Introduction to Computer Graphics

What is Computer Graphics?

- Computer graphics is a broad field of computer science that focuses on the creation, modification, and display of visual data by computers.
- Computer graphics can be used to create anything from straightforward 2D shapes to intricate 3D models and animations, supporting a wide range of applications in various fields such as the entertainment, design, science, and educational sectors and others.

Three Main Tasks of Computer Graphics

- *MODELING* (shape) creating and representing the geometry of objects in the 3D world
- *RENDERING*: (light, perspective) generating 2D images of the objects
- *ANIMATION*: (movement) describing how objects change in time

Key Concepts of Computer Graphics

1. Rendering - the process of creating an image from a model (shown tremendous progress). Ray tracing has grown in popularity as a method of creating incredibly realistic graphics by mimicking the way light interacts with objects. Real-time ray tracing has been made possible by the introduction of GPUs with specialized ray tracing technology, such as NVIDIA's RTX series, which has improved virtual reality and gaming experiences.

Key Concepts of Computer Graphics

2. AI and Real-Time Graphics - Real-time rendering has changed as a result of artificial intelligence (AI) being included into computer graphics. Real-time upscales of lower-resolution photos are achieved by AI techniques like Deep Learning Super Sampling (DLSS), which dramatically reduce processing load while preserving good visual quality. This is particularly crucial for VR and gaming, as keeping frame rates high is essential to the user experience.

Key Concepts of Computer Graphics

3. 3D Modeling and Simulation - Over the last five years, there have also been considerable advancements in 3D modeling. Programs such as Blender and Autodesk Maya have included more capable and user-friendly tools for 3D model creation. With the advancement of physics-based simulations, more realistic representations of materials and physical interactions are now possible, leading to increasingly precise and intricate animations in a variety of industries, including science visualization, video games, and movies.

Key Concepts of Computer Graphics

4. Augmented and Virtual Reality - Both augmented reality (AR) and virtual reality (VR) are becoming more and more common. VR and AR are now more widely available thanks to recent advancements in technology and software. Real-time tracking and rendering in conjunction with high-fidelity visuals have produced more dynamic and immersive environments that are utilized in professional training, education, and gaming.

Key Concepts of Computer Graphics

Digital twins and the metaverse - The idea of a communal virtual shared environment called the Metaverse has gained popularity. Businesses like Epic Games and Meta (previously Facebook) are making significant investments in building massive virtual worlds. The representation of expansive, dynamic three-dimensional worlds is one area where these settings mostly rely on advancements in computer graphics. Advances in real-time 3D visualization and simulation have led to the emergence of digital twins, which are virtual reproductions of actual phenomena, as vital tools in engineering, healthcare, and urban planning.

Application Fields of Computer Graphics

- Graphical User Interface (GUI)
- Arts/ advertising (artificial, modified image/s sequences)
- Visualisations (graphs of functions, bar chart & pie diagrams, temperature distribution on the surface of the earth, visualization of high-dimensional data, etc.)

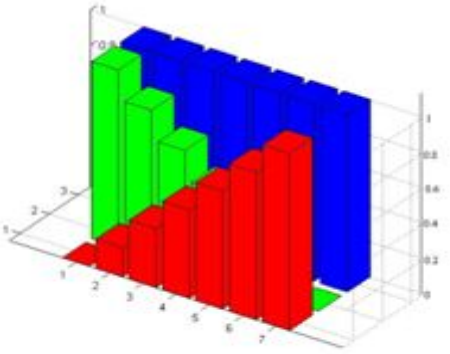
Application Fields of Computer Graphics

- Reconstructing 3D-objects from measured data (3-D scanner, ultrasonic images, etc.)
- CAD/CAM (Computer Aided Design/ Manufacturing) (Design of objects like cars, building, etc)
- Simulation and animation (flight simulators, computer games, movies, etc)

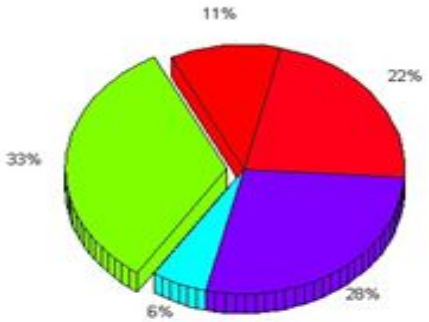
Application Fields of Computer Graphics

- Interactive TV (free choice of the viewers position, computation of image based on information from a small number of cameras.)
- Virtual reality (realistic 3D view + free movement + acoustics)
- Augmented reality (auxiliary information superimposed to the real world by a semi-transparent glasses.)

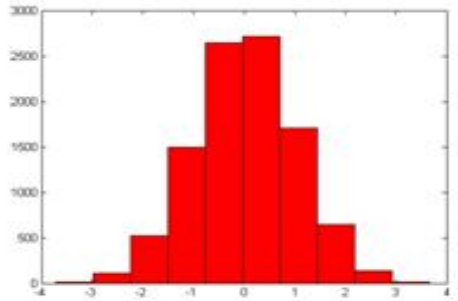
Application Fields of Computer Graphics (Examples)



