The short films were great last night at the Electronic Theatre,
and they were a catalog of phenomena that we can’t render robustly in real-time today:

- subpixel translucent hair and grass,
- volumetric lighting on fog and smoke
- multiple scattering in clouds and rain
- correct refraction, diffusion and extinction in water and glass...

and of course, pixel-perfect subsurface scattering, motion blur, bloom, lens flare, and depth of field.

Now, a game studio with a strong art team can approximate any of these for a specific scene, but there’s no real-time engine in the world where I can model clouds or water and get a correct, robust result in comparable to what even a graphics student’s first OFFLINE path tracer can render for transparency. So, transparency is clearly a hard, open problem for real-time rendering. Let’s take a closer look at some phenomena...
Here’s a real photograph. We see many different effects that are all grouped under transparency...
By now you should have pretty good intuition for the scope of what we casually call transparency. Let’s try and define it more formally....
For all of the effects that we just looked at,

“transparency effects are those where multiple primitives contribute to one sample”

That’s not very exciting. It also isn’t very specific, and doesn’t relate to physically
based rendering or even to sampling theory in a meaningful way.

The problem is that there are two, similar modeling scenarios going on here, which
are often conflated.
If we separate them, then we’ll see that all of the phenomena we observe arise
directly from one or the other....
Transmission models materials like this red gel on the left. Note that it casts a red shadow.

Partial coverage models materials like this sheer red scarf on the right. It is actually composed of many tiny opaque threads that have binary coverage, but within a pixel there are so many threads that it appears as fractional coverage. Note that it casts a gray shadow.

A simple way to know which of these you’re dealing with is to ask the thought experiment of what you’d expect a red transparent object in front of a blue object to look like. If the answer is black, which is what would happen with glass or a gel, then you have transmission. If the answer is purple, which is what you’d see for a fine metal screen or smoke, then you have partial coverage.

Here’s what we’re going to cover in the next 40 minutes...
I’m going to spend the first half of the talk building a deeper understanding of the physics of transmission and computer science of partial coverage.

Once we understand the problem we’re trying to solve, then we’ll look at a set of strategies for tackling one or both of these core phenomena.

Finally, I’ll propose short and long term research and development agendas for improving real-time transparency.

The slides from this talk are online and contain additional information, including a large bibliography of real-time transparency publications.
Transmission

A phenomenon and open problem from nature
Ray Optics of Transparency*

* Rendering typically assumes steady-state light transport and ignores polarization, phase, interference/diffraction, and most frequency-dependent phenomena. Transparency is hard enough, so let’s assume those simplifications largely will be maintained in the future for entertainment applications.
Ok, here’s our ray so we can model some optics.

We’re concerned with what happens to the light initially travelling along it. That ray is in an **optically homogeneous medium**, such as “air” (at a fixed temperature, pressure, and composition).

The medium has some refractive index. In fact, that is the definition of an optically homogeneous medium: the refractive index is uniform. When the ray intersects a medium with a different refractive index, we call the interface between them a **surface**.

Let’s insert another medium, such as...orange jell-o
(If you’re reading these slides after the talk...the Heckbert citation is a real paper, but that paper is itself a SIGGRAPH community in-joke)

Now, as you know, when a ray of light travels from air into orange jell-o, four interesting phenomena occur:

- First, all of the non-orange light is quickly absorbed in the jell-o
- Second, even the orange light is absorbed if the jell-o is deep enough
- Third, the light changes direction at the surface between air and jell-o due to refraction.
- Fourth, some of the light is reflected back into the air

You’ve know about the refractive index and Snell’s law since high school, and if you’re up to date on physically-based rendering you probably even know about Fresnel’s laws...but let me point out that refractive indices are a little more complex than what we learned in high school...
So, when I said “a homogeneous medium as a uniform refractive index”, I meant the complex refractive index, which includes an extinction coefficient tucked away in the imaginary part. That extinction coefficient describes how quickly light is absorbed over distance.

All of these depend on wavelength, which is why we see chromatic aberration in lenses, prisms separate colors, and there are rainbows.
So here’s our model again, with proper coefficients. We’re ignoring wavelength for the moment.

