Vulkan Subpasses
or
The Frame Buffer is Lava

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Vulkan: Making use of the GPU more efficient

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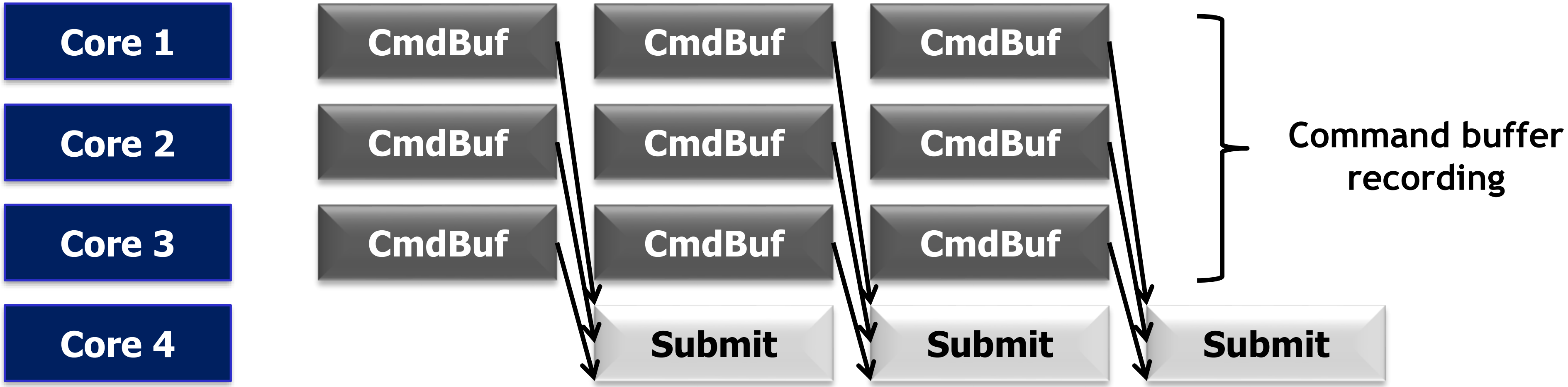

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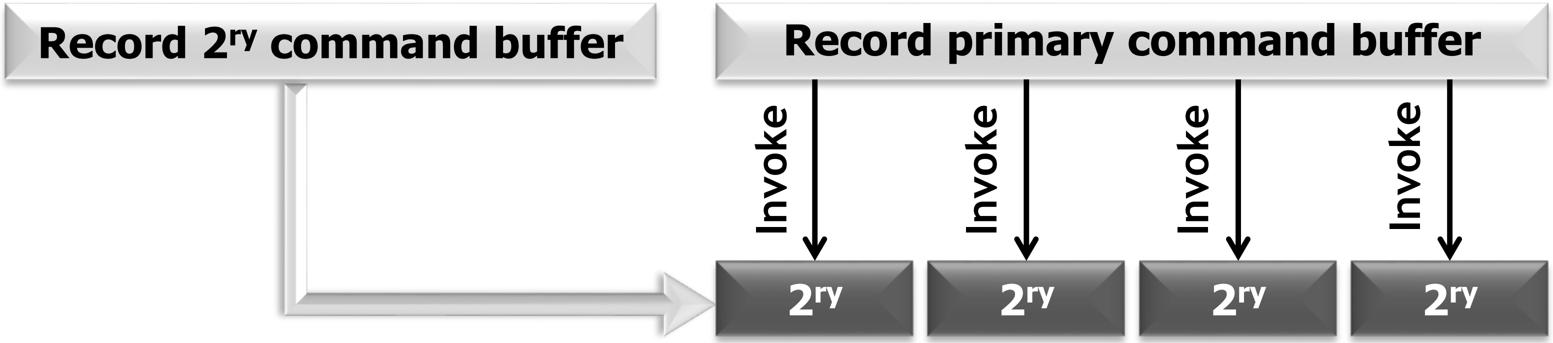
  - Reuse of command buffers to avoid CPU build time



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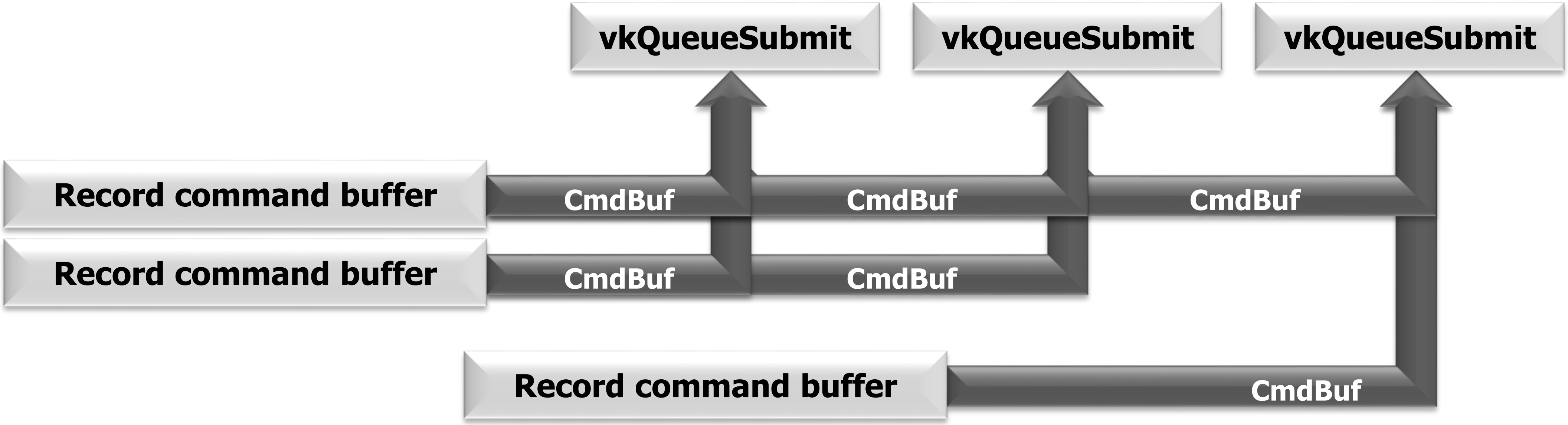
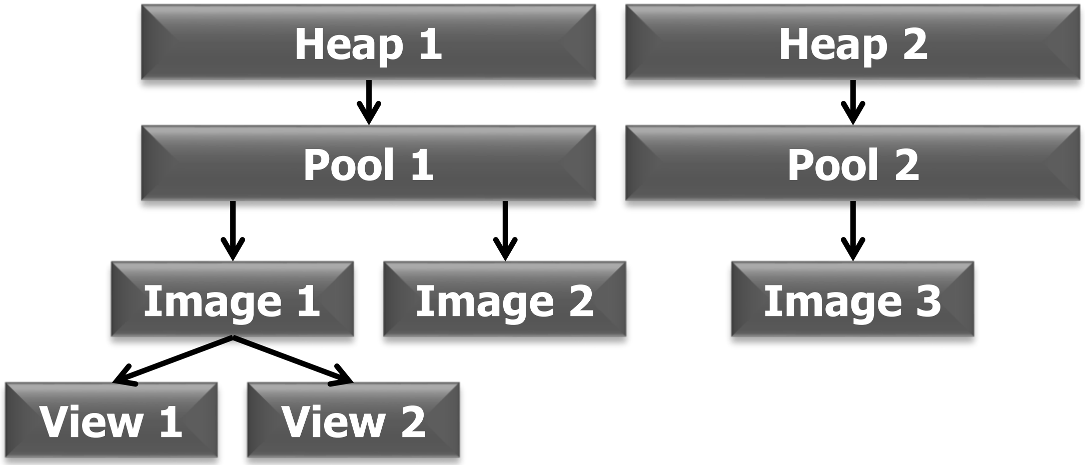


Vulkan: Making use of the GPU more efficient

- Vulkan aims to reduce the overheads of keeping the GPU busy
  - Efficient generation of work on multiple CPU cores
  - Reuse of command buffers to avoid CPU build time
  - Potentially more efficient memory management



