REYNEP's Vulkan "Adventure Guide"

Where, you adventure on your own ☺, I only 'guide', showing you the roadmap

Chapter 0: Prerequisites 📹

📖 Suggested Reading (before embarking on this journey)

1. ***Brendan Galea's Vulkan C++ [Youtube Series]***
   - 🔗 *https://www.youtube.com/watch?v=Y9U9IE0gVHA&list=PL8327DO66nu9qYVKLDmdLW_84-yE4auCR*
   - *For now, just watch the first* `3:40minute` *video* 🧑‍💻♀
     - *I don't recommend going down the playlist, right now, tho.*
2. ***Alternatively:- https://paminerva.github.io/docs/LearnVulkan/01.A-Hello-Window***
   - *Read the* `1 - Introduction` *part from here only* ☺ *[untill* `1.2. Why Vulkan?` *end]*
   - ☺ *00-Introduction-and-prerequisites.pdf*
   - 😜 *01.A-Hello-Window.pdf*
3. ***Alternatively:- you can give this page a try too:-***
   - *https://vkdoc.net/chapters/fundamentals*
   - *that is, if you are into "official formal-documentation" [i sure am not....]*

🙋♀ The 5 Questions

- ***1️⃣What is*** `Vulkan` ***? ....🤔.... Why*** `Vulkan` ***?***
  - 🔗 *Suggested Reading 2:-* `p.a.minerva`
- ***2️⃣Why should 'you' learn/use*** `Vulkan` ***?***
  1. *5-10% Faster*
  2. *More Control*
  3. *Lower Level API*
  4. *You can ask and know **'what actuaaallyyy happens under the hood of the gpu?'***
- ***3️⃣Why is this Important?***
  - *Well if you are planning on becoming a game dev, then yeah, this kinda is important!*
  - ***otherwise**, if you are just here for **CreatingShaders**:-* `OpenGL` *is fine enough*
    1. `Shader Enthusiast:-` *https://www.shadertoy.com/*
       1. *https://www.youtube.com/playlist?list=PL9Zb80ovNLWGRFZVL4LcckTWnEGN73dFS*
       2. *https://www.youtube.com/playlist?list=PLGmrMu-IwbguU_nY2egTFmlg691DN7uE5*
       3. *https://www.youtube.com/playlist?list=PLCAFZV4XJzP-jGbTke6Bd3PNDpP1AbIKo*
       4. *https://www.youtube.com/playlist?list=PLGmrMu-IwbgtMxMiV3x4IrHPlPmg7FD-P*
       5. *https://www.youtube.com/watch?v=5J-0sy2pu_8&t=357s&pp=ygUVc2hhZGVyVG95IHJheW1hcmNoaW5n*
       6. *https://www.youtube.com/watch?v=khblXafu7iA&pp=ygUJc2hhZGVyVG95*
    2. `Making an App/UI :-` *doing everything with* `OpenGL` *-> would be just fine*
       1. *TheCherno OpenGL Playlist [YT]*
       2. *TheCherno Game Engine Playlist [YT]*

- ***4️⃣When will 'you' need*** `vulkan` ***?***
  - *kinda never -> unless you have grown tired of OpenGL*
  - *kinda yes -> when you wanna understand "How the heck does the GPU Work?"*
    - *but yes, Big AAA games would need* `vulkan` *for even that last 5-10% performance*
- ***5️⃣How does*** `vulkan` ***work?***
  - *Rest of this entire guide is dedicated to answer this question* ☺

1. ⍰ grab `vulkan-sdk`, `cmake`, `amGHOST`

1. ***if you don't have*** `vscode` ***&*** `C++ Compiler`
   - ➡🔗 *4.guide.CH0.vscode.md*

2. 📥 ***https://vulkan.lunarg.com/sdk/home***
   - *make sure* `VULKAN_SDK` *&* `VK_SDK_PATH` *environment variables are set*
   - *restart vscode after installing*

3. 📥 ***https://cmake.org/download/***
   - 🎓 `Intro/Tutorials`
     - *https://enccs.github.io/intro-cmake/hello-cmake/*
     - `OR` *: Watch 6/7 videos from this playlist:-*
       - *https://www.youtube.com/playlist?list=PLK6MXr8gasrGmIiSuVQXpfFuE1uPT615s*
   - *restart vscode after installing*
   - 📜 `REY_DOCs`
     - *This is how it usually looks. Read through it* 🧑‍🏫♀.
     - *The app that we will make using* `amGHOST`*, will need to have these commands*

```
cmake_minimum_required(VERSION 3.25 FATAL_ERROR)

project("idk_PROJECT" VERSION 0.1)

    set(CMAKE_CXX_STANDARD 23)
    set(CMAKE_CXX_STANDARD_REQUIRED ON)

# --------------------
    set(SRC
        "main.cpp"
    )

    set(INC
        ${CMAKE_CURRENT_SOURCE_DIR}
    )
# --------------------

# --------------------
# set_source_files_properties(main.cpp PROPERTIES COMPILE_FLAGS "/P /C")
# Output Preprocessed File
            add_executable (idk ${SRC})
target_include_directories (idk PUBLIC ${INC})

# ------amGHOST-------
         add_subdirectory  (amGHOST)
    target_link_libraries  (idk PUBLIC amGHOST)

# ------install-------
    install(TARGETS idk
        DESTINATION ${CMAKE_CURRENT_SOURCE_DIR})
```

4. `amGHOST`
   - *amateur's Generic Handy Operating System Toolkit*
     - *[secretly inspired by* `blender's GHOST` *xP* 😁*]*
   - `git clone -b win32-intro https://github.com/REYNEP/amGHOST`
   - *Open it with VSCode*
   - `F1` --> `CMake: Configure`
   - `F1` --> `CMake: Build`
   - `F1` --> `CMake: Install` --> `.insall` *dir*
   - *check's* ***amGHOST's Usage Example*** *inside* `amGHOST/README.md`

  - `Option 1` :- use `cmake` for your project too.... using `add_subdirectory(amGHOST)`
  - `Option 2` :- use `libamGHOST.lib` after installing & `#include amGHOST/<header>`
- just copy paste **amGHOST's Usage Example** into a `main.cpp` for your program

```cpp
#include "amGHOST/amGHOST_System.hh"

int main(int argumentCount, char* argumentVector[])
{
    amGHOST_System::create_system();    // initializes amG_HEART

    amGHOST_Window* W = amG_HEART->new_window_interface();
    W->create(L"Whatever", 0, 0, 500, 600);

    REY::cin.get();     // wait for terminal input
    W->destroy();
}
```

  - [shorter than `readme ex. 1`]
  - now you shall have a OS-Window ☺

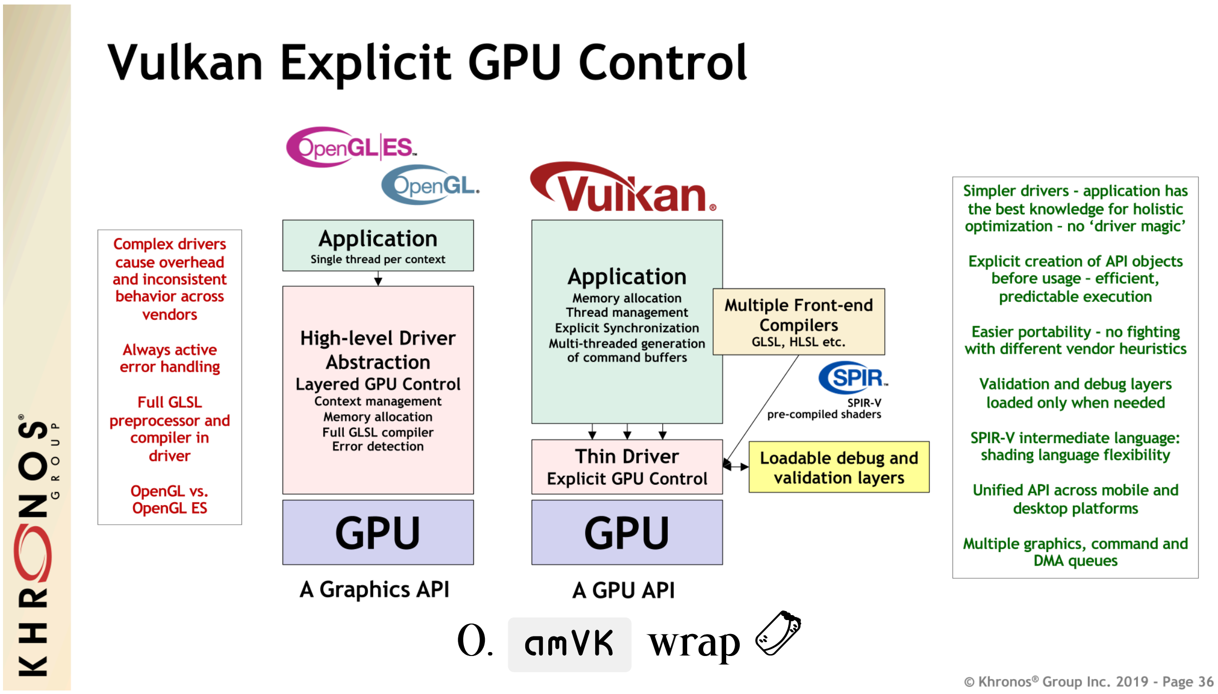
5. Viewing these readmes in a Nice Way

- https://github.com/REYNEP/amGHOST/blob/main/amVK_Guide/P1/bkup/style-bkup.less
- `vscode extension` :- shd101wyy.markdown-preview-enhanced
- `scoop install princexml`
- `vscode F1` :- Markdown Preview Enhanced:- Customize CSS (Global)
- Paste my `style-bkup.less`
- `vscode F1` :- Markdown Preview Enhanced:- Open Preview 🧑‍💻♀

The Real "Adventure" begins here!

[well, not really. I believe the real adventure is in SHADERs and Algorithms!]

Chapter 1: `VkInstance`



Vulkan Explicit GPU Control

Complex drivers cause overhead and inconsistent behavior across vendors

Always active error handling

Full GLSL preprocessor and compiler in driver

OpenGL vs. OpenGL ES

Simpler drivers - application has the best knowledge for holistic optimization - no 'driver magic'

Explicit creation of API objects before usage - efficient, predictable execution

Easier portability - no fighting with different vendor heuristics

Validation and debug layers loaded only when needed

SPIR-V intermediate language: shading language flexibility

Unified API across mobile and desktop platforms

Multiple graphics, command and DMA queues

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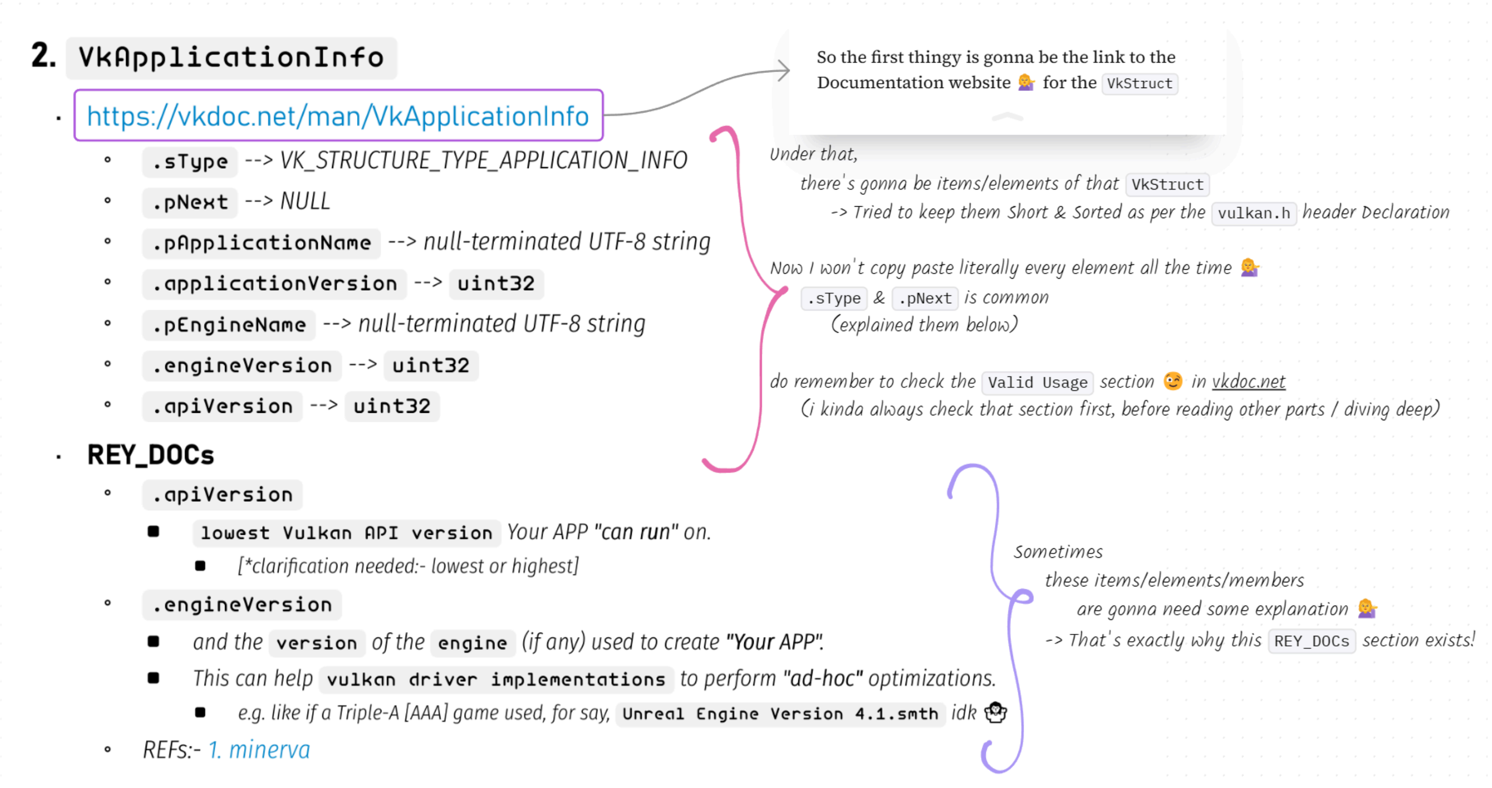
0. `amVK` wrap

```
#include "amVK_Instance.hh"
    // TwT
amVK_Instance::AppInfo              // VkApplicationInfo        [public]
amVK_Instance::CI                   // VkInstanceCreateInfo     [public]
    // You can modify these as you wish ☺
amVK_Instance::CreateInstance();    // initializes amVK_HEART
```

1. Notes on `Notes`



2. `VkApplicationInfo`

- https://vkdoc.net/man/VkApplicationInfo
  - `.sType` --> *VK_STRUCTURE_TYPE_APPLICATION_INFO*
  - `.pNext` --> *NULL*
  - `.pApplicationName` --> *null-terminated UTF-8 string*
  - `.applicationVersion` --> `uint32`
  - `.pEngineName` --> *null-terminated UTF-8 string*
  - `.engineVersion` --> `uint32`
  - `.apiVersion` --> `uint32`
- **REY_DOCs**
  - `.apiVersion`
    - `lowest Vulkan API version` *Your APP "can run" on.*
      - *[*clarification needed:- lowest or highest]*
  - `.engineVersion`
    - *and the* `version` *of the* `engine` *(if any) used to create "Your APP".*
    - *This can help* `vulkan driver implementations` *to perform "ad-hoc" optimizations.*
      - *e.g. like if a Triple-A [AAA] game used, for say,* `Unreal Engine Version 4.1.smth` *idk* 🤷
  - *REFs:- 1. minerva*

So the first thingy is gonna be the link to the Documentation website 💁 for the `VkStruct`

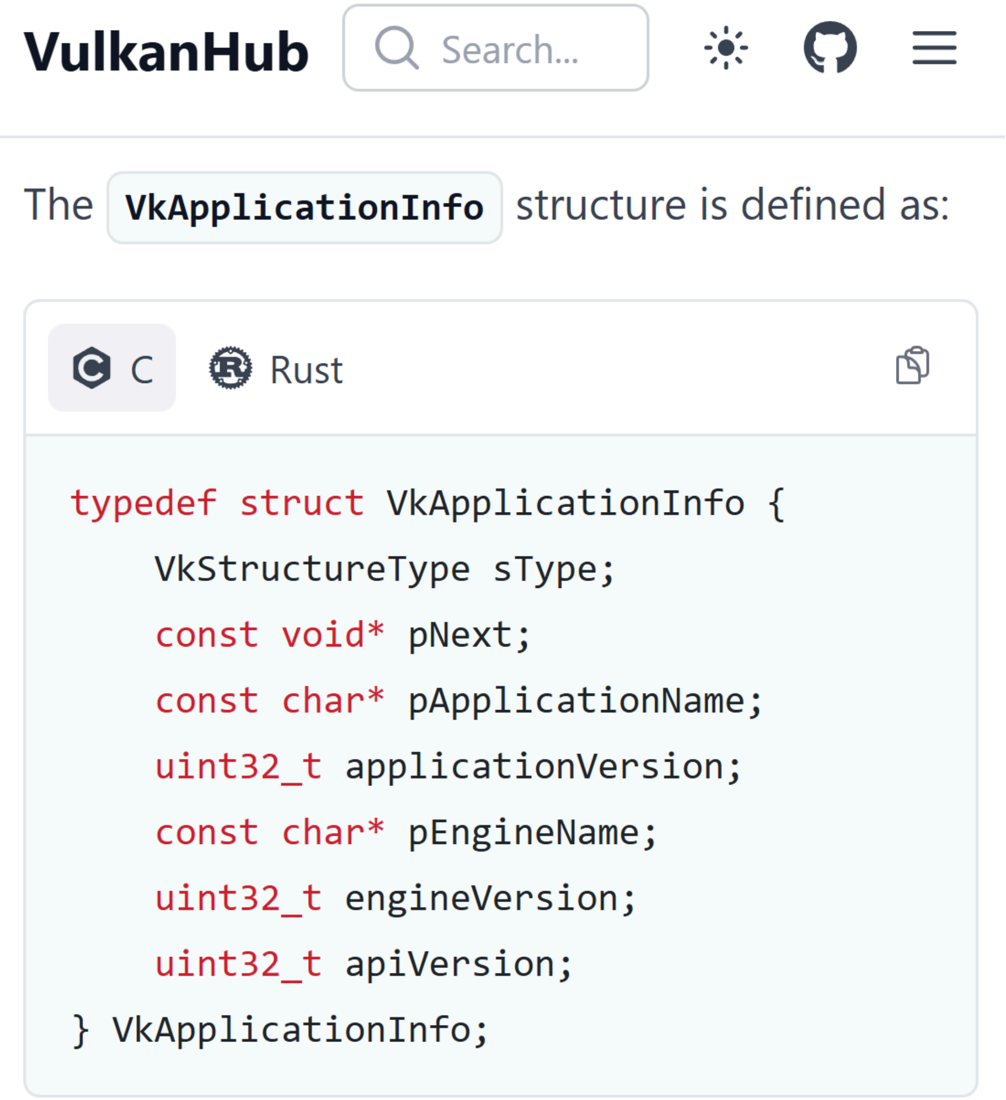
Under that,
there's gonna be items/elements of that `VkStruct`
-> Tried to keep them Short & Sorted as per the `vulkan.h` *header Declaration*

Now I won't copy paste literally every element all the time 💁
`.sType` *&* `.pNext` *is common*
(explained them below)

do remember to check the `Valid Usage` *section* 😉 *in vkdoc.net*
(i kinda always check that section first, before reading other parts / diving deep)

Sometimes
these items/elements/members
are gonna need some explanation 💁
-> That's exactly why this `REY_DOCs` *section exists!*

made with affine.pro [+ Screenshot of my `4.guide.CH0.pdf` *]*



The `VkApplicationInfo` structure is defined as:

```c
typedef struct VkApplicationInfo {
    VkStructureType sType;
    const void* pNext;
    const char* pApplicationName;
    uint32_t applicationVersion;
    const char* pEngineName;
    uint32_t engineVersion;
    uint32_t apiVersion;
} VkApplicationInfo;
```

- *https://vkdoc.net/man/VkApplicationInfo*
    - `.sType` :-
        - ▨ *almost every* `VkStruct` *is gonna have this field/member* 💁♀
        - *must be*
            - `VK_STRUCTURE_TYPE_APPLICATION_INFO` *for* `VkApplicationInfo`
            - `VK_STRUCTURE_TYPE_INSTANCE_CREATE_INFO` *for* `VkInstanceCreateInfo`
            - `VK_STRUCTURE_TYPE_DEVICE_CREATE_INFO` *for* `VkDeviceCreateInfo`
            - *and so on... (you get the idea)*

    - `.pNext` :-
        - ▨ *almost every* `VkStruct` *is gonna have this field/member* 💁♀
        - *Mostly* `NULL` 💁♀
        - *but it has an interesting use case:-*
            - *https://vkdoc.net/man/VkDeviceCreateInfo#VUID-VkDeviceCreateInfo-pNext-pNext*
            - *you can kinda like pass in pointer to* `VkStructEXT` *when you need those Extension features* 💁♀

    - `.pApplicationName` --> *null-terminated UTF-8 string*
    - `.applicationVersion` --> `uint32`
        - *you as the developer of your application can set it to arbitrarily anything you want it to* 💁♀*, say*
            - *101*
            - *005*
            - *1*
            - *2025*
    - `.pEngineName` --> *null-terminated UTF-8 string*
    - `.engineVersion` --> `uint32`
    - `.apiVersion` --> `uint32`

- ***again.... yeah, do remember to check the*** `Valid Usage` ***section*** ☺

- ***There's a alternative to*** ***vkdoc.net***
    - *https://github.com/ivirtex/vulkan-hover-docs/tree/master/vscode_ext/vulkan_man_md_pages/VkInstanceCreateFlagBits.md*
    - *it is also available as an extension in* `vscode` --> `ivirtex.vulkan-hover-docs`

- ***Symbols***
    - ▨:- *kinda means nothing*
        - *i kinda used to like make it look like a bit pattern-ish iguess* ��
    - ░:- *"Yellow Card"*
        - *it means, you don't need to hesitate about this thingy right now* 💁♀ *we will focus on this element later* �
    - ▓:- *"Orange Card"*
        - *it means, this element is probably never gonna be 'necessary' for vulkan applications* 💁♀

    - *[The extended list can be found in* 🔗 ***Chapter3.14****]*

2. 🛠 `VkApplicationInfo`

- ***https://vkdoc.net/man/VkApplicationInfo***
    - `.sType` ▨ `VK_STRUCTURE_TYPE_APPLICATION_INFO`
    - `.pNext` ▨ `NULL`
    - `.pApplicationName` --> *null-terminated UTF-8 string*
    - `.applicationVersion` 🏷 `uint32`
    - `.pEngineName` --> *null-terminated UTF-8 string*
    - `.engineVersion` 🏷 `uint32`
    - `.apiVersion` 🏷 `uint32`
- 📜 *REY_DOCs*
    - `.apiVersion`
        - `lowest Vulkan API version` *Your APP **"can run"** on.*
            - *[*clarification needed:- lowest or highest]*
    - `.engineVersion`
        - *and the* `version` *of the* `engine` *(if any) used to create **"Your APP"**.*
        - *This can help* `vulkan driver implementations` *to perform **"ad-hoc"** optimizations.*
            - *e.g. like if a Triple-A [AAA] game used, for say,* `Unreal Engine Version 4.1.smth` *idk* 🤷‍♀
    - *REFs:- 1. minerva*

- ***yes, what are you waiting for 🤷‍♀ go go, shooo.... (�)***

i. `#include <vulkan/vulkan.h>`
ii. *take an instance of that* `Struct` *-> Fill it up [😉][have the vkdoc.net as assist]*

3. 🛠 `VkInstanceCreateInfo`

- ***https://vkdoc.net/man/VkInstanceCreateInfo***
    - `.sType` ▨ `VK_STRUCTURE_TYPE_INSTANCE_CREATE_INFO`
    - `.pNext` � `NULL`
        - *�: "Extensions"*
        - *Some intresting ones actually 😉 (will talk about them later)*
    - `.flags` 🏳 `VkInstanceCreateFlagBits`
        - *https://vkdoc.net/man/VkInstanceCreateFlagBits | ivirtex-github*
    - `.pApplicationInfo` ▨ 💁‍♀ *Duh!*
    - `.ppEnabledLayerNames` ▒ ChapterZZZ
    - `.ppEnabledExtensionNames` ▒ *Chapter4.2*
        - *Don't hesitate about* `EnabledLayer` *&* `EnabledExtensions` *right now*
            - *come back and add them when you need to 😉*
            - *This is what I would mean, when i would point smth to a later chapter*
            - *I will add the ▒ ("Yellow Card") too!*
- 📜 *REY_DOCs*
    - *Nothing that I need to add, in this section*
    - *Tho if this section gets big, I will create a separate* `.md` *file for that thingy*

