CSE 528 Computer Graphics (Fall 2024)
Homework One

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Non-programming Part

1. (30 points)

(a) Brief definition of Computer Graphics:

Ans) Computer graphics is the field that focuses on generating, manipulating, and interacting with visual representations of objects or data through the use of computers. It enables the creation of both realistic and imaginary scenes based on computational models, offering a powerful medium for visualization. The famous adage "a picture is worth a thousand words" highlights the importance of visual communication, where complex data can be understood more effectively through images than text alone.

(b) Why is Computer Graphics also called Image Synthesis:

Ans) Computer Graphics is sometimes known as "Image Synthesis" since it deals with the creation of pictures using computer-based models or information. This method entails constructing visual representations, whether realistic or imagined, by imitating the look of real-world things or abstract notions. For example, in the entertainment sector, 3D animations of characters in films such as *Toy Story* are totally created using computer models. Similarly, in video games, virtual worlds are created from digital data, providing players with interactive experiences that resemble real-life landscapes or fanciful settings.

In scientific visualization, computer graphics are used to create visualizations of complicated data, such as weather simulations or medical scans, allowing researchers to evaluate events that would otherwise be impossible to view firsthand. The title "Image Synthesis" conveys the spirit of this process, which involves synthesizing visual material by combining algorithms, geometric models, and data to generate pictures that can range from photorealistic sceneries to abstract visualizations.

(c)Please provide at least ten reasons why Computer Graphics is necessary and critical to information technologies and computer science and engineering! :

Ans) Here are ten reasons why computer graphics is essential to information technologies and computer science:

1. **User Interface (UI) and User Experience (UX) Design:** Graphics are crucial for creating visually appealing and intuitive interfaces for software, websites, and mobile applications. Clear visual elements like icons, buttons, and layouts enhance usability and user satisfaction.

2. **Data Visualization:** As the need to process and analyze large datasets increases, computer graphics help visualize complex information through charts, graphs, and dashboards. These visual tools make it easier to understand trends, patterns, and relationships, leading to better decision-making and insights.

3. **Gaming and Entertainment:** Computer graphics are widely used to create 3D environments, characters, and animations. Advanced graphics technologies provide immersive experiences, whether in virtual worlds for video games or special effects in movies.

4. **Web Development:** Modern websites rely on graphics to improve interactivity and visual appeal. Technologies like WebGL, CSS3, and SVG allow developers to integrate dynamic elements, animations, and 3D visualizations directly into web pages, enhancing the overall user experience.

5. **Remote Collaboration and Conferencing:** Graphics-enabled video conferencing platforms allow for real-time video rendering, virtual backgrounds, and interactive whiteboards. These features improve virtual meetings and collaboration, making remote work more efficient and engaging.

6. **Augmented Reality (AR) and Virtual Reality (VR):** AR and VR are transforming industries such as training, remote assistance, and product development. These technologies use graphics to create immersive, interactive environments that can simulate real-world experiences or offer new ways to engage with digital content.

7. **Software Development Tools:** Development environments and tools use visual representations of code, workflows, and system architectures. These graphical elements help developers better understand software structure and logic, accelerating the development and debugging process.

8. **Cybersecurity Monitoring:** Graphics play a key role in visualizing network traffic, attack patterns, and system vulnerabilities. Visual dashboards, heatmaps, and threat maps enable cybersecurity professionals to detect potential threats and respond more effectively to security incidents.

9. **Artificial Intelligence (AI) and Machine Learning (ML) Visualization:** Graphics help visualize complex models like neural networks, decision trees, and algorithmic outputs. These visualizations aid in understanding how the model works and in fine-tuning its performance.

10. **Cloud Computing and System Management:** Cloud platforms and virtualization tools use graphical interfaces to display resource usage, virtual machine statuses, and system performance. Visual tools help administrators manage and monitor infrastructure, simplifying the complexity of large-scale systems.

To summarize, computer graphics are essential for making complex processes more accessible, improving user interactions, and driving innovation in fields such as gaming, AI, cybersecurity, and cloud computing.

