Anti-aliased, distribution, accelerated ray tracing

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Aliasing

Ray tracing is a form of sampling and can suffer from annoying visual artifacts...
Consider a continuous function \( f(x) \). Now sample it at intervals \( \Delta \) to give \( f[i] = \text{quantize}(f(i\Delta)) \).

Q: How well does \( f[i] \) approximate \( f(x) \)?
Consider sampling a sinusoid:

In this case, the sinusoid is reasonably well approximated by the samples.

Aliasing (con’t)

Now consider sampling a higher frequency sinusoid

We get the exact same samples, so we seem to be approximating the first lower frequency sinusoid again.

We say that, after sampling, the higher frequency sinusoid has taken on a new “alias”, i.e., changed its identity to be a lower frequency sinusoid.

Reading

Required:
- Shirley 10.9, 10.11 (online handout)

Further reading:
Aliasing in rendering

One of the most common rendering artifacts is the “jaggies”. Consider rendering a white polygon against a black background:

We would instead like to get a smoother transition:

Anti-aliasing

Q: How do we avoid aliasing artifacts?
1. Sampling:
2. Pre-filtering:
3. Combination: super-sampling and averaging down

Example - polygon:

Antialiasing in a ray tracer

We would like to compute the average intensity in the neighborhood of each pixel.

When casting one ray per pixel, we are likely to have aliasing artifacts.

To improve matters, we can cast more than one ray per pixel and average the result.

A.k.a., super-sampling and averaging down.

Temporal aliasing

Suppose we are rendering a “clock” with a fast turning hand:

What happens if we sample too infrequently? (This is sometimes called the “wagon wheel” effect.)

Another more common scenario is something moving quickly across the frame, e.g., a fast-moving particle:

How might we address these temporal aliasing effects?
**Gloss and translucency**

The mirror-like form of reflection, when used to approximate glossy surfaces, introduces a kind of aliasing, because we are under-sampling reflection (and refraction).

For example:

Distributing rays over reflection directions gives:

![Distributing rays over reflection directions](image)

**Soft shadows**

Distributing rays over light source area gives:

![Distributing rays over light source area](image)

**Depth of field**

To simulate a camera, we can model the refraction of light through a lens. This will give us a “depth of field” effect: objects close to the in-focus plane are sharp, and the rest is blurry.

![Depth of field](image)

**Depth of field (cont’d)**

This is really similar to the pinhole camera model:

\[
\mathbf{p} = \mathbf{COP} + \frac{\mathbf{d} \cdot (\mathbf{A} - \mathbf{p})}{||\mathbf{A} - \mathbf{p}||}
\]

But now:

- Put the image plane at the depth you want to be in focus.
- Treat the aperture as multiple COPs (samples across the aperture).
- For each pixel, trace multiple viewing/primary rays for each COP and average the results.
**Motion blur**

Distributing rays over time gives:

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**Speeding it up**

Brute force ray tracing is really slow!

Consider rendering a single image with:

- $m \times m$ pixels
- $k \times k$ supersampling
- $a \times a$ sampling of camera aperture
- $n$ primitives
- $\ell$ area light sources
- $s \times s$ sampling of each area light source
- $r \times r$ rays cast recursively per intersection (gloss/translucency)
- $d$ is average ray path length of $d$

Asymptotic # of intersection tests $= O(m^2 k^2 a^2 n \ell s^2 r^2 d^2)$

For $m=1,000$, $k=a=s=r=8$, $n=1,000,000$, $\ell=10$, $d=8$...very expensive!!

In practice, some acceleration technique is almost always used.

We’ve already looked at reducing $d$ with adaptive (early) ray termination.

Now we look at reducing the effect of the $a, s, r, k$ and $n$ terms…

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**Penumbra revisited**

Let’s revisit the area light source…

We can trace a ray from the viewer through a pixel, but now when we hit a surface, we cast rays to samples on the area light source.

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We should anti-alias to get best looking results.

Whoa, this is a lot of rays…just for one pixel!!
Penumbra revisited

We can get a similar result with much less computation:

- Break up the light source into points with ID’s.
- Similarly, give an ID to each sub-pixel rays.
- Only send shadow ray to point with same ID.

For even (statistically) better results, “jitter” the rays:

- Break pixel and light source into regions.
- Choose random locations within each regions.
- Trace rays to/through those jittered locations.

Distribution ray tracing

This idea is called distribution ray tracing [Cook84]:

- uses non-uniform (jittered) samples.
- replaces aliasing artifacts with noise.
- provides additional effects by distributing rays to sample:
  - Reflections and refractions
  - Light source area
  - Camera lens area
  - Time

[This approach was originally called “distributed ray tracing,” but we will call it distribution ray tracing (as in probability distributions) so as not to confuse it with a parallel computing approach.]

Antialiasing by adaptive sampling

Casting many rays per pixel can be unnecessarily costly. If there are no rapid changes in intensity at the pixel, maybe only a few samples are needed.

Solution: adaptive sampling.

Q: When do we decide to cast more rays in a particular area?
Faster ray-polyhedron intersection

Let's say you were intersecting a ray with a triangle mesh:

Straightforward method
- intersect the ray with each triangle
- return the intersection with the smallest $t$-value.

Q: How might you speed this up?

Hierarchical bounding volumes

We can generalize the idea of bounding volume acceleration with hierarchical bounding volumes.

Key: build balanced trees with tight bounding volumes.

Uniform spatial subdivision

Another approach is uniform spatial subdivision.

Idea:
- Partition space into cells (voxels)
- Associate each primitive with the cells it overlaps
- Trace ray through voxel array using fast incremental arithmetic to step from cell to cell

Non-uniform spatial subdivision

Still another approach is non-uniform spatial subdivision.

Other variants include k-d trees and BSP trees.

Various combinations of these ray intersection techniques are also possible.
Summary

What to take home from this lecture:

- The meanings of all the boldfaced terms.
- An intuition for what aliasing is.
- How to reduce aliasing artifacts in a ray tracer
- The limitations of Whitted ray tracing (no glossy surfaces, etc.)
- The main idea behind distribution ray tracing and what effects it can simulate (glossy surfaces, etc.)
- An intuition for how ray tracers can be accelerated.