High Performance Vulkan

Lessons Learned from Source 2

John McDonald

VALVE

Sections

- Introduction and Goals
- Source 2 Overview
- General Guidance
- Command Buffers
- Pipelines
- Descriptor Set Updates
- Memory Management
- Image Management
- Internal Fragmentation
- Final Thoughts

Disclaimer

- Largely based on Dan Ginsburg's Siggraph 2015 Vulkan talk, but updated for 1.0.
- 3385 changes to Vulkan since that talk.
  - So hopefully not a rehash even if you were there ☺
- Slides may be buggy!
- Guidance based on Desktop GPUs (AMD, Intel, NVIDIA)
  - Everything should *work* on mobile GPUs, but may not be optimal performance

Goals

- Thorough understanding of Vulkan concepts
- Concrete examples to follow for common resource updates

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- Avoid repeating our mistakes

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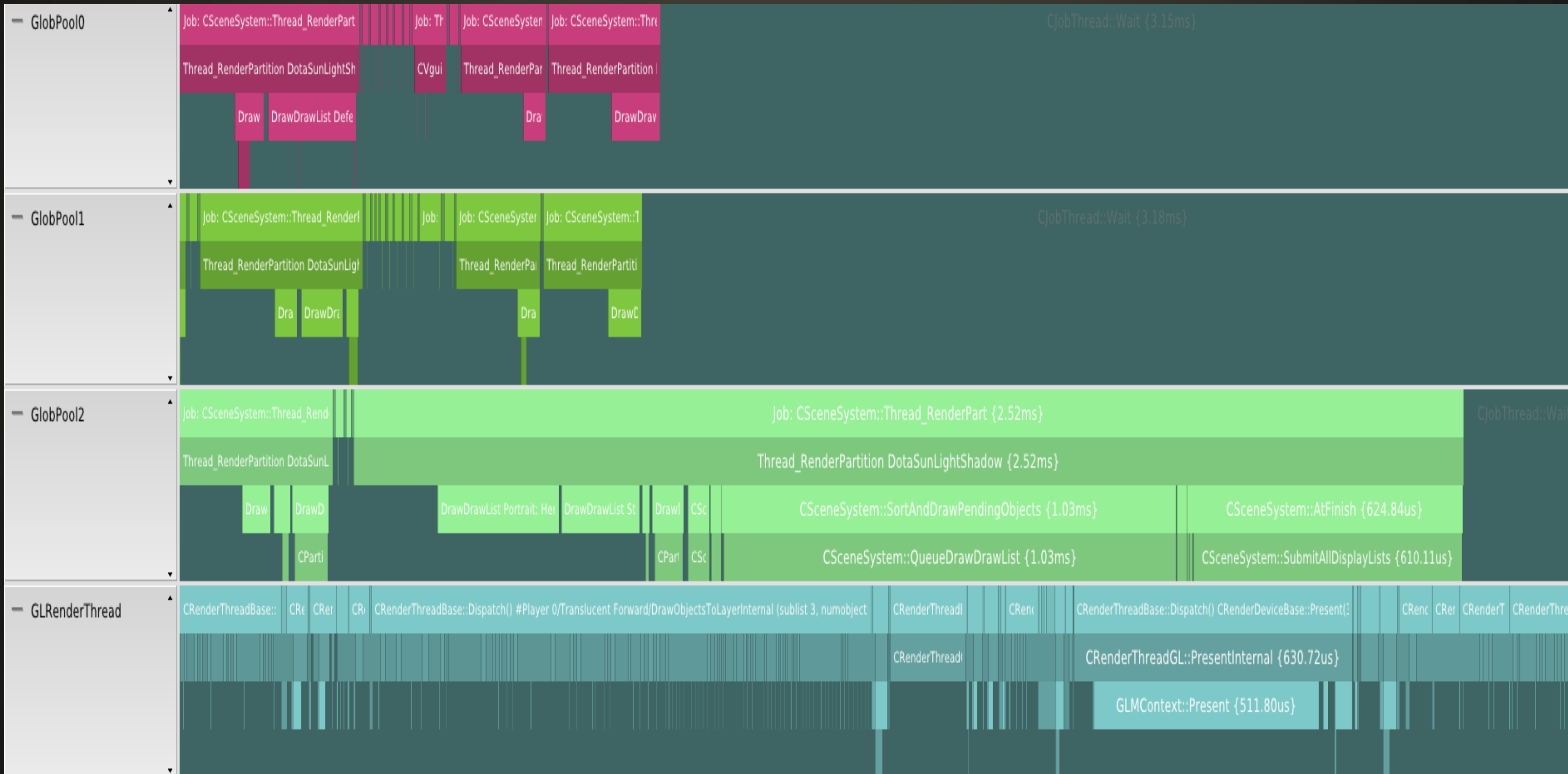
Source 2 Overview

- OpenGL, Direct3D 9, Direct3D 11, Vulkan
- Windows, Linux, Mac
- Dota 2 Reborn

Source 2 Rendering

- Direct3D 11-like Rendersystem abstraction
- Multithreaded
  - D3D9/GL: software command buffers
  - D3D11: deferred contexts
  - Single submission thread

Source 2 Rendering (GL)



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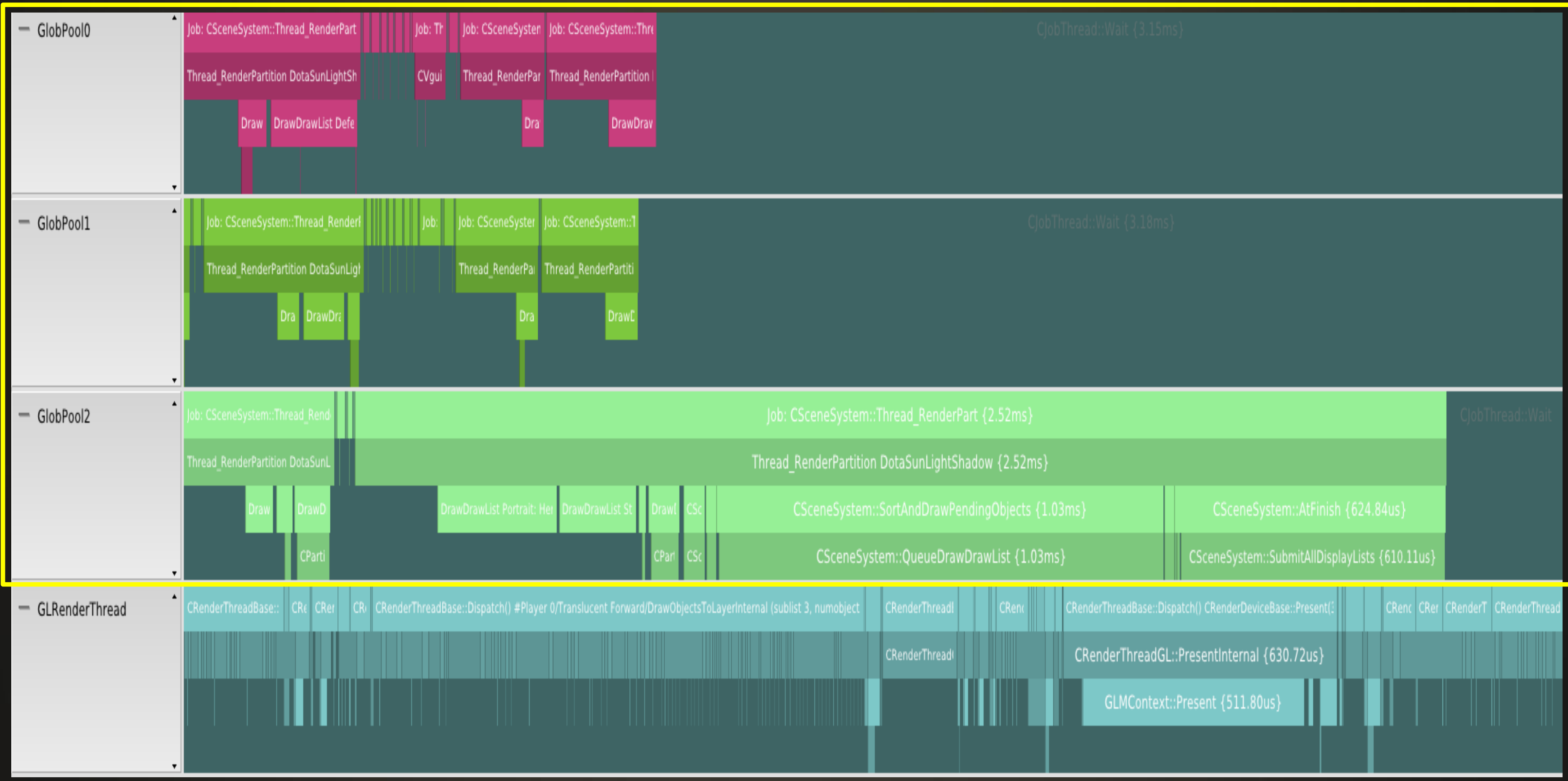

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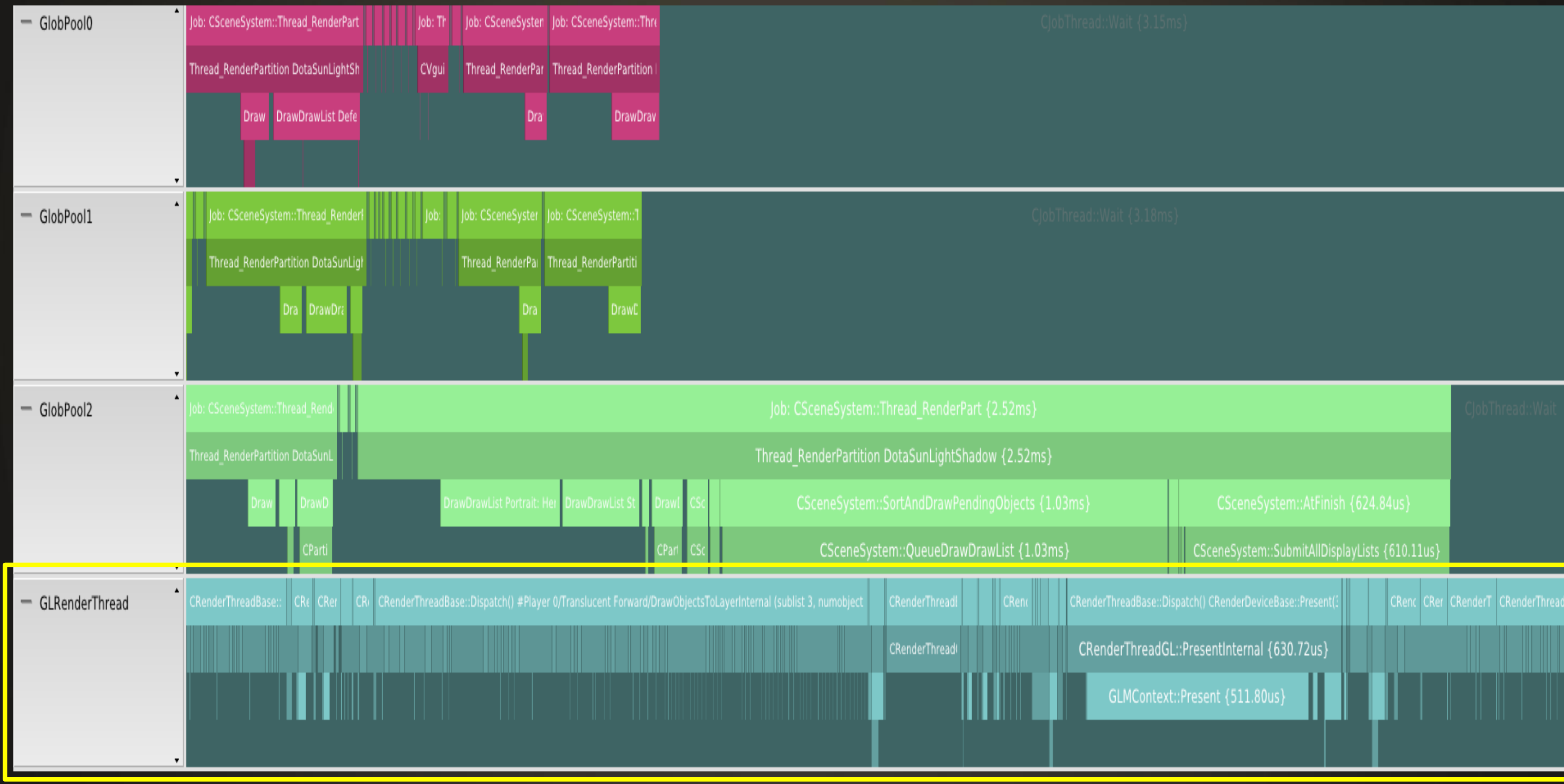

Source 2 Vulkan Port

- Started with GL and D3D11 renderer
  - D3D11 deferred contexts mapped well to Vulkan command buffers
  - Leveraged GLSL shader conversion already in GL layer

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General Guidance

- Setting up the Validation layer should be part of day 1 tasks.
  - Validation should be enabled all through development
  - Without Validation, Vulkan **will not** report errors back to you, most likely will simply crash if given invalid parameters / commands.
- Spend a little time investing in app thread debugging tools
  - Single Threaded Job mode
  - Heap Validation tools (malloc/debug)
  - CPU-GPU sync point detection
- Invest in tools that can visualize threads well

General Guidance - Threading

- Threads should be as independent as possible
- Any cross talk between threads significantly reduces benefit from multithreading

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- Any cross talk between threads significantly reduces benefit from multithreading

Bad threading is worse than no threading

General Guidance Caveats

- However, per-thread resources lead to memory bloat
  - Over time, all threads consume the same large memory footprint
- Conceptually a form of internal fragmentation
- Can be difficult to stay on top of

Internal fragmentation visualized

Internal fragmentation visualized

Internal fragmentation visualized

Internal fragmentation visualized

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Internal fragmentation visualized

Internal Fragmentation Consumption

- Ideal
  - Total = Sum(Per Thread Memory)
- Worst Case
  - Total = Max(Per Thread Memory) * Num Threads
- Possible Solution Later

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Command Buffer Core Concepts

- Conceptually similar to D3D11 Deferred Context
- Inherit no* state from other command buffers
- **`VkCommandBuffer`**s are central to the split between specification of work and scheduling of work.
  - Between **`vkBeginCommandBuffer`** and **`vkEndCommandBuffer`**, a command buffer is said to be recording. This is the specification of work.
  - Once a Command Buffer has been Ended, it can be scheduled for execution with **`vkQueueSubmit`**.

