Local Shading Coherence Extraction for SIMD-Efficient Path Tracing on CPUs

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Path tracing

- Standard method for production rendering
- Main steps:
  - Ray traversal
  - Shading
    - Usually more than half of the rendering time

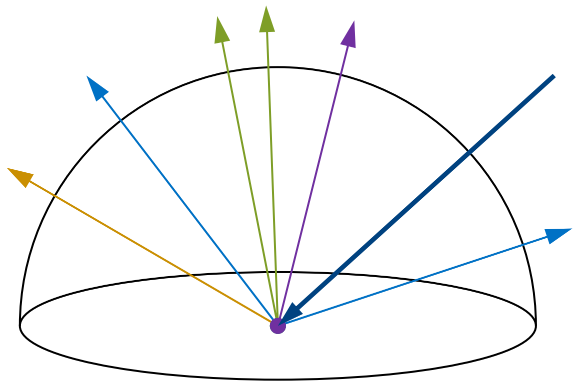
Path tracing

- Single-ray tracing
  - SIMD single-ray traversal
  - Scalar shading

- Packet tracing
  - SIMD single-ray traversal (or packet traversal)
  - SoA-based SIMD packet shading

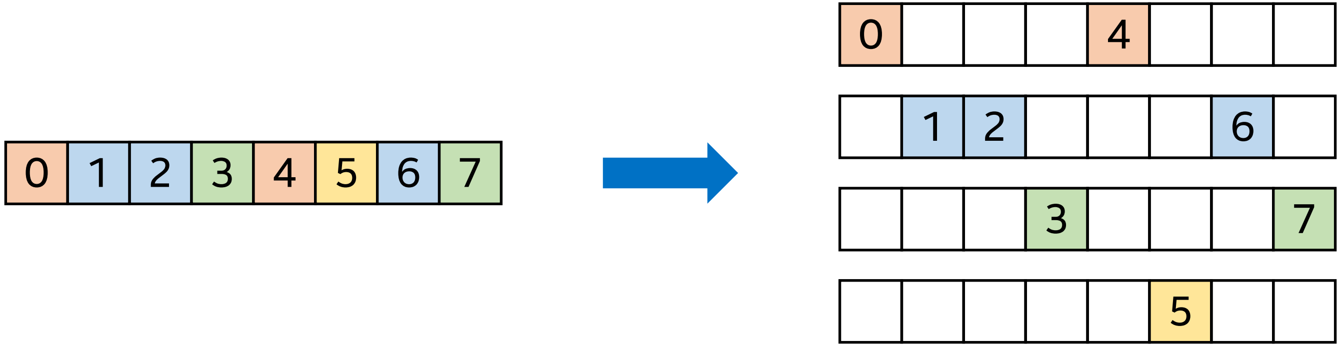
Path tracing

- Random rays → incoherent traversal and shading ☹
  - Low utilization of vector units
    - The wide (8-32) vector units of modern CPUs and GPUs are wasted
  - Incoherent memory accesses



Incoherent shading

- SIMD divergence
  - Many different shaders are evaluated within a SIMD batch
  - Low SIMD utilization



- Incoherent texture access
  - Non-cached reads form memory, disk, or network

Coherence extraction

- Performance can be improved by extracting coherence
  - Find batches of similar rays and process them together
- Most previous research focused on traversal
- Stream shading
  - Trace streams of rays and sort them on various criteria (e.g., material)
- Previous methods operate on a single large, global stream (millions of rays):
  - Wavefront path tracing on GPUs [Laine et al. 2013]
  - Sorted deferred shading for production path tracing [Eisenacher et al. 2013]

Our algorithm

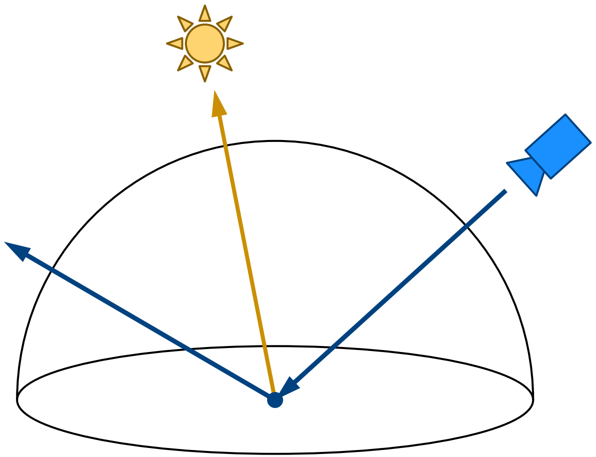
- Traces and sorts small local streams independently on each CPU thread
  - 2K-8K rays per stream
- Enables efficient SIMD shading with low overhead

- Why local?
  - Has much lower overhead than global!
  - Cache-friendly: the streams fit into the CPU's last-level cache (LLC)
  - Avoids expensive cross-core communication
  - Very fast (and simple) ray sorting
  - Sufficient for high (> 90%) SIMD utilization

Path tracing integrator

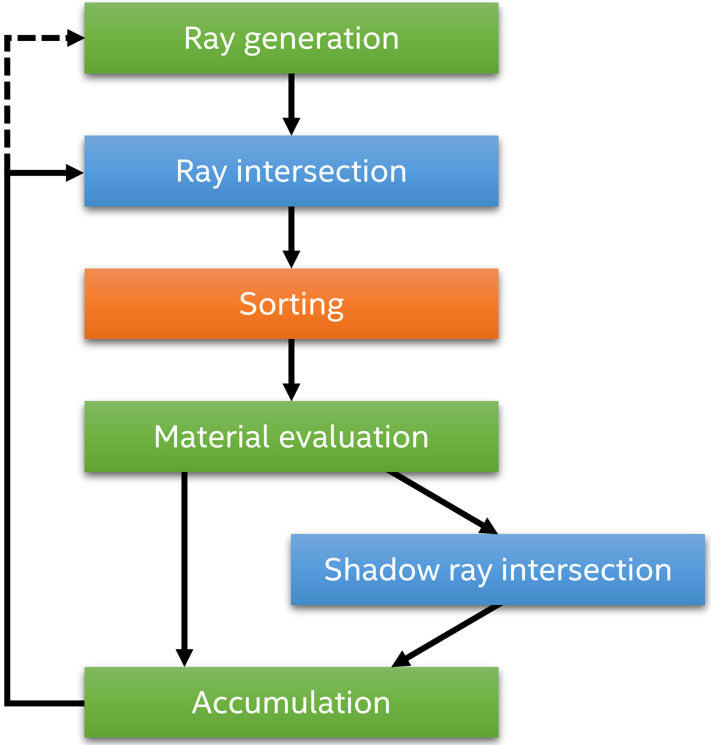
- Unidirectional path tracer with next event estimation

- Cast a ray from the camera
- Evaluate the material at the hit point
  - Material ID
  - Material shader which constructs a BSDF
- Cast a shadow ray toward a light source
- Cast an extension ray and repeat



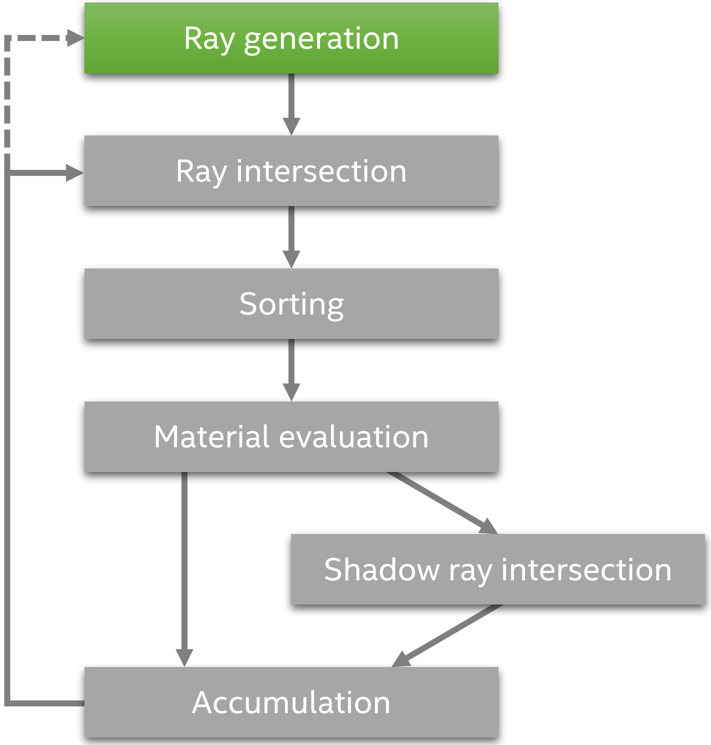
Stream tracing

- Two ray streams:
  - Extension ray stream
  - Shadow ray stream
- SoA memory layout
  - SIMD-friendly
- Compact
  - No gaps (inactive rays)
- Algorithm consists of stages
  - Each stage involves a stream iteration



