Half-precision Floating-point Ray Traversal

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Abstract: Ray tracing is a memory-intensive application. This paper presents a new ray traversal algorithm for bounding volume hierarchies. The algorithm reduces the required memory bandwidth and energy usage, but requires extra computations. This is achieved with a new kind of utilization of half-precision floating-point numbers, which are used to store axis aligned bounding boxes in a hierarchical manner. In the traversal the ray origin is moved to the edges of the intersected nodes. Additionally, in order to retain high accuracy for the intersection tests the moved ray origin is converted to the child's hierarchical coordinates, instead of converting the child's bound coordinates into world coordinates. This means that both storage and the ray intersection tests with axis aligned bounding boxes can be done in half-precision. The algorithm has better results with wider vector instructions. The measurements show that on a Mali-T628 GPU the algorithm increases frame rate by 3% and decreases power consumption by 9% when wide vector instructions are used.

1 INTRODUCTION

Ray tracing has been a commonly used method to render off-line images. Due to active research in the field, there are now multiple frameworks which can achieve real-time frame rates on high-end hardware. However, significant progress must be made in the field before ray tracing is fast enough for consumer applications on mobile hardware.

The basic operation in ray tracing is *ray casting*, which finds the closest intersection of a ray with the set of scene primitives. In order to reach high performance in large scenes with many primitives, ray tracers organize the scene using special acceleration data structures. The most popular of these structures is the *Bounding Volume Hierarchy* (BVH). In BVH, primitives are stored in the leaves of the tree, and each node contains the *Axis Aligned Bounding Boxes* (AABB) of its children. During ray casting, entire subtrees are then rapidly eliminated by finding that the ray does not intersect a high-level AABB, without making separate checks against each leaf primitive in the subtree.

Ray tracing is an expensive operation both in terms of computation and memory traffic. In recent years, performance has been improved by leaps and bounds due to the increased parallel resources available in modern computing systems. Therefore, the memory system is often a bottleneck since the scene hierarchy may be more than tens of megabytes in size and is accessed in an almost unpredictable order. There is a large body of research on reducing memory traffic by representing the AABBs in BVHs in a more compact or approximate manner. For instance, in a *Shared-Plane Bounding Volume Hierarchy* (SPBVH) (Ernst and Woop, 2011), a tree node infers some of the AABB coordinates from the parent AABB. In practice this halves the memory footprint of the nodes.

BVH compression techniques are of high interest for mobile systems due to their limited memory bandwidth and low power requirement. Several CPU and GPU vendors have introduced architectural support for a half-precision (16-bit) floating-point format (IEEE, 2008), which poses an interesting opportunity for the compression. Furthermore, current desktop hardware only supports half-floats as a storage format, but this is changing in the near future, as the next-generation of NVidia's GPUs is also scheduled to have half-precision computing support (Huang, 2015).

In this paper, a novel hierarchical half-precision BVH traversal scheme which computes AABB intersection tests natively in half-precision format is proposed. This removes the format conversion overheads which slowed down prior work (Koskela et al., 2015), which exploited half-precision only as a storage format. In the measurements using wide vector instructions the proposed method improves frame rate by an average of 3% and energy efficiency by 9%.

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2 BACKGROUND

Ray tracing is well suited for many ways of parallel computations. Threads can be used, for example, to trace multiple rays in parallel. On the other hand, there are at least two ways in which ray traversal can use vector instructions. First, multiple rays can be traced together in parallel, which is called *packet tracing*. Second, multiple ray-AABB tests can be calculated in parallel. In order to use wider vectors, BVHs with a greater branching factor than two can be used, which is called *Multi Bounding Volume Hierarchy* (MBVH) (Ernst and Greiner, 2008). Usually MBVHs are labelled based on their branching factor in a way that MBVH4 means that the tree has a branching factor of 4 and MBVH8 means that the tree has a branching factor of 8, et cetera. The two ways of using vector instructions can be combined. In that case multiple rays are traced in parallel and all of them test intersections with multiple AABBs.

