Porting pbrt to the GPU
While Preserving its Soul

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NVIDIA
15 July 2020
pbrt at HPG???
pbrt Background

- Ray-tracer implemented as a literate program
- Book goes all the way from equations / ideas to C++ code
- Book: ~1000 pages
- Renderer: ~72k LOC, C++
- First edition in 2004, some code dates to 1998
pbpt Context / Constraints

• System’s goals are primarily pedagogical

• Value proposition: C++ and calculus are the only prerequisites

• Try to be relevant for 5-10 years

• Avoid external APIs (beyond the stdlib)

• Portability is important
Tension: Performance vs. Clarity

• Want to teach something about system organization and design

• Performance is a big part of rendering

• But maximizing performance can get grungy…

• Example: pbrt is multi-threaded—can discuss mutual exclusion, atomics, false sharing, …
template <typename T>
inline bool Bounds3<T>::IntersectP(const Point3f &o, const Vector3f &d, Float tMax,
                                     Float *hitt0, Float *hitt1) const {
  Float t0 = 0, t1 = tMax;
  for (int i = 0; i < 3; ++i) {
    // Update interval for i th bounding box slab
    Float invRayDir = 1 / d[i];
    Float tNear = (pMin[i] - o[i]) * invRayDir;
    Float tFar = (pMax[i] - o[i]) * invRayDir;

    // Update parametric interval from slab intersection $t$ values
    if (tNear > tFar)
      std::swap(tNear, tFar);

    // Update _tFar_ to ensure robust ray--bounds intersection
    tFar *= 1 + 2 * gamma(3);
    t0 = tNear > t0 ? tNear : t0;
    t1 = tFar < t1 ? tFar : t1;
    if (t0 > t1)
      return false;
  }
  if (hitt0) *hitt0 = t0;
  if (hitt1) *hitt1 = t1;
  return true;
}
Not pbrt’s Ray-AABB Intersection Code

```c
static bool ray_box(const Bounds3f &box, const Ray &ray, float *tMin, float *tMax) {
    const __m128 plus_inf = _mm_load_ps((const float *const)(ps_cst_plus_inf));
    const __m128 minus_inf = _mm_load_ps((const float *const)(ps_cst_minus_inf));
    const __m128 box_min = _mm_load_ps((const float *const)(&box.pMin));
    const __m128 box_max = _mm_load_ps((const float *const)(&box.pMax));
    const __m128 pos = _mm_load_ps((const float *const)&ray.o);
    const __m128 inv_dir = _mm_load_ps((const float *const)&ray.inv_dir);
    const __m128 l1 = _mm_mul_ps(_mm_sub_ps(box_min, pos), inv_dir);
    const __m128 l2 = _mm_mul_ps(_mm_sub_ps(box_max, pos), inv_dir);
    const __m128 filtered_l1a = _mm_min_ps(l1, plus_inf);
    const __m128 filtered_l2a = _mm_min_ps(l2, plus_inf);
    const __m128 filtered_l1b = _mm_max_ps(l1, minus_inf);
    const __m128 filtered_l2b = _mm_max_ps(l2, minus_inf);
    __m128 lmax = _mm_max_ps(filtered_l1a, filtered_l2a);
    __m128 lmin = _mm_min_ps(filtered_l1b, filtered_l2b);
    lmax = _mm_shuffle_ps(lmax, lmax, 0x39);
    lmin = _mm_shuffle_ps(lmin, lmin, 0x39);
    lmax = _mm_min_ss(lmax, lmax);  // May be replaced by _mm_min_ss(lmax, lmax0)
    lmin = _mm_max_ss(lmin, lmin);  // May be replaced by _mm_max_ss(lmin, lmin0);
    __m128 lmax1 = _mm_movehl_ps((lmax), (lmax));
    __m128 lmin1 = _mm_movehl_ps((lmin), (lmin));
    lmax = _mm_min_ss(lmax, lmax1);
    lmin = _mm_max_ss(lmin, lmin1);
    const bool ret =
        _mm_comige_ss(lmax, _mm_setzero_ps()) & _mm_comige_ss(lmax, lmin);
    _mm_store_ss((float *const)tMin, lmin);
    _mm_store_ss((float *const)tMax, lmax);
    return ret;
}
```
pbrt ∩ ispc = Ø

• Though based on C, ispc is a new language

• It’s too much to require learning a new language to read the book…

• But yet…

• SIMD is important for CPU production rendering

• Would like to discuss ray packets, multi-BVHs, sorting for shading…
“Try to be relevant…”
Porting Approach

• CUDA + OptiX or bust
  • CUDA: only option given C++ and portability requirements
    • Prospect of maximizing shared code between CPU and GPU
  • OptiX: GPU-accelerated intersection tests
    • And can side-step explaining highly-parallel creation of BVHs, ...
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Ray intersection is a black-box for the GPU path. But still have all the details for the CPU…
Porting Approach

- CUDA + OptiX or bust
- GPU path as alternative to CPU, not replacement
- Fail fast: is it going to work in the first place?
  - (Work == doesn’t complexify code excessively + perf. is decent)
- ➡ Start making pictures ASAP
Crossing The Chasm

- Extensive __host__ __device__ annotations...
- Data structure initialization all CPU-side, like before
- Ubiquitous plumbing of std::pmr::polymorphic_allocator
- GPUParallelFor + __device__ lambda functions
- Tagged-dispatch in place of virtual function calls
using Allocator = std::pmr::polymorphic_allocator<std::byte>;

class PiecewiseConstant1D {
    PiecewiseConstant1D(std::vector<Float> f, Allocator alloc = {})
        : func(f.begin(), f.end(), alloc), cdf(f.size() + 1, alloc) {
        // Compute integral of step function at $x_i$
        cdf[0] = 0;
        size_t n = f.size();
        for (size_t i = 1; i < n + 1; ++i)
            cdf[i] = cdf[i - 1] + func[i - 1] / n;

        ...
    }

    ...

    pstd::vector<Float> func, cdf;
};
Memory Allocations

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        for (size_t i = 1; i < n + 1; ++i)
            cdf[i] = cdf[i - 1] + func[i - 1] / n;
        ...
    }

    pstd::vector<Float> func, cdf;
};
PathState pathState[NumPixels];
FilmHandle film;
// ...

