Chapter 6
Applications of Ray Tracing

Abstract Ray tracing has been traditionally used with applications for media and entertainment (3D animation, rendering), product development (CAD/CAM/CAE), life sciences (medical, molecular), energy, and other operations. The ray-tracing programs are used by engineers and artist proposing a project concept or new product design, by designers who bring the first renditions of the project or product for evaluation, by manufacturing people who build and test the project, or product virtually in the computer. And then when everything is proven and acceptable, marketing people use ray tracing to create images to sell the product. Ray tracing is used in all four stages from project concept to fulfillment. The concept of virtual prototyping and in the film industry pre-viz has been embraced by most industries and has saved millions of dollars by eliminating redos and expensive after-sales repairs.

Ray tracing can be used in almost every industry, government agency, academic institution, and even private parties. There are ray-tracing programs from over a hundred sources, many of them are free, and new hardware and software developments have made the rendering time shorter than ever.

Ray tracing is used to design systems and to represent the data generated by those systems, and it is used to conceptualize a product and then to sell the product. It is used to create simulations of real-world situations and imaginary worlds. It is used to model and visualize proteins and molecules and to design new compounds that do not yet exist, and then, if created and manufactured, it is used to display the pill, and the package it comes in, the store it is sold in, the trucks that deliver it, the road the truck travels on, and all the components within all those elements. Ray tracing is like electricity and air; it is used everywhere and can be found in everything. How then does one categorize a ray-tracing application?

Some of the other applications for ray tracing are:

- Product design and virtual prototyping
- Engineering and architecture
- Advertising (print to video)
- Optical engineering and design
- Audio engineering and design

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- Geophysical modeling and presentation
- Medical and scientific
- Entertainment (games to movies and TV)
- Simulations and visualizations
- Interference and design checking
- New media—e.g., VR.

This is not an exhaustive list, and the applications for ray tracing have steadily increased over the years as techniques and processors have improved.

6.1 The Pipeline

I have approached it by visualizing a four-stage pipeline, starting with conceptualization, into design, then manufacturing, and finally marketing.

And please note, by a product I mean, and include anything from a washing machine to a movie, from a surgical training scenario to an analysis of a body scan, from an airplane or car design to the simulation of the airplane flying or the car crashing. Physically accurate modeling, virtual prototyping, and data analysis are absolutely essential for product satisfaction, safety, reproducibility, and reliability.

When one has a target customer in mind, there is nothing better than presenting in a virtual environment that allows the prospective customer or user to understand how the product would fit in the real world. Ray tracing accomplishes this relatively quickly and inexpensively, enriching design reviews and helping stakeholders connect with the design.

The ability to show a physically accurate (or fantasy imagined) image, possibly with animation, conveys the designer's, the imaginer's, and the support's message to levels not possible before. The famous saying—a picture is worth 1000 words—is truly realized with a perfectly rendered image. And, unlike story boards, or artists renditions, the customer or investor, gets what he or she bought—*what you see is what you get*.

Since the design, the model, has been developed in a 3D domain, the renderings of it are accurate to the design. That enables two benefits to the developers. First it leads directly to virtual prototyping which is a genuine try it (fly it) before you buy it. Virtual prototyping allows the developer or director to make tweaks, adjustments, to realize their visualization, the thing they saw in their mind's eye.

Production can take longer than expected, and even if it is done on time, the marketing team needs as much lead time as possible to generate interest, excitement, and ultimately the demand for the new product or movie. Therefore, taking advantage of the digital model, final marketing material can be produced prior to final products. That way consumers are primed and ready to buy when the product is available. It is estimated 95% of the automobile commercials are simulations and the cars they are showing haven't been built at the time of the viewing. The same is true of outtakes of movies and games, and other consumer products. This is certainly true of all space ventures and projects.

In the following sections of this chapter, I will describe the use of ray tracing in the stages of development of a product in the four stages of the pipeline from idea to consumer.

Later in this book, I discuss cloud-based visualization (CBV). Cloud-based visualization can be used at the conception/proposal stage and the presentation (selling) stage.

6.1.1 Conception—STAGE ONE

Ray tracing is used in the proposal and planning stage to visualize what the final product should look like. This is often referred to virtual prototyping, and in the movie industry as pre-vis (also known as pre-viz). Architects, automobile and aerospace firms, consumer goods and clothing designers, and industrial machinery designers to name a few use ray tracing to create concepts to sell the idea or product to management, prospective customers or patients, and government agencies. In some cases, in the very early brainstorming concept creation sessions, rasterization rending is used in the interest of time. In the TV and movie industry, that is known as storyboarding.

The concept starts with the construction of a 3D model. The model may not (usually doesn't) represent the final product and usually lacks detailed aspects needed for manufacturing, testing, and certification. A building or car, for example, will simply be a shell with none of the important parts underneath it.

The following are some of the popular examples of using ray tracing in the concept stage.

6.1.1.1 Simulations of Things that Don't Exist

Ray tracing is used for showing how a product might look. Buildings, airplanes, automobiles, and even clothes are simulated and then rendered with ray tracing to see how potential buyers will react. Almost all automobile ads, printed models, and TV are computer-produced with ray tracing. Cars that aren't built yet are shown to dealers and as a teaser to TV viewers. The cost and delays associated with photographing a car are so great, and they are almost never used anymore. Obviously, the skyscrapers being proposed couldn't be built first. The use of scale models is declining and is often replaced by 3D virtual and/or printed models. Ray-traced models are being to show city planners and adjacent property owners how the building will create shadows and reflect light over a 24-h period, and at various seasons all are done using ray tracing.

Ray tracing is used to create models of simulations and of products or designs not (yet) actually built.

The following examples show some examples of things that were designed, but not built, and yet the images are photorealistic and totally believable—not too unlike the fantastic worlds that are created for special effects in the movies (Figs. 6.1, 6.2, 6.3 and 6.4).

Fig. 6.1 This is an example of a Boeing 797 blended wing concept airplane that was never built - realistic looking isn't it. *Source* Wikipedia—Popular Science magazine

Fig. 6.2 The Ford GT90 was never built. *Source* Ford

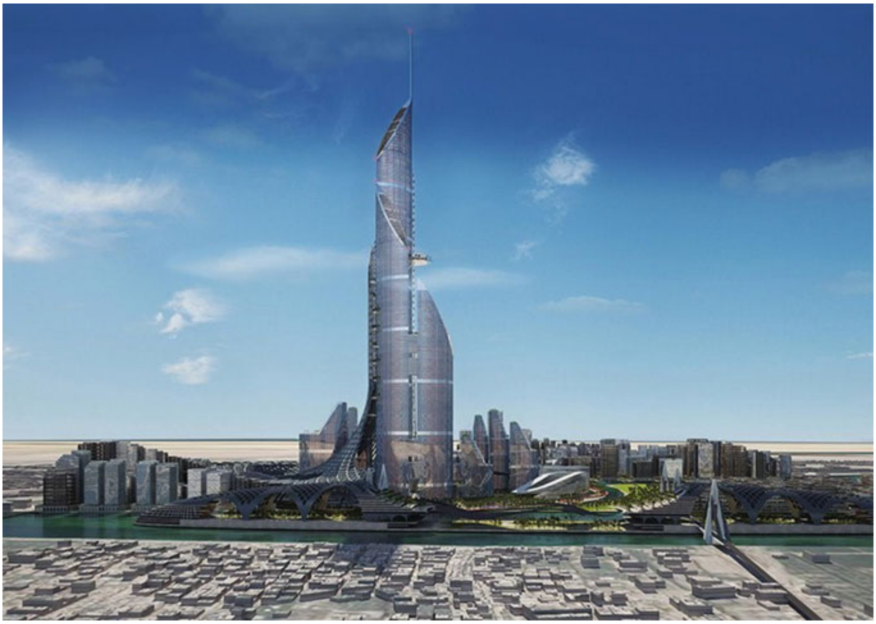

Fig. 6.3 241-floor, 3162-ft-high structure would be named “The Bride” and sit in the middle of Basra, Iraq. Courtesy of AMBS architects

Fig. 6.4 Proposed Airbus A390. *Source* Airbus

Virtual prototyping is a method in the process of product development. It involves using computer-aided design (CAD), computer-automated design (CAutoD), and computer-aided engineering (CAE) software to validate a design before committing to making a physical prototype. This is done by creating (usually 3D) computer-generated geometrical shapes (parts) and either combining them into an "assembly" and testing different mechanical motions, fit and function. The assembly or individual parts could be opened in CAE software to simulate the behavior of the product in the real world.