There have been many proposed algorithms and data structures to reduce the amount of data needed for the ray tracing traversal step. These algorithms can be divided into two categories.

First, some of the child AABB bounds can be inferred from the parent AABB. Because in the BVH the AABBs are tightly bound to their child geometry, all of the parent bounds are used by at least one of the children. Some examples of this are *Bounding Interval Hierarchy* (BIH), which stores only two coordinate values and one axis in each node (Wächter and Keller, 2006) and the SPBVH (Ernst and Woop, 2011). Nevertheless, these ideas are not as good with MBVHs since there are more children, which means that fewer values for each child can be inferred.

3 RELATED WORK

Another approach is to compress data to reduced precision data types, at the cost of decompression during traversal and reduced data quality. Low quality data causes extra work at traversal, as the ray-AABB intersection tests might give false positive hits. Moreover, algorithms must be carefully designed to avoid false negatives in intersection tests, which would cause visible gaps in the scene geometry.

One way to compress the data is to use reduced precision integer formats (Mahovsky and Wyvill, 2006). Most of the hardware commonly used today is capable of doing calculations in different integer precisions. Using integers, the scene is divided into equally sized quantization steps. This is beneficial if the details of the geometry are equally divided around the whole scene.

To avoid too big quantization steps, the data type can be used hierarchically. In this representation the value range of the data type is scaled to the parent node's AABB bounds, so that the smallest possible value of the data type corresponds to the parent's lower bound and the greatest possible value to the upper bound. In a deep tree, even with two integer bits, this kind of hierarchical encoding can achieve more accuracy per coordinate than single-precision floating-point format. This is possible because on every lower level of the tree the quantization steps get smaller in world coordinates. However, this extra precision is not useful since the triangles are usually stored in single-precision format.

The previous work on half-precision floating-point BVHs (Koskela et al., 2015) only considers the use of half-precision floating-point numbers as a storage format. This reduces BVH inner node memory bandwidth and space usage by half, which corresponds to an average of 16% reduction in cache misses and 7% reduction in memory space usage with MBVH4. Their work evaluates both the BVH with world coordinate half-precision floating-point numbers and the hierarchical representation similar to the work on integers (Mahovsky and Wyvill, 2006). The world coordinate half-precision traversal performance is reduced by the extra traversal caused by the false positives and the overhead of format conversion when AABBs are loaded from memory. The hierarchical half-precision BVH avoids most of the false positives, at the cost of extra computational overhead.

Instead of converting the hierarchical AABB bound coordinates into world coordinates, the ray origin can be converted into hierarchical coordinates (Keely, 2014). This allows intersection tests to be computed in a low-precision format, which reduces the required bit counts significantly. Moreover, this is beneficial since fewer coordinates need to be converted to different coordinate base (there are six values in the AABB bounds and only three values in the ray origin). To avoid overflows in the hierarchical coordinates, the ray origin has to be moved to the edge of the coordinate range on every traversal step.

4 PROPOSED ALGORITHM

This paper follows the compression category by using half-precision floating-point numbers. The traversal algorithm used in this paper is based on a similar idea as the (Keely, 2014) algorithm. The difference is that instead of adding custom integer hardware to the GPU, the proposed algorithm uses ex-

```
00 int nodeIndex = indexStack.pop();
01 half3 rayOrigin = rayOriginStack.pop();
02 half scaleSofar = scaleStack.pop();
03 half disSoFar = distanceStack.pop();
04
05 if(nodeIndex is inner node index){
06   // vectorised ray-AABB slab hit tests
07   // for every ray in the packet against
09   // every child node's AABB in parallel
10   foreach hitNode that is hit by any ray
11     in the packet and is closer than
12     closest found triangle{
13
14     indexStack.push(hitNode.index);
15
16    // Move ray origin to edge of hitNode
17    half hitDis = max(hitDistance, 0.0);
18    half3 newRayOrigin = rayOrigin +
19      0.99 * hitDis * rayDirection;
20
21   // Convert to deeper hierarchical coords
22   half3 axisRanges = hitNode.upperBound
23      - hitNode.lowerBound;
24   half range = max(axisRanges.x,
25     axisRanges.y, axisRanges.z);
26   float3 mover = 0.5 *
27     (float3)(hitNode.lowerBound +
28      hitNode.upperBound - range);
29    newRayOrigin = (half3)(VAL_RANGE *
30      (((float3)newRayOrigin - mover) /
31      (float)range) + VAL_MIN);
32    rayOriginStack.push(newRayOrigin);
33
34     // Update distance values
35     half newScale = scaleSoFar *
36       (range / VAL_RANGE);
37     distanceStack.push(disSoFar + hitDis *
38       scaleSoFar);
39     scaleStack.push(newScale);
40   }
41 }else{ // Node is leaf node
42   // ray-Triangle tests
43 }
```