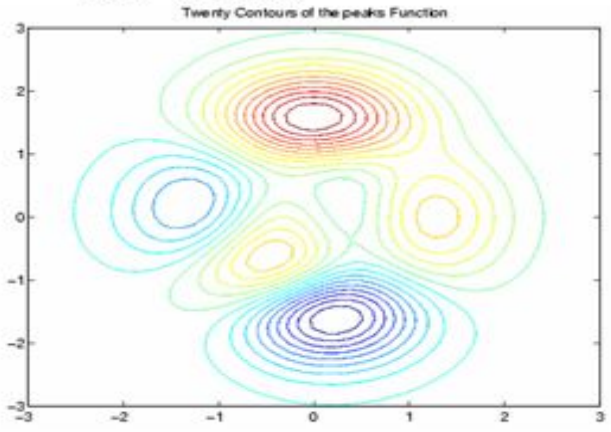
A 3D – Bar chart



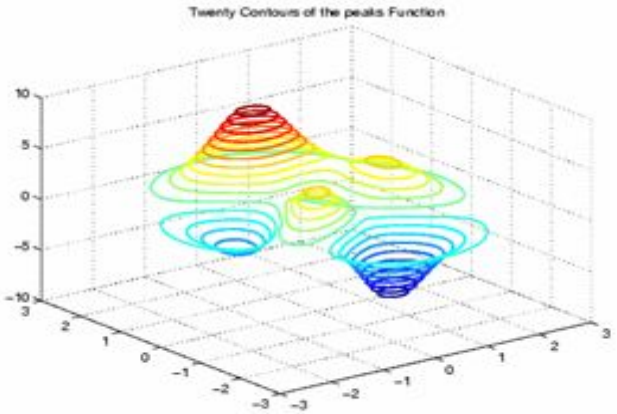
A 3D – Pie Chart



A Histogram



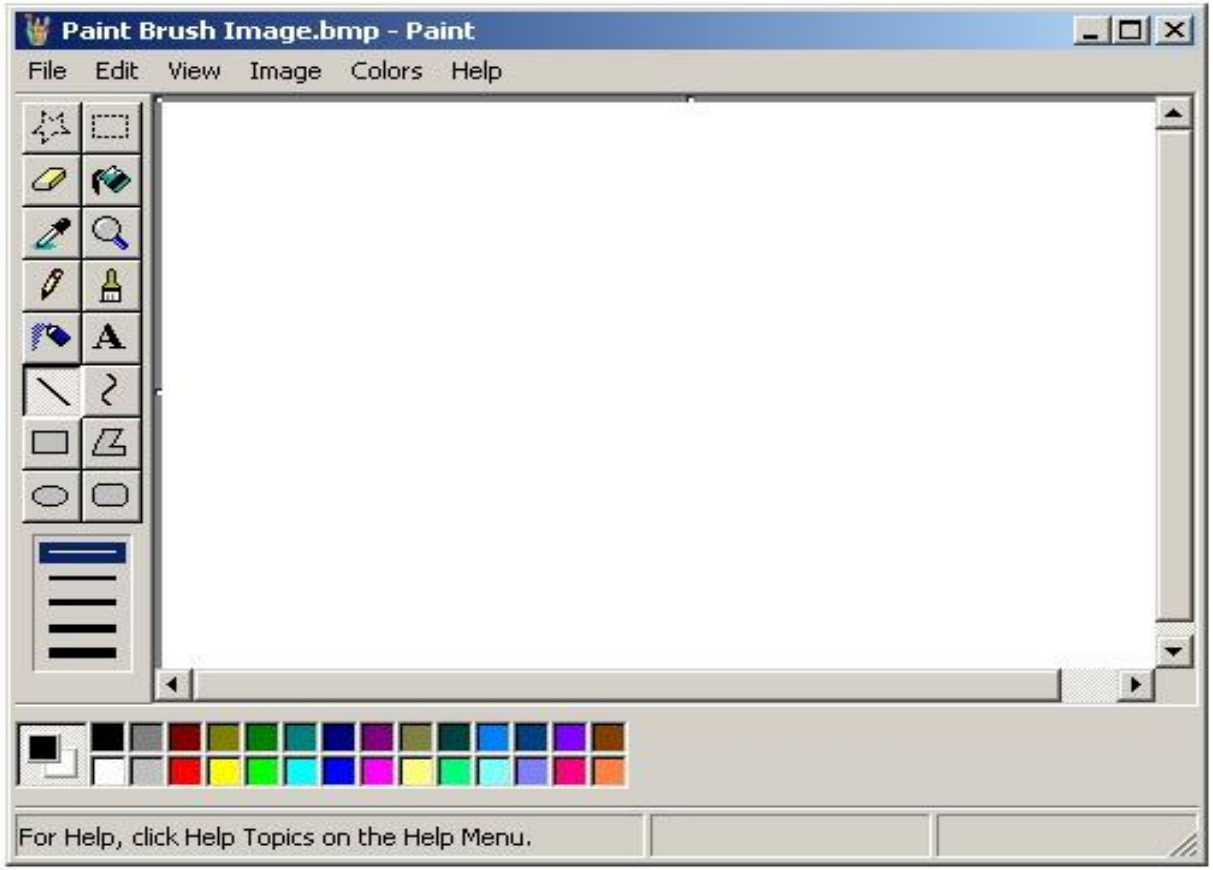
A 2D Contour Plot



A 3D Contour Plot

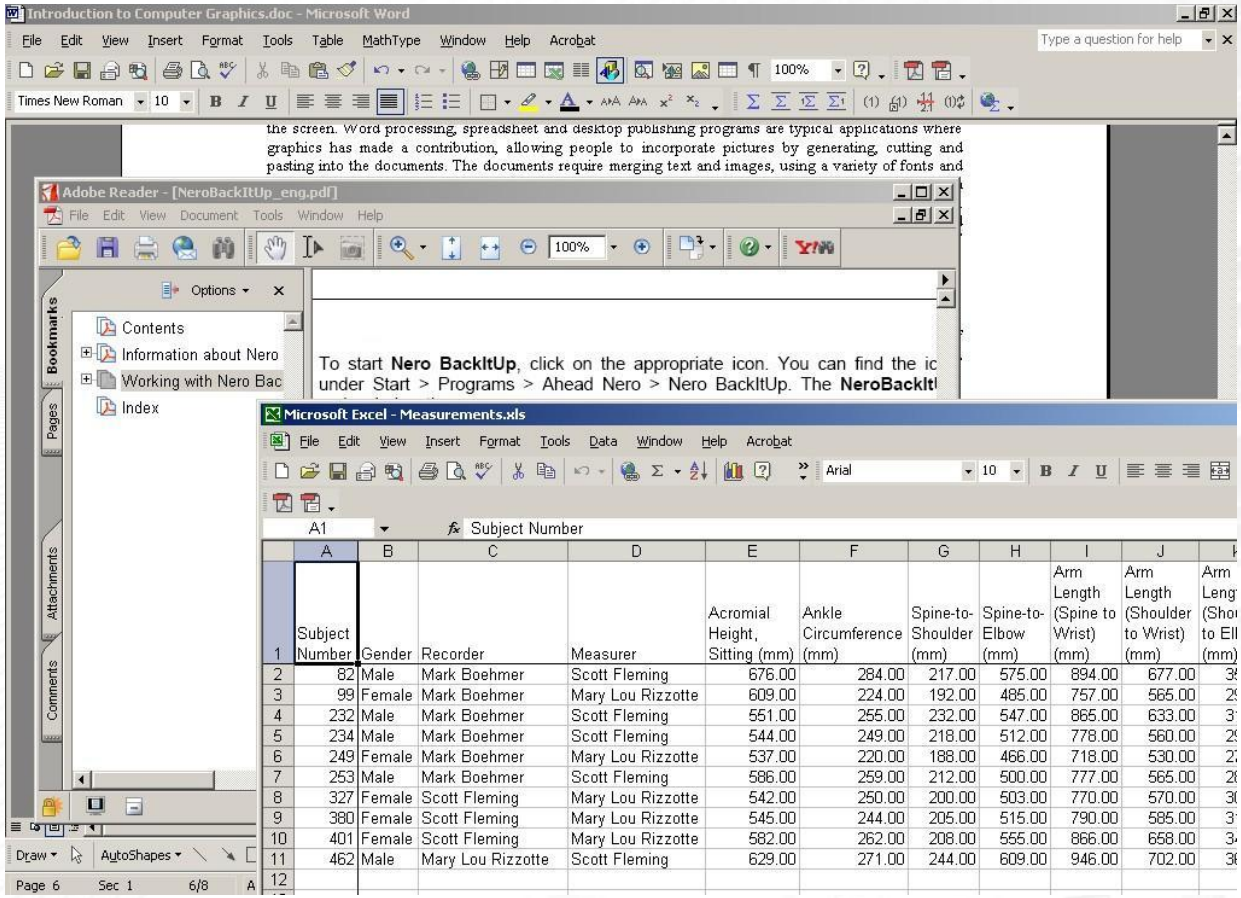
Plots, Charts

Application Fields of Computer Graphics (Examples)



Paint Systems

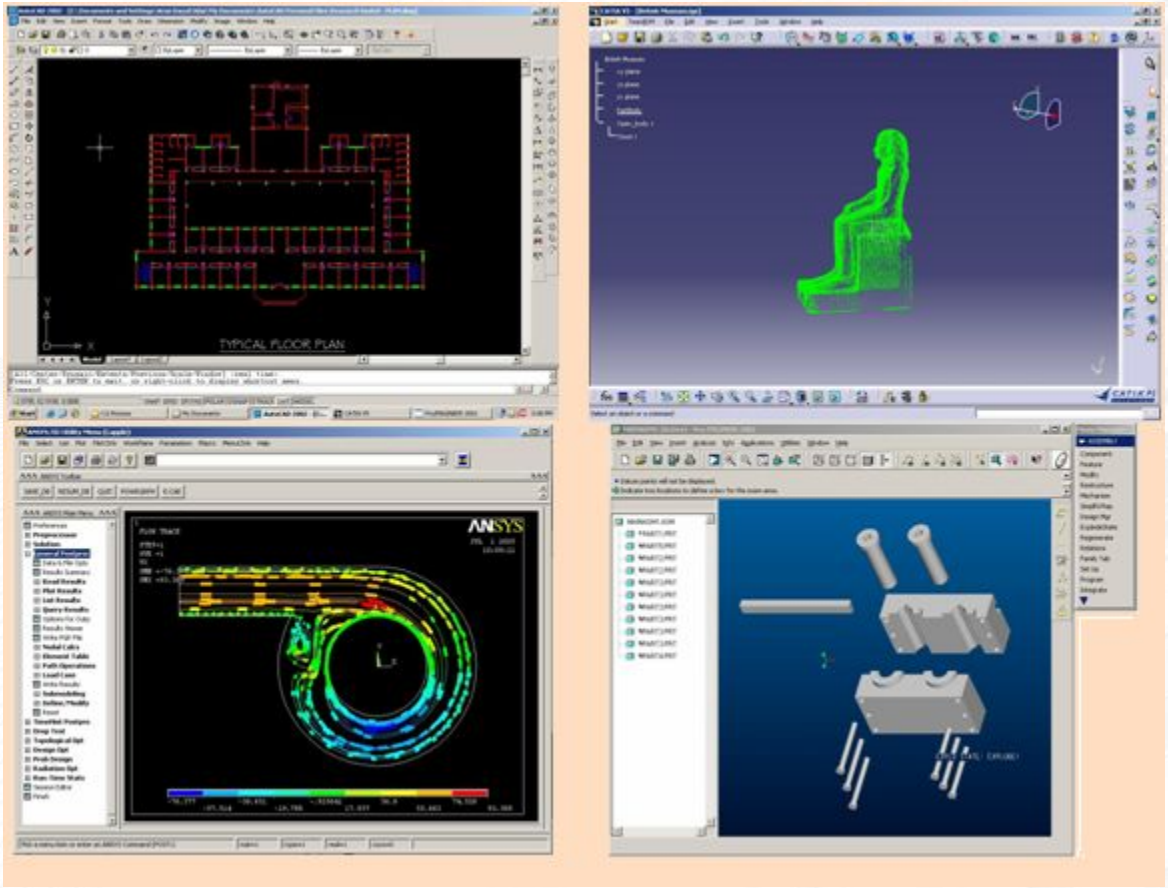
Application Fields of Computer Graphics (Examples)



	A	B	C	D	E	F	G	H	I	J
1	Subject Number	Gender	Recorder	Measurer	Acromial Height, Sitting (mm)	Ankle Circumference (mm)	Spine-to-Shoulder (mm)	Spine-to-Elbow (mm)	Arm Length (Spine to Wrist) (mm)	Arm Length (Shoulder to Wrist) (mm)
2	82	Male	Mark Boehmer	Scott Fleming	676.00	284.00	217.00	575.00	894.00	677.00
3	99	Female	Mark Boehmer	Mary Lou Rizzotte	609.00	224.00	192.00	485.00	757.00	565.00
4	232	Male	Mark Boehmer	Scott Fleming	551.00	255.00	232.00	547.00	865.00	633.00
5	234	Male	Mark Boehmer	Scott Fleming	544.00	249.00	218.00	512.00	778.00	560.00
6	249	Female	Mark Boehmer	Mary Lou Rizzotte	537.00	220.00	188.00	466.00	718.00	530.00
7	253	Male	Mark Boehmer	Scott Fleming	586.00	259.00	212.00	500.00	777.00	565.00
8	327	Female	Scott Fleming	Mary Lou Rizzotte	542.00	250.00	200.00	503.00	770.00	570.00
9	380	Female	Scott Fleming	Mary Lou Rizzotte	545.00	244.00	205.00	515.00	790.00	585.00
10	401	Female	Scott Fleming	Mary Lou Rizzotte	582.00	262.00	208.00	555.00	866.00	658.00
11	462	Male	Mary Lou Rizzotte	Scott Fleming	629.00	271.00	244.00	609.00	946.00	702.00
12										

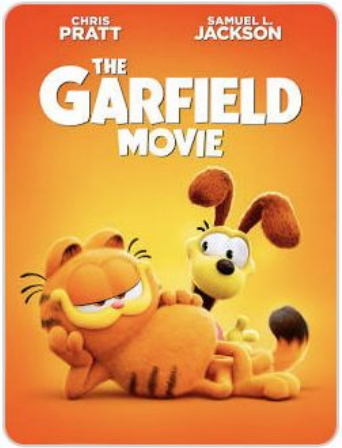
Word Processing, Spreadsheets, Desktop Publishing

Application Fields of Computer Graphics (Examples)



Computer Aided Design

Application Fields of Computer Graphics (Examples)

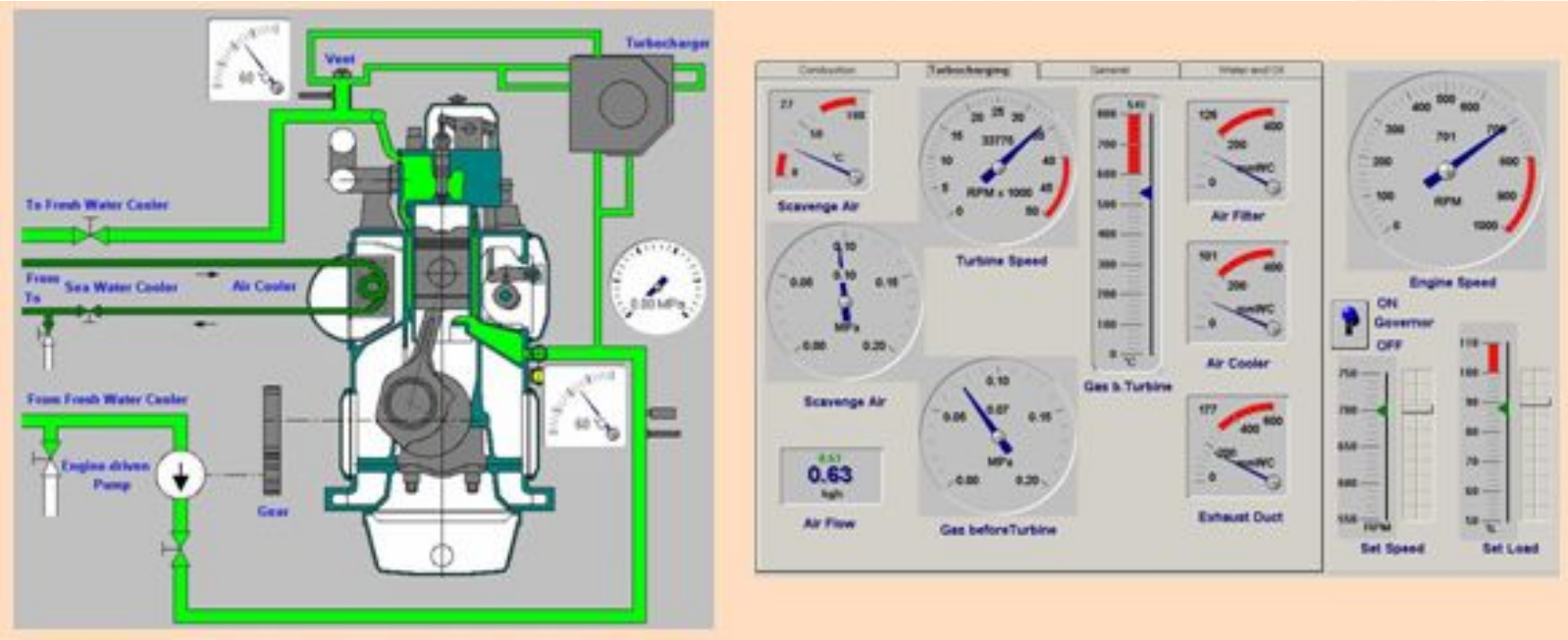


Animations

Application Fields of Computer Graphics (Examples)