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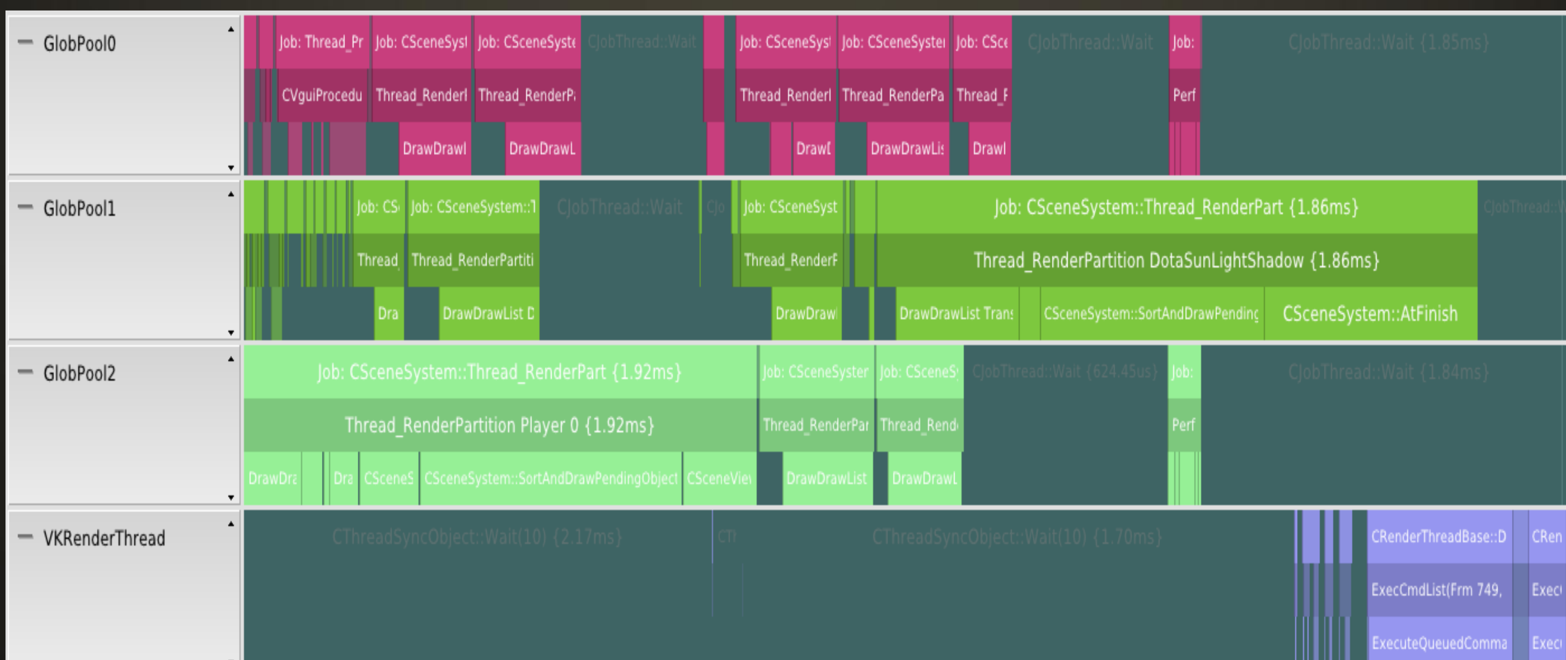
* Except Renderpass information between primary->secondary command buffers, which are beyond the scope of this presentation.

Command Buffer Core Concepts

- A `VkCommandBuffer` is allocated from a `VkCommandPool` via a call to `vkAllocateCommandBuffers`
- `VkCommandPool`s, like other pools, allow for lock-free allocation.
- Each `VkCommandBuffer`—and `VkCommandPool`—is "externally synchronized." This means the application promises not to act on the same Command Buffer or Command Pool from two threads simultaneously.

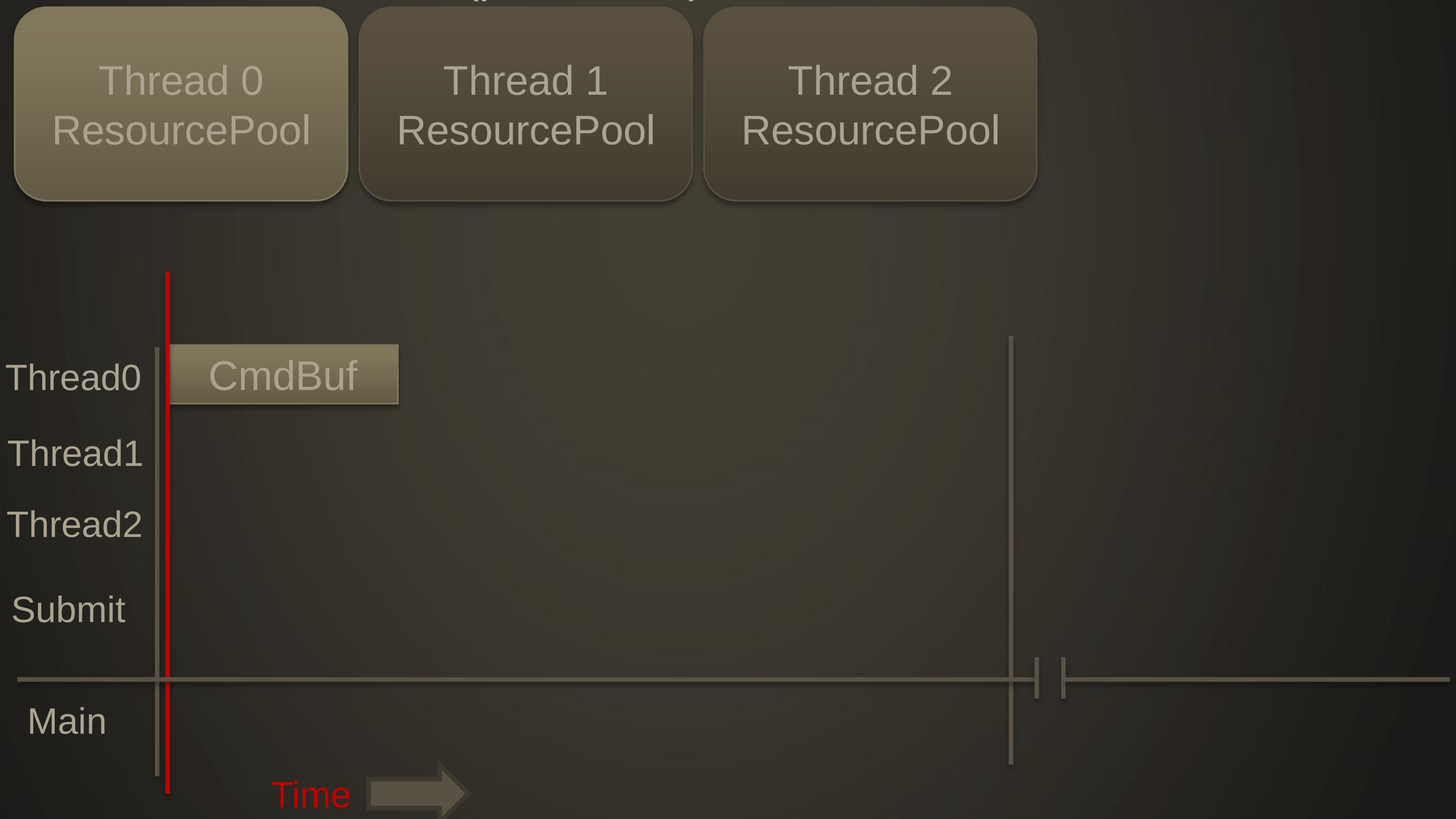
Command Buffers in Source 2

- Used where D3D11 deferred contexts were used
- One `VkCommandBuffer` per thread per render target
  - Except full screen passes—one command buffer only
- Single thread performs submission to queue



Command Buffer Allocation and Reuse

- ResourePool is per thread. The ResourcePool spills to `VkCommandPool` (per thread)



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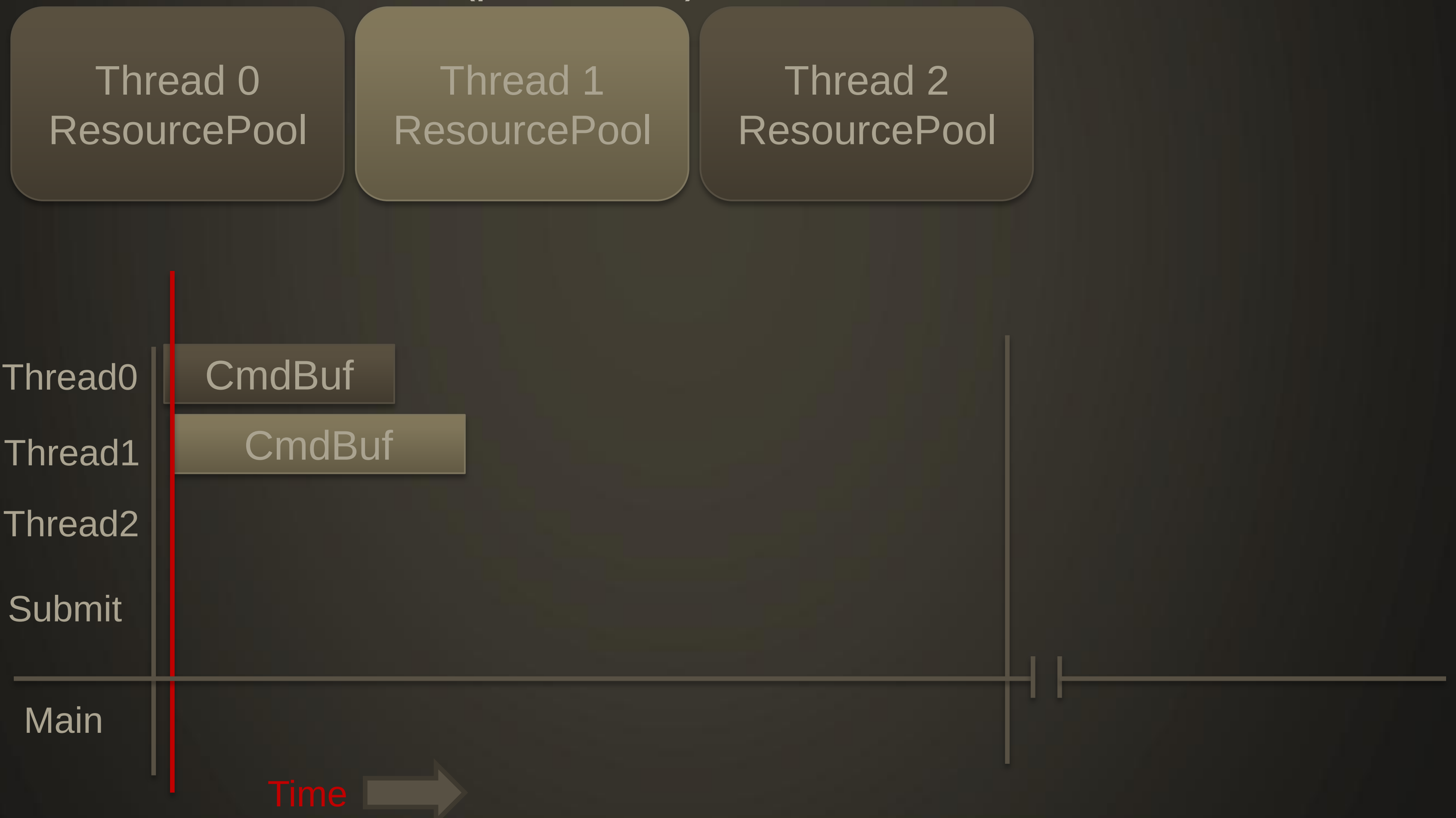

