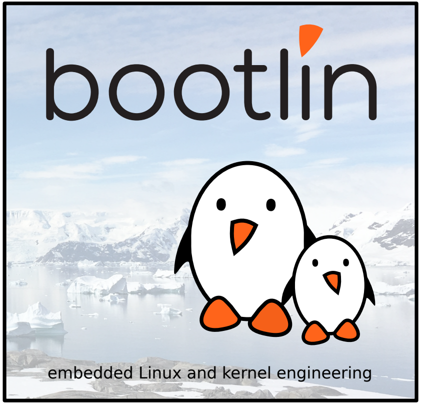
Walking Through the Linux-Based Graphics Stack

Paul Kocialkowski
paul@bootlin.com



Paul Kocialkowski

- Embedded Linux engineer at Bootlin
  - Embedded Linux **expertise**
  - **Development**, consulting and training
  - Strong open-source focus
- Open-source contributor
  - Co-maintainer of the **cedrus** VPU driver in V4L2
  - Author of the **ov5648** and **ov8865** V4L2 camera sensor drivers
  - Author of the **logicvc-drm** DRM display controller driver
  - Contributor to the **sun4i-drm** DRM display controller driver
  - Developed the **displaying and rendering graphics with Linux** training
- Living in **Toulouse**, south-west of France

Talk Outline

Agenda:

- Big Picture Overview of Graphics
- Early Graphics
- Graphics on a Running System

Focus:

- System-level aspects
- Shed light on little-known aspects
- Code references to popular/reference projects

Big Picture Overview of Graphics

Graphics Hardware: Memory

Rationale: where is the graphics data stored, how is it accessed?

Graphics data (pixels) storage:

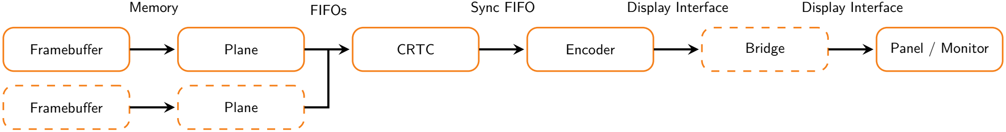
- **Framebuffers** are the memory areas for pixles
- **Memory location** depends on the situation:
  - System memory or dedicated graphics memory
  - Paged (fragmented) or contiguous memory
- Specific formats, modifiers, compression, lack of meta-data

Graphics memory access:

- Hardware-side memory access: **DMA, IOMMU**
- System-side memory access: **bus mapping, cache**

Rationale: going from memory to photons

- Pixels mixing: **planes/layers** (rotation, scaling, format and more)
- Timings generation: **CRTC**
- Interface layer: **encoder** (controller, PHY)
- Transcoding: **bridge**
- Surface: **panel, monitor**, various technologies



Graphics Hardware: Rendering

Rationale: generating pixels from primitives

- **GPUs** are the all-in-one approach for rendering 3D and 2D
  - Vector drawing units exist but are rarely used
  - Pixels mixers also left out in most cases
- Specific hardware features for the task:
  - **Programmable pipeline** with **shaders**: vertex, geometry, fragment
  - Dedicated **vector/SIMD** instruction set(s)
  - **Texture mapping units**, cache
  - **Tiled framebuffer** representations
- Requires a **dedicated compiler** for shaders
- Configured via a **command stream** in memory
- **High complexity** and power usage

Graphics APIs: Linux kernel

Rationale: providing low-level applications access to hardware features

Linux kernel subsystms and uAPIs:

- **Fbdev**: covers display, legacy: missing many many features
- **DRM**: modern subsystem for graphics
  - **KMS**: covers display, up-to-date
  - **KMS atomic**: extension for atomic state changes
  - **GEM**: memory management, zero-copy (PRIME), fences (Syncobj)
  - **Render**: covers rendering, driver-specific

Low-level libraries:

- **libdrm**: wrapper for DRM syscalls

Graphics APIs: Displaying in Userspace

Rationale: allowing applications to display their contents

Low-level display server APIs:

- **X11**: legacy protocol with various issues, various extensions
- **Wayland**: modern protocol, various extensions

Associated low-level libraries:

- **Xlib**, **XCB**: X11 protocol and extensions wrapper
- **libwayland-{display,server}**: Wayland protocols marshalling

Higher-level graphics libraries/toolkits:

- **Qt, GTK, EFL**: widget-based toolkits
- **SDL**: drawing-oriented toolkit

Graphics APIs: 2D Rendering in Userspace

Rationale: providing high-level access to 2D rendering/operations

Base drawing libraries:

- **Cairo**: vector drawing
- **Skia**: vector drawing

Pixel-level libraries:

- **Pixman**: pixel-level operations
- **FFmpeg swscale**: format, scaling
- **G'MIC**: processing

Font rendering:

- **FreeType**: Font rendering
- **Harfbuzz**: Font rendering

UI rendering:

- Graphics toolkits
- **ImGui, nuklear**: Immediate-mode

Rationale: providing high-level access to 3D rendering

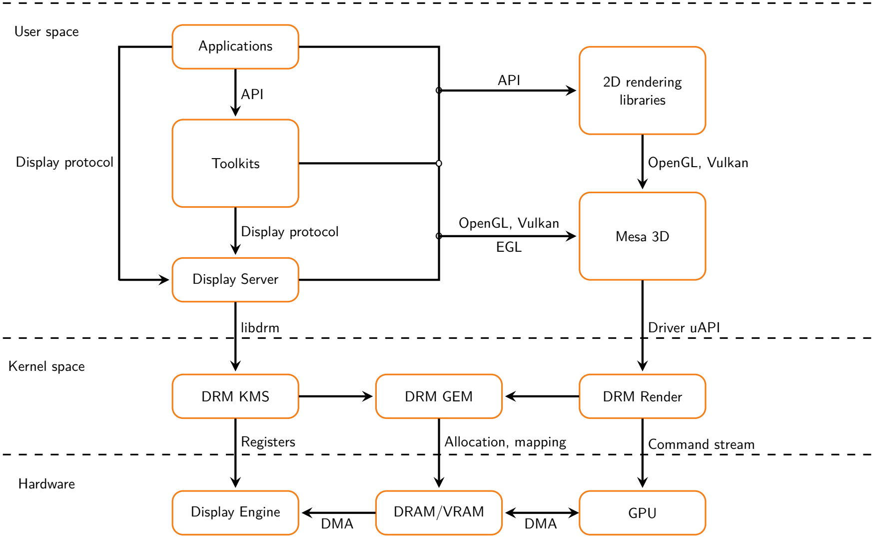
Standard APIs/formats:

- **OpenGL (ES)**: Stateful high-level rendering
  - **GLSL**: OpenGL shading language
- **EGL**: Window system integration
  - **GBM**: EGL-DRM KMS glue
- **Vulkan**: Stateless lower-level, low-overhead rendering
  - **SPIR-V**: Intermediate representation for shaders

Implementations:

- **Mesa 3D**: reference free software, using DRM
- **Proprietary**: hardware-specific, various issues

Graphics APIs: Summary Diagram



Early Graphics

Framebuffer Console

- Why do we need early graphics?
  - Show a **sign of life** before init
  - **Kernel and init logs** for debugging
  - **LUKS** password entry in initramfs
- **fbcon** implements a VT/TTY bridge with graphics:
  - **stdin** is grabbed via the **input** subsystem
  - **stdout** is rendered and displayed via **fbdev**
  - Can be used for kernel logs: `console=tty1`
  - Enabled with `CONFIG_FRAMEBUFFER_CONSOLE`
  - Can also display a logo: `CONFIG_LOGO`
- Framebuffer device provided by:
  - **Boot software**: VESA, EFI, device-tree (simple-framebuffer)
  - **Dedicated driver**: hardware-specific
  - **DRM fb helper**: compatibility layer

Framebuffer Console: Code Highlights

Linux kernel:

- `drivers/video/fbdev/core/fbcon.c`:
  - `struct consw fb_con`
  - `fbcon_set_bitops()`
  - `fbcon_prepare_logo()`
  - `do_fbcon_takeover()`
  - `fbcon_redraw()`
  - `fbcon_putc()`
- `drivers/video/fbdev/core/bitblit.c`:
  - `bit_putcs()`
- `drivers/tty/vt/vt.c`:
  - `struct tty_operations con_ops`
  - `do_update_region()`
  - `do_take_over_console`

