LuisaRender

A High-Performance Rendering System

Shaokun Zheng[1], Zhiqian Zhou[1], Xin Chen[1], Difei Yan[1], Chuyan Zhang[1], Yuefeng Geng[2], Yan Gu[3], and Kun Xu[1]

[1] Tsinghua University [2] Recreate Games [3] University of California, Riverside

luisa-render.com

LuisaRender

A High-Performance Rendering System

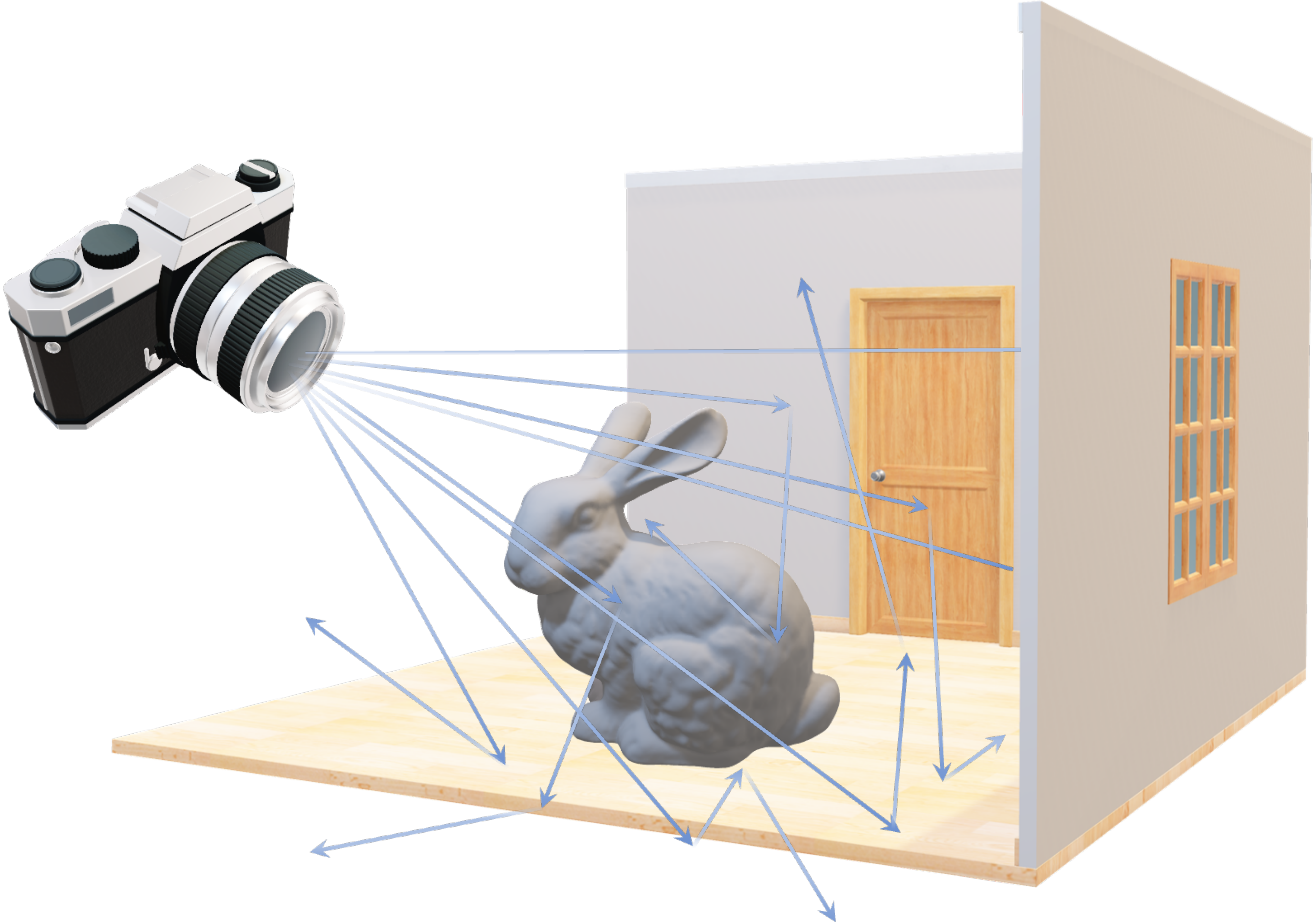
LuisaRender

A High-Performance Rendering System with Layered and Unified Interfaces on Stream Architectures

LuisaCompute

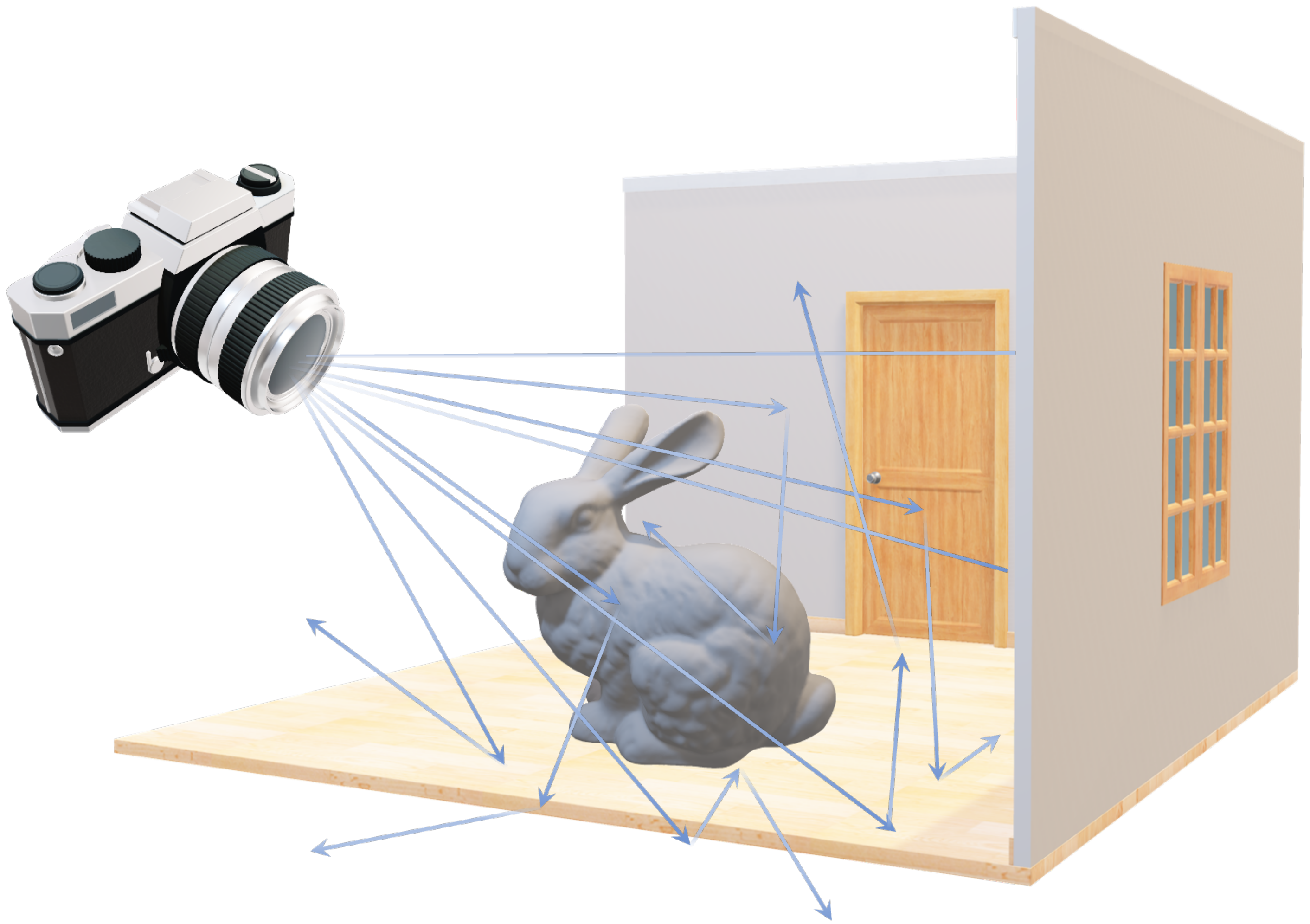
A Computing Framework on Stream Architectures for Rendering and beyond

我们为什么要做一个
新的渲染计算框架？



Step 1: CPU 上的玩具渲染器

```
for pixel in image:
  Li = [0, 0, 0]
  ray = camera.generate_ray(pixel)
  for depth in range(bounces):
    hit = scene.trace_closest(ray)
    Li += hit.material.shade(ray, hit)
    ray = hit.material.sample(ray, hit)
  film[pixel] += Li
```



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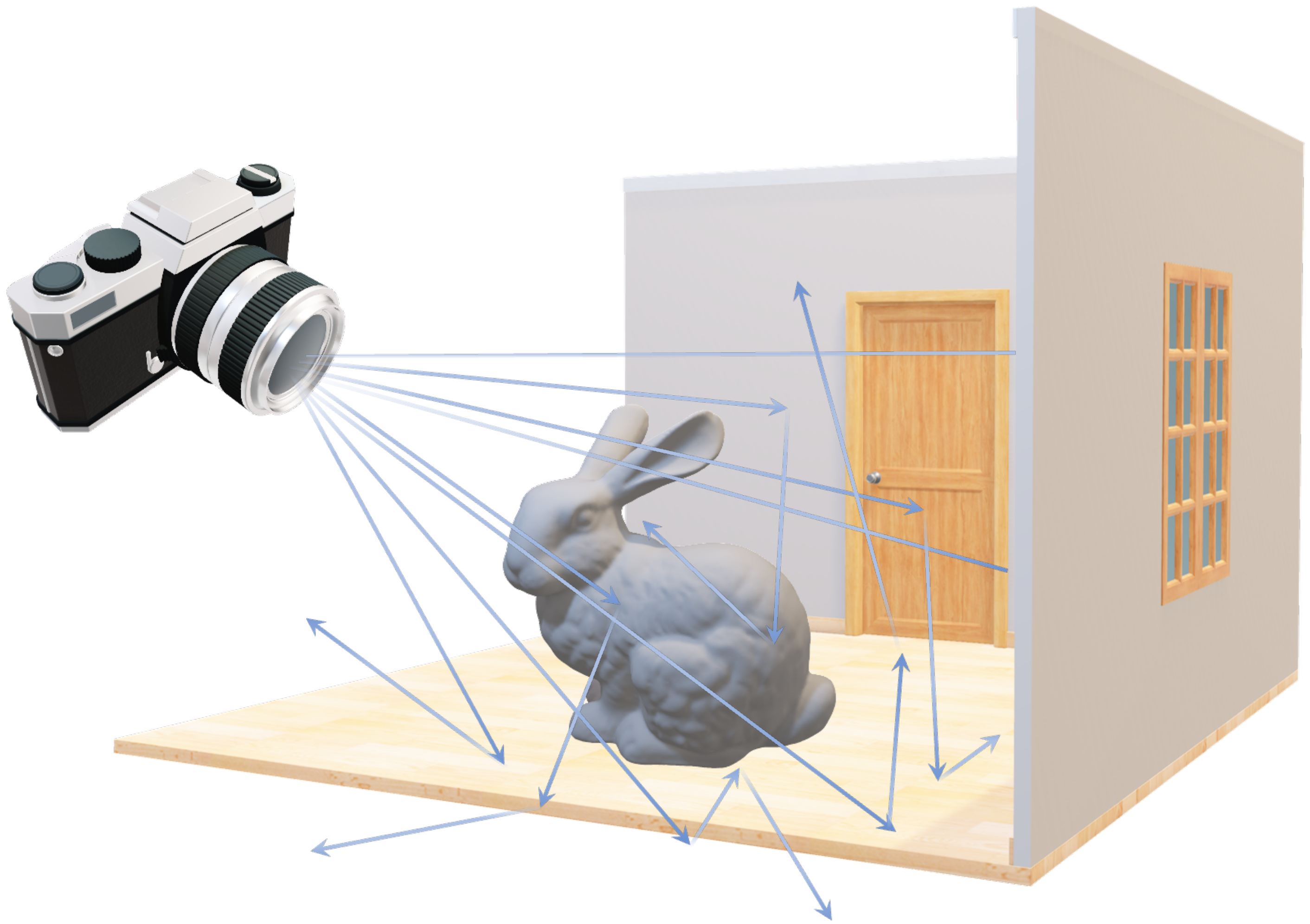
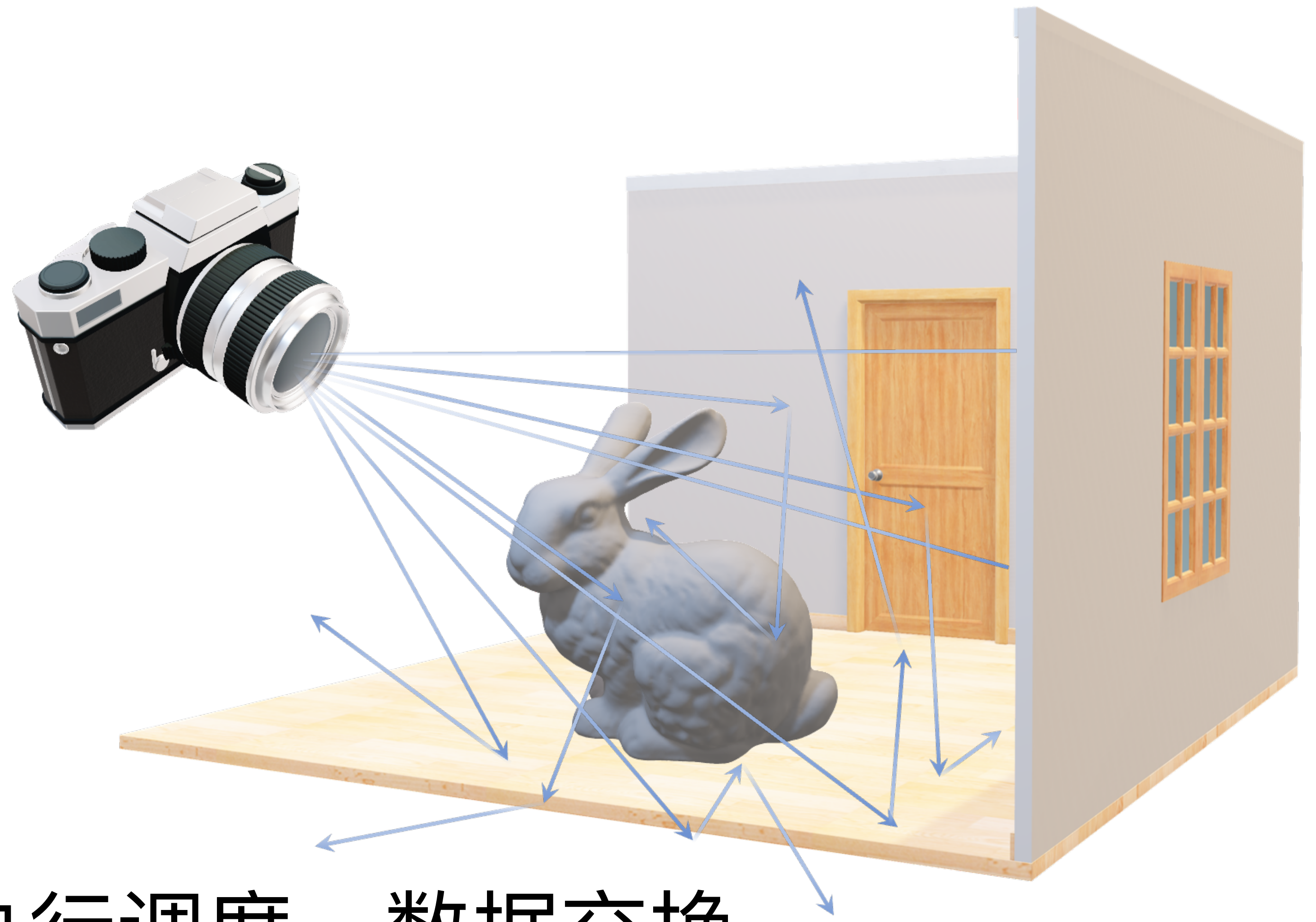


Step 2: GPU 上的玩具渲染器

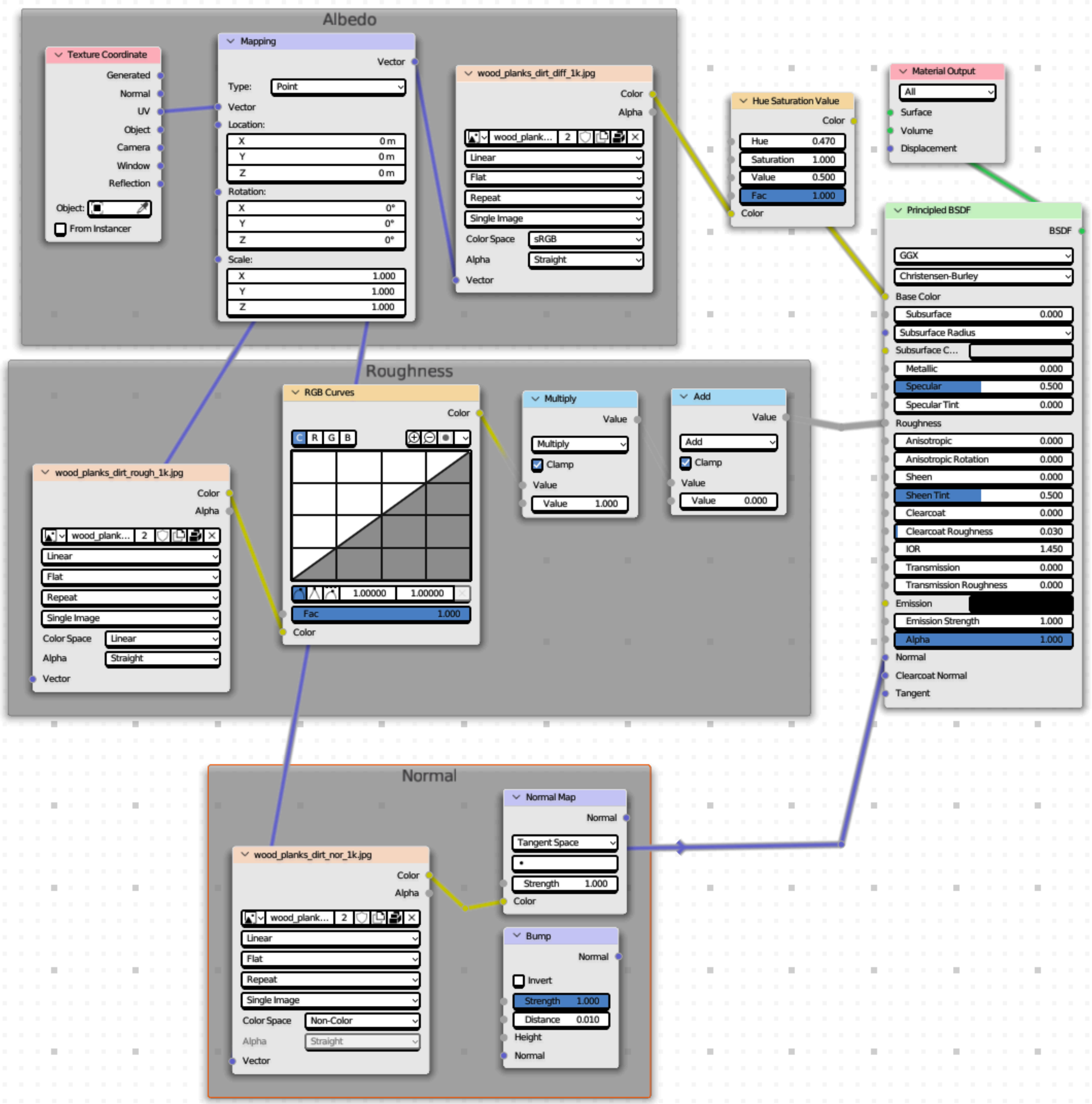
```
kernel render(scene, camera, film):
  Li = [0, 0, 0]
  ray = camera.generate_ray(pixel)
  for depth in range(bounces):
    hit = scene.trace_closest(ray)
    Li += hit.material.shade(ray, hit)
    ray = hit.material.sample(ray, hit)
  film[pixel] += Li

gpu_device.dispatch(render, pixels)
```



复杂度提升：着色器编写、资源管理、执行调度、数据交换...

Step 3.1: 丰富 GPU 渲染器的材质/光照/...



❌ 着色语言表达力不佳

- 大量的运行时分支/着色器变体?
- 如何动态扩展新插件?
- 如何支持 Shader Graph?

Step 3.2: 支持其他硬件/平台...

```
kernel void add_arrays(device const float* inA,
                       device const float* inB,
                       device float* result,
                       uint index [[thread_position_in_grid]])
{
    // the for-loop is replaced with a collection of threads, each of which
    // calls this function.
    result[index] = inA[index] + inB[index];
}
```

```
__global__ void vecAdd(int *A,int *B,int *C,int N)
{
    int i = blockIdx.x * blockDim.x + threadIdx.x;
    C[i] = A[i] + B[i];
}
```

❌ 着色语言表达力不佳

❌ 分裂的 API 和着色语言

- 相同的逻辑编写 N 遍?
- 使用大量宏统一语法?
- 复杂的着色器交叉编译?

DirectX XII ULTIMATE

NVIDIA CUDA

Vulkan™

LLVM

oneAPI

Step 4: 维护和性能优化...

❌ 着色语言表达力不佳

❌ 分裂的 API 和着色语言

❌ 维护复杂，优化困难，极易出错

Step 4: 维护和性能优化...

❌ 着色语言表达力不佳

❌ 分裂的 API 和着色语言

❌ 维护复杂，优化困难，极易出错

- 扩展能力低下
- 大量的着色器变体
- 多平台的大量重复代码
- 繁杂的编译/配置流程
- 大量的运行时分支
- 性能低下的 Shader Virtual Machine
- 混乱的宏开关

可编程性

跨平台

高性能

❌ 着色语言表达力不佳

❌ 分裂的 API 和着色语言

❌ 维护复杂，优化困难，极易出错

可编程性

跨平台

高性能

相关工作

- Slang [He et al. 2017]
  - 扩展 HLSL，提供泛型和接口语法，用于多态编程与着色器特化
  - 引入“参数块”功能以提升着色器参数绑定效率
- Rodent [Pérard-Gayot et al. 2019]
  - 利用 AnyDSL [Leißa et al. 2018] 的 Partial Evaluation 能力为每个场景特化渲染器
- Dr.JIT [Jakob et al. 2022]
  - 嵌入 C++ 和 Python 的追踪式的可微分领域特定语言（DSL）
- 渲染之外：Halide [Ragan-Kelley et al. 2012]、Taichi [Hu et al. 2019]

相关工作

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即时编译

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领域特定语言

即时编译

特化

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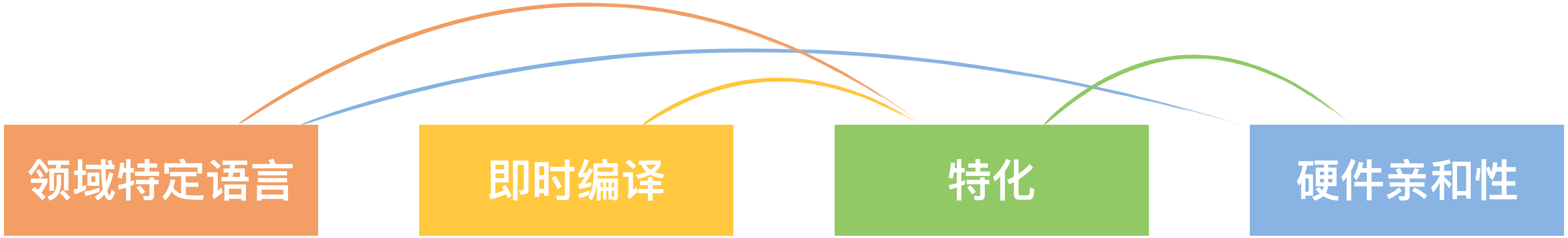
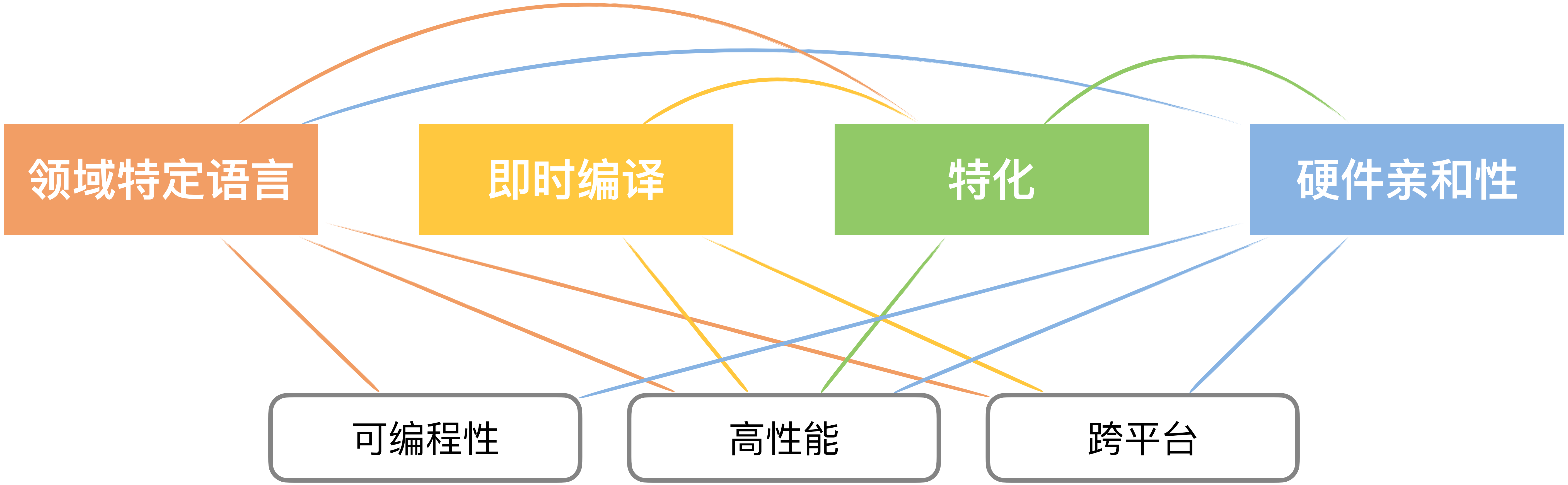
领域特定语言

硬件亲和性

即时编译

特化


领域特定语言
即时编译
特化
硬件亲和性



领域特定语言
即时编译
特化
硬件亲和性
可编程性
高性能
跨平台

可编程性

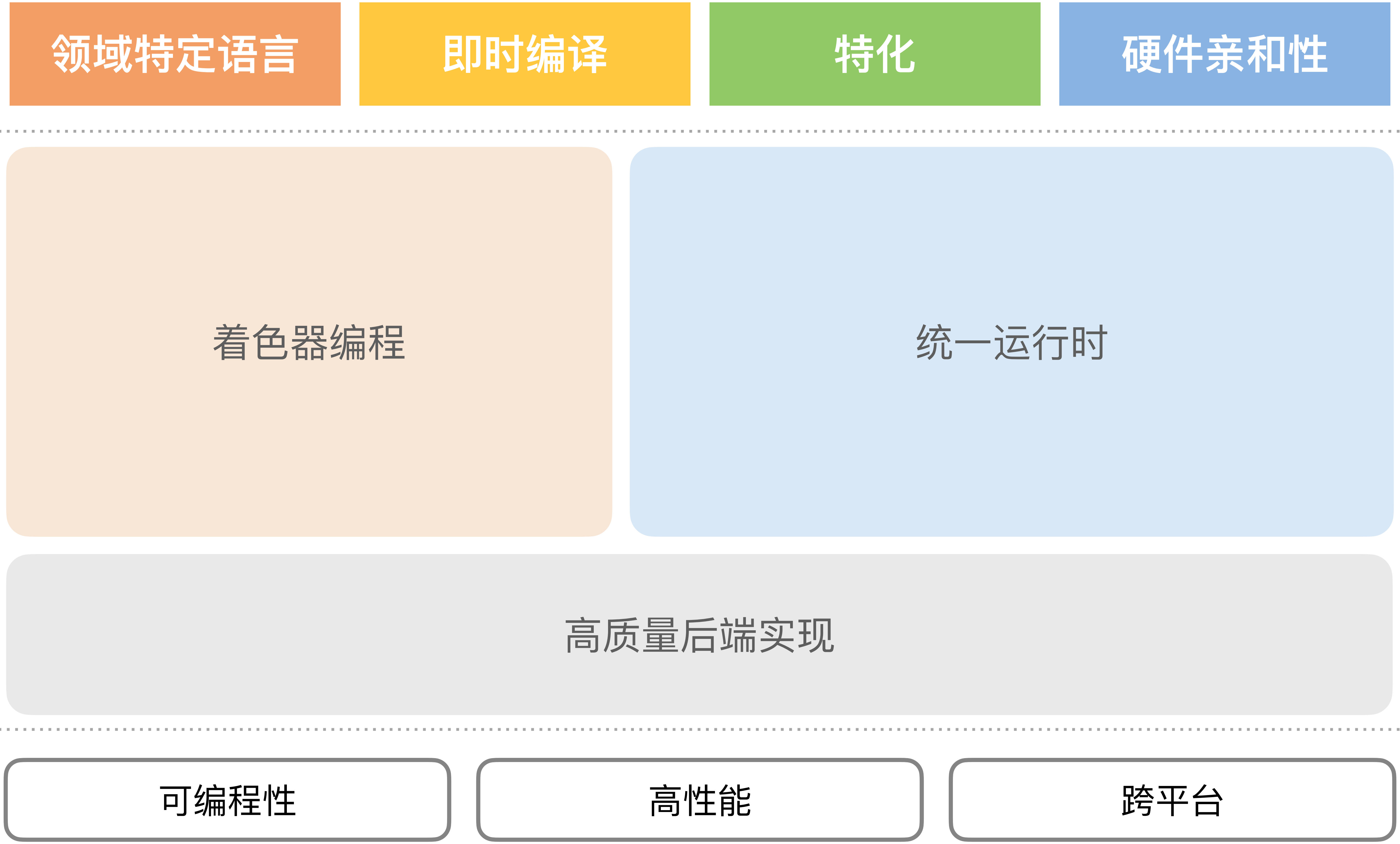
- **嵌入式领域特定语言**
  - 设备端与宿主端代码交互便利：参数绑定、布局兼容...
  - 支持高级抽象模式的语法元素，如动态多态、泛型、模板...
  - 复用宿主语言的类型检查与推断、提供丰富的内置函数...

跨平台

- 利用**抽象层**实现“一次编写，各处运行”
  - 跨平台统一的**运行时编程接口**
  - 跨平台统一的**着色器编程 DSL**
- **适配各平台特性**，无需逐平台性能调优
  - 不同后端根据硬件平台特性，充分利用相应资源

高性能

- **动态代码生成**与**编译优化**
- 良好的**分层设计**，粒度合适的**低开销抽象**
- **高硬件亲和性**的后端实现
  - **单指令多线程**（SIMT）的编程模式
  - 根据硬件特性利用**专有硬件**和**编译器指令**


领域特定语言
即时编译
特化
硬件亲和性
着色器编程
统一运行时
高质量后端实现
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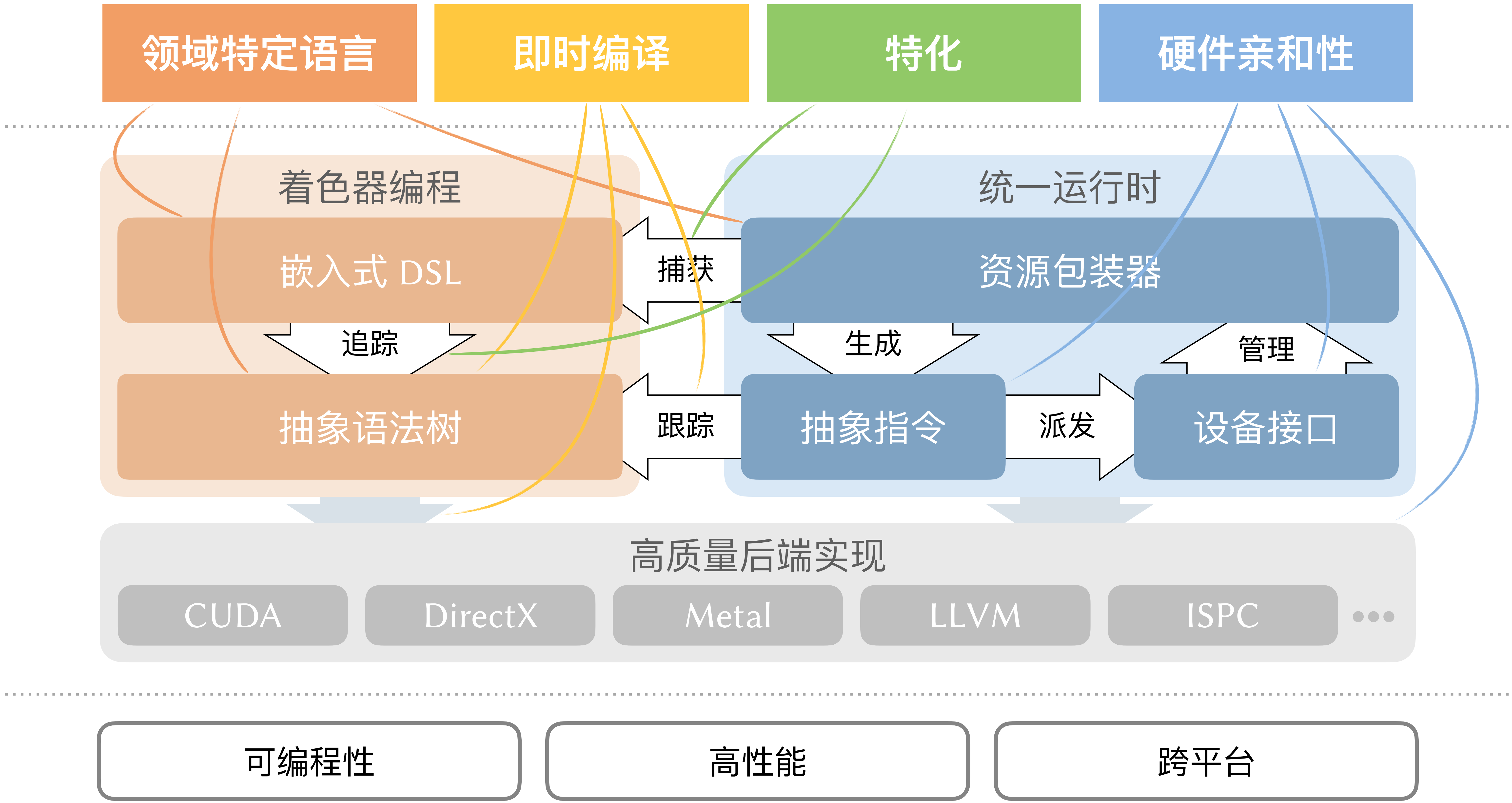
高性能
跨平台



领域特定语言
即时编译
特化
硬件亲和性
着色器编程
统一运行时
嵌入式 DSL
捕获
资源包装器
追踪
生成
管理
抽象语法树
跟踪
抽象指令
派发
设备接口
高质量后端实现
CUDA
DirectX
Metal
LLVM
ISPC
可编程性
高性能
跨平台

样例

```cpp
// initialize the device
auto device = context.create_device("cuda");

// define the rendering kernel
Kernel2D kernel = [&](ImageFloat image) {
  auto pos = dispatch_id().xy();
  auto color = sin(make_float2(p)) * .5f + .5f;
  image.write(pos, make_float4(color, 1.f, 1.f));
};

// create resources on the device and on the host
auto size = make_uint2(1024u);
auto render = device.compile(kernel);
auto image = device.create_image<float>(BYTE4, size);
auto host_image = std::vector<float4>(size.x * size.y);

// create a stream for submitting tasks
auto stream = device.create_stream();

// dispatch tasks and wait for completion
stream << render(image).dispatch(size)
       << image.copy_to(host_image.data())
       << synchronize();
```

技术细节

编程模型

- Single instruction, multiple threads (SIMT)

编程模型

- Single instruction, multiple threads (SIMT)

```
Kernel2D fill = [&](ImageFloat image) {
  auto coord = dispatch_id().xy();
  auto size = make_float2(dispatch_size().xy());
  auto rg = make_float2(coord) / size;
  // invoke the callable
  auto srgb = to_srgb(make_float3(rg, 1.f));
  image.write(coord, make_float4(srgb, 1.f));
};
```

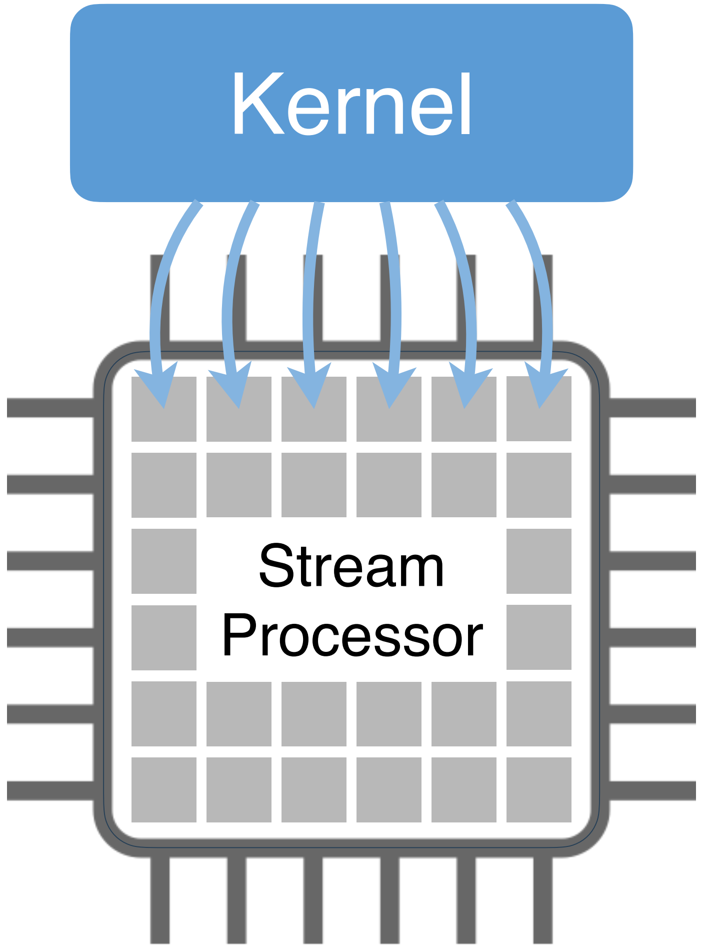
编程模型

- Single instruction, multiple threads (SIMT)

Kernel

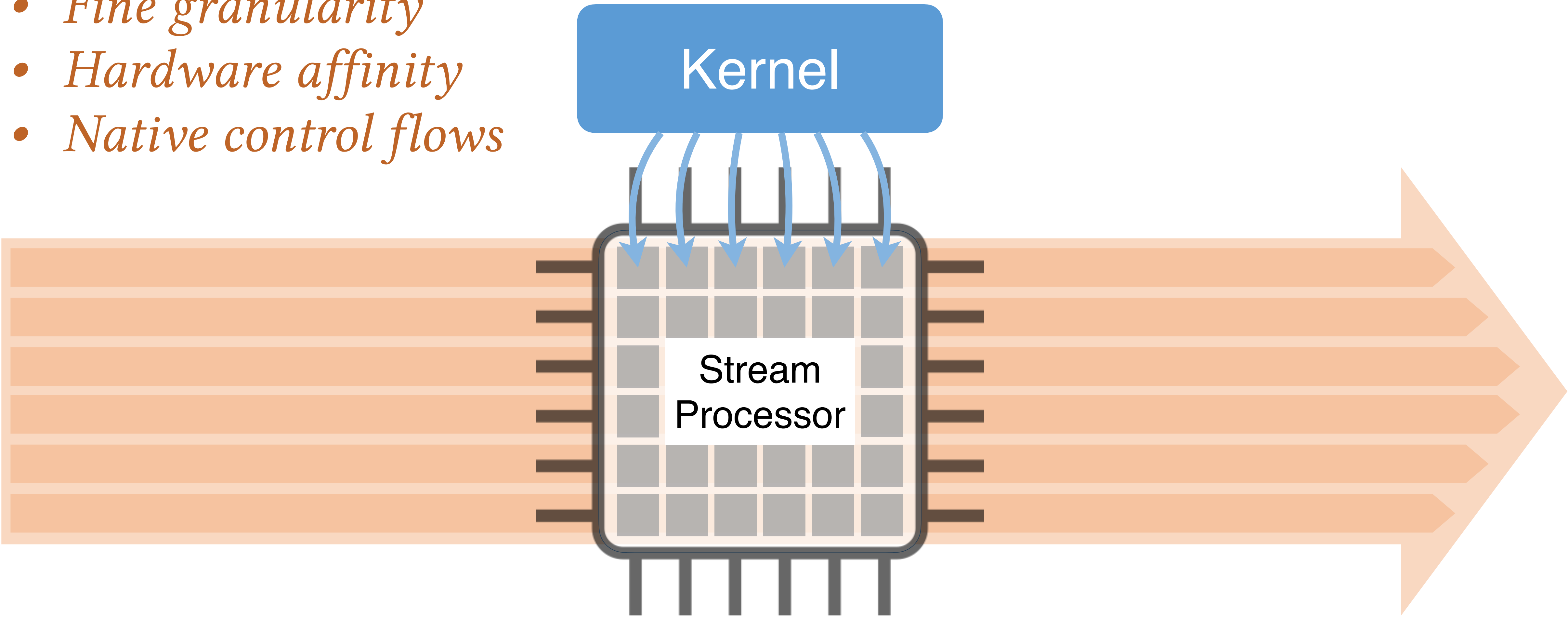
编程模型

- Single instruction, multiple threads (SIMT)



编程模型

- Single instruction, multiple threads (SIMT)
  - *Fine granularity*
  - *Hardware affinity*
  - *Native control flows*



DSL 语法

- Types

```
/* aliases for commonly used instantiations */
using Int  = Var<int>;
using Int2 = Var<int2>;
using Int3 = Var<int3>;
using Int4 = Var<int4>;
/* ... */

/* aliases for runtime resources */
using BufferInt = Var<Buffer<int>>;
using ImageInt  = Var<Image<int>>;
/* ... */
```

- Expressions and statements

```
auto a = def(0u);            // Var<uint> defined in DSL
auto b = def(1u);            // Var<uint> defined in DSL

/* operators, assignments, and type inference */
auto c = a + b;       // operator+: (uint, uint) -> uint
auto d = a < b;       // operator<: (uint, uint) -> bool
b = a - c * 3u;       // operator- and *, and assignment

/* static type check and conversion */
auto u = 1 + c;      // literal int(1) converted to uint
// float3(1.f) + u => compile-time error: float3 + uint
```

- Control flows

```
$if (cond) { /*...*/ } $else { /*...*/ };
$if (cond) { /*...*/ } $elif (cond2) { /*...*/ };
$while (cond) { /*...*/ };
$for (variable, n) { /*...*/ };
$for (variable, begin, end) { /*...*/ };
$for (variable, begin, end, step) { /*...*/ };
$loop { /*...*/ }; // infinite loop, unless $break'ed
$switch (variable) {
  $case (value) { /*...*/ };
  $default { /*...*/ };
};
$break; $continue;
```

- Built-in and custom functions

```
Callable to_srgb = [](Float3 x) {
  $if (x <= 0.00031308f) {
    x = 12.92f * x;
  } $else {
    x = 1.055f * pow(x, 1.f / 2.4f) - .055f;
  };
  return x;
};
```

  - Including ray tracing and texture sampling

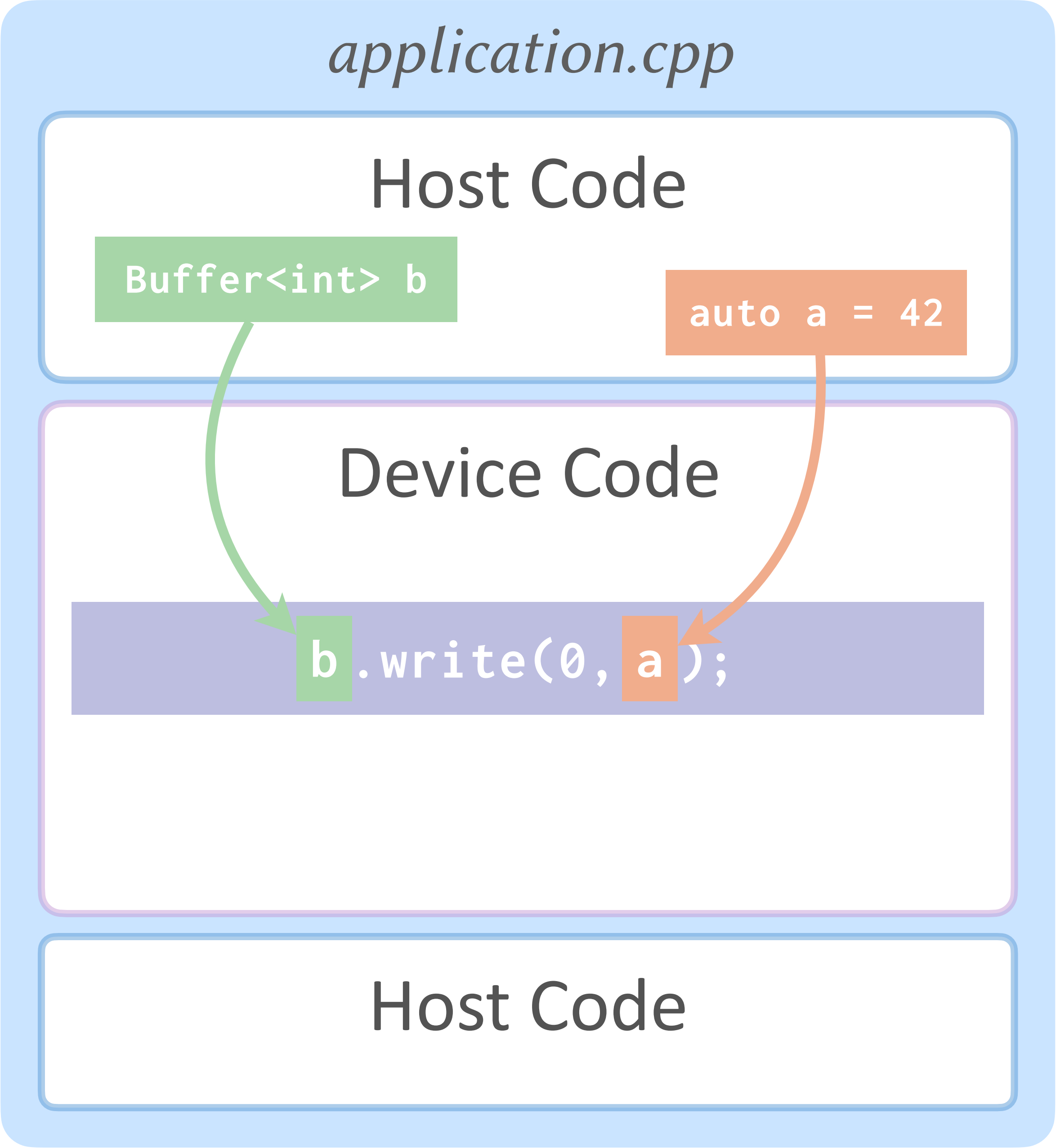
DSL 语法

- Embedded in pure C++20
  - No need for custom preprocessors or compilers
  - Static type checking and inference, templates, classes, etc.

```cpp
template<typename T1, typename T2>
inline auto cosine_sample_hemisphere(T1 u1, T2 u2) {
  auto r = sqrt(u1);
  auto phi = 2.f * pi * u2;
  auto x = r * cos(phi);
  auto y = r * sin(phi);
  auto z = sqrt(1.f - u1);
  return make_float3(x, y, z);
};
```

DSL 语法

- Embedded in pure C++20
  - No need for custom preprocessors or compilers
  - Static type checking and inference, templates…
- Easy interactions between the host and the device
  - Mix host and device code in a single file
  - Inlining host variables as DSL literals
  - Capturing resources without explicit binding



DSL 语法

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  - Static type checking and inference, templates, classes, etc.
- Easy interactions between the host and the device

```cpp
auto image = device.create_image<float>(/* ... */);
Kernel2D fill = [&] {
  auto coord = dispatch_id().xy();
  auto rg = make_float2(coord) /
            make_float2(dispatch_size().xy());
  auto srgb = to_srgb(make_float3(rg, 1.f));
  image.write(coord, make_float4(srgb, 1.f));
};
```

AST 追踪

- Abstract syntax trees are the intermediate representation
  - Traced through proxy objects

```
auto l = def<float3>();
l = dot(lumi, beta);
```

抽象语法树

- Abstract syntax trees are the intermediate representation
  - Traced through proxy objects

Proxy object

```
auto l = def<float3>();
l = dot(lumi, beta);
```

```
LOCAL l
```

抽象语法树

- Abstract syntax trees are the intermediate representation
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Proxy objects

LOCAL **l**

REF **lumi**

REF **beta**

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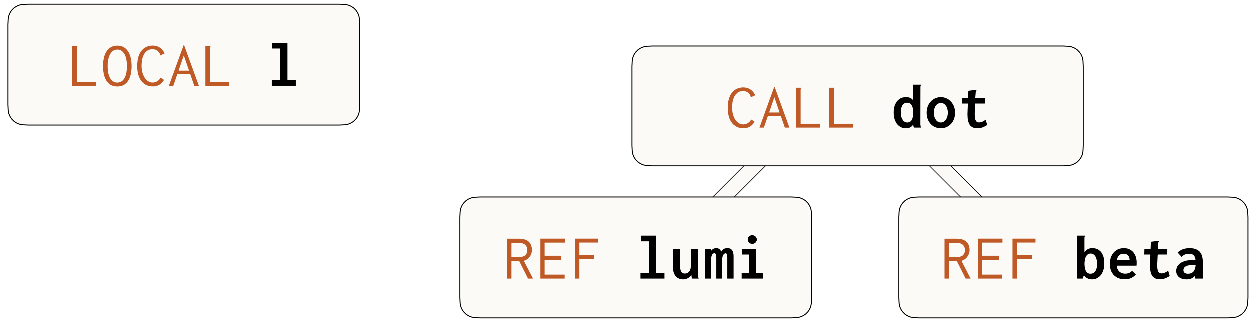
Overloaded functions for proxy objects



抽象语法树

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```
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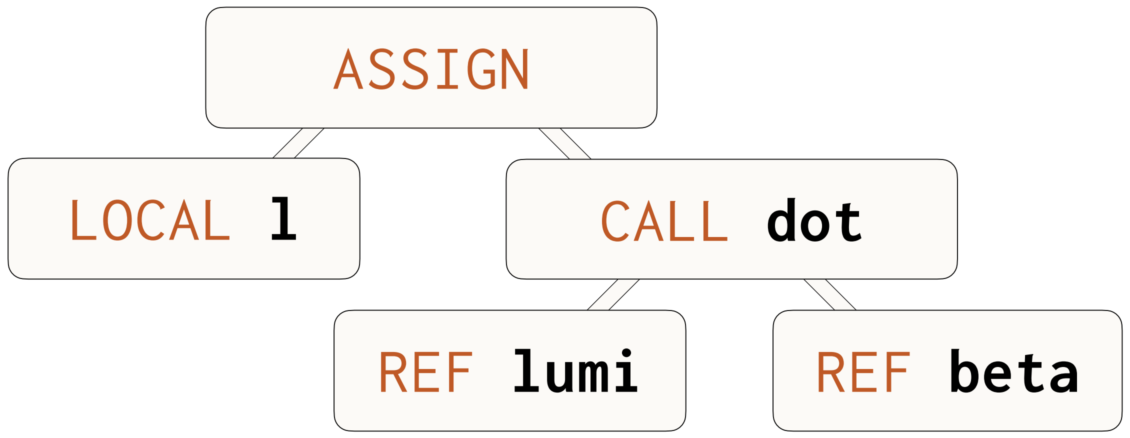
Overloaded assignment operator



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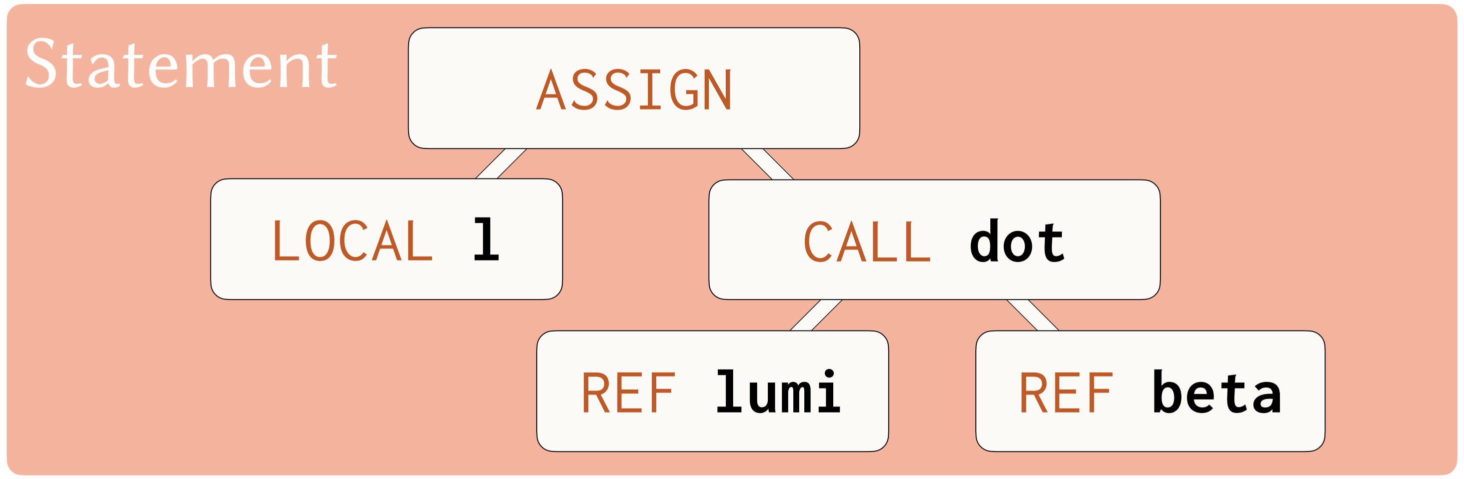


即时代码生成与编译

即时代码生成与编译

Kernel AST

Backends

Shader Code Generation

Dynamic Compilation

即时代码生成与编译

- Dynamic multi-stage programming
  - User-controlled loop unrolling, function inlining, constant folding, dead code elimination, de-virtualization, etc.

```
inline auto tea(UInt s, UInt v0, UInt v1) {
  for (auto i = 0; i < 4; i++) { // 该循环会被展开 4 次
    s += 0x9e3779b9u;
    v0 += ((v1 << 4) + 0xa341316cu) ^ (v1 + s) ^
          ((v1 >> 5u) + 0xc8013ea4u);
    v1 += ((v0 << 4) + 0xad90777du) ^ (v0 + s) ^
          ((v0 >> 5u) + 0x7e95761eu);
  }
  return v0;
};
```

即时代码生成与编译

- Dynamic multi-stage programming
  - User-controlled loop unrolling, function inlining, constant folding, dead code elimination, de-virtualization, etc.
  - Dynamically load parts of device code from plug-ins

```
// defined in plug-in: tonemapping_aces.dll
Float3 apply(Float3 in) { /*...*/ }
```

```
// defined in plug-in: tonemapping_uncharted2.dll
Float3 apply(Float3 in) { /*...*/ }
```

```
// defined in plug-in: tonmapping_filmic.dll
Float3 apply(Float3 in) { /*...*/ }
```

```
auto create_kernel(function<Float3(Float3)> op) {
  Kernel2D kernel = [&op](ImageFloat image) {
    auto p = dispatch_id().xy();
    auto color = image.read(p);
    // op(): a host-side dynamic call, expanding the
    // polymorphic logic into the shader, which is
    // effectively de-virtualized on the device side
    auto mapped = op(color.xyz());
    image.write(p, make_float4(mapped, color.w));
  };
  return kernel;
}

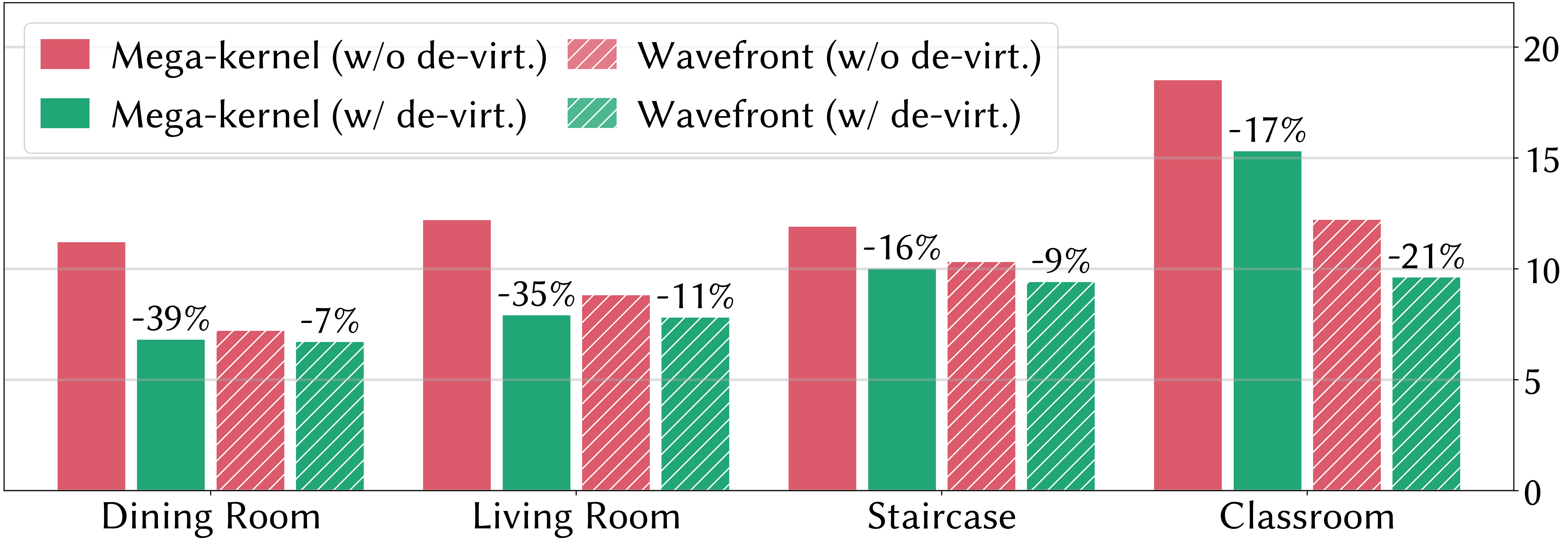
// at runtime, load a tonemapping plug-in dynamically
auto tm_plugin = load_module(/*...*/);
// now use the dynamically loaded op to create kernels
auto tm_kernel = create_kernel(tm_plugin.get("apply"));
```

```cpp
class BRDF {
  virtual Eval eval(Float3 wo, Float3 wi) = 0;
};
class Lambertian : public BRDF {
  Eval eval(Float3 wo, Float3 wi) override { /*...*/ }
};
class Microfacet : public BRDF {
  Eval eval(Float3 wo, Float3 wi) override { /*...*/ }
};
```

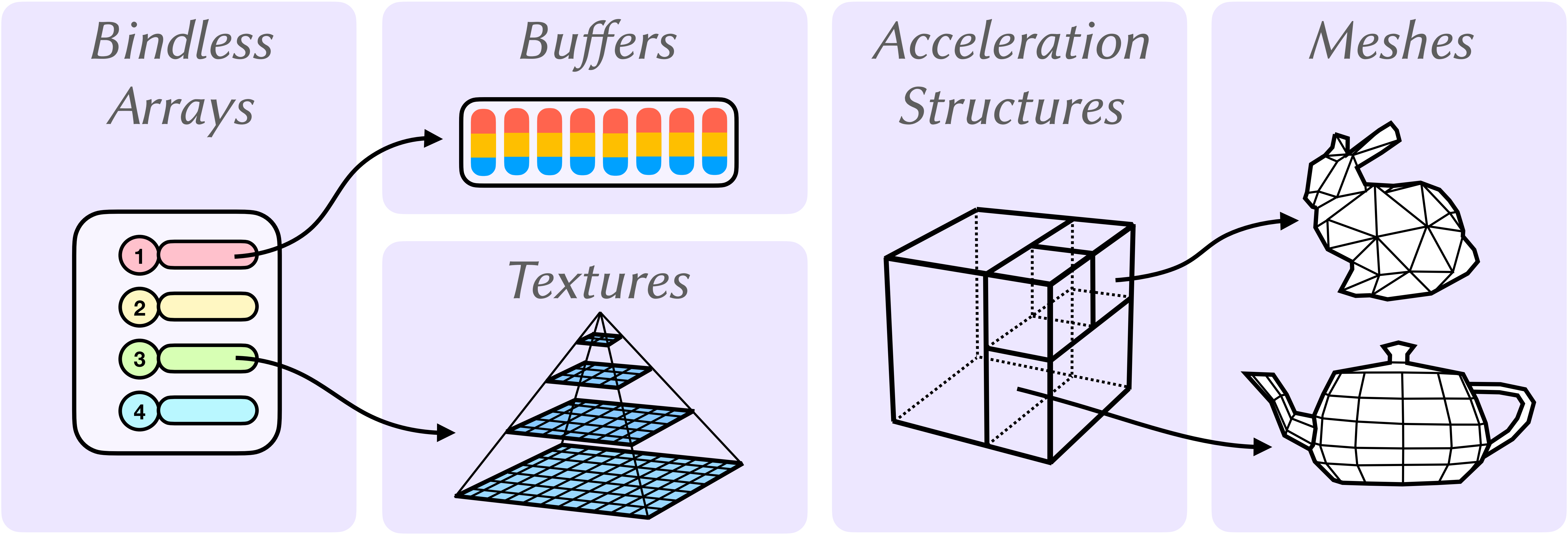
```cpp
class BRDFEvaluator {
private:
  Polymorphic<BRDF> _f;
public:
  void do_registration() {
    auto tag1 = _f.create<Lambertian>(); // tag1 == 0
    auto tag2 = _f.create<Microfacet>(); // tag2 == 1
    // register other BRDFs...
  }
  auto evaluate(Hit hit, Float3 wo, Float3 wi) {
    Eval eval;
    _f->dispatch(hit->brdf_tag(), [&](auto f) {
      eval = f->eval(wo, wi);
    });
    // equivalently expands to
    // $switch (hit->brdf_tag()) {
    //   /* calling Lambertian::eval() */
    //   $case(0) { eval = _f[0]->eval(wo, wi); };
    //   /* calling Microfacet::eval() */
    //   $case(1) { eval = _f[1]->eval(wo, wi); };
    //   ...
    // };
    return eval;
  }
};
```

即时代码生成与编译

Example: de-virtualized texture evaluation reduces rendering time up to 39%



设备资源



Bindless Arrays
1
2
3
4
Buffers
Textures
Acceleration Structures
Meshes

资源包装

- Texture copy in CUDA

```
CUDA_MEMCPY3D copy{};
copy.srcMemoryType = CU_MEMORYTYPE_DEVICE;
copy.srcDevice = /* buffer address */;
copy.srcPitch = /* texture pitch (in bytes) */;
copy.srcHeight = /* texture height (in texels) */;
copy.dstMemoryType = CU_MEMORYTYPE_ARRAY;
copy.dstArray = /* texture handle */;
copy.WidthInBytes = /* texture pitch (in bytes) */;
copy.Height = /* texture height (in texels) */;
copy.Depth = /* texture depth (in texels) */;
cuMemcpy3DAsync(&copy, /* stream handle */);
```

- Texture copy in LuisaRender

```
stream << texture.copy_from(buffer);
```

资源包装

- Texture copy in DirectX

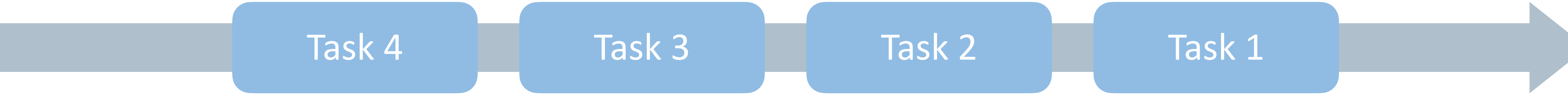
```
// with native DirectX
uint32_t width = texture->Width();
uint32_t height = texture->Height();
uint32_t depth = texture->Depth();
auto c = cb->cmdList.Get();
D3D12_TEXTURE_COPY_LOCATION src;
src.pResource = buffer.buffer->GetResource();
src.Type =
  D3D12_TEXTURE_COPY_TYPE_PLACED_FOOTPRINT;
src.PlacedFootprint.Offset = buffer.offset;
src.PlacedFootprint.Footprint = {
  static_cast<DXGI_FORMAT>(texture->Format()),
  width,
  height,
  depth,
  ((width / texture->PixelSize()) +
  (D3D12_CONSTANT_BUFFER_DATA_PLACEMENT_ALIGNMENT-1)) &
  ~(D3D12_CONSTANT_BUFFER_DATA_PLACEMENT_ALIGNMENT-1),
};
D3D12_TEXTURE_COPY_LOCATION dst;
dst.Type =
  D3D12_TEXTURE_COPY_TYPE_SUBRESOURCE_INDEX;
dst.SubresourceIndex = 0;
dst.pResource = texture->GetResource();
c->CopyTextureRegion(&dst, 0, 0, 0,
                     &src, nullptr);
```

- Texture copy in LuisaRender

```
stream << texture.copy_from(buffer);
```

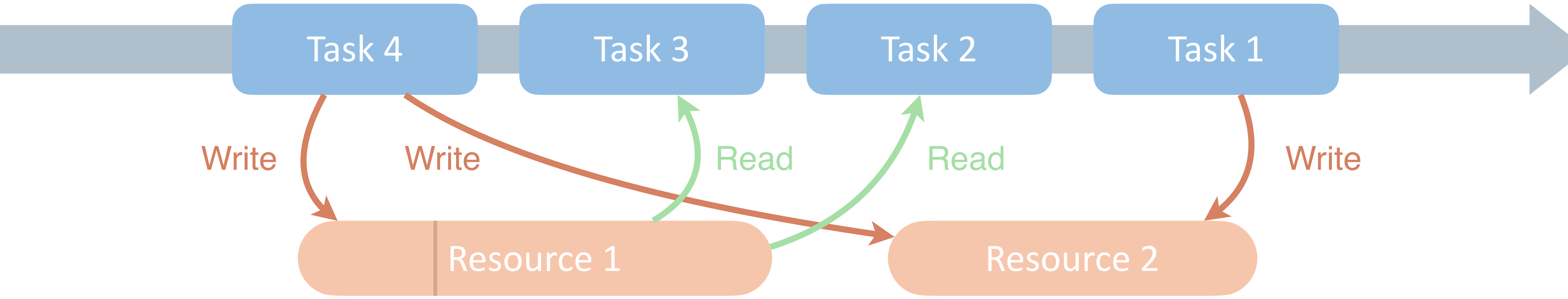
命令调度

- Usage information in ASTs helps re-schedule commands



命令调度

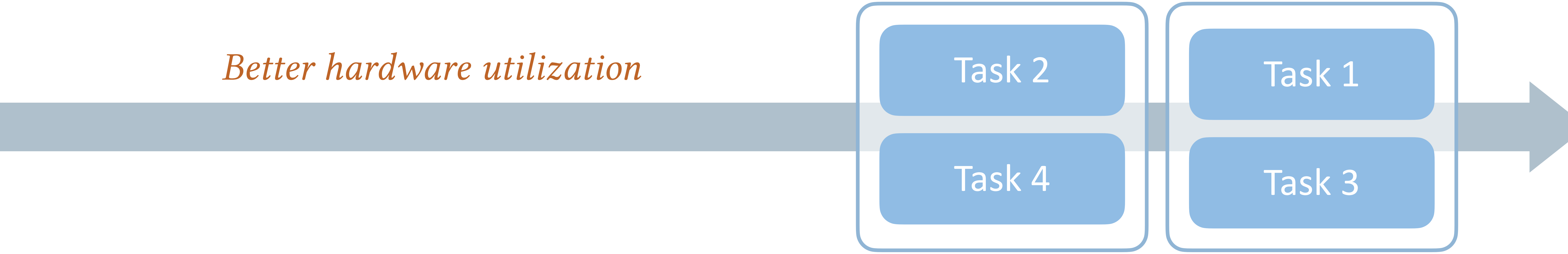
- Usage information in ASTs helps re-schedule commands



命令调度

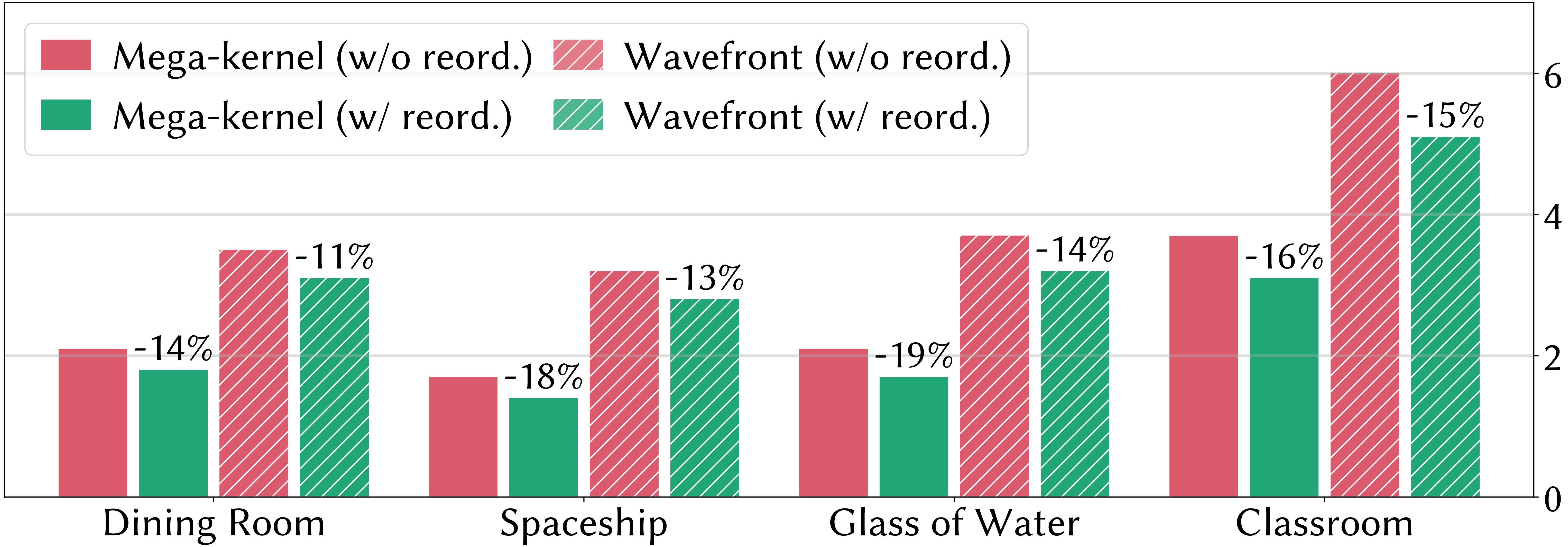
- Usage information in ASTs helps re-schedule commands

Better hardware utilization



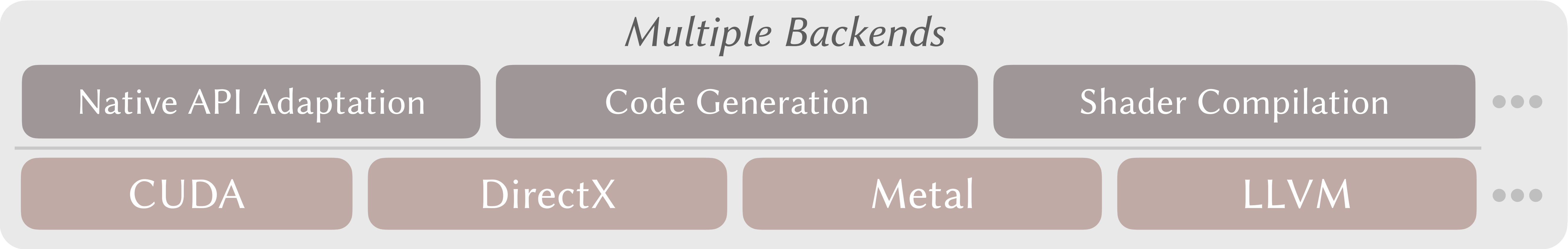
命令调度

Example: reordering wavefront path tracing commands reduces rendering time up to 19%



后端实现

- Various parallel computing backends are supported
  - CPU: LLVM (scalar)
  - GPU: DirectX, CUDA, Metal
  - Optimized and tuned for the underlying platform APIs
- Abstraction layers ease addition of new backend
  - Vulkan & Remote (WIP)

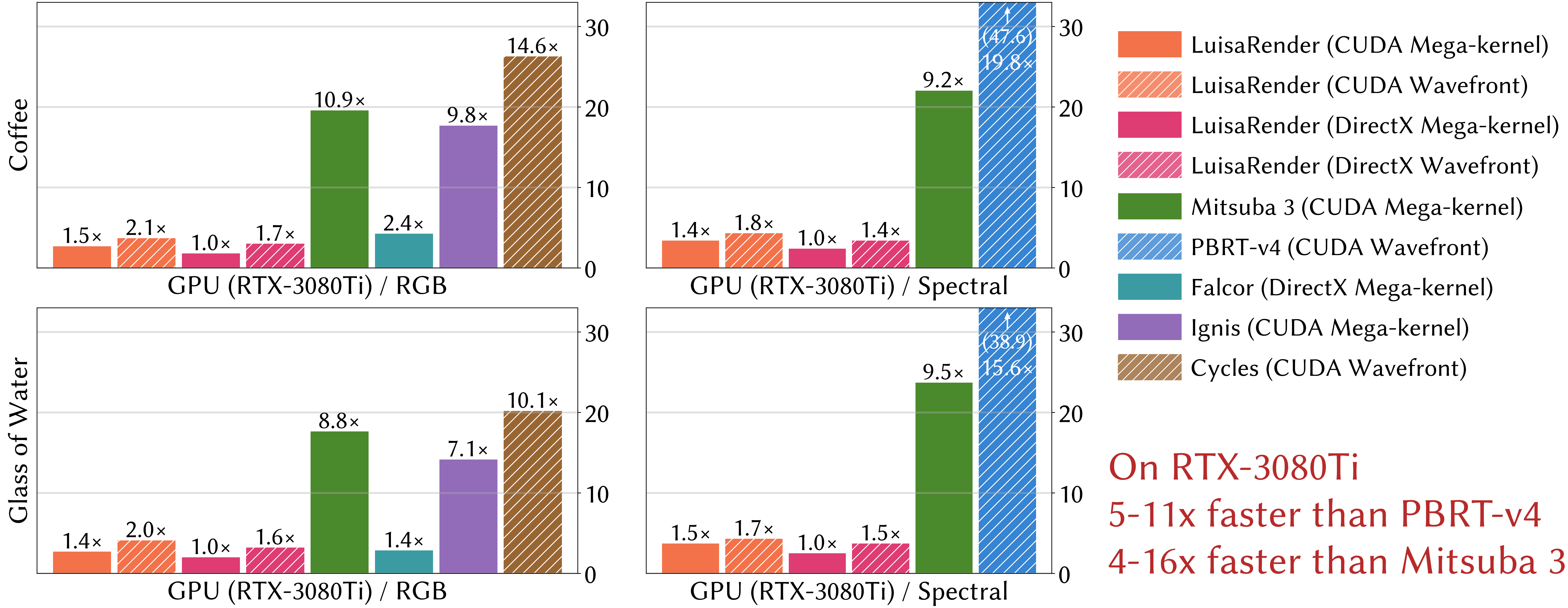


应用

蒙特卡洛渲染系统 LuisaRender

[Rendering Resources, Bitterli 2016]

蒙特卡洛渲染系统 LuisaRender



On RTX-3080Ti
5-11x faster than PBRT-v4
4-16x faster than Mitsuba 3

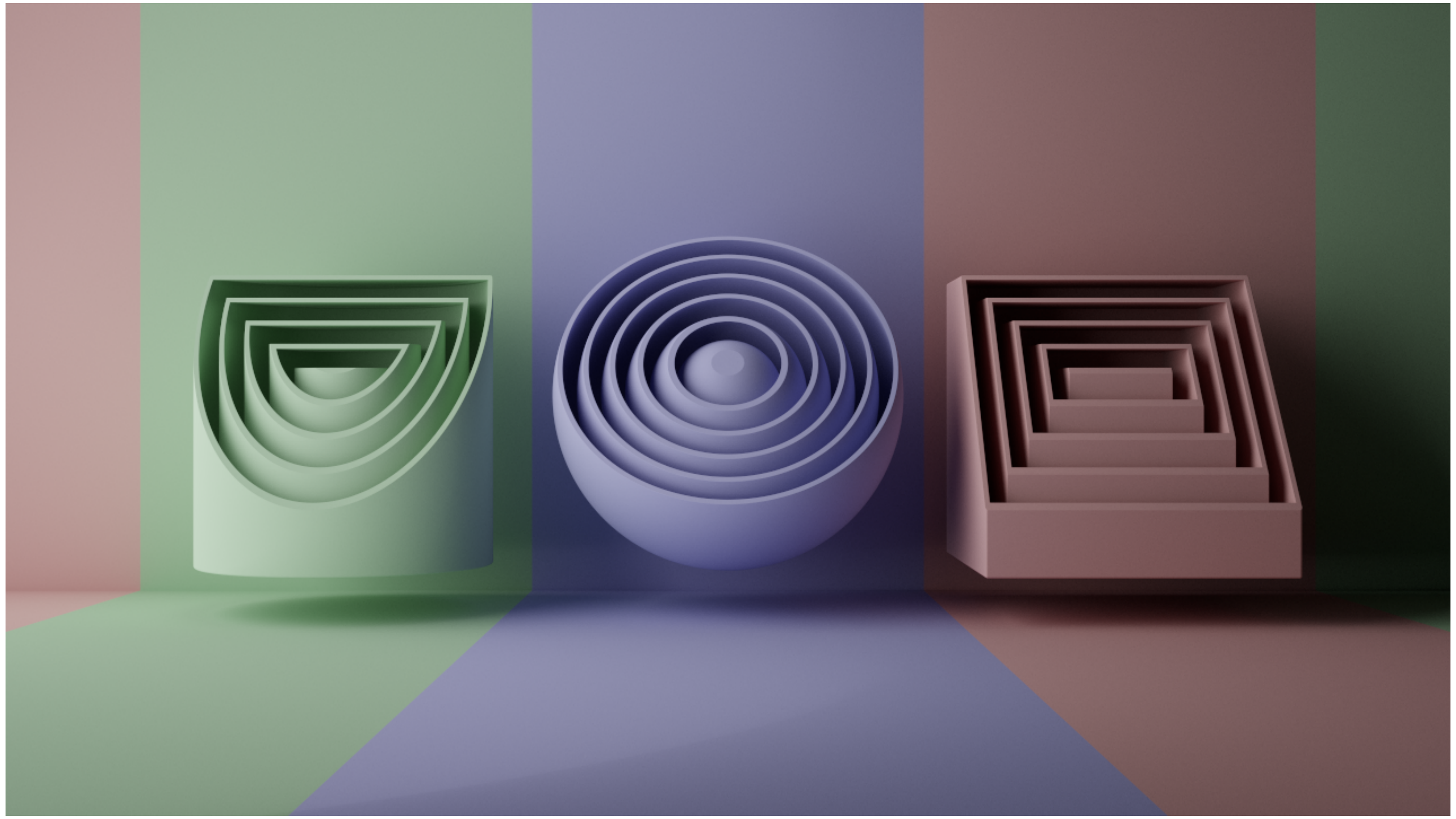
可微分渲染

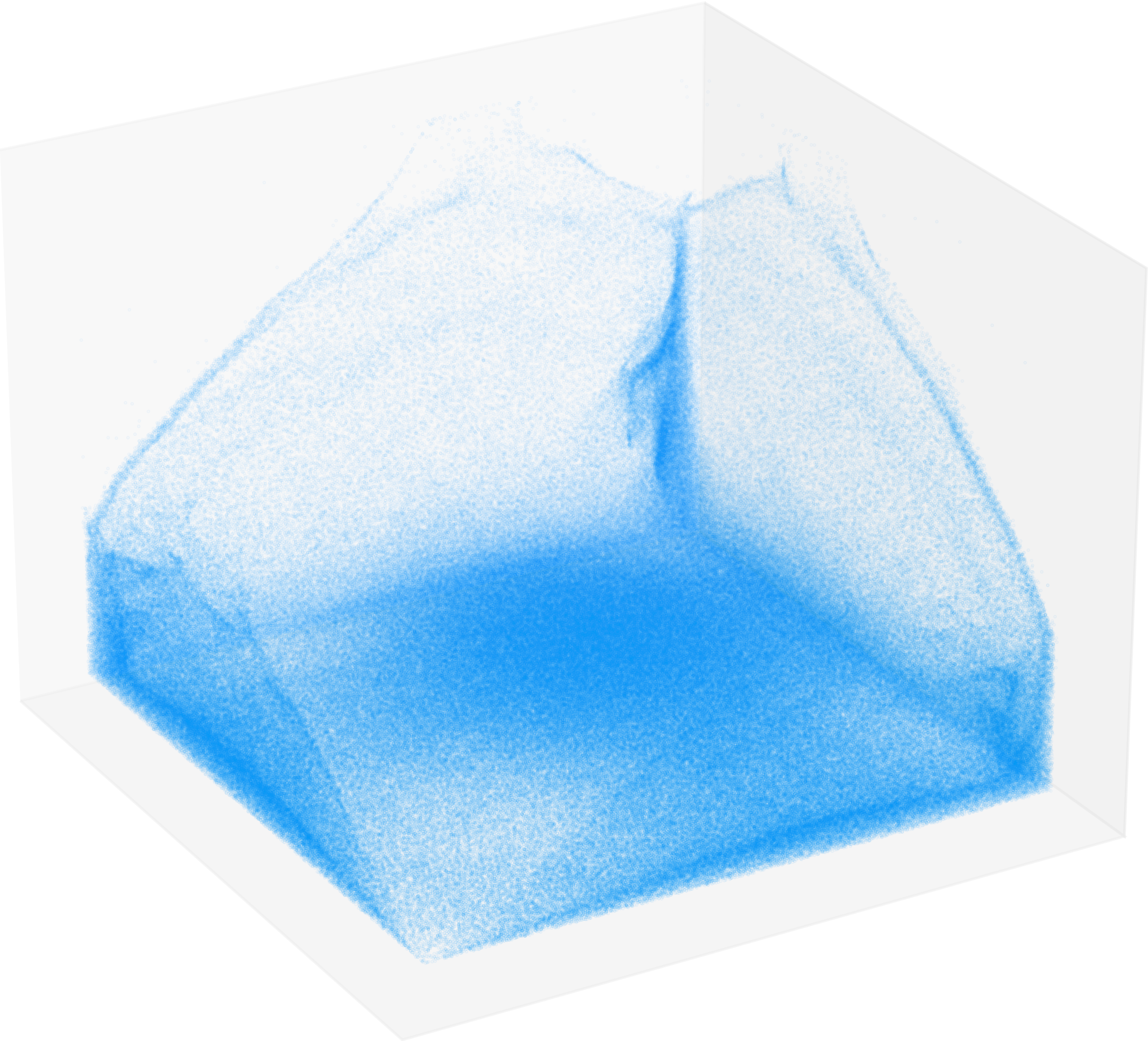
- Path Replay Backpropagation [Vicini et al. 2021]

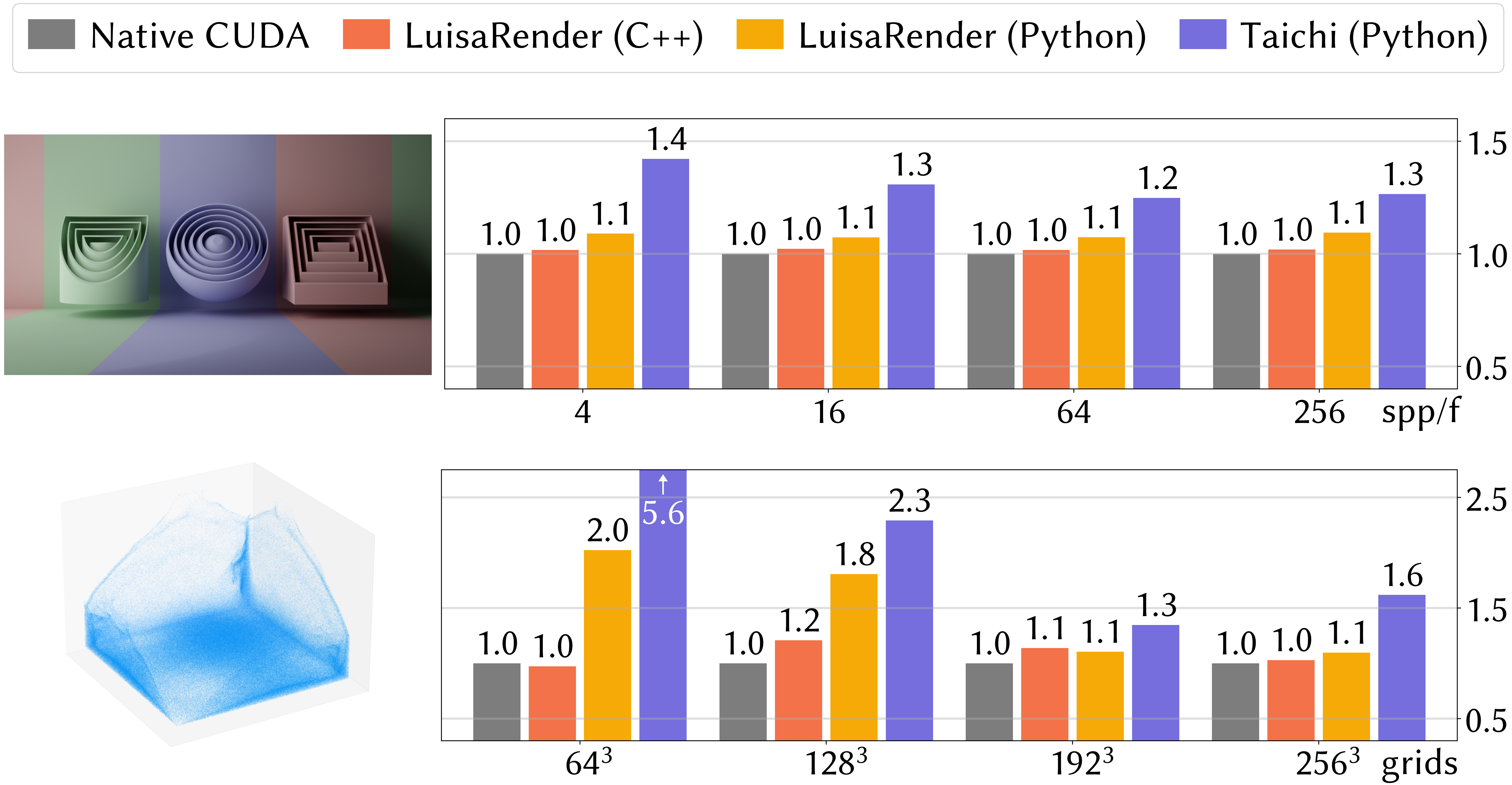
LUISA

luisa-render.com

通用计算（来自 Taichi Examples）






Native CUDA
LuisaRender (C++)
LuisaRender (Python)
Taichi (Python)
1.0 1.0 1.1 1.4
1.0 1.0 1.1 1.3
1.0 1.0 1.1 1.2
1.0 1.0 1.1 1.3
1.5
1.0
0.5
4
16
64
256
spp/f
1.0 1.0 2.0 5.6
1.0 1.2 1.8 2.3
1.0 1.1 1.1 1.3
1.0 1.0 1.1 1.6
2.5
1.5
0.5
64^3
128^3
192^3
256^3
grids

未来工作

Python 前端

- 强调易用性与快速原型设计
  - 动态语言，无需编译
  - 完整支持各种设备资源：Buffers, Textures, Acceleration Structures, …
  - 重计算任务上性能与 C++ 一致
- 与 C++ 一致的 SIMT 编程模型和流式执行模型，可控性高
- 翻译 Python 原生 AST 至 LC AST
  - 可作为脚本为核心模块扩展功能

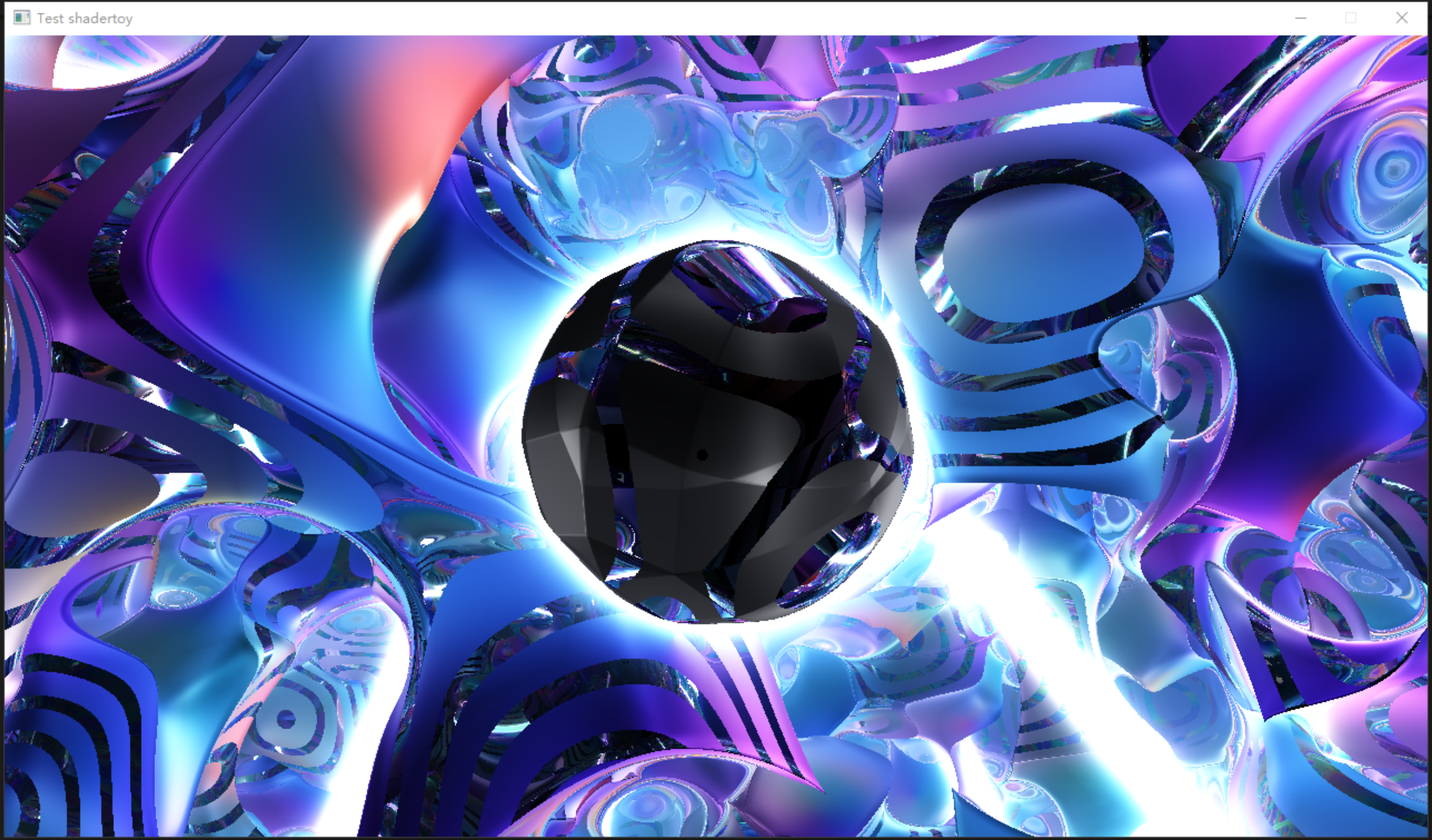
test-shader-visuals-present.py

src > tests > python > test-shader-visuals-present.py > render_kernel

```python
    fact = length(sin(r * (ite(dl, 4., 3.)))
                  * .5 + .5) / sqrt(3.) * .7 + .3
    matcol = lerp(float3(.9, .4, .3), float3(.3, .4, .8),
                  smoothstep(-1., 1., sin(data.d1 * 5. + time * 2.)))
    matcol = lerp(matcol, float3(.5, .4, 1.), smoothstep(
        0., 1., sin(data.d2 * 5. + time * 2.)))
    matcol = ite(dl, lerp(1., matcol, .1) * .2 + .1, matcol)
    col = matcol * fact * ss + pow(fact, 10.)
    col = ite(lz, float3(4.), col)
    fragColor = col * atten + glo * glo + fogcol * glo
    fragColor = lerp(fragColor, fogcol, fog)
    fragColor = ite(dl, fragColor, abs(
        erot(fragColor, normalize(sin(p * 2.)), .2 * (1. - fog))))
    fragColor = ite(trg or dl, fragColor, fragColor +
                    dlglo * dlglo * .1 * float3(.4, .6, .9))
    fragColor = sqrt(fragColor)
    color = smoothstep(0., 1.2, fragColor)
    image.write(dispatch_id().xy, float4(pow(color, 2.2), 1.))


@func
def clear_kernel(image):
    coord = dispatch_id().xy
    image.write(coord, float4(0.3, 0.4, 0.5, 1.))


res = 1280, 720
image = Texture2D(*res, 4, float, storage="BYTE")
gui = GUI("Test shadertoy", res)
clear_kernel(image, dispatch_size=(*res, 1))
time = 0.0
while gui.running():
    gui.set_image(image)
    render_kernel(image, time, dispatch_size=(*res, 1))
    # use seconds
    time += gui.show() / 1000.0
synchronize()
```



Rust 前端

- 使用**过程宏**实现语法
  - if/while/switch 等控制流
  - 动态多态、资源捕获等
- （几乎）**安全**的 Rust 风格 API
- IR 与**自动微分**

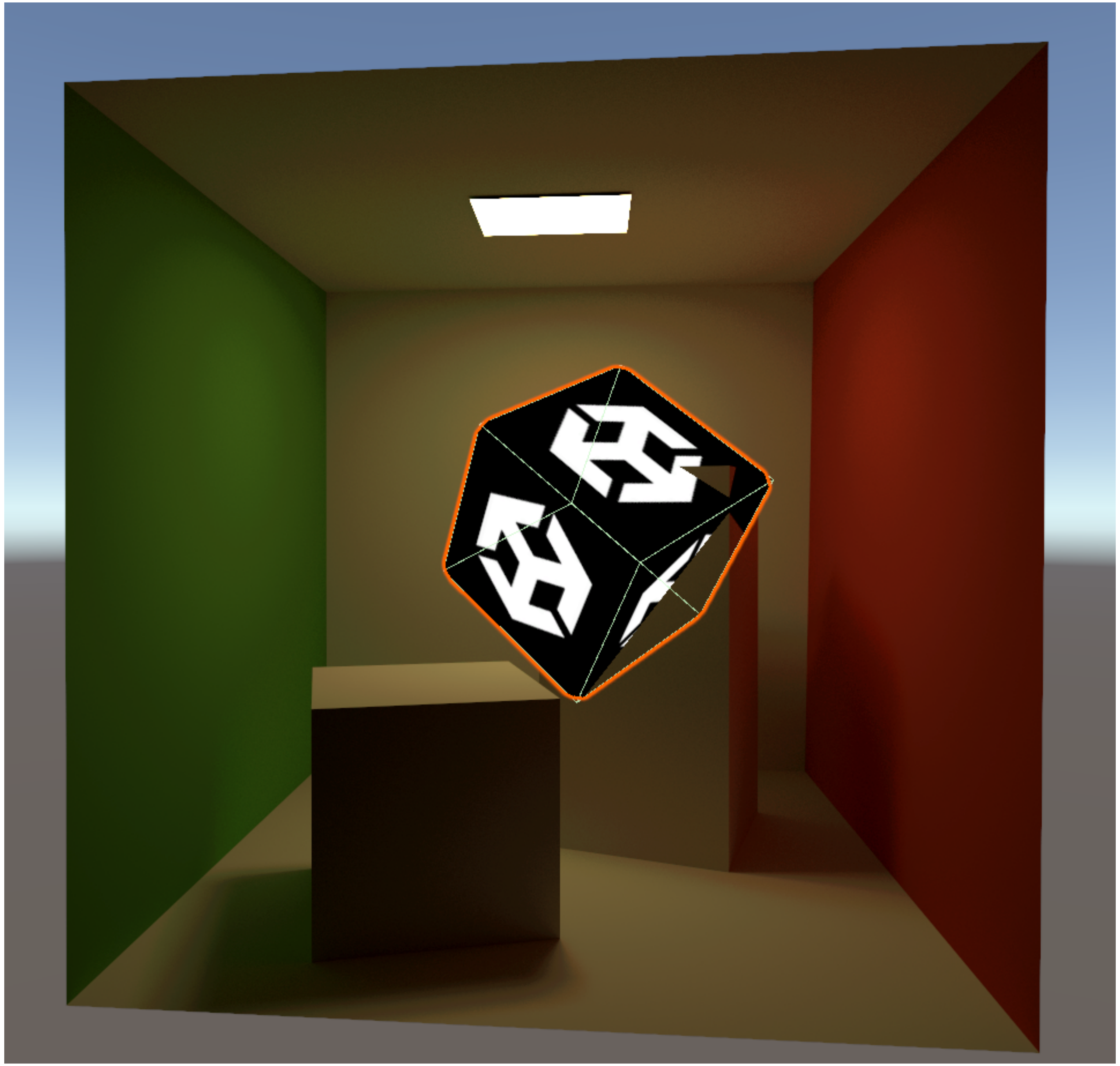
```rust
if_!(cond, { /* then */});
if_!(cond, { /* then */}, { /* else */});
if_!(cond, { value_a }, { value_b })
while_!(cond, { /* body */});
break_();
continue_();
let (x,y) = switch::<(Expr<i32>, Expr<f32>)>(value)
    .case(1, || { ... })
    .case(2, || { ... })
    .default(|| { ... })
    .finish();
```

```rust
use luisa::prelude::*;
use luisa_compute as luisa;

fn main() {
    init();
    let device = create_cpu_device().unwrap();
    let x = device.create_buffer::<f32>(1024).unwrap();
    let y = device.create_buffer::<f32>(1024).unwrap();
    let z = device.create_buffer::<f32>(1024).unwrap();
    x.view(..).fill_fn(|i| i as f32);
    y.view(..).fill_fn(|i| 1000.0 * i as f32);
    let kernel = device
        .create_kernel::<(Buffer<f32>,)>(&|buf_z| {
            // z is pass by arg
            let buf_x = x.var(); // x and y are captured
            let buf_y = y.var();
            let tid = dispatch_id().x();
            let x = buf_x.read(tid);
            let y = buf_y.read(tid);
            buf_z.write(tid, x + y);
        })
        .unwrap();
    kernel.dispatch([1024, 1, 1], &z).unwrap();
    let z_data = z.view(..).copy_to_vec();
    println!("{:?}", &z_data[0..16]);
}
```

扩展与集成

- 提供 DeviceExtension 接口
  - 方便对框架做自定义扩展，如贴图压缩、毛发求交等
  - 支持资源导入/导出，实现与其他系统的交互



总结

总结

- 我们实现了一个适用于渲染等场景的并行计算框架 LuisaCompute
  - 提供嵌入于 C++ 和 Python 等前端的高表达力 DSL
  - 可利用最新光线追踪硬件的统一运行时抽象层
  - 在此框架基础上实现了高性能渲染系统 LuisaRender
- 在未来…
  - 支持更多的前端（如 Rust 前端正在开发中）、后端
  - 更方便灵活的编程模式与更好的性能
  - 更多功能与应用场景（如自动微分、光栅化渲染功能正在开发中）

Thanks

luisa-render.com

github.com/LuisaGroup