A deeper look into GPUs and the Linux Graphics Stack

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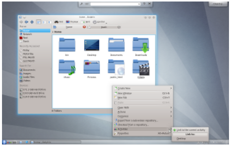
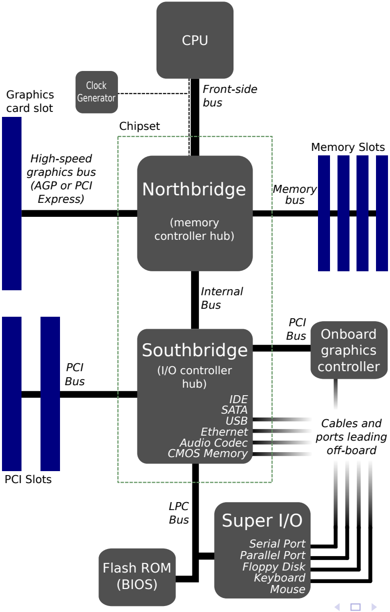
Outline

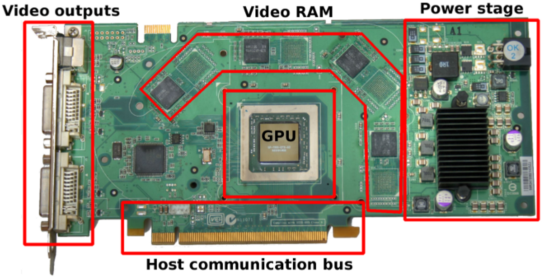


General overview of a modern GPU's functions

- Display content on a screen
- Accelerate 2D operations
- Accelerate 3D operations
- Decode videos
- Accelerate scientific calculations

General overview



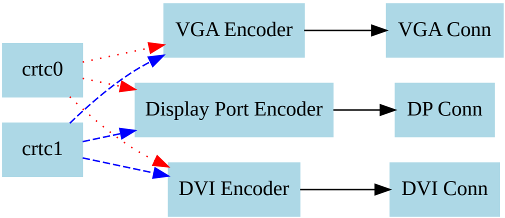


Source: http://www.flickr.com/photos/stefan_ledwina/557505323

Hardware architecture

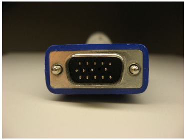
- GPU: Where all the calculations are made
- VRAM: Stores the textures or general purpose data
- Video Outputs: Connects to the screen(s)
- Power stage: Lower the voltage, regulate current
- Host communication bus: Communication with the CPU

Outline



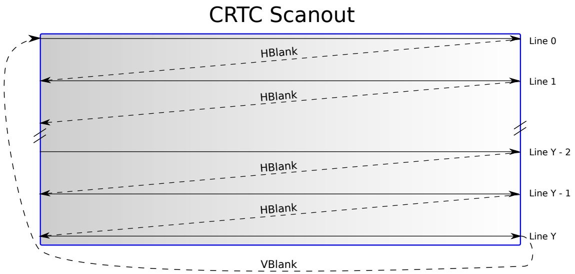
Driving screens : the big picture

- Framebuffer: The image to be displayed on the screen(VRAM)
- CRTC: Streams the framebuffer following the screen's timings
- Encoder: Convert the CRTC's output to the right PHY signal
- Connector: The actual connector where the screen is plugged

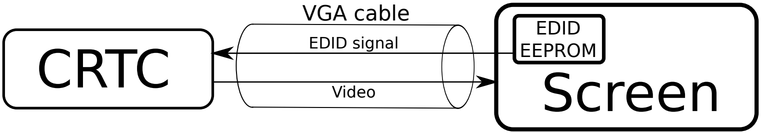
Screen connectors

- VGA: Video, introduced in 1987 by IBM
- DVI: Video, introduced in 1999 by DDWG
- DP: Video & Audio, introduced in 2006 by VESA
- HDMI: Video & Audio, introduced in 1999 by HDMI Founders



