Beyond Porting

How Modern OpenGL can Radically Reduce Driver Overhead

NVIDIA

Who are we?

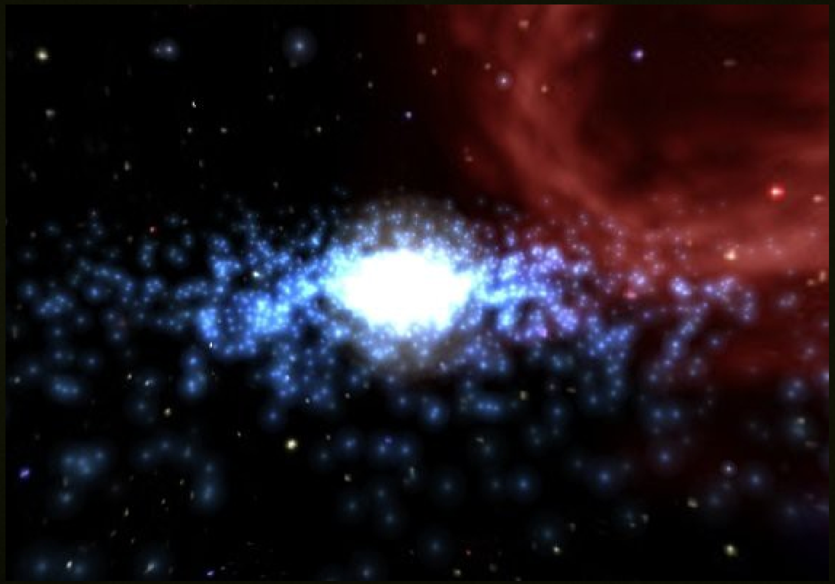
- Cass Everitt, NVIDIA Corporation
- John McDonald, NVIDIA Corporation

What will we cover?

- Dynamic Buffer Generation
- Efficient Texture Management
- Increasing Draw Call Count

Dynamic Buffer Generation

- Problem
  - Our goal is to generate dynamic geometry directly in place.
  - It will be used one time, and will be completely regenerated next frame.
    - Particle systems are the most common example
    - Vegetation / foliage also common



Typical Solution

```
void UpdateParticleData(uint _dstBuf) {
  BindBuffer(ARRAY_BUFFER, _dstBuf);
  access = MAP_UNSYNCHRONIZED | MAP_WRITE_BIT;
  for particle in allParticles {
    dataSize = GetParticleSize(particle);
    void* dst = MapBuffer(ARRAY_BUFFER, offset, dataSize, access);
    (*(Particle*)dst) = *particle;
    UnmapBuffer(ARRAY_BUFFER);
    offset += dataSize;
  }
};
// Now render with everything.
```

The horror

```
void UpdateParticleData(uint _dstBuf) {
  BindBuffer(ARRAY_BUFFER, _dstBuf);
  access = MAP_UNSYNCHRONIZED | MAP_WRITE_BIT;
  for particle in allParticles {
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    (*(Particle*)dst) = *particle;
    UnmapBuffer(ARRAY_BUFFER);
    offset += dataSize;
  }
};
// Now render with everything.
```
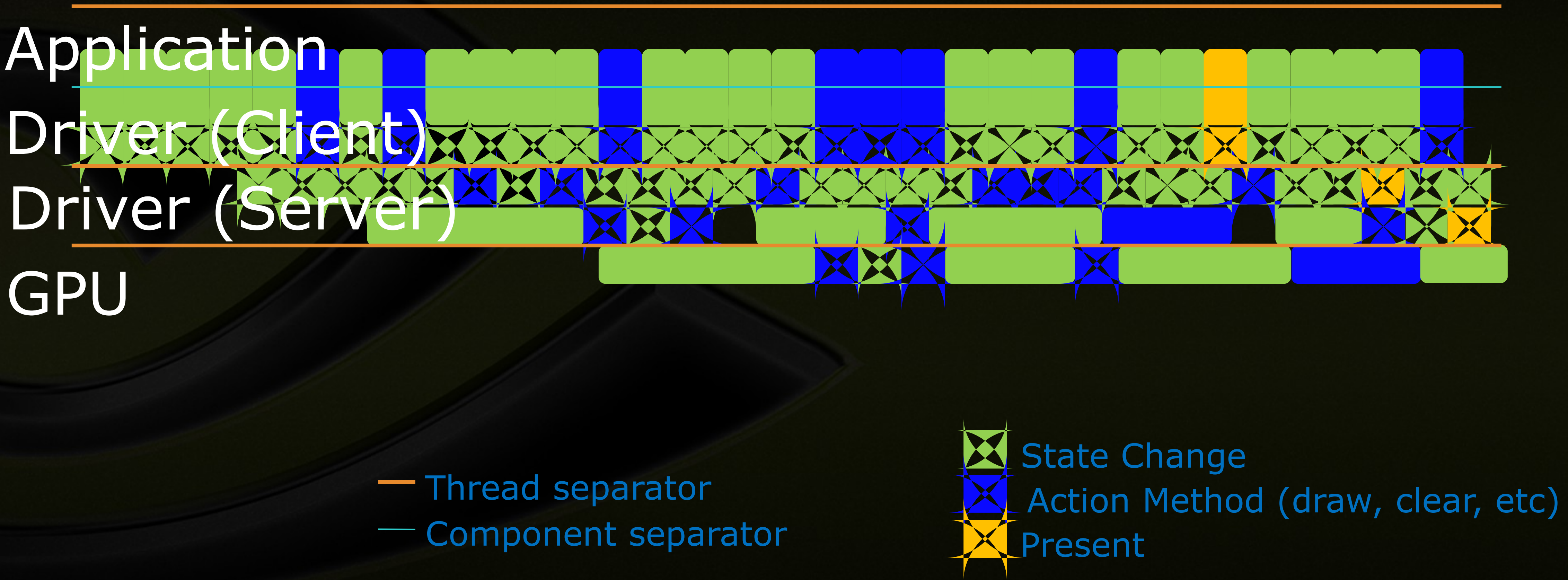

This is *so slow.*

Driver interlude

- First, a quick interlude on modern GL drivers
- In the application (client) thread, the driver is very thin.
  - It simply packages work to hand off to the server thread.
- The server thread does the real processing
  - It turns command sequences into push buffer fragments.