2. (30 points)

(a) Based on the reading assignment from the instructor, please do a sufficient amount of readings (based on the textbook and/or the Internet resources) and document in details at least ten areas (fields) with concrete examples in such areas why Computer Graphics technologies are of fundamental significance to the success of these fields/areas :

Ans) Computer Graphics technologies are of fundamental significance to the success of the following fields/areas

1. **Entertainment: Movies, Video Games:**

    - Filmmakers are now able to produce visually amazing and immersive experiences thanks to computer graphics, which have completely changed the film industry. Some of the uses in movies include VFX, CGI Integration, animation, character creation using MoCap (motion capture), compositing like layering techniques, depth of field and lighting adjustments etc.
    - Video game creators can build vivid worlds, engaging characters, and interactive components using computer graphics, which are essential to the production and gameplay of video games.
    - Some features like real time rendering, 3D modelling with asset creation and level design, animation, texturing, lighting and shading etc.

2. **Graphical User Interface (GUI):**

    - A crucial component of daily computing is the graphical user interface (GUI). Graphics comprehension is a prerequisite for almost all professional programmers in order to receive input and use visual elements to provide output to consumers.

- Graphical components such as Windows, menus, check boxes, radio buttons, dialog boxes, icons, and text boxes can be used by users to interact.
- Excellent visual feedback, user-friendly interaction, accessibility, and visual representation are all provided by GUIs.

3. **Computer-Aided Design and Manufacturing (CAD/CAM):**

   - Computer-aided design, or CAD, is the process of creating, modifying, analyzing, and optimizing designs using computer software.
   - 3D and 2D modelling, accuracy and precision, visualization, simulation, and analysis are some of the salient characteristics. It is extensively utilized in many different domains, such as product design, industrial design, civil engineering, architecture, and more.
   - Computer-aided design Manufacturing or CAM Controls machine tools and automates production operations with software. It turns CAD models into instructions that a machine can understand.
   - Production planning, simulation, toolpath generation, and CAD integration are some of the important features. A wide range of industries, including manufacturing, automotive, aerospace, and medical devices, employ it.

4. **Business:**

   - Engineering & Architecture Software of buildings, aircraft, automobile, computers, appliances, etc. It includes interactive design (mesh editing, wire-frame display, etc.), standard shape database, design of structural components through numerical simulation of the physical operating environment and testing: real-time animation.
   - Some applications in this field also include final product appearance: surface rendering, realistic lighting, construction planning: architects, and clients can study appearance before actual construction.

5. **Medical Applications:**

   - Computers graphics plays significant role in saving lives.
   - Also helps in training, education, diagnosis, treatment, creation of complete anatomically detailed 3D representation of human bodies.
   - Key Application include medical imaging, surgical planning and simulation, Computer-Aided Diagnosis (CAD), educational tools, telemedicine, rehabilitation and therapy, drug visualization and molecular modelling, patient education and simulation of medical conditions.

6. **Computer Art:**

   - Used in Escher Drawing which combines interlocking shapes with tessellation to convey the beauty in structure and infinity.

- Artistic tools for digital art include: Mathematical software (Matlab, Mathematica), CAD software– Sculpting, painting, calligraphy systems, graphical user interfaces, special input devices (pressure-sensitive stylus, graphical tablet, etc.)
- Also used for fine arts, commercial art, digital sculpting, digital painting, digital calligraphy.

7. **Engineering Analysis:**
   - Through improved visualization, simulation, and data interpretation in a variety of engineering domains, including mechanical, civil, electrical, and aerospace engineering, computer graphics play a critical part in engineering analysis.
   - Some of the uses of computer graphics include: visualization of complex data, finite element analysis (FEA), computational Fluid Dynamics (CFD), simulation and modelling, CAD software, structural analysis and optimization, Geographic Information Systems (GIS), machine learning and data analysis, Virtual Reality (VR) and Augmented Reality (AR), communication and presentation

8. **Scientific Visualization/Simulation:**
   - It is the scientific data representation of the picture vs. the stream of numbers.
   - Techniques used are contour plots, color coding, constant value surface rendering, custom shapes.
   - Used in life sciences in providing quantitative, three dimensional electron microscopy, scientists can see structures as they were before being sectioned for viewing in the electron microscope, medical imaging & visualization

9. **Virtual Reality (VR):**
   - Virtual Reality is a fully immersive experience that replaces the real world with a simulated environment. User interacts with objects in a 3D scene that provide a 360-degree view of the virtual world through devices like headsets. It has special input and output devices.
   - Used in various education using computer generated system & process models; used for Visual simulation: Aircraft simulator, Spacecraft simulator, Naval craft simulator– Automobile simulator, Heavy machinery simulator, Surgery simulator; virtual colonoscopy; virtual tour of historical remains.