Driving screens : the CRT Controller

- Streams the framebuffer following the screen's timings
- After each line, the CRTC must wait for the CRT to go back to the beginning of the next line (Horizontal Blank)
- After each frame, the CRTC must wait for the CRT to go back to the first line (Vertical Blank)
- Timings are met by programming the CRTC clock using PLLs



Configuring the CRTC : Extended display identification data

- Stored in each connector of the screen (small EEPROM)
- Is usually accessed via a dedicated I2C line in the connector
- Holds the modes supported by the screen connector
- Processed by the host driver and exposed with the tool xrandr (see `xrandr --verbose`)

Example: Some display standards

- 1981 : Monochrome Display Adapter (MDA)
    - text-only
    - monochrome
    - 720 * 350 px or 80*25 characters (50Hz)
- 1981 : Color Graphics Adapter (CGA)
    - text & graphics
    - 4 bits (16 colours)
    - 320 * 200 px (60 Hz)
- 1987 : Video Graphics Array (VGA)
    - text & graphics
    - 4 bits (16 colours) or 8 bits (256 colours)
    - 320*200px or 640*480px ($<=$ 70 Hz)

Initial video mode

- Very low resolution (640*480px, 4 bits);
- Provide a simple "accelerated" terminal;
- Allow per-pixel access;
- Accessible from real mode, 10h BIOS call.

VESA BIOS Extensions (VBE)

- Bios call to change the mode;
- High-resolution video mode ($<=$ 1600*1200);
- 16 or 24 bits colour resolution;
- Page flipping, access from the protected mode;
- etc...

Outline

Modern host communication busses

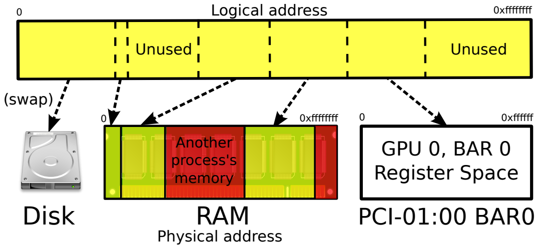
- 1993 : Peripheral Component Interconnect (PCI)
  - 32 bit & 33.33 MHz
  - Maximum transfer rate: 133 MB/s
- 1996 : Accelerated Graphics Port (AGP)
  - 32 bit & 66.66 MHz
  - Maximum transfer rate: 266 to 2133 MB/s (1x to 8x)
- 2004 : PCI Express (PCIe)
  - 1 lane: 0.25 − > 2 GB/s (PCIe v1.x − > 4.0)
  - up to 32 lanes (up to 64 GB/s)
  - Improve device-to-device communication (no arbitration)

Features

- Several generic configuration address spaces (BAR)
- Interruption RQuest (IRQ)

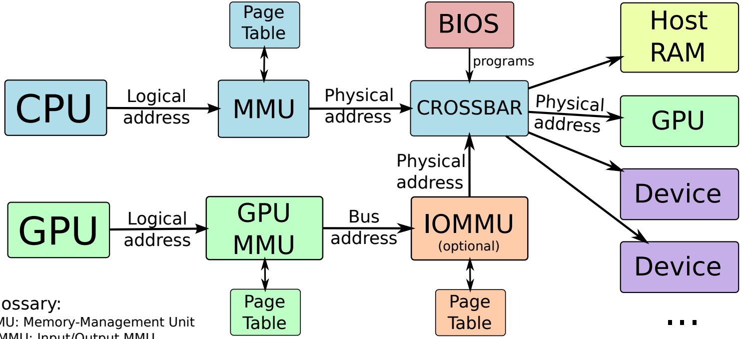
Programming the GPU : Register access via MMIO

- A GPU's configuration is mostly stored in registers;
- A register is usually identified by an address in a BAR;
- Device's BARs are all accessible in the physical address space;
- They are thus mappable in the CPU's virtual memory;
- Registers are then accessed like a "uint32_t array";
- This is called Memory-Mapped Input/Output (MMIO).



