mathbf{P}) = \sum_{i=1}^{N} \frac{\rho}{\pi} L_{in}(\omega_i) V(\omega_i) \cos\theta_i \Delta\omega$$

Während der Berechnung von Ambient Occlusion wird für jeden Punkt auf der Oberfläche ein Schätzwert für die Durchsichtbarkeit berechnet. Diese Informationen werden in Form von SH-Koeffizienten gespeichert und in einer Textur gespeichert, die pro Vertex verfügbar ist.



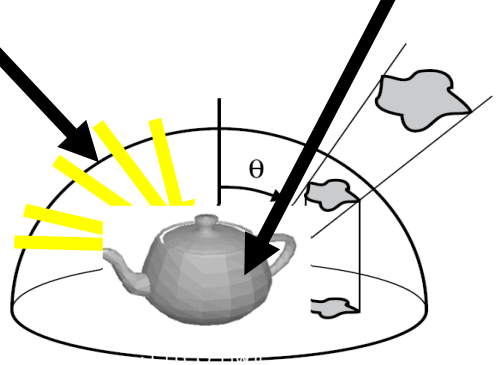

Shading | Illumination $L_{in}$ | Visibility $V$

# PRT Rendering

Light coefficients beschreiben, wie viel Licht von einer Lichtquelle auf ein bestimmtes Objekt trifft. Diese Informationen werden berechnet, indem eine bestimmte Anzahl von Strahlen aus der Lichtquelle in alle Richtungen gesendet werden und die Menge an Licht, die auf ein Objekt trifft, berechnet wird.

Ojkw#vrxufh#hsuhvhqwhg#dv
VK#frhiilflqw#FO

Ojkw#wdqvihu#hsuhvhqwhg#dv
VK#frhiilflqw#FW shu#vxuidfh srlqw




Light transfer coefficients beschreiben, wie das Licht von einem Punkt zu einem anderen Punkt auf einem Objekt übertragen wird. Diese Informationen werden berechnet, indem eine bestimmte Anzahl von Strahlen von einem Punkt zu einem anderen Punkt auf einem Objekt gesendet werden und die Menge an Licht, die übertragen wird, berechnet wird.

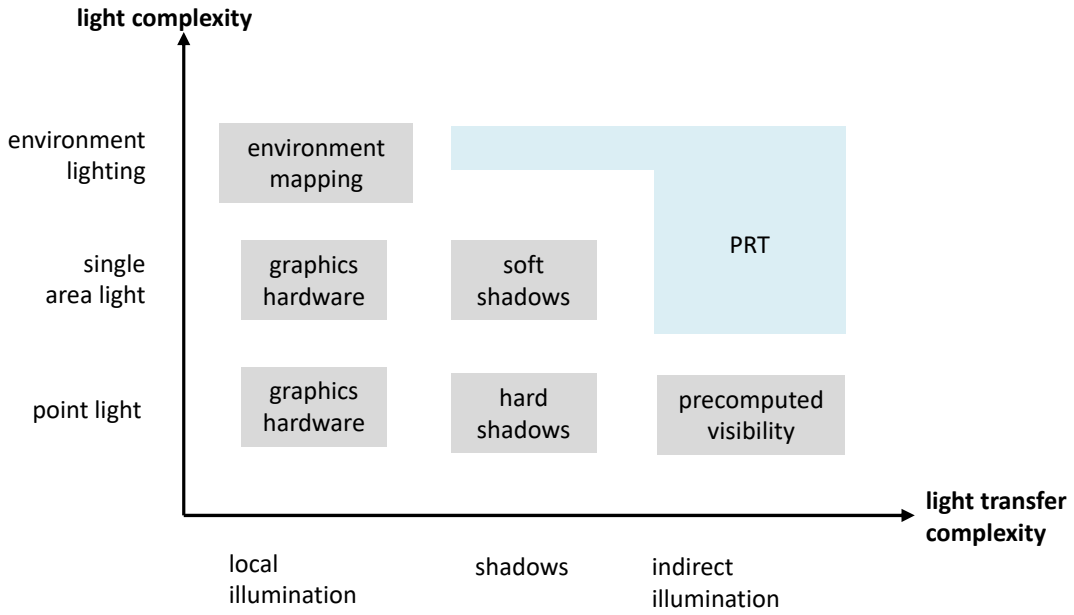
light coefficients **CL** →

light transfer coefficients **CT** →

rendering equation
$I_{dir}$ = **CL** dot **CT** → image

Durch Berechnen des Dot-Produkts dieser beiden Werte kann die Gesamtmenge an Licht berechnet werden, die von einer bestimmten Lichtquelle auf einen bestimmten Punkt auf einem Objekt trifft

# PRT – Applications



# PRT – Summary

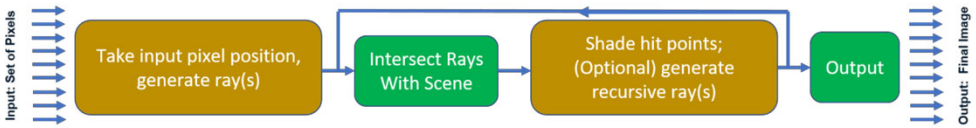
- Advantages
  - Fast rendering (1 dot product)
  - Dynamic lighting environments
  - Supports complex light transfer (ambient occlusion and interreflections)
- Disadvantages
  - Only efficient for lighting environments of low-frequency
  - Typically 9 to 16 SH coefficients (3 to 4 bands)
  - Static scenes
  - Only diffuse surfaces (if using SH-based compression)

