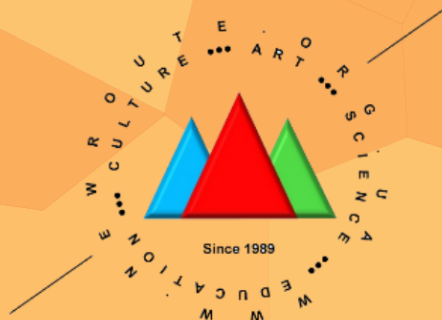


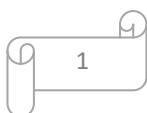
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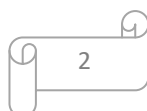


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Монографія

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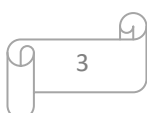
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	Зміст	Стор.
Передмова	...	7
Розділ перший		
Освітні, культурно-мистецькі та гуманітарні напрями розвитку (освітні науки, педагогіка, культура, мистецтво, філософія, релігієзнавство, історія, археологія, філологія, журналістика)	...	8
1.1. Когнітивна війна в парадигмі лінгвістики впливу: мовні механізми конструювання інтерпретаційної реальності <i>Бондаренко Олександр Олександрович</i>	...	8
1.2. Ethical challenges in translating hybrid war communication: between disinformation, strategic narratives, and translator responsibility <i>Yaroslava Fedoriv, Iryna Semiankiv, Iryna Pirozhenko, Mariya Fedoriv</i>	...	13
1.3. Позитивний пропагандистський потенціал військового контенту від першої особи в умовах інформаційної війни <i>Власов Гліб Олексійович, Васильченко В'ячеслав Миколайович</i>	...	23
1.4. Соціальний плакат у системі сучасної візуальної культури: дизайнерські та педагогічні аспекти <i>Рублевська Наталія Володимирівна</i>	...	25
1.5. Трансформація шкільної математичної освіти в Україні: стратегії подолання освітніх втрат та розривів у сучасному вимірі <i>Волошена Вікторія Вікторівна</i>	...	34
1.6. Розвиток практичних творчих навичок у здобувачів початкової школи в процесі образотворчої діяльності <i>Форостюк Віталій Олександрович</i>	...	41
Розділ другий		
Symphony of Resilience: управлінська модель музикотерапевтичного супроводу в Одеському ЗДО №103 <i>Островецька Ольга Олегівна</i>	...	56
2.1. Досвід роботи закладу з використання класичної музики як засобу гармонізації дитячого колективу	...	57
2.1.1. Разом до гармонії: підготовка та діалог з батьками	...	57
2.1.2. Соціальне партнерство «жива струна	...	59
2.1.3. Інклюзивний простір без кордонів	...	61
2.1.4. Робота з батьківською спільнотою («Батьківська рапсодія»)	...	62
2.2. Емпіричне дослідження «Емоційний камертон» (моніторинг ментального здоров'я вихованців)	...	64
2.2.1. Організація підготовчого етапу	...	65
2.2.2. Основний етап експерименту	...	67
2.2.3. Результати дослідження	...	68
Розділ третій		
Соціально-поведінкові процеси та суспільний розвиток (психологія, соціологія, соціальна робота)	...	74
3.1. Психологічні феномени у формуванні професійної мотивації <i>Юрчук Людмила Василівна</i>	...	74
3.2. Психологічні особливості комунікації з близькими осіб, зниклих безвісти в умовах війни <i>Репіна Олена Леонідівна</i>	...	78

Розділ четвертий

Економічні та управлінські засади розвитку (економіка, підприємництво, торгівля, фінанси, банківська справа, облік, оподаткування, менеджмент, маркетинг, державне управління, міжнародні відносини, політологія, туризм, сфера послуг) ... 82

- | | | |
|------|---|---------|
| 4.1. | Статистичне дослідження взаємозв'язку показників екологічної відповідальності за забруднення довкілля під час військового стану
<i>Лайчук Світлана Михайлівна, Поліщук Ірина Романівна</i> | ... 82 |
| 4.2. | Вплив цифровізації hr-процесів на зниження трансакційних витрат підприємства
<i>Склярук Тетяна Василівна</i> | ... 91 |
| 4.3. | ESG transformation of enterprises in the context of the circular economy
<i>Olena Tsikhanovska</i> | ... 98 |
| 4.4. | Трансформація систем мотивації персоналу в епоху інтелектуалізації економіки
<i>Verbytska Halyna Liubomyrivna</i> | ... 107 |
| 4.5. | Економічні та управлінські засади розвитку туризму на Сумщині
<i>Новікова Анна Віталіївна</i> | ... 114 |
| 4.6. | Антикризовий менеджмент в умовах цифровізації економіки
<i>Костецький Ярослав Іванович</i> | ... 116 |
| 4.7. | Стійкість національної економіки в умовах зовнішніх шоків: теоретичні засади та індикатори оцінювання
<i>Марущак Світлана Миколаївна</i> | ... 126 |

Розділ п'ятий

Інженерно-технологічні та інфраструктурні рішення

(ІТ, комп'ютерні науки, інженерія, виробничі технології, архітектура, будівництво) ... 144

- | | | |
|------|---|---------|
| 5.1. | Methods for generation of photorealistic images
<i>Romaniuk Oleksandr Nikiforovich, Stakhov O. Ya</i> | ... 144 |
| 5.2. | Disinformation in Social Networks: Dissemination Mechanisms, Monitoring Methods, and Designing a Countermeasure System Using the Example of Facebook and X
<i>Mariana Musiiivska</i> | ... 159 |
| 5.3. | Алгоритмізація та проектування інтерактивних модулів у цифровому середовищі STEM-освіти
<i>Мицишин Руслана Петрівна</i> | ... 169 |
| 5.4. | Intelligent planning and production dispatching
<i>Lesko Oleksandr Yosypovich, Tsikhanovskaya Olena Mykhailivna</i> | ... 178 |
| 5.5. | Архітектура як інструмент формування просторів для соціально-психологічного відновлення військових
<i>Якубовський В'ячеслав Броніславович, Кудасюк Надія Ігорівна</i> | ... 192 |

Розділ шостий

Природничі, аграрні та екологічні аспекти сталого розвитку (екологія, природничі науки, сільське господарство, харчові технології, ветеринарія, зоотехнія) ... 199

- | | | |
|------|--|---------|
| 6.1. | Карстові печери урочища Гребінь та скали Чур як об'єкти розвитку геологічного туризму в Тячівському районі Закарпатської області Прохорова Лариса Анатоліївна,
<i>Гришко Світлана Вікторівна, Непша Олександр Вікторович, Зав'ялова Тетяна Василівна, Коваль Дмитро Олексійович</i> | ... 199 |
|------|--|---------|

Розділ сьомий

Медико-біологічні та фізкультурно-оздоровчі аспекти (фізична культура, спорт, медицина, фармація) ... 206

- | | | |
|------|--|---------|
| 7.1. | Профілактика професійних захворювань, пов'язаних з використанням комп'ютерів: рекомендації для студентів і фахівців ІТ-сектора
<i>Церковна Олена Вікторівна, Гелета Діана Дмитрівна, Семашко Світлана Анатоліївна</i> | ... 206 |
|------|--|---------|

Післямова ... 211

Розділ п'ятий
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5.1. Methods for generation of photorealistic images

Modern computer graphics [1] is one of the most important areas of information technology development. Its use covers computer games, cinematography, architectural visualization, virtual and augmented reality systems, medicine, scientific simulations, and digital design. One of the key tasks of computer graphics is to create photorealistic images that are as close as possible to the real human perception of the world around them.

The realism of a digital image [1-7] is determined by the accuracy of modeling geometry, lighting, materials, textures, and physical properties of surfaces. The development of graphics processors and specialized algorithms has allowed us to move from simple raster scenes to complex real-time global illumination and ray tracing systems. In modern image generation systems, neural network methods are actively used, which significantly expand the capabilities of classical rendering.

The purpose of the monograph is to analyze modern methods for generating photorealistic images, study their mathematical and hardware foundations, and study the prospects for the development of digital visualization technologies.

Theoretical foundations of photorealistic computer graphics.

Photorealistic computer graphics [1-7] is an interdisciplinary field that combines methods of applied mathematics, physics, computer science, digital signal processing and the psychology of visual perception. Its development became possible due to the rapid progress of computer technology, the emergence of graphics accelerators and the development of specialized visualization algorithms. The main goal of photorealistic graphics is to create images that the human eye perceives as photographs of the real world. For this, it is necessary to take into account not only the shape of objects, but also the complex processes of interaction of light with surfaces.

