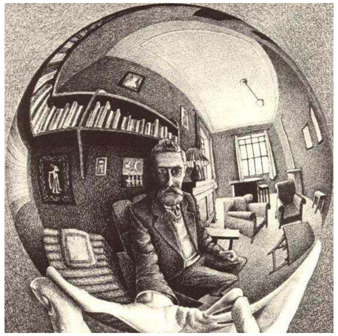
Virtual Reality &
Physically-Based Simulation
Techniques for Real-time Rendering



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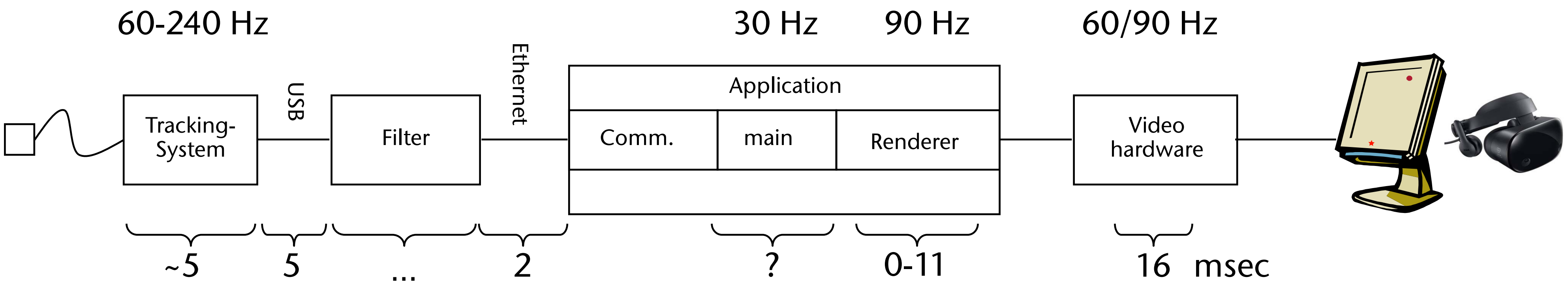
Latency (Lag, Delay)

- Definition: Latency = duration from a user's action (e.g., head motion) until display shows a change caused by the user's action ("from motion to photons")
- Some *human factors* (here for visual displays):

Latency (msec)	Effect on the user
> 5	Noticeable
> 30	*User performance* decreases
> 500	Presence vanishes (and simulation fidelity)

Note: a user's head can rotate by as much as 1000 degrees/sec !

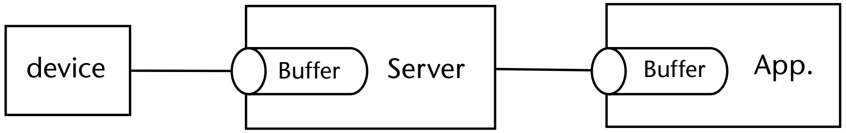
The Latency Pipeline

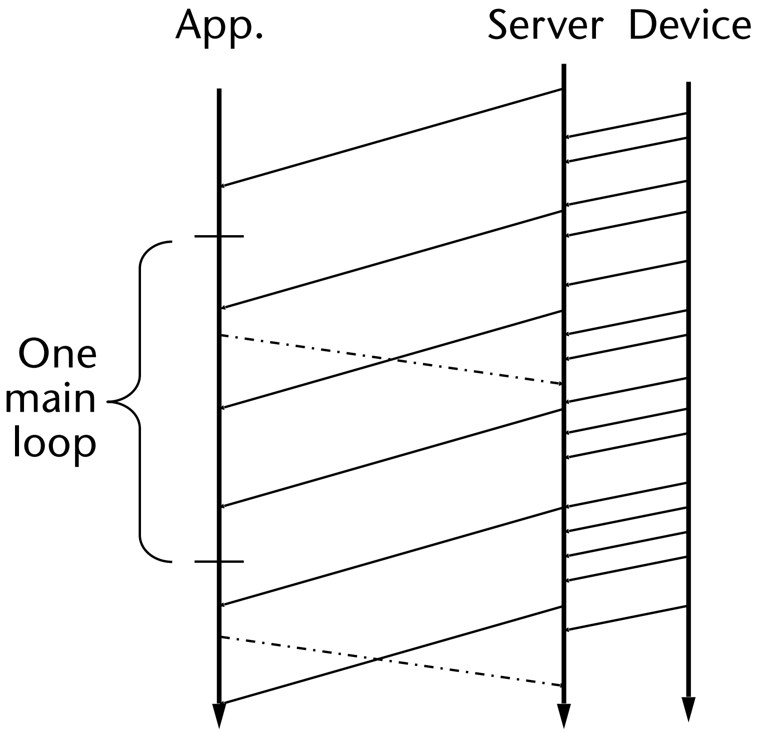


- Types/causes of lag:
  - Internal to devices
  - Transportation of data over communication channel (e.g., Ethernet)
  - Software (time for processing the data)
  - Synchronization delay

General Strategies for Solutions

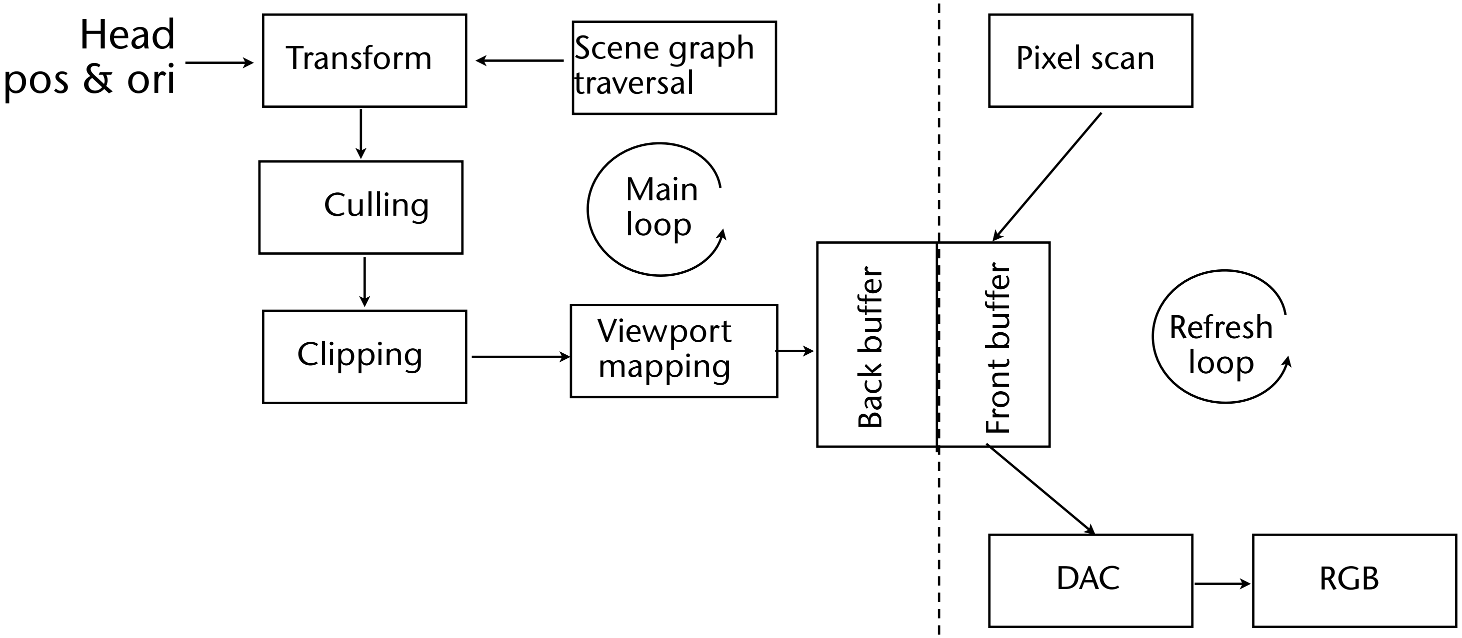
1. Device-server-app communication:
   - Put device and server into continuous mode
   - Send "keep alive" messages from client to server
2. Do time-critical computing:
   - Each and every module of the app receives a specific time budget
   - Module tries to compute a usable(!) partial solution as good as possible within the time budget
   - Stop when time is up
3. Try to predict user/tracker position in *x* msec's time



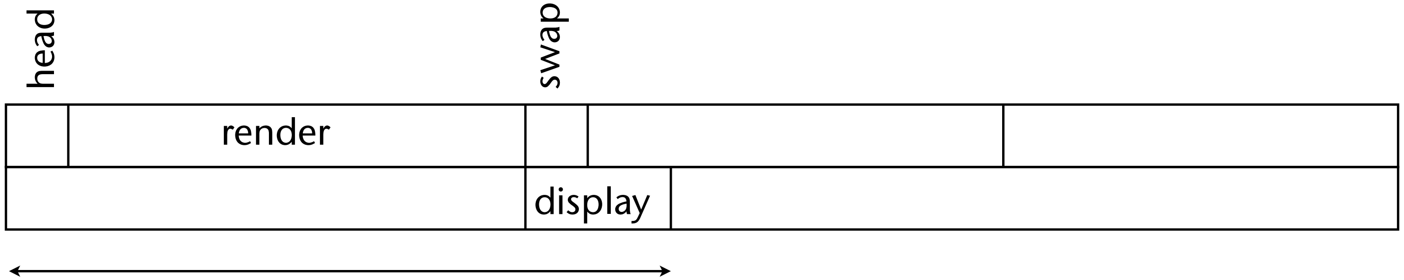


Sources of Latency During Rendering

- The classical graphics pipeline, at least parts of it, visualized as a loop:

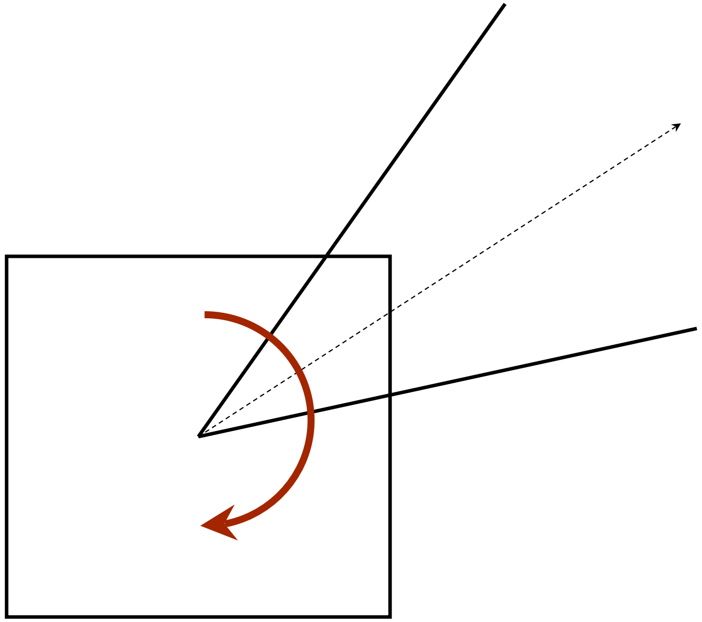


- Latency:

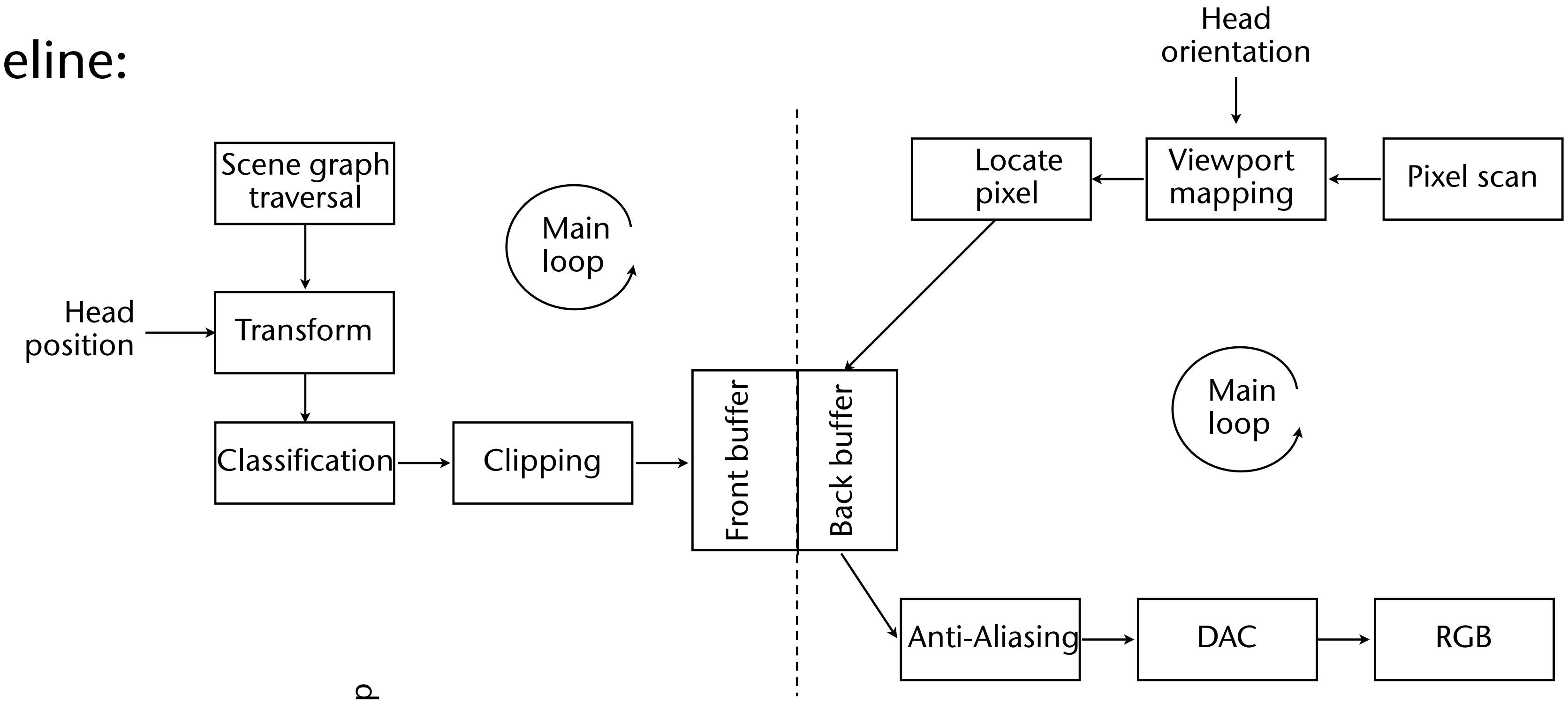


Viewport-Independent Rendering

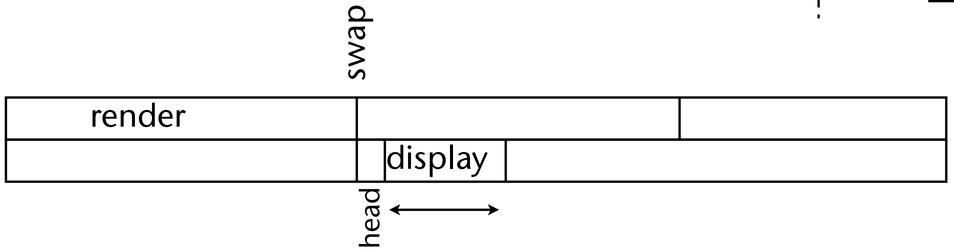
- Conceptual idea:
  - Render the scene onto a *sphere* around the viewer ⟶ spherical viewport
  - If viewpoint rotates: just determine new cutout of the spherical viewport
- Practical implementation:
  - Use a cube as a viewport around user, instead of sphere
  - Remark: this was also one of the motivations to build Cave's



- New pipeline:

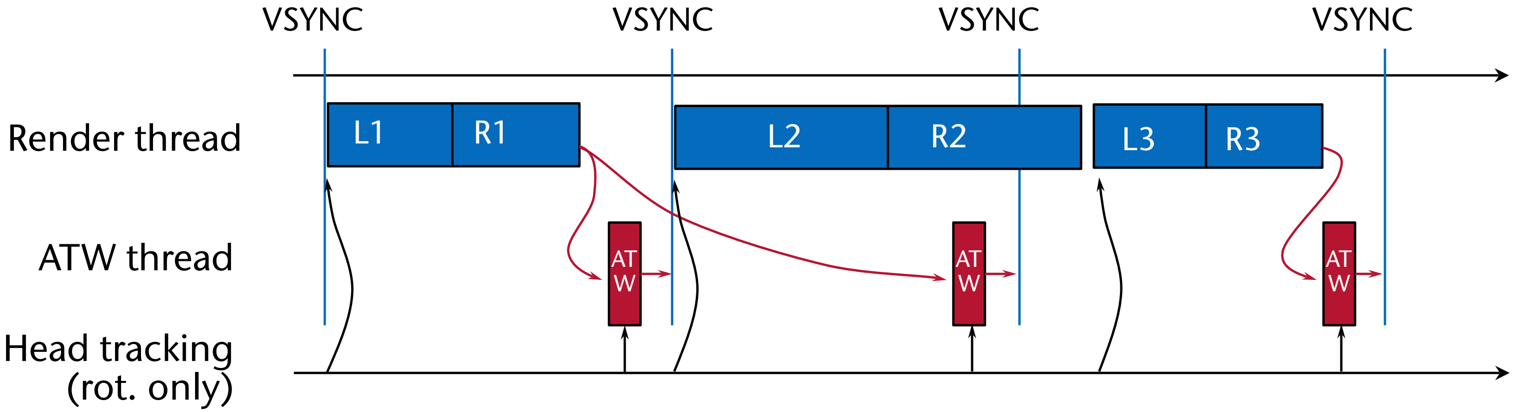


- Latency:



"Asynchronous Timewarp" (Oculus)

- Render a bigger-than-visible viewport (not the whole cube)
- Shift image using current orientation of head
- Do this only in case the renderer is not finished in time:



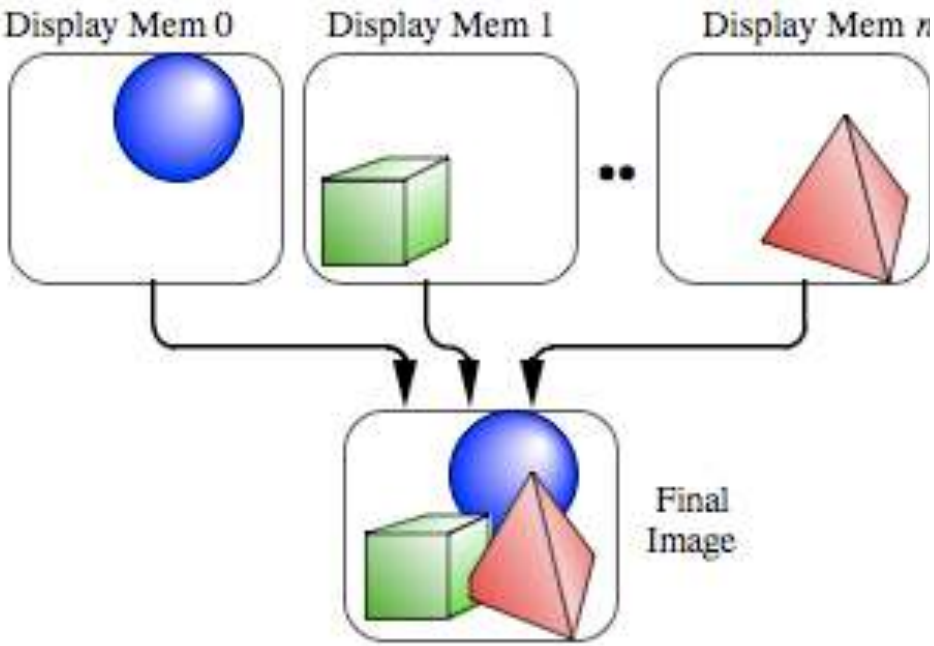
- Requires GPU preemption (i.e., stop GPU's pipeline, including shaders, immediately)

Limitations

- Judder of animated objects
- Incorrect positions of highlights and specular lighting
- Head rotation also changes position of the viewpoint, but the image is shifted only according to rotation of viewing direction ⟶ judder for near objects (even static objects)