User-defined memory reuse

Explicit state transitions

Cost invoked at defined points

Vulkan: Making use of the GPU more efficient

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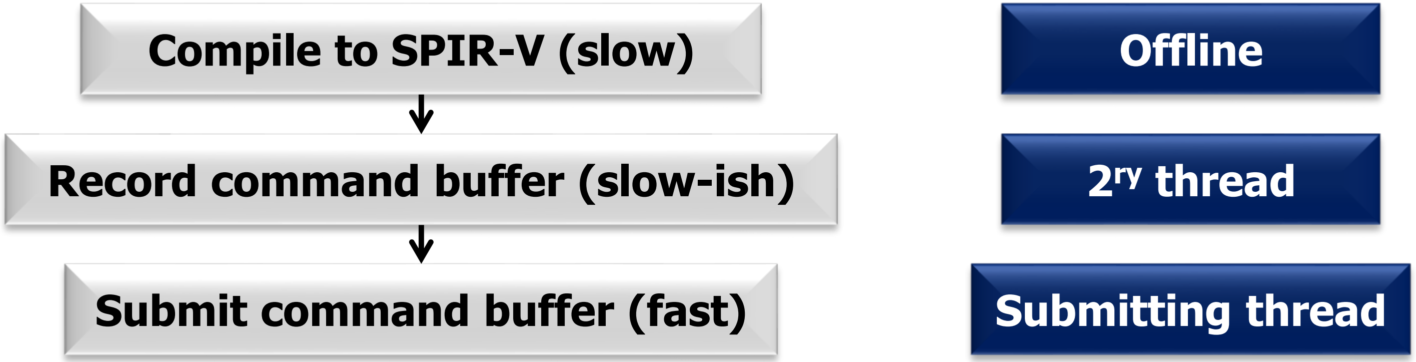
  - Reuse of command buffers to avoid CPU build time
  - Potentially more efficient memory management
  - Avoiding unpredictable shader compilation



Compile to SPIR-V (slow) — **Offline**

↓

Record command buffer (slow-ish) — **2ry thread**

↓

Submit command buffer (fast) — **Submitting thread**

Vulkan: Making use of the GPU more efficient

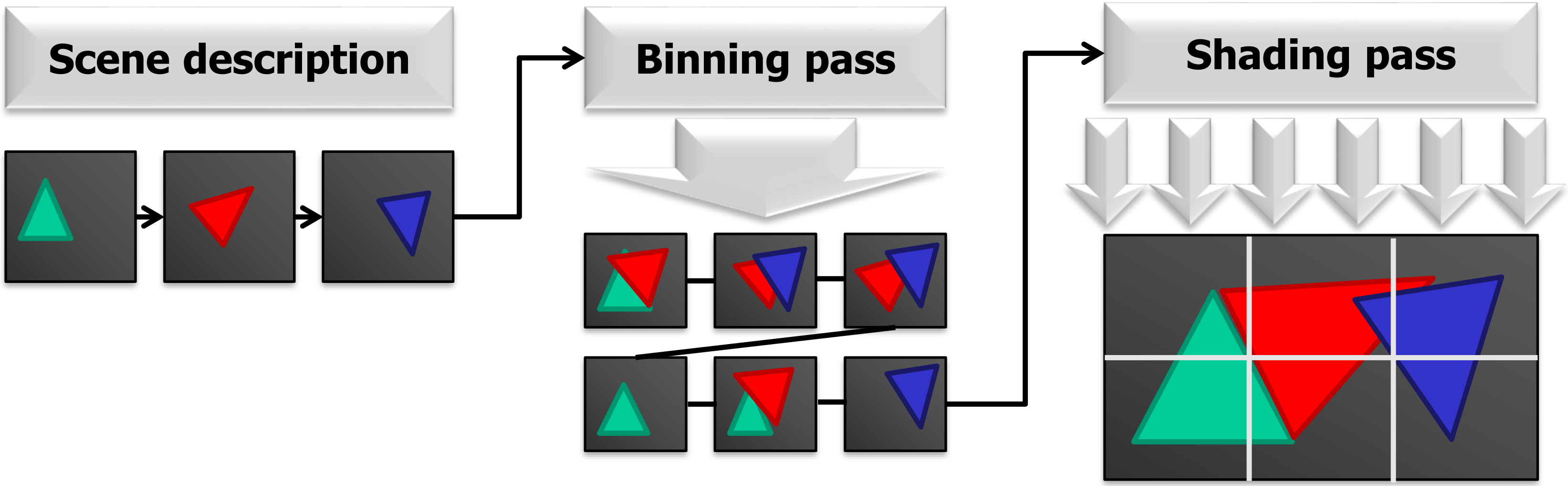
- **Vulkan aims to reduce the overheads of keeping the GPU busy**
  - Efficient generation of work on multiple CPU cores
  - Reuse of command buffers to avoid CPU build time
  - Potentially more efficient memory management
  - Avoiding unpredictable shader compilation
- **Mostly, the message has been that if you're entirely limited by shader performance or bandwidth, Vulkan can't help you (there is no magic wand)**

Vulkan: Making ~~use of~~ the GPU more efficient

- Actually, that’s not entirely true…
- APIs like OpenGL were designed when the GPU looked very different (or was partly software)
- The way to design an efficient mobile GPU is not a perfect match for OpenGL
  - Think a CPU’s command decode unit/microcode
- But the translation isn’t always perfectly efficient

Tiled GPUs

- Most (not all) mobile GPUs use tiling
  - It’s all about the bandwidth (size and power limits)

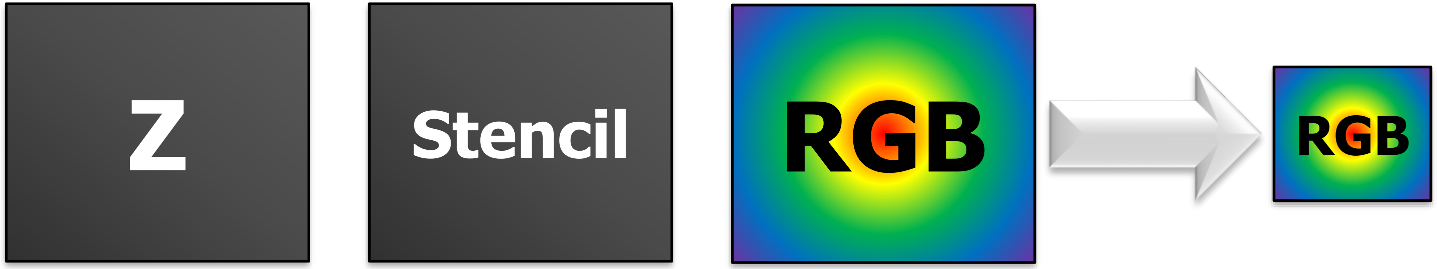


- On-chip tile memory is much faster than the main frame buffer

Not everything reaches memory

- Rendering requires lots of per-pixel data
  - Z, stencil
  - Full multisample resolution

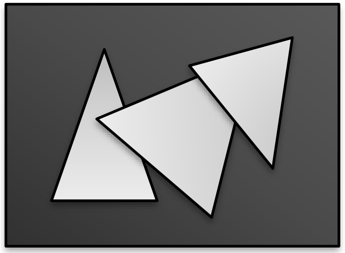
- We usually only care about the final image



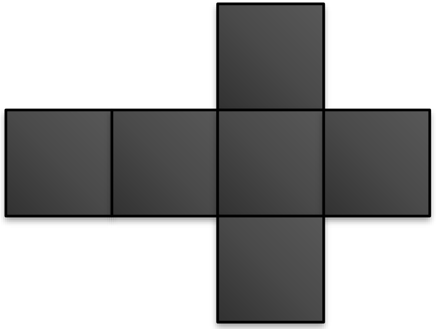
  - We can throw away Z and stencil
  - We only need a downsampled (A)RGB
  - Don’t need to load anything from a previous frame

Sometimes we want the results of rendering

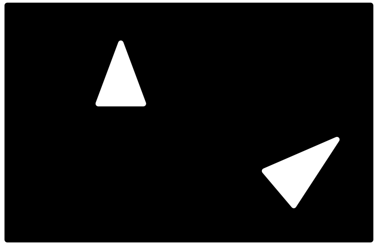
- Output from one rendering job can be used by the next