One of the fundamental problems of computer graphics is the transformation of a three-dimensional scene into a two-dimensional image. This process is called rendering. In the simplest case, the scene is described by a set of geometric primitives, light sources and camera parameters. However, this is not enough to obtain a realistic result. It is necessary to take into account the properties of materials, the effects of indirect lighting, atmospheric scattering, depth of field and other factors.

The mathematical apparatus of linear algebra is of great importance. In computer graphics, transformation matrices, vectors, normals, and homogeneous coordinates are actively used. They allow scaling, rotation, translation, and projection of three-dimensional objects onto the screen plane. In addition, parametric and spline methods are used to model complex surfaces.

The physics of light is another fundamental element of photorealistic graphics. In the real world, light is reflected, refracted, absorbed, and scattered. Modeling these processes requires the use of the equations of optics and the theory of radiative transfer. For practical rendering systems, simplified models are created that provide a compromise between accuracy and speed.

A special place is occupied by the problem of color. The human eye has a complex nonlinear reaction to brightness and color transitions. Therefore, computer graphics systems use color spaces RGB, XYZ, Lab and other color representation models. To ensure realism, gamma correction and tone mapping algorithms are used.

An important stage in the development of graphics was the introduction of programmable shaders. They allowed to transfer a significant part of the calculations to the GPU and provide flexibility in image formation. Vertex shader, fragment shader and compute shader became the basic elements of modern graphics pipelines.

Modern image generation systems actively use HDR technologies. They allow you to work with a large dynamic range of lighting, which is especially important for scenes with bright light sources and deep shadows. Without HDR, even complex scenes can look unnatural.

Another important direction is procedural content generation. Using mathematical algorithms, textures, terrain, vegetation, and even entire worlds can be created. This significantly reduces memory requirements and simplifies the creation of large digital environments.

A separate role is played by the problem of visual perception. A person evaluates realism not only by the physical accuracy of a scene, but also by psychological factors. That is why sometimes a less accurate, but artistically adapted rendering looks more convincing.

Photorealistic graphics continue to evolve along with hardware advancements. The advent of specialized RT cores, AI accelerators, and high-speed memory has opened up new possibilities for generating realistic digital scenes in real time.

Ray tracing and global illumination techniques.

Ray tracing is one of the most important and effective methods for generating photorealistic images in modern computer graphics. The main idea of this approach is to mathematically model the propagation of light in three-dimensional space. Unlike classical rasterization, where the main focus is on quickly projecting geometry onto the screen, ray tracing is focused on physically correct reproduction of light processes. This is what allows the method to create complex optical effects: reflection, refraction, transparency, soft shadows, caustics and indirect lighting. The realism provided by ray tracing has made it the basis of modern systems for cinematic rendering, architectural visualization and high-quality computer graphics.

The principle of ray tracing is based on the inverse modeling of light propagation. In the real world, light rays propagate from light sources to objects and then to the human eye. In computer graphics, it is computationally more advantageous to perform the reverse process - to launch rays from the camera through the pixels of the screen towards the scene. For each pixel, a primary ray is generated, which is checked for intersection with the geometry of the scene. If an intersection is found, the coordinates of the point, the surface normal and the material properties are determined. After this, local illumination is calculated and, if necessary, additional secondary rays are created to simulate reflection or refraction.

One of the main advantages of ray tracing is the natural modeling of specular reflections. In classic rasterization, approximate methods such as environment mapping or screen-space reflections are used to create reflections. They have limitations and do not always provide the correct result. Ray tracing allows you to physically accurately calculate the direction of the reflected ray and obtain realistic specular surfaces. This is especially important for metals, mirrors, car bodies and other materials with a high reflectivity.

Equally important is the modeling of light refraction. Transparent materials such as glass, water, ice, or crystals change the direction of light propagation depending on the refractive index. Ray tracing allows you to accurately reproduce these processes, taking into account the physical laws of optics. This allows you to create complex optical effects, such as image deformation through glass or refraction of light in water. Combined with dispersion models, this allows you to simulate spectral effects characteristic of gemstones and optical systems.

An important component of ray tracing is the calculation of shadows. In classic graphics, shadow maps are often used, which have problems with accuracy and artifacts. In ray tracing, shadows are formed by generating shadow rays - rays from a point on the surface to the light source. If there is an obstacle in the path of the ray, the point is considered shaded. This approach allows you to create soft shadows that naturally change shape and intensity depending on the size of the light source and the distance to the object.

One of the main problems with ray tracing is its high computational complexity. A large number of rays can be generated for each pixel, and each ray is checked for intersection with the scene geometry. In complex scenes, this can require billions of operations. That is why special acceleration structures have been created. The most common is BVH - bounding volume hierarchy. It groups objects into nested containers, which allows you to quickly discard large areas of the scene without checking each primitive individually. Another popular approach is kd-trees, which recursively divide the space into regions.

Global illumination is another key component of photorealistic graphics. Unlike local illumination models, it takes into account multiple reflections of light energy between the surfaces of the scene. It is indirect lighting that creates soft shadows, color reflections, and a natural filling of the scene with light. Without global illumination, even detailed scenes look artificial and unnatural. The real world is characterized by a constant exchange of light energy between objects, so taking into account indirect reflections is critical for photorealism.

One of the first global illumination methods was radiosity. This approach was based on modeling the energy exchange between the surfaces of a scene and was particularly effective for diffuse lighting. Radiosity allowed for realistic indirect lighting in architectural scenes, but it did not work well with specular surfaces and complex materials. Despite this, the method became an important stage in the development of computer graphics and laid the foundation for further research into global illumination.

Photon mapping is the next step in the development of photorealistic rendering. In this method, light energy is represented as photons, which are emitted by light sources and propagated through the scene. Information about the collisions of photons with surfaces is recorded in a special data structure – photon map. During the final rendering, this information is used to calculate indirect lighting and caustics. Photon mapping works well with complex optical effects, including refraction and concentrated light reflections.

The modern standard for global illumination is path tracing. This method is based on Monte Carlo integration and allows for an approximate solution to the rendering equation. A large number of random light paths are generated for each pixel, which allows for modeling complex light interactions. Path tracing provides high physical accuracy and is the basis of most professional renderers. However, its main drawback is noise, which occurs when there is an insufficient number of samples. Adaptive sampling and AI-based denoising are used to combat noise.

An important stage in the development of ray tracing was the emergence of hardware acceleration. Modern GPUs contain specialized RT cores that perform ray-intersection checks with geometry much faster than general-purpose computing cores. This has allowed real-time ray tracing to be implemented in computer games and interactive systems. NVIDIA, AMD, and Intel are actively developing hardware ray tracing technologies, integrating them into modern graphics architectures.

Hybrid rendering has become a compromise between performance and quality. In this approach, rasterization is used to quickly display the geometry of the scene, and ray tracing is used for complex lighting effects. This approach allows you to achieve high frame rates while maintaining photorealistic reflections, shadows, and global illumination. It is hybrid rendering that has become the basis of modern game engines.

Ray tracing is widely used in cinematography. Pixar, Disney, DreamWorks and others use path tracing to create digital effects and animated films. The high physical accuracy of lighting allows you to create scenes that are almost indistinguishable from real shooting. In addition, ray tracing is used in architectural visualization, industrial design, the automotive industry and medical simulations.

Thus, ray tracing and global illumination techniques are the foundation of modern photorealistic graphics. They provide physically correct modeling of light, realistic shadows, reflections, refraction and indirect lighting. The development of GPU, hardware acceleration and neural network noise reduction methods has made ray tracing available not only for offline rendering, but also for real-time systems. In the future, these technologies will determine the development of digital visualization and interactive computer graphics.

Physically correct rendering and modern graphics engines.

Physically correct rendering has become one of the main directions of development of modern computer graphics and has actually become the standard for creation of photorealistic digital scenes. Its basic idea is to model light, materials and optical effects in accordance with the laws of physics. Unlike early graphics systems, where lighting was often created using simplified empirical models, physically correct rendering is focused on real characteristics of surfaces and behavior of light energy. This allows to obtain stable and predictable results regardless of lighting conditions. That is why PBR has become the basis of modern game engines, professional renderers and digital visualization systems.

The basis of physically correct rendering is the use of BRDF models, which describe the behavior of light at the microlevel of the surface. BRDF determines the ratio between incident and reflected light depending on the angles of incidence and observation. In practice, various BRDF models are used, in particular Cook-Torrance, GGX, Beckmann and Lambertian. They allow you to reproduce both diffuse and specular reflection. Thanks to this, surfaces acquire a natural appearance characteristic of real materials.

