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LOS ANGELES • 28 JULY – 1 AUGUST

Open Problems in Real-Time Rendering

The Path To Performance: Scaling Game Path Tracing

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GOALS: TALK TAKEAWAYS

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- Problem: Re-envision light transport algorithms under real-time constraints
- Reminder: What constraints are important for real time?
- Observations: Insights useful for redesigning algorithms

REVISIT: WHY DO YOU CARE?

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- Maybe we're already there??
  - Better shadows, reflections, diffuse GI

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- Maybe we're already there?
  – Path traced game, simple assets and limit path types

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- Promises of path tracing
  - Simpler asset creation
  - Simpler rendering / fewer rendering combinatorics
  - Enables new artistic looks & dynamism

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- Is it possible to achieve these promises?
  - That's the big open problem

- This talk:
  - Suggests maybe not be as distant as you imagine…

What this talk is not…

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Often see path traced images like this & think:

- How long did it take?
- We could do with raster

BUT WAIT!

- What if…
  – Artist simply paints light via emissive textures and materials?

Entirely Changes Look

Shadows a Major Component

Direct Light Only; No GI

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~20,000 emissive triangles
Hard to do with shadow maps

Baking Misses View Dependencies

But Can It Run Fast Enough?


Soon? Yes.
8 shadow rays per pixel
~20 ms total frame
No denoising

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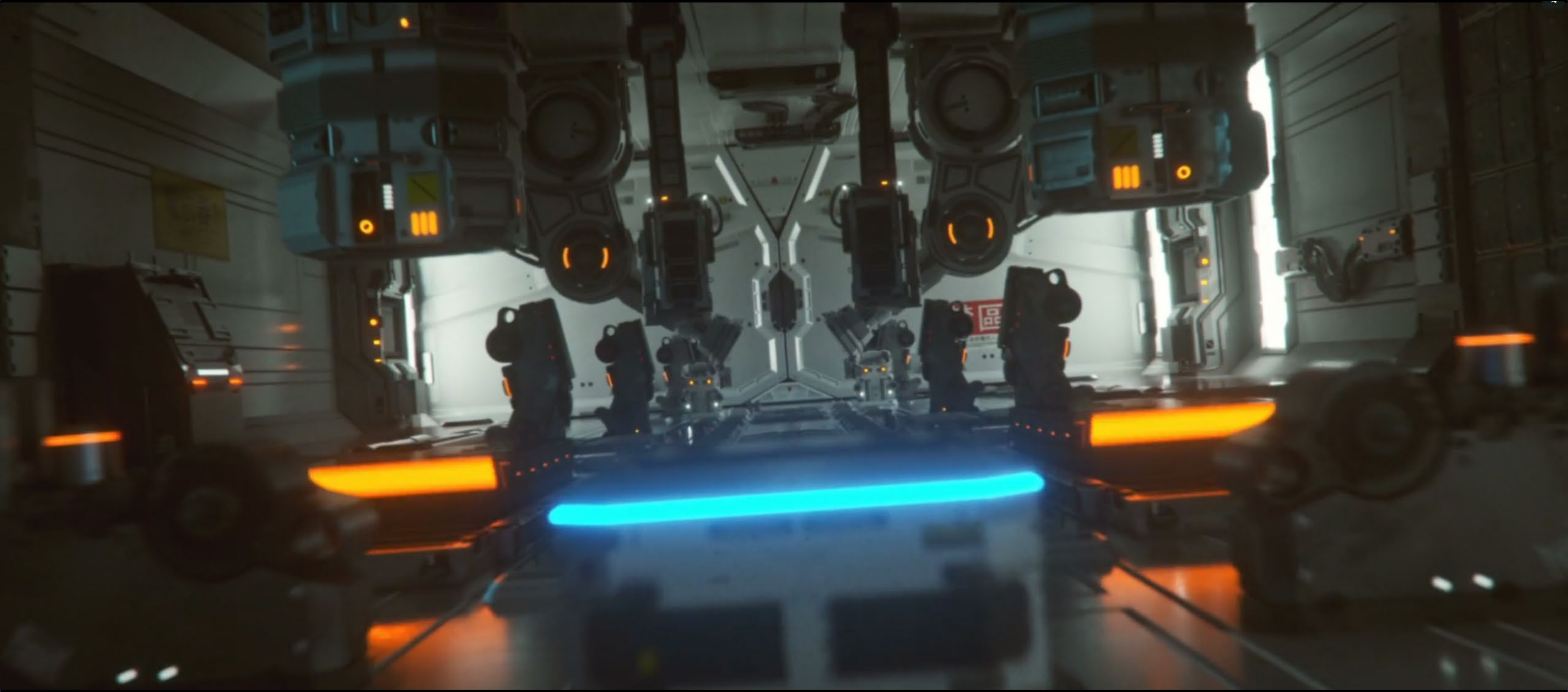
- Draw inspiration from artists' without time constraints
  - Zero Day video from Mike Winkelmann (aka *beeple*) available on Vimeo
  - Freely provides assets from his videos
  - Most lights dynamic
  - ~10,500 emissive triangles
  - ~350 emissive meshes

Rendered offline



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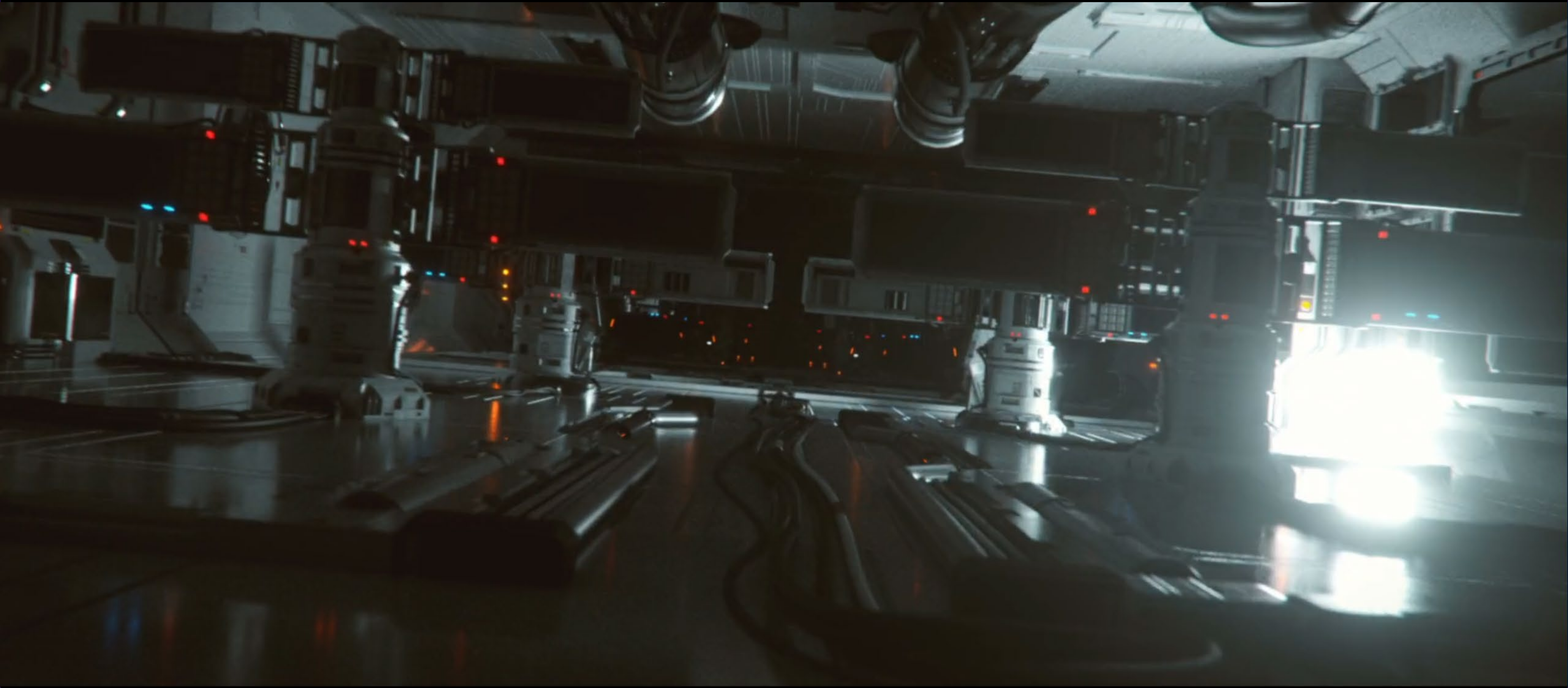

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  - We imported asset, finessed for our framework
    - Thanks to Maxon and OTOY
  - Not yet captured all details (no flashing lights)
  - Will release FBX later this year

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- “Dynamic Many-Light Sampling for Real-Time Ray Tracing”
  - — Pierre Moreau, Matt Pharr, and Petrik Clarberg, HPG 2019
  - — Pierre giving more technical details:
    - Wednesday 2pm - 5:15, Room 501AB
    - During “Ray Tracing Gems” NVIDIA sponsored session