- Z buffer for shadow maps
- Rendering for environment maps



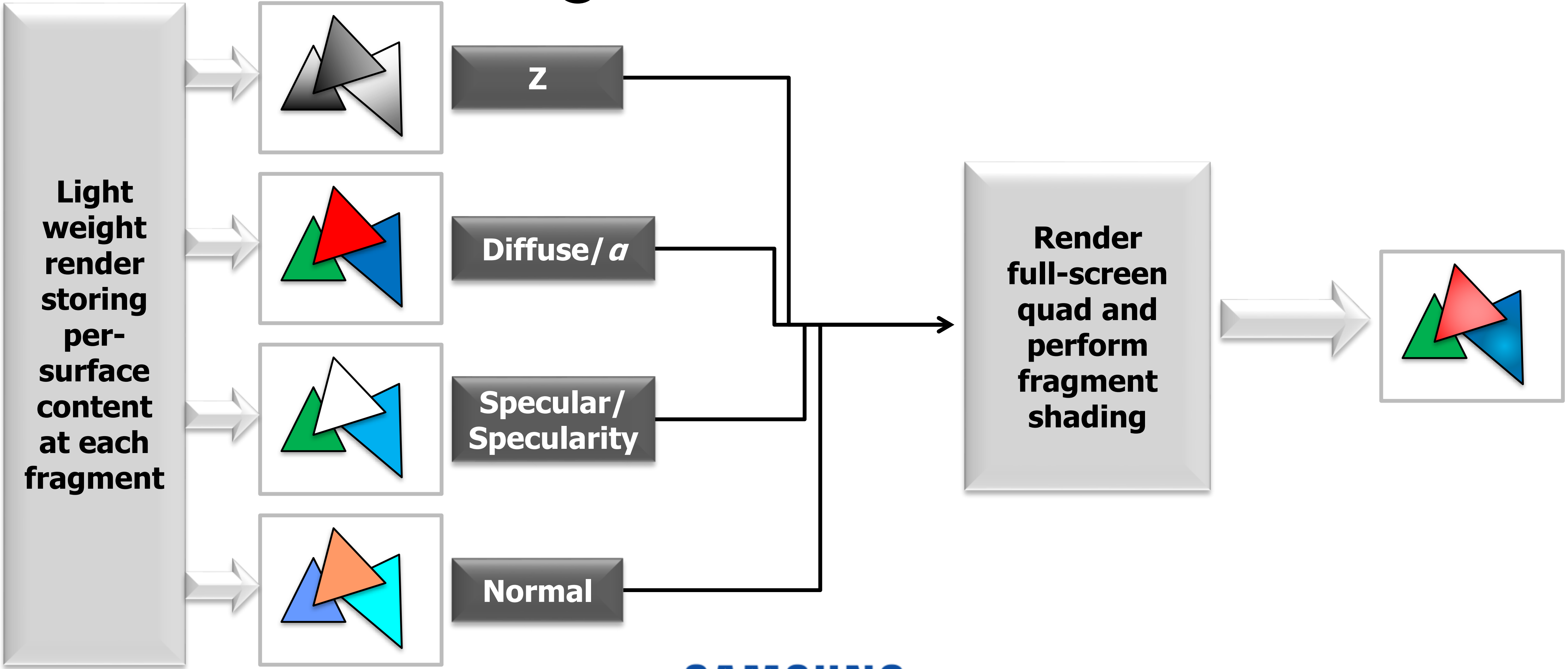
- HDR bloom



- These can have low resolution and may not take much bandwidth

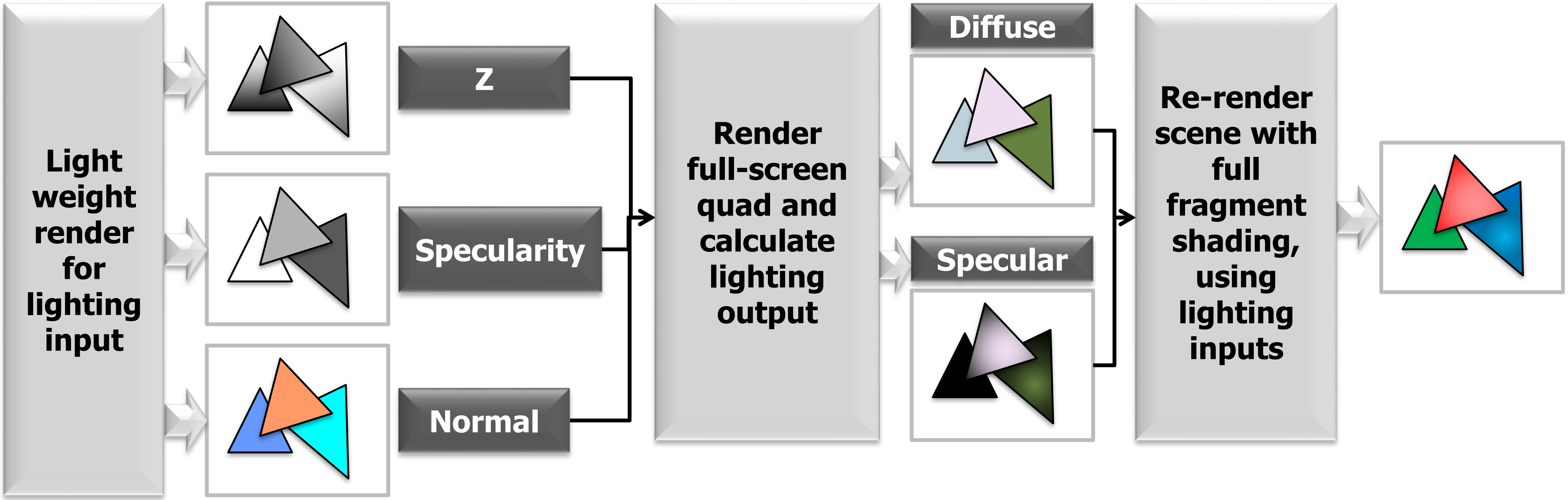
Sometimes you *do* need framebuffer resolution

- Deferred shading


Light weight render storing per-surface content at each fragment
Z
Diffuse/ *a*
Specular/ Specularity
Normal
Render full-screen quad and perform fragment shading

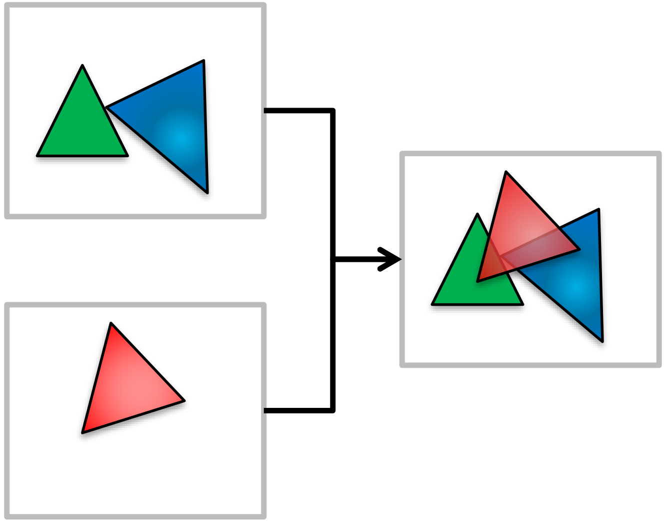
Sometimes you *do* need framebuffer resolution

- Deferred shading
- Deferred lighting


Light weight render for lighting input
Z
Specularity
Normal
Render full-screen quad and calculate lighting output
Diffuse
Specular
Re-render scene with full fragment shading, using lighting inputs

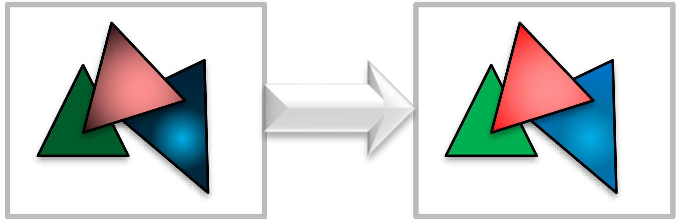
Sometimes you *do* need framebuffer resolution

- Deferred shading
- Deferred lighting
- Order-independent transparency



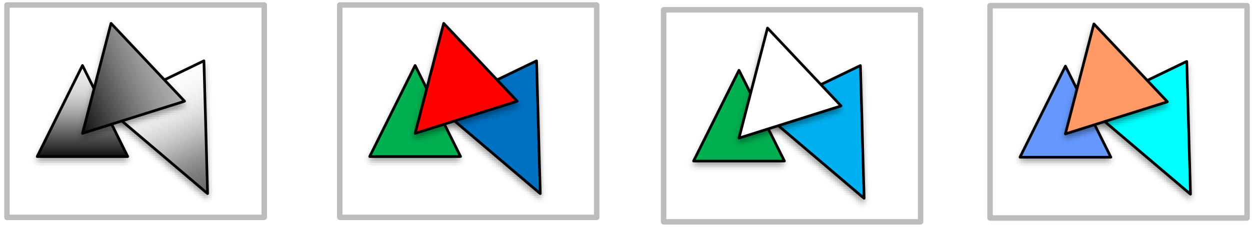
Sometimes you *do* need framebuffer resolution

- Deferred shading
- Deferred lighting
- Order-independent transparency
- HDR tone mapping