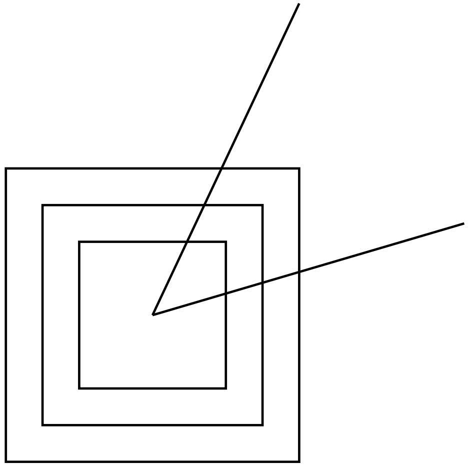
Multi-Threaded Rendering and Image Composition

- Conceptual idea:
  - Each thread renders only its "own" object in its own framebuffer
  - Video hardware reads framebuffer *including* Z-buffer
  - Image compositor combines individual images by comparing the Z values of corresponding pixels
- In practice:
  - Partition set of objects
  - Render each subset on one PC



Another Technique: Prioritized Rendering

- Observation: images of objects far away from viewpoint (or slow relative to viewpoint) change slowly
- Idea: render onto several cuboid viewport "shells" around user
  - Fastest objects on innermost shell, slowest/distant objects on outer shell
  - Re-render innermost shell very often, outermost very rarely
- How many shells must be re-rendered depends on:
  - Framerate required by application
  - Complexity of scene
  - Speed of viewpoint
  - Speed of objects (relative to viewpoint)



- Human factors have influence on priority, too:
  - Head cannot turn by 180° in one frame → update objects "behind" only rarely
  - Objects being manipulated must have highest priority
  - Objects in peripheral field of vision can be updated less often

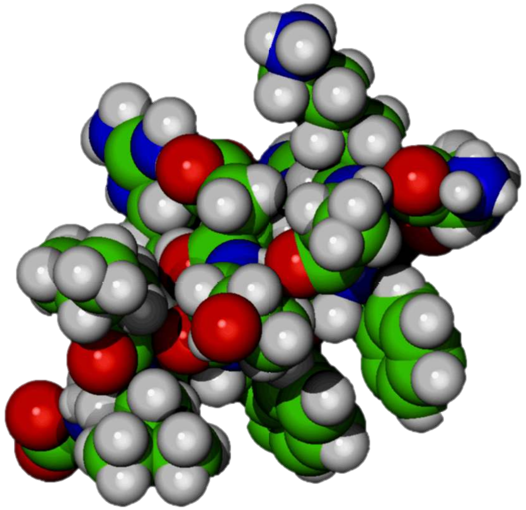
Efficient Memory-Layout for Fast Rendering

- Frequent problem: the elegant way to structure data (from the perspective of software engineering) is inefficient for fast rendering
- Example for illustration: visualization of molecules
    - Following good SE practice, we should design classes like this

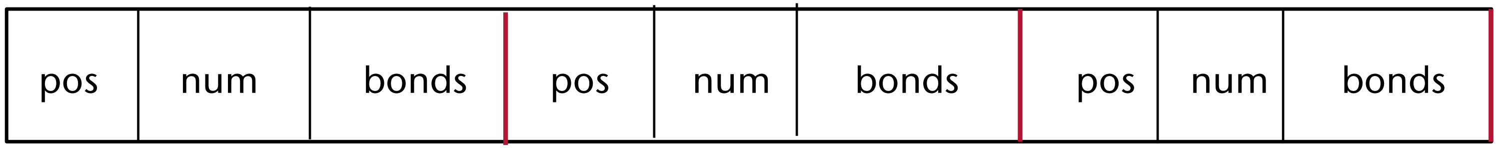
```
 class Atom
 {
 public:
    Atom( uint atom_number, Vec3 position, ... );
 private:
    Vec3   position_;
    uint   atom_number_;
    Atom * bonds_[max_num_bonds];
    ...
};
```

- And the class for a molecule:

```
class Molecule
{
public:
   Molecule( const std::vector<Atom> & atoms );
private:
   std::vector<Atom> atoms_;
   ...
};
```



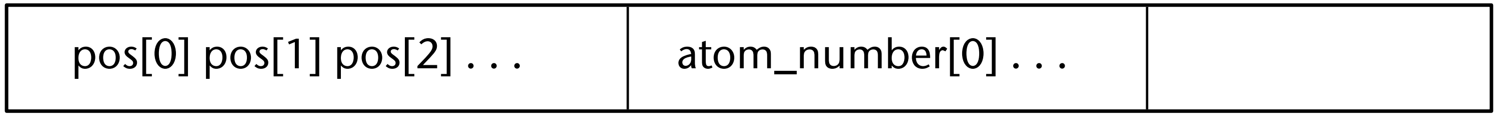
- Memory layout of a molecule is now an array of structs (AoS):



pos	num	bonds	pos	num	bonds	pos	num	bonds

- Problem with that: memory transfer becomes slow
- Alternative: Struct of Arrays (SoA)

```
 class Molecule
 {
 private:
     std::vector<Vec3>  position;
     std::vector<uint>  atom_number;
    ...
};
```



- Terminology: "Array of Structs (AoS)" vs. "Struct of Arrays (SoA)"

Constant Framerate by "Omitting"

- Reasons for the need of a constant framerate:
  - Prediction in *predictive filtering* of tracking data of head/hands works only, if all subsequent stages in the pipeline run at a known (constant) rate
  - Jumps in framerate (e.g., from 90 to 45 Hz) are very noticeable (stutter/judder)
- Consider rendering as "*time-critical computing*":
  - Rendering gets a certain time budget (e.g., 11 msec)
  - Rendering algorithm has to produce an image "as good as possible"
- Techniques for "*omitting*" stuff:
  - Levels-of-Detail (LODs)
  - Omit invisible geometry (Culling)
  - *Image-based rendering*
  - Reduce the *lighting model*, reduce amount of textures,

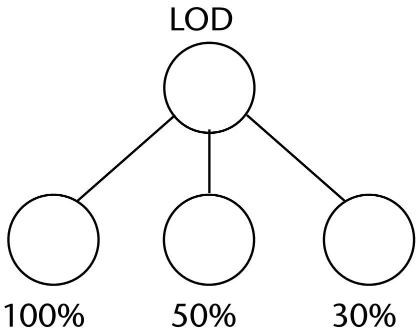
The Level-of-Detail (LoD) Technique

- Example: do you see a difference?

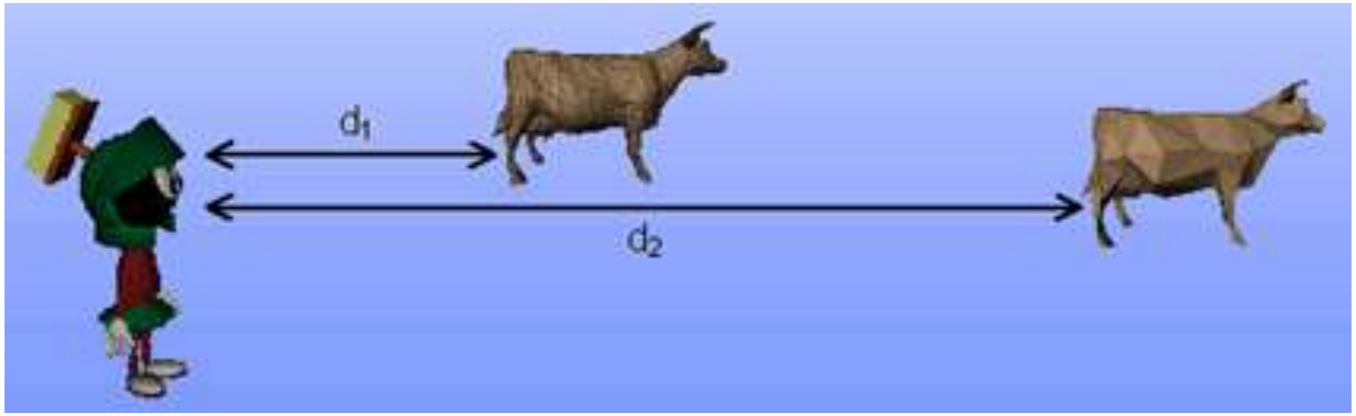
- Idea: render a reduced version of the object, where the amount of reduction is chosen such that users cannot see the difference from the full-resolution version

- Definition:
  A level-of-detail (LOD) of an object is a simplified version,
  i.e., a model that has less polygons.
- The technique consists of two tasks:
  1. Preprocessing: for each object in the scene, generate *k* LODs
     - For instance, we generate LODs at 100%, 80%, 60%, ..., of the number of polygons of the original model
  2. Runtime: select "right" LOD, make switches between LODs unnoticeable

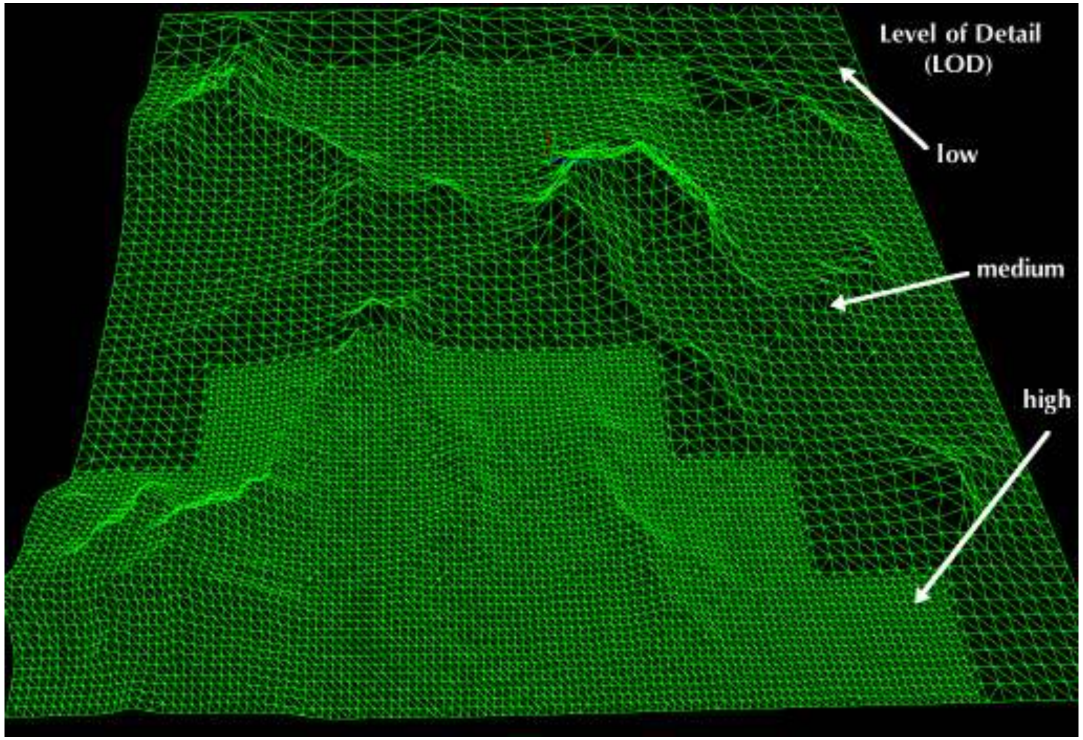
Selection of the LOD

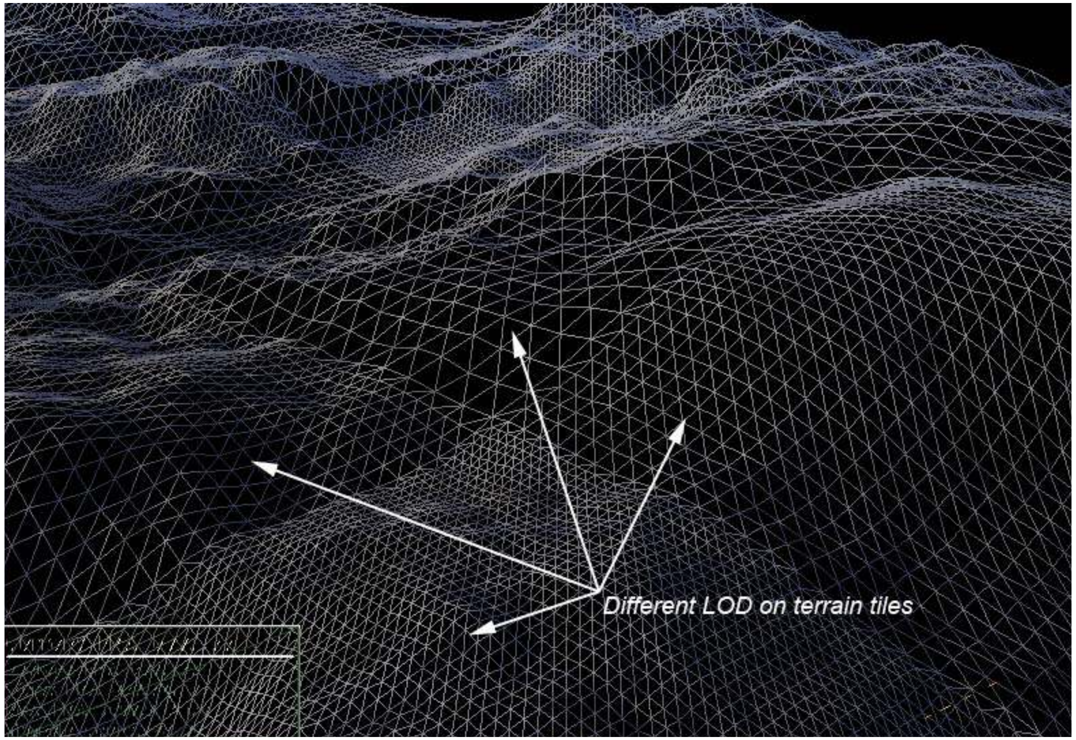


- Balance visual quality against "temporal quality"
- Static selection algorithm:
  - Level i for a distance range (d_i, d_{i+1})
  - Optimal distance ranges depend on FoV
  - Problem: size of objects is not considered



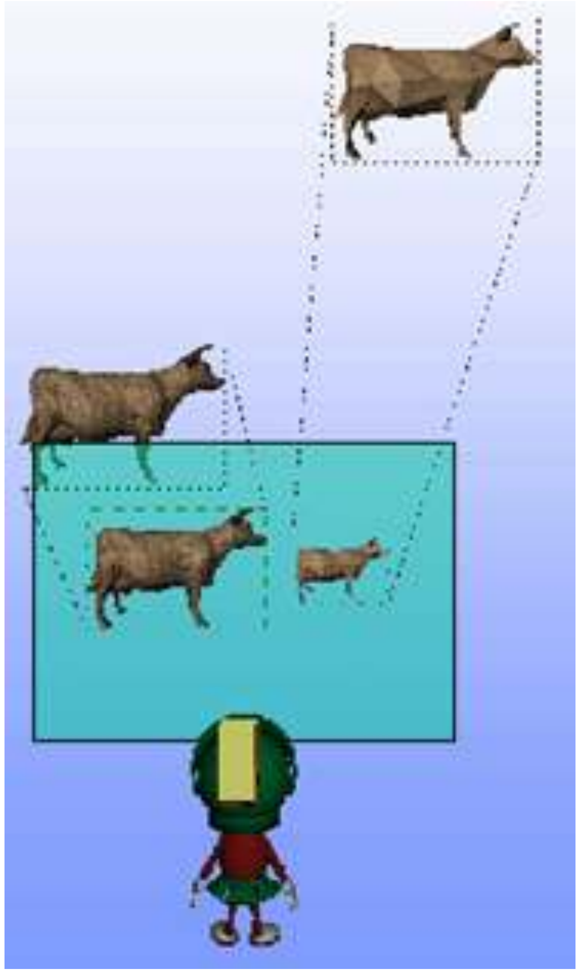
Typical Use Case: Terrain Rendering





Improved Static Selection

- Estimate size of object on the screen
- Advantage: independent from screen resolution, FoV, size of objects
- LOD depends on distance *automatically*

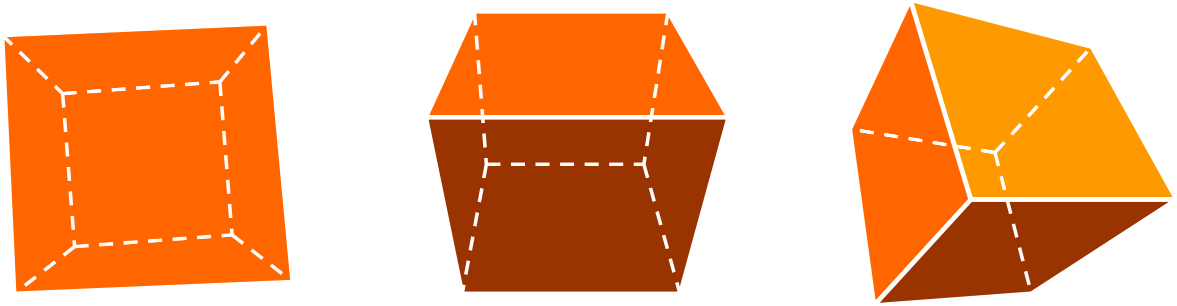


Estimation of the Size of an Object on the Screen

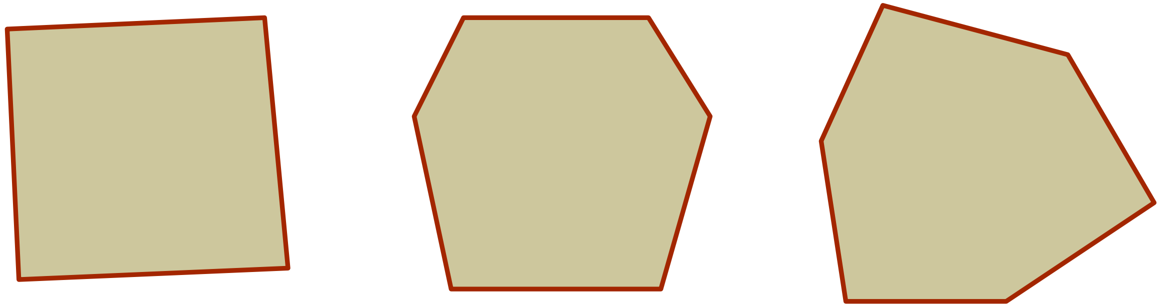
- Naïve method:
  - Compute bounding box (bbox) of object in 3D (probably already known by scenegraph for occlusion culling)
  - Project bbox onto 2D → 8x 2D points
  - Compute 2D bbox (axis aligned) around 8 points
- Better method:
  - Compute true area of projected 3D bbox on screen

Idea of the Algorithm

- Determine number of sides of 3D bbox that are visible:



- Project only points on the silhouette (4 or 6) onto 2D:



- Compute area of this (convex!) polygon

Implementation

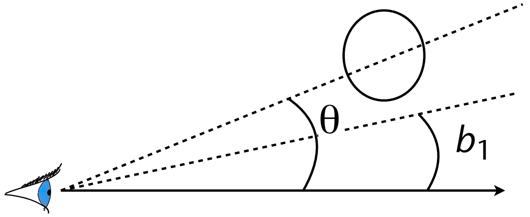
FYI

- For each pair of (parallel) box sides (i.e., each *slab*): classify viewpoint with respect to this pair into "below", "above", or "between"
- Yields 3x3x3 = 27 possibilities
  - In other words: the sides of a cube partition space into 27 subsets
- Utilize bit-codes (à la out-codes from clipping) and a lookup-table
  - Yields LUT with 2^6 entries (conceptually)
- Each of the 27-1 entries of the LUT lists the 4 or 6 vertices of the silhouette
- Then, project, triangulate (determined by each case in LUT), and accumulate areas

Psychophysiological LOD Selection

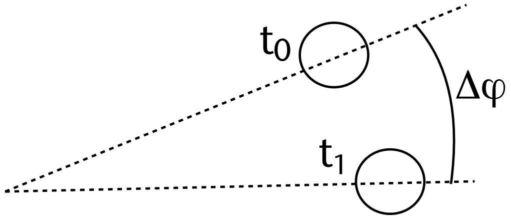
- Idea: exploit human factors with respect to visual acuity
  - Central / peripheral vision:

$$k_1 = \begin{cases} e^{-(\theta - b_1)/c_1} & , \theta > b_1 \\ 1 & \text{, sonst} \end{cases}$$



