Compiler Technology in Open Shading Language

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Open Shading Language (OSL)

- Designed for physically-based GI
- Scales to production use
- A language spec that could be used by any renderer
- A library that can be embedded in CPU renderers
- Open source
- In production now!

Motivation

- (Alice in Wonderland images omitted)

What's wrong with shaders

- Black boxes, can't reason about them
- Can't sample, defer, or reorder
- Suboptimal for a modern ray tracer
- Units are sloppy, hard to be physically correct
- If C/C++: difficult, versionitis, can crash, hard to globally optimize.
- Hardware dependence & limitations

Radiance closures

- OSL shaders don’t return colors
- Return a symbolic rep that can be “run” later
  - Act “as if” they are a radiance value
  - But aren’t evaluated until later
- View independent
- Consistent units (radiance)
- Can be sampled
- Unify reflection, transparency, emission

OSL goals

- Similar to RSL/GSL, but evolved & easier
- Separate description vs implementation
  - End versionitis nightmare
  - Late-stage optimization
  - Hide renderer internals
  - No crashing, NaN, etc.
  - Allow multiple back-ends
- Renderer control of rays / physical shading
  - no light loops or trace calls
- Lazy running of layers
- Closures describe materials/lights
- Automatic differentiation

System workflow

- Compiler (oslc) precompiles individual source modules (.osl) to bytecode (.oso)
- At render time, material networks are assembled
- JIT to x86 to execute
- OSL runtime execution is a library
- Renderer provides a callback interface

Compiling shaders

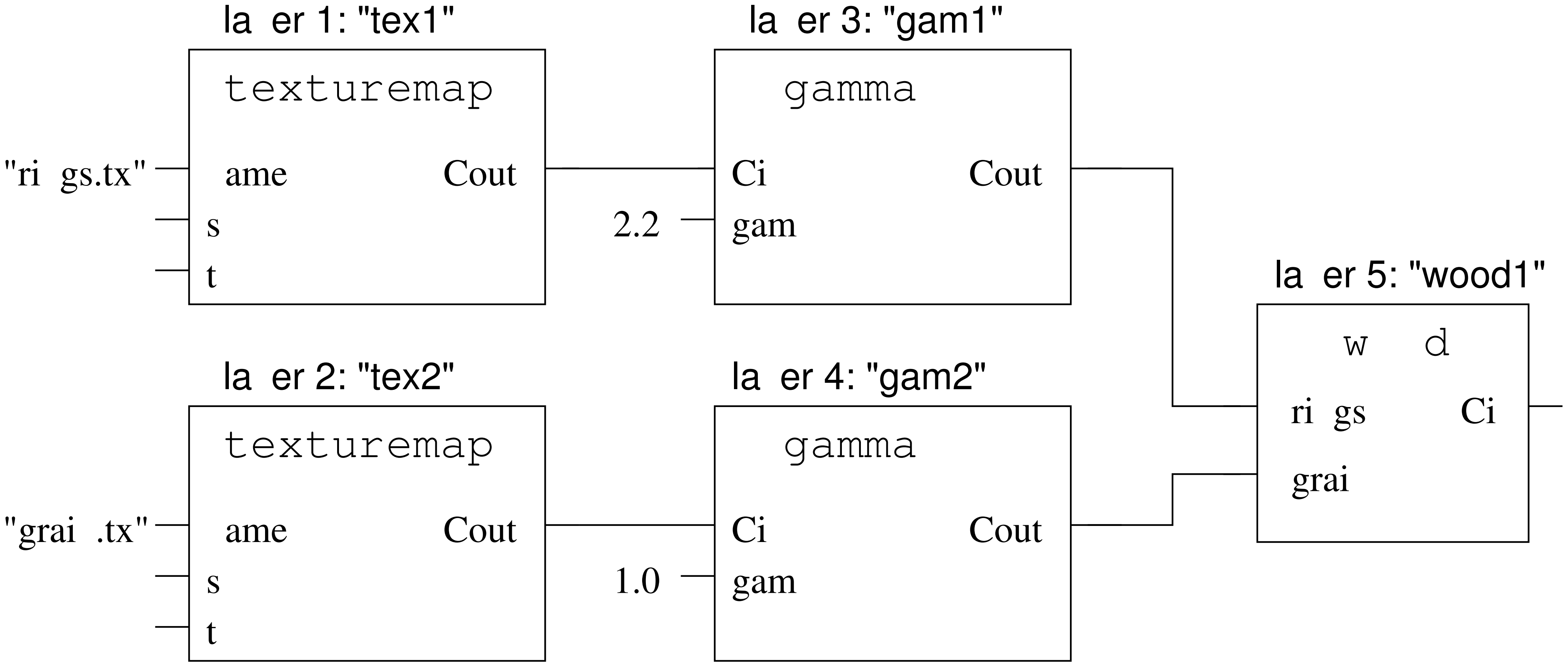
gamma.osl

```
shader gamma (color Cin = 1,
              float gam = 1,
              output color Cout = 1)
{
    Cout = pow (Cin, 1/gam);
}
```