Rendering outputs separately

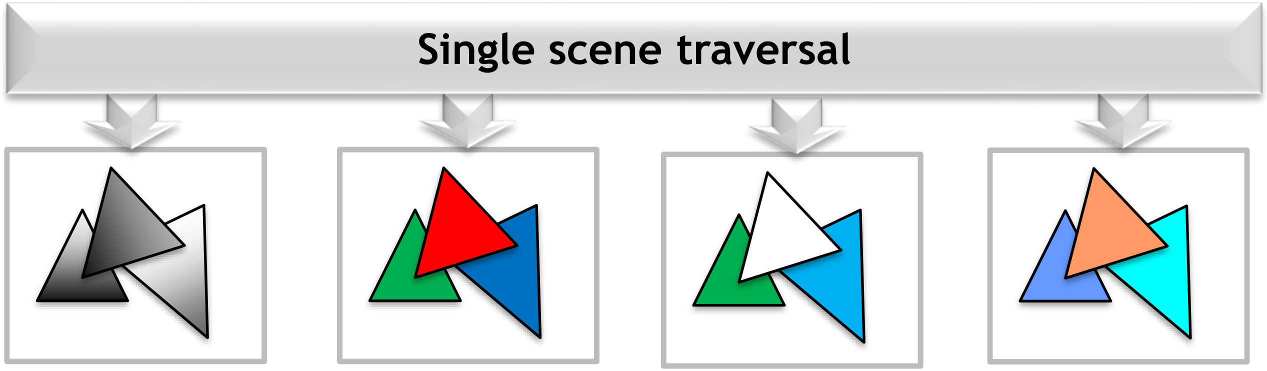
- Rendering to each surface separately is *bad*



- Geometry has a per-bin cost
  - Sometimes the cost is low, but it's there
  - Vertices in multiple bins get processed repeatedly
  - Rendering the scene repeatedly is painful
- Even immediate-mode renderers hate this!

Multiple render targets don’t help much

- Using MRTs means multiple buffers in one pass

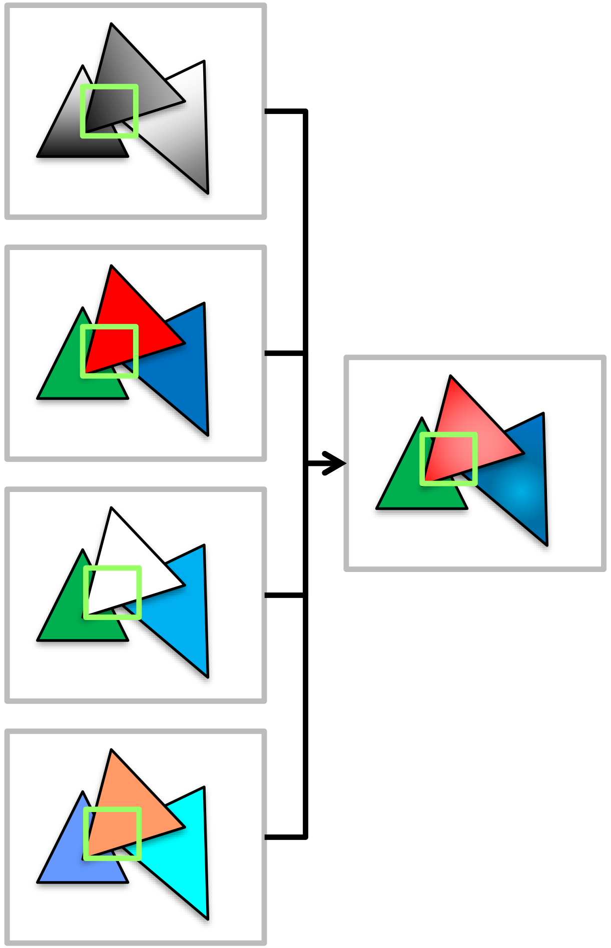


This is a typical approach for immediate-mode renderers (e.g. desktop/console systems)

- Reduces the geometry load (only process once)
- Still writing a *lot* of data off-chip
  - Tilers are all about trying not to do this!
  - Increases use of shader resources may slow some h/w

Pixel Local Storage (OpenGL ES extension)

- **Tiler-friendly (at last)**
  - Store only the current tile values
  - Read them later in the tile processing
- **But not portable!**
  - Not practical on immediate renderers
  - Debugging on desktop won’t work!
  - Capabilities vary between devices
  - Driver doesn’t have visibility
  - Data access is restricted

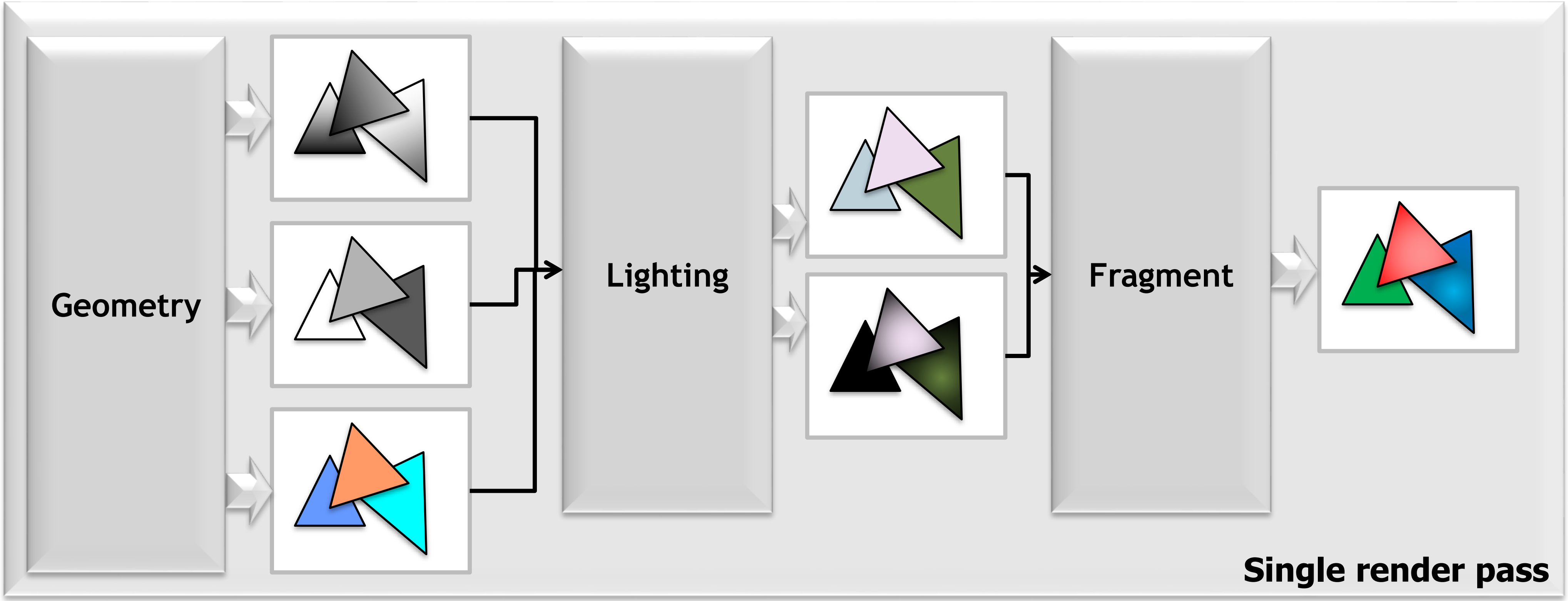


Vulkan: Explicit dependencies

- Vulkan has direct support for this type of rendering work load
- By telling the driver how you intend to use the rendered results, the driver can produce a better mapping to the hardware
  - The extra information is a little verbose, but simpler than handling all possible cases yourself!

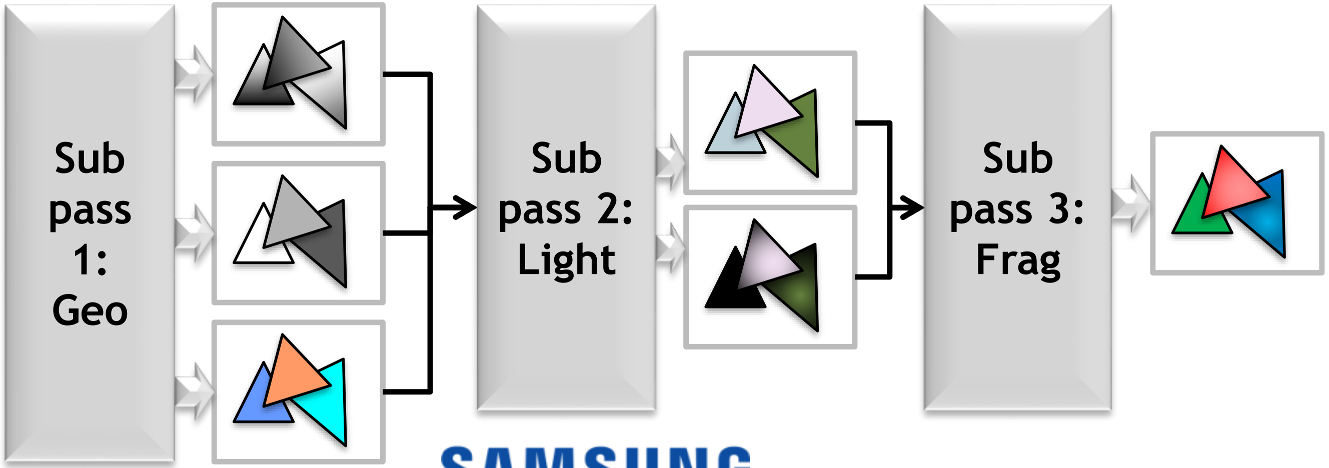
Vulkan render passes and subpasses

- **A render pass groups dependent operations**
  - All images written in a render pass are the same size