Typically, virtual prototype models are actual CAD models, and when it comes to rendering, the models are rebuilt in design products such as 3ds Max, Maya, Modo, and Cinema 4D. Increasingly, the leading CAD programs have been developing features that enable easier simplification of models for the purposes of rendering (and analysis), but I believe there is still quite a bit of model rebuilding and cleaning.

6.1.1.2 Animation Games and Simulation

Animation and games mostly use rasterization to portray the concept and action scenes of a story. Occasionally, parts of a scene or frame will be ray-traced to convey the feeling of the scene. The casting of shadows, lighting, and colors are critical in getting the right mood conveyed, and artists and directors will spend days tweaking elements to get it just right.

Gaming has the potential (in terms of users) of being the biggest market for ray tracing.

Ray Tracing in Games

PC, console, and mobile games are available in several genres, and there is no single list of them; rather, it is more like a matrix. It is beyond the scope of this study to provide an exhaustive list, description, and taxonomy of all the gaming genre, but a few need to be discussed to understand the role of ray tracing in games.

Ray tracing today is hard to use and expensive—more expensive than the raster-based solutions we are used to. Tools and workflows exist to give a baked or dynamic lighting as well as somewhat convincing reflections. These have arisen in response to a demand for those effects, so they are wanted; it is just that they are expensive and time consuming to produce, so they are the first to be thrown out when gameplay (frame rate) is the priority.

If they were available at no performance or production cost, they would be universally used and as a consequence would become an integral part of gameplay (Fig. 6.5).

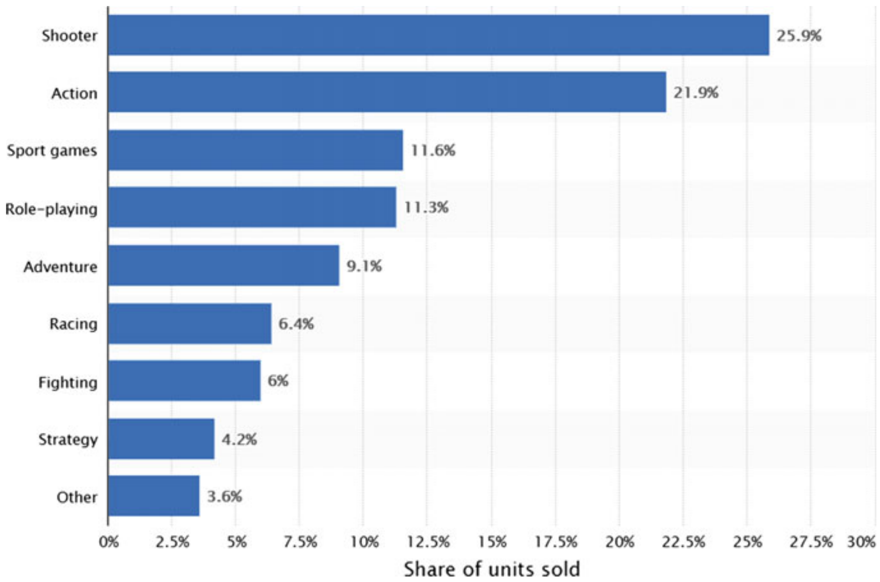

Fig. 6.5 The most popular video games sold in the USA in 2017. *Source* Statista

First-person shooter (FPS) is a video game genre centered around gun and other weapon-based combat in a first-person perspective; that is, the player experiences the action through the eyes of the protagonist. The genre shares common traits with other shooter games, which in turn makes it fall under the heading **action game** and is also referred to **action-adventure** (which gets confusing with adventure games). Since the genre's inception, advanced 3D and pseudo-3D graphics have challenged hardware development.

FPS games are very fact action with severe win/lose consequences more often described as kill or be killed. As such, the player has little to no time to carefully observe the environment and therefore ray tracing has little value in an FPS. Also, FPSs are the most demanding on the processors and any cannibalization of processing cycles for pretty effects is undesirable by the players.

Sport games don't seem to offer much opportunity for enhancement by ray tracing other than maybe shadows and sun flare/glare. Uniforms and fields will not benefit from ray tracing.

A **role-playing game** (RPG) also known as a computer role-playing game (CRPG) is a video game genre where the player controls the actions of a character (and/or several party members) immersed in some well-defined world. The world can be 2D or 2.5D.

An **adventure game** is a video game in which the player assumes the role of a protagonist in an interactive story driven by exploration and puzzle-solving. Included in the adventure game genre is a category known as **walking simulators**.

Walking simulators feature few or even no puzzles at all, and win/lose conditions may not exist. Such games allow players to roam around the game environment and discover objects like books, audio logs, or other clues that develop the story, because they are based on 3D models, they are an example of a game that could benefit from ray tracing.

Using ray tracing in games is controversial. Back in 1992, a few PC games used ray-casting algorithms. That was quite an accomplishment given the level of processor performance of that time.

Like ray casting, ray tracing "determines the visibility of surfaces by tracing imaginary rays of light from viewer's eye to the object in the scene" (Foley 701[1]). Ray casting, however, is faster than ray tracing (see Sect. 4.3.5).

Ray casting is faster because its world is limited by one or more geometric constraints (simple geometric shapes), a ray-tracing world can be almost any shape. Ray casting was developed in the early 1980s and was successfully exploited by John Carmack in his groundbreaking 3D shooter, *Wolfenstein 3D* (id Software) in 1992.[2] Ray casting is a technique that transforms a limited form of data (a very simplified map or floor plan) into a 3D projection by tracing rays from the viewpoint into the viewing volume.

Early PC games such as *Wolfenstein 3D* and the *Comanche* series[3] made use of ray-casting algorithms. In *Wolfenstein 3D*, the world was built using a square-based grid of walls which were of a uniform height. They were merged with solid colored floors and ceilings. While illuminating the world, a single ray was traced for every column of pixels on the screen. A vertical slice of the wall texture was then selected and scaled based on where it collided with the ray. This way the distance could be calculated, and the walls could be scaled accordingly. Since the ceiling and floors were uniformly colored, there was no need to worry about them. That also reduced the computational and memory overhead. The savings could then be utilized to render the bodies which were in motion in the open areas of the map (Fig. 6.6).

The *Comanche* series handled ray casting in a slightly different manner. Individual rays were traced for each column of screen pixels, and when the rays interacted with an object, it was plotted against a height map. It was then possible to determine which of the pixels were visible and which weren't and then use a texture map to pick the corresponding color for the pixel.

Ray Tracing in Contemporary Games

When *Quake*, a first-person shooter video game, developed by id Software and published by GT Interactive came out in 1996, it was a breakthrough,

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[1] Foley, "Computer Graphics: Principles and Practice," p 701.

[2] https://en.wikipedia.org/wiki/Wolfenstein_3D.

[3] "Comanche," was a series of simulation games published by NovaLogic. The goal of each of these games is to fly military missions in a RAH-66 Comanche attack helicopter.

Fig. 6.6 Wolfenstein 3D made use of ray casting algorithms in 1992. *Source* Wikipedia

transformative, disruptive milestone in PC gaming and has been a legend and foundational example ever since.

Quake II release one year later had improved graphics and game mechanics and was an all-time hit—run, shoot, duck, die.