NOTE: RECENT FOCUS ON MANY-LIGHT SOLUTIONS

- Ranging from offline to real-time:
  - “Adaptive BRDF-Oriented Multiple Importance Sampling of Many Lights,” Liu et al., EGSR 2019
  - “Stochastic Lightcuts,” Yuksel, HPG 2019
  - “Dynamic Many-Light Sampling for Real-Time Ray Tracing,” Moreau et al., HPG 2019
  - “Real-Time Rendering with Lighting Grid Hierarchy,” Lin and Yuksel, I3D 2019
  - “Sampling Projected Spherical Caps in Real Time,” Peters and Dachsbacher, I3D 2019
  - “Importance Sampling of Many Lights with Adaptive Tree Splitting,” Esteves and Kulla, HPG 2018
  - “Bayesian Online Regression for Adaptive Direct Illumination Sampling,” Vevoda et al., SIGGRAPH 2018
  - “Real-Time Polygonal-Light Shading with Linearly Transformed Cosines,” Heitz et al., SIGGRAPH 2016

  - And many others…

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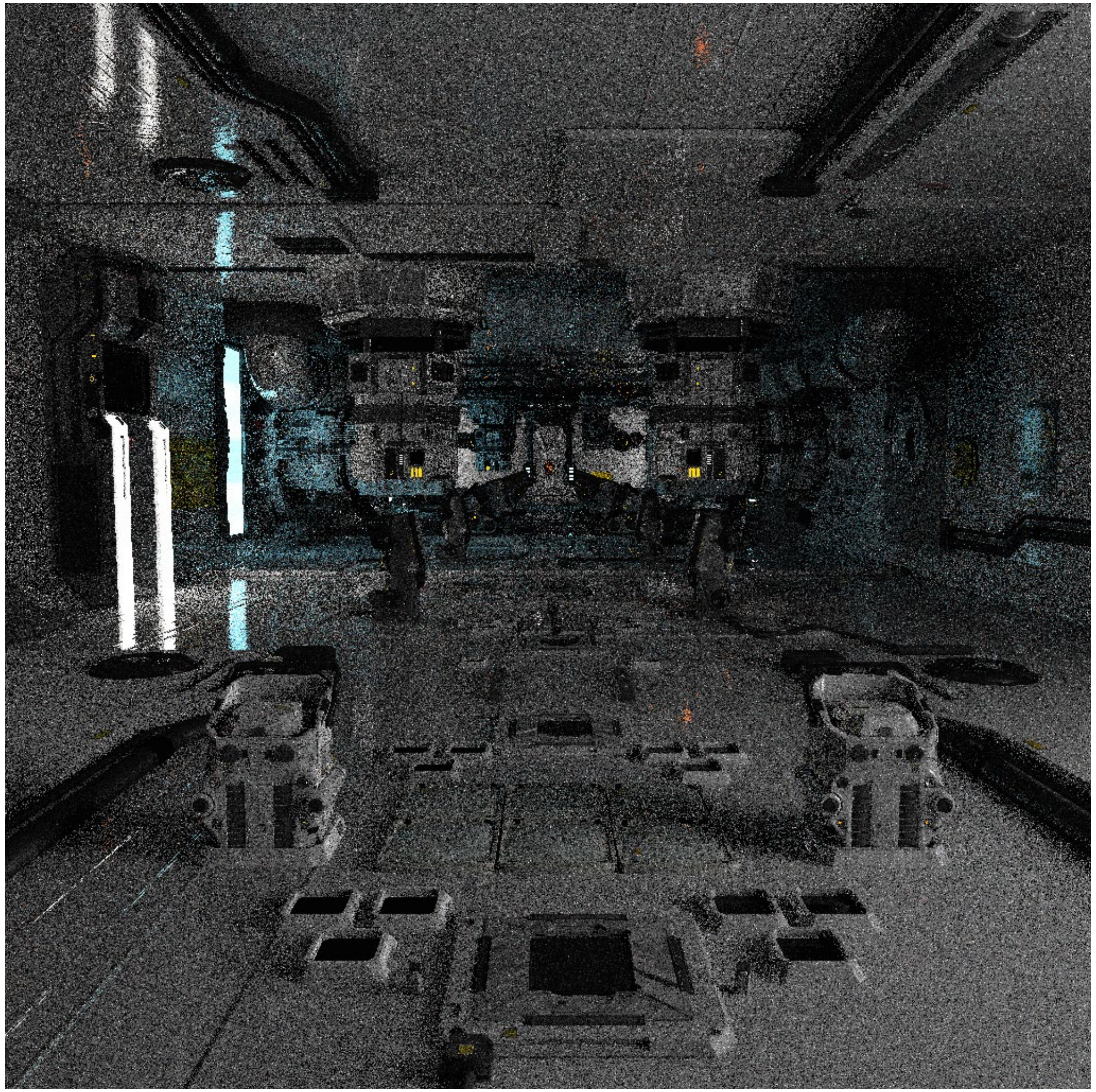
Using *“Dynamic Many-Light Sampling for Real-Time Ray Tracing”* by Moreau et al., HPG 2019

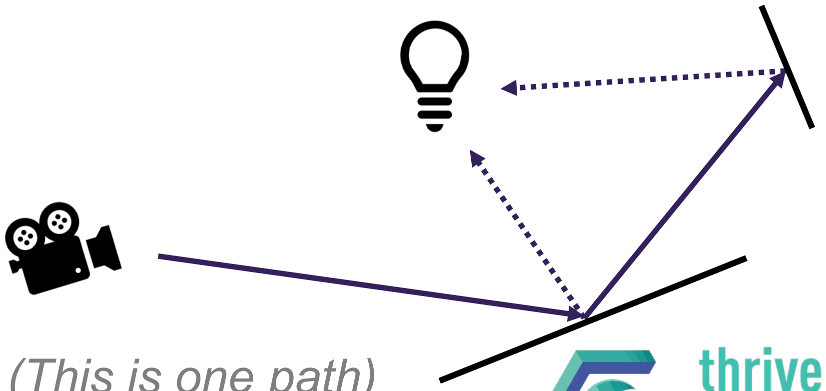


Why? We already have fast implementation

1 bounce path tracing

4 paths per pixel, 1 shadow ray per hit

→ 16 rays in total



(This is one path)

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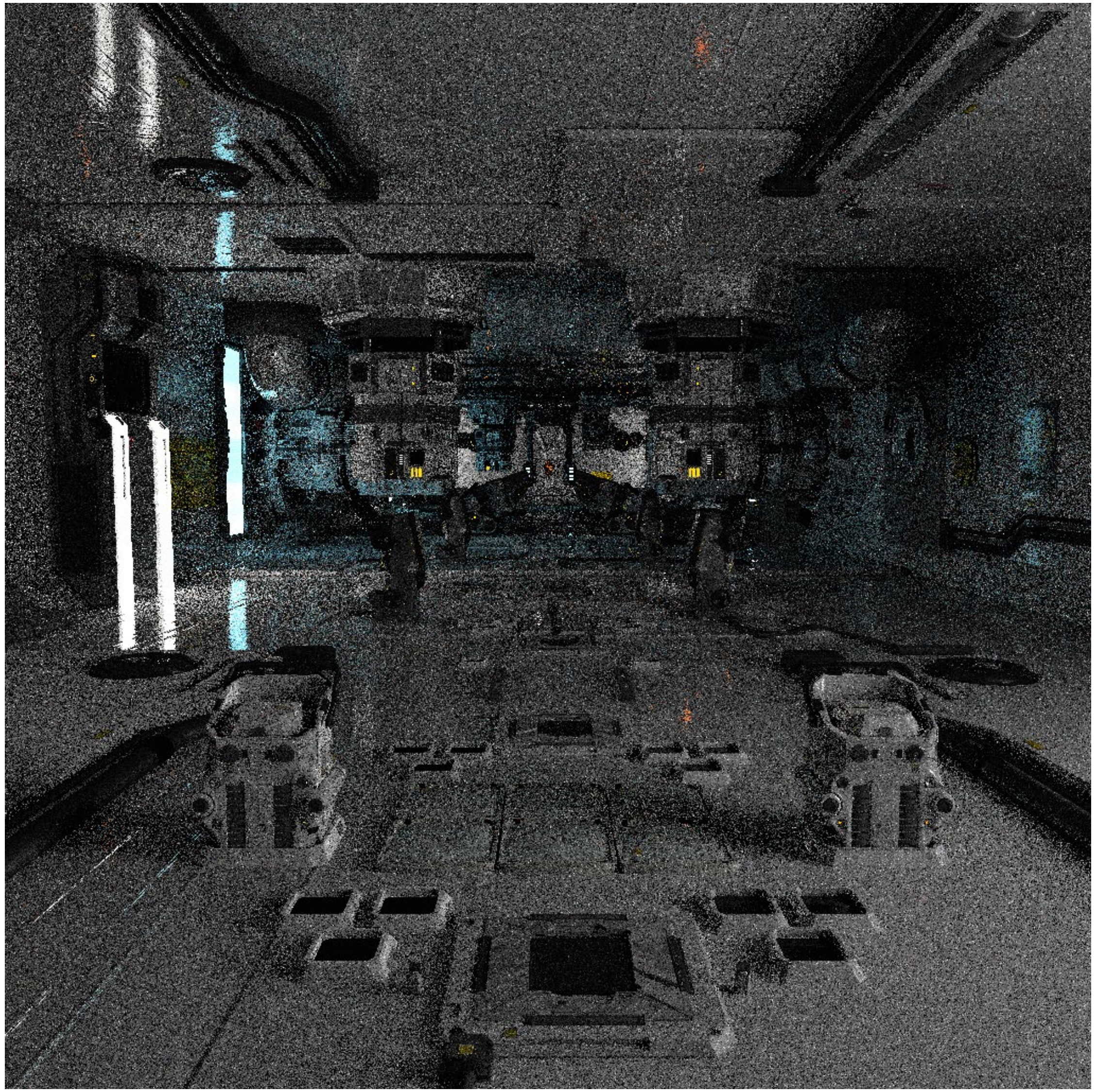