Vulkan render passes and subpasses

- **A render pass groups dependent operations**
  - All images written in a render pass are the same size
- **A render pass contains a number of *subpasses***
  - Subpasses describe access to *attachments*
  - Dependencies can be defined between subpasses



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Vulkan render passes and subpasses

- **A render pass groups dependent operations**
  - All images written in a render pass are the same size
- **A render pass contains a number of *subpasses***
  - Subpasses describe access to *attachments*
  - Dependencies can be defined between subpasses
- **Each render pass instance has to be contained within a single command buffer (unit of work)**
  - Some tilers schedule by render pass

Defining a render pass

- **VkRenderPassCreateInfo**
  - VkAttachmentDescription *pAttachments
    - Just the descriptions, not the actual attachments!
  - VkSubpassDescription *pSubpasses
  - VkSubpassDependency *pDependencies
- **vkCreateRenderPass(device, createInfo,.. pass)**
  - Gives you a VkRenderPass object
  - This is a *template* that you can use repeatedly
    - When we use it, we get a *render pass instance*

Describing attachments for a render pass

- **VkAttachmentDescription**
  - format/samples
  - loadOp
    - VK_ATTACHMENT_LOAD_OP_LOAD to preserve
    - VK_ATTACHMENT_LOAD_OP_DONT_CARE for overwrites
    - VK_ATTACHMENT_LOAD_OP_CLEAR uniform clears (e.g. Z)
  - storeOp
    - VK_ATTACHMENT_STORE_OP_STORE to output it
    - VK_ATTACHMENT_STORE_OP_DONT_CARE may discard after the render pass

Defining a subpass

- **VkSubpassDescription**
  - pInputAttachments
    - Which of the render pass's attachments this subpass reads
  - pColorAttachments
    - Which ones this subpass writes (1:1 - optional)
  - pResolveAttachments
    - Which ones this subpass writes (resolving multisampling)
  - pPreserveAttachments
    - Which attachments need to persist across this subpass
  - Subpasses are numbered and ordered

Defining subpass dependencies

- **VkSubpassDependency**
  - srcSubpass
  - dstSubpass
    - Where the dependency applies (can be external)
  - srcStageMask
  - dstStageMask
    - Execution dependencies between subpasses
  - srcAccessMask
  - dstAccessMask
    - Memory dependencies between subpasses

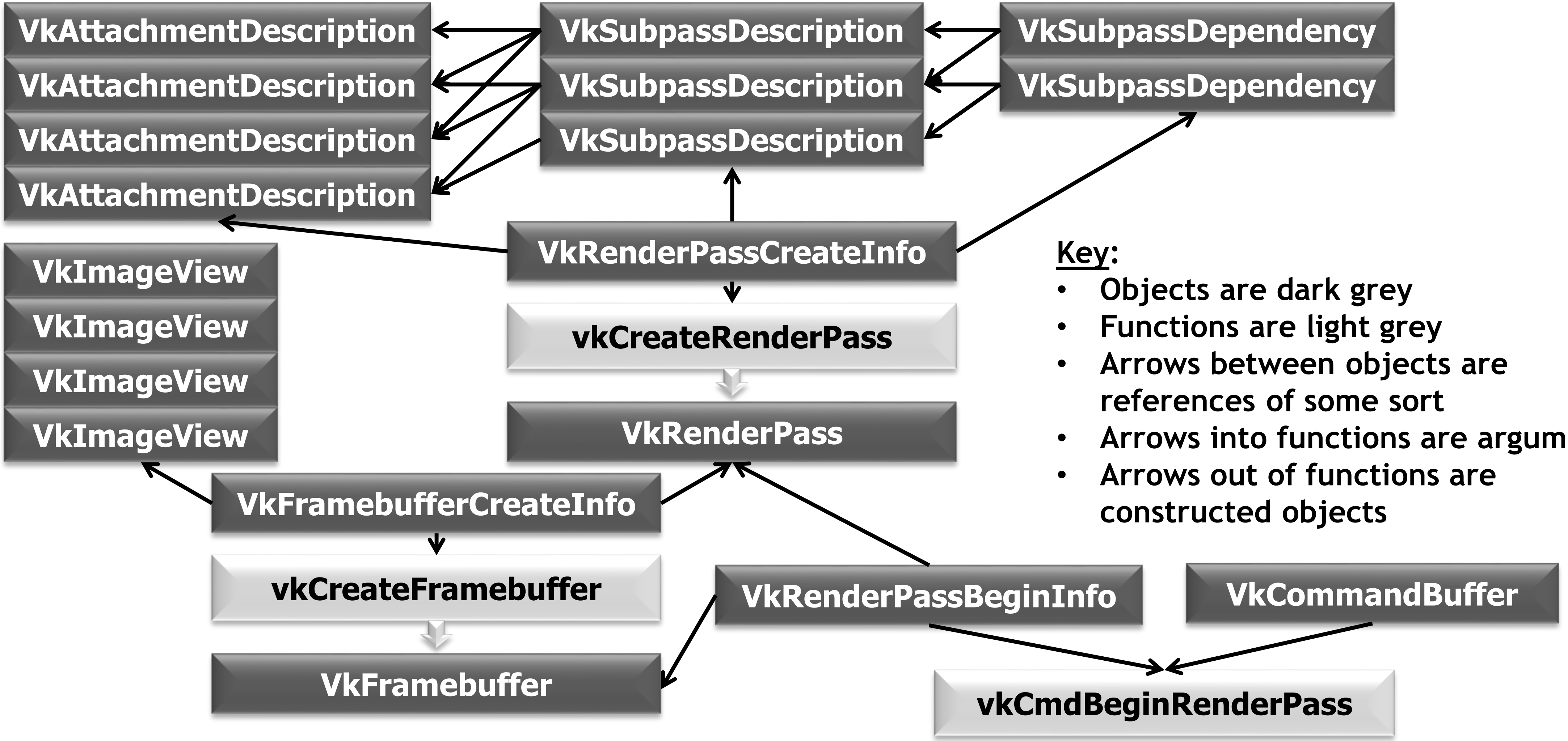
Vulkan framebuffers

- **A VkFramebuffer defines the set of attachments used by a render pass instance**
- VkFramebufferCreateInfo
  - renderPass
  - pAttachments
    - These are actual VkImageViews this time!
  - width
  - height
  - layers

Starting to use a render pass

- **vkCmdBeginRenderPass/vkCmdEndRenderPass**
  - Starts a render pass *instance* in a command buffer
    - You start in the first (maybe only) subpass implicitly
  - pRenderPassBegin contains configuration
- **VkRenderPassBeginInfo**
  - VkRenderPass renderPass
    - The render pass “template”
  - VkFrameBuffer framebuffer
    - Specifies targets for rendering

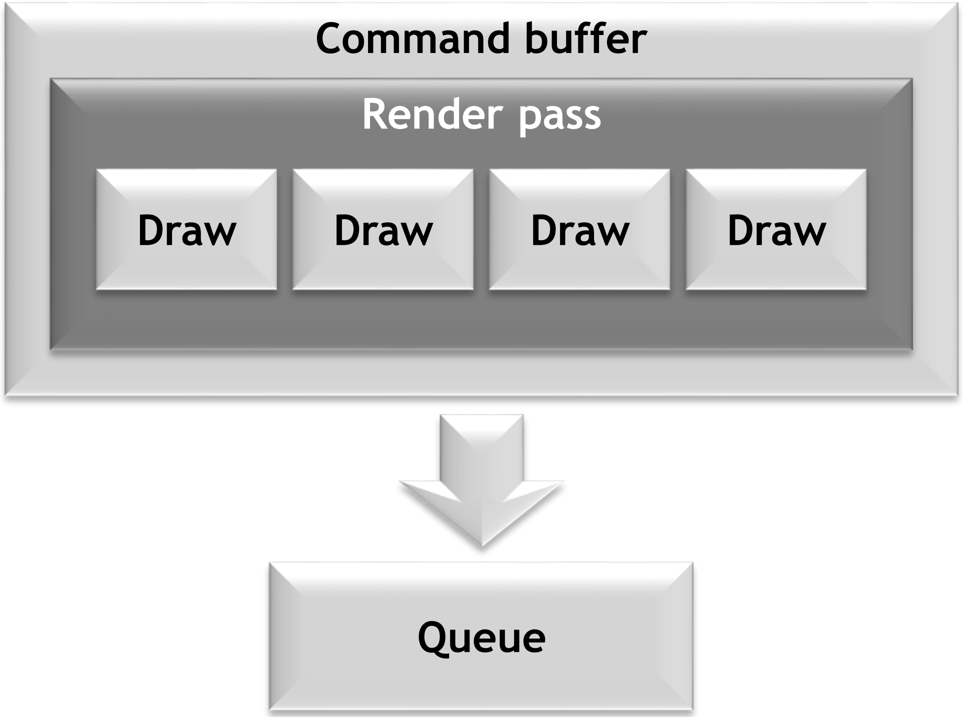
Putting it all together…



Key:
- Objects are dark grey
- Functions are light grey
- Arrows between objects are references of some sort
- Arrows into functions are arguments
- Arrows out of functions are constructed objects