Materials in PBR systems are defined by a set of physical parameters. The most common are albedo, roughness, metallic, ambient occlusion, and normal map. The albedo parameter determines the base color of the surface without taking into account lighting. Roughness characterizes the microroughness of the surface and affects the degree of reflection blur. Metallic determines whether the material behaves as a metal or as a dielectric. Ambient occlusion is used to simulate local dimming in hard-to-reach areas of the geometry. Normal map allows you to simulate small irregularities without increasing the number of polygons.

One of the main advantages of PBR is the versatility of materials. In classic systems, artists had to configure shaders separately for each scene and light source. In a physically correct approach, the material behaves the same under any lighting conditions, since its properties are determined by physical parameters. This greatly simplifies the process of content creation and ensures consistent image quality.

Modern graphics engines, such as Unreal Engine, Unity, CryEngine, and Frostbite, actively use physically correct rendering. Unreal Engine has become one of the most famous examples of real-time PBR implementations. Its material system allows artists to create complex surfaces without the need for deep shader programming. Unity also actively supports PBR and provides tools for creating realistic scenes in various types of applications - from mobile games to VR systems.

Shaders play an important role in modern engines. Vertex shaders are responsible for processing geometry, fragment shaders are responsible for calculating the color of pixels, and compute shaders are responsible for performing general parallel calculations on the GPU. It is programmable shaders that have made it possible to implement complex lighting and material models in real time. The flexibility of shaders allows you to create individual effects for different types of surfaces and scenes.

Deferred rendering has become one of the most common approaches in modern real-time graphics. Its main idea is to divide the rendering process into two stages: first, the geometric information of the scene is written to special buffers, and then the lighting is performed in a separate pass. This approach allows you to work efficiently with a large number of light sources. In traditional forward rendering, each light source requires separate calculations for each object, which significantly reduces performance. Deferred rendering significantly optimizes this process.

The G-buffer is a key component of deferred rendering. It stores normals, depth, material colors, and other scene parameters. After that, lighting is no longer performed for geometry, but for screen pixels. This allows you to significantly reduce the number of calculations and ensure high performance even in complex scenes with a large number of light sources.

An important component of modern graphics is HDR and tone mapping. The real world is characterized by a very wide range of brightness – from dark shadows to bright sunlight. Conventional monitors cannot display such a range without losing detail. HDR allows you to maintain brightness values in a wide range, and tone mapping adapts them to the capabilities of the display. It is thanks to HDR that scenes look more natural and cinematic.

Modern graphics engines support a large number of additional effects that increase the level of realism. Volumetric lighting allows you to model fog, smoke, atmospheric scattering and light rays. Ambient occlusion creates local darkening in places where surfaces are close together. Screen-space reflections provide approximate modeling of reflections without full ray tracing. Contact shadows add detail to shadows in small elements of the scene.

Anti-aliasing plays a special role. Due to the discrete nature of the pixel grid, jaggedness appears at the boundaries of objects, which reduces image quality. Temporal anti-aliasing, supersampling, FXAA and MSAA are used to eliminate it. Temporal anti-aliasing accumulates information from previous frames, which allows you to effectively reduce flicker and noise. Supersampling provides high quality by rendering the scene at a higher resolution with subsequent scaling.

The development of GPUs has significantly influenced the evolution of graphics engines. Modern GPUs contain thousands of parallel cores, caches, texture units, and specialized RT cores for ray tracing. This allows for the implementation of complex lighting and post-processing algorithms in real time. Hardware acceleration of ray tracing has become one of the biggest breakthroughs in the field of computer graphics in recent years.

Hybrid rendering is a compromise between classic rasterization and full ray tracing. In this approach, the geometry of the scene is processed by fast rasterization, and complex lighting effects are processed by ray tracing. This allows you to get realistic reflections, shadows, and global illumination without a critical drop in performance. It is hybrid rendering that is used in most modern AAA games.

Modern engines are also actively integrating neural network technologies. DLSS and FSR use AI to reconstruct high-resolution images. This allows you to reduce the load on the GPU and at the same time improve image quality. AI technologies are also used for denoising, texture generation and character animation.

Thus, physically correct rendering and modern graphics engines are the basis of photorealistic computer graphics. They combine mathematical lighting models, high-performance GPUs, programmable shaders and neural network technologies. This is what allows modern digital visualization to create scenes that are practically indistinguishable from real photographs.

Neural network image generation technologies.

Neural network image generation technologies have become one of the most important directions in the development of modern computer graphics, as they have significantly changed the approach to creating digital visual content. While classical computer graphics methods are based on a mathematical description of geometry, lighting, materials and the camera, neural network methods use statistical patterns obtained during training on large sets of images. Such systems do not necessarily model physical processes directly, but are able to create images that are visually perceived as realistic. This makes artificial intelligence a powerful tool for accelerating rendering, generating textures, reconstructing scenes, improving image quality and creating completely new photorealistic compositions.

The first important direction of neural network generation was generative adversarial networks, or GANs. Their idea is the interaction of two neural networks: a generator and a discriminator. The generator creates synthetic images, and the discriminator evaluates how similar they are to real ones. During the training process, the generator gradually improves, as it tries to create images that the discriminator cannot distinguish from real ones. Thanks to this, GANs have made it possible to create realistic faces, textures, objects, interiors, and natural scenes.

An important advantage of GANs is their ability to learn complex distributions of visual data. This means that the network does not simply copy individual samples from the training set, but forms a generalized idea of the structure of images. For example, after training on a large number of photos of faces, the system can create new faces that never existed. This approach has become the basis of many applications in digital art, character design, visual effects and game content generation. At the same time, GANs have certain disadvantages, including instability of training, the possibility of artifacts and the difficulty of controlling the fine details of the image.

The next important stage in the development of generative graphics was diffusion models. They work on a different principle: during training, the model gradually adds noise to the image, and then learns to perform the reverse process - to restore the image from the noise. As a result, the system is able to generate new images, gradually transforming random noise into a visually meaningful scene. Diffusion models have shown high generation quality, stability of training and the ability to create complex compositions with a large number of details. They have become the basis of many modern image generation systems based on text descriptions.

Text-to-image systems have opened a new stage in the creation of graphic content. The user can describe the desired image in natural language, and the neural network generates the corresponding visual scene. This approach significantly expands the capabilities of artists, designers, architects and game developers. Instead of lengthy manual modeling, you can quickly get a sketch, concept or even a full-fledged photorealistic image. It is especially important that the text description can contain information about the style, lighting, composition, materials, camera angle and mood of the scene.

Neural network technologies are actively used not only to create new images, but also to improve the results of classical rendering. One of the most important applications is noise reduction, or denoising, in path tracing. Physically correct path tracing requires a large number of samples to obtain a clean image without noise. This requires significant computational resources and time. Neural network denoising allows you to obtain a high-quality result with a significantly smaller number of samples, since the model analyzes the noisy image and restores a likely clean version of the scene. This is especially important for real-time rendering.

Another important direction is neural network image scaling, or super resolution. Its goal is to create a higher resolution image based on a lower one. Classical scaling methods often lead to blurring or loss of detail, while neural networks are able to restore small structures, contours and textures. In modern graphics systems, such technologies allow rendering a scene at a lower resolution and then restoring it to the target quality. This reduces the load on the GPU and increases the frame rate without significant loss of visual quality.

Examples of practical applications include technologies like DLSS, FSR, and XeSS. They are used in modern games and graphics engines to improve performance and image quality. Neural network scaling is particularly useful for real-time ray tracing, as ray tracing is computationally expensive. By rendering a scene at a lower resolution and then reconstructing it with high quality, you can get a photorealistic image with acceptable performance. Thus, AI becomes not only a creative tool, but also an important component of optimizing the graphics pipeline.

Neural networks are also used to generate textures and materials. In the classic approach, the artist creates textures manually or takes photos of real surfaces, and then processes them in graphic editors. AI systems can automatically generate textures for wood, metal, stone, fabric, leather, soil and other materials. In addition, they are able to create a full set of PBR maps: albedo, roughness, normal map, displacement map and ambient occlusion. This significantly speeds up the process of creating realistic materials for games, films and VR scenes.

A separate area is neural network image restoration and reconstruction. Such methods are used to improve old photographs, remove noise, increase sharpness, reconstruct damaged areas, and colorize black-and-white images. In the context of computer graphics, these technologies allow you to improve the quality of renders, eliminate artifacts, and automatically fill in missing parts of a scene. This is especially useful in digital cinema and post-processing.