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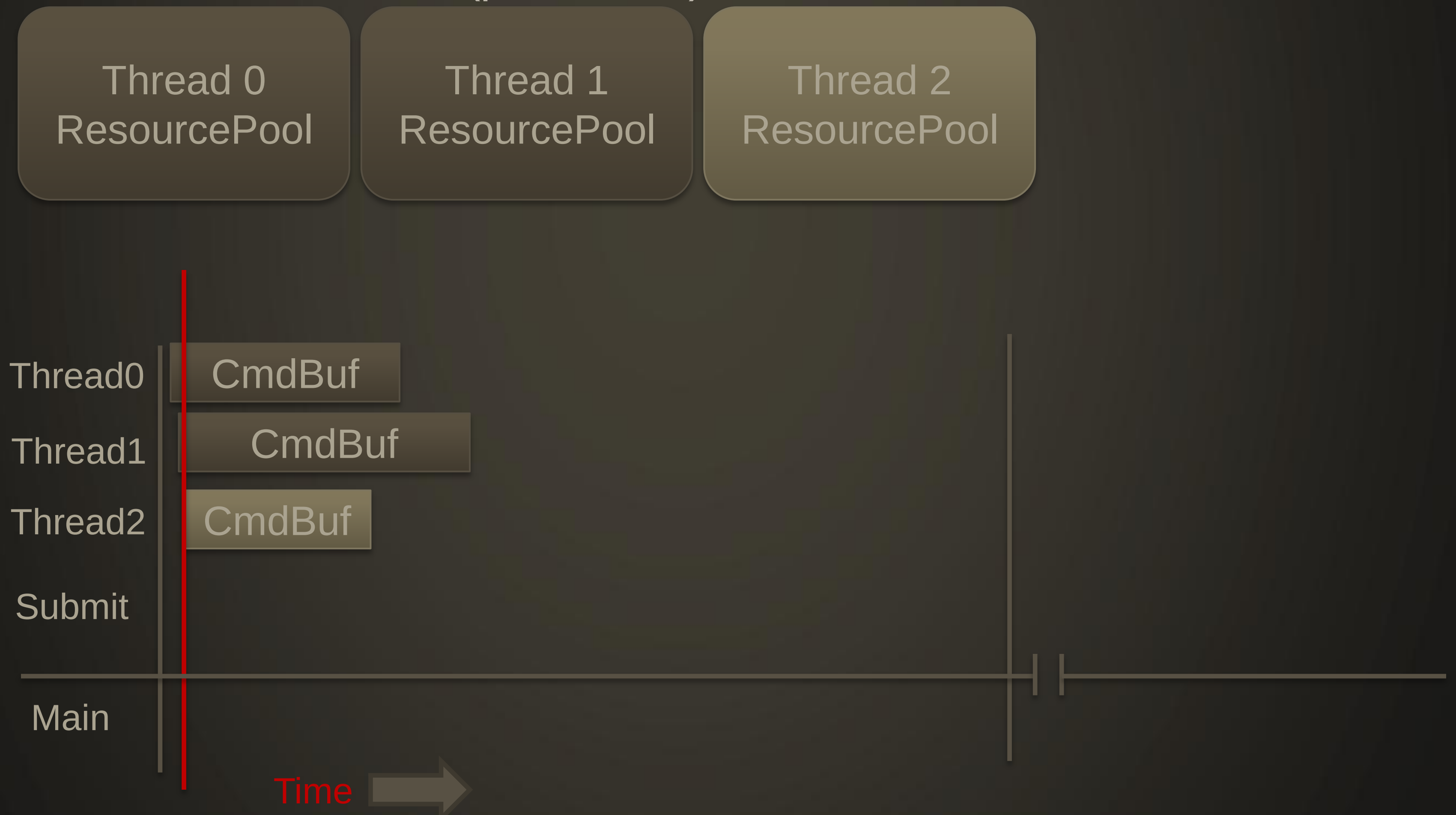

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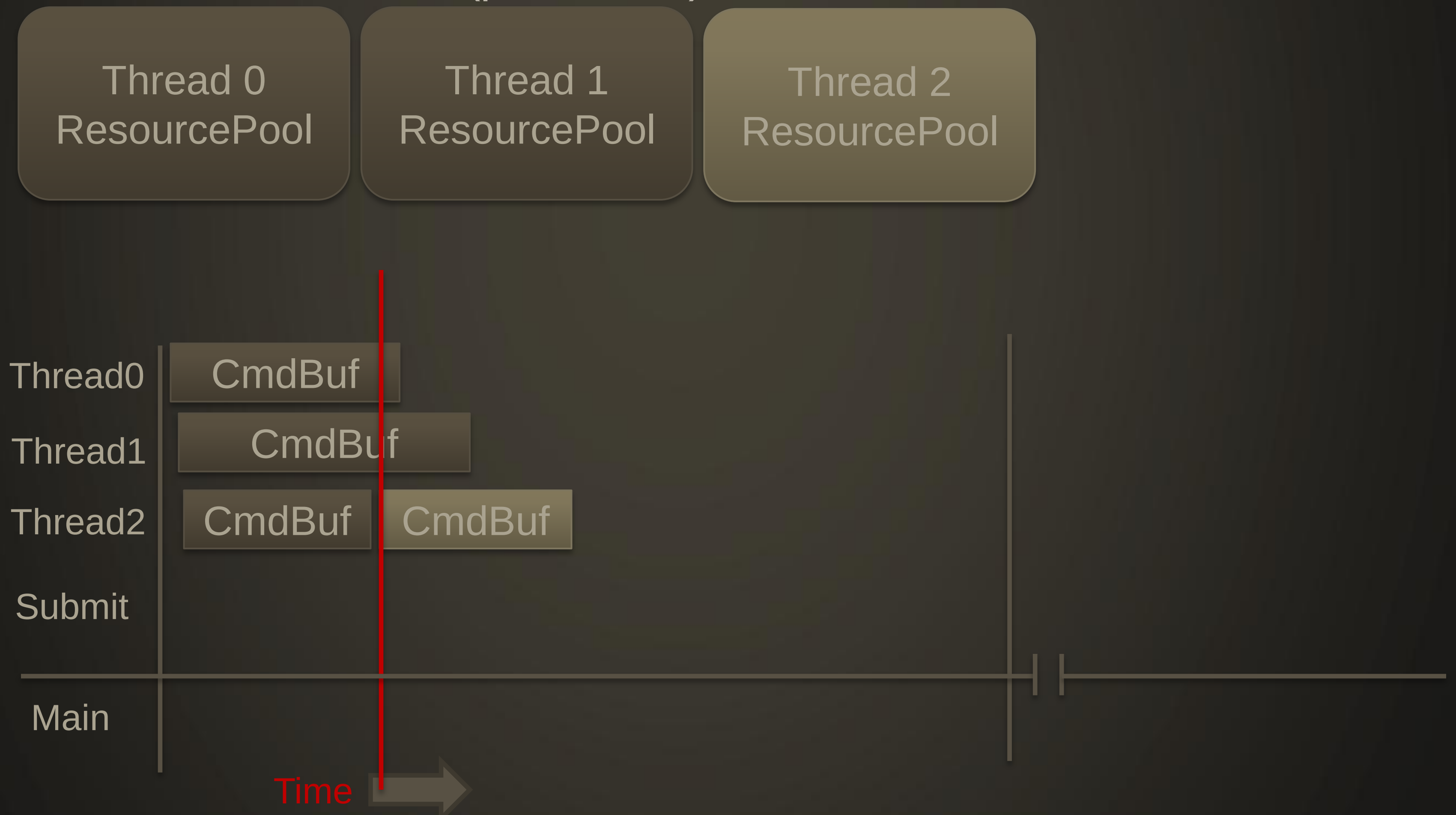

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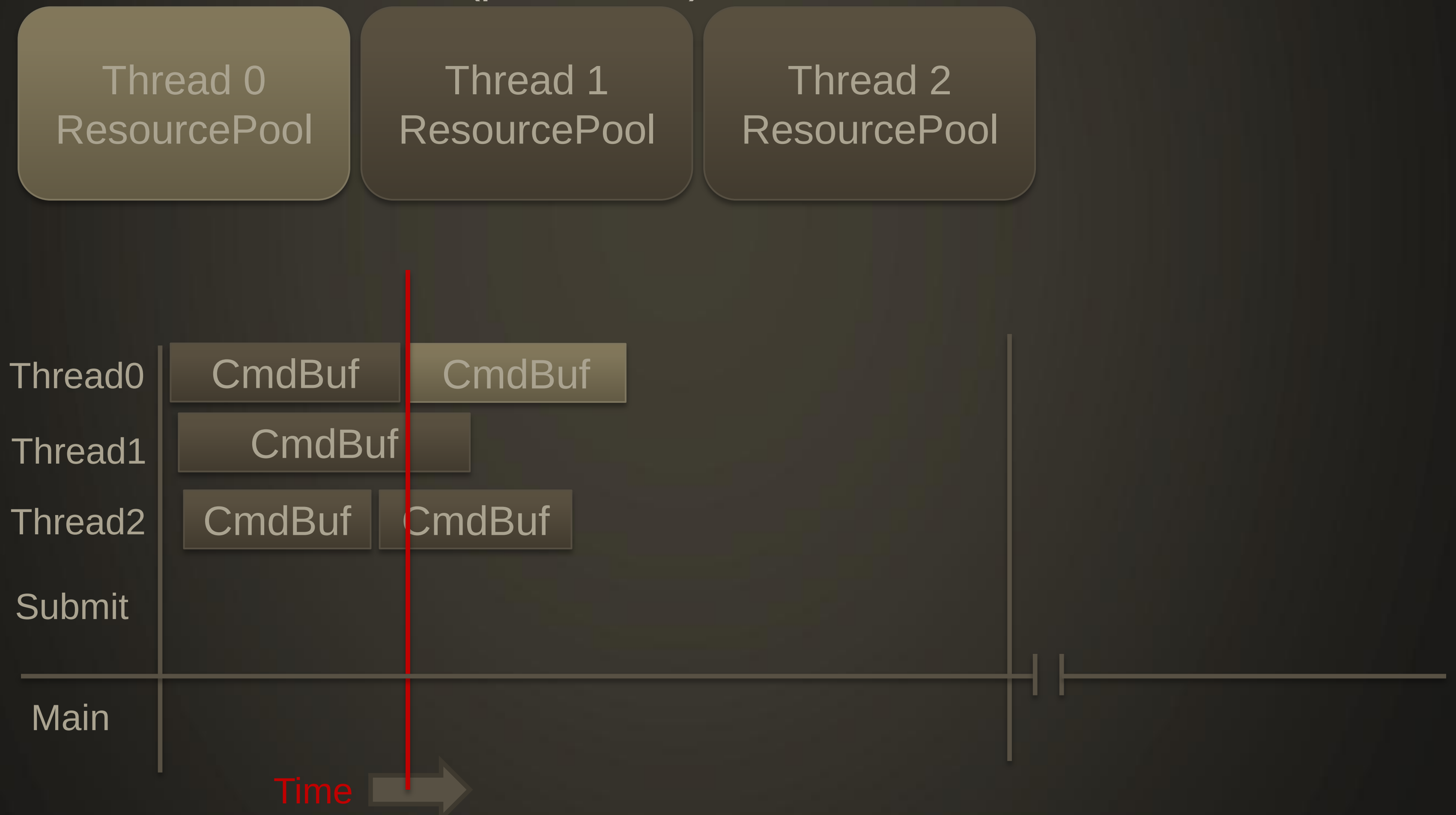

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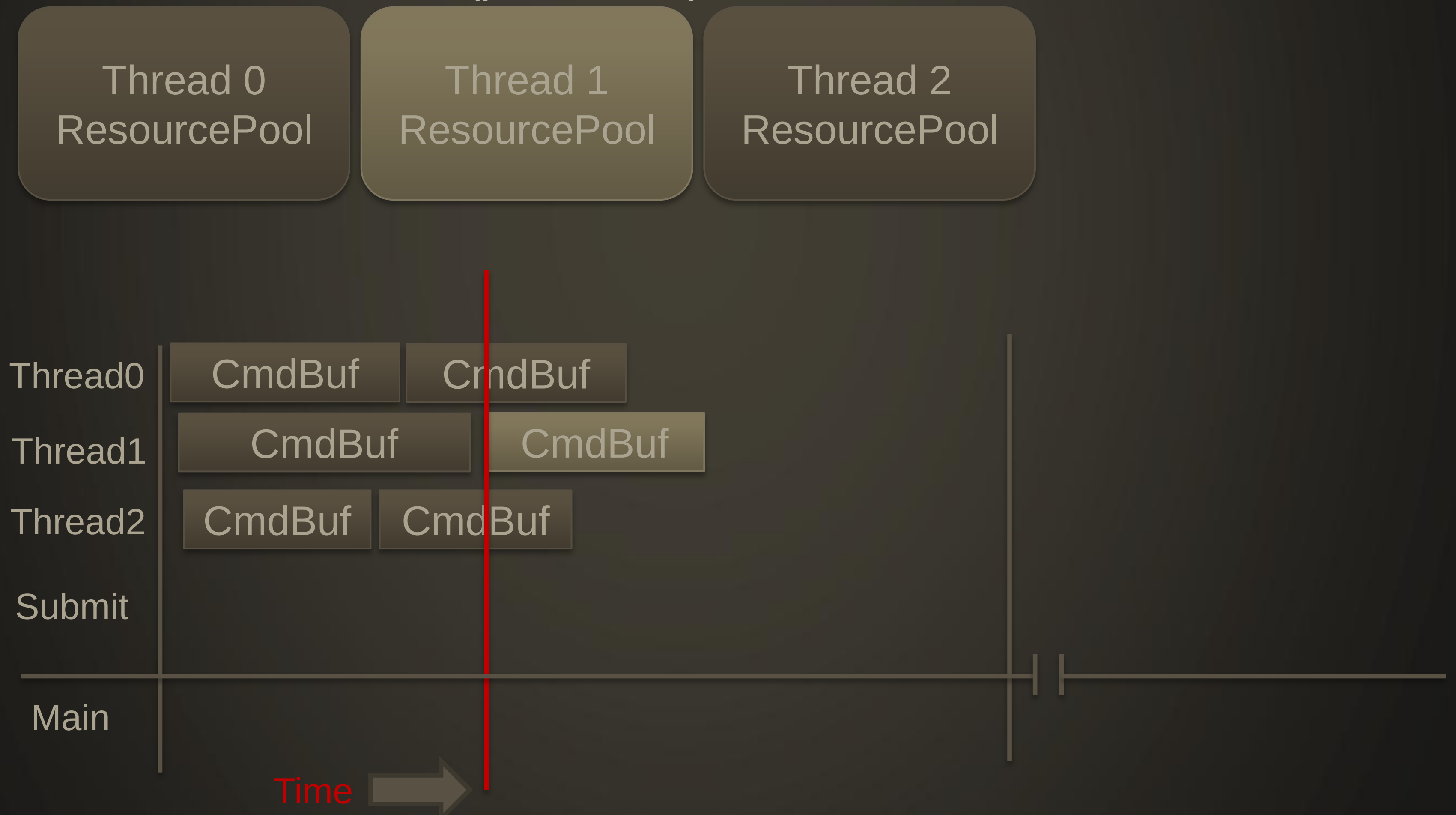