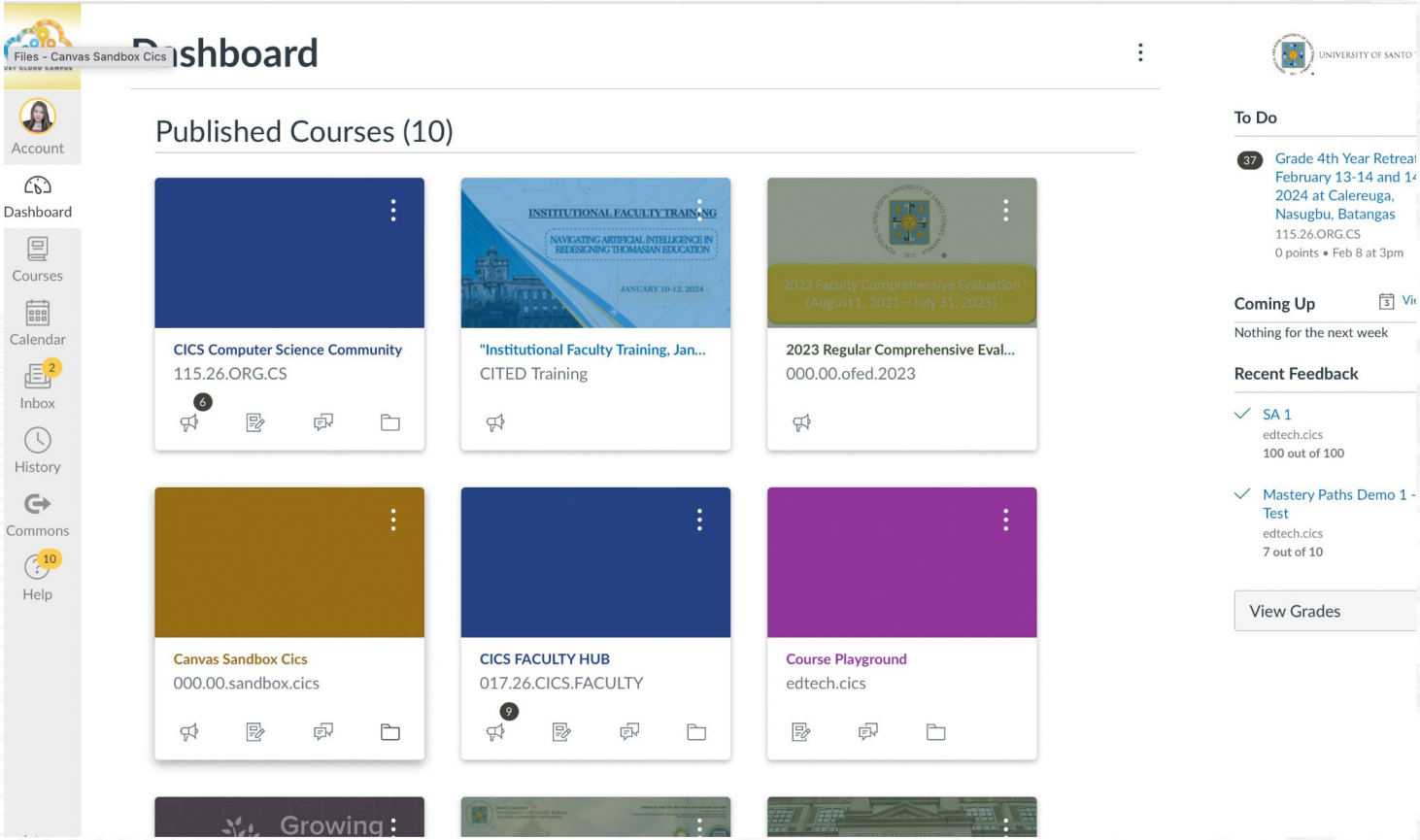
Game Modeling and Simulations

Application Fields of Computer Graphics (Examples)



Process Control

Application Fields of Computer Graphics (Examples)



Education and Training

Application Fields of Computer Graphics (Examples)

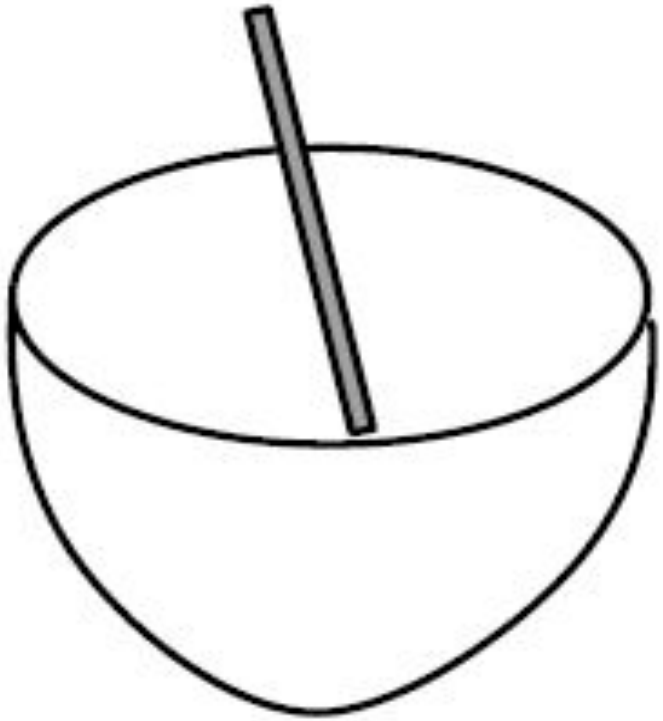
A Comprehensive Map

Map showing Population Density

Cartography

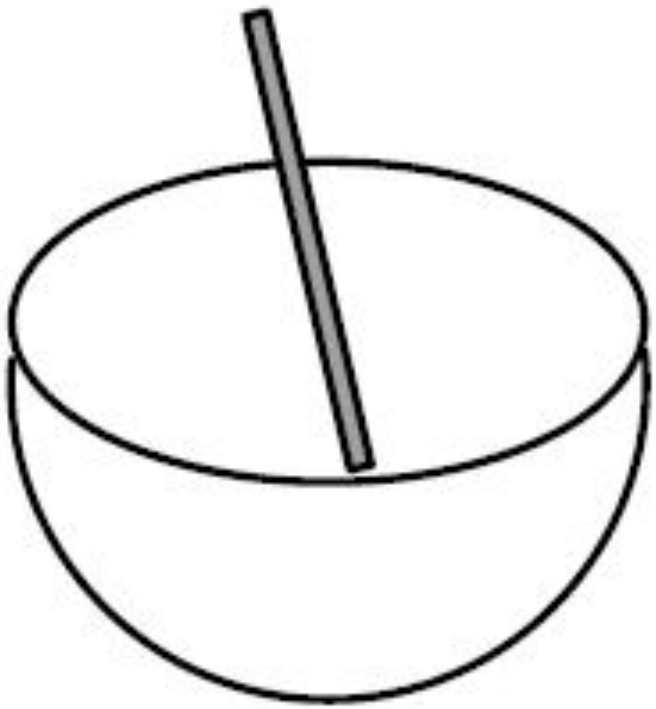
Real Scene to an Image

REAL SCENE whose details/ objects have to be modeled.



Real Scene to an Image

MODEL OF THE SCENE in which the objects of the real scene are represented by the available modelling techniques (basic geometric objects, transformations, ...). The true geometry might only be approximated by the model