Example of a CPU process's virtual memory space

CPU & GPU Memory Requests Routing



Glossary:
MMU: Memory-Management Unit
IOMMU: Input/Output MMU
BIOS: Basic I/O System

Location of functions:

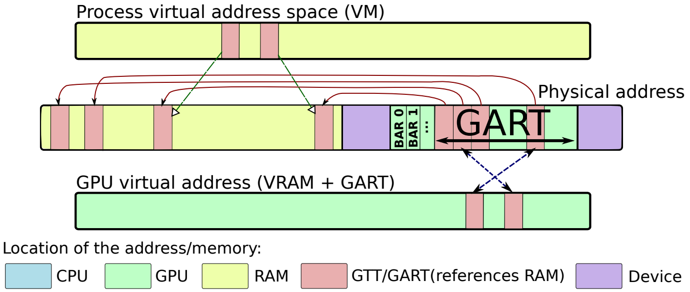
CPU Chipset GPU RAM BIOS Device

GPU-accessible memory areas

- Video RAM (VRAM) : Blazing fast
- Host RAM via Direct Memory Access (DMA) : Fast
  - Graphics Translation Table (GTT/GART);
    - Exposes a linear buffer from multiple RAM pages;
  - VGA window (physical address range: 0xa0000-0xbffff).

GTT/GART

Providing the GPU with easy access to the Host RAM



GTT/GART as a CPU-GPU shared-buffer for communication

- GPU feature to gather some RAM pages in the physical space;
- Can be seen as a host-managed MMU on the GPU;
- The host maps a RAM buffer into GART and then maps this new address into a GPU virtual address space. Shared Mem!

GTT/GART usage

- Upload textures or scientific data;
- Store the pushbuffer (GPU command submission).

Event reporting : Interruption RQuest(IRQ)

- GPUs often report events such as screen (un)plugged, processing error, etc... They should be processed ASAP;
- A device can send an IRQ to wake/interrupt the CPU;
- The CPU jumps to some code to handle the IRQ;
- Once the event is acknowledged, the CPU can continue what it was doing before the event occurred.

Outline

The GPU needs the host for:

- Setting the screen mode/resolution (mode setting);
- Configuring the engines and communication busses;
- Handling power management;
  - Thermal management (fan, react to overheating/power);
  - Change the GPU's frequencies/voltage to save power;
- Processing data:
  - Allocate processing contexts (GPU VM + context ID);
  - Upload textures or scientific data;
  - Send commands to be executed in a context.

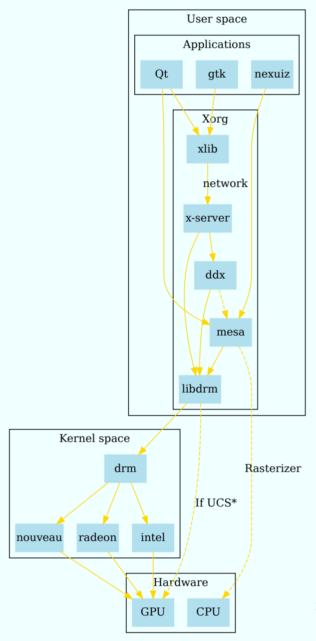
Overview of the components of a graphics stack

- A GPU with its screen;
- One or several input devices (mouse, keyboard);
- A windowing system (such as the X-Server and Wayland);
- Accelerated-rendering protocols (such as OpenGL);
- Graphical applications (such as Firefox or a 3D game).

Components of the Linux Graphics stack

- Direct Rendering Manager (DRM) : exports GPU primitives;
- X-Server/Wayland : provide a windowing system;
- Mesa : provides advanced acceleration APIs;

General overview



Outline

Direct Rendering Manager

- Inits and configures the GPU;
- Performs Kernel Mode Setting (KMS);
- Exports privileged GPU primitives:
  - Create context + VM allocation;
  - Command submission;
  - VRAM memory management: GEM & TTM;
  - Buffer-sharing: GEM & DMA-Buf;
- Implementation is driver-dependent.

libDRM

- Wraps the DRM interface into a usable API;
- Factors-out some code;
- Is meant to be only used by Mesa & the DDX;

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3. DRM
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   - Kernel Mode Setting
   - Graphics buffer management
   - How to contribute code
4. Mesa
   - Mesa
   - OpenGL
   - Video Acceleration
5. X11 and the XServer
   - Overview
   - X11
   - X-Server

Kernel Mode Setting (KMS)

- Opposed to User Mode Setting (UMS);
- The kernel manages modesetting;
- Enables:
  - root-less graphic server;
  - glitch-free boot;
  - fast VT-Switching;
  - better power management;
  - kernel crash logs.