Neural radiance fields, or NeRF, play a key role. This approach allows us to reconstruct a three-dimensional scene from a set of two-dimensional photographs taken from different angles. The neural network learns to represent space as a continuous field of density and color. After training, it is possible to generate new images of the scene from arbitrary viewpoints. NeRF has become an important direction in the photorealistic reconstruction of real objects and environments, as well as in the creation of digital twins.

Neural network methods are also changing the approach to modeling three-dimensional objects. Modern systems are able to create 3D models based on a text description, image, or set of photos. This opens up new opportunities for automating the production of graphic content. In the future, an artist or engineer will be able to describe the desired object in words, and the system will automatically create geometry, textures, and materials. This approach can significantly reduce the time for developing digital scenes.

In the field of animation, neural networks are used to synthesize character movements. Motion capture allows you to record real movements, but requires special equipment and time. AI models can generate natural movements based on short descriptions or examples. They can also smooth animation, adapt it to new characters, and create transitions between different actions. This makes the animation process more flexible and faster.

Neural network technologies are actively used in cinematography. They are used to create digital actors, rejuvenate or age faces, reconstruct facial expressions, synthesize backgrounds and complex visual effects. Thanks to AI, some tasks that previously required a large team of artists can be performed faster and at lower costs. However, this also creates new ethical and legal issues related to the reliability of images and the use of images of real people.

In computer games, neural networks are gradually becoming part of the graphics pipeline. They are used for scaling, noise reduction, texture generation, landscape creation, character animation, and lighting enhancement. AI allows for the creation of larger and more detailed worlds without a proportional increase in manual labor. This is especially important for open game worlds, where a huge amount of diverse content needs to be created.

Another promising direction is real-time scene generation. In traditional graphics, the scene is modeled in advance by artists and then rendered by the engine. Neural network systems can potentially generate parts of the scene dynamically, according to user actions, a script, or a text description. This opens the way to interactive worlds that are created directly during user interaction.

Despite their significant advantages, neural network technologies have a number of limitations. First, they require large amounts of training data. The quality of the result depends largely on the images on which the model was trained. Second, AI can produce visually convincing but physically incorrect results. This is important to consider in scientific, medical, and engineering visualization, where reliability is more important than external attractiveness. Third, generative models can create artifacts, inaccuracies, or logical errors in complex scenes.

There is also the problem of controllability of neural network generation. In classical rendering, every parameter of the scene is controlled explicitly: camera position, light sources, geometry, materials. In neural network systems, the result is often probabilistic in nature. This means that the same query can produce different images, and exact repetition or correction of the result can be difficult. Therefore, modern research is actively aimed at developing controlled generative models.

An important direction is the combination of neural network methods with physically correct rendering. This approach allows you to use the strengths of both technologies. Classic rendering provides physical accuracy and controllability, while neural networks accelerate calculations, improve quality and automate content creation. For example, AI can generate textures, perform denoising, reconstruct details or predict lighting, but the final result is still checked by a physical model.

In the future, neural network technologies may become the basis of new graphics engines. Such engines will not only render pre-created scenes, but also generate them based on the description, context and behavior of the user. This may change the very nature of computer graphics: instead of manually creating each element, the scene will be formed semi-automatically or fully automatically. This is especially promising for virtual reality, metaverses, educational simulators and digital twins.

Thus, neural network image generation technologies are not just an additional tool for computer graphics, but one of the key factors in its transformation. They allow you to create realistic images, accelerate rendering, improve the quality of scenes, automate the generation of textures and models, and open up new forms of digital creativity. The combination of artificial intelligence with classical rendering methods creates the basis for future photorealistic visualization systems. In the coming years, it is AI, GPU acceleration, and physically correct rendering that will together determine the development of the next generation of computer graphics.

Features of generating photorealistic images on GPU.

Modern generation of photorealistic images is directly related to the use of graphics processors, since it is GPUs that provide the necessary performance to perform complex calculations in real time. Unlike central processors, graphics processors have a massively parallel architecture optimized for simultaneous execution of a large number of operations of the same type. This makes GPUs especially effective for rendering, ray tracing, texture processing, lighting simulation, and image post-processing tasks. Generating photorealistic scenes requires millions and even billions of mathematical operations for each frame, which is why GPUs have become the basis of modern computer graphics.

One of the main features of GPUs is their parallel structure. A graphics processor consists of a large number of computing cores that can simultaneously execute the same instructions on different data. In rendering tasks, this means that thousands of pixels or fragments of a scene can be processed in parallel. This approach is significantly different from the CPU architecture, where the main emphasis is on the sequential execution of complex operations. For the generation of photorealistic images, parallelism is critical, since the calculations of lighting, textures and materials for each pixel can be performed independently.

The basis of a modern GPU is a graphics pipeline, which consists of several stages of data processing. First, the vertices of geometric objects pass through a vertex shader, where coordinate transformations, animation and other operations on the geometry are performed. This is followed by rasterization, during which triangles are converted into fragments corresponding to screen pixels. Next, a fragment shader or pixel shader calculates the color of each pixel, taking into account lighting, textures and material properties. The final stage is to write the result to the frame buffer and perform post-processing.

An important feature of the GPU is the support for programmable shaders. They provide the flexibility of modern computer graphics. Shaders allow you to implement complex lighting algorithms, procedural texture generation, simulation of physical effects and post-processing. In modern graphics engines, a significant part of photorealistic rendering is performed using shader programs. Thanks to this, you can implement complex BRDF models, volumetric lighting, ambient occlusion and other effects.

One of the most important aspects of generating photorealistic images is working with lighting. In GPUs, lighting calculations are performed in parallel for a large number of scene fragments. For this, mathematical models of diffuse, specular and global illumination are used. Modern graphics systems use physically correct rendering, where lighting is based on real physical laws. GPUs perform a huge number of operations to calculate light directions, reflections, shadows and indirect lighting.

Ray tracing plays a special role in modern photorealistic graphics. Classic ray tracing requires a large number of checks of the intersection of rays with the geometry of the scene. To accelerate these operations, modern GPUs contain specialized RT cores. They are optimized for working with BVH structures and allow you to quickly determine the intersections of rays with the triangles of the scene. Thanks to RT cores, it became possible to use ray tracing in real time, which was previously available only for offline rendering.

An important component of the GPU are texture blocks. They are responsible for reading, filtering, and interpolating texture data. In photorealistic graphics, textures are used to describe color, normals, roughness, surface height, and other material characteristics. GPUs support various texture filtering modes, including bilinear, trilinear, and anisotropic filtering. These mechanisms provide high detail and smoothness of the image.

One of the main challenges in generating photorealistic scenes is the huge amount of data. Modern scenes can contain millions of polygons, large textures, and complex lighting effects. To work efficiently, GPUs use multi-level caches and high-speed video memory. Memory bandwidth is a critical performance factor. That is why modern GPUs are equipped with GDDR6 or HBM memory, which provides extremely high data transfer rates.

Tiled rendering is important. The GPU processes the scene in small blocks, or tiles, which allows for more efficient use of cache memory and reduces the number of VRAM accesses. Tiled rendering is especially important for mobile GPUs, where power efficiency is critical. On desktop systems, it is also used to optimize complex scenes and reduce memory usage.

Modern GPUs actively use compute shaders for tasks not directly related to the classical graphics pipeline. Compute shaders allow for arbitrary parallel computations, which makes them effective for physics simulation, procedural content generation, particle processing, and neural network algorithms. In photorealistic graphics, compute shaders are often used for global illumination, denoising, and post-processing.

An important feature of generating photorealistic images is the use of HDR. The GPU works with a high dynamic range of lighting, which allows you to simulate very bright light sources and deep shadows. This is followed by tone mapping, which adapts the result to the capabilities of the display. Without HDR, scenes often look unnatural and lose detail in dark or bright areas.

AI accelerators play a special role in modern GPUs. Neural network technologies are actively integrated into the graphics pipeline. AI is used for denoising in path tracing, image scaling, frame generation, and texture quality improvement. Technologies like DLSS use neural networks to reconstruct a high-quality image from a lower resolution. This allows for a significant increase in performance without a noticeable loss of quality.

Another important feature is support for asynchronous computing. The GPU can perform graphics and computing tasks simultaneously, which allows for more efficient use of processor resources. For example, while one part of the GPU is performing rasterization, another can perform denoising or AI processing. This significantly improves performance in complex scenes.