# GPU Raytracing

Dieter Schmalstieg

# DirectX Ray Tracing Pipeline

- Pipeline is split into five new shaders:
  - **Ray generation shader** defines how to start ray tracing
  - **Intersection shader** define how rays intersect geometry
  - **Miss shader** define behavior when rays miss geometry
  - **Closest-hit shader** run once per ray (e.g., to shade final hit)
  - **Any-hit shader** run once per hit (e.g., to determine transparency)

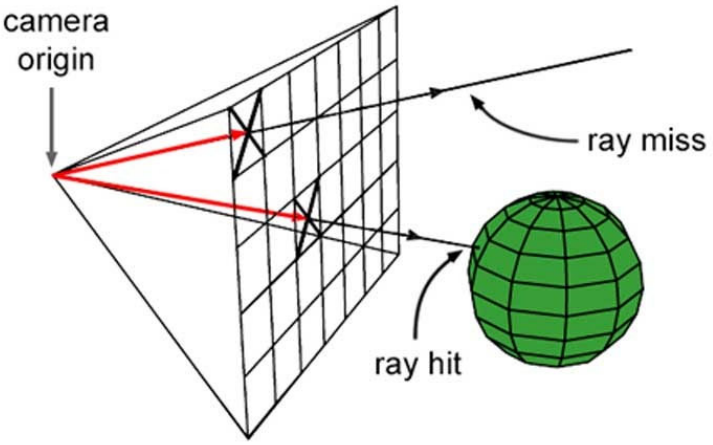



**Runs once per algorithm (or per pass)**

**Defines geometric shapes, widely reusable**

**Defines behavior of rays**

**Different between shadow, primary, indirect rays**




Dieter Schmalstieg

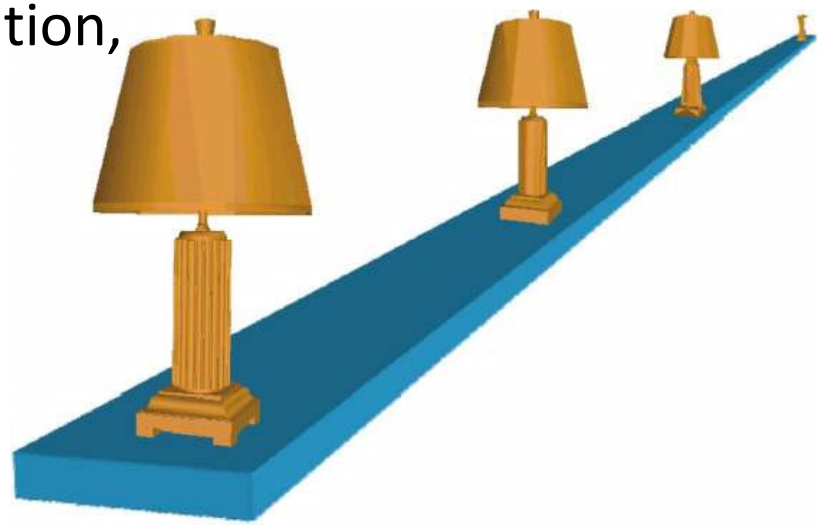
# Levels of Detail

Based on material from Michael Wimmer and Markus Grabner

# LOD - Basic Idea

- Problem: even after visibility, model may contain too many polygons
- Idea: Simplify the amount of detail used to render small or distant objects
- Known as levels of detail (LOD)

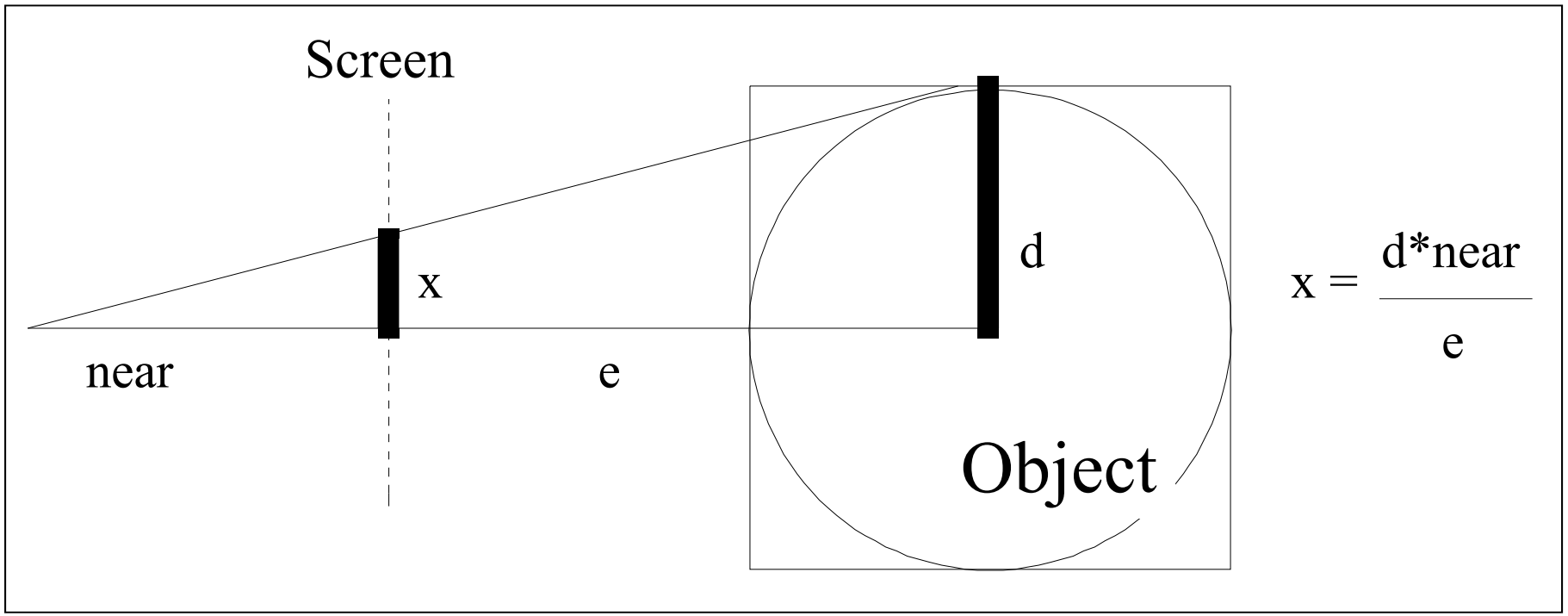
  A.k.a. multiresolution modeling, polygonal/geometric simplification, mesh reduction/decimation, …