I have no source for the extinction coefficient of orange jell-o is, but working backwards from observation, it must be about $10^{-6}$ because you can see through a few centimeters of jell-o.

Once we know these coefficients, we actually have all of the parameters needed for rendering. Longstanding physics models tell us how much light is reflected and refracted and in which directions, as well as how the light is absorbed as it travels through the medium.

The reflection direction is trivial—it is the geometric mirror reflection direction. So, those two angle measures labelled “theta 1” are the same. The refraction direction is given by Snell’s law, which relates the angle measure labelled theta 2 to theta 1...
So, the refraction angle depends solely on the refractive index. What about the amount of reflection and refraction? That’s given by the Fresnel Reflection Coefficient

\[
\frac{\sin \theta_2}{\sin \theta_1} = \frac{\eta_1}{\eta_2}
\]
Which is somewhat complicated and depends on the chemical properties of the surface... for jell-o and air it looks like this.

Note that it depends solely on the refractive indices and the angles... which also depend only on the refractive indices.

Christophe Schlick approximated the equation with the simpler one below, which is what is typically used in rendering. It is written in terms of the reflection at normal incidence...

\[
F(\theta_1, \theta_2) = \frac{1}{2} \left[ \frac{\eta_2 \cos \theta_1 - \eta_1 \cos \theta_2}{\eta_2 \cos \theta_1 + \eta_1 \cos \theta_2} \right]^2 + \frac{1}{2} \left[ \frac{\eta_1 \cos \theta_1 - \eta_2 \cos \theta_2}{\eta_1 \cos \theta_1 + \eta_2 \cos \theta_2} \right]^2
\]

\[
F(\theta_1) \approx F_0 + (1 - F_0)(1 - \max(0, \cos \theta_1))^5
\]

Schlick, A customizable reflectance model for everyday rendering, EGSR’93
which depends only on the refractive indices.

Finally, how much light is absorbed in the medium? That’s given by the Beer-Lambert law
Beer-Lambert Law

Light falls off exponentially with distance in a homogeneous medium

\[ L(X, \hat{\omega}) = L(Y, \hat{\omega}) \exp \left( \frac{-4\pi \kappa(\lambda)}{\lambda} \|Y - X\| \right) \]

- \( L \): Radiance, the amount of light along a ray.
- \( \kappa \): Extinction coefficient.
- \( \lambda \): Wavelength, the spectral “color”.
- \( X, Y \): Two points in the same medium.

Which says that transmission decreases exponentially with distance.

The exponent depends on the extinction coefficient, which was the imaginary part of the complex index of refraction.

There’s one important simplification here that will eventually cause us some trouble. We’ve assumed a single scattering model... in physics, the extinction coefficient accounts not only for absorbed light but light that is diffusely scattered within the medium. Let’s set that multiple scattering aside however.

\[ L(X, \hat{\omega}) = L(Y, \hat{\omega}) \exp \left\{ \frac{-4\pi \kappa(\lambda)}{\lambda} \|Y - X\| \right\} \]
The extinction (kappa) term also takes into account that some light is scattered out from the ray based on the molecular and chemical structure of the medium. And of course, the light scattered out from other paths has a chance to be scattered in to this ray. So, there’s some diffusion...if you look through orange jell-o, you’d expect the image to be a little blurry.

I’m going to set this aside for a moment to keep the story simple, but diffusion is well understood in physics and something that can be well-modeled by the best physically best renderers.
The key point of this entire derivation was that we can model the entire interaction of light and matter based solely on the complex index of refraction of media and knowing where their boundaries are.

Except for one point in the Fresnel model where I assumed the media were dielectrics, I didn’t say anything about what the materials were. (and there’s a similar set of equations for conductors, I just didn’t show it.)

There was no notion of “opaque”, “shiny”, “mirror”, “transparent”, or any of the other usual computer graphics abstractions. That’s really important. It means that the model I just described still holds when I change materials...
Ray Optics of Transparency

Air
\[ \eta_1 = 1.0003 \]
\[ \kappa_1 \approx 0.0 \]

Water
\[ \eta_2 = 1.4 \]
\[ \kappa_2 = 10^{-8} \]

Hale and Querry, Optical constants of water in the 200-nm to 2000-nm wavelength region, Applied Optics 1973
Wait, can I send light through skin? Yes... The extinction coefficient is just relatively large.
Through an ear lobe, eyelid, or finger you observe significant transmitted light.

