AnySL: Efficient and Portable Shading for Ray Tracing

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Motivation

- Setting
  - Realtime ray tracer (packet-based)
- Goal
  - Visually appealing effects in high-performance ray tracer

Option 1: Native Shading

- Internal
- Renderer language

- Pro: Fast!
- Con: Flexibility? Portability?
- Con: Don't want to make artists write SIMD shaders!

Option 2: Shading Languages

- External
- Domain-specific languages (e.g. RenderMan, OpenSL)

- Pro: Designed for this purpose
- Pro: Widely adopted
- Pro: Existing shaders can be reused
- Con: Have to interpret or write entire compiler toolchain

Option 3: AnySL

- A Library for high-performance shading
- Interface for the integration of shading languages into rendering engines

- Embedded just-in-time compiler (LLVM)
- Customized linker
- Special code transformation passes

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- Pro: “Best of options 1 & 2”

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- Con: Nothing, of course ;-)

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- An embedded just-in-time compiler (LLVM)
- A customized linker

- Pro: “Best of options 1 & 2”
- Con: ~~Nothing, of course~~ → Later ;-)

AnySL: Benefits

- *Efficiency*
  Use existing shading languages in your renderer without sacrificing performance
- *Portability*
  Reuse the same shader in different renderers
- *Simplicity*
  Minimize the integration effort
- *Flexibility*
  Edit, recompile & specialize shaders at runtime

AnySL: Shader Compilation

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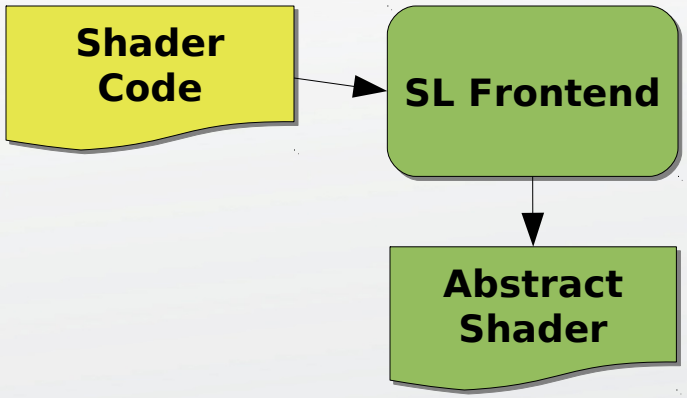

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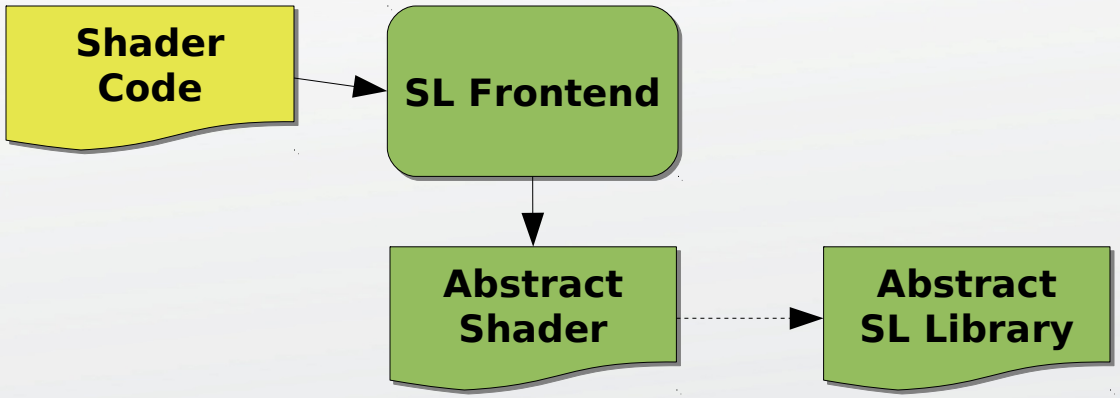