DRM FB Helper: Code Highlights

Linux kernel:

- drivers/gpu/drm/drm_fb_helper.c:
  - struct fb_ops drm_fbdev_fb_ops
  - drm_fbdev_generic_setup
  - drm_fb_helper_generic_probe()
  - __drm_fb_helper_initial_config_and_unlock()
  - drm_fb_helper_single_fb_probe()
  - drm_fb_helper_pan_display

Bootsplash

- Users expect a **waiting screen** rather than logs
- Not a kernel-level feature:
  - Dedicated applications for the task
  - Running after init, as root
  - Typically in the initramfs
- Using either **fbdev** or **DRM KMS** directly
- Often show systemd boot progress
- Various implementations exist:
  - **Plymouth**: most advanced, progress, animations, supports DRM KMS and fbdev
  - **Psplash**: from Yocto Project, progress, uses fbdev
  - **Fbsplash**: themable, progress, uses fbdev

Running System

VT Mode

- fbcon **takes over VT** at boot
  - As soon as framebuffer is available
- **VT sharing** between fbcon/userspace:
  - Access to the display must be **exclusive**
  - Privileged operations
  - Fbcon needs to be detached
  - Requires active cooperation
- **VT modes** reflect the current VT state:
  - `KD_TEXT`: fbcon is attached to the VT
  - `KD_GRAPHICS`: ready for userspace graphics use
  - **Switched** upon request with `KDSETMODE` ioctl, using the TTY fd (controlling terminal or not)
- Similar mechanism exists for input

VT Switching

- Multiple VTs/TTYs are **spawned at boot**:
  - A single VT is **active** at a time (`tty1` at boot)
  - Switching triggered with: `Ctrl + Alt + F[n]`
  - No userspace intervention for fbcon
- **Coordination required** when userspace uses graphics:
  - Kernel needs to notify application of VT switching
  - Signal-based release/acquire handlers registered with `VT_SETMODE` ioctl
  - Graphics **resources** need to be **released/re-acquired**
  - Kernel waits for acknowledge (can hang)
- Implications for **complex systems**:
  - Multiple graphics sessions can run in **parallel**!
  - Typically the case with the login manager
  - Other limitations might restrict this ability

VT Mode and Switching: Code Highlights

Linux kernel:

- `drivers/tty/vt/vt_ioctl.c`:
  - `vt_k_ioctl()`
  - `vt_kdsetmode()`
  - `change_console()`
  - `complete_change_console()`
- `drivers/tty/vt/vt.c`:
  - `set_console()`
  - `console_callback()`

Weston:

- `libweston/weston-launch.c`:
  - `setup_tty()`
  - `handle_signal()`
- `libweston/launcher-direct.c`:
  - `setup_tty()`
  - `vt_handler()`

Sytemd Logind

- Configuring graphics (and VT) are **privileged** operations
  - Corresponds to DRM KMS **master** privilege: `DRM_IOCTL_SET_MASTER`/`DRM_IOCTL_DROP_MASTER` on DRM KMS fd
  - Typically restricted to the **root** user
  - Used to require running the display server as root
  - (Very) problematic **security implications**
- **Systemd** introduced `systemd-logind`:
  - Runs as root and opens DRM KMS and VT TTY fds
  - Provides a **D-Bus service** for applications (display servers): `org.freedesktop.login1`
  - DRM KMS fd is passed over UNIX socket
  - VT operations are made available as methods
  - Applications can run as **regular users**!