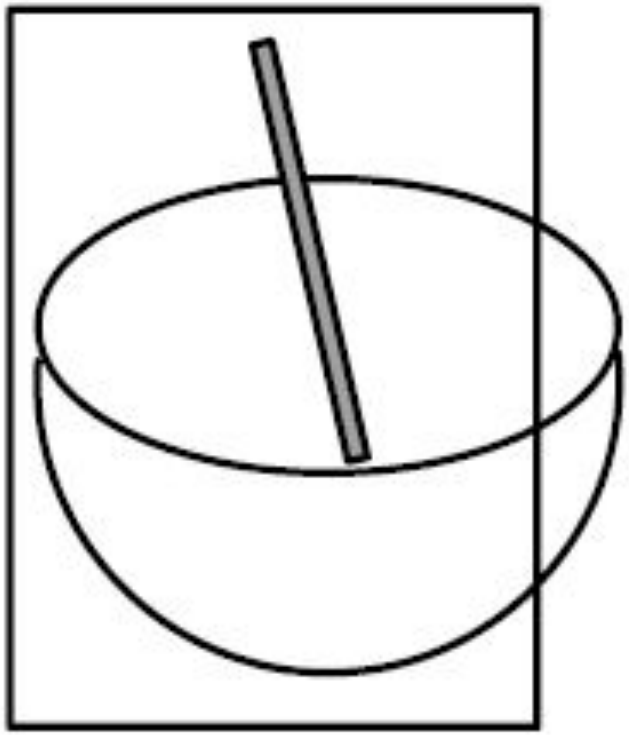


Real Scene to an Image

CHOICE OF A VIEW/PART OF THE VIRTUAL WORLD to be displayed

CLIPPING: Computation which objects are within the chosen view

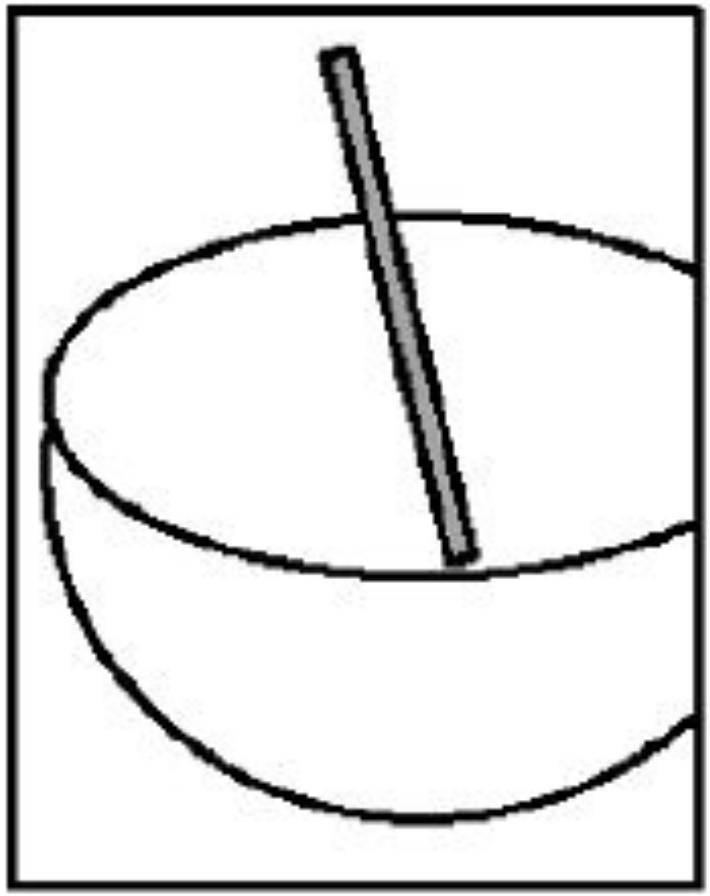
VISIBILITY CONSIDERATIONS: objects in the clipping region are visible for the viewer .



Real Scene to an Image

RESULT: pixel image

- Illumination effects, shading
- Two-dimensional clipping



Summative Assessment 1

4. Based on the given application fields, identify existing software that is now being used. Give at least one for each field. Describe shortly the identified software.

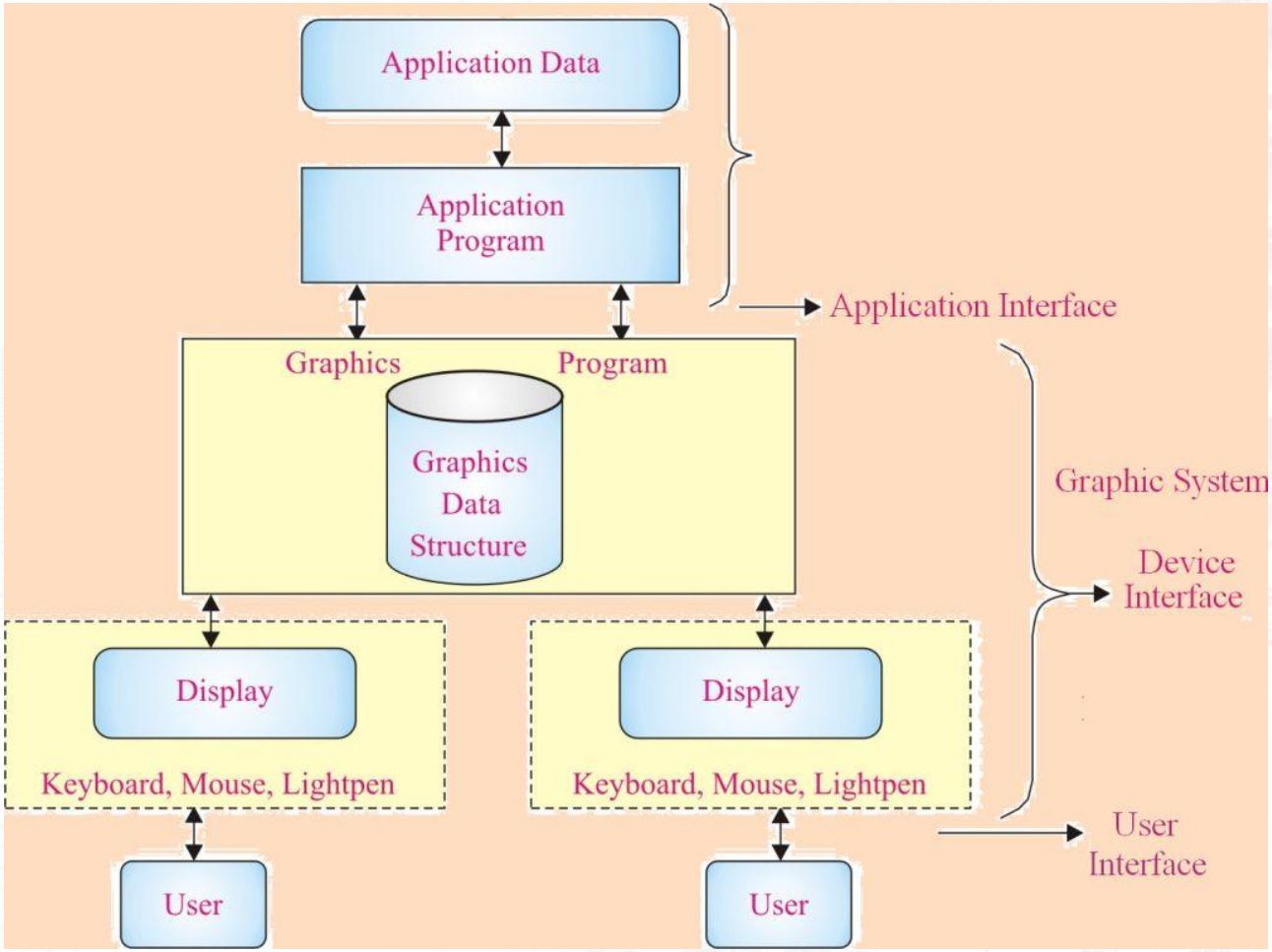
5. Assume you want to develop application software in monitoring stock market. Give a particular scenario wherein the computer graphics will show the trend of the monitored stock market.

Graphic Systems Configuration

Graphic systems configuration describes how hardware and software are set up and optimized within a computer system to guarantee effective visual processing and rendering. For graphics-intensive applications like gaming, video editing, 3D rendering, and others, this is essential. An outline of the essential components necessary in setting up a graphic system ar as follows:

1. Hardware Components
2. Software Components
3. Power Supply
4. Operating Systems and Updates

Graphic Systems Configuration



Graphic Systems Configuration

1. Hardware Components

Graphics Processing Unit (GPU) - The most critical component in a graphic system, responsible for rendering images, video, and animations. Modern GPUs are highly parallel processors optimized for handling complex calculations required in graphic rendering.

Configuration: Selecting the right GPU based on the workload (e.g., gaming, professional 3D rendering, or AI processing) is crucial. For gaming, high refresh rates and resolution support are important, while for rendering, VRAM and processing power are key.

Central Processing Unit (CPU) - While the GPU handles most of the graphic rendering tasks, the CPU is still crucial for processing game logic, AI, and other tasks that affect performance.

Configuration: A balanced CPU-GPU pairing is important to avoid bottlenecks. High core count and clock speed are beneficial for tasks that are both CPU- and GPU-intensive.

Graphic Systems Configuration

1. Hardware Components

Memory (RAM) - RAM is essential for handling the data being processed by both the CPU and GPU. More RAM allows for smoother multitasking and handling larger datasets in applications like 3D modeling or video editing.

Configuration: Typically, 16GB to 32GB of RAM is recommended for graphic-intensive tasks, though more may be required for professional workloads.

Storage - Fast storage options like SSDs are crucial for loading large textures, games, or video files quickly.

Configuration: NVMe SSDs are preferred for their high speed, which reduces load times in games and applications.

Graphic Systems Configuration

1. Hardware Components

Monitor - The display resolution, refresh rate, and color accuracy of the monitor impact the visual experience.

Configuration: High-refresh-rate monitors (120Hz or higher) are ideal for gaming, while 4K monitors with good color accuracy are preferred for video editing and graphic design.

Cooling System - Graphics-intensive tasks generate significant heat, so effective cooling (both air and liquid) is necessary to maintain performance and longevity of the hardware.

Configuration: High-performance fans, liquid cooling systems, and good airflow in the case are important for preventing thermal throttling.

Graphic Systems Configuration

2. Software Components

Graphics Drivers - Drivers are software that enables communication between the operating system and the GPU.

Configuration:Keeping graphics drivers up to date is essential for optimizing performance and compatibility with the latest games and applications.

Graphics APIs - APIs like DirectX, Vulkan, and OpenGL provide a standardized way for software to interact with the GPU.

Configuration: Selecting the right API (often determined by the application or game) can improve performance. For instance, Vulkan and DirectX 12 are optimized for multi-threaded workloads.

Graphic Systems Configuration

2. Software Components

Overclocking Software - Tools that allow users to increase the clock speed of the GPU and CPU to boost performance.

Configuration: Overclocking can provide performance gains but should be done cautiously to avoid overheating and instability.

Graphics Settings- In applications and games, settings such as resolution, texture quality, anti-aliasing, and shadows can be adjusted to balance performance and visual quality.

Configuration: Tweaking these settings depending on the hardware capabilities can optimize the gaming or work experience. Lowering settings can improve frame rates, while higher settings enhance visual fidelity.

Graphic Systems Configuration

3. Power Supply

A sufficient power supply unit (PSU) is necessary to handle the power demands of the GPU, CPU, and other components.

Configuration: Ensuring that the PSU has enough wattage and proper efficiency (like 80 Plus Gold or higher) is crucial for stable system performance, especially when overclocking.