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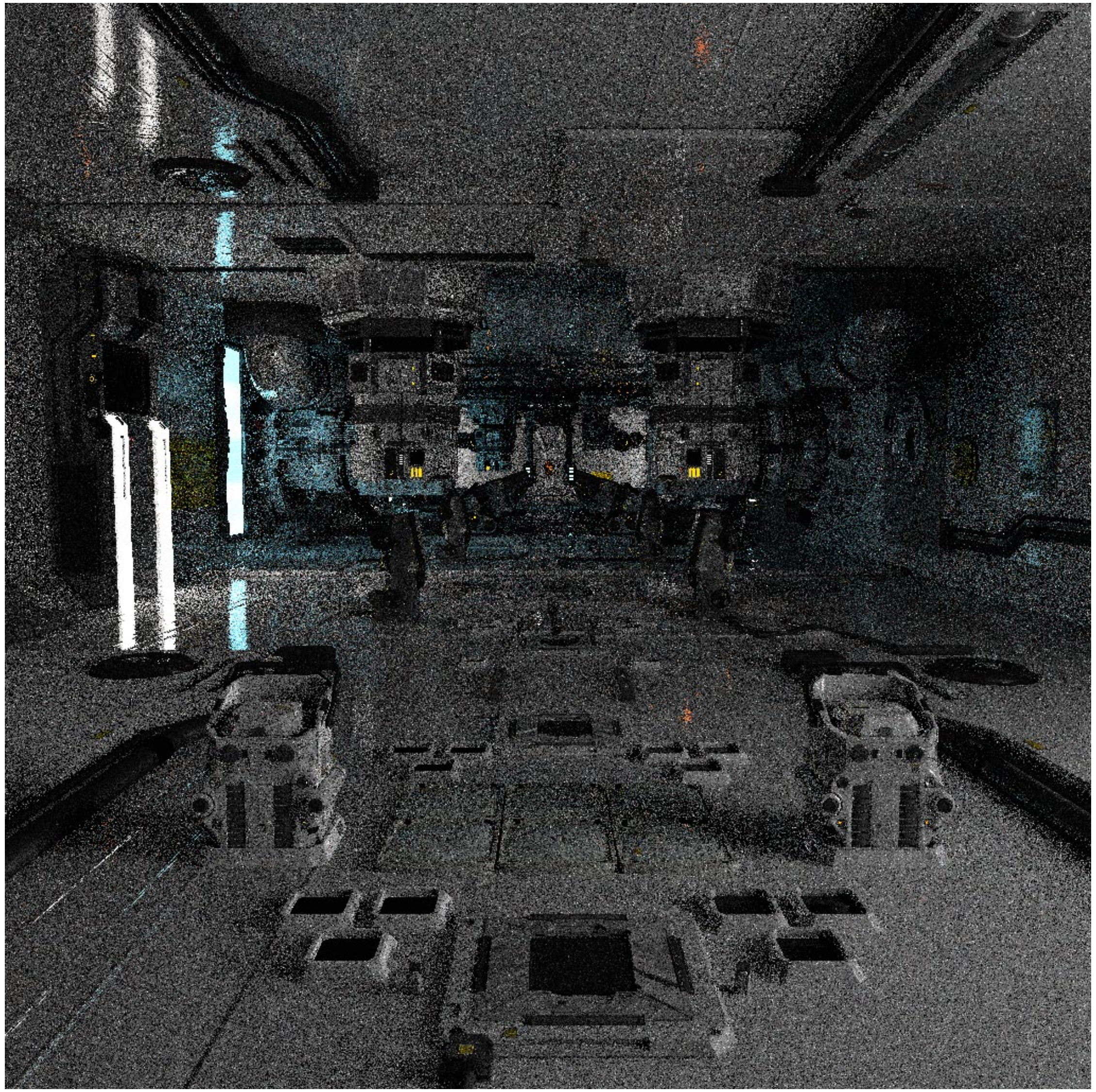

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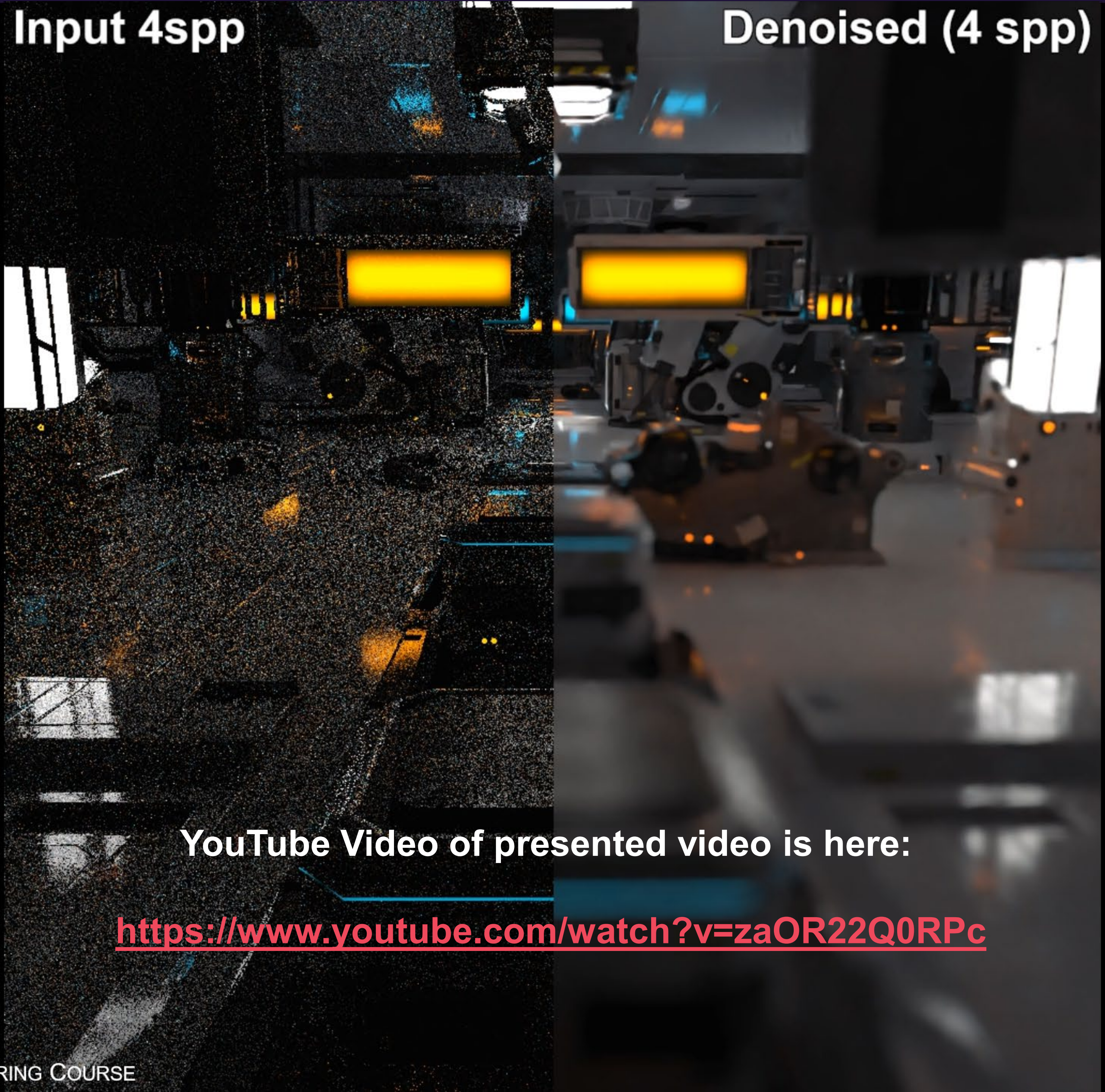
Applying a prototype DL denoiser
(for a total of 150 ms)

Rendered at ~7 Hz; 4 paths, 1 bounce, 16 rpp

YouTube Video roughly equivalent to presented video is here:

https://www.youtube.com/watch?v=3-DTB18tf4I

Rendered at ~7 Hz
1 bounce
16 rays per pixel



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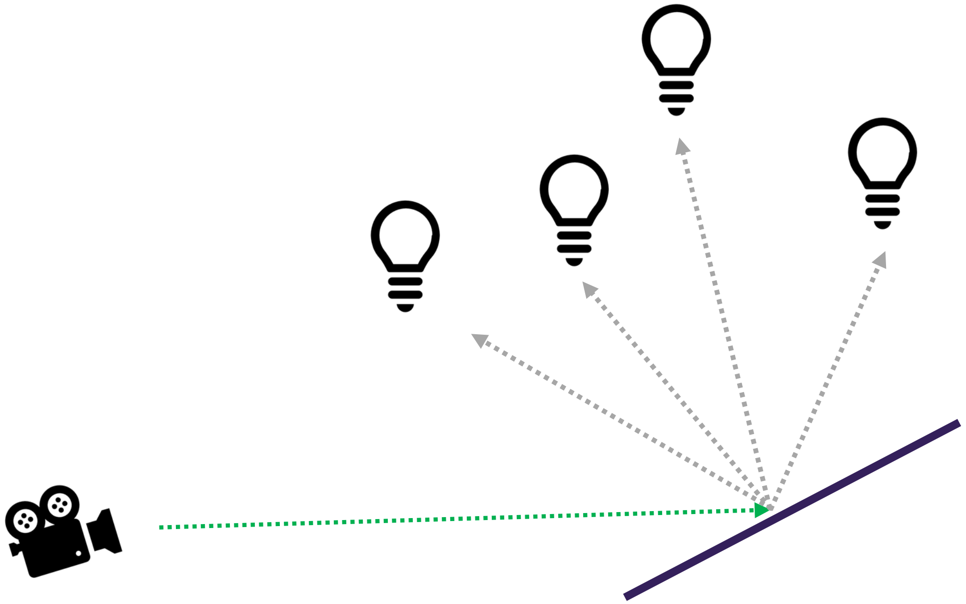