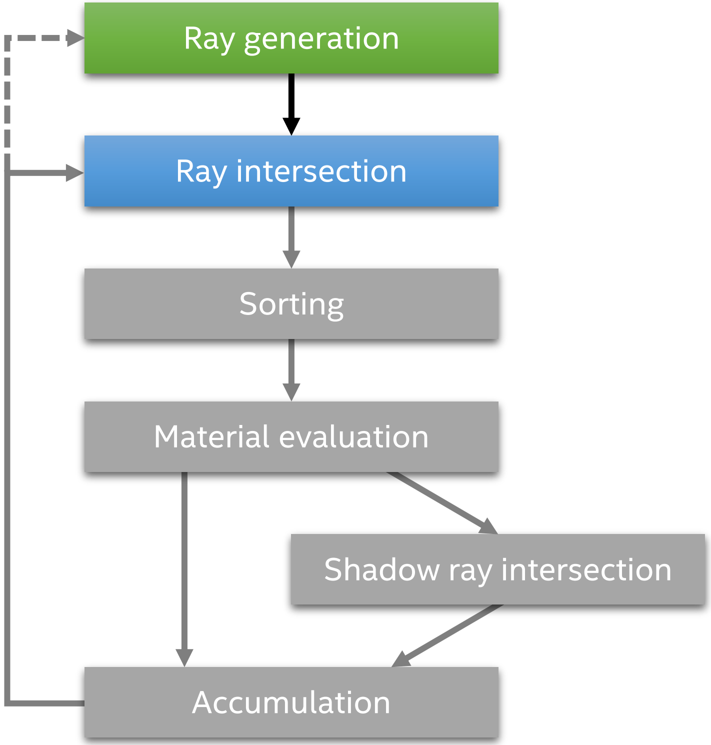
Stream tracing

- Ray generation
  - Generate primary rays from an image tile
    - e.g., 16x16 pixels, 8 samples per pixel



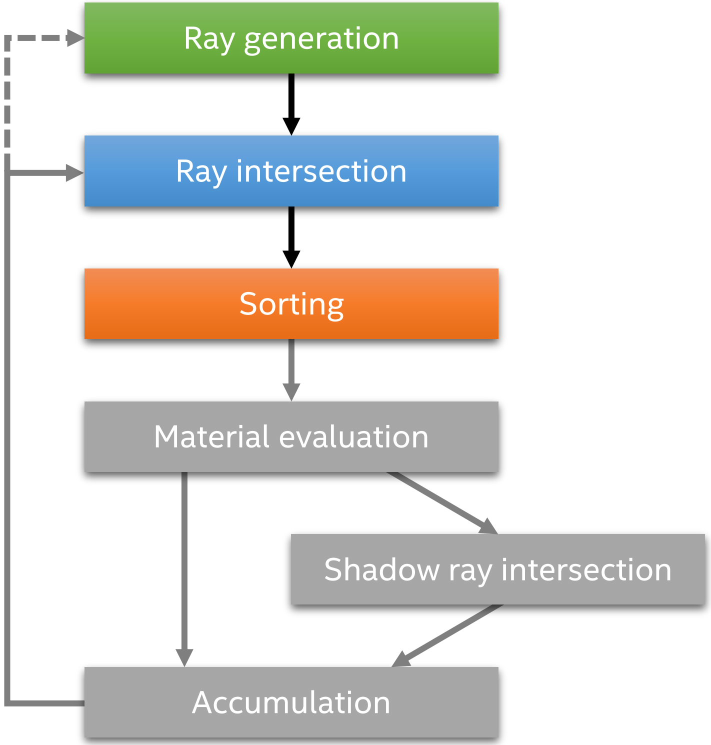
Stream tracing

- Ray generation
  - Generate primary rays from an image tile
    - e.g., 16x16 pixels, 8 samples per pixel
- Ray intersection
  - Intersect all extension rays in the stream
  - Single-ray traversal
  - Stream traversal
    - DRST [Barringer & Akenine-Möller 2014]
    - ORST [Fuetterling et al. 2015]



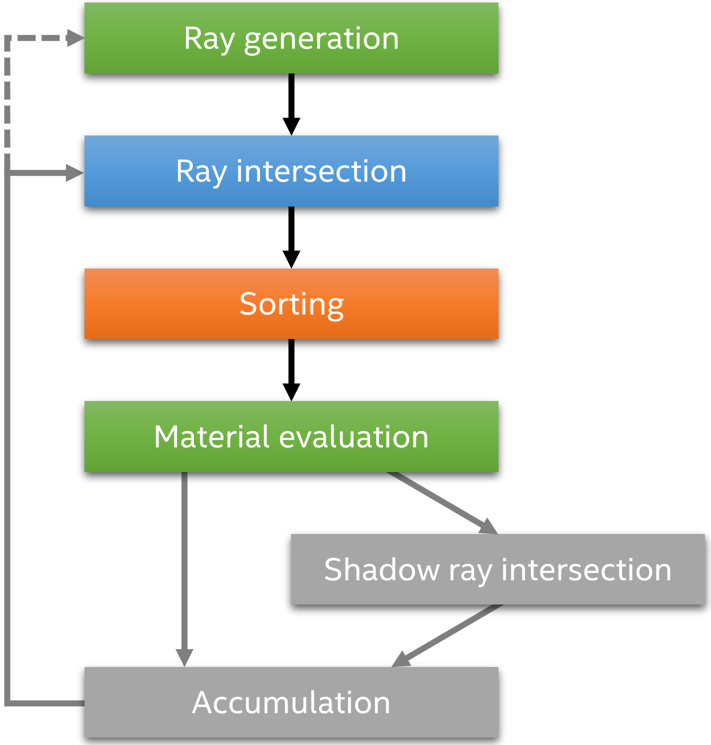
Stream tracing

- Sorting
  - Sort ray IDs by material ID
  - Counting sort → fast!



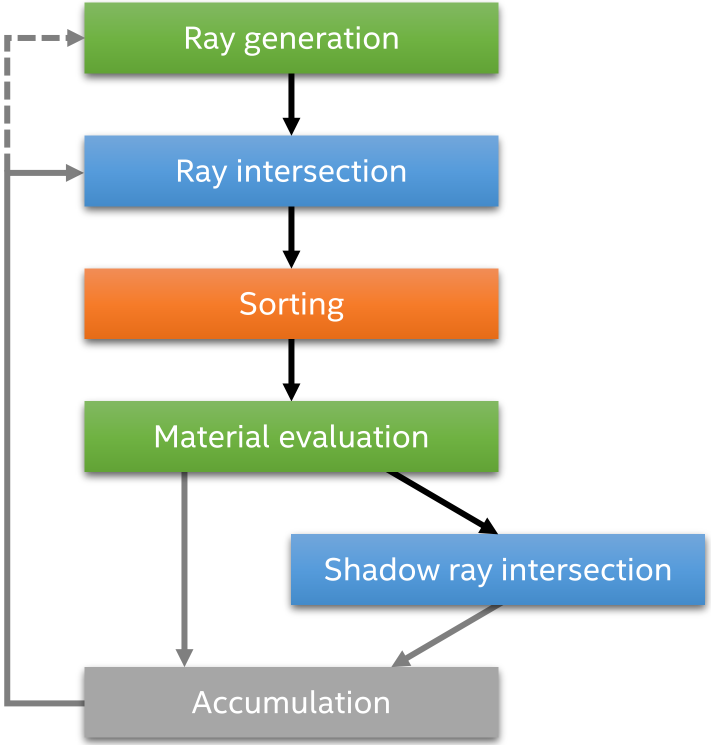
Stream tracing

- Sorting
  - Sort ray IDs by material ID
  - Counting sort → fast!
- Material evaluation
  - Iterate over the sorted ray IDs
  - Execute shaders for coherent SIMD batches
  - Generate extension and shadow rays
  - Append to new streams using pack-stores
    - Filter out terminated paths
    - Double buffering



