Appendix A

In this section, you will find miscellaneous and related information and reference material supporting various sections of the book.

The next page contains a sample of the view of all the ray tracing programs. The accompanying spreadsheet is an in-depth database of those programs.

A.1. Ray-Tracing Programs and Plug-Ins

See Table A.1.

A.2. Early Photorealism—Who Invented Ray Tracing

Long before computers, and even before cameras, artists sought to create a photorealistic image. One artist, Albrecht Dürer rendered with almost photographic accuracy, *A Young Hare.* In addition to being a fine artist, Dürer wrote two books that discussed geometry. In chapters of his books, he provides instructions for the construction of perspective projections (also with lights and shadows). The methods, as they were described in his *Underweysung der messung*, book can be, according to Georg Rainer Hofmann, clearly identified as "object scanning" and "ray tracing." Hofmann therefore concludes that the great Renaissance artist, mathematician, and painter, Albrecht Dürer, who was responsible for two important books published in Nuremberg, Germany, is the father of ray tracing.[1]

[1]Hofmann (1990).

J. Peddie, *Ray Tracing: A Tool for All*,
https://doi.org/10.1007/978-3-030-17490-3

Table A.1 Ray tracing plug-in programs

Product	Int.	Stand-alone	Plug-in	Biased	License	Win	OS X	Linux	Other	GPU	Org.
Blender Cycles	Yes	Yes	Yes	No	Apache 2.0	Yes	Yes	Yes	No	Yes	Blender Foundation
Bryce	Yes				Proprietary	Yes	Yes	No	No		DAZ 3D (Daz Productions)
Dimension CC	Yes				Proprietary	Yes	Yes			Yes	Adobe
FinalRender	Yes		Yes	No	Subscription	Yes				YES	Cebas
Form-Z 8.5	Yes				Proprietary						AutoDesSys
NxtRender	Yes		Yes	Yes/No	EULA	Yes					RenderPlus
Octane Render	Yes				Proprietary	Yes	Yes	Yes	No	Yes	OTOY / Refractive Software
Raytracer	Yes			No		Yes				No	Autodesk
Redshift	Yes		Yes	Yes	Floating	Yes	Yes	Yes		Y	Redshift Rendering Technologies
3Delight		Yes	Yes		Proprietary	Yes	Yes	Yes	No		DNA Research subsidiary of Taarna Studios.
Appleseed		Yes	yes		MIT License						Appleseed
Arion		Yes	Yes	No	Proprietory	Yes	No	No		Yes	Random Control
Corona Render		Yes	Yes	No	Floating	Yes	Yes			No	Render Legion s.a..., - Chaos Software (parent)
Flamingo nXt		Yes	Yes	Yes	EULA	Yes					McNeel & Associates (Tlm, Inc.)
FluidRay RT		Yes	Yes	No	Proprietary	Yes	Yes				Fluidray (Fluid Interactive)
FryRender		Yes	Yes							No	RandomControl
Houdini - Mantra		Yes	Yes	Yes	Proprietary	Yes	Yes	Yes	No	Yes	Side Effects Software
Indigo Renderer		Yes	Yes	No	Proprietary	Yes	Yes	Yes		Yes	Glare Technologies
Iray		Yes	Yes	No	Floating	Yes		Yes		Yes	Nvidia
KeyShot	Yes	Yes	Yes		Floating	Yes	Yes			YES	Luxion
Maxwell Render		Yes	Yes		Proprietary	Yes	Yes	Yes	No	Yes	Next Limit Technologies
Moskito Render		Yes	Yes	No	subscription	Yes				Yes	Cebas
OneRender		Yes	Yes								Prefixa
Poser FireFly		Yes	Yes	Yes	Trialware	Yes	Yes				SmithMicro
POV-Ray		Yes	Yes	Exporter	AGPLv3	Yes		Yes			Persistence of Vision Raytracer Pty. Ltd
Renditoner Pro		Yes	Yes			Yes		Yes			IMSI Design (Turbo CAD)
Visualize		Yes	Yes	Yes	Term & Network	Yes	No	No		Yes	SolidWorks/Dassault-Systems
V-Ray		Yes	Yes		Proprietary	Yes	Yes	Yes	No	Yes	Chaos Group
Air 14		Yes			Proprietary						Sitex Graphics
Arnold		**Yes**									Autodesk (Solid Angle)
Art of Illusion		Yes			GPL	Yes	Yes	Yes	No		Peter Eastman
Artlantis 6		Yes			Proprietary						Abvent
BiGrender 3.0		Yes			Proprietary						Tomas Cayuela / hydragrafix
Cheetah3D		Yes		No	Proprietary	No	Yes	No	No		Dr. Martin Wengenmayer
Clarisse FX		Yes			Proprietary						Isotropix
Click-VR Visualizer		Yes									Code Blend
Fujiyama		Yes			MIT License						Hiroshi Tsubokawa
Guerilla Render		Yes			Proprietary						Mercenaries-engineering
Infinity 3D		Yes			free						Infinity3D
LightWave 3D		Yes			Proprietary	Yes	Yes	No	Amiga		NewTek, Inc
LumionRT		Yes			Proprietary						Act-3D
Manta		Yes			MIT	No	Yes	Yes	No		Univserity Utah
Mitsuba		Yes				Yes	Yes	Yes	No	No	Wenzel Jakob
MODO		Yes			Proprietary	Yes	Yes	No	No		The Foundry / Luxology
Nebula Renderer		Yes		No	Freeware	Yes			No	Yes	Nebula Render
NOX		Yes		No	Proprietary						Evermotion
NuGraf		Yes			Proprietary						Okino
OSPray		Yes			Appache	Yes				No	Intel
Picogen		Yes			GPLv3	Yes	No	Yes	No		Sebastian Mach
Pixie		Yes			GPL	Yes	Yes	Yes	No		Okan Arikan
Radeon ProRender		Yes		No	MIT License	Yes				Yes	AMD
Radiance		Yes			BSD	Yes	Yes	Yes	No		Greg Ward
RenderDotC		Yes			Proprietary						Dot C Software
RenderMan		Yes			Proprietary	Yes	Yes	Yes	No		Pixar
Tachyon		Yes			GPL	No	Yes	Yes	No		University of Illinois at Urbana–Champaign
Visionaray		Yes			MIT	Yes	Yes	Yes	No	Yes	Universitat zu Koln
Bloom			Yes		Proprietary						Bloom Unit
Brighter 3D			Yes	No							Brighter 3D
Caravaggio			Yes								Caravaggio DevGroup
CentiLeo			Yes								CentiLeo
Enscape			Yes		Proprietary	Yes	No	No		Yes	Enscape3D
Kerkythea			Yes		Proprietary	Yes	Yes	Yes	No		Solid Iris Technologies (Parent Altair Engineering)
Kray			Yes								MindBerries
LocalRay			Yes		Proprietary				Android		Adshir Ltd.
LuxRender			Yes		Apache v2.0	Yes	Yes	Yes	No		LuxRender
Raylectron			Yes		Proprietary						Softbyte Labs
Shaderlight			Yes		Proprietary	Yes					Artvps
SU Podium 2.5			Yes		Proprietary						Cadalog Inc.
Thea			Yes	Yes						Yes	Altair Company (Parent) / Solid Iris Technologies
Twilight 2			Yes		Proprietary						Twilight Redner
Visualizer			Yes								Imagination technologies
Vue			Yes		Proprietary	Yes	Yes	No	No		E-On Software, Inc. (Bentley Systems)
YafaRay			Yes		LGPL	Yes	Yes	Yes	No		YafaRay developers