Modern graphics APIs such as Vulkan, DirectX 12, and Metal provide low-level access to the GPU. This allows developers to more efficiently manage memory, command queues, and compute synchronization. Low-level APIs are especially important for photorealistic rendering because they allow you to take full advantage of the GPU's hardware capabilities.

In modern photorealistic image generation systems, post-processing plays an important role. After the main rendering, the GPU performs additional frame processing: bloom, depth of field, motion blur, chromatic aberration, color grading, and other effects. It is post-processing that often creates a cinematic look to the scene and enhances the impression of realism.

The complexity of modern graphics requires efficient optimization techniques. GPUs use level of detail, frustum culling, occlusion culling, and adaptive sampling to reduce the number of calculations. Such techniques allow maintaining high frame rates even in highly detailed scenes. Without optimization, even the most powerful GPUs would not be able to render photorealistic scenes in real time.

A promising direction of development is full path tracing in real time. This requires further growth in GPU performance and the development of AI technologies. It is expected that future GPUs will integrate ray tracing, neural network reconstruction, and physically correct rendering even more closely. As a result, the boundary between offline and real-time rendering will gradually disappear.

Thus, the features of generating photorealistic images on GPUs are determined by the massively parallel architecture of graphics processors, programmable shaders, specialized RT cores, high-speed memory and integration of AI technologies. It is GPUs that provide the ability to perform complex lighting algorithms, ray tracing and post-processing in real time. Further development of graphics processors and neural network technologies will become the basis of a new generation of photorealistic computer graphics.



Figure 1. GPU architecture

Figure 1 shows a simplified modern graphics processing unit (GPU) architecture, represented as rectangular functional blocks. The diagram shows the main components of the GPU and how they interact to perform graphics and computational tasks.

At the top of the figure is the PCI Express interface. It is through it that the graphics processor communicates with the central processor and the computer's RAM. PCI Express provides the transfer of commands, textures, geometry and other data between the CPU and the GPU.

The GPU service blocks are shown below: the command processor, the graphics engine, the DMA engine, the video encoding engine, the video decoding engine, and the system control unit. The command processor is responsible for receiving and processing commands from the driver and the CPU. The graphics engine performs basic graphics operations. The DMA engine provides fast data copying between memory without loading the central processor. The video encoding and decoding blocks are used for hardware processing of video streams. The system control unit coordinates the operation of all GPU components.

The central part of the scheme is occupied by the global task scheduler. It distributes calculations between individual GPU graphics clusters and controls the execution of parallel threads.

The architecture is based on GPCs – graphics processor clusters. Each GPC contains a rasterizer, SM blocks, L1 cache, and texture blocks. The rasterizer converts geometric primitives into pixel fragments. SM blocks are the main GPU computing modules. They are where shaders, ray tracing, lighting calculations, and other graphics operations are performed. A large number of SMs provides massively parallel data processing.

The L1 cache is used for fast access to frequently used data within the cluster. Texture blocks perform texture reading, filtering, and interpolation, which is critical for generating photorealistic materials.

On the sides of the circuit are memory controllers and memory channels. They provide data exchange between the GPU and video memory. A large number of memory channels is needed for high bandwidth, since modern graphics operate with huge volumes of textures, geometry and intermediate buffers.

The bottom shows the L2 cache. It is shared by all GPU clusters and is used to speed up access to global memory. Below is the interconnect or memory bus that connects all GPU components to the video memory.

The last layer of the circuit is the video memory of the HBM or GDDR6X type. It is here that textures, frame buffers, scene geometry, shader data and calculation results are stored. High speed of video memory is critical for generating photorealistic images.

Thus, the figure demonstrates a modern modular GPU architecture, in which a large number of parallel computing units, caches, and memory controllers provide high-performance generation of photorealistic graphics, ray tracing, and execution of complex AI algorithms.

Prospects for the development of photorealistic graphics.

Modern photorealistic computer graphics is at a stage of extremely rapid development and constant transformation. If earlier the main task of graphics systems was to display geometric objects with basic lighting, today digital visualization strives for the most accurate reproduction of the real world. Further development of graphics is determined by the simultaneous improvement of hardware, rendering algorithms, neural network methods and interactive interaction systems. Photorealistic scenes are already used in cinematography, computer games, architectural visualization, medicine, engineering and scientific research. In the future, the role of such technologies will only grow, as digital environments will become an integral part of everyday human life.

One of the main directions of development is the improvement of ray tracing in real time. Today, most interactive systems use hybrid rendering, where rasterization is combined with individual elements of ray tracing. However, the industry is gradually moving towards full path tracing, in which all light interactions in the scene are calculated physically correctly. This will eliminate the approximate methods characteristic of classical graphics and provide the most natural lighting. As a result, digital scenes will have correct reflections, refractions, soft shadows and global illumination without the need for complex manual settings. The transition to full path tracing will be one of the biggest breakthroughs in the field of photorealistic visualization.

The further development of ray tracing directly depends on the evolution of graphics processors. Modern GPUs already contain RT cores optimized for checking ray intersections with scene geometry. However, to implement full path tracing in complex scenes, even greater performance is required. In the future, an increase in the number of specialized computing units, increased memory bandwidth, and the development of new types of data caching are expected. Reducing power consumption will also be an important direction, since modern high-performance GPUs consume a significant amount of electricity. Energy efficiency will be one of the key factors in the development of next-generation graphics systems.

Artificial intelligence will play a special role in the future. Neural networks are already used for denoising, super resolution and texture generation, but their capabilities are constantly expanding. In the future, AI can become a major component of the graphics pipeline. For example, instead of full physical rendering, a neural network can predict the result of lighting based on partial scene data. This will significantly reduce the amount of calculations and increase the speed of rendering. In addition, AI systems will be able to automatically create geometry, textures, animation and character behavior, which will greatly simplify content production.

Neural network methods for generating images are opening up new approaches to creating digital scenes. Text-to-image systems are already capable of generating photorealistic images based on text descriptions. In the future, they may evolve into full-fledged systems for generating interactive three-dimensional worlds. The user will be able to describe the environment in words, and AI will automatically create geometry, lighting, textures, and animation. This will radically change the computer graphics industry, as a significant part of the work of artists and designers will be automated. At the same time, the role of creative management and control of the result will increase.

A promising direction is neural rendering – rendering based on neural networks. In such systems, the classic stages of the graphics pipeline are partially or completely replaced by AI models. For example, a neural network can reconstruct a high-quality image based on simplified geometry or predict complex lighting effects without full physical modeling. This will significantly reduce the load on the GPU and increase performance. Neural rendering is especially important for mobile devices, VR systems, and cloud rendering, where computing resources are limited.

Physically correct rendering will remain an important area of development. Modern systems are already capable of realistically modeling solid surfaces, liquids, fabrics, and atmospheric effects, but many physical processes are still implemented in a simplified manner. In the future, the development of spectral rendering is expected, which will take into account not only the RGB color channels, but the full spectrum of light. This will allow for more accurate modeling of refraction, dispersion, and the interaction of light with materials. Subsurface scattering models will also be improved, which is especially important for leather, wax, marble, and organic materials.

Virtual and augmented reality systems will develop significantly. To ensure the effect of presence, VR requires not only high scene detail, but also a stable frame rate and minimal latency. The human eye is very sensitive to artifacts in a VR environment, so even minor rendering errors can disrupt the sense of reality. In the future, VR systems will use full ray tracing, AI reconstruction and new types of displays with high refresh rates. This will allow the creation of digital environments that will be almost indistinguishable from the real world.

Augmented reality will also be an important driver for the development of photorealistic graphics. In AR, digital objects are integrated into the real environment, so they must correctly interact with the light, shadows and perspective of the real world. This requires high-precision tracking systems, computer vision and physically correct rendering. In the future, AR can be used not only in entertainment, but also in medicine, industry, education and engineering.

One of the most promising areas is the creation of digital twins. A digital twin is a highly accurate virtual copy of a real object or environment. Photogrammetry, scanning, AI reconstruction, and photorealistic rendering are used to create it. Such systems can be used to model cities, production processes, medical facilities, and even the human body. In the future, digital twins will become an important part of engineering, medicine, and control systems.

The approach to creating content in computer games will also change significantly. Open worlds are becoming larger and more complex, so manually creating all the elements of a scene is practically impossible. Procedural generation and AI systems will allow you to automatically create landscapes, vegetation, cities, characters and textures. As a result, digital worlds will become more dynamic and adaptive. Content will be able to change in real time depending on the user's actions or the game scenario.