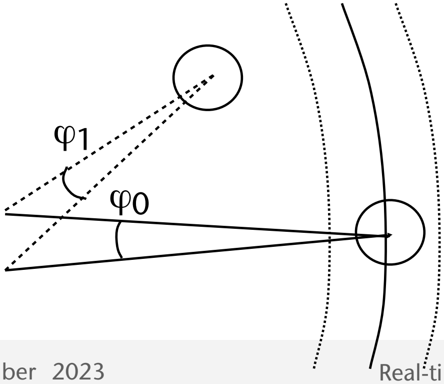
  - Motion of obj (relative to viewpoint):

$$k_2 = e^{-\frac{\Delta\varphi - b_2}{c_2}}$$



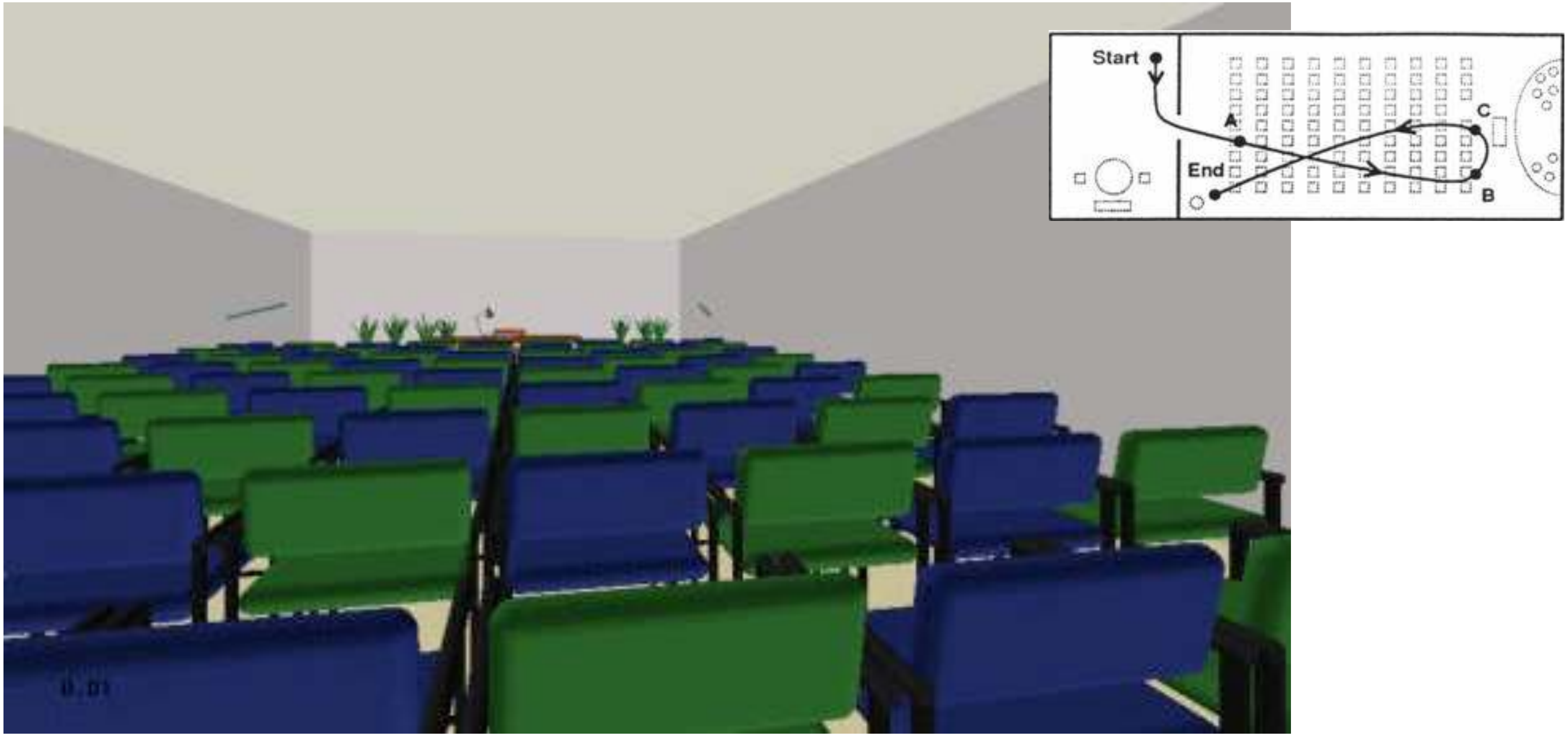
  - Depth of obj (relative to horopter):

$$k_3 = e^{-\frac{|\varphi_0 - \varphi| - b_3}{c_3}}$$

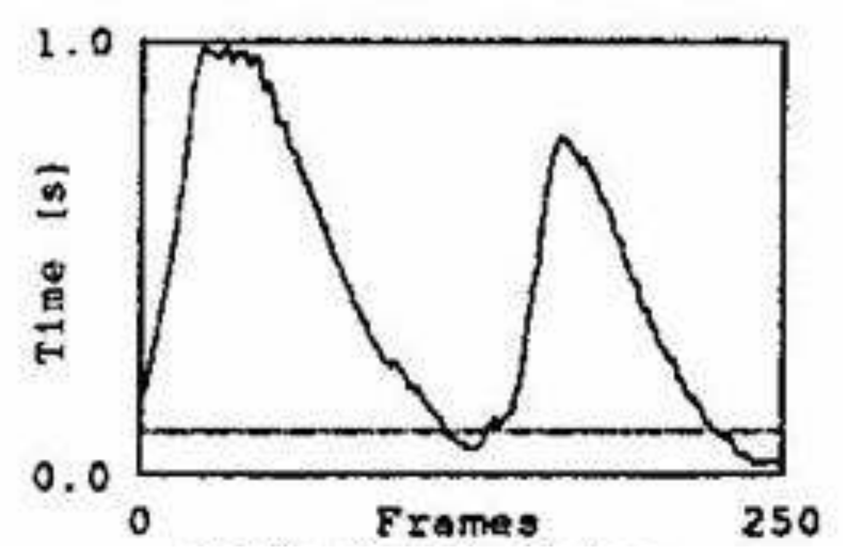


- Determination of LODs:
  1. $k = \min\{k_i\} \cdot k_0$, oder $k = \prod k_i \cdot k_0$
  2. $r_{\min} = 1/k$ (or similar transfer function)
  3. Select level l such that $\forall p \in P_l : r(p) \geq r_{\min}$, where P_l is the set of polygons of level l of an object, and $r(p)$ = radius of polygon p
- Do we need *eye tracking* for this to work?
  - Maybe …
  - Psychophysiology: eyes usually never deviate > 15° from head direction
  - So, assume eye direction = head direction, and choose $b_1 = 15°$

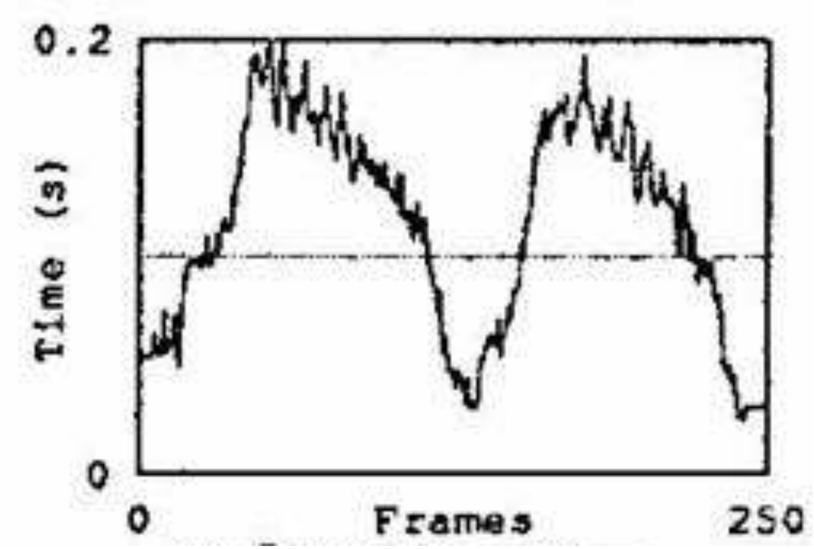
Example Scenario



Problems of Static LoD Selection



a) No LoD's



b) Static LoD selection

Reactive vs. Predictive LOD Selection

- Reactive LOD selection:
  - Keep history of rendering durations
  - *Based on the history*, estimate duration T_r for next frame,
  - Let T_b = time budget that can be spent for next frame
    - Usually constant, e.g., 11 msec for 90 Hz framerate
  - If $T_r > T_b$: decrease LODs (use coarser levels)
  - If $T_r < T_b$: increase LODs (finer levels)
  - Then, render frame and record actual rendering time in history
- Reactive LOD selection can produce severe outliers

Predictive LOD Selection

- Definition object tuple (O,L,R):
  O = object,   L = level,
  R = rendering quality (#textures, #light sources, ...)

- Evaluation functions on object tuples:
  cost(O,L,R)   = time needed for rendering
  benefit(O,L,R)   = "contribution to image"

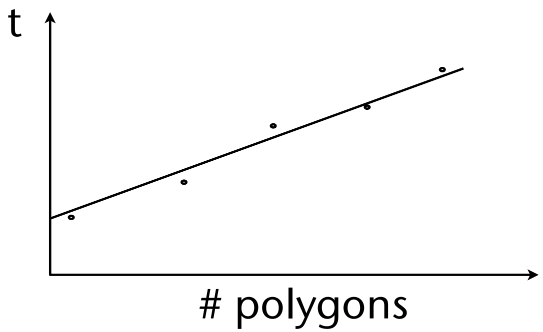
- Optimization task: find $\max_{S' \subset S} \sum_{(O,L,R) \in S'} \text{benefit}(O,L,R)$

  under the condition $T_r = \sum_{(O,L,R) \in S'} \text{cost}(O,L,R) \leq T_b$

  where S = { all possible object tuples in the scene }

- Cost function depends on:
  - Number of vertices (≈ # *coord. transforms* + *lighting calcs* + *clipping*)
  - Setup time per polygon
  - Number of pixels (*scanline conversions, alpha blending, texture fetching, anti-aliasing, Phong shading*)
  - Theoretical cost model: $\text{Cost}(O, L, R) = \max \begin{Bmatrix} C_1 \cdot \text{Poly} + C_2 \cdot \text{Vert} \\ C_3 \cdot \text{Pixels} \end{Bmatrix}$

- Better determine the cost function by experiments: Render a number of different objects with all different parameter settings possible



- Benefit function: "contribution" to image is affected by
  - Size of object
  - Shading method: $\text{Rendering}(O, L, R) = \begin{cases} 1 - \frac{c}{\#\text{pgons}} & \text{, flat} \\ 1 - \frac{c}{\#\text{vert}} & \text{, Gouraud} \\ 1 - \frac{c}{\#\text{vert}} & \text{, per-pixel} \end{cases}$
  - Distance from center (periphery, depth)
  - Velocity (similar to psychophysiological LOD factors)
  - Semantic "importance" (e.g., grasped objects are very important)
  - Hysteresis for penalizing LOD switches: $\text{Hysteresis}(O, L, R) = \frac{c_1}{1 + |L - L'|} + \frac{c_2}{1 + |R - R'|}$
  - Together: $\text{Benefit}(O, L, R) = \text{Size}(O) \cdot \text{Rendering}(O, L, R) \cdot \text{Importance}(O) \cdot \text{OffCenter}(O) \cdot \text{Vel}(O) \cdot \text{Hysteresis}(O, L, R)$

- Optimization problem = multiple-choice knapsack problem → NP-complete
- Idea: compute sub-optimal solution
  - Reduce it to continuous knapsack problem (see algorithms class)
  - Define

$$\text{value}(O, L, R) = \frac{\text{benefit}(O, L, R)}{\text{cost}(O, L, R)}$$

  - Solve this greedily:
    - Sort all object tuples by value(O,L,R)
    - Choose the first k tuples until knapsack is full
  - Additional constraint: no 2 object tuples must represent the same object!

- Incremental solution:
  - Start with solution $(O_1, L_1, R_1), \ldots, (O_n, L_n, R_n)$ as of last frame
  - If $\sum_i \text{cost}(O_i, L_i, R_i) \leq \text{max. frame time}$

    then find object tuple (O_k, L_k, R_k),

    such that

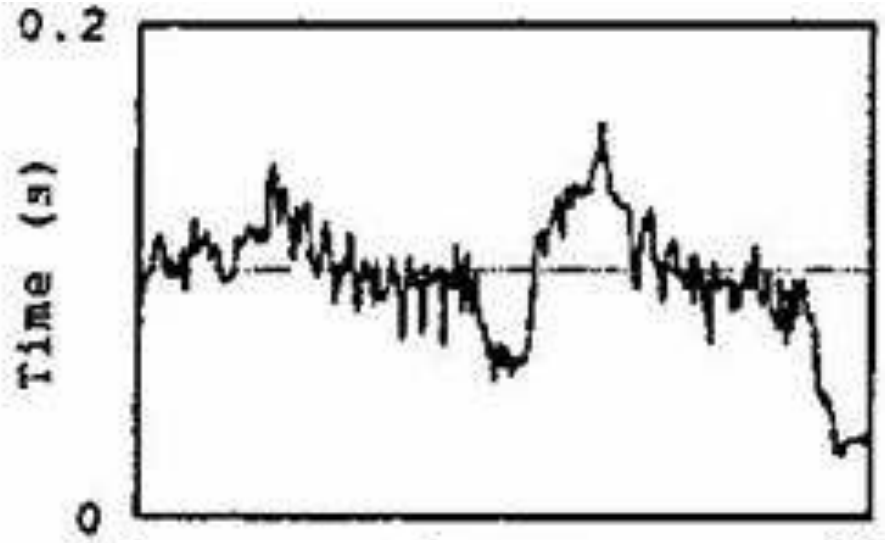
    $$\text{value}(O_k, L_k + a, R_k + b) - \text{value}(O_k, L_k, R_k) = \max$$

    and

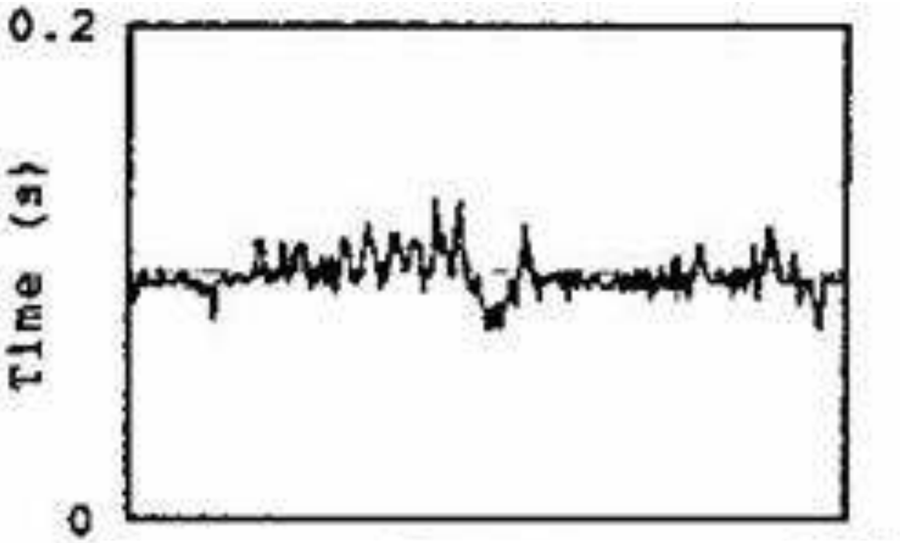
    $$\sum_{i \neq k} \text{cost}(O_i, L_i, R_i) + \text{cost}(O_k, L_k + a, R_k + b) \leq \text{max. frame time}$$

- Proceed analog, if $\sum_i \text{cost}(O_i, L_i, R_i) > \text{max. frame time}$

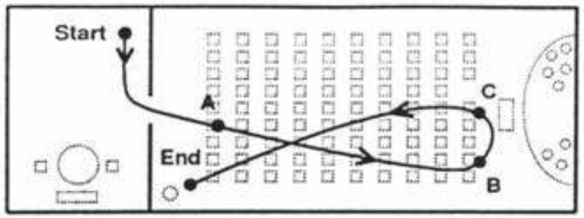
Performance in the Example Scenes



c) Reactive LoD selection



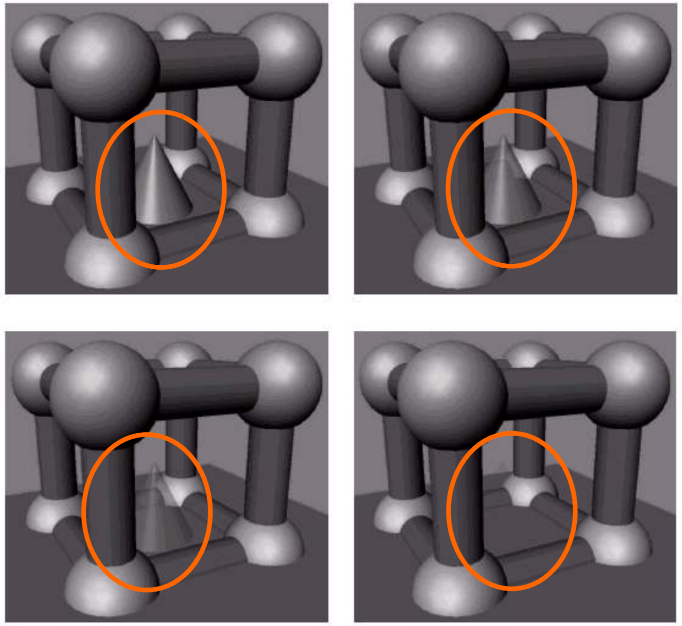
c) Predictive LoD selection



Problem with Discrete LODs

- "Popping" when switching to next higher/lower level

1. Simplest solution: temporal hysteresis (reduces frequency of pops, especially filters out short back-and-forth pops)
2. Alpha blending of the two adjacent LOD levels ("Alpha-LODs"):
   - Instead of switching from level *i* to *i*+1, fade out level *i* until gone, *at the same time* fade in level *i*+1
   - "Man kommt vom Regen in die Traufe"
   - Don't use them!
3. Continuous, view-dependent LODs using progressive meshes



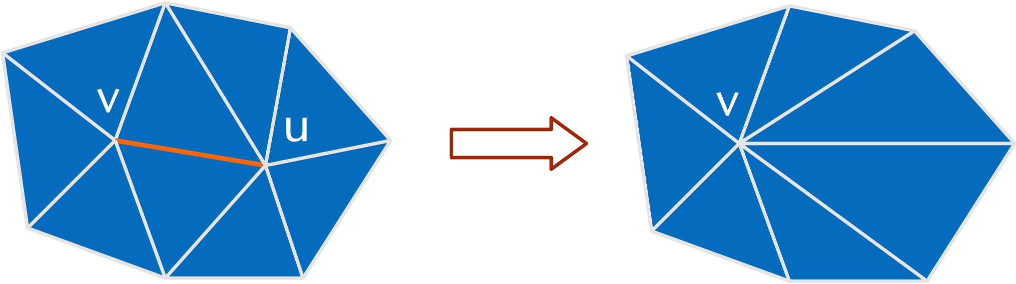
Progressive Meshes

- A.k.a. Geomorph-LODs
- Initial idea / goal:
  - Given two LODs M_i and M_{i+1} of the same object
  - Construct mesh M' "in-between" M_i and M_{i+1}

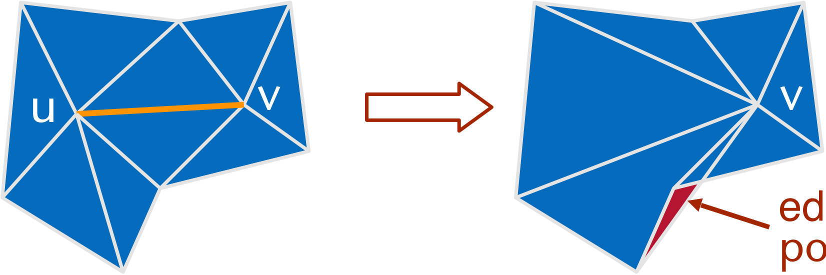
- Definition: progressive mesh = representation of an object, starting with a high-resolution mesh M_0, with which one can continuously (up to the vertex level) generate "in-between" meshes ranging from 1 polygon up to M_0 (and do that extremely fast).