10. **Textile Industry:**
    - The design, production, and marketing processes in the textile business have all been greatly improved by computer graphics.
    - Computer graphics is also helpful in fashion designing, real-time cloth animation, web-based virtual try-on applications.

(b) Please do further readings on key components of hardware and software in Computer Graphics and explain in detail the key components of hardware and software critically relevant to Computer Graphics systems and software environments.

Ans: Computer graphics (CG) systems combine hardware and software components to produce, alter, and display visual material. Let's break down the major components of each and how they're vital to CG systems and software environments.

Hardware Components in Computer Graphics

Computer graphics hardware is essential for swiftly and accurately rendering and showing pictures. Key components are:

Graphics Processing Unit (GPU)

- The GPU is undoubtedly the most important piece of hardware in computer graphics. It specializes in parallel processing and does the majority of the computations necessary to produce pictures, textures, and visual effects.
- The GPU's parallelism enables the quick rendering of complex 3D environments in real-time applications (for example, video games and simulations). Modern GPUs also enable shaders, which allow for enhanced lighting, texture mapping, and physics-based rendering.

Raster Devices

- A raster device is any hardware or system that depicts pictures with a raster, which is a grid of small dots or pixels organized in rows and columns. Monitors, printers, and other displays fall under the category of raster devices. Each pixel in the grid has a unique color and brightness value, which when combined produce a picture when viewed from a distance.

Video Controllers

- A video controller is hardware that controls the output of video signals from a computer to a display device (e.g., monitor or TV). It creates the signals required to display images and maintains synchronization between the graphics processor and the display.

Raster-Scan Display Processors

- A raster-scan display processor manages the flow of data from the graphics memory to the screen, organizing the pixel information into a sequence of horizontal lines (or "scan lines") that the display device can understand.

Input Devices (Mouse, Graphics Tablet, Joysticks, Motion Sensors)

- These devices enable user interaction with the graphics system. In professional settings, input devices like graphics tablets provide accuracy for jobs such as digital painting and 3D modeling.
- In creative industries, input device quickness and accuracy significantly impact workflow productivity. Motion sensors and controllers, for example, are essential components of interactive systems such as game consoles and virtual reality headsets.

Memory (RAM & VRAM)

- RAM and VRAM store data for easy access by the CPU and GPU. VRAM, in particular, holds textures, frame buffers, and other image-related data that the GPU needs rapid access to.
- More VRAM allows the GPU to process higher-resolution textures and complex scenarios without running out of memory, preventing performance bottlenecks.

Central Processing Unit (CPU)

- The Central Processing Unit (CPU) manages system functions such as job scheduling, simulation logic, and physics and lighting computations, while GPUs focus on rendering.
- In many CG systems, especially those running simulations or complex 3D environments (e.g., physics in games or CAD applications), CPU performance can become a bottleneck if it's underpowered relative to the GPU.

Storage (HDD, SSD, NVMe)

- Storage systems store materials, models, textures, and applications needed in computer graphics.
- SSDs and NVMe drives enhance loading speeds for huge assets, such as high-resolution textures and 3D models, which is crucial in disciplines like animation, VFX, and video editing.

Software Components in Computer Graphics

On the software side, CG systems are built on an ecosystem of tools, frameworks, and libraries that enable the creation, rendering, and manipulation of visual data.

Graphics Software/Engines

- Graphics software helps artists, designers, and developers generate and render 2D/3D visuals. This encompasses modeling, texturing, lighting, rigging, and animation.
- These technologies are crucial for producing films, video games, simulations, and architectural representations. A graphics engine's efficiency and feature set have a direct impact on output quality and speed.
- Examples include Maya and Blender for 3D modeling and animation.

Graphics APIs (Application Programming Interfaces)

- APIs are libraries that allow software to communicate with the hardware (mainly the GPU) to render graphics. They provide a standardized way for the CPU and GPU to execute graphics tasks like rendering shapes, applying textures, or performing transformations. Examples include OpenGL (cross-platform, used in many 3D applications).

