Porting pbrt to the GPU While Preserving its Soul

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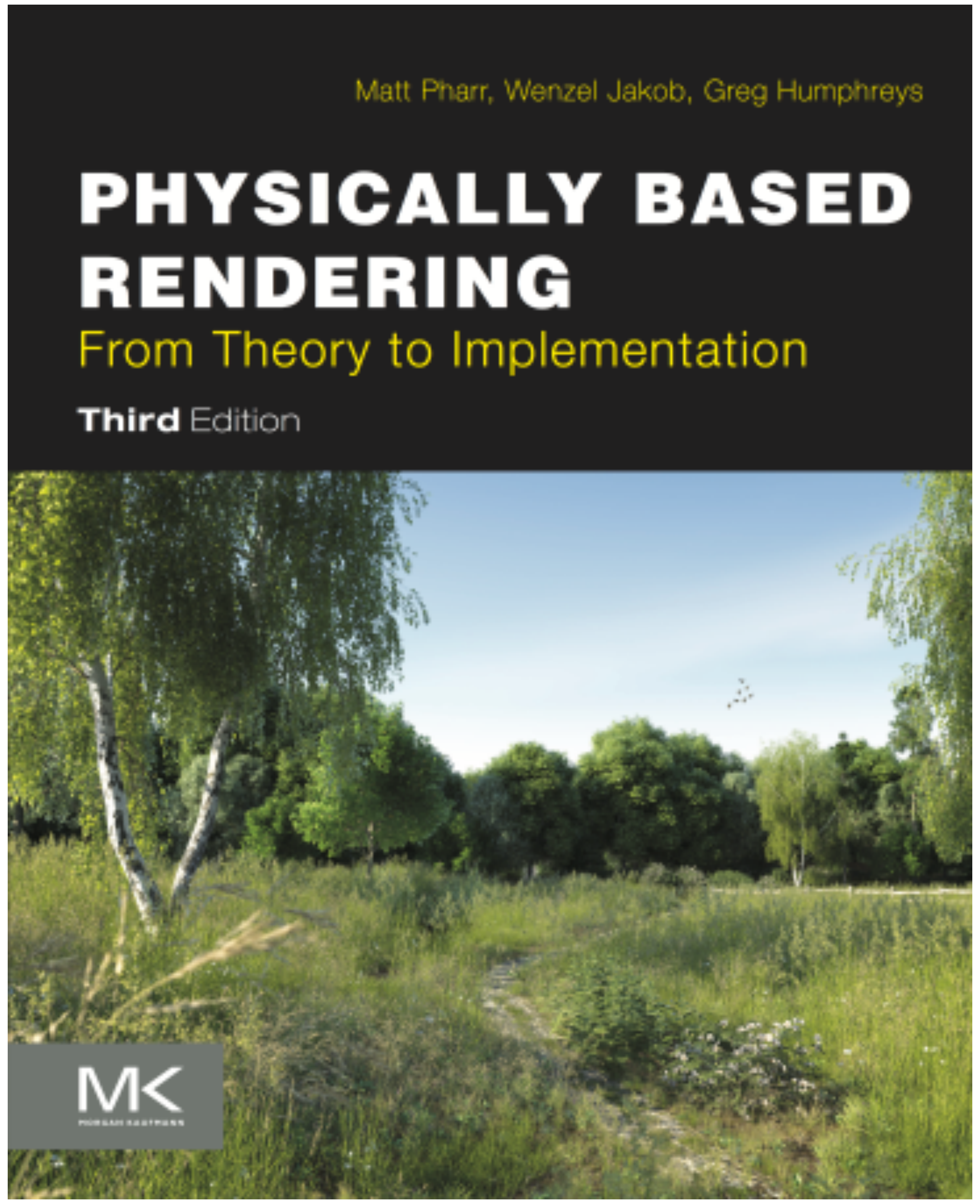
pbrt at HPG???