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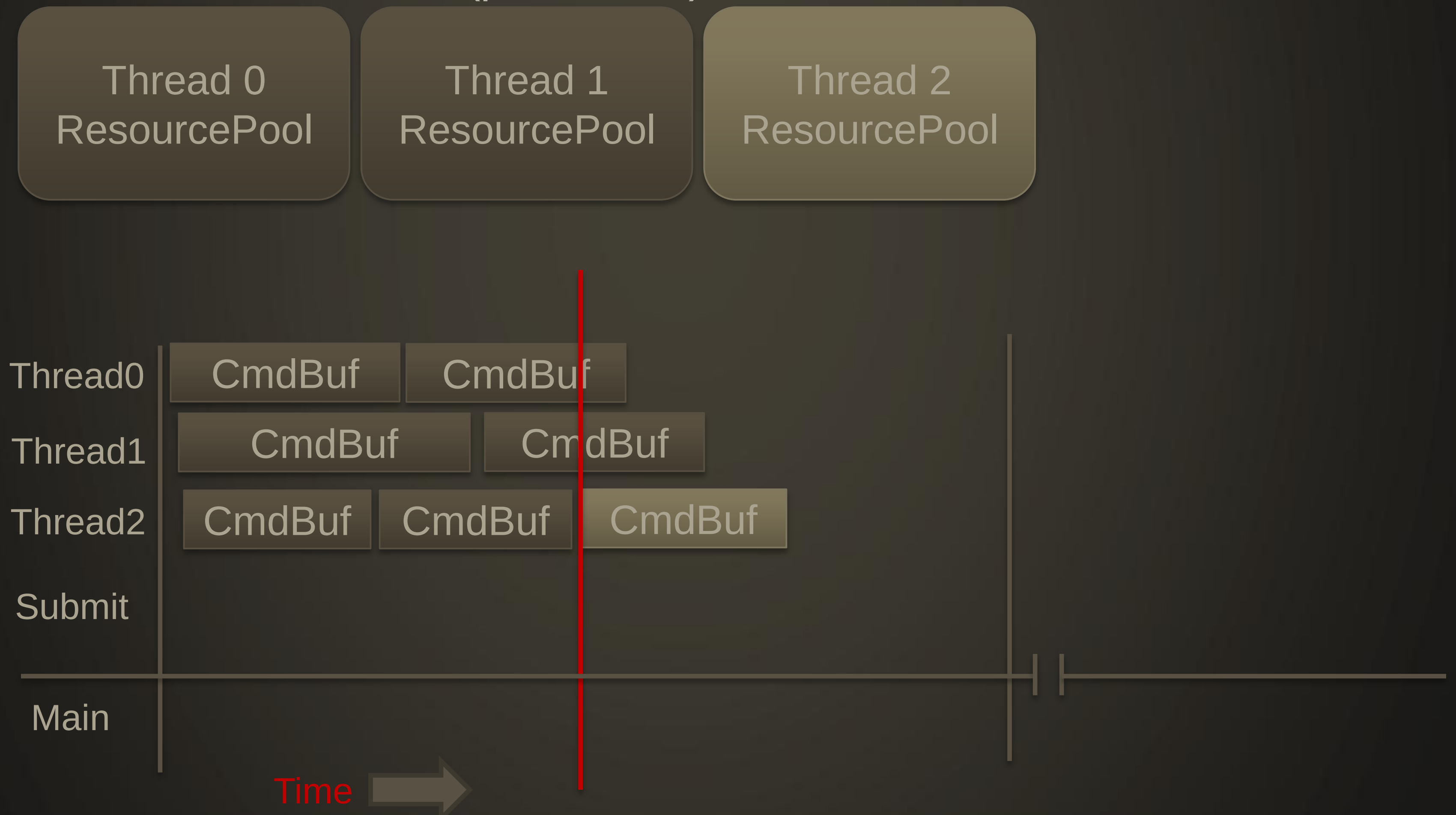

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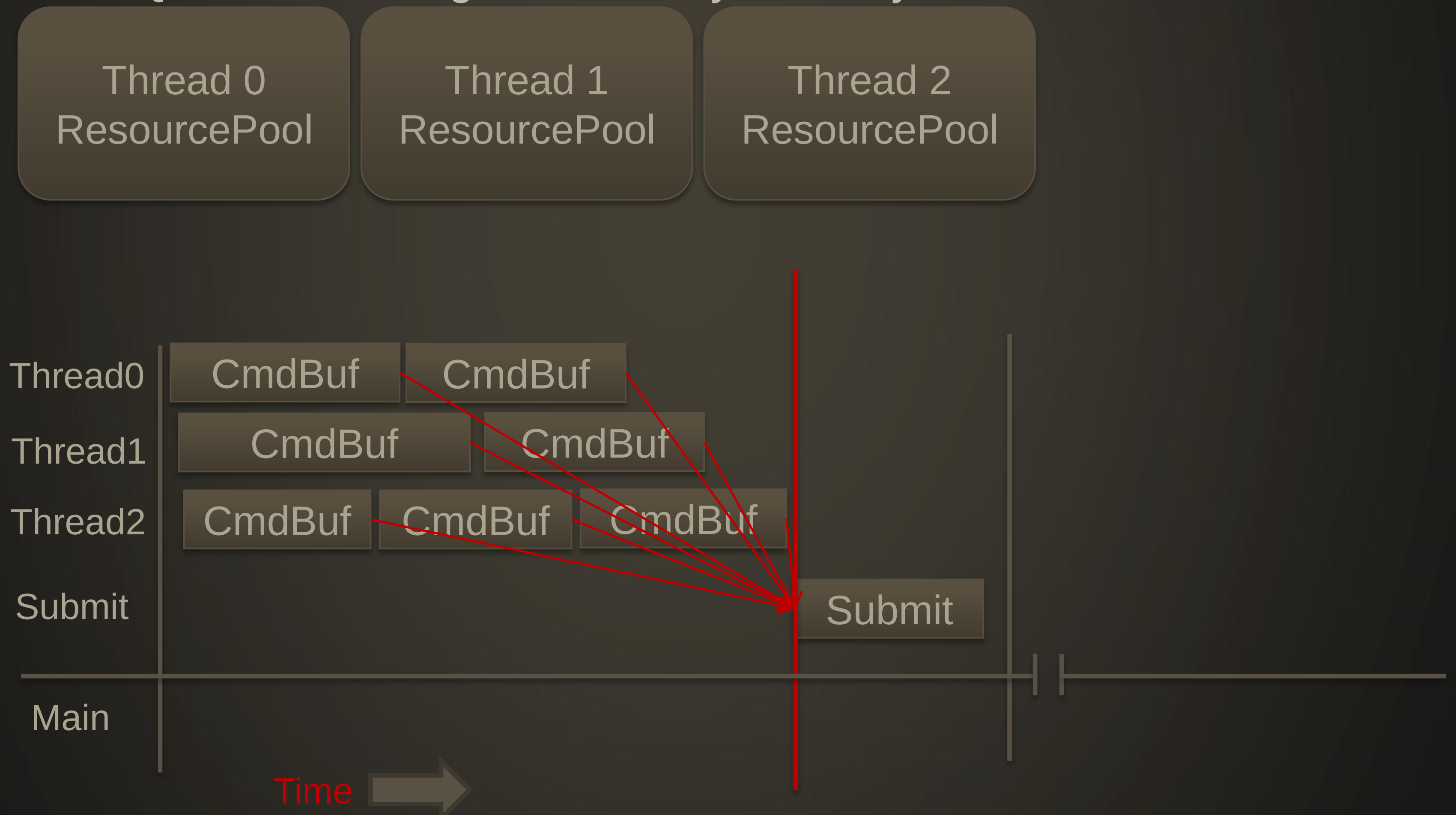
- All work passed to Submit thread via ThreadSafe Queue. Ordering is effectively arbitrary.



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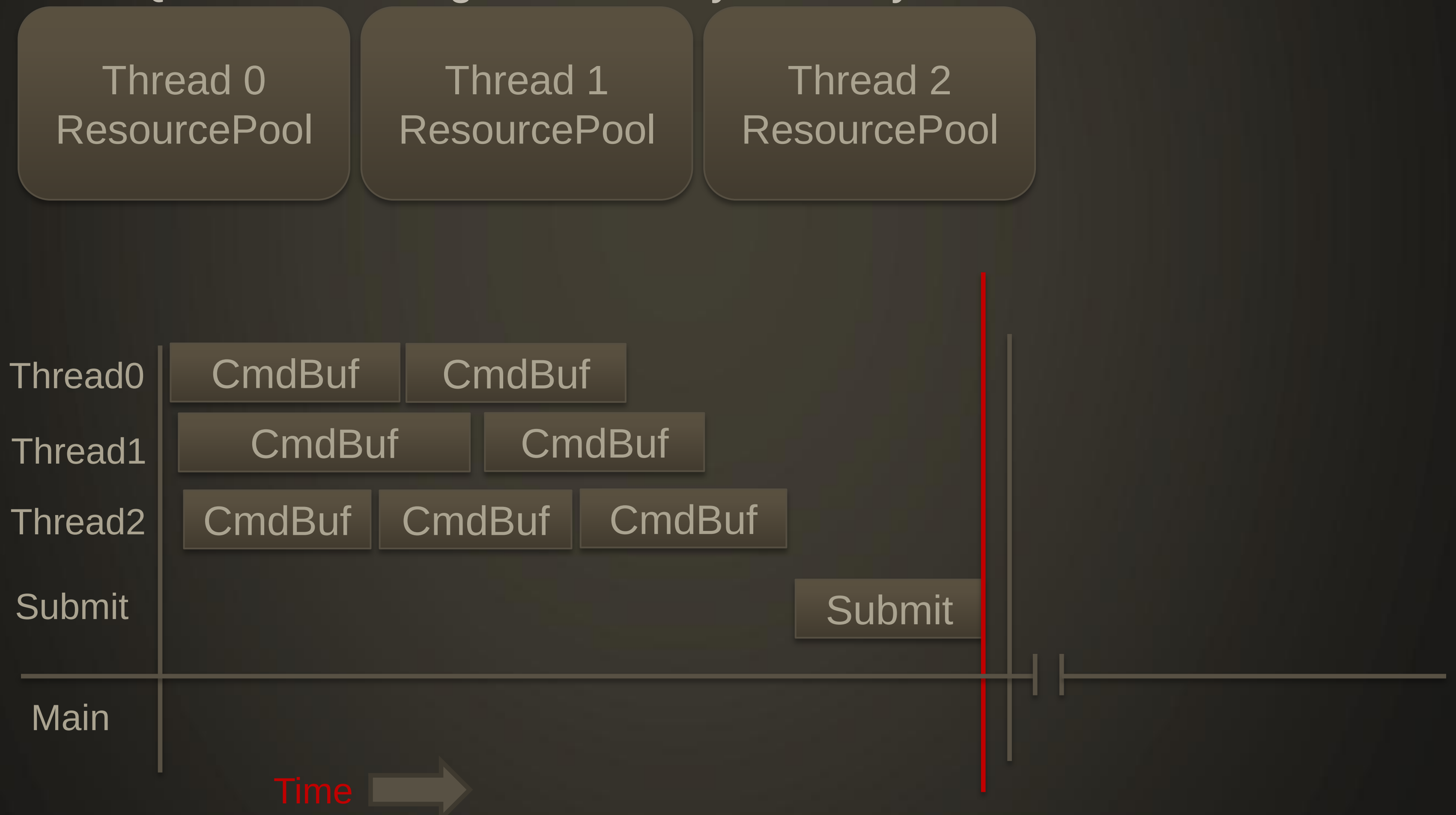