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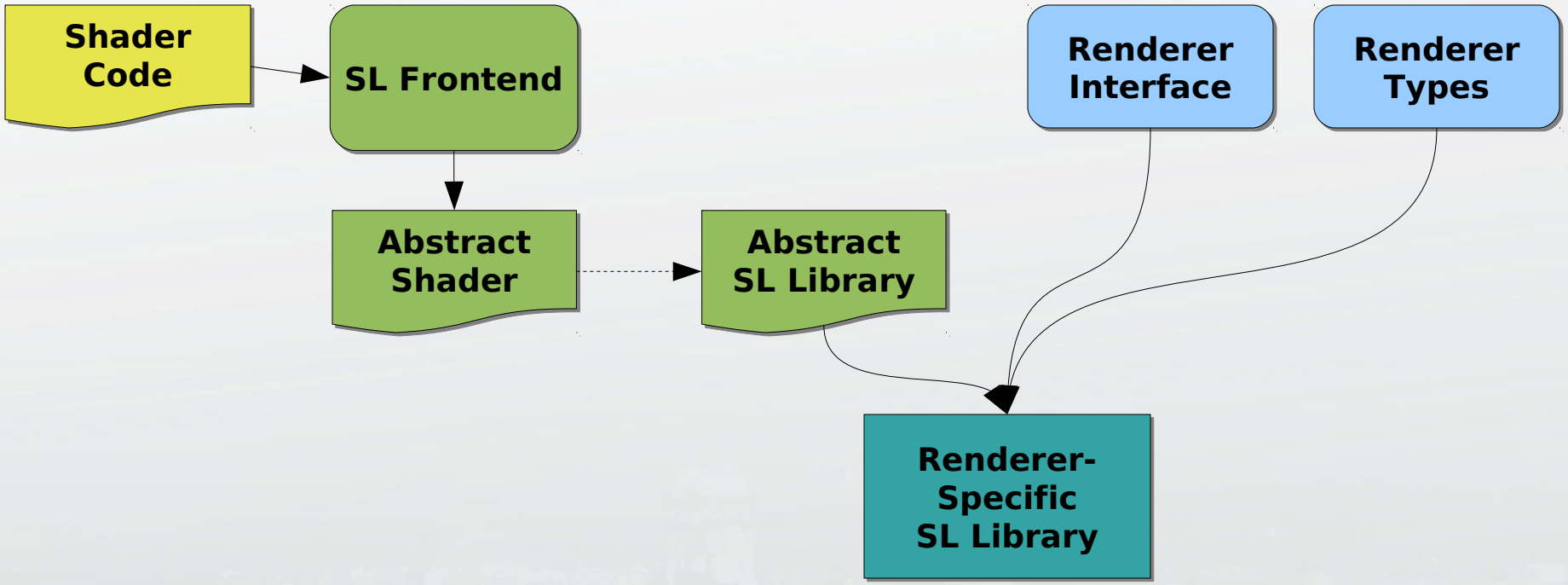
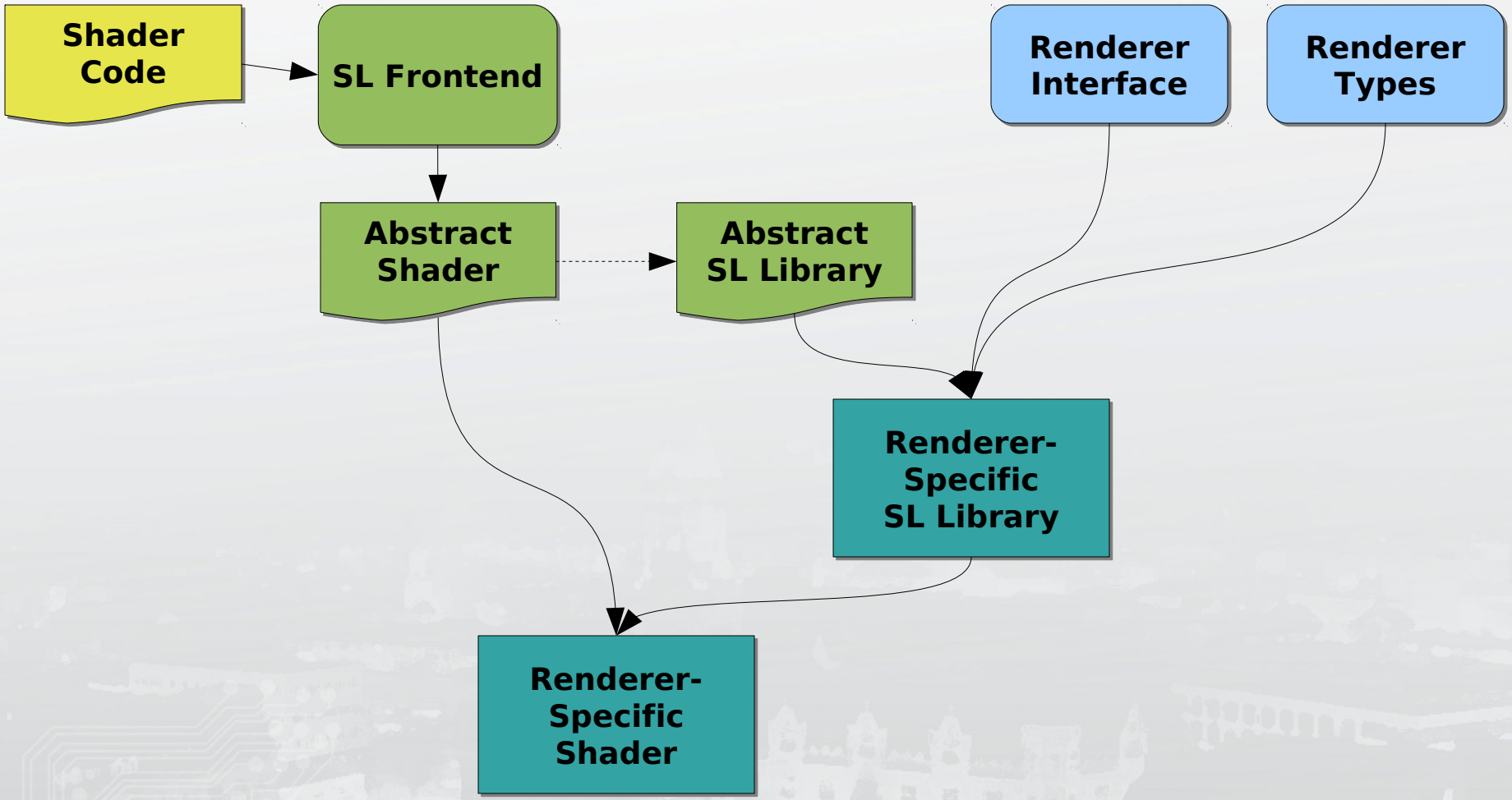
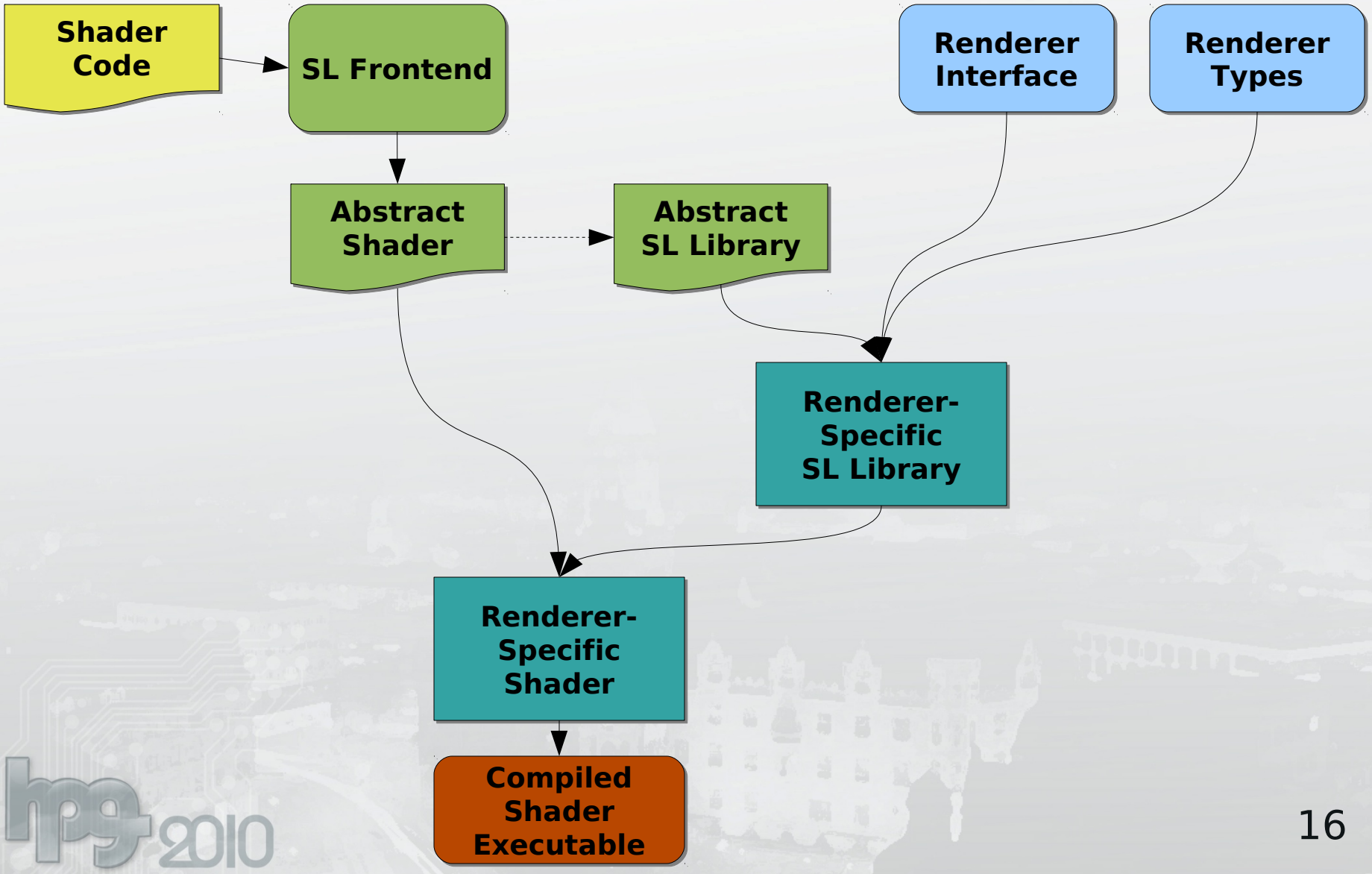


