Improving the World's Slowest Raytracer

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Contents

Raytracing: A Quick Recap

Acceleration Structures

- Opaque from the app's POV
- Contains scene geometry in format understood by ray accelerator HW
- Built by the driver, app provides "primitive soup"
- Three primitive types: Triangles, AABBs and instances of other BVHs
  - With AABB primitives, a shader can execute custom code to determine if a ray hits the surface
  - Vulkan defines two levels of acceleration structures: Top-Level and Bottom-Level
    - TLAS can only have BLAS instances as primitives
    - BLAS can only have triangles or AABBs as primitives

Raytracing Pipelines

- Special type of pipeline for performing raytracing
- New shader stages: Ray Generation, Any Hit, Intersection, Closest Hit, Miss, Callable

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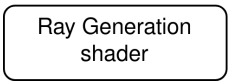

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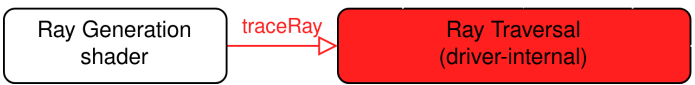

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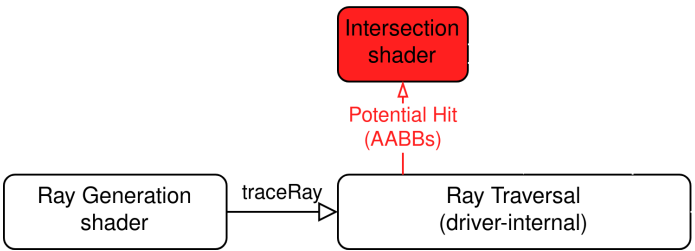

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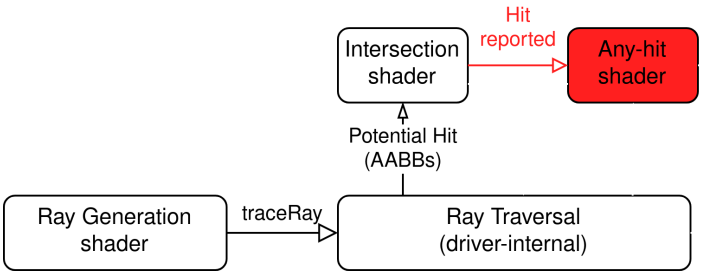

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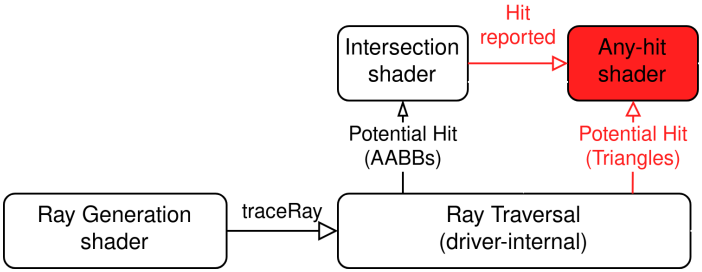

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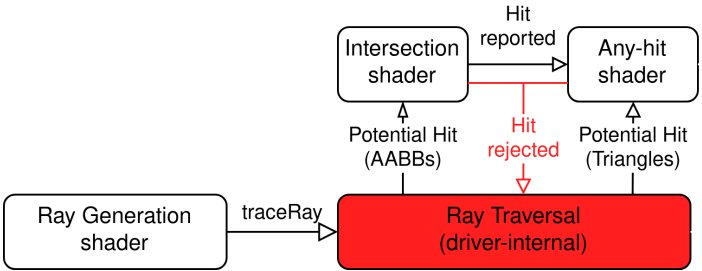

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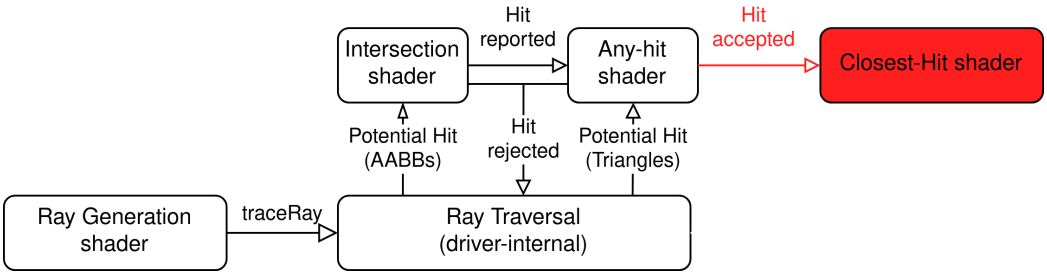