Battlefield V has fantastic graphics and is almost totally outside (no small rooms or long corridors like the original Quake), and yet the gameplay is almost exactly the same. Run, shoot, duck, die.

But Battlefield V could brag about something Quake couldn't—ray tracing. It *could*, but it can't anymore.

In 2017, Christoph Schied started adding ray tracing to Quake II as a spare-time project to validate the results of his computer graphics research in an actual game while at Karlsruher Institut für Technologie. The project was completed in 2018 and encompasses 12K lines of code, completely replacing the original Quake II graphics code. Take a look at the results in Fig. 6.7 and in this video (https://tinyurl.com/y7v5le3g). The explosions may seem disappointing, but that is due to the limited geometry in them, not the ray tracing.

However, Herr Schied was not the first to render a ray-traced version of Quake. Countryman Daniel Pohl was experimenting and demonstrating using ray tracing in real-time games, specifically Quake 3, in a cooperation of the Erlangen University and Saarland University in Germany in 2008. Pohl's work so impressed Intel, one of the patrons of Saarland, that they hired him after his master's thesis for the Larrabee project. In 2009, Herr Pohl faced the crowds at Intel's Research Day. But even that wasn't a first because as a student Herr Pohl was showing off his work at

Fig. 6.7 A scene from Schied's ray-traced version of Quake II. *Source* Christoph Schied (2018)

CeBit in 2007.[4] He actually started working on ray tracing in games in 2004 as part of his student research project under the guidance of graphics professor Philipp Slusallek. As part of his studies and diploma thesis, Pohl rewrote parts 3 and 4 of the first-person shooter Quake so that their graphics were calculated using the ray-tracing method. The source for Q3 and Q4 was not available. He actually never used the real Quake engine, and it was all rewritten from scratch to load the maps, models, textures, sounds, animations, even up to some simple AI to make it feel like a real game (Fig. 6.8).[5]

That was over 12 years before Nvidia showed their RTX-based Turing chip, and Pohl's results were not playable on a single PC. It took a high-end computer in the Munich Intel test laboratory, equipped with the latest quad-core processor to get barely 17 fps at 640 × 480—but the promise was there—Moore's law would prevail.

Pohl's work was visionary, and one might say ahead of his or the times. Schied's work is more accessible and testable. You can download his code (https://tinyurl.com/y7udr587), assemble it, and run the *Q2VKPT* game. If one has an RTX-equipped Nvidia add-in board (AIB), you can actually play the game—with real-time ray tracing turned on at greater than HD resolution.

Q2VKPT is implemented in the Vulkan API to be able to use the new hardware-accelerated ray-tracing features that were made available earlier this year. Thanks to those developments in 2017, the game could actually come close to

[4]Kremp (2007).

[5]Pohl (2008).

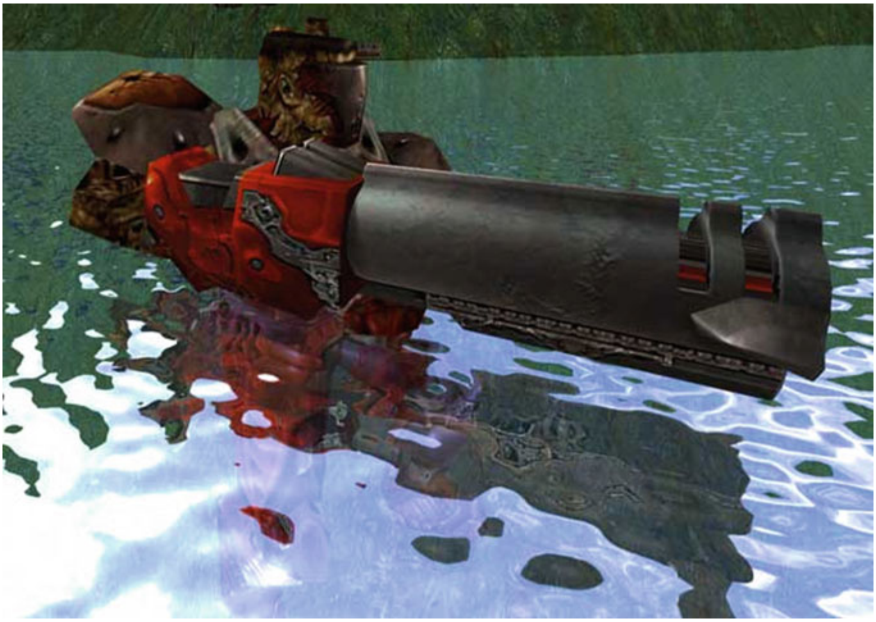

Fig. 6.8 Ray-traced Quake: the water reflects the environment and the player. *Source* Pohl (2006)

60 frames per second (fps) (2560 × 1440, RTX2080Ti), while being fully ray-traced and dynamically shaded with realistic global lighting models in real time.

Using Path Tracing for fully dynamic lighting, says Schied, allows for a lot more detail in the shading of game scenes, naturally producing complex interplay of hard and soft shadows, glossy material appearances, and perspectively correct reflections everywhere. Moreover, light can naturally flow anywhere, tying the scene together in the ways we would expect from the real world. Traditional approaches like precomputed lighting or coarse real-time raster approximations could never interactively reach this detail at a comparable resolution, since full storage of this lighting information would exceed any memory bounds.

The original *Quake II* engine uses precomputed light maps that contain soft shadows and diffuse indirect illumination. In contrast, Q2VKPT entirely replaces the static illumination using a fully dynamic simulation that unifies both the static and dynamic light sources.

Besides the use of hardware-accelerated ray tracing, Q2VKPT mainly gains its efficiency from an adaptive image filtering technique that intelligently tracks changes in the scene illumination to reuse as much information as possible from previous computations.

The first wave of PC games to employ some real-time ray tracing using DirectX 12 and Nvidia's RTX and running on a Nvidia RTX 2070/80/Ti AIB were all AAA first-person adventure shooters. As such with one notable exception, the ray tracing was actually wasted and not only didn't enhance the game but was distracting and silly.

The new *Shadow of the Tomb Raider* (SotTR) is an example of the issue and the exception. As mentioned above, in an action game where its kill-or-be-killed one doesn't have time to look around at the scenery, which in many senses is a shame because today's games have amazing and beautiful artwork and gigantic world models. The protagonist, the ever-suffering and indefatigable Lara Croft, quickly gets mud on her face and arms from jumping, crawling, failing, and fighting. But the mud is unrealistic, it looks like painted on makeup, and there is no depth or texture to it (Fig. 6.9).

However, once one stops gawking at the scenery and character and gets into the game, one no longer notices her mud (which comes and goes at odd times) or her hair. When one pauses and looks around at the scenery, one marvels at: A. the awesome size and complexity of the 3D models and map size and B. the textures and artwork. This is a delightful game world to be in. But does it need ray tracing? No. Would the game be any better with it? Not really. Except (read on).

I also looked at the demos of 4A's *Metro Exodus* and EA/DICE's *Battlefield V* (Fig. 6.10).

Metro is one of our all-time favorites. *Metro* and *Tomb Raider* have a story and really get one involved. As a take no prisoners, stressful game *Battlefield*, tests one's composure. There's no time for gawking—gawk and die. So why then do we need a ray-traced car that is in the middle of an intense sniper-filled house-to-house cleanup mission? No. One doesn't have time to look at it or appreciate it, and it could just as well be a big black box (Fig. 6.11).

And where is a war-torn place like Amsterdam is one going to find a perfectly clean, undamaged car with all its windows and no bullet holes?