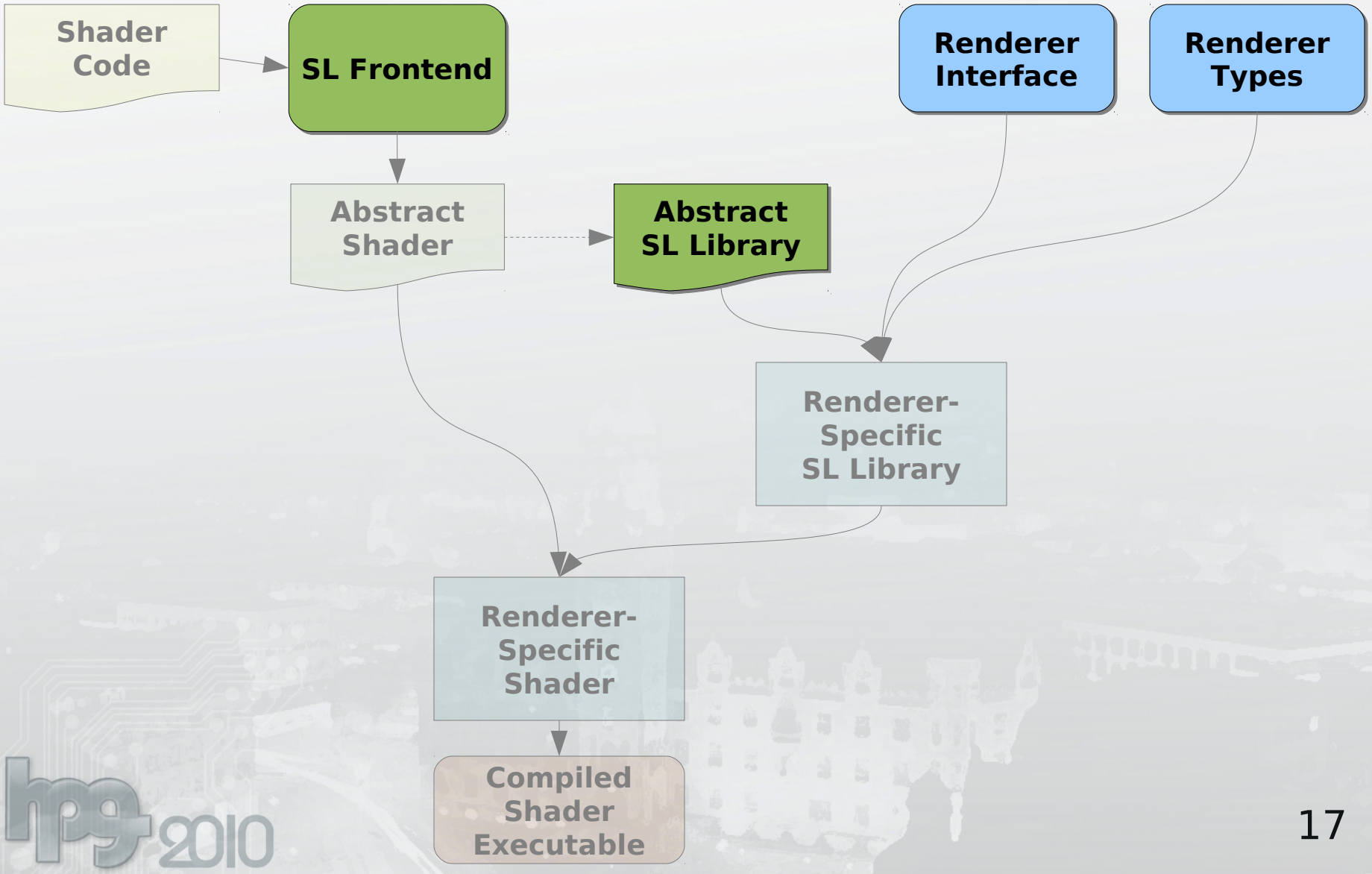
AnySL: Shader Compilation



AnySL: Shader Compilation

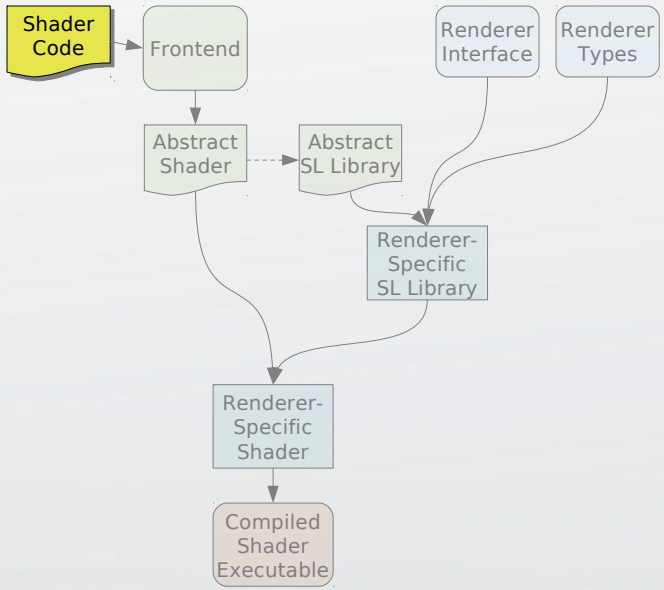


AnySL: External “Plugins”



Example: RenderMan Mirror Shader

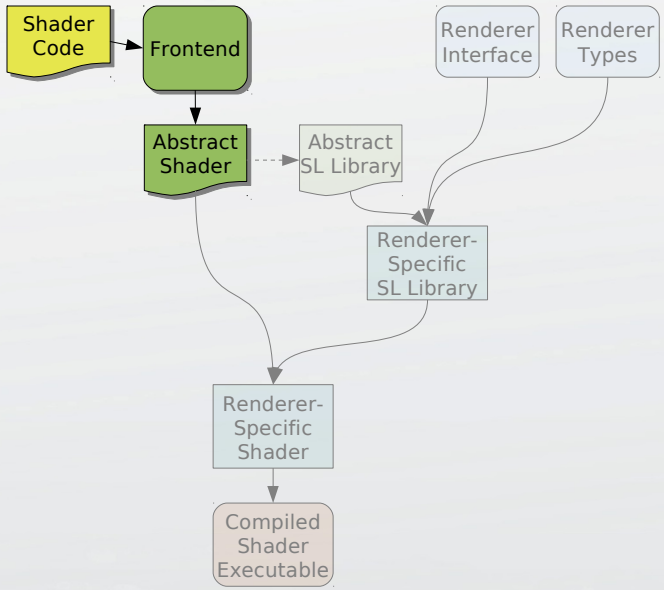
```
surface mirror() {
    vector dir = reflect(I, N);
    Ci = trace(P, dir);
}
```



Subroutine-Threaded Code (STC)

```
void shade(void* context) {
   void* dir = anysl_rsl_alloca("vector");

   anysl_rsl_reflect(dir, I, N);
   anysl_rsl_trace(Ci, context, P, reflDir);
}
```

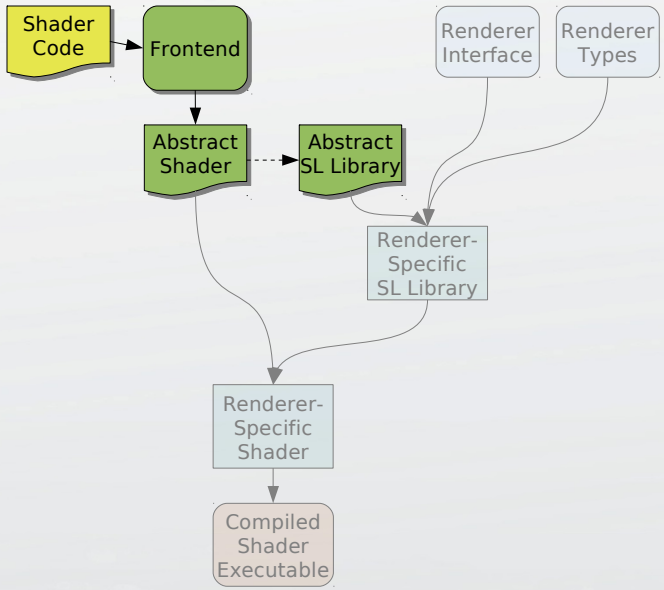


- All operations encoded in function calls
- Only abstract types
- Represented in LLVM bitcode

Generic Shading Library

```
void anysl_rsl_reflect(void* RES, void* I, void* N) {
    void* tmpv = anysl_rsl_alloca("vector");
    void* tmpf = anysl_rsl_alloca("float");
    void* c = anysl_rsl_float(2.f);

    anysl_rsl_dot(tmpf, i, n);
    anysl_rsl_mulff(tmpf, tmpf, c);
    anysl_rsl_mulvf(tmpv, n, tmpf);
    anysl_rsl_subvv(res, i, tmpv);
}
```