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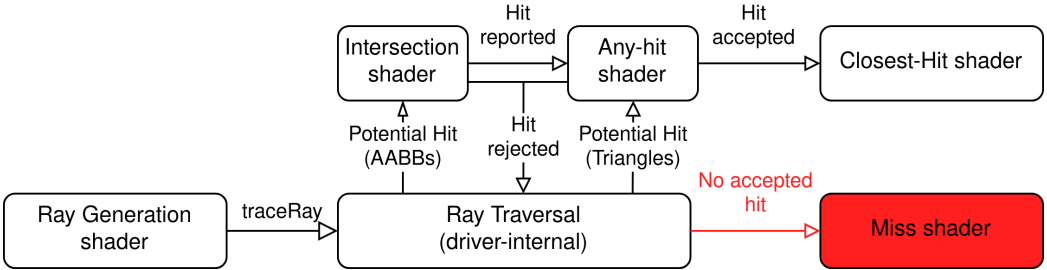

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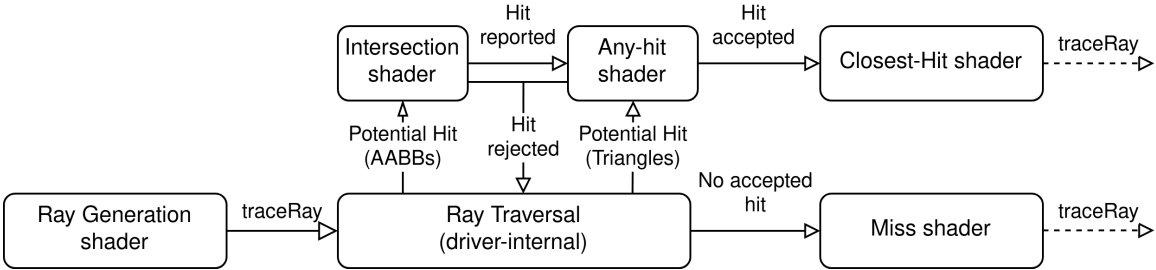

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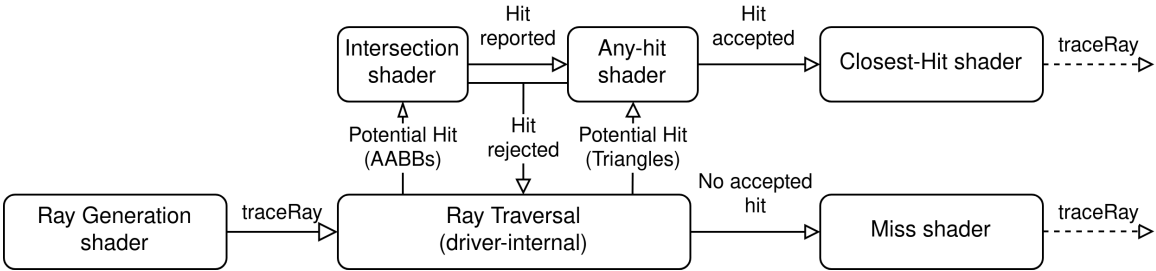

- Callable shaders can be called from RGen/CHit/Miss(/Callable)

Other RT Pipeline concepts

- Shader Binding Tables (SBTs)
  - More than one shader for each stage!
  - App tells the driver which shader to call with a Shader Binding Table
  - Jump Table on the GPU
- Pipeline Libraries
  - Incomplete pipelines that can be linked with other pipelines
  - Useful for e.g. moving commonly-used shaders into common library
    - Pipelines using these shaders only need to link to the previously-created library

Implementing Acceleration Structures

Acceleration Structure Building

- RADV implements acceleration structures as BVHs
  - Tree of AABBs and triangles
  - Internal nodes are AABBs, each leaf node represents a primitive
  - A node's AABB is the AABB of its child nodes
- Hardware format is BVH4
  - Each internal node can have up to 4 child nodes