(By the way, skin is the kind of material where a multiple scattering model is useful)

Ok, let’s keep going. How about .... Brick?
What? I can apply the transmission model to a brick? Bricks are obviously opaque.

Well, you can see through a brick if it is thin enough. Bricks just absorb visible light really quickly. The have high extinction coefficients. They also have high real refractive indices...a brick lens will refract pretty severely.

The faulty conclusion that a brick will block light is based on two assumptions:  
- That the brick is thick enough that almost all light is absorbed  
- That we’re using visible wavelengths of light...the model applies to all wavelengths, and if you hit a brick with microwaves, radio waves, or X-rays, they penetrate very differently than visible wavelengths but they’re all just “light”. Remember, bricks aren’t just red—they have a color spectrum outside what we can see

(Actually, I don’t know what the extinction coefficient of brick is at visible wavelengths. But there’s a lot of experimental data on building materials at microwave and radio wave frequencies:  

I can even do this:
So, the point is...that’s all. I’m not just telling you about transparency. I just described the geometric and physical model of all computer rendering:
Ray Optics of Rendering

- Model optically homogeneous media parameterized by complex refractive index
- Apply Beer-Lambert within a medium
- Compute reflection and refraction by applying Fresnel and Snell at interfaces

(and use “some model” of diffusion/multiple scattering within a medium)

That’s all of computer graphics.

And all of the other fancy effects fall out of this same model. For example, lens flare, bloom, and chromatic aberration occur because of these reflections and refraction in the lenses of a camera.

There are even three algorithms for correctly rendering from this model...
Unfortunately, they're all really slow. These will probably never be real-time algorithms for complex scenes.

[click] Even with some aggregate models to speed convergence for heterogenous volumes...

[click] offline film rendering still approximates and essentially fakes transport in clouds, skin, and other complex materials. So, we're probably not going to directly apply these algorithms to real-time rendering.

<table>
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<th>Complete Rendering Algorithms</th>
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<td>• Metropolis Light Transport [Veach97]</td>
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<td>• Path Tracing with Photon Mapping [Jensen96]</td>
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<td>• Bidirectional Path Tracing [Lafortune93]</td>
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<td>• BSSSRDF [Jensen01]</td>
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<td>• Photon Beams [Jarosz08]</td>
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Transmission Conclusions

• A large part of the “open problem in transparency” is... truly physically-based rendering

• Offline algorithms exist to render correctly, given correct scene models

• The current versions of those algorithms likely won’t ever scale to real-time for media with mid-range extinction coefficients (κ) and high diffusion
That was a lot of math, very quickly! Read the slides at your own pace at
http://advances.realtimerendering.com/

A more detailed explanation and all equations appear in *The Graphics Codex*
http://graphicscodex.com
Now that we understand transmission, let’s look at the other half of the problem... partial coverage
Transmission:  
A Phenomenon from Nature