Shaders

- Shaders are small GPU-based programs that govern the appearance of objects on screen. They choose the color, lighting, and texture for 3D models.
- Shaders provide realistic visual effects including reflections, shadows, refractions, and surface textures.
- For example, Physically-Based Rendering (PBR) shaders are used in modern games and simulations to improve lighting and surface interaction accuracy.

Rendering Software

- Rendering software simulates physical features like light, shadows, and reflections to create 2D images or videos from 3D models and situations. It supports both real-time and offline rendering.
- Real-time rendering is critical in games and simulations, but offline rendering (used in film production) values quality and photorealism above speed.

Middleware and Physics Engines

- Middleware offers specific functionality such as physics simulations, AI behavior, and animation systems. Physics engines are responsible for collision detection, particle systems, and accurate simulations of motion and materials.
- Physics engines are required in interactive applications such as video games and simulations to provide realistic interactions.
- Havok (a physics engine utilized in several video games) is an example.

3. (40 points) Please define and explain the following commonly-used terms in computer graphics:

ANS)

Raster graphics:

- OpenGL graphics pipeline takes the generic vertex attribute arrays as input and outputs the rendered raster image. Raster graphics are the final images that consist of pixels.
- They represent the output after rasterization, which is the process of converting floating point geometry (vector graphics or 3D models) to integer pixel (raster image).
- Raster devices: Computer monitors (CRT, LCD, etc.), TVs. These are raster devices because they display images on a raster, which is a regular n-D grid. Each point on the grid is called a pixel.

Virtual reality and augmented reality:

Virtual reality:

- Virtual Reality is a fully immersive experience that replaces the real world with a simulated environment. Users interact with objects in a 3D scene that provide a 360-degree view of the virtual world through devices like headsets. It has special input and output devices.
- Used in various education using computer generated system & process models; used for visual simulation: Aircraft simulator, spacecraft simulator, naval craft simulator, automobile simulator, heavy machinery simulator, surgery simulator; virtual colonoscopy; virtual tour of historical remains.

Augmented reality:

- Augmented Reality is a partially immersive experience that overlays digital information onto the real world. It enhances the user's perception of their environment by adding computer-generated elements, typically viewed through a smartphone, tablet, or AR glasses.
- Used in surgical visualization especially in neurosurgery through:
  - Enhanced Imaging: AR can overlay critical imaging data (like MRI or CT scans) directly onto the surgeon's view of the patient's anatomy. This allows for a more intuitive understanding of the structures involved.
  - 3D Reconstructions: Surgeons can visualize complex brain structures in 3D, making it easier to navigate intricate pathways and identify tumors or other anomalies.

Graphical user interface:

- Graphical user interface (GUI) is an integral part of everyday computing. Nearly all professional programmers must have an understanding of graphics in order to accept input and present output to users using visual elements.
- Users can interact through graphical elements like – Windows, cursors, menus, icons, dialog boxes, text boxes, check boxes, radio buttons, etc.
- GUIs provide great visual representation, interaction, accessibility, user-friendly interaction, and visual feedback.

Computer aided design and manufacturing:

Computer aided design (CAD):

- Uses computer software to create, modify, analyze, and optimize designs.
- Key features include: 2D and 3D modeling, precision and accuracy, visualization, simulation and analysis.
- It is widely used in various fields, including architecture, engineering, industrial design, civil engineering, product design, and more.

Computer aided manufacturing (CAM):

- Uses software to control machine tools and automate manufacturing processes. It converts CAD models into machine-readable instructions.
- Key features include: toolpath generation, integration with CAD, simulation, production planning.

- It is widely used in manufacturing, automotive, aerospace, medical devices, and more.

Data visualization:

- Data visualization in computer graphics refers to the graphical representation of data and information, enabling users to understand and access complex data sets more intuitively. This technique transforms numerical data into visual formats, making it easier to identify trends, patterns, and anomalies.
- Few applications include: business intelligence, marketing analysis, public health reporting, social research.
- Key features include: clarity, interactivity, storytelling, and variety of formats in which data can be visualized in various formats, including charts, graphs, maps, and infographics, each suited to different types of data and analysis.