A.2.1. Young Hare

A Young Hare (German: Feldhase) is a 1502 watercolor and body color painting by Albrecht Dürer. Painted in 1502 in his workshop, it is acknowledged as a masterpiece of observational art alongside his Great Piece of Turf from the following year. The subject is rendered with almost photographic accuracy, and although the piece is normally given the title, "Young Hare," the portrait is sufficiently detailed for the hare to be identified as a mature specimen—the German title translates as "Field Hare" and the work is often referred to in English as the Hare or Wild Hare (Fig. A.1).

The subject was particularly challenging: The hare's fur lay in different directions and the animal was mottled with lighter and darker patches all over, Dürer had

Fig. A.1 A young Hare but Albrecht Dürer, 1502. *Source* Wikipedia

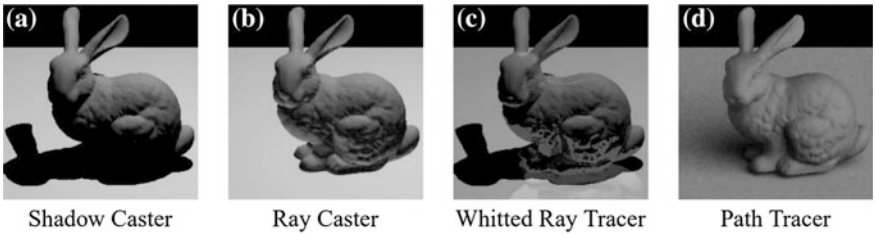


Fig. A.2 Rendering examples using a hare: **a** shadow casting, **b** ray casting, **c** Whitted ray tracing, and **d** Path Tracing. *Source* Ray Tracing on Programmable Graphics Hardware (Purcell et al. 2002)

to adapt the standard conventions of shading to indicate the outline of the subject by the fall of light across the figure. Despite the technical challenges presented in rendering the appearance of light with a multi-colored, multi-textured subject, Dürer not only managed to create a detailed, almost scientific, study of the animal but also infuses the picture with a warm golden light that hits the hare from the left, highlighting the ears and the run of hair along the body, giving a spark of life to the eye, and casting a strange shadow to the right.

This then should be the gold standard of realized photorealistic rendering, not a chrome teapot (Fig. A.2).

It is ironic, and perhaps no coincidence that a young hare has been used as a rendering model by several researchers.

A.2.2. Varieties of Realism; Geometries of Representational Art

Margaret A. Hagen's "Varieties of Realism"[2] argues that it is not possible to represent the layout of objects and surfaces in space outside the dictates of formal visual geometry, the geometry of natural perspective. The book examines most of the world's coherent representational art styles, both in terms of the geometry of their creation and in terms of their perceptual effects on the viewer. A lucid exposition of modern geometrical principles and relations, accessible to the non-mathematical reader, is followed by an analysis of all known styles as variants of natural perspective, as true varieties of realism. Delineating the physical and mechanical constraints that determine the act of visual representation in painting and drawing, the author traces the intimate relations among seemingly distant styles and considers the kind of perceptual information about the world each can carry. Margaret Hagen is a perceptual psychologist with an ecological point of view. Her rigorous but readable presentation of visual theory and research offers provocative new insights into the connections among vision, geometry, and art.

[2]http://www.amazon.com/Varieties-Realism-Geometries-Representational-Cambridge/dp/0521313295.

A.2.2.1. More About Bunnies Than You Probably Wanted to Know

The Stanford Bunny is one of the most commonly used test models in computer graphics. It is a collection of 69,451 triangles, and it was assembled from range images of a clay bunny that is roughly 7.5 in. high. Figure A.2 is a synthetic rendering of the model, courtesy of Peter Lindstrom. This Web page describes where the model came from, tells why it was created in the first place, discusses the relative merits of using it as a test model in graphics research, and shows some example images (https://www.cc.gatech.edu/∼turk/bunny/bunny.html).

Durer was discovering linear perspective. Newton traced rays in Optiks, and Feinman mentions a job opportunity he passed up ray tracing for a lens company in, "Surely You're Joking." But to name anyone other than Turner as the Father of Ray Tracing really diminishes one of the main contributions of computer graphics to all of the sciences.

A.3. Biased Versus Unbiased Rendering

In computer graphics, unbiased rendering refers to a rendering technique that does not introduce any systematic error, or bias, into the radiance approximation. Because of this, it is often used to generate the reference image to which other rendering techniques are compared. It is important to note that an unbiased technique may not consider all possible paths. Path Tracing cannot consistently handle caustics generated from a point light source, as it is highly unlikely to randomly generate the path that directly reflects into the point.