Node ID packing:

- Node offset in BVH / 8
- 3 LSBs used for node type

```
struct radv_bvh_box32_node {
   uint32_t children[4];
   radv_aabb coords[4];
   uint32_t reserved[4];
};
```

```
struct radv_bvh_triangle_node {
   float coords[3][3];
   uint32_t reserved[3];
   uint32_t triangle_id;
   /* flags in upper 4 bits */
   uint32_t geometry_id_and_flags;
   uint32_t reserved2;
   uint32_t id;
};
```

Acceleration Structure Building

- Building acceleration structures is a multi-step process
  1. Convert input primitives to leaf nodes
  2. Sort nodes
  3. Construct binary BVH
  4. Convert binary BVH to BVH4
- Need barriers in between each step!
  - Bad for building many tiny acceleration structures
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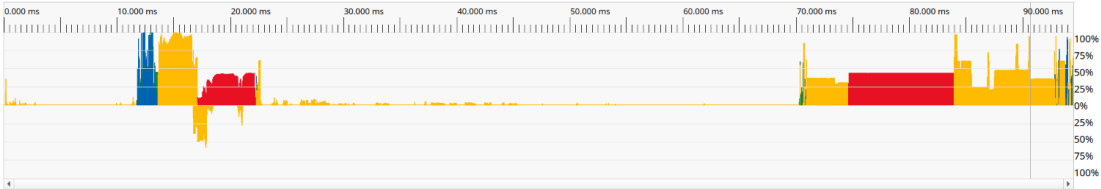
- This is what happens when you don’t batch:



BVH Building Algorithms

Linear BVH

- Algorithm from 2014
- Builds a radix tree from generated morton codes
- Tree can be built up independently for each node
  - Great for parallelization!
- Used for quick builds

Parallel Locally-Ordered Clustering

- Algorithm from 2017
- Better quality than LBVH, though slower
- Original reference implementation was written in CUDA
- Heavily relies on device-wide synchronization
  - No global synchronization primitives available
  - Have to make our own!

The Poor Man’s Global Synchronization

- All build shaders are written in Vulkan GLSL
- Compiler and target hardware is known
- Can assume more guarantees in certain aspects
  - Forward Progress
  - Launch ordering
- Work Stealing Queue
  - Each task receives a unique ID
  - Runtime-defined number of tasks to launch before synchronizing

Launching new tasks:

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Launching new tasks:

```
taskID = atomicAdd(taskStartedCounter, 1);
```

The Poor Man's Global Synchronization

Making sure previous work has finished:

- Maintain a "tasks finished" counter and increment it when finished
- If the new work ID is larger than the maximum task ID to launch before synchronizing, busy-wait until the maximum task ID is updated
- The last task to finish updates the maximum task ID

```
finishID = atomicAdd(taskFinishCounter, 1);
if (finishID == maxTaskID) {
  atomicAdd(maxTaskID, nextNumberOfTasks);
} else {
  while (taskID > maxTaskID) {}
}
```

Implementing Raytracing Pipelines

Hardware Acceleration Features on AMD

- Instruction for hardware-accelerated ray-BVH intersection: `image_bvh_intersect_ray`
  - Calculates intersection results for a single BVH node
  - Returns child nodes sorted by intersection distance for internal AABB nodes
  - Returns intersection results (incl. barycentrics for triangles) for leaf nodes
  - New in RDNA3: Ray flag handling and more box sorting modes
- New in RDNA3: Instruction for LDS traversal stack: `ds_bvh_stack_rtn`
  - Optimization for stack handling
  - Not used in RADV (yet)

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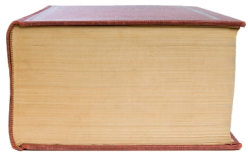
- All the rest: Implemented in software



Raytracing Pipelines

Raytracing Pipelines: The Hardware-Accelerated Part

Layout of a Raytracing pipeline - XDC 2022

- Inline all raytracing shaders into a single compute shader
- Shaders are referred to by IDs
- Wrapped in a loop that continues executing shaders unless exit is requested

```
void main() {
  uint32_t shader_id = raygen_sbt[0];
  while (shader_id != 0) {
    switch (shader_id) {
      // paste all shader code in here
    }
  }
}
```