Fig. 6.9 Lara's unrealistic dirty face and arms

Fig. 6.10 Artyom's perfectly clean mask and gun after a decade of fighting in tunnels and snow storms

Fig. 6.11 Car reflecting a nearby fire in Battlefield V

The scene in *Battlefield V* is in Amsterdam after many years of war, in the early 1940s. In the 1940s, in Holland, there was no such thing as flat glass like we have today. It all had (and still does) ripples in it. Secondly, after many years of war deprivation, there weren't any clean windows. As fastidious as the Dutch are, during the war they were being starved to death by the Germans and didn't have

Fig. 6.12 Perfectly flat, perfectly clean Dutch windows in WWII Amsterdam

time or interest in washing their windows. Therefore, the depiction of perfectly reflecting windows like mirrors in the *Battlefield V* is superfluous and gimmicky (Fig. 6.12).

Rivers and pools of water, maybe, but you really don't need ray tracing for that, ray casting is fine, you're not going to be there long enough to appreciate it, and it's just burning cycles.

Now, if someone were to make a truly interactive, non-cartoonish fantasy game like *Myst*, that would invite you and let you wander around and discover things without fear of someone killing you, then ray tracing could, and would, be really great. But in action kill-or-be-killed games like *Tomb Raider*, *Metro*, or *Battlefield*, forget it. Give back those cycles, so they can be used for better physics, mechanics, and no latency, all with high frame rate and high resolution and FOV. Give better bump maps, so the mud on Lara is caked, and Artyom's stuff is dirty.

The Exception

There is one scene, the only scene, in SotTR where Lara is in a village, at night during a festival. She is not being chased and is safe. She is following some men. The village scene is very pretty with all the lights, their shadows, and reflections. In this situation, ray tracing does add something (Fig. 6.13).

Fig. 6.13 Market scene in Shadow of the Tomb Raider

So why, if ray tracing isn't really needed, plus it required a new and expensive AIB, and the first implementations were not very realistic, were the suppliers doing it? Because they could.

Computer graphics has always been about *because we can*. And, as has been pointed out many times, it is going to take years for the game developers to figure out what can (and what shouldn't) be done with ray tracing.

However, another point of view is that it is not eye candy that ray tracing will supply but visual cues to help gameplay. Reflections and shadows that alert gamers to a developing situation is the obvious one. So as with all media, the content needs to be more cleverly developed, and that just takes time as the developers figure out how to use it. Remember however, they never figured out how to use stereo 3D and as a result it died.

4A Games Metro Exodus

A4 has employed Nvidia's GeForce RTX for real-time ray-traced global illumination in PC-based games.

Game developer 4A Games has a video (https://youtu.be/Ms7d-3Dprio) of gameplay footage from its game, *Metro Exodus*. The story-driven first-person shooter (FPS) was one of the first titles to support real-time ray tracing. The video is narrated by Benjamin Archard, a rendering programmer at 4A Games. In it, he explains some of the intricacies of real-time ray tracing and specifically global illumination (Fig. 6.14).

Nvidia's Turing-based add-in boards are designed to bring real-time ray tracing to consumers. The GeForce RTX 2080 Ti, 2080, and 2070 feature Nvidia's RT (ray tracing) and Tensor (AI) Cores and are used in conjunction with Microsoft's DirectX Raytracing (DXR) API. This combination makes realistic lighting effects attainable in gameplay.

Fig. 6.14 A ray-traced scene from A4's "Metro Exodus"

In the video referenced above, one can see several occasions where Nvidia's RTX ray-tracing operation is turned on and off to show what a difference real-time ray tracing makes.

Nvidia explained in a blog post (https://www.nvidia.com/en-us/geforce/news/metro-exodus-rtx-ray-traced-global-illumination-ambient-occlusion/), "By introducing real-time ray-traced global illumination (RTGI), 4A can have natural lighting from the sun and moon realistically illuminate a scene and have it genuinely affect the scene as the time of day changes. Before now, this was impossible—GPUs lacked the necessary hardware and performance to calculate real-time ray tracing, and no one had crafted technology and techniques to accelerate the process to such a degree that it could be used in graphically complex games."

Real-time ray-traced ambient occlusion (RTAO) can also be seen in the video. RTAO enables developers to calculate and display AO's contact shadowing based on the geometry of the scene. This is a different approach than traditional rasterization rendering, which uses rough approximations to generate shadows surrounding an object, rather than being based on an object's specific size, shape, and material construction.

The video also provides an indication of what kind of visuals GeForce RTX graphics add-in board owners will experience.

6.1.1.3 Architecture

Often lumped together as architectural, engineering, and construction (AEC), I make the distinction of not doing that because engineering and construction can be considered design and manufacturing respectively.

Fig. 6.15 Proposed mixed-use development. *Source* Tom Svilans, rendered with Indigo Renderer

Architectural conceptualization is what architects used to do with balsa wood and cardboard models, to give the prospect and idea of what his or her building or home would look like, or what a modification to a building, home, or garden would (could) look like. Ray tracing adds the ability to show the design concept in all hours of the day and all seasons, to show the secondary effects from the proposed building (such as reflections and/or shadows cast by it) (Fig. 6.15).

It is very common that architecture offices need to make renderings during the development of projects. For some stages and some types of projects, it makes sense to hire the services of a professional rendering company. But sometimes, it is too costly and the time consuming of the coordination doesn't fit in a tight schedule of a small project for example. However, even in these cases, one needs to be able to communicate to the client or other members involved in the development of a project how the space is going to look like.

Sun and Shadows

Because a ray-traced image is physically accurate and photorealistic, they are also used to show the shadow and reflections from a proposed building. Sometimes, such analysis is done after the fact. A classic case of doing the analysis afterward occurred in 2015 (Fig. 6.16).

London's 20 Fenchurch Street tower is known to Londoners as the "Walkie-Talkie," because if its concave shape. The glass-ensconced building has long been controversial among residents and architects alike. Built with sweeping curves, 20 Fenchurch inadvertently became the ideal platform for concentrating solar energy. As a result, the unfortunate owner of a new Jaguar found the interior of his car melted due to the concentration of sun rays from the building (Fig. 6.17).

Fig. 6.16 London's 20 Fenchurch Street tower. *Source* Nvidia

Fig. 6.17 Doing the analysis before would have revealed the risk. *Source* Nvidia

However, 20 Fenchurch wasn't the only building in the world to fall victim to its own designs. Los Angeles' Walt Disney Concert Hall has also been singled out for its solar harnessing properties and so there are such buildings in Las Vegas and other metropolises.

6.1.1.4 Film and TV

The film is similar to animations and games with regard to the use of ray tracing in the conceptualization stage. In the case of TV, ray tracing of products, especially products with shiny surfaces like ketchup bottles, clean floors, and even teeth, gives the sponsor the exact look and feel of the proposed commercial (Fig. 6.18).

Pitchvis can be used to create a pre-vis trailer to show investors and production companies that could help get one's project funded or greenlit. As the name suggests, Pitchvis is when one pre-visualizes some or all of a film, often for very complex scenes. That can include using storyboards and animatics (as well as asset building) to get a 3D visualization of the world of the story, therefore letting one try out every angle before filming.

Fig. 6.18 HBO logo ray-traced and animated as molten metal. *Source* © HBO

6.1.1.5 Medical and Scientific

Medical and scientific instruments have to be functional and at the same time pleasing and attractive to look at. Whether it is a dentist's chair, a full-body MRI scanner, a blood analyzer, or an electronic testing device, every supplier has competition and a differentiated and stylish look helps sell the product, makes the user and patient feel good about it, and helps the supplier get the maximum price. So, ray tracing contributes to the bottom line in several respects.

6.1.1.6 Vehicles

Automobiles, trucks, boats, airplanes, space ships, rovers, and satellites are all conceptualized using ray tracing. After the design has been accepted, it is then moved to final detailed engineering. During the presentation period, it is possible with many programs to make changes in the rendered image and have them be reflected back to the preliminary model. In the past, automobiles were conceptualized with a clay model and then measurements were made from it to create the manufacturing drawings. It was a very time-consuming and unreliable technique, but one that was critical to convey the slopes, angles, and surfaces. Ray tracing has all but eliminated the clay model practice (although it is still used in some cases). The same is true in the aerospace sector, and physical miniature scale models are still built for conceptualization. One person in the industry commented that people in these industries just like to build models, and others like to look at them; that is something ray tracing or any other computer simulation can never replace.