4. A 😎 Cool `vscode` / `visual-studio` extension if you want 🤷‍♀️

- `vscode extension name` --> `ivirtex.vulkan-hover-docs`
  - https://github.com/ivirtex/vulkan-hover-docs

---

5. 🏷️ `VkInstance m_instance = nullptr;`

- ***https://vkdoc.net/man/VkInstance***

6. 🎁 `vkCreateInstance(CI, nullptr, &m_instance)`

- ***https://vkdoc.net/man/vkCreateInstance***
  - `param pCreateInfo` ▨ 🤷‍♀️ *Duh!*
  - `param pAllocator` ▨ `nullptr`
  - `param pInstance` ▨ `&m_instance`
- 📜 *REY_DOCs*
  - `param pAllocator`
    - `VkAllocationCallbacks` ▨ ChapterZZZ
      - *I will make a chapter on this ◈ [https://vkdoc.net/chapters/memory#memory-allocation]*
    - *Vulkan provides applications the opportunity to perform host memory allocations*
    - *If this feature is not used*
      - *the implementation will perform its own memory allocations.*
    - *Since most memory allocations are off the critical path, this is not meant as a performance feature. Rather, this can be useful for certain embedded systems, for debugging purposes (e.g. putting a guard page after all host allocations), or for memory allocation logging.*

---

7. 🚨 Error Handling / Checking / ◈ Logging

- ***check out my*** `amVK_log.hh`
  - *uses REY_LoggerNUtils inside amGHOST*
  - *has a simple* `stackTracer()` *that i basically stripped from blender3D codebase ◈*

8. `📽️ So far, The result` :- *4.guide.chapter1.hh*

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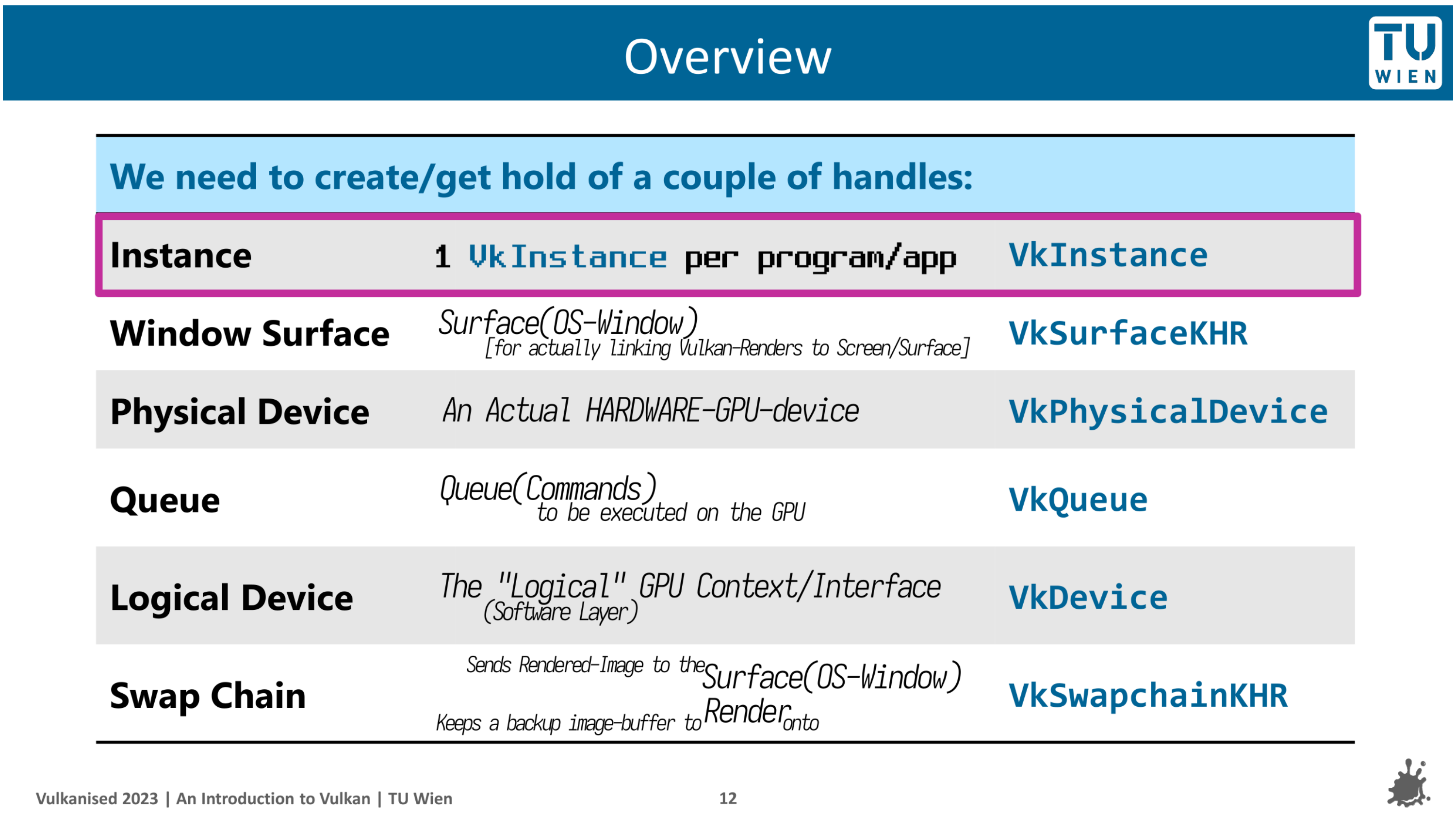
9. The Unused ones

1. `vkEnumerateInstanceExtensionProperties()` --> ▨ *Chapter4.2*
   - *https://vkdoc.net/man/vkEnumerateInstanceExtensionProperties*
2. `Add_InstanceEXT_ToEnable(const char* extName)` --> ▨ *Chapter4.2*
   - *this is a **amVK/REY** Custom Function*

Chapter 2: `VkDevice`



Overview

We need to create/get hold of a couple of handles:

Instance	1 `VkInstance` per program/app	`VkInstance`
Window Surface	*Surface(OS-Window)* *[for actually linking Vulkan-Renders to Screen/Surface]*	`VkSurfaceKHR`
Physical Device	*An Actual HARDWARE-GPU-device*	`VkPhysicalDevice`
Queue	*Queue(Commands) to be executed on the GPU*	`VkQueue`
Logical Device	*The "Logical" GPU Context/Interface (Software Layer)*	`VkDevice`
Swap Chain	*Sends Rendered-Image to the Surface(OS-Window)* *Keeps a backup image-buffer to Render onto*	`VkSwapchainKHR`

Vulkanised 2023 | An Introduction to Vulkan | TU Wien 12

Take a look into this awesome *slide* from slide-26 onwards
...to understand what each of these steps above *"feel like"/mean/"how to imagine them"*.
*slide = *Vulkanised 2023 Tutorial Part 1*

0. `amVK` wrap 🌯

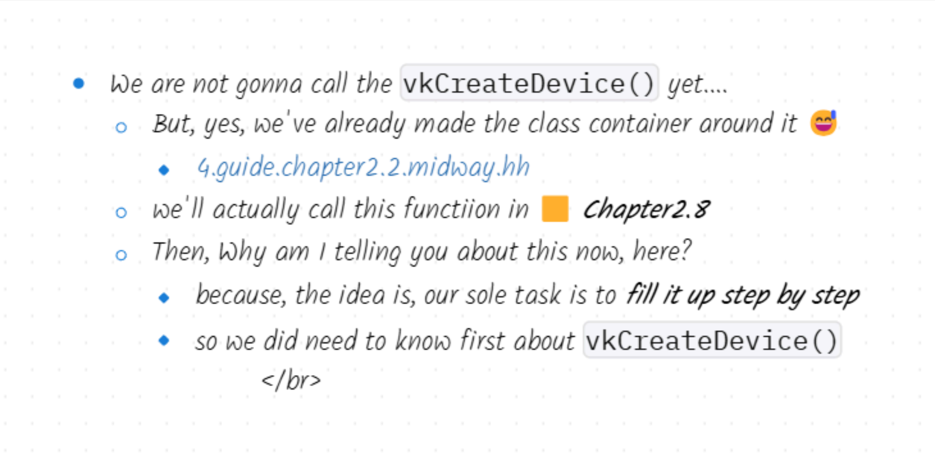
```
#include "amVK_Instance.hh"
#include "amVK_DeviceQueues.hh"
#include "amVK_Device.hh"

    // TwT
    REY_LOG("");
amVK_Instance::EnumeratePhysicalDevices();
amVK_GPUProps  *GPUProps = amVK_InstanceProps::GetARandom_GPU();
                GPUProps->GetPhysicalDeviceQueueFamilyProperties();
                GPUProps->REY_CategorizeQueueFamilies();

amVK_Device* D = new amVK_Device(GPUProps);
    D->CI                           // VkDeviceCreateInfo       [public]
    D->Queues                       // amVK_DeviceQueues        [public] [take a look inside 😜]
    D->add_1D_QFAMs_QCount_USER()   // amVK_DeviceQueues
    D->CreateDevice(1);             // param1 = GraphicsQueueCount =
    D->GetDeviceQueues();           //     see:- Queues.TheArrays 😜
    D->Queues.GraphicsQ(0)          // returns   Queues.TheArrays.Graphics[0]
```

1. 🎁 `vkCreateDevice()`

- *https://vkdoc.net/man/vkCreateDevice*
    - `physicalDevice` ▨ `HardwareGPU_List[0]` / `amVK_InstanceProps::GetARandom_GPU()`
        - *Enumerate* ▩ ***Chapter2.3***
        - *How to 'choose'?* ▩ ***Chapter2.End***
    - `pCreateInfo` ▨💁‍♀
        - 🔗 *SubChapter 2*
    - `pAllocator` ▩ ChapterZZZ
    - `pDevice` ↩🎁 `&m_Device`
        - ↩🎁: *"Returned by vkFunc()"*



- *We are not gonna call the* `vkCreateDevice()` *yet....*
    - *But, yes, we've already made the class container around it* 😅
        - *4.guide.chapter2.2.midway.hh*
    - *we'll actually call this functiion in* 🟧 ***Chapter2.8***
    - *Then, Why am I telling you about this now, here?*
        - *because, the idea is, our sole task is to* ***fill it up step by step***
        - *so we did need to know first about* `vkCreateDevice()`

            </br>

- 📽 `So far, The result` :-
    - 4.guide.chapter2.2.midway.hh

2. 🛠 `VkDeviceCreateInfo`

- *https://vkdoc.net/man/VkDeviceCreateInfo*
    - `.sType` ▨ `VK_STRUCTURE_TYPE_DEVICE_CREATE_INFO`
    - `.pNext` ◈ `nullptr`
        - ◈ *almost any EXT that you are gonna enable.... is prolly gonna end up being passed on here.... tied to* `VkDeviceCI` 💁‍♀
    - `.flags` 🏴 `0`
        - 🏴: *"No Flag"*
        - `VkSpecs` *Says:-* `reserved for future use`

    - `.pQueueCreateInfos` 🔗 *SubChapter 5*
        - *Multiple Queue Create Infos:-* ▩ ***Chapter2.8***
    - `.ppEnabledLayerNames` ⚠ *deprecated [by Vulkan]*
    - `.ppEnabledExtensionNames` ▩ ***Chapter4.2***
    - `.pEnabledFeatures` ▩ ChapterZZZ
        - *This should be really interesting*
- 📜 ***REY_DOCs***
    - `.pQueueCreateInfos` *-> yes, you 'can' pass multiple* ☺
    - *Sometimes there will be* `.zzzCreateInfoCount` & `.pZZZCreateInfos`
        - *So you could like pass in an array/vector*
        - *You will see this in lots of other places*
- 📽 `So far, The result` :-
    - 4.guide.chapter2.3.midway.hh

3. 📜 `vkEnumeratePhysicalDevices()`

- *https://vkdoc.net/man/vkEnumeratePhysicalDevices*
- `</> TheCode`

```
uint32_t deviceCount = 0;
    // [implicit valid usage]:- must be 0 [if 3rd-param = nullptr]
    vkEnumeratePhysicalDevices(m_instance, &deviceCount, nullptr);
        // it's kinda like the function is 'output-ing into' deviceCount

std::vector<VkPhysicalDevice> HardwareGPU_List(gpuCount);
    // best to save this as a class member variable
    vkEnumeratePhysicalDevices(m_instance, &deviceCount, HardwareGPU_List.data());
        // note: it does return     VkResult return_code
```

  - `👀 Visualization / [See it] / JSON Printing` :- *4.guide.chapter2.1.json.hh*
  - `📽 So far, The result` :- *4.guide.chapter2.1.midway.hh*
  - `🔗 GitHub` :- *amVK_GPUProps.hh*

4. ⯑ `amVK_InstanceProps::GetARandom_GPU()`

`</> TheCode` 🔗 `GITHUB` *amVK_InstanceProps.hh#L39*

5. 🛠 `VkDeviceQueueCreateInfo` - *'The Real Deal'*

- *https://vkdoc.net/man/VkDeviceQueueCreateInfo*
  - `.sType` ▨ `VK_STRUCTURE_TYPE_DEVICE_QUEUE_CREATE_INFO`
  - `.pNext` ⯑ `nullptr`
    - ⯑ *2 Extensions ☺ (will talk about them later)*
  - `.flags` 🏳 `0`
    - ⯑ *https://vkdoc.net/man/VkDeviceQueueCreateFlagBits | ivirtex-github*
    - ⚑ *: "Only Option"*
      - `VK_DEVICE_QUEUE_CREATE_PROTECTED_BIT` *[Protected Queue]*
  - `.queueFamilyIndex` 🔗 *Next 3 SubChapters*
    - `vkGetPhysicalDeviceQueueFamilyProperties()` *--> look for a QueueFamily that supports* `VK_QUEUE_GRAPHICS_BIT`
  - `.queueCount` ▨ `1` *[Specify, how many you need 🙋‍♀]*
  - `.pQueuePriorities` *--> yes, this can be multiple "Priorities"* ⯑ *[idk yet why tho]*
    - *Range = (0.0 -> 1.0) [inclusive]*
    - *Within the same device, queues with higher priority may be allotted more processing time than queues with lower priority.*
- `📽 So far, The result` :-
  - *We are gonna take a Big Leap & Start connecting to* 🔗 `GITHUB`
  - *amVK_DeviceQCI.hh*

6. 📜 `vkGetPhysicalDeviceQueueFamilyProperties()`

- *https://vkdoc.net/man/vkGetPhysicalDeviceQueueFamilyProperties*
- 📜 *REY_DOCs*
    - *a GPU can have "multiple QueueFamilies"*
        - *a* `QueueFamily` *might support* `VK_QUEUE_GRAPHICS_BIT`
        - *another* `QueueFamily` *might support* `VK_QUEUE_COMPUTE_BIT`
        - *another* `QueueFamily` *might support* `VK_QUEUE_TRANSFER_BIT`
        - *another* `QueueFamily` *might support* `VK_QUEUE_VIDEO_ENCODE_BIT_KHR`
        - *another* `QueueFamily` *might support a-mixture of multiple*
        - *talking about this in -> 🔗 Next SubChapter*

- `</> TheCode` *[OldWay]*

```
#define GPUs                                amVK_InstanceProps::s_HardwareGPU_List
#define amVK_2D_GPUs_QFAMs                     amVK_Instance::s_HardwareGPU_QFamProps_List2D
static inline REY_Array<REY_Array<VkQueueFamilyProperties>>   s_HardwareGPU_QFamProps_List2D;
    // REY_Array --> "REY_LoggerNUtils/REY_Utils.hh" 😊
    // 1 System/PC
        // multiple GPU
            // multiple QFamProps
```

```
static inline void GetPhysicalDeviceQueueFamilyProperties(void) {
    amVK_2D_GPUs_QFAMs.reserve(GPUs.n);            // malloc using "new" keyword
    for ( uint32_t k = 0;  k < GPUs.n; k++ )       // for each GPU
    {
        REY_Array<VkQueueFamilyProperties> *k_QFamProps = &amVK_2D_GPUs_QFAMs.data[k];

        uint32_t QFamCount = 0;
            vkGetPhysicalDeviceQueueFamilyProperties(GPUs[k], &QFamCount, nullptr);

        k_QFamProps->n  = QFamCount;
        k_QFamProps->data = new VkQueueFamilyProperties[QFamCount];
            vkGetPhysicalDeviceQueueFamilyProperties(GPUs[k], &k_QFamProps->n, k_QFamProps->data);
    }
    #undef GPUs
}
```

-
    - `👀 Visualization / [See it] / JSON Printing` :- *4.guide.chapter2.5.json.hh*
        - *Check the 3070 JSON by REY*
    - `📽 So far, The result` :- *[OldWay] 4.guide.chapter2.5.amVK_Instance.hh*
        - *Compare to -> 4.guide.chapter2.1.midway.hh*
            - `2DArray_QFAM_Props` *part & below were added only compared to* `Chapter2.1.`

- `📽 So far, The result` :- 🔗 `GITHUB` *[NewWay]*
    - *amVK_GPUProps.hh*
    - *amVK_GPUProps.cpp#L5-L17*

7. 🏷 `VkQueueFamilyProperties`

- *https://vkdoc.net/man/VkQueueFamilyProperties*
- 📜 *REY_DOCs*
  - `.queueFlags`
    - *we are gonna choose a* `QCI.queueFamilyIndex` *based on these flags*
    - *primarily, for the least, we wanna choose a* `QueueFamily` *that supports* `VK_QUEUE_GRAPHICS_BIT`
    - *all kinds of amazing things can be done using*
      - `VK_QUEUE_COMPUTE_BIT`
      - `VK_QUEUE_TRANSFER_BIT`
      - `VK_QUEUE_VIDEO_ENCODE_BIT_KHR`
  - `.queueCount`
    - *yes there is a limit to 'how many* `Queues` *we are allowed to work with'* ❓
  - `.timestampValidBits`
  - `.minImageTransferGranularity`

8. `VkDeviceQCI.queueFamilyIndex` [OldWay]

- 🎯 `Task`
  - *is to choose a* `QueueFamily` *that supports* `VK_QUEUE_GRAPHICS_BIT` ☺
  - *(if you've followed on so far -> this should be easy ☺)*
- `</> amVK_Device.hh`

```
void amVK_Device::Select_QFAM_GRAPHICS(void) {
    if (!amVK_Instance::called_GetPhysicalDeviceQueueFamilyProperties) {
        amVK_Instance::EnumeratePhysicalDevices();
    }

    if (!amVK_Instance::called_GetPhysicalDeviceQueueFamilyProperties) {
        amVK_Instance::GetPhysicalDeviceQueueFamilyProperties();
    }

    amVK_Instance::amVK_PhysicalDevice_Index index = amVK_HEART->GetARandom_PhysicalDevice_amVK_Index();
    this->QCI.Default.queueFamilyIndex = amVK_Instance::ChooseAQueueFamily(VK_QUEUE_GRAPHICS_BIT,
index);
        // If you wanna see the implementation for this function
}
```

  - `🐿 So far, The result` :- ***OldWay*** *(Don't spend time inside this, more than 1 minute)*
    - *4.guide.chapter2.9.Props.hh*
    - *4.guide.chapter2.9.amVK.cpp*

  - `🐿 So far, The result` :- ***NewWay*** 🔗 `GITHUB` *(NewWay is like 10x more organized and easier to understand)*
    - *amVK_GPUProps.hh*
    - *amVK_GPUProps.cpp#L266-L286*

9. ❓ `REY_CategorizeQueueFamilies()` [NewWay]

`</> TheCode` 🔗 `GITHUB`
amVK_GPUProps.hh#L50
amVK_GPUProps.cpp#L260

10. back to 🎁 `vkCreateDevice()` finally calling it 😉

- *https://vkdoc.net/man/VkDeviceCreateInfo*
- `</> main.cpp`

```cpp
amVK_Device* D = new amVK_Device(GPUProps);
    D->CI                           // VkDeviceCreateInfo       [public]
    D->Queues                       // amVK_DeviceQueues        [public] [take a look inside 😛]
    D->add_1D_QFAMs_QCount_USER()   // amVK_DeviceQueues
    D->CreateDevice(1);             // param1 = GraphicsQueueCount = 1
    D->GetDeviceQueues();           //     see:- Queues.TheArrays 😛
    D->Queues.GraphicsQ(0)          // returns   Queues.TheArrays.Graphics[0]
```

  - *Think of this as a PSeudoCode / or / check out my code if you wanna*
  - `CreateInfo` => *By default has initial values inside* `amVK_Device`

11. ⍰ `amVK_DeviceQueues`

🔗 *amVK_DeviceQueues.hh*

▨ eXtras / TheEnd

11. multiple `VkDeviceCreateInfo.pQueueCreateInfos`
- ***VUID-VkDeviceCreateInfo-queueFamilyIndex-02802***
  - *The* `.queueFamilyIndex` *member of each element of* `.pQueueCreateInfos` *must be unique* 🤷‍♀️
  - *So, randomly* `push_back()` *ing without any kinda safety* ➞ *kinda feels absurd.* 🤷‍♀️ *doesn't it? .... e.g.*

```
/* ============ REY_LoggerNUtils::REY_Utils.hh ============ */
REY_ArrayDYN<VkDeviceQueueCreateInfo> Array = REY_ArrayDYN<VkDeviceQueueCreateInfo>(2);
    REY_ARRAY_PUSH_BACK(Array) = this->Default_QCI;
    REY_ARRAY_PUSH_BACK(Array) =          Your_QCI;
```

    - [OldWay]:- *amVK_DeviceQCI.hh*
  - *So what i did is:- to introduce a* `QCount` *array as per* `QFamily` 🤷‍♀️
    - [NewWay]:- *amVK_DeviceQueues.hh#L56*
  - *& then have a function for the user to increase the* `QCount`
    - [NewWay]:- 🔗 `GITHUB_WIP` --> `amVK_Device::add_1D_QFAMs_QCount_USER()`

12. *OldWay* 🗓 `March, 2025`
  - *i.* `class amVK_InstanceProps`
    - `EnumeratePhysicalDevices()`
    - `GetPhysicalDeviceQueueFamilyProperties()`
  - *(Don't spend time inside this, more than 1 minute)*
    - 📝 *4.guide.chapter2.9.Props.hh*
    - 📝 *4.guide.chapter2.9.amVK.cpp*
  - *https://github.com/REYNEP/amGHOST/tree/3e44b982902a3f3fa4ac584aefb19da3d4cdfcc6*

13. *NewWay* 🗓 `May, 2025`
  - 🔗 `GITHUB` (NewWay *is like 10x more organized and easier to understand)*
    - 📝 *amVK_GPUProps.hh*
    - 📝 *amVK_GPUProps.cpp#L266-L286*

14. `vkGetPhysicalDeviceProperties()` ▩ *Chapter11*
15. ***GetFeatures*** ▩ *Chapter11*
16. ***MemoryTypes*** ▩ *Chapter11*
17. ***Guide on*** `amVK_Array` ▩ *Chapter6.6*

Chapter 3: Common Patterns: *if someone missed to catch it yet* ☺

```
Object  Vk      VkInstance
Types   Vk      VkInstanceCreateInfo
Funcs   vk      vkCreateInstance()
Enums   VK_     VK_STRUCTURE_TYPE_INSTANCE_CREATE_INFO

Extensions
    KHR:- Khronos authored,
    EXT:- multi-company authored

Creating "VkZZZ" object
    1. take `VkZZZCreateInfo` --> fill it up
    2. call `vkCreateZZZ()`
    3. also `vkDestroyZZZ()` before closing your app

    4. Some objects get "allocated" rather than "created"
        `VkZZZAllocateInfo` --> `vkAllocateZZZ` --> `vkFreeZZZ`

    5. Sometimes there will be `.zzzCreateInfoCount` & `.pZZZCreateInfos`
                        e.g. `.queueCreateInfoCount` & `.pQueueCreateInfos``
            -> So you could like pass in an array/vector
            -> You will see this in lots of other places

Getting List/Properties
    6. vkEnumerateZZZ() --> \see `[Chapter2.1.] vkEnumeratePhysicalDevices()` example
```