https://www.youtube.com/watch?v=mIkIMgEVnX0

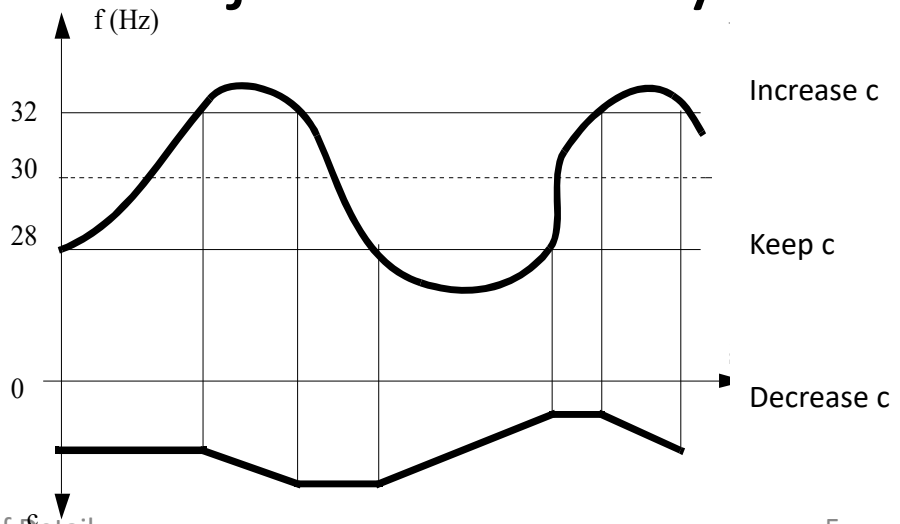
# Static LOD Selection

- LOD Selection steered by size of object in image
- Cannot control resulting frame rate



# Reactive LOD Selection

- Multiply object size with factor *c*
- If frame rate too low → decrease *c*
- If frame rate too high → increase *c*
- Results in roughly constant frame rate
- Problems occur, if complex objects suddenly become visible
- Requires hysteresis