- Under the ray optics model*, rays travel through piecewise-homogeneous media
  - Homogeneous = constant refractive index (speed) and extinction coefficient (absorption). Both are functions of frequency ("spectral color")
- Radiance absorbed exponentially with distance, according to the Beer-Lambert model. It also in- and out-scatters from the ray due to diffusion ("multiple scattering")
- A surface is just the interface between two different media. At a surface:
  - Fractal (determined by Fresnel, etc.) of the light ray reflects in the mirror direction
  - Fractal (diffuse) at times, at a direction given by Snell
- Actually, that covers all of rendering! Everything else you’ve heard of is a special case or approximation of this general scenario.
  - "Opaque" surfaces just have really high reflection and absorption rates for visible light. Recall that those are functions of the refractive index... which is why X-rays see through "opaque" materials and "clear" materials blocks UV light
  - Glossy reflection is just mirror reflection on surfaces with complex geometry
  - Subsurface scattering arises from transmission into partly-absorbing mediums with lots of substructure
- Cameras create some high-level effects because of transmission in the lenses
  - A camera’s objective contains multiple physical lenses, each of which is imperfect. There’s a tiny amount of diffusion and reflection, which is not noticeable unless you’re looking at something really bright: low f-stop and blazer
  - Wide aperture causes "depth of field" - a region where points blue less than one pixel and so appear sharp; outside of that, defocus is obvious. This also creates vignetting
  - Even if the frequency dependence chromatic aberration is evident at edges of the frame, each lens is a every prior
- Offline Metropolis Light Transport, Path Tracing with Photon Mapping, and Bidirectional Path Tracing are the only complete rendering algorithms.
  - They model the light scattering described here to arbitrary accuracy... but can be really slow
  - When there is a lot of surfaces ("participating medium"), convergence is too slow to use. Even film companies fake clouds
  - Photon maps are one technique for improving convergence
  - BSSRDF’s approximate subsurface case
  - Rays march approximately the "participating medium" case
- There is no comparable real-time complete rendering solution. Instead, renderers approximate each of the effects on this page independently and phenomenologically (that is, they are hacks). That’s fragile and requires a lot of art direction to avoid surprising visual failures.

* Under a full quantum model, these effects are much more complicated. At that level, we can’t even model transmission and reflection without also modeling diffraction/interference and polarization. But let’s set that aside: we have enough open problems.
Partial Coverage (α)

A phenomenon and open problem we created to reduce ray aliasing

All modern graphics is based on sampling light along rays. This includes GPU rasterization, which is an efficient way of amortizing the cost of sampling triangles with a bundle of rays.
Now, a ray either intersects a triangle or it doesn’t. Coverage is fundamentally a binary property. We can model a scene using triangles with parts cut out using a binary alpha mask, but the coverage is still binary. This is physically correct—rays don’t sort-of interact with surfaces, they either do or don’t.

In this diagram, the red lines show the pixel grid and the white objects are the geometry that we’d like to render.

The problem with sampling along rays is that it causes aliasing when we don’t use enough rays to measure the subpixel coverage within a pixel. This is why the center image has jagged edges.

For a pixel that is partially covered by several surfaces, we’d need a lot of rays to average the 0’s and 1’s to the correct ratios...

The idea of partial coverage is that we want the image on the right, but we only want to pay for a small number of rays at each pixel.
Now, a ray either intersects a triangle or it doesn’t. Coverage is fundamentally a binary property. We can model a scene using triangles with parts cut out using a binary alpha mask, but the coverage is still binary. This is physically correct—rays don’t sort-of interact with surfaces, they either do or don’t.

The problem with sampling along rays is that it causes **aliasing** when we don’t use enough rays to measure the subpixel coverage within a pixel.

For a pixel that is partially covered by several surfaces, we’d need a lot of rays to average the 0’s and 1’s to the correct ratios...
Partial coverage was introduced early in the history of computer graphics as a way to describe the statistics of unmodeled subpixel geometric structure. The models of partial coverage in place today date to Porter and Duff’s 1984 compositing paper.

Partial coverage allows us to reduce or eliminate sampling noise when rendering all of the situations listed on this slide, and are an indispensable part of today’s real-time renderers. Here’s an example of how they work:

**Partial coverage $0 < \alpha < 1$** [Porter84, Smith96, Glassner15]
- Prefilter coverage for many rays to reduce noise
- Assumes objects have uncorrelated subpixel positions
- Assumes visibility is independent of shading

**Arises from:**
- Edge antialiasing
- Subpixel primitives
- MIP-mapped binary $\alpha$ textures
- Depth of field (rays with different origins)
- Motion blur (rays in time)
- Artists repurposing $\alpha$ to simulate transmission!
“Over” Compositing

\[ L(C, \hat{\omega}) = L(A, \hat{\omega})\alpha_A + L(B, \hat{\omega})(1 - \alpha_A) \]

On the left is my eye, or a camera, looking rightwards. In line with a sampling point on the image plane are a pine tree and then a mountain on the far right.

Under **binary** coverage, a light ray from the mountain either hits the tree leaves and is blocked, or passes through to my eye. So, a point on the image plane has a value determined by one object or the other but never both.