Unbiased renderers are usually physically based and photorealistic renderer which simulates the physics of light to achieve near-perfect image realism. With an advanced Physical Camera model, a super-realistic materials system and the ability to simulate complex lighting situations through Metropolis Light Transport, Indigo Renderer is capable of producing the highest levels of realism demanded by architectural and product visualization.

A biased rendering method is not necessarily wrong, and it can still converge to the correct answer if the estimator is consistent. It does, however, introduce a certain bias error, usually in the form of a blur.

A.4. Technical Papers and Books on Ray Tracing

Looking at just the leading technical journals from ACM and IEEE, I found over 700 technical papers on ray tracing have been published since 1982 (Table A.2).

Table A.2 Technical papers on ray tracing published since 1982

Year	SIGGRAPH	SIGGRAPH Asia	Eurograph	IEEE
1982	1			1
1983	2			2
1984	6		2	5
1985	3		3	3
1986	3		3	6
1987	5		4	6
1988	4		4	5
1989	6		6	7
1990	8		6	11
1991	2		2	12
1992	3		8	4
1993	2		2	6
1994	3		5	6
1995	3		3	6
1996	1			3
1997	3		1	3
1998	4		1	4
1999	4		3	6
2000	1			3
2001	1		7	7
2002	7		5	4
2003	2		6	8
2004	8		5	7
2005	21		6	12
2006	13		6	25
2007	18		9	29
2008	12		9	31
2009	10		8	15
2010	10	2	9	17
2011	14	3	6	17
2012	7	1	8	15
2013	15	3	10	20
2014	6	4	6	16
2015	7	3	7	12
2016	8	2	10	7
2017	9	2	10	4
2018	6		1	2
Total	238	20	181	347

A.4.1. Books on ray tracing

See Table A.3.

Table A.3 Books on ray tracing

Last, first name	Title	Publisher	Date	Description
Glassner, Andrew S.	*An Introduction to Ray Tracing*	Academic Press	1989	The first book on ray tracing, from 1989, is now free to download http://www.realtimerendering.com/raytracing/An-Introduction-to-Ray-Tracing-The-Morgan-Kaufmann-Series-in-Computer-Graphics-.pdf
Shirley, Peter Mr. Morley, R. Keith Mr.	*Realistic Ray Tracing*	A K Peters, Ltd.	19-Dec-08	Concentrating on the "nuts and bolts" of writing ray tracing programs, this book emphasizes on practical and implementation issues. It also takes the reader through all the details needed to write a modern rendering system. It also adds many C++ code segments and adds new details to provide the reader with a better intuitive understanding of ray tracing algorithms
Suffern, Kevin Dr.	*Ray Tracing from the Ground Up*	CRC Press	09-Mar-2016	This book takes readers through the whole process of building a modern ray tracer from scratch in C++. All concepts and processes are explained in detail with the aid of various diagrams, ray-traced images, and sample codes
Tracy, E. R. Brizard, A. J. Richardson A. S.	*Ray Tracing and Beyond: Phase Space Methods in Plasma Wave Theory*	Cambridge University Press	27-Dec-14	This book is a complete introduction to the use of modern ray tracing techniques in plasma physics. It describes the powerful mathematical methods generally applicable to vector wave equations in non-uniform media and clearly demonstrates the application of these methods to simplify and solve important problems in plasma wave theory. It also covers variational principles, covariant formulations, caustics, tunneling, mode conversion, weak dissipation, wave emission from coherent sources, incoherent wave fields, and collective wave absorption and emission, all within an accessible framework using standard plasma physics notation
Choudhury, Balamati Dr. Jha, Rakesh Mohan Mr.	*Refined Ray Tracing inside Single- and Double-Curvatured Concave Surfaces*	Springer	24-Sep-15	This book describes the ray tracing effects inside different quadric surfaces such as right circular cylinder, general paraboloid of revolution (GPOR), GPOR frustum of different shaping parameters and the corresponding visualization of the ray path details. Finally, ray tracing inside a typical space module, which is a hybrid of a finite segment of the right circular cylinder and a frustum of GPOR, is analyzed for practical aerospace applications

(continued)

Table A.3 (continued)

Last, first name	Title	Publisher	Date	Description
Driemeyer, Thomas Mr.	*Rendering with mental ray®*	Springer	21-Dec-13	Mental ray is the leading rendering engine for generating photorealistic images, built into many 3D graphics applications. This book gives a general introduction into rendering with mental ray, as well as step-by-step recipes for creating advanced effects, and tips and tricks for professional users. A comprehensive definition of mental ray's scene description language and the standard shader libraries are included and used as the basis for all examples
Kulungowski, Alexander Ward Mr.	*Ray tracing acceleration techniques using k-d trees*	University of California	2005	Many computer graphics rendering algorithms and techniques use ray tracing for the generation of natural and photorealistic images. The efficiency of the ray tracing algorithms depends, among other techniques, upon the data structures used in the background. kd-trees are some of the most commonly used data structures for accelerating ray tracing algorithms. Data structures using cost optimization techniques based upon surface area heuristics (SAH) are generally considered to be best and of high quality. The book describes various techniques to accelerate ray tracing with the help of Kd-trees
Eric Haines and Tomas Akenine-Möller	*Ray Tracing Gems*	Nvidia	Mar-19	Real-time ray tracing—the holy grail of graphics—is now possible for video games. Thanks to advances in GPU hardware and integration in standards like DirectX, game developers will eagerly add ray tracing to take the next step in visual quality and ease of content creation

References

Hofmann GR (1990) Who invented ray tracing? A historical remark. Vis Comput 6(3):120–124. https://link.springer.com/article/10.1007/BF01911003

Purcell TJ, Buck I, Mark WR, Hanrahan P (2002) Ray tracing on programmable graphics hardware. In: Proceedings of SIGGRAPH 2002. ACM Trans Graph 21(3):703–712

Glossary

AFIPS The American Federation of Information Processing Societies (AFIPS) was an umbrella organization of professional societies established on May 10, 1961, and dissolved in 1990. Its mission was to advance knowledge in the field of information science and to represent its member societies in international forums. The IEEE-CS joined the ACM to form the Federation on Computing in the United States (FOCUS) in 1991, to take the place of AFIPS as the US' representative in International Federation of Information Processing (IFIP).