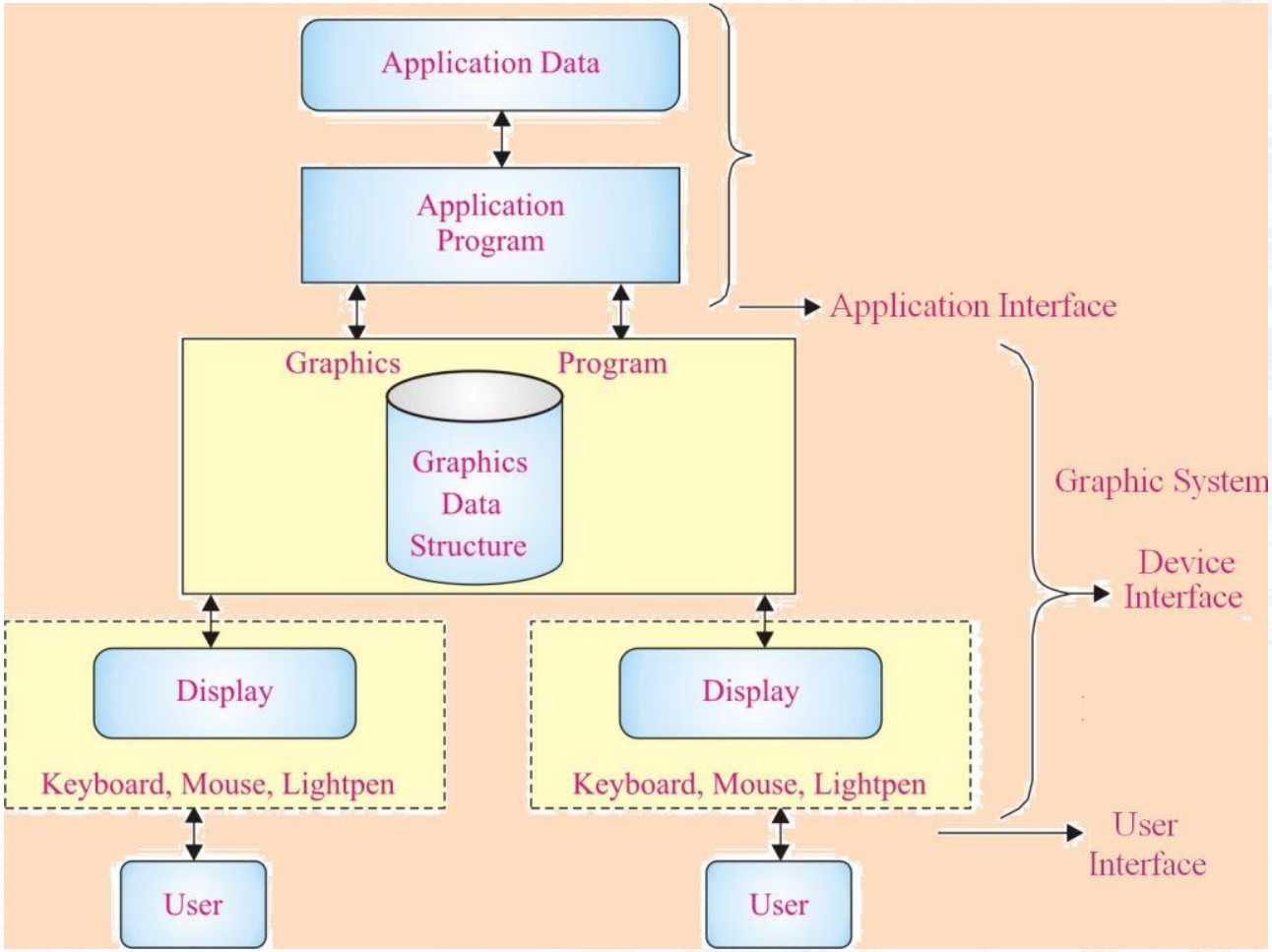
Graphic Systems Configuration

4. Operating Systems and Updates

The operating system must be configured to support the latest graphic technologies, with updates installed to ensure compatibility and performance.

Configuration: Using the latest OS version, with optimizations for gaming or graphic workstations, can enhance overall system stability and performance.

Graphic Systems Configuration



Graphic Systems Configuration

System consists of HARDWARE & SOFTWARE.

3 COMPONENTS OF SOFTWARE

1. APPLICATION PROGRAM creates, store and retrieves the data/objects to be pictured on the screen from (2)
2. APPLICATION DATA helps in producing images by sending a series of graphics output command in (3)

Graphic Systems Configuration

System consists of HARDWARE & SOFTWARE.

3 COMPONENTS OF SOFTWARE

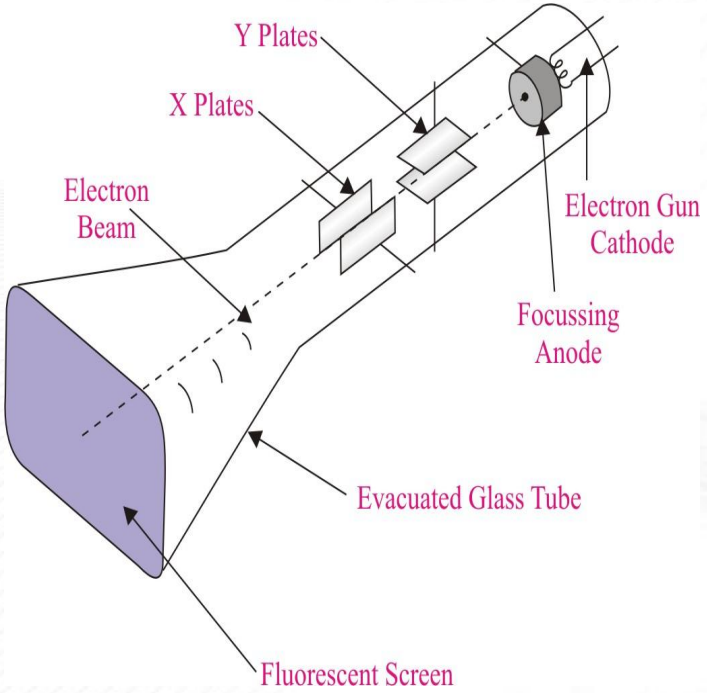
3. GRAPHICS SYSTEMS interacts between the user and the application program and responsible for producing the picture from the detailed descriptions and for passing the user input to the application program for processing.

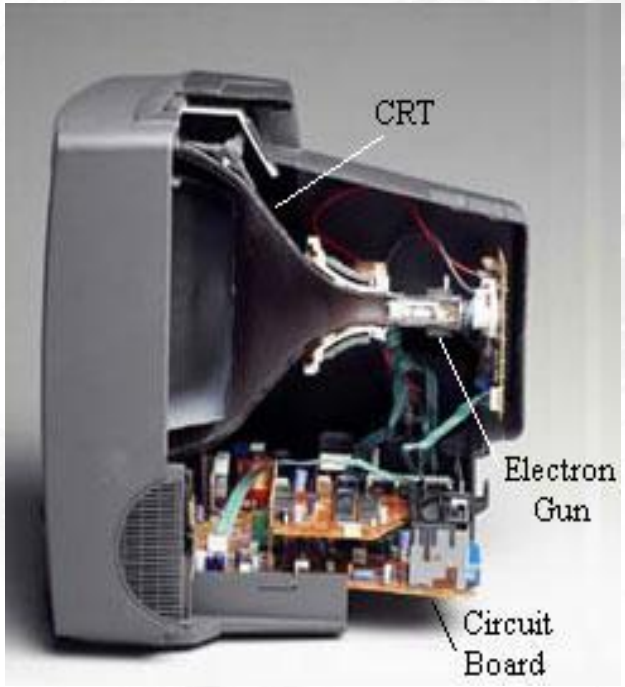
Graphic Systems

In computer graphics, the system's visual quality, performance, and energy efficiency are all greatly impacted by the display technology selected. Over the years, four primary display technologies have been employed: CRT, LCD, LED, and plasma. Each has pros and cons of its own.

Graphic Systems

1. CRT (Cathode Ray Tube)





Graphic Systems

1. CRT (Cathode Ray Tube)

Operation

- CRT displays work by firing electron beams from an electron gun towards a phosphorescent screen. The screen is coated with red, green, and blue phosphors that emit light when struck by the electrons, creating an image.
- The electron beam scans the screen in a raster pattern, refreshing the image multiple times per second (usually 60Hz or more).

Graphic Systems

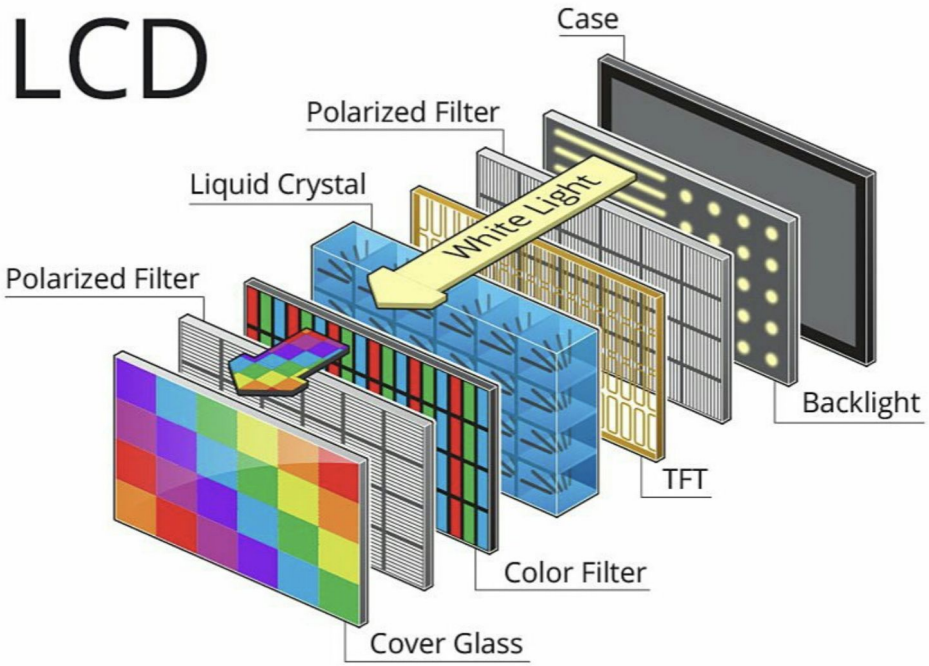
1. CRT (Cathode Ray Tube)

Characteristics

- *Color and Brightness*: CRTs offer excellent color reproduction and deep blacks, as they can individually control the intensity of each pixel.
- *Response Time*: They have very fast response times, making them ideal for fast-moving images like in gaming.
- *Drawbacks*: CRTs are large, heavy, and consume a lot of power. They also suffer from screen burn-in and are prone to flickering at lower refresh rates.

Graphic Systems

2. LCD (Liquid Crystal Display)



Source: www.linsnled.com

Source: www.hp.com

Graphic Systems

2. LCD (Liquid Crystal Display)

Operation

- LCDs use liquid crystals that do not emit light themselves but instead modulate light from a backlight. The liquid crystals are sandwiched between two layers of glass or plastic and are manipulated to block or allow light to pass through colored filters (red, green, and blue) to create an image.
- The backlight is typically provided by CCFLs (Cold Cathode Fluorescent Lamps) in older LCDs.