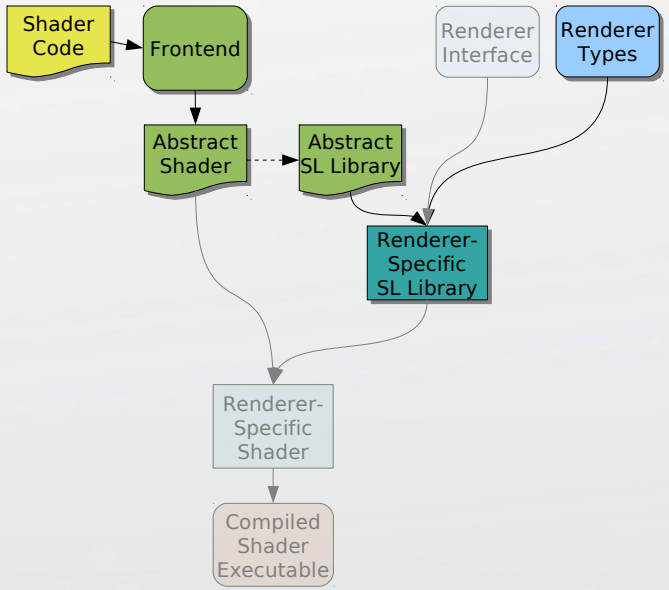


Low-Level Operation Implementation

```
#include “Renderer/Types.h”


void anysl_rsl_mulvf(void* RES, void* V, void* F) {
   Renderer::Vector* res = (Renderer::Vector*)RES;
   Renderer::Vector v = *(Renderer::Vector*)V;
   Renderer::Float f = *(Renderer::Float*)F;

   Renderer::mulvf(res, v, f);
}
```



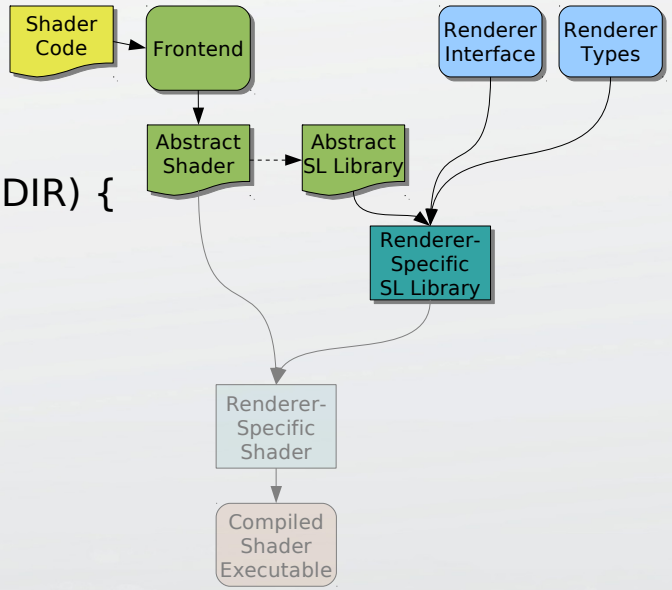
- Low-level operations have to be implemented with renderer's types

Renderer-Dependent Language Features

```
#include “Renderer/Interface.h”


void anysl_rsl_trace(void* RES, void* context, void* P, void* DIR) {
   Renderer::Color* res = (Renderer::Color*)RES;
   Renderer::Point p = *(Renderer::Point*)P;
   Renderer::Vector dir = *(Renderer::Vector*)DIR;

   Renderer::traceRay(context, res, p, dir);
}
```



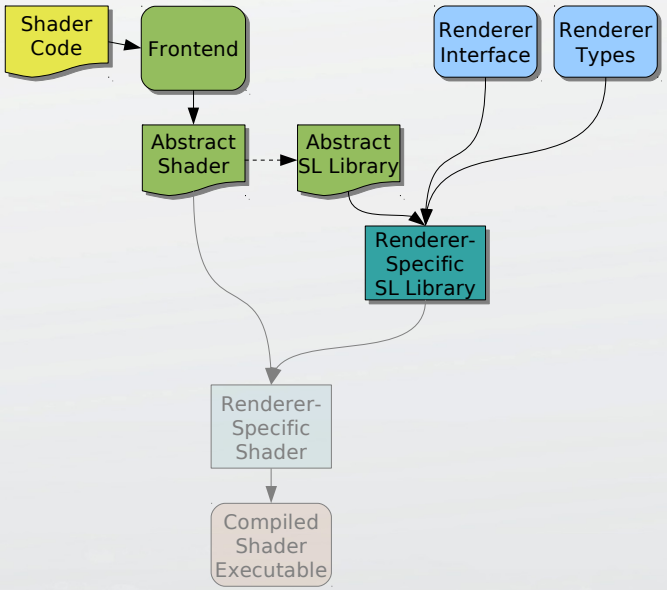
- Functionality of renderer required for *trace()*, *illuminance()*, etc.

Inlining 1: Concrete Types → Low-Level

```
typedef float Renderer::Float;
typedef struct { float x; float y; float z; } Renderer::Vector;

void anysl_rsl_mulvf(void* RES, void* V, void* F) {
    Renderer::Vector* res = (Renderer::Vector*)RES;
    Renderer::Vector v = *(Renderer::Vector*)V;
    Renderer::Float f = *(Renderer::Float*)F;

    res->x = v.x * f;
    res->y = v.y * f;
    res->z = v.z * f;
}
```

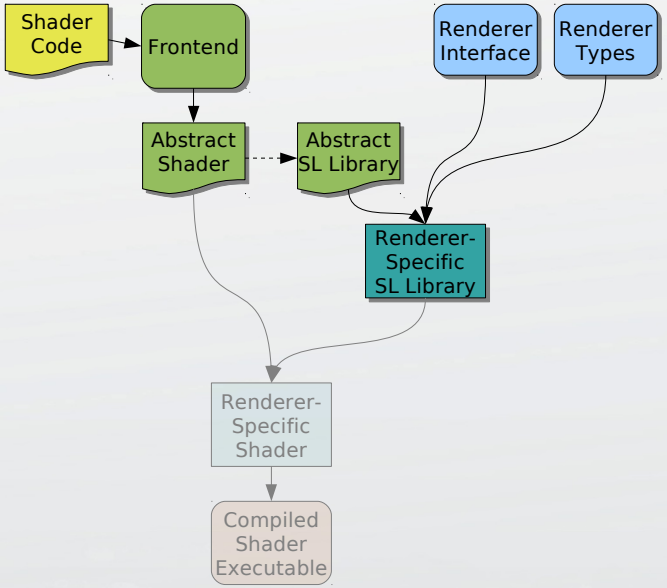


Inlining 2: Low-Level → Generic Library

```
typedef float Renderer::Float;
typedef struct { float x; float y; float z; } Renderer::Vector;

void anysl_rsl_reflect(void* RES, void* I, void* N) {
    Renderer::Vector* res = (Renderer::Vector*)RES;
    Renderer::Vector i = *(Renderer::Vector*)I;
    Renderer::Normal n = *(Renderer::Normal*)N;
    Renderer::Float c = Renderer::Float(2.f);
    Renderer::Vector v;
    Renderer::Float f;


    f = i.x * n.x + i.y * n.y + i.z * n.z;  // dot
    f *= c;                                 // mulff
    v.x = n.x * f;                          // mulvf
    v.y = n.y * f;
    v.z = n.z * f;
    res->x = i.x - v.x;                     // subvv
    res->y = i.y - v.y;
    res->z = i.z - v.z;
}
```