The development of cloud rendering will be of great importance. In this approach, complex graphics calculations are performed on remote servers, and the user receives a ready-made video stream. This will allow running high-quality graphics even on low-power devices. Cloud rendering is especially promising for VR, streaming games, and metaverses. In the future, the user will not need to have a powerful GPU - a fast network connection will be enough.

The development of metaverses will also stimulate the improvement of photorealistic graphics. The metaverse involves the creation of a permanent interactive digital space where users can work, communicate, learn and have fun. This requires realistic avatars, complex digital environments and high-quality real-time graphics. That is why the development of metaverses is closely related to ray tracing, AI and physically correct rendering.

A promising direction is the integration of computer graphics with computer vision. Systems of the future will not only generate scenes, but also analyze the environment. This is especially important for autonomous robots, AR systems and digital twins. The combination of graphics and computer vision will allow you to create adaptive environments that respond to user actions and changes in the real world.

In cinematography, photorealistic graphics are gradually replacing traditional sets and special effects. Virtual studios and LED screens are already used in film production. In the future, most scenes may be created entirely digitally. AI systems will help automatically generate backgrounds, characters, and visual effects. This will significantly reduce costs and speed up production.

Despite the huge prospects, the development of photorealistic graphics also poses certain risks. In particular, deepfake technologies allow you to create extremely convincing fake videos and images. This can be used to manipulate information or violate human rights. In the future, there will be a need for special systems for verifying the authenticity of digital content and legal mechanisms for regulating AI generation.

Thus, the prospects for the development of photorealistic graphics are associated with the complex development of GPU, ray tracing, artificial intelligence, VR/AR, metaverses and physically correct rendering. In the future, the boundary between real and digital images will become almost invisible. Computer graphics will become not only a visualization tool, but also the basis of new digital environments, where a person will interact with information, objects and other users in the most realistic way.

Trends in the development of graphics engines.

The modern development of computer graphics and interactive systems necessitates the constant improvement of graphics engines, which are the basis for creating video games, virtual and augmented reality systems, simulators, automated design systems, and interactive visualizations. A graphics engine is a set of software tools that provide scene construction, three-dimensional graphics rendering, physical modeling, lighting, animation, sound processing, user interaction, and support for network technologies. In the coming years, significant development of graphics engines is planned in the direction of increasing image realism, rendering performance, integration of artificial intelligence, and adaptation to new hardware platforms. One of the main trends is the introduction of real-time ray tracing technologies. Traditional rasterization methods are gradually being supplemented or partially replaced by ray tracing and path tracing algorithms, which allow modeling physically correct light propagation. This provides a much more realistic display of shadows, specular surfaces, global illumination and translucent materials. These technologies are especially actively implemented in modern versions of Unreal Engine, where the Lumen and Nanite systems are used. Lumen provides dynamic global illumination without the need for prior calculation of light maps, and Nanite implements virtualized geometry, which allows the use of scenes with an extremely large number of polygons without a significant decrease in performance. It is expected that in the next generations of engines, ray tracing will become a standard component of the graphics pipeline, and specialized GPU hardware units will be even more optimized for performing such calculations.

Another important direction of development of graphics engines is the integration of artificial intelligence technologies. Modern engines are already beginning to use AI for automatic generation of content, character animation, creation of textures and optimization of scenes. In the future, artificial intelligence will be able to automatically form significant fragments of the game world, generate the behavior of non-game characters and adapt graphics to the capabilities of the user's hardware. Neural image reconstruction methods such as DLSS, FSR and XeSS are of particular importance, which allow forming high-resolution images based on rendering in a lower resolution. This makes it possible to significantly increase performance without a noticeable loss of quality. It is planned that future engines will use AI not only for image scaling, but also for lighting generation, smoothing of contours, optimization of geometry and procedural creation of animations.

Much attention is also paid to the development of procedural generation technologies. Modern game worlds are becoming extremely large and detailed, so the manual creation of all objects requires significant time and resources. Procedural generation allows you to automatically form landscapes, vegetation, architectural objects and even plot elements based on mathematical algorithms and rules. In future graphics engines, it is planned to use procedural systems in combination with artificial intelligence even more widely. This will allow you to create practically unlimited virtual worlds with a high level of detail and minimal manual labor. Such technologies are especially relevant for open worlds, metaverses and VR environments.

An important direction of development is the improvement of anti-aliasing and image reconstruction technologies. With the increase in display resolution, the problem of aliasing is gradually decreasing, but at high scene speeds and the use of complex shaders it remains relevant. Therefore, further improvement of TAA, DLAA, SMAA and hybrid AI smoothing algorithms is planned. The use of neural networks to restore small scene details and eliminate noise after ray tracing is especially promising. It is expected that in the future, traditional smoothing algorithms will gradually be replaced by intelligent image reconstruction systems.

A separate trend is the development of engines for virtual and augmented reality. The spread of XR devices, AR glasses, and spatial computing systems stimulates the creation of new approaches to rendering. For VR, high frame rates and minimal latency are critically important, so engines are optimized for multi-threaded processing and adaptive rendering. In the future, widespread implementation of foveated rendering is planned - a technology in which full detail is formed only in the area where the user is looking. This allows significantly reducing the load on the GPU and increasing the performance of VR systems. OpenXR standards are also actively developing, providing universal support for various XR platforms.

An important aspect of the development of graphics engines is the transition to cloud rendering and distributed computing. The increase in the speed of Internet connections and the development of data centers allow complex graphics calculations to be transferred to remote servers. This opens up the possibility of running high-quality graphics even on low-power devices. In the future, graphics engines will increasingly integrate support for cloud rendering, streaming rendering, and edge computing. Similar technologies are already used in streaming gaming services. It is expected that with the development of 5G and future communication networks, cloud rendering will become a full-fledged alternative to local execution of graphics calculations.

One of the key trends is also the universalization of engines. If earlier graphics engines were focused mainly on creating games, today they are actively used in cinema, architectural visualization, medicine, education and industrial modeling. For example, Unreal Engine is already widely used to create virtual film studios and digital scenery. In the

future, the line between game engines and professional visualization systems will gradually disappear. Engines will support photorealistic rendering, simulation of physical processes, integration of CAD systems and work with digital twins of industrial objects.

Special attention is paid to optimizing the operation of graphics engines on multi-core processors and modern GPUs. New APIs such as Vulkan, DirectX 12 and Metal allow for more efficient use of hardware resources and minimize driver overhead. Further improvements are planned for asynchronous computing, shader execution reordering and mesh shaders. This will ensure more efficient use of the GPU's parallel architecture and will allow for the implementation of complex scenes with billions of polygons in real time. Considerable attention is also paid to energy efficiency, especially for mobile devices and portable gaming systems.

In parallel, open-source engines are actively developing, among which Godot stands out. Its popularity is growing due to its open source code, Vulkan support, and the absence of expensive licenses. In the coming years, improvements in global lighting systems, physical modeling, and animation tools are expected. Open engines can become a serious alternative to commercial platforms, especially for indie developers and educational projects.

Thus, the future development of graphics engines will be associated with increasing the realism of graphics, the integration of artificial intelligence, the development of XR technologies, procedural generation and cloud rendering. It is expected that the scope of application of engines will significantly expand, their adaptation to new hardware platforms and the transition to intelligent methods of image construction. All this will contribute to the creation of high-quality interactive environments of a new generation that will combine photorealism, high performance and extensive possibilities for automating the development process.

Modern lighting models (BRDF).

Modern BRDF models are one of the key directions in the development of photorealistic computer graphics. BRDF is a bidirectional reflectance distribution function that describes how light is reflected from a surface depending on the direction of incidence and the direction of observation. It is the BRDF that determines the nature of the gloss, roughness, intensity of reflections and the overall visual appearance of the material. The development of new BRDF models has become necessary due to the increasing demands for realism in graphics in video games, the film industry, virtual reality systems and digital design.

The first BRDF models were quite simple and based on empirical dependencies. They allowed to form basic specular reflections, but did not take into account the complex microstructure of surfaces. As a result, the materials looked artificial, and the lighting did not comply with physical laws. Modern BRDF models are focused on physically correct modeling of the behavior of light and take into account the features of real materials.

One of the most important modern trends is microfacet BRDF models. In such models, the surface is considered as a set of a large number of microscopic facets, each of which reflects light differently. It is the microfacet approach that allows you to create realistic specular reflections, smooth gloss transitions and the natural appearance of materials. The rougher the surface, the wider and softer the light reflection becomes.