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Overview

- Graphics memory allocator;
- Manages VRAM and GART;

Buffer management: Constraints

- Contrarily to a CPU MMU, a page fault is “fatal”;
- We don’t know when the GPU will actually need the buffers;
- This means all pages should be available and addresses shouldn’t change during processing;
- What actually defines the processing time frame?

Detecting when a buffer is needed

- Buffers shoud be managed by the driver;
- A user should reference which buffers are needed in what command batch;
- When the kernel emits a command batch, it should pin the buffers that are used by this command batch.

When should we unpin a buffer?: Fencing

- Detecting the end of the execution of a command batch is done by fencing;
- Fencing can be implemented by adding an instruction at the end of the command batch to increment a counter (fence);
- When the counter's value is higher or equal to the fence, we know the batch has been executed correctly.
- Alternatively, an IRQ could be sent instead of incrementing a counter.

Auto-deallocation

- Buffers are reference-counted to allow buffer deallocation;
- When a command batch references a buffer, the buffer's reference counter is incremented;
- When a command batch has been processed, the reference counter is decremented;
- When the reference counter drops to 0, free the BO.

Translation Table Maps (TTM)

- Open-sourced by Tungsten Graphics (now VMware);
- Does what was described before (fencing, validation (forcing pinning));
- Used by Radeon and Nouveau.

Graphics Execution Manager (GEM)

- The standard interface for creating, sharing, mapping and modifying buffers;
- Intel only implements GEM, radeon and nouveau use a GEMified-TTM;
- Allow buffer sharing: flink() to share (returns an ID), open() to open a shared buf;
- Doesn't specify fences/validation mechanisms.

DMA-Buf

- GEM flink is unsecure (once flinked, a buffer can be accessed with few controls');
- GEM flink doesn't work across drivers;
- DMA-Buf solves the latter and uses file descriptors to identify shared buffers;
- This fd can then be passed on to another process using unix sockets;
- The requesting process is responsible for transmitting the buffer.

More information on security

- `https://lwn.net/Articles/517375/`

Outline

How to contribute code

- 1: Get in touch with the X.org/DRM community;
- 2: Get to know how they work;
- 3: Pick something of interest to you and study it;
- 4: Can you improve current support? If not, goto 3
- 5: Write and propose a patch
- 6: Accepted? If not, listen their feedback and goto 5
- 7: Well done! Goto 3

Outline

Mesa

- Provides advanced acceleration APIs:
  - 3D acceleration: OpenGL / Direct3D
  - Video acceleration: XVMC, VAAPI, VDPAU
- Mostly device-dependent (requires many drivers);
- Divided between mesa classics and gallium 3D;