Autonomous vehicles however may pose a threat to the utilization of ray tracing for automotive design.

In the future, when self-driving cars represent the majority of vehicles on the road, car ownership and even driving licenses will be a thing of the past. If driverless vehicles become on-call transportation pods, taxis, or minibuses, the incentive to design beautifully looking vehicles will end. Consumers will no longer be subjected to advertisements for slick-looking cars, and the need for ray tracing and car designers will diminish (Fig. 6.19).

However, it will take decades for autodrive vehicles to replace the existing fleet of cars in service, unless there are insurance pressures or government mandates to accelerate the transition.

Fig. 6.19 Is this the future for automobiles?

And, while we may be seeing “peak cars” in our lifetime still, there are others who do not subscribe to the dystopian view that all pods the world over will look the same—on the contrary: services will likely distinguish themselves by offering rides in very different vehicles.

6.1.1.7 Products in General

Consumer products like an electric toothbrush, shaver, milk or whiskey bottles, lamps, and all sorts of other products used to be constructed with balsa wood, bits of plastic, and even tinfoil to try and convey the proposed design concepts. They were fragile and like the clay models of automobiles. They were time consuming to construct and not very easy to translate into a manufactured product. Watches were often built, a single copy, to show management and the sales department what could be developed. Today, it is all done with computer simulation. Also, most of the extraordinarily talented craftsman who handmade those models have died or retired and a new class of such people has not been trained to do it. So, ray tracing and computer simulation were essential in saving the watch design industry. Several other industries have a similar debt to ray tracing.

6.1.2 Design and Engineering—STAGE TWO

Once the concept has been accepted, it can move to the final, accurate, and detailed (including all subsystems) design. When a product, whether it’s a robotic vacuum cleaner, a wing-tip fuel tank, or a 20 second TV commercial, manufacturing constraints, standards, and associated parts (including actors) will impact the design and shift it from the original concept into what’s practical and possible. Now, the engineers and designers have to render it accurately and show it once again to the customer to get approval for the changes. If standards bodies are involved, the approval may involve certifications. To satisfy all those requirements, the ray tracer must be physically accurate and photorealistic.

Pre-visualization (also known as previs, pre-vis, pre-rendering, preview, or wireframe windows) is the visualizing of complex scenes in a movie before filming. It is also a concept in still photography. Pre-visualization is used to describe techniques such as storyboarding or the planning and conceptualization of movie scenes.

6.1.2.1 Photorealistic

Photorealism would seem like a basic characteristic in ray tracing, and it is the whole reason for ray tracing. However, many ray-tracing programs use the Monte Carlo stochastic technique and can, depending upon how many rays are cast and how long the ray tracer is allowed to run, give a slightly distorted representation known as biasing. Also, critically important is the material library used for the model. If the product is to be a certain type of leather, then the material model used has to be exactly that type of leather with exactly the correct tanning, dying, and surface texture. Anything less is not photorealistically accurate.

Physically Accurate

Automobile headlamps today employ complex illumination optics and are using projector-type headlamps which produce flexible and accurate illumination distribution. Such projector-type lenses for headlamp have tiny features on the exit surfaces to diverge a part of ray. Moreover, the headlamp light distribution is regulated by law in each country.

Physically accurate should not be confused with physically based rendering. Physically based refers to the fact that the algorithm in question is derived from physically based principles. It is not physically correct, and some approximations usually have to be made. In rendering, we always have to balance realism with computational cost, and physically based rendering is used when such compromises have to be made.

As mentioned above, a ray tracer can be biased. Nearly, every renderer is biased to some extent. Unbiased basically means that no shortcuts are taken when calculating a render. Every ray is treated equally, and there is no bias in terms of any importance whatsoever. If one's ray tracer is fast, it is more than likely biased. The degree to which it is biased depends on the developers of the ray tracer as well as the settings of the user.

6.1.2.2 Jewelry Design

Jewelers used to make elaborate multi-view drawings or revert to the actual construction of jewelry prior to selling it. Now, they use ray tracing to design the ring, necklace, brooch, or bracelet and make adjustments to suit the client before melting one drop of gold or silver. This gives the client exactly what he or she wants and eliminates very expensive waste (Fig. 6.20).

Ironically, Piñeiro Solsona worked so hard on the jewel and the diamonds and doesn't seem to have been interested in the band, which sadly detracts from the whole image.

6.1.2.3 Fashion Design

Using ray tracing in fashion design seems like an obvious application. But the dynamics of cloth and the many types of it is extremely challenging.

Design, development, and production in the fashion industry have largely relied on the same, often manual, methods despite all the technological advances happening in the world outside of fashion and apparel.

Fig. 6.20 Cut glass and jewelry design requires ray tracing to catch all the reflections of the piece and show it off best (Rendered in FluidRay RT, design by Manuel Angel Piñeiro Solsona)

Digital technologies in fashion are becoming more accessible, and now, any creative with a basic knowledge of fashion design and computing can create convincing still or animated 3D visualizations of styles, designs, and products. With this technology, the designer can present a lifelike design that shows how the fabrics will look and how the garment fits on the body. However, fashion designers must now learn about 3D software and the principles of working in three dimensions. They must learn about creating the mannequin avatar, garments, accessories, and textures and how to present and publish the finished article.[6]

Various programs are available now including Clo3D and Marvellous Designer for fashion-orientated design, and Maya, Mudbox, Rhino, and Photoshop for more general digital design, visual effects, and rendering.

Virtual Simulation in the Fashion Industry

Ten years ago, academic research investigated clothing companies' complaints on the lack of effective garment-oriented CAD packages to design directly in 3D and provide the model list with tools for shape modeling and cloth behavior simulation.[7] Although commonplace in other sectors, 3D virtual prototyping in the apparel industry had been slow and complex.

Digital prototyping in the textile and clothing industry enables the process of product development where various operators are involved in the different stages.

[6]Makryniotis (2015).

[7]Papachristou and Bilalis (2017).

Taking into account the recent trends in the industry and using new and various skills, and formalizing in a deterministic way the result of their activities, the product development cycle, and the use of new digital technologies can overcome the “typical cycle”.[8]

Design, development, and production have largely relied on the same, often manual, methods despite all the technological advances happening in the world outside of fashion. Today with the demand from better-educated consumers, mass customization, e-commerce, and advances in virtual reality applications, the virtual garment development is seeking to optimize the apparel industry’s design and development processes.[9] Although this is now commonplace in the aeronautical, automotive, furniture, and shoe sectors, development in the apparel industry has been slow and complex; mainly due to the dropping and stretching properties inherent in fabric, which are not only radically different between different fabric types and constructions, but also in the direction of weave or knit within the piece.

The 3D concept is an important development in the design process. It allows designers to create real-life visualization of designs that could previously only be imagined through 2D sketches. According to Dassault Systèmes though, many processes still do not live up to their full potential. Creative 3D materials have always been painful, whereas vendor software companies claim that with 3D virtualization is a fantastic way of starting the process of apparel product development.

The clothing industry has been transformed from a traditional labor-intensive industry into a highly automated and computer-aided one. However, the primary drawback for most of the existing commercial CAD systems in the past was that they relied on mere geometrical modeling and did not provide virtual simulation tools (with few exceptions). 3D technology started to get in that market but needed technological advancements to get there.[10]

Marvelous Designer offers the user the ability to create 3D virtual clothing with its design software. From basic shirts to intricately pleated dresses and rugged uniforms, one can, according to the company, virtually replicate fabric textures and physical properties to the last button, fold, and accessory (Fig. 6.21).

The program offers compatibility with other 3D software and interactive design interface so that one can instantaneously edit and drape garments onto 3D forms with high-fidelity simulation.