Figure 1: The proposed algorithm in pseudo code. This consists the inner loop of the BVH traversal.

isting half-precision floating-point hardware, therefore, available power savings are more modest. This kind of hardware is currently found especially in mobile platforms. In addition, this paper describes how the hierarchical half-precision format, which was designed so that values are converted to world coordinates prior to intersection testing, is modified so that it better fits calculations in hierarchical coordinates.

On high level the proposed traversal has two new stages. First, the ray origin is moved to the edges of the intersected nodes. Second, in order to retain high accuracy for the intersection tests the moved ray origin is converted to the child's hierarchical coordinates, instead of converting the child's bound coordinates into world coordinates. The main point of these modifications is to keep the values within the range of the half-precision format. This way the ray-AABB tests can be done with native half-precision calculations and the AABBs can be stored in half-precision. Some hardware floating-point units can compute twice as many half-precision values with same latency as single-precision values (Hariharakrishnan et al., 2013). The pseudo code of the proposed algorithm can be found in Figure 1.

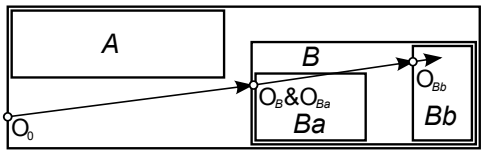


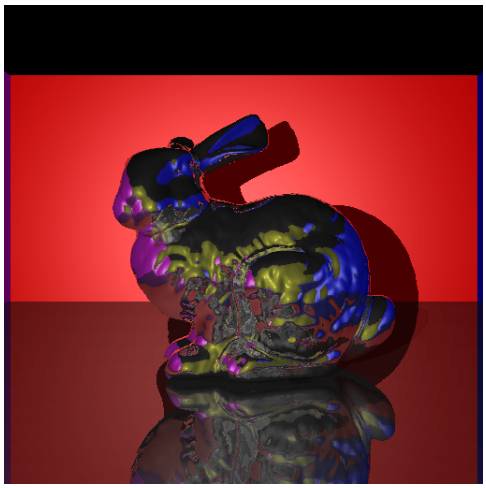
Figure 2: Ray origin movement through the hierarchy. The initial origin is O_0 and because the ray intersects the node B the origin is moved to O_B. In the node B, the ray intersects both nodes Ba and Bb, so the origin is moved to their edges in corresponding branches of the tree traversal.

On lines 00 – 01 the algorithm loads the index of the current node and the current ray origin. The ray origin is already in the same relative coordinate base as the child nodes' AABB bounds, which means that the ray-AABB test can be performed for every child AABB with vector instructions without any extra preparations. In the measurements an unmodified version of the slab method (Smits, 1998) was used for ray-AABB hit tests in half-precision.