Under **partial** coverage, the renderer estimates how much of the entire pixel was covered by tree leaves. The remainder is then covered by the mountain.

Now, the value of the pixel is a combination of the tree at A and the mountain at B, based on the partial coverage alpha by the tree. The “OVER” compositing operator models this. There are other operators that you’d use for other ways of considering the problem, but they’re equivalent.

Here’s the challenge for real-time rendering. Imagine that I have a scene with more than a single tree in it...
A ray tracer would encounter each of these objects in order and could simply apply the OVER operator. It doesn’t care about partial vs. binary coverage.

But a rasterizer processes object primitives, not rays. That was fine under binary coverage because each sample was covered by a single object…we could write those objects to the frame buffer and the depth buffer in any order and let which ever one was closest at the end of the frame color the pixel.

Under partial coverage, we have two choices for perfect compositing, both of which are undesirable:

1. Save every single primitive that affects a sample, and then sort and composite them at the end. This is called an A buffer and takes too much space to use.
2. Sort the primitives and then composite them as they are rendered. This is slow, and impossible in the general case.
Volumetric light and shadowing occurs under both transmission (due to in and out scattering) and partial coverage (due to lots of small particles).

Depth of field is funny... it is a partial coverage phenomenon that is caused by transmission through a lens.

“Can’t I just use alpha for transmission as well as partial coverage?”
This is art. You can use anything you want to achieve the look that you want.

But if you want your glass, fog, and water to look realistic, then... no. Alpha isn’t enough.

You can use transmission to model partial coverage, but I don’t think it is a good idea. Do you really want to figure out the extinction coefficient and thickness that will exactly equal the coverage of a telephone wire through a given pixel?
Partial Coverage: A Phenomenon We Created

- Coverage is not natively a transparency problem: an object either interacts with a light ray, or it doesn’t.
- All mainstream renderers:
  - Sampling along rays (intersection is an efficient way of checking a lot of rays against one triangle at once)
  - Output pixel values (eventually)
- Aliasing results if we sample too few rays to measure a pixel’s value:
  - Camera visibility: “edge aliasing”
  - Light visibility: “shadow aliasing”
  - Orientation: “specular aliasing”
  - Material: “texture aliasing”
  - Motion: “temporal aliasing”
- Can blur the signal, losing some correctness to avoid flicker and jaggies:
  - MIP-mapping, PCF shadow filtering, MLAA & FXAA antialiasing
- “Alpha” is a model of sub-pixel coverage for blurring many binary visibility samples into a single continuous value:
  - MIP-mapped mask texture
  - GPU numerical coverage mask to alpha, e.g. glTranslatef(GL_LINE_SMOOTH)
  - TEXT antialiasing
  - Research analytic coverage
  - Motion blur and depth of field
  - CAD/CAD game nonphotorealistic hidden surface views
- Turns partial coverage into a transparency problem:
- Not the same as transmission:
  - Examples of 0% “transparent” glass and a 1% coverage (alpha = 0.01) surface with Fresnel effects
  - Can’t model wavelength-specificity with partial coverage
  - Statistical independence assumption of coverage (see Porter & Duff, Smith & Biltn)
  - Not a real-world phenomenon! This is an artifact of our ray-based renderers
  - Historically used to approximate glass and other effects
We have built some understanding of what the transparency problem is and we know how to solve it for offline rendering. Now let’s look at real-time constraints and approaches to a real-time solution.
Ideal Solution

• **General-purpose**
  – E.g., look through a double-pane window at a smoky room with a fish tank in it…different media composite correctly
  – Transparent shadows consistent with visible transparency

• **Support for *non*-physical rendering**
  – Hidden surface views, artistically lit clouds, magic/sci-fi FX

• **Robust** (predictable)
  – No light/dark leaks, energy conserving, temporally stable

• **Minimal compromises**
  – *All* glass reflects, *all* fog has multiple scattering, etc.
I’m just going to throw this out there as the first rarely-acknowledged challenge in real-time transparency. Modern renderers are fundamentally designed around z-buffers in a way that assumes no transparency.

**Deferred shading** assumes ONE point to shade at each sample location on screen. Transparency necessarily has multiple points.