Construction of Progressive Meshes

- Approach: successive *simplification*, until only 1 polygon left
- The fundamental operation: *edge collapse*

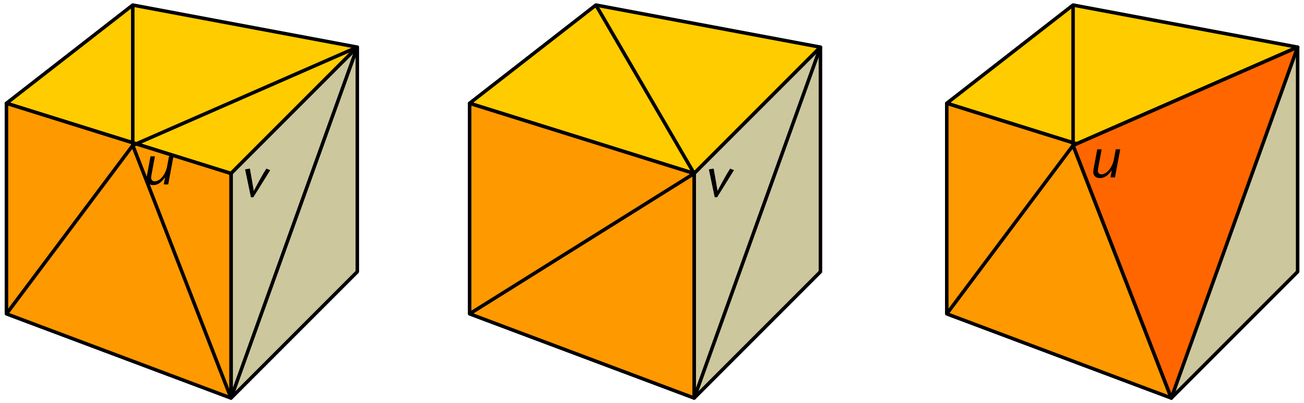


  - Reverse operation = vertex split
- Not every edge can be chosen: beware of bad edge collapses



edge crossing!
polygon overlap!

- The direction of edge collapses is important, too:

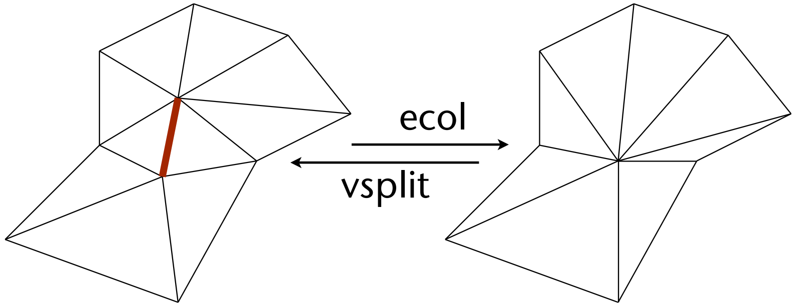


- Introduce measure of edge collapses that evaluates "visual effect"
- Goal: first perform edge collapses that have the least visual effect
- Remark: after every edge collapse, all remaining edges need to be evaluated again, because their "visual effect" (if collapsed) might be different now

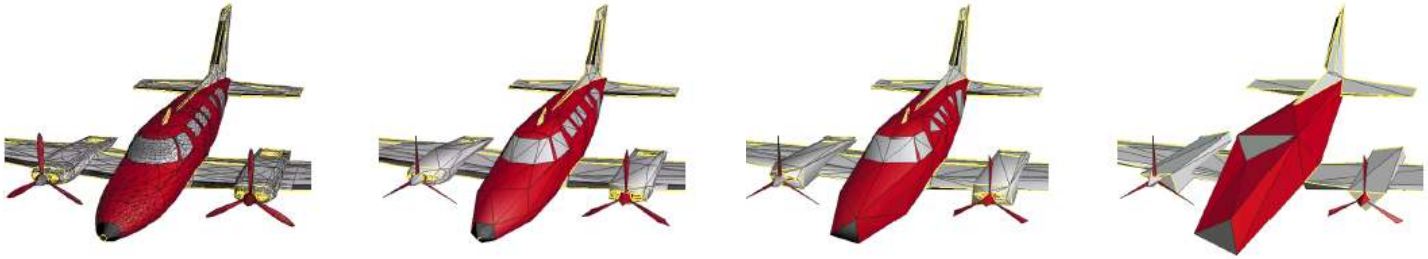
- Progressive mesh = sequence of edge collapses / vertex splits:

$$M = M^n \underset{\text{vsplit}_{n-1}}{\overset{\text{ecol}_{n-1}}{\longleftrightarrow}} \ldots \underset{\text{vsplit}_1}{\overset{\text{ecol}_1}{\longleftrightarrow}} M^1 \underset{\text{vsplit}_0}{\overset{\text{ecol}_0}{\longleftrightarrow}} M^0$$

  - M^i = i-th refinement = 1 vertex more than M^{i-1}
- Representation of progressive mesh = list of ecol/vsplit operations
- Representation of an edge collapse / vertex split:
  - Edge (= pair of vertices) affected by the collapse/split
  - Position of the "new" vertex
  - Triangles that need to be deleted / inserted

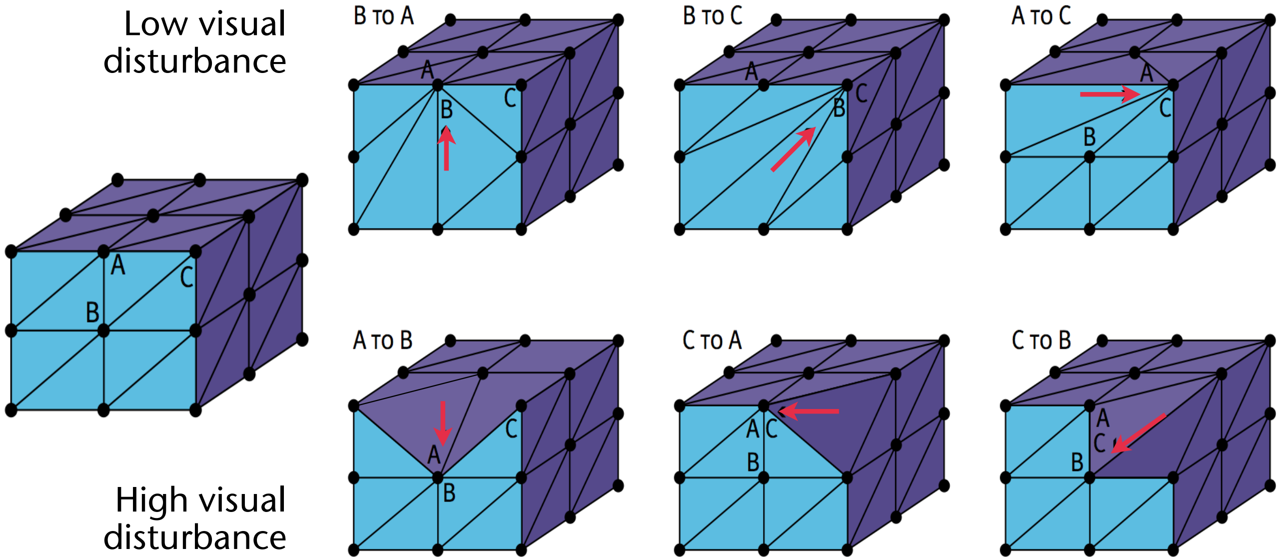


- Evaluation function for edge collapses is not trivial and, more importantly, perception-based!
- Factors influencing "visual effect":
  - Curvature of edge / surface
  - Lighting, texturing, viewpoint (highlights!)
  - Semantics of the geometry (e.g., eyes & mouth are very important in faces)
- Examples of a progressive mesh:



A Simple Edge Evaluation Function

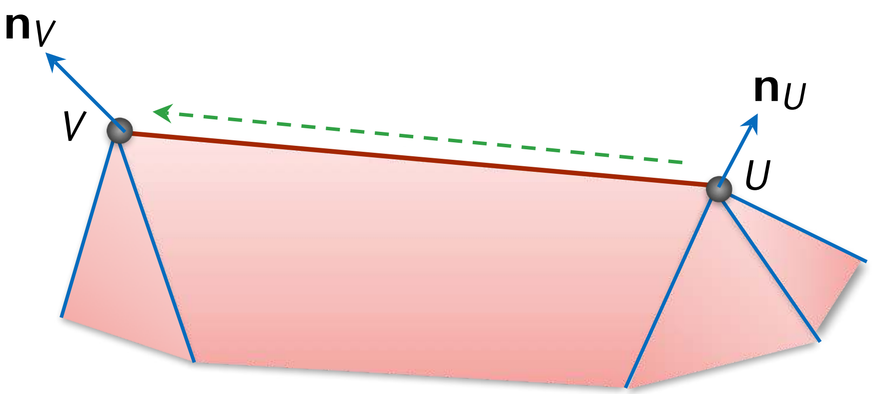
- Motivation:



- Follow this heuristic:
  - Delete small edges first; and,
  - If surface incident to *U* has a smaller (discrete) curvature than surface around *V*, then move vertex *U* onto vertex *V*

- A simple measure for the "costs" of an edge collapse from U onto V:

$$\text{cost}(U, V) = \|U - V\| \cdot \text{curv}(U)$$



  - Note: the cost function is *not* symmetric (which is good):

$$\text{cost}(U, V) \neq \text{cost}(V, U)$$

Simple Method to Calculate a Rough Estimate of the Discrete Curvature

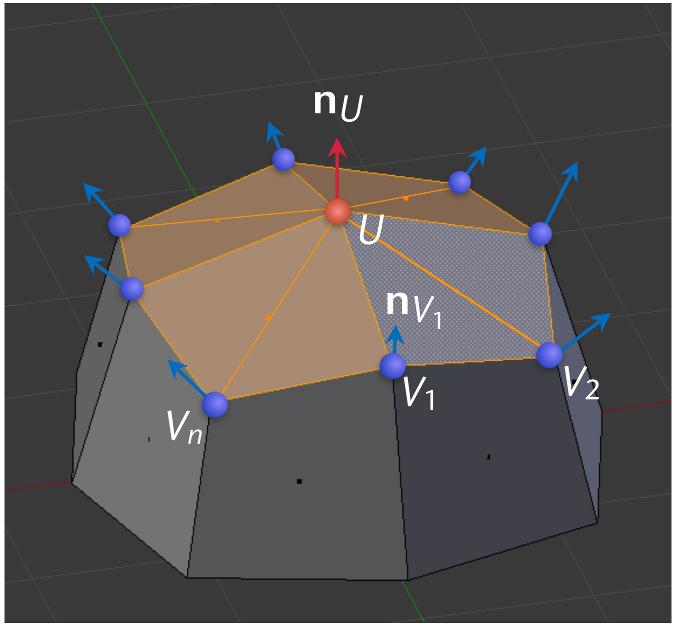
- Calculate "curvature" *along* each edge $e_i = (U, V_i)$:

$$\text{curv}(e_i) = \frac{(\mathbf{n}_{V_i} - \mathbf{n}_U)\cdot(V_i - U)}{|V_i - U|^2}$$

- Calculate estimate of "curvature" at U as geometric mean of incident edges:

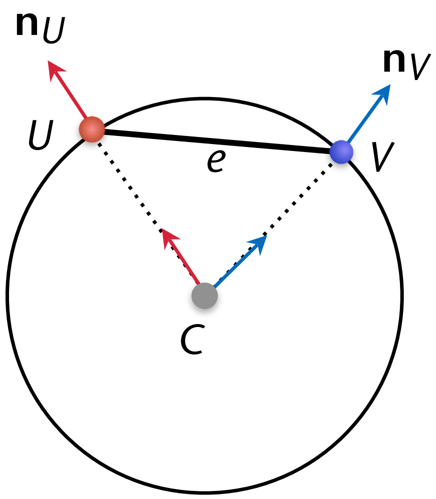
$$\text{curv}(U) = \left(\prod_{i=1}^{n} \text{curv}(e_i)\right)^{\frac{1}{n}}$$

- Alternative to step 2:
  - Find the two edges e_1 and e_2 with minimal and maximal curvature, k_1 and k_2, resp.
  - Set $\text{curv}(U) = \frac{1}{2}(k_1 + k_2)$



Vertex normals must have unit length!

Reasoning Behind the Curvature Formula



- Consider a cross-section through *U*, one of the *V*'s and the edge *e*=(*U*,*V*)
- Assume a circle through *U*, *V* with radius *r* and center C , and assume the normals are perpendicular to the circle; then

$$V = C + r\mathbf{n}_V \qquad U = C + r\mathbf{n}_U$$

$$V - U = r(\mathbf{n}_V - \mathbf{n}_U)$$

$$\text{curv}(e) = \frac{1}{r} = \frac{\|\mathbf{n}_V - \mathbf{n}_U\|}{\|V - U\|}$$

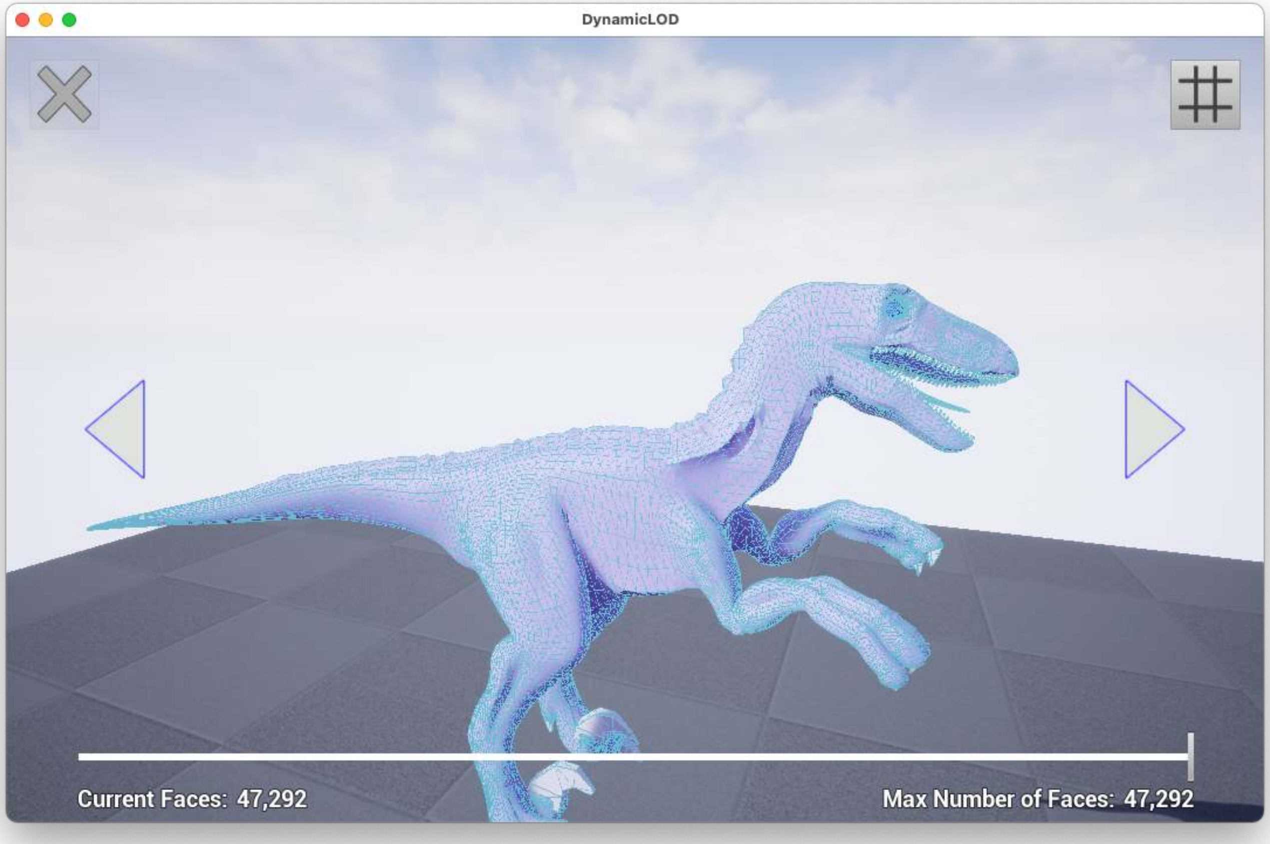
- Make it more "robust" in 3D by first projecting $(\mathbf{n}_V - \mathbf{n}_U)$ onto the edge:

$$\text{curv} = \frac{(\mathbf{n}_V - \mathbf{n}_U)\cdot(V-U)^0}{\|V-U\|}$$

$$= \frac{(\mathbf{n}_V - \mathbf{n}_U)\cdot\frac{V-U}{\|V-U\|}}{\|V-U\|}$$

$$= \frac{(\mathbf{n}_V - \mathbf{n}_U)\cdot(V-U)}{\|V-U\|^2}$$

Demo



Current Faces: 47,292

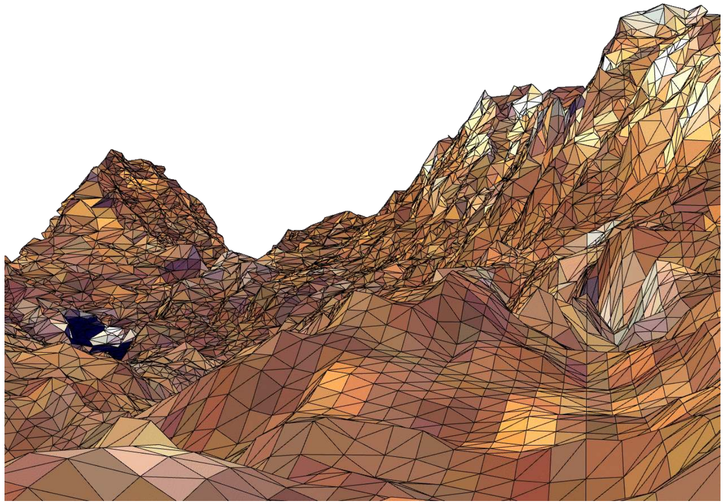
Max Number of Faces: 47,292

How can the Funkhouser-Sequin algorithms be combined with progressive meshes? And implemented on the GPU?

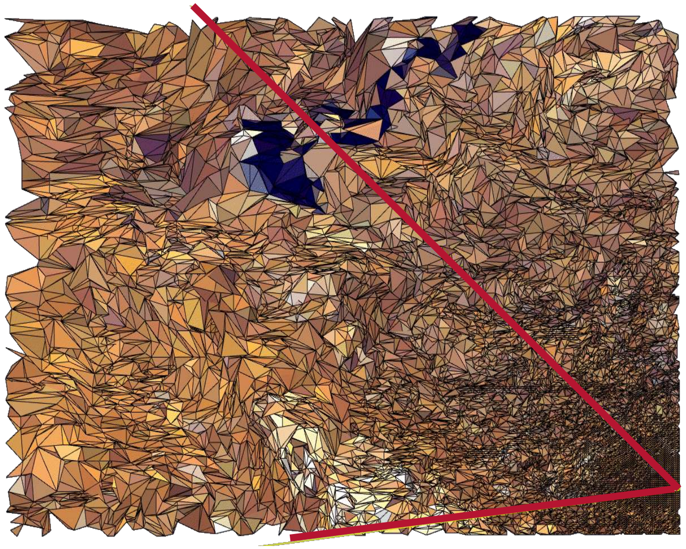
Master Thesis ...

View-Dependent LOD's

- Select *different resolution* within the *same object*, depending on the view point, i.e., different parts of one object are rendered at different resolutions
- Define a metric measuring screen space error (measured in pixels)
- Example: terrain – choose resolution according to projected area

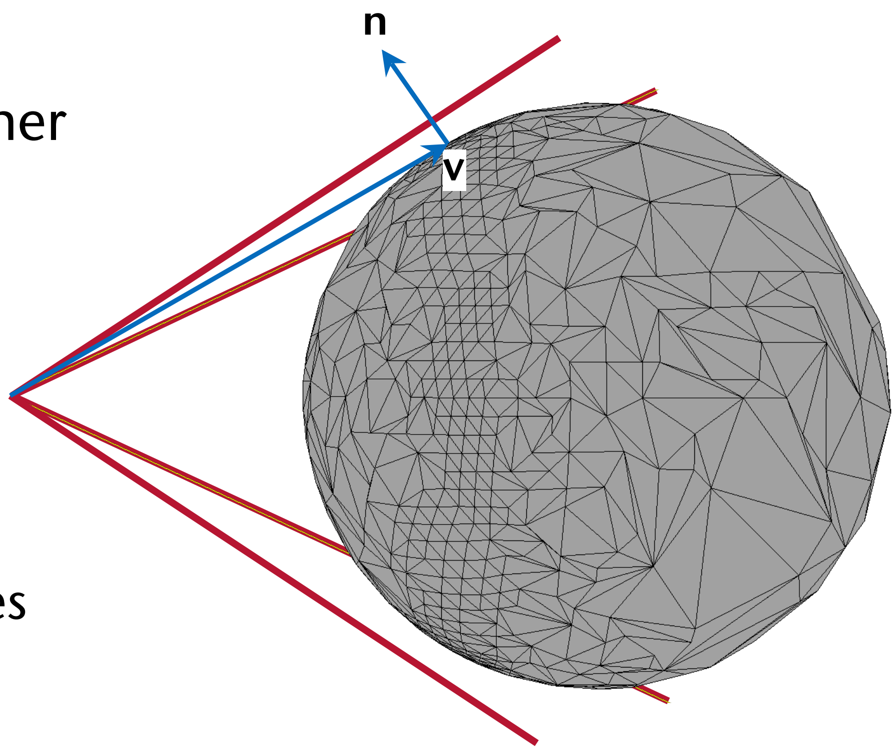


View from eye point



Birds-eye view

- Additional factor: visual importance
- Example: render closed objects with higher resolution near silhouette border
  - Maximal screen space error is modulated by (**v**·**n**)
- Other potential criteria:
  - Specular highlights
  - Salient features, e.g., feature points in faces
- Overall criteria:
  - Triangle budget
  - Time budget (remember *time critical computing*)



Pros and Cons

- Advantages of Dynamic LODs (e.g., progressive meshes):
  - No popping artefacts
  - Can be turned into view-dependent LOD
  - Better rendering fidelity for given polygon count
- Advantages of Static LODs:
  - Extremely simple for the renderer
    - Simple for the programmer, too, i.e., easy to implement
    - No CPU overhead during rendering
  - Can upload LODs to GPU as vertex buffer objects (VBO)

Master's Thesis topic: is it possible to implement progressive meshes (or other kind of dynamic LOD) in the GPU's vertex buffers?