Graphic Systems

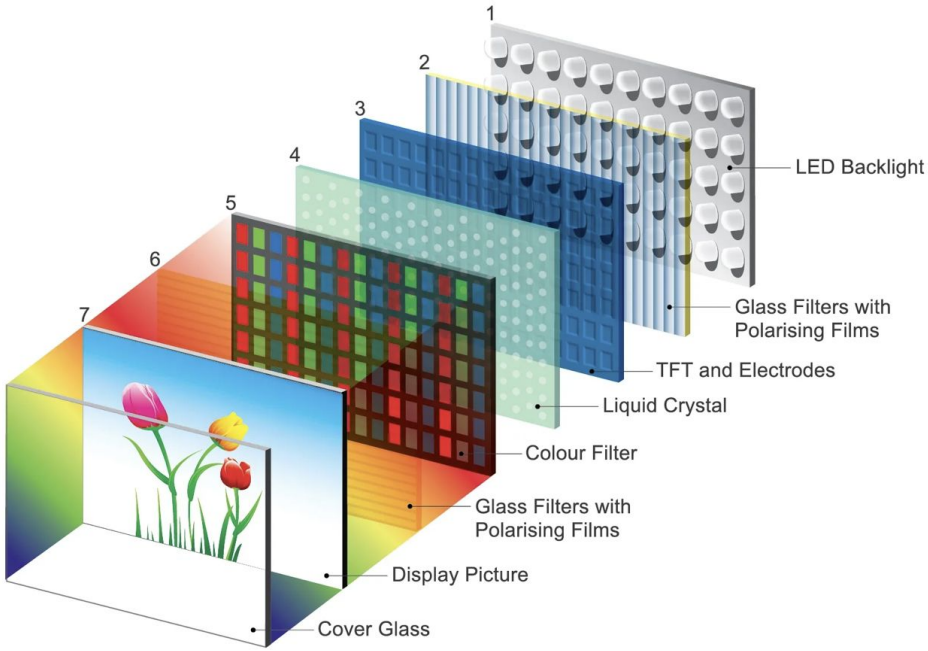
2. LCD (Liquid Crystal Display)

Characteristics

- Resolution: LCDs have a fixed native resolution. Running at non-native resolutions can degrade image quality.
- Color and Brightness: LCDs generally offer good color reproduction, but blacks may appear as dark gray due to the backlighting.
- Drawbacks: Slower response times can lead to motion blur, and viewing angles are often limited.

Graphic Systems

3. LED (Light Emitting Diode)



Source: www.digitalview.com

Source: www.bibled.com

Graphic Systems

3. LED (Light Emitting Diode)

Operation

- LED displays are a type of LCD where the backlight is provided by LEDs instead of CCFLs. LEDs can be either edge-lit or full-array, with some models featuring local dimming to improve contrast.

Graphic Systems

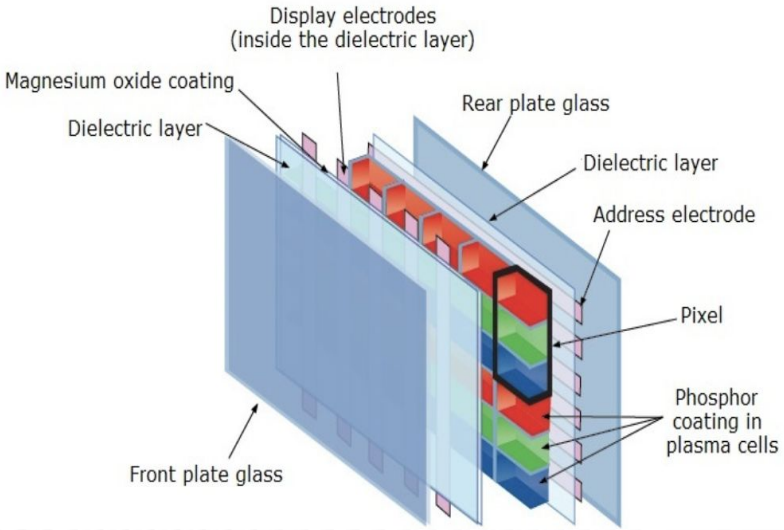
3. LED (Light Emitting Diode)

Characteristics

- **Brightness and Contrast:** LED displays offer better brightness and contrast ratios compared to traditional LCDs, especially with local dimming technology.
- **Energy Efficiency**: LEDs are more energy-efficient, resulting in lower power consumption and heat generation.
- **Drawbacks:** Like LCDs, they have a fixed native resolution and can suffer from limited viewing angles, though these have improved in newer models.

Graphic Systems

4. Plasma



Source: www.sciencelearn.org.nz

Graphic Systems

4. Plasma

Operation

- Plasma displays use small cells containing electrically charged ionized gases (plasma) to produce light. Each cell is essentially a tiny fluorescent lamp that emits UV light when excited by an electric current, which then excites phosphors to emit visible light.

Graphic Systems

4. Plasma

Characteristics

- **Color and Brightness**: Plasma displays are known for deep blacks and good color accuracy, similar to CRTs, because they can control light emission on a per-pixel basis.
- **Viewing Angles**: They offer wide viewing angles with minimal color shift.
- **Drawbacks**: Plasma displays consume more power, generate more heat, and are heavier compared to LCDs and LEDs. They are also susceptible to screen burn-in, especially with static images.

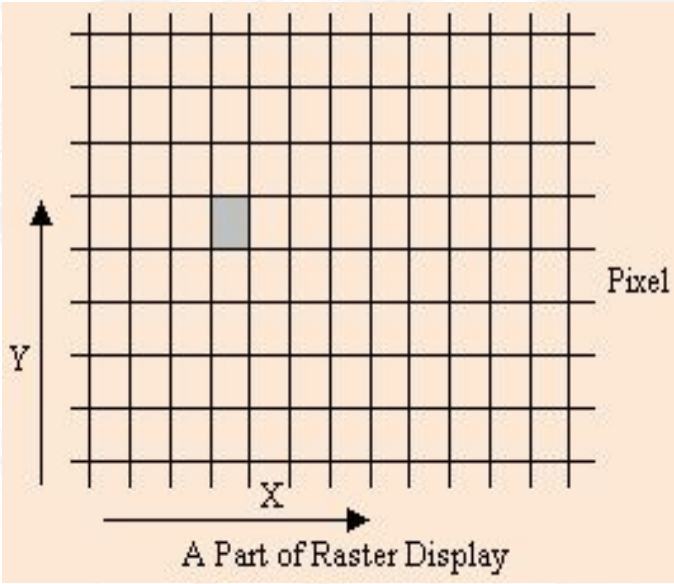
Raster Display

- A raster display is a type of screen or display system that renders images by illuminating pixels on a grid of individual points or dots, usually in a rectangular matrix.
- This grid is composed of rows and columns, where each point on the grid, or pixel, can be individually controlled to display a specific color or brightness level.
- Frame buffer is a memory area in which picture in the form of pixel is stored.

Raster Display: Characteristics

1. Pixel-Based: The image is composed of thousands or millions of individual pixels. The quality of the image depends on the resolution, which is defined by the number of pixels in the grid.

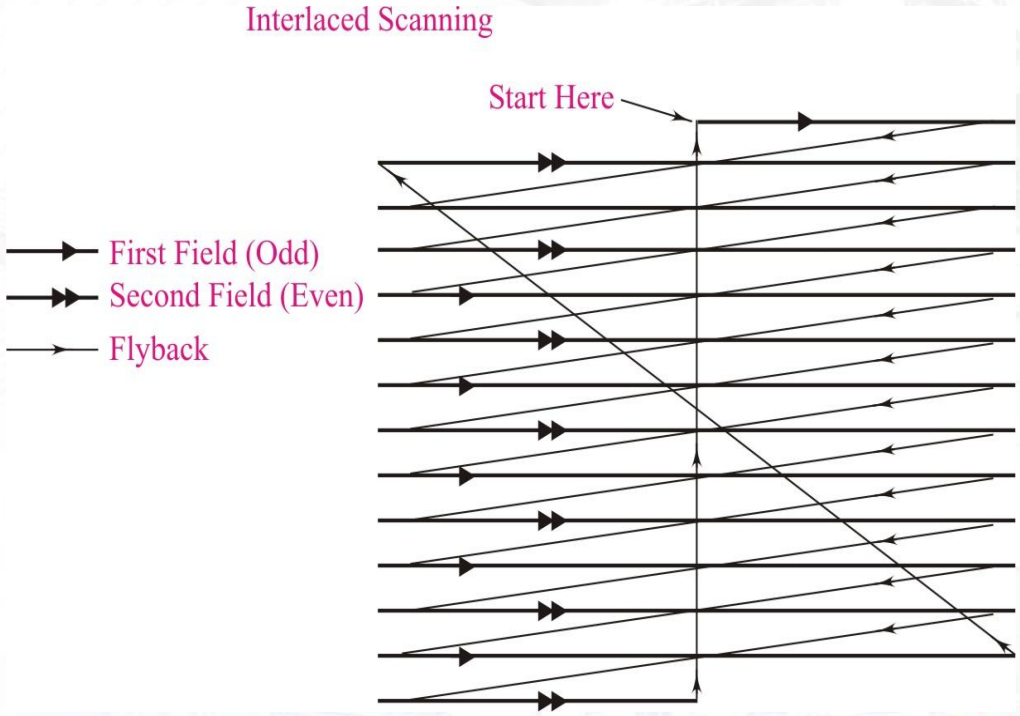
A 512×512 i.e. $2^9 \times 2^9$, elements square raster require 2^{18} or 262144 memory bits in single bit plane



Raster Display: Characteristics

2. Scan Lines: The display refreshes the image by scanning the pixels row by row, from top to bottom. This is known as a raster scan.

The screen is scanned from left to right, top to bottom all the time to generate graphics



Raster Display: Characteristics

3. Color Depth: Each pixel can display a range of colors depending on the color depth, which is determined by the number of bits used to represent the color of a pixel.

4. Common in Screens: Raster displays are the most common type of display used in devices such as televisions, computer monitors, and smartphones.