Among modern models, the Cook–Torrance model has gained particular popularity. It is the basis of most modern physically based rendering systems. The model takes into account the distribution of microfacets, the effect of self-shadowing and mutual shielding of surface micro-irregularities. This ensures realistic formation of glare for metals, plastics, glass and other materials. The Cook-Torrance model is actively used in modern graphics engines Unreal Engine, Unity and Blender Cycles.

The GGX and Trowbridge-Reitz models were important developments in the development of BRDF. They allow for more accurate modeling of the long specular tails that are characteristic of real rough surfaces. Compared to the older Blinn–Phong or Beckmann models, GGX provides more natural reflections and behaves better at low viewing angles. That is why GGX is now the standard for modern PBR rendering.

The new BRDF models also actively take into account the anisotropy of surfaces. In the real world, many materials have a directional structure, due to which light is reflected unevenly in different directions. This is typical for polished metal, hair, fabrics, CDs or carbon surfaces. Anisotropic BRDFs allow you to model elongated glare and complex lighting effects, which significantly increases the realism of the visualization.

A separate direction is multi-layer BRDF models. Real materials often consist of several layers, each of which interacts with light differently. For example, car paint contains a base color layer, metal particles, and a clear varnish. Modern multi-layer BRDFs allow you to model complex optical effects, including internal reflections, color casts, and changes in gloss depending on the viewing angle.

An important achievement was the BRDF models for subsurface scattering. Some materials partially transmit light into their structure, where it is scattered many times before exiting. This is the case with human skin, marble, wax, milk, or plant leaves. For such cases, classic BRDFs are no longer sufficient, so more complex BSSRDF models are used. They allow for the formation of soft natural lighting and provide high realism of digital characters.

Modern research is actively developing measured BRDF models. In such systems, the characteristics of materials are not set manually, but are obtained by scanning real surfaces using special equipment. This allows for very accurate reproduction of the properties of metals, fabrics, leather, wood and other materials. Databases of measured BRDFs are used in professional film production and industrial visualization systems.

A new trend is neural BRDF models. These approaches use machine learning algorithms that can automatically reproduce the complex lighting characteristics of materials. Neural networks analyze photographs of surfaces and build compact mathematical representations of their behavior. This allows for significant data reduction and faster rendering without any noticeable loss of quality.

Another promising direction is spectral BRDFs. Traditional RGB models work with only three color channels, while spectral approaches take into account a wide range of wavelengths of light. This allows for more accurate modeling of rainbow effects, dispersion, interference, and other complex optical effects. Spectral BRDFs are especially important for scientific visualization and high-quality cinematic rendering.

Modern graphics engines widely use optimized BRDF models for real-time operation. Since complex physical calculations require large resources, various approximation and pre-calculation methods are used. This allows combining high realism with sufficient performance even in complex interactive scenes.

BRDF models for fabrics and organic materials have been significantly developed. Textile surfaces have a complex fiber structure, due to which light is scattered repeatedly between the threads. For such materials, specialized models are used that take into account the direction of the fibers, the microstructure of the fabric and the peculiarities of light scattering. This allows you to create realistic clothing in modern games and animated films.

In the future, the development of BRDF will be associated with even more accurate physical modeling of materials, the use of artificial intelligence and the integration of real-time ray tracing. It is expected that future rendering systems will be able to automatically determine material properties based on photographs or videos and instantly generate high-quality photorealistic scenes.

Thus, modern BRDF models are the basis of photorealistic graphics and provide accurate modeling of the interaction of light with materials. The main trends in their development are the use of microfacet models, multilayer structures, spectral analysis, subsurface scattering and neural technologies. It is these approaches that form a new level of quality of modern computer graphics and provide the maximum approximation of digital images to the real world.

Photorealistic graphics in modern conditions is one of the most dynamic areas of development of computer technologies. The rapid growth of the computing power of graphics processors, the spread of ray tracing algorithms, the improvement of global illumination models and the development of artificial intelligence have led to the emergence of new software products capable of generating images that are almost indistinguishable from photographs. If earlier photorealism was available only to large film studios or specialized research centers, today the corresponding technologies are actively used in computer games, architectural design, design, virtual reality, advertising, medicine, digital art and industrial modeling. Modern software complexes combine physically correct lighting models, methods of procedural content generation, global shading algorithms and artificial intelligence systems to automate complex processes of scene creation.

Photorealistic graphics software products.

One of the most important areas of development of software products for photorealistic graphics is the implementation of real-time ray tracing technology. Traditional rasterization methods have long remained the basis of graphics engines due to their high speed, but they did not provide physically accurate modeling of light. Modern graphics platforms have begun to actively use hybrid methods, where rasterization is combined with ray tracing. This has made it possible to realistically reproduce reflections, light refraction, global illumination, soft shadows and complex lighting effects. One of the leading software products in this area is the Unreal Engine 5 graphics engine from Epic Games . This engine uses Lumen and Nanite technologies, which allow you to implement dynamic global illumination and work with extremely detailed geometric models without a significant drop in performance. Lumen technology automatically calculates indirect lighting and reflections in real time, which significantly increases the level of photorealism of the scene.

Another important software product is Unity , which is actively developing the HDRP (High Definition Render Pipeline) direction. HDRP is focused on creating high-quality graphics with support for physically correct lighting, volumetric effects, procedural materials, and ray tracing. A feature of modern graphics engines is the integration of machine learning algorithms to improve image quality. For example, image scaling technologies based on neural networks allow for the formation of high-quality images with less load on the GPU. Such approaches are implemented in NVIDIA 's DLSS and AMD 's FSR technologies . Their integration into modern software products provides a significant increase in performance without a noticeable loss of quality.

A special place among software for photorealistic graphics is occupied by professional 3D modeling and rendering systems. One of the most popular solutions is Autodesk Maya . This system is widely used in the film and animation industry due to its support for complex lighting models, procedural texture generation, character animation, and integration with physically correct renderers. Modern versions of Maya support GPU rendering, which significantly reduces the time for creating photorealistic scenes. An important advantage is the ability to integrate with Arnold Renderer, which provides highly accurate modeling of light and materials. Arnold uses the Monte Carlo method for global illumination, supports BRDF and BSDF models, and also provides high-quality simulation of light scattering in translucent materials.

Blender software product has also become widely used, having transformed from an amateur system into a powerful professional complex for creating photorealistic graphics in recent years. Blender contains the Cycles and Eevee renderers. Cycles implements physically correct ray tracing and supports modern lighting models, while Eevee is focused on fast real-time rendering. An important feature of Blender is the integration of procedural node systems for creating materials. Thanks to the use of node architecture, it is possible to model complex surfaces of metals, fabrics, leather, glass and other materials with a high degree of realism. Blender is actively used by independent studios, designers and scientists due to its open source code and constant updating of functionality.

Among modern visualization systems, specialized renderers play an important role. One of the most popular is V-Ray from Chaos. This software product is used for architectural visualization, interior design and the creation of advertising products. V-Ray provides high-quality modeling of global illumination, photometric light sources, atmospheric effects and complex materials. Of particular importance is the support of a physically correct camera, which allows you to simulate the parameters of real optics: depth of field, exposure, chromatic aberrations and cinematic effects. New versions of V-Ray actively use GPU acceleration and artificial intelligence to reduce image noise during rendering.

Significant progress has also been observed in the development of procedural content creation systems. One of the leading software products in this area is Adobe 's Substance 3D Designer . This system allows you to generate procedural textures and materials based on a nodal architecture. The use of a procedural approach provides high surface detail and the ability to quickly modify material parameters. This is especially important for creating large scenes in computer games and the film industry. Together with Substance Painter, the system provides the creation of PBR materials that take into account the physical properties of surfaces, in particular roughness, metallicity, transparency and microrelief.

Houdini from SideFX is actively used to simulate smoke, fire, liquids, and destruction . Houdini is a procedural platform that allows you to create complex visual effects using mathematical and physical models. The software product is widely used in cinematography to create large-scale disaster scenes, simulate natural phenomena, and generate large virtual worlds. Modern versions of Houdini integrate GPU computing algorithms and support physically correct lighting, which significantly increases the realism of the final result.

A separate direction in the development of software products has become the integration of generative artificial intelligence into the process of creating graphics. Systems based on diffusion models are able to automatically generate photorealistic images based on a text description. The software solutions Stable Diffusion, Midjourney and DALL·E have had a significant impact on the development of this industry . These systems use large-scale neural networks trained on huge sets of images. They are able to form complex scenes, imitate a photographic style, generate textures and even create three-dimensional concepts. Although such systems do not yet completely replace traditional 3D modeling, they significantly accelerate the stage of conceptual design and reference creation.