AIB (Add-in board) An add-in board, also known as a card, is a board that gets plugged into the PC. When an AIB contains a GPU and memory, it is known as a graphics AIB or graphics card. It plugs into either PCI Express or the older bus AGP.

Albedo Albedo is the base color input, commonly known as a diffuse map. An albedo map defines the color of diffused light. One of the biggest differences between an albedo map in a PBR system and a traditional diffuse map is the lack of directional light or ambient occlusion. Directional light will look incorrect in certain lighting conditions, and ambient occlusion should be added in the separate AO slot. The albedo map will sometimes define more than the diffuse color as well, for instance, when using a metalness map, the albedo map defines the diffuse color for insulators (non-metals) and reflectivity for metallic surfaces.

Alembic An interchange file format for computer graphics used by visual effects and animation. Alembic is used for the interchange of geometry (models) between different groups working on the same shots or the same assets in the same company or different studios working on the same projects. Alembic supports the common geometric representations used in the industry, including polygon meshes, subdivision surface, parametric curves, NURBS patches, and particles.

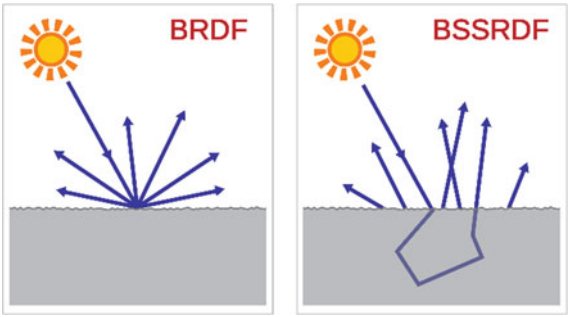
Ambient occlusion To create realistic shadowing around objects, developers use an effect called ambient occlusion (AO); sometimes called "poor man's ray

J. Peddie, *Ray Tracing: A Tool for All*,
https://doi.org/10.1007/978-3-030-17490-3

tracing." AO can account for the occlusion of light, creating non-uniform shadows that add depth to the scene. Most commonly, games use screen-space ambient occlusion (SSAO) for the rendering of AO effects. There are many variants, though all are based on early AO tech, and as such suffer from a lack of shadow definition and quality, resulting in a minimal increase in image quality (IQ) compared to the same scene without AO.

Anisotropic filtering (AF) A method of enhancing the image quality of textures on the surfaces of computer graphics that are at oblique viewing angles with respect to the camera where the projection of the texture (not the polygon or other primitive on which it is rendered) appears to be non-orthogonal (thus the origin of the word: "an" for not, "iso" for same, and "tropic" from tropism, relating to direction; anisotropic filtering does not filter the same in every direction).

Bidirectional reflectance distribution function (BRDF) A function of four real variables that defines how light is reflected at an opaque surface. It is employed in the optics of real-world light, in computer graphics algorithms, and in computer vision algorithms. The function takes an incoming light direction, and outgoing direction (taken in a coordinate system where the surface normal lies along the z-axis) and returns the ratio of reflected radiance exiting to the irradiance incident on the surface from direction the light source. A BRDF is a simplified BSSRDF, assuming that light enters and leaves at the same point.



Bidirectional scattering distribution function (BSDF) Introduced in 1980 by Bartell, Dereniak, and Wolfe, it is often used to name the general mathematical function which describes the way in which the light is scattered by a surface. However, in practice, this phenomenon is usually split into the reflected and transmitted components, which are then treated separately as BRDF (bidirectional reflectance distribution function) and BTDF (bidirectional transmittance distribution function). BSDF is a superset and the generalization of the BRDF and BTDF.

Bidirectional scattering-surface reflectance distribution function (BSSRDF) or B surface scattering RDF describes the relation between outgoing radiance and the incident flux, including the phenomena-like subsurface scattering (SSS). The BSSRDF describes how light is transported between any two rays that hit a surface.

Bidirectional texture functions (BTF) Bidirectional texture function is a six-dimensional function depending on planar texture coordinates as well as on view and illumination spherical angles. In practice, this function is obtained as a set of several thousand color images of a material sample taken during different camera and light positions.

Bilinear filtering When a small texture is used as a texture map on a large surface, a stretching will occur, and large block pixels will appear. Bilinear filtering smoothens out this blocky appearance by applying a blur.

Bokeh The aesthetic quality of the blur produced in the out-of-focus parts of an image produced by a lens. Bokeh has been defined as "the way the lens renders out-of-focus points of light." Smartphone cameras have algorithms in their processor that can create artificial bokeh on images when their lenses fail to produce the effect.

Bounding volume hierarchy (BVH) A BVH is a tree structure on a set of geometric objects. All geometric objects are wrapped in bounding volumes that form the leaf nodes of the tree. These nodes are then grouped as small sets and enclosed within larger bounding volumes.

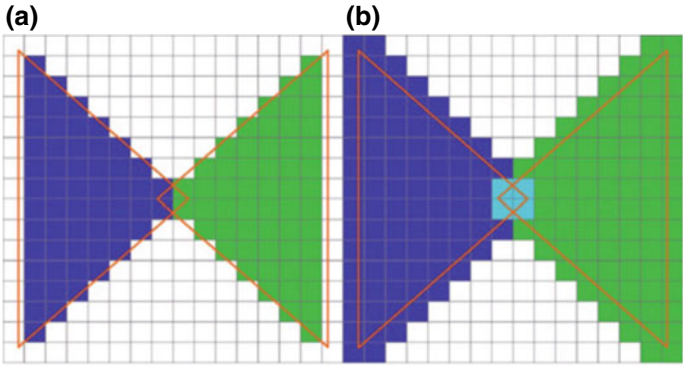
Chrominance Chrominance (chroma or C for short) is the signal used in video systems to convey the color information of the picture, separately from the accompanying luma signal (or Y for short). Chrominance is usually represented as two color difference components: $U = B' - Y'$ (blue − luma) and $V = R' - Y'$ (red − luma). Each of these different components may have scale factors and offsets applied to it, as specified by the applicable video standard.