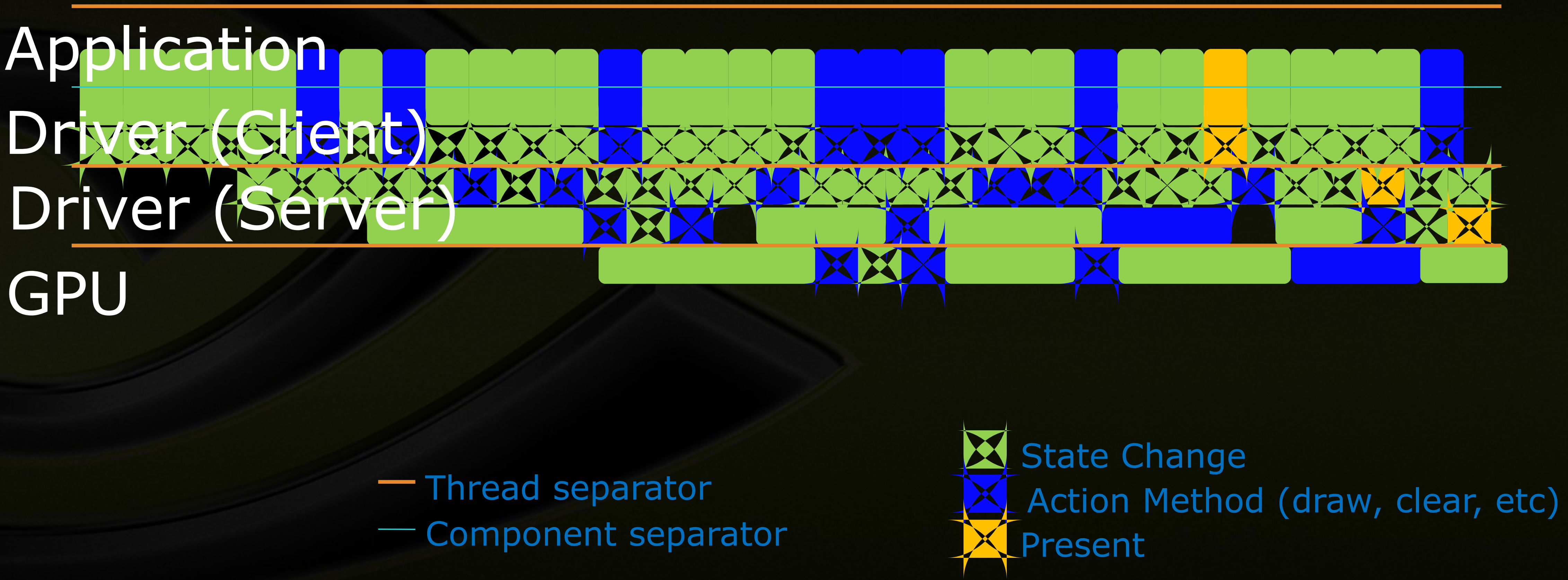
Healthy Driver Interaction Visualized



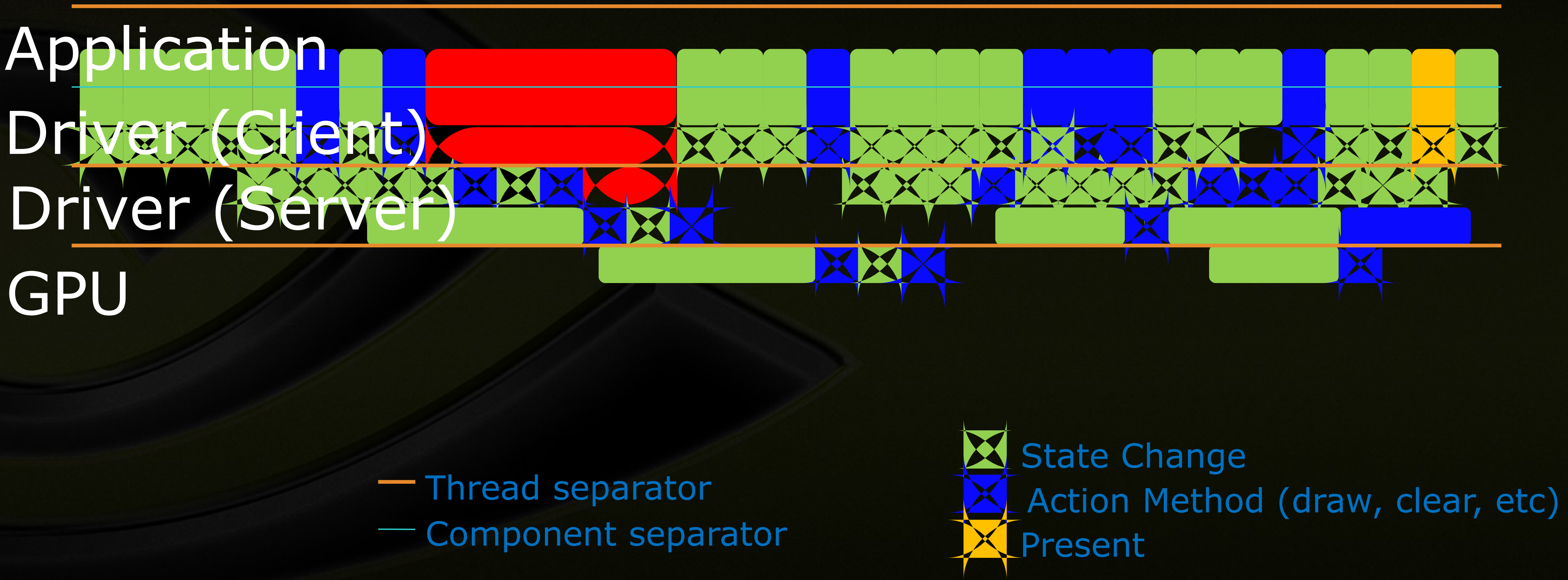
MAP_UNSYNCHRONIZED

- Avoids an application-GPU sync point (a CPU-GPU sync point)
- But causes the Client and Server threads to serialize
  - This forces all pending work in the server thread to complete
  - It's quite expensive (almost always needs to be avoided)

Healthy Driver Interaction Visualized



Client-Server Stall of Sadness



It's okay

- Q: What's better than mapping in an unsynchronized manner?
- A: Keeping around a pointer to GPU-visible memory *forever*.
- Introducing: ARB_buffer_storage

ARB_buffer_storage

- Conceptually similar to ARB_texture_storage (but for buffers)
- Creates an immutable pointer to storage for a buffer
  - The pointer is immutable, the contents are not.
  - So BufferData cannot be called—BufferSubData is still okay.
- Allows for extra information at create time.
- For our usage, we care about the PERSISTENT and COHERENT bits.
  - PERSISTENT: Allow this buffer to be mapped while the GPU is using it.
  - COHERENT: Client writes to this buffer should be immediately visible to the GPU.
- http://www.opengl.org/registry/specs/ARB/buffer_storage.txt

ARB_buffer_storage cont'd

- Also affects the mapping behavior (pass persistent and coherent bits to MapBufferRange)
- Persistently mapped buffers are good for:
  - Dynamic VB / IB data
  - Highly dynamic (~per draw call) uniform data
  - Multi_draw_indirect command buffers (more on this later)
- Not a good fit for:
  - Static geometry buffers
  - Long lived uniform data (still should use BufferData or BufferSubData for this)

Armed with persistently mapped buffers

```
// At the beginning of time
flags = MAP_WRITE_BIT | MAP_PERSISTENT_BIT | MAP_COHERENT_BIT;
BufferStorage(ARRAY_BUFFER, allParticleSize, NULL, flags);
mParticleDst = MapBufferRange(ARRAY_BUFFER, 0, allParticleSize,
                              flags);
mOffset = 0;

// allParticleSize should be ~3x one frame's worth of particles
// to avoid stalling.
```