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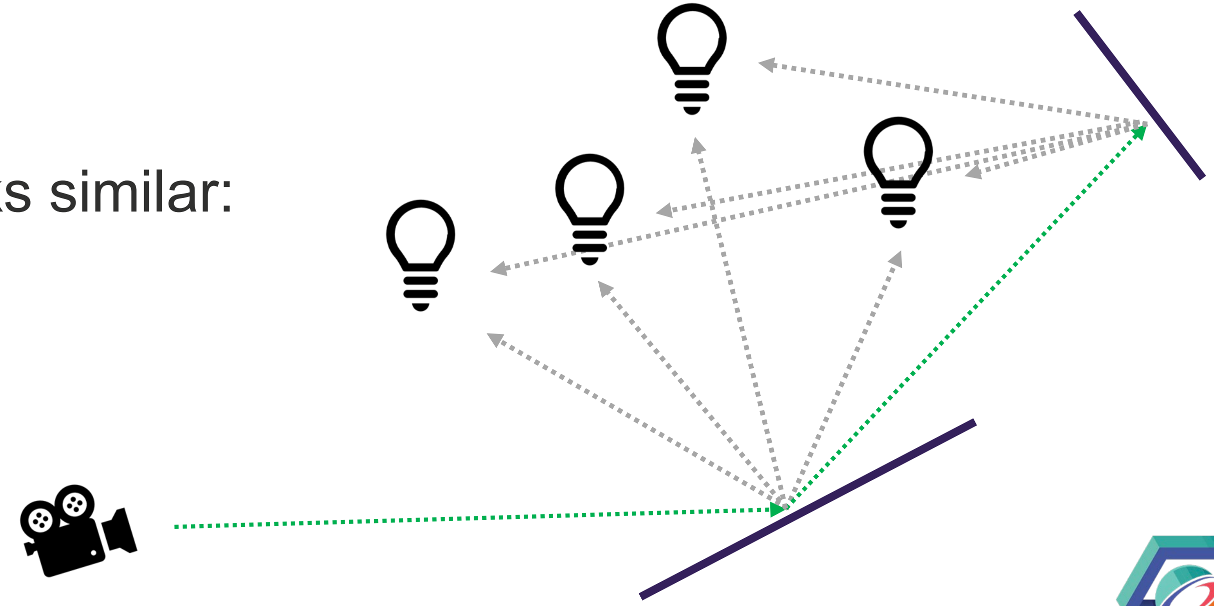

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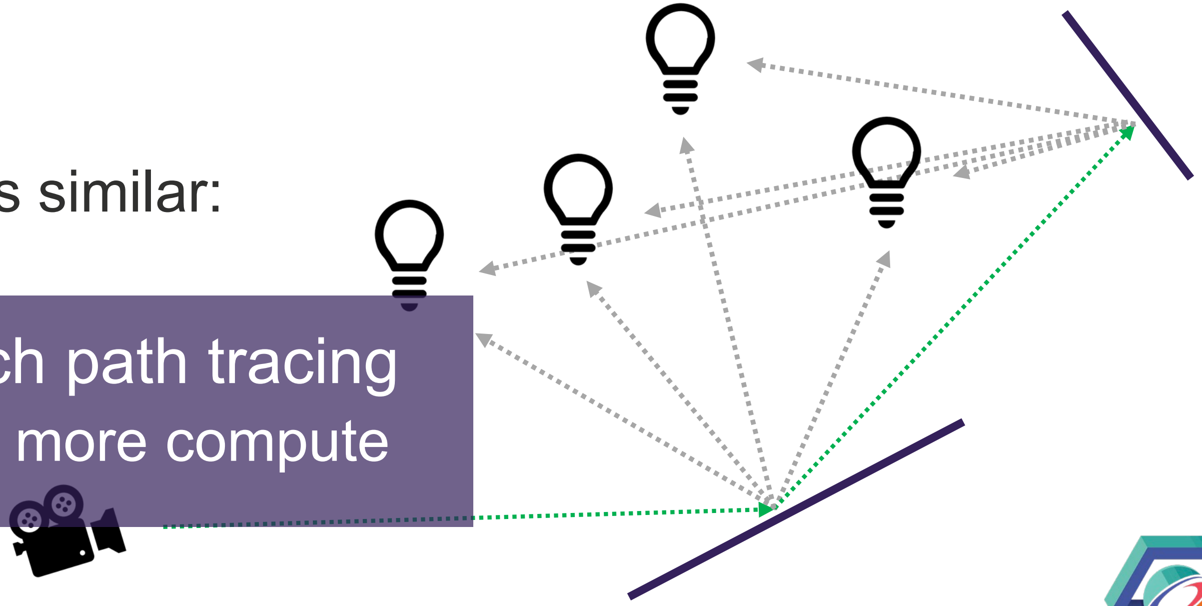

- Incrementally approach path tracing
  - Naturally extend with more compute

RENDERING "ZERO DAY"

Using *"Dynamic Many-Light Sampling for Real-Time Ray Tracing"* by Moreau et al., HPG 2019

- With direct light only…
  - Costs 35ms with 4 shadow rays
  - 50ms with denoising

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- With direct light only…
  - Costs 35ms with 4 shadow rays
  - 50ms with denoising
  - Still expensive, but more reasonable

Direct light only at ~20 Hz

YouTube Video roughly equivalent to presented video is here:

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CASE STUDY:

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  - "Dynamic Many-Light Sampling for Real-Time Ray Tracing"

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- Let’s do a quick overview to extract insights
  - “Dynamic Many-Light Sampling for Real-Time Ray Tracing”
- Takes offline many-light algorithm
  - Designed for importance sampling
  - Using only shadow rays (for direct light)
  - Refactors light BVH for efficient, parallelizable updates

DYNAMIC MANY-LIGHT SAMPLING

(Moreau et al., HPG 2019)

- Basics of light BVH:
  - Traverse tree of lights based roughly on contribution
  - Allow light PDF to vary per shade and per light cluster
  - Traversal is logarithmic with number of sources

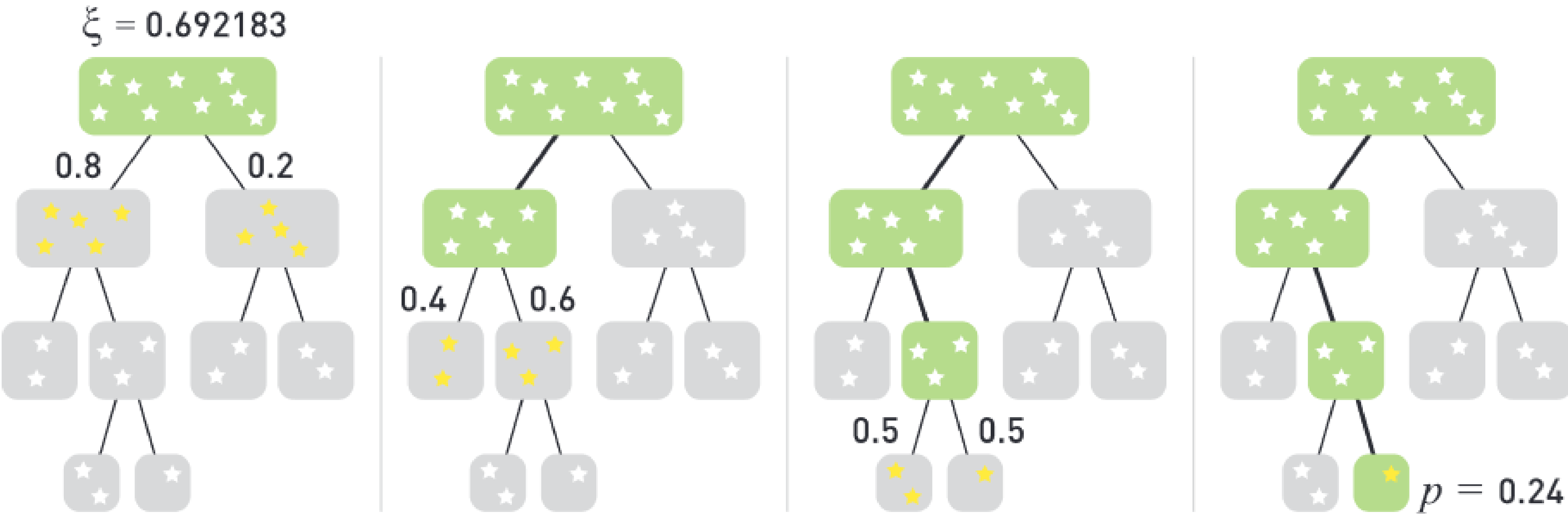

Figure from Ray Tracing Gems chapter "Importance Sampling of Many Lights on the GPU"