Complementary metal–oxide–semiconductor (CMOS) sensor A CMOS sensor is an array of active pixel sensors in complementary metal–oxide–semiconductor (CMOS) or N-type metal-oxide-semiconductor (NMOS, Live MOS) technologies.

Color gamut The entire range of colors available on a particular device such as a monitor or printer. A monitor, which displays RGB signals, typically has a greater color gamut than a printer, which uses CMYK inks. Also, see Gamut and wide color gamut.

Color space See color gamut and gamut.

Conservative raster When standard rasterization does not compute, the desired result is shown, where one green and one blue triangle have been rasterized. These triangles overlap geometrically, but the standard rasterization process does not detect this fact.



Comparing Standard and conservative rasterization

With conservative rasterization, the overlap is always properly detected, no matter what resolution is used. This property can enable collision detection.

Constant dither A constant dither is the application of a dither value which doesn't change over the course of a set of dithering operations.

Contrast ratio The contrast ratio is a property of a display system, defined as the ratio of the luminance of the brightest color (white) to that of the darkest color (black) that the system is capable of producing. A high contrast ratio is a desired aspect of displays.

CNN (Convolutional neural network) A deep neural network (DNN) that has the connectivity in one or more of its layers arranged so that each node in Layer N is a convolution between a rectangular subset of the nodes in layer $N - 1$ and a convolution kernel whose weights are found by training. The arrangement is designed to mimic the human visual system and has proven to be very successful at image classification as long as very large training datasets are available.

Direct3D Also known as D3D, Direct3D is the 3D graphics API that's part of Microsoft DirectX foundation library for hardware support. Direct3D actually has two APIs, one which calls the other (called Direct3D Retained Mode or D3D RM) and hides the complexity of the lower level API (called Direct3D Immediate Mode or D3D IM). Direct3D is becoming increasingly popular as a method used by games and application developers to create 3D graphics, because it provides a reasonable level of hardware independence, while still supporting a large variety of 3D graphics functionality (see "3D").

Display Port Display Port is a VESA digital display interface standard for a digital audio/video interconnect, between a computer and its display monitor, or a computer and a home theater system. Display Port is designed to replace digital (DVI) and analog component video (VGA) connectors in the computer monitors and video cards.

EDF Emissive Distribution Functions.

Electro-optical transfer function (EOTF) HDR provides a means by which to describe and protect the content creator's intentions via metadata. It contains in essence a language used by the content creator to instruct the decoder. HDR provides metadata about how content was created to a display device in an organized fashion such that the display can maximize its own capabilities. As displays evolve, HDR will allow existing devices to always make the best effort in rendering images rather than running up against unworkable limitations. A formula called the electro-optical transfer function (EOTF) has been introduced to replace the CRT's gamma curve. Some engineers refer to EOTF more simply as perceptual quality or PQ. Whatever the name, it offers a far more granular way of presenting the luminance mapping according to the directions given by the content creator. EOTF is a part of the High-Efficiency Video Coding (HEVC) standard.

Energy conservation The concept of energy conservation states that an object cannot reflect more light than it receives.

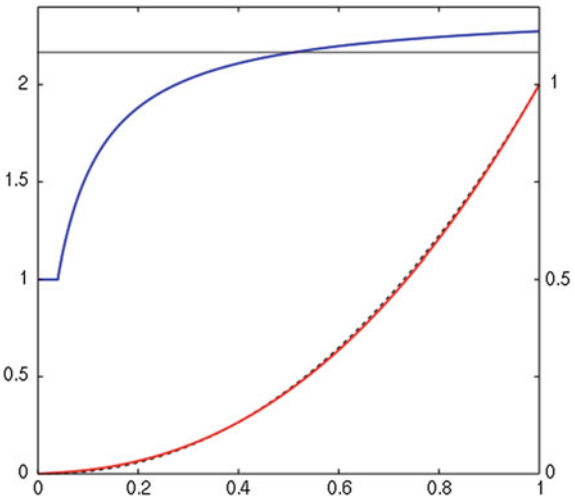
Energy conservation scales

For practical purpose, more diffuse and rough materials will reflect dimmer and wider highlights, while smoother and more reflective materials will reflect brighter and more condensed highlights.

Fragment shader Pixel shaders, also known as fragment shaders, compute color and other attributes of each fragment. The simplest kinds of pixel shaders output one screen pixel as a color value; more complex shaders with multiple inputs/outputs are also possible. Pixel shaders range from always outputting the same color, to applying a lighting value, to doing bump mapping, shadows, specular highlights, translucency, and other phenomena. They can alter the depth of the fragment for z-buffering.

Frame buffer The separate and private local memory for a GPU on a graphics AIB. The term frame buffer is a bit out of date since the GPU's local memory holds much more than just a frame or an image for the display as they did when originally developed. Today the GPU's local memory holds programs (known as shaders) and various textures, as well as partial results from various calculations, and two to three sets of images for the display as well as depth information known as a z-buffer.

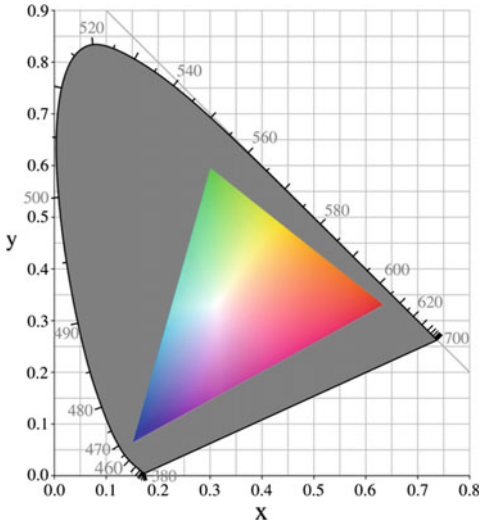
Gamma correction Gamma correction, gamma nonlinearity, gamma encoding, or often simply gamma, is the name of a nonlinear operation used to code and decode luminance or tristimulus values in video or still image systems. Gamma correction is, in the simplest cases, defined by the following power-law expression.