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



pbrt 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, …

pbrt’s Ray-AABB Intersection Code

```
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;
}
```

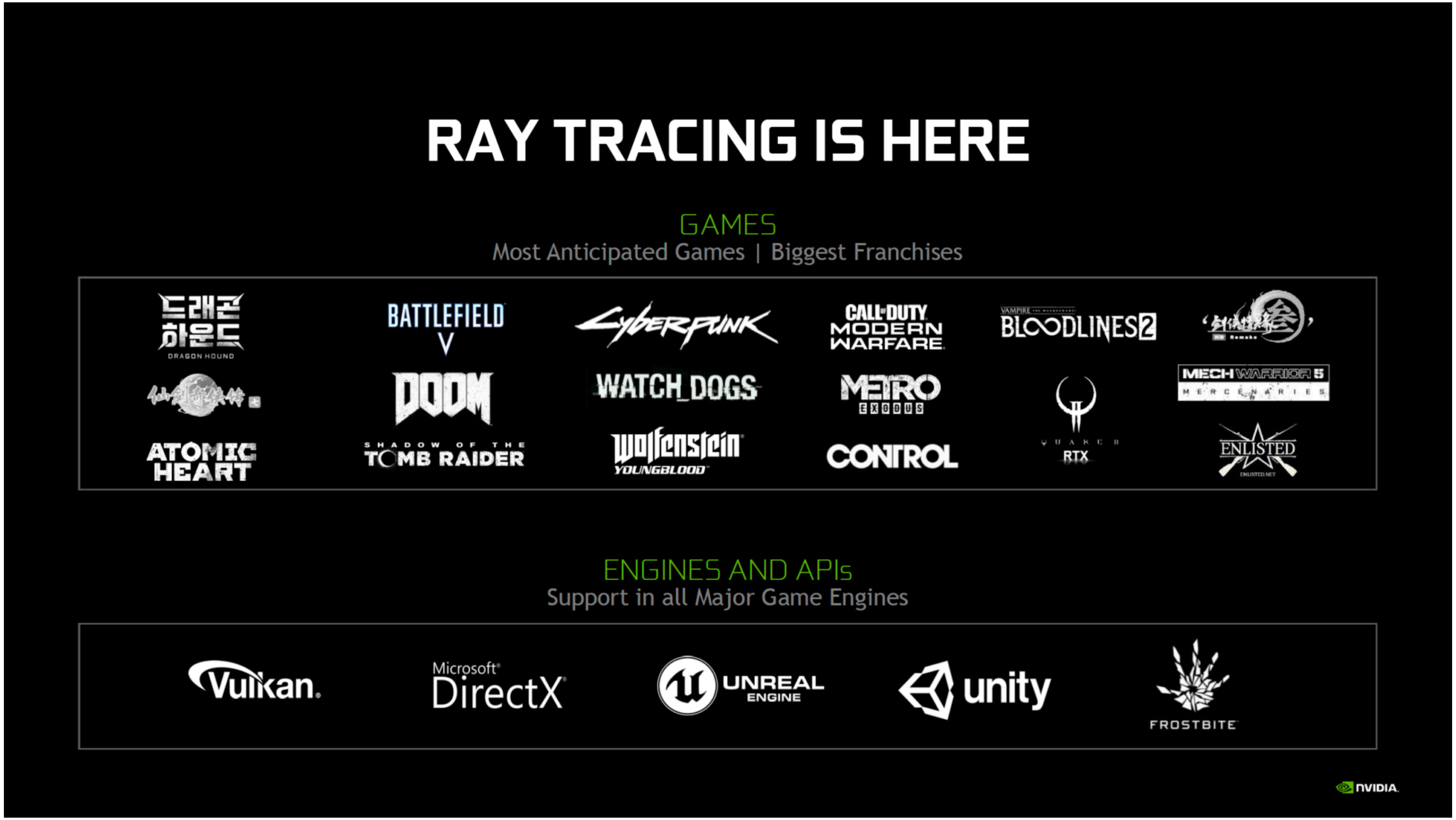
Not pbrt's Ray-AABB Intersection Code

```
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);
    const __m128 lmax0 = _mm_shuffle_ps(lmax, lmax, 0x39);
    const __m128 lmin0 = _mm_shuffle_ps(lmin, lmin, 0x39);
    lmax = _mm_min_ss(lmax, lmax0);
    lmin = _mm_max_ss(lmin, lmin0);
    const __m128 lmax1 = _mm_movehl_ps((lmax), (lmax));
    const __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 $\cap$ ispc $= \emptyset$

- 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


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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

Memory Allocations

```
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;
};
```

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    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;
};
```

Pass allocator that allocates unified memory for GPU rendering…

GPU Kernel Launch

```
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);
});
```

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});
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Virtual Functions →Tagged Dispatch