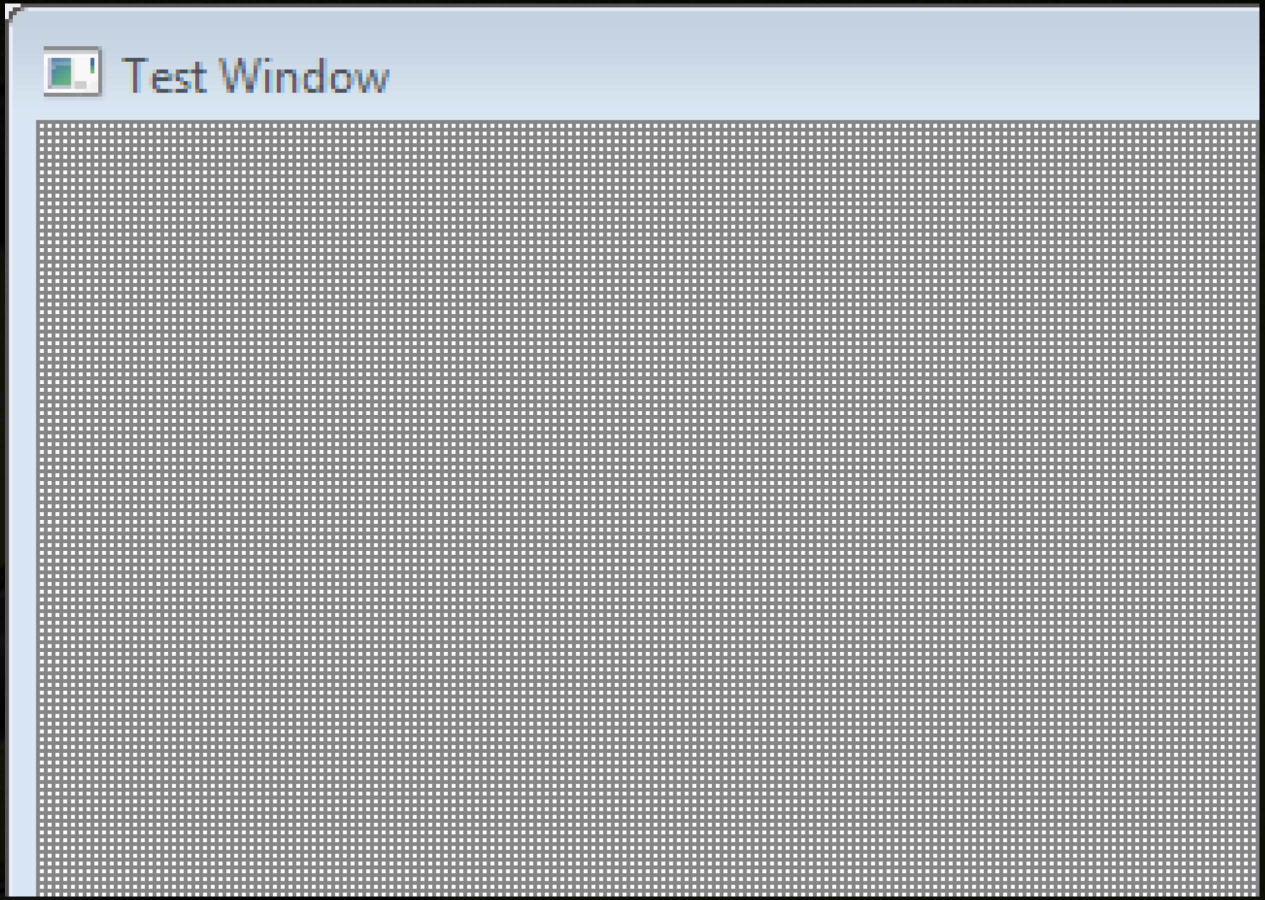
Update Loop (old and busted)

```
void UpdateParticleData(uint _dstBuf) {
  BindBuffer(ARRAY_BUFFER, _dstBuf);
  access = MAP_UNSYNCHRONIZED | MAP_WRITE_BIT;
  for particle in allParticles {
    dataSize = GetParticleSize(particle);
    void* dst = MapBuffer(ARRAY_BUFFER, offset, dataSize, access);
    (*(Particle*)dst) = *particle;
    offset += dataSize;
    UnmapBuffer(ARRAY_BUFFER);
  }
};
// Now render with everything.
```

Update Loop (new hotness)

```
void UpdateParticleData() {


  for particle in allParticles {
    dataSize = GetParticleSize(particle);

    mParticleDst[mOffset] = *particle;
    mOffset += dataSize; // Wrapping not shown

  }
};
// Now render with everything.
```

Test App



Performance results

- 160,000 point sprites
- Specified in groups of 6 vertices (one particle at a time)
- Synthetic (naturally)

Method	FPS	Particles / S
Map(UNSYNCHRONIZED)	1.369	219,040
BufferSubData	17.65	2,824,000
D3D11 Map(NO_OVERWRITE)	20.25	3,240,000

Performance results

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BufferSubData	17.65	2,824,000
D3D11 Map(NO_OVERWRITE)	20.25	3,240,000
Map(COHERENT|PERSISTENT)	79.9	12,784,000

- Room for improvement still, but much, much better.

The other shoe

- You are responsible for not stomping on data in flight.
- Why 3x?
  - 1x: What the GPU is using right now.
  - 2x: What the driver is holding, getting ready for the GPU to use.
  - 3x: What you are writing to.
- 3x should ~ guarantee enough buffer room*…
- Use fences to ensure that rendering is complete before you begin to write new data.

Fencing

- Use FenceSync to place a new fence.
- When ready to scribble over that memory again, use ClientWaitSync to ensure that memory is done.
  - ClientWaitSync will block the client thread until it is ready
  - So you should wrap this function with a performance counter
  - And complain to your log file (or resize the underlying buffer) if you frequently see stalls here
- For complete details on correct management of buffers with fencing, see Efficient Buffer Management [McDonald 2012]

Efficient Texture Management

- Or “how to manage all texture memory myself”

Problem

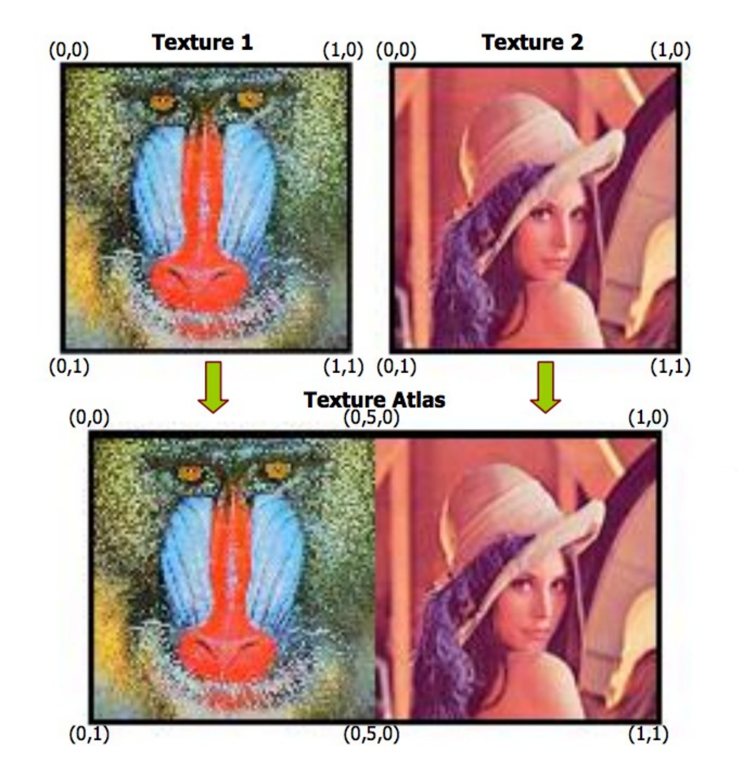
- Changing textures breaks batches.
- Not all texture data is needed all the time
  - Texture data is large (typically the largest memory bucket for games)
- Bindless solves this, but can hurt GPU performance
  - Too many different textures can fall out of TexHdr$
  - Not a bindless problem per se

Terminology

- Reserve – The act of allocating virtual memory
- Commit – Tying a virtual memory allocation to a physical backing store (Physical memory)
- Texture Shape – The characteristics of a texture that affect its memory consumption
  - Specifically: Height, Width, Depth, Surface Format, Mipmap Level Count

Old Solution

- Texture Atlases
- Problems
  - Can impact art pipeline
  - Texture wrap, border filtering
  - Color bleeding in mip maps

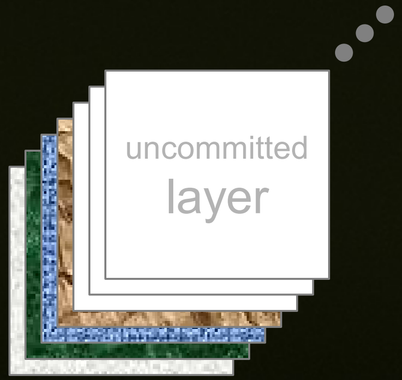


Texture Arrays

- Introduced in GL 3.0, and D3D 10.
- Arrays of textures that are the same shape and format
- Typically can contain many “layers” (2048+)
- Filtering works as expected
- As does mipmapping!