gamma.oso

```
OpenShadingLanguage 1.00
# Compiled by oslc 0.6.0
shader gamma
param   color   Cin     1 1 1
param   float   gam     1
oparam  color   Cout    1 1 1
temp    float   $tmp1
const   float   $const2 1
code ___main___
# gamma.osl:5
        div             $tmp1 $const2 gam
        pow             Cout Cin $tmp1
        end
```

Shader networks



Interpreter vs LLVM

- First try: SIMD interpreter
  - render batches of points at once
  - interpret one instruction at a time, all points in lockstep
  - analyze to find uniform values
  - amortize overhead over the grid

Interpreter vs LLVM

- Works great if batches are big enough
- Easy for primary rays, secondary rays incoherent
- Batches small, too much overhead cohering

Interpreter vs LLVM

- Next try: translate oso into LLVM IR, JIT
    - no exploitation of ‘uniform’ values
    - but no interpreter overhead
    - no need to try to scrape together coherent rays
    - LLVM optimizer
- Generate full IR for some ops
- Others “call” functions, inlined by LLVM
- Generate enter/exit code
- Lazy evaluation of shader nodes

Interpreter vs LLVM

- LLVM vastly outperformed interpreter
- Greatly simplified the entire system
  - other than LLVM dependency
- Simplified renderer, no need for batches

Derivatives

C = texture (“foo.exr”, s, t, ...)

- To properly filter this texture lookup, you want to know how s & t vary over a pixel area.
- dsdx, dsdy, dtdx, dtdy

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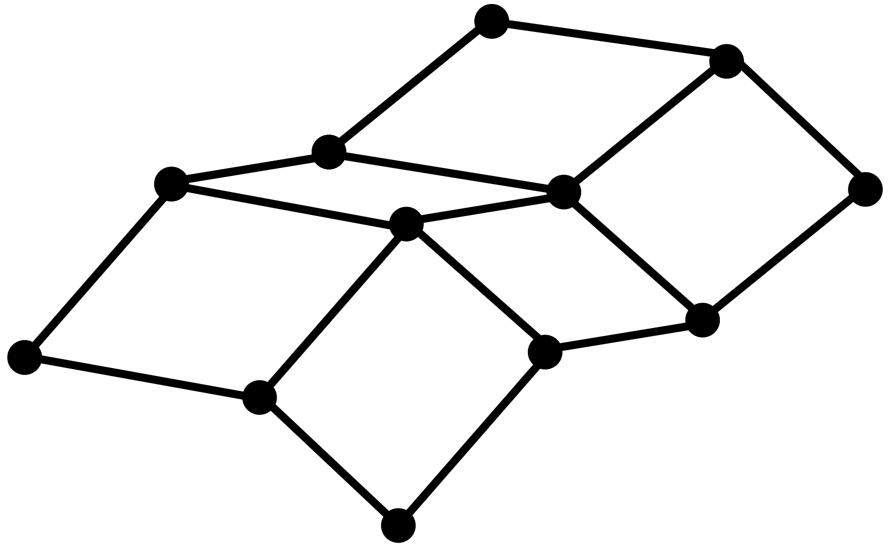