Ray casting:

- Ray casting, also known as Ray Shooting, is the process of creating photorealistic rendering images which involves projecting rays from the viewpoint (camera) into the scene to determine what objects are visible. For each pixel, a ray is cast into the scene, and the first object it intersects is determined.
- Basic principles of ray casting include:
  - Only rays that reach the eye matter
  - Reverse direction and cast rays
  - Need at least one ray per pixel
- Used in applications like 2D games or simple 3D environments.
- Complexity: O(n * m), where n is the number of objects and m is the number of pixels.

Calligraphic display:

- Calligraphic display in computer graphics is a technique or system that enables the rendering of text and graphics with an artistic, handwriting-like quality, resembling traditional calligraphy.
- Key features of calligraphic display include: brush effects, variable line width, smooth curves, stylized fonts, etc.

- Some of the techniques are vector graphics which give high-quality output, stroke-based rendering, dynamic rendering, and pen pressure sensitivity which helps in more expressive calligraphic rendering.
- This approach often emphasizes the aesthetics of the written word and the fluidity of lines, creating visually appealing outputs for various applications.

Frame buffer:

- Frame buffer is essential to the processing and presentation of visuals in real-time applications, like video games and simulations, and plays a crucial part in displaying images on screens.
- A frame buffer is a section of memory used to store pixel data for an upcoming screen display. Every pixel has a unique location in the frame buffer, and its color and intensity are represented by the data that is stored there.
- Color Buffer, depth Buffer, and stencil Buffer are a few types.
- Few applications include: real-time rendering, image processing, and user interfaces.

Spatial coherence:

- Spatial coherence in computer graphics refers to how adjacent pixels or objects in an image tend to display comparable attributes like color, brightness, or texture. This idea is essential for enhancing the effectiveness of graphics algorithms and rendering processes.
- Applications of spatial coherence include ray tracing, rasterization, image filtering, and texture mapping.
- Few computer graphics techniques that use spatial coherence are tile-based rendering, level of detail, and deferred shading.

Image resolution:

- Image resolution is very important in graphics rendering. Image resolution is the amount of detail an image contains. Resolution is measured in terms of pixels, which decides the quality of the image.
- It is an important parameter for building structures and also ray generation.
- Important in computer graphics to improve the quality and detail, user experience, performance of rendering time, and file management.
- Image resolution also plays importance in the health sector for diagnostic accuracy in medical imaging, treatment planning, and also for research.

Image processing:

- In computer graphics, image processing refers to the analysis and enhancement of digital images through the use of techniques and algorithms to extract, convert, or improve information. It is important for many applications, ranging from enhancing visual quality to making intricate data processing possible.
- Image processing converts 2D images to 3D models using computer vision and computer graphics.
- Frequently used techniques in image processing are filtering, enhancement, transformations, segmentation, morphological operations, and compression.
- Applications of image processing include remote sensing, medical imaging, computer vision, augmented and virtual reality, digital photography, remote sensing, and forensics.

Linear transformation:

- In computer graphics, linear transformations are basic operations that alter geometric objects in a predictable and consistent way. These transformations, which are necessary for a number of operations like translating, rotating, scaling, and shearing objects in a 2D or 3D space, can be mathematically represented using matrices.
- Linear transformations are combinations of: Scale, Rotation, Shear, and Mirror.
- Properties of linear transformations satisfy:
  - Origin maps to origin
  - Lines map to lines
  - Parallel lines remain parallel
  - Ratios are preserved
  - Closed under composition

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- Basic principles of ray casting include:

  - Only rays that reach the eye matter
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  - Need at least one ray per pixel
- Used in applications like 2D games or simple 3D environments.
- Complexity: O (n * m), n: number of objects, m: number of pixel.

Polygon clipping:

- Polygon clipping is a crucial technique in computer graphics that involves determining which parts of a polygon lie within a specified area, typically the viewport or window. This process helps optimize rendering by discarding parts of polygons that won't be visible in the final output.
- One of the polygon clipping algorithms includes the Sutherland-Hodgman Algorithm, which is a more pipelined approach that clips each edge of a polygon individually against each side of a convex clipping window (often rectangular).
- It processes each edge of the polygon in relation to the edges of the clipping window and treats the clipper as a "black box" pipeline stage. It works well for convex regions.
- Steps for Sutherland-Hodgman Algorithm:
  - Start with the full polygon.
  - For each edge of the clipping window, clip the polygon against that edge.
  - Repeat until all edges of the clipping window have been processed.