FYI (not relevant for exam)

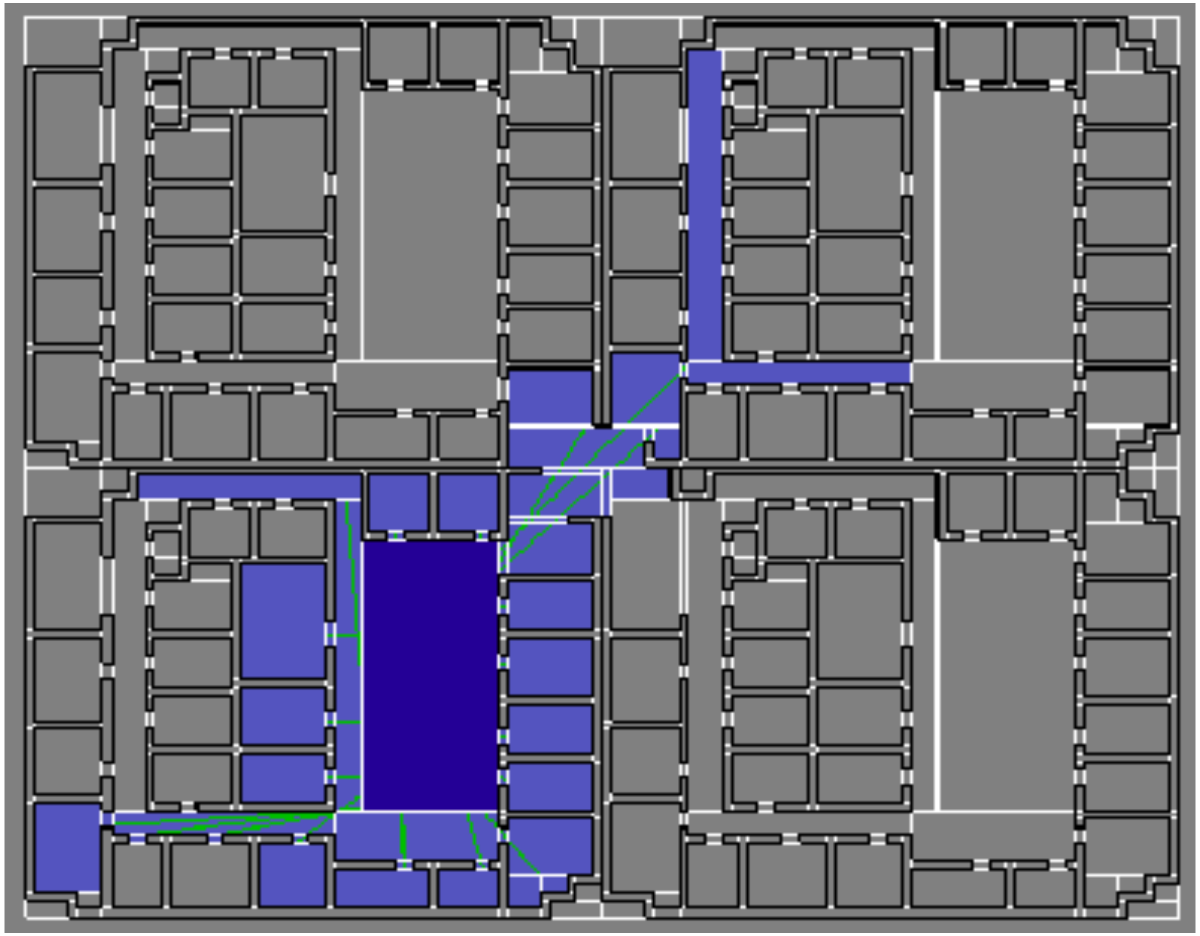
Other Kinds of LODs

- Idea: apply LOD technique to other, non-geometric content
- E.g. "*behavioral LOD*":
  - If in focus, simulate the behavior of an object exactly, otherwise simulate it only "approximately"

FYI (not relevant for exam)

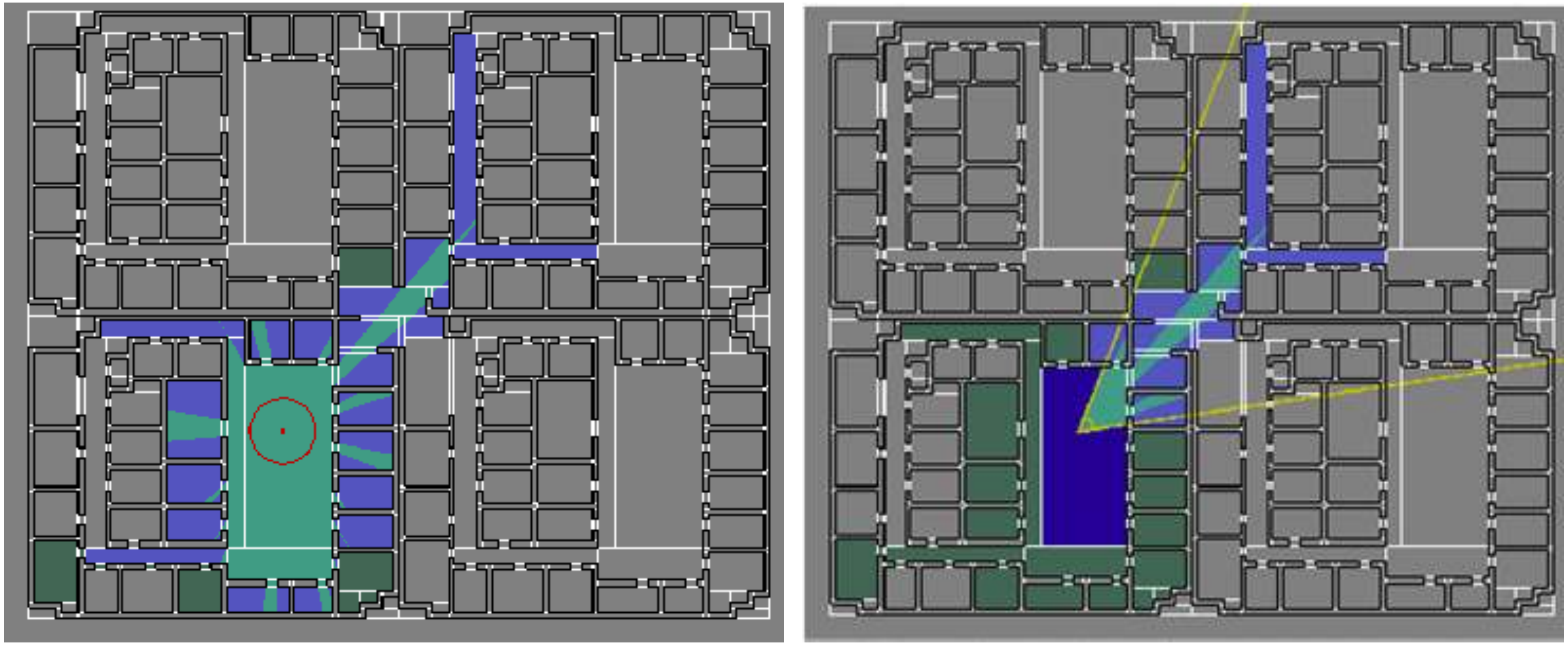
Portal Culling (Culling in Buildings)

- Observation: many rooms within the viewing frustum are not visible
- Idea:
    - Partition the VE into "cells"
    - Precompute *cell-to-cell-visibility* ⟶ visibility graph



FYI (not relevant for exam)

- During runtime, filter cells from visibility graph by viewpoint and viewing frustum



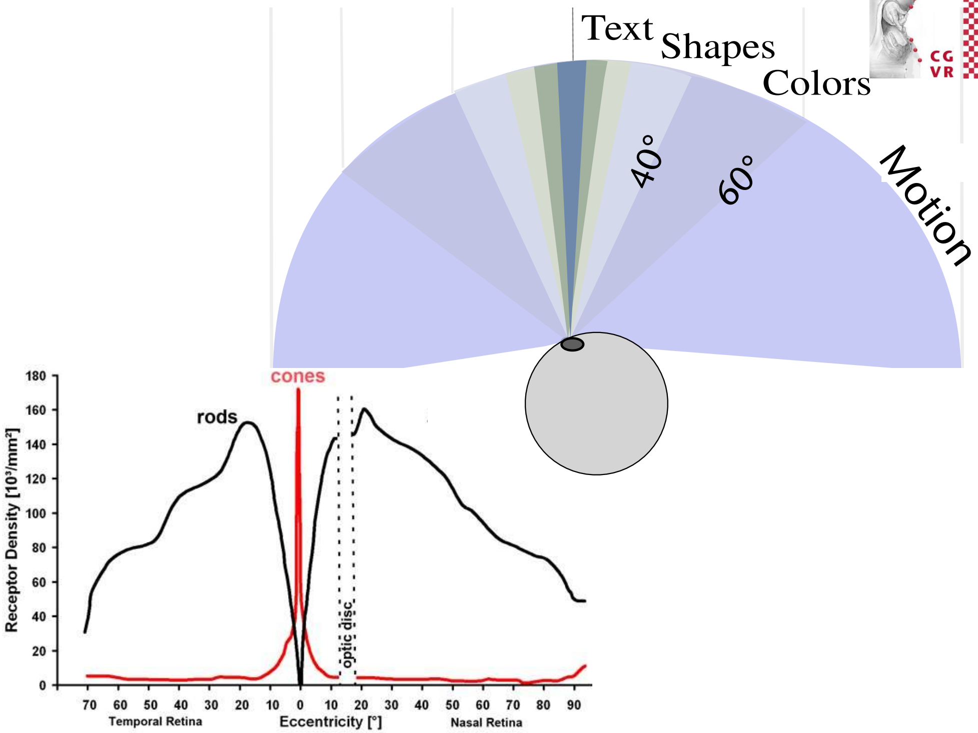
Test Your Knowledge of the Human Visual System

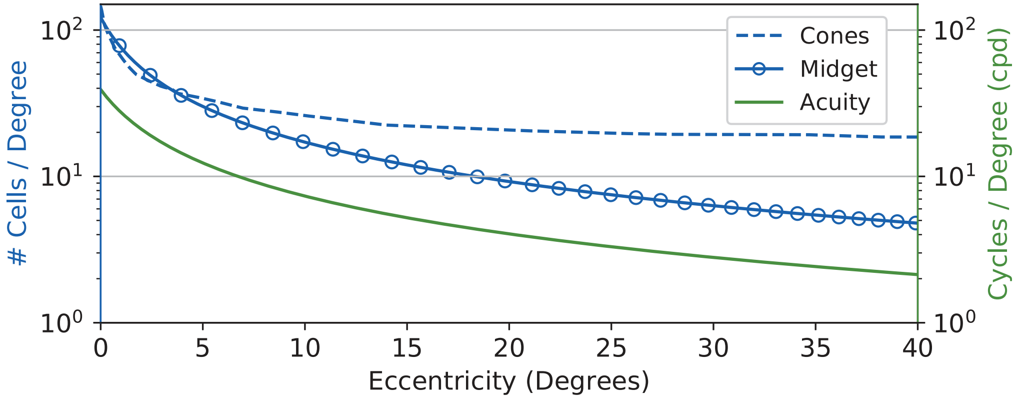
Please,
don't spoil by
"look-ahead"!

https://www.menti.com/smvndia2ss

Foveated Rendering

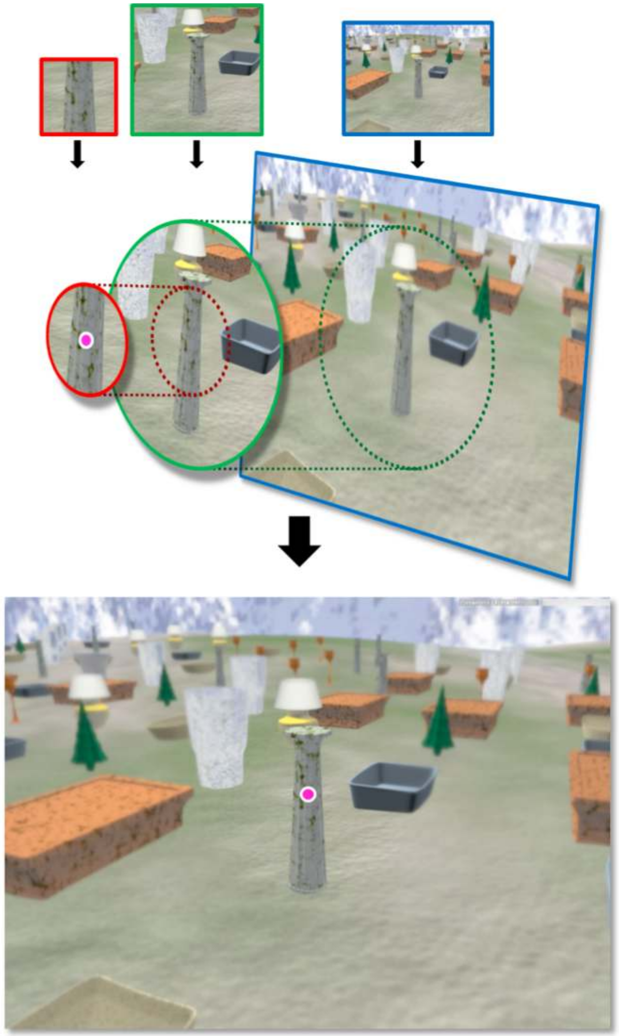
- Recap of some factors of our human visual system (HVS):
    - Critical flicker frequ. in periphery ≈ 85 Hz
    - Fovea = area of high visual acuity ≈ 5°
    - Resolution in fovea ≈ 1 arcmin !
    - At 20° eccentricity, spatial res. ≈ 7.5 arcmin
    - Midget (ganglion) cells collect and process cones' signals, then forward to brain ⟶ their density influences our visual acuity
    - Fovea covers ≈ 4% pixels of HMD
- Most pixels in HMD's are wasted!





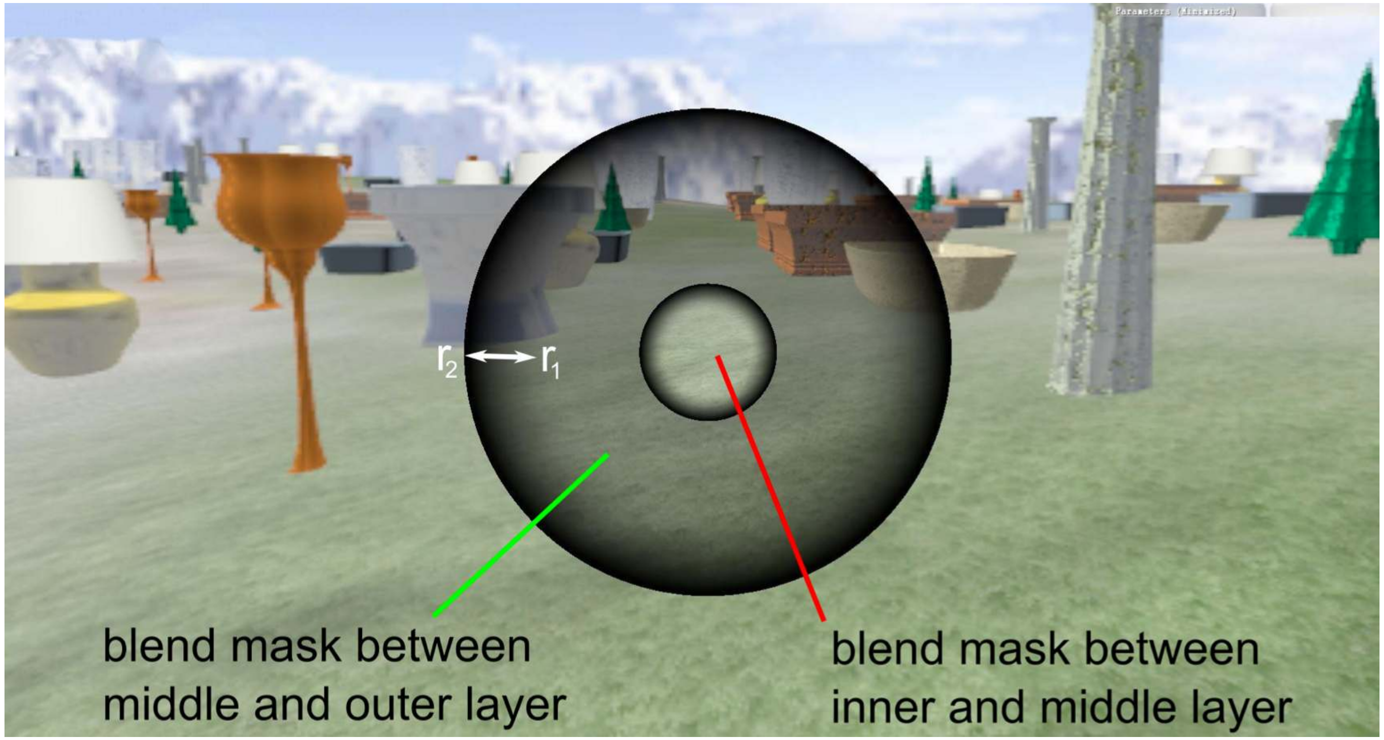
Foveated Rendering Technique

- Prerequisite: eye gaze tracking
- Goal: reduce image resolution towards periphery (*subsampling*)
- Approach:
  - Render 3 overlapping, nested "eccentricity layers" (render targets)
  - Each layer has its own image resolution (and LOD levels) → different sampling spacing!
  - Interpolate outer layers to final display resolution, then blend together
  - Optionally: update outer layers with lower frame rate



Blending the Layers

- Overlay on top of each other
- Calculate blend weights, depending on radius of pixel from center (i.e., gaze direction)
- Visualization of blending weights:

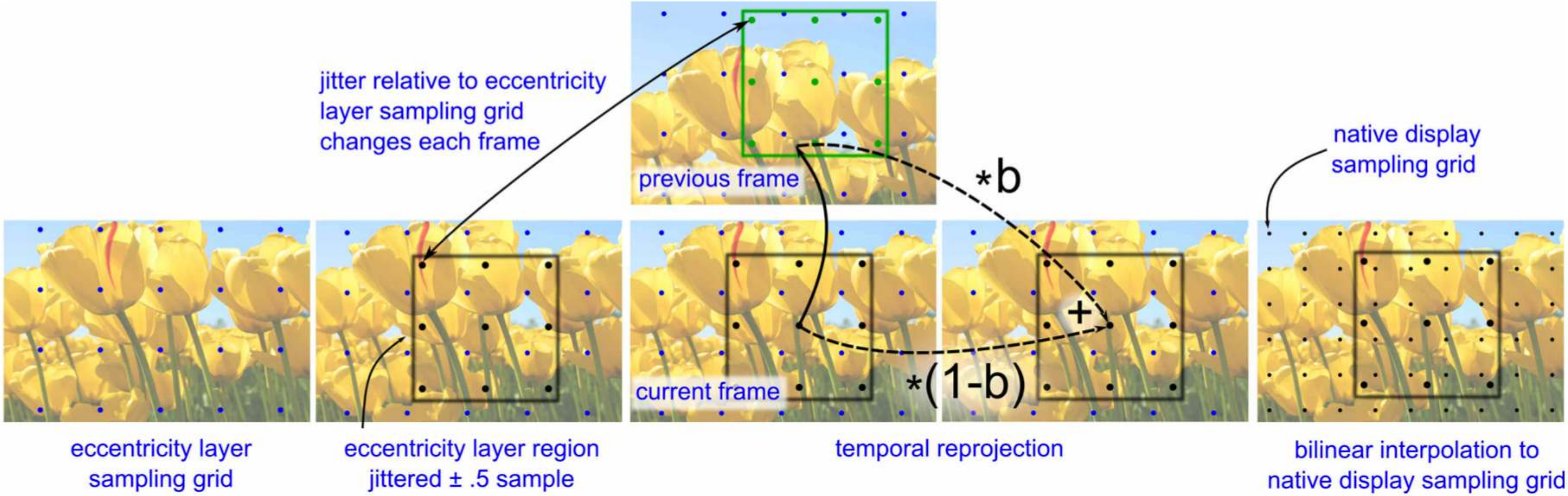


Challenges

- Latency: time elapsed between capturing the eye gaze direction and displaying the corresponding foveated image
- Experience shows:
  - 60 Hz monitor, 50 Hz eye tracker, 35 ms latency ⟶ obvious "pop" in image resolution
  - 120 Hz monitor, 300 Hz eye tracker, 10 ms latency ⟶ no visible "pop"
- Aliasing:
  - Outer layers have wide "pixel" stride ⟶ aggravates aliasing artifacts
  - Periphery is very sensitive to temporal changes ⟶ moving aliasing artifacts are extremely distracting / annoying

Anti-Aliasing Methods

- MSAA (Multi-Sample Anti-Aliasing): standard in GPU's, sample each pixel multiple times (e.g., by grid, or other pattern, within each pixel)
- Whole frame jitter sampling plus temporal reprojection:



Blending and Anti-Aliasing at Work

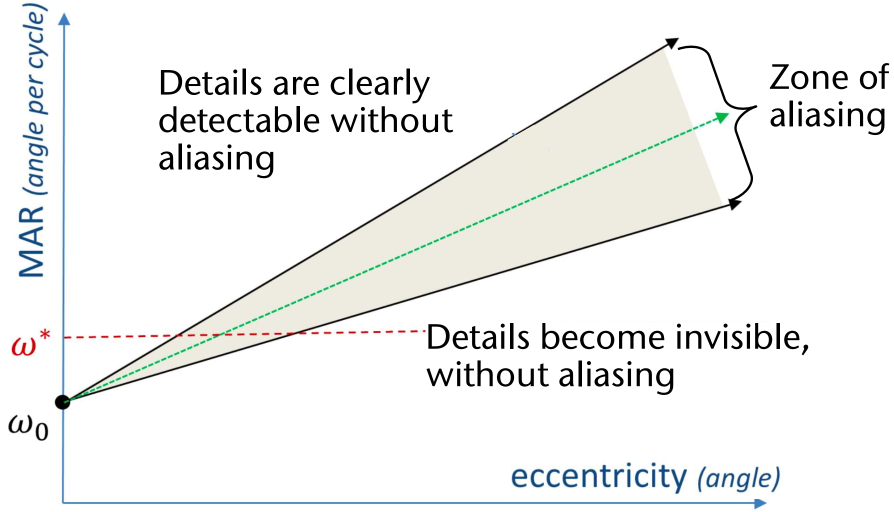
Smooth Composition

More on the Human Visual System

- Definition:
  - Imagine a grating of black and white lines next to each other
  - Minimum angle of resolution (MAR) ω = smallest angle of a cycle of white-black lines still visible
  - Visual acuity $= \dfrac{1}{\text{minimum angle of resolution}}$
  - Units:
    - MAR = degrees (°) = degrees per cycle
    - Acuity = frequency (Hz) = cycles per degree
- Standard model for MAR:

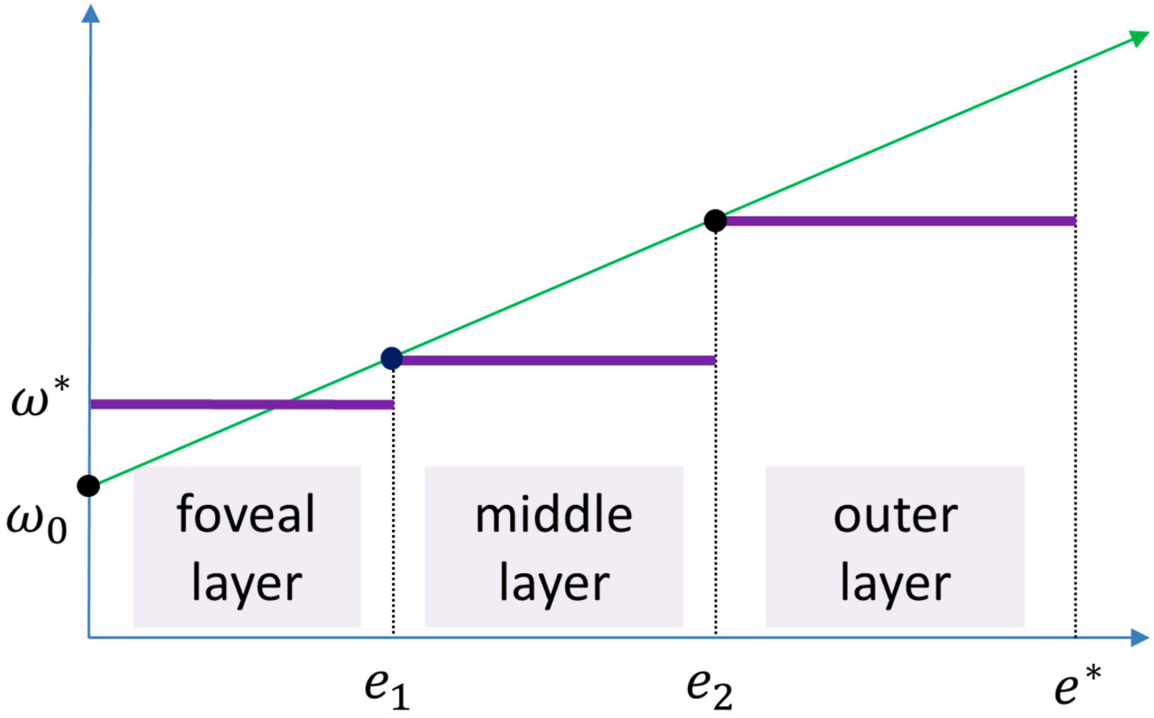
$$\omega = me + \omega^0$$

with e = eccentricity, ω^0 = MAR at fovea



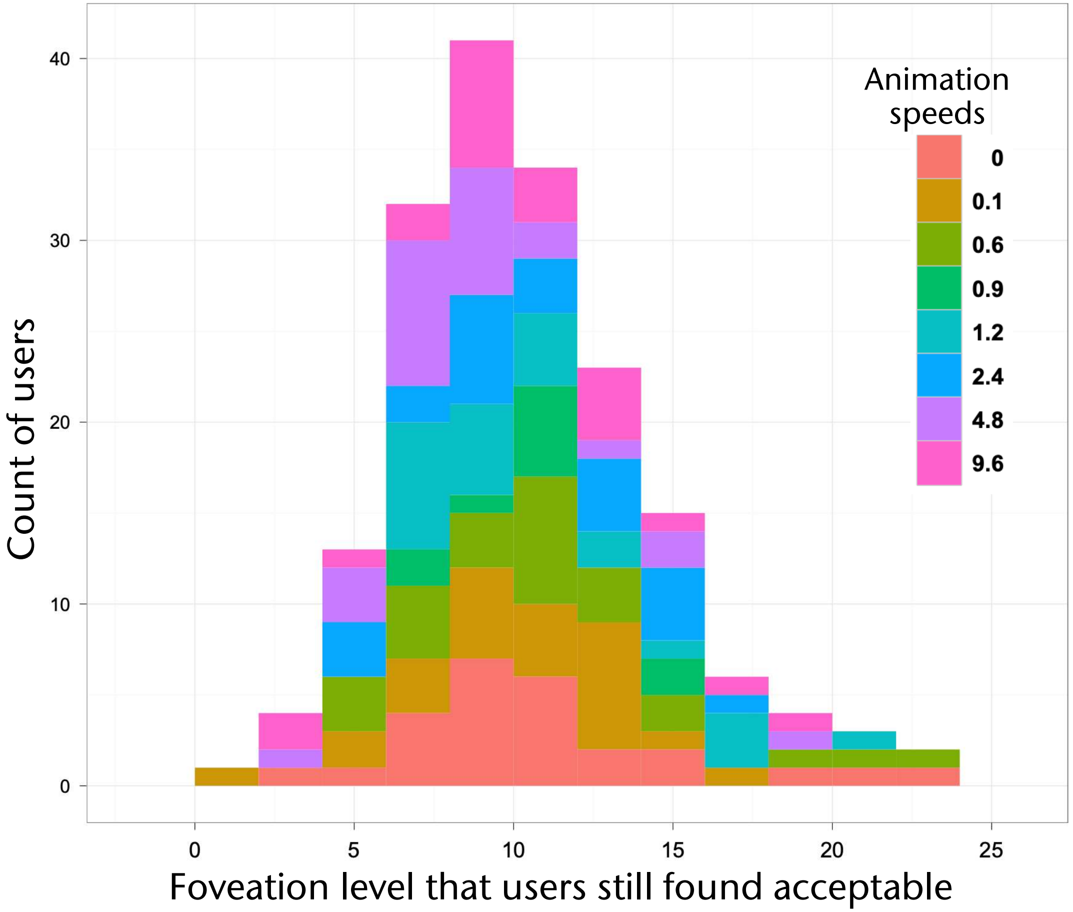
Connection Between Model and Rendering Speed

- Task: given a specific slope in the MAR model, *m*, and the number of eccentricity layers, choose the radii of the layers
  - Radii e_1, e_2 determine the total number of pixels to be rendered
- Determine by optimization
  - E.g.: brute force, choose e_1, e_2, with $0 < e_1 < e_2 < e^*$, then count the number of pixels
- Question: what is the best parameter *m*?
  - Smaller *m* → larger radii, more pixels to be rendered, less savings



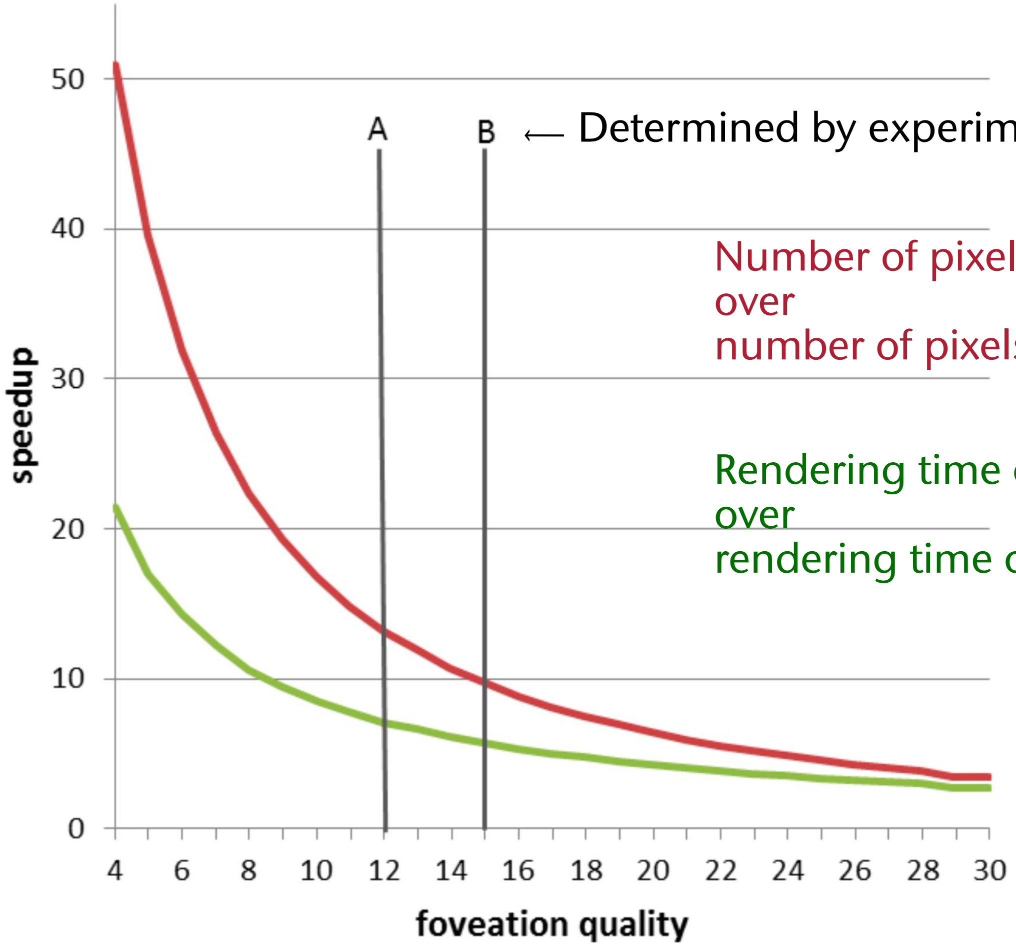
User Study to Determine Parameters

- Slider test:
  - Present participants the non-foveated animation sequence first
  - Then start with low degree of foveation (high rendering quality)
  - Let users increase level of foveation (decrease rendering quality) until just noticeable artifacts appear
  - Conditions: different animation speeds
- Results:



Video of User Study

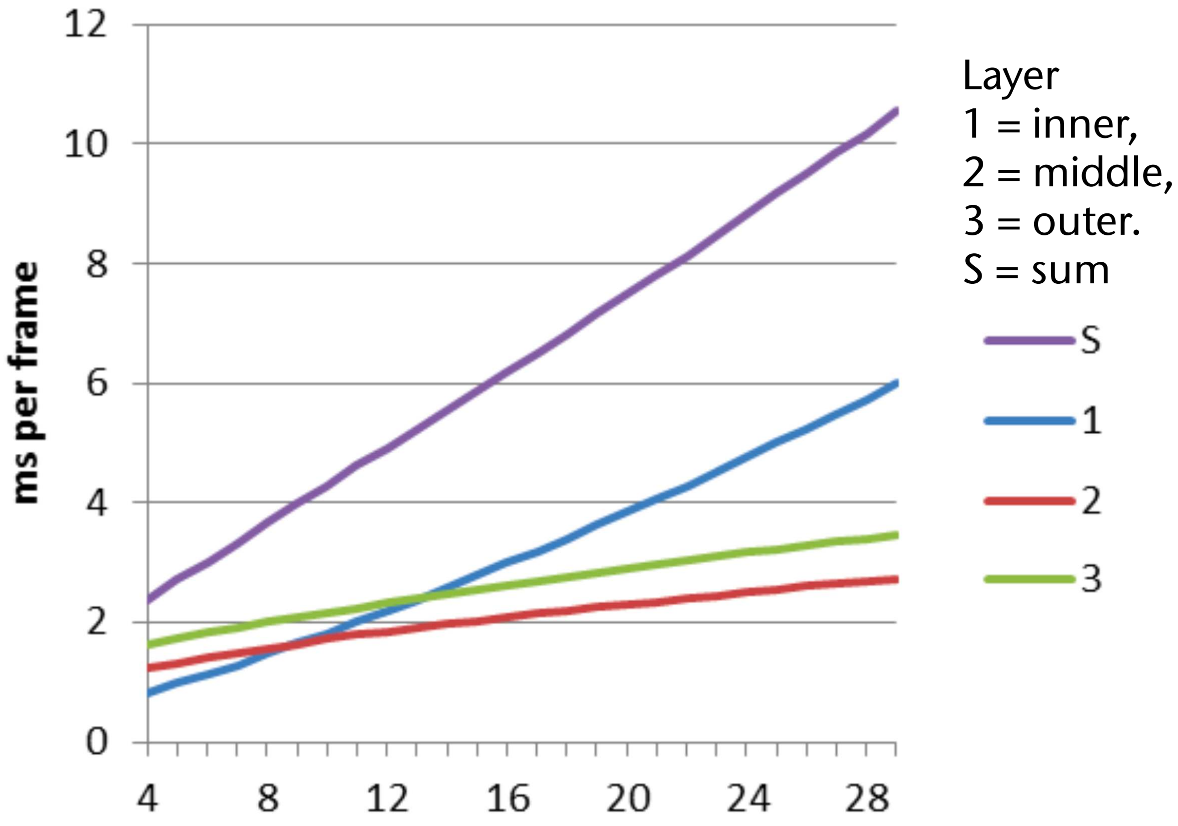
Speedup, Overall Results



← Determined by experiments

Number of pixels on display
over
number of pixels rendered

Rendering time of foveated version
over
rendering time of un-foveated version

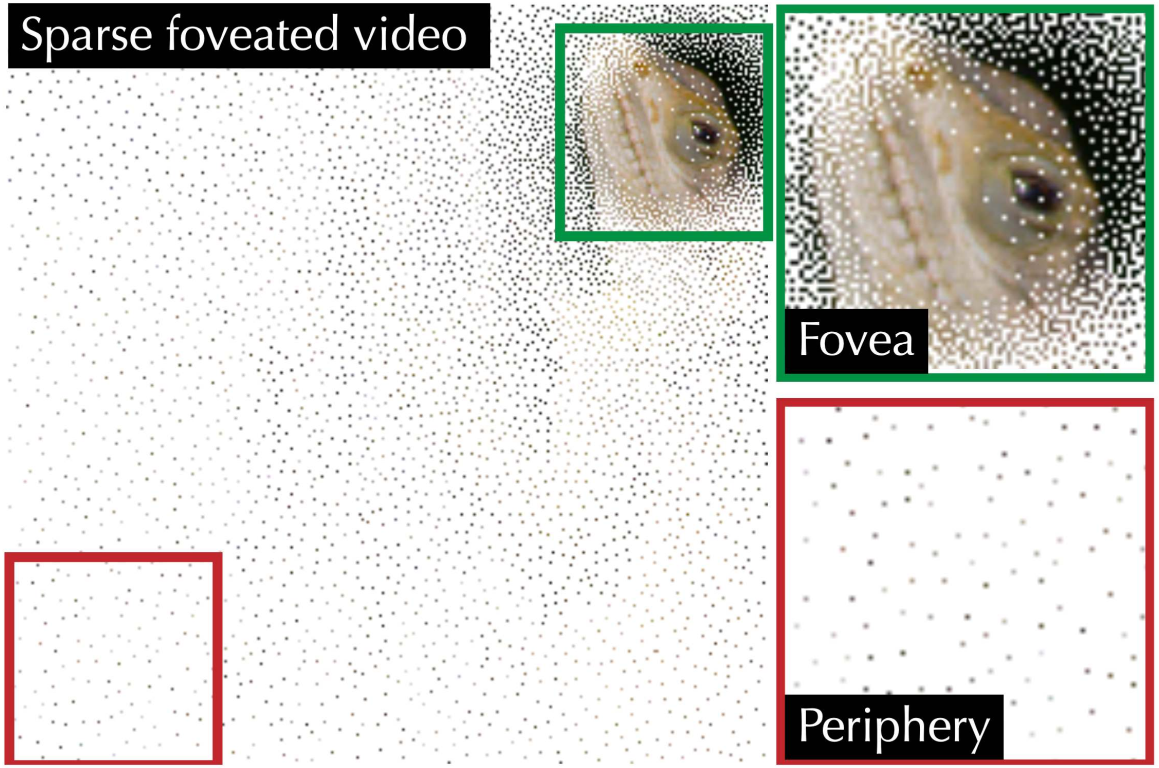


Layer
1 = inner,
2 = middle,
3 = outer.
S = sum

foveation quality ~ inner radii of layers 2 and 3

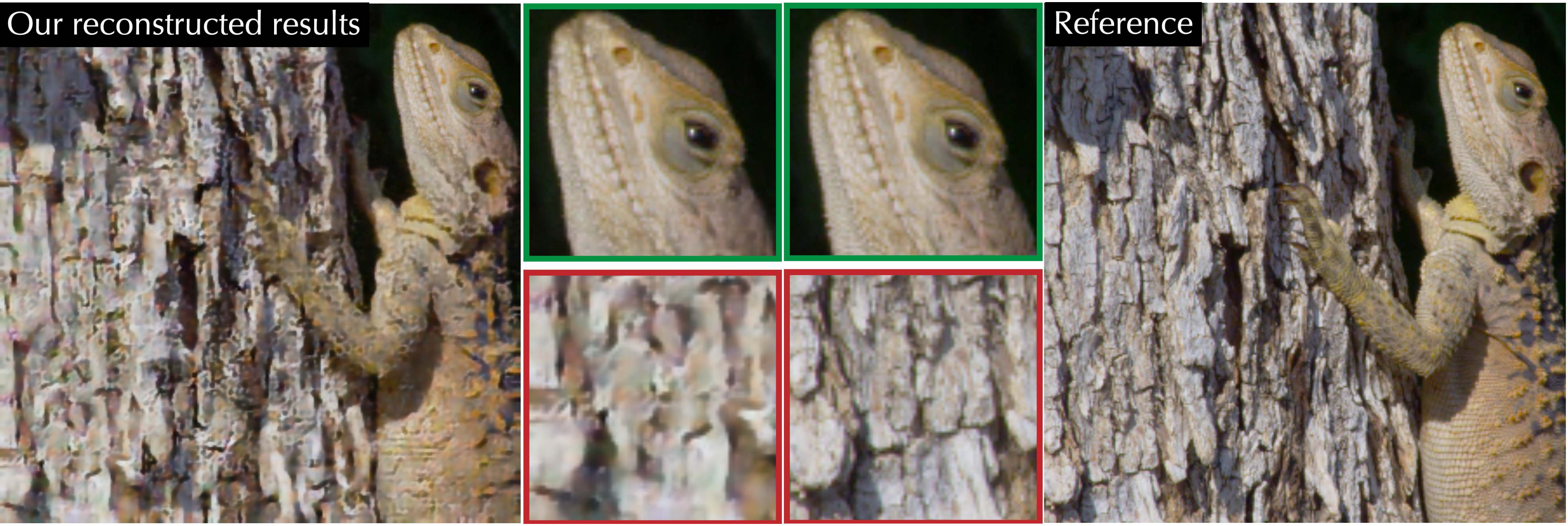
Further Improvements

- In order to reconstruct the whole image, use GANs (generator adversarial networks), instead of layered rendering, followed by anti-aliasing and blending
- Idea:
  - Generate mask with high density at fovea, low density in periphery
  - Render image at mask points
  - Fill in other pixels using GAN
  - Train GAN on large number of frames from video games and natural scene