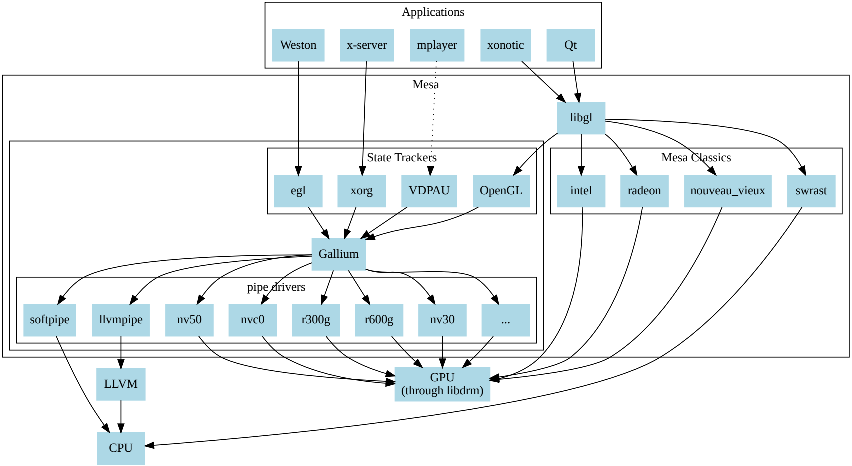
Mesa classics

- Old code-base, mostly used by drivers for old cards;
- No code sharing between drivers, provide only OpenGL;

Gallium 3D

- Built for code-sharing between drivers (State Trackers);
- Pipe drivers follow the instructions from the Gallium interface;
- Pipe drivers are the device-dependent part of Gallium3D;

Mesa


Applications
Weston
x-server
mplayer
xonotic
Qt
Mesa
libgl
State Trackers
egl
xorg
VDPAU
OpenGL
Mesa Classics
intel
radeon
nouveau_vieux
swrast
Gallium
pipe drivers
softpipe
llvmpipe
nv50
nvc0
r300g
r600g
nv30
...
LLVM
GPU
(through libdrm)
CPU

Outline

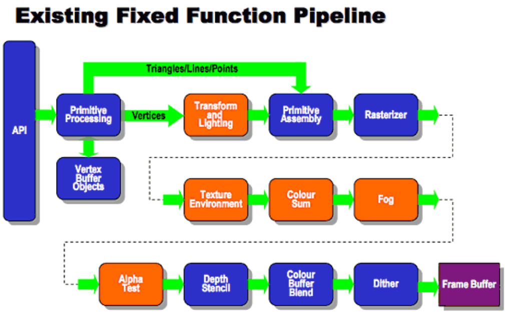
Overview: Summary of OpenGL's history

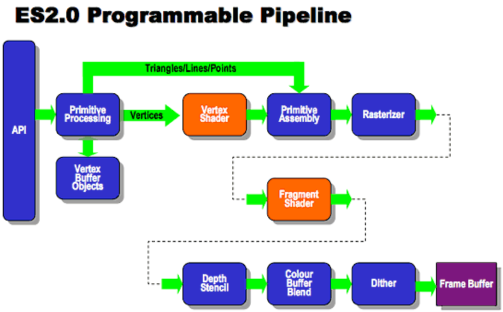
- OpenGL is edited and managed by the Khronos Group;
- First version accelerated transforming 3D coordinates to 2D;
- Later version added Transform, Clipping and lightning (TCL);
- These instructions were too fixed and limited creativity;
- This pipeline got replaced by a programmable one: Shaders!

Shaders

Shaders are roughly separated in 2 stages:

- Vertex Shaders: To implement coordinate transforming;
- Fragment Shaders: To implement post-processing effects.


Existing Fixed Function Pipeline
API
Triangles/Lines/Points
Primitive Processing
Vertices
Transform and Lighting
Primitive Assembly
Rasterizer
Vertex Buffer Objects
Texture Environment
Colour Sum
Fog
Alpha Test
Depth Stencil
Colour Buffer Blend
Dither
Frame Buffer

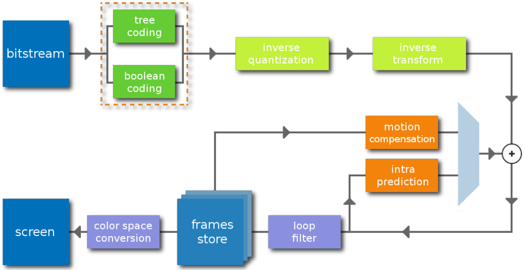

ES2.0 Programmable Pipeline
API
Triangles/Lines/Points
Primitive Processing
Vertices
Vertex Shader
Primitive Assembly
Rasterizer
Vertex Buffer Objects
Fragment Shader
Depth Stencil
Colour Buffer Blend
Dither
Frame Buffer

Outline

Video Acceleration : Overview

The video pipeline is composed of the following stages:

- Decoding the video
- Convert the colourspace from YUV to RGB;
- Scale each frame to the wanted size;
- Composite the subtitles and the OSDs.