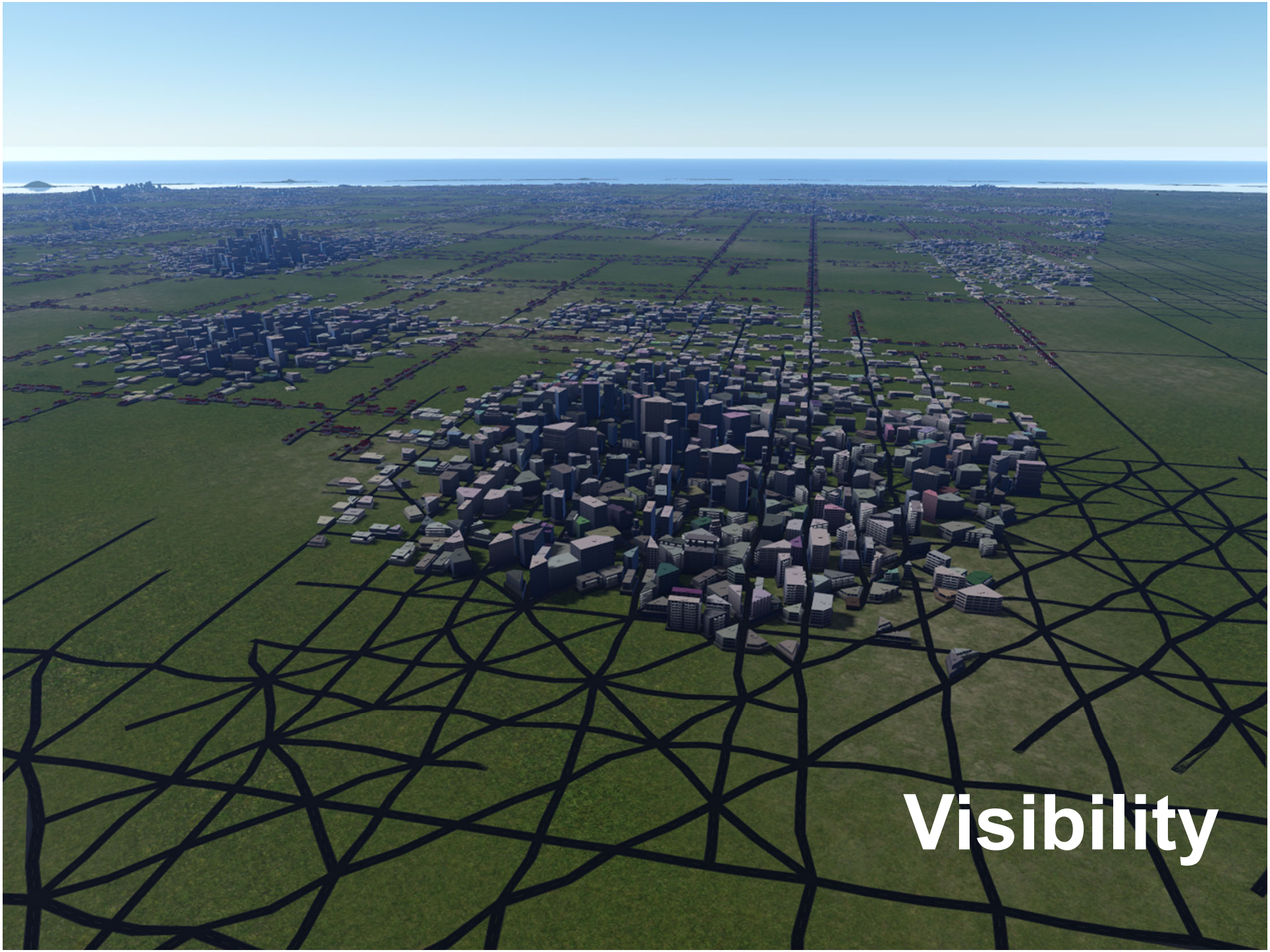
# Predictive LOD Selection

[Funkhouser & Sequin 1993]

- COST = time for drawing object with a given LOD
- Goal: best possible image quality
- BENEFIT = contribution of object to image quality
  - Most important: screen-size of object
- Optimization (*Rucksack*) problem
  - Sum(BENEFITS) → max, BUT
  - Sum(COSTS) ≤ FRAMETIME

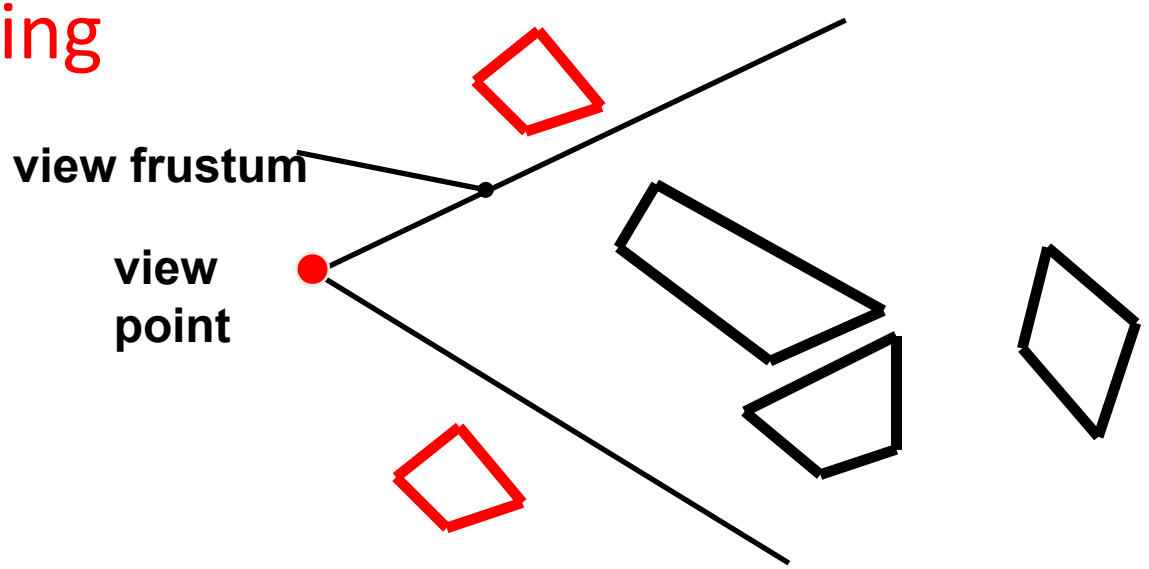
# LOD Switching

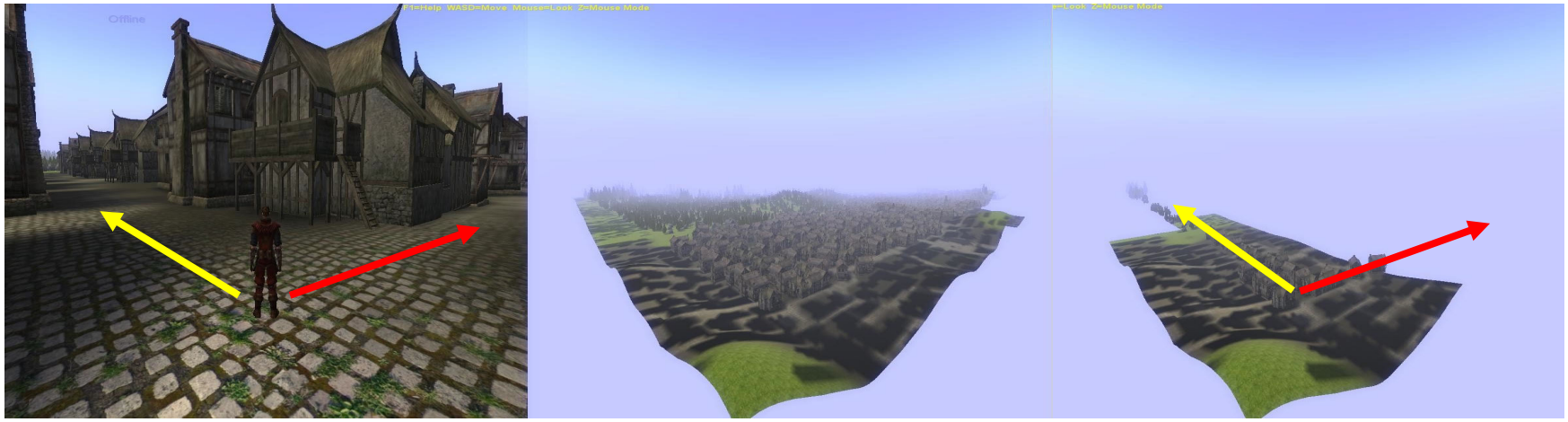
- Hard Switching
  - \+ Simple
  - \- “Popping” artefacts
- Blending
  - \+ For all types of LOD
  - \- Temporarily increased rendering load
  - \- Problems with transparences, shadows, etc…
- Geomorphing https://www.youtube.com/watch?v=I20Zyr4U_Xk
  - → Interpolate triangles shapes from 1st to 2nd LOD
  - \+ Best quality
  - \- Requires geometric correspondence between LODs


