Megakernels Considered Harmful: Wavefront Path Tracing on GPUs

Samuli Laine
Tero Karras
Timo Aila

NVIDIA

Path Tracing Overview

- Cast a ray from the camera through the pixel
- At hit point, evaluate material
  - Determine new incoming direction
  - Update path throughput
- Cast a shadow ray towards a light source
- Cast the extension ray and repeat

- At some depth, start using Russian roulette to terminate path probabilistically
  - Avoids infinitely long paths

Problems in Megakernel Path Tracer

- You can put all code in one kernel, even on a GPU
  - Ray casts, evaluators and samplers for all materials, evaluators and samplers for all light source types, path tracing logic, MIS, new path generation, etc.

BUT:

- Lots of code
  - Bad for instruction cache
- Lots of registers used (based on hottest spot)
  - Bad for latency hiding capacity
- Lots of execution divergence
  - Bad for SIMT execution model (warps of 32 threads)

Problems in Megakernel Path Tracer

- **You can put all code in one kernel, even on a GPU**
  - **Ray casts, evaluators and samplers for all materials, evaluators and samplers for all light source types, path tracing logic, MIS, new path generation, etc.**

BUT:

- **Lots of code**
  - **Bad for instruction cache**
- **Lots of registers used (based on hottest spot)**
  - **Bad for latency hiding capacity**
- **Lots of execution divergence**
  - **Bad for SIMT execution model (warps of 32 threads)**

Execution Divergence in Path Tracing

- Paths may hit different materials
  - Each material has its own code
- Paths may terminate at different lengths
  - Various reasons
  - This issue has been investigated before
    - Solutions, e.g., path regeneration are known, but they are not very effective
- Not all materials produce a shadow ray
  - BSDFs with Dirac distribution (mirror, glass)

Execution Divergence in Path Tracing

- Paths may hit different materials
  - Each material has its own code
- Paths may terminate at different lengths
  - Various reasons
  - This issue has been investigated before
    - Solutions, e.g., path regeneration are known, but they are not very effective
- Not all materials produce a shadow ray
  - BSDFs with Dirac distribution (mirror, glass)

Real-World Materials

or

How Bad Can It Be?

Materials Are Expensive

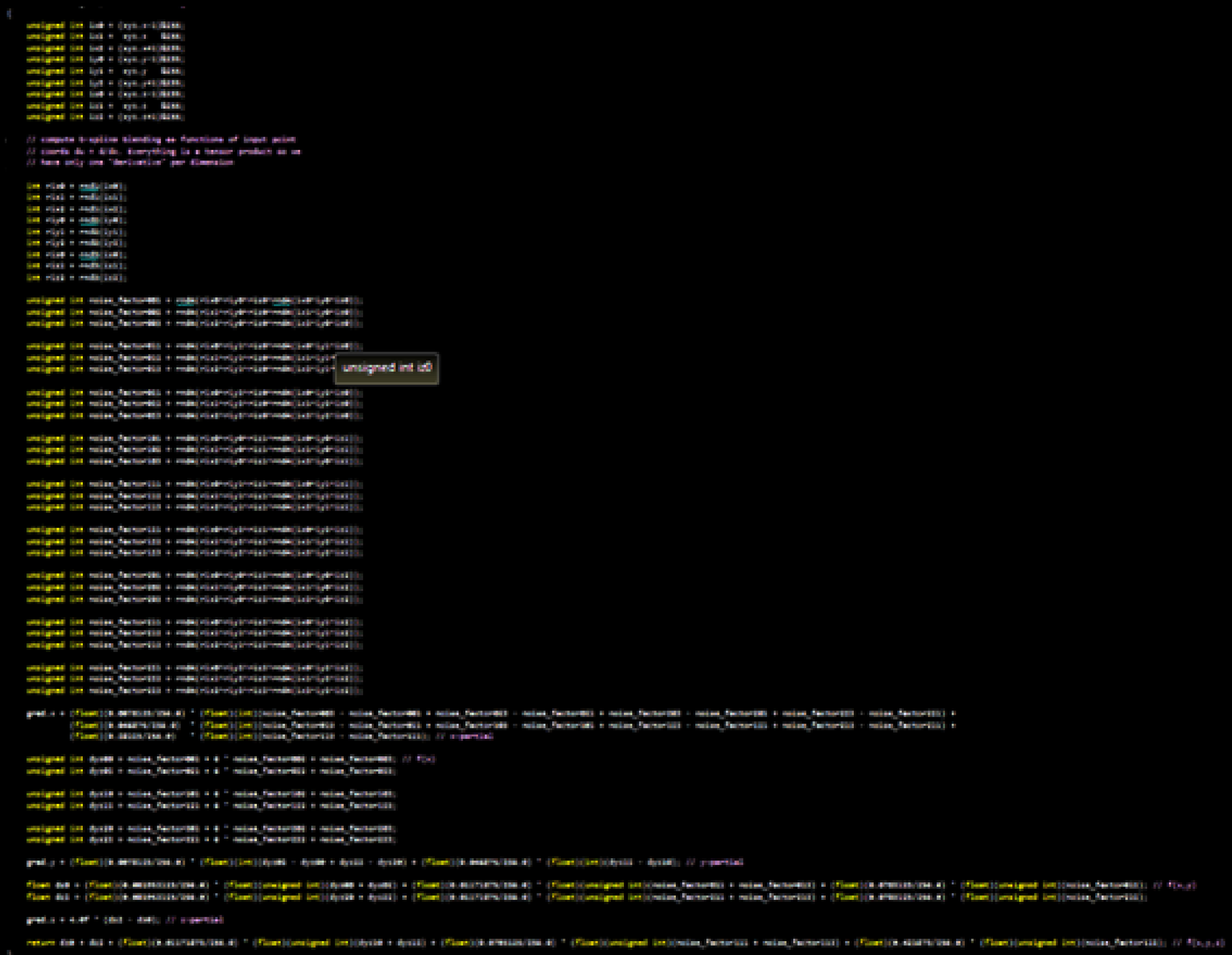
- Composed of multiple BSDF layers
- Non-trivial BSDFs
- Procedural noise everywhere
- Huge textures*

