Virtual worlds feature increasing geometric and shading complexities, resulting in a constant need for effective solutions to avoid rendering objects invisible for the viewer. This observation is particularly true in the context of real-time rendering of highly occluded environments such as urban areas, landscapes or indoor scenes. This problem has been intensively researched in the past decades, resulting in numerous optimizations building upon the well-known Z-buffer technique. Among them, extensions of graphics hardware such as early Z-culling [Morein 2000] efficiently avoid shading most of invisible fragments. However, this technique is not applicable when the fragment shader discards fragments or modifies their depth value, or if alpha testing is enabled [nVidia 2008].

We introduce \textit{Triple Depth culling} for fast and controllable per-pixel visibility at the fragment shading stage using multiple depth buffers. Based on alternate rendering of object batches, our method effectively avoids the shading of hidden fragments in a single pass, hence reducing the overall rendering costs. Our approach provides an effective control on how culling is performed prior to shading, regardless of potential discard or alpha testing operations. \textit{Triple Depth culling} is also complementary with the existing culling stages of graphics hardware, making our method easily integrable as an additional stage of the graphics pipeline.

\section{Triple Depth Culling}

Our algorithm builds upon the Z-Buffer approach, in which a fragment is kept or discarded after shading by testing its depth against the current depth stored in the depth buffer. Early Z-culling performs this elimination beforehand, but involves restrictions on shading operations, or requires a depth-only prepass to populate the depth buffer [nVidia 2008]. Conversely, our method works in a single pass by introducing a depth culling step between the early Z-culling and the shading of fragments (Figure 2).

Starting with a roughly depth-sorted list of objects batches, the first batch is rendered into a classical RGBA buffer $Z_1$ and a depth buffer. For each fragment we store its depth into the alpha channel of $Z_1$ (or an additional render target). Then, upon rendering of a second batch of objects into $Z_2$, each fragment undergoes the following steps: its depth is first compared to the corresponding alpha value in $Z_1$. If the fragment is occluded by the first batch of objects, its output is simply discarded. Otherwise, the fragment is shaded and stored. The remainder of the object batches is then rendered using alternatively $Z_1$ and $Z_2$ as render targets.

Note that as the objects are sorted according to the viewing distance the batches tend to spread over the entire image space, increasing the screen coverage of each batch and hence the efficiency of our method.

An overhead of our method lies in the alternation of render buffers, which tends to generate pipeline stalls. We amortize the cost by adjusting the size of the object batches. This size can be adjusted either manually or automatically using a simple convergence based on the render time of the last frame. While the overhead does not completely vanish, the savings are significant especially in scenes containing many objects.

Our technique allows the shader to determine whether the shading must be carried out, depending on its depth output. The expensive shading is then performed only if the fragment is determined as visible. Note that this visibility determination is approximate: as each of the additional depth buffers holds only a part of the rendered fragments, some fragments may be erroneously considered as visible. While this results in unnecessary computations, this also ensures the conservativeness of our visibility algorithm and does not introduce artifacts as the corresponding fragments eventually get discarded after shading by classical depth testing.

\section{Results}

Our method has been implemented within fragment shaders on an nVidia GeForce GTX480. The presented scenes contains 15K and 50K objects with complex shader operations rendered at a resolution of $1280 \times 720$. Compared to classical Z-buffering, Triple Depth culling provides performance increases of 8 to 50\% using batches of 50 objects, while remaining applicable in any context. We believe further performance could be achieved by implementing our approach in an additional stage in future graphics hardware for programmable fragment elimination, potentially taking advantage of the hierarchical representation of depth buffers.

<table>
<thead>
<tr>
<th>Scene</th>
<th># tri</th>
<th># obj</th>
<th>$Z$ Early</th>
<th>Triple Depth</th>
</tr>
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<tbody>
<tr>
<td>Forest</td>
<td>70M</td>
<td>50K</td>
<td>90 ms</td>
<td>N/A</td>
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<tr>
<td>Asteroids</td>
<td>35M</td>
<td>15K</td>
<td>215 ms</td>
<td>N/A</td>
</tr>
</tbody>
</table>

\section{References}


nVidia. 2008. GPU programming guide version for GeForce 8 and later GPUs.