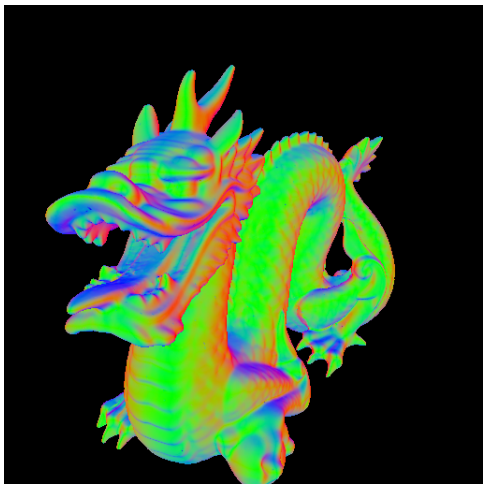
When using the half-precision floating-point format, as small a number as 65520 is rounded up to infinity. In order to prevent values from being rounded up to infinity, the hierarchical storage format was modified to use the interval from `VAL_MIN` (-16384) to `VAL_MAX` (16384), which is one fourth of the maximum non-infinite half-precision interval.

4.1 Ray Origin Movement

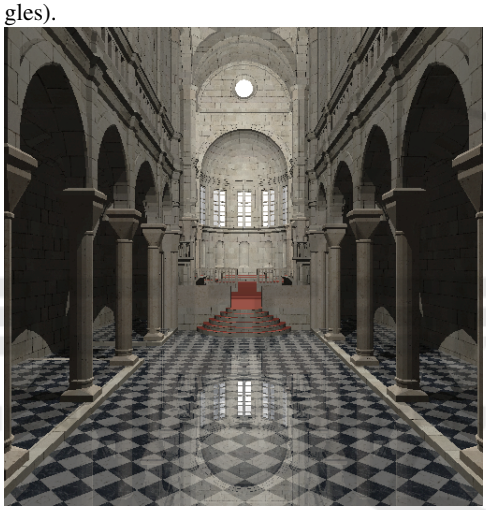
The code after line 10 is executed only for those children which are actually intersected. This part could also be done for all of the children with vector instructions, but in the authors' experiments with MBVH4, a ray hits almost only one AABB in a inner node on average. In this case vectorizing the lines after 10 to all of the child AABBs would cause almost three of the four pieces of data to be trash values. This requires many registers for the trash values. For these reasons there was an improvement when the loop was used to go through the intersected children. Furthermore, if the hardware supports instruction level parallelism, i.e., calculating vector and scalar instructions at the same time, it might be possible to optimize the inner loop so that in the single ray case at least some parts of



(a) Shiny Bunny with one point light (69K triangles).

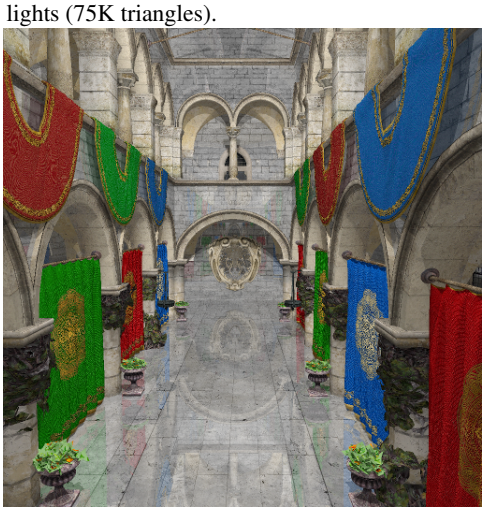


(b) Normals of Dragon, in other words, just ray casting (871K triangles).

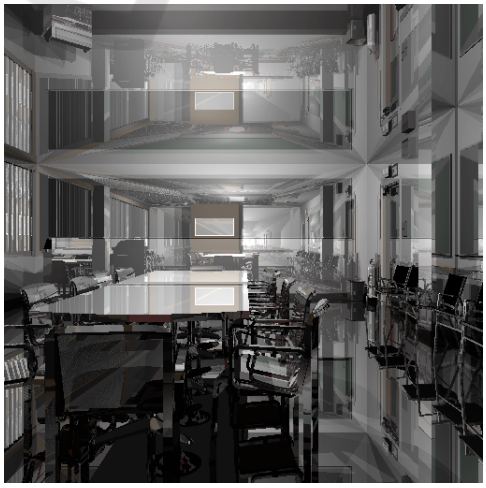


(c) Sibenik with reflecting floor and two point lights (75K triangles).