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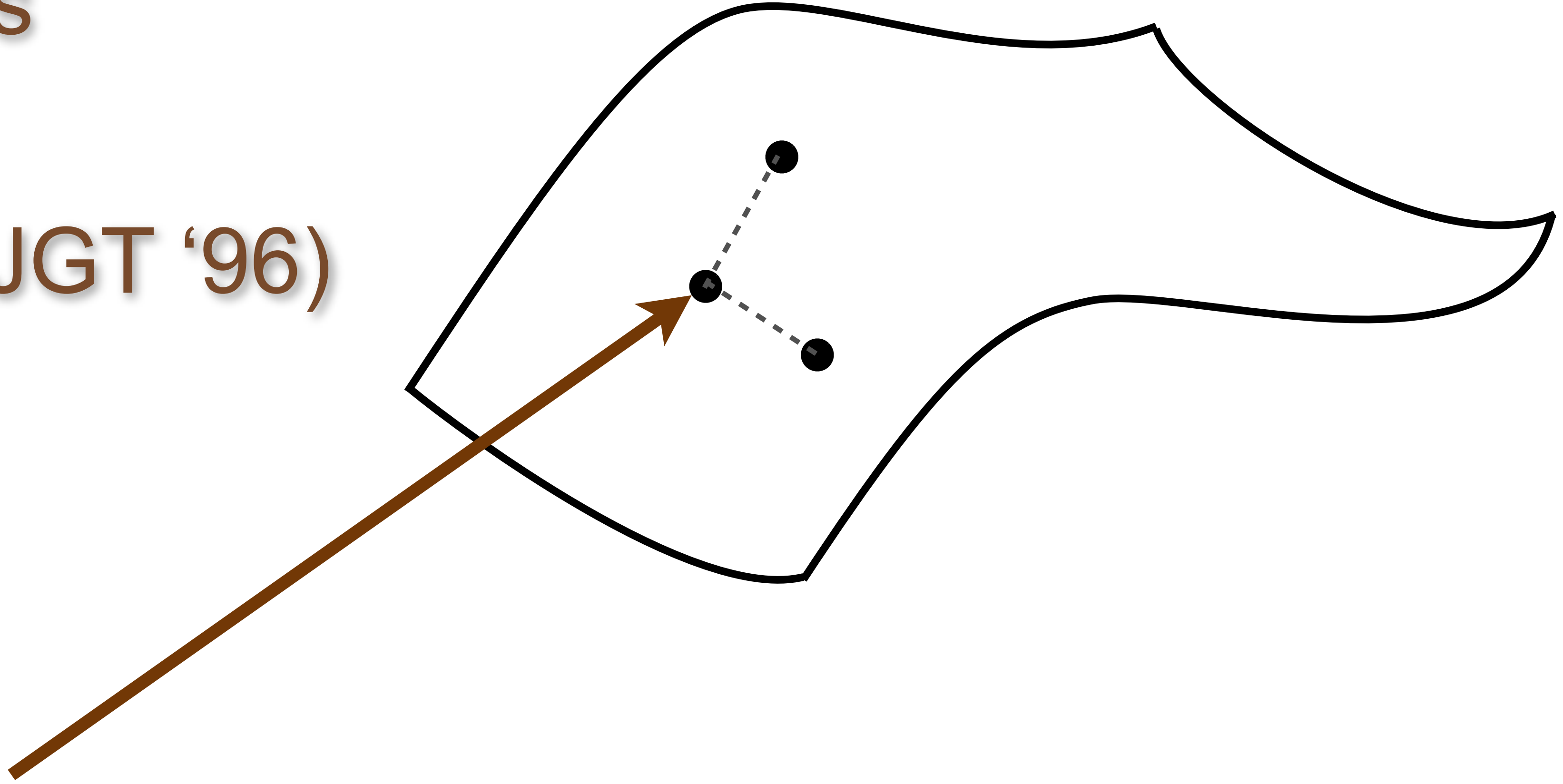

Derivatives

- Most renderers calculate derivatives by:
    - Ignoring the problem
    - Having “special” texture coordinates
    - Computing on grids (Reyes)
    - Shade rays as 3 point grids (Gritz, JGT ‘96)
- We don’t have grids
- We don’t want to compute extra points
- We want derivs of arbitrary expressions

Automatic differentiation

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- Use dual arithmetic (Piponi, JGT 2004)
- Each variable can carry d/dx and d/dy differentials: x = {val, dx, dy}
- Define math ops on these dual variables

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Automatic differentiation

```
template<class T>
Dual2<T> operator* (const Dual2<T> &a,
                    const Dual2<T> &b)
{
  return Dual2<T> (a.val()*b.val(),
                   a.val()*b.dx() + a.dx()*b.val(),
                   a.val()*b.dy() + a.dy()*b.val());
}
```

Only some symbols need derivs

- Find all data dependencies
  - add R, A, B → R depends on A and B
  - “w” args to an op depend on all the “r” args to that op
- Only some ops take derivs of their args

  aastep, area, displace, Dx, Dy, environment, texture
- Mark those symbols as “needing derivatives”
- And so on for their dependencies...
- Careful about connected shader parameters