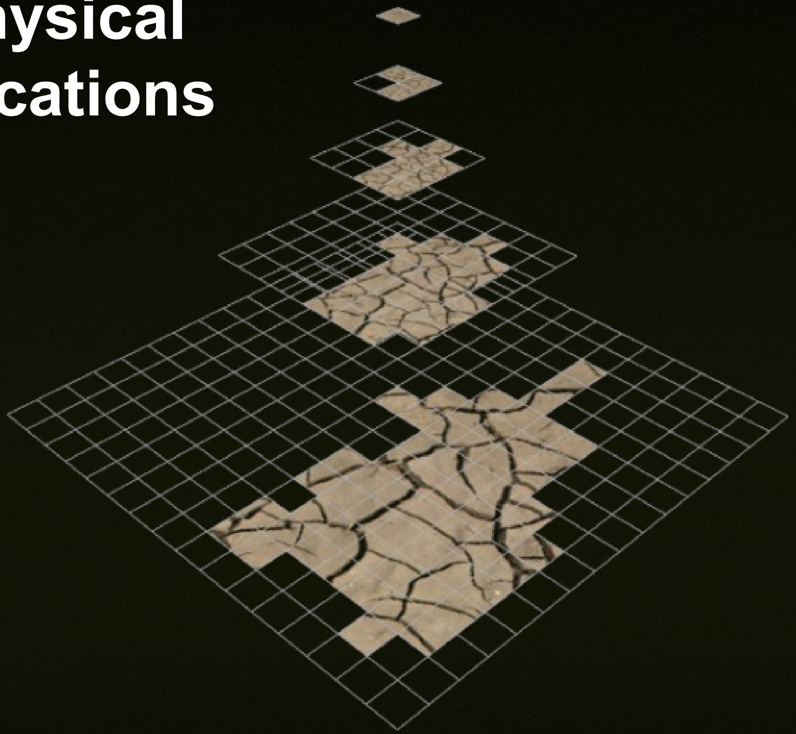
Sparse Bindless Texture Arrays

- Organize loose textures into Texture Arrays.
- Sparsely allocate Texture Arrays
  - Introducing ARB_sparse_texture
  - Consume virtual memory, but not physical memory
- Use Bindless handles to deal with as many arrays as needed!
  - Introducing ARB_bindless_texture



ARB_sparse_texture

- Applications get fine-grained control of physical memory for textures with large virtual allocations
- Inspired by Mega Texture
- Primary expected use cases:
  - Sparse texture data
  - Texture paging
  - Delayed-loading assets



- http://www.opengl.org/registry/specs/ARB/sparse_texture.txt

ARB_bindless_texture

- Textures specified by GPU-visible “handle” (really an address)
  - Rather than by name and binding point
- Can come from ~anywhere
  - Uniforms
  - Varying
  - SSBO
  - Other textures
- Texture residency also application-controlled
  - Residency is “does this live on the GPU or in sysmem?”
- https://www.opengl.org/registry/specs/ARB/bindless_texture.txt

Advantages

- Artists work naturally
- No preprocessing required (no bake-step required)
  - Although preprocessing is helpful if ARB_sparse_texture is unavailable
- Reduce or eliminate TexHdr$ thrashing
  - Even as compared to traditional texturing
- Programmers manage texture residency
- Works well with arbitrary streaming
- Faster on the CPU
- Faster on the GPU

Disadvantages

- Texture addresses are now structs (96 bits).
  - 64 bits for bindless handle
  - 32 bits for slice index (could reduce this to 10 bits at a perf cost)
- ARB_sparse_texture implementations are a bit immature
  - Early adopters: please *bring us your bugs*.
- ARB_sparse_texture requires base level be a multiple of tile size
  - (Smaller is okay)
  - Tile size is queried at runtime
  - Textures that are power-of-2 should almost always be safe.

Implementation Overview

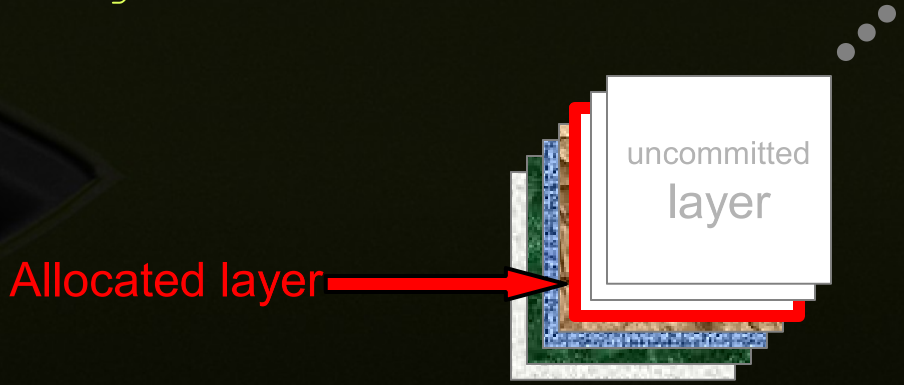
- When creating a new texture…
- Check to see if any suitable texture array exists
  - Texture arrays can contain a large number of textures of the same shape
  - Ex. Many `TEXTURE_2D`s grouped into a single `TEXTURE_2D_ARRAY`
- If no suitable texture, create a new one.

Texture Container Creation (example)

- `GetIntegerv( MAX_SPARSE_ARRAY_TEXTURE_LAYERS, maxLayers );`
  - Choose a reasonable size (e.g. array size ~100MB virtual)
- If new internalFormat, choose page size
  - `GetInternalformativ( …, internalformat, NUM_VIRTUAL_PAGE_SIZES, 1, &numIndexes);`
    - Note: `numIndexes` can be 0, so have a plan
    - Iterate, select suitable **`pageSizeIndex`**
- `BindTexture( TEXTURE_2D_ARRAY, newTexArray );`
- `TexParameteri( TEXTURE_SPARSE, TRUE );`
- `TexParameteri( VIRTUAL_PAGE_SIZE_INDEX, pageSizeIndex );`
- Allocate the texture's *virtual memory* using `TexStorage3D`

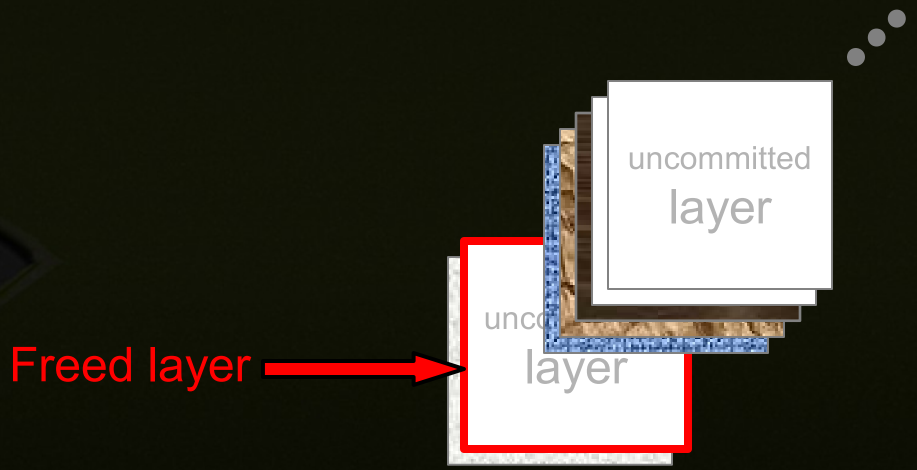
Specifying Texture Data

- Using the located/created texture array from the previous step
- Allocate a layer as the location of our data
- For each mipmap level of the allocated layer:
  - Commit the entire mipmap level (using `TexPageCommitment`)
  - Specify actual texel data as usual for arrays
    - `gl(Compressed|Copy|)TexSubImage3D`
    - PBO updates are fine too