Layout of a Raytracing pipeline - XDC 2022

Problem: Raytracing pipelines can get **big** (2000+ shaders)

- Size of shaders caused stack overflows during passes that operated recursively on blocks
- Does not work well with pipeline libraries - have to copy shader code around and defer actual compilation

Layout of a Raytracing pipeline - XDC 2023

“Monolithic” mode:

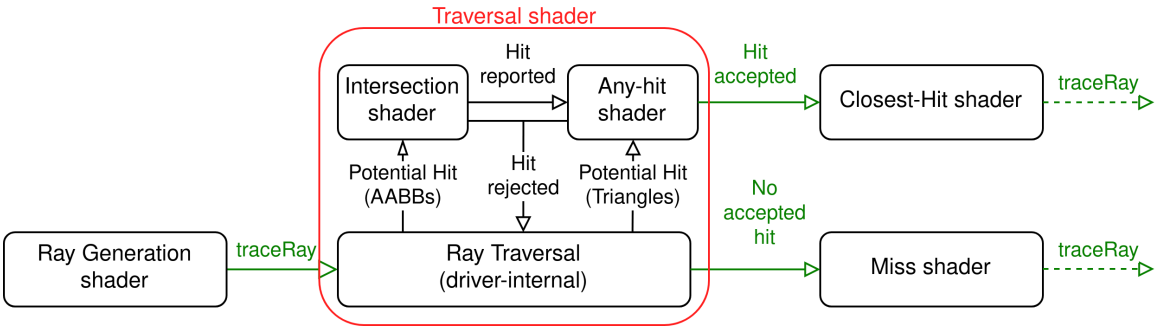
- All shaders are fully inlined
- No shader call overhead, potential for constant propagation
- No recursion, no support for pipeline libraries

```
void traceRay() // always inlined {
  // paste traversal shader
  if (hit)
    // paste closest-hit shader;
  else
    // paste miss shader
}
void main() {
  // paste raygen shader
}
```

Layout of a Raytracing pipeline - XDC 2023

"Separate Compilation" mode:

- "True" shader calls - actual indirect jump
- Allows shaders from pipeline libraries to be compiled ahead of time



Layout of a Traversal Shader

```
void main() {
  while (!traversal_complete) {
    uint32_t node_pointer = get_next_node();
    intersection_result result = image_bvh_intersect_ray(node_pointer);
    if (result.hit) {
      // paste any-hit/intersection shaders here
      if (!hit_accepted)
        continue;
    }
  }
  if (hit)
    call_closest_hit();
  else
    call_miss();
}
```

Why not separately-compile the traversal shader?

- Ray Traversal has lots of live state
- Any-Hit/Intersection shaders are relatively small yet called often
- High shader call overhead, negatively impacts performance

Implementing “True” Shader Calls

- Jump execution to arbitrary addresses stored in SBT
- Each invocation in a wavefront may have a different address
- Only one program counter per wavefront
- Naive solution: Choose program counter of first valid invocation
- Guard shader invocations to prevent invocations from executing wrong shaders
- Problem: Reconvergent shader calls become inefficient!

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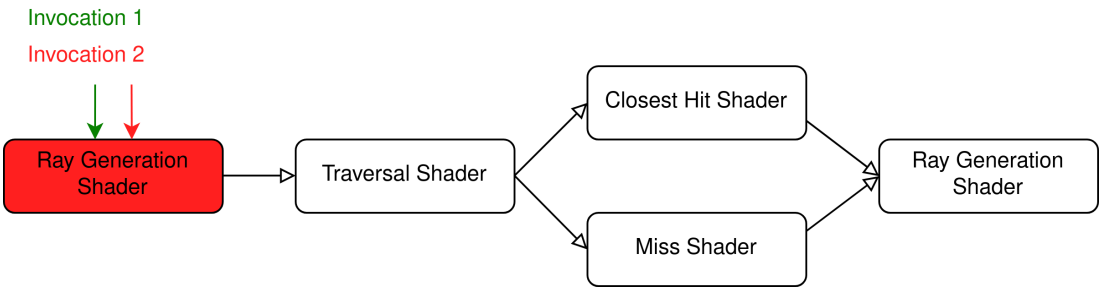