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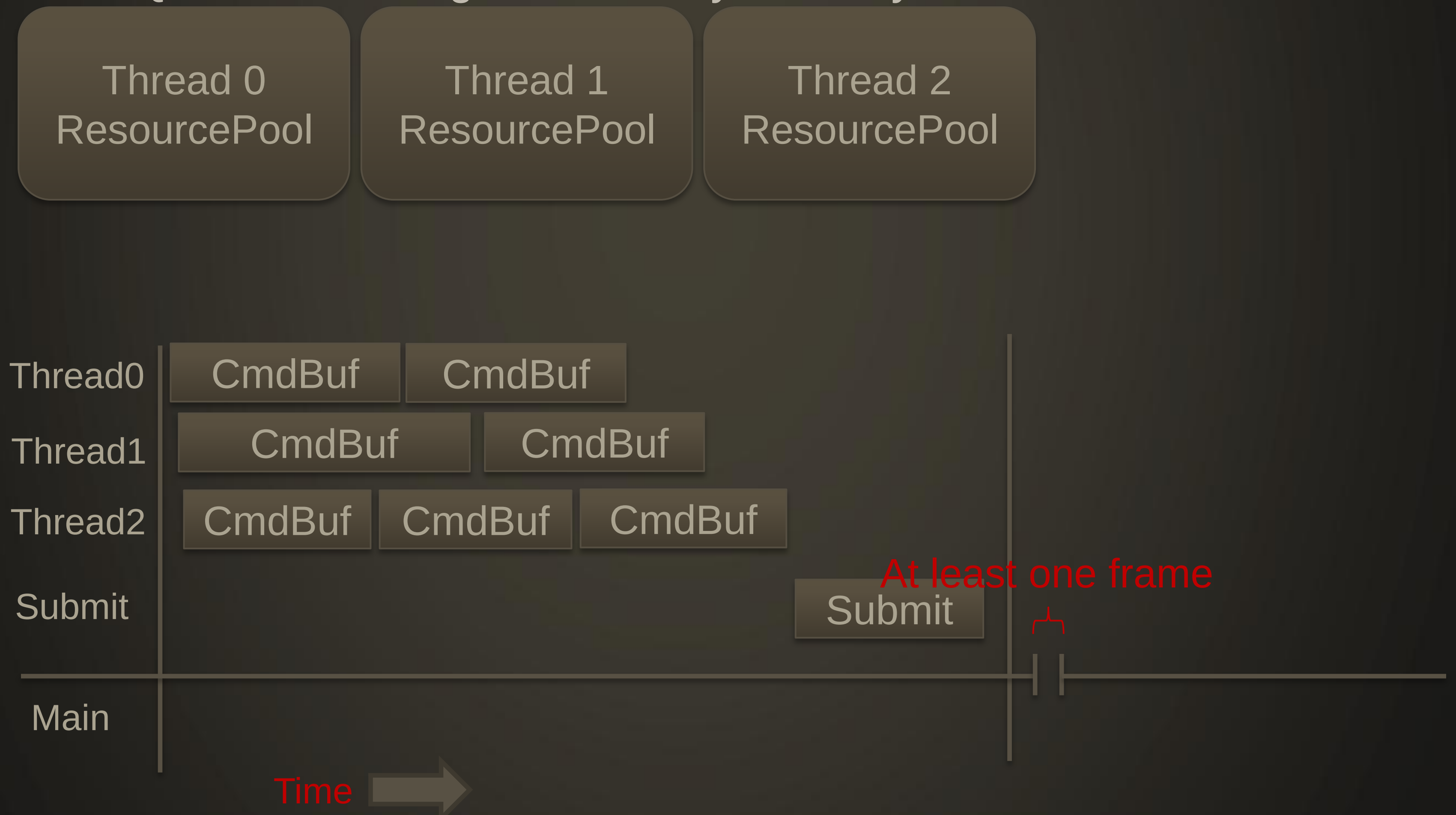
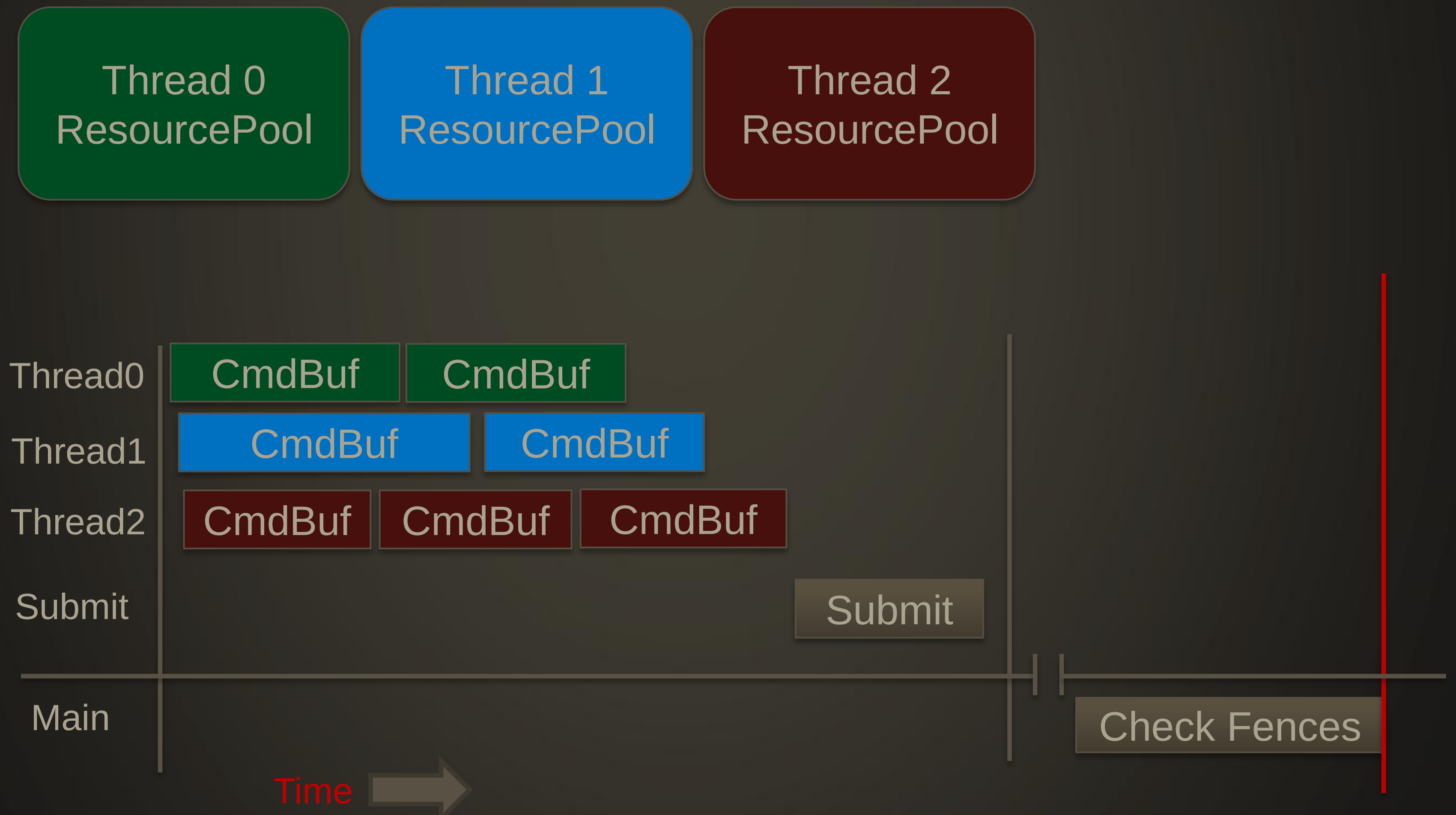


Command Buffer Allocation and Reuse

- Recycle **`VkCommandBuffer`** back to the thread they came from for next time.



Command Buffer Performance

- Submit in batches
  - `vkQueueSubmit` flushes—so generally 1-2 per frame max.
  - Faster to group submissions together
- Minimize number of command buffers
  - We are still investigating how to decrease our count
- Use `VK_CMD_BUFFER_OPTIMIZE_ONE_TIME_SUBMIT_BIT`
  - Optimize for one-time submission

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Pipeline Core Concepts

- All Pipeline state data is encapsulated in a reusable `VkPipeline` object.
  - Which Shaders are set and active
  - Stencil Test
  - Scissor Mode
  - Blend State
  - etc
- A `VkPipeline` is created by calling `vkCreateGraphicsPipelines` or `vkCreateComputePipelines`.
  - Creation of these may be **very** expensive, the cost may be alleviated by using `VkPipelineCache` objects.
- Once created a `VkPipeline` is immutable, but can be used from many threads at once.

VkPipelineCache

- `VkPipelineCache` is ARB_program_binary for Vulkan.
- Load from disk
- Give to Vulkan
- Makes `VkPipeline` creation magically faster (~20x faster)
- Before shutdown
  - Ask size
  - Get bytes from Vulkan
  - Write to disk

- Dota 2 Reborn’s `VkPipelineCache` is ~4 MB on disk.

Efficient Pipeline Construction

- Problem: Need efficient access to `VkPipeline`s from many threads at once
- Bonus Problem: `VkPipeline`s may be large, don't want to multiply cost by N threads.
- Solution: Two Tiered Cache
  - Two Pipeline Maps
    - 1 Read Only Pipeline Map (Current)
    - 1 Read/Write Pipeline Map (Pending)

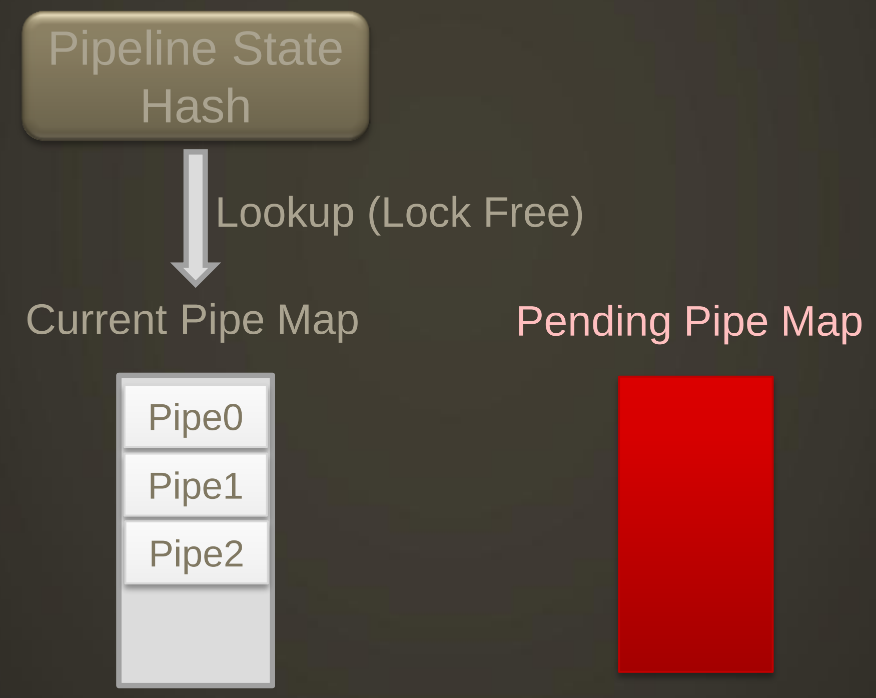
Pipeline State Creation Visualized

- Application is issuing D3D11-like rendering commands…

Pipeline State Hash

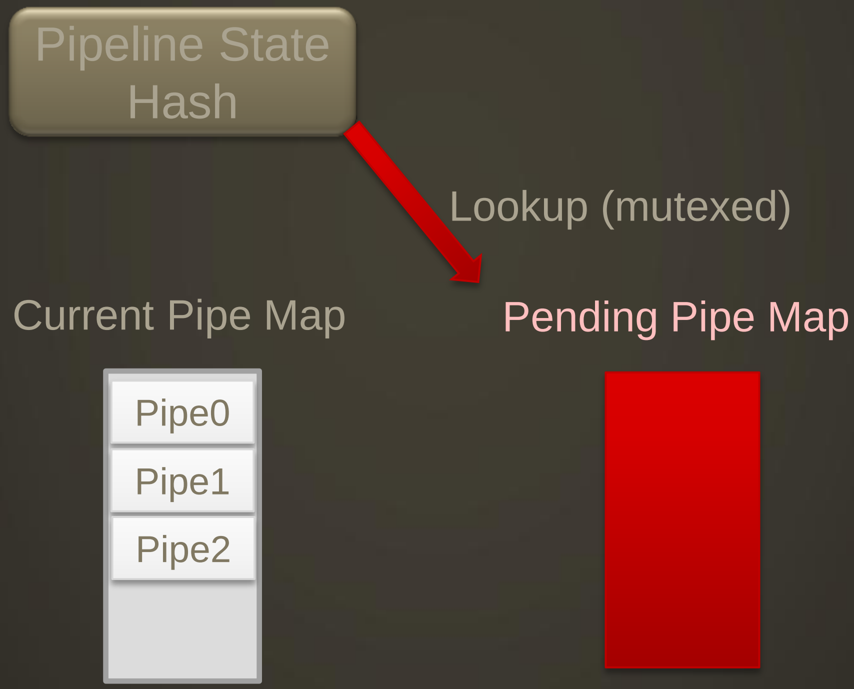
Pipeline State Creation Visualized

- At draw time, state is hashed. Current cache is checked for existing `VkPipeline`.



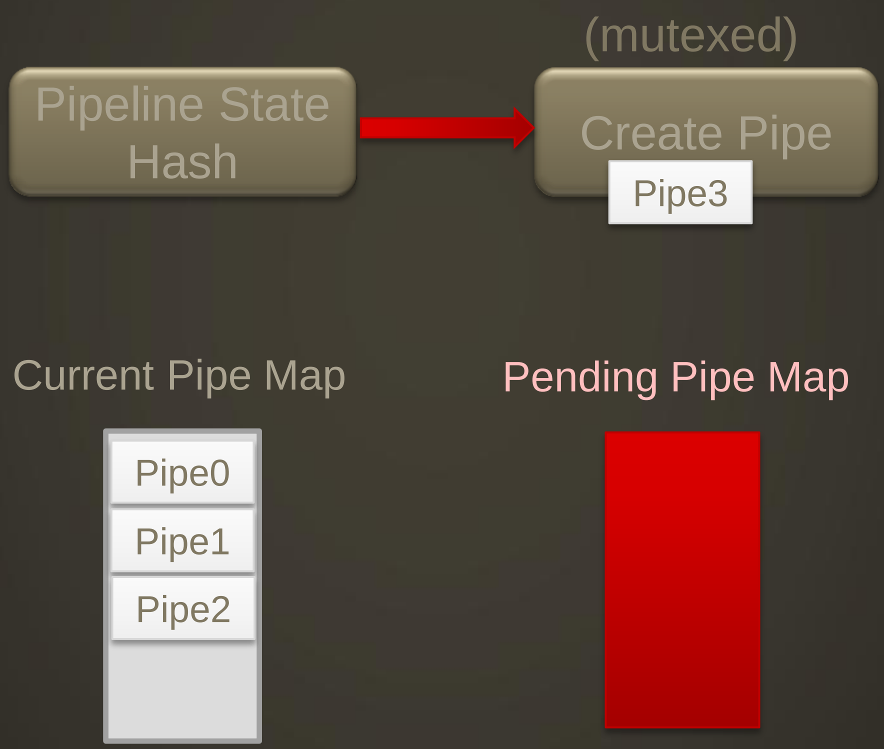
Pipeline State Creation Visualized

- If doesn't exist in Current, lock is grabbed and Pending cache is checked.