-- | -- | -- | --

7. ▨ *almost every* `VkStruct` *is gonna have these 3 field/member* 🙇‍♀

i. `sType` :-
   - *It may seem somewhat redundant, but this information can be useful for the* `vulkan-loader` *and actual* `gpu-driver-implementations` *to know what type of structure was passed in through* `pNext`.

ii. `pNext` :-
   - *allows to create a linked list between structures.*
   - *It is mostly used when dealing with extensions that expose new structures to provide additional information to the* `vulkan-loader`, `debugging-validation-layers`, *and* `gpu-driver-implementations`.
     - *i.e. they can use the* `pNext->stype` *field to know what's ahead in the linked list*

iii. `.flags` :-
   - *this one goes mostly ignored / set to* `0`

8. `.pQueueCreateInfos` *:- yes, you 'can' pass multiple* ☺

- *Sometimes there will be* `.zzzCreateInfoCount` & `.pZZZCreateInfos`
  - *So you could like pass in an array/vector*
  - *You will see this in lots of other places*

-- | -- | -- | --

9. *CreateInfo StartingPoint*

```
VkRenderPassCreateInfo CI = {
    .sType = VK_STRUCTURE_TYPE_SWAPCHAIN_CREATE_INFO_KHR,
    .pNext = nullptr,
    .flags = 0
};
```

```
10.  Do remember to check the `Valid Usage` section within each manual-page
```

11. Getting/Enumerating VkObject list 💁‍♀️

```
uint32_t deviceCount = 0;
    // [implicit valid usage]:- must be 0 [if 3rd-param = nullptr]
    vkEnumeratePhysicalDevices(m_instance, &deviceCount, nullptr);
        // it's kinda like the function is 'output-ing into' deviceCount

std::vector<VkPhysicalDevice> HardwareGPU_List(gpuCount);
    // best to save this as a class member variable
    vkEnumeratePhysicalDevices(m_instance, &deviceCount, HardwareGPU_List.data());
        // note: it does return     VkResult return_code
```

-- | -- | -- | ---

12. `Symbols` :-

- ▨:- *kinda means nothing*
    - *i kinda used to like make it look like a bit pattern-ish iguess ⯑⯑*

    - ▨💁♀: *"Pretty Obvious"*
- ░:- *"Yellow Card"*
    - *it means, you don't need to hesitate about this thingy right now 💁♀ we will focus on this element later ⯑*

```
1. ChapterZZZ => Unknown WIP/TBD Chapter
2. Chapter2.4 =>
    If LATER-CHAPTER => Dont hesitate right now, Do this when you each that LATER-Chapter
    If  PREV-CHAPTER => You can go back and check 😛
        🔗 `SurfCAP.currentTransform`
        🔗 Chapter2.4
```

- ▓:- *"Orange Card"*
    - *it means, this element is probably never gonna be 'necessary' for vulkan applications 💁♀*

- ⯑: *"Extensions"*
    - *Same as ░ "Yellow Card". But marks a little bit more, that, "Here goes Extension" Features*

- 🔠: *"Options"*
    - *Sometimes you'd "Must Need" to choose between a few options*

- 🏳: *"I Lose, You Win!" / General Flag Icon / Sometimes means -> "Lots of Flags" / IDK / Didn't check [IDC]*
- 🎌: *"Nice/Important Flags"*
- 🚩: *"One Flag" [IDC]*
- 🏴: *"No Flag" [IDC]*
- ⚠: *"Deprecated Feature" / "Other Kinds of Warnings" / I will try to name when using this emoji/sign*
- 🏷: *"Type"*
- ░ **ChapterZZZ**
- 🔗 ***Chapter2.1***
- 🔗 `GITHUB_WIP`
- 📋🔄 ***Chapter2.1***
    - `vkEnumeratePhysicalDevices()`
    - *it means, Implement Exactly like in* ***Chapter2.1*** 😉

- ℹ: *"Create Info"*
- 🌯: `amVK_Wrap`
- ↩🎁: *"Object Getting return by Vulkan Function"*
- `📜 REY_DOCs`
    - *Actual Notes*
    - *Mostly, vkdoc.net documentation is good enough. But if I wanna add smth extra, it goes here*
    - *This section might get big & robust sometimes ⯑*
- `</> TheCode`
- `📽 So far, The result`
    - 📝:- *"File Icon"*
- `👀 Visualization / [See it] / JSON Printing`

- `🔬🛠 2DriverIMPL`
    - *To The People Who are gonna Implement the Driver*
    - *Other Keyword:- "DriverGurantee"*

-- | -- | -- | ---

1. *Emojis List*

- ▨ ░ ▩ ◇ 🔠 ➡ 🏷 📝 ℹ 📥 🌋 ◇
- ▨💁♀
- ↩🎁
- 🔗 *SubChapter 2*
- 🔗 *Next SubChapter*
- 🔗 *Chapter2.1*
- ░ ChapterZZZ
- 📋🔄 *Chapter2.1*
- 🔗 `GITHUB_WIP`
- ↩ Return Codes
- 📜 REY_DOCs
- `</> TheCode`
- `</> main.cpp`
- `🎥 So far, The result`
- `🔬🛠 2DriverIMPL`
- `👀 Visualization / [See it] / JSON Printing`

2. *Templates Below*

- https://vkdoc.net/man/VkGraphicsPipelineCreateInfo
    - `.sType` ▨ `VK_STRUCTURE_TYPE_GRAPHICS_PIPELINE_CREATE_INFO`
    - `.pNext` ◇ `nullptr`
    - `.flags` 🏳 `0`
        - ◇ https://vkdoc.net/man/VkPipelineCreateFlagBits | ivirtex-github

- https://vkdoc.net/man/VkGraphicsPipelineCreateInfo
    - `.sType` ▨ `VK_STRUCTURE_TYPE_GRAPHICS_PIPELINE_CREATE_INFO`
    - `.pNext` ◇ `nullptr`
    - `.flags` 🏳 `VkBufferCreateFlagBits`
        - https://vkdoc.net/man/VkBufferCreateFlagBits | ivirtex-github
            - `SPARSE` ░ ChapterZZZ
    - `.pSwapchains` ▨💁♀
    - `.pNext` ◇ `nullptr`
        - ◇ `VkDeviceGroupCommandBufferBeginInfo`
        - ◇ *Maybe some interesting extensions, idk*
    - `.flags` 🔠 `VkCommandBufferUsageFlagBits`
        - https://vkdoc.net/man/VkCommandBufferUsageFlagBits | ivirtex-github
            - 🔠 `ONE_TIME_SUBMIT`
            - 🔠 `RENDER_PASS_CONTINUE` *[secondary command buffer]*
            - 🔠 `SIMULTANEOUS_USE`

3. *Extra Emojis*

📟📠
🪦🎌🏳
🔌🚀
🚫📜
⚠◇
☢◇
☢💀
⚠🏚

4. *Number BLocks*

1️⃣
2️⃣
3️⃣
4️⃣
5️⃣
6️⃣

7⃣

8⃣

9⃣

🔟

11⃣

12⃣

13⃣

14⃣

15⃣

16⃣

17⃣

18⃣

19⃣

20⃣

5. Possible Function Naming Verbs-Emojis

```
1. query_SurfCap 🕵♂
2. update_SurfCap 🔄
3. load_SurfCap 📥
4. acquire_SurfCap 🔗
5. get_SurfCap 📤
6. grab_SurfCap        🙌
7. snag_SurfCap        🎣 (Quick pull)
8. pluck_SurfCap        ✂ (Precision)
9. selected_gpu_surfCap        🎯 (Targeted)        Emphasizes the GPU_Index selection.
10. current_surfCap        ⌛ (Stateful)
11. yoink_SurfCap        🦄 (Playful)        VkSurfaceCapabilitiesKHR* cap = yoink_SurfCap();
12. procure_SurfCap        🕴 (Formal)        procure_SurfCap() → Sounds like a business transaction!
13. obtain_SurfCap        🏆 (Success)
14. collect_SurfCap        📚 (Gathering)
15. retrieve_SurfCap        🎯 (Accuracy)
16. sync_SurfCap        🔄 (Sync State)
17. pull_SurfCap        � (Tug-of-war)
18. refresh_SurfCap        💫 (Update)
19. reload_SurfCap        ♻ (Reload)
20. populate_SurfCap        🌱 (Fill Data)
21. enumerate_SurfCap        🗃 (Listing)
22. summon_SurfCap        �♂ (Magic)
23. harvest_SurfCap        🌾 (Farm)
24. fish_SurfCap        🎣 (Fishing)
25. dial in        🎛 (Precision)
26. shape up        ✨ (Polishing)
27. rig        🛠 (Hacky)
28. tailor        👗 (Custom-fit)
29. access_SurfCap 🔍
30. craft        �♂ (Artisan)
31. surfCap 📋 (property-style)
32. surfCap_ptr 🎯 (or surfCapRef)
```

6. Extra Emojis

```python
#!/usr/bin/env python3
# 🎮 Ultimate Vulkan Emoji Guide (1-35)

vulkan_steps = [
    # Core Setup (Original 1-5)
    "1. 🌍 Instance Creation",
    "2. 🖥 Physical Device Selection",
```

```
    "3. ⚙ Logical Device Setup",
    "4. 🎨 Graphics Pipeline",
    "5. 🖼 SwapChain Initialization",

    # Resource Management (Original 6-10)
    "6. 🗄 Buffer Allocation",
    "7. � Memory Binding",
    "8. 🖌 Descriptor Sets",
    "9. 🎁 Image Creation",
    "10. 🎮 Command Pools",

    # Execution Flow (Original 11-12)
    "11. 📜 Command Buffers",
    "12. ⏱ Synchronization",

    # Debugging (Original 13-14)
    "13. 🔍 Validation Layers",
    "14. 🐛 Debug Messenger",

    # Advanced Features (Original 15-17)
    "15. 💫 Ray Tracing",
    "16. 🤖 Compute Pipeline",
    "17. � Multi-Threading",

    # Cleanup (Original 18-20)
    "18. � Resource Destruction",
    "19. 💥 Device Cleanup",
    "20. 🚀 Instance Shutdown",

    # New Additions (21-35)
    "21. � Device Memory",
    "22. 🔄 Memory Barriers",
    "23. 📊 Buffer Views",
    "24. 🎛 Pipeline Layout",
    "25. 🔮 Shader Modules",
    "26. � Pipeline Cache",
    "27. 🎆 Render Passes",
    "28. 🖌 Dynamic Rendering",
    "29. 🌐 Multi-View Rendering",
    "30. ⏳ Timeline Semaphores",
    "31. 🚦 Fences",
    "32. 📡 Debug Markers",
    "33. 📈 Performance Queries",
    "34. 🌀 Compute Dispatches",
    "35. 🚀 Acceleration Structures"
]
```

```
#!/usr/bin/env python3
# 🏆 Ultimate Vulkan Emoji Cheatsheet (50+ Concepts)

vulkan_concepts = {
    # === Core Setup ===
    "🌍": "Instance Creation (vkCreateInstance)",
    "🖥": "Physical Device Selection (vkEnumeratePhysicalDevices)",
    "⚙": "Logical Device (vkCreateDevice)",
    "📜": "Extensions/Layers (ppEnabledExtensionNames)",

    # === Resources ===
```

```
    "🗄": "Buffers (vkCreateBuffer)",
    "�": "Device Memory (vkAllocateMemory)",
    "🎁": "Images (vkCreateImage)",
    "🔄": "Memory Barriers (vkCmdPipelineBarrier)",
    "�": "Image Views (vkCreateImageView)",
    "�": "Sparse Resources (VkSparseImageMemoryBind)",

    # === Pipeline ===
    "🎨": "Graphics Pipeline (vkCreateGraphicsPipelines)",
    "🤖": "Compute Pipeline (vkCreateComputePipelines)",
    "🔮": "Shader Modules (vkCreateShaderModule)",
    "🎛": "Pipeline Layout (vkCreatePipelineLayout)",
    "�": "Pipeline Cache (vkCreatePipelineCache)",

    # === Descriptors ===
    "🖌": "Descriptor Sets (vkAllocateDescriptorSets)",
    "🧰": "Descriptor Pool (vkCreateDescriptorPool)",
    "🎹": "Descriptor Set Layout (vkCreateDescriptorSetLayout)",

    # === Rendering ===
    "🎆": "Render Passes (vkCreateRenderPass)",
    "🖼": "Framebuffers (vkCreateFramebuffer)",
    "🎚": "Dynamic Rendering (VK_KHR_dynamic_rendering)",
    "👁": "Multi-View (VK_KHR_multiview)",

    # === Commands ===
    "🎮": "Command Pools (vkCreateCommandPool)",
    "📜": "Command Buffers (vkAllocateCommandBuffers)",
    "⏱": "Queue Submission (vkQueueSubmit)",

    # === Synchronization ===
    "🚦": "Fences (vkCreateFence)",
    "⏳": "Timeline Semaphores (VK_KHR_timeline_semaphore)",
    "🤝": "Events (vkCreateEvent)",

    # === Advanced ===
    "🌌": "Ray Tracing (VK_KHR_ray_tracing_pipeline)",
    "🚀": "Acceleration Structures (vkCreateAccelerationStructureKHR)",
    "🌀": "Mesh Shading (VK_EXT_mesh_shader)",
    "💫": "Task Shaders (VK_EXT_mesh_shader)",

    # === Debugging ===
    "🔍": "Validation Layers (VK_LAYER_KHRONOS_validation)",
    "🐛": "Debug Utils (vkCreateDebugUtilsMessengerEXT)",
    "📡": "Debug Markers (vkCmdDebugMarkerBeginEXT)",
    "📈": "Performance Queries (VK_QUERY_TYPE_PERFORMANCE_QUERY_KHR)",

    # === Cleanup ===
    "�": "Resource Destruction (vkDestroy*)",
    "💥": "Device Cleanup (vkDestroyDevice)",
    "🚀": "Instance Shutdown (vkDestroyInstance)",

    # === New Additions ===
    "🔄": "Push Constants (vkCmdPushConstants)",
    "🎚": "Dynamic States (VkPipelineDynamicStateCreateInfo)",
    "�": "Pipeline Derivatives (VK_PIPELINE_CREATE_DERIVATIVE_BIT)",
    "📌": "Specialization Constants (VkSpecializationInfo)",
    "🌐": "External Memory (VK_KHR_external_memory)",
```

```
    "🔗": "Linked GPUs (VK_KHR_device_group)"
}
```

```python
#!/usr/bin/env python3
# 🏆 Ultimate Vulkan Cheatsheet (70+ Concepts) 🏆

vulkan_steps = [
    # === Core Setup (1-8) ===
    "1. 🌍 Instance Creation",
    "2. 🖥 Physical Device Selection",
    "3. ⚙ Logical Device Setup",
    "4. 🔌 Device Features",
    "5. 📜 Extensions/Layers",
    "6. 🖼 SwapChain Initialization",
    "7. 🌐 Surface Creation",
    "8. � Queue Families",

    # === Resources (9-24) ===
    "9. 🗄 Buffer Allocation",
    "10. � Device Memory",
    "11. 🎁 Image Creation",
    "12. � Image Views",
    "13. 🔄 Memory Barriers",
    "14. � Sparse Resources",
    "15. 📊 Buffer Views",
    "16. � Host-Coherent Memory",
    "17. 🚚 Memory Transfers",
    "18. � Staging Buffers",
    "19. 🔗 External Memory",
    "20. � Protected Memory",
    "21. 💿 Buffer Device Address",
    "22. 🏷 Resource Naming",
    "23. 📏 Memory Requirements",
    "24. �🔧 Memory Budget",

    # === Pipeline (25-40) ===
    "25. 🎨 Graphics Pipeline",
    "26. 🤖 Compute Pipeline",
    "27. 🔮 Shader Modules",
    "28. 🎛 Pipeline Layout",
    "29. � Pipeline Cache",
    "30. 🔄 Push Constants",
    "31. 🎚 Dynamic States",
    "32. 📌 Specialization Constants",
    "33. � Pipeline Derivatives",
    "34. 💾 Pipeline Libraries",
    "35. 🌀 Tessellation",
    "36. 💫 Geometry Shaders",
    "37. � Subpasses",
    "38. ✂ Depth/Stencil",
    "39. 🌈 Blend States",
    "40. � Multiview Rendering",

    # === Commands (41-50) ===
    "41. 🎮 Command Pools",
    "42. 📜 Command Buffers",
    "43. ⏱ Queue Submission",
    "44. 🔁 Secondary Command Buffers",
```

```
    "45. �🎯 Indirect Commands",
    "46. 🎛 Device Groups",
    "47. 🤝 Queue Priorities",
    "48. ⏳ Timeline Semaphores",
    "49. 🚦 Fences",
    "50. 🤝 Events",

    # === Advanced (51-70) ===
    "51. 🌌 Ray Tracing",
    "52. 🚀 Acceleration Structures",
    "53. 🌀 Mesh Shading",
    "54. 💫 Task Shading",
    "55. 📡 Debug Markers",
    "56. 📈 Performance Queries",
    "57. 🕵♀ Object Tracking",
    "58. � Bindless Resources",
    "59. 🚧 Pipeline Barriers",
    "60. 💾 Pipeline Statistics",
    "61. 🌐 External Semaphores",
    "62. 🔄 Present Modes",
    "63. 🖌 Dynamic Rendering",
    "64. � Fragment Density Maps",
    "65. 🌀 Variable Rate Shading",
    "66. � Protected Swapchains",
    "67. 📜 Shader Printf",
    "68. � Pipeline Robusness",
    "69. 🛡 Validation Features",
    "70. � Resource Cleanup"
]
```

-- | -- | -- | --

Chapter 4: `VkSwapchainKHR` ⯑

0. `VkSwapchainCreateInfoKHR` ℹ

- *https://vkdoc.net/man/VkSwapchainCreateInfoKHR*
    - `.sType` ▨ `VK_STRUCTURE_TYPE_SWAPCHAIN_CREATE_INFO`
    - `.pNext` ⯑ `nullptr`
    - `.flags` 🏳 ChapterZZZ
    - `.surface` 🏄‍♀ *Chapter4.2*
    - 🖼 *Image options* 🔗 *Chapter4.4*
        - `.minImageCount`
        - `.imageFormat` ⯑
        - `.imageColorSpace` ⯑
        - `.imageExtent` ☺
        - `.imageArrayLayers`
        - `.imageUsage`
        - `.imageSharingMode` ▨ `EXCLUSIVE/CONCURRENT` *[Toggle]*
    - `VK_SHARING_MODE_CONCURRENT` ▒ ChapterZZZ
        - `.queueFamilyIndexCount` *--> if using, must be* `greated than 1`
        - `.pQueueFamilyIndices` *--> These two are used only if* `.imageSharingMode = CONCURRENT` *iguess*
    - ⯑♂ *Compositing Options* 🔗 *Chapter4.5*
        - `.preTransform` :- `VkSurfaceTransformFlagBitsKHR`
        - `.compositeAlpha` :- `VkCompositeAlphaFlagBitsKHR`
        - `.presentMode` :- `VkPresentModeKHR`
        - `.clipped` :- `VkBool32`
    - `.oldSwapchain` ▒ ChapterZZZ
        - ▒ *SwapchainReCration*

1. `amVK` wrap 🌯 Part I

```
#include "amGHOST_VkSurfaceKHR.hh"

    // TwT
    REY_LOG("");
amVK_Instance::EnumerateInstanceExtensions();
amVK_Instance::addTo_1D_Instance_EXTs_Enabled("VK_KHR_surface");
amVK_Instance::addTo_1D_Instance_EXTs_Enabled(amGHOST_System::get_vulkan_os_surface_ext_name());
    // amGHOST_VkSurfaceKHR::create_surface() needs that extension enabled
amVK_Instance::CreateInstance();

    REY_LOG("");
VkSurfaceKHR  VK_S = amGHOST_VkSurfaceKHR::create_surface(W, amVK_Instance::vk_Instance);

// another 🌯 amVK_Wrap, at the end of this file
```

2. `VkSurfaceKHR` 🏄‍♀️

Part I:- Enabling `VK_KHR_surface` Vulkan Extension

https://vkdoc.net/man/VkSurfaceKHR
https://vkdoc.net/extensions/VK_KHR_surface
Yaaaay, we have reached our first extension to enable
we need to enable it back in `vkCreateInstance()` from 🔗 *Chapter1.2*

1. 📜 `vkEnumerateInstanceExtensionProperties()`

- https://vkdoc.net/man/vkEnumerateInstanceExtensionProperties
- 📋🔄 *Chapter2.1*
    - *This symbol/emoji means "Implement Exactly like in **Chapter2.1** 🙃"*

2. ⯑ `IS_InstanceEXT_Available(const char* extName)`

```
bool amVK_InstanceProps::IS_InstanceEXT_Available(const char *extName) {
    for (uint32_t k = 0, lim = amVK_EXT_PROPs.n; k < lim; k++) {
        if (strcmp(amVK_EXT_PROPs[k].extensionName, extName) == 0) {    // <cstring>
            return true;
        }
    }
    return false;
}
```

3. ⯑ `Add_InstanceEXT_ToEnable(const char* extName)`

```
static inline REY_ArrayDYN<char*> s_Enabled_EXTs = REY_ArrayDYN<char*>(nullptr, 0, 0);
    // It will be automatically allocated, resize, as we keep adding ☺
#include <string.h>
void amVK_Instance::Add_InstanceEXT_ToEnable(const char* extName)
{
    if (!amVK_InstanceProps::called_EnumerateInstanceExtensions) {
         amVK_InstanceProps::EnumerateInstanceExtensions();
    }

    if (amVK_InstanceProps::IS_InstanceEXT_Available(extName)) {
        char   *dont_lose = new char[strlen(extName)];
        strcpy(dont_lose, extName);

        s_Enabled_EXTs.push_back(dont_lose);

        amVK_Instance::CI.enabledExtensionCount = s_Enabled_EXTs.neXt;
        amVK_Instance::CI.ppEnabledExtensionNames = s_Enabled_EXTs.data;
    }
    else {
        REY_LOG_notfound("Vulkan Extension:- " << extName);
    }
}
```

Part II:- OS Specfic SurfaceEXT & Creating it

```
amVK_Instance::Add_InstanceEXT_ToEnable(amGHOST_System::get_vulkan_os_surface_ext_name());
    // or
amVK_Instance::Add_InstanceEXT_ToEnable("VK_KHR_win32_surface");
    // or some other surface name
```

1. `Win32SurfaceCI`
   - https://vkdoc.net/man/VkWin32SurfaceCreateInfoKHR
2. `vkCreateWin32SurfaceKHR()`
   - https://vkdoc.net/man/vkCreateWin32SurfaceKHR
3. `</> TheCode`

```
pure-virtual VkSurfaceKHR amGHOST_VkSurfaceKHR_WIN32::create(VkInstance I)
{
    amGHOST_SystemWIN32 *heart_win32 = (amGHOST_SystemWIN32 *) amGHOST_System::heart;
    VkWin32SurfaceCreateInfoKHR CI = {
        .sType = VK_STRUCTURE_TYPE_WIN32_SURFACE_CREATE_INFO_KHR,
        .pNext = NULL,
        .flags = 0,
        .hinstance = heart_win32->_hInstance,
        .hwnd = this->W->m_hwnd
            // W = amGHOST_WindowWIN32
    };

    VkSurfaceKHR S = nullptr;
    VkResult return_code = vkCreateWin32SurfaceKHR(I, &CI, nullptr, &S);
    amVK_return_code_log( "vkCreateWin32SurfaceKHR()" );
    return S;
}
```

4. `VkXlibSurfaceCreateInfoKHR` *&* `vkCreateXlibSurfaceKHR()` 🛠 *[wip]*
5. 📜 *REY_DOCs*
   - *you can also check* `amGHOST_VkSurfaceKHR::create_surface()` 😉
6. `📽 So far, The result`
   - *[4.guide.chapter4.2.amGHOST.hh]()*
   - *in the end people will just use 1 line*

```
VkSurfaceKHR VK_S = amGHOST_VkSurfaceKHR::create_surface(amG_WindowOBJ, amVK_Instance::s_vk);
```

3. Naming Patterns

example naming patterns for storing all these data.... cz it's gonna get overwhelming pretty soon, pretty fast