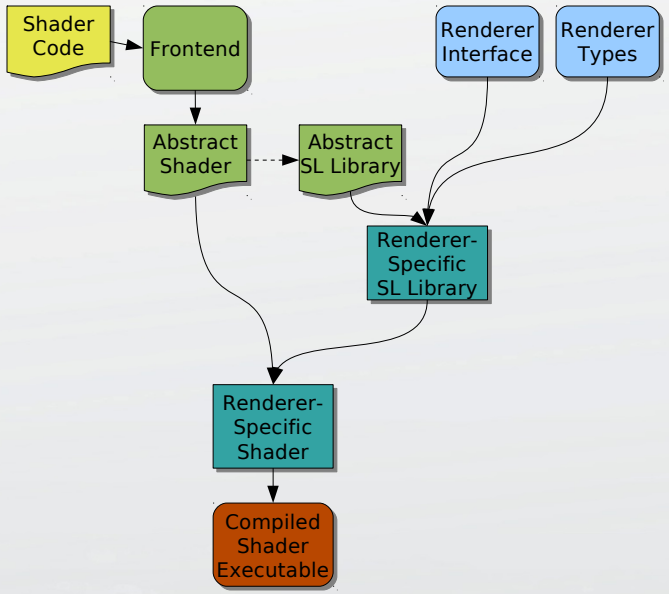
Inlining 3: Generic Library → Shader

```
typedef float Renderer::Float;
typedef struct { float x; float y; float z; } Renderer::Vector;

void shade(void* context) {
    Renderer::Color* ci = (Renderer::Color*)Ci;
    Renderer::Vector i = *(Renderer::Vector*)I;
    Renderer::Normal n = *(Renderer::Normal*)N;
    Renderer::Point p = *(Renderer::Point*)P;
    Renderer::Vector dir;
    Renderer::Vector v;
    Renderer::Float f;

    f = i.x * n.x + i.y * n.y + i.z * n.z;
    f *= 2.f;
    v.x = n.x * f;
    v.y = n.y * f;
    v.z = n.z * f;
    dir.x = i.x - v.x;
    dir.y = i.y - v.y;
    dir.z = i.z - v.z;

    Renderer::traceRay(context, ci, p, dir);
}
```



Not distinguishable from native code anymore!

STC: Flexible Type Replacement

```
void anysl_rsl_mulff(void* RES, void* A, void* B) {
   Renderer::Float* res = (Renderer::Float*)RES;
   Renderer::Float a = *(Renderer::Float*)A;
   Renderer::Float b = *(Renderer::Float*)B;

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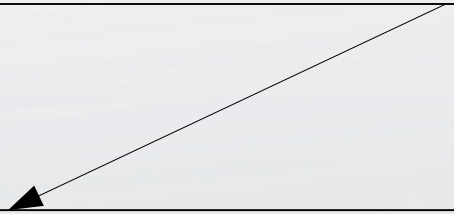

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typedef float
        Renderer::Float;
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```

Standard Arithmetic

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```

```
typedef struct { float f; float u; float v; }
        Renderer::Float;
```

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   Renderer::Float b = *(Renderer::Float*)B;

   *res = a * b;
}
```

Automatic Differentiation

```
typedef struct { float f; float u; float v; }
        Renderer::Float;

void anysl_rsl_mulff(void* RES, void* A, void* B) {
   Renderer::Float* res = (Renderer::Float*)RES;
   Renderer::Float a = *(Renderer::Float*)A;
   Renderer::Float b = *(Renderer::Float*)B;

   res->f = a.f * b.f;
   res->u = a.u * b.f + a.f * b.u;
   res->v = a.v * b.f + a.f * b.v;
}
```

AnySL: Benefits

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- *Flexibility*

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- *Efficiency*
- *Portability* ✓
  STC is renderer- and platform-independent
- *Simplicity* ✓
  Implement frontend + interpreter instead of compiler toolchain
- *Flexibility* ✓
  STC is resolved at runtime → edit, recompile, AD, ...

AnySL: Benefits

- *Efficiency?*
  Inlining & optimizations remove all overhead
- *Portability* ✓
  STC is renderer- and platform-independent
- *Simplicity* ✓
  Implement frontend + interpreter instead of compiler toolchain
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- Worst case: 4x slower than native SIMD shader

- Solution: AnySL transforms shader to execute *k* instances of original code in parallel

Automatic SIMD Code Generation

- Where is the problem?

scalar

```
float scalarFn(float a, float b) {
   for (int i=0; i < b; ++i) {
      if (a > b) ++b;
      else ++a;
   }
   return a * b;
}
```

Automatic SIMD Code Generation

- Where is the problem?
  - Control-flow of scalar instances can diverge (requires blending)

scalar

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```

Automatic SIMD Code Generation

- Where is the problem?
  - Control-flow of scalar instances can diverge (requires blending)
  - Don't want to write that code by hand...

scalar

```
float scalarFn(float a, float b) {
   for (int i=0; i < b; ++i) {
      if (a > b) ++b;
      else ++a;
   }
   return a * b;
}
```

packetized

```
__m128 simdFn(__m128 a, __m128 b) {
   __m128 _mm_one = _mm_set_ps1(1.f);
   __m128 i = _mm_set_ps1(0.f);
   do {
      __m128 loopMask = _mm_cmpgt_ps(i, b);
      i = _mm_add_ps(i, _mm_one);
      __m128 ifcmp = _mm_cmpgt_ps(a, b);
      __m128 maskT = _mm_and_ps(loopMask, ifcmp);
      __m128 maskF = _mm_and_ps(loopMask, _mm_neg_ps(ifcmp));
      __m128 b' = _mm_add_ps(b, _mm_one);
      __m128 a' = _mm_add_ps(a, _mm_one);
      b = _mm_blendv_ps(maskT, b', b);
      a = _mm_blendv_ps(maskF, a', a);
   } while (_mm_movemask_ps(loopMask));
   return _mm_mul_ps(a, b);
}
```

RenderMan Glass Shader

RenderMan Glass Shader: Code

```
surface
glass ( float Ka = 0.2, Kd = 0, Ks = 0.5;
        float Kr = 1, Kt = 1, roughness = 0.05, blur = 0, eta = 1.5;
        color specularcolor = 1, transmitcolor = 1;
        float samples = 1; )
{
    normal Nf;              /* Forward facing normal vector */
    vector IN;              /* normalized incident vector */
    vector Rfldir, Rfrdir;   /* Smooth reflection/refraction directions */
    vector uoffset, voffset; /* Offsets for blur */
    color ev = 0;           /* Color of the environment reflections */
    color cr = 0;           /* Color of the refractions */
    vector R, Rdir;          /* Direction to cast the ray */
    uniform float i, j;
    float kr, kt;

    /* Construct a normalized incident vector */
    IN = normalize (I);

    /* Construct a forward facing surface normal */
    Nf = faceforward (normalize(N), I);

    /* Compute the reflection & refraction directions and amounts */
    fresnel (IN, Nf, (I.N < 0) ? 1.0/eta : eta, kr, kt, Rfldir, Rfrdir);
    kr *= Kr;
    kt *= Kt;

    /* Calculate the reflection color */
    if (kr > 0.001) {
        /* Rdir gets the perfect reflection direction */
        Rdir = normalize (Rfldir);
        if (blur > 0) {
            /* Construct orthogonal components to Rdir */
            uoffset = blur * normalize (vector (zcomp(Rdir) - ycomp(Rdir),
                xcomp(Rdir) - zcomp(Rdir),
                ycomp(Rdir) - xcomp(Rdir)));
            voffset = Rdir ^ uoffset;
            for (i = 0;  i < samples;  i += 1) {
                for (j = 0;  j < samples;  j += 1) {
                    /* Add a random offset to the smooth reflection vector */
                    R = Rdir +
                        ((i + float random())/samples - 0.5) * uoffset +
                        ((j + float random())/samples - 0.5) * voffset;
                    ev += trace (P, normalize(R));
                }
            }
            ev *= kr / (samples*samples);
        } else {
            /* No blur, just do a simple trace */
            ev = kr * trace (P, Rdir);
        }
    }

    /* Calculate the refraction color */
    if (kt > 0.001) {
        /* Rdir gets the perfect refraction direction */
        Rdir = normalize (Rfrdir);
        if (blur > 0) {
            /* Construct orthogonal components to Rdir */
            uoffset = blur * normalize (vector(zcomp(Rfrdir) - ycomp(Rfrdir),
                    xcomp(Rfrdir) - zcomp(Rfrdir),
                    ycomp(Rfrdir) - xcomp(Rfrdir)));
            voffset = Rfrdir ^ uoffset;
            for (i = 0;  i < samples;  i += 1) {
                for (j = 0;  j < samples;  j += 1) {
                    /* Add a random offset to the smooth reflection vector */
                    R = Rdir +
                        ((i + float random())/samples - 0.5) * uoffset +
                        ((j + float random())/samples - 0.5) * voffset;
                    cr += trace (P, R);
                }
            }
            cr *= kt / (samples*samples);
        } else {
            /* No blur, just do a simple trace */
            cr = kt * trace (P, Rdir);
        }
    }

    Oi = 1;
    Ci = ( Cs * (Ka*ambient() + Kd*diffuse(Nf)) +
        specularcolor * (ev + Ks*specular(Nf,-IN,roughness)) +
        transmitcolor * cr );
}
```

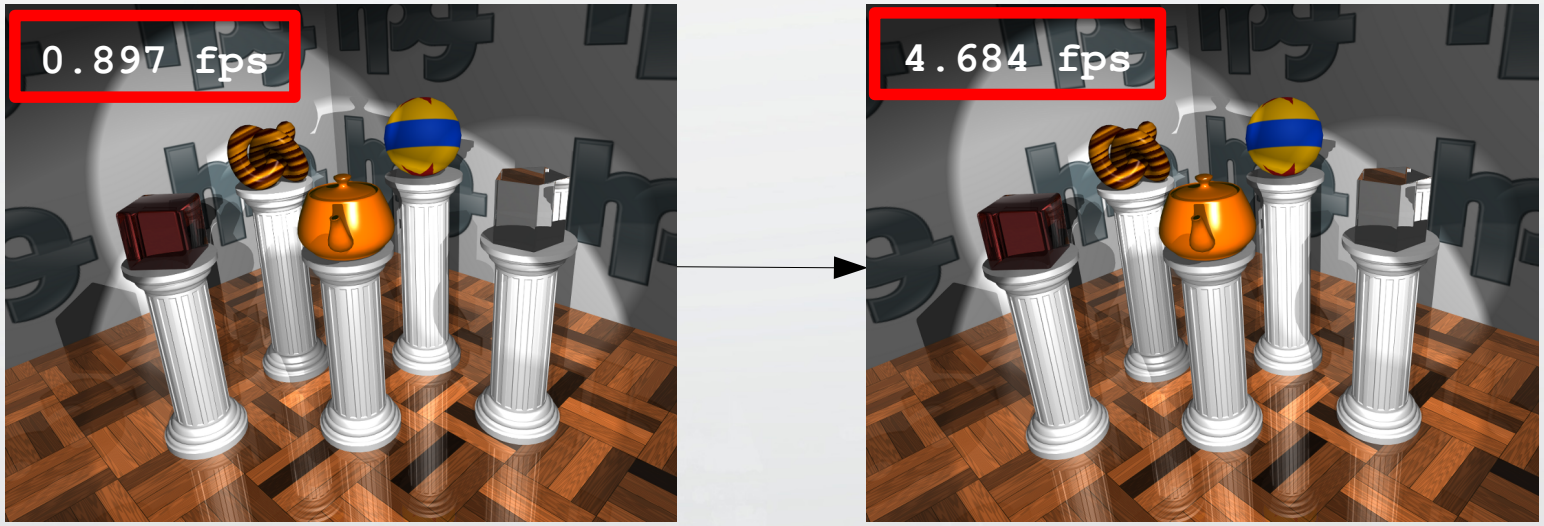
Evaluation

- Automatic SIMD Code Generation

sequential

Evaluation

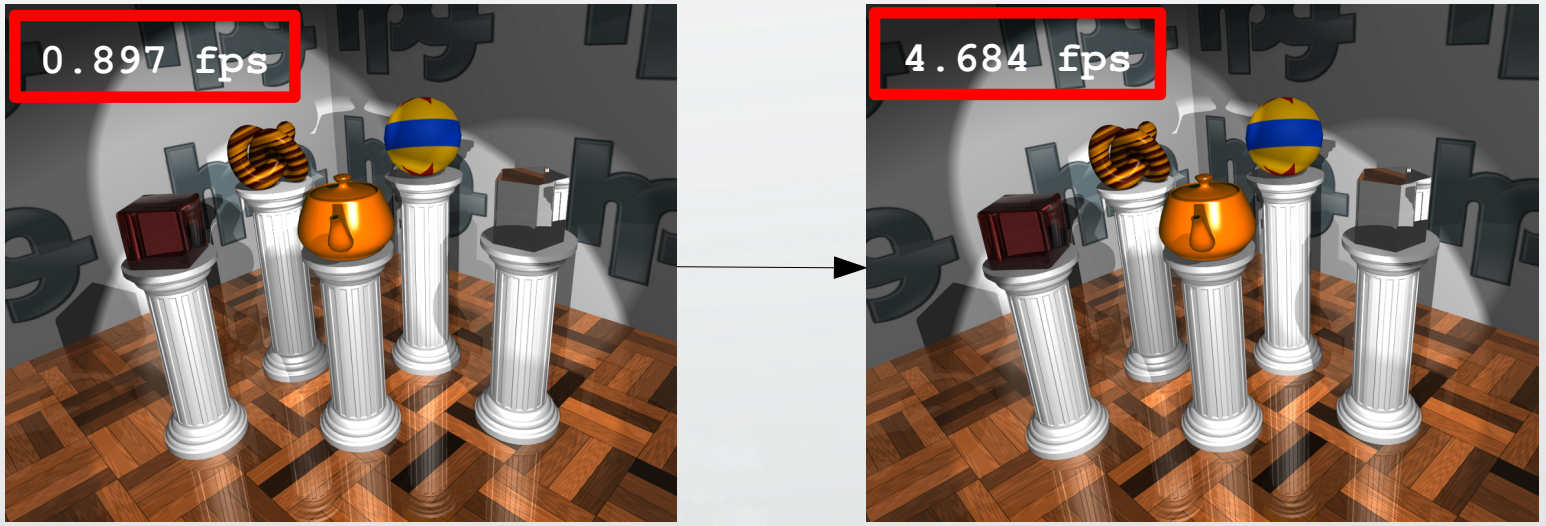
- Automatic SIMD Code Generation



sequential **packetized**

Evaluation

- Automatic SIMD Code Generation

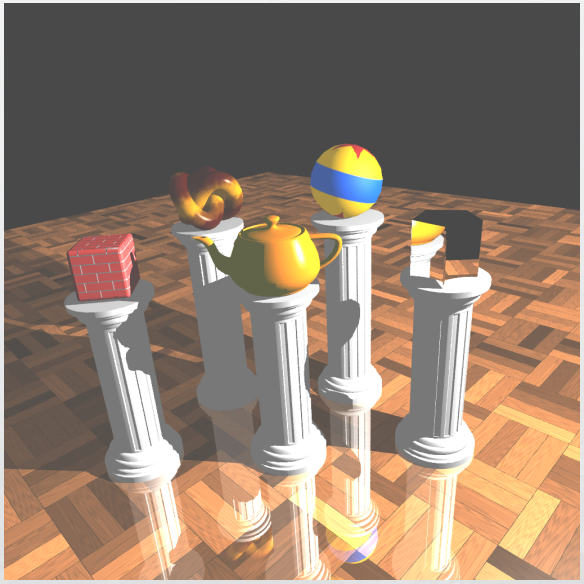


sequential packetized

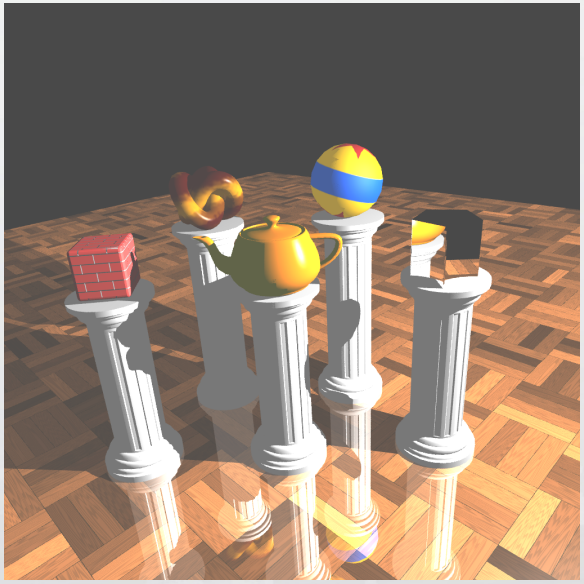
- RTfact: average speedup vs. sequential shading: 3.9x !
  - SIMD width 4 (SSE4.1)
  - Within 10% of performance of hand-optimized shaders

Evaluation

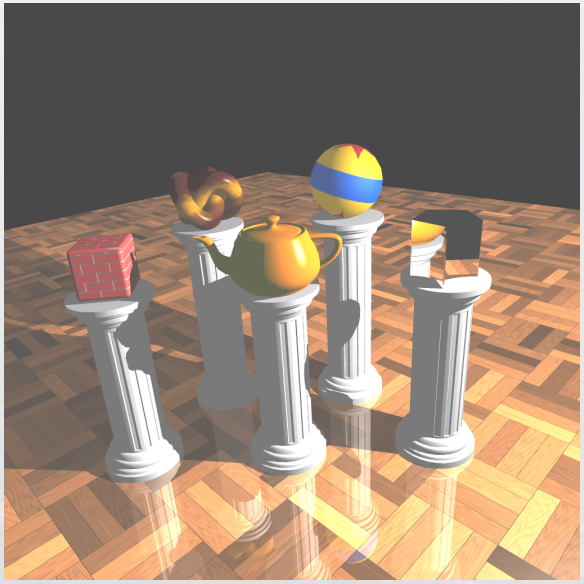
- Equal visual appearance across renderers



Manta



PBRT



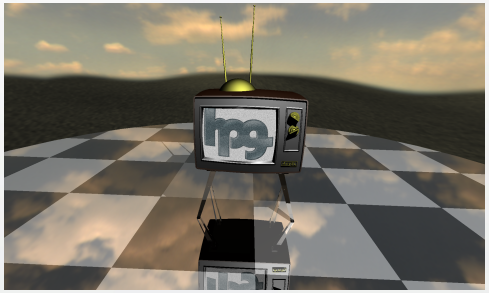
RTfact

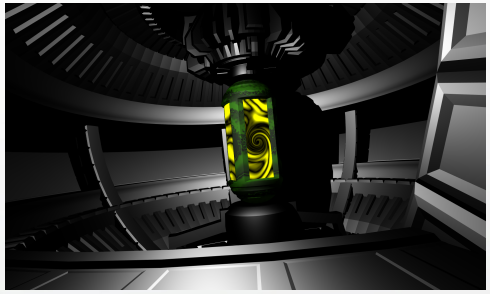
Limitations

- Performance vs. hand-tuned native shading
- Currently only surface shaders
- No unified API for shading languages

Future Work

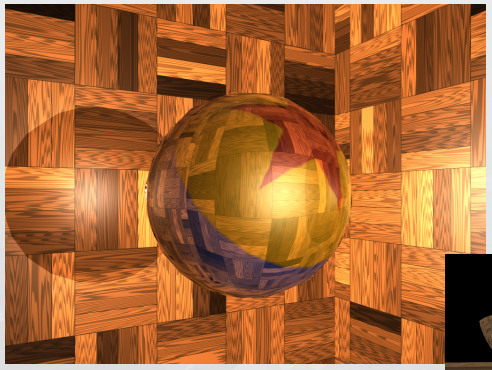
- Rasterization support
  - PTX Back-end for LLVM
    http://sourceforge.net/projects/llvmptxbackend/
  - First results with deferred shading in OGRE
  - Native shading via GLSL/HLSL in progress
- GPU Ray Tracer (OptiX?)
- Front-ends: OpenSL, GLSL/HLSL

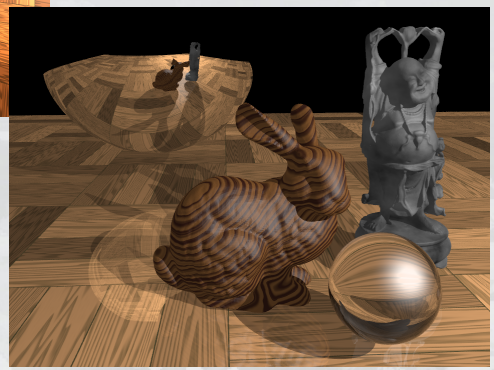




Thank you!

Questions?



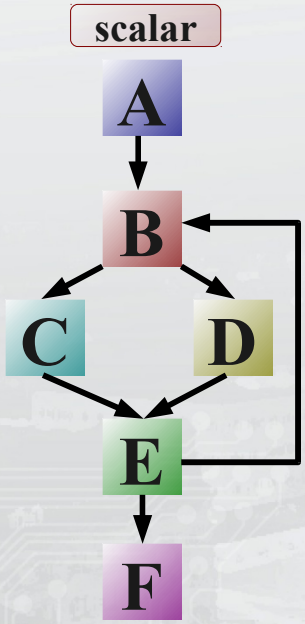


Summary

- Efficient Integration of shading languages into a renderer made easy:
  - Use/Write front-end that produces threaded code
  - Integrate AnySL into renderer via slim API
  - Implement renderer-dependent language features (e.g. illuminance)
  - No more implementation of full-fledged compiler toolchain!
- Subroutine-Threaded Code & Type Replacement
  - Portable shader format
  - Automatic differentiation
- Efficiency & Flexibility:
  - Inlining & Optimization of STC → no performance sacrifice
  - Runtime recompilation & specialization
- Automatic SIMD Code Generation → 3.9x speedup

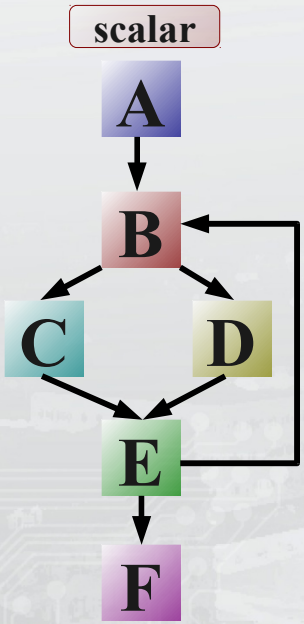
Automatic Packetization

- Where is the problem?



Automatic Packetization

- Where is the problem?
  - Control-flow of scalar instances can diverge!