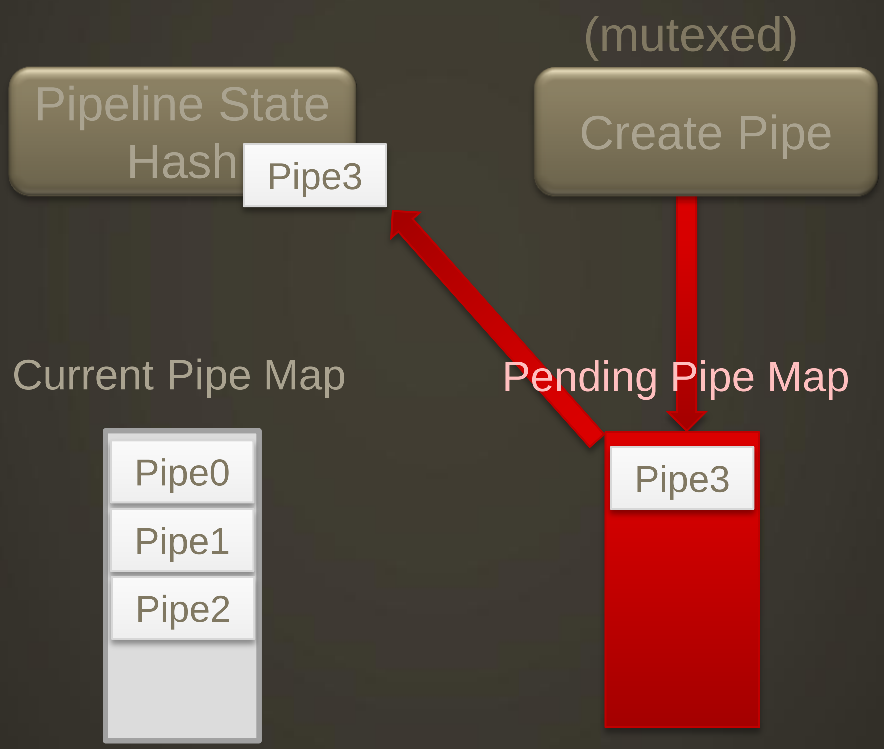
Pipeline State Creation Visualized

- Still can’t find it—create now.



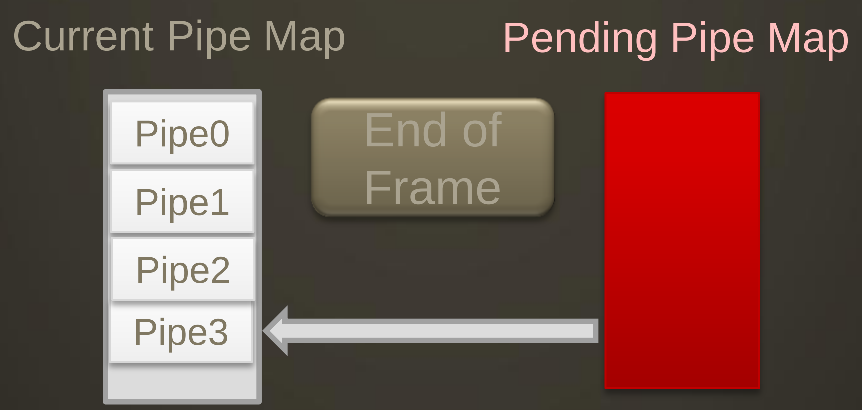
Pipeline State Creation Visualized

- Push into Pending Pipe Map, and return to caller



Pipeline State Creation Visualized

- During serial portion of frame, Current is updated with the contents of Pending.



Two Tier Pipeline Caching System

- This somewhat elaborate strategy reduces mutexing tremendously (to nearly 0 once we're a few frames in)
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  - Currently, only one **`VkPipeline`** will be created at a time (because of the mutex)
  - Could create Reservation for pending **`VkPipeline`** but release mutex
  - Other threads would only block if they were waiting for that specific Reservation to be satisfied.

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  - Could create Reservation for pending `VkPipeline` but release mutex
  - Other threads would only block if they were waiting for that specific Reservation to be satisfied.
- In practice, we don't see this causing stalls, so haven't implemented—largely because `VkPipelineCache` makes construction cheap after the first run

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Descriptor Core Concepts

- No exact analog in D3D9/11.
- Shader accessible resources are represented by **`VkDescriptor`**s
  - **`VkDescriptor`** are arranged in Sets
  - Sets are allocated from Pools
  - Sets have Layouts, known at Pipeline creation time

```
vkCreateDescriptorPool(...);
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```

- Layouts can be thought of as shader ABI.
- DescriptorSet is a concrete set of parameters being passed into the shader.

Sellers, Graham. “A Whirlwind Tour of Vulkan.” Siggraph 2015. Los Angeles Convention Center, Los Angeles, CA. 11 August 2015. Conference Presentation.

Descriptor Set Updates - Ideal

- Allocate and bake descriptor sets up front
- Group sets by frequency
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- Group sets by frequency
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- This has been roughly the advice since Direct3D 10
- But APIs don’t *require* it (nor does Vulkan)

DescriptorSet - Reality

- Difficult to bake descriptors with Direct3D 11-like abstraction
- Our approach
  - Pre-allocate descriptor sets with fixed slots
  - Only bind to used slots
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  - Only bind to used slots
  - Update descriptors each draw

- This is a performance problem for us, but not yet clear how much.

How Much Performance Lost?

- Not actually sure.
- To answer the question requires changing the abstraction.
  - Chicken => Egg => Chicken => …
- And changing the abstraction requires significant effort for unknown gains.

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General Strategies

- Pool resources together
  - Sub-allocate from large pools
- Use per-thread pools to reduce contention
- Recycle dynamic pools on frame boundaries

Resources – Current strategy

Static Resources	Dynamic Resources

• Global Pools
• Device Only
• Textures/Render Targets
    • 128MB Pools
• VB/IB/CBs
    • 8MB Pools
	• Per-Thread Pools
	• Host Visible (Persistently Mapped)
	• VB/IB/CBs
	    • 8MB Pools

Dynamic Vertex/Index Buffers

- To update:
  - Grab new offset from per-thread pool
  - memcpy into pool
  - Bind VBs with: **`vkCmdBindVertexBuffers`**(..,buffer,offset)
  - Bind IBs with: **`vkCmdBindIndexBuffer`**(..,buffer,offset,..)
- Recycle pools when last GPU fence of frame retires

http://www.slideshare.net/basisspace/efficient-buffer-management

Dynamic Uniform Buffers

- Differences from VB/IBs:
  - UBOs are bound via descriptors
  - Use dynamic UBOs to avoid `vkUpdateDescriptors`
  - Pass UBO offset to `vkCmdBindDescriptorSets`

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Image Core Concepts

- ID3D11Texture == `VkImage`
- Images are created in fiveish steps:
  1. The image header is created using `vkCreateImage`
  2. The data store is suballocated from an appropriate pool
  3. The data store is bound to the header via `vkBindImageMemory`
  4. The image is transitioned to `VK_IMAGE_LAYOUT_GENERAL`
  5. The image is filled from a staging buffer using `vkCmdCopyBufferToImage`
- Initial (pool) allocation can be expensive (100s µs).
  - Suballocation is cheap (100s ns)
  - Binding also cheap (100s ns)
- Can reuse same data store for different purposes in different parts of the frame.
  - Huge memory savings!

Five_{ish}?

- Glossed over “some” details in step 5.

Five~ish~?

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```
const ImageFormatInfo_t &fmt = ImageLoader::ImageFormatInfo( nDstFormat );
int nMinDimension = fmt.m_bIsCompressed ? 4 : 1;

int nRegion = 0;
VkBufferImageCopy *pRegions = new VkBufferImageCopy[ nMipmapCount * nArrayCount ];
VkDeviceSize nOffset = nDataSize;
for ( int nMip = 0; nMip < nMipmapCount; nMip++ )
{
    for ( int a = nArrayCount - 1; a >= 0; a-- )
    {
        int nMipDataSize = ImageLoader::GetMemRequired( nWidth, nHeight, nDepth, 1, nDstFormat );
        nOffset -= nMipDataSize;
        Assert( nOffset >= 0 );
        pRegions[ nRegion ].bufferOffset = nOffset; // We store mip levels in reverse order, from smallest to highest
        pRegions[ nRegion ].bufferRowLength = 0;
        pRegions[ nRegion ].bufferImageHeight = 0;
        pRegions[ nRegion ].imageSubresource.baseArrayLayer = a;
        pRegions[ nRegion ].imageSubresource.layerCount = 1;
        pRegions[ nRegion ].imageSubresource.mipLevel = nMip;
        pRegions[ nRegion ].imageSubresource.aspectMask = VK_IMAGE_ASPECT_COLOR_BIT;
        pRegions[ nRegion ].imageOffset.x = 0;
        pRegions[ nRegion ].imageOffset.y = 0;
        pRegions[ nRegion ].imageOffset.z = 0;
        if ( fmt.m_bIsCompressed )
        {
            pRegions[ nRegion ].imageExtent.width = MAX( nMinDimension, nWidth );
            pRegions[ nRegion ].imageExtent.height = MAX( nMinDimension, nHeight );
        }
        else
        {
            pRegions[ nRegion ].imageExtent.width = nWidth;
            pRegions[ nRegion ].imageExtent.height = nHeight;
        }
        pRegions[ nRegion ].imageExtent.depth = nDepth;
        nRegion++;
    }
    nWidth = MAX( nMinDimension, nWidth >> 1 );
    nHeight = MAX( nMinDimension, nHeight >> 1 );
    if ( bIsVolumeTexture )
    {
        nDepth = MAX( nMinDimension, nDepth >> 1 );
    }
}

// Add memory reference to the image object
pCommandBuffer->m_memRefs.AddMemoryReference( pVulkanImage->m_pGPUMemory );

// Transition memory to data transfer state
//VK_TODO - could transition subresources instead of whole resource for better performance
pCommandBuffer->m_memRefs.AddImageTransition( this, pCommandBuffer->m_pCmdBuffer, pVulkanImage, 0, VK_REMAINING_MIP_LEVELS, 0, VK_REMAINING_ARRAY_LAYERS, VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL,
    RENDER_MULTISAMPLE_NONE, false );

// Add the resource as a per-command buffer staging resource so that it is marked for free after the command buffer is
// submitted
pCommandBuffer->m_memRefs.AddTransientGPUMemoryReference( pGPUStagingMemory );
pCommandBuffer->m_memRefs.AddTransientBufferReference( pStagingBuffer );

VkImageLayout nLayout = g_pRenderDeviceVulkan->UseImageLayoutGeneral() ? VK_IMAGE_LAYOUT_GENERAL : VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL;
vkCmdCopyBufferToImage( pCommandBuffer->m_pCmdBuffer, pStagingBuffer, pVulkanImage->m_pImage, nLayout, nRegion, pRegions );
```

Five_{ish}?

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pCommandBuffer->m_memRefs.AddTransientBufferReference( pStagingBuffer );

VkImageLayout nLayout = g_pRenderDeviceVulkan->UseImageLayoutGeneral() ? VK_IMAGE_LAYOUT_GENERAL : VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL;
vkCmdCopyBufferToImage( pCommandBuffer->m_pCmdBuffer, pStagingBuffer, pVulkanImage->m_pImage, nLayout, nRegion, pRegions );
```

Fiveish?

- Glossed over “some” details in step 5.

```
const ImageFormatInfo_t &fmt = ImageLoader::ImageFormatInfo( nDstFormat );
int nMinDimension = fmt.m_bIsCompressed ? 4 : 1;

int nRegion = 0;
VkBufferImageCopy *pRegions = new VkBufferImageCopy[ nMipmapCount * nArrayCount ];
VkDeviceSize nOffset = nDataSize;
for ( int nMip = 0; nMip < nMipmapCount; nMip++ )
{
    for ( int a = nArrayCount - 1; a >= 0; a-- )
    {
        int nMipDataSize = ImageLoader::GetMemRequired( nWidth, nHeight, nDepth, 1, nDstFormat );
        nOffset -= nMipDataSize;
        Assert( nOffset >= 0 );
        pRegions[ nRegion ].bufferOffset = nOffset; // We store mip levels in reverse order, from smallest to highest
        pRegions[ nRegion ].bufferRowLength = 0;
        pRegions[ nRegion ].bufferImageHeight = 0;
        pRegions[ nRegion ].imageSubresource.baseArrayLayer = a;
        pRegions[ nRegion ].imageSubresource.layerCount = 1;
        pRegions[ nRegion ].imageSubresource.mipLevel = nMip;
        pRegions[ nRegion ].imageSubresource.aspectMask = VK_IMAGE_ASPECT_COLOR_BIT;
        pRegions[ nRegion ].imageOffset.x = 0;
        pRegions[ nRegion ].imageOffset.y = 0;
        pRegions[ nRegion ].imageOffset.z = 0;
        if ( fmt.m_bIsCompressed )
        {
            pRegions[ nRegion ].imageExtent.width = MAX( nMinDimension, nWidth );
            pRegions[ nRegion ].imageExtent.height = MAX( nMinDimension, nHeight );
        }
        else
        {
            pRegions[ nRegion ].imageExtent.width = nWidth;
            pRegions[ nRegion ].imageExtent.height = nHeight;
        }
        pRegions[ nRegion ].imageExtent.depth = nDepth;
        nRegion++;
    }
    nWidth = MAX( nMinDimension, nWidth >> 1 );
    nHeight = MAX( nMinDimension, nHeight >> 1 );
    if ( bIsVolumeTexture )
    {
        nDepth = MAX( nMinDimension, nDepth >> 1 );
    }
}

// Add memory reference to the image object
pCommandBuffer->m_memRefs.AddMemoryReference( pVulkanImage->m_pGPUMemory );

// Transition memory to data transfer state
//VK_TODO - could transition subresources instead of whole resource for better performance
pCommandBuffer->m_memRefs.AddImageTransition( this, pCommandBuffer->m_pCmdBuffer, pVulkanImage, 0, VK_REMAINING_MIP_LEVELS, 0, VK_REMAINING_ARRAY_LAYERS, VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL,
    RENDER_MULTISAMPLE_NONE, false );

// Add the resource as a per-command buffer staging resource so that it is marked for free after the command buffer is
// submitted
pCommandBuffer->m_memRefs.AddTransientGPUMemoryReference( pGPUStagingMemory );
pCommandBuffer->m_memRefs.AddTransientBufferReference( pStagingBuffer );

VkImageLayout nLayout = g_pRenderDeviceVulkan->UseImageLayoutGeneral() ? VK_IMAGE_LAYOUT_GENERAL : VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL;
vkCmdCopyBufferToImage( pCommandBuffer->m_pCmdBuffer, pStagingBuffer, pVulkanImage->m_pImage, nLayout, nRegion, pRegions );
```

Fiveish?

- Glossed over "some" details in step 5.