["DeepFovea ...", 2019]

Comparison with Ground Truth



Runtime performance: 9 ms, using 4x NVIDIA Tesla V100 GPUs (2019)

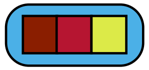
Get Creative: Are You Aware of Any Other Human Factors of the HVS that Might, Perhaps, be Utilized to Improve Rendering Performance?

https://www.menti.com/smvndia2ss

FYI (not relevant for exam)

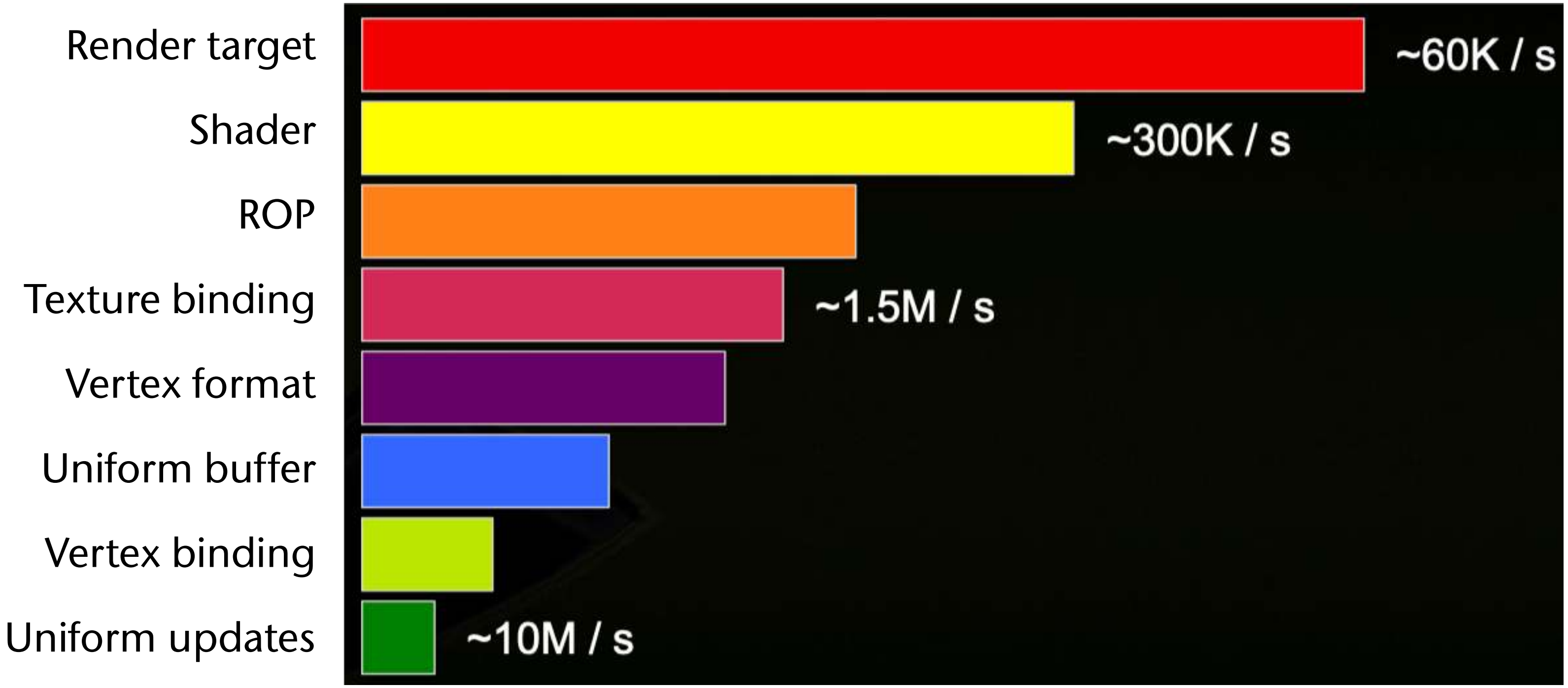
State Sorting

- A state in OpenGL rendering =
  - Combination of all attributes

    
  - Examples for attributes: color, material, lighting parameters, textures being used, shader program, render target, etc.
  - At any time, each attribute has exactly 1 value out of a set of possible attributes (e.g., color ∈ { (0,0,0), …, (255,255,255) }
- State changes are a serious performance killer!

FYI (not relevant for exam)

Costs of state changes in modern OpenGL [2014]



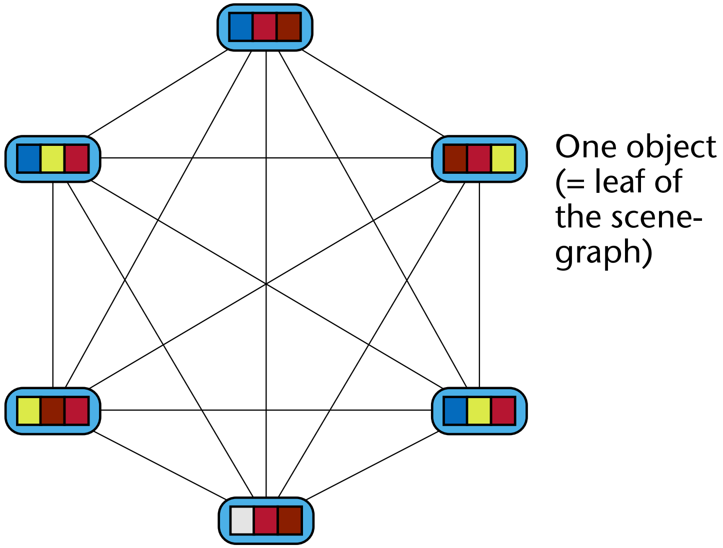
Not to scale!

- Goal: render complete scene graph with *minimal* number of state changes

FYI (not relevant for exam)

Solution: Sorting by State

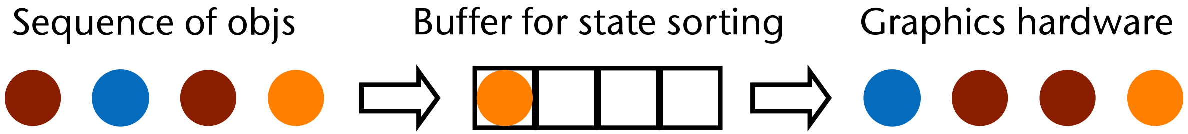
- Problem: optimal solution is NP-complete
- Proof:
    - Each leaf of the scene graph can be regarded as a node in a complete graph
    - Costs of an edge = costs of the corresponding state change (different state changes cost differently, e.g., changing the transform is cheap)
    - Wanted: shortest path through graph
    - ▸ Traveling Salesman Problem
- Further problem: precomputation doesn't work with dynamic scenes and occlusion culling



FYI (not relevant for exam)

Introducing the Sorting Buffer

- For the sake of argument: consider only *one* kind of attribute ("color")
- Introduce a buffer between application and graphics card
    - (Could be integrated into the driver, since an OpenGL command buffer already exists)



- Buffer contains *k* elements
- Perform one of 3 operations with each draw call (= app sends a "colored element" to the hardware/buffer):

1. Pass element directly on to graphics hardware; or,
2. Store element in buffer; or,
3. Extract subset of elements from buffer and send them to graphics hardware

FYI (not relevant for exam)

Interlude: Online Algorithms

- There are 2 categories of algorithms:
  - "Online" algorithms: the algorithm does *not* know which elements will be received in the future!
  - "Offline" algorithms: algo *does* know elements that will be received in the future (for a fair comparison, it still has to implement a buffer, but it *can* utilize its knowledge of the future to decide whether to store elements)
- In the following, we consider only "lazy" online strategies:
  - Extract elements from the buffer only in case of buffer overflow
  - This is wlog., because every non-lazy online strategy can be converted into a lazy one with the same complexity (= costs)
- Question (in our case): which elements should be extracted from the buffer (in case of buffer overflow), so that we achieve the minimal number of color changes?

FYI (not relevant for exam)

Interlude: Competitive Analysis

- Definition *c-competitive* :

  Let $C_{\text{off}}(k)$ = costs of *optimal* offline strategy,

  let $C_{\text{on}}(k)$ = costs of *some* online strategy,

  "cost" = number of color changes, k = buffer size.

  Then, the online strategy is called "*c*-competitive", iff

$$C_{\text{on}}(k) = c \cdot C_{\text{off}}(k) + a$$

  where a must not depend on k (c may depend on k).

  The ratio $\frac{C_{\text{on}}(k)}{C_{\text{off}}(k)} \approx c$ is called the competitive-ratio.

- Wanted: an online strategy with $c = c(k)$ as small as possible (i.e., $c(k)$ should be in a low complexity class)

FYI (not relevant for exam)

Example: LRU strategy (Least-Recently Used)

- The strategy:
  - Maintain a timestamp per color (not per element!)
  - When element gets stored in buffer → timestamp *of its color* is set to current time
    - Notice: this way, timestamps of other elements in buffer can change, too
  - Buffer overflow → extract elements, whose color has oldest timestamp
- The lower bound on the competitive-ratio: $\Omega(\sqrt{k})$
- Proof by example:
  - Set $m = \sqrt{k-1}$, wlog. m is even
  - Choose the input $\left(c_1 \cdots c_m x^k c_1 \cdots c_m y^k\right)^{\frac{m}{2}}$
  - Costs of the online LRU strategy: $(m+1) \cdot 2 \cdot \frac{m}{2}$ color changes
  - Costs of the offline strategy: $2 \cdot \frac{m}{2} + m = 2m$ color changes,

    because its output is $(x^k y^k)^{\frac{m}{2}} c_1^m \cdots c_m^m$

FYI (not relevant for exam)

The Bounded Waste & the Random Choice Strategy

- Idea:
  - Count the number of all elements in the buffer that have the *same* color
  - Extract those elements whose color is most prevalent in the buffer
- Introduce waste counter $W(c)$:
  - With new element on input side: increment $W(c)$, c = color of new element
- Bounded waste strategy:
  - With buffer overflow, extract all elements of color c', whose $W(c')$ = max
- Competitive ratio (w/o proof): $O\left(\log^2 k\right)$
- Random choice strategy:
  - Randomized version of bounded waste strategy
  - Choose uniformly a *random* element in buffer, extract all elements *with same color* (note: most prevalent color in buffer has highest probability)
  - Consequence: more prevalent color gets chosen more often, over time each color gets chosen $W(c)$ times

FYI (not relevant for exam)

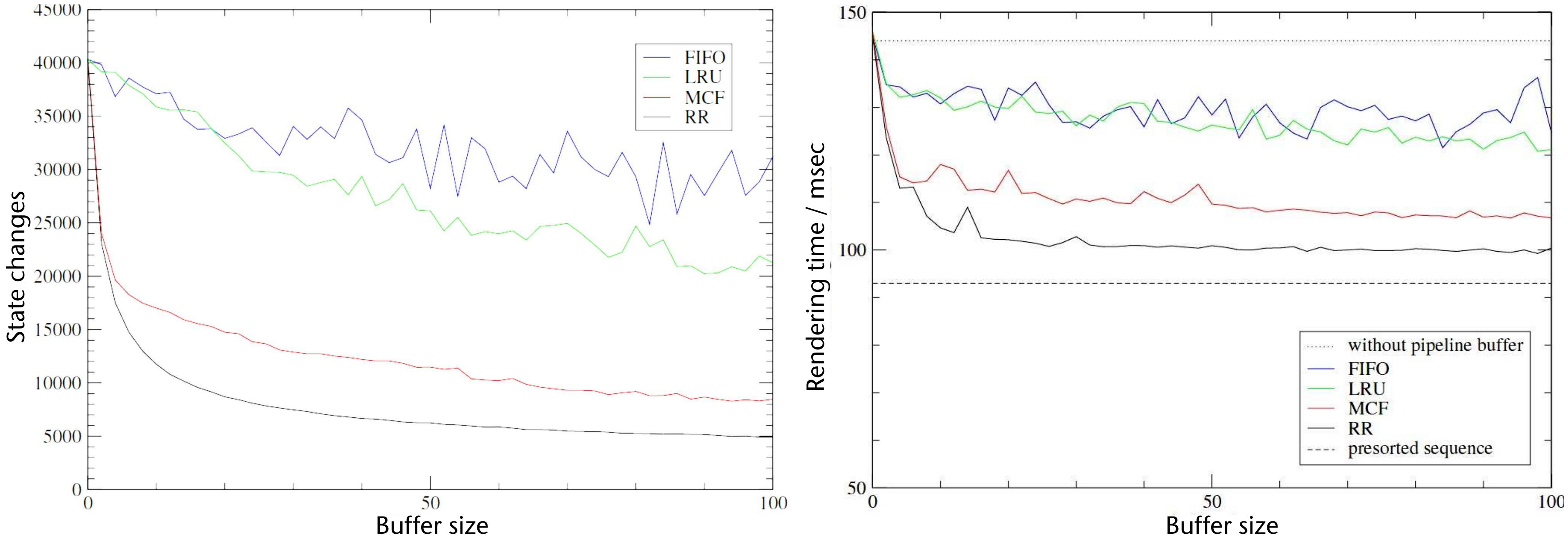
The Round Robin Strategy

- Problem: generation of good random numbers is fairly costly
- Round robin strategy = variant of random choice strategy:
  - Don't choose a random slot in the buffer
  - Instead, every time choose the *next* slot (hence, "round robin")
  - Maintain pointer to current slot, move pointer to next slot every time a slot is chosen

FYI (not relevant for exam)

Comparison

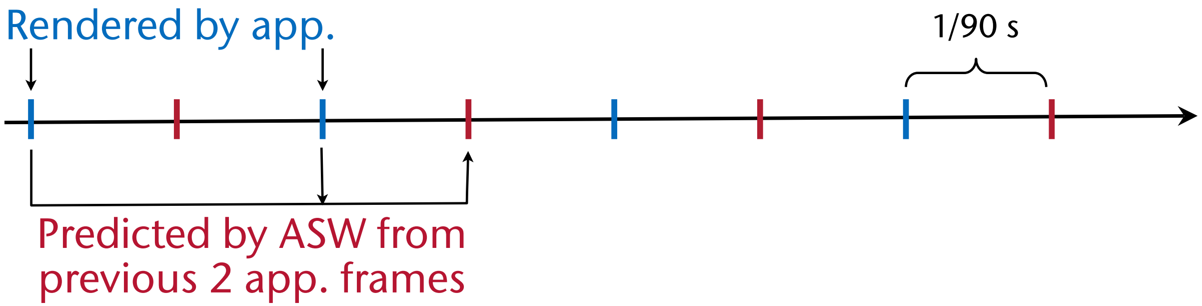
- Take-home message:
  - Round-robin yields very good results (although/and it is very simple)
  - Worst case doesn't say too much about performance in real-world applications

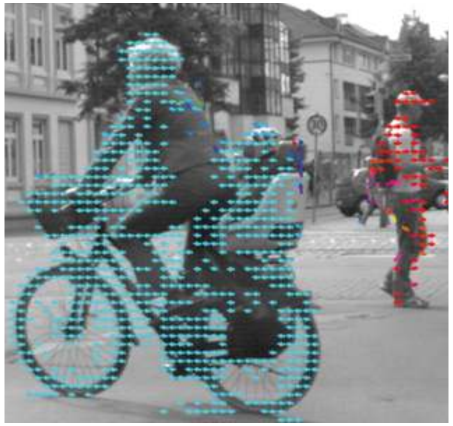


FYI (not relevant for exam)

"Asynchronous Spacewarp" (Oculus)

- Oculus display refreshes at 90 Hz; if application can render only at 45 Hz, ASW produces frames "in between" by prediction:





- Some details about the method (speculative):
  - Extra thread kicks in, if app has not finished rendering in time; stops rendering and graphics pipeline (*GPU preemption*)
  - Take previous two images, try to predict 2D motion of image parts
    - Optical flow algorithms? use GPU video encoding hardware?
  - Fill holes by stretching neighborhood (image inpainting)

FYI (not relevant for exam)

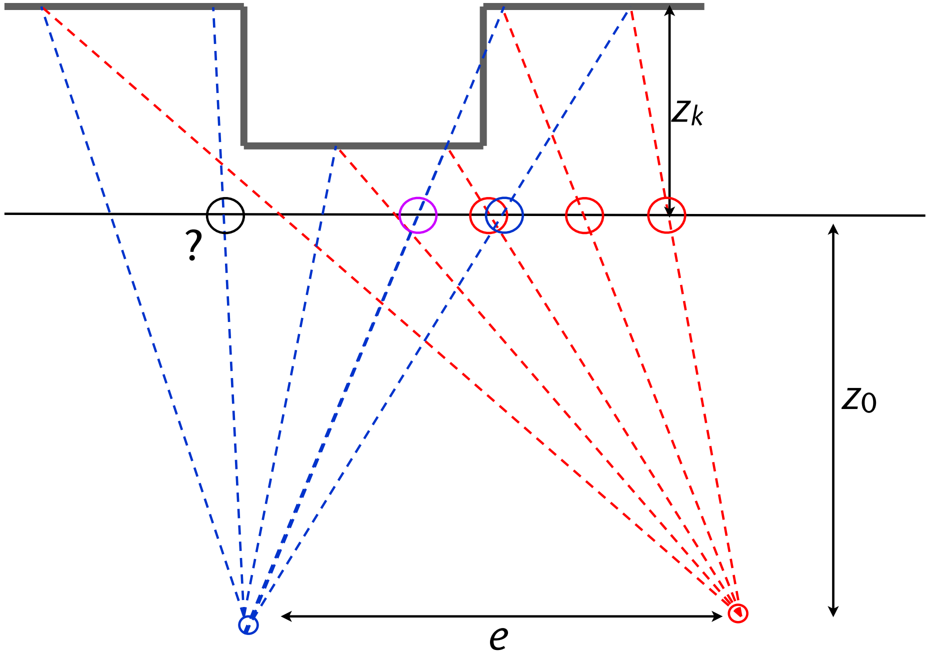
Example Frames (Can You Spot the Artefacts?)