GPUParallelFor("Update Film", pixelsPerPass,
    [=] PBRT_GPU (PixelIndex pixelIndex) {
        const PathState &pathState = pathStates[pixelIndex];
        Point2i pPixel = pathState.pPixel;
        if (!InsideExclusive(pPixel, film.PixelBounds()))
            return;

        SampledSpectrum L = pathState.L * pathState.cameraWeight;
        film.AddSample(pPixel, L, pathState.filterWeight);
    });
GPU Kernel Launch

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FilmHandle film;
// …

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        film.AddSample(pPixel, L, pathState.filterWeight);
    });
Virtual Functions → Tagged Dispatch

class CameraHandle :
    public TaggedPointer<PerspectiveCamera, OrthographicCamera, SphericalCamera, RealisticCamera> {

    public:
        PBRT_CPU_GPU
        pstd::optional<CameraRay> GenerateRay(const CameraSample &sample, const SampledWavelengths &lambda) const {
            switch (Tag()) {
                case TypeIndex<PerspectiveCamera>():
                    return Cast<PerspectiveCamera>()->GenerateRay(sample, lambda);
                case TypeIndex<OrthographicCamera>():
                    return Cast<OrthographicCamera>()->GenerateRay(sample, lambda);
                case TypeIndex<SphericalCamera>():
                    return Cast<SphericalCamera>()->GenerateRay(sample, lambda);
                case TypeIndex<RealisticCamera>():
                    return Cast<RealisticCamera>()->GenerateRay(sample, lambda);
            }
        }

    (TaggedPointer builds on DiscriminatedPtr from Facebook’s folly library)
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    public TaggedPointer<PerspectiveCamera, OrthographicCamera, SphericalCamera, RealisticCamera> {

public:
    PBRT_CPU_GPU
    pstd::optional<CameraRay> GenerateRay(const CameraSample &sample,
                                          const SampledWavelengths &lambda) const {
        auto generateRay = [&](auto ptr) -> pstd::optional<CameraRay> {
            return ptr->GenerateRay(sample, lambda);
        };
        return Apply(generateRay);
    }
}
Path-Tracing Pipeline

Generate Camera Rays

Intersect Closest

Sample Medium

Handle Emission at Intersection

Evaluate Material (Simple)

Evaluate Material (Complex)

Sample Light BVH

Sample Light

Sample Light Shadow

Intersect BSDF

Sample Subsurface

OptiX

OptiX
Parallelism Domains:
Maximize Control Convergence

For each Pixel

For each Ray

For each BxDF type, For Each Ray
BxDF Sorting

Evaluate Material

DiffuseBxDF Queue

DielectricBxDF Queue

ConductorBxDF Queue

MeasuredBxDF Queue

Sample Light (DiffuseBxDF)

Sample Light (DielectricBxDF)

Sample Light (ConductorBxDF)

Sample Light (MeasuredBxDF)

Intersect Shadow

Resulting improved control convergence gave ~2x speedup (overall) on San Miguel
Performance vs. CPU pbrt

(RTX2080 vs 6c/12t @ 3.4GHz)
Performance vs. Optimized DX12 RT*

~1 order of magnitude slower

* (Not an exact apples-to-apples to comparison)
Demo interlude...
Performance Breakdown: San Miguel @ 1080p, 1spp

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<td>5.7%</td>
</tr>
<tr>
<td>Sample indirect - DiffuseBxDF</td>
<td>4</td>
<td>7.36 ms</td>
<td>6.1%</td>
</tr>
<tr>
<td>Sample indirect - CoatedDiffuseBxDF</td>
<td>4</td>
<td>2.07 ms</td>
<td>1.7%</td>
</tr>
<tr>
<td>Sample indirect - DielectricInterfaceBxDF</td>
<td>4</td>
<td>0.69 ms</td>
<td>0.6%</td>
</tr>
<tr>
<td>Update Film</td>
<td>2</td>
<td>1.98 ms</td>
<td>1.6%</td>
</tr>
<tr>
<td>Other</td>
<td>86</td>
<td>1.83 ms</td>
<td>1.5%</td>
</tr>
</tbody>
</table>
Code Complexity

• pbrt is ~72k LOC (excluding tests, Sobol’ / blue noise tables, etc.)

• 7k LOC CPU-specific (accel structures, integrators): ~10%

• 4k LOC GPU-specific(*) (infrastructure + path tracer, OptiX interop): ~6%

• Shared (lights, BSDFs, materials, sampling code, …): ~84%

(*) Plus diffused impact of Allocator and tag-based dispatch
pbrt-v4 Release Plans

- SIGGRAPH: beta source code available on github
- Late 2020: online book
- Spring 2021: printed book
Summary

- GPU ray tracing is fast!

- …even with non-ninja optimized code

- C++ was the only option for a legacy code base that still has to run on CPU; it’s not necessarily the end-all GPU programming model

- Idiomatic C++ is not necessarily optimal on the GPU.

- Programming model model design tension: does it all vs. provides mechanisms that let you do it all
Thanks!

• Steve Parker, Frank Jargstorf

• David Luebke, Aaron Lefohn

• James Bigler, Detlef Roettger, Keith Morley, David Hart, Ingo Wald

• Tim Foley