DYNAMIC MANY-LIGHT SAMPLING

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- During light sampling:
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- During light sampling:
  - Traverse light tree based on various factors
  - Distance, source flux, light orientation, visibility, node importance
- Traversal gives:
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  - Probability of sampling selected light
- Key insights:
  - Fast BVH refits possible without much quality loss
  - Use a multi-level BVH
  - Similar to structure used in DirectX

DYNAMIC MANY-LIGHT SAMPLING

(Moreau et al., HPG 2019)

- Multi-level light BVH
  - Top level
    - Good for large scale motion
    - Cheap to rebuild each frame
  - Bottom level
    - Good for small-scale local motion
    - Refit quickly on GPU assuming tree topology static

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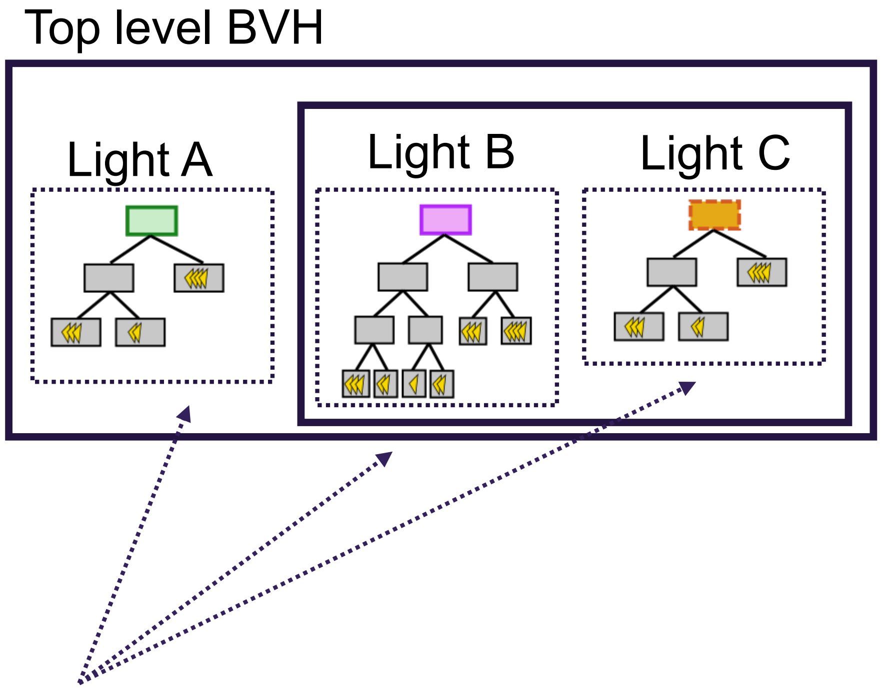

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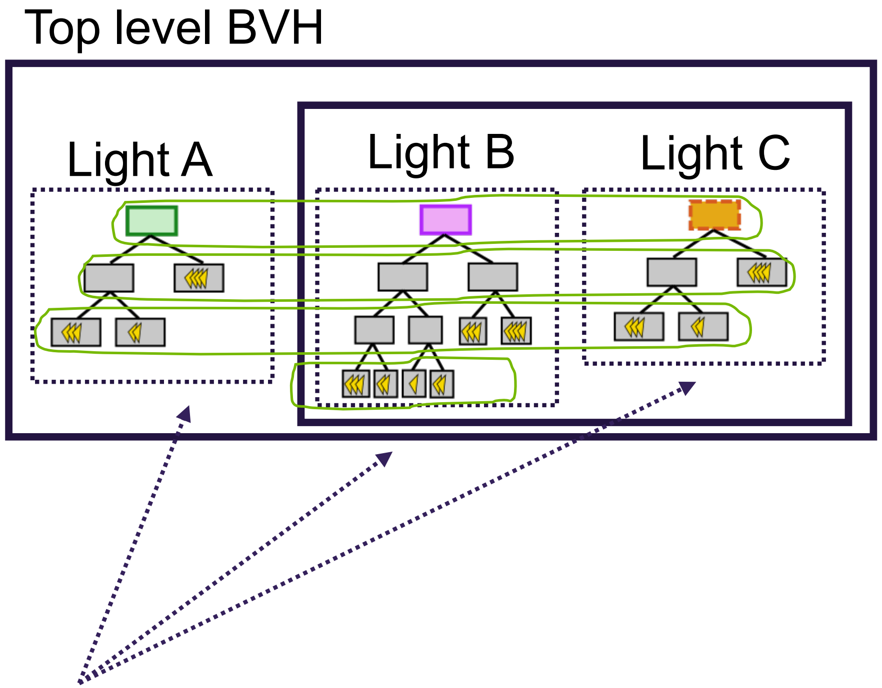
  - Refit: Bottom-up approach parallelizing over tree nodes at same level



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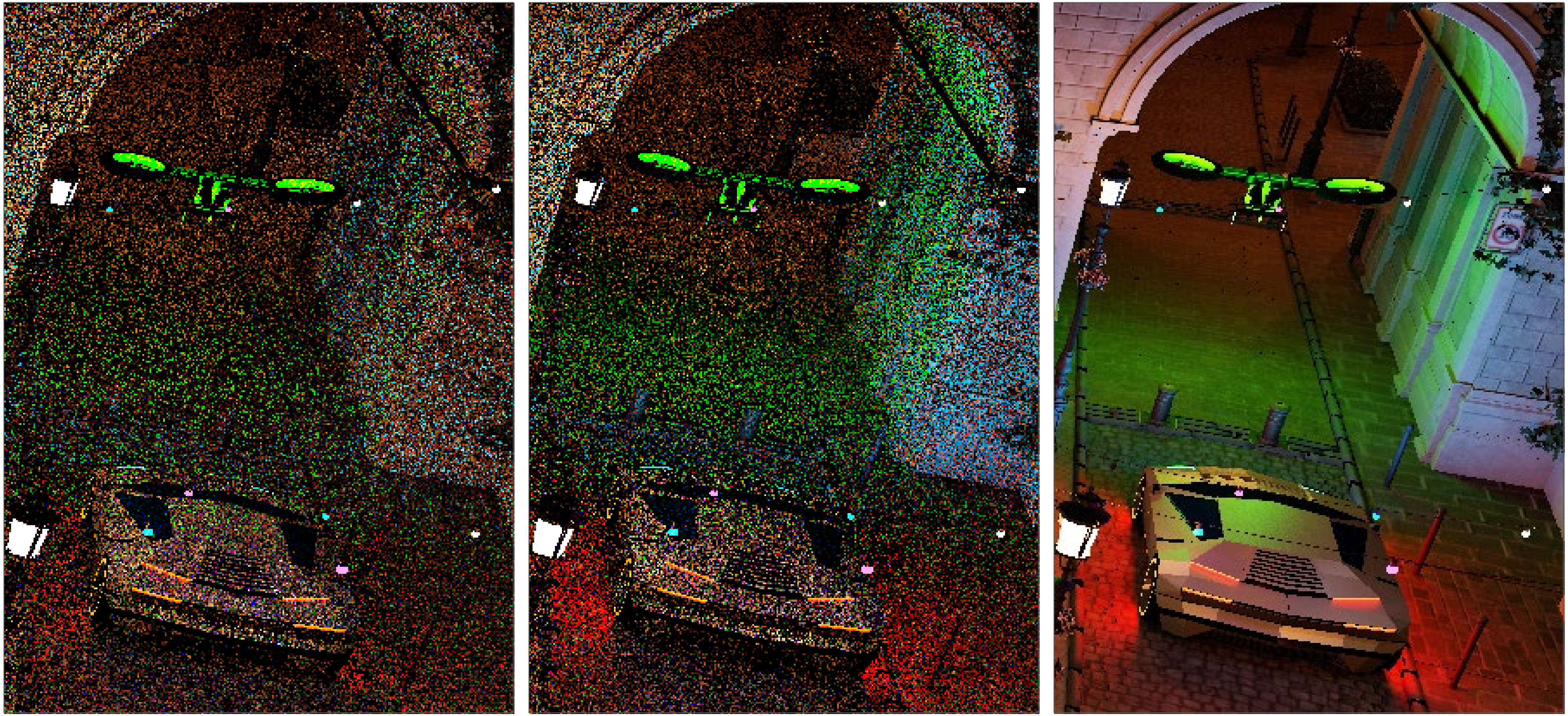

1 level BVH (0.2 ms BVH, 10.8 total) 2 level BVH (1.1 ms BVH, 12.0 ms total) Reference (Computed offline)

THAT'S ONE DATA POINT

- Possible to migrate offline algorithm to interactive context

MOVING TO GAME-READY ALGORITHMS

- Not always clear:
  - How to take offline algorithm from minutes or hours → milliseconds?
  - Offline research *rarely* considers constraints of real-time

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- **Major open problem:**
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- What do I mean?

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- Robust under (mostly) arbitrary user-controls
- Spatial and temporal sample reuse assumed
- No data reuse from future frames

SO… WAIT!

- Adding constraints to an already hard problem…
  - Is that supposed to make you feel better?

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- Adding constraints to an already hard problem…
  - Is that supposed to make you feel better?