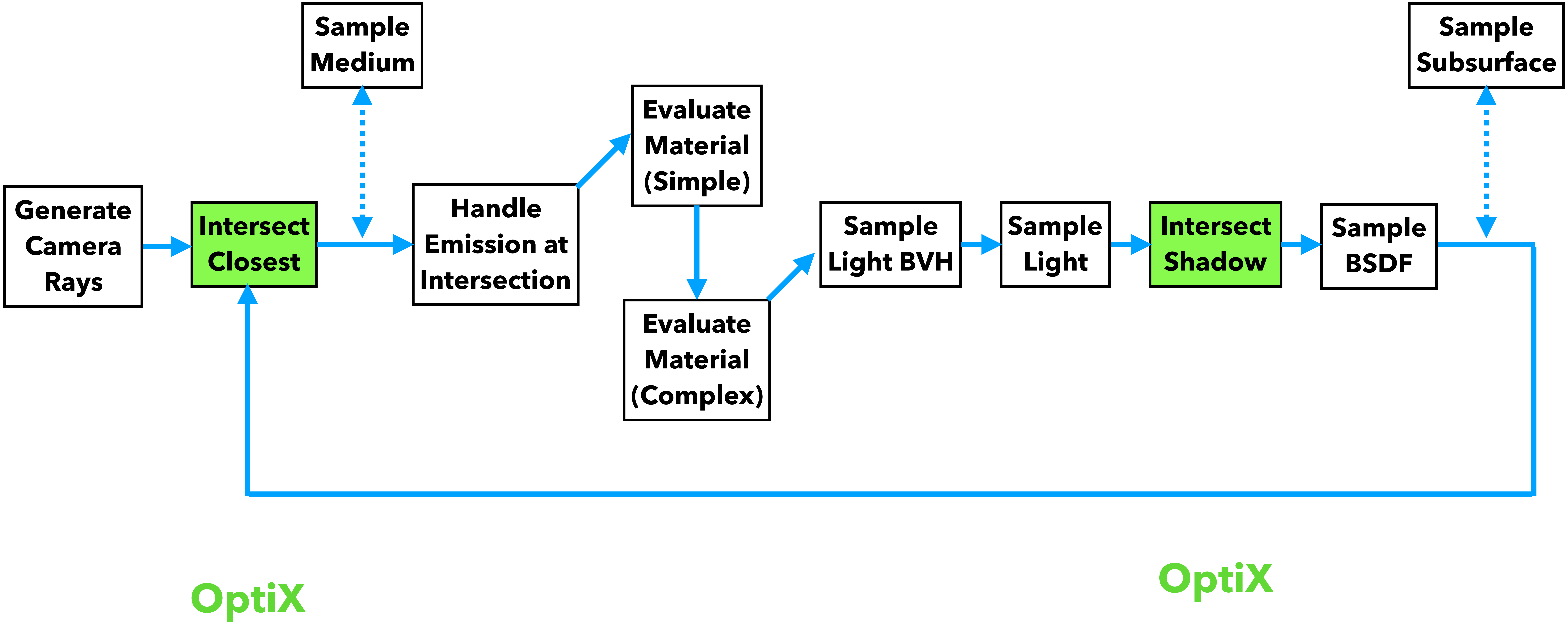
```
class CameraHandle :
    public TaggedPointer<PerspectiveCamera, OrthographicCamera,
                         SphericalCamera, RealisticCamera> {
public:
  PBRT_CPU_GPU
  pstd::optional<CameraRay> GenerateRay(const CameraSample &sample,
                                        const SampledWavelengths &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)

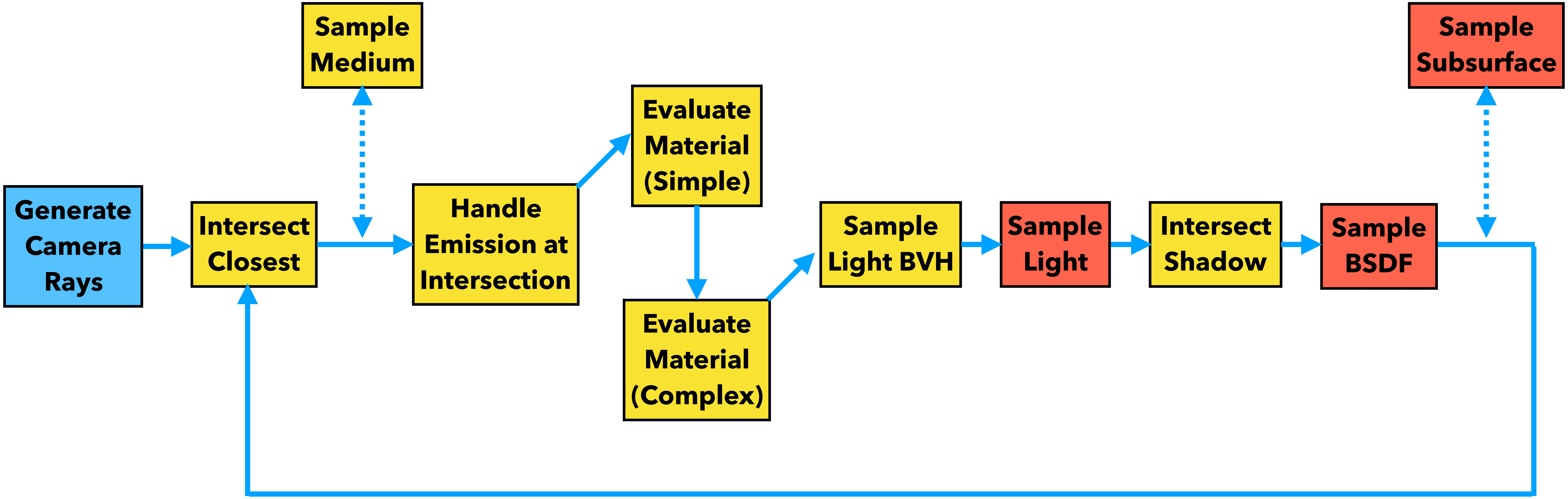
Tagged Dispatch v2