(d) Fairy with one point light (174K triangles).



(e) Sponza with reflecting stone and metal materials and with two point lights (278K triangles).



(f) Conference with all materials reflecting and with two point lights (331K triangles).

Figure 3: The test scenes used in the measurements.

the ray-AABB tests and coordinate conversions could be calculated simultaneously.

The index of every intersected child is stored in the stack on line 14. Next, the ray origin is moved to the edge of the intersected child AABB on the lines 17 – 19, which can also be seen visualized in Figure 2. The distance to the child AABBs intersection is clamped from the lower end to zero, because negative distances mean that the ray origin is inside the child AABB. In this case the ray origin is not moved, but it is still converted to the child's hierarchical coordinates. The distance is shortened with an epsilon of 0.01, because if the child AABB is planar, i.e., the size is 0 on some axis, moving the ray origin inside of it causes false negatives. This was one working epsilon value found by testing different values. Since the algorithm avoids infinities by using one fourth of the total half-precision range, the value of the epsilon is not important. If the BVH tree is unbalanced and contains child AABBs which are extremely small compared to their parents, the epsilon value starts to have an effect.

4.2 Coordinate Conversion

The coordinate conversion to the new ray origin is shown on lines 22 – 32. This conversion changes the coordinates into a deeper level of hierarchical coordinates. The idea of the conversion is first to convert the new ray origin values so that the coordinates of the intersected child nodes lower bounds are represented by 0.0 and the coordinates of the upper bounds are represented by 1.0. Then this value is multiplied with the total used range `VAL_RANGE = VAL_MAX - VAL_MIN`, which makes it a value from 0 to 32768. Then the interval is moved with `VAL_MIN` to be from -16384 to 16384, which was the desired interval.

A slightly different algorithm than in the previous work was used, because usually the whole range of the data type is used on every axis. This means that going deeper into the hierarchy scales different axes at different rates. Without correction, this would bend the rays. More importantly, correcting the direction would require more computations and one more stack to store the corrected ray directions. The issue was solved by scaling all of the axes with just one value `range`. The largest range of all of the axes was used for the scaling. An example is provided in Figure 4.

In the previous work the variable `mover` was just set to `VAL_MIN`, but since in this work only one range was used on all of the axes, a more complicated `mover` was needed. The idea is to move the interval of the child node into the center of the half-precision total range. If conventional `VAL_MIN` was used as

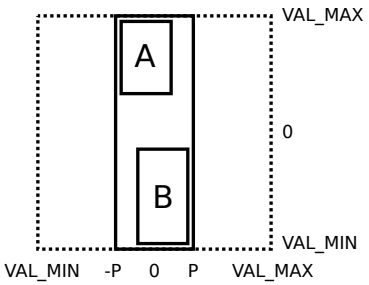


Figure 4: In contrast to conventional hierarchical BVH storage the proposed approach scales every axis on the largest range. In the previous work x-axis value `VAL_MAX` would have been in location P and value `VAL_MIN` in -P. This reduces the need for ray direction correction but loses precision.

`mover`, the value interval would have started from the `VAL_MIN` and the algorithm would have suffered from the poor precision of the floating-point format with values far from zero. In Figure 4, this would have meant that the bounding box had been on the left side of the dashed square, not in the center.

Single-precision data types were used for the coordinate conversion, since half-precision was causing errors for small triangles. This part was vectorized only for the rays in the packet, not for the child nodes. The child nodes were handled by looping through the actually intersected ones. This means that even with the wider data type these lines do not require wider vector units and the performance impact was only the type conversions and the extra register space requirement. This impact was so small compared to memory bandwidth savings that it was unmeasurable.

4.3 Maintaining the Traversed Distance

Finally in the lines 35 – 39 the distance that has been traversed is maintained. This distance in world coordinates is required because the traversal can terminate as soon as it has found a triangle intersection and all of the AABBs in the stack are further away than it. In the lines 02 – 03 the distance values are popped from the stacks. The world coordinate distance from the current moved ray origin to the found AABB can be calculated by multiplying the distance to the AABB, which is in the hierarchical coordinates, with the value popped from the scale stack. The value popped from the distance stack is the distance before intersecting current node. The sum of the distance before intersecting current node and the scaled distance to the intersected AABB equals the total world coordinate traversal distance to the AABB. This value is needed on line 10 to determine if the AABB is further than closest found triangle.