An important trend is the use of photogrammetry technologies and scanning of real objects. One of the modern software products in this area is RealityCapture. The system allows you to create highly accurate three-dimensional models based on a set of photographs. The resulting models can contain millions of polygons and highly detailed textures, which provides an extremely high level of photorealism. Such approaches are widely used in creating digital twins of architectural objects, historical monuments and natural landscapes.

Modern software products actively support virtual and augmented reality technologies. Photorealistic graphics in a VR environment require not only high image quality, but also stable performance, since any delays can negatively affect user comfort. New generation graphics engines implement special optimization algorithms, adaptive rendering, and ray tracing for VR systems. One of the promising areas is foveated rendering, a technology that performs high-quality rendering only in the area that the user is looking at. This allows you to significantly reduce the computational load without losing visual quality.

Cloud technologies play a significant role in the development of photorealistic graphics. Modern software products increasingly use remote GPU servers to perform complex rendering. This is especially important for animation studios and engineering companies that work with large scenes. Cloud rendering allows you to reduce image generation

time and reduce requirements for local equipment. Such services are supported by Amazon Web Services, Microsoft Azure, and Google Cloud. The integration of cloud platforms with graphics systems provides scalability and efficient allocation of computing resources.

One of the most innovative areas is neural rendering. This approach combines classical computer graphics methods with neural networks. Modern software products are starting to use neural representations of scenes to generate photorealistic images and

Conclusions.

Thus, the analysis of modern methods for generating photorealistic images showed that computer graphics today is one of the most dynamic and technologically complex branches of information technology. The development of hardware, specialized graphics processors, rendering algorithms and neural network systems has made it possible to move from simplified visualization models to the creation of digital scenes that are practically indistinguishable from real photographs. Photorealistic graphics have become an important tool in cinematography, computer games, architectural visualization, medicine, engineering design, virtual and augmented reality systems, as well as in scientific research. Its development is determined by a combination of mathematical models, physical laws, high-performance GPUs and artificial intelligence technologies.

The study found that the foundation of modern photorealistic graphics is physically correct modeling of light. It is the accurate reproduction of the processes of reflection, refraction, scattering and global illumination that ensures the natural perception of a digital scene. Ray tracing and path tracing methods have become the basis of modern rendering, as they allow you to create realistic shadows, reflections, transparency and indirect lighting. Unlike classic rasterization, ray tracing is focused not only on speed, but also on the physical accuracy of visualization. That is why modern graphics engines and professional renderers are increasingly actively integrating ray tracing algorithms into real-time systems.

An important result of the study is the confirmation that the development of graphics processors has become a key factor in the evolution of photorealistic graphics. GPUs with massively parallel architecture provide the ability to simultaneously perform a large number of calculations necessary for the formation of complex digital scenes. The use of programmable shaders, RT cores, high-speed memory and modern graphics APIs allows for the implementation of physically correct rendering in real time. Of particular importance was the emergence of hardware acceleration ray tracing, thanks to which photorealistic effects ceased to be exclusively a tool for offline rendering and became available for interactive systems and computer games.

The study showed that physically correct rendering technologies PBR play a significant role in modern graphics. The use of BRDF models, roughness, metallic, normal map and ambient occlusion maps allows you to accurately describe the properties of materials and ensure their uniform behavior under different lighting conditions. It is PBR that has become the standard for modern graphics engines, as it provides a stable level of realism and simplifies the creation of digital content. In addition, the development of HDR, volumetric lighting, deferred rendering and modern anti-aliasing methods has significantly improved image quality and allowed to eliminate a large number of visual artifacts.

Special attention is paid to neural network technologies for image generation. The analysis showed that artificial intelligence is already significantly transforming approaches to creating graphic content. Generative models, diffusion systems, and neural rendering allow automating a significant part of processes that were previously performed manually. Neural networks are used for texture generation, noise reduction, image scaling, scene reconstruction, animation synthesis, and the creation of photorealistic compositions based on text descriptions. The combination of AI with classical rendering methods opens up new prospects for accelerating calculations and automating the creation of digital environments.

The research also found that modern photorealistic graphics are increasingly focused on interactivity. If previously high-quality rendering required long offline calculations, today a significant part of complex lighting effects is formed in real time. Hybrid rendering, which combines rasterization and ray tracing, has become a compromise between speed and quality. This approach is the basis of modern AAA games, VR systems and professional visualization platforms. Further development of hardware will allow in the future to switch to full path tracing in real time.

An important conclusion is that the prospects for the development of photorealistic graphics are directly related to the further integration of artificial intelligence. Neural network technologies are gradually becoming not only an auxiliary tool, but a full-fledged component of the graphics pipeline. It is expected that future graphics systems will be able to automatically generate geometry, textures, lighting and animation based on a text description or user behavior. This will significantly change the approaches to creating digital content and will allow the formation of interactive worlds of a new generation.

A promising direction of development is also the creation of digital twins and virtual and augmented reality systems. Such systems require the most accurate reproduction of the physical properties of the real world, the correct

interaction of light with materials, and high rendering speed. It is photorealistic graphics that will become the basis of future metauniverses, engineering simulators, medical visualizations, and interactive learning environments. In this context, neural rendering, AI reconstruction, and cloud rendering technologies are of particular importance.

Thus, modern photorealistic graphics are the result of a synthesis of mathematical methods, physical lighting models, high-performance graphics processors and neural network technologies. Its development is aimed at achieving maximum visual fidelity while maintaining high performance of interactive systems. Further improvement of GPU, ray tracing algorithms, physically correct rendering and artificial intelligence will become the basis of a new generation of digital visualization. In the future, the boundary between real and digital images will gradually disappear, and photorealistic computer graphics will become an integral part of most information technologies.

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5.2. Disinformation in Social Networks: Dissemination Mechanisms, Monitoring Methods, and Designing a Countermeasure System Using the Example of Facebook and X

Given the current state of affairs in the information field of Ukraine, researching the impact of disinformation on public opinion is highly relevant, as information is a key resource in shaping social reality. Disinformation and fake news can influence political decisions, public sentiment, and state security. The importance of combating disinformation is confirmed by numerous international studies demonstrating its role in hybrid warfare and the manipulation of public opinion.

For instance, in 2016, disinformation influenced the results of the presidential election in the United States, when fake news was massively disseminated on social networks. In 2022, Russian propaganda actively used manipulative narratives regarding the war in Ukraine to disorient the international community. During the COVID-19 pandemic, fake news about vaccines contributed to an increase in the level of distrust toward medicine and vaccination.

In recent years, a significant shift in communication channels among Ukrainians has been observed. Specifically:

- Social networks and messengers have become the dominant sources of information.
- Television continues to play a significant role, but its importance is gradually decreasing.

According to research data: 56% of Ukrainians place the responsibility for fighting fake news on the state, 35% – on the citizens themselves; 40% of Ukrainians note that it is difficult for them to determine truthful sources of information, while 52% believe they can distinguish reliable information.

Another important indicator is that 60% support the possibility of criticizing the authorities in the media, but at the same time, the same percentage believes that the state should tighten control over information on the Internet.

In modern conditions, social networks such as Facebook and the X network have become the main platforms for disseminating information. They allow users to instantly share news, comment on events, and shape public opinion. However, the speed of content distribution complicates the verification of its authenticity, which facilitates the spread of fakes and manipulations. At the same time, platforms attempt to combat disinformation by introducing fact-checking and labels for dubious content.

According to DataReportal data, in January 2024, there were 24.30 million active social network users in Ukraine. Analysis showed that the number of social network users in Ukraine decreased by 2.4 million (-9.0%) from the beginning of 2023 to the beginning of 2024. The number of social network users in Ukraine at the beginning of 2024 accounted for 64.9% of the total population, but it is important to emphasize that social network users may not represent unique individuals.

At the same time, data published in the advertising planning tools of leading social media platforms indicate that at the beginning of 2024, 21.18 million users aged 18 and older used social networks in Ukraine, which equaled 69.3% of the total population aged 18 and older at that time.

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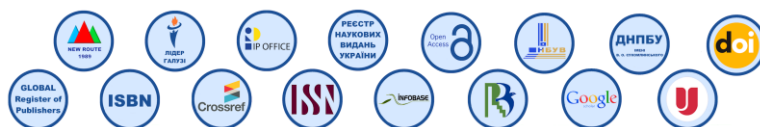
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