```
class CameraHandle :
    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



Parallelism Domains:
Maximize Control Convergence



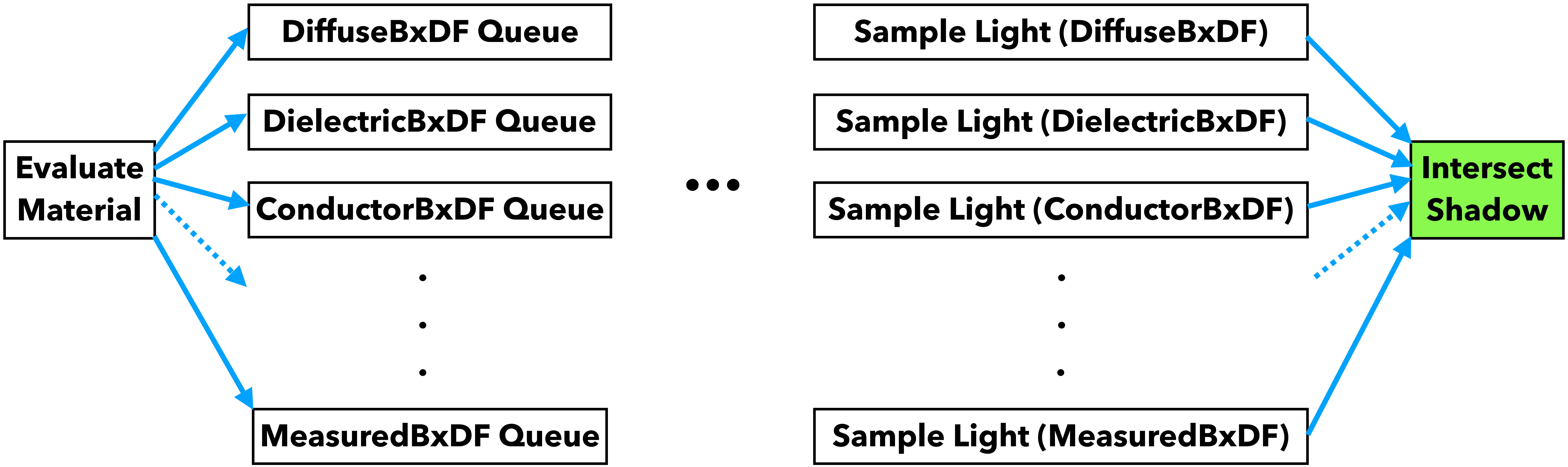
For each Pixel

For each Ray

For each BxDF type,
For Each Ray

HPG 2020

BxDF Sorting



Resulting improved control convergence gave ~2x speedup (overall) on San Miguel

Performance vs. CPU pbrt

(RTX2080 vs 6c/12t @ 3.4GHz)