Table 1: Frame rates [frames per second] (more is better). The values are compared to single-precision and all results that improve on it are bolded. Other measured algorithms were the proposed algorithm and storing the values in half-precision and converting them to single-precision before computation.

Model	Algorithm	BVH	MBVH4	MBVH8	MBVH4 2 rays	MBVH4 4 rays
Bunny	single	2.22	2.13	1.67	1.74	1.38
	half storage	-5.9%	-3.2%	**0%**	-4.0%	-2.9%
	proposed	-30%	-23%	-11%	-19%	**0%**
Dragon	single	2.80	2.60	1.93	2.17	1.66
	half storage	-3.6%	-3.8%	**2.0%**	**3.7%**	**0%**
	proposed	-19%	-12%	-1.0%	-8.8%	**3.0%**
Sibenik	single	0.933	0.934	0.685	0.804	0.716
	half storage	-4.4%	**0.4%**	**0.3%**	-4.3%	-4.2%
	proposed	-13%	-4.6%	-6.9%	-5.5%	**8.5%**
Fairy	single	1.43	1.43	1.04	1.28	1.03
	half storage	-2.8%	-0.7%	**2.9%**	-2.3%	-1.9%
	proposed	-26%	-18%	-10%	-19%	**1.0%**
Sponza	single	0.445	0.448	0.327	0.372	0.298
	half storage	-4.0%	**0.2%**	**2.1%**	-4.6%	-3.7%
	proposed	-23%	-15%	-5.2%	-12%	**12%**
Conference	single	0.613	0.614	0.500	0.529	0.463
	half storage	-8.2%	-6.2%	-3.4%	-9.1%	-10%
	proposed	-27%	-21%	-13%	-20%	-9.7%

5 TEST SETUP

For the measurements a ray tracer was implemented using OpenCL. OpenCL was chosen because it has the *cl_khr_fp16* extension, which provides support for native half-precision calculations. The tests were run on the ODROID XU3 board's Mali-T628 GPU because it supports most of the features of this extension. The board also has built-in sensors for power readings, which were used for the measurements.

During the measurements, the software traced rays for as long as it took for the variations in the frame rates to settle. Then, 10 frames of frame rate and power usage was recorded. The reported numbers are averages of these numbers. The frame rate did not improve after the first frames, which indicates that the scenes were so massive that they overfilled the small caches of the Mali.

The images of different test setups can be seen in Figure 3. The ray tracer used Whitted style ray tracing (Whitted, 1979). In the scenes with reflections, two bounces were allowed. In the scenes with lighting, every regular ray sent one shadow ray to each point light if the result was not already known from the normal of the surface. Explicit vector instructions were used to test all child nodes simultaneously in BVH, MBVH4 and MBVH8. MBVH16 measurements were not included, because it was already hard to fill all branches of the tree in a MBVH8. Therefore, MBVH16 measurements would not have been representative.

To achieve wider vector instructions packet tracing was also used, yet it is not good for performance with incoherent secondary rays (Wald et al., 2008). Because the packet size is the same with all of the compared methods, all of them should have the same performance drawback. With packet tracing MBVH4 was used, since the implemented *Surface Area Heuristic* (SAH) (MacDonald and Booth, 1990) tree builder was best suited for building MBVH4 trees. The rays were assigned to packets based on their screen space coordinates. With 4 rays testing hits against 4 AABBs ray-AABB tests were done with 16 elements wide vector instructions, which is the widest vector width supported by the OpenCL framework.

6 RESULTS

The measured frames per second can be found in Table 1 and the measured power usage can be found in Table 2. Both of the measurements show similar results. The wider the vector instruction used in the calculations, the better the proposed algorithm is.