FYI (not relevant for exam)

Stereoscopic Image Warping (Stereo Without 2x Rendering)

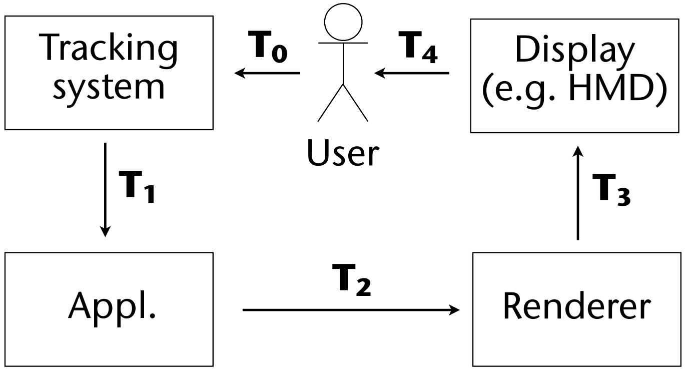
- Observation: left & right image differ not very much
- Idea: render once for right image, then move pixels to corresponding positions in left image → image warping
- Algoritm: consider all pixels on each scanline *from right to left*, draw each pixel *k* at the new x-coordinate $x'_k = x_k + \frac{e}{\Delta}\frac{z_k}{z_k + z_0}$

  where Δ = pixel width
- Problems:
  - Up-vector must be vertical
  - Holes!
  - Ambiguities & aliasing
  - Reflections and specular highlights are at wrong position

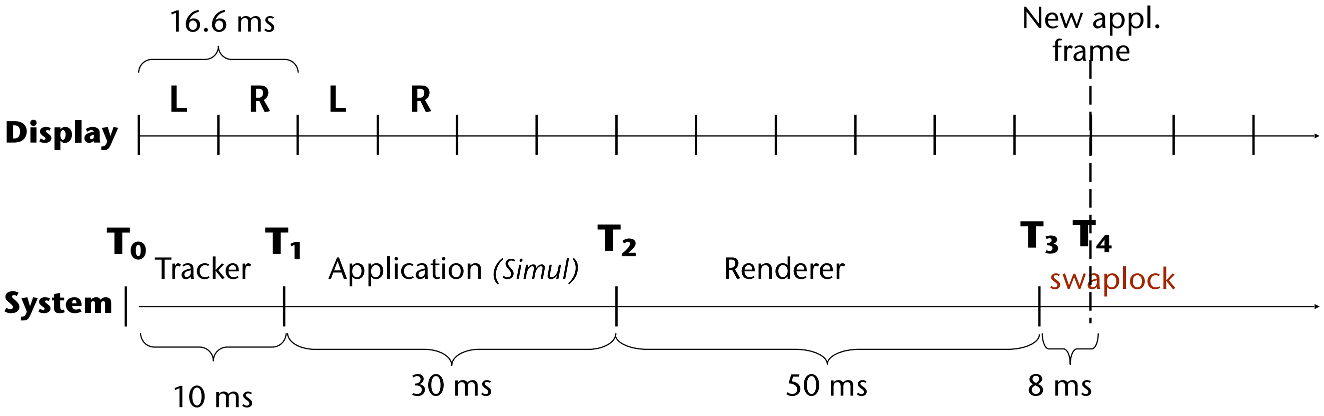


Reducing Latency by 3D Image Warping

- A simple VR system:



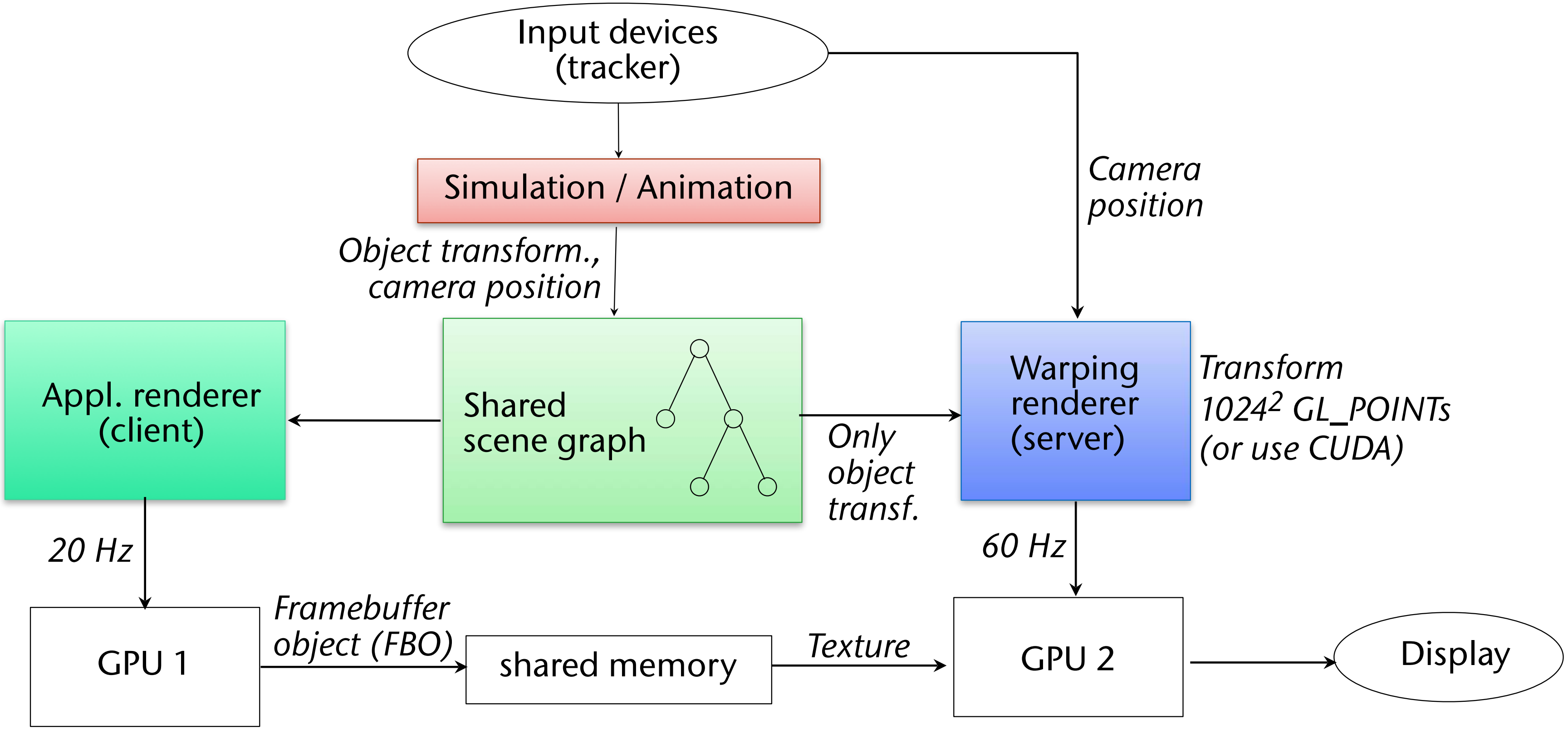
- Latency in this system (stereo with 60 Hz ⟶ display refresh = 120 Hz):



Issues & Observations

- The appl. framerate (incl. rendering) could be much slower than the display refresh rate
- The tracking data, which led to a specific image, were valid some time in the past
- The tracker could deliver data more often
- Consecutive frames differ from each other (most of the time) only relatively little (→ temporal coherence)

Idea: Decouple Simulation/Animation, Rendering, and Tracker Polling



An Application Frame (Client)

- At time t_1, the application renderer generates a normal frame
  - Color buffer and Z-buffer
  - Henceforth called "application frame"
- … but also saves additional information:

1. With each pixel, save ID of object visible at that pixel (e.g., into separate frame buffer object)
2. Save camera transformations at time t_1 : $T_{t_1,cam \leftarrow img}$ and $T_{t_1,wld \leftarrow cam}$
3. With each object i, save its transformation $T^i_{t_1,obj \leftarrow wld}$

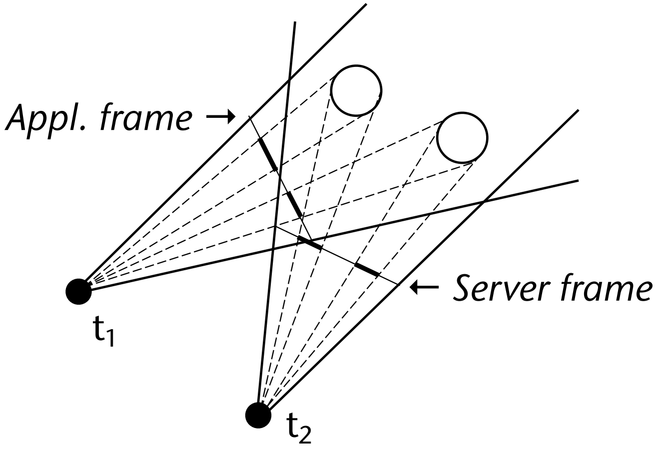
Warping of a Frame (Server)

- At a later time, t_2 , the server generates an image from an application frame by 3D warping
- Transformations known at this time:

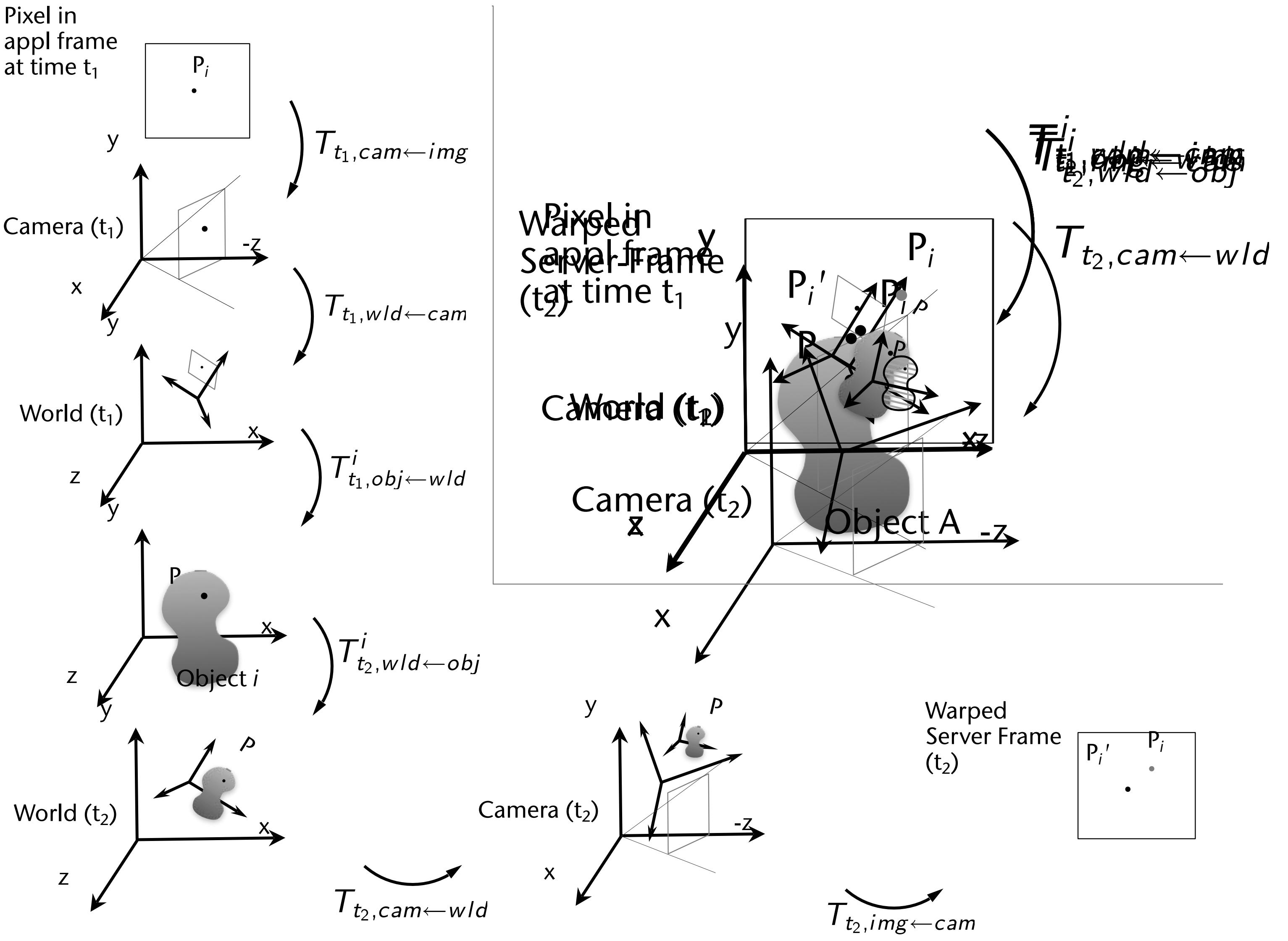
$$T^i_{t_2,wld\leftarrow obj} \qquad T_{t_2,img\leftarrow cam} \qquad T_{t_2,cam\leftarrow wld}$$

- A pixel $P_A = (x, y, z)$ in the application frame will be "warped" (transformed) to its correct position in the (new) server frame:

$$P_S = T_{t_2,img\leftarrow cam} \cdot T_{t_2,cam\leftarrow wld} \cdot T^i_{t_2,wld\leftarrow obj} \cdot \\ T^i_{t_1,obj\leftarrow wld} \cdot T_{t_1,wld\leftarrow cam} \cdot T_{t_1,cam\leftarrow img} \cdot P_A$$



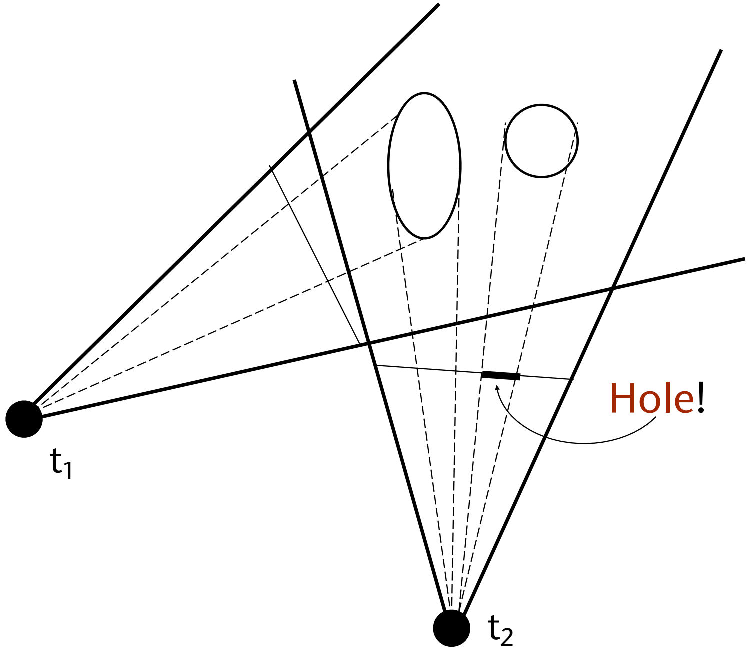
- This transformation matrix can be precomputed for each object and each new server frame


Pixel in
appl frame
at time t_1
P_i
y
$T_{t_1,cam \leftarrow img}$
Camera (t_1)
-z
x
y
$T_{t_1,wld \leftarrow cam}$
World (t_1)
x
z
y
$T^i_{t_1,obj \leftarrow wld}$
P
x
z
y
Object i
$T^i_{t_2,wld \leftarrow obj}$
P
World (t_2)
x
z
$T_{t_2,cam \leftarrow wld}$
y
P
Camera (t_2)
-z
x
Warped
Server Frame
(t_2)
P_i'
P_i
$T_{t_2,img \leftarrow cam}$
$T_{t_2,cam \leftarrow wld}$
P_i
P_i'
Camera (t_2)
Object A
-z
x

Remarks

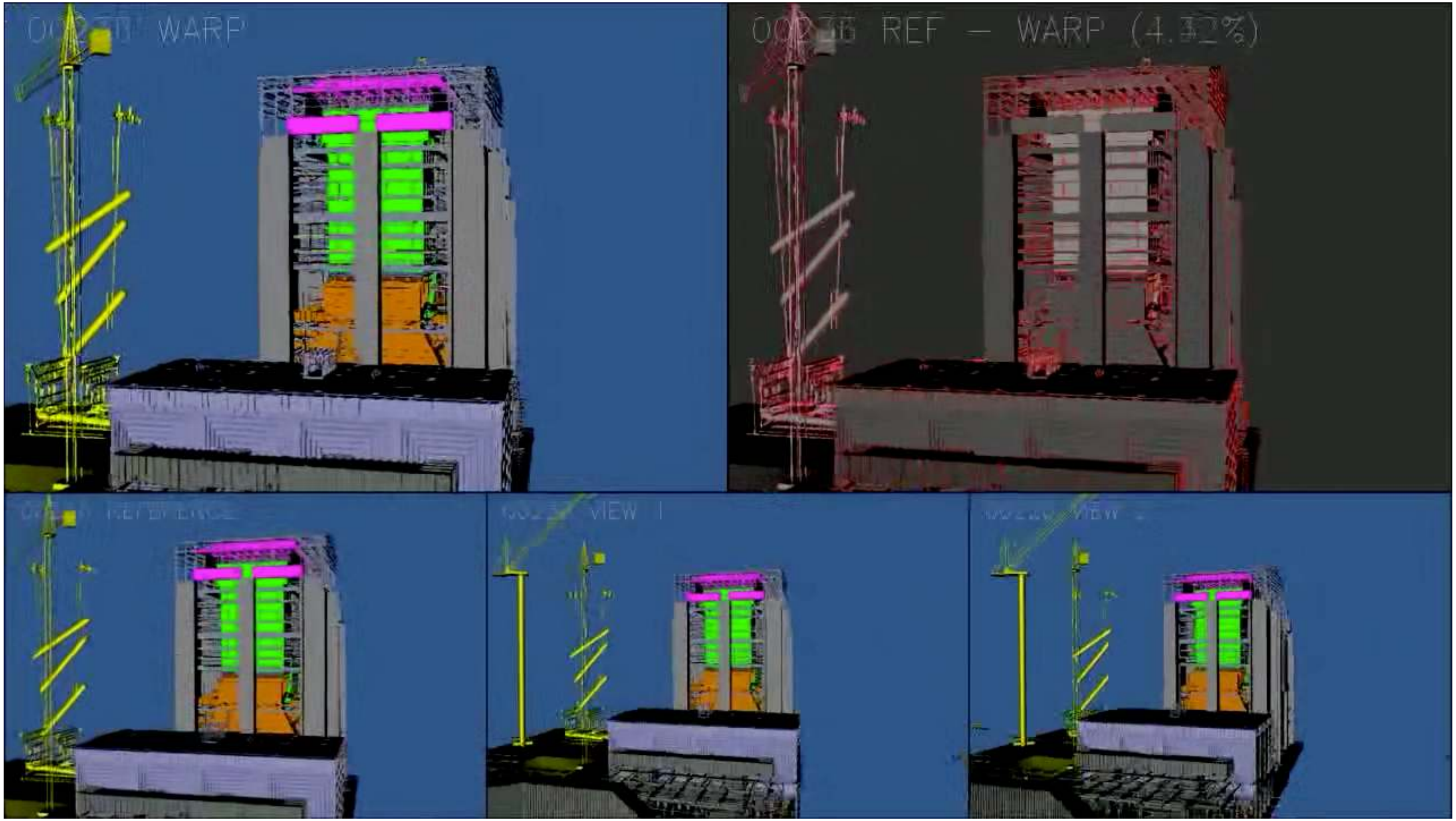
- Implementation of the warping:
  - Could be done in the vertex shader
    - Doesn't work in the fragment shader, because the output (= pixel) position is fixed in fragment shaders!
  - Better do the warping in CUDA, one thread per pixel in the appl frame
- Note: the server (warping) renderer does use current (t_2) positions of animated/simulated objects!
- Advantages:
  - The frames (visible to the user) are now "more current", because of more current camera *and* object positions (i.e., animated objects)
  - Server framerate is independent of number of polygons
  - With additional tricks, re-lighting is possible (to some extent)

Problems



- Holes in server frame
  - Need to fill them, e.g., by ray casting
- Server frames are fuzzy (because of point splats)
- How large should the point splats be?
- The application renderer (full image renderer) can be only so slow (if it's too slow, then server frames contain too many holes)
- Unfilled parts along the border of the server frames
  - Potential remedy: make the viewing frustum for the appl. frames larger
- Performance gain:
  - 12M polygons, 800 x 600 frame size
  - Factor ~20 faster

Videos



WARP
00236 REF — WARP (4.32%)
REFERENCE
VIEW 1
VIEW 2