Plot of the sRGB standard gamma-expansion nonlinearity (red), and its local gamma value, slope in log–log space (blue)

In most computer systems, images are encoded with a gamma of about 0.45 and decoded with a gamma of 2.2. The sRGB color space standard used with most cameras, PCs, and printers does not use a simple power-law nonlinearity as above but has a decoding gamma value near 2.2 over much of its range. Gamma is sometimes confused and/or improperly used as "Gamut".

Gamut In color reproduction, including computer graphics and photography, the gamut or color gamut is a certain complete subset of colors.The most common



Typical gamut map. The grayed-out horseshoe shape is the entire range of possible chromaticities, displayed in the CIE 1931 chromaticity diagram format

usage refers to the subset of colors which can be accurately represented in a given circumstance, such as within a given color space or by a certain output device.Also, see Color gamut and wide color gamut.

GDDR An abbreviation for double data rate-type six synchronous graphics random-access memory is a modern type of synchronous graphics random-access memory (SGRAM) with a high-bandwidth ("double data rate") interface designed for use in graphics cards, game consoles, and high-performance computation.

Geometry shaders Geometry shaders, introduced in Direct3D 10 and OpenGL 3.2, generate graphics primitives, such as points, lines, and triangles, from primitives sent to the beginning of the graphics pipeline. Executed after vertex shader geometry, shader programs take as input a whole primitive, possibly with adjacency information. For example, when operating on triangles, the three vertices are the geometry shader's input. The shader can then emit zero or more primitives, which are rasterized, and their fragments ultimately passed to a pixel shader.

Global illumination "Global illumination" (GI) is a term for lighting systems that model this effect. Without indirect lighting, scenes can look harsh and artificial. However, while light received directly is fairly simple to compute, indirect lighting computations are highly complex and computationally heavy.

GPC A graphics processing cluster (GPC) is group, or collection, of specialized processors known as shaders, or simultaneous multiprocessors, or stream processors. Organized as a SIMD processor, they can execute (process) a similar instruction (program or kernel) simultaneously or in parallel. Hence, they are known as a parallel processor (A shader is a computer program that is used to do shading: the production of appropriate levels of color within an image).

GPU (Graphics processing unit) The GPU is the chip that drives the display (monitor) and generates the images on the screen (and has also been called a visual processing unit or VPU). The GPU processes the geometry and lighting effects and transforms objects every time a 3D scene is redrawn—these are mathematically intensive tasks, and hence, the GPU has upwards to hundreds of floating-point processors (also called shaders or stream processors). Because the GPU has so many powerful 32-bit floating-point processors, it has been employed as a special-purpose processor for various scientific calculations other than display ad is referred to as a GPGPU in that case. The GPU has its own private memory on a graphics AIB which is called a frame buffer. When a small (less than five processors) GPU is put inside a northbridge (making it an IGP) the frame buffer is dropped, and the GPU uses system memory. The GPU has to be compatible with several interface standards including software APIs such as OpenGL and Microsoft's DirectX, physical I/O standards within the PC such as Intel's Accelerated Graphics Port (AGP) technology and PCI Express, and output standards known as VGA, DVI, HDMI, and Display Port.

GPU-Compute (GPGPU—General-Purpose Graphics Processor Unit) The term "GPGPU" is a bit misleading in that general-purpose computing such as the type an x86 CPU might perform cannot be done on a GPU. However, because GPUs have so many (hundreds in some cases) powerful (32-bit) floating-point processors, they have been employed in certain applications requiring massive vector operations and mathematical intensive problems in science, finance, and aerospace applications. The application of a GPU can yield several orders of magnitude higher performance than a conventional CPU. These days, there is not much that a GPU can't do. The main missing piece is operating system work (opening files and sockets).

GPU preemption The ability to interrupt or halt an active task (context switch) on a processor and replace it with another task, and then later resume the previous task this is a concept in the era of single-core CPUs preemption was how multitasking was accomplished. Interruption in a GPU, which is designed for streaming processing, is problematic in that it could necessitate a restart of a process and thereby delay a job. Modern GPUs can save state and resume a process as soon as the interruptive job is finished.

Graphics driver A device driver is a software stack that controls computer graphics hardware and supports graphics rendering APIs and is released under a free and open-source software license. Graphics device drivers are written for specific hardware to work within the context of a specific operating system kernel and to support a range of APIs used by applications to access the graphics hardware. They may also control output to the display, if the display driver is part of the graphics hardware.

G-Sync A proprietary adaptive sync technology developed by Nvidia aimed primarily to eliminate screen tearing and the need for software deterrents such as V-sync. G-Sync eliminates screen tearing by forcing a video display to adapt to the frame rate of the outputting device rather than the other way around, which could traditionally be refreshed halfway through the process of a frame being output by the device, resulting in two or more frames being shown at once.

HBAO+ Developed by Nvidia, HBAO+ claims the company, improves upon existing ambient occlusion (AO) techniques and adds richer, more detailed, more realistic shadows around objects that occlude rays of light. Compared to previous techniques, Nvidia claims HBAO+ is faster, more efficient, and significantly better.

HBM (High-Bandwidth Memory) HMB is a high-performance RAM interface for 3D-stacked DRAM from AMD and Hynix. It is to be used in conjunction with high-performance graphics accelerators and network devices. The first devices to use HBM are the AMD Fiji GPUs.

HDMI (High-Definition Multimedia Interface) HDMI is a digital, point-to-point interface for audio and video signals designed as a single-cable solution for home theater and consumer electronics equipment and also supported in

graphics AIBs and some PC motherboards. Introduced in 2002 by the HDMI consortium, HDMI is electrically identical to video-only DVI.