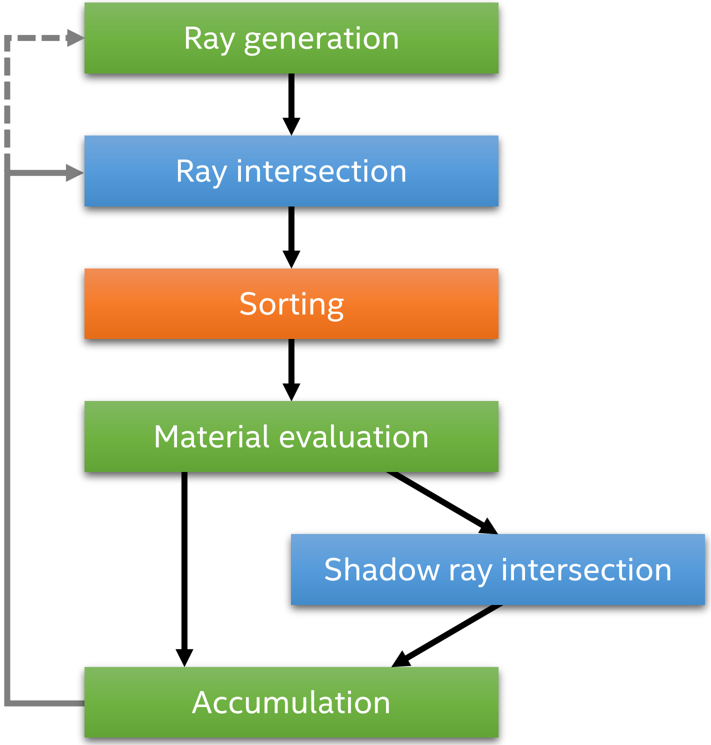
Stream tracing

- Shadow ray intersection
  - Test all shadow rays for occlusion



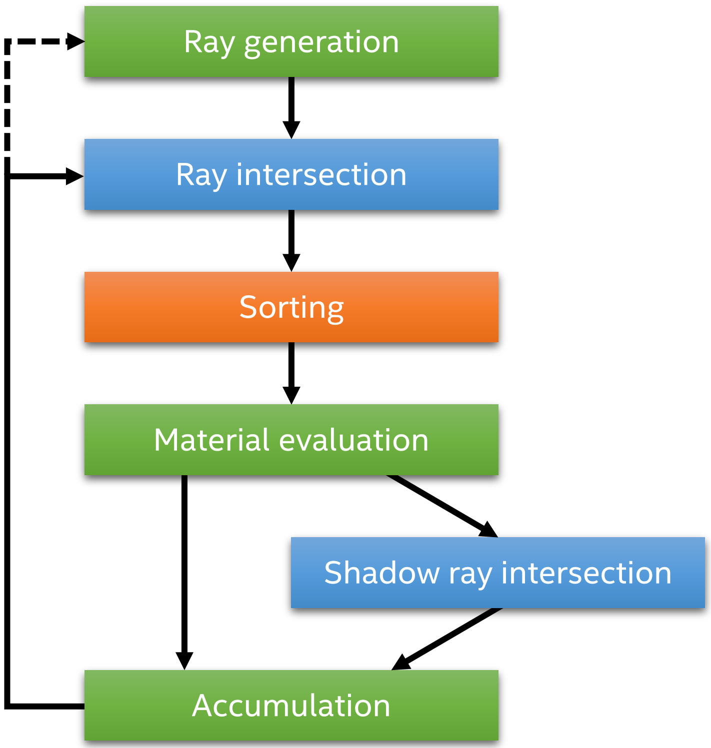
Stream tracing

- Shadow ray intersection
  - Test all shadow rays for occlusion
- Accumulation
  - For unoccluded shadow rays, add direct light
  - For terminated paths, accumulate to image

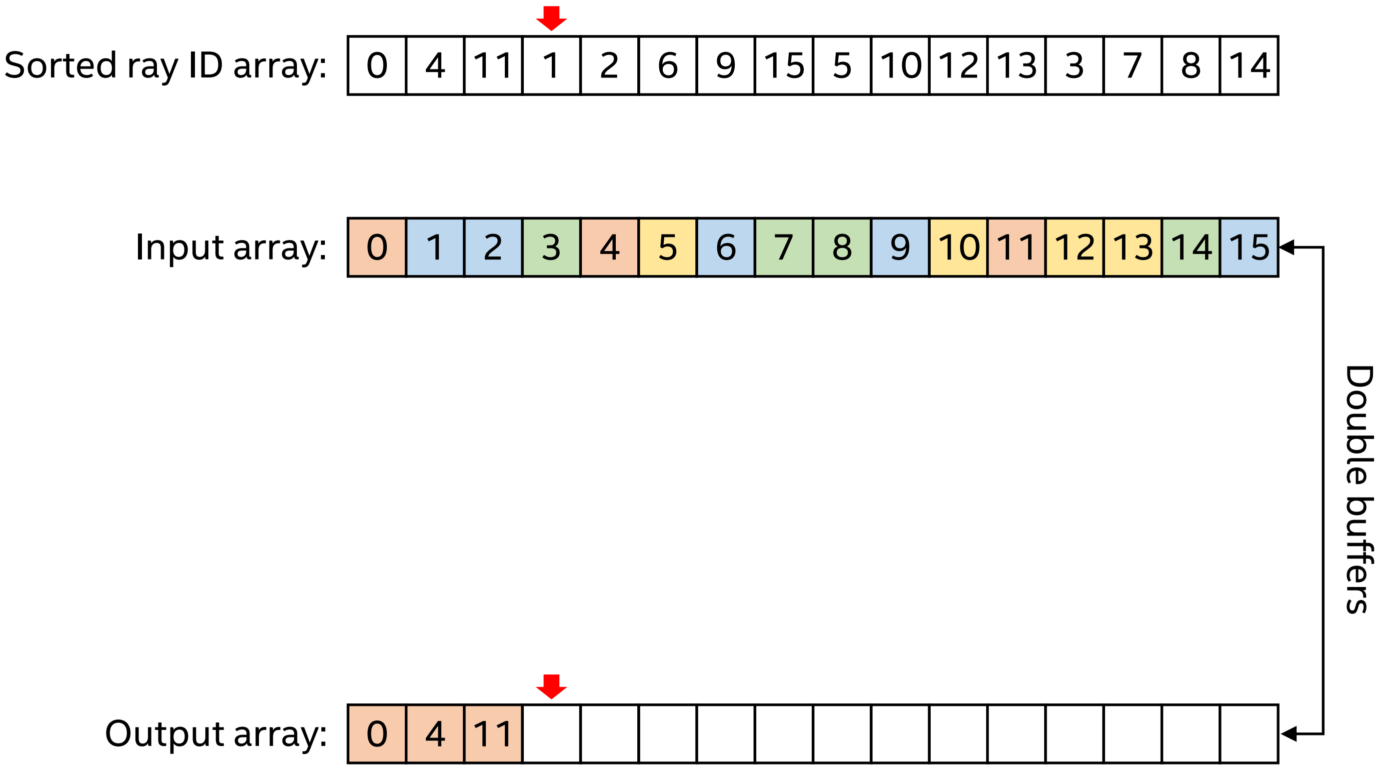


Stream tracing

- Shadow ray intersection
  - Test all shadow rays for occlusion
- Accumulation
  - For unoccluded shadow rays, add direct light
  - For terminated paths, accumulate to image
- Path regeneration (optional)
  - Append new primary rays to the stream
    – Replace terminated paths