Visibility

# View Frustum Culling

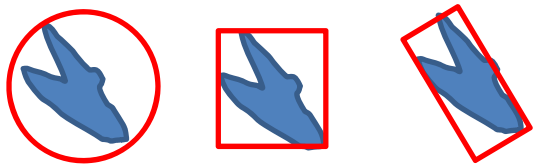
- View-frustum culling
- Occlusion culling
- Backface culling



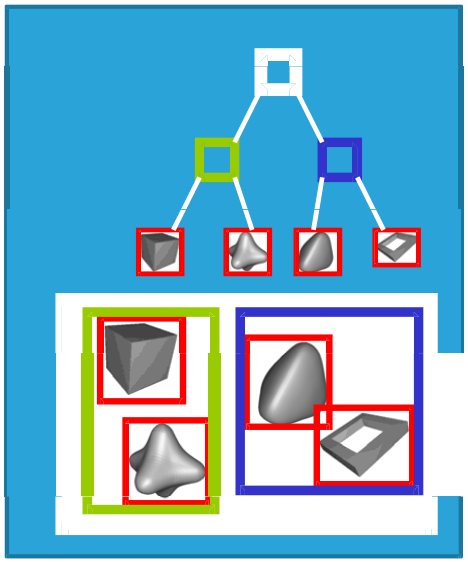



# Bounding Volume Hierarchy

- Most important spatial data structure
- Common bounding volume types
  - Spheres
  - Axis-aligned bounding box (AABB)
  - Oriented bounding box (OBB)

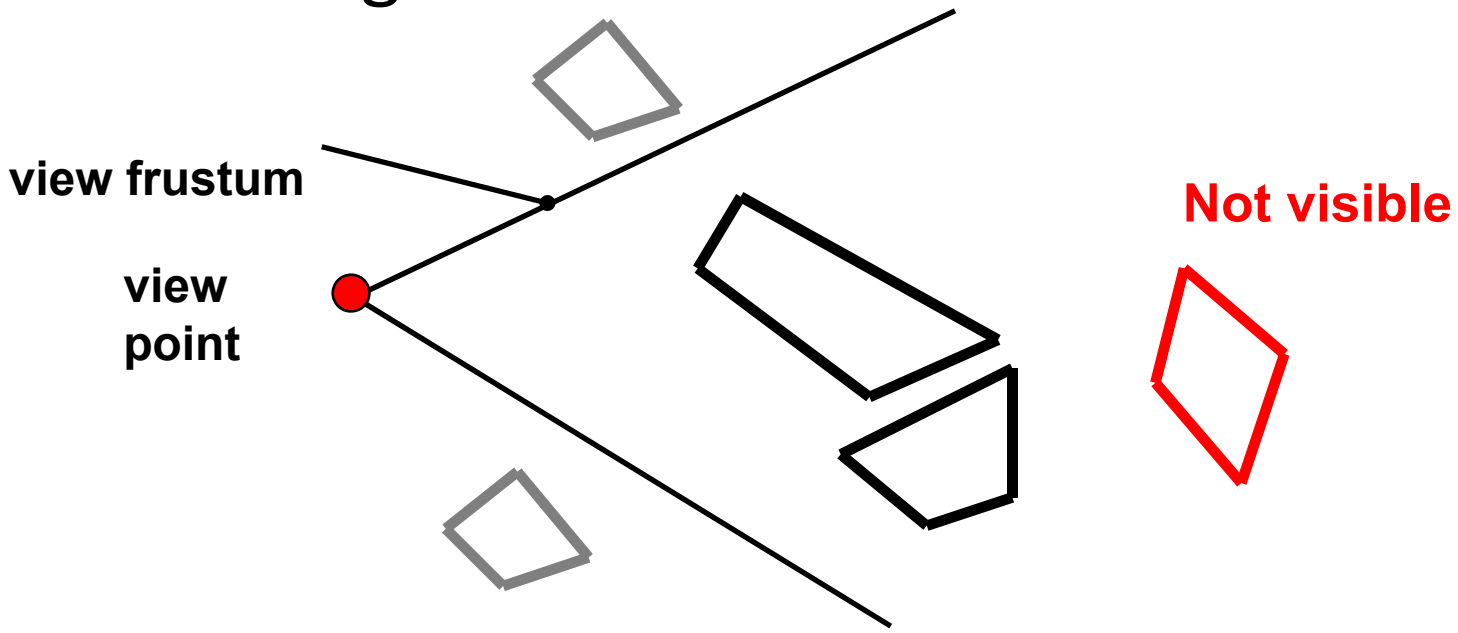


- Encloses the bounded object
- Hierarchical data structure
  - Tree (binary or *n*-ary)
  - Leaves: store objects
  - Interior nodes: stores bounding volume enclosing all contained bounding volumes