Freeing Textures

- To free the texture, reverse the process:
  - Use `TexPageCommitment` to mark the entire layer (slice) as free.
    - Do once for each mipmap level
  - Add the layer to the free list for future allocation



Combining with Bindless to eliminate binds

- At container create time:
  - Specify sampling parameters via `SamplerParameter` calls first
  - Call `GetTextureSamplerHandleARB` to return a GPU-visible pointer to the texture+sampler container
  - Call `MakeTextureHandleResident` to ensure the resource lives on the GPU
- At delete time, call `MakeTextureHandleNonResident`
- With bindless, you explicitly manage the GPU's working set

Using texture data in shaders

- **When a texture is needed with the default sampling parameters**
  - **Create a GLSL-visible TextureRef object:**

```
struct TextureRef {
    sampler2DArray container;
    float slice;
};
```

- **When a texture is needed with custom sampling parameters**
  - **Create a separate sampler object for the shader with the parameters**
  - **Create a bindless handle to the pair using** `GetTextureSamplerHandle`**, then call** `MakeTextureHandleResident` **with the new value**
  - **And fill out a TextureRef as above for usage by GLSL**

C++ Code

- Basic implementation (some details missing)
- BSD licensed (use as you will)

https://github.com/nvMcJohn/apitest/blob/pdoane_newtests/sparse_bindless_texarray.h

https://github.com/nvMcJohn/apitest/blob/pdoane_newtests/sparse_bindless_texarray.cpp

Increasing Draw Call Count

- Let's draw *all the calls!*

All the Draw Calls!

- Problem
  - You want more draw calls of smaller objects.
  - D3D is slow at this.
  - Naïve GL is faster than D3D, but not fast enough.

XY Problem

- Y: How can I have more draw calls?
- X: You don't really care if it's more draw calls, right?
  - Really what you want is to be able to draw more small geometry groupings. More *objects*.

Well why didn't you just say so??

- First, some background.
  - What makes draw calls slow?
  - Real world API usage
  - Draw Call Cost Visualization

Some background

- What causes slow draw calls?
  - Validation is the biggest bucket (by far).
  - Pre-validation is “difficult”
  - “Every application does the same things.”
    - Not really. Most applications are in completely disjoint states
    - Try this experiment: What is important to you?
    - Now ask your neighbor what’s important to him.

Why is prevalidation difficult?

- The GPU is an exceedingly complex state machine.
  - (Honestly, it's probably the most complex state machine in all of CS)
- Any one of those states may have a problem that requires WAR
- Usually the only problem is overall performance
  - But sometimes not. ☹
- There are millions of tests covering NVIDIA GPU functionality.

FINE.

- How can app devs mitigate these costs?
  - Minimize state changes.
    - All state changes are not created equal!
  - Cost of a draw call:

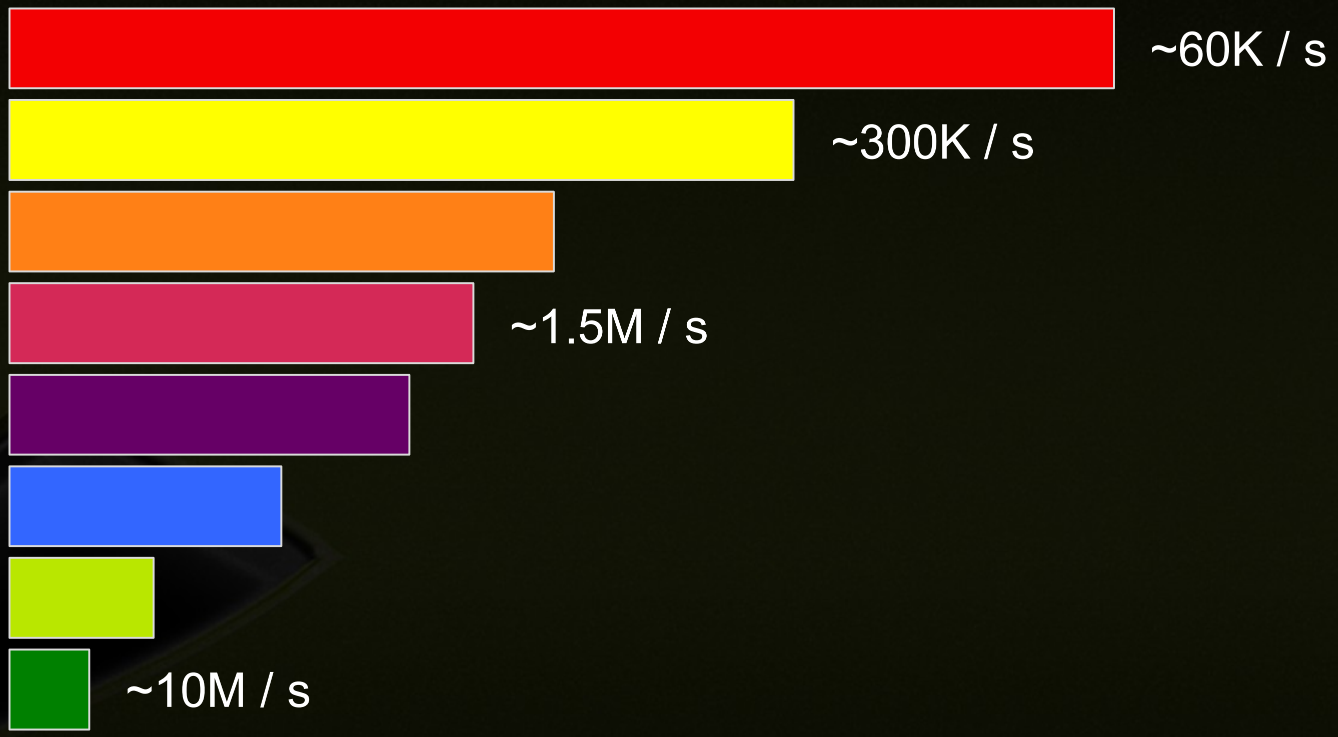
    Small fixed cost + Cost of validation of changed state

Feels limiting…

- Artists want lots of materials, and small amounts of geometry
- Even better: What if artists just didn't have to care about this?
  - Ideal Programmer->Artist Interaction
    - "You make pretty art. I'll make it fit."