SIMD stream shading example



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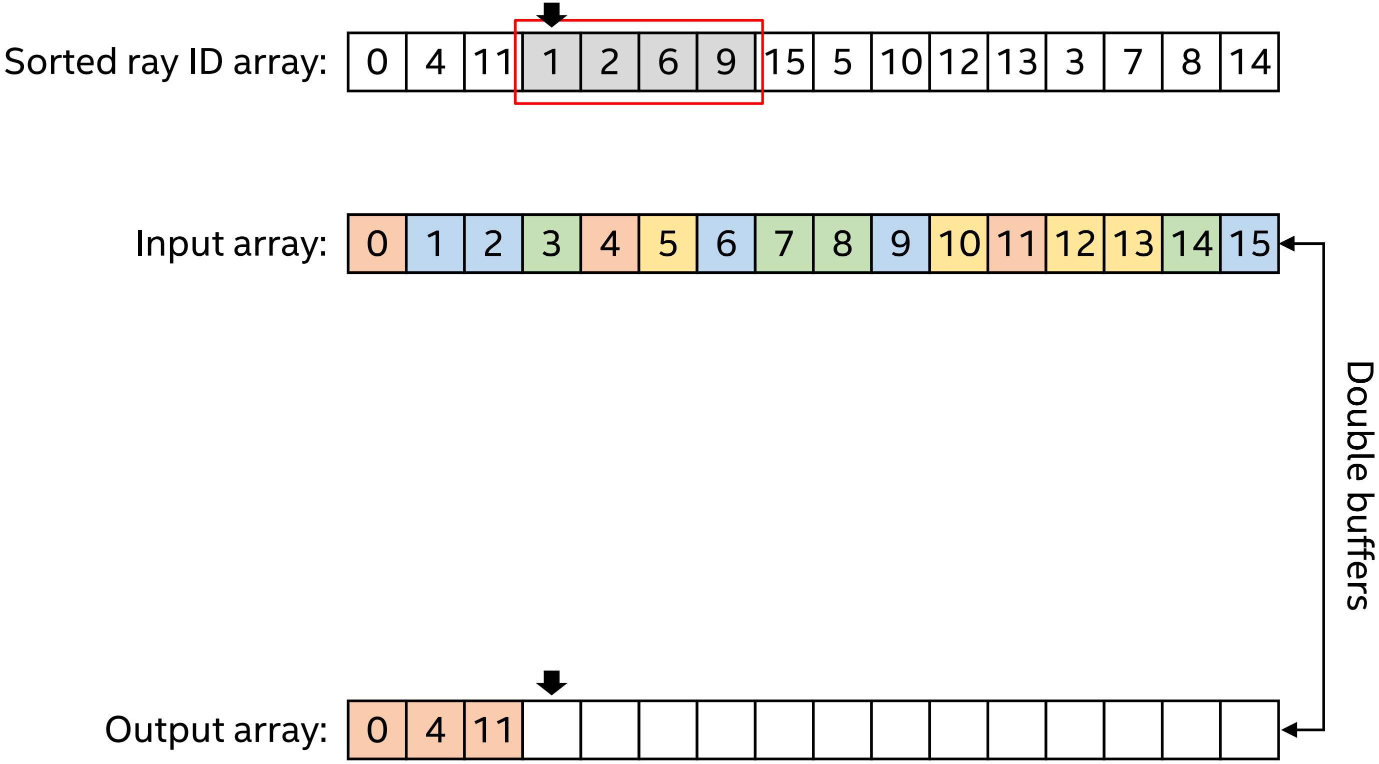

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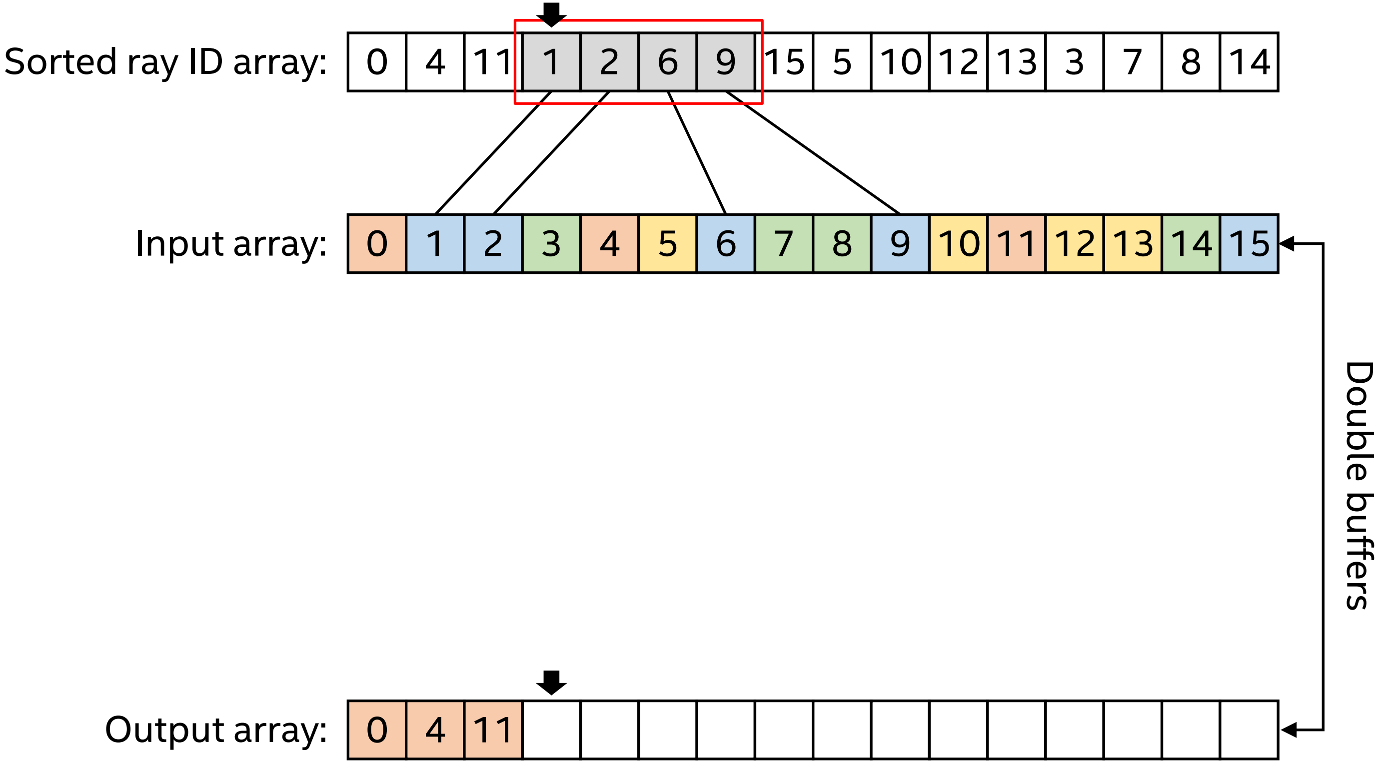
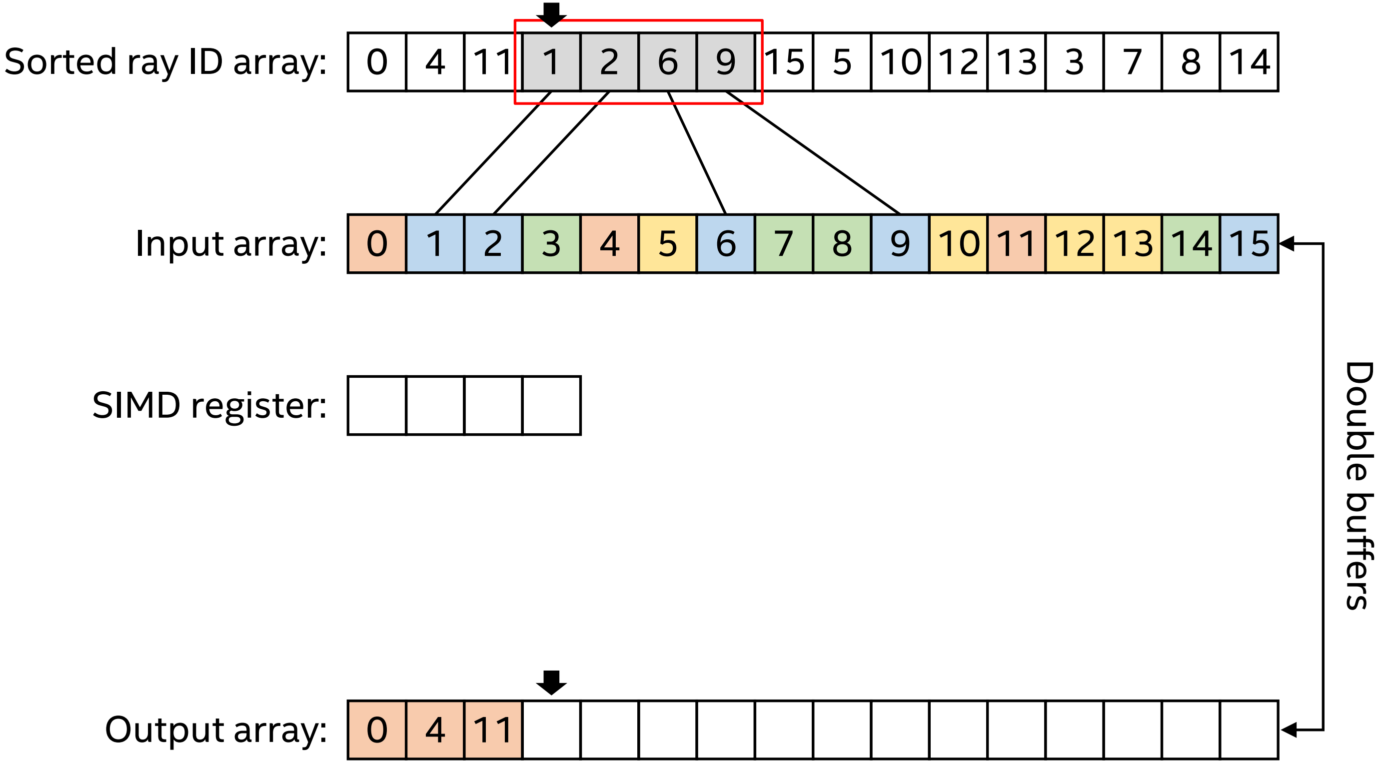