Decoding a VP8 video stream

Complex operations that can be implemented in hardware.

XVideo Motion Compensation (XVMC)

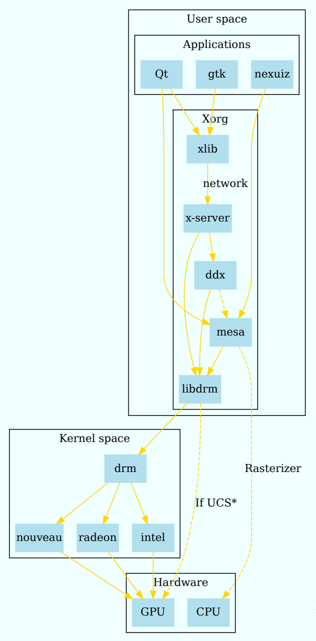
- Entire video-decoding offloading of:
  - MPEG and MPEG2 formats (DVD).
- Limits:
  - non-accelerated OSD/subtitles compositing.

Video Decode and Presentation API (VDPAU)

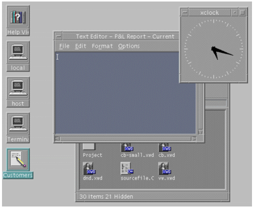
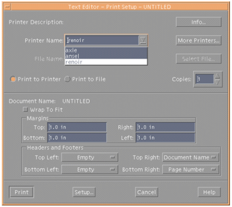
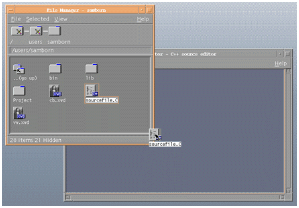
- Entire video-decoding offloading for most common formats;
- The presentation allows compositing the subtitles/OSD;
- OpenGL/CL-compat: use the output in GL/CL;
- Limits:
  - The hardware must support every format (not really a problem on firmware-based hw like NVidia).

Outline

Overview


User space
Applications
Qt
gtk
nexuiz
Xorg
xlib
network
x-server
ddx
mesa
libdrm
Kernel space
drm
nouveau
radeon
intel
Rasterizer
If UCS*
Hardware
GPU
CPU

Outline

X11 : The X protocol version 11

- Rendering protocol over a socket;
- Provides a very simple rendering API;
- Was meant for mainframe environment (programs run on the mainframe and rendering on thin clients);
- Applications used to be rendered on a CPU;
- Is over 25 years old but supports extensions;
- Motif is a X11-based toolkit (see above).

XLib: Drawing applications with X11

- The X-Server is oftenly accessed through the XLib;
- It provides an interface to generate X11 commands;
- The XLib shouldn't be used anymore, use XCB!

XCB: The X protocol C-language Binding

- New attempt to create a wrapper for X11;
- Designed to be lightweight, asynchronous;
- Provide a clean thread-safe interface;
- Allow direct access to the protocol as needed;
- Designed for toolkits and X-specific applications;

Outline

Objectives

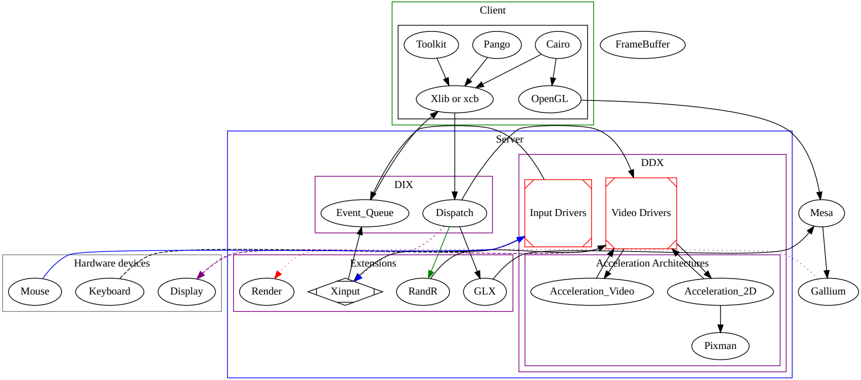
- Receive drawing commands from X Clients;
- Render them as efficiently as possible (acceleration!);
- Handle input events and client attributes;
- Work with the window manager.