1. Arrays

```
class amVK_InstanceProps {
    public:
        // Array of `HardWare amVK_1D_GPUs` connected to motherboard
    static inline REY_Array<VkPhysicalDevice>                         amVK_1D_GPUs;
    static inline REY_Array<REY_Array<VkQueueFamilyProperties>>       amVK_2D_GPUs_QFAMs;
    static inline REY_Array<VkExtensionProperties>                    amVK_1D_InstanceEXTs;
    static inline REY_ArrayDYN<char*>                                 amVK_1D_InstanceEXTs_Enabled;
    static inline REY_ArrayDYN<SurfaceInfo>                           amVK_1D_SurfaceInfos; // See
Below
    static inline REY_Array<REY_Array<VkExtensionProperties>>         amVK_2D_GPUs_EXTs;
        // REY_Array  doesn't allocate any memory by default

    #define amVK_LOOP_GPUs(_var_)           \
        for (uint32_t _var_ = 0, lim = amVK_1D_GPUs.n;             _var_ < lim;  _var_++)
    #define amVK_LOOP_QFAMs(_k_, _var_)     \
        for (uint32_t _var_ = 0, lim = amVK_2D_GPUs_QFAMs[_k_].n;  _var_ < lim;  _var_++)
};
```

2. ChildrenStructs

```
class amVK_InstanceProps {
    class SurfaceInfo {
      public:
        VkSurfaceKHR S = nullptr;
        SurfaceInfo(void) {}
        SurfaceInfo(VkSurfaceKHR pS) {this-> S = pS;}

                REY_Array<REY_Array<VkSurfaceFormatKHR>>          amVK_2D_GPUs_ImageFMTs;

        bool called_GetPhysicalDeviceSurfaceFormatsKHR = false;
        void        GetPhysicalDeviceSurfaceFormatsKHR(void);  // amVK_2D_GPUs_ImageFMTs
    };
};
```

3. VkFuncCalls

```
class amVK_InstanceProps {
    public:
    static inline bool called_EnumeratePhysicalDevices = false;
    static inline bool called_GetPhysicalDeviceQueueFamilyProperties = false;
    static inline bool called_EnumerateInstanceExtensions = false;

    public:
    static void EnumeratePhysicalDevices(void);                         // amVK_1D_GPUs
    static       void GetPhysicalDeviceQueueFamilyProperties(void);     // amVK_2D_GPUs_QFAMs
    static void EnumerateInstanceExtensions(void);                      // amVK_1D_InstanceEXTs
};
```

- **REY_DOCs**
    - *Lots of other nice stuffs are happening inside* `amVK_InstanceProps.hh`

- `📽 So far, The result` :-
    - 📝 *4.guide.chapter4.3.Props.hh*
    - 📝 *4.guide.chapter4.3.Props.cpp*
    - 📝 *4.guide.chapter4.3.PropsOLD.hh*

4. `SwapChain Image Options` 🖼

`.imageFormat + .imageColorSpace`

1. `vkGetPhysicalDeviceSurfaceFormatsKHR()`
   - *https://vkdoc.net/man/vkGetPhysicalDeviceSurfaceFormatsKHR*
     - `param surface`
   - 📋🔄 *Chapter2.5*
     - *Only difference is,* `Formats` *might be a bit different as per* `VkSurfaceKHR`
     - `📽 So far, The result` :- *4.guide.chapter4.4.5.midway.cpp*
2. `VkSurfaceFormatKHR` 🖥
   - *https://vkdoc.net/man/VkSurfaceFormatKHR*
     - `||| .format` 🖼🔢 *ImageFormat*
     - `.colorSpace` 🖼🌈 *ImageColorSpace*
     - *No Other options*
   - 📜 REY_DOCs
     - *This is basically a Combo of* 🖼🔢 `ImageFormat` & 🖼🌈 `ColorSpace`
       - *so, the gpu kinda expects you to respect these combos, when you are gonna set these into* `VkSwapchainCreateInfoKHR`*. instead of mumbo-jumbo-ing & mixing random stufs alltogether....*
       - *altho, even if you do so, gpu is probably gonna show you the result of WRONG COLORSPACE/IMAGEFORMATs on the screen*

---

3. `Life is Hard without Images/Visualization`
   - *So we are gonna Export to JSON/YAML*
     - *4.guide.chapter4.4.3.Enum2String.hh*
     - *4.guide.chapter4.4.3.data.jsonc*
     - *4.guide.chapter4.4.3.Export.cpp*
       - *aaaaggghhhhh.... ik, the export file, looks a little bit messy.* 😅 *but, dw, we won't use this export code in the end, it will be refactored & organized in* 🔗 ***Chapter4.4.6***

`.minImageCount`
🖼 `+ .imageExtent + .imageArrayLayers + .imageUsage`
⍰♂ `.compositeAlpha + .preTransform`

4. `VkSurfaceCapabilitiesKHR`

- ***https://vkdoc.net/man/VkSurfaceCapabilitiesKHR***
  - 🖼 Image options 🔗 *Chapter4.4*
    - `.minImageCount`
    - `.currentExtent`
      - *as the OS Window size changes,* `SurfCaps` *also change*
      - *call* `vkGetPhysicalDeviceSurfaceCapabilitiesKHR()` *to get updated* `WindowSize` / `SurfCaps`
    - `.maxImageArrayLayers`
    - `.supportedUsageFlags`
  - ⍰♂ Compositing Options 🔗 *Chapter4.5*
    - `.supportedTransforms`
    - `.supportedCompositeAlpha`
      - `ALPHA-Blending/Transparency/GlassEffect` :- *you'd have to enable blending/transparency @ OS-Level first, iguess* 🤔

  - Transparency ▩ ChapterZZZ

  - `🔬🛠 2DriverIMPL`
    - *This section changed the perspective a little bit. Like, what I mean is that, Official Vulkan Specs requires GPU Driver*

Implementations to abide by these requirements 💁‍♀

- `.minImageCount` :- ***must*** *be at least 1*
- `.maxImageArrayLayers` :- ***must*** *be at least 1*
- `.supportedTransforms` :- *at least 1 bit* ***must*** *be set.*
- `.supportedUsageFlags` :-
    - `VK_IMAGE_USAGE_COLOR_ATTACHMENT_BIT` ***must*** *be included in the set.*
    - *Implementations* ***may*** *support additional usages.*

5. `vkGetPhysicalDeviceSurfaceCapabilitiesKHR()`

- *https://vkdoc.net/man/vkGetPhysicalDeviceSurfaceCapabilitiesKHR*
- 📜 REY_DOCs
    - *we add right beside the function from* 🔗 ***Chapter4.4.1*** 😉
    - `📽 So far, The result` :- *4.guide.chapter4.4.5.midway.cpp*

---

6. `Life is Hard without Images/Visualization 2`

- *Sooooooo many things to keep track of, So here we go again*
    - *4.guide.chapter4.4.6.Export.cpp*
    - *4.guide.chapter4.4.6.data.jsonc*

`.imageSharingMode`

7. `VkSharingMode`

- *https://vkdoc.net/man/VkSharingMode*
- *it's like a Toggle/Button ->* `EXCLUSIVE/CONCURRENT`

---

8. `📽 So far, The result` :-

```
amVK_SwapChain *SC = new amVK_SwapChain(VK_Surface);
    SC->CI.imageFormat = VK_FORMAT_B8G8R8A8_UNORM;
    SC->CI.imageColorSpace = VK_COLOR_SPACE_SRGB_NONLINEAR_KHR;
    SC->CI.minImageCount    =
amVK_InstanceProps::amVK_1D_SurfaceInfos[0].amVK_1D_GPUs_SurfCAP[0].minImageCount;
    SC->CI.imageExtent      =
amVK_InstanceProps::amVK_1D_SurfaceInfos[0].amVK_1D_GPUs_SurfCAP[0].currentExtent;
    SC->CI.imageArrayLayers =
amVK_InstanceProps::amVK_1D_SurfaceInfos[0].amVK_1D_GPUs_SurfCAP[0].maxImageArrayLayers;
        // You can just use "1" too, which is guranteed by DRIVER_IMPLEMENTATION [2DriverIMPL]
    SC->CI.imageSharingMode = VK_SHARING_MODE_EXCLUSIVE;
        // `EXCLUSIVE/CONCURRENT` [Toggle]
    SC->CI.imageUsage       = VK_IMAGE_USAGE_COLOR_ATTACHMENT_BIT;
        // 2DriverIMPL:- VK_IMAGE_USAGE_COLOR_ATTACHMENT_BIT is guranteed to be supported by SurfCAP
```

---

9. `Abbreviations`

- `PD` -> *PhysicalDevice*
- `GPUs` -> *PhysicalDevices*
- `CI` -> *CreateInfo*

- `QCI` -> *QueueCreateInfo*
- `QFAM` -> *QueueFamily*
- `SurfCAP` -> *https://vkdoc.net/man/VkSurfaceCapabilitiesKHR*
- `SurfFMT` -> *https://vkdoc.net/man/VkSurfaceFormatKHR*
- `SC` -> *SwapChain*

---

10. `VkSwapchainCreateInfoKHR`

- ***https://vkdoc.net/man/VkSwapchainCreateInfoKHR***
  - `.flags` 🏳 ChapterZZZ
  - `.surface` 🏄‍♀ *Chapter4.2*
  - 🖼 *Image options* 🔗 *Chapter4.4*
    - `.minImageCount` = ▨☺ `SurfCAP.minImageCount`
    - `.imageFormat` = ▨☺ `SurfFMT[x].format`
    - `.imageColorSpace` = ▨⯑ `SurfFMT[x].colorSpace`
      - *Choosing a Combo* ▩ ChapterZZZ
      - *Compositing & ColorSpaces* ▩ ChapterZZZ
    - `.imageExtent` = ▨☺ `SurfCAP.minImageCount`
    - `.imageArrayLayers` = ▨ `1`
      - 🔬🛠 *2DriverIMPL Gurantee*
    - `.imageUsage` -> `VK_IMAGE_USAGE_COLOR_ATTACHMENT_BIT`
      - 🔬🛠 *2DriverIMPL Gurantee*
    - `.imageSharingMode` = ▨ `EXCLUSIVE/CONCURRENT` *[Toggle]*
      - `VK_SHARING_MODE_CONCURRENT` ▩ ChapterZZZ
        - *we aren't gonna use concurrent for now*
        - `.queueFamilyIndexCount` -> `0`
        - `.pQueueFamilyIndices` -> `nullptr`

5. `SwapChain Compositing Options` ❔♂

1. `.compositeAlpha`

- *https://vkdoc.net/man/VkCompositeAlphaFlagBitsKHR*
- 📜 REY_DOCs
  - `Options` *:- Don't use / Pre-multiplied / Post-multiplied / inherit from OS-native window system*
  - `Requirement` *:-*
    - *You would have to enable @ OS level first, to enable ALPHA/Transparency/GlassEffect for window-s/surfaces*
    - *then after that, if you query for* `vkGetPhysicalDeviceSurfaceCapabilitiesKHR()`
      - `SurfCAP.supportedCompositeAlpha` *will change*
    - *by default, it's prolly always gonna support*
      - `VK_COMPOSITE_ALPHA_OPAQUE_BIT_KHR`
      - *i.e. if you haven't done any mastery wizardry yet, to enable ALPHA/Transparency/GlassEffect*

2. `.preTransform`

- *https://vkdoc.net/man/VkSurfaceTransformFlagBitsKHR*
- 📜 REY_DOCs
  - 🔗 `SurfCAP.currentTransform`
  - *you should probably log it if* `currentTransform` *isn't*
    - `VK_SURFACE_TRANSFORM_IDENTITY_BIT_KHR`

3. `.clipped`

- 📜 REY_DOCs
  - *Setting clipped to* `VK_TRUE` *allows the implementation to discard rendering outside of the surface area*

4. `.presentMode` 🏷 `VkPresentModeKHR`

- *https://vkdoc.net/man/VkPresentModeKHR*
- 📜 REY_DOCs
  - `Options` *:- IMMEDIATE / MAILBOX / FirstInFirstOut / FIFO_Relaxed*

5. `.oldSwapChain`

- 📜 REY_DOCs
  - *if you are "re-creating" swapchain & you had an oldSwapchain*
  - *We do this when*
    a. *Window Size / WindowExtent / Surface was Changed*

6. `So far, The result`

```
amVK_SwapChain *SC = new amVK_SwapChain(VK_Surface);
    ... Image Stuffs
    SC->CI.compositeAlpha = VK_COMPOSITE_ALPHA_OPAQUE_BIT_KHR;
    SC->CI.preTransform   =
amVK_InstanceProps::amVK_1D_SurfaceInfos[0].amVK_1D_GPUs_SurfCAP[0].currentTransform;
    SC->CI.clipped        = VK_TRUE;
    SC->CI.presentMode    = VK_PRESENT_MODE_FIFO_KHR;
    SC->CI.oldSwapchain   = nullptr;
```

6. `SwapChain Extension Enabling` ⯑ [`VK_KHR_swapchain`]

1. `vkEnumerateDeviceExtensionProperties()`

- *https://vkdoc.net/man/vkEnumerateDeviceExtensionProperties*
    - *honestly this should be named* `vkEnumeratePhysicalDeviceExtensionProperties()`
    - *bcz,*
        - *it doesn't associate with* `VkDevice`
        - *but rather with* `VkPhysicalDevice`
- 📜 REY_DOCs

```
class amVK_InstanceProps {
    ...
    static inline bool called_EnumerateDeviceExtensionProperties = false;
    static void               EnumerateDeviceExtensionProperties(void); // amVK_2D_GPUs_EXTs

    static inline REY_Array<REY_Array<VkExtensionProperties>>              amVK_2D_GPUs_EXTs;
    #define amVK_LOOP_GPU_EXTs(_k_, _var_)  for (uint32_t _var_ = 0,  lim = amVK_2D_GPUs_EXTs[_k_].n; _var_ < lim;  _var_++)

    static bool      IS_GPU_EXT_Available(PD_Index GPU_k, const char *extName); // amVK_2D_GPUs_EXTs
    // kinda copy of IS_InstanceEXT_Available
    ...
};
```

2. `amVK_Device::Add_GPU_EXT_ToEnable(const char* extName)`

```
class amVK_Device {
    ...
    REY_ArrayDYN<char*>   amVK_1D_DeviceEXTs_Enabled;
    void Log_GPU_EXTs_Enabled(VkResult ret);
    void Add_GPU_EXT_ToEnable(const char* extName);
        // Copy of `amVK_InstanceProps::Add_InstanceEXT_ToEnable()` -> but not static anymore.... 🙆‍♀️
};
```

3. 📽 `So far, The result`

- *4.guide.chapter4.6.newStuffs.hh*
- *4.guide.chapter4.7.Props.hh*
- *4.guide.chapter4.7.Props.cpp*

7. 🌱 `vkCreateSwapchainKHR()`

- *https://vkdoc.net/man/vkCreateSwapchainKHR*
- *[TODO]:- Add the commit-tree Link*
- *It took me 5days to complete Chapter4 �*
    - *(well, i worked on a houdini project � for 2 days.... so yeah �)*

8. `amVK` wrap 🩹 Part II

```
amVK_InstanceProps::EnumerateDeviceExtensionProperties();

amVK_Device* D = new amVK_Device(amVK_InstanceProps::GetARandom_GPU());
    D->select_QFAM_Graphics();
    D->Add_GPU_EXT_ToEnable("VK_KHR_swapchain");
    D->CreateDevice();
```

9. `amVK` wrap 🩹 Part III

```
#include "amVK_Surface.hh"
#include "amVK_SwapChain.hh"

    // TwT
    REY_LOG("")
amVK_Surface           *S   = new amVK_Surface(VK_S);
amVK_SurfacePresenter  *PR  = S->PR;
                        PR->bind_Surface(S);
                        PR->bind_Device(D);
                        PR->create_SwapChain_interface();
                            // This amVK_SwapChain is Bound to this amVK_Surface

amVK_SwapChain *SC =    PR->SC;
    SC->konf_ImageSharingMode(VK_SHARING_MODE_EXCLUSIVE);
    SC->konf_Images(
        amVK_IF::RGBA_8bpc_UNORM,   // VK_FORMAT_R8G8B8A8_UNORM
        amVK_CS::sRGB,              // VK_COLOR_SPACE_SRGB_NONLINEAR_KHR
        amVK_IU::Color_Display      // VK_IMAGE_USAGE_COLOR_ATTACHMENT_BIT
    );
    SC->konf_Compositing(
        amVK_PM::FIFO,              // VK_PRESENT_MODE_FIFO_KHR
        amVK_CC::YES,               // Clipping:- VK_TRUE
        amVK_TA::Opaque             // VK_COMPOSITE_ALPHA_OPAQUE_BIT_KHR
    );
    SC->sync_SurfCaps();            // refresh/fetch & set/sync ---> latest SurfCaps

    SC->CI.oldSwapchain     = nullptr;
    SC->CreateSwapChain();
```

�♂ Part 2: The True Arcane Secrets of RenderPass
(SubPass + Image Layer Transition) & FrameBuffers

Welcome to the inner sanctum where GPU gods decide how fast your pixels live or die.

- ChatGPT

Chapter 5: `RenderPass` �

> " `subpasses` *are the soul of RenderPass!* . But it's not just about `subpasses` only...." - ChatGPT

0. Why `RenderPass` ?

- ***"This is one of the most convoluted parts of the Vulkan specification, especially for those who are just starting out." - P.A. Minerva***
- *ex. 1:-* `PostProcessing Effects`

```
RenderPass:
- color attachment
- depth attachment

subpasses:
- Subpass 0: render geometry
- Subpass 1: post-process effects
    // multiple rendering steps without switching FrameBuffers/AttachMents

// All defined in ONE render pass
```

- *ex. 2:-* `Deferred Shading`

```
attachments:
- position: offscreen image
- normal: offscreen image
- albedo: offscreen image
- depth: depth image
- finalColor: swapchain image
subpasses:
- Subpass 0: G-buffer generation (write position, normal, albedo)
- Subpass 1: Lighting pass (read G-buffers, write to finalColor)
```

  - *Without* `subpasses` *, you'd need to switch framebuffers (expensive!).*
  - *With* `subpasses` *, Vulkan can optimize this by keeping data in GPU memory (especially tile-based GPUs).*

- *ex. 3:-* `Post-Processing Chain`

```
attachments:
- scene: offscreen image
- postProcessOut: swapchain image
subpasses:
- Subpass 0: scene render → scene
```

```
- Subpass 1: post-process → postProcessOut
```

  - *Purpose:- After rendering the main scene, do effects like bloom, blur, or color correction.*
  - *Why a RenderPass?*
    - *Again, Vulkan sees the full plan and can optimize the transitions.*
    - *You can define layout transitions (e.g.* `COLOR_ATTACHMENT_OPTIMAL → SHADER_READ_ONLY_OPTIMAL` *)*

- ***ex. 4:-*** `Shadow Map Pass` ***/ Render from light's POV, to a depth-only image***

```
attachments:
- depth: depth image
subpasses:
- Subpass 0: write to depth only (no color)
```

  - *Why a RenderPass?*
    - *This pass is often done offscreen, then used as a texture later.*

- ***ex. 5:-*** `3D Scene -> Depth Testing`

```
attachments:
- color: swapchain image
- depth: depth image
subpasses:
- Subpass 0:
    - color attachment: color
    - depth attachment: depth
```

1. What is `RenderPass`? ◈

1. `RenderPass` ***is designed around*** `subpasses`.

- *The core purpose of a* `RenderPass` *is to tell Vulkan:*

  > - *“Hey, I’m going to do these* ***rendering stages*** *(* `subpasses` *), in this order, using these* ***attachments****.”*

- *So yeah,* `subpasses` *are the main reason for a RenderPass to exist.* ***subpasses are the soul of RenderPass!***
- *But it's not just about* `subpasses` *only:-*
  a. 🌟 `Load/Store Ops` — *"What should I do with the image before & after rendering?"*
    - 🚪 *loadOp — When RenderPass begins:*

      ```
            LOAD: Keep whatever was already in the attachment.
           CLEAR: Wipe it to a specific value (e.g., clear color to black).
       DONT_CARE: Vulkan can throw away old contents (faster, if you don’t care).
      ```

    - 🚪 *storeOp — When RenderPass ends:*

      ```
           STORE: Save the result (e.g., to present to the screen or use later).
       DONT_CARE: Vulkan can discard the result (like shadow maps or intermediate stuff you don't
       need to read later).
      ```

    - *ex.*

      ```
      colorAttachment.loadOp = VK_ATTACHMENT_LOAD_OP_CLEAR;
      colorAttachment.storeOp = VK_ATTACHMENT_STORE_OP_STORE;
          // Meaning: Clear the image before rendering, and store the result so we can present it.
      ```

  b. 🎯 `Image Layout Transitions` — *"How should the GPU access this image during the pass?"*

    ```
                                  [ VK_IMAGE_LAYOUT_UNDEFINED ]
                                              👇 clear
                                  [ VK_IMAGE_LAYOUT_COLOR_ATTACHMENT_OPTIMAL ]
                                              👇 render
                                  [ VK_IMAGE_LAYOUT_SHADER_READ_ONLY_OPTIMAL ]
                                              👇 post-process
                                  [ VK_IMAGE_LAYOUT_PRESENT_SRC_KHR ]
    ```

  c. 📜 `Attachments` — *"What images are we using?"*
    - `RenderPass Attachment` ***is not an actual thing!***
    - `RenderPass Attachment Description/Descriptor` *is a thing!*
      - *However, the idea is....* ***We do "define"*** *the* `Attachments` *right here, as we send the* `AttachmentDescriptions` *->* `RenderPass`
    - `RenderPass Attachment` *!=* `FrameBuffer Attachment`
    - `FrameBuffer Attachment`
      - *----> actual* `VkImageView` *s of* `SwapChain Images`

2. 🎯 `Image Layout Transitions`

i. 🏭 *1. Different hardware units = different memory access patterns*

```
GPU Unit                          Access Pattern
------------------     -----------------------
Fragment Shader             Texture-like (random)
Render Output Unit            Tiled or linear (write-heavy)
Compute Shader                Raw buffer-style
Display Engine                Linear format

- for ex.
```

- *When an image is used as a* ***color attachment****, it might be stored tiled in memory for fast write performance.*
- *But when you use the same image as a texture, the shader expects it to be in a format optimized for random read access.*
- *👉 If you tried to read from a tiled format as if it were a texture, you'd either:*
    - *Get* `garbage`
    - *Or pay a* `huge perf penalty` *as the driver does conversion.... (every single time you access a single pixel) (a single pixel would = an element in an 2D Array) (Texture might have Millions of Pixel)*

ii. 🔷 *Physical Layout in VRAM (Tiles vs Linear)*

- *Most modern GPUs store* ***image data*** *in* ***tiles*** *internally.*
    - *(like Z-order, Morton order, or other optimized memory layouts).*
    - *This helps GPUs fetch memory in cache-friendly blocks for faster rendering.*
- *But when an image is to be presented to the* ***screen/monitor****, it must be* ***Flat (linear)*** *(as HDMI/display engines can't decode tiles).*
    - *Yes — by "linear", we mean a simple 2D array where pixels are stored in a straightforward, left-to-right, top-to-bottom format.*
- *So when you do this:-*

```
finalLayout = VK_IMAGE_LAYOUT_PRESENT_SRC_KHR;
```

- 💡 *What you're really telling Vulkan is:*

> - *"Yo, I'm done rendering — please un-tile this, decompress it, and arrange it in scanlines for display."*

- *If you don't tell Vulkan, it has to guess or stall — or worse, copy the whole thing behind your back.*

iii. 🔄 *Transitions let the driver do reordering, compression, or memory reallocation*

```
    //  When you declare:-
finalLayout = VK_IMAGE_LAYOUT_SHADER_READ_ONLY_OPTIMAL;
    // you are not just giving a hint....
    // ---- you are saying:-
```

> - *"After rendering, I'm going to sample this as a texture — so prepare it."*

```
This allows the GPU driver to:
- flush caches
- Decompress the image (some GPUs compress attachments during render!)
- Move memory or restructure tiles
- Or even alias memory with another attachment in a single memory block
- In modern GPUs, there's hardware image compression, like:-
    - ARM's AFBC (Arm Frame Buffer Compression)
    - AMD's DCC (Delta Color Compression)
    - NVIDIA has their own secret sauce too
```

iv. 🌀 *Aliasing & Tile Memory Reuse [* `ImageLayouts + Barriers` *]*

- *One of the sickest optimizations is this one*
- *You can use the same memory for multiple attachments (e.g. shadow map, depth, HDR buffer), as long as you don't use*

them at the same time.