Raster Display: Characteristics

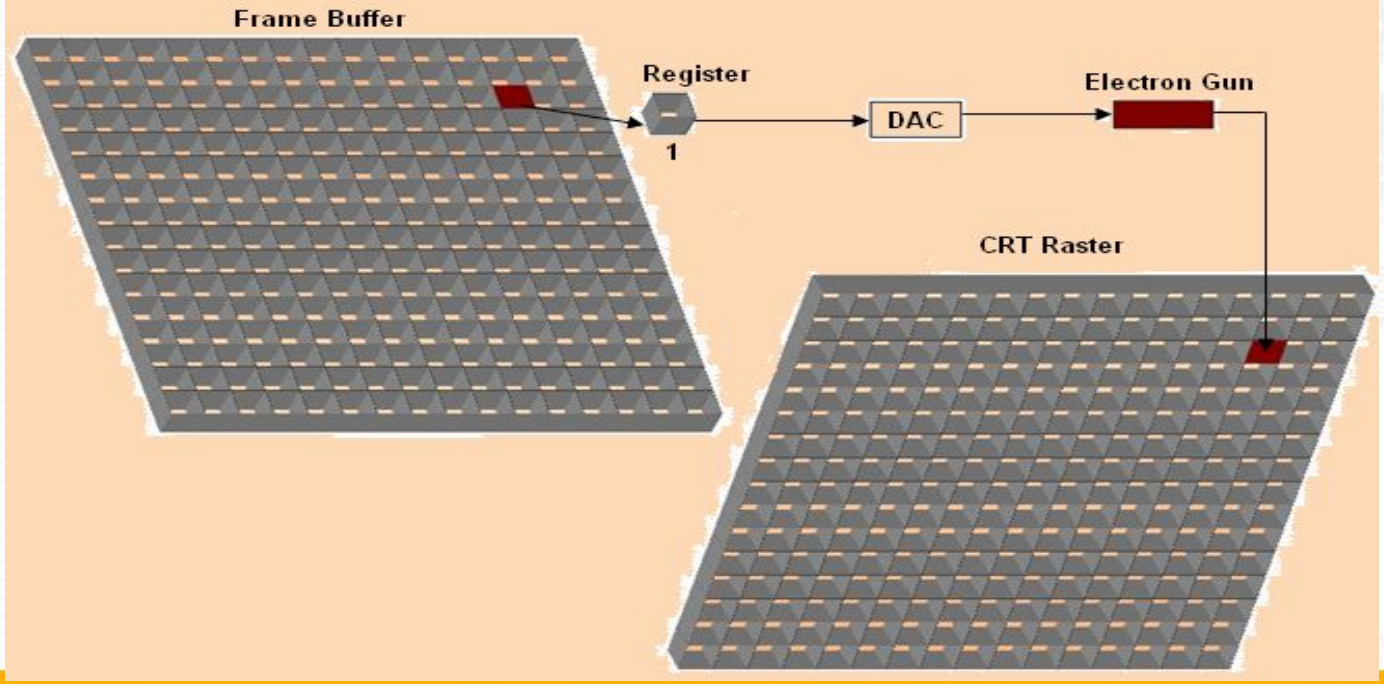
5. Resolution and Refresh Rate: The resolution defines how many pixels the display can show horizontally and vertically. The refresh rate indicates how often the image is updated per second.

- Screen must be refreshed or redrawn minimum 30 to 60 times per second (30 to 60Hz) to maintain flicker free image

Raster Display: Characteristics

Information transfer from Frame buffer to CRT

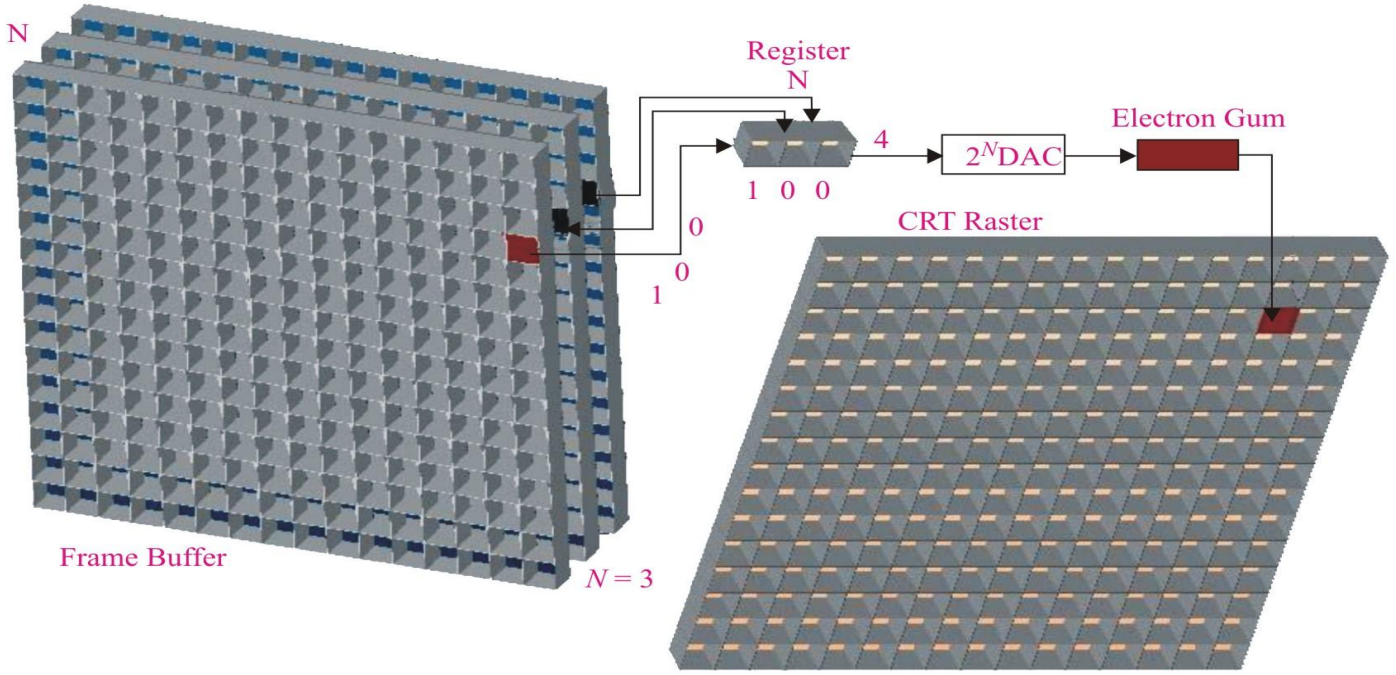
The picture is built up in the frame buffer one bit at a time (either 0 or 1) causing black or white (monochrome) display.



Raster Display: Characteristics

N Bit plane frame buffer for (Monochrome Displays)

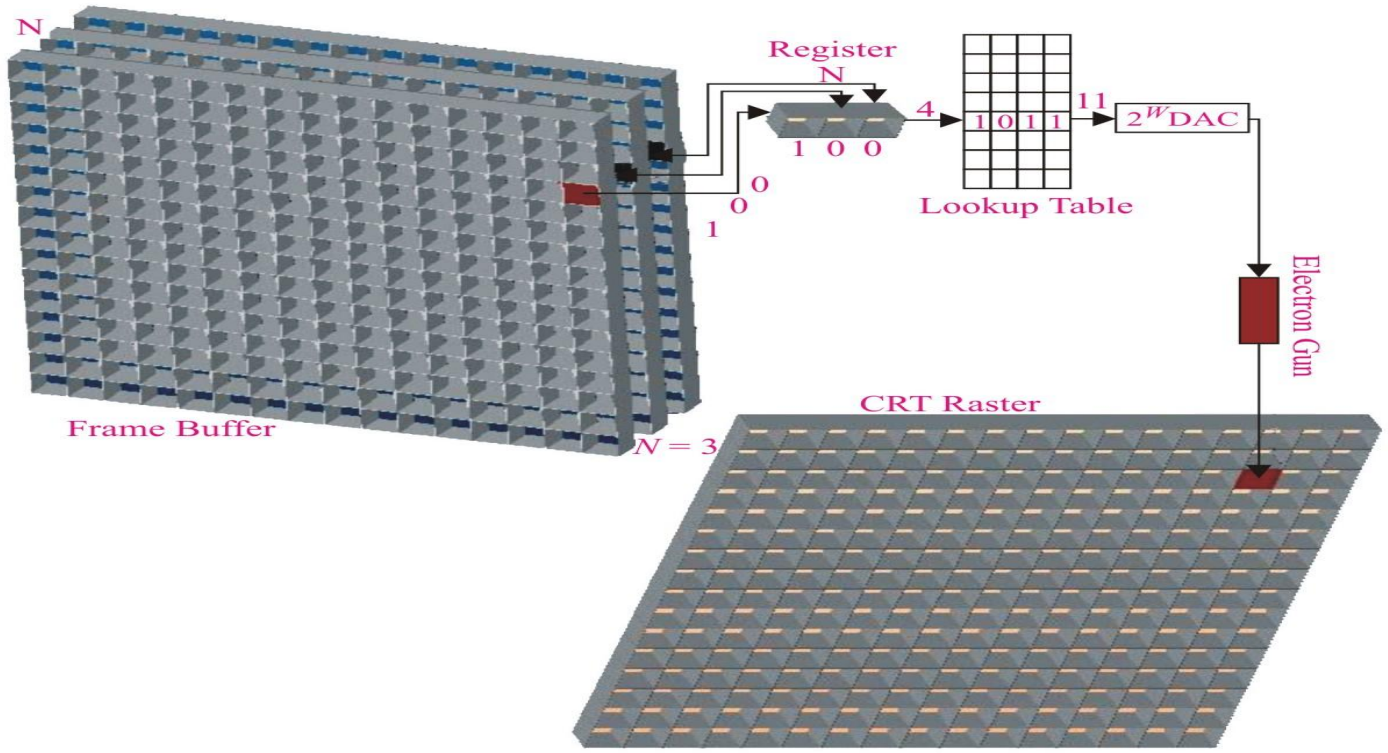
Intensity level between 0 (dark) and $2^N - 1$ (full intensity)



Raster Display: Characteristics

Increasing number of Intensity with Lookup Table

Lookup tables contains 2^N entries for N bit planes and with W width. Each entry will now have 2^W values