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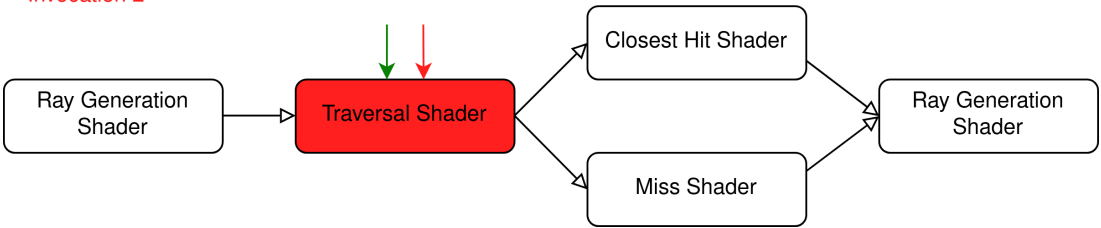

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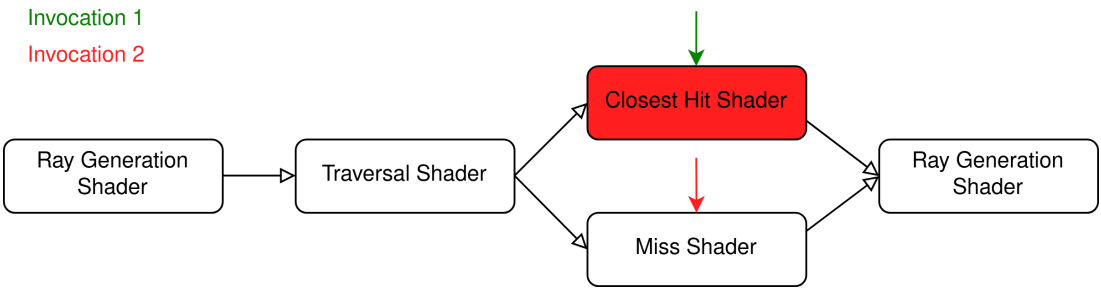

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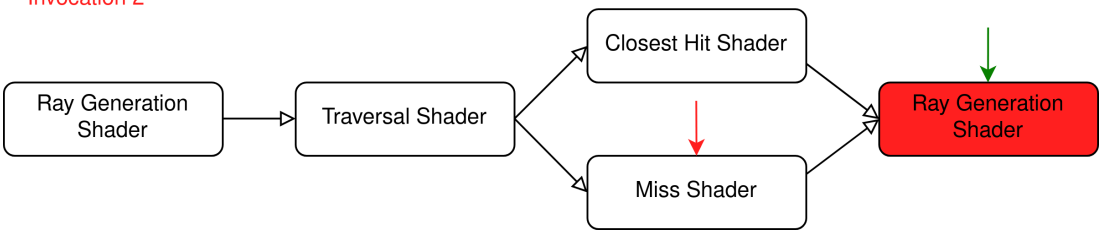

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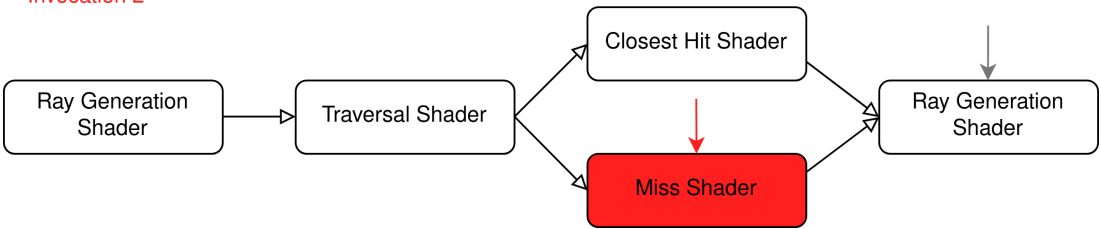