- *But to do that safely, Vulkan needs to know:*

  > - *“When does this memory stop being ‘render target’ and start being ‘texture’ or ‘compute input’?”*

```
Layouts + barriers = safe aliasing.

Drivers can now:
- Use the same memory pool
- Skip clearing
- Not double allocate

You become a GPU memory ninja 💨🗡️
```

v. 📜 *Predictability = Performance*

```
Explicit layouts give Vulkan this power:
- It knows exactly when and how you are going to use an image.
- So it can avoid runtime guessing, which causes:
    - CPU stalls
    - Cache flushes
    - Sync fences
    - Or even full GPU pipeline bubbles 😵💫

- Compared to OpenGL or DirectX11, where the driver had to guess what you meant and do hidden magic
– Vulkan is like:
```

> - *“If you don’t tell me what layout you want, I’ll trip and fall flat on my face 😭”*

vi. *🍪 You can skip transitions altogether if you do it right*

- *This is the reward -> If your RenderPass is smart — using* `VK_ATTACHMENT_LOAD_OP_DONT_CARE` *and reusing image layouts cleverly — you can avoid layout transitions entirely.*
    - *This is massive for tile-based GPUs (like on mobile phones):*
    - *No layout transition = no VRAM flush*
    - *Everything happens on-chip, like magic 💨*

vii. *🎮 Analogy: Baking Cookies 🍪*

```
Let's say you're:
- Baking cookies (rendering)
- Then you plate them for display (presenting)
- Later you want to show them off or decorate them (sample in shaders)
```

- *Here's the deal:*

```
Vulkan Image Layout                          Cookie Stage
-------------------------      ---------------------------------
UNDEFINED                            Empty tray, nothing on it yet
COLOR_ATTACHMENT_OPTIMAL            You're baking the cookies 🔥
SHADER_READ_ONLY_OPTIMAL            You've finished baking and wanna decorate (like sampling in a
post-process shader) 🎨
PRESENT_SRC_KHR                        You're plating the cookies to serve 🥂 (sending to the
screen)
```

- *But… here's the twist:*
    - *💥 You can't decorate cookies while they're still baking in the oven.*
    - *💥 And you definitely can't serve someone cookies that are still stuck in a 200°C tray.*
- *So Vulkan says:*

> - *“Please transition between layouts, so I know what stage your cookie is in — and I'll move it to the right place, with oven mitts, spatulas, etc.”*

viii. *💠 Why does this matter?*

- *If you don't do the transitions:*

```
You may try to grab a cookie off a 200°C tray and get burned (💀 invalid reads)
The cookies may not be fully baked (💀 undefined writes)
Or worse: you show your customer an empty plate because Vulkan never moved them to the
PRESENT_SRC_KHR plate 😩
```

ix. *🚀 What makes Vulkan powerful?*

```
You get to say:
1. "Bake in tray A"
2. "Decorate using buffer B"
3. "Present from plate C"

But you must tell Vulkan when to move cookies from one surface to another.
Layouts = telling Vulkan exactly thaaat!
```

x. � *Subpass Optimization (Tile-Based GPUs)*

```
On tile-based GPUs (like PowerVR or Mali):
- Entire framebuffers live on-chip, in tiles
- You can run all subpasses without touching VRAM!

But it only works if Vulkan knows:
- The image will stay in the same layout
- No unnecessary STORE or layout transitions

By carefully using:
    layout = VK_IMAGE_LAYOUT_ATTACHMENT_OPTIMAL;
    loadOp = DONT_CARE;
    storeOp = DONT_CARE;

You unlock � zero-cost rendering.
```

- *That's why subpasses and layouts are so closely linked — **no layout change → no memory movement**.*

3. 🏁 *TL;DR:* `Image Layout Transitions` *Aren't Just Bureaucracy*

```
🎯 They are literal instructions to the driver:
   - "Where this image lives"
   - "How it's structured"
   - "What GPU unit will touch it next"
   - "Whether you need to prepare, flush, decompress, or alias it"

🎯 And by explicitly telling the GPU, you:
   - Avoid expensive guesses
   - Skip hidden memory ops
   - Unlock mobile-level optimizations
   - Prevent subtle bugs and undefined behavior
```

4. 📜 `RenderPass Attachments Desc.`

- `RenderPass Attachment` ***is not an actual thing!***
- `RenderPass Attachment Description/Descriptor` *is a thing!*
  - *However, the idea is.... **We do "define"** the* `Attachments` *right here, as we send the* `AttachmentDescriptions` *->* `RenderPass`
- `RenderPass Attachment Description/Descriptors` *are not actual images — they're a template for what the RenderPass expects!*
  - *& The FrameBuffers must delivery* `RenderPass` *exactly with that*

- `RenderPass Attachment` != `FrameBuffer Attachment`

RenderPass Attachments	*Framebuffers*
Define what is needed	*Provide which resources to use*
Abstract (format, usage, layout)	*Concrete (image views)*
Reusable across Framebuffers	*Swapchain-dependent (often 1:1)*

```
Think of it like a Socket & Plug
    - `RenderPass`  � = The RenderPass defines the socket (shape, voltage).
    - `Framebuffer` 🎁 = The Framebuffer provides the plug (actual wires) that fits the socket.
```

5. 🎁 `FrameBuffer Attachment`

- *Actual* `VkImageView`

```
Image Views (VkImageView):
    Handles to specific images (e.g., swapchain images, depth textures).
Compatibility:
    Must match the RenderPass's attachment definitions (format, sample count, size).
Swapchain Link:
    Typically, one Framebuffer per swapchain image.
```

6. 🛒 `FrameBuffers` *[🥖🍅🥚🍗]*

- *Binds concrete* `ImageViews` *(e.g.,* `SwapChain Images`*,* `Depth Textures`*) to the* `attachments` *defined in the* `RenderPass`.
- *Must match the* `RenderPass's Attachment Descriptions` *(format, size, sample count).*
- *Is* `SwapChain`*-dependent (e.g., each* `SwapChainImage` *typically has its own* `Framebuffer`*).*
- *Analogy*

```
- `RenderPass`  � = A recipe requiring "2 eggs and 1 cup of flour" (attachments).
- `Framebuffer` 🛒 = The actual eggs and flour (image views) you use to bake a cake (render a
frame).
```

7. 🎁 `Attachments`

```
RenderPass Attachments (Blueprint)   →      Framebuffer (Instance)
┌--------------------------------┐         ┌-----------------------------┐
| Attachment 0: Color (SRGB)     |         | Image View 0: Swapchain IMG |
| Attachment 1: Depth (D32_SF)   |         | Image View 1: Depth Texture |
└--------------------------------┘         └-----------------------------┘
```

- *Attachments are simply images (or buffers) where Vulkan stores or reads data during a RenderPass.*
- *Attachments are the actual framebuffer images (swapchain images, depth buffers, offscreen render targets, etc.)*

i. *🖌️ Color Attachments = where the pretty pixels (RGBA) are painted and stored. This is like your paint palette! 🎨*
ii. *🏔️ Depth Attachments = the landscapes that prevent objects from clipping or showing up out of order. Imagine topography maps for depth! 🗺️*
iii. *🖍️ Stencil Attachments = the guides that show where we can paint, like drawing a "map" where only certain areas can be modified. 🗺️*

- *What's inside?*
  - *A framebuffer that stores things like RGBA values (Red, Green, Blue, Alpha/Transparency).*
  - *For example,*
    - *Color Attachment 0 might hold the albedo or the final color of an object, while*
    - *Color Attachment 1 could store the lighting information or additional passes like ambient occlusion.*

```
Each attachment you declare includes:
- Format (VK_FORMAT_B8G8R8A8_SRGB, etc.)
- Sample count (for MSAA)
- Load/store ops
- Layouts (see above)
```

- *Then, each subpass tells Vulkan:*

  > - *"From all the attachments I've declared, I'm gonna use these ones in this subpass."*

- *in Code:*

```
attachments[0] = colorAttachment;   // swapchain image
attachments[1] = depthAttachment;   // depth image

subpass.colorAttachment = &attachments[0];
subpass.depthAttachment = &attachments[1];
```

```
So even if your RenderPass only has one subpass, the Vulkan driver still wants to know:
- How many attachments
- What to do with them (clear/store?)
- What layouts they go into and come out as
```

8. 🛒 `FrameBuffers` *v/s* 🎁 `Attachments` *:- The Last Fight, (If Above stuffs got you confused):-*

i. Quick Comparison Table

Aspect	*Attachments (RenderPass)* ❌	*Framebuffers* 🖼
Purpose	*Define what resources are needed (format, usage, layout transitions)* 📝	*Specify which actual images (image views) to use for those resources* ➖
Concrete/ Abstract	*Abstract (blueprint)* 🏷	*Concrete (instance)* 🏗
Lifetime	*Long-lived (reused across frames)* ♻	*Short-lived (often recreated with swapchain)* ↻
Dependencies	*Independent of images/swapchain* ⛔ 🖼	*Tied to swapchain images or specific textures* 🔗
Example	*"Need a color attachment (SRGB) and depth attachment (D32_SFLOAT)"* 🎨➕⚫	*"Use this swapchain image and that depth texture"* 🖼 1️⃣+ 🖼 2️⃣

ii. *Lifecycle Flowchart*

```
RenderPass Creation 🏗
|
├── Define Attachments 📄 (format, load/store ops, layouts)
|   └── "I need a color slot (B8G8R8A8_SRGB) and depth slot (D32_SFLOAT)" 🎨⚫
|
└── Define Subpasses 🔗 (how attachments are used in rendering steps)


↓


Framebuffer Creation 🛠
|
├── Bind Image Views to Attachment Slots 🔌
|   └── "Slot 0 = Swapchain Image View 🖼, Slot 1 = Depth Texture View 💠"
|
└── Validate Compatibility ✅ (size, format, sample count)
```

iii. Use-Case Scenarios

Scenario	*Attachments (RenderPass)* 💠	*Framebuffers* 🖼
Swapchain Rendering	*Define color/depth formats and layouts.* 🎨🔄⚫	*Bind swapchain images + depth texture.* 🖼🔗💠
Deferred Rendering	*Define G-Buffer attachments (Albedo, Normal, Position).* 🎁🎁🎁	*Bind actual G-Buffer image views.* 🖼1️⃣🖼2️⃣🖼3️⃣
Post-Processing	*Define input (e.g., HDR color) + output (e.g., SRGB).* 🌟➡🎨	*Bind input texture + swapchain image.* 💠🖼

iv. *Key Interactions*

```
RenderPass Begin Command 🚦
|
├── Uses RenderPass Attachments ⯑ (format, load/store rules)
|
└── Uses Framebuffer 🖼 (actual images to write to)


↓


GPU Renders 🎮
|
├── Reads/Writes to Framebuffer’s Image Views 🎹
|
└── Follows Attachment Rules (clearing, layout transitions) 🔄
```

v. *Emoji Analogy Time!* ⯑

- *Attachments = Recipe Ingredients List* 📜 *(e.g., "2 eggs* 🥚🥚*, 1 cup flour* 🍚*").*
- *Framebuffers = Actual Ingredients* 🛒 *(e.g., "This egg* 🥚 *from the fridge, that flour* 🍚 *from the pantry").*
- *Rendering = Baking the Cake* 🎂 *(combine them using the recipe steps!).*

9. Next Chapter will be on 🛒 `FrameBuffers` ***!!!!*** ⯑

Everything above is written with help from chatGPT

Everything below is not!

0. `amVK` Wrap ☺

```
#include "amVK_RenderPass.hh

    // TwT
    SC->GetSwapChainImagesKHR();
    SC->CreateSwapChainImageViews();

amVK_RenderPass *RP = PR->create_RenderPass_interface();
```

2. `vkCreateRenderPass()`

- ***https://vkdoc.net/man/vkCreateRenderPass***
- *REY_DOCs*
    - *Copy Paste* `amVK_SwapChain.hh` *Current Implementation & Change it as needed*
        - *Trust me, this is the most fun way of doing this, xP*

3. `VkRenderPassCreateInfo()`

- ***https://vkdoc.net/man/VkRenderPassCreateInfo***
    - `.flags` ⚑ *Only Option:- used for Qualcom Extension*
    - `.pAttachments` 🔗 *this->SubChapter4*
    - `.pSubpasses` 🔗 *this->SubChapter5*
    - `.pDependencies` 🔗 *this->SubChapter6*

4. `ImageViews`

1. `vkGetSwapchainImagesKHR()`

- *https://vkdoc.net/man/vkGetSwapchainImagesKHR*
- *Implement Exactly like* ***Chapter2.5*** ☺
    - `vkGetPhysicalDeviceQueueFamilyProperties()`
- REY_DOCs

```
class amVK_SwapChain  {
    ...
  public:
    amVK_Device *D = nullptr;
    VkSwapchainKHR SC = nullptr;
    REY_Array<VkImage>    amVK_1D_SC_IMGs;
    REY_Array<amVK_Image> amVK_1D_SC_IMGs_amVK_WRAP;
    bool called_GetSwapchainImagesKHR = false;

  public:
    ...
```

2. `vkCreateImageView()`

- *https://vkdoc.net/man/vkCreateImageView*
- REY_DOCs

```
void CreateSwapChainImageViews(void) {
    REY_Array_LOOP(amVK_1D_SC_IMGs_amVK_WRAP, i) {
        amVK_1D_SC_IMGs_amVK_WRAP[i].createImageView();
    }
}
```

- `amVK_Image.hh` :- *4.guide.chapter5.3.2.Image.hh*

3. `VkImageViewCreateInfo`
    - *https://vkdoc.net/man/VkImageViewCreateInfo*
    - REY_DOCs

```cpp
void amVK_SwapChain::CreateSwapChainImageViews(void) {
    REY_Array_LOOP(amVK_1D_SC_IMGs_amVK_WRAP, i) {
            // ViewCI.image
            // ViewCI.format
                // should be set inside amVK_SwapChain::GetSwapchainImagesKHR()
        amVK_1D_SC_IMGs_amVK_WRAP[i].ViewCI.viewType = VK_IMAGE_VIEW_TYPE_2D;

        amVK_1D_SC_IMGs_amVK_WRAP[i].ViewCI.components = { // Equivalent to:
            VK_COMPONENT_SWIZZLE_R,        // VK_COMPONENT_SWIZZLE_IDENTITY
            VK_COMPONENT_SWIZZLE_G,        // VK_COMPONENT_SWIZZLE_IDENTITY
            VK_COMPONENT_SWIZZLE_B,        // VK_COMPONENT_SWIZZLE_IDENTITY
            VK_COMPONENT_SWIZZLE_A         // VK_COMPONENT_SWIZZLE_IDENTITY
        };

        amVK_1D_SC_IMGs_amVK_WRAP[i].ViewCI.subresourceRange.aspectMask = VK_IMAGE_ASPECT_COLOR_BIT;
        amVK_1D_SC_IMGs_amVK_WRAP[i].ViewCI.subresourceRange.baseMipLevel = 0;
        amVK_1D_SC_IMGs_amVK_WRAP[i].ViewCI.subresourceRange.levelCount = 1;
        amVK_1D_SC_IMGs_amVK_WRAP[i].ViewCI.subresourceRange.baseArrayLayer = 0;
        amVK_1D_SC_IMGs_amVK_WRAP[i].ViewCI.subresourceRange.layerCount = 1;

        amVK_1D_SC_IMGs_amVK_WRAP[i].createImageView();
    }
}
```

5. `VkAttachmentDescription`

- *https://vkdoc.net/man/VkAttachmentDescription*

6. `VkSubpassDescription`

- *https://vkdoc.net/man/VkSubpassDescription*

7. `VkSubpassDependency`

- *https://vkdoc.net/man/VkSubpassDependency*

8. All the last 3 together --> Code

```
class amVK_RenderPass  {
  public:
    REY_ArrayDYN<VkAttachmentDescription> attachments;
    REY_ArrayDYN<VkSubpassDescription> subpasses;
    REY_ArrayDYN<VkSubpassDependency> dependencies;

    void set_attachments_subpasses_dependencies(void);
}
```

- `amVK_RenderPass.hh` *[Full Implementation]:- 4.guide.chapter5.8.RenderPass.hh*

```
amVK_RenderPass *RP = new amVK_RenderPass(D);
    RP->attachments.push_back({
        .format = SC->CI.imageFormat,                       // Use the color format selected by the swapchain
        .samples = VK_SAMPLE_COUNT_1_BIT,                    // We don't use multi sampling in this example
        .loadOp = VK_ATTACHMENT_LOAD_OP_CLEAR,               // Clear this attachment at the start of the
render pass
        .storeOp = VK_ATTACHMENT_STORE_OP_STORE,
            // Keep its contents after the render pass is finished (for displaying it)
        .stencilLoadOp = VK_ATTACHMENT_LOAD_OP_DONT_CARE,
            // Similar to loadOp, but for stenciling (we don't use stencil here)
        .stencilStoreOp = VK_ATTACHMENT_STORE_OP_DONT_CARE,
            // Similar to storeOp, but for stenciling (we don't use stencil here)
        .initialLayout = VK_IMAGE_LAYOUT_UNDEFINED,
            // Layout at render pass start. Initial doesn't matter, so we use undefined
        .finalLayout = VK_IMAGE_LAYOUT_PRESENT_SRC_KHR,
            // Layout to which the attachment is transitioned when the render pass is finished
            // As we want to present the color attachment, we transition to PRESENT_KHR
    });

    VkAttachmentReference colorReference = {
        .attachment = 0,
        .layout = VK_IMAGE_LAYOUT_COLOR_ATTACHMENT_OPTIMAL
    };
    RP->subpasses.push_back({
        .pipelineBindPoint = VK_PIPELINE_BIND_POINT_GRAPHICS,

        .inputAttachmentCount = 0,
            // Input attachments can be used to sample from contents of a previous subpass
        .pInputAttachments = nullptr,          // (Input attachments not used by this example)
        .colorAttachmentCount = 1,             // Subpass uses one color attachment
        .pColorAttachments = &colorReference,  // Reference to the color attachment in slot 0

        .pResolveAttachments = nullptr,
            // Resolve attachments are resolved at the end of a sub pass and can be used for e.g. multi
```

```
sampling
        .pDepthStencilAttachment = nullptr,    // (Depth attachments not used by this sample)
        .preserveAttachmentCount = 0,
            // Preserved attachments can be used to loop (and preserve) attachments through subpasses
        .pPreserveAttachments = nullptr        // (Preserve attachments not used by this example)
    });

    RP->dependencies.push_back({
        // Setup dependency and add implicit layout transition from final to initial layout for the color
attachment.
        // (The actual usage layout is preserved through the layout specified in the attachment reference).
        .srcSubpass = VK_SUBPASS_EXTERNAL,
        .dstSubpass = 0,
        .srcStageMask = VK_PIPELINE_STAGE_COLOR_ATTACHMENT_OUTPUT_BIT,
        .dstStageMask = VK_PIPELINE_STAGE_COLOR_ATTACHMENT_OUTPUT_BIT,
        .srcAccessMask = VK_ACCESS_NONE,
        .dstAccessMask = VK_ACCESS_COLOR_ATTACHMENT_WRITE_BIT | VK_ACCESS_COLOR_ATTACHMENT_READ_BIT,
    });

    RP->set_attachments_subpasses_dependencies();
    RP->createRenderPass();

    ------------------------------------- Made with help from P.A.Minerva Vulkan Guide
-------------------------------------
    https://paminerva.github.io/docs/LearnVulkan/01.A-Hello-Window#416---creating-a-render-pass
```

- `main.cpp` *[Full Implementation]:- 4.guide.chapter5.8.main.cpp*

9. By This time. VkSurfaceKHR deserves it's very own class `amVK_Surface`

- `amVK_Surface.hh` *[Full Implementation]:- 4.guide.chapter5.9.Surface.hh*

Chapter 6

`amVK_ColorSpace.hh` , `amVK_Surface` , `amVK_SurfacePresenter` , *Renaming Things in amVK*

1. `amVK_ColorSpace.hh`

```
/**
 * ex. 1   amVK_IF::RGBA_8bpc_UNORM
 */
namespace amVK_ImageFormat {
    // 8bpc = 8-bits per channel
    inline constexpr VkFormat RGBA_8bpc_UNORM    = VK_FORMAT_R8G8B8A8_UNORM;    // 37
    inline constexpr VkFormat RGBA_8bpc_SNORM    = VK_FORMAT_R8G8B8A8_SNORM;    // 38
    inline constexpr VkFormat RGBA_8bpc_USCALED  = VK_FORMAT_R8G8B8A8_USCALED;  // 39
    inline constexpr VkFormat RGBA_8bpc_SSCALED  = VK_FORMAT_R8G8B8A8_SSCALED;  // 40
    inline constexpr VkFormat RGBA_8bpc_UINT     = VK_FORMAT_R8G8B8A8_UINT;     // 41
    inline constexpr VkFormat RGBA_8bpc_SINT     = VK_FORMAT_R8G8B8A8_SINT;     // 42
    inline constexpr VkFormat RGBA_8bpc_SRGB     = VK_FORMAT_R8G8B8A8_SRGB;     // 43

    // Common Depth/Stencil Formats
    inline constexpr VkFormat D32_SFLOAT         = VK_FORMAT_D32_SFLOAT;
    inline constexpr VkFormat D24_UNORM_S8_UINT  = VK_FORMAT_D24_UNORM_S8_UINT;
}
#define amVK_IF amVK_ImageFormat
#define amVK_PF amVK_ImageFormat
#define amVK_PixelFormat amVK_ImageFormat
```

- ***Entire Code:-*** *amVK_ ColorSpace.hh*

2. `amVK_Surface`

```
/**
 * VULKAN-EXT:- `VK_KHR_surface`
 *       IMPL:- `amVK_1D_SurfaceInfos`
 */
class amVK_Surface {
  public:
    VkSurfaceKHR S = nullptr;       // Set in CONSTRUCTOR
    amVK_SurfacePresenter *PR = nullptr;   // Set in CONSTRUCTOR

    amVK_Surface(void) {}
    amVK_Surface(VkSurfaceKHR pS);

                REY_Array<REY_Array<VkSurfaceFormatKHR>>              amVK_2D_GPUs_ImageFMTs;
                REY_Array<VkSurfaceCapabilitiesKHR>                   amVK_1D_GPUs_SurfCAP;

    bool called_GetPhysicalDeviceSurfaceFormatsKHR = false;
    bool called_GetPhysicalDeviceSurfaceCapabilitiesKHR = false;
    void        GetPhysicalDeviceSurfaceInfo(void);
    void        GetPhysicalDeviceSurfaceCapabilitiesKHR(void);
};
```

- ***Entire Code:-*** *4.guide.chapter6.3.Surface.hh*

3. `amVK_SurfacePresenter`

```
class amVK_SurfacePresenter {
  public:
    amVK_Surface  *S  = nullptr;
    amVK_SwapChain *SC = nullptr;
    amVK_RenderPass *RP = nullptr;
        //   SC.VkDevice = RP.VkDevice
    amVK_Device        *D = nullptr;
    VkPhysicalDevice   GPU = nullptr;
        // amVK_Device.m_PD = this->GPU;
    amVK_GPU_Index GPU_Index = 0;

  public:
    void bind_Device(amVK_Device *D);
    amVK_SurfacePresenter  (amVK_Surface* pS) {this->S = pS;}

  public:
    amVK_SwapChain*  create_SwapChain(void);
    amVK_RenderPass* create_RenderPass(void);
    // Defined currently inside amVK_SwapChain.cpp

    void                      refresh_SurfCaps(void) { this->S->GetPhysicalDeviceSurfaceCapabilitiesKHR(); }
    VkSurfaceCapabilitiesKHR* fetched_SurfCaps(void) {
        return &( this->S->amVK_1D_GPUs_SurfCAP[this->GPU_Index] );
    }
};
```

- ***Entire Code:-*** *4.guide.chapter6.3.Surface.hh*

4. `amVK` Naming Conventions ☺

1. ***Calling Vulkan Library Functions:-***

```
bool called_GetPhysicalDeviceSurfaceFormatsKHR = false;
bool called_GetPhysicalDeviceSurfaceCapabilitiesKHR = false;
void        GetPhysicalDeviceSurfaceInfo(void);
void        GetPhysicalDeviceSurfaceCapabilitiesKHR(void);
```

2. `vkCreateZZZ()` *wrappers*

```
amVK_SwapChain {
    void CreateSwapChain(void) {
        VkResult return_code = vkCreateSwapchainKHR(this->D->m_device, &CI, nullptr, &this->SC);
        amVK_return_code_log( "vkCreateSwapchainKHR()" );     // above variable "return_code" can nott
be named smth else
    }
}
```

3. `amVK_Object` */Instance-Creation*

```
amVK_SwapChain* amVK_SurfacePresenter::create_SwapChain(void);
```