Basic Acceleration

Implemented by the DDX:

- 2D acceleration (XAA, EXA, etc...);
- Simple video acceleration (video overlay XV).

X-Server



The X-Server's internals

2D Acceleration

- XAA: Mostly accelerates lines and solid fills;
- EXA: Meant to accelerate XRender;
- SNA: Intel's Sandy bridge New Acceleration;
- Glamor: Basing acceleration over OpenGL;
- Towards a Gallium3D-based common acceleration;

Video Acceleration: XVideo extension (XV)

- Offloads:
    - video scaling (with cubic filtering): Up scaling;
    - colour conversion: Converting YUV to RGB;
    - display.
- Limits:
    - Doesn't offloads video decoding and OSD compositing.

The X Resize, Rotate and Reflect Extension (XRandR)

- Common X API to configure screens and multi head;
- Implemented by the open and proprietary drivers;

Composite extension

- Keep a copy of each window in memory;
- Re-calculate the framebuffer when a window moves;
- Moving a window doesn't force the redraw of the windows under it;
- Also allow window-closing animation.

OpenGL X Extension (GLX)

- Allow the use of OpenGL on X;
- 2 modes:
  - Direct: The prefered rendering method (local rendering);
  - Indirect: The application asks the X-Server to be a GL proxy.

GLX direct rendering

The behaviour of this mode depends on the DRI protocol version:

- DRI1: X tells the app the size of its window and where to draw in the framebuffer;
- DRI2: The app renders to a buffer and passes it to the window manager via GEM;
- DRI-next: like DRI2 but uses DMA-Buf instead of GEM flink.

On DRI1, moving the window of a direct-rendered application resulted in strange behaviours.

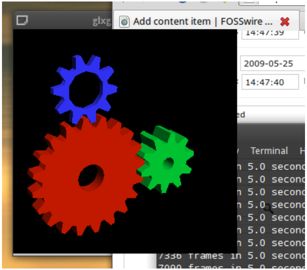
Direct rendering with DRI1

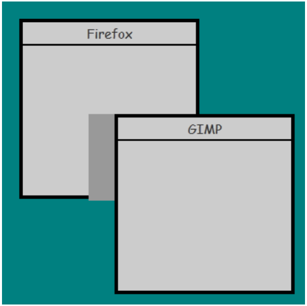
- An application willing to use direct rendering (OpenGL, video dec, other);
- Asks the XServer for its position on the framebuffer and clipping rectangles (SAREA);
- Asks the XServer to put a lock on this SAREA;
- Render the frame.

Limits to direct rendering with DRI1

- Rendering not synchronized with applications (tearing!);
- Requires synchronisation between clients & the server;
- Doesn't integrate well with compositing environments;
- Saving video memory is not needed anymore.

X-Server





Some of the DRI1 problems

Direct rendering with DRI2

- An application willing to use direct rendering (OpenGL, video decoding) renders to a buffer and GEM flink it to send it to the XServer/compositor;
- The compositor keeps this buffer until it needs to render a new frame;
- $\rightarrow$ works on compositing environments, synchronized rendering, no locks :).

Limits to direct rendering with DRI2

- GEM Flink is unsafe (a flinked buffer is accessible with few controls);
- Increases the number of context switches, slower performance;
- Takes more memory than DRI1 (who cares?).

Direct rendering with DRI-next

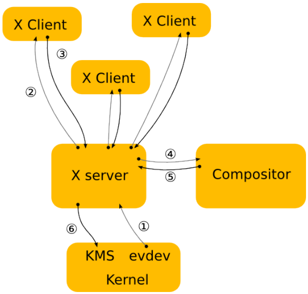
- Same as DRI2 but use DMA-Buf instead of GEM_flink;

Limits to direct rendering with DRI-next

- Same as DRI2 but no security problem.