- Often constraining the problem makes me more creative
  - Some observations may make things easier…

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- Some rays are ***significantly*** cheaper than others
  - Consider rephrasing problems to use cheaper rays

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- Visibility rays cheaper than color rays
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  - Reduces control divergence (fewer shaders)
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- Short rays cheaper than infinite rays
- "Validation rays" cheaper than shadow rays**

*** Not fully proven; initial data promising*

KEY OBSERVATION #2

- Importance sampling key
  - Limited ray budgets on current and future GPUs
  - Must use rays as intelligently as possible

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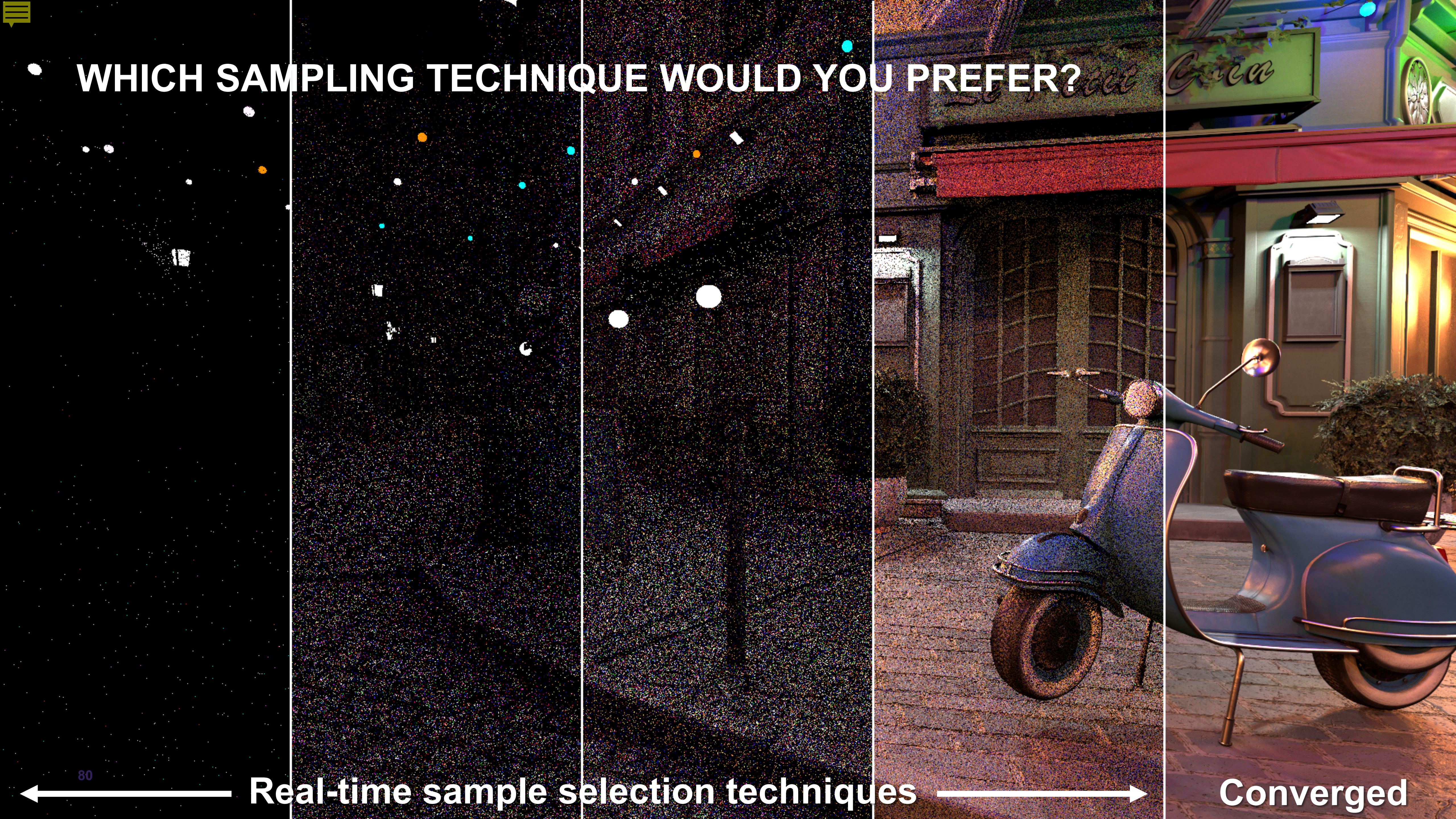
- If not yet a convert, one more comparison…


WHICH SAMPLING TECHNIQUE WOULD YOU PREFER?
Real-time sample selection techniques
Converged

KEY OBSERVATION #3

- Remember Ahmdal's Law
  - Serial computations become bottleneck

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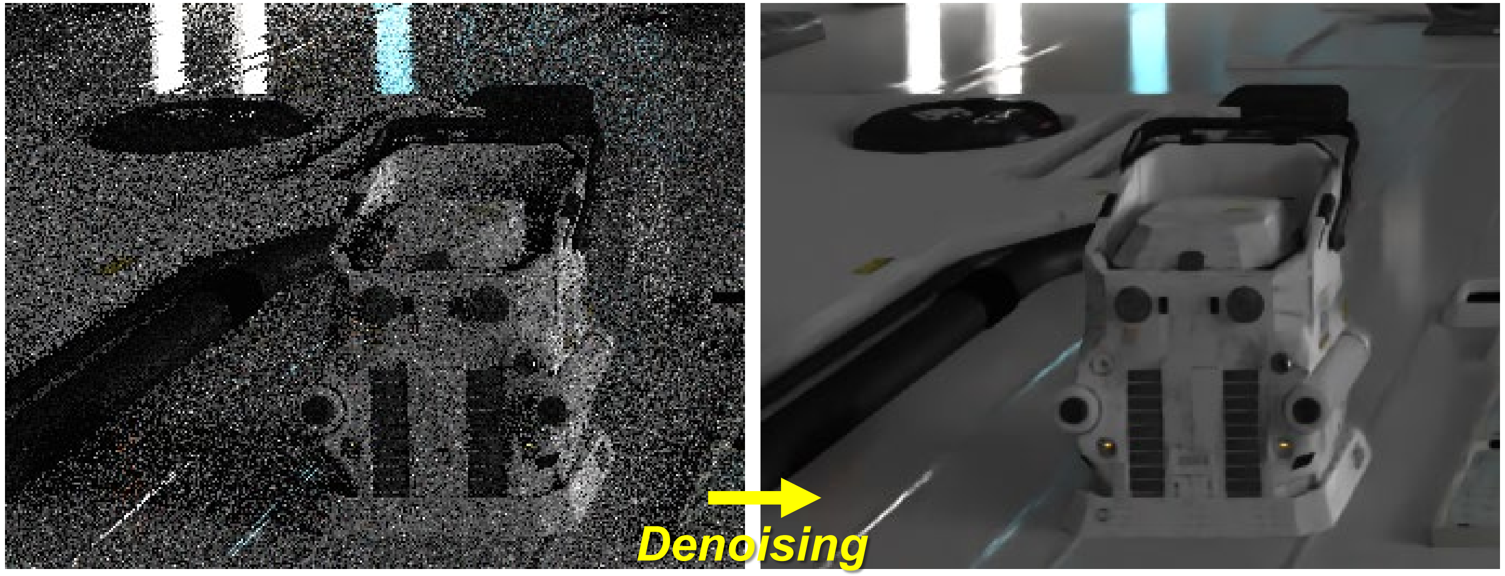
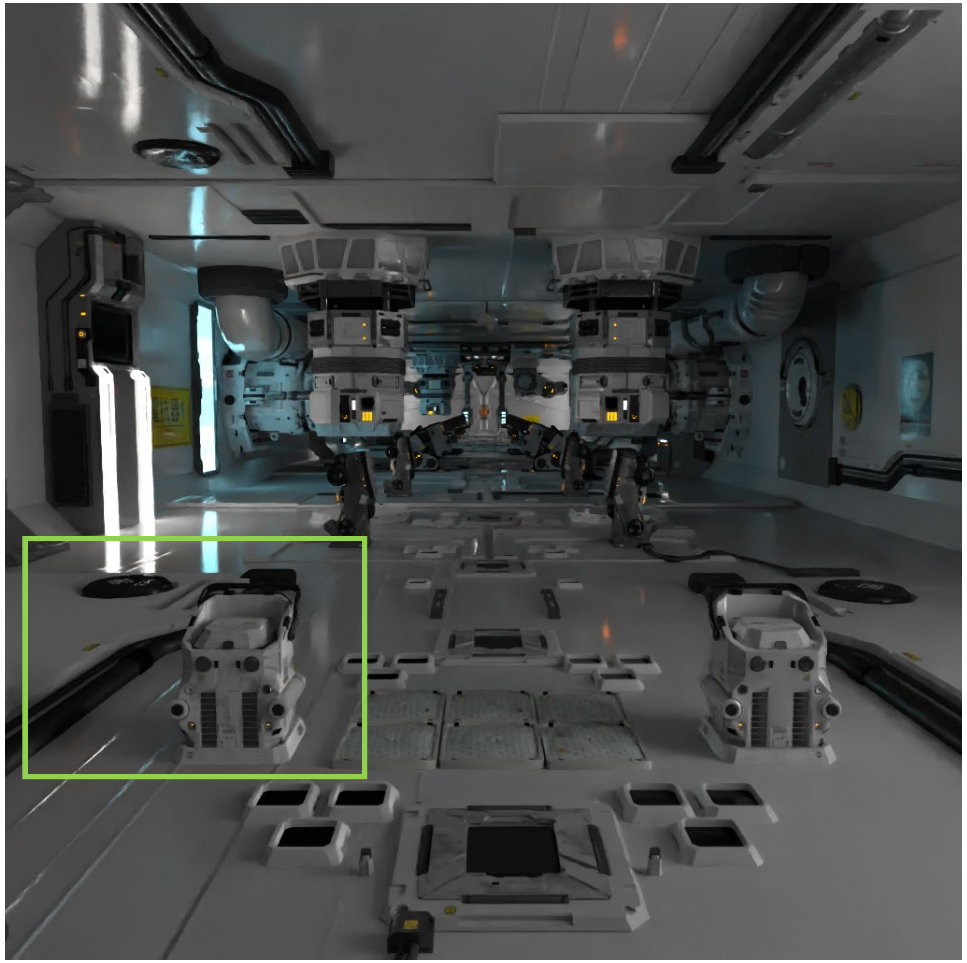
- Remember Ahmdal's Law
  - Serial computations become bottleneck
- Related:
  - Constant factors very important
  - O(N) and O(N log N) are slow for real-time
  - Want high algorithmic speedup under parallelization