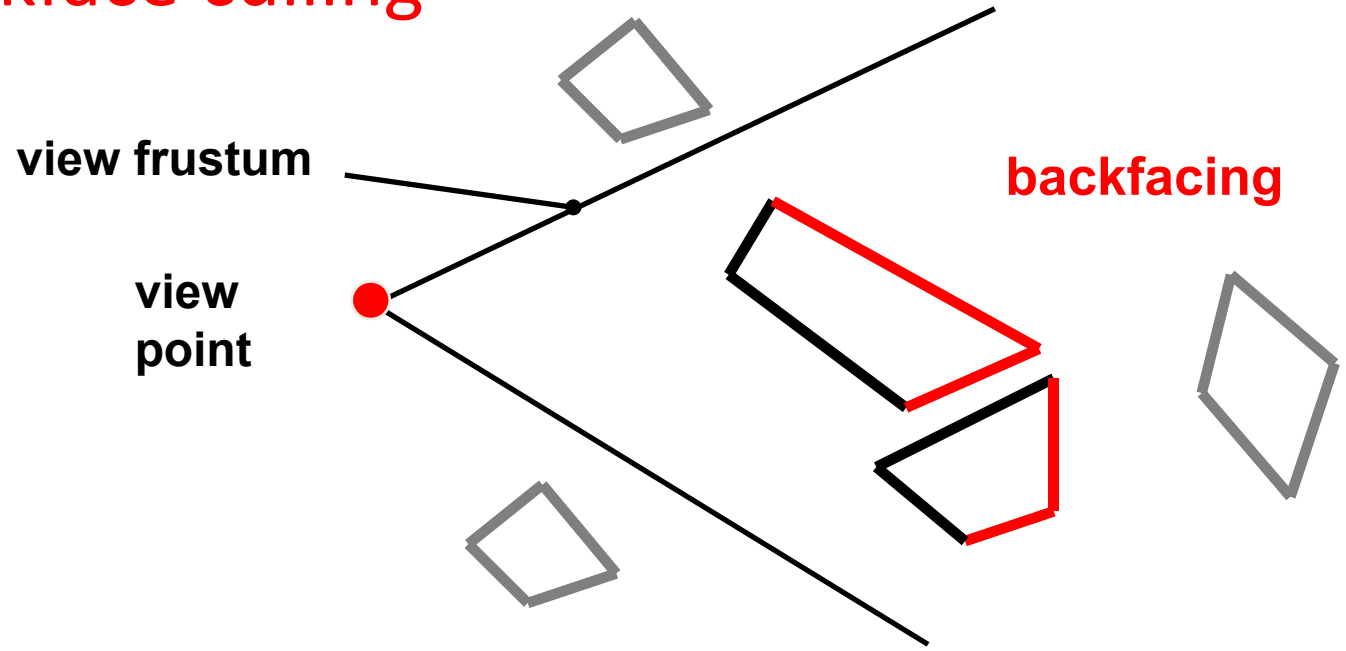
# Occlusion Culling

- View-frustum culling
- Occlusion culling
- Backface culling



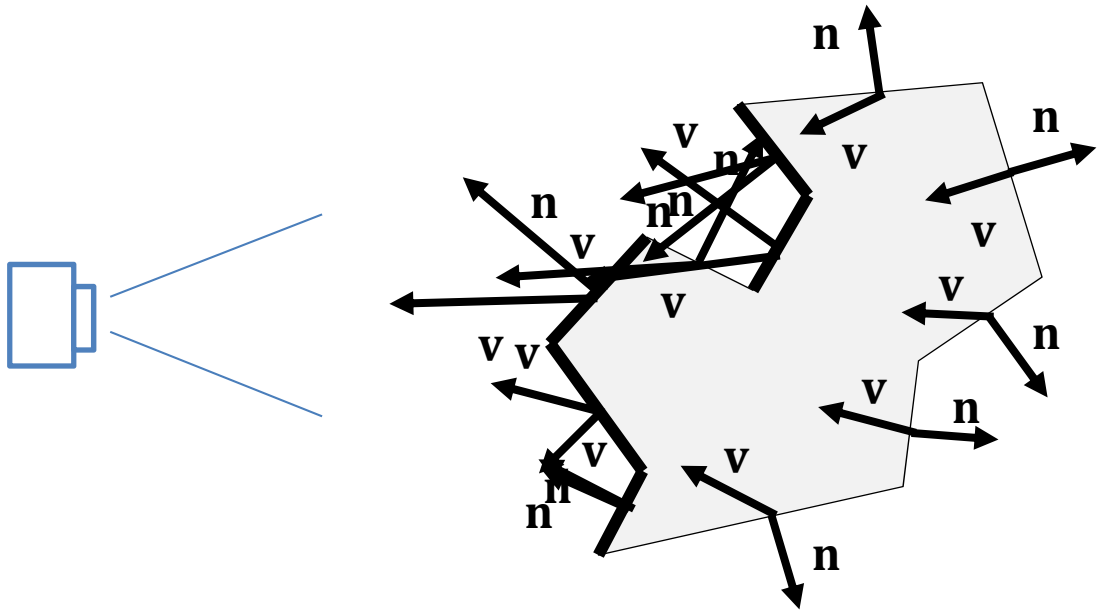
# Backface Culling

- View-frustum culling
- Occlusion culling
- Backface culling



# Backface Culling

- If an object is watertight, we cannot see the interior
- We only must draw those primitives facing the camera
- Can save up to 50% of primitives on average
- Simple to implement using dot product of normal $\mathbf{n}$ + view vector $\mathbf{v}$