GLX Indirect rendering

- The application asks the X-Server to be a GL proxy;
- Supports up to OpenGL 1.4 on opensource drivers;
- At first, it meant no acceleration (swrast);
- With AIGLX (Accelerated Indirect GLX), commands are redirected to the right mesa driver.



Reaction to an input event

- 1: The kernel driver evdev sends an event to the X-Server;
- 2: The X-Server forwards it to the window with the focus;
- 3: The client updates its window and tell the X-Server;
- 4 & 5: The X-Server let the compositor update its view;
- 6: The X-Server updates sends the new buffer to the GPU.

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Overview

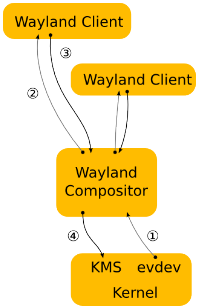
- Protocol started in 2008 by Kristian Høgsberg;
- Aims to address some of X11 shortcomings;
- Wayland manages:
  - Input events: Send input events to the right application;
  - Copy/Paste & Drag'n'Drop;
  - Window buffer sharing (the image representing the window);

Wayland Compositor

- Implements the server side of the Wayland protocol;
- Talks to Wayland clients and to the driver for compositing;
- The reference implementation is called Weston.

Current implementation of buffer-sharing

- Wayland applications share buffers using GEM_flink;
- They then send the share_ID to wayland which opens it;



Reaction to an input event

- 1: The kernel driver evdev sends an input event to "Weston";
- 2: "Weston" forwards the event to the right Wayland client;
- 3: The client updates its window and send it to "Weston";
- 4: Weston updates its view and send it to the GPU.

Outline

X11 vs Wayland

- Rendering protocol vs compositing API:
  - X11 provides old primitives to get 2D acceleration (such as plain circle, rectangle, ...);
  - Wayland lets applications render their buffers the way they want;
- Complex & heavy-weight vs minimal & efficient:
  - X11 is full of old and useless functions that are hard to implement;
  - Wayland is minimal and only cares about efficient buffer sharing;
- Cannot realistically be made secure vs secureable protocol.

X11 : Security

- X doesn't care about security and cannot be fixed:
  - Confidentiality: X applications can spy other applications;
  - Integrity: X applications can modify other apps' buffers;
  - Availability: X applications can grab input and be fullscreen.
- An X app can get hold of your credentials or bank accounts!
- An X app can make you believe you are using SSL in Firefox!

Wayland : Security

- Wayland is secure if using a secure buffer-sharing mechanism;
- See https://lwn.net/Articles/517375/.

Outline

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- lynxeye
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- ahuillet
- ymanton
- airlied
- RSpliet

Attributions : Hardware

- Moxfyre: https://en.wikipedia.org/wiki/File:Motherboard_diagram.svg
- Boffy b: https://en.wikipedia.org/wiki/File:IBM_PC_5150.jpg
- Katsuki: https://fr.wikipedia.org/wiki/Fichier:VGA_plug.jpg
- Evan-Amos: https://fr.wikipedia.org/wiki/Fichier:Dvi-cable.jpg
- Evan-Amos: https://en.wikipedia.org/wiki/File:HDMI-Connector.jpg
- Andreas -horn- Hornig: https://en.wikipedia.org/wiki/File:Refresh_scan.jpg
- Own work: https://en.wikipedia.org/wiki/File:Virtual_memory.svg

Attributions : Host : The Linux graphics stack

- X.org community: X.org schematic
- Kristian Høgsberg: `http://wayland.freedesktop.org/`
- Emeric Grange: `http://emericdev.wordpress.com/2011/08/26/a-comprehensive-guide-to-parallel-video-decoding/`
- http://blog.mecheye.net/2012/06/the-linux-graphics-stack/
- http://fosswire.com/post/2009/05/xorg-dri2-uxa/