With narrow vector instructions such as BVH with one ray (which stores only two elements in a vector) the proposed algorithm performs much worse than regular single-precision traversal. This is because the little benefit from the smaller AABB memory footprint is hidden by the use of extra stacks and the computation overhead from the coordinate conversions.

Table 2: Power readings [W] from GPU and memory, which is shared with the CPU (less is better). The values are compared to single-precision by dividing the values with the corresponding frame rate. This means that the results are comparable in terms of actual work performed by the ray tracer. All results that improve on single-precision are bolded. Other measured algorithms were the proposed algorithm and storing the values in half-precision and converting them to single-precision before computation.

Model	Algorithm	BVH	MBVH4	MBVH8	MBVH4 2 rays	MBVH4 4 rays
Bunny	single	1.22	1.26	1.44	1.46	1.61
	half storage	8.9%	4.7%	**-5.9%**	4.8%	10.8%
	proposed	46%	27%	4.6%	26%	**-0.6%**
Dragon	single	0.98	1.12	1.41	1.40	1.58
	half storage	4.6%	**-3.3%**	**-10%**	**-6.4%**	5.2%
	proposed	47%	18%	**-7.3%**	7.1%	**-8.0%**
Sibenik	single	1.32	1.35	1.51	1.62	1.80
	half storage	9.0%	**-0.1%**	1.6%	3.5%	10%
	proposed	24%	9.5%	**-0.3%**	7.0%	**-12%**
Fairy	single	1.32	1.32	1.53	1.65	1.81
	half storage	**-0.2%**	**-2.1%**	**-4.5%**	0.5%	3.7%
	proposed	36%	23%	4.0%	20%	**-11%**
Sponza	single	1.32	1.29	1.58	1.72	2.01
	half storage	2.8%	3.6%	**-3.3%**	5.3%	**-0.1%**
	proposed	44%	29%	5.1%	17%	**-17%**
Conference	single	1.05	1.13	1.35	1.39	1.65
	half storage	19%	0.3%	**-3.8%**	5.4%	10%
	proposed	58%	30%	8.1%	21%	**-5.9%**

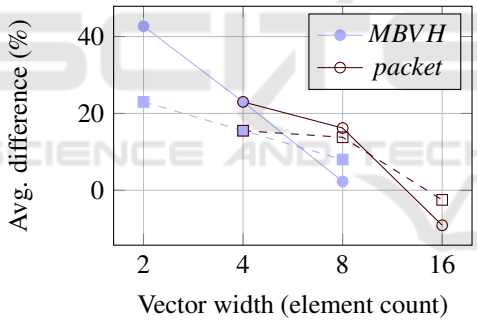


Figure 5: The average difference of the proposed algorithm for regular single-precision traversal (less is better). Circles and solid lines are power usage. Squares and dashed lines are computation time. This shows a clear trend that the wider the vector instructions used the better the performance is with the proposed algorithm.

In addition to actual coordinate calculations, the data for the conversion needs to be parsed from the stored BVH. Each AABB bound coordinate for every child node was stored in one vector, which makes the ray-AABB intersection test faster. However, the proposed algorithm needs to fetch one value for every intersected child node from all of the six bound vectors.

With 16-element-wide vector instructions, the proposed algorithm starts to outperform its counterpart single-precision algorithm. These wide instructions were only run with the packet tracing, but the Figure 5 shows a similar trend without packets. This means that if a ray tracer successfully utilizes wide vector instructions and the targeted hardware has support for native half-precision computations the proposed algorithm should be faster. Of course the limit of 16 elements might be lower or higher on other platforms depending on the vector computation hardware and the structure of the whole memory hierarchy.

The proposed algorithm's worse performance in the *Conference* scene is likely explained by the poor precision in the edges of the scene on the first levels of the BVH. Poor precision leads to many extra rays continuing traversal to the branches where the computationally heavy parts like the curtains and the chairs are stored. This only adds extra work to BVH traversal for finding out that a ray is not actually intersecting any primitives in an area of the scene. In the similar test set-up of the *Sponza* scene the curtains are located closer to the origin of the scene where there is more precision. Furthermore, computationally expensive parts have reflections in the *Conference* scene, which makes both the incoming rays and the outgoing rays heavier to compute than in single-precision.