* Not addressed in this work

Example: Car Paint

- Four layers
  - Fresnel coat
  - Glossy flakes 1 & 2
  - Diffuse base
- Coat is a simple dielectric BSDF with Fresnel weight
- Flakes are Blinn-Phong BSDFs with procedural colors and normals
- Base is a diffuse BSDF with angle-dependent color

Example: Noise Evaluator



Example: The Entire Car Paint

And This Isn't Even a Difficult Case

- Only four layers
- No textures
  - No procedural texcoords
  - No filtering
  - No out-of-core
- No iterative stuff
- Still ~2x as expensive to evaluate as a ray cast
  - In this scene, probably closer to 10x

Problem: How to Evaluate Materials Efficiently?

- Worst case: Every thread hits a different, expensive material
- Megakernel runs each sequentially with abysmal SIMD utilization
- We really need to do better than that
    - Otherwise the materials will dominate

Let’s Solve Everything

It's Business Time

- The recipe to reorganize path tracing to be more GPU-friendly:
- 1. Remove the loop around path tracer
  - Avoid consequences of variable path length
  - Also enables the two other optimizations
- 2. Place requests for operations into queues
  - Ray casts, material evaluations, etc.
  - Avoids threads idling when executing conditional code
- 3. Execute operations in separate kernels
  - Minimize register pressure and instruction cache usage
    - Avoid losing latency hiding capacity unnecessarily

Step 1: Remove the Loop

- **Keep a pool of paths alive all the time**
  - **E.g., one million paths**
- **At each iteration, advance each of them by one segment**
  - **Cast rays, evaluate materials and lights, accumulate radiance, update throughput, run the roulette, etc.**
- **If path terminates, generate a new one in its place**
  - **Ensure there’s always paths to work on**
- **Similar to previous work**
  [e.g. Wald 2011, Van Antwerpen 2011, etc.]

Pros and Cons

- \+ Variable path length is not an issue anymore
  - As previously noted
- \+ Allows further optimizations
  - Collecting requests in operation-specific queues and scheduling them individually
  - This is the big one! Really hard to do in the megakernel approach
- – Path state must reside in memory
  - A simple loop-based method can keep it in registers
  - Not as bad as it sounds if we use a good memory layout (SOA)
- – Less "natural" to implement
  - But only until you get used to it
- – Doesn't buy you much performance alone

Step 2: Per-Operation Queues

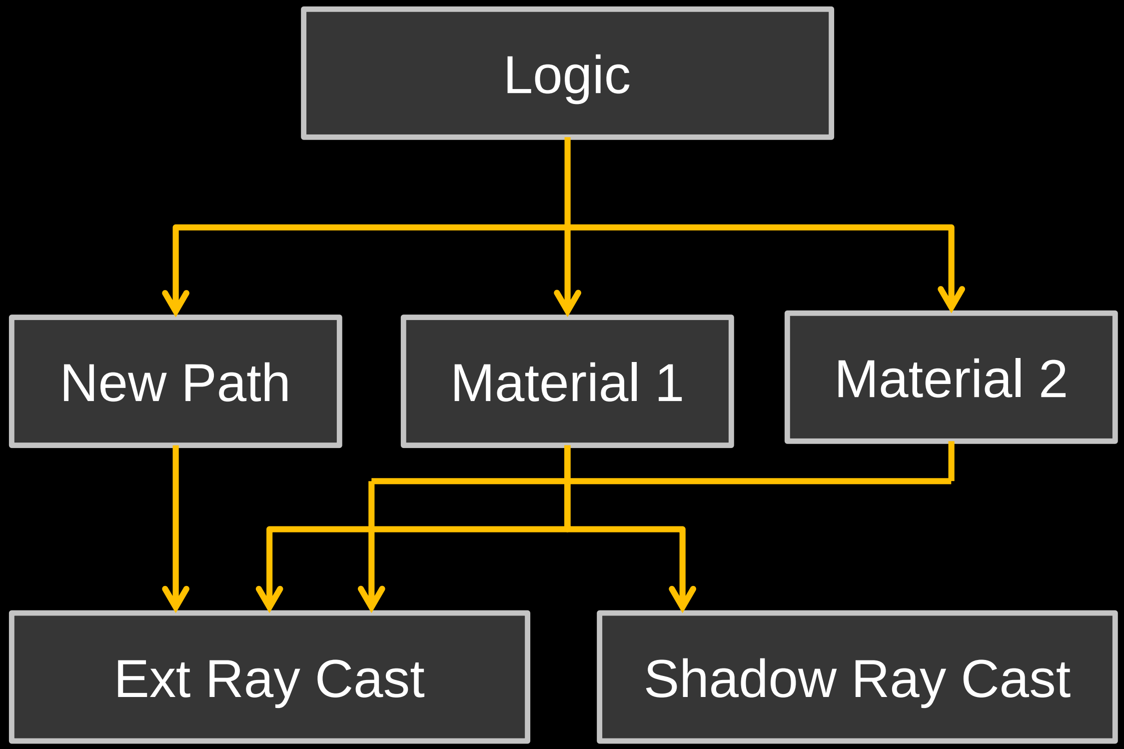
- Allocate a queue for each primitive operation request
  - Extension ray casts
  - Shadow ray casts
  - New path generation
  - Material evaluations
    - *With separate queues for individual materials*
- Place requests compactly (i.e., no gaps) into queues
- When executing, use one thread per request
  - Every thread will have an item to work on
  - Every thread will be doing the same thing, so there’s very little execution divergence!