```cpp
const ImageFormatInfo_t &fmt = ImageLoader::ImageFormatInfo( nDstFormat );
int nMinDimension = fmt.m_bIsCompressed ? 4 : 1;

int nRegion = 0;
VkBufferImageCopy *pRegions = new VkBufferImageCopy[ nMipmapCount * nArrayCount ];
VkDeviceSize nOffset = nDataSize;
for ( int nMip = 0; nMip < nMipmapCount; nMip++ )
{
    for ( int a = nArrayCount - 1; a >= 0; a-- )
    {
        int nMipDataSize = ImageLoader::GetMemRequired( nWidth, nHeight, nDepth, 1, nDstFormat );
        nOffset -= nMipDataSize;
        Assert( nOffset >= 0 );
        pRegions[ nRegion ].bufferOffset = nOffset; // We store mip levels in reverse order, from smallest to highest
        pRegions[ nRegion ].bufferRowLength = 0;
        pRegions[ nRegion ].bufferImageHeight = 0;
        pRegions[ nRegion ].imageSubresource.baseArrayLayer = a;
        pRegions[ nRegion ].imageSubresource.layerCount = 1;
        pRegions[ nRegion ].imageSubresource.mipLevel = nMip;
        pRegions[ nRegion ].imageSubresource.aspectMask = VK_IMAGE_ASPECT_COLOR_BIT;
        pRegions[ nRegion ].imageOffset.x = 0;
        pRegions[ nRegion ].imageOffset.y = 0;
        pRegions[ nRegion ].imageOffset.z = 0;
        if ( fmt.m_bIsCompressed )
        {
            pRegions[ nRegion ].imageExtent.width = MAX( nMinDimension, nWidth );
            pRegions[ nRegion ].imageExtent.height = MAX( nMinDimension, nHeight );
        }
        else
        {
            pRegions[ nRegion ].imageExtent.width = nWidth;
            pRegions[ nRegion ].imageExtent.height = nHeight;
        }
        pRegions[ nRegion ].imageExtent.depth = nDepth;
        nRegion++;
    }
    nWidth = MAX( nMinDimension, nWidth >> 1 );
    nHeight = MAX( nMinDimension, nHeight >> 1 );
    if ( bIsVolumeTexture )
    {
        nDepth = MAX( nMinDimension, nDepth >> 1 );
    }
}

// Add memory reference to the image object
pCommandBuffer->m_memRefs.AddMemoryReference( pVulkanImage->m_pGPUMemory );

// Transition memory to data transfer state
//VK_TODO - could transition subresources instead of whole resource for better performance
pCommandBuffer->m_memRefs.AddImageTransition( this, pCommandBuffer->m_pCmdBuffer, pVulkanImage, 0, VK_REMAINING_MIP_LEVELS, 0, VK_REMAINING_ARRAY_LAYERS, VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL,
    RENDER_MULTISAMPLE_NONE, false );

// Add the resource as a per-command buffer staging resource so that it is marked for free after the command buffer is
// submitted
pCommandBuffer->m_memRefs.AddTransientGPUMemoryReference( pGPUStagingMemory );
pCommandBuffer->m_memRefs.AddTransientBufferReference( pStagingBuffer );

VkImageLayout nLayout = g_pRenderDeviceVulkan->UseImageLayoutGeneral() ? VK_IMAGE_LAYOUT_GENERAL : VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL;
vkCmdCopyBufferToImage( pCommandBuffer->m_pCmdBuffer, pStagingBuffer, pVulkanImage->m_pImage, nLayout, nRegion, pRegions );
```

Five*ish*?

- Glossed over “some” details in step 5.

```
const ImageFormatInfo_t &fmt = ImageLoader::ImageFormatInfo( nDstFormat );
int nMinDimension = fmt.m_bIsCompressed ? 4 : 1;

int nRegion = 0;
VkBufferImageCopy *pRegions = new VkBufferImageCopy[ nMipmapCount * nArrayCount ];
VkDeviceSize nOffset = nDataSize;
for ( int nMip = 0; nMip < nMipmapCount; nMip++ )
{
    for ( int a = nArrayCount - 1; a >= 0; a-- )
    {
        int nMipDataSize = ImageLoader::GetMemRequired( nWidth, nHeight, nDepth, 1, nDstFormat );
        nOffset -= nMipDataSize;
        Assert( nOffset >= 0 );
        pRegions[ nRegion ].bufferOffset = nOffset; // We store mip levels in reverse order, from smallest to highest
        pRegions[ nRegion ].bufferRowLength = 0;
        pRegions[ nRegion ].bufferImageHeight = 0;
        pRegions[ nRegion ].imageSubresource.baseArrayLayer = a;
        pRegions[ nRegion ].imageSubresource.layerCount = 1;
        pRegions[ nRegion ].imageSubresource.mipLevel = nMip;
        pRegions[ nRegion ].imageSubresource.aspectMask = VK_IMAGE_ASPECT_COLOR_BIT;
        pRegions[ nRegion ].imageOffset.x = 0;
        pRegions[ nRegion ].imageOffset.y = 0;
        pRegions[ nRegion ].imageOffset.z = 0;
        if ( fmt.m_bIsCompressed )
        {
            pRegions[ nRegion ].imageExtent.width = MAX( nMinDimension, nWidth );
            pRegions[ nRegion ].imageExtent.height = MAX( nMinDimension, nHeight );
        }
        else
        {
            pRegions[ nRegion ].imageExtent.width = nWidth;
            pRegions[ nRegion ].imageExtent.height = nHeight;
        }
        pRegions[ nRegion ].imageExtent.depth = nDepth;
        nRegion++;
    }
    nWidth = MAX( nMinDimension, nWidth >> 1 );
    nHeight = MAX( nMinDimension, nHeight >> 1 );
    if ( bIsVolumeTexture )
    {
        nDepth = MAX( nMinDimension, nDepth >> 1 );
    }
}

// Add memory reference to the image object
pCommandBuffer->m_memRefs.AddMemoryReference( pVulkanImage->m_pGPUMemory );

// Transition memory to data transfer state
//VK_TODO - could transition subresources instead of whole resource for better performance
pCommandBuffer->m_memRefs.AddImageTransition( this, pCommandBuffer->m_pCmdBuffer, pVulkanImage, 0, VK_REMAINING_MIP_LEVELS, 0, VK_REMAINING_ARRAY_LAYERS, VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL,
    RENDER_MULTISAMPLE_NONE, false );

// Add the resource as a per-command buffer staging resource so that it is marked for free after the command buffer is
// submitted
pCommandBuffer->m_memRefs.AddTransientGPUMemoryReference( pGPUStagingMemory );
pCommandBuffer->m_memRefs.AddTransientBufferReference( pStagingBuffer );

VkImageLayout nLayout = g_pRenderDeviceVulkan->UseImageLayoutGeneral() ? VK_IMAGE_LAYOUT_GENERAL : VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL;
vkCmdCopyBufferToImage( pCommandBuffer->m_pCmdBuffer, pStagingBuffer, pVulkanImage->m_pImage, nLayout, nRegion, pRegions );
```

Five_{ish}?

- Glossed over “some” details in step 5.

```
const ImageFormatInfo_t &fmt = ImageLoader::ImageFormatInfo( nDstFormat );
int nMinDimension = fmt.m_bIsCompressed ? 4 : 1;

int nRegion = 0;
VkBufferImageCopy *pRegions = new VkBufferImageCopy[ nMipmapCount * nArrayCount ];
VkDeviceSize nOffset = nDataSize;
for ( int nMip = 0; nMip < nMipmapCount; nMip++ )
{
    for ( int a = nArrayCount - 1; a >= 0; a-- )
    {
        int nMipDataSize = ImageLoader::GetMemRequired( nWidth, nHeight, nDepth, 1, nDstFormat );
        nOffset -= nMipDataSize;
        Assert( nOffset >= 0 );
        pRegions[ nRegion ].bufferOffset = nOffset; // We store mip levels in reverse order, from smallest to highest
        pRegions[ nRegion ].bufferRowLength = 0;
        pRegions[ nRegion ].bufferImageHeight = 0;
        pRegions[ nRegion ].imageSubresource.baseArrayLayer = a;
        pRegions[ nRegion ].imageSubresource.layerCount = 1;
        pRegions[ nRegion ].imageSubresource.mipLevel = nMip;
        pRegions[ nRegion ].imageSubresource.aspectMask = VK_IMAGE_ASPECT_COLOR_BIT;
        pRegions[ nRegion ].imageOffset.x = 0;
        pRegions[ nRegion ].imageOffset.y = 0;
        pRegions[ nRegion ].imageOffset.z = 0;
        if ( fmt.m_bIsCompressed )
        {
            pRegions[ nRegion ].imageExtent.width = MAX( nMinDimension, nWidth );
            pRegions[ nRegion ].imageExtent.height = MAX( nMinDimension, nHeight );
        }
        else
        {
            pRegions[ nRegion ].imageExtent.width = nWidth;
            pRegions[ nRegion ].imageExtent.height = nHeight;
        }
        pRegions[ nRegion ].imageExtent.depth = nDepth;
        nRegion++;
    }
    nWidth = MAX( nMinDimension, nWidth >> 1 );
    nHeight = MAX( nMinDimension, nHeight >> 1 );
    if ( bIsVolumeTexture )
    {
        nDepth = MAX( nMinDimension, nDepth >> 1 );
    }
}

// Add memory reference to the image object
pCommandBuffer->m_memRefs.AddMemoryReference( pVulkanImage->m_pGPUMemory );

// Transition memory to data transfer state
//VK_TODO - could transition subresources instead of whole resource for better performance
pCommandBuffer->m_memRefs.AddImageTransition( this, pCommandBuffer->m_pCmdBuffer, pVulkanImage, 0, VK_REMAINING_MIP_LEVELS, 0, VK_REMAINING_ARRAY_LAYERS, VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL,
    RENDER_MULTISAMPLE_NONE, false );

// Add the resource as a per-command buffer staging resource so that it is marked for free after the command buffer is
// submitted
pCommandBuffer->m_memRefs.AddTransientGPUMemoryReference( pGPUStagingMemory );
pCommandBuffer->m_memRefs.AddTransientBufferReference( pStagingBuffer );

VkImageLayout nLayout = g_pRenderDeviceVulkan->UseImageLayoutGeneral() ? VK_IMAGE_LAYOUT_GENERAL : VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL;
vkCmdCopyBufferToImage( pCommandBuffer->m_pCmdBuffer, pStagingBuffer, pVulkanImage->m_pImage, nLayout, nRegion, pRegions );
```

Five*ish*?

- Glossed over “some” details in step 5.

```
// Allocate GPU memory for staging resource
VkDeviceMemory pGPUStagingMemory = VK_NULL_HANDLE;
VkBuffer pStagingBuffer = VK_NULL_HANDLE;
g_pRenderDeviceVulkan->MemoryManager()->Allocate( nDataSize,
                                                  VK_MEMORY_PROPERTY_HOST_VISIBLE_BIT,
                                                  VK_BUFFER_USAGE_TRANSFER_SRC_BIT,
                                                  &pGPUStagingMemory,
                                                  &pStagingBuffer );
Assert( pGPUStagingMemory );

// Copy to the GPU staging memory
void *pStagingMemory = NULL;
DOVK( vkMapMemory( m_pDeviceVulkan, pGPUStagingMemory, 0, nDataSize, 0, ( void** ) &pStagingMemory ) );
Assert( pStagingMemory != NULL );
V_memcpy( pStagingMemory, pData, nDataSize );
vkUnmapMemory( m_pDeviceVulkan, pGPUStagingMemory );
```

```
        pRegions[ nRegion ].imageOffset.y = 0;
        pRegions[ nRegion ].imageOffset.z = 0;
        if ( fmt.m_bIsCompressed )
        {
            pRegions[ nRegion ].imageExtent.width = MAX( nMinDimension, nWidth );
            pRegions[ nRegion ].imageExtent.height = MAX( nMinDimension, nHeight );
        }
        else
        {
            pRegions[ nRegion ].imageExtent.width = nWidth;
            pRegions[ nRegion ].imageExtent.height = nHeight;
        }
        pRegions[ nRegion ].imageExtent.depth = nDepth;
        nRegion++;
    }
    nWidth = MAX( nMinDimension, nWidth >> 1 );
    nHeight = MAX( nMinDimension, nHeight >> 1 );
    if ( bIsVolumeTexture )
    {
        nDepth = MAX( nMinDimension, nDepth >> 1 );
    }
}

// Add memory reference to the image object
pCommandBuffer->m_memRefs.AddMemoryReference( pVulkanImage->m_pGPUMemory );

// Transition memory to data transfer state
//VK_TODO - could transition subresources instead of whole resource for better performance
pCommandBuffer->m_memRefs.AddImageTransition( this, pCommandBuffer->m_pCmdBuffer, pVulkanImage, 0, VK_REMAINING_MIP_LEVELS, 0, VK_REMAINING_ARRAY_LAYERS, VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL,
    RENDER_MULTISAMPLE_NONE, false );

// Add the resource as a per-command buffer staging resource so that it is marked for free after the command buffer is
// submitted
pCommandBuffer->m_memRefs.AddTransientGPUMemoryReference( pGPUStagingMemory );
pCommandBuffer->m_memRefs.AddTransientBufferReference( pStagingBuffer );

VkImageLayout nLayout = g_pRenderDeviceVulkan->UseImageLayoutGeneral() ? VK_IMAGE_LAYOUT_GENERAL : VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL;
vkCmdCopyBufferToImage( pCommandBuffer->m_pCmdBuffer, pStagingBuffer, pVulkanImage->m_pImage, nLayout, nRegion, pRegions );
```

Five_{ish}?

- Glossed over “some” details in step 5.