Comparing the half-precision storage and single-precision methods shows they perform at a similar level. There is no clear pattern visible for which results half-precision storage outperforms single-precision. In contrast, the proposed method is better when using widest vectors and also has far greater differences compared to single-precision. This is be-

cause the SAH tree construction has to make very different trees with far fewer quantization points provided by the non-hierarchical format. On the other hand, the proposed algorithm has even more precision in the lower levels of the tree than single-precision so it builds similar trees.

7 CONCLUSIONS

This paper describes a new kind of ray traversal for BVHs, which utilizes half-precision floating-point computations. The traversal is done by moving the ray origin to the edge of the intersected child AABB and then converting the coordinates of the ray origin into the hierarchical coordinates of the child AABB. This way the traversal stays in a more suitable range for the lower precision format. In addition, the hierarchical half-precision coordinates can provide even more accuracy than single-precision world coordinates. This is possible since on every lower level the quantization step in world coordinates gets smaller.

The proposed algorithm works better than single-precision with wider vector instructions. This means that if a ray tracing application is fastest with wide vector instructions then changing to the proposed traversal should make it even faster. This requires that the hardware is capable of calculating twice the amount of half-precision values with same latency as single-precision calculations, which is quite common with the hardware that supports native half-precision calculations.

In the future, the authors are interested in extending the use of half-precision floating-point numbers to the rest of the ray tracing algorithm. Another potential future work is to optimize the proposed algorithm for possible desktop GPUs with support for native half-precision calculations.

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REFERENCES

Ernst, M. and Greiner, G. (2008). Multi bounding volume hierarchies. In *Proceedings of the IEEE Symposium on Interactive Ray Tracing*, pages 35–40.

Ernst, M. and Woop, S. (2011). Ray tracing with shared-plane bounding volume hierarchies. *Journal of Graphics, GPU, and Game Tools*, 15(3):141–151.

Hariharakrishnan, K., Barbier, A., and Hedley, F. (2013). *OpenCL on Mali FAQs*. ARM.

Huang, J.-H. (2015). Leaps in visual computing. In *Opening Keynote of GPU Techonology Conference* Available at: http://on-demand.gputechconf.com/gtc/2015/presentation/S5715-Keynote-Jen-Hsun-Huang.pdf (Referenced: 9/18/2015).

IEEE (2008). Standard for floating-point arithmetic. Std 754-2008.

Keely, S. (2014). Reduced precision for hardware ray tracing in GPUs. In *Proceedings of the High Performance Graphics Conference*, pages 29–40.

Koskela, M., Viitanen, T., Jääskelainen, P., Takala, J., and Cameron, K. (2015). Using half-precision floating-point numbers for storing bounding volume hierarchies. In *Proceedings of the 32nd Computer Graphics International Conference*.

MacDonald, J. and Booth, K. (1990). Heuristics for ray tracing using space subdivision. *The Visual Computer*, 6(3):153–166.

Mahovsky, J. and Wyvill, B. (2006). Memory-conserving bounding volume hierarchies with coherent raytracing. *Computer Graphics Forum*, 25(2):173–182.

Smits, B. (1998). Efficiency issues for ray tracing. *Journal of Graphics Tools*, 3(2):1–14.

Wächter, C. and Keller, A. (2006). Instant ray tracing: The bounding interval hierarchy. In *EuroGraphics Symposium on Rendering Techniques*, pages 139–149.

Wald, I., Benthin, C., and Boulos, S. (2008). Getting rid of packets – efficient SIMD single-ray traversal using multi-branching BVHs. In *Proceedings of the IEEE Symposium on Interactive Ray Tracing*, pages 49–57.

Whitted, T. (1979). An improved illumination model for shaded display. *ACM SIGGRAPH Computer Graphics*, 13:343–349.