Heterogeneous processors Heterogeneous computing refers to systems that use more than one kind of processor or cores. These systems gain performance or energy efficiency not just by adding the same type of processors, but by adding dissimilar coprocessors, usually incorporating specialized processing capabilities to handle particular tasks.

Luminance A photometric measure of the luminous intensity per unit area of light traveling in a given direction. It describes the amount of light that passes through, is emitted or reflected from a particular area, and falls within a given Solid Angle. The SI unit for luminance is candela per square meter (cd/m^2). A non-SI term for the same unit is the "nit." The CGS unit of luminance is the stilb, which is equal to one candela per square centimeter or 10 kcd/m^2.

MAGIC Mathematical Applications Group, Inc., code, a program developed for ray tracing by MAGI corporation in 1968.

M&E Media and entertainment.

NURBS Non-uniform rational basis spline (NURBS) is a mathematical model commonly used in computer graphics for generating and representing curves and surfaces. It offers great flexibility and precision for handling both analytic (surfaces defined by common mathematical formulae) and modeled shapes.

OLED (Organic light-emitting diode) A light-emitting diode (LED) in which the emissive electroluminescent layer is a film of organic compound that emits light in response to an electric current. This layer of organic semiconductor is situated between two electrodes; typically, at least one of these electrodes is transparent. OLEDs are used to create digital displays in devices such as television screens, computer monitors, and portable systems such as mobile phones.

Open Graphics Library (OpenGL) A cross-language, cross-platform application programming interface (API) for rendering 2D and 3D vector graphics. The API is typically used to interact with a graphics processing unit (GPU), to achieve hardware-accelerated rendering.

OpenRL A low-level interactive ray tracing API, available for download as an SDK for accelerating ray tracing in both graphics and non-graphics (e.g., physics) applications. OpenRL was developed by the Caustic Professional division of Imagination Technologies.

OpenVDB OpenVDB is an Academy Award-winning open-source C++ library comprising a novel hierarchical data structure and a suite of tools for the efficient storage and manipulation of sparse volumetric data discretized on three-dimensional grids. It was developed by DreamWorks Animation for use in volumetric applications typically encountered in feature film production and is

now maintained by the Academy Software Foundation (ASWF). https://github.com/AcademySoftwareFoundation/openvdb.

Penumbra The partially shaded outer region of the shadow cast by an opaque object, such as the shadow cast by the earth or moon over an area experiencing a partial eclipse.

Phong shading Refers to an interpolation technique for surface shading in 3D computer graphics. It is also called Phong interpolation or normal-vector interpolation shading. Specifically, it interpolates surface normals across rasterized polygons and computes pixel colors based on the interpolated normals and a reflection model. Phong shading may also refer to the specific combination of Phong interpolation and the Phong reflection model.

Reflective shadow maps Reflective shadow maps (RSMs) are an extension to a standard shadow map, where every pixel is considered as an indirect light source. The illumination due to these indirect lights is evaluated on the fly using adaptive sampling in a fragment shader. By using screen-space interpolation of the indirect lighting, it is possible to achieve interactive rates, even for complex scenes. Since visualizations and games mainly work in screen space, the additional effort is largely independent of scene complexity. The resulting indirect light is approximate but leads to plausible results and is suited for dynamic scenes.

Relative luminance Relative luminance is formed as a weighted sum of linear RGB components, not gamma-compressed ones. Even so, luma is often erroneously called luminance. SMPTE EG 28 recommends the symbol Y′ to denote luma and the symbol Y to denote relative luminance.

Render farm A render farm is a high-performance computer system, e.g., a computer cluster, built to render computer-generated imagery (CGI), typically for film and television visual effects.

Resolution, screen resolution The number of horizontal and vertical pixels on a display screen. The more pixels, the more information is visible without scrolling. Screen resolutions have a pixel count such as 1600 × 1200, which means 1600 horizontal pixels and 1200 vertical pixels.

RGB Red, Green, and Blue. Color components of a pixel blended to create a specific color on a display monitor. See "Color" for additional details.

ROP ROP stands for Raster Operator; Raster Operators (ROPs) handle several chores near the end of the pixel pipeline. ROPs handle anti-aliasing, Z and color compression, and the actual writing of the pixel to the output buffer.

RT Ray tracer or ray tracing.

SaaS Software as a service.

SAM Served available market.

Scanline rendering An algorithm for visible surface determination, in 3D computer graphics, that works on a row-by-row basis rather than a polygon-by-polygon or pixel-by-pixel basis.

SDK Software development kit.

SECAM Analog TV system used in France and parts of Russia and the Mid-east.

SDR Standard Dynamic Range TV (Rec.601, Rec.709, Rec.2020).

Shaders Shaders is a broadly used term in graphics and can pertain to the processing of specialized programs for geometry (known as vertex shading or transform and lighting) or pixels shading.

SIMD Same Instruction Multiple Data describes computers with multiple processing elements that perform the same operation on multiple data points simultaneously. Such machines exploit data-level parallelism, but not concurrency: there are simultaneous (parallel) computations, but only a single process (instruction) at a given moment. SIMD is particularly applicable to common tasks like such as adjusting the contrast in a digital image.

Subdivision surface Subdivision smooths and adds extra resolution to curves and surfaces at display and/or renders time. The renderer subdivides the surface until it's smooth down to the pixel level. The smooth surface can be calculated from the coarse mesh as the limit of recursive subdivision of each polygonal face into smaller faces that better approximate the smooth surface. This lets one work with efficient low-polygon models and only add the smoothing "on demand" on the graphics card (for display) or in the renderer. The trade-off is that subdivision curves/surfaces take slightly longer to render. However, smoothing low-resolution polylines using curve subdivision is still much faster than working with inherently smooth primitives such as NURBS curves.

Subsurface scattering (SSS) Also known as subsurface light transport (SSLT), is a mechanism of light transport in which light penetrates the surface of a translucent object, is scattered by interacting with the material, and exits the surface at a different point.

Subpixel Morphological Anti-aliasing (SMAA) This filter detects edges in a rendered image and classifies edge crossings into various shapes and shades, in an attempt to make the edges or lines look smoother. Almost every GPU developer has their own version of anti-aliasing.