The company says their pattern-based approach has been adopted by game studios such as EA Konami and can be seen on the big screen in animation films including The Hobbit and The Adventures of Tintin, created by Weta Digital.

Clo3d offers 3D garment visualization technologies that the company claims to cultivate a more creative and sustainable landscape for the fashion and apparel

[8]Papachristou and Bilalis (2016).

[9]Fontana et al. (2005).

[10]Fontana et al. (2005).

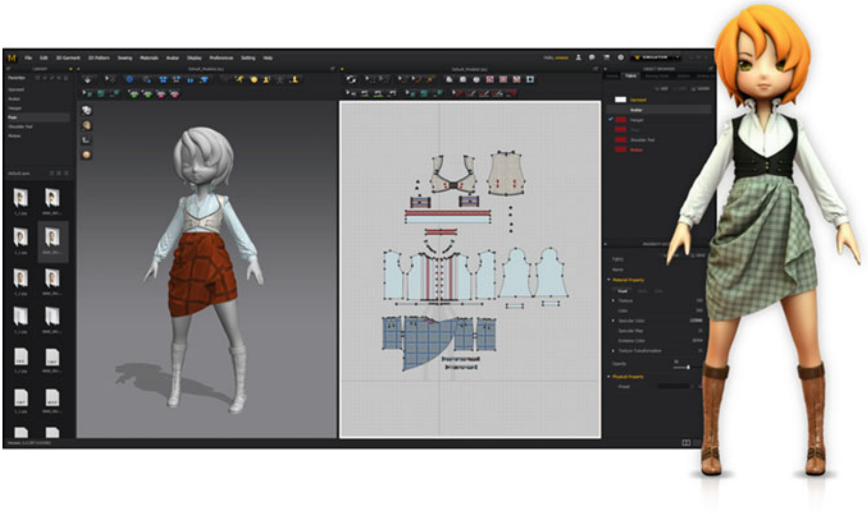

Fig. 6.21 Marvelous Designer's user interface and design tools. *Source* Marvelous Designer

industries. Boasting of over 15 years of extensive research and development, and multiple successful enterprise-wide adoptions, the company has a policy of maintaining a 1:1 ratio between expert engineers and fashion-industry veterans, which it says brings together the best of both worlds to build a user experience that focuses on the most essential element of one's process (Fig. 6.22).

The company uses Chaos Group's V-Ray ray-tracing engine for its final output.

6.1.2.4 Mechanical Engineering

3D simulation of ray-tracing model is developed for studying the radiation heat transfer, associated with laser-based additive manufacturing, in both thick and thin particulate beds by using the Monte Carlo method.

Another clever use of ray tracing was accomplished by Lunenburg Industrial Foundry & Engineering (LIFE), a company situated in the town of Lunenburg, Nova Scotia, that came up with a new geometry for solar concentrators to use solar energy to melt metal in their Foundry, reducing at the same time their use of fossil fuel.

Parabolic dish solar concentrator combined, and parabolic trough reflectors can achieve temperatures in the 350–400 °C range, while a solar tower can achieve temperature as high as 1000 °C but requires a large array of computer-controlled mirrors making it expensive. LIFE used ray tracing to design the parabolic mirrors and accomplish the concentration of solar radiation needed to melt metals (http://tcsme.org/Papers/Vol34/Vol34No2Paper6.pdf).

Fig. 6.22 Fashion design with Clo3d. *Source* Clo3d

6.1.2.5 Molecular Modeling

Developed primarily for modeling and animation, ray tracing offers a high level of flexibility with reference to photorealistic and surrealistic image rendering. Through the use of existing software, the application of ray-tracing attributes to molecular graphics is possible on a desktop computer. This application is especially pertinent in view of rapid speed enhancements in PCs, which have enabled molecular modeling and dynamics on such systems. In this regard, ray tracing provides enhanced capabilities for molecular graphics rendering that are potentially equivalent to those achieved by workstations.

These effects require almost no additional effort to implement and are guaranteed to be precise, unlike similar techniques in rasterization. The impact of the light effects on depth perception is one can see that without the light attenuation and shadows, any sense of depth is completely lost. The presence of shadows helps to clarify the relationship of the coils and molecule's surfaces, as well as the position of an ion or molecule attached to a metal atom by bonding (i.e., ligands) in binding pockets in proteins.

6.1.2.6 Packaging Design

To achieve photographic renders, packaging professionals and brand owners have relied on ray tracing, the current drawback being speed. This is especially noticeable when the scene contains materials such as glass and liquids.

Creative Edge Software was the first company to deliver full ray-tracing capabilities to all levels of packaging creatives with the launch of iC3D v4.0 in May 2016. By integrating ray-tracing technology into the iC3D all-in-one package, creatives and brand owners were able to achieve photorealistic design mock-ups at any stage without the need for specialist programs or third-party services (Fig. 6.23).

With the development of the iC3D Real-Time Ray Tracer, Creative Edge Software claims that they have succeeded in combining the speed benefits of OpenGL technology, but using ray tracing to enable simultaneous photographic

Fig. 6.23 Ray tracing used in packing design and marketing. *Source* iC3D

rendering of changes as they are made. This capability has the potential to replace previous methods for achieving high-speed ray-traced renders, such as via a render farm whereby the processing is shared between a group of top-specification computers.

6.1.2.7 Geophysical

Seismic tomography is a major research topic on geophysics and concerns the reconstruction of the Earth's interior. Accurate Source: Localization is a critical component of seismic monitoring. A seismic model accepts a description of the subsurface of the Earth as input and produces a synthetic seismic record as output. In raypath modeling, ray tracing is carried out for models of multilayered folded structures so as to generate ray diagrams and synthetic time sections. The purpose of seismic modeling is to provide the seismic interpreter with a tool to aid in the interpretation of difficult geological structures. Over the past few decades, the growing need for fast and accurate prediction of high-frequency wave properties (most commonly travel time) in complex subterranean structures has spawned a number of grid- and ray-based solvers. Traditionally, the method of choice has been ray tracing, in which the trajectory of paths corresponding to wave front normals is computed between two points. This approach is often highly accurate and efficient and naturally lends itself to the prediction of various seismic wave properties.

6.1.2.8 Optical Design

Optical designers use ray tracing to visualize rays in a CAD design to check optical properties, paths, and geometry. This improves optical performance and saves time by eliminating manual tests of design iterations. Ray tracers, especially those designed specifically for optical systems, provide analysis of multiple aspects of imaging systems, including stray light and polarization effects. Bulk properties including absorption, scattering, and fluorescence enable the design and analysis of devices for a wide variety of applications. They can be used to simulate and optimize light pipes, light guides, and non-imaging lenses and mirrors. Designers can simulate surface effects including absorption, specular reflection and transmission, and scattering.

6.1.2.9 Audio

Ray tracing has also been employed to visualize the acoustics of a space. Ray tracing is a way of following the sonic energy that is emitted through space. Rays are traced to generate an impulse response which represents the decay of sonic energy in time at the place of the listener. The impulse responses are generated for multiple frequency bands because material and air absorption parameters are different in respect to different wavelengths. Sound propagation, direct and indirect paths. Audio ray tracing takes into account occlusion for direct and indirect paths, directionality/head-related transfer function (HRTF), attenuation, approximate direct path diffraction, and material reflection, absorption, and transmission.

6.1.3 Manufacturing and Production—STAGE THREE

Virtual prototyping is not a new concept and dates back to the early 1990s.[11]

Virtual prototyping is a method in the process of product development. It involves using CAD, computer-automated design (CAutoD), and computer-aided engineering (CAE) software to validate a design before committing to making a physical prototype. This is done by creating 3D computer-generated geometrical shapes (parts) and either combining them into an assembly or testing different mechanical motions, fit and function. The assembly or individual parts could be opened in CAE software to simulate the behavior of the product in the real world.