KEY OBSERVATION #4

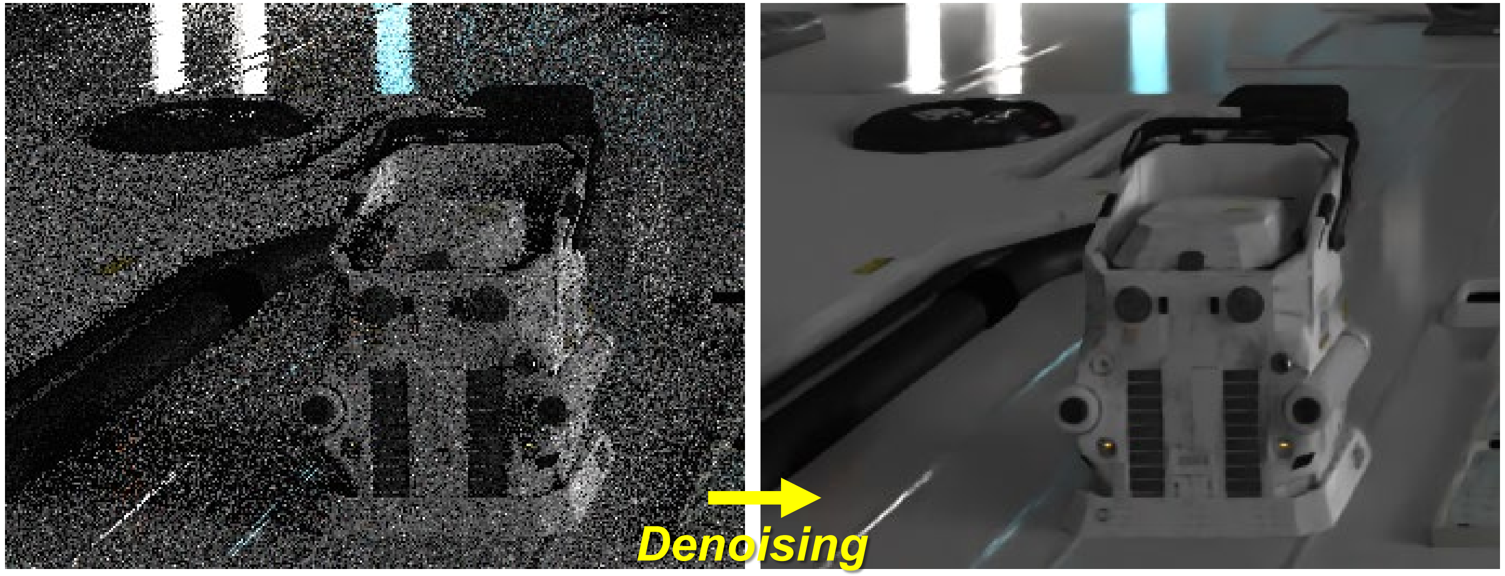
- Not “rendering” a final frame any more
  - Generating ***samples*** for denoiser to consume

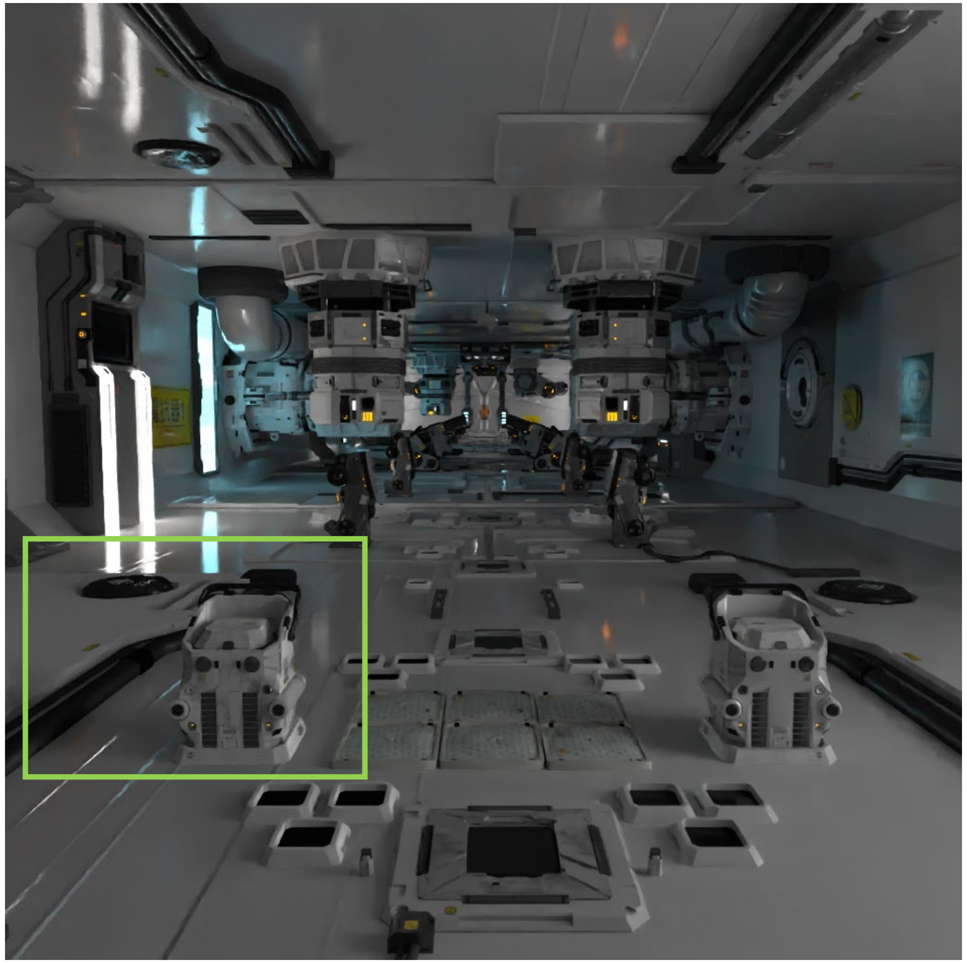




KEY OBSERVATION #4

- Not “rendering” a final frame any more
  - Generating ***samples*** for denoiser to consume
- Not new; rasterizers moving here, too:
  - Temporal antialiasing
  - Stochastic SSR and AO
  - Checkerboard rendering





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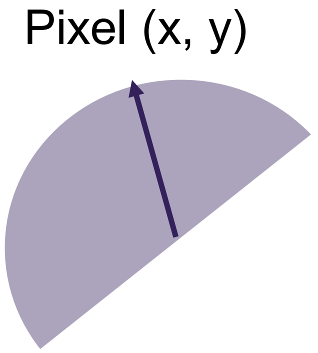
  - Adjacent rays → ideally maximally incoherent



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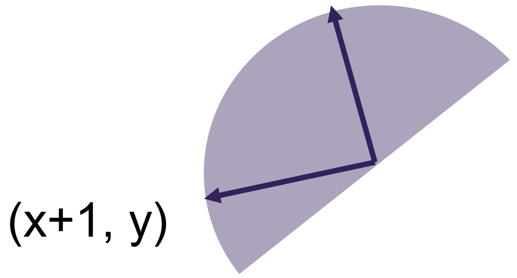

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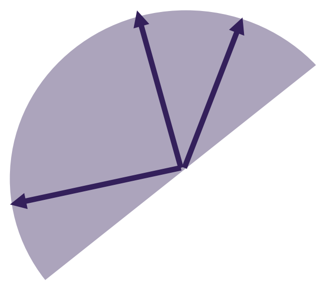

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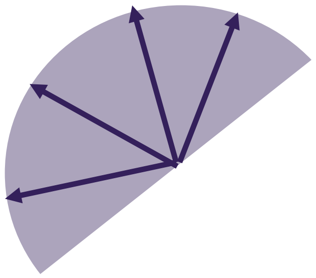
(x+1, y+1)



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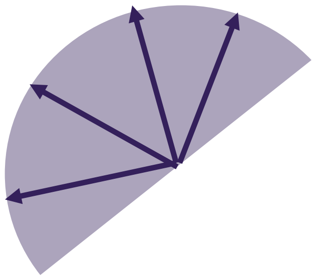
  - I always thought raster's coherence was an advantage



KEY OBSERVATION #6

- Leverage GPU streaming model
  – Raster: Streams triangles
  – Ray tracing: Streams rays

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- Leverage GPU streaming model
  - Raster: Streams triangles
  - Ray tracing: Streams rays
- Other things to stream?
  - Paths? Photons? Beams? Samples? Path connections?
- Ideally data comes in, process it, then forget

KEY OBSERVATION #7

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- Easy to thrash caches with stochastic reads
  - Stratification can reduce working set
  - Simplify data undergoing stochastic sampling to minimize footprint

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- Q: Are we over-engineering our non-learned algorithms?
  - Apply same principles, leverage graphics domain knowledge?