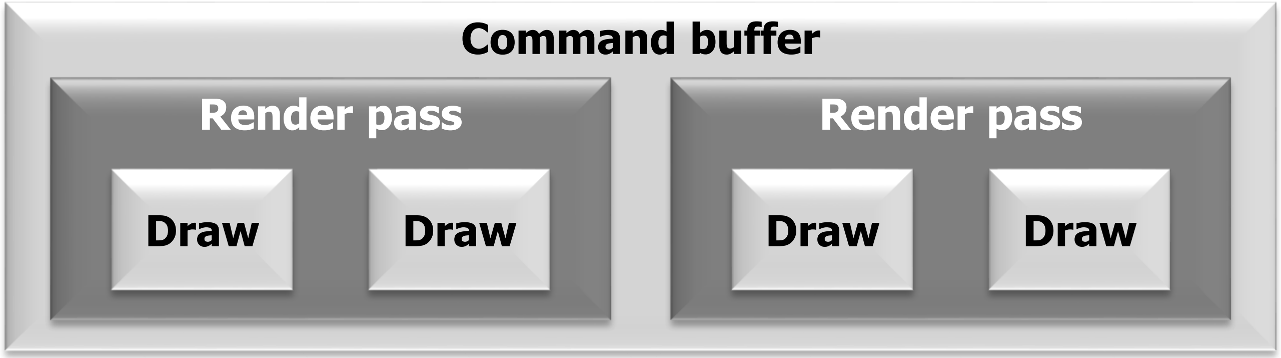
Simple rendering

- vkAllocateCommandBuffers (VK_COMMAND_BUFFER_LEVEL_PRIMARY)
- vkBeginCommandBuffer
- vkCmdBeginRenderPass
- vkCmdDraw (etc.)
- vkCmdEndRenderPass
- vkEndCommandBuffer
- vkQueueSubmit



Multiple render passes

- You can have more than one render pass in a command buffer
  - Yes, Leeloo multipass, we know…



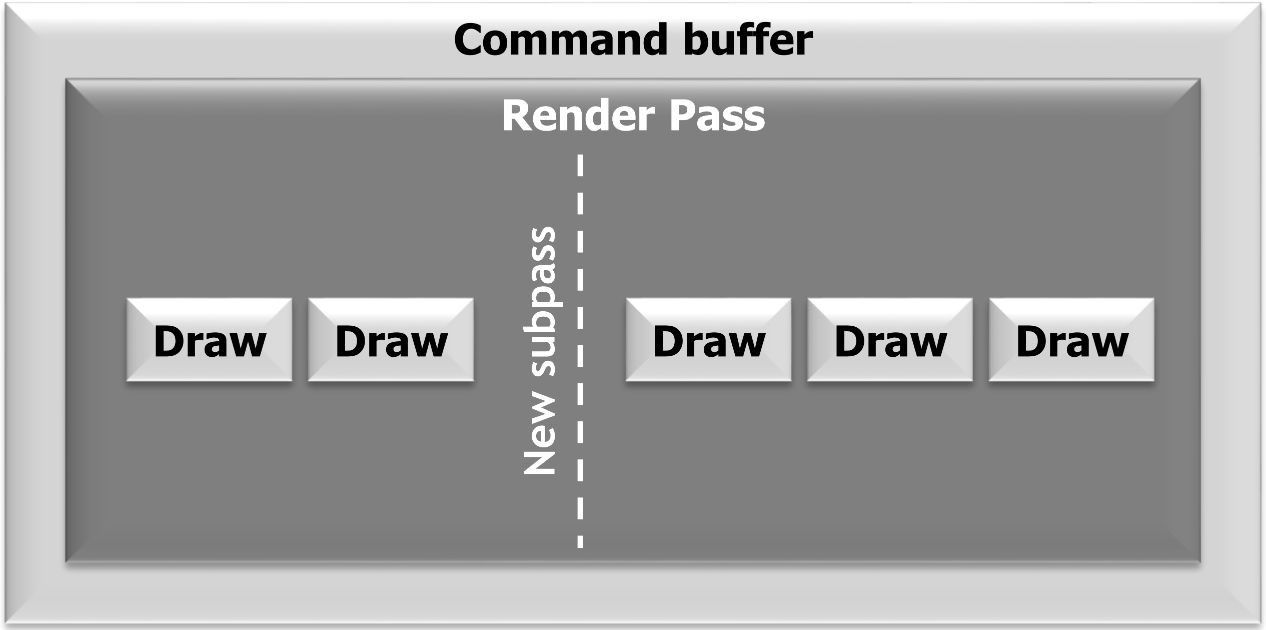
- So a command buffer can render to many outputs
  - E.g. you could render to the same shadow and environment maps every frame by reusing the same command buffer
- But it must be the *same* outputs each time you submit
  - A specific render pass instance has fixed vkFrameBuffers!

Two limitations…

- **Different render passes ⇒ independent outputs**
  - Rendering goes off-chip, there’s no PLS-style on-chip reuse of pixel contents
- **You can’t reuse the same command buffer with a different render target**
  - E.g. for double buffering or streamed content
  - We’ll come back to this…
- **Still sometimes all you need, though!**

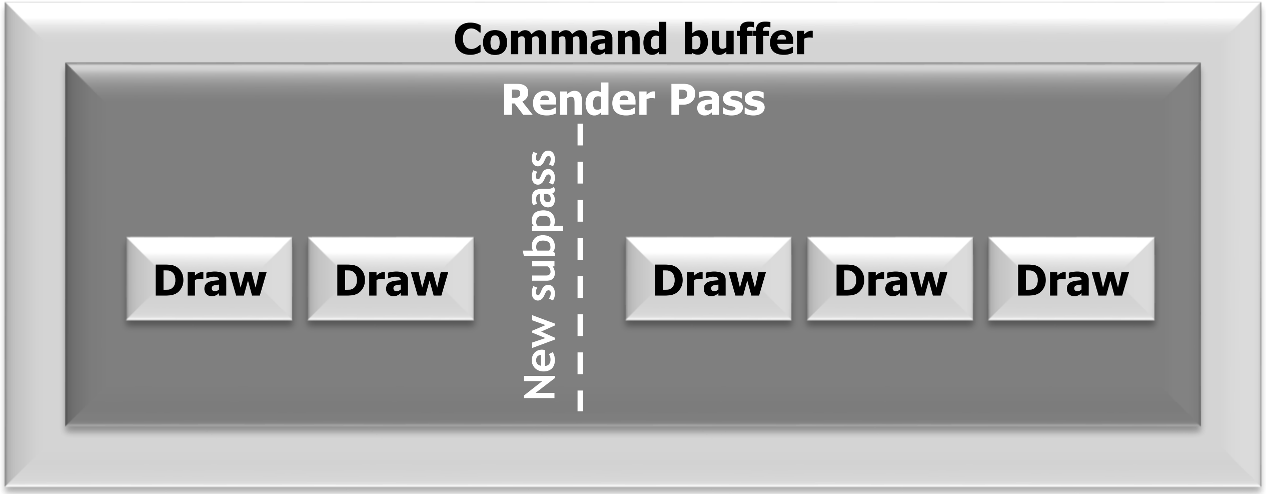
More than one subpass

- **vkCmdNextSubpass moves to the next subpass**
  - Implicitly start in the first subpass of the render pass
  - Dependencies say what you’re accessing from previous subpasses
  - Same render pass so accesses stay on chip (if possible)



Using multiple subpasses

- vkCmdBeginCommandBuffer
- vkCmdBeginRenderPass
- vkCmdDraw (etc.)
- vkCmdNextSubpass
- vkCmdDraw (etc.)
- vkCmdEndRenderPass
- vkCmdEndCommandBuffer