In the movie industry, virtual prototyping is sometimes considered pre-visualization, but that is an incorrect designation. Pre-vis is the trial and design stage (see Sect. 6.1.2). Pre-vis often gets confused with virtual production.

The holy grail for filmmakers is to be able to work in real time, iterate in photorealistic environments, and do anything you want at the moment. As the technology of virtual production evolves and becomes more intuitive, the biggest benefactor may be the indie director.

One can't really discuss virtual production without discussing the stages that lead up to, or follow, it. Filmmakers don't often start production without a long period of pre-production, and so virtual production is often preceded by pre-vis, a world-building, planning aspect that is so closely linked to production that it is often inseparable.

The product design and development process used to rely primarily on engineers' experience and judgment in producing an initial concept design. A physical prototype was then constructed and tested in order to evaluate its performance. Without any way to evaluate its performance in advance, the initial prototype was highly unlikely to meet expectations. Engineers usually had to redesign the initial concept multiple times to address weaknesses that were revealed in physical testing. The world of virtual production is changing rapidly and getting faster.

Virtual Rapid Prototyping (VRP) is being opened up to all kinds of industries, and in filmmaking, it is getting the industry closer to that real-time iteration. VRP is a unique adaptation of the pre-vis process, accelerated with virtual production techniques. Utilizing only a small crew and an actor in motion capture suit, a

[11] "Virtual Prototyping: Concept to Production," Report of the DSMC 1992–93 Military Research Fellows, Defense Systems Management College, March 1994, https://apps.dtic.mil/dtic/tr/fulltext/u2/a279287.pdf.

director can stage, shoot, and edit sequences in real time, sketching the sequence quickly.

An entire film can be quickly and inexpensively pre-vised using VRP to test for marketability, providing a feature-length Pitchvis. An incredibly scalable solution, VRP can be executed with a compact team or full-scale production.

6.1.3.1 Fixture Design and Placement

Fixture design for interior spaces such as homes, lobbies, and conference rooms requires multiple forms of lighting to meet different needs. Linear fluorescent lamp fixtures commonly produce the general ambient light, and reflectorized halogen lamp fixtures produce the directional lighting, while light fixtures with LEDs to provide different beam distributions. Current lighting practice uses multiple light source technologies and fixtures to achieve the required illumination for various tasks. However, many light fixtures can create an unappealing architectural design, especially in a small space, and multiple light source technologies can cause maintenance difficulties.

Some companies such as Synopsys and DIAL specialized in the application of lighting design.

LightTools is a 3D optical engineering and design software program from Synopsys that supports virtual prototyping, simulation, optimization, and photo-realistic renderings of illumination applications (Fig. 6.24).

DIAL develops DIALux—the world's leading software for planning, calculation, and visualization of indoor and outdoor lighting (Fig. 6.25).

The company claims that their software makes professional lighting design easier and accessible to everyone as a platform and tool that connects planners and manufacturers.

6.1.3.2 Ray Tracing in Games' Manufacturing

Several game developers have used ray tracing in the generation of images in the game, then recorded those scenes or objects in the scene, and used them as texture maps. That is known as baking from baking in the image.

Japanese game designer Polyphony Digital, founded in 1998, is a subsidiary of Sony and the developer of the very popular racing game *Gran Turismo* for the PlayStation console. Polyphony Digital has developed their own ray-tracing software for in-house image generation and used it to create baked-in image that is applied in real time when the game is playing (Fig. 6.26).[12]

[12]http://cdn2.gran-turismo.com/data/www/pdi_publications/cedec2018_raytracing.pdf.

Fig. 6.24 LightTools' illumination and lighting design. *Source* LightTools

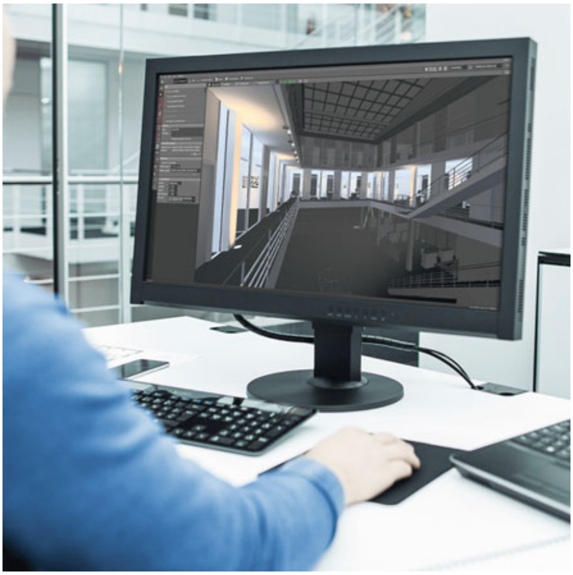

Fig. 6.25 DIAL's lighting design software user's interface. *Source* DIAL

The company and game are famous for beautiful exotic cars that the player can race on a track like Nuremberg or through the streets of Tokyo and other cities or places like the Circuit de Barcelona-Catalunya shown above.

Fig. 6.26 Gran Turismo the Circuit de Barcelona-Catalunya. *Source* Sony's Polyphony Digital

Polyphony used Nvidia Quadro RTX AIBs to render the scenes and objects they will place in the final game.

As mentioned in the hardware summary (Sect. 7.4.6), it doesn't take specialized hardware to do ray tracing. Polyphony did do ray tracing on the PS4, it is just a matter of how quickly it could render a scene, and it is doubtful it could be considered real time. However, a driving sim could do hybrid ray tracing in real time more easily than a first-person shooter because the scenery doesn't need to be ray-traced, just the automobiles.

6.1.4 Marketing—STAGE FOUR

As illustrated in the ray-tracing pipeline shown below, the marketing of a product using ray tracing can occur before the product is actually built. In the case of selling automobiles, for example, this is almost essential. Likewise, in the case of architectural design it is necessary to use the image of the proposed building to sell it, long before the building is built (Fig. 6.27).

In order to have customers lined up and hopefully prepaid, photorealistic images are used ahead of production. In the case of buildings, and product design, such rendering offers the opportunity of making changes before a design is committed to production and manufacturing. The line between virtual prototyping and marketing in some cases is very thin.

For most projects, marketing is done at the end, but for many projects, especially big ones (big being measured in either dollars, actual physical size, or number of units), marketing is done as soon as a design is finalized or almost finalized.

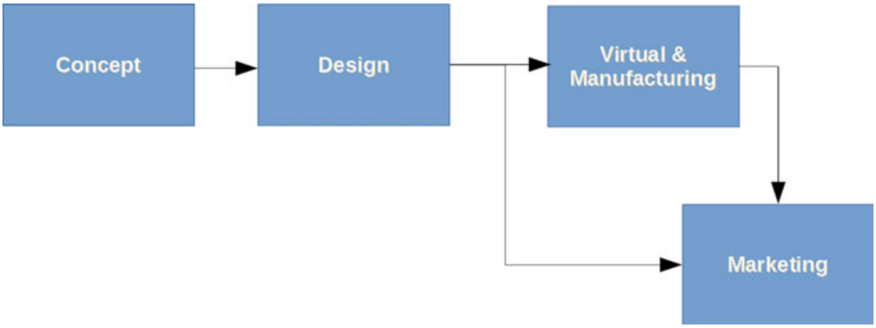

Fig. 6.27 Ray-tracing pipeline

Typically, the images used for marketing are the same as those used for manufacturing, why should they be any different. One of the advantages of a 3D model and ray tracing is the reality of the result. However, products may be put in situations or scenes that are not real, or difficult to obtain as some of the illustrations in the following paragraphs will reveal.

6.1.4.1 Advertising

In the case of product advertising, ray tracing is an advertiser's dream come true. It eliminates time-consuming product shoots which may be thwarted by weather, difficult lighting, actors, and product availability. It allows the advertiser to experiment and get just the image desired and at a fraction of the cost and time (Fig. 6.28).