**Post-processed effects** assume one surface per sample.
Game development targets a wide range of platforms. Projects are dominated by art, so it is usually ok to spend more engineering time to have platform-specific implementations, but it is not acceptable to have to re-model or re-tune art assets for each platform. Nobody can afford to ship a game with one strategy for transparency on PC and a different strategy on Xbox One...so a multiplatform title or engine is likely to adopt the lower-end Xbox One’s constraints even on PC.

There’s also more to real-time rendering than Games...
Content creation applications, like those by Autodesk, are the greatest consumers of real-time transparency algorithms. They have to render models with realistic glass for architects, as well as subpixel wireframes and hidden surfaces.

Here, robustness is essential, and there’s no room for an artist to tune the materials and insert hints. The algorithms need to just work correctly...which is what game developers want anyway.
I’m going to categories today’s strategies, but first,
Playdead’s “Inside” (2016)

There is no question that the game with the best transparency today is Playdead’s “Inside”, which was released three weeks ago.

The game is full of overlapping water, bubbles and debris in water, fog, smoke, fire, and glass, with diffusion, refraction, and volumetric shadows. There's also zero aliasing in this game...partial coverage is handled perfectly.

However, I suspect that most of what’s going on here is really masterful art direction and modeling for the fixed camera and specific scenes. This is how good we want all real-time transparency to look, but this probably isn’t a practical way for us to achieve it in most applications.

The bibliography for this course (which won’t be shown on screen) contains hundreds of citations. The recent GDC and SIGGRAPH Advances presentations are where you should look for today’s best practices. I’m largely NOT going to summarize those.

Instead, for the next ten minutes I will focus on some forward-looking techniques, which often aren’t quite ready for deployment today. These are what I’d start from when inventing new techniques for games now in preproduction, and which might to hold the seeds for future research of a comprehensive transparency solution.
Explain: Two problems, some techniques for one or the other, some for both
Sorted Transparency

- Can handle coverage and transmission
- Useless for shadows and indirect light
- Inefficient on modern architectures
- Dominates modern practice ("forward transparent pass")
Ray Tracing / Ray Marching

- Bulletproof transmission strategy
- Handles most partial coverage well
- Works for indirect light and shadows
- OptiX/Embree/FireRays real-time implementations
  - Too slow for full game rendering, but within 10x
  - A second CPU/GPU could trace one path per pixel at 720p/30Hz for modern game assets right now
Low-Resolution Models of Visibility
Visibility function

...issue: do you use the SAME approximation for eye-paths and light paths? E.g., visible samples and shadows?

Many errors can be concealed when making approximations along eye light paths because you’re seeing the ray end-on and only noticing the accumulation [click]...but when we consider volumetric lighting, you can see this function from the side and can’t cheat it so easily...[click]
Lokovic and Veach’s deep shadow maps introduced the notion that

**Low-Resolution Models of Visibility**

- Deep shadow maps [Lokovic00]
- $k$-buffers, blended OIT, Fourier opacity maps
**k-Buffers**

- Consistency Principle: submitting primitives in the same order produces the same result, but it is not purely “z-order independent”
- Modern implementations: atomics or interlock
- $k = 1$: Store min depth, choose over/under blending based on depth test [Salvi14]
[Maule13] Atomic k-buffer partial coverage

Atomics-only k-buffer like approach: accumulate and sort, then composite. Works on current consoles, faster than pixel sync on some platforms.
More sophisticated and modern version of Maule...

I think this is the best current solution for hair.
Order-Independent Blending

• Completely hallucinate the visibility function [Meshkin07]
• Makes colored transmission and partial coverage practical on current hardware [McGuire15]
• Allows some screen-space tricks for refraction and diffusion
[McGuire15] Phenomenological order-independent transparency

Console-friendly order-independent transparency with no atomics or pixel sync.
Also fake refraction, diffusion,
Stochastic Transparency