51x

53x

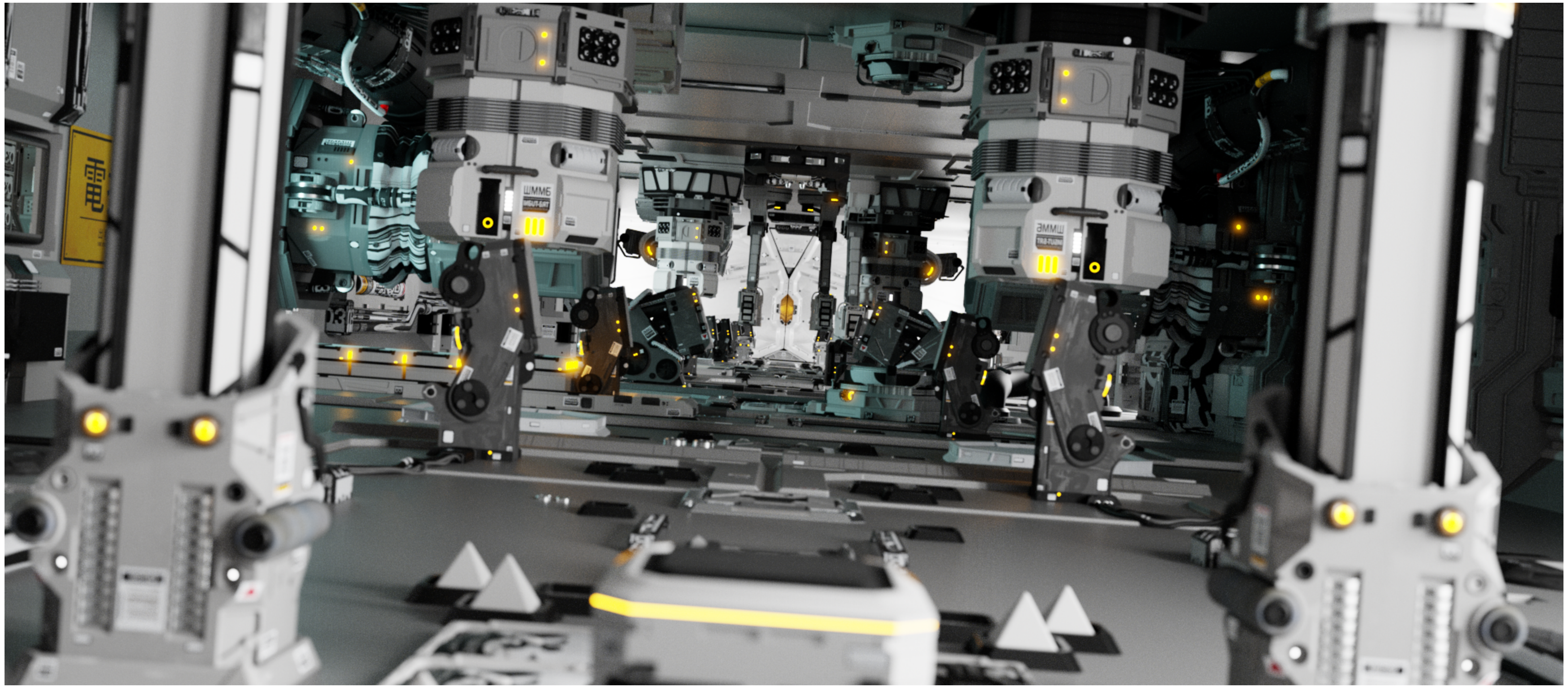
30x

32x

27x

28x

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

Reset sampler dimension	2 launches	3.72 ms /	3.1%
Generate Camera rays	2 launches	9.72 ms /	8.1%
Initialize PathState	2 launches	2.71 ms /	2.3%
Clear intersections	6 launches	5.82 ms /	4.8%
Path tracing closest hit rays	6 launches	32.97 ms /	27.4%
Handle ray-found emission	6 launches	2.65 ms /	2.2%
Bump and Material::GetBSDF/GetBSSRDF	4 launches	17.60 ms /	14.6%
Bump and Material::GetBSDF/GetBSSRDF	4 launches	3.98 ms /	3.3%
Choose Light to Sample	4 launches	7.59 ms /	6.3%
Sample direct - DiffuseBxDF	4 launches	9.85 ms /	8.2%
Sample direct - CoatedDiffuseBxDF	4 launches	2.83 ms /	2.4%
Path tracing shadow rays	4 launches	6.84 ms /	5.7%
Sample indirect - DiffuseBxDF	4 launches	7.36 ms /	6.1%
Sample indirect - CoatedDiffuseBxDF	4 launches	2.07 ms /	1.7%
Sample indirect - DielectricInterfaceBxDF	4 launches	0.69 ms /	0.6%
Update Film	2 launches	1.98 ms /	1.6%
Other	86 launches	1.83 ms /	1.5%

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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!

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- Tim Foley