Raster Display: Characteristics

Color Raster Display

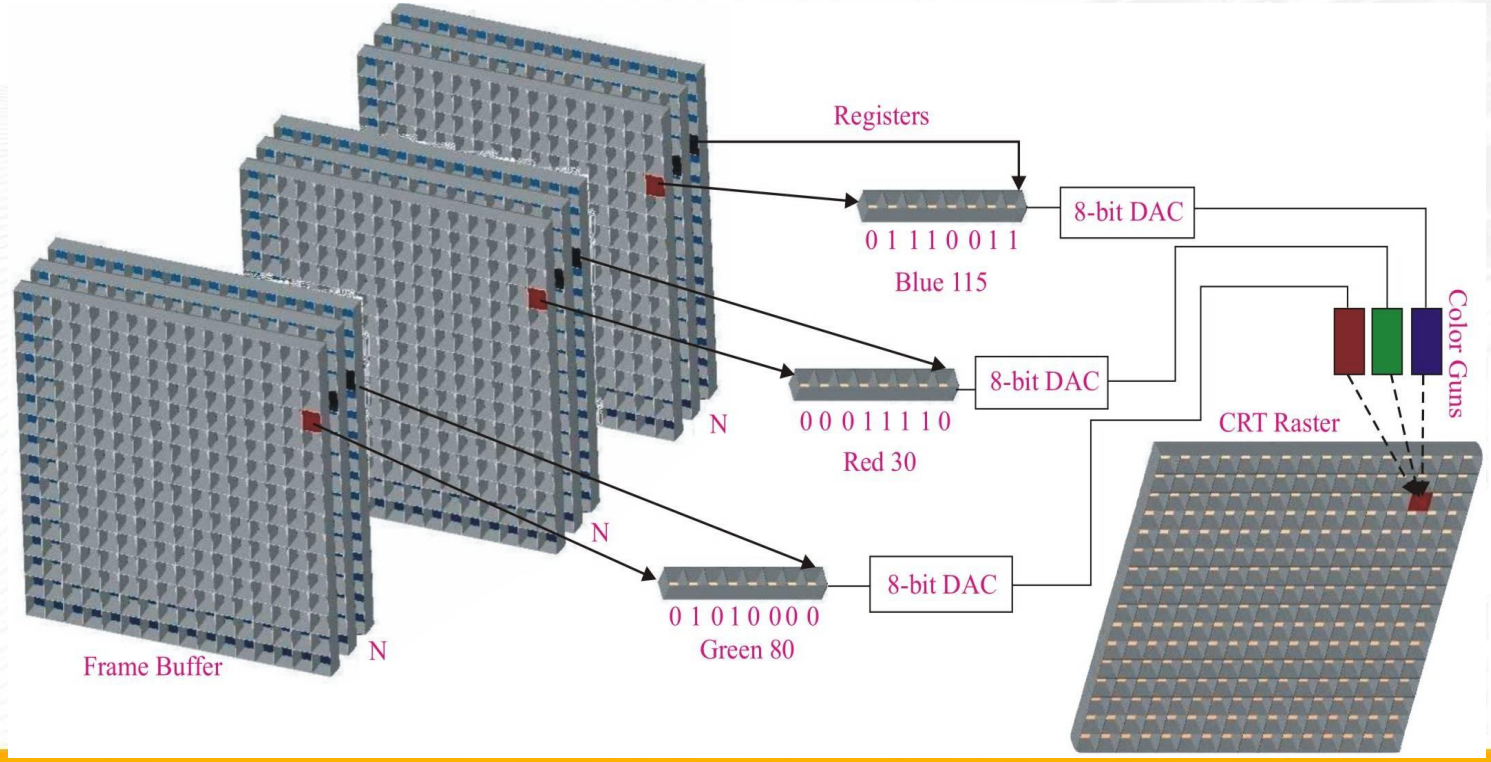
- Color frame buffer contains three bit planes for each primary color i.e. red (R), green (G) and blue (B)
- Each bit plane drives an individual color gun for each of the primary color used in color video
- Table on the right plane shows a sample color table
- Figure in the next slide demonstrates Simple Color Frame Buffer

	Red	Green	Blue
Black	0	0	0
Red	1	0	0
Green	0	1	0
Blue	0	0	1
Yellow	1	1	0
Cyan	0	1	1
Magenta	1	0	1
White	1	1	1

Raster Display: Characteristics

Color Frame Buffer with Lookup Table

(Increases number of shades of each color
$(2^8)^3 = 2^{24} = 16{,}777{,}216$ possible colors)



Supporting Discipline

- Computer science *(algorithms, data structures, software engineering, ...)*
- Mathematics *(geometry, numerical, matrices...)*
- Physics *(Optics, mechanics, ...)*
- Psychology *(Colour, perception)*
- Art and design

Exercise

1. Compute the following:

   Size of 800 x 600 image at 240 pixels per inch
2. Resolution of 2 x 2 inch image that has 512 x 512 pixels
3. Height of the resized image 1024 x 768 to one that is 640 pixels wide with the same aspect ratio
4. Width of an image having height of 5 inches and aspect ratio 1.5

Exercise

5. Find the number of colours a frame buffer of 8 bit planes each of red, green and blue, and 10 bit wide lookup table can produce.

6. Find the amount of memory required by an 8 plane frame buffer each of red, green and blue, having 1024 x 768 resolution.

7. Find the refresh rate of a 512 x 512 frame buffer, if the access time for each pixel is 200 nanoseconds (ns).

Answers in Exercise

1. **Compute the following:**

   Size of 800 x 600 image at 240 pixels per inch

240 corresponds to 1 inch

800 pixel correspond to 800/240 inch= 3 1/3 inch or approx 3.3333

600 pixel correspond to 600/240 inch = 2 1/2 inch or approx 2.5

Thus,

The size of the image is 31/3 inch by 21/2

Answers in Exercise

2. Resolution of 2 x 2 inch image that has 512 x 512 pixels

512/2 = 256 pixels per inch

Answers in Exercise

3. Height of the resized image 1024 x 768 to one that is 640 pixels wide with the same aspect ratio

Aspect ratio of 1024 * 768 image is 768/1024
= ¾

Then, height of the image having width of 640 pixels having aspect ratio ¾ is 640 * ¾ = 480.

Answers in Exercise

4. Width of an image having height of 5 inches and aspect ratio 1.5

With of the image of aspect ratio 1.5 = 5 * 1.5
= 7.5

Answers in Exercise

5. Find the number of colours a frame buffer of 8 bit planes each of red, green and blue, and 10 bit wide lookup table can produce.

- Since each color channel (Red, Green, Blue) has 8 bits, it means each channel can represent ($2^8 = 256$) different intensity levels.
- Then the total number of colors the frame buffer can produce, based on the RGB channels, is given by: 256 * 256 * 256 = 16,777,216 colors This is often referred to as "24-bit color."
- The lookup table (LUT) is 10 bits wide, meaning it can map each of the 256 possible values from each channel to one of 2^{10}= 1024 different possible values for output.
- However, the LUT typically adjusts the color output (like gamma correction) but doesn't change the number of colors that can be produced by the frame buffer itself. The LUT refines the output but does not increase the basic number of colors from the frame buffer's RGB planes.
- Thus, the total number of colors that can be produced is 16,777,216.

Answers in Exercise

6. Find the amount of memory required by an 8 plane frame buffer each of red, green and blue, having 1024 x 768 resolution.

- Each pixel has 8 bits for the red channel, 8 bits for the green channel, and 8 bits for the blue channel. Therefore, each pixel requires: 8 bits (red) + 8 bits (green) + 8 bits (blue)= 24 bits
- The resolution is 1024 x 768, so the total number of pixels is: 1024 * 768 = 786,432 pixels
- The total number of bits required for the entire frame buffer is: 786,432 pixels * 24 bits/pixels = 18,874,368 bits
- Convert this to bytes (since there are 8 bits in a byte): 18,874,368 bits / 8 bits/bytes = 2,359,296 bytes
- Convert bytes to kilobytes (KB): 2,359,296 bytes / 1024 bytes/KB= 2,304 KB
- Convert kilobytes to megabytes (MB): 2,304 KB/ 1024 KB/MB = approx 2.25 MB
- Thus, the total amount of memory required by the 8-plane frame buffer for each of the red, green, and blue channels at a 1024 x 768 resolution is approx. 2.25 MB.

Answers in Exercise

7. Find the refresh rate of a 512 x 512 frame buffer, if the access time for each pixel is 200 nanoseconds (ns).

- The frame buffer resolution is 512 x 512 pixels, then total number of pixels is: 512 *512 = 262,144 pixels
- The access time for each pixel is 200 nanoseconds (ns). The time required to refresh the entire frame is: 262,144 pixels * 200 ns/pixe = 52,428,800 ns
- Convert nanoseconds to seconds (since there are (10^9) nanoseconds in a second): 52,428,800 ns/ 10^9 ns/second = 0.0524288 seconds
- The refresh rate is the reciprocal of the time taken to refresh the entire frame:
- Refresh Rate = 1/0.0524288 seconds = approx 19.07 Hz

Summative Assessment 1

(1) Find the amount of memory required by a 3 plane frame buffer each of red, green and blue of 800 x 600 screen resolution.

(2) Find the refresh rate of a 1024 x 1024 frame buffer, if it can access 32 pixels in a group of simultaneously, in an access time of 200 ns.

(3) Find the number of colors that is possible on a 512 x 512 raster screen with 3 plane buffer each for red, green and blue.

Summative Assessment 1

4. Based on the given application fields, identify existing software that is now being used. Give at least one for each field. Describe shortly the identified software.

5. Assume you want to develop application software in monitoring stock market. Give a particular scenario wherein the computer graphics will show the trend of the monitored stock market.

References

- Karras, T., Laine, S., Aila, T. (2020). "A Style-Based Generator Architecture for Generative Adversarial Networks." IEEE Transactions on Pattern Analysis and Machine Intelligence.
- NVIDIA Corporation. (2020). "NVIDIA DLSS 2.0: A Big Leap in AI Rendering."
- Autodesk. (2021). "Maya 2022 - New Features and Enhancements."
- Meta Platforms, Inc. (2021). "The Metaverse: How We're Building the Next Evolution in Social Connection."
- Zhang, Y., et al. (2022). "Real-Time Rendering in AR and VR Environments." Computer Graphics Forum.
- IBM Corporation. (2023). "Digital Twins and the Metaverse: The Future of Interactive 3D Visualization."
- Hearn, D., & Baker, M. P. (2010). Computer Graphics with OpenGL. Pearson Education.
- Eberly, D. H. (2006). 3D Game Engine Architecture: Engineering Real-Time Applications with Wild Magic. Morgan Kaufmann.
- Blinn, J. (2012). Jim Blinn's Corner: A Trip Down the Graphics Pipeline. Morgan Kaufmann.
- NVIDIA Developer Documentation. Retrieved from https://developer.nvidia.com/documentation.
- AMD Developer Central Documentation. Retrieved from https://developer.amd.com/.
- Tom's Hardware. (2024). "How to Build a Gaming PC 2024: Step-by-Step Guide." Retrieved from https://www.tomshardware.com.
- AnandTech. "Understanding Graphics Settings for Gaming Performance." Retrieved from https://www.anandtech.com.
- PC Gamer. "The Best Graphics Cards 2024." Retrieved from https://www.pcgamer.com.
- GPU Boss. Retrieved from https://www.gpuboss.com.
- PassMark Software. Retrieved from https://www.passmark.com.
- Blinn, J. (2012). Jim Blinn's Corner: A Trip Down the Graphics Pipeline. Morgan Kaufmann.
- - Explores different aspects of graphics hardware, including detailed insights into CRT and LCD technologies.
- Tom's Hardware. (2024). "Understanding Display Technologies: CRT, LCD, LED, and Plasma." Retrieved from https://www.tomshardware.com.