Relative costs of State Changes

- In decreasing cost…
- Render Target
- Program
- ROP
- Texture Bindings
- Vertex Format
- UBO Bindings
- Vertex Bindings
- Uniform Updates

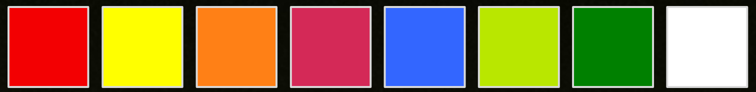


Note: Not to scale

Real World API frequency

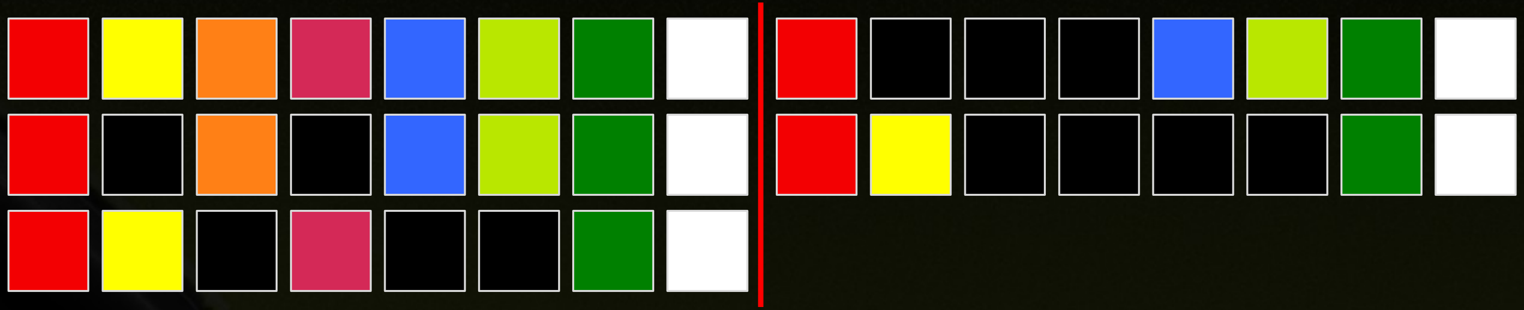
- API usage looks roughly like this…
- Increasing Frequency of Change
  - Render Target (scene)
  - Per Scene Uniform Buffer + Textures
  - IB / VB and Input Layout
  - Shader (Material)
  - Per-material Uniform Buffer + Textures
  - Per-object Uniform Buffer + Textures
  - Per-piece Uniform Buffer + Textures
  - Draw

Draw Calls visualized



- Render Target
- Program
- ROP
- Texture
- UBO Binding
- Vertex Format
- Uniform Updates
- Draw

Draw Calls visualized (cont'd)



Read down, then right
Black—no change

Render Target	Texture	Uniform Updates
Program	UBO Binding	Draw
ROP	Vertex Format	

Goals

- Let’s minimize validation costs without affecting artists
- Things we need to be fast (per app call frequency):
  - Uniform Updates and binding
  - Texture Updates and binding
- These happen most often in app, ergo driving them to ~0 should be a win.

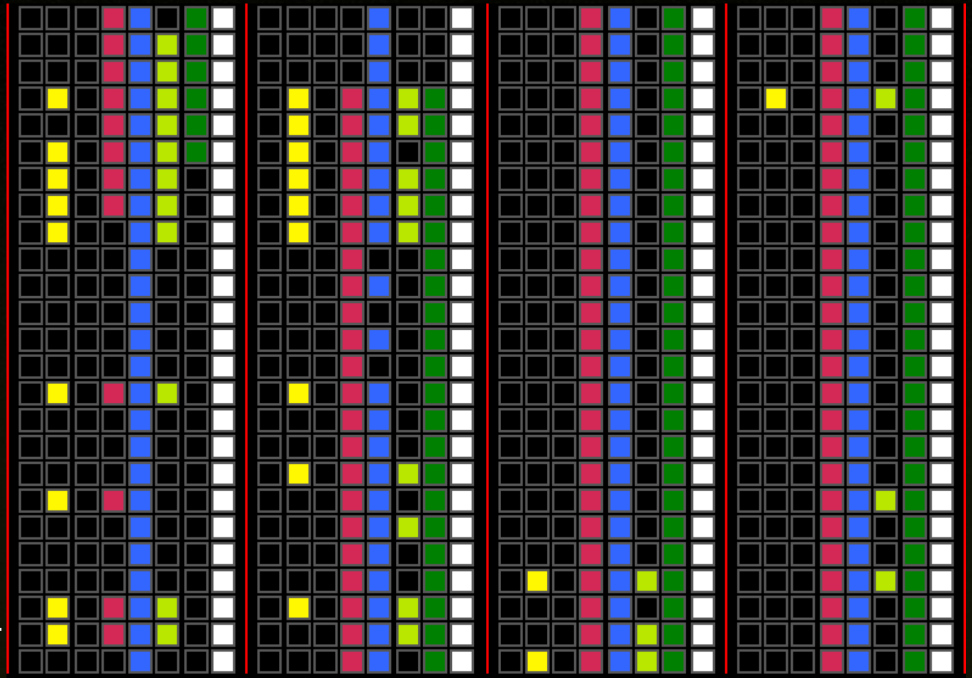
Textures

- Using Sparse Bindless Texture Arrays (as previously described) solves this.
  - All textures are set before any drawing begins
  - (No need to change textures between draw calls)
- Note that from the CPU's perspective, *just* using bindless is sufficient.

- That was easy.

Eliminating Texture Binds -- visualized

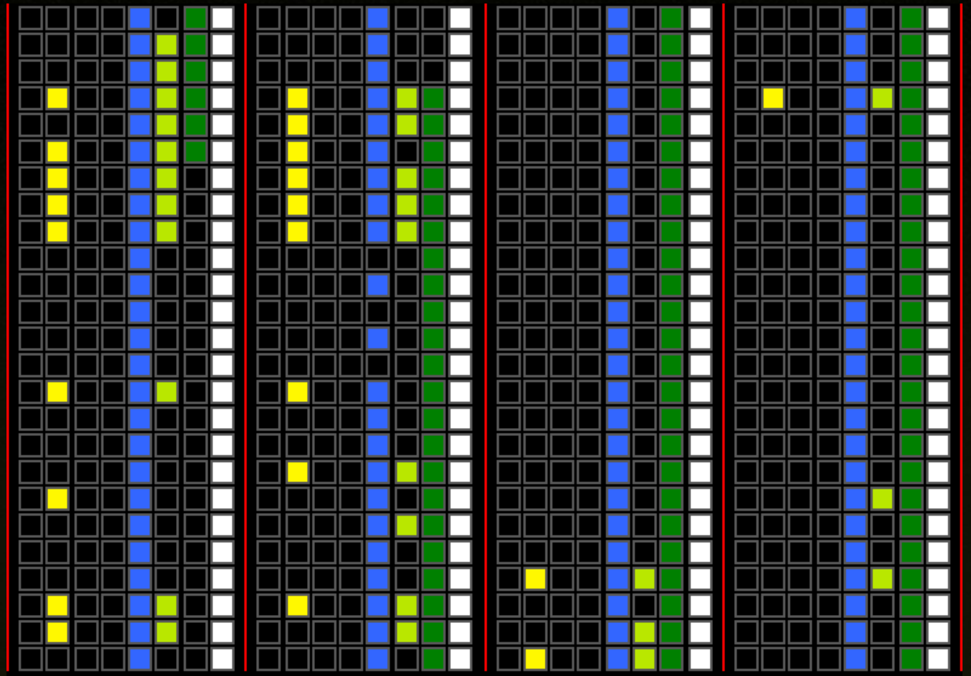
- Increasing Frequency of Change
  - Render Target (scene)
  - Per Scene Uniform Buffer ~~+ Textures~~
  - IB / VB and Input Layout
  - Shader (Material)
  - Per-material Uniform Buffer ~~+ Textures~~
  - Per-object Uniform Buffer ~~+ Textures~~
  - Per-piece Uniform Buffer ~~+ Textures~~
  - Draw



Render Target
Program
ROP
Texture
UBO Binding
Vertex Format
Uniform Updates
Draw

Boom!