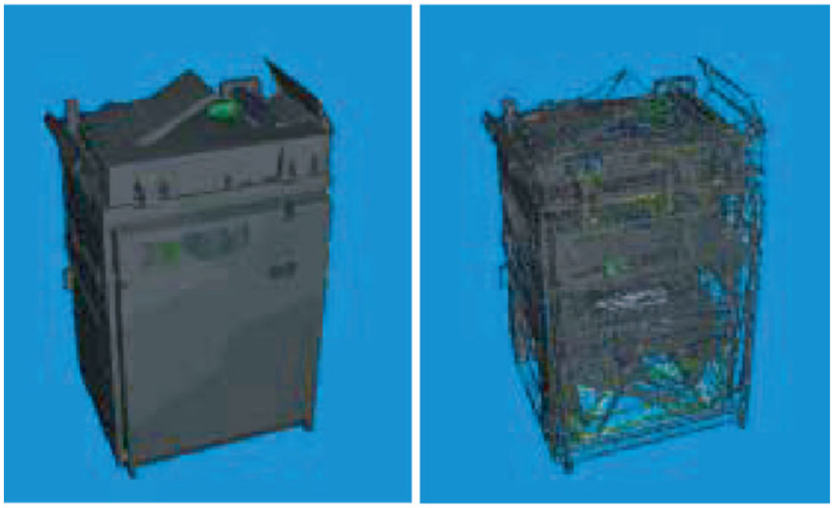



$\mathbf{n} \cdot \mathbf{v} > 0$
→ must draw

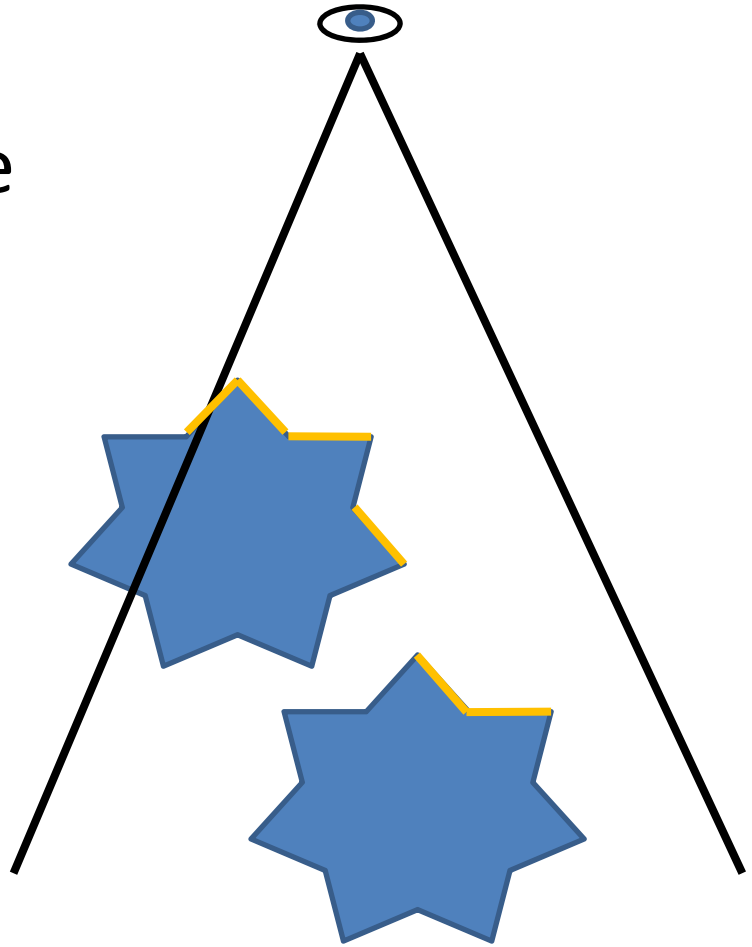
$\mathbf{n} \cdot \mathbf{v} < 0$
→ not visible