Derivative ops

- Now we know which symbols need derivs
  - Renderer supplies derivs of (P, u, v, interpolated vars)
- Ops involving them generate deriv IR
  - shortcut: if the w args of an op don't need derivs, just do the non-deriv computations
- In practice, ~5% of symbols need to carry derivs
- Total execution cost of arbitrary derivs is <10%

Runtime optimization

- At runtime, we know:
  - layout and connectivity of the shader network
  - parameter values
- So we optimize the shader oso right before LLVM IR

Runtime optimization

- Unconnected, uninterpolated params → constants
  - also connected if upstream layer knows output value

Track “aliasing” within blocks

- Until A is reassigned, or control flow

- This lets us treat a lot of variables as if they were constant within a basic block.

Track “aliasing” within blocks

`assign A $constB` (now we know A’s value)

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Track “aliasing” within blocks

```
assign A $constB
```

(now we know A’s value)

```
assign A B
```

(now we know A == B)

- Until A is reassigned, or control flow
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Constant folding

Constant folding

`add A $constB $constC`

`assign A $constD`

Constant folding

`add A $constB $constC`	`assign A $constD`
`add A B $const0`	`assign A B`

Constant folding

```
add A $constB $constC          assign A $constD

add A B $const0                assign A B

div A A $const1                nop
```

Constant folding

```
add A $constB $constC          assign A $constD

add A B $const0                assign A B

div A A $const1                nop

mul A B $const0                assign A $const0
```

Useless op elimination

Useless op elimination

```
add A A 0           nop
```

Useless op elimination

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```
add A A 0          nop


add A A C          nop
sub A A C
```

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Useless op elimination

`add A A 0`	`nop`	
`add A A C` `sub A A C`	`nop`	
`assign A B`	`nop`	(B is an alias of A)

Useless op elimination

`add A A 0`	`nop`	
`add A A C` `sub A A C`	`nop`	
`assign A B`	`nop`	(B is an alias of A)
`assign A B`	`nop`	(A & B have the same value)

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  - entire conditionals, loops
  - assignments to variables that aren't used again

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- Dead shader parameter/output elimination
- Dead shader layer elimination
- Coalesce temporaries with nonoverlapping lifetimes

Runtime optimization results

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- Reduce code & symbols 95-98% before LLVM
  - IR gen, LLVM opt, JIT in seconds, not minutes
  - LLVM also optimizes its IR

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- 20-25% faster execution than old C shaders
  - and safe! (no buffer overflows, crashes, etc.)

Putting it all together

- (“The Amazing Spider-Man” shot omitted, sorry.)

Some stats: frame 1350

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- 43 different shader masters (distinct .osl/oso)
- 1885 shader groups (materials)
- 140,964 shader instances (master + params)
- average 75 instances per group
- Load, runtime opt, LLVM IR/opt/JIT:
  - 5m22s across all threads (~26s per thread)
  - out of a 3h22:00 render with 12 threads
  - aside: more time assembling/loading than rendering

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Some stats: frame 1350

- Typical shader group pre-optimized:
  - 50-100k ops
  - 20-40k symbols (including temporaries)
- After runtime optimization:
  - 1k-5k ops
  - 100-2k symbols
  - many shader groups eliminated entirely

Some stats: frame 1350

- Texture:
  - 497M texture queries (each of which is a bicubic mipmap lookup, more when anisotropic)
  - ~9500 textures (~6700 with unique texels)
  - 700 GB of texture referenced (not counting dupes)
  - Runtime memory: 500 MB cache
  - www.openimageio.org

This is already old

- I’ve seen shader groups with 1.5M ops
- Not uncommon for >> 1 TB texture referenced

Where are we?

- Our shader library is converted
- Our shader writers are exclusively writing OSL
- All new shows using OSL
  - The Amazing Spider-Man
  - Men in Black 3
  - Oz, the Great and Powerful
  - other things I can't say
- We've ripped out support for C shaders

Open source

- opensource.imageworks.com
- github.com/imageworks/OpenShadingLangage
- “New BSD” license
- This is really our live development tree!

Main takeaways

- Small domain-specific language
- Separate implementation from description
- LLVM to JIT native code at runtime
- Extensive runtime optimization when network and parameters are known
- Outperforms compiled C shaders
- Open source

Acknowledgements / Q&A

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- Participants on the mail list

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