- Increasing Frequency of Change
  - Render Target (scene)
  - Per Scene Uniform Buffer
  - IB / VB and Input Layout
  - Shader (Material)
  - Per-material Uniform Buffer
  - Per-object Uniform Buffer
  - Per-piece Uniform Buffer
  - Draw



Buffer updates (old and busted)

- **Typical Scene Graph Traversal**

```
for obj in visibleObjectSet {
  update(buffer, obj);
  draw(obj);
}
```

Buffer updates (new hotness)

- Typical Scene Graph Traversal

```
for obj in visibleObjectSet {
   update(bufferFragment, obj);
}

for obj in visibleObjectSet {
   draw(obj);
}
```

bufferFragma-wha?

- Rather than one buffer per object, we share UBOs for many objects.
- ie, given struct ObjectUniforms { /* … */ };

```
// Old (probably not explicitly instantiated,
// just scattered in GLSL)
ObjectUniforms uniformData;

// New
ObjectUniforms uniformData[ObjectsPerKickoff];
```

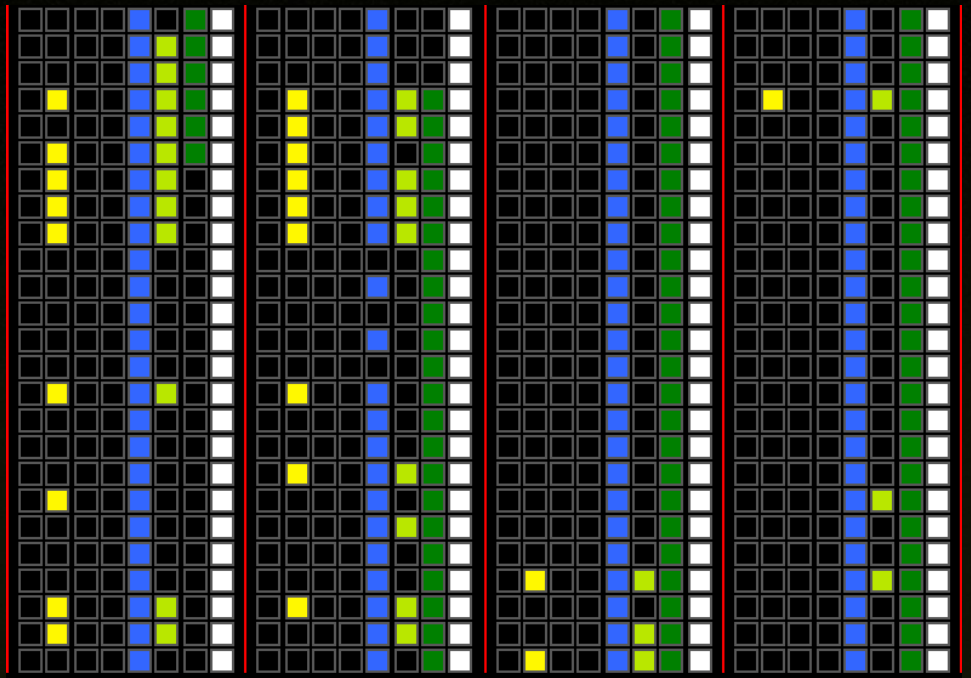
- Use persistent mapping for even more win here!
- For large amounts of data (bones) consider SSBO.
  - Introducing ARB_shader_storage_buffer_object

SSBO?

- Like “large” uniform buffer objects.
  - Minimum required size to claim support is 16M.
- Accessed like uniforms in shader
- Support for better packing (std430)
- Caveat: They are typically implemented in hardware as textures (and can introduce dependent texture reads)
  - Just one of a laundry list of things to consider, not to discourage use.
- http://www.opengl.org/registry/specs/ARB/shader_storage_buffer_object.txt

Eliminating Buffer Update Overhead

- Increasing Frequency of Change
  - Render Target (scene)
  - ~~Per Scene Uniform Buffer~~
  - IB / VB and Input Layout
  - Shader (Material)
  - ~~Per-material Uniform Buffer~~
  - ~~Per-object Uniform Buffer~~
  - ~~Per-piece Uniform Buffer~~
  - Draw

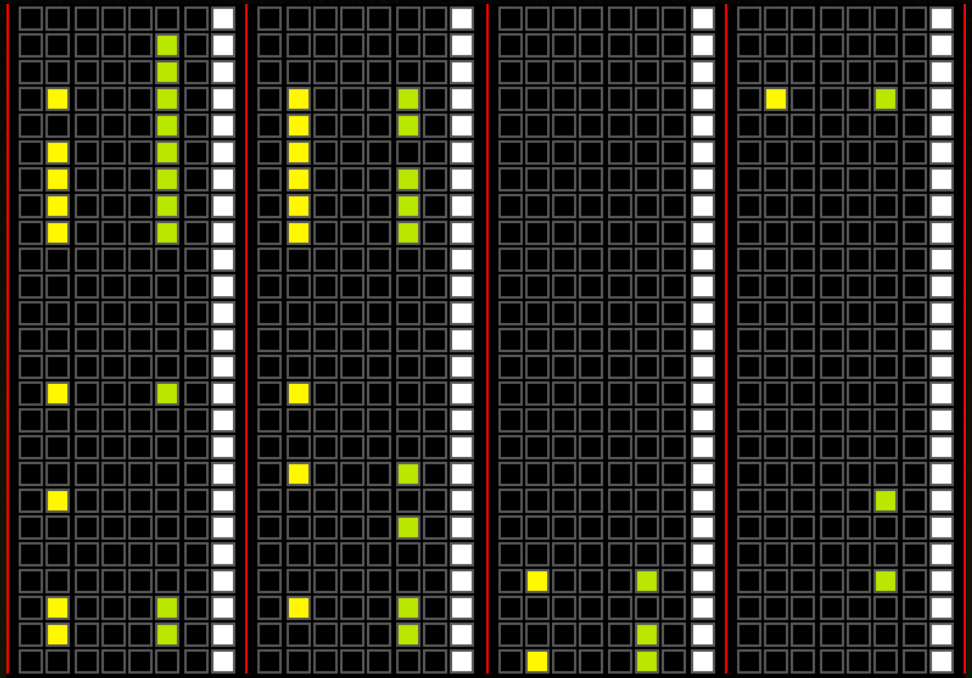


Render Target
Program
ROP
Texture
UBO Binding
Vertex Format
Uniform Updates
Draw

Sweet!

- Increasing Frequency of Change
  - Render Target (scene)
  - IB / VB and Input Layout
  - Shader (Material)
  - Draw (* each object)

- Hrrrrmmmmmm….



Render Target
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So now…

- It’d be awesome if we could do all of those kickoffs at once.
- Validation is already only paid once
- But we could just pay the constant startup cost once.
- If only…….

So now…

- It’d be awesome if we could do all of those kickoffs at once.
- Validation is already only paid once
- But we could just pay the constant startup cost once.
- If only…….