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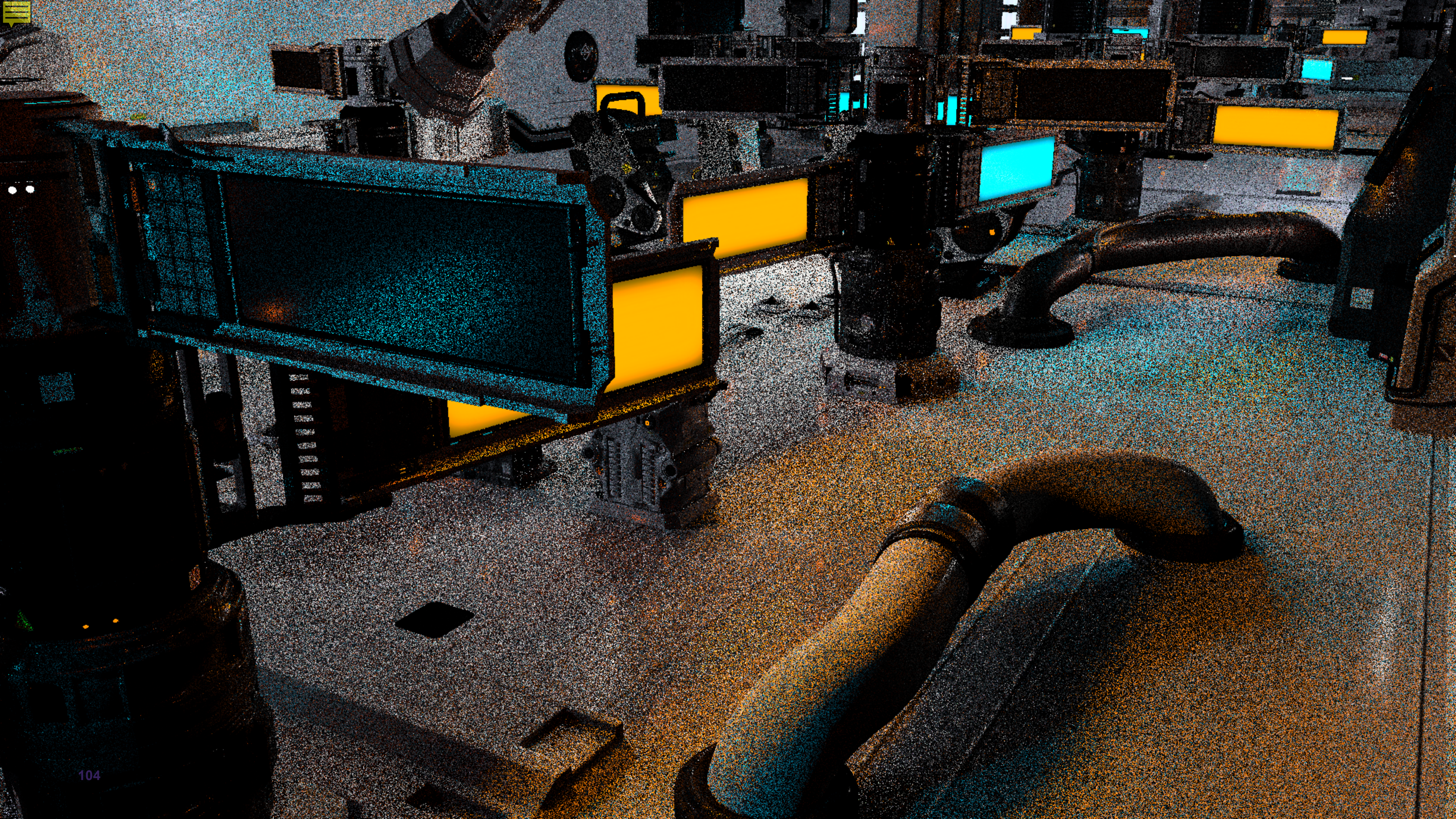
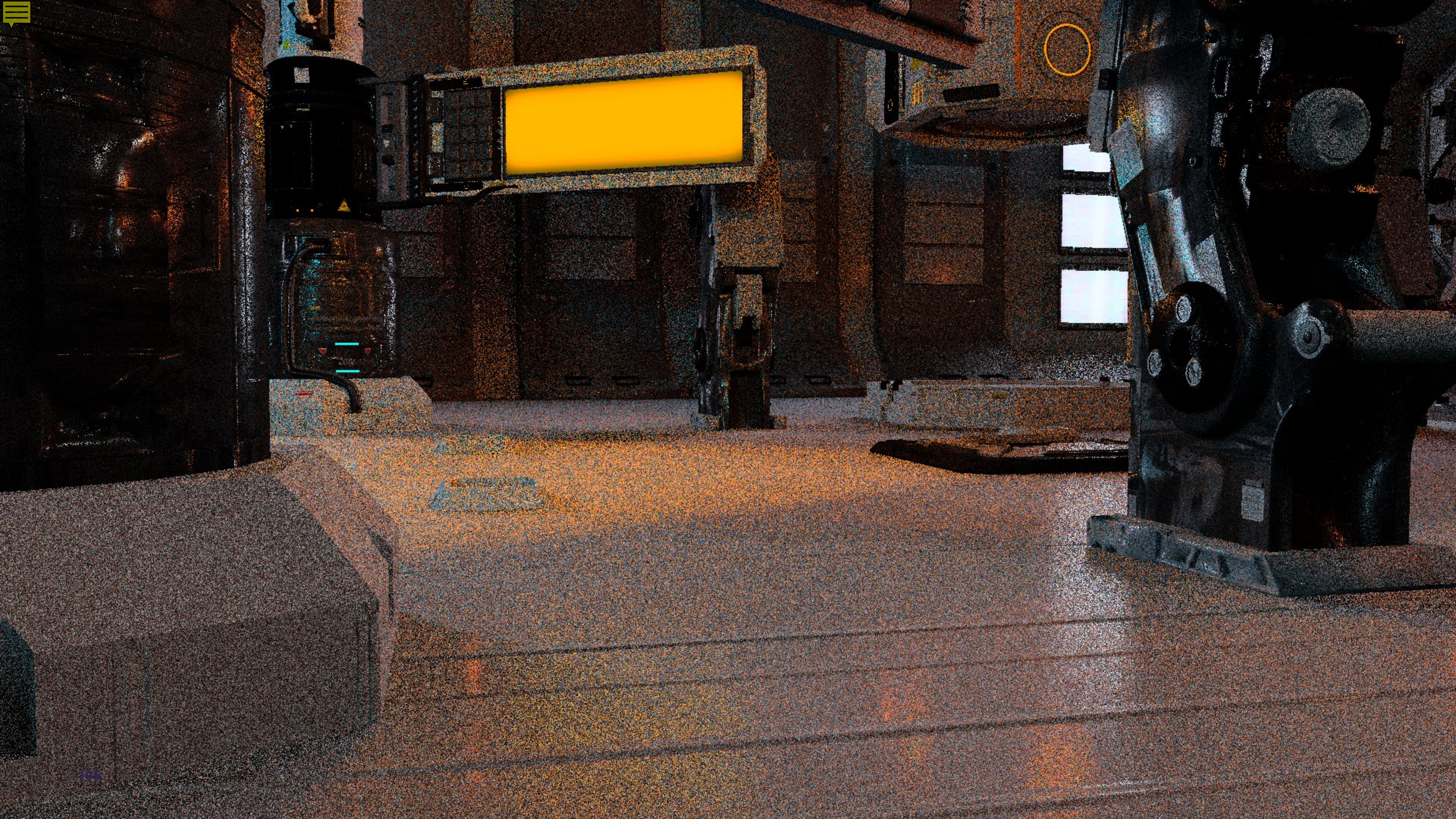
- Building O(N log N) data structures each frame → very hard
  - Especially if you traverse ***stochastically***
  - Why deterministically build something only to traverse randomly?

DEMO

(To prove I'm not entirely crazy)

- Again using "Zero Day" assets
  - Direct lighting, 8 shadow rays per pixel
  - No traditional lights, only emissive materials
  - 346 emissive meshes (>10500 emissive triangles) nearly all animated
  - No complex data structure
  - Per-frame updates: only change light positions
  - Extremely naïve algorithm (much improvement possible)





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- Important:
  - Apply same ***constraints*** and ***observations*** to other key problems

WIDE-OPEN PROBLEMS

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- Denoising
  - How can you unify per-effect denoisers?
  - Dealing with complex, varying materials; fast moving lights?
  - What can we reuse spatially?
  - What can we reuse temporally?
  - What space do we denoise in?
  - Sampling patterns tied to denoiser?

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- Multi-bounce transport
  - What can we reuse along a path?
  - Efficient reuse between paths?
  - Terminate path into approximate solution (e.g., DDGI or light probes)

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- Path-guiding
  - Can we guide paths in best directions?
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- Where does deep learning fit in?
  - Does it? What's it do more efficiently than hand-crafted algorithms?
  - Does it provide inspiration for revamping existing ideas?
  - DL-based importance sampling? (Some recent work there)

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  - Usable denoising of low sample count images
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- But this is **major opportunity**!
  - Almost nobody has truly explored the area; potentially low-hanging fruit
  - Offline research: focused primarily on quality (over performance)
  - Real-time research: only beginning to explore path tracing
  - You: ???

THANK YOU!

Questions?

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