Accessing subpass output in fragment shaders

- **In SPIR-V, previous subpass content is read with OpImageRead**
  - Coordinates are sample-relative, and need to be 0
  - OpTypeImage Dim = SubpassData
- **In GLSL (using GL_KHR_vulkan_glsl):**
  - Types for subpass access are [ui]subpassInput(MS)
    - layout(input_attachment_index = i, …) uniform subpassInput t; to select a subpass
  - subpassLoad() to access the pixel

C.f. __pixel_localEXT layouts in EXT_shader_pixel_local_storage when using OpenGL ES

Avoiding unnecessary allocations

- **If we're using subpasses, we likely don't need the images in memory**
  - A tiler may be able to process the subpasses entirely on-chip, without needing an allocation
  - Still need to "do the allocation" in case the tiler can't handle the request/on an immediate-mode renderer!
    - Won't commit resources unless it actually needs to
- **vkCreateImage flags for "lazy committal"**
  - VK_IMAGE_USAGE_TRANSIENT_ATTACHMENT_BIT

Vulkan subpasses: advantages

- **The driver knows what you’re doing**
  - It can reorder subpasses
  - It can change the tile size
  - It can balance resources between subpasses
  - *It will fall back to memory for you* if it has to
  - Under the hood, mechanism likely matches PLS

EXT_shader_pixel_local_storage is actually *more* explicit than Vulkan here (and may still be offered as an extension)

- **Works on immediate mode renderers**
  - Probably MRTs and normal external writes
  - Desktop debugging tools will work!

There's more: Secondary command buffers

- **Vulkan has two levels of command buffers**
  - Determined by vkAllocateCommandBuffers
- **VK_COMMAND_BUFFER_LEVEL_PRIMARY**
  - Main command buffer, as we've seen so far
- **VK_COMMAND_BUFFER_LEVEL_SECONDARY**
  - Command buffer that can be invoked from the primary command buffer

Use of secondary command buffers

- **vkBeginCommandBuffer**
  - Takes a VkCommandBufferBeginInfo
- **VkCommandBufferBeginInfo**
  - flags include:
    - VK_COMMANDBUFFER_USAGE_RENDER_PASS_CONTINUE_BIT
  - pInheritanceInfo
- **VkCommandBufferInheritanceInfo**
  - renderPass and subpass
  - framebuffer (can be null, more efficient if known)

Secondary command buffers and passes

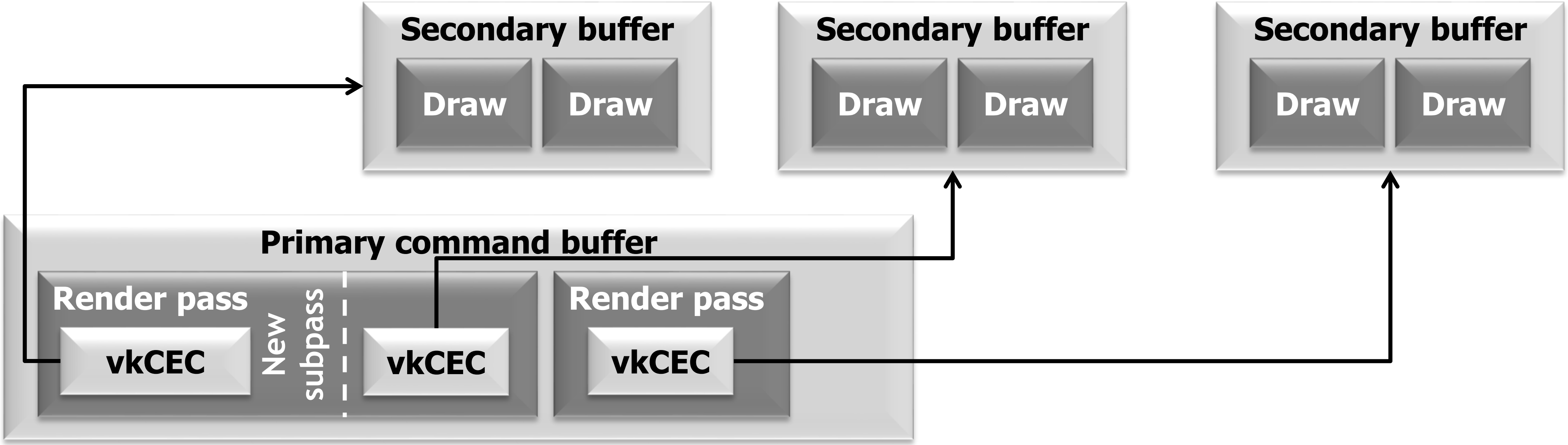
- **Why do we need the “continue bit”?**
  - *Render passes (and subpasses) can’t start in a secondary command buffer*
  - Non-render pass stuff can be in a secondary buffer
    - You *can* run a compute shader outside a render pass
  - Otherwise, the render pass is inherited from the primary command buffer

Secondary command buffers and passes

- **Why specify render pass/framebuffer?**
  - Command buffers needs to know this when recording
    - Some operations depends on render pass info (e.g. format)
  - Framebuffer is optional (can *just* inherit)
    - If you *can* specify the actual framebuffer, the command buffer can be less generic and therefore may be faster

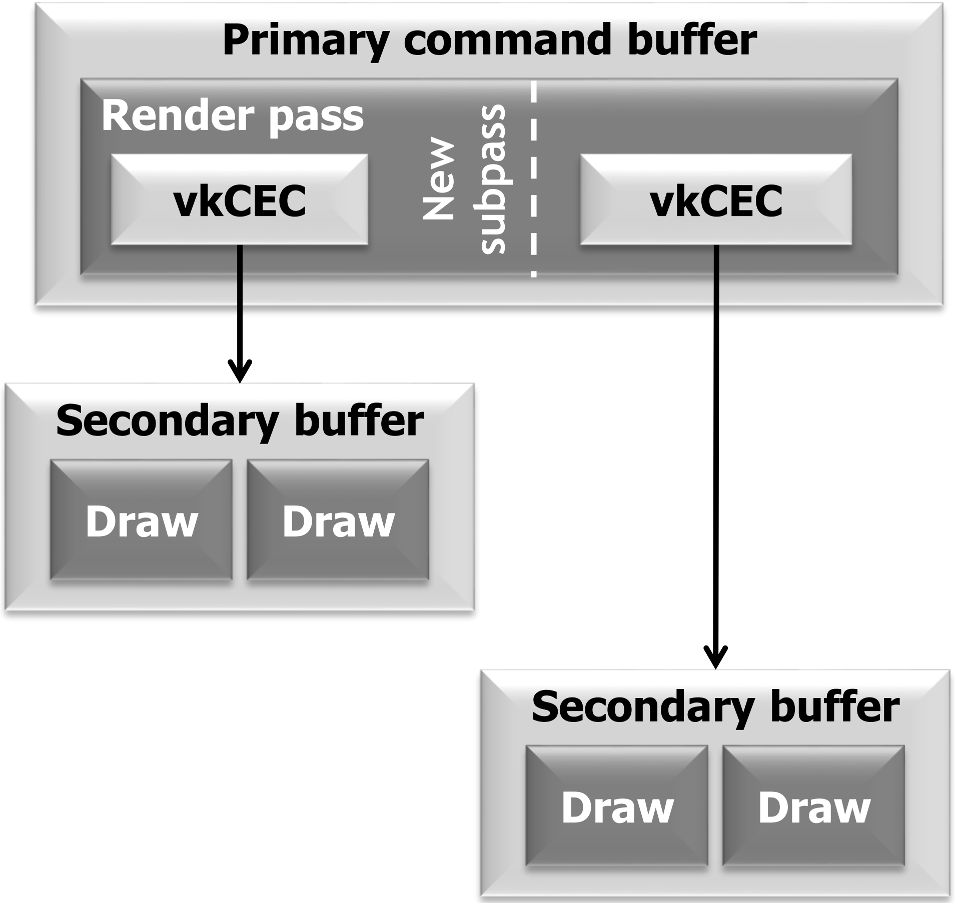
Invoking the secondary command buffer

- You can't submit a secondary command buffer
- You have to invoke it from a primary command buffer with vkCmdExecuteCommands



Secondary command buffer code

- vkCmdBeginCommandBuffer
- vkCmdBeginRenderPass
- vkCmdExecuteCommands
- vkCmdNextSubpass
- vkCmdExecuteCommands
- vkCmdEndRenderPass
- vkCmdEndCommandBuffer



Performance and parallelism

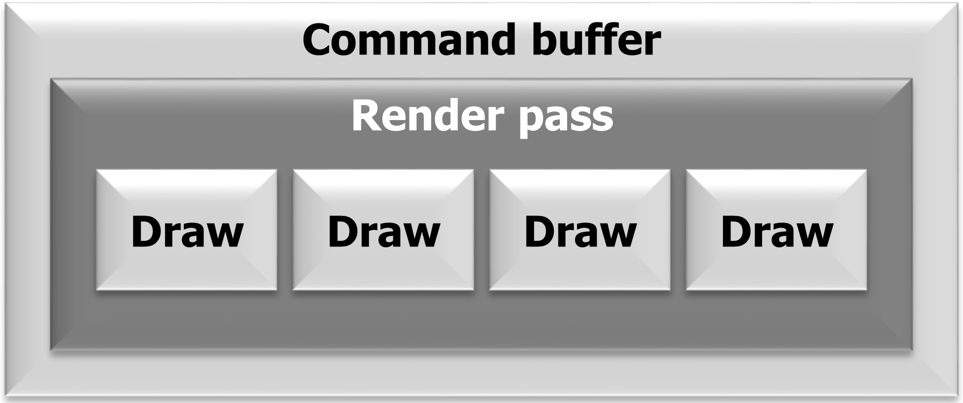
- **Creating a command buffer can be slow**
  - Lots of state to check, may require compilation
    - This happens in GLES as well, you just don’t control when!
- **So create secondary command buffers on different threads**
  - Lots of 4- and 8-core CPUs in cell phones these days
- **Invoking the secondary buffer is lightweight**
  - Primary command buffer generation is quick(er)

What does this have to do with passes?