- Introducing ARB_multi_draw_indirect

ARB_multi_draw_indirect

- Allows you to specify parameters to draw commands from a buffer.
  - This means you can generate those parameters wide (on the CPU)
  - Or even on the GPU, via compute program.
- http://www.opengl.org/registry/specs/ARB/multi_draw_indirect.txt

ARB_multi_draw_indirect cont'd

```
void MultiDrawElementsIndirect(enum mode,
                               enum type
                               const void* indirect,
                               sizei primcount,
                               sizei stride);
```

ARB_multi_draw_indirect cont'd

```
const ubyte * ptr = (const ubyte *)indirect;
for (i = 0; i < primcount; i++) {
   DrawArraysIndirect(mode,
                               (DrawArraysIndirectCommand*)ptr);
   if (stride == 0)
   {
      ptr += sizeof(DrawArraysIndirectCommand);
   } else {
      ptr += stride;
   }
}
```

DrawArraysIndirectCommand

```
typedef struct {
   uint  count;
   uint  primCount;
   uint  first;
   uint  baseInstance;
} DrawArraysIndirectCommand;
```

Knowing which shader data is mine

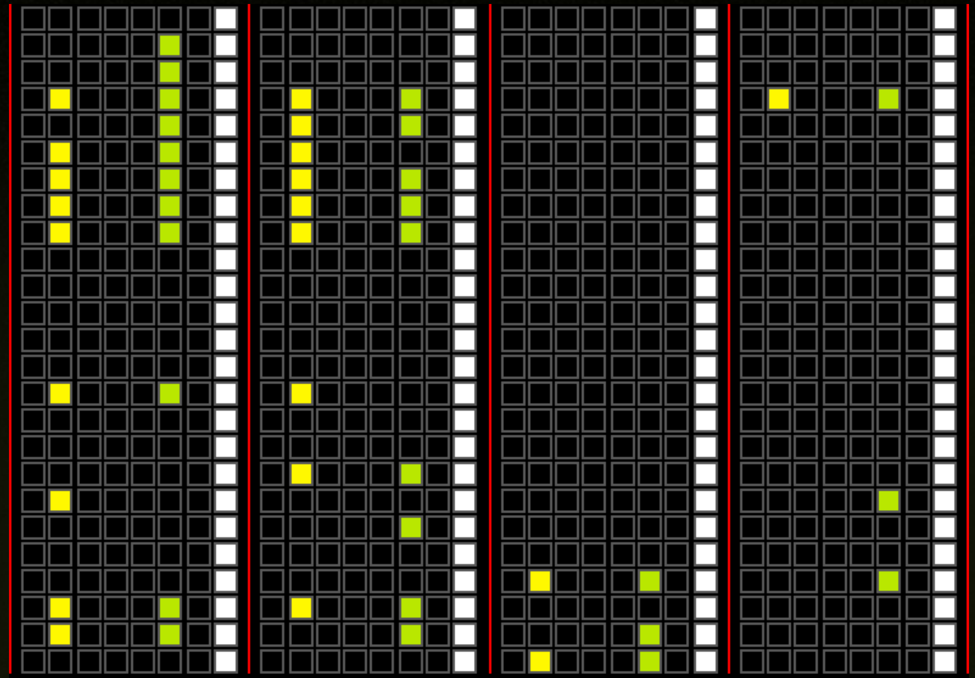
- Use ARB_shader_draw_parameters, a necessary companion to ARB_multi_draw_indirect
- Adds a builtin to the VS: DrawID (InstanceID already available)
  - This tells you which command of a MultiDraw command is being executed.
  - When not using MultiDraw, the builtin is specified to be 0.
- Caveat: Right now, you have to pass this down to other shader stages as an interpolant.
  - Hoping to have that rectified via ARB or EXT extension “real soon now.”
- http://www.opengl.org/registry/specs/ARB/shader_draw_parameters.txt

Applying everything

- CPU Perf is massively better
  - 5-30x increase in number of distinct objects / s
- Interaction with driver is decreased ~75%
- Note: GPU perf can be affected negatively (although not too badly)

- As always: Profile, profile, profile.

Previous Results



Render Target
Program
ROP
Texture
UBO Binding
Vertex Format
Uniform Updates
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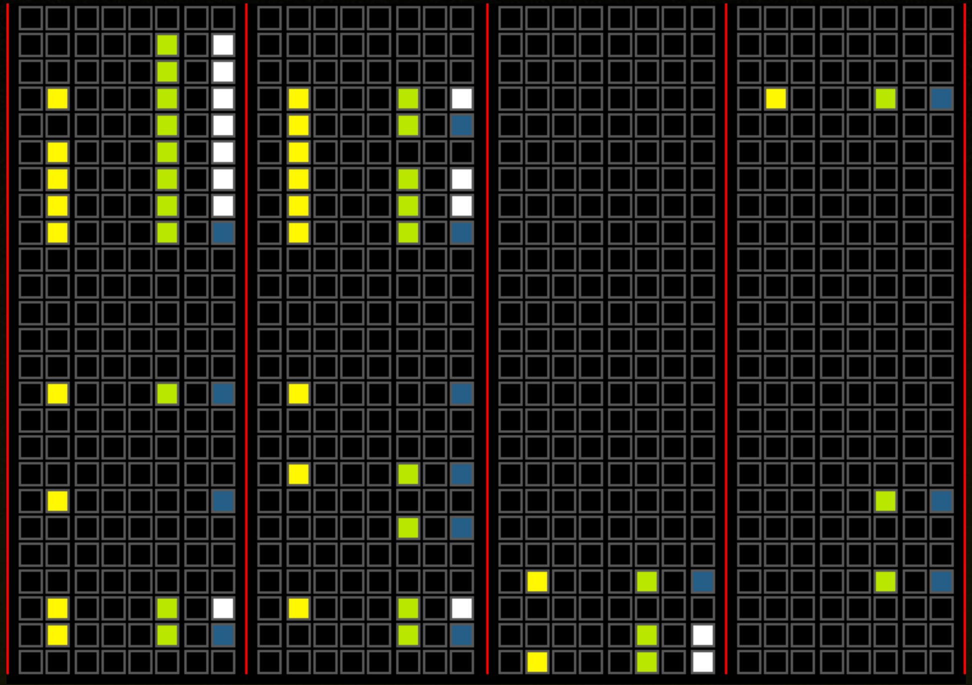
Visualized Results



Render Target
Program
ROP
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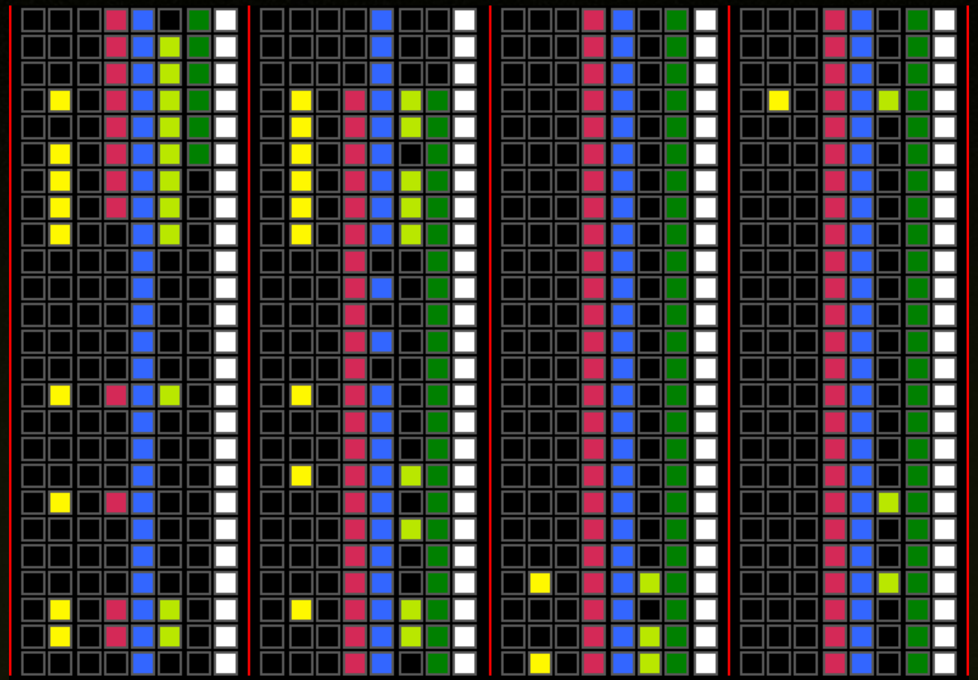
Uniform Updates
Draