AnyDSL: A Partial Evaluation Framework for Programming High-Performance Libraries

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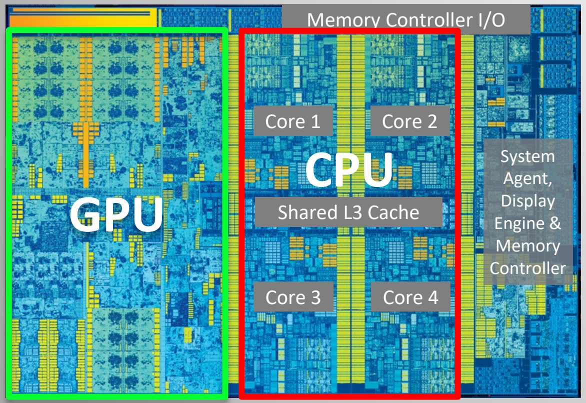
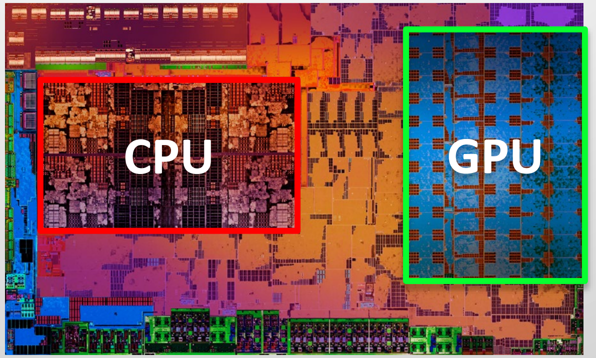
Many-Core Dilemma

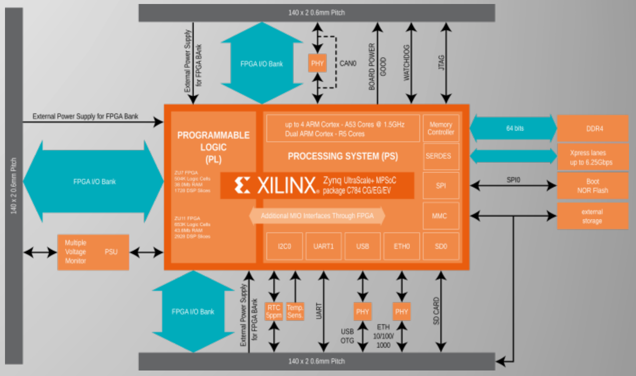
- Many-core hardware is everywhere – but programming it is still hard



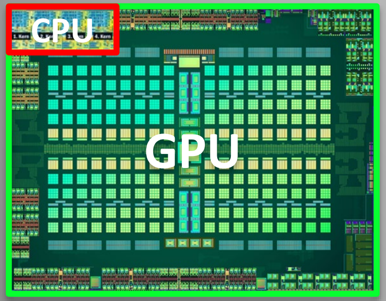
Intel Skylake (1.8B transistors)



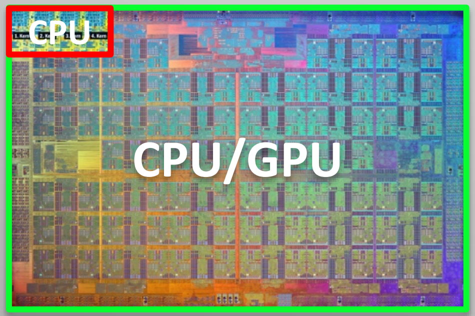
AMD Zen + Vega (4.9B transistors)



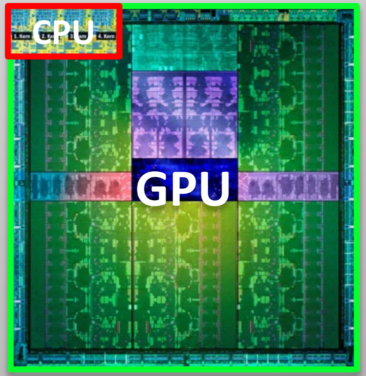
Xilinx Zynq



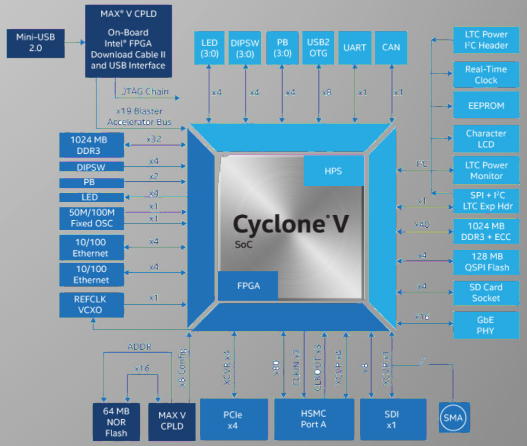
AMD Polaris
(~5.7B transistors)



Intel Knights Landing
(~8B transistors)



NVIDIA Kepler
(~7B transistors)



Intel / Altera Cyclone

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Still State-of-the-Art …

Math

Pseudo-Code

C sequential

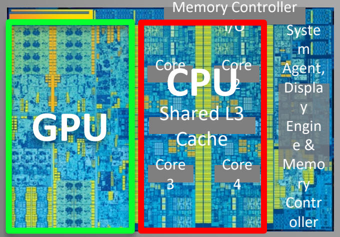
X1 | X2 | X3 | X4

abstract
maintainable
readable
portable
“slow”

manual

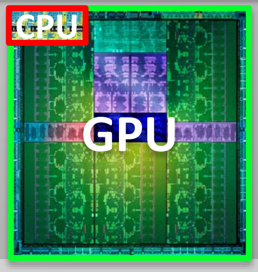
automated

concrete
fast



$X_i \subseteq$ { C, OpenMP, OpenACC, CUDA, OpenCL, OpenCL4X, OpenCL4Y, … }

…



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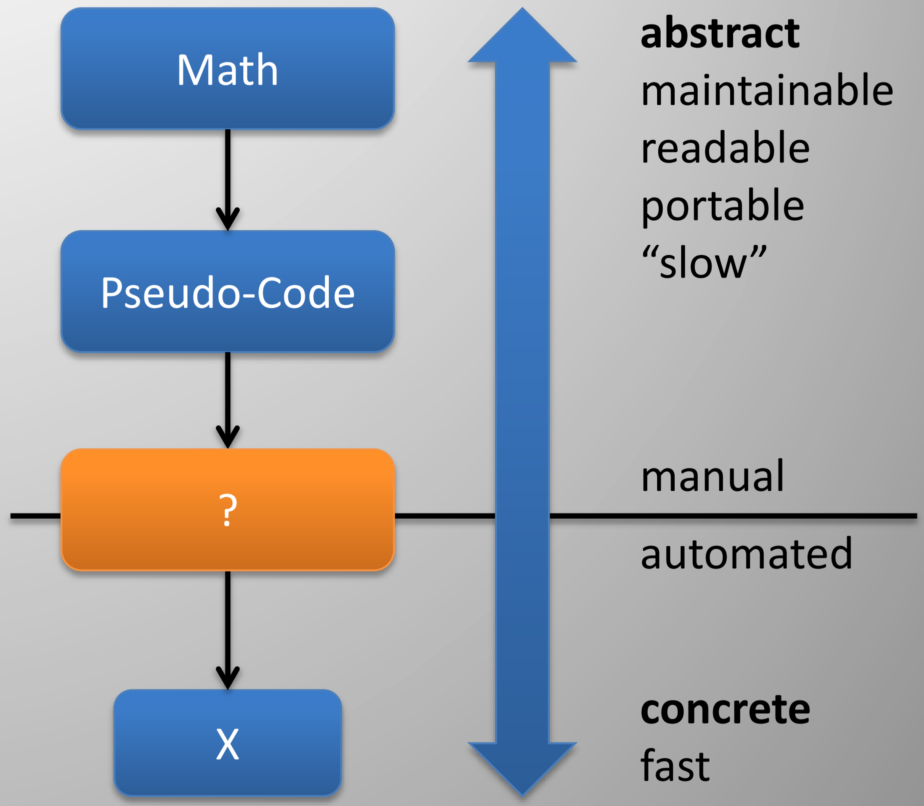
What can we do?

Challenges: **Productivity**, **portability**, and **performance**.

- Manual tuning
  rewrite code yourself
- Annotations
  use the compiler to rewrite code
- Program generation
  use a script to write code
- Meta programming
  write program to rewrite program
- Domain-specific languages
  write compiler to rewrite program



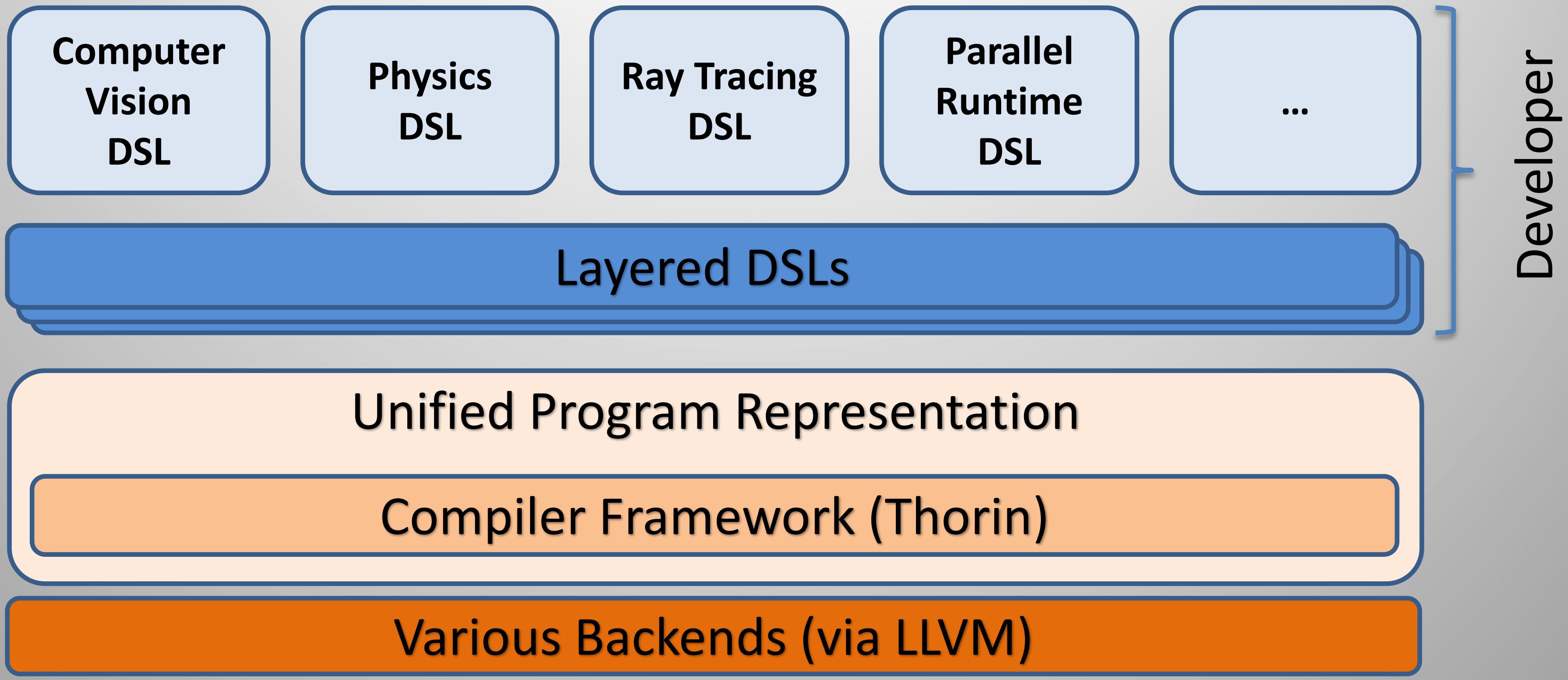
The Vision

- Single high-level representation of our algorithms
- Simple transformations to wide range of target hardware architectures

- First step: RTfact [HPG'08]
  - Use of C++ Template Metaprogramming
  - Great performance (-10%) – but largely unusable due to template syntax

- AnyDSL: New compiler technology, enabling arbitrary Domain-Specific *Libraries* (DSLs)
  - High-level algorithms + HW mapping of used abstractions + cross-layer specialization
  - **Computer Vision:** 10x shorter code, 25-50% *faster* than OpenCV on GPU & CPU
  - **Ray Tracing:** First cross-platform algorithm, beating best code on CPUs & GPUs

AnyDSL: Overview



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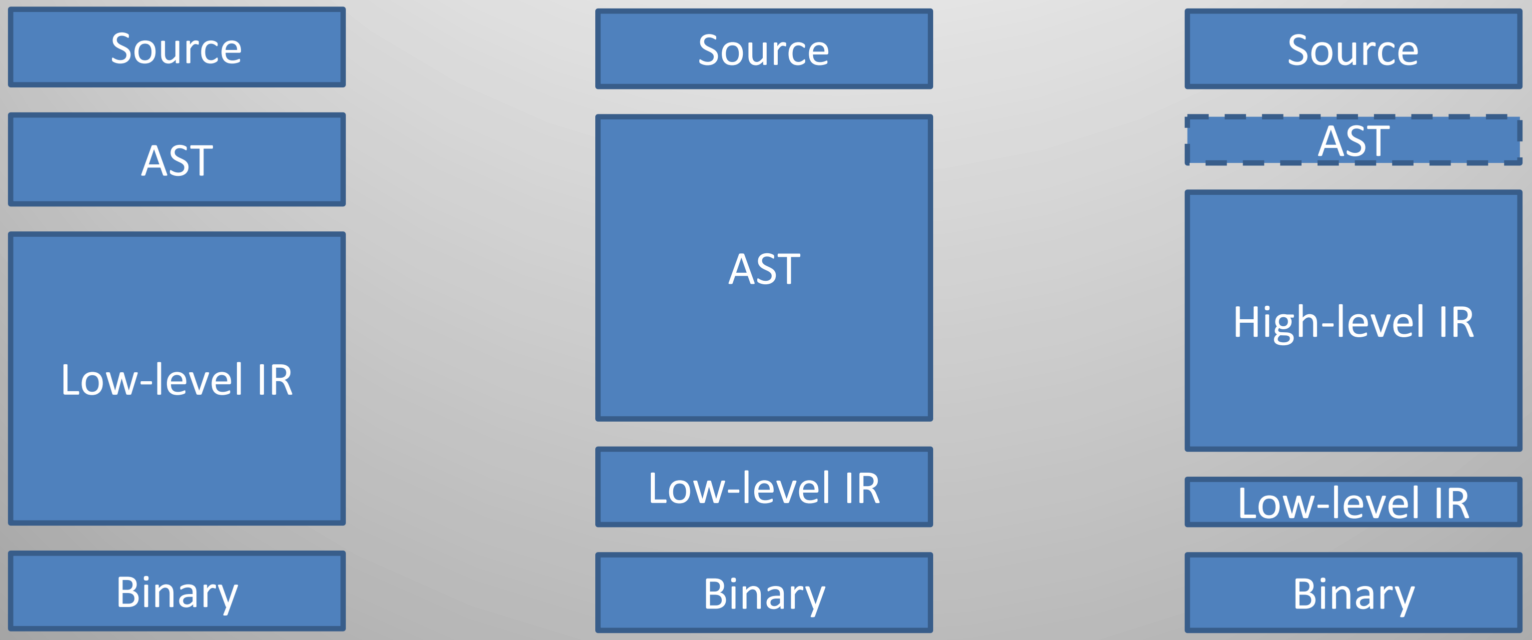
High-Level Program Representation

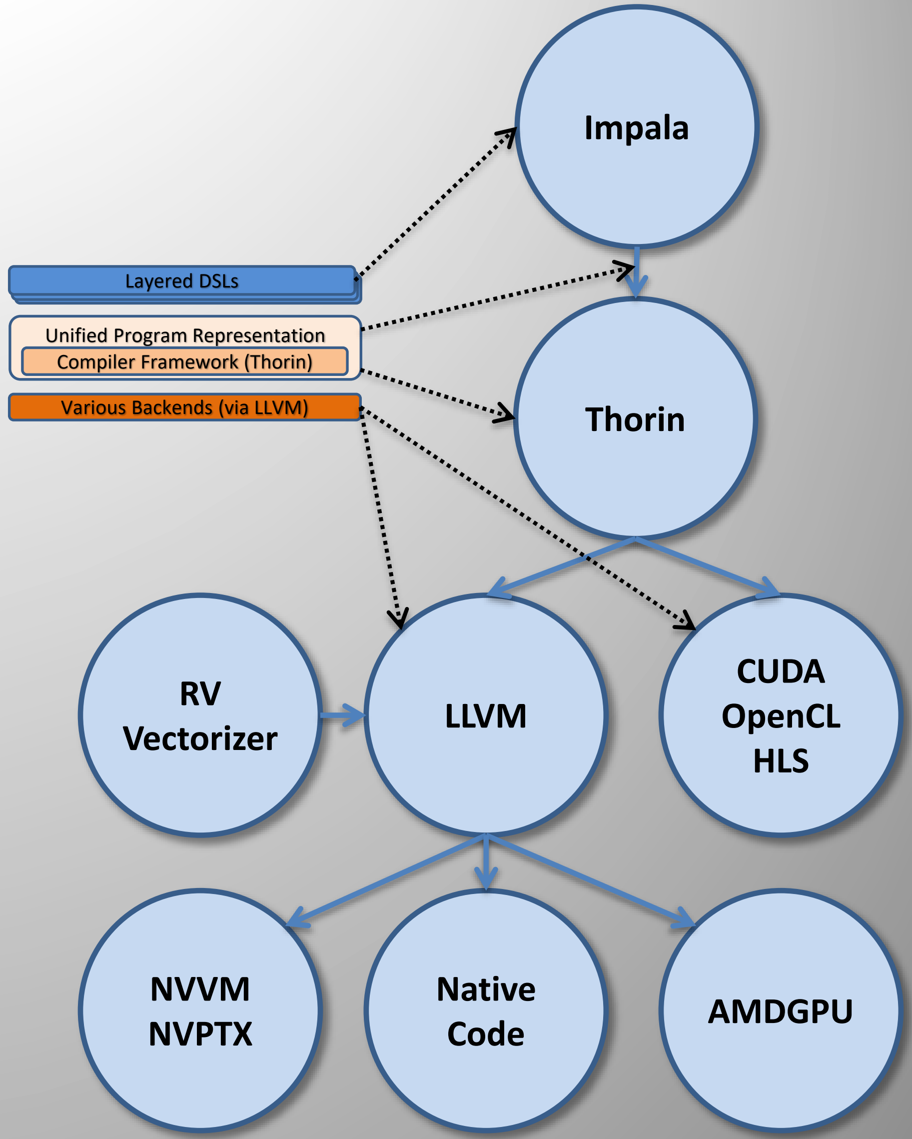
- Uses functional Continuation Passing Style (CPS) and graph-based structure
  - All language constructs as higher-order functions
  - Structure well suited for transformations using “lambda mangling”



Traditional Compilers „Functional“ Compilers AnyDSL

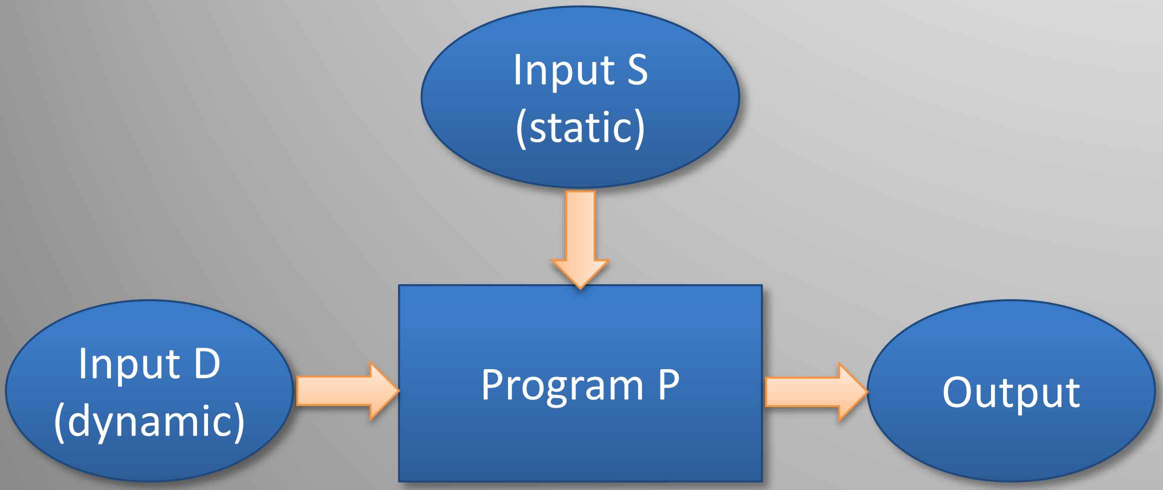
Compiler Framework

- Impala language (Rust dialect)
  - Functional & imperative language
- Thorin compiler [GPCE'15, OOPSLA'18]
  - Higher-order functional IR [CGO'15]
    - Special optimization passes
    - No overhead during runtime
- Region Vectorizer [PLDI'18]
- LLVM-based back ends
  - Full compiler optimization passes
  - Multi-target code generation
    - NVVM/NVPTX, AMDGPU
    - CPUs, GPUs, FPGAs, SX-Aurora, …

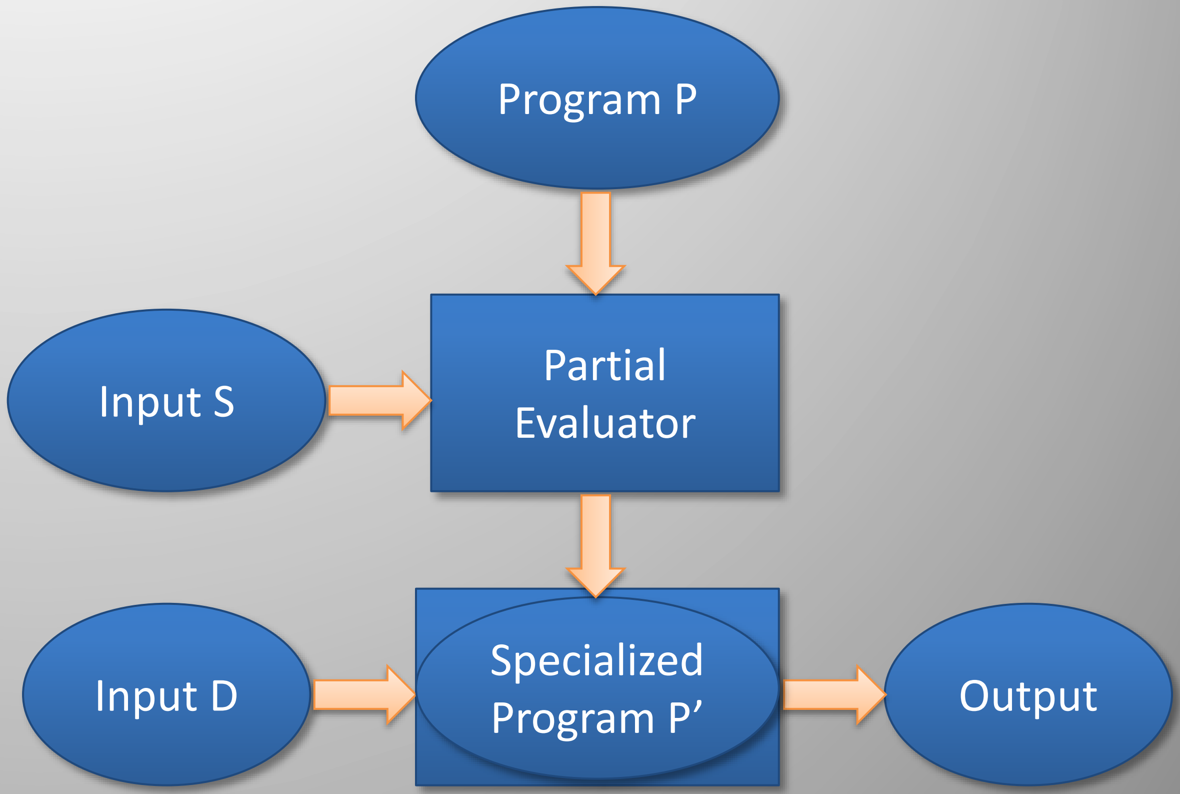


AnyDSL Key Feature: Partial Evaluation (in a Nutshell)

- Normal program execution



- Execution with program specialization
  - PE as part of normal compilation process!!



Impala: A Base Language for DSL Embedding

- Impala is an imperative & functional language
  - A dialect of Rust (https://rust-lang.org)
  - Specialization when instantiating @-annotated functions [OOPSLA'18]
  - Partial evaluation executes all possible instructions at compile time

```
fn @(?n) dot(n: int,
             u: &[float],
             v: &[float]
             ) -> float {
  let mut sum = 0.0f;

  for i in unroll(0, n) {
    sum += u(i)*v(i);
  }

  sum
}

// specialization at call-site
result = dot(3, a, b);
```

```
// specialized code for dot-call
result = 0;
result += a(0)*b(0);
result += a(1)*b(1);
result += a(2)*b(2);
```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Case Study: Image Processing

[GPCE’15, OOPSLA’18]

Stincilla – A DSL for Stencil Codes

https://github.com/AnyDSL/stincilla

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Sample DSL: Stencil Codes in Impala

- Application developer: Simply wants to use a DSL
  - Example: Image processing, specifically Gaussian blur
  - Using OpenCV as reference

```
fn main() -> () {
  let img = read_image("lena.pgm");
  let result = gaussian_blur(img);
  show_image(result);
}
```


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Sample DSL: Stencil Codes in Impala

- Higher level domain-specific code: DSL implementation
  - Gaussian blur implementation using generic apply_convolution
  - iterate function iterates over image (provided by machine expert)

```
fn @gaussian_blur(img: Img) -> Img {
  let mut out = Img { data:   ~[img.width*img.height:float],
                      width:  img.width,
                      height: img.height };
  let filter = [[0.057118f, 0.124758f, 0.057118f],
                [0.124758f, 0.272496f, 0.124758f],
                [0.057118f, 0.124758f, 0.057118f]];

  for x, y in iterate(out) {
    out.data(x, y) = apply_convolution(x, y, img, filter);
  }

  out
}
```


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Sample DSL: Stencil Codes in Impala

- Higher level domain-specific code: DSL implementation
  - for syntax: syntactic sugar for lambda function as last argument

```
fn @gaussian_blur(img: Img) -> Img {
  let mut out = Img { data:   ~[img.width*img.height:float],
                      width:  img.width,
                      height: img.height };
  let filter = [[0.057118f, 0.124758f, 0.057118f],
                [0.124758f, 0.272496f, 0.124758f],
                [0.057118f, 0.124758f, 0.057118f]];

  iterate(out, |x, y| -> () {
    out.data(x, y) = apply_convolution(x, y, img, filter);
  });

  out
}
```


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Sample DSL: Stencil Codes in Impala

- Domain-specific code: DSL implementation for image processing
  - Generic function that applies a given stencil to a single pixel
  - Partial evaluation
    - Unrolls stencil
    - Propagates constants
    - Inlines function calls

```
fn @apply_convolution(x: int, y: int,
                      img: Img,
                      filter: [float]
                     ) -> float {
  let mut sum = 0.0f;
  let half = filter.size / 2;

  for j in unroll(-half, half+1) {
    for i in unroll(-half, half+1) {
      sum += img.data(x+i, y+j) * filter(i, j);
    }
  }

  sum
}
```


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Mapping to Target Hardware: CPU

- Scheduling & mapping provided by machine expert
  - Simple sequential code on a CPU
  - body gets inlined through specialization at higher level

```
fn @iterate(img: Img, body: fn(int, int) -> ()) -> () {
  for y in range(0, img.height) {
    for x in range(0, img.width) {
      body(x, y);
    }
  }
}
```


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Mapping to Target Hardware: CPU with Optimization

- Scheduling & mapping provided by machine expert
  - CPU code using parallelization and vectorization (e.g. AVX)
  - parallel is provided by the compiler, maps to TBB or C++11 threads
  - vectorize is provided by the compiler, uses region vectorization

```
fn @iterate(img: Img, body: fn(int, int) -> ()) -> () {
  let thread_number = 4;
  let vector_length = 8;
  for y in parallel(thread_number, 0, img.height) {
    for x in range_step(0, img.width, vector_length) {
      for lane in vectorize(vector_length) {
        body(x + lane, y);
      }
    }
  }
}
```


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Mapping to Target Hardware: GPU

- Scheduling & mapping provided by machine expert
  - Exposed NVVM (CUDA) code generation
  - Last argument of nvvm is function we generate NVVM code for

```
fn @iterate(img: Img, body: fn(int, int) -> ()) -> () {
  let grid  = (img.width, img.height, 1);
  let block = (32, 4, 1);

  with nvvm(grid, block) {
    let x = nvvm_tid_x() + nvvm_ntid_x() * nvvm_ctaid_x();
    let y = nvvm_tid_y() + nvvm_ntid_y() * nvvm_ctaid_y();
    body(x, y);
  }
}
```


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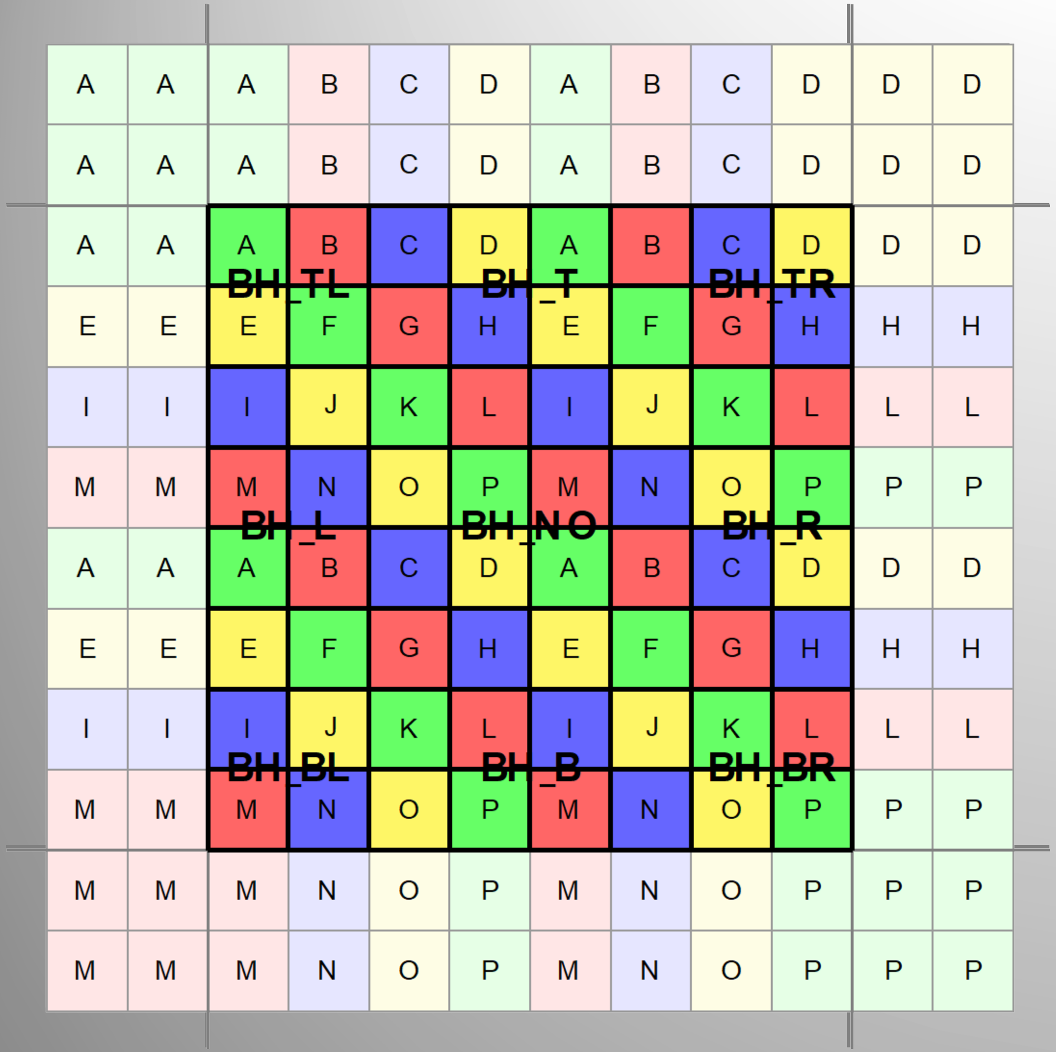
Exploiting Boundary Handling (1)



- Boundary handling
  - Evaluated for all points
  - Unnecessary evaluation of conditionals
- Specialized variants for different regions
- Automatic generation of variants
  → Partial evaluation

Exploiting Boundary Handling (2)

- Specialized implementation
  - Wrap memory access to image in an access() function
    - Distinction of variant via <u>region</u> variable (here only in horizontally)
  - Specialization discards unnecessary checks

A	A	A	B	C	D	A	B	C	D	D	D

```
fn @access(mut x: int, y: int,
           img: Img,
           region,
           bh_lower: fn(int, int) -> int,
           bh_upper: fn(int, int) -> int,
          ) -> float {
  if region == left  { x = bh_lower(x, 0); }
  if region == right { x = bh_upper(x, img.width); }
  img(x, y)
}
```

Exploiting Boundary Handling: CPU & AVX

- Specialized implementation
  - outer_loop maps to parallel and inner_loop calls either range (CPU) or vectorize (AVX)
  - unroll triggers image region specialization
  - Speedup over OpenCV: 40% (Intel CPU, vectorized)

```
fn @iterate(img: Img, body: fn(int, int, int) -> ()) -> () {
  let offset = filter.size / 2;
  //        left    right                center
  let L = [0,       img.width - offset, offset];
  let U = [offset, img.width,            img.width - offset];

  for region in unroll(0, 3) {
    for y in outer_loop(0, img.height) {
      for x in inner_loop(L(region), U(region)) {
        ...
        body(x, y, region);
      }
    }
  }
}
```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Exploiting Boundary Handling: GPU

- Specialized implementation
  - unroll triggers image region specialization
  - Generates multiple GPU kernels for each image region
  - Speedup over OpenCV: 25% (Intel GPU), 50% (AMD GPU), 45% (NVIDIA GPU)

```
fn @iterate(img: Img, body: fn(int, int, int) -> ()) -> () {
  let offset = filter.size / 2;
  //        left    right                 center
  let L = [0,       img.width - offset, offset];
  let U = [offset, img.width,           img.width - offset];

  for region in unroll(0, 3) {
    let grid = (U(region) - L(region), img.height, 1);
    with nvvm(grid, (128, 1, 1)) {
      ...
      body(L(region) + x, y, region);
    }
  }
}
```


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Mapping to Target Hardware: FPGA (WIP)

- Scheduling & mapping provided by machine expert
  - Exposed AOCL code generation via opencl
  - Exposed VHLS code generation via hls
  - Mapping for simple point operators

```
fn @iterate(img: Img, body: fn(int, int) -> ()) -> () {
  with opencl((1, 1, 1), (1, 1, 1)) {
    for y in range(0, img.height) {
      for x in range(0, img.width) {
        body(x, y);
      }
    }
  }
}
```


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Other Domains [OOPSLA'18]

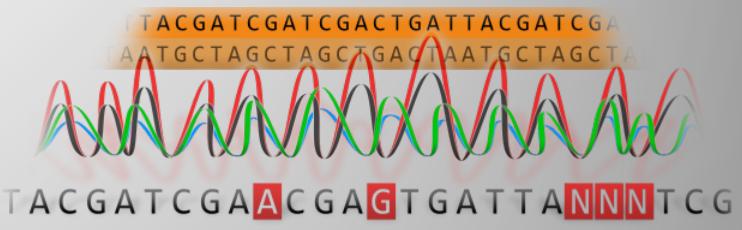
Image Processing

OpenCV: +45% to +50% (Blur)
Halide: +7% to +12 (Blur)
Halide: +37% to +44% (Harris Corner)

Ray Tracing

Ray Traversal
Embree: -15% to +13%
OptiX: -19% to -2%

Genome Sequence Alignment



SeqAn: -19% to -7%
NVBIO: -8% to -2%

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Separation of Concerns

- Separation of concerns through code refinement
  - Higher-order functions
  - Partial evaluation
  - Triggered code generation

Application developer

```
fn main() {
  let result = gaussian_blur(img);
}
```

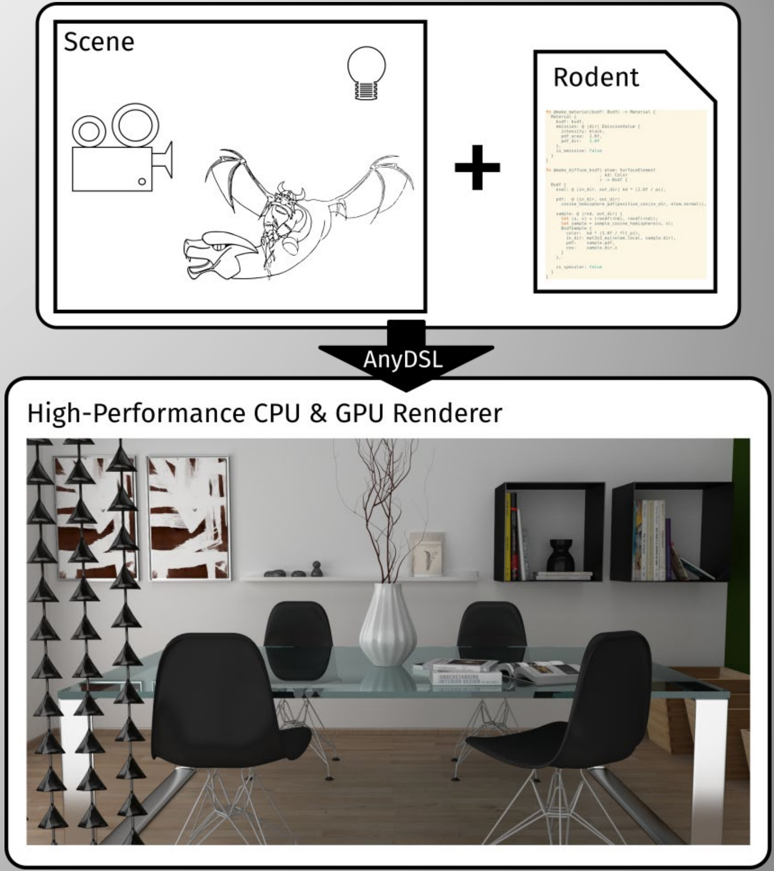
DSL developer

```
fn @gaussian_blur(img: Img) -> Img {
  let filter = /* ... */; let mut out = Img { /* ... */ };

  for x, y in iterate(out) {
    out(x, y) = apply(x, y, img, filter);
  }
  out
}
```

Machine expert

```
fn @iterate(img: Img, body: fn(int, int) -> ()) -> () {
  let grid  = (img.width, img.height);
  let block = (128, 1, 1);

   with nvvm(grid, block) {
    let x = nvvm_tid_x() + nvvm_ntid_x() + nvvm_ctaid_x();
    let y = nvvm_tid_y() + nvvm_ntid_y() + nvvm_ctaid_y();
    body(x, y);
  }
}
```

Case Study: Ray Tracing [SIGGRAPH’19]

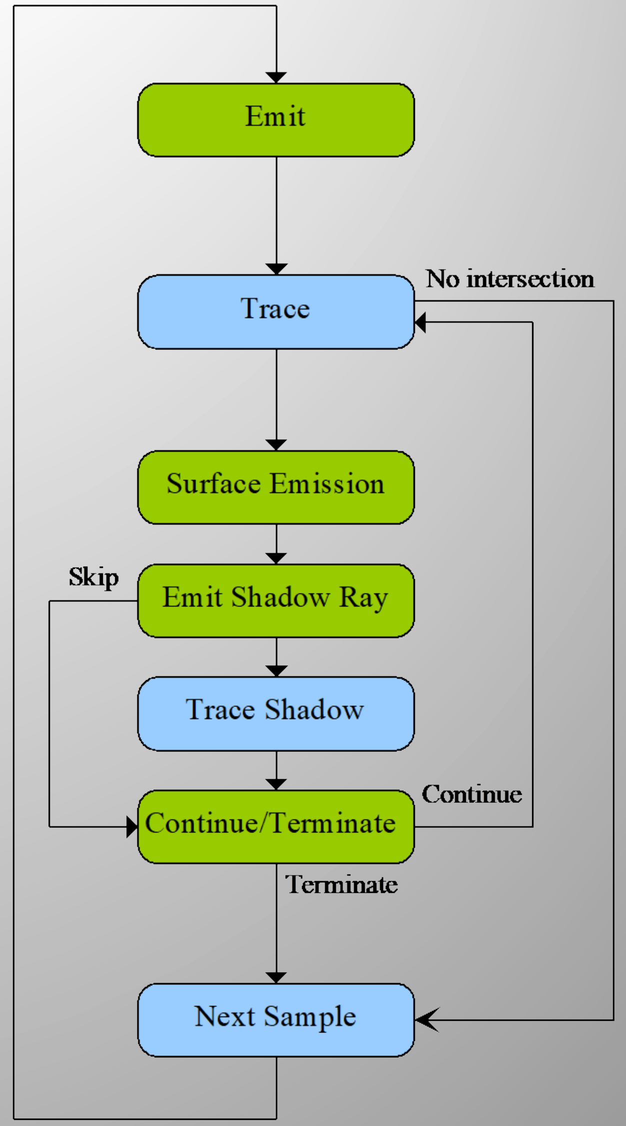


Rodent: Generating Renderers without Writing a Generator

https://github.com/AnyDSL/rodent

Rodent: Renderer + Traversal Library

- Renderer-generating library:
  Generate renderer that is optimized/specialized for a given input scene (or a class of scenes)
  - Generic, high-level, textbook code for
    - Shaders, lights, geometry, integrator, …
  - No low-level aspects
    - Strategy, scheduling, data layout, …
  - Separate mapping for each hardware
- 3D scenes are converted into code
  - E.g. from within Blender via exporter
  - Code triggers code generation



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Features

- OptiX (NVIDIA)
  - NVIDIA GPU only
  - Generates megakernel (MK)
  - Not easy to extend (closed source)
- Embree + *ispc* (Intel)
  - amd64 only
  - Low-level, write-only code
- Rodent
  - NVIDIA & AMD GPUs
  - Megakernel & wavefront (WF)
  - Open source
  - amd64 & ARM support
  - High-level, textbook style code

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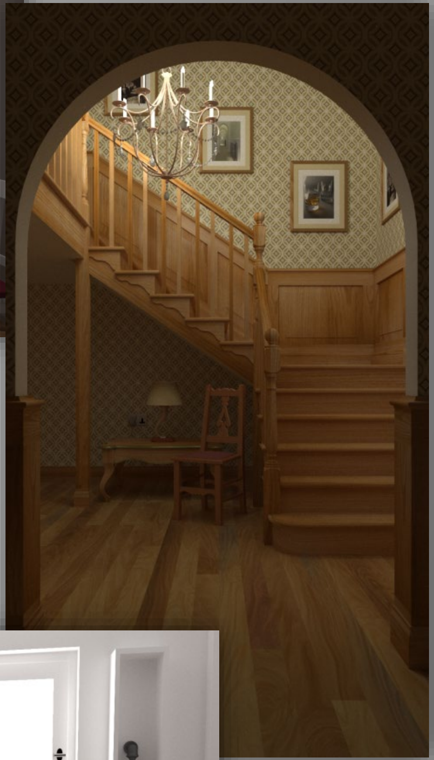
Test Scenes



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Performance Results

- Cross-layer specialization (traversal + shading)
  - ~20% speedup vs. no specialization
- Optimal scheduling for each device
  - Megakernel vs. wavefront

	CPU (Intel^{TM} i7 6700K)		GPU (NVIDIA^{TM} Titan X)			GPU (AMD^{TM} R9 Nano)	
Scene	Rodent^{WF}	Embree^{WF}	Rodent^{MK}	Rodent^{WF}	OptiX^{MK}	Rodent^{MK}	Rodent^{WF}
Living Room	9.77 (+23%)	7.94	38.59 (+25%)	43.52 (+42%)	30.75	24.87	35.11
Bathroom	6.65 (+13%)	5.90	27.06 (+31%)	35.32 (+42%)	20.64	14.95	27.31
Bedroom	7.55 (+ 4%)	7.24	30.25 (+ 9%)	38.88 (+29%)	27.72	19.25	32.90
Dining Room	7.08 (+ 1%)	7.01	30.07 (+ 5%)	40.37 (+29%)	28.58	16.22	30.83
Kitchen	6.64 (+12%)	5.92	22.73 (+ 2%)	32.09 (+31%)	22.22	16.68	28.13
Staircase	4.86 (+ 8%)	4.48	20.00 (+18%)	27.53 (+39%)	16.89	11.74	22.21

Msamples/s (higher is better). MK: Megakernel, WF: Wavefront.

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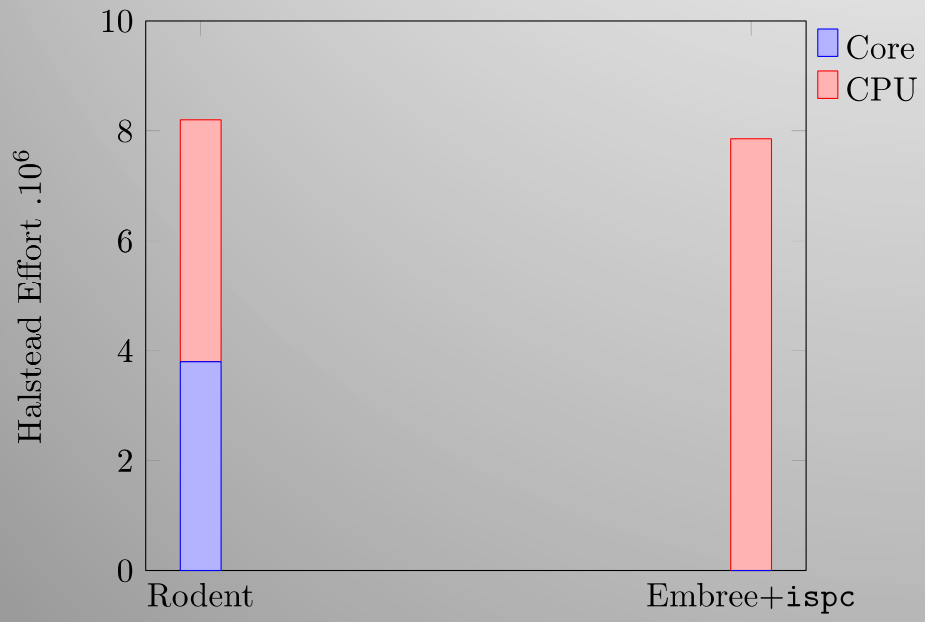
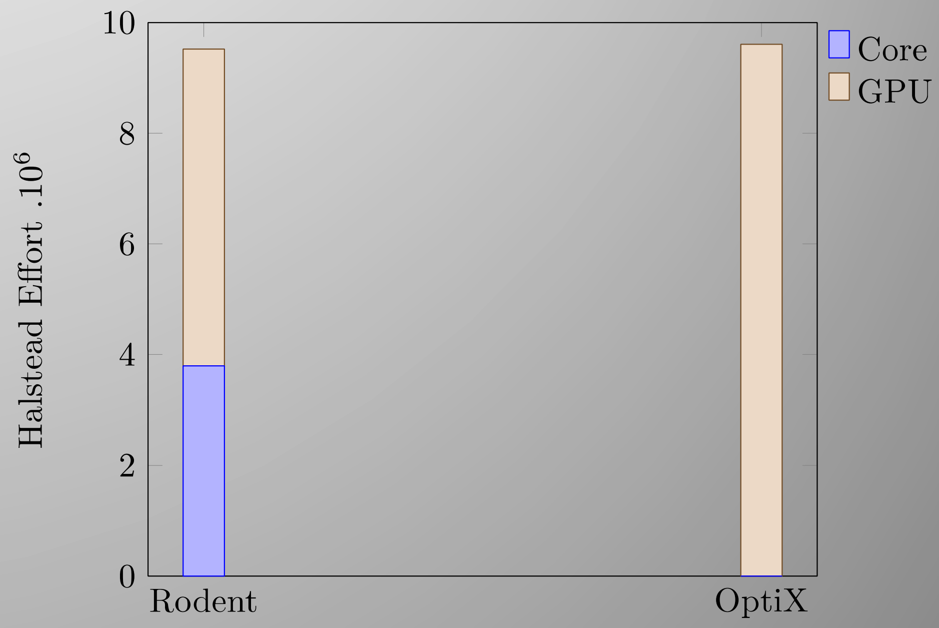
Code Complexity

- Halstead's complexity measures
  - Reusable renderer core
  - More accurate than LoC
- Polyvariant and nested vectorization
  - Reusable code across architectures
  - Change vector width within vectorized region (e.g. hybrid traversal)





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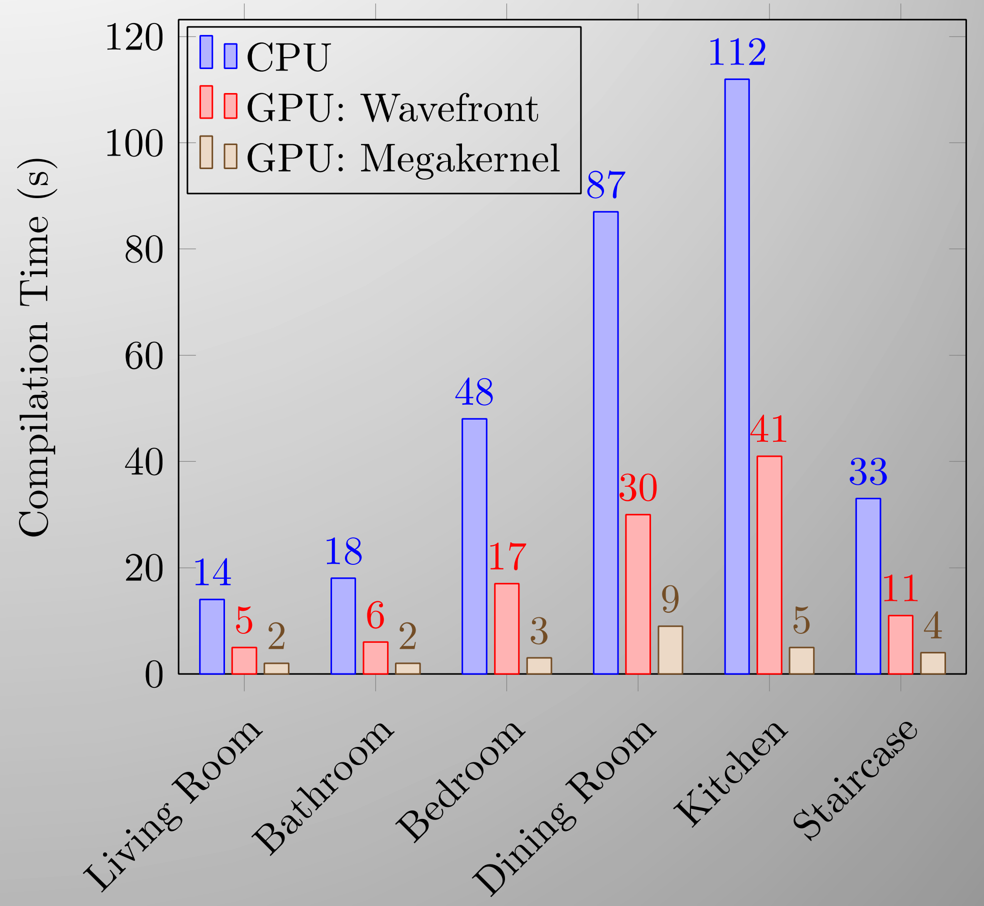
Scene Statistics: Compile Time & Shader Fusion

- Megakernel only: shader fusion #initial → #unique → #fused
  - Living room: 19 → 16 → 6
  - Bathroom: 16 → 15 → 5
  - Dining room: 58 → 51 → 28
  - Kitchen: 129 → 95 → 19
  - Staircase: 31 → 27 → 11
  - Bedroom: 41 → 38 → 13

- Compilation times



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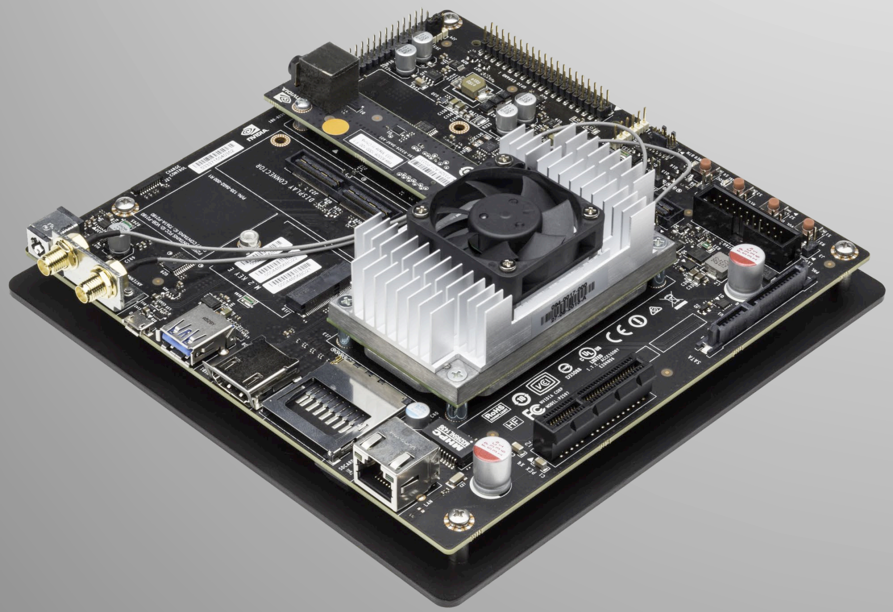
Thank you for your attention.
Questions?

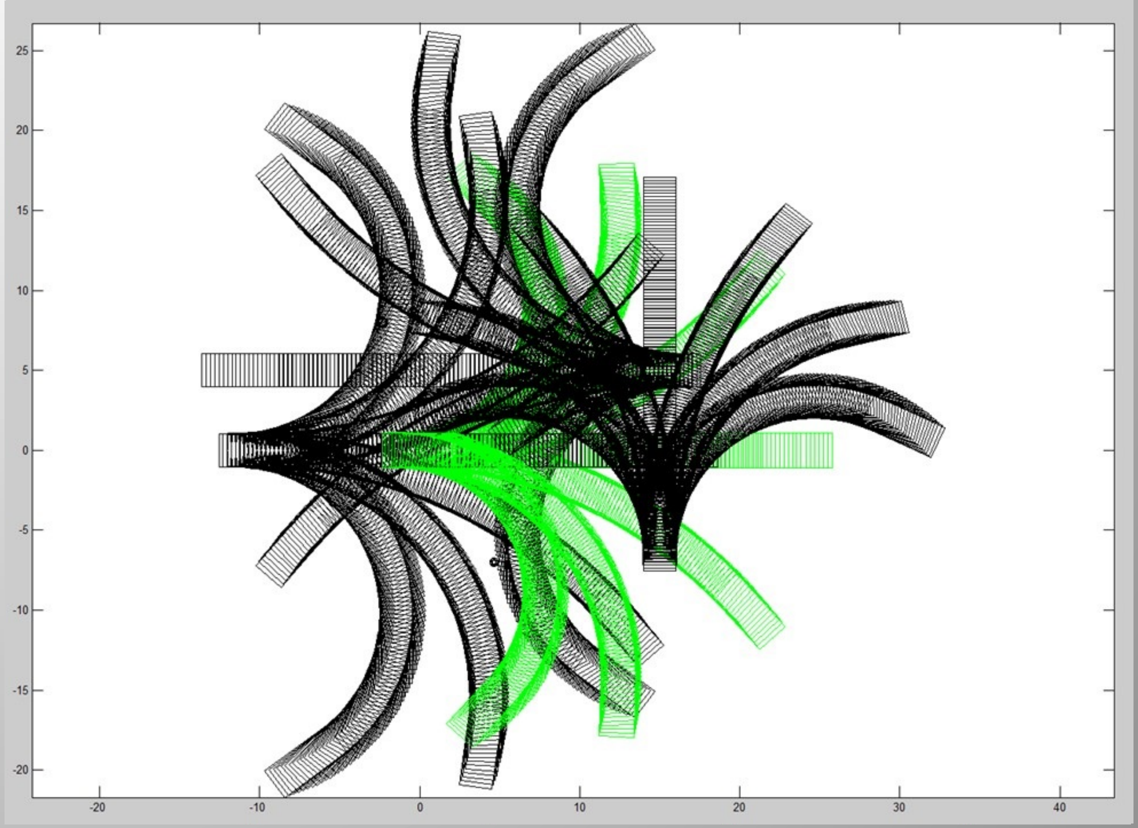
Case Study: Collision Avoidance & Crash Impact Point Optimization [GTC'16,IV'19]

Joint Project with Audi and THI

Prediction Approach to Environment Analysis

- Objects are described by their physical properties
- Movement is sampled and extrapolated
- All object hypotheses are combined with each other





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Performance Results

- Collision Avoidance
  - 8.6 million hypotheses combinations per collision object
- Scenario: 3 collision object + EGO vehicle
  - 26 million hypotheses combinations

Lang	HW	Time
MatLab	Intel Core i5	6 min
AnyDSL	Tegra X1 CPU	2 s
AnyDSL	Tegra X1 GPU	36 ms
AnyDSL	Drive PX2 GPU	15 ms

- Crash Impact Point Optimization
  - 0.9 million hypotheses combinations per collision object
- Scenario: 2 critical objects + EGO vehicle
  - 1.8 million hypotheses combinations

Lang	HW	Time
MatLab	Intel Core i5	16.5 s
AnyDSL	Tegra X1 CPU	0.3 s
AnyDSL	Tegra X1 GPU	8 ms
AnyDSL	Drive PX2 GPU	12 ms

DreamSpace

Case Study: DreamSpace EU Project

High Quality Rendering of Virtual Production Scenes

Key Achievements

Goals:

- High quality, global illumination rendering for real-time use
- With quality allowing creative use already during onset work
- Fully integrated into the Dreamspace ecosystem

Technology Developments:

- Improve and use of novel compiler framework (AnyDSL)
- Optimize core ray traversal and intersection engine
- Design a scalable, high-performance rendering architecture
- Create real-time distribution framework

Conclusion

- AnyDSL Framework
  - High-level, higher-order functional program representation
  - Novel code-refinement concept
  - Control over partial evaluation, vectorization, target code-generation

- Sample high-performance, domain-specific libraries (DSLs)
  - Stincilla: Stencil codes, image processing
  - RaTrace: Ray traversal kernels
  - Rodent: Renderer generator
  - AnySeq: Genome sequence alignment

Future Work

- Other high-performance libraries
  - Deep learning
  - Computer vision pipelines
  - Simulation, string matching, …
- Hardware synthesis as a backend
  - Very promising results with FPGAs!

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RODENT: GENERATING RENDERERS WITHOUT WRITING A GENERATOR

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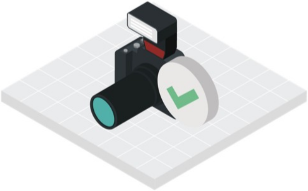

PHOTOGRAPHY & RECORDING ENCOURAGED

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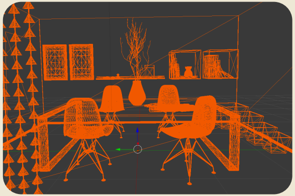
Overview



Scene

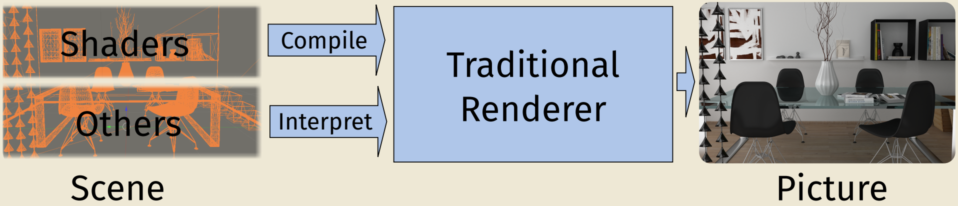
Traditional Renderer

Picture

What this talk is about

- Generating renderers from high-level, textbook-like code
- Specialized/optimized for a scene type
- High-performance: Up to 40%/20% faster than OptiX/Embree+`ispc`

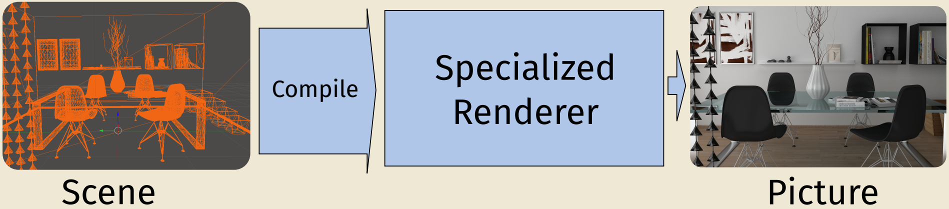
Rendering



In a traditional renderer

- Shaders are compiled by a (shader) compiler
  - Standard compiler optimizations
- Rest of the scene is interpreted during rendering
  - `if`/`else` branches (e.g. for renderer config/options)
  - Virtual function calls (e.g. for geometry types)
  - …

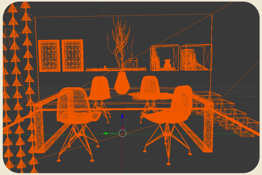
Rendering



In Rodent

- We compile the entire scene into a renderer
- We only use the scene type, not the actual scene data
  - No benefit from knowing e.g. the position of triangle 544
- We use Partial Evaluation
  - To avoid writing a *Renderer Generator*

Traditional Execution vs. Partial Evaluation



Scene

Traditional Renderer

Picture

Traditional program execution

Traditional Execution vs. Partial Evaluation

High-level Rendering Code

Partial Evaluation

Traditional Execution vs. Partial Evaluation

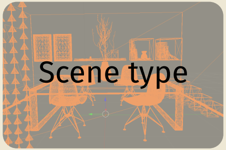
High-level Rendering Code

Rodent

Traditional Execution vs. Partial Evaluation

High-level Rendering Code

Rodent

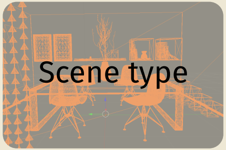


Partial Evaluation

Traditional Execution vs. Partial Evaluation

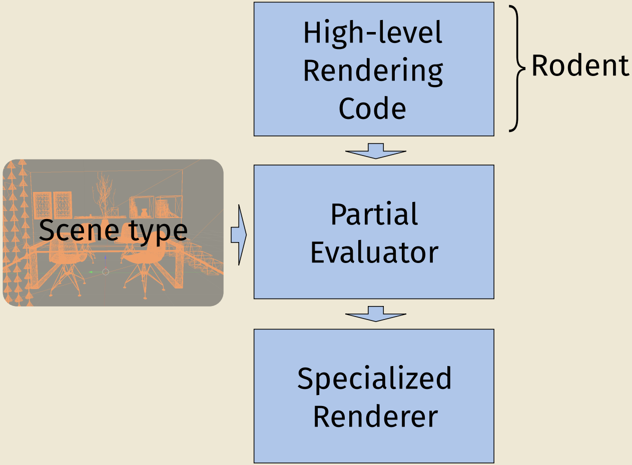
High-level Rendering Code

Rodent



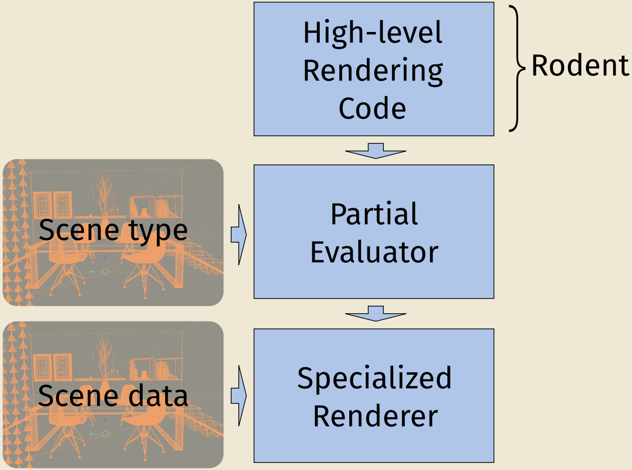
Partial Evaluator

Traditional Execution vs. Partial Evaluation



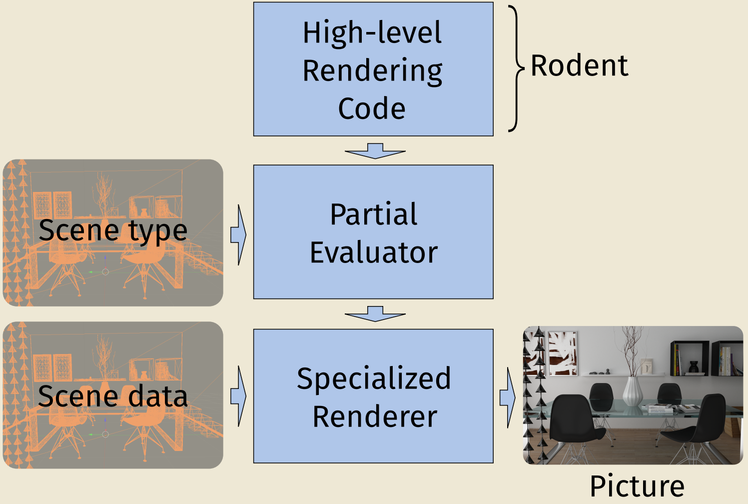
Partial Evaluation

Traditional Execution vs. Partial Evaluation



Partial Evaluation

Traditional Execution vs. Partial Evaluation



Partial Evaluation

AnyDSL

- This work leverages the AnyDSL compiler framework
  - `https://github.com/AnyDSL`
- Provides user-guided Partial Evaluation
- High-performance code generation using LLVM
- Can target/optimize for CPUs or GPUs
  - Intel/AMD/NVIDIA/ARM/...

Rendering Library Design

- High-level, textbook-like
  - In the spirit of PBRT
- Descriptive and modular
  - Separate the algorithm (”what”) from the schedule/hardware mapping (”how”)
- High-performance
  - Different hardware *mappings*
  - CPUs/GPUs have different execution models
  - Need efficient and flexible abstractions

The ”What”

BSDF

```
struct Bsdf {
  // Evaluation of the function given a pair of directions
  eval: fn (Vec3, Vec3) -> Color,

  // Probability density function used during sampling
  pdf: fn (Vec3, Vec3) -> f32,

  // Samples a direction (importance sampled according to this BSDF)
  sample: fn (Vec3) -> BsdfSample,
}
```

Example: Diffuse BSDF

```
fn @make_diffuse_bsdf(surf: SurfaceElement, kd: Color) -> Bsdf {
  Bsdf {
    eval: @ |in_dir, out_dir| kd * (1.0f / pi),
    pdf:  @|in_dir, out_dir|
      cosine_hemisphere_pdf(positive_cos(in_dir, surf.normal)),
    sample: @ |out_dir| {
      let sample = sample_cosine_hemisphere(rand(), rand());
      let color  = kd * (1.0f / pi);
      make_bsdf_sample(surf, sample, color)
    }
  }
}
```

- `@` triggers partial evaluation/specializes the function
- Replaces the function by its contents at the call site to allow optimizations

Defining a scene with Rodent

- BSDFs:

```
let diff = make_diffuse_bsdf(kd);
let spec = make_phong_bsdf(ns, ks);
let bsdf = make_mix_bsdf(spec, diff, k);
```

Defining a scene with Rodent

- BSDFs:

```
let diff = make_diffuse_bsdf(kd);
let spec = make_phong_bsdf(ns, ks);
let bsdf = make_mix_bsdf(spec, diff, k);
```

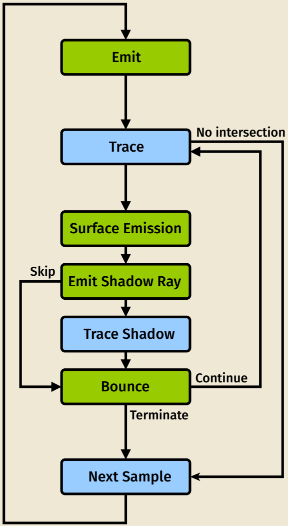
- Light sources, textures, geometric objects, ...

Rodent is a Scene Description Language

```
let renderer = make_path_tracing_renderer(/* ... */);
let geometry = make_tri_mesh_geometry(/* ... */);

let tex = make_image_texture(/* ... */);

let shader = |ray, hit, surface| {
    let uv = surface.attribute(0).as_vec2;
    make_diffuse_bsdf(surface, tex(uv1));
};

let scene = make_scene(geometry, /* ... */);
```

BSDF DSL + Light DSL + Geometry DSL + ... = Scene language embedded in AnyDSL

Abstracting the Rendering Process




```
struct Tracer {
  on_emit:   OnEmitFn,
  on_hit:    OnHitFn,
  on_shadow: OnShadowFn,
  on_bounce: OnBounceFn,
}
```

- Can also be used for bidir. algorithms
- Green nodes: the algorithm
  What should be computed
- Blue nodes: the schedule
  How it should be computed

The ”How”

Mapping Renderers to Hardware

- The `Device` contains hardware-specific routines:

```
struct Device {
  trace: fn (Scene, Tracer) -> (),
  /* ... */
}
```

- Schedule renderers differently depending on the platform
  - Wavefront: Batches (larger than SIMD width) of rays together
  - Megakernel: Large compute kernel, one ray at a time (used in OptiX)
- Rodent implements 3 devices:
  1. CPU: Wavefront
  2. GPU: Megakernel
  3. GPU: Wavefront

Wavefront Devices

On CPUs

- Processes a small (∼1000 rays) batch of rays together
  - Maximize cache efficiency
- Sort rays by shader and process contiguous ranges
- Uses vectorization and specialization, simplified:

```
for shader in unroll(0, scene.num_shaders) {
  // Get the range of rays for this shader
  let (begin, end) = ray_range_by_shader(shader);
  for i in vectorize(vector_width, begin, end) {
    // Scalar code using on_hit(), on_shadow(), ...
    // => automatically vectorized
  }
}
```

Wavefront Devices

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    // => automatically vectorized
  }
}
```

```
i∈unroll(0,3)
└j∈vectorize(w,begin(i),end(i))
                ⬇
j0∈vectorize(w,begin(0),end(0))
j1∈vectorize(w,begin(1),end(1))
j2∈vectorize(w,begin(2),end(2))
```

Wavefront Devices

On GPUs

- Processes a larger ($\sim$1M rays) batch of rays
  - Maximize parallelism
- Sort rays by shader and process contiguous ranges
- Generates one kernel per shader, with specialization, simplified:

```
for shader in unroll(0, scene.num_shaders) {
  // Get the range of rays for this shader
  let (begin, end) = ray_range_by_shader(shader);
  let grid = (round_up(end - begin, block_size), 1, 1);
  let block = (block_size, 1, 1);
  with work_item in cuda(grid, block) {
    // Use on_hit(), on_shadow(), ...
  }
}
```

Wavefront Devices

On GPUs

- Processes a larger (~1M rays) batch of rays
  - Maximize parallelism
- Sort rays by shader and process contiguous ranges
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  with work_item in cuda(grid, block) {
    // Use on_hit(), on_shadow(), ...
  }
}
```

```
i∈unroll(0,3)
 ┗cuda(grid(i),block(i))
          ⬇
cuda(grid(0),block(0))
cuda(grid(1),block(1))
cuda(grid(2),block(2))
```

Megakernel GPU Device

- Rays are local to the current execution thread
- Rendering loop *inside* the kernel, simplified:

```
fn trace(scene: Scene, tracer: Tracer) -> () {
  with work_item in cuda(grid, block) {
    let (x, y) = (work_item.gidx(), work_item.gidy());
    let (ray, state) = tracer.on_emit(x, y);
    let mut terminated = false;
    while !terminated {
      // Trace + use on_hit(), on_shadow(), ...
    }
  }
}
```

Evaluation

- Versus high-performance, state-of-the-art frameworks:
  - Embree + `ispc`: only for x86/amd64
  - OptiX: only for CUDA hardware
- Built custom, simple renderers based on those frameworks
  - Following documentation
  - Only implemented features required to render the test scenes
- Measured:
  - Performance
  - Code complexity
- Workflow: Convert scene to AnyDSL $\Rightarrow$ compile $\Rightarrow$ render

Scenes

786k tris./ 13 mats.

1.231M tris./14 mats.

545k tris./35 mats.

718k tris./44 mats.

612k tris./61 mats.

263k tris./23 mats.

Scenes by Wig42, nacimus, SlykDrako, MaTTeSr, Jay-Artist, licensed under CC-BY 3.0/CC0 1.0. See paper for details.

Results: Performance

Scene	CPU (Intel™ i7 6700K)		GPU (NVIDIA™ Titan X)			GPU (AMD™ R9 Nano)	
	Rodent[2]	Embree	Rodent[1]	Rodent[2]	OptiX	Rodent[1]	Rodent[2]
Living Room	9.77 (+23%)	7.94	38.59 (+25%)	43.52 (+42%)	30.75	24.87	35.11
Bathroom	6.65 (+13%)	5.90	27.06 (+31%)	35.32 (+42%)	20.64	14.95	27.31
Bedroom	7.55 (+ 4%)	7.24	30.25 (+ 9%)	38.88 (+29%)	27.72	19.25	32.90
Dining Room	7.08 (+ 1%)	7.01	30.07 (+ 5%)	40.37 (+29%)	28.58	16.22	30.83
Kitchen	6.64 (+12%)	5.92	22.73 (+ 2%)	32.09 (+31%)	22.22	16.68	28.13
Staircase	4.86 (+ 8%)	4.48	20.00 (+18%)	27.53 (+39%)	16.89	11.74	22.21

(1) Megakernel, (2) Wavefront

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(1) Megakernel, (2) Wavefront

- Between $+1 - 23\%$ vs. Embree
    - Around $60 - 70\%$ of the time tracing rays
    - Traversal algorithms in Embree are already specialized
    - Rodent's shading alone is around $2\times$ faster than with `ispc`

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  - Around $60 - 70\%$ of the time tracing rays
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  - Rodent's shading alone is around $2\times$ faster than with `ispc`
- Between $+2 - 31\%$ vs OptiX (Megakernel)

Results: Performance

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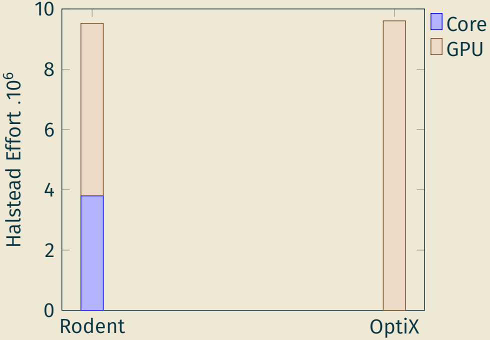
- Between $+1-23\%$ vs. Embree
  - Around $60-70\%$ of the time tracing rays
  - Traversal algorithms in Embree are already specialized
  - Rodent's shading alone is around $2\times$ faster than with `ispc`
- Between $+2-31\%$ vs OptiX (Megakernel)
- Between $+29-42\%$ vs OptiX (Wavefront)
  - Wavefront scales better with shader complexity
  - Not limited by register pressure

Results: Code Complexity



- Embree: only on x86/amd64
- Rodent: also on ARM
  + other LLVM targets (RISC-V?)

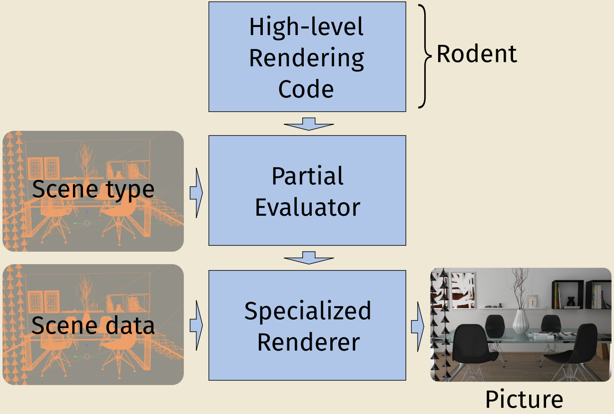
- OptiX: only Megakernel, only CUDA hw.
- Rodent: also on AMD™ GPUs
  + other LLVM targets (Intel™ GPU?)

Conclusion

Rodent *generates* high-performance renderers *without writing a generator*

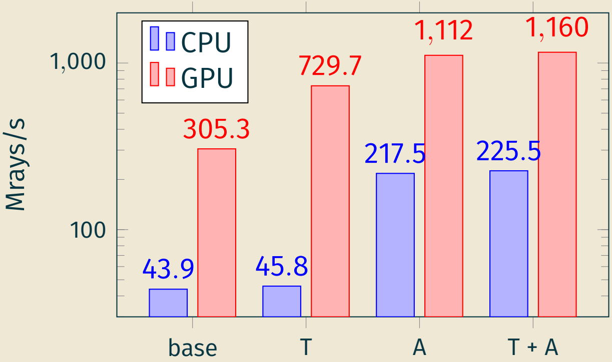
- Defines textbook-like, generic algorithms
- Provides tailored hardware schedules for different CPUs and GPUs
- Specializes code according to the scene via AnyDSL
- Runs up to 40% faster than state-of-the-art

Questions?



https://github.com/AnyDSL/rodent

Results: Impact of Specialization

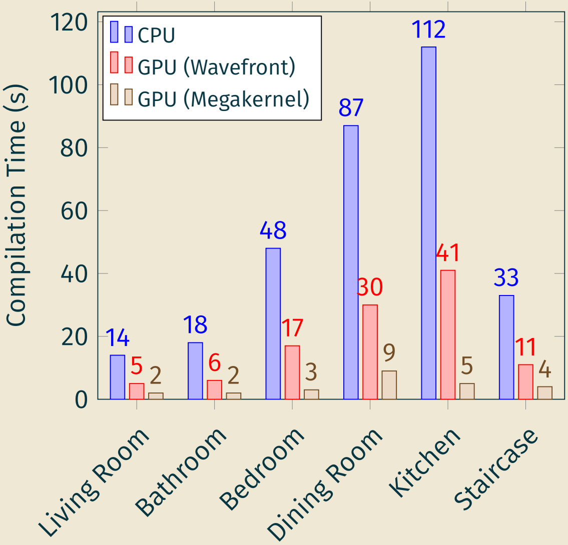


- Base: No specialization
- T: Specialize the interface (shader $\longleftrightarrow$ texturing function)
- A: Specialize the interface (shader $\longleftrightarrow$ mesh attribute)

Specialization: Caveats

- Specialization may lead to increased compilation times
- Specializing to much may increase register pressure
  - Dangerous for the megakernel device
  - Not a problem for the wavefront device
- Rodent fuses simple/similar shaders together
  - Only for the megarkernel device
  - Mitigates problems of divergence and reg. pressure

Results: Compilation Times



Improving Compilation Times

- The more there is to specialize, the slower
- Compiler itself is not particularly optimized for speed
- Parts of the renderer can be pre-compiled
- Does not need to know *everything* in the scene
  - The less is known the less specialization will happen
  - Automatically done by the compiler thanks to annotations
  - Can be exploited to make compilation faster