Super-ray A grouping of rays within and across views, as a key component of a light-field processing pipeline.

TAM Total available market.

Tearing and frame dropping Vsync, where the monitor is synchronized to the powerline frequency, can cause the screen to be refreshed halfway through the

process of a frame being output by the GPU, resulting in two or more frames being shown at once.

Texel Acronym for TEXture ELement or TEXture pixEL—the unit of data which makes up each individually addressable part of a texture. A texel is the texture equivalent of a pixel.

Texture mapping The act of applying a texture to a surface during the rendering process. In simple texture mapping, a single texture is used for the entire surface, no matter how visually close or distant the surface is from the viewer. A somewhat more visually appealing form of texture mapping involves using a single texture with bilinear filtering, while an even more advanced form of texture mapping uses multiple textures of the same image but with different levels of detail, also known as mipmapping. See also "Bilinear Filtering," "Level of Detail," "Mipmap," "Mipmapping," and "Trilinear Filtering."

Texture map Same thing as "Texture."

Texture A texture is a special bitmap image, much like a pattern, but which is intended to be applied to a 3D surface in order to quickly and efficiently create a realistic rendering of a 3D image without having to simulate the contents of the image in 3D space. That sounds complicated, but in fact it's very simple. For example, if you have a sphere (a 3D circle) and want to make it look like the planet Earth, you have two options. The first is that you meticulously plot each nuance in the land and sea onto the surface of the sphere. The second option is that you take a picture of the Earth as seen from space, use it as a texture, and apply it to the surface of the sphere. While the first option could take days or months to get right, the second option can be nearly instantaneous. In fact, texture mapping is used broadly in all sorts of real-time 3D programs and their subsequent renderings, because of its speed and efficiency. 3D games are certainly among the biggest beneficiaries of textures, but other 3D applications, such as simulators, virtual reality, and even design tools take advantage of textures too.

Tile-Based Deferred Rendering (TBDR) defers the lighting calculations until all objects have been rendered, and then it shades the whole visible scene in one pass. This is done by rendering information about each object to a set of render targets that contain data about the surface of the object this set of render targets is normally called the G-buffer.

Tiled rendering The process of subdividing a computer graphics image by a regular grid in optical space and rendering each section of the grid, or tile, separately. The advantage of this design is that the amount of memory and bandwidth is reduced compared to immediate mode rendering systems that draw the entire frame at once. This has made tile rendering systems particularly common for low-power handheld device use. Tiled rendering is sometimes known as a "sort middle" architecture, because it performs the sorting of the geometry in the middle of the graphics pipeline instead of near the end.

Tone mapping A technique used in image processing and computer graphics to map one set of colors to another to approximate the appearance of high-dynamic range images in a medium that has a more limited dynamic range.

Trilinear Filtering A combination of bilinear filtering and mipmapping, which enhances the quality of texture mapped surfaces. For each surface that is rendered, the two mipmaps closest to the desired level of detail will be used to compute pixel colors that are the most realistic by bilinearly sampling each mipmap and then using a weighted average between the two results to produce the rendered pixel.

UDIM An enhancement to the UV mapping and texturing workflow that makes UV map generation easier and assigning textures simpler. The term UDIM comes from U-Dimension and design UV ranges. UDIM is an automatic UV offset system that assigns an image onto a specific UV tile, which allows one to use multiple lower resolution texture maps for neighboring surfaces, producing a higher resolution result without having to resort to using a single ultra-high resolution image. UDIM was invented by Richard Addison-Wood and came from Weta Digital (circa 2002).

Voxel A voxel is a value in three-dimensional space. Voxel is a combination of "volume" and "pixel" where pixel is a combination of "picture" and "element." This is analogous to a texel, which represents 2D image data in a bitmap (also referred to as a pixmap). Voxels are used in the visualization and analysis of medical and scientific data (Some volumetric displays use voxels to describe their resolution. For example, a display might be able to show $512 \times 512 \times 512$ voxels). Both ray tracing and ray casting, as well as rasterization, can be applied to voxel data to obtain 2D raster graphics to depict on a monitor.

VPU (Vector Processing Unit) A vector processor or array processor implements an instruction set containing instructions that operate on one-dimensional arrays of data called vectors.Today's CPUs architectures have instructions for a form of vector processing on multiple (vectorized) datasets, typically known as SIMD (single instruction, multiple data). Common examples include Intel x86's MMX, SSE and AVX instructions, AMD's 3DNow! Extensions as well as Arm's Neon and its scalable vector extension (SVE).

VXGI is a new approach to computing a fast, approximate form of global illumination (GI) dynamically in real-time on the GPU. This new GI technology uses a voxel grid to store scene and lighting information and a novel voxel cone tracing process to gather indirect lighting from the voxel grid. The purpose for VXGI is to run in real-time and doing full ray tracing of the scene is too computationally intense, so approximations are required.

VXGI Voxel Global Illumination (VXGI), developed by Nvidia, features one-bounce indirect diffuse, specular light, reflections, and area lights. It is an advancement in realistic lighting, shading, and reflections. VGXI is a three-step

process: Voxelization, light injection, and final gathering and is employed in the next-generation games and game engines.

WCG Wide Color Gamut—anything wider than Rec.709, DCI P3, Rec.2020—See wide color gamut.

Wide color gamut High Dynamic Range (HDR) displays a greater difference in light intensity from white to black, Wide Color Gamut (WGC) provides a greater range of colors. The wide-gamut RGB color space (or Adobe Wide Gamut RGB) is an RGB color space developed by Adobe Systems that offers a large gamut by using pure spectral primary colors. It is able to store a wider range of color values than sRGB or Adobe RGB color spaces.Also see HDR, and Color gamut.

Z-buffer A memory buffer used by the GPU that holds the depth of each pixel (*Z*-axis). When an image is drawn, each (*X*–*Y*) pixel is matched against the z-buffer location. If the next pixel in line to be drawn is below the one that is already there, it is ignored.

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