```
// Allocate GPU memory for staging resource
VkDeviceMemory pGPUStagingMemory = VK_NULL_HANDLE;
VkBuffer pStagingBuffer = VK_NULL_HANDLE;
g_pRenderDeviceVulkan->MemoryManager()->Allocate( nDataSize,
                                                  VK_MEMORY_PROPERTY_HOST_VISIBLE_BIT,
                                                  VK_BUFFER_USAGE_TRANSFER_SRC_BIT,
                                                  &pGPUStagingMemory,
                                                  &pStagingBuffer );
Assert( pGPUStagingMemory );

// Copy to the GPU staging memory
void *pStagingMemory = NULL;
DOVK( vkMapMemory( m_pDeviceVulkan, pGPUStagingMemory, 0, nDataSize, 0, ( void** ) &pStagingMemory ) );
Assert( pStagingMemory != NULL );
V_memcpy( pStagingMemory, pData, nDataSize );
vkUnmapMemory( m_pDeviceVulkan, pGPUStagingMemory );
```

```
        pRegions[ nRegion ].imageOffset.y = 0;
        pRegions[ nRegion ].imageOffset.z = 0;
        if ( fmt.m_bIsCompressed )
        {
            pRegions[ nRegion ].imageExtent.width = MAX( nMinDimension, nWidth );
            pRegions[ nRegion ].imageExtent.height = MAX( nMinDimension, nHeight );
        }
        else
        {
            pRegions[ nRegion ].imageExtent.width = nWidth;
            pRegions[ nRegion ].imageExtent.height = nHeight;
        }
        pRegions[ nRegion ].imageExtent.depth = nDepth;
        nRegion++;
    }
    nWidth = MAX( nMinDimension, nWidth >> 1 );
    nHeight = MAX( nMinDimension, nHeight >> 1 );
    if ( bIsVolumeTexture )
    {
        nDepth = MAX( nMinDimension, nDepth >> 1 );
    }
}

// Add memory reference to the image object
pCommandBuffer->m_memRefs.AddMemoryReference( pVulkanImage->m_pGPUMemory );

// Transition memory to data transfer state
//VK_TODO - could transition subresources instead of whole resource for better performance
pCommandBuffer->m_memRefs.AddImageTransition( this, pCommandBuffer->m_pCmdBuffer, pVulkanImage, 0, VK_REMAINING_MIP_LEVELS, 0, VK_REMAINING_ARRAY_LAYERS, VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL,
    RENDER_MULTISAMPLE_NONE, false );

// Add the resource as a per-command buffer staging resource so that it is marked for free after the command buffer is
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pCommandBuffer->m_memRefs.AddTransientGPUMemoryReference( pGPUStagingMemory );
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VkImageLayout nLayout = g_pRenderDeviceVulkan->UseImageLayoutGeneral() ? VK_IMAGE_LAYOUT_GENERAL : VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL;
vkCmdCopyBufferToImage( pCommandBuffer->m_pCmdBuffer, pStagingBuffer, pVulkanImage->m_pImage, nLayout, nRegion, pRegions );
```

Five*ish*?

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```
// Allocate GPU memory for staging resource
VkDeviceMemory pGPUStagingMemory = VK_NULL_HANDLE;
VkBuffer pStagingBuffer = VK_NULL_HANDLE;
g_pRenderDeviceVulkan->MemoryManager()->Allocate( nDataSize,
                                                  VK_MEMORY_PROPERTY_HOST_VISIBLE_BIT,
                                                  VK_BUFFER_USAGE_TRANSFER_SRC_BIT,
                                                  &pGPUStagingMemory,
                                                  &pStagingBuffer );
Assert( pGPUStagingMemory );

// Copy to the GPU staging memory
void *pStagingMemory = NULL;
DOVK( vkMapMemory( m_pDeviceVulkan, pGPUStagingMemory, 0, nDataSize, 0, ( void** ) &pStagingMemory ) );
Assert( pStagingMemory != NULL );
V_memcpy( pStagingMemory, pData, nDataSize );
vkUnmapMemory( m_pDeviceVulkan, pGPUStagingMemory );
```

```
        pRegions[ nRegion ].imageOffset.y = 0;
        pRegions[ nRegion ].imageOffset.z = 0;
        if ( fmt.m_bIsCompressed )
        {
            pRegions[ nRegion ].imageExtent.width = MAX( nMinDimension, nWidth );
            pRegions[ nRegion ].imageExtent.height = MAX( nMinDimension, nHeight );
        }
        else
        {
            pRegions[ nRegion ].imageExtent.width = nWidth;
            pRegions[ nRegion ].imageExtent.height = nHeight;
        }
        pRegions[ nRegion ].imageExtent.depth = nDepth;
        nRegion++;
    }
    nWidth = MAX( nMinDimension, nWidth >> 1 );
    nHeight = MAX( nMinDimension, nHeight >> 1 );
    if ( bIsVolumeTexture )
    {
        nDepth = MAX( nMinDimension, nDepth >> 1 );
    }
}

// Add memory reference to the image object
pCommandBuffer->m_memRefs.AddMemoryReference( pVulkanImage->m_pGPUMemory );

// Transition memory to data transfer state
//VK_TODO - could transition subresources instead of whole resource for better performance
pCommandBuffer->m_memRefs.AddImageTransition( this, pCommandBuffer->m_pCmdBuffer, pVulkanImage, 0, VK_REMAINING_MIP_LEVELS, 0, VK_REMAINING_ARRAY_LAYERS, VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL,
    RENDER_MULTISAMPLE_NONE, false );

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VkImageLayout nLayout = g_pRenderDeviceVulkan->UseImageLayoutGeneral() ? VK_IMAGE_LAYOUT_GENERAL : VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL;
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```
// Allocate GPU memory for staging resource
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                                                  &pGPUStagingMemory,
                                                  &pStagingBuffer );
Assert( pGPUStagingMemory );

// Copy to the GPU staging memory
void *pStagingMemory = NULL;
DOVK( vkMapMemory( m_pDeviceVulkan, pGPUStagingMemory, 0, nDataSize, 0, ( void** ) &pStagingMemory ) );
Assert( pStagingMemory != NULL );
V_memcpy( pStagingMemory, pData, nDataSize );
vkUnmapMemory( m_pDeviceVulkan, pGPUStagingMemory );
```

```
            pRegions[ nRegion ].imageOffset.y = 0;
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            if ( fmt.m_bIsCompressed )
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                pRegions[ nRegion ].imageExtent.height = nHeight;
            }
            pRegions[ nRegion ].imageExtent.depth = nDepth;
            nRegion++;
        }
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        {
            nDepth = MAX( nMinDimension, nDepth >> 1 );
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}

// Add memory reference to the image object
pCommandBuffer->m_memRefs.AddMemoryReference( pVulkanImage->m_pGPUMemory );

// Transition memory to data transfer state
//VK_TODO - could transition subresources instead of whole resource for better performance
pCommandBuffer->m_memRefs.AddImageTransition( this, pCommandBuffer->m_pCmdBuffer, pVulkanImage, 0, VK_REMAINING_MIP_LEVELS, 0, VK_REMAINING_ARRAY_LAYERS, VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL,
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// submitted
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VkImageLayout nLayout = g_pRenderDeviceVulkan->UseImageLayoutGeneral() ? VK_IMAGE_LAYOUT_GENERAL : VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL;
vkCmdCopyBufferToImage( pCommandBuffer->m_pCmdBuffer, pStagingBuffer, pVulkanImage->m_pImage, nLayout, nRegion, pRegions );
```

Five*ish*?

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```
// Allocate GPU memory for staging resource
VkDeviceMemory pGPUStagingMemory = VK_NULL_HANDLE;
VkBuffer pStagingBuffer = VK_NULL_HANDLE;
g_pRenderDeviceVulkan->MemoryManager()->Allocate( nDataSize,
                                                  VK_MEMORY_PROPERTY_HOST_VISIBLE_BIT,
                                                  VK_BUFFER_USAGE_TRANSFER_SRC_BIT,
                                                  &pGPUStagingMemory,
                                                  &pStagingBuffer );
Assert( pGPUStagingMemory );

// Copy to the GPU staging memory
void *pStagingMemory = NULL;
DOVK( vkMapMemory( m_pDeviceVulkan, pGPUStagingMemory, 0, nDataSize, 0, ( void** ) &pStagingMemory ) );
Assert( pStagingMemory != NULL );
V_memcpy( pStagingMemory, pData, nDataSize );
vkUnmapMemory( m_pDeviceVulkan, pGPUStagingMemory );
```

```
        pRegions[ nRegion ].imageOffset.y = 0;
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        if ( fmt.m_bIsCompressed )
        {
            pRegions[ nRegion ].imageExtent.width = MAX( nMinDimension, nWidth );
            pRegions[ nRegion ].imageExtent.height = MAX( nMinDimension, nHeight );
        }
        else
        {
            pRegions[ nRegion ].imageExtent.width = nWidth;
            pRegions[ nRegion ].imageExtent.height = nHeight;
        }
        pRegions[ nRegion ].imageExtent.depth = nDepth;
        nRegion++;
    }
    nWidth = MAX( nMinDimension, nWidth >> 1 );
    nHeight = MAX( nMinDimension, nHeight >> 1 );
    if ( bIsVolumeTexture )
    {
        nDepth = MAX( nMinDimension, nDepth >> 1 );
    }
}

// Add memory reference to the image object
pCommandBuffer->m_memRefs.AddMemoryReference( pVulkanImage->m_pGPUMemory );

// Transition memory to data transfer state
//VK_TODO - could transition subresources instead of whole resource for better performance
pCommandBuffer->m_memRefs.AddImageTransition( this, pCommandBuffer->m_pCmdBuffer, pVulkanImage, 0, VK_REMAINING_MIP_LEVELS, 0, VK_REMAINING_ARRAY_LAYERS, VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL,
    RENDER_MULTISAMPLE_NONE, false );

// Add the resource as a per-command buffer staging resource so that it is marked for free after the command buffer is
// submitted
pCommandBuffer->m_memRefs.AddTransientGPUMemoryReference( pGPUStagingMemory );
pCommandBuffer->m_memRefs.AddTransientBufferReference( pStagingBuffer );

VkImageLayout nLayout = g_pRenderDeviceVulkan->UseImageLayoutGeneral() ? VK_IMAGE_LAYOUT_GENERAL : VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL;
vkCmdCopyBufferToImage( pCommandBuffer->m_pCmdBuffer, pStagingBuffer, pVulkanImage->m_pImage, nLayout, nRegion, pRegions );
```

Mo' Copies Mo' Problems

- Asking to do a large allocation just-in-time (staging buffer)
- Extra copies of texture data make me sad
  1. Load in raw bits from disk into host memory.
  2. Convert to usable GPU format.
  3. Copy into Staging Buffer.
- This could be reduced by 1 (and usually 2 copies)!
  - ie, read directly from disk into a GPU accessible buffer!

Better Image Data Downloads

- Apply GL Concepts to Vulkan
  - Pixel Buffer Objects (PBO)
  - Persistently Mapped Buffers (PMB)
- PBO + PMB = “malloc’d” staging memory
- Suballocation wins again!

Better Image Data Downloads

- In the Renderer
  - At the beginning of time, allocate a single staging buffer with the `VK_MEMORY_PROPERTY_HOST_VISIBLE_BIT` and `VK_BUFFER_USAGE_TRANSFER_SRC_BIT`.
  - Map it
- In loading code
  - Read in image header from disk
  - Ask Renderer whether format can be directly consumed
  - If so, ask Renderer for allocation to read image bytes into
  - Once data has been read, notify Renderer
- No extra maps!
- No large allocations during image streaming!

Better Image Data Downloads

- In the Renderer
  - At the beginning of time, allocate a single staging buffer with the `VK_MEMORY_PROPERTY_HOST_VISIBLE_BIT` and `VK_BUFFER_USAGE_TRANSFER_SRC_BIT`.
  - Map it
- In loading code
  - Read in image header from disk
  - Ask Renderer whether format can be directly consumed
  - If not, read image bytes into temporary buffer
    - Then ask Renderer for allocation to read converted bytes
    - Convert from temporary buffer to Renderer allocation
  - Once data has been converted, notify Renderer
- No extra maps!
- No large allocations during image streaming!

Sections

- Goals
- Source 2 Overview
- General Guidance
- Command Buffers
- Pipelines
- Descriptor Set Updates
- Memory Management
- Image Management
- Internal Fragmentation
- Final Thoughts

Internal Fragmentation

- Remember this?

Internal Fragmentation

- Remember this?
- Can’t solve for everything (notably opaque pools)
- But can make better for per-thread pools (dynamic VB/IB/CB)

Improving Internal Fragmentation

- In the Renderer (dawn of time)
  - At the beginning of time, allocate a single staging buffer with the `VK_MEMORY_PROPERTY_HOST_VISIBLE_BIT` and `VK_BUFFER_USAGE_TRANSFER_SRC_BIT`.
  - Map it, store pointer as pBase
  - Create a head offset, started at 0.
- In the Renderer (on the fly)
  - When asked for an allocation, atomic increment head by the size of the allocation.
    - If returned value + allocSize < totalSize, we can simply return pBase + returned Value for writer
    - If not, decide whether to create a new pool (requires lock), stall waiting for more data (CPU-GPU sync point) or return NULL.
  - Recycle

```
LONG InterlockedAdd( LONG volatile *Addend, LONG Value );
```

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Final thoughts

- Vulkan provides a modern, multithreaded API to GPU programming
- In exchange for peak performance and proportional taxation, Vulkan requires more from applications

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- Questions?
  - mcjohn at valvesoftware dot com
  - @basisspace on twitter