SIMD stream shading example



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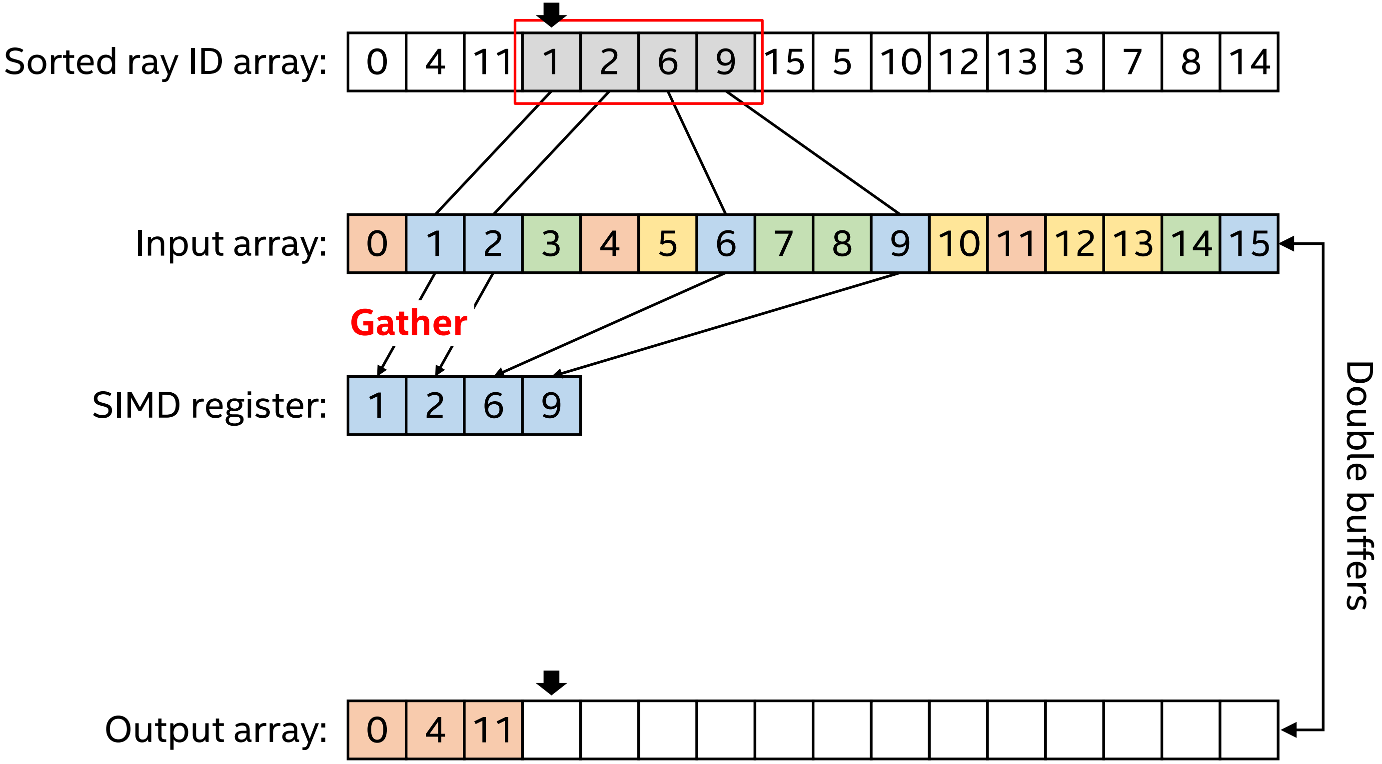