# Exactly Visible Set

- All primitives that are visible
- No more, no less

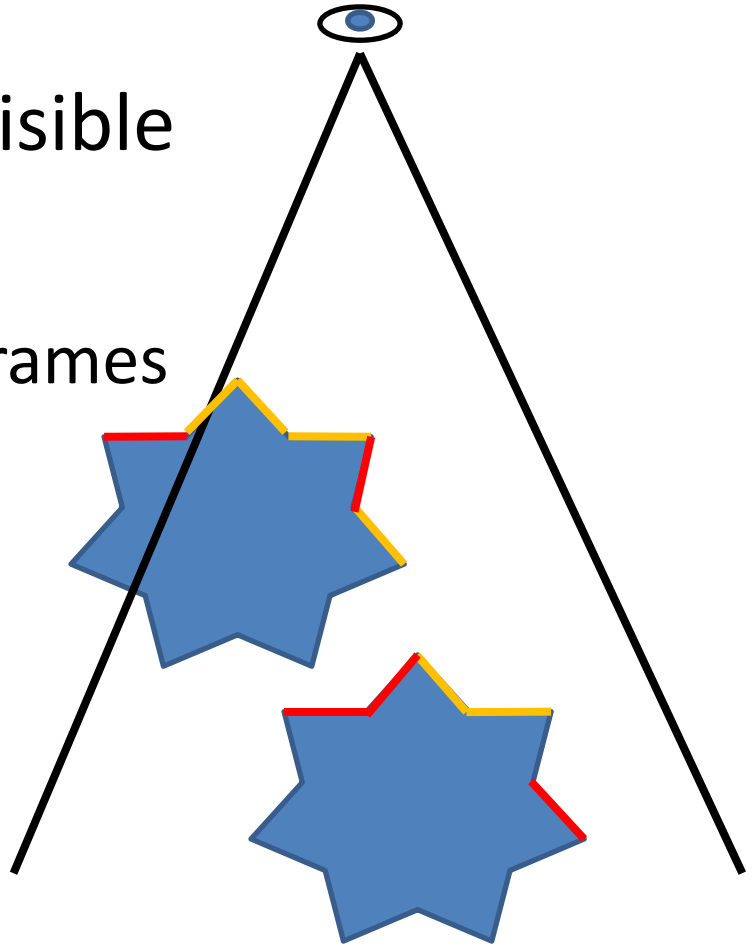


(a) (b)



# Potentially Visible Set

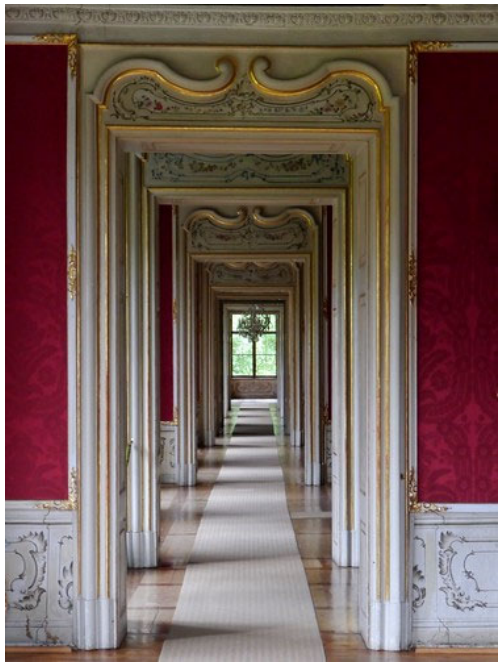
- PVS = all primitives that are visible
- And a bit more
  - E.g., visible within the next n frames
  - Exact hidden surface removal done later by z-buffer
- How much more?
- What do we want to do with the PVS?



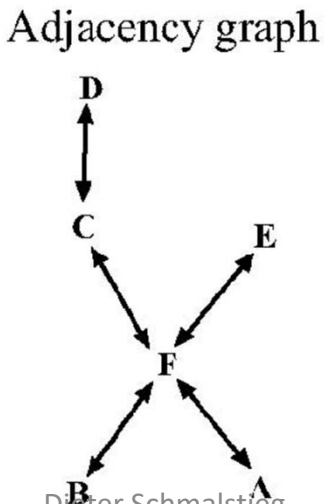
# PVS Classification

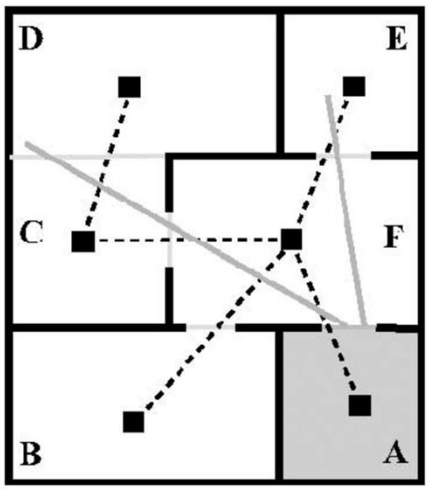
- The exact visible set (EVS) is unknown: $O(N^9)$…
- Potentially visible set (PVS) =
  set of objects that *could* be visible
- PVS can be
  - Aggressive, PVS $\subseteq$ EVS
  - Conservative, PVS $\supseteq$ EVS (preferred)
  - Approximate, PVS ~ EVS
- PVS can be precomputed
  - But we need discretize viewpoints into view *regions*

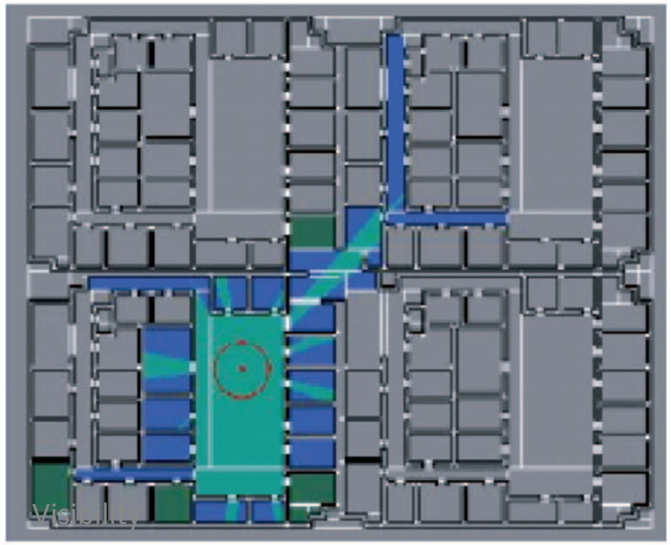
# Cells and Portals



- Indoors
  - Most rooms (*cells*) occluded by walls
  - Store *portals* (windows, doors) instead of occluders (walls)
- Cells and portals form nodes and edges of a *portal graph*



# Screen-Space Portals

- In runtime, find the portals of the current cell that are in the frustum
- Traverse through all found portals to the adjacent cells and find all portals that are visible to the camera through the original portal