Almost 95% of all vehicle advertisements for print and TV are done using ray-traced images of the vehicle which includes boats, buses, cars, forklifts, tanks, and trucks to name a few. All architectural advertisements are done using ray tracing which can be set at any time of day, with or without adjoining properties and geographic features (Fig. 6.29).

New consumer products from white goods to electric toothbrushes and frying pans are rendered for advertising using ray tracing. In several cases, the advertisers never get to see the actual product (Fig. 6.30).

Clever product placement programs such as MirriAd and Ryft can put ray-traced images in videos, movies, and games after the fact or in real time.

MirriAd is able to digitally place brand imagery into any video on demand and at scale using computer-vision-based technology for mobile and TV advertising. The software can replace a can of Coke with a can of Pepsi for instance or put a can of Coke in a scene that didn't have one (Fig. 6.31).

Ryff offers dynamic product placement in video streaming. Want to put a can of Diet Coke in the hand of the president while he is giving a press conference? Ryff can do that using AI-driven techniques; the company calls itself an "intelligent

Fig. 6.28 Ray-traced car with neutral background; any scene could be applied. *Source* Chevrolet

Fig. 6.29 Modern office buildings. *Source* Mike Mareen

image platform" company, which means the company does product placement in live or prerecorded video broadcast content. What makes it unique is that content can be placed dynamically, even changed. As a result, content can be tailored to the audience.

Advertising agencies and the studios who work for them have become one of the major customers of ray-tracing software and represent one of the growth segments for the technology.

Fig. 6.30 Consumer product with neutral background. *Source* V-Ray

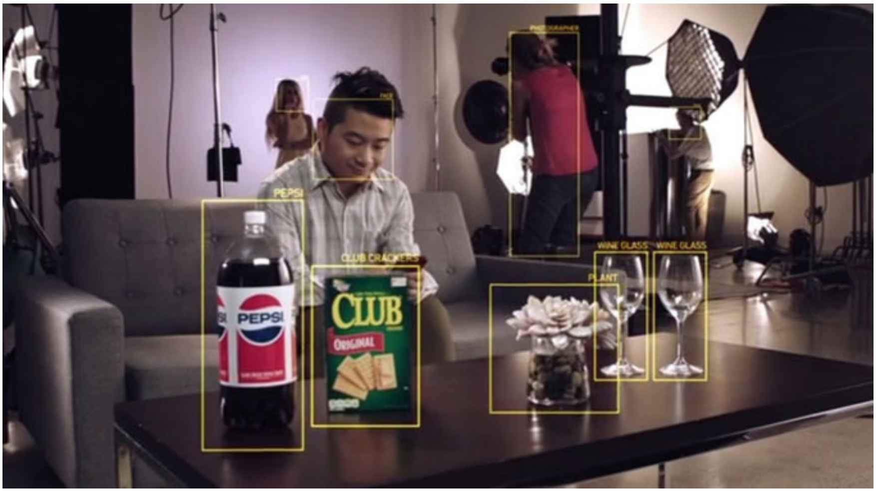

Fig. 6.31 Ryff lets advertisers place any virtual object into commercials and films. *Source* Ryff

6.1.4.2 Packaging

Akin to and sometimes a subset of advertising is the packaging used for a product. The box that a bottle of water or whiskey comes in is as important as the product itself in attracting a consumer's interest. Products that may not actually be shown, such as flower or salt, will be sold often based on its package (Fig. 6.32).

Curved and odd-shaped packages which reflect light in interesting ways much as an automobile's fender does are primary candidates for ray tracing in packing presentation.

6.1.4.3 Projection Mapping

Businesses and theatrical production companies have been using multi-projector systems to light buildings, storefronts, and stages creating amazing and sometimes startling images that delight audiences and passersby. The images have usually been prerendered videos. With the advent of HDR and lasers in projectors, a new quality capability presented itself for image projection and at 4K resolutions with up to 32K across multiple projectors.

One of the leading companies in that segment is Notch which has done major events at rock concerts, company presentation, museums, and events and offers ray-tracing capabilities in its visual creation tool for interactive motion graphics (Fig. 6.33).

Fig. 6.32 Packaging complex, nonlinear reflective surface containers. *Source* Creative Edge Software

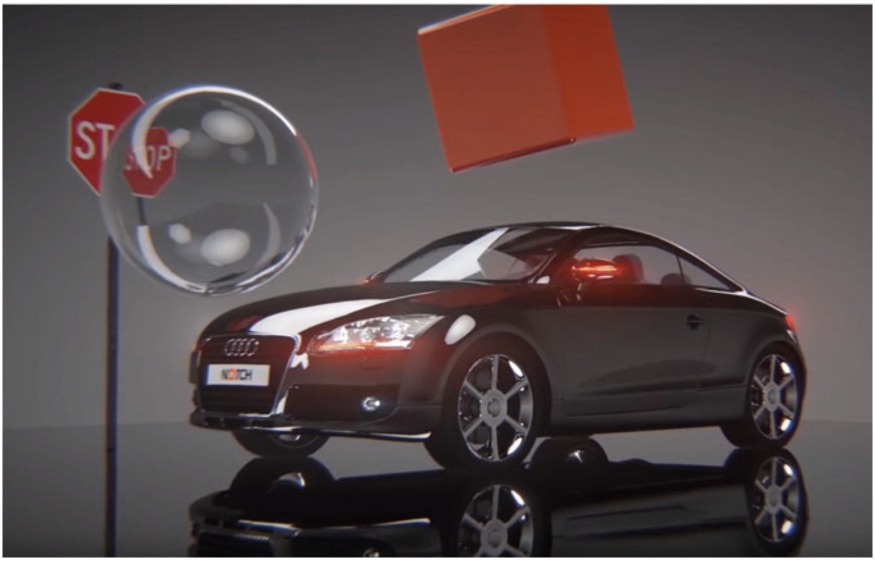

Fig. 6.33 Notch makes clever uses of denoising filters to produce high-quality ray-traced videos in real time. *Source* Notch

Notch's content creation tool, Builder, allows creation from scratch as well as the ability to import elements from other industry tools. The company claims that a user can always see their final results in real time.

6.2 Summary

As the demand for photorealism continues to accelerate in all four stages, with no real end in sight, the demand for high-quality ray tracing will continue to grow with it. Anywhere that rendering is in use, ray tracing will be found. The users at all sizes of companies and in all stages will have multiple choices for how they obtain and employ ray tracing. And in many industries, the users in the pipeline, the four stages, will employ different ray-tracing programs from various suppliers. The goal and challenge for the supplier is to make the integrations with specific tools smooth and provide support for specific workflows—the suppliers must work to remove barriers to integration.

Speed Until recently, the primary barrier to wider ray-tracing adoption has been the hardware limitations of CPU and GPU architectures. With the advent of multi-core CPUs from Intel and AMD, as well as Nvidia's latest Turing architecture, those barriers are being eliminated, meaning that ray tracing will see even greater adoption as the rendering times are reduced.

Materials The ray-tracing suppliers are continuing to expand their material's libraries, as well as opening them up for sharing with other programs and making their own programs capable of accepting other libraries. Third-party material library suppliers are also expanding. Materials are the black hole of ray tracing, and there will never be enough. That suggests a meta-language, and taxonomy is needed to classify and make materials easier to select. That will require a consortium to balance open libraries from proprietary ambitions. Nonetheless, many suppliers will always maintain their own material libraries as will various users who want a differentiated look or have special paint, surface treatment, or characterization such as in animations.

Presentation The results of a ray-tracing rendering will be restricted in its portrayal of realism, or fantasy, by the presentation device. Local screens on workstations and mobile devices have reached densities of one billion colors, and 68 billion colors are available on some devices. Projectors follow that development, and printers do also. However, the presentation device will always be the limiting factor in how an image looks.

Future Looking forward, I expect suppliers to begin to incorporate more extensive techniques such as radiosity, light field, voxels, and other global illumination techniques in the quest for the ultimate realism in rendering.

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