Implicit representation of a line equation:

- Implicit representation of a line equation in computer graphics refers to the use of a mathematical equation to define a line in a two-dimensional space instead of endpoints or other geometric attributes. For some computing tasks, such as visibility computations and intersection tests, this method is quite helpful.
- Equation: The implicit equation of a line in a 2D Cartesian coordinate system can be expressed in the general form:

  $$Ax + By + C = 0$$

  where:

  - A, B, and C are constants,
  - x and y are the coordinates of any point on the line.
- Applications include: collision detection, ray casting, rendering algorithms, geometric calculations.

Parametric representation:

- In computer graphics, a parametric representation is almost always used.
- Geometric objects are specified by one or more parameters in parametric representation. For instance, a parameter that varies within a given range can be used to define a curve in two dimensions.
- Parametric representation of a line:

$$p(t) = (1 - t)p_1 + tp_2$$

  - Same form for horizontal and vertical lines.
  - Parameter values from 0 to 1 are on the segment.
  - Values ¡ 0 off in one direction; ¿ 1 off in the other direction.
  - Vector operations can be generalized to higher-dimensional geometry or general data representation.
- Applications in computer graphics include curve and surface modeling, animation, rendering, and simulation.

Window and viewport:

Window:

- It describes a specific area within the global coordinate system that indicates the area of the scene that you wish to see. Utilizing a specific viewpoint, it functions as a "camera" to frame the scene.
- Coordinate System: World coordinates are usually used to define the window. You may, for instance, establish a window that contains all of the objects in the scene from $(x_{\min}, y_{\min})$ to $(x_{\max}, y_{\max})$.
- The window's main function is to define the bounds of the scene that will be displayed into the viewport. It lets you concentrate on a certain area of a bigger scene without changing the scene itself.

Viewport:

- It refers to the rectangular region on the screen (i.e., the device coordinate system) that displays the content of the window. It controls how the window is represented on the screen.
- Coordinate System: The screen coordinates that determine the viewport usually span from $(0, 0)$ to $(\text{width}, \text{height})$ of the display window.
- The viewport's function is to project the window's content onto the screen. It manages the scene's scaling and placement during rendering.

Affine transformation:

- Affine transformations are combinations of linear transformations and translations that can be expressed in the form: $y = Ax + b$, where y is the output vector (transformed point), x is the input vector (original point), A is a linear transformation matrix, and b is a translation vector.
- Properties of affine transformations include:
  - Origin does not necessarily map to origin
  - Lines map to lines
  - Parallel lines remain parallel
  - Ratios are preserved
  - Closed under composition
- Also used in image processing and 3D modelling.

Homogeneous coordinates:

- OpenGL graphics pipeline is a 3D rendering pipeline, and it processes 3D homogeneous coordinates. Inside this pipeline, we are actually representing a 2D coordinate (x, y) or a 2D homogeneous coordinate $(x, y, 1)$ with a 3D homogeneous coordinate $(x, y, 0, 1)$. That is, we "mimic" 2D scenes by drawing 3D objects inside the plane $z = 0$.
- In homogeneous coordinates, each point (x, y) is represented as $(x, y, 1)$: append a 1 at the end of the vector.
- Rather than represent 3D points using three coordinates (x, y, z), we will use four: (x, y, z, w), because some transformations – including translation – cannot be represented by 3×3 matrices. Most of the time, $w = 1$, but there are special transformations for which $w \neq 1$.
- Composite transformation becomes much easier and can be represented as matrix multiplication. Homogeneous coordinates seem unintuitive, but they make graphics operations much easier.

Halftoning:

- How do you render a colored image when colors can only be on or off (e.g., inks, for print)? It can be accomplished by halftoning, which is a technique used to simulate continuous tones in images by creating patterns of dots.
- Halftoning involves dots of varying sizes, shapes, or spacing to create the illusion of different shades or gradients. Larger or denser clusters of dots appear darker, while smaller or more spaced-out dots appear lighter. It is also similar to dithering, which creates an illusion of color depth.

- It is commonly used in printing to reproduce detailed images with a limited number of colors, such as newspapers and magazines.