Sytemd Logind: Code Highlights

Systemd:

- `src/login/logind-session-device.c`:
  - `session_device_open()`
- `src/login/logind-session.c`:
  - `manager_vt_switch()`
- `src/login/logind-session.c`:
  - `session_open_vt()`/`session_prepare_vt()`
  - `session_restore_vt()`/`session_leave_vt()`
- `src/login/logind-session-dbus.c`:
  - `method_take_device()`/`method_release_device()`

Weston:

- `libweston/launcher-logind.c`:
  - `launcher_logind_take_device()`/`launcher_logind_release_device`
  - `launcher_logind_activate_vt()`

Login manager

Rationale: users needs to login in multi-user/general-purpose setups

- Login managers provide a **graphical equivalent** to `getty`
- Run their **own display server** under their own user
- Started at the end of the boot process (on first VT)
- Allow selecting between different **sessions**:
  - **X.org**: `/usr/share/xsessions/` desktop files
  - **Wayland**: `/usr/share/wayland-sessions/` desktop files
- Starts display server in **user context**:
  - Usually authenticated via PAM
  - Usually in a dedicated VT

Display Server: Submitting Pixels

Rationale: applications want to submit pixels to the display server

- Actualy **transfer of pixels** is **deprecated**:
  - **Zero-copy** buffer sharing with display server is used instead
  - Buffers are identified by API-specific **identifiers** (e.g. fds)
- **Buffer sharing** has two major instances:
  - **SHM**: Typically drawn by the CPU
  - **EGL**: Typically drawn by the GPU
- **Allocation** is often managed by APIs
  - Zero-copy import may be possible:
    e.g. `EGL_EXT_image_dma_buf_import`
  - Might cause hardware access issues (but usually works)
- **Coordination** with the display server for presentation:
  - Damage region provided by application (e.g. `wl_surface_damage`)
  - Sync point when ready for presentation (e.g. `wl_surface_commit`)

Display Server: Submitting Pixels: Code Highlights

Weston:

- `clients/simple-damage.c`:
  - `create_window()`
  - `redraw()`
- `clients/simple-shm.c`:
  - `create_display()`
  - `redraw()`
- `clients/simple-egl.c`:
  - `create_surface()`
  - `init_egl()`
  - `redraw()`
- `clients/simple-dmabuf-egl.c`:
  - `create_dmabuf_buffer()`
  - `redraw()`

Display Server: Compositing

Rationale: display servers need to gather applications buffers

- A **unique buffer** is submitted to the display hardware:
  - Contains the contents of all visible applications
  - Stacked according to window manager policy
  - Needs to be redrawn upon (visible) application indication
- Compositing is a **very demanding** task:
  - Full redraw must be avoided at all costs!
  - Can run up to display frame rate (e.g. 60 Hz)
  - Damage is tracked and used for clipping regions
- **Hardware acceleration** is leveraged (if not necessary):
  - Typically renderd with the GPU, buffers as textures
  - Hardware planes can be leveraged, but usually not (prinary only)
  - Cursor is typically composited by the hardware with a dedicated plane

Display Server: Compositing: Code Highlights

Weston:

- `libweston/pixman-renderer.c`:
  - `pixman_renderer_repaint_output()`
  - `draw_view()`
  - `repaint_region()`
  - `composite_clipped()`
- `libweston/renderer-gl/gl-renderer.c`:
  - `gl_renderer_repaint_output()`
  - `draw_view()`
  - `repaint_region()`
  - `texture_region()`

Display Server: Page Flipping

Rationale: achieving glitch-free display contents update

- **Tearing** is a well-known issue with display sync:
  - Display hardware scans out buffer at given address
  - Scanout happens continuouslty at refresh rate
  - Display server needs to update the presented contents
  - Concurrent read (hardware) and write (displays erver) causes a glitch
- Tearing is resolved with a **double-buffering** approach:
  - Front buffer is shown, back buffer is being prepared
  - Roles are exchanged at next vertical sync (vblank) point
  - More buffers can be used but increase latency
- DRM KMS ensures **page flipping** happens at vblank:
  - Scheduled using `DRM_IOCTL_MODE_PAGE_FLIP` (with target)
  - Scheduled with atomic commit using `DRM_IOCTL_MODE_ATOMIC`
  - Can notify userspace (blocking or async event) when done

Display Server: Page Flipping: Code Highlights

Weston:

- `libweston/backend-drm/kms.c`:
  - `drm_output_apply_state_atomic()`
  - `drm_pending_state_apply_atomic()`
  - `drm_output_apply_state_legacy()`
  - `drm_output_set_cursor()`
  - `atomic_flip_handler()/page_flip_handler()`

Questions? Suggestions? Comments?

Paul Kocialkowski
paul@bootlin.com