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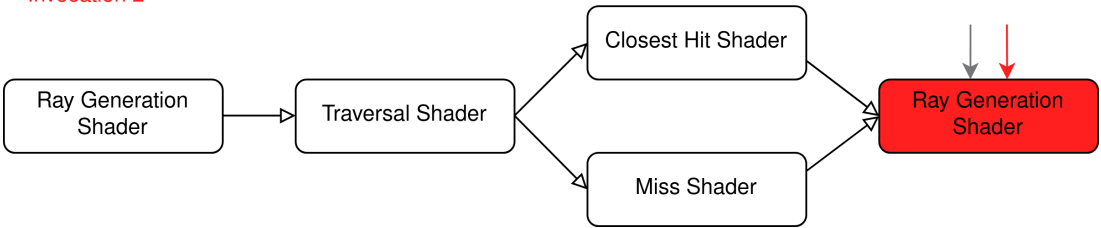

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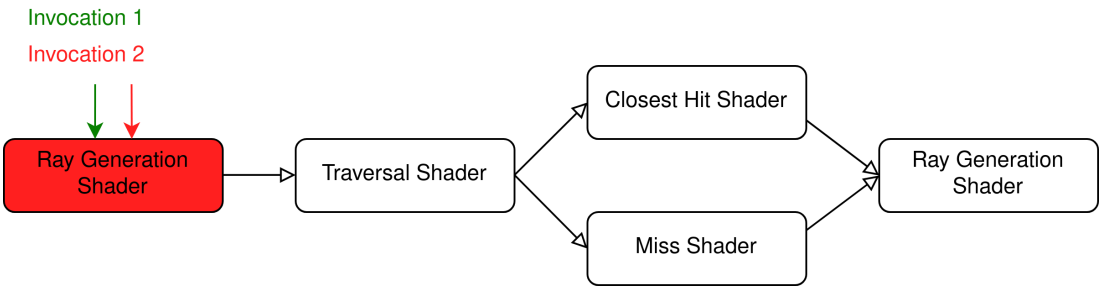
- Solution: Select shader based on type
- Certain shader types will always be preferred over others
- Prefer Hit/Miss over Traversal shaders
- Execute Raygen only when no other shaders are available
- Shader type is packed into the 2 LSBs of the shader’s address



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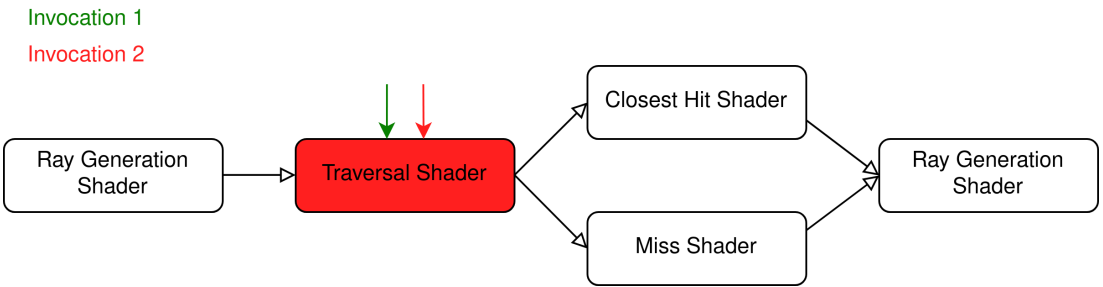

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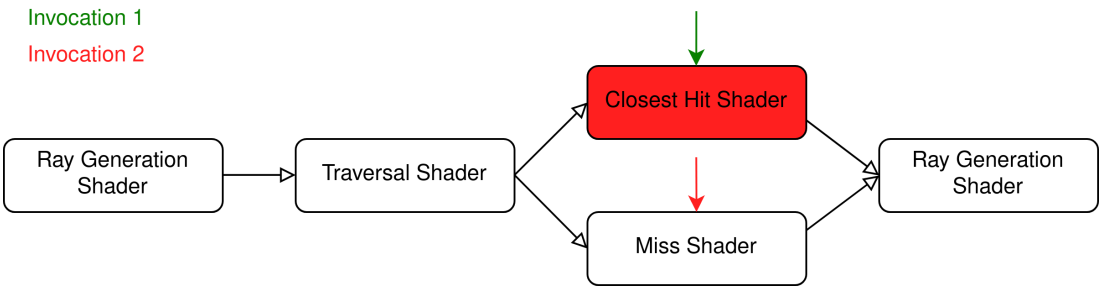