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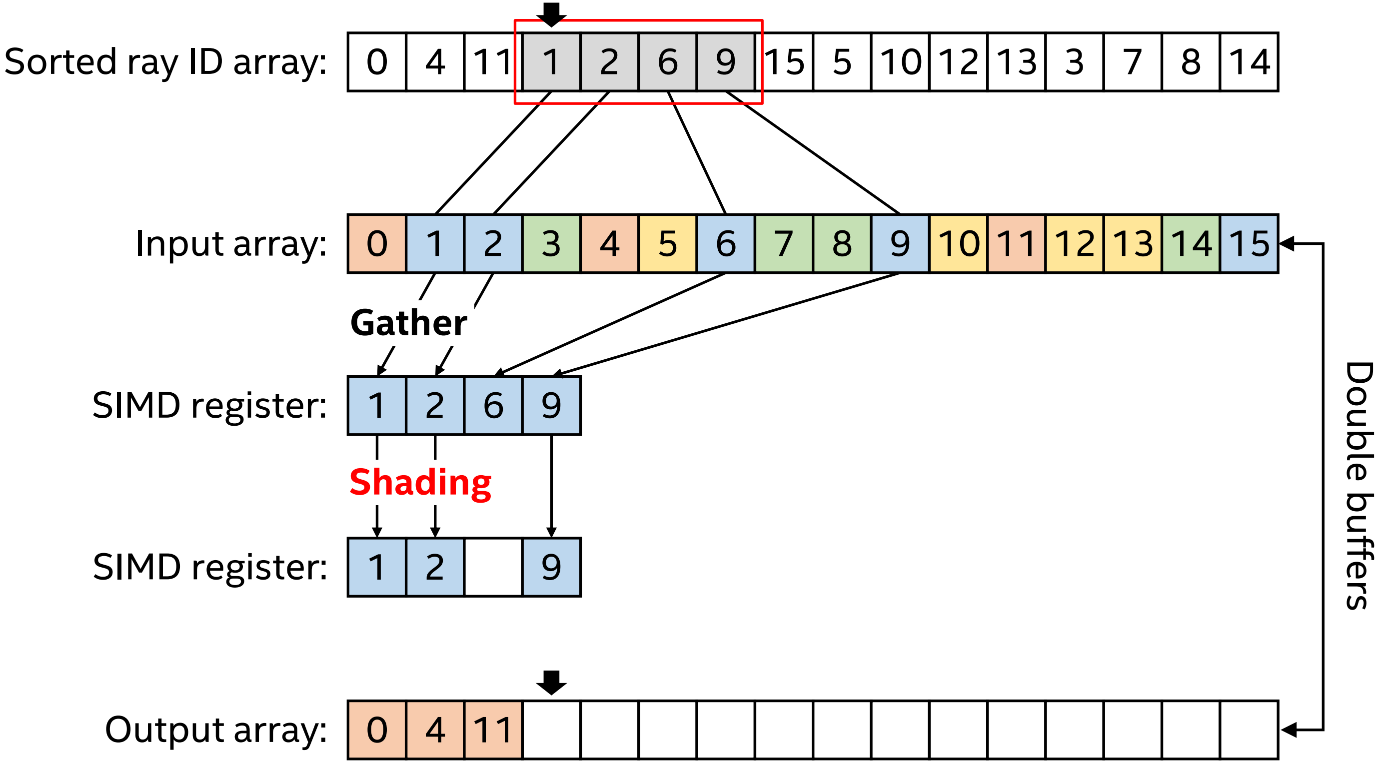

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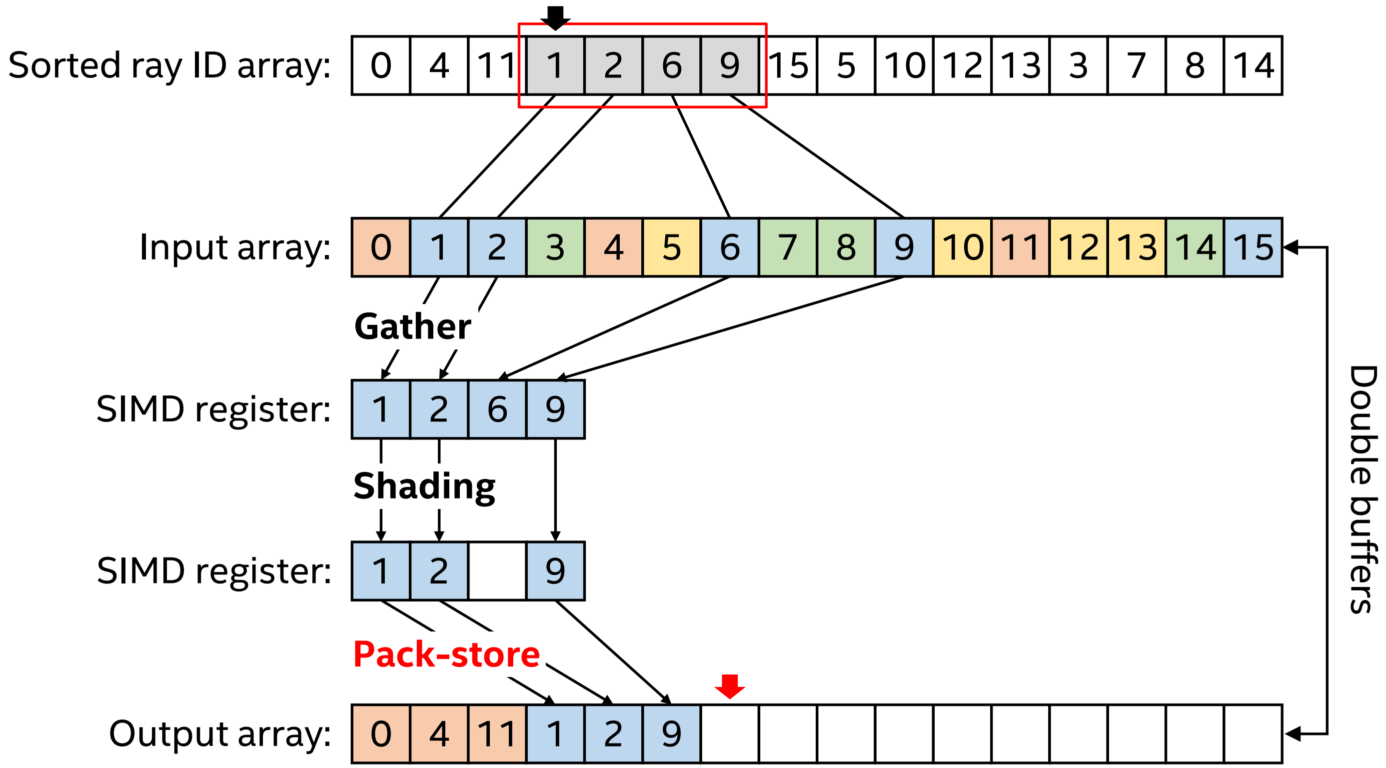


Results

- Stream tracing (Our)
  - Stream size: 2K rays (376 KB/thread)
- Single-ray tracing w/ scalar shading
- Packet tracing w/ SIMD shading

- Same SIMD single-ray traversal kernel
- 8-wide SIMD, AVX2 instruction set
- Hardware: dual-socket Xeon E5-2699 v3
  - 36 cores, 72 threads, 90 MB LLC (30% used for streams)