Executed Blocks ($k = 4$)

A B D E F

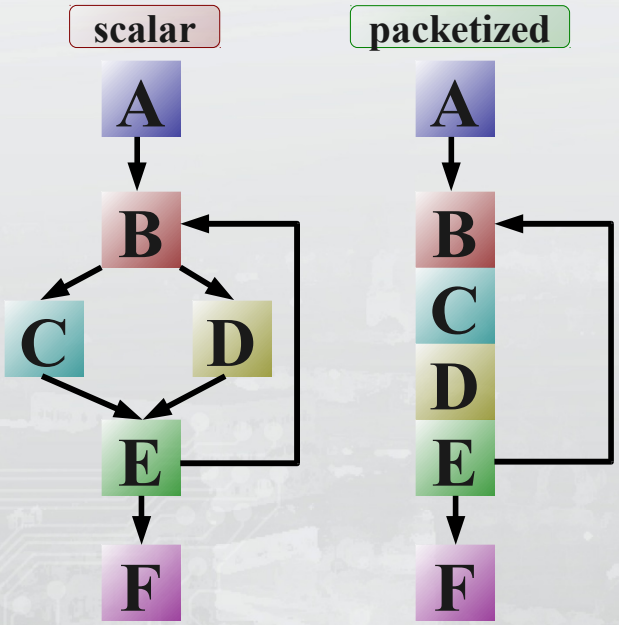
A B C E F

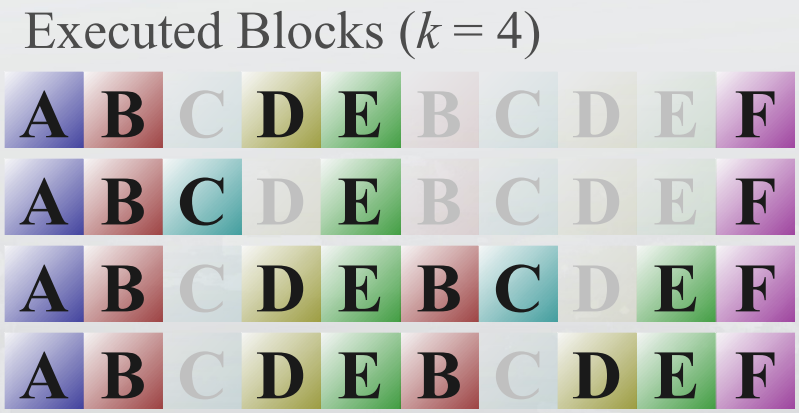
A B D E B C E F

A B D E B D E F

Automatic Packetization

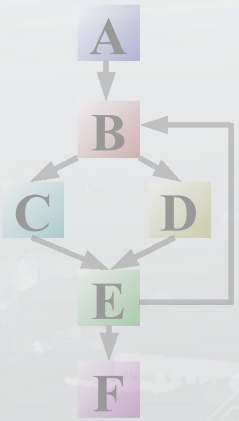
- Where is the problem?
  - Control-flow of scalar instances can diverge!
  - Packet code: mask out results of inactive instances





Automatic SIMD Code Generation

- Where is the problem?
  - Control-flow of scalar instances can diverge!
  - Don't want to write that code by hand...



scalar

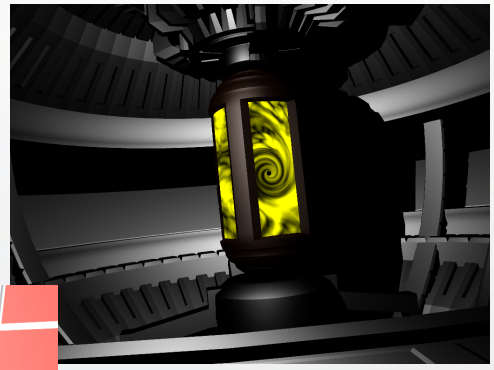
```
float scalarFn(float a, float b) {
   for (int i=0; i < b; ++i) {
      if (a > b) ++b;
      else ++a;
   }
   return a * b;
}
```

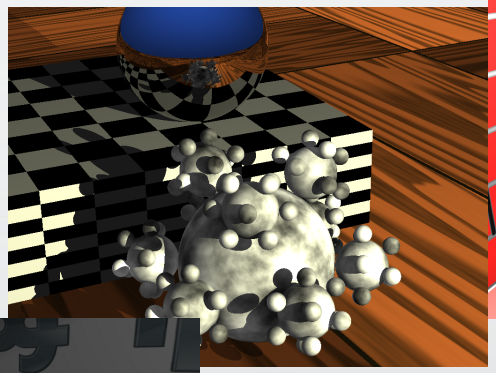
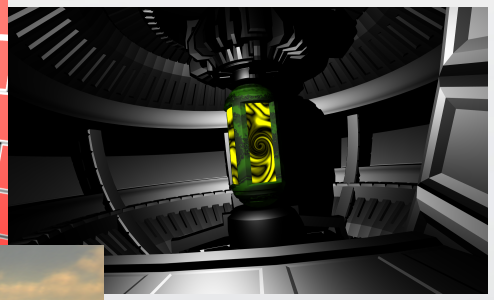
packetized

```
__m128 simdFn(__m128 a, __m128 b) {
   __m128 _mm_one = _mm_set_ps1(1.f);
   __m128 i = _mm_set_ps1(0.f);
   do {
      __m128 loopMask = _mm_cmpgt_ps(i, b);
      i = _mm_add_ps(i, _mm_one);
      __m128 ifcmp = _mm_cmpgt_ps(a, b);
      __m128 maskT = _mm_and_ps(loopMask, ifcmp);
      __m128 maskF = _mm_and_ps(loopMask, _mm_neg_ps(ifcmp));
      __m128 b' = _mm_add_ps(b, _mm_one);
      __m128 a' = _mm_add_ps(a, _mm_one);
      b = _mm_blendv_ps(maskT, b', b);
      a = _mm_blendv_ps(maskF, a', a);
   } while (_mm_movemask_ps(loopMask));
   return _mm_mul_ps(a, b);
}
```

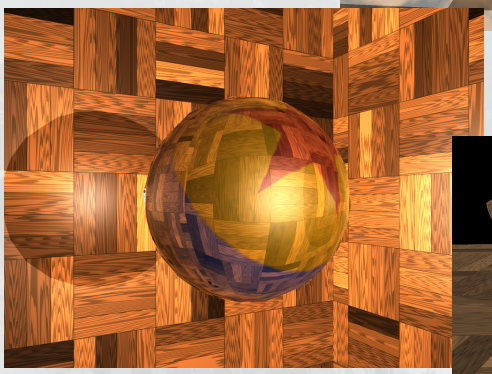
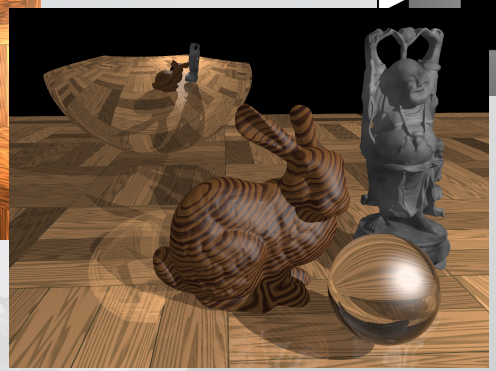
Wohin...

...mit den huebschen Bildchen?





Subroutine-Threaded Code (STC)

- Every operation encoded in function call
  - Pointers to results are passed around
- Only abstract type information
  - Concrete types provided by renderer
- Traditionally:
  Interpreter resolves STC at runtime by calling renderer for each operation

Resolving Threaded Code (aka “Type Replacement”)

- Renderer provides “runtime”-module
  - Defines types “float”, “vector”, and “matrix”
    → replace abstract types in STC
  - Implements low-level arithmetic operations on top of these
  - Implements renderer-dependent language functionality
    → illuminance(), traceRay(), …
- AnySL links runtime with shader-STC, inlines, and optimizes
  → Code not distinguishable from a native shader

Generic Shader Library

- Shading languages require set of standard operations
  - normalize, faceforward, smoothstep, fresnel, …
- Only depend on data types of renderer, no special functionality required
- STC: implement operations on top of abstract data types “float” and “vector”

→ Renderer- and language-independent library!