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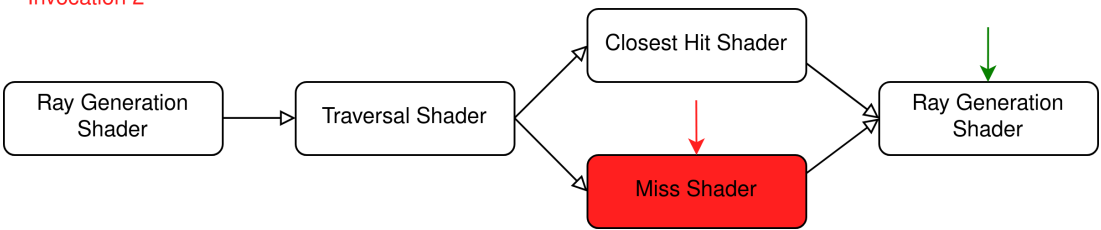

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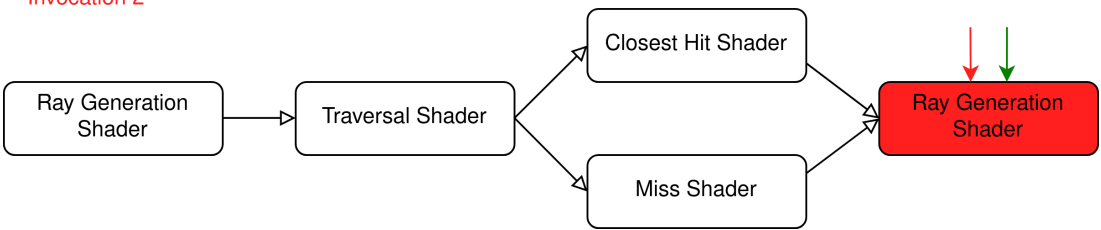

Status And What’s To Come

Compatibility

XDC 2022:

- Quake II RTX
- Control
- Deathloop
- Resident Evil: Village
- Metro Exodus Enhanced Edition

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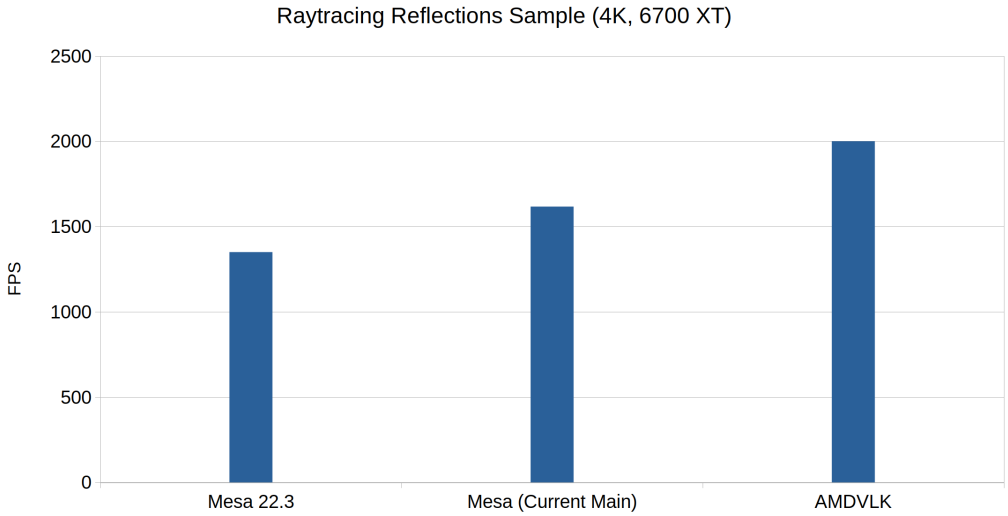
XDC 2023:

- General expectation is that new stuff works
- Some known issues (Witcher 3, Cyberpunk 2077 can hang currently)
- Something else broken?
  - https://gitlab.freedesktop.org/mesa/mesa/-/issues/new

Performance



Future Work

- Make remaining games work
- Make remaining games work **fast**
- Explore more sophisticated shader call techniques
  - Shader Execution Reordering?
- Make the monolithic path work with pipeline libraries
- Take advantage of RDNA3 features
- Build higher quality BVHs
- AS Updates
- Tons of microoptimizations

Thank You!

Questions?