- Bulletproof coverage strategy
- Works for indirect light and shadows
- Typically requires high-rate MSAA
- Inferred lighting for deferred shading [Kircher09]
- 1spp + temporal antialiasing [Evans15]
Very popular for game hidden-surface rendering, LOD transitions, and some particle effects.
[Evans15] Single-sample stochastic transparency (Dreams)
Colored shadows, caustics, and volumetric lighting and shadows using a stochastic variance shadow map
Valuable in two ways: new way of thinking about partial coverage algorithms, and a new proof-of-concept algorithm.
I think that the notion of mixing stochastic with k-buffers is a possible path to stochastic transparency that also supports physically-based transmission
Volumetric
Stochastic transparency on objects, also using epipolar-style ray march integration for uniform volumetrics with some noise
Shadow map -> extrude light volumes, assume uniform density medium and solve the integral
Ray marching at low resolution. Cleverness in compositing with other transparencies by using a very low resolution voxel representation of coverage.
Camera-space ray marching with stable sampling depths. The idea is to compute at low resolution along the z-axis, but make those samples relatively coherent between frames so that the aliasing is at least consistent over time.

Bowles showed a simple proof of concept at SIGGRAPH last year. I think there’s a lot of potential here...ray marching is the one high-quality method that we know rendering of dense transmissive media like fog, and this gives a large speedup while concealing the major error source.
Scattering, emission, extinction, albedo... (this is describing materials that contain lots of small particle, so are inhomogeneous) stored in camera-space voxels. Primarily on fog volumes with noise textures, but also some particles.

Integrate lighting along rays, with some tricks for in/out scattering based on knowledge of the volumes

State of the art. Desired features: fix some leaking, not need special modeling knowledge about the volumes and lights, integrate with other non-fog like material transparency.
Faces

- Very sensitive cases
- Does not interact with other transparencies
- Localized, output can be treated as an “opaque” surface
Special cases for human figures, which we’re very perceptually sensitive to.

Skin inspired by d’Eon 2007...screen space blurring, red blurs further than other colors, lots of ambient occlusion darkening.
Also very careful handling of reflection and refraction in eyes.
Post-Process Effects

- Motion Blur
- Depth of Field
- Bloom
- Lens Flare
[Jimenez14, Guertin14] Post-process motion blur (Call of Duty Advanced Warfare)
[Jimenez14] Post-processed depth of field (Call of Duty Advanced Warfare)
[Jimenez14] Post-processed bloom (Call of Duty Advanced Warfare)
• Ray Tracing
  - Diffuse-reflected light, not necessarily expensive and requires a different data structure for transmission. EnviromeTechRayOptex can trace one ray per pixel in 720p for about 20 ms. (Assuming a forward link, but not processed in parallel.)
  - Challenges with transparent surfaces: modeling is actually hard for any transparent surfaces

• Stochastic "vanilla" depth [for paraxial convergence]
  - Diffuse-reflected light for average (shading, reflection, refraction, and depth of field)
  - High-speed MSAA or post-process antialiasing/interpolation needed
  - Some tricks for global transmission in this case: Lambertian absorption for shadows, reducing noise in the coverage case using multiple passes
  - Doesn’t help with transmission/refraction
  - Anisotropic reflection?
  - [Special case, e.g., internal]
  - App.: TAA can work for some content (Dooms PS4)
  - Yawless RGP 1.5

• Smooth models of transmission-long-way
  - Solved transparency
    - Fades to varying degree, especially on 3D objects, e.g., transparent Buenos Aires box
    - Improved showing blending error and shadows frequently in a reasonable cost: a combination of partial coverage, transmission, reflection, refraction, and convolution
    - Moving geometry, etc
    - Hard to be measurable without actual interaction

• 3D Indirect Illumination
  - Propagation: 1-buff, 2-buff, 3-buff
  - (assumptions, k = 0.5, 0.05, 0.01, etc)
  - General: correlation (decomposition into sample functions)
  - Yawless recently reported [efficient for the coverage only case]
  - [Details of the paper]
  - [Other papers]
  - [Reusability: transparency, 3D meshes, etc; doesn’t need Photoshop; its order independent and order dependent, non-convolution similar to stochastic]
  - [Fur, Volumetric, and Sheen: shear, transparency; 3D meshes, shadowing, 3D paths]

• Volumetrics
  - Volume scence, transfer, lighting, and world space effects
  - Work well if “participating medium” uses the fig and stroke, but may look like solid
  - Fixed, weakly selective
  - Too to look through walls
  - Non-refraction and non-area
  - Solution: substitute’s friends

• Post-processed bloom, DOF, Motion blur (see COD talk)
Excepting the special case techniques, I might coarsely summarize the properties of each strategy like this.