- **Remember:**
  - Render passes exist within (primary) command buffers
    - The command buffer sets up the GPU for the render pass
  - On-chip rendering happens within a render pass
    - If you want content to persist between render passes, it'll reach memory (or at least cache), not stay in the tile buffer
  - You can't use multiple threads to build work for a primary command buffer in parallel
    - You *can* build many secondary command buffers at once

You can’t mix and match

- **Within a subpass you can either (but not both):**
  - Execute rendering commands directly in the primary command buffer
    - VK_SUBPASS_CONTENTS_INLINE



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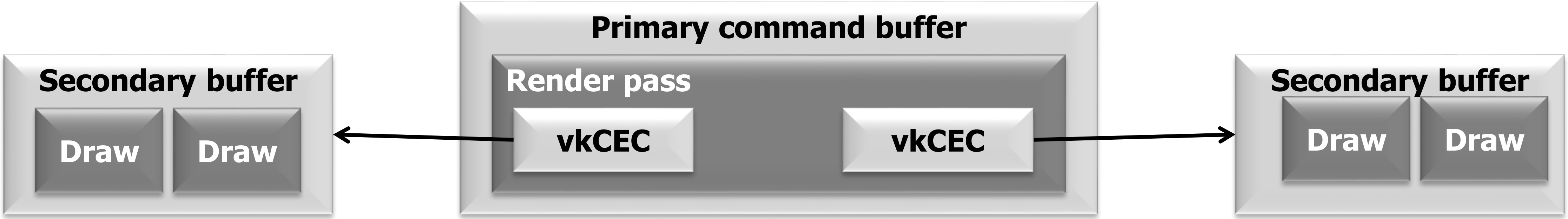
    - VK_SUBPASS_CONTENTS_SECONDARY_COMMAND_BUFFERS



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  - Invoke secondary command buffers from the primary command buffer with vkCmdExecuteCommands
    - VK_SUBPASS_CONTENTS_SECONDARY_COMMAND_BUFFERS
  - Chosen by vkCmdBeginRenderPass/vkCmdNextSubpass
    - Remember: you can only do these in a primary command buffer!

Command buffer reuse: even faster

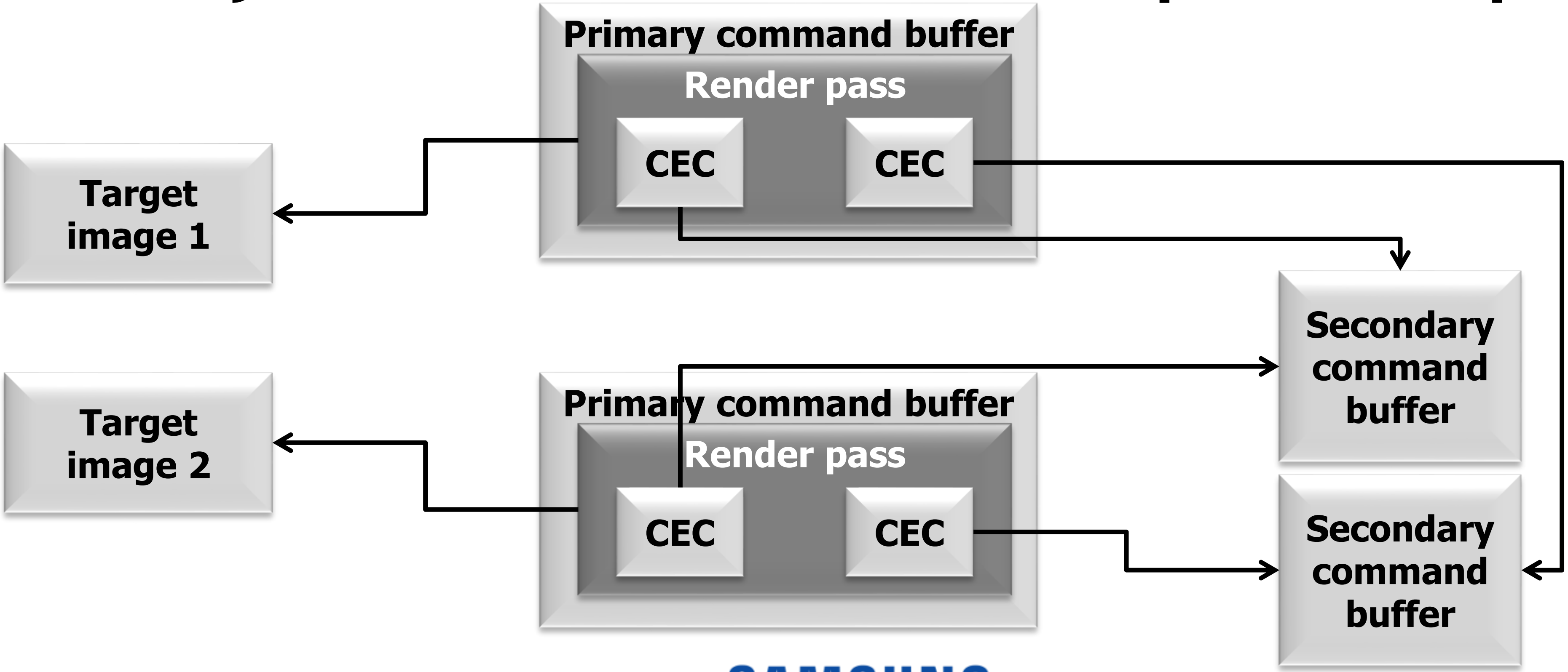
- **Primary command buffers work with a fixed render pass and framebuffer**
  - You can reuse a primary command buffer, but it will always access the same images – often good enough
    - May have to wait for execution to end; can’t be “one-time”
- **What if you want to access different targets?**
  - E.g. a cycle of framebuffers or streamed content?
  - You *can* round-robin several command buffers
  - Or you can use secondary command buffers!

Compatible render passes and frame buffers

- The render pass a secondary command buffer uses needn't be the one it was recorded with
  - It can be "compatible"
    - Same formats, number of sub-passes, etc.
- You can have primary command buffers with different outputs, and they can re-use secondary command buffers
  - The primary has to be different to record new targets
  - The primary may have to patch secondary addresses

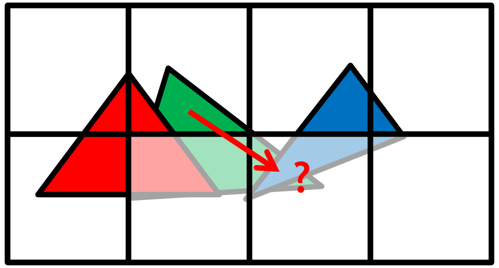
Almost-free use with changing framebuffers

- No cost for secondary command buffers
- Primary command buffer is simple and quick



So I can do bloom/DoF/rain/motion blur…!

- **No! Remember, you can only access the current pixel**



- **Tilers process one tile at a time**
  - If you could try to access a different pixel, the tile containing it may not be there
  - You have to write out the whole image to do this
    - Slow, painful, last resort!
  - Yes, we can think of possible solutions too
    - Give it time (lots of different hardware out there)

Coming out of the shadow(buffer)s

- **Render passes are integral to the Vulkan API**
  - Reflects modern, high-quality rendering approaches
- **The driver has more information to work with**
  - It can do more for you
    - Remember this if you complain it's verbose!
- **Hardware resource management is *hard***
  - Expect drivers to get better over time
- **Another tool for better mobile gaming**

Thank you

- Over to you…

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