Test scenes

Art Deco / 111 materials

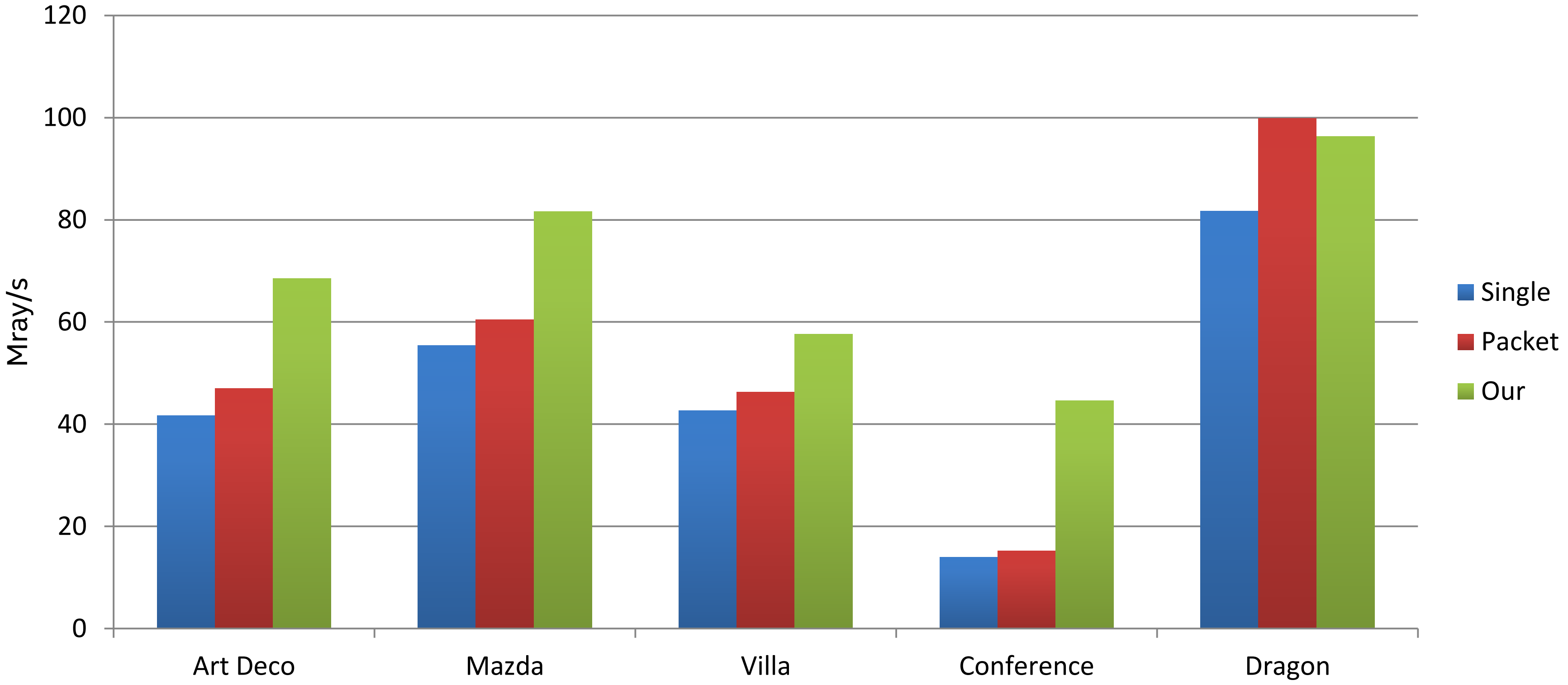
Mazda / 76 materials

Villa / 97 materials

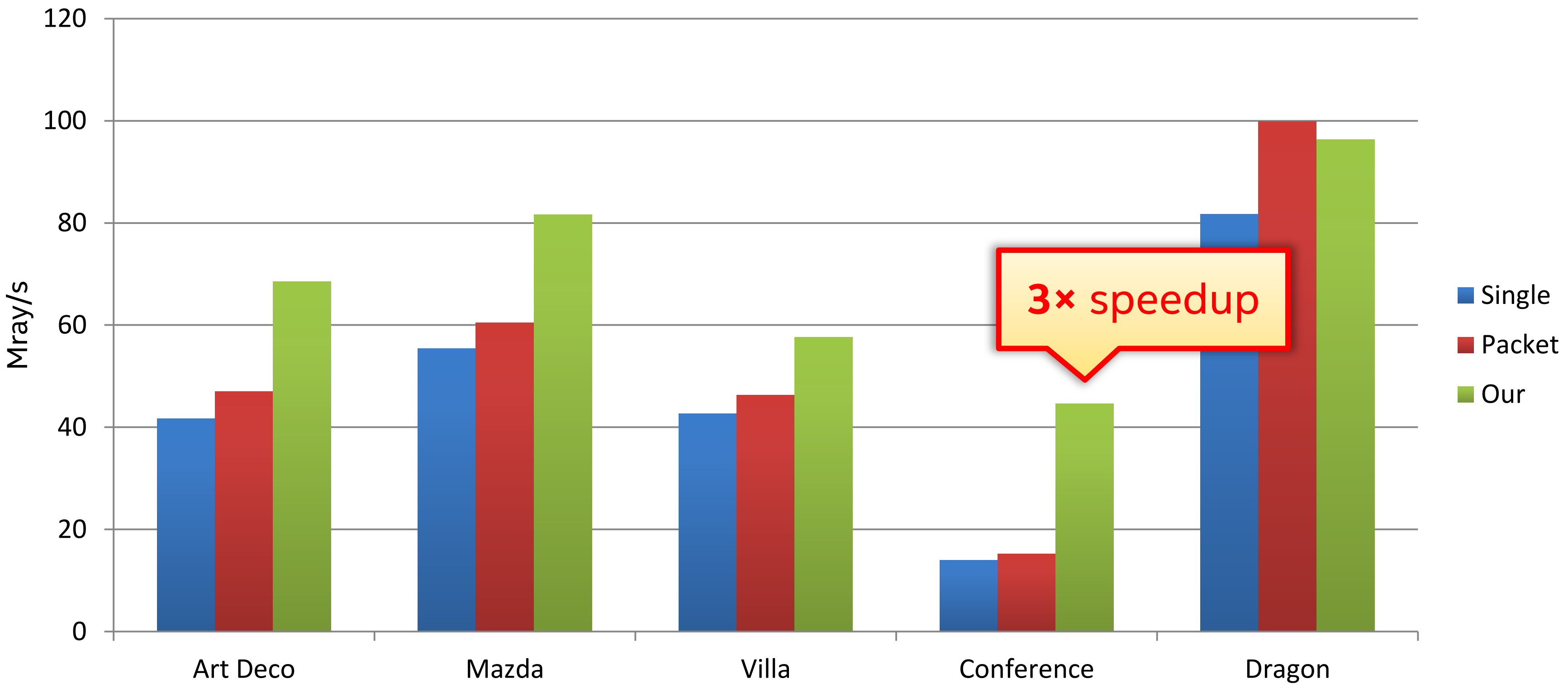
Conference / 36 materials
complex procedural shaders

Dragon / 5 materials
simple shaders

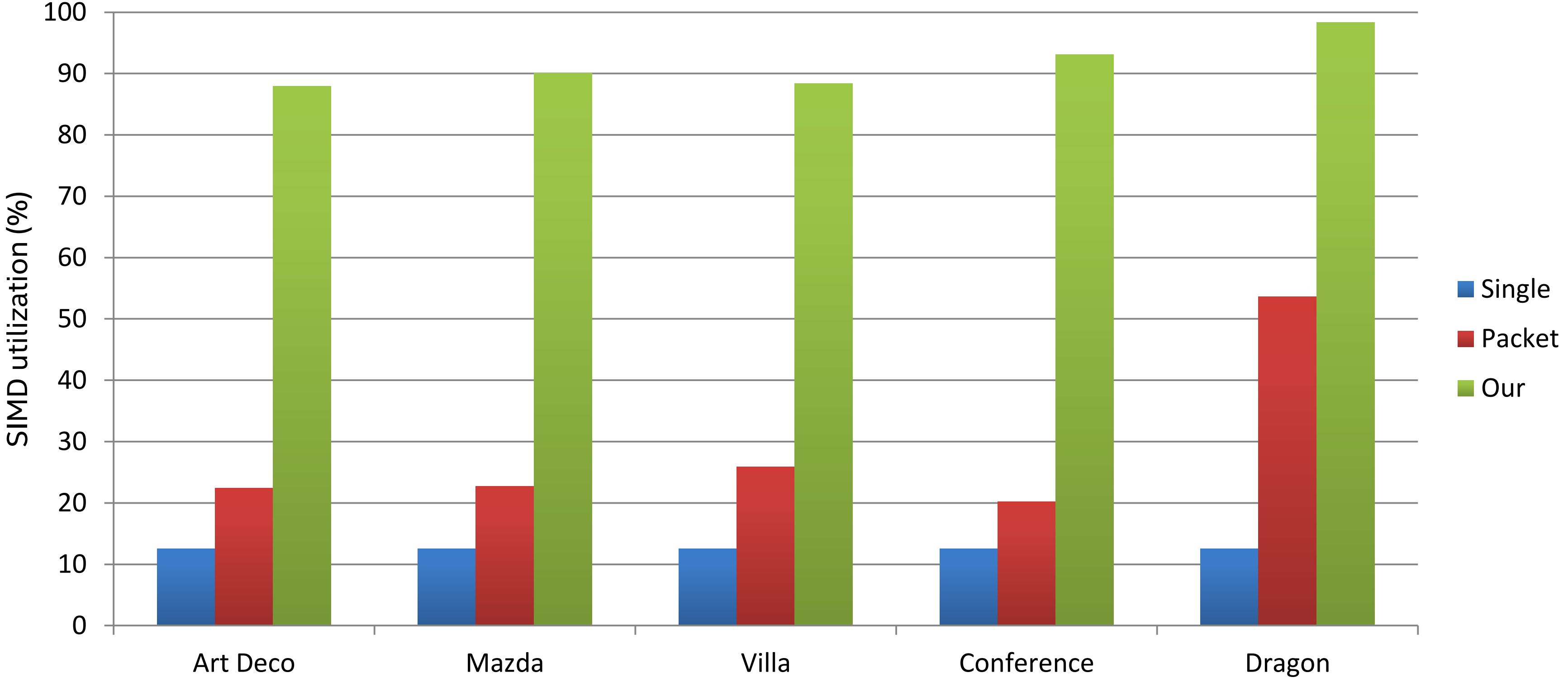
Path tracing performance (Mray/s)