4. `amVK_Object::Functions()`

```
amVK_SwapChain*   create_SwapChain(void);           // Creates amVK_Object
amVK_RenderPass*  create_RenderPass(void);          // Creates amVK_Object
void                      refresh_SurfCaps(void);   // SurfCapabilities changes if Window is Resized
VkSurfaceCapabilitiesKHR* fetched_SurfCaps(void);   // Returns the REFRESHED/FETCHED element

void            amVK_SwapChain::sync_SurfCaps(void);/** Refreshes & Syncs `SurfaceCapabilites` */
void            amVK_SwapChain::konf_Images(
    VkFormat IF,
    VkColorSpaceKHR CS,
    VkImageUsageFlagBits IU,
    bool autoFallBack = true
)
void            amVK_SwapChain::konf_Compositing(
    VkPresentModeKHR PM,
    amVK_CompositeClipping CC,
    VkCompositeAlphaFlagBitsKHR CA
);
void            amVK_SwapChain::konf_ImageSharingMode(VkSharingMode ISM);
VkFormat        amVK_SwapChain::active_PixelFormat(void)                    {return CI.imageFormat;}
VkColorSpaceKHR amVK_SwapChain::active_ColorSpace (void)                    {return CI.imageColorSpace;}
```

5. `VkObject` *Variables*

```
class amVK_Image {
  public:
    amVK_Device *D = nullptr;
    VkImage     vk_Image = nullptr;
    VkImageView vk_ImageView = nullptr;
};

class amVK_FrameBuffer {
  public:
    amVK_SurfacePresenter *PR = nullptr;       // Basically, Parent Pointer
    VkFramebuffer vk_FrameBuffer = nullptr;
};

class amVK_RenderPass {
  public:
    amVK_SurfacePresenter *PR = nullptr;       // Basically, Parent Pointer
    VkRenderPass vk_RenderPass = nullptr;
};

class amVK_Surface {
  public:
    amVK_SurfacePresenter *PR = nullptr;   // Created in CONSTRUCTOR
    VkSurfaceKHR vk_SurfaceKHR = nullptr;   //     Set in CONSTRUCTOR
}
```

5. `amVK_RenderPass_Descriptors.hh`

```
namespace amVK_RP_AttachmentDescription
{
        // Change .format before using
    inline VkAttachmentDescription ColorPresentation = {
        .format = VK_FORMAT_UNDEFINED,            // you should use the ImageFormat selected by the swapchain
        .samples = VK_SAMPLE_COUNT_1_BIT,         // We don't use multi sampling in this example
        .loadOp = VK_ATTACHMENT_LOAD_OP_CLEAR,    // Clear this attachment at the start of the render pass
        .storeOp = VK_ATTACHMENT_STORE_OP_STORE,
            // Keep its contents after the render pass is finished (for displaying it)
        .stencilLoadOp = VK_ATTACHMENT_LOAD_OP_DONT_CARE,
            // Similar to loadOp, but for stenciling (we don't use stencil here)
        .stencilStoreOp = VK_ATTACHMENT_STORE_OP_DONT_CARE,
            // Similar to storeOp, but for stenciling (we don't use stencil here)
        .initialLayout = VK_IMAGE_LAYOUT_UNDEFINED,
            // Layout at render pass start. Initial doesn't matter, so we use undefined
        .finalLayout = VK_IMAGE_LAYOUT_PRESENT_SRC_KHR,
            // Layout to which the attachment is transitioned when the render pass is finished
            // As we want to present the color attachment, we transition to PRESENT_KHR
    };
};

#define amVK_RPADes amVK_RP_AttachmentDescription
#define amVK_RPARef amVK_RP_AttachmentReference
#define amVK_RPSDes amVK_RP_SubpassDescription
#define amVK_RPSDep amVK_RP_SubpassDependency
```

- *You should kinda check the* `amVK_RenderPass_Descriptors.hh` *file yourself* ⯑

```
amVK_RenderPass *RP = PR->create_RenderPass_interface();
    amVK_RPADes::ColorPresentation.format = SC->CI.imageFormat;

    RP->AttachmentInfos .push_back(amVK_RPADes::ColorPresentation);
    RP->SubpassInfos    .push_back(amVK_RPSDes::ColorPresentation);
    RP->Dependencies    .push_back(amVK_RPSDep::ColorPresentation);

    RP->sync_Attachments_Subpasses_Dependencies();
    RP->CreateRenderPass();
```

6. `REY_Utils.hh`

1. `REY_Array`

```
REY_ArrayDYN<VkDeviceQueueCreateInfo> Array = REY_ArrayDYN<VkDeviceQueueCreateInfo>(nullptr, 0, 0);
    // No MemoryAllocation by default ☺
    //      1. REY_ArrayDYN.initialize(10)
    //      2. REY_ARRAY_PUSH_BACK(Array) = your_QueueCI;        [not a function. but rather a preprocessor
macro]
```

Chapter 7: 🛒 `FrameBuffer` [🥖🍅🥚🍗]

1. 🛠 `vkCreateFramebuffer()`

- ***https://vkdoc.net/man/vkCreateFramebuffer***
- 📜 *REY_DOCs*
  - *Copy Paste* `amVK_RenderPass.hh` *Current Implementation & Change it as needed*
    - *Trust me, this is the most fun way of doing this, xP*

2. 🎁 `VkFramebufferCreateInfo()`

- ***https://vkdoc.net/man/VkFramebufferCreateInfo***
  - `.flags` 🏳 `0`
    - *https://vkdoc.net/man/VkFramebufferCreateFlagBits* | *ivirtex-github*
    - ⚑ `VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT` *[ImageLess FrameBuffer]*
  - `.renderPass` ▨💁‍♀️
  - `.pAttachments` 🔗 *SubChapter 3*
  - `.width`
  - `.height`
  - `.layers`
- 📜 *REY_DOCs*
  - *Start With basic copy paste of* `amVK_RenderPass.hh` *:-*
- `📽 So far, The result` *amVK_RenderPassFBs.hh*

3. `VkImageView .pAttachments`

- ***https://vkdoc.net/man/VkImageView***
  - *For Now, We are gonna choose 1 VkImageView per FrameBuffer*
- `</> TheCode`

```
void amVK_RenderPassFBs::CreateFrameBuffers(void) {
    if (this->SC_IMGs->called_GetSwapChainImagesKHR == false)    {
        this->SC_IMGs->       GetSwapChainImagesKHR();           }
    if (this->SC_IMGs->called_CreateSwapChainImageViews == false)    {
        this->SC_IMGs->       CreateSwapChainImageViews();          }

    VkExtent2D imageExtent = this->SC_IMGs->active_ImageExtent();
        this->CI.width  = imageExtent.width;
        this->CI.height = imageExtent.height;

    this->amVK_1D_RP_FBs.reserve(this->SC_IMGs->amVK_1D_SC_IMGs.n);

    REY_Array_LOOP(this->amVK_1D_RP_FBs, k) {
        this->CI.attachmentCount = 1;
        this->CI.pAttachments = &(this->SC_IMGs->amVK_1D_SC_IMGViews[k]);

                #define VK_DEVICE this->RP->D->vk_Device

        VkResult return_code = vkCreateFramebuffer(VK_DEVICE, &CI, nullptr, &this->amVK_1D_RP_FBs[k]);
        amVK_return_code_log( "vkCreateFramebuffer()" );
    }
}
```

- `📽 So far, The result` *amVK_RenderPass.cpp#L34-L55*

Chapter 8: `CommandBuffer` 📝

Rendering commands have to be Recorded in a CommandBuffer.
Only then the GPU can work on it 👩‍💻.
That's the idea, since decades ago, so yeah, xD.

0. `amVK` wrap 📎

```
#include "amVK_Synchronization.hh"
#include "amVK_CommandPoolMAN.hh"

    // TwT
    REY_LOG("");
    #define amVK_S amVK_Sync
    #define CPCF CommandPoolCreateFlags
amVK_CommandPoolMAN*CPMAN = new amVK_CommandPoolMAN(D);
                    CPMAN->init_CMDPool_Graphics(amVK_S::CPCF::RecordBuffer_MoreThanOnce);
                    CPMAN->CreateCommandPool_Graphics(flags);
                    CPMAN->AllocateCommandBuffers1_Graphics(1);

amVK_CommandBufferPrimary *CB = new amVK_CommandBufferPrimary(CPMAN->BUFFs1.Graphics[0]);
```

1. `VkCommandPool`

🛠 `VkCommandPoolCreateInfo`

- 🌋 ***https://vkdoc.net/man/VkCommandPoolCreateInfo***
  - `.sType` ▨ `VK_STRUCTURE_TYPE_COMMAND_POOL_CREATE_INFO`
  - `.pNext` ▨ `NULL`
  - `.flags` 🏳 `VkCommandPoolCreateFlagBits`
    - *https://vkdoc.net/man/VkCommandPoolCreateFlagBits* | *ivirtex-github*
      - 🏳 `TRANSIENT`
      - 🏳 `RESET_COMMAND_BUFFER` *:- Lets you call* `vkBeginCommandBuffer()` *on same* `CMDBUF` *more than once*
      - 🏳 `PROTECTED`
    - ▨ `0` *:- Can't call* `vkBeginCommandBuffer()` *more than once on the same* `CMDBUF`
  - `.queueFamilyIndex`
    - ▨ *CommandPool =* `as per queueFamily`
    - *i am not sure if you can have multiple CommandPool on the same QueueFamily*

🎁 `vkCreateCommandPool()`

- 🌋 ***https://vkdoc.net/man/vkCreateCommandPool***
  - `.device` ▨ 👩‍💻
  - `.pCreateInfo` ▨ 👩‍💻
  - `.pAllocator` ▩ ChapterZZZ
  - `.pSemaphore` ↩🎁

📜 REY_DOCs

- ***Copy Paste*** `amVK_FrameBuffer.hh` ***Current Implementation & Change it as needed***
  - *Trust me, this is the most fun way of doing this, xP*

◈ `amVK` 🔗 *amVK_CommandPoolMAN.hh*

2. `VkCommandBuffer`

🛠 `VkCommandBufferAllocateInfo`

- *https://vkdoc.net/man/VkCommandBufferAllocateInfo*
    - `.sType` ▨ `VK_STRUCTURE_TYPE_COMMAND_BUFFER_ALLOCATE_INFO`
    - `.pNext` ▨ `NULL`
    - `.commandPool` ▨ 🧑‍💻♀
    - `.level` 🔀 `PRIMARY/SECONDARY` *[Toggle]*
    - `.commandBufferCount` ▨ 🧑‍💻♀

🎁 `vkAllocateCommandBuffers()`

- *https://vkdoc.net/man/vkAllocateCommandBuffers*
    - `.device`
    - `.pAllocateInfo` ▨ 🧑‍💻♀
    - `pCommandBuffers` ⤶🎁

◇ `amVK` 🔗 *amVK_CommandPoolMAN.hh#L63*

- ***both Primary & Secondary commandBuffers are supported***
    - *But, as off* `01 May, 2025`
        - *amVK Users must use one of the* `amVK_CommandPoolCATs` *(Categories) e.g. Graphics/Compute* 🧑‍💻♀
- 🔗 *amVK_ Synchronization.hh*

```
EntryNotFound (FileSystemError): Error: ENOENT: no such file or directory, open 'c:\Users\
```

Chapter 10: 📽 `So far, The result`

```
#include "amGHOST_System.hh"
#include "amVK_Instance.hh"
#include "amVK_Device.hh"

#include "amGHOST_VkSurfaceKHR.hh"
#include "amVK_Surface.hh"

#include "amVK_SwapChain.hh"
#include "amVK_ColorSpace.hh"
#include "amVK_RenderPass.hh"
#include "amVK_RenderPass_Descriptors.hh"
#include "amVK_CommandPoolMAN.hh"

int main(int argumentCount, char* argumentVector[]) {
    REY::cout << "\n";

    // ------------------------- amGHOST ----------------------------
        amGHOST_System::create_system();

        amGHOST_Window *W = amGHOST_System::heart->new_window_interface();
        W->create(L"Whatever", 0, 0, 500, 600);
    // ------------------------- amGHOST ----------------------------

    REY_LOG("");
    REY_LOG("");
    // --------------------------- amVK -----------------------------
            REY_LOG("");
        amVK_Instance::EnumerateInstanceExtensions();
        amVK_Instance::EnumerateInstanceLayerProperties();
        amVK_Instance::addTo_1D_Instance_Layers_Enabled("VK_LAYER_KHRONOS_validation");
        amVK_Instance::addTo_1D_Instance_EXTs_Enabled("VK_KHR_surface");
        amVK_Instance::addTo_1D_Instance_EXTs_Enabled(amGHOST_System::get_vulkan_os_surface_ext_name());
        amVK_Instance::CreateInstance();

            REY_LOG("");
        VkSurfaceKHR  VK_S = amGHOST_VkSurfaceKHR::create_surface(W, amVK_Instance::vk_Instance);

            REY_LOG("");
        amVK_Instance::EnumeratePhysicalDevices();
        amVK_GPUProps  *GPUProps = amVK_InstanceProps::GetARandom_GPU();
                        GPUProps->GetPhysicalDeviceQueueFamilyProperties();
                        GPUProps->EnumerateDeviceExtensionProperties();
                        GPUProps->REY_CategorizeQueueFamilies();

        amVK_Device* D = new amVK_Device(GPUProps);
            D->addTo_1D_GPU_EXTs_Enabled("VK_KHR_swapchain");
            D->CreateDevice(1);
            D->GetDeviceQueues();

            REY_LOG("")
        amVK_Surface   *S  = new amVK_Surface(VK_S);
            S->GetPhysicalDeviceSurfaceInfo();
            S->GetPhysicalDeviceSurfaceCapabilitiesKHR();
```

```
        // -------------------------- SwapChain, RenderPass, FrameBuffers ----------------------------
            REY_LOG("")
        amVK_SwapChain *SC = new amVK_SwapChain(this->S, this->D);;
            SC->konf_ImageSharingMode(VK_SHARING_MODE_EXCLUSIVE);
            SC->konf_Images(
                amVK_IF::RGBA_8bpc_UNORM,   // VK_FORMAT_R8G8B8A8_UNORM
                amVK_CS::sRGB,              // VK_COLOR_SPACE_SRGB_NONLINEAR_KHR
                amVK_IU::Color_Display      // VK_IMAGE_USAGE_COLOR_ATTACHMENT_BIT
            );
            SC->konf_Compositing(
                amVK_PM::FIFO,              // VK_PRESENT_MODE_FIFO_KHR
                amVK_CC::YES,               // Clipping:- VK_TRUE
                amVK_TA::Opaque             // VK_COMPOSITE_ALPHA_OPAQUE_BIT_KHR
            );
            SC->sync_SurfCaps();            // refresh/fetch & set/sync ---> latest SurfCaps

            SC->CI.oldSwapchain     = nullptr;
            SC->CreateSwapChain();

        amVK_SwapChainIMGs *SC_IMGs = new amVK_SwapChainIMGs(this->SC);
            SC_IMGs->   GetSwapChainImagesKHR();
            SC_IMGs->CreateSwapChainImageViews();



        amVK_RenderPass *RP = new amVK_RenderPass(this->D);
            amVK_RPADes::ColorPresentation.format = SC->CI.imageFormat;

            RP->AttachmentInfos.push_back(amVK_RPADes::ColorPresentation);
            RP->SubpassInfos   .push_back(amVK_RPSDes::ColorPresentation);
            RP->Dependencies   .push_back(amVK_RPSDep::ColorPresentation);

            RP->sync_Attachments_Subpasses_Dependencies();
            RP->CreateRenderPass();

        amVK_RenderPassFBs *RP_FBs = PR->create_FrameBuffers_interface();
            RP_FBs->CreateFrameBuffers();
        // -------------------------- SwapChain, RenderPass, FrameBuffers ----------------------------



        amVK_CommandPoolMAN  *CPMAN = PR->create_CommandPoolMAN_interface();
                              CPMAN->init_CMDPool_Graphics();

CPMAN->CreateCommandPool_Graphics(amVK_Sync::CommandPoolCreateFlags::RecordBuffer_MoreThanOnce);
                              CPMAN->AllocateCommandBuffers1_Graphics(1);

        amVK_CommandBufferPrimary *CB = new amVK_CommandBufferPrimary(CPMAN->BUFFs1.Graphics[0]);
    // -------------------------- amVK ----------------------------
    REY_LOG("");
    REY_LOG("");


    // ------------------------ CleanUp & ExportJSON ---------------------------
        REY::cin.get();     // wait for terminal input
```

```
            amVK_InstancePropsEXPORT::Export_nilohmannJSON_EXT();
                destroy_everything_serially();         // Last Chapter, copy code from there
                W->m_amGHOST_VkSurface->destroy();
                amVK_Instance::DestroyInstance();
            W->destroy();
    // ------------------------- CleanUp & ExportJSON ----------------------------

    REY::cout << "\n";
}
```

Chapter 11: 🔮 `Shader`

Vertex Shader

```
#version 450

layout(location = 0) out vec3 fragColor;

vec2 positions[3] = vec2[](
    vec2(0.0, -0.5),
    vec2(0.5, 0.5),
    vec2(-0.5, 0.5)
);

vec3 colors[3] = vec3[](
    vec3(1.0, 0.0, 0.0),
   vec3(0.0, 1.0, 0.0),
    vec3(0.0, 0.0, 1.0)
);

void main() {
    gl_Position = vec4(positions[gl_VertexIndex], 0.0, 1.0);
    fragColor = colors[gl_VertexIndex];
}
```

- *Sooner or later, will have to switch to VertexBuffers* 💁‍♀️

Fragment Shader

```
#version 450

layout (location = 0) in vec3 fragColor;

layout (location = 0) out vec4 outColor;

void main() {
    outColor = vec4(fragColor, 1.0);
}
```

Compiling & Loading

```
glslangValidator -V triangle.vert -o triangle.vert.spv
glslangValidator -V triangle.frag -o triangle.frag.spv
```

- *Github* 🔗 *LoadSPIRVShaderModule()*

Stay Tuned, Adding more in this Chapter 💁‍♀️

Chapter 12: 🛠 `Pipeline`

0. ℹ `VkGraphicsPipelineCreateInfo`

- ***https://vkdoc.net/man/VkGraphicsPipelineCreateInfo***
  - `.sType` ▨ `VK_STRUCTURE_TYPE_GRAPHICS_PIPELINE_CREATE_INFO`
  - `.pNext` ⍰ `nullptr`
  - `.flags` ChapterZZZ
    - ⍰ *https://vkdoc.net/man/VkPipelineCreateFlagBits* | *ivirtex-github*

  - `.stageCount` `uint32_t`
  - `.pStages` *Shaders* `VkPipelineShaderStageCreateInfo`

  - 🔀 *Pipeline States / Stages*
    - `.pVertexInputState` ⍰
    - `.pInputAssemblyState`
    - `.pTessellationState`
    - `.pViewportState`
    - `.pRasterizationState`
    - `.pMultisampleState`
    - `.pDepthStencilState`
    - `.pColorBlendState`
    - `.pDynamicState`

  - `.layout` 🔗 *SubChapter 2*
  - `.renderPass` ⍰
  - `.subpass` ▨ `0`
  - `.basePipelineHandle` ▨ `VK_NULL_HANDLE`
  - `.basePipelineIndex` ▨ `INT32_MIN`

⍰ `amVK` wrap

```
amVK_PipelineGRAPHICS* PLG = new amVK_PipelineGRAPHICS(RP_FBs);
    PLG->CreateGraphicsPipeline();
```

1. `Pipeline Objects`

🔗 *amVK_Vertex.hh*
🔗 *amVK_GeoMetry.hh*
🔗 *amVK_PipelineGRAPHICS.cpp*

3. `VkPipelineLayout`

1. ℹ `VkPipelineLayoutCreateInfo`
   - *https://vkdoc.net/man/VkPipelineLayoutCreateInfo*
     - `.sType` ▨ `VK_STRUCTURE_TYPE_PIPELINE_LAYOUT_CREATE_INFO`
     - `.pNext` ⯑ `nullptr`
     - `.flags` ⚐ `0`
       - ⯑ *https://vkdoc.net/man/VkPipelineLayoutCreateFlagBits* | *ivirtex-github*

     - `.pSetLayouts` ▨ `nullptr` 🏷 `VkDescriptorSetLayout` ▦ ChapterZZZ
     - `.pPushConstantRanges` ▨ `nullptr` 🏷 `VkPushConstantRange` ▦ ChapterZZZ
2. 🎁 `vkCreatePipelineLayout()`
   - *https://vkdoc.net/man/vkCreatePipelineLayout*

Chapter 13: `RenderLoop` 📟🎨

🌋 `Vulkan` wrap 🩹

```
while(true) {
    vkAcquireNextImageKHR();

    vkResetCommandBuffer();     // req:- VK_COMMAND_POOL_CREATE_RESET_COMMAND_BUFFER_BIT
    vkBeginCommandBuffer();
        vkCmdBeginRenderPass();
            vkCmdSetViewport();
            vkCmdSetScissor();
            vkCmdBindPipeline();
                vkCmdDraw();
        vkCmdEndRenderPass();
    vkEndCommandBuffer();

    vkQueueSubmit();
    vkQueuePresentKHR();

    vkQueueWaitIdle();
    PROCESS_InputEvents();
    REY_NoobTimer::wait(10); // wait 10ms
}
```

◇ `amVK` wrap 🩹

```
while(true) {
    W->dispatch_events_with_OSModalLoops();

    RP_FBs->RPBI_AcquireNextFrameBuffer();

    CB->BeginCommandBuffer(amVK_Sync::CommandBufferUsageFlags::Submit_Once);
    // ------------------------- CommandBufferRecording ----------------------------

        RP_FBs->CMDBeginRenderPass(CB->vk_CommandBuffer);
            RP_FBs->CMDSetViewport_n_Scissor(CB->vk_CommandBuffer);
            PLG->CMDBindPipeline(CB->vk_CommandBuffer);
                VB.CMDDraw(CB->vk_CommandBuffer);
        RP_FBs->CMDEndRenderPass(CB->vk_CommandBuffer);

    // ------------------------- CommandBufferRecording ----------------------------
    CB->EndCommandBuffer();

    // This was Done Before in CH4 : SwapChain
        amVK_SurfacePresenter  *PR = new amVK_SurfacePresenter();
                                PR->bind_Surface(S);
                                PR->bind_Device(D);
    // This was Done Before in CH4 : SwapChain

    PR->set_CommandBuffer(CB->vk_CommandBuffer);
    PR->submit_CMDBUF(D->Queues.GraphicsQ(0));
    PR->Present(D->Queues.GraphicsQ(0));

    vkQueueWaitIdle(D->Queues.GraphicsQ(0));
    REY_NoobTimer::wait(10); // wait 10ms
}
```

1. `vkAcquireNextImageKHR()`

- *https://vkdoc.net/man/vkAcquireNextImageKHR*
    - `.device` ▨ *Same as* `SwapChain` 👩‍💻
    - `.swapchain` ▨👩‍💻
    - `.timeout` ⏱⚡ `nanoseconds`
        - *specifies how long the function waits, in* ⏱⚡ `nanoseconds` *, if no image is available.*

          ```
          uint64_t ns_per_second = 1'000'000'000;
          ```
    - `.semaphore` 🔗 *SubChapter 2*
    - `.fench` ▩ ChapterZZZ
    - `.pImageIndex` ↩🎁
        - *Well, this function doesn't return an* `VkImage` *but an index to it* 👩‍💻

- 📜 *REY_DOCS*
  - Acquires the next image from SwapChain
  - *So, now you know which class this function has got to be inside* ⯑

- ↩ *Return Codes*
  - ↩ `VK_SUBOPTIMAL_KHR`
    - *if the window has been resized but the OS/platform's* `GPU-DriverImplementation` / `PresentationEngine` *is still able to scale the presented images to the new size to produce valid surface updates.*
    - *It is up to the application to decide whether it prefers to continue using the current swapchain in this state, or to re-create the swapchain to match resized window.*
  - ↩ `VK_ERROR_OUT_OF_DATE_KHR`
    - *the images in the swapchain no longer matches the surface properties (e.g., the window was resized)*
    - *and the presentation engine can't present them,*
    - *so the application needs to create a new swapchain that matches the surface properties.*
  - REFs:- 1. minerva

- 📜 *REY_DOCs*
  - *For rendering, we need an image to render on to.*
  - *And before we start rendering onto an image, vulkan wants us to call* `AcquireNextImage()` *from* `SwapChain`