Step 3: Individual Kernels for Each Operation

- We already have well-optimized kernels for ray casts from previous research
  - Now we can use them directly
  - Optimized for low register count and high perf
- Let each material have its own kernel
  - Some are simple and need few registers
    - Combining these into one kernel is sometimes a good idea
  - Some are complex and need many registers
- Smaller code → Won't overrun instruction caches

Implementation

Schematic



Always operates on all paths in pool

Each kernel has its own queue

Each type of ray has its own queue

The Logic Kernel

Logic

- Does not need a queue, operates on all paths
- Does "everything except rays and materials"
  - If shadow ray was unblocked, add light contribution
  - Find material and/or light source that ext ray hits
  - Apply Russian roulette if limit depth exceeded
  - If path terminated, accumulate to image
  - Apply depth-dependent extinction for translucent materials
  - Generate light sample by sampling light sources
  - Place path in proper queue according to material at hit
    - Or in "new path" queue if path terminated

New Path Kernel

New Path

- Generate a new image-space sample
  - Based on a global path index
- Generate camera ray
  - Place it into extension ray queue
- Initialize path state
  - Init radiance, throughput, pixel position, etc.
  - intialize low-discrepancy sequence for the path, used when generating random numbers in samplers

Material Kernels

Material *n*

- Generate incoming direction
- Evaluate light contribution based on light sample generated in the logic kernel
  - Even though we haven’t cast the shadow ray yet
- Get the probability of acquiring the light sample from the sampling of incoming direction
  - Needed for MIS weights
- By evaluating all of these in one go, we can discard the BSDF stack immediately afterwards
- Generate extension ray and potential shadow ray
  - Place in respective queues

Ray Cast Kernels

Ext Ray Cast

Shadow Ray Cast

- **Extension rays**
  - **Find first intersection against scene geometry**
  - **Utilize optimized kernels from previous research**
  - **Store hit data into path state**
- **Shadow rays**
  - **We only need to know if the shadow ray is blocked or not**
  - **Cheaper than finding the first intersection**

Results

Test Scenes and Performance

Carpaint

City

Conference

scene	#tris	performance (Mpaths/s)		**speedup**
		megakernel	wavefront	
CARPAINT	9.5K	42.99	58.38	36%
CITY	879K	5.41	9.70	79%
CONFERENCE	283K	2.71	8.71	221%

Note: Megakernel has path regeneration

Execution Time Breakdown

scene	logic	new path	materials	ray cast
CARPAINT	2.40	0.86	2.31	4.31
CITY	3.42	0.86	5.47	12.53
CONFERENCE	3.01	0.79	6.37	9.62

(times in milliseconds / 1M path segments)

- **The most important takeaway: Ray casts are not the only expensive part!**
  - **Optimizations yield diminishing returns already**

Conclusions

- Path tracing can be reorganized to suit GPUs better
  - Bonus: Also works in practice
- Going to the future, there is no limit on the number and complexity of materials
  - Divergence will only get worse
  - Megakernels will only get bigger
  - → The proposed approach becomes even more appealing
- Time to look beyond accelerating ray casts?

Future Work

- **Look at other rendering algorithms**
  - **Bidir path tracing, MLT, etc.**
  - **There is already good work in this direction**
    [Van Antwerpen, Davidovič et al.]
  - **Should add complex materials in the mix!**

- **What to do about gigantic textures?**
  - **Run materials that have their textures resident while transferring missing textures on the GPU simultaneously?**
  - **Put paths "on hold" while their textures are being loaded, and let other paths continue?**
  - **Always run everything you can, try to make everything else runnable at the same time by async transfers?**

Thanks!

- Questions