And based on that, you can probably see why I’d call the bottom of this table better short-term strategies and the top better long term strategies.
I’ll now conclude with two slides of recommendations for how I’d approach short and long-term transparency research and development.
Two R&D Agendas

Recommendations for approaching transparency in three- and ten-year windows
Shape of Solutions

- Agenda: More complete transparency solution
  - Consistent transmission functions for light and camera
  - No light/dark leaks
  - Refraction
  - Colored transmission
  - Mixing materials: looking through glass at smoke…and the camera in the middle of them

- Good news: Lots of new tools to experiment
  - DX12 Fragment shader interlock/pixel sync now shipping on all new vendor GPUs
  - Lots of recent research results on very different techniques
  - OptX Prime/Embed/Redis: high-performance ray tracing solutions
  - Deferred k-buffer/deeper aggregates?

- Bad news:
  - For the next 5 years, most games must still run on current (XB1 & PS4) as well as upgraded consoles (Scorpio & NEO)
    - Techniques with platforms-specific engineering are ok. Platforms-specific art direction and having art too expensive
    - Room for duration in a console market?
    - Another window for indie PC games to publish technically

- 10 years: probably more film-like
  - Ray tracing + stochastic super-sampling is very attractive. Need:
    - Better ray tracing: optical data structures, shaders
    - Deferred MSAA solutions
    - Compressed MSAA (alas of CAA?)
    - Mesh hierachy drawing (TAA?)
  - Volumetric effects without leaks or overblurring: veins or massive particle systems
  - Deep k-buffers buffers for screen-space post processing & compositing: Some effects will probably always be post-processed depth of field, motion blur, lens flare, bloom

Coda: We call rendering phenomena “effects” when we have to special-case them because the renderer doesn’t just handle them implicitly. There was a time when “highlights” and “shadows” were effects...now we take them for granted. I want to take transparency for granted.

View-model filtering for DoF done today
If I was in preproduction on a game right now, I’d be looking to extend these techniques. There’s still room between them for innovation within the constraints of current GPU architectures.

The key ideas of working with sparse sampling in depth and ensuring temporal stability even at the cost of biasing the result are really important. Wyman and Maule’s hybrid ideas haven’t been sufficiently explored either.

For a longer term or academic research agenda, I think the solutions might look very different, however…
Next Decade Research Target

- Transmission: Ray trace triangles and ray march voxels
- Partial coverage: Stochastic or layered G-buffer
- Either 64x super-sampling or very good denoising/antialiasing filters
- Layered Forward+/G-buffers produced by all rendering for use in post-processing

I think we’re absolutely going to be ray tracing transmission (and probably sharp reflections) within a decade in production. There are a lot of open sub problems on how to get us there on both the software and hardware side, and if you look at the HPG proceedings for the past few years, you’ll see that this work is already in progress.

Ray tracing and ray marching are so robust and flexible that there’s no way we’ll settle for a pile of hacks once they are performant. There’s a lot of work to be done on denoising and upsampling the results to get the most out of every ray, however!

We might see a comeback of MSAA or supersampling to help with this. That makes partial coverage work with deferred effects...essentially, by going back to binary coverage!

...but transmission isn’t ever going to work with purely stochastic methods, so I believe that just as film renderers produce multiple layers for compositing and post, we’re going to produce layered G-buffers for use in post processing and compositing. While there’s lots of good work to do on further tweaks to the post-processing pipeline, I wouldn’t pursue doing any of those effects in-camera except maybe stochastic motion blur. Film is satisfied with the quality of post-processing these and I don’t see us having higher standards.
Film Compositing

Transformers Age of Extinction FX reel, ILM 2014

https://www.youtube.com/watch?v=bm2PZj8sA

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- The computer graphics community on Twitter
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[these techniques are refined and applied in hundreds of other papers]
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