1.1. Can you use `1` SwapChainIMG? 🧑‍💻♀

1. `1 IMG Modes`
   - `VK_PRESENT_MODE_IMMEDIATE_KHR`
     - *You will see* Tearing
     - `vkAcquireNextImageKHR()` *:- Returns* `VK_SUCCESS` *immediately (no synchronization).*
   - `VK_PRESENT_MODE_FIFO_RELAXED_KHR`
     - *If you submit frames slower than the display refresh rate, it might work with 1 image (but risky).*
2. `Multi IMG Modes`
   - `VK_PRESENT_MODE_FIFO_KHR` *a.k.a* VSync *:- Needs ≥2 images (front + back buffer).*
   - `VK_PRESENT_MODE_MAILBOX_KHR` (Triple buffering) *:- Needs ≥3 images.*
     - *Some games will also flag this as* VSync
3. *GPU Driver:-*

```
vkGetPhysicalDeviceSurfaceCapabilitiesKHR(...);
// caps.minImageCount is often 2+ (driver may ignore your request when creating SwapChain)
```

1.2. `vkQueueWaitIdle()`

- *https://vkdoc.net/man/vkQueueWaitIdle*
- 📜 *REY_DOCs*
  - *So that we can Acquire the next image without causing errors.*

1.3. Synchronization

2. Command Recording I

- *Recall Back* : 🛠 `VkCommandPoolCreateInfo`
    - 🌋 *https://vkdoc.net/man/VkCommandPoolCreateInfo*
        - `.flags` 🏳 `VkCommandPoolCreateFlagBits`
            - *https://vkdoc.net/man/VkCommandPoolCreateFlagBits* | *ivirtex-github*
                - 🏳 `TRANSIENT`
                - 🏳 `RESET_COMMAND_BUFFER` :- *Lets you call* `vkBeginCommandBuffer()` *on same* `CMDBUF` *more than once*
                - 🏳 `PROTECTED`
            - ▨ `0` :- *Can't call* `vkBeginCommandBuffer()` *more than once on the same* `CMDBUF`

1. `VkCommandBufferBeginInfo`
    - *https://vkdoc.net/man/VkCommandBufferBeginInfo*
        - `.sType` ▨ `VK_STRUCTURE_TYPE_COMMAND_BUFFER_BEGIN_INFO`
        - `.pNext` ▨ `nullptr`
            - ⍰ `VkDeviceGroupCommandBufferBeginInfo`
        - `.flags` 🔠 `VkCommandBufferUsageFlagBits`
            - *https://vkdoc.net/man/VkCommandBufferUsageFlagBits* | *ivirtex-github*
                - 🔠 `SIMULTANEOUS_USE`
                - 🔠 `RENDER_PASS_CONTINUE` *[secondary command buffer]*
                - 🔠 `ONE_TIME_SUBMIT` :- *usually coupled with* 🏳 `RESET_COMMAND_BUFFER`
            - ▨ `0` :- *Now you can submit this command buffer multiple times*

        - `.pInheritanceInfo` ⍰ *[secondary command buffer]*

    - 📜 REY_DOCs
        - *Rendering commands have to be Recorded in a CommandBuffer.*
        - *Only then the GPU can work on it* 🤷‍♀️.
        - *That's the idea, since decades ago, so yeah, xD.*

    - 📜 REY_DOCs : There are a few ways that you can record `CMDBUF`
        a. *Recording a* `VkCommandBuffer` *only Once*
        b. *Recording a* `VkCommandBuffer` *more than Once*
            - *more than Once --> requires,* `CMDBUF` *to be reset by* `vkResetCommandBuffer()` *before recording again*
                - *Note:-* `vkBeginCommandBuffer()` *also does do an implicit reset*
                - *which I don't believe should exist* 🤷‍♀️
                - *I always believe* ***"Explicit is better than implicit"***
            - *REQ:-*
                - `VkCommandPoolCreateInfo.flags` ▨ `VK_COMMAND_POOL_CREATE_RESET_COMMAND_BUFFER_BIT`

        c. *Submitting a* `VkCommandBuffer` *only Once*
            - *REQ:-*
                - `VkCommandBufferBeginInfo.flags` ▨ `VK_COMMAND_BUFFER_USAGE_ONE_TIME_SUBMIT_BIT`
            - *People usually uses* `SUBMIT_ONCE` *with a* `RESET_CMDBUF`
        d. *Implementing Synchronization features is so fked up. After Present Image, call* `vkQueueWaitIdle()`

2. `VkRenderPassBeginInfo`
    - *https://vkdoc.net/man/VkRenderPassBeginInfo*
        - `.sType` ▨ `VK_STRUCTURE_TYPE_RENDER_PASS_BEGIN_INFO`
        - `.pNext` ⍰ `nullptr`
        - `.renderPass` ▨🤷‍♀️
        - `.framebuffer` ▨🤷‍♀️
        - `.renderArea` ➡ *https://vkdoc.net/man/VkRect2D*
        - `.pClearValues` ➡ *https://vkdoc.net/man/VkClearValue*

    - 📜 REY_DOCs
        - *After hitting Start on the* `RecordCommandBuffer()`
        - *Generally the first thing we gotta do is call* `BeginRenderPass()`
        - *So that we can do & transition between the* `DepthPass`, `NormalPass`, `ShadowPass`, `AlbedoPass`, *other necessary subpasses*

2. Command Recording II

3. `vkBeginCommandBuffer()`
   - *https://vkdoc.net/man/vkBeginCommandBuffer*
     - `.commandBuffer` ▨ 💁‍♀
     - `.pBeginInfo` ▨ 💁‍♀
   - `</> TheCode`

```
amVK_CommandPool {
  public:
    REY_Array<VkCommandBuffer>      vk_CommandBuffers;
    REY_Array<VkCommandBuffer> AllocateCommandBuffers(void);

  public:
    VkCommandBufferBeginInfo BI = {
        .sType = VK_STRUCTURE_TYPE_COMMAND_BUFFER_BEGIN_INFO,
        .pNext = 0,
        .flags = VK_COMMAND_BUFFER_USAGE_ONE_TIME_SUBMIT_BIT,
            // People usually uses `SUBMIT_ONCE` with a `RESET_CMDBUF` & records CMDBUF every frame
        .pInheritanceInfo = nullptr
    };
    void BeginCommandBuffer(uint32_t CMDBUF_Index) {
        VkResult return_code = vkBeginCommandBuffer(vk_CommandBuffers[CMDBUF_Index], &BI);
        amVK_return_code_log( "vkBeginCommandBuffer()" );
    }
}
```

4. `vkCmdBeginRenderPass()`
   - *https://vkdoc.net/man/vkCmdBeginRenderPass*
     - `.commandBuffer` ▨ 💁‍♀
     - `.pRenderPassBegin` ▨ 💁‍♀
     - `.contents` 🔠 `VK_SUBPASS_CONTENTS_INLINE`
       - *https://vkdoc.net/man/VkSubpassContents* | *ivirtex-github*
         - 🔠 `INLINE`
         - 🔠 `SECONDARY_COMMAND_BUFFERS` *[secondary command buffer]*
         - 🔠 `INLINE_AND_SECONDARY_COMMAND_BUFFERS_KHR` *[VK_KHR_maintenance7]*
         - 🔠 `INLINE_AND_SECONDARY_COMMAND_BUFFERS_EXT` *[VK_EXT_nested_command_buffer]*

---

5. `vkCmdSetViewport()`
   - *https://vkdoc.net/man/vkCmdSetViewport*
     - `.commandBuffer` ▨ 💁‍♀
     - `.firstViewport` ▨ `0`
     - `.viewportCount` ▨ `1`
     - `.pViewports` ▨ `VkViewport`
       - *https://vkdoc.net/man/VkViewport*
   - 📜 REY_DOCs
     - *This is smth i consider part of the RenderPass*

6. `vkCmdSetScissor()`
   - *https://vkdoc.net/man/vkCmdSetScissor*
     - `.pScissors` ▨ `VkRect2D`
       - *https://vkdoc.net/man/VkRect2D*
   - 📜 REY_DOCs
     - *This is smth i consider part of the RenderPass*

7. `vkBindPipeline()`
    - *https://vkdoc.net/man/vkBindPipeline*
        - `.commandBuffer` ▨ 💁♀
    - 📜 REY_DOCs
        - *Once we bind a pipeline, then we can call* `Draw()`
        - *After binding pipeline, is where you specify* `VertexBuffers`
            - *More on VertexBuffer* ▒ **Chapter16**
8. `vkCmdDraw()`
    - *https://vkdoc.net/man/vkCmdDraw*

9. `vkCmdEndRenderPass()`
    - *https://vkdoc.net/man/vkCmdEndRenderPass*
        - `.commandBuffer` ▨ 💁♀
10. `vkEndCommandBuffer()`
    - *https://vkdoc.net/man/vkEndCommandBuffer*
        - `.commandBuffer` ▨ 💁♀

3. `Submit Command Buffer` & Present

1. `VkSubmitInfo`
   - https://vkdoc.net/man/VkSubmitInfo
     - `.sType` ▨ `VK_STRUCTURE_TYPE_SUBMIT_INFO`
     - `.pNext` ⯑ `NULL`
     - `.pWaitSemaphores` 🔗 *Chapter9.1*
       - ▨ `amVK_SwapChain::AcquireNextImage_SemaPhore`
     - `.pWaitDstStageMask` ▨ `VK_PIPELINE_STAGE_COLOR_ATTACHMENT_OUTPUT_BIT`
     - `.pCommandBuffers` ▨ 💁♀
     - `.pSignalSemaphores`
       - ▨ `amVK_SurfacePresenter::RenderingFinished_SemaPhore`

2. `vkQueueSubmit()`
   - https://vkdoc.net/man/vkQueueSubmit
     - `.queue` ▨ `GraphicsQueue`
     - `.submitCount` ▨ `1`
     - `.pSubmits` ▨ 💁♀
     - `.fench` ▨ `VK_NULL_HANDLE`
3. `vkGetDeviceQueue()`
   - https://vkdoc.net/man/vkGetDeviceQueue
     - `.device`
     - `.queueFamilyindex` 🔗 *Chapter2.7*
       - `amVK_Device::amVK_1D_QCIs::select_QFAM_Graphics()`
     - `.queueIndex` 🔗 *Chapter2.4*
       - `VkDeviceQueueCreateInfo.queueCount`
     - `.pQueue` ↩🎁

4. `VkPresentInfoKHR`
   - https://vkdoc.net/man/VkPresentInfoKHR
     - `.sType` ▨ `VK_STRUCTURE_TYPE_PRESENT_INFO_KHR`
     - `.pNext` ⯑ `NULL`
       - ⯑ *Maybe some interesting extensions, idk*
     - `.pWaitSemaphores` 🔗 *Chapter9.6*
       - ▨ `amVK_SwapChain::RenderingFinished_SemaPhore`
     - `.pSwapchains` ▨ 💁♀
     - `.pImageIndices`
     - `.pResults`

5. `vkQueuePresentKHR()`
   - https://vkdoc.net/man/vkQueuePresentKHR
     - `.queue` ▨ 💁♀
     - `.pPresentInfo` ▨ 💁♀

6. *Coloring Window*
7. `📽 So far, The result` 🔗 `GITHUB`
   - https://github.com/REYNEP/amGHOST/tree/805df077be97835083dd7716c3597b2f0e9347cb/amVK

4. The RenderLoop

0. `amVK` wrap 🌯

```
    while(true) {
        W->dispatch_events_with_OSModalLoops();         // No way to disable ModalLoop so far in win32

        RP_FBs->RPBI_AcquireNextFrameBuffer();

        CB->BeginCommandBuffer(amVK_Sync::CommandBufferUsageFlags::Submit_Once);
        // ------------------------- CommandBufferRecording ----------------------------

            RP_FBs->CMDBeginRenderPass(CB->vk_CommandBuffer);
                RP_FBs->CMDSetViewport_n_Scissor(CB->vk_CommandBuffer);
                PLG->CMDBindPipeline(CB->vk_CommandBuffer);
                    VB.CMDDraw(CB->vk_CommandBuffer);
            RP_FBs->CMDEndRenderPass(CB->vk_CommandBuffer);

        // ------------------------- CommandBufferRecording ----------------------------
        CB->EndCommandBuffer();

        // This was Done Before in CH4 : SwapChain
            amVK_SurfacePresenter  *PR = new amVK_SurfacePresenter();
                                    PR->bind_Surface(S);
                                    PR->bind_Device(D);
        // This was Done Before in CH4 : SwapChain

        PR->set_CommandBuffer(CB->vk_CommandBuffer);
        PR->submit_CMDBUF(D->Queues.GraphicsQ(0));
        PR->Present(D->Queues.GraphicsQ(0));

        vkQueueWaitIdle(D->Queues.GraphicsQ(0));
        REY_NoobTimer::wait(10); // wait 10ms
    }
```

- 📜 *REY_DOCs*
    - *We must respond to OS InputEvents (Mouse/Keyboard)* ▩ Chapter14
        - *Otherwise, the OS might flag the app as Not Responsive*
        - *gotta make sure to call the Operating System APIs* `OS::ProcessEvents()`
        - *& that is exactly why* `amGHOST` *exists* 🚣‍♀️
    - *Then do all the rendering shit that I talked about, in this* ▩ Chapter13
    - win32
        - *if you don't ask* win32 *for the Events of the WINDOW, then windows is gonna go insane, it's gonna flag your app as* "Not Reposnding"
    - ModalLoop ▩ Chapter14

---

5. Synchronization & SemaPhores

`VkSemaphore` ▩ ChapterZZZ

- ***https://vkdoc.net/man/VkSemaphore***
    - *I wouldn't suggest reading it right now tho* 😂
    - *But, basically,*
        - `SemaPhore` *will be used to synchronize the rendering and presentation of images*

1. `VkSemaphoreCreateInfo`

- *https://vkdoc.net/man/VkSemaphoreCreateInfo*
    - `.sType` ▨ `VK_STRUCTURE_TYPE_SEMAPHORE_CREATE_INFO`
    - `.pNext` ⍰ `NULL`
    - `.flags` 🏳 `0`

2. `vkCreateSemaphore`

- https://vkdoc.net/man/vkCreateSemaphore
    - `.device`
    - `.pCreateInfo` ▨ 💁♀
    - `.pAllocator` ▩ ChapterZZZ
    - `.pSemaphore` ↩🎁

▨ eXtras / neXt chapters

- *6. Handling OS 🖱 InputEvents 🕹 ▩ Chapter14*
- *7. Resizing & SwapChain ReCreation ▩ Chapter15*
- *8. MultiThreading ▩ Chapter16*

Chapter 14: Handling OS 🖱 InputEvents 🕹

we are gonna take an backwards unfolding approach here

1. 📨 dispatch_events

- `amGHOST` *StackTrace [Surface ---> Deep]*

```
amGHOST:- lets your headache dissappear about OS::Stuffs/Functions

1. amGHOST_Window     ::dispatch_events_with_OSModalLoops()     🔗[github][1]
2. amGHOST_WindowWIN32::dispatch_events_with_OSModalLoops()     🔗[github][2]
3. amGHOST_System     ::dispatch_events_with_OSModalLoops()     🔗[github][3]
4. amGHOST_SystemWIN32::dispatch_events_with_OSModalLoops()     🔗[github][4]
5. amGHOST_SystemWIN32.cpp::actual_implementaion                🔗[github][5]
```

  - *1. amGHOST_Window*
  - *2. amGHOST_WindowWIN32*
  - *3. amGHOST_System*
  - *4. amGHOST_SystemWIN32*
  - *5. amGHOST_SystemWIN32.cpp*

- ***[win32] it has 6 parts***
  - *The plan is to get this section generalized for all OS & have separate* `win32` / `xlib` / `x11` / `wayland` / `macOS` *sections below*

```
1. ::PeekMessage() or ::GetMessage()
2. ::TranslateMessage()
3. ::DispatchMessage() ---->   WndProc()
4. static WndProc() -------> ::DefWindowProcessor()
5. ::DefWindowProcessor() -> ModalLoop
6. ModalLoop
```

vii. `::PeekMessage()`
  - *Kinda like pop & grab the last InputEvent/Message from EventQueue*

viii. `::TranslateMessage()`
  - *This is needed on some OS, for some specific ops, e.g. KeyBoard events*

ix. `::DispatchMessage()` --> `WndProc`
  - *For now, i only know about one kind of Dispatching*
  - a. *Calls* **WindowProcessorFunction** / `WndProc`
    - *must have been registered & tired to a window duriing WindowCreationg*

x. `static WndProc()`
  - *InputEvent Processor as per Window*

xi. `::DefWindowProcessor()`
  - *Operating System's very own little* **InputEvent** *Processor*
  - *Properly Unhandled events must be passed on to this function*
  - *Some InputEvents/Messages*
    - *can't really be Properly Handled, e.g.* `WM_SYSCOMMAND`
  - *Get's Into* **ModalLoops** *during events like WINDOW-RESIZING*

xii. *Modal Loops*
  - *See below* 💁‍♀️

2. `win32` 🗎

1. *General Info* ℹ

i. `::CreateWindowA()`
  - *Every* **win32** **window** *needs a* `WNDCLASSA` *during* `::CreateWindowA()` 🌱 \
  - *Window gets* **bound** *to the* **calling/creating thread** *as* **owner thread**

ii. `::Peek/Get/DispatchMessage()`
  - *does not peek/get/dispatch messages of windows from other threads*

iii. `WNDCLASSA.lpfnWndProc` 🔗
  - *Binds the window to a* `static WndProc()` ⚙

iv. `static WndProc()`
  - **WindowProcessorFunction**
  - *This is a function that you need to implement.*
  - *It needs to be* `static`
  - ⚠ **Beware of Static Initialization Order Fiasco**
    - 🖥 *50-min CppCon Talk*
    - ⏳ *12-min explainer*
    - 🔍 *Extras: 1*
    - 🎥 *Extras: Singleton pitfalls*

---

3. ModalLoop 🔄

- ## *I: Core Behavior* ⚙
  - *Starts @* `MouseButtonDown` 🖱
  - **Peeks, Dispatches** *(OtherMessages)*, **Waits** *till* `MouseButtonReleased`
  - *Ends @* `MouseButtonReleased` 🖱

- ## *II: Triggered During* 🎬 *events like*
  - **ReSizing** ↔
  - *Minimize/Maximize* **animations** *(Windows Aero effects)* ◈

- ## *III: Halts / Blocks* `Thread`

ModalLoop 🔄 : `win32`

- ## *IV:* `ModalLoop` *Under The Hood:-*
  - *OS has it's own little* `dispatch_events()` *implementation.*
  - *It keeps on* **peeking** & **dispatching** & **waiting** *till* `MouseButtonReleased` *is received*

```
while(true) {
    ::GetMessage()           // Blocks Thread if no message is there till smth arrives
    ::TranslateMessage()
    ::DispatchMessage()
        calls -> static WndProc()      [userProvided]

    if (msg == WM_EXITSIZEMOVE) {break;}
        // Obviously there will be a heck ton other extra processing going on, but you get the idea
}
```

  - *It's so darn similar to* **MainLoop**

- *V:-* `win32` *Sample Implementation (odin32):-*
  - i. ➡ *win32wbase.cpp#L1581*
  - ii. ➡ *win32wbase.cpp#L1922*
  - iii. ➡ *win32wbasenonclient.cpp#L1318*
  - iv. *SC_SIZE: This is the key for Window Resizing event*
  - v. ➡ *wintrack.cpp#L441*
  - vi. *& Here goes the ModalLoop*
  - vii. ➡ *wintrack.cpp#L564*

1. *FAQ* ?

- Exactly where does the ModalLoop gets Trigger? 🎬
  - *When we pass* `WM_SYSCOMMAND` *to* `::DefWindowProc()`
- `WM_LBUTTONDOWN` *vs* `WM_NCLBUTTONDOWN` 👆
  - *Pressing mouse on* OS-Window Frame/Corner/Border ➡ *sends* `WM_NCLBUTTONDOWN` *(not* `WM_LBUTTONDOWN` *)*
  - NC *= Non-Client* 🏷
  - LBUTTON *= Left Mouse Button*
- What if we ignore `WM_NCLBUTTONDOWN` ? ⛔
  - `WM_SYSCOMMAND` *won't generate!*
  - Must call `::DefWindowProc()` on `WM_NCLBUTTONDOWN` ✓
  - *Passing This one to* `::DefWindowProc()` *is exactly how the OS internally keeps track of* MouseButtonDown 🏌‍♀
- When does `WM_ENTERSIZEMOVE` occur? 🔄
  - *When you call* `::DefWindowProc()` *with* `WM_SYSCOMMAND`
- ModalLoop starts on passing `WM_SYSCOMMAND` or `WM_ENTERSIZEMOVE` ? 🤔
  - *I believe, it's* `WM_SYSCOMMAND` *[gotta test* ◈*]*
- If. `WM_SYSCOMMAND` starts the `ModalLoop` . why'd we even catch `WM_ENTERSIZEMOVE` in our `static WndProc()` ?
  - *Well, it's because,* `win32` *wanted us to catch all those events, but still wanted us to call* `::DefWindowProc()` *on those*

ModalLoop 🔄 : `xlib`

- *IV:* `X11` / `XCB` / `Wayland` *[Linux] & [MacOS]*
  - *To be added, really soon! (when i port amGHOST to x11/xcb/wayland/macOS)*

ModalLoop 🔄 : `summary`

- *VI: In Words:-*
  - *Operating System enters it's very own* `Loop` *when* `MouseButton` *is* PressedDown
  - *This is what's called* `ModalLoop`
  - *The* `ModalLoop` *doesn't* `return/break` *till* `MouseButton` *is* Released
    - *Yes, that does mean that your* mainThread is blocked and waiting!

4. Resizing ↔

- ***Generates*** `WM_SYSCOMMAND`
    - *right when we pass* `WM_NCLBUTTONDOWN` *-->* `::DefWindowProcessor()`
- ***Triggers ModalLoop***
    - *right when we pass* `WM_SYSCOMMAND` *-->* `::DefWindowProcessor()`
- ***Messages sent while inside ModalLoop***

```
[REPEATED]:- WM_NCMOUSEMOVE --> WM_NCHITTEST --> WM_SETCURSOR
[REY_MODAL_LOOP]:- WM_NCLBUTTONDOWN  --> Entering: DefWindowProc
[REY_MODAL_LOOP]:- WM_SYSCOMMAND  --> Entering: DefWindowProc
    [Win32GUI]:- WM_GETMINMAXINFO
    [Win32GUI]:- WM_ENTERSIZEMOVE
    [Win32GUI]:- WM_NCMOUSELEAVE
    [Win32GUI]:- WM_CAPTURECHANGED
    [Win32GUI]:- WM_WINDOWPOSCHANGING
    [Win32GUI]:- WM_GETMINMAXINFO
    [Win32GUI]:- WM_EXITSIZEMOVE
[REY_MODAL_LOOP]:- WM_SYSCOMMAND  --> Returned: DefWindowProc
[REY_MODAL_LOOP]:- WM_NCLBUTTONDOWN  --> Returned: DefWindowProc
[REPEATED]:- WM_NCMOUSEMOVE --> WM_NCHITTEST --> WM_SETCURSOR
```

- ***📜 REY_DOCs***
    - *Well, if you wanna do anything inside the Window, while it's being resized, You must do it in a different thread* 💁‍♀️ *because of the* MainThread *being stuck in the* `modalLoop`

5. Window Creation & Destruction

- *TBA: WM_CREATE, WM_DESTROY, WM_KEYDOWN, + Show Code / Redirect to my WndProc implementations*

1. *amGHOST Events <-- (Win32/XCB/X11/Wayland/macOS)*
    1. *EventTypes*
        - *https://www.youtube.com/watch?v=xnopUoZbMEk&list=PLlrATfBNZ98dC-V-N3m0Go4deliWHPFwT*

Chapter 15: `Resizing` & SwapChain Recreation

🌋 `Vulkan` wrap 🌯

```
void reSize(void) {
     RP_FBs->DestroyFrameBuffers();
    SC_IMGs->DestroySwapChainImageViews();

    SC->reCreateSwapChain();        // calls --> sync_SurfCaps();

    SC_IMGs->GetSwapChainImagesKHR();
    SC_IMGs->CreateSwapChainImageViews();
     RP_FBs->CreateFrameBuffers();
}
```

⯑ `amVK` wrap 🌯

```
amGHOST_SwapChainResizer* SC_Resizer = new amGHOST_SwapChainResizer(RP_FBs, W);
```

Chapter 16: Multi-Threading

0. `amVK` wrap 🩹

```
// ------------------------- Render Loop -------------------------
amTHREAD phoenix;
phoenix.run([&]() {
    REY_LOG("Thread started.");

    while(true) {
        RP_FBs->RPBI_AcquireNextFrameBuffer();
        // ------------------------- CommandBufferRecording -------------------------
        // -------------------------    Submit & Present    -------------------------
        vkQueueWaitIdle(D->Queues.GraphicsQ(0));
        REY_NoobTimer::wait(10); // wait 10ms
    }

    REY_LOG("Thread finished.");
});

while(true) {
    W->dispatch_events_with_OSModalLoops(); // dispatch events
    REY_NoobTimer::wait(1);               // wait 100ms
}
// ------------------------- Render Loop -------------------------
```

Chapter 17: `Vertex` 📍 & `VertexBuffer` 🗄

1. `Mesh/Vertices`

1. `amVK_Vertex`

   ```
   struct amVK_Vertex {
       float position[3];
       float color[4];
   };
   ```

2. `Vertex Buffer`

---

3. `VkBufferCreateInfo`
   - https://vkdoc.net/man/VkBufferCreateInfo
     - `.sType` ▨ `VK_STRUCTURE_TYPE_BUFFER_CREATE_INFO`
     - `.pNext` ⯑ `nullptr`
     - `.flags` ⯑ `VkBufferCreateFlagBits`
       - https://vkdoc.net/man/VkBufferCreateFlagBits | ivirtex-github
         - `SPARSE` ▦ ChapterZZZ
     - `.size` ▨ `sizeof(amVK_Vertex) * N`
     - `.usage` ▨ `VK_BUFFER_USAGE_VERTEX_BUFFER_BIT`
     - `.sharingMode` ▩ ChapterZZZ
       - `.queueFamilyIndexCount`
       - `.pQueueFamilyIndex`
4. `vkCreateBuffer()`
   - https://vkdoc.net/man/vkCreateBuffer
     - `.device` ▨🧑‍💻♀
     - `.pCreateInfo` ▨🧑‍💻♀
     - `.pAllocator`
     - `.pBuffer` ↩🎁
5. `📽 So far, The result` :- *CH11.1.VertexBuffer.hh*

2. `A lesson in Memory`

https://www.youtube.com/watch?v=uXgKXfVMeFw
(obviously i am not talking about `Vulkan` / `Implementation Programming`)
(i am talking about `Algorithms/CP/CodeForces/MIT6.046`)

1. `vkGetBufferMemoryRequirements()`
   - *https://vkdoc.net/man/vkGetBufferMemoryRequirements*
     - `.device` ▨🧑‍💻♀
     - `.buffer` ▨🧑‍💻♀
     - `.pMemoryRequirements` ↩🎁
2. `VkMemoryRequirements`
   - *https://vkdoc.net/man/VkMemoryRequirements*
     - `.size` ➞ `VkMemoryAllocateInfo.allocationSize`
     - `.alignment`
     - `.memoryTypeBits`

---

3. `.memoryTypeIndex` / `VkPhysicalDeviceMemoryProperties`
   - *https://vkdoc.net/man/VkPhysicalDeviceMemoryProperties*
     - 🏷 `VkMemoryType memoryTypes[VK_MAX_MEMORY_TYPES];`
     - 🏷 `VkMemoryHeap memoryHeaps[VK_MAX_MEMORY_HEAPS];`
   - `VkMemoryType`
     - *https://vkdoc.net/man/VkMemoryType*
       - `.propertyFlags` 🏷 `VkMemoryPropertyFlags`
         - *https://vkdoc.net/man/VkMemoryPropertyFlags*
         - `VK_MEMORY_PROPERTY_DEVICE_LOCAL_BIT`
         - `VK_MEMORY_PROPERTY_HOST_VISIBLE_BIT`
         - `VK_MEMORY_PROPERTY_HOST_COHERENT_BIT`
         - `VK_MEMORY_PROPERTY_HOST_CACHED_BIT`
         - `VK_MEMORY_PROPERTY_LAZILY_ALLOCATED_BIT`
       - `.heapIndex` 🏷 `uint32_t`
   - `VkmemoryHeap`
     - *https://vkdoc.net/man/VkMemoryHeap*
       - `.size` 🏷 `VkDeviceSize`
       - `.flags` 🏷 `VkMemoryHeapFlags`
         - *https://vkdoc.net/man/VkMemoryHeapFlagBits* | *ivirtex-github*
         - `VK_MEMORY_HEAP_DEVICE_LOCAL_BIT`
         - `VK_MEMORY_HEAP_MULTI_INSTANCE_BIT`
         - `VK_MEMORY_HEAP_TILE_MEMORY_BIT_QCOM`
         - `VK_MEMORY_HEAP_MULTI_INSTANCE_BIT_KHR`
   - `vkGetPhysicalDeviceMemoryProperties()`
     - *https://vkdoc.net/man/vkGetPhysicalDeviceMemoryProperties*
       - `.physicalDevice` ▨🧑‍💻♀
       - `.pFeatures` ↩🎁
4. `VkPhysicalDeviceFeatures`
   - *https://vkdoc.net/man/VkPhysicalDeviceFeatures*
     - Lots of `VkBool32`
       - `Shaders`
       - `Texures`
       - `Sparse`
   - `vkGetPhysicalDeviceFeatures()`
     - *https://vkdoc.net/man/vkGetPhysicalDeviceFeatures*
       - `.physicalDevice` ▨🧑‍💻♀
       - `.pMemoryProperties` ↩🎁
5. `🐭 So far, The result`

```
class amVK_InstanceProps {
    static      void GetPhysicalDeviceFeatures(void);               // amVK_1D_GPUs_Features
```

```
    static       void GetPhysicalDeviceMemoryProperties(void);       // amVK_1D_GPUs_MEMProps

    static inline REY_Array<VkPhysicalDeviceFeatures>                   amVK_1D_GPUs_Features;
    static inline REY_Array<VkPhysicalDeviceMemoryProperties>           amVK_1D_GPUs_MEMProps;
}
    // The other one is copy of this one
void amVK_InstanceProps::GetPhysicalDeviceFeatures(void) {
    amVK_1D_GPUs_Features.reserve(amVK_1D_GPUs.n);
    amVK_LOOP_GPUs(k) {
        vkGetPhysicalDeviceFeatures(amVK_1D_GPUs[k], &amVK_1D_GPUs_Features[k]);
    }
    called_GetPhysicalDeviceFeatures = true;
}
```

---

6. `👀 Visualization / [See it] / JSON Printing` *:-* 🔗 `GITHUB` *amVK InstancePropsExport nlohmann.cpp#L1-L117*
7. `REY_CategorizeMemoryHeaps()` 🔗 `GITHUB` *amVK_ GPUProps.cpp#L56-264*
    - *Just Copy-Paste this one yk....*
    - *I Believe. the tags that I Created for this one, Vulkan should have given us those by default* ◇🙇‍♀
8. `Refactoring` *is pretty smooth now, I did it again, in this commit* ◇ 🔗 `GITHUB`
    - *https://github.com/REYNEP/amGHOST/tree/82311d2bd8586d07836be900448d8b7b9961c0ef*

---

9. `VkMemoryAllocateInfo`
    - *https://vkdoc.net/man/VkMemoryAllocateInfo*
        - *This documentation page is pretty big* 😮‍💨
        - `.sType` ▨ `VK_STRUCTURE_TYPE_MEMORY_ALLOCATE_INFO`
        - `.pNext` ◇ `nullptr`
            - ◇ *interesting extensions*
        - `.allocationSize` ▨ `VkMemoryRequirements.size`
        - `.memoryTypeIndex` 🏷 `uint32_t`
10. `vkAllocateMemory()`
    - *https://vkdoc.net/man/vkAllocateMemory*
        - `.device`
        - `.pAllocateInfo`
        - `.pAllocator`
        - `.pMemory`
11. `</> TheCode`

```
void amVK_VertexBuffer::AllocateMemory(void) {
    if(called_GetBufferMemoryRequirements == false) {
        this->GetBufferMemoryRequirements();
    }
    if (this->D->GPU_Props->called_REY_CategorizeMemoryHeaps == false) {
        this->D->GPU_Props->       REY_CategorizeMemoryHeaps();
    }
        AI.allocationSize  = vk_MemoryReq.size;
        AI.memoryTypeIndex = this->D->GPU_Props->MEMTypeID.CPU_GPU_Synced;

    VkResult return_code = vkAllocateMemory(this->D->vk_Device, &AI, nullptr, &this->vk_DeviceMemory);
    amVK_return_code_log( "vkAllocateMemory()" );
}
```

12. `vkMapMemory()`

  - https://vkdoc.net/man/vkMapMemory

13. `vkUnmapMemory()`
    - https://vkdoc.net/man/vkUnmapMemory
14. `vkBindBufferMemory()`
    - https://vkdoc.net/man/vkUnmapMemory

15. `</> TheCode`

```
void      amVK_VertexBuffer::MapMemory(void) {
    VkResult return_code = vkMapMemory(D->vk_Device, vk_DeviceMemory, 0, vk_MemoryReq.size, 0,
&vk_MappedMemoryData);
    amVK_return_code_log( "vkMapMemory()" );
}
void   amVK_VertexBuffer::CopyIntoMemory(void) {
    REY_memcpy(vk_MappedMemoryData, Vertices.data, CI.size);
}
void      amVK_VertexBuffer::UnMapMemory(void) {
    vkUnmapMemory(D->vk_Device, vk_DeviceMemory);
}
void      amVK_VertexBuffer::BindBufferMemory(void) {
    VkResult return_code = vkBindBufferMemory(D->vk_Device, vk_Buffer, vk_DeviceMemory, 0);
    amVK_return_code_log( "vkBindBufferMemory()" );
}
```

Chapter 18: ImageRendering / TextureBuffer

6. `amVK_SurfacePresenter`

Can't have everything scatterred now, everything is getting too much sophisticating.... 🤔 🤦‍♀ must ***Refactor....***

Major Decision Change

Right now, `amVK_Surface::CTOR` creates `amVK_SurfacePresenter`. & `SwapChain, RenderPass, CommandPool` are supposed to be created from `amVK_SurfacePresenter`.

```
class amVK_Surface
    amVK_SurfacePresenter {
        create_SwapChain_interface()
            new amVK_SwapChain(this)
                this->CI.surface = PR->S->vk_SurfaceKHR;
                // later amVK_SwapChain::CreateSwapChain(void) uses this->PR->D->vk_Device
        create_RenderPass_interface()
            new amVK_RenderPass(this)
                this->PR = PR;
        create_CommandPool_interface()
            new amVK_CommandPool(this)
                this->CI.queueFamilyIndex = this->PR->D->amVK_1D_QCIs.ptr_Default()->queueFamilyIndex;
        create_FrameBuffers()
            new amVK_FrameBuffer(this)
                this->CI.renderPass = this->PR->RP->vk_RenderPass;
```

Problem #1:- I think this is just a little too much deep to handle....
Problem #2:- if `amVK_SwapChain.hh` included `amVK_SurfacePresenter.hh`, then the reverse can't happen. 🤷‍♀
Thus a lot of 1-liner functions would have to be put inside `.cpp` even tho i don't want it to.

1. `Problem #2:- in Details`

- *amVK_SurfacePresenter.hh#L37*
- *amVK_SwapChain.hh#L48*
- *The Solution*
  - `C1` *:- Don't include* `amVK_SurfacePresenter.hh` *in* `amVK_SwapChain.hh` *but rather inside* `amVK_SwapChain.cpp`
  - `C2` *:- Don't include* `amVK_SwapChain.hh` *in* `amVK_SurfacePresenter.hh` *but rather inside* `amVK_SurfacePresenter.cpp`
- `Case 1` :-
  - `amVK_SwapChain::CONSTRUCTOR`
  - `sync_SurfCaps()`
  - *both of these have to go inside* `amVK_SwapChain.cpp`
- `Case 2` :-
  - `amVK_SurfacePresenter::sync_SC_SurfCaps()`
  - `amVK_SurfacePresenter::synced_ImageExtent()`
  - *both of these (& as of my plan right now, heck ton of other 1 liner function) are gonna have to go inside* `amVK_SurfacePresenter.cpp`

2. *Weeelll*

- *There is one other solution.... That is to change the design.... Which is what I figured is should do.... Not everybody would want to use* `amVK_SurfacePresenter` *anyway* 🤷‍♀
- *2 Ways:-*

i. *Making* `amVK_SurfacePresenter` *Optional*
   a. *None of the other amVK_Class is gonna depend on this anymore*
   b. *amVK_SurfacePresenter serving as like a top level NODETREE system with extra PRESET Functions / soo. (If you are looking from a NodeEditor perspective)*
   c. *This is like having a BIG BAD NODE, and then connecting everything into it*
   d. *You can have anything you want in the header*
   e. *Let's try the other one and see what happens*

ii. *Making* `amVK_SurfacePresenter` *Code part*
   a. *EveryBody is gonna depend on this*
   b. *They are only gonna keep a pointer to this parent*
   c. *from this one, they are gonna get everything that they need*
   d. *even the VkDevice*
   e. *It's like having all the nodes inside a TOP LEVEL FRAME NODE*
   f. *Separating Code into .hh & .cpp is kinda crazy..... You basically can't have anything in the header....*
   g. *i already tried this*

Middle (Discarded) Commit:- *https://github.com/REYNEP/amGHOST/blob/30e7cfca1540383cd98783d302408f63fdd06180/amVK/amVK_SurfacePresenter.hh*

Final Commit:- *https://github.com/REYNEP/amGHOST/blob/7376cdb5c2c6eee19655dae436e6cf8edd02e1d5/amVK/amVK_SurfacePresenter.hh*

`📽 So far, The result` [🔗 `GITHUB`]

- 📁 `common`
  - 📝 amVK.hh
  - 📝 amVK_ColorSpace.hh
  - 📝 amVK_Enum2String.cpp
  - 📝 amVK_Enum2String.hh
  - 📝 amVK_GPU.hh
  - 📝 amVK_RenderPass_Descriptors.hh
  - 📝 amVK_log.cpp
  - 📝 amVK_log.hh
- 📁 `core`
  - 📝 amVK_Instance.hh
  - 📝 amVK_Device.hh
  - 📝 amVK_DeviceQCI.hh
  - 📝 amVK_Surface.hh
  - 📝 amVK_SwapChain.hh
  - 📝 amVK_SwapChainIMGs.hh
  - 📝 amVK_RenderPass.hh
  - 📝 amVK_RenderPassFBs.hh
  - 📝 amVK_CommandPool.hh
- 📝 *amVK_SurfacePresenter.hh*

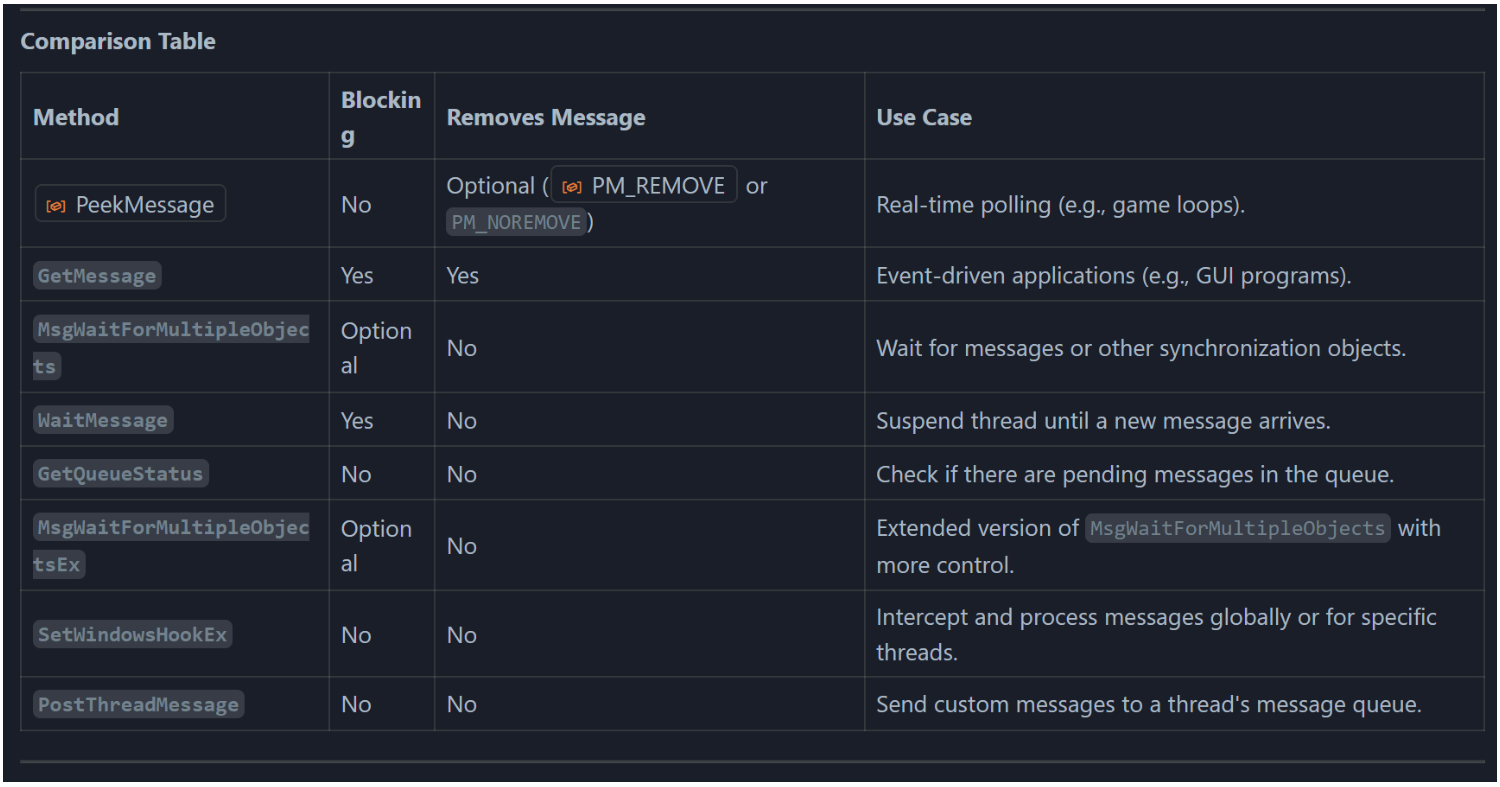
- 📁 `extras`
  - 📝 SCREENSHOT_STUDIO.hh
  - 📝 amVK_CommandBuffer.hh
  - 📝 amVK_FrameBuffer.hh
  - 📝 amVK_Image.hh
  - 📝 amVK_SemaPhone.hh
- 📁 `guide`
  - *(Directory placeholder – add guide files here if any)*
- 📁 `impl`
  - 📝 amVK_Device.cpp
  - 📝 amVK_Instance.cpp
  - 📝 amVK_InstanceProps.cpp
  - 📝 amVK_InstancePropsExport.cpp
  - 📝 amVK_InstancePropsExport_nloh...
  - 📝 amVK_Surface.cpp
  - 📝 amVK_SurfacePresenter.cpp
  - 📝 amVK_SwapChain.cpp

SCREENSHOT1

Feature	**WM_PAINT**	**WM_PRINT**
Purpose	Sent by the system to request that a window redraw its client area.	Sent by an application to request that a window draw itself into a specified device context (e.g., for printing or capturing).
Trigger	Automatically triggered by the system when the client area becomes invalid (e.g., resizing, minimizing).	Explicitly sent by an application using SendMessage to request the window to draw itself.
Message ID	0x800F	0x0317
Who Sends It	Sent by the system.	Sent by the application (e.g., using SendMessage(hwnd, WM_PRINT, ...)).
Default Behavior	Calls the window's WndProc to handle the redraw.	Calls the window's WndProc to handle the drawing into the specified device context.
Device Context	Uses the device context provided by BeginPaint and EndPaint.	Uses the device context passed in wParam.
Use Case	Used for normal window redrawing (e.g., after invalidation or resizing).	Used for off-screen rendering, printing, or capturing the window's content.
System-Generated	Yes, automatically generated when the client area is invalid.	No, must be explicitly sent by the application.
Parameters	- `wParam` : Not used. - `lParam` : Not used.	- `wParam` : Handle to the device context (HDC). - `lParam` : Flags specifying what to draw.
Flags in lParam	Not applicable.	Flags include: - `PRF_CHECKVISIBLE` : Only draw if the window is visible. - `PRF_CHILDREN` : Draw child windows. - `PRF_CLIENT` : Draw the client area. - `PRF_NONCLIENT` : Draw the non-client area. - `PRF_ERASEBKGND` : Erase the background.
Child Windows	Does not automatically draw child windows.	Can optionally draw child windows if the PRF_CHILDREN flag is set.
Non-Client Area	Does not draw the non-client area (e.g., title bar, borders).	Can optionally draw the non-client area if the PRF_NONCLIENT flag is set.
Example Usage	Used in the WndProc to handle normal window painting.	Used for capturing the window's content into a bitmap or for printing.

When to Use Each

Scenario	Use WM_PAINT	Use `WM_PRINT`
Normal window redrawing	Yes	No
Off-screen rendering (e.g., capturing)	No	Yes
Printing the window's content	No	Yes
Drawing only the client area	Yes	Yes (with `PRF_CLIENT` flag).
Drawing the non-client area (e.g., borders, title bar)	No	Yes (with `PRF_NONCLIENT` flag).
Drawing child windows	No	Yes (with `PRF_CHILDREN` flag).



Comparison Table

Method	Blocking	Removes Message	Use Case
PeekMessage	No	Optional (PM_REMOVE or `PM_NOREMOVE`)	Real-time polling (e.g., game loops).
`GetMessage`	Yes	Yes	Event-driven applications (e.g., GUI programs).
`MsgWaitForMultipleObjects`	Optional	No	Wait for messages or other synchronization objects.
`WaitMessage`	Yes	No	Suspend thread until a new message arrives.
`GetQueueStatus`	No	No	Check if there are pending messages in the queue.
`MsgWaitForMultipleObjectsEx`	Optional	No	Extended version of `MsgWaitForMultipleObjects` with more control.
`SetWindowsHookEx`	No	No	Intercept and process messages globally or for specific threads.
`PostThreadMessage`	No	No	Send custom messages to a thread's message queue.

Feature	PeekMessage	`GetMessage`
Purpose	Retrieves messages from the message queue without blocking the thread.	Retrieves messages from the message queue and blocks the thread if no messages are available.
Blocking Behavior	Non-blocking by default. Returns immediately, even if no messages are available.	Blocking. Waits until a message is available in the queue.
Message Removal	Can either remove the message from the queue (PM_REMOVE) or leave it (`PM_NOREMOVE`).	Always removes the message from the queue.
Message Range	Can retrieve messages within a specific range (e.g., WM_KEYDOWN to `WM_KEYUP`).	Retrieves all messages, regardless of type or range.
Use Case	Used for polling the message queue in real-time (e.g., in a game loop).	Used for traditional event-driven applications where blocking is acceptable.
Return Value	Returns `TRUE` if a message is available, `FALSE` otherwise.	Returns `-1` on error, `0` if `WM_QUIT` is received, and non-zero otherwise.
Retrieves Multiple Messages	No, retrieves one message at a time.	No, retrieves one message at a time.
Thread Behavior	Does not yield control to other threads.	May yield control to other threads while waiting for a message.
Typical Usage	Real-time applications (e.g., games, rendering loops).	Event-driven applications (e.g., GUI programs).

classDiagram class WM_PAINT { <<Message>> Purpose: "Request window redraw (client area)" Trigger: "System (automatic)" MessageID: "0x800F" DefaultBehavior: "Calls WndProc" DeviceContext: "BeginPaint/EndPaint" UseCase: "Normal window redrawing" Parameters: "wParam/lParam unused" ChildWindows: "No" NonClientArea: "No" } class WM_PRINT { <<Message>> Purpose: "Request window draw into HDC" Trigger: "Application (manual)" MessageID: "0x0317" DefaultBehavior: "Calls WndProc" DeviceContext: "HDC in wParam" UseCase: "Printing/capturing" Parameters: "wParam: HDC \n lParam: Flags \n (PRF_CHECKVISIBLE, PRF_CHILDREN...)" ChildWindows: "Optional (PRF_CHILDREN)" NonClientArea: "Optional (PRF_NONCLIENT)" } WM_PAINT --|> SystemGenerated WM_PRINT --|> ApplicationGenerated