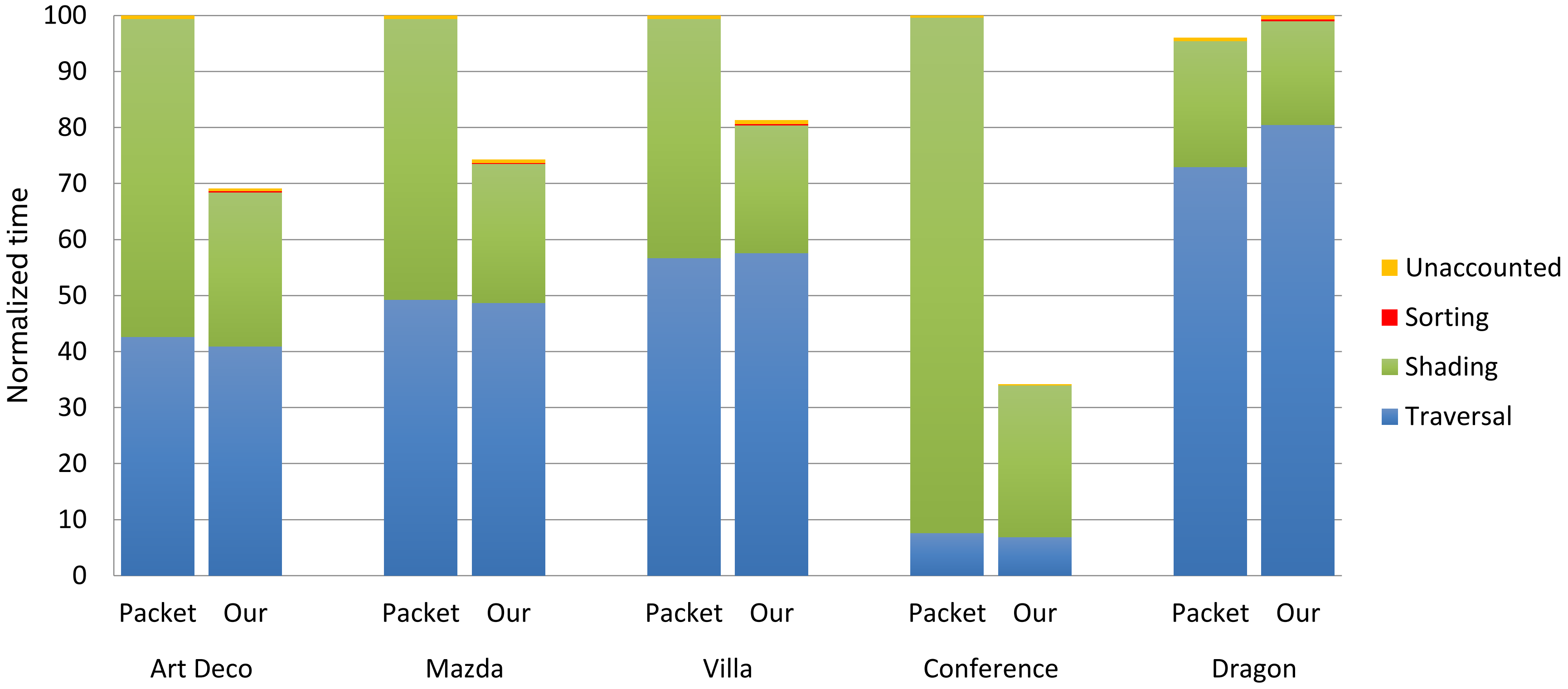
Path tracing performance (Mray/s)



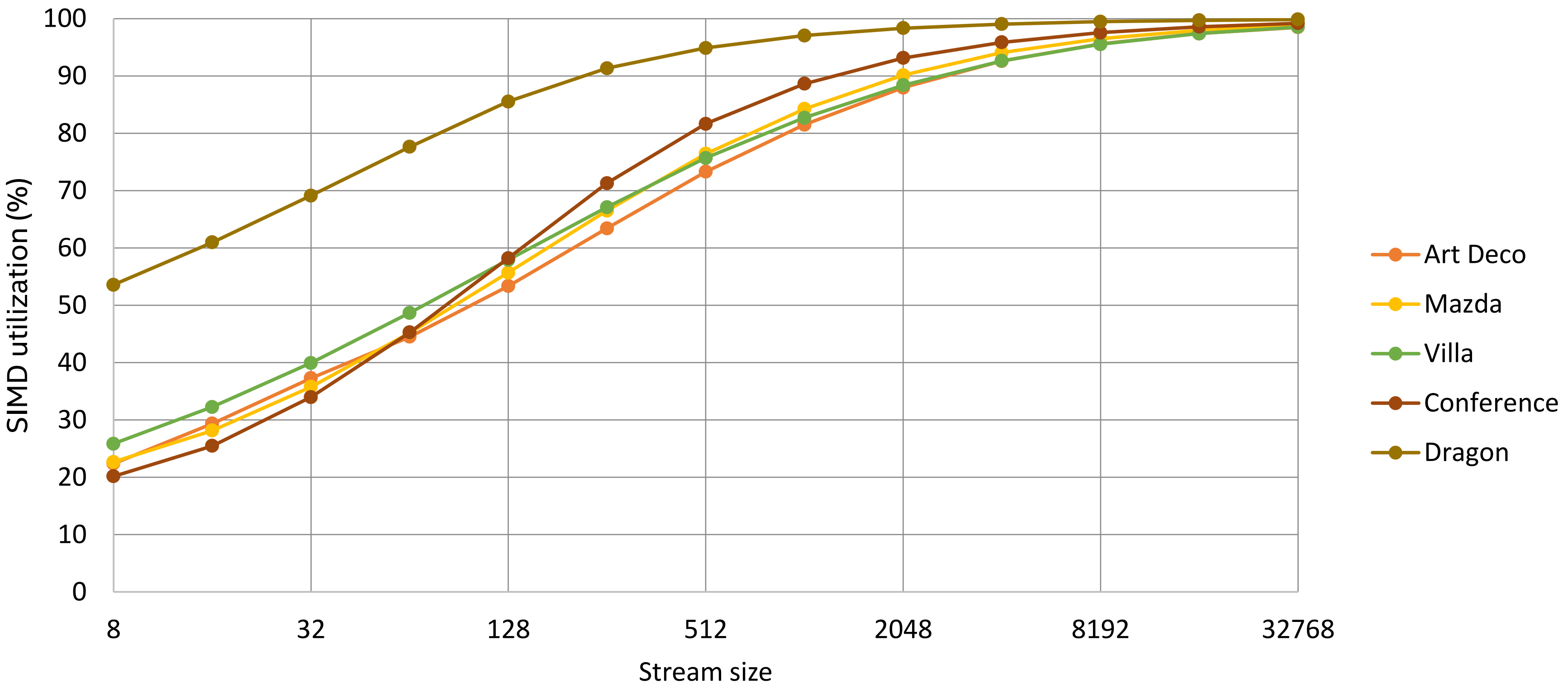
SIMD utilization for shading (%)



Rendering time breakdown



SIMD utilization vs. stream size



Conclusion

- Achieves much higher SIMD utilization than single-ray and packet shading
- Reduces shading time by 2-3× for complex scenes with hundreds of shaders
- Could perform even better with production-quality shaders
- Scales well to hundreds of CPU cores, wider SIMD (16), and bigger caches

- Future work:
  - Additional sorting steps (e.g., textures)
  - Bidirectional path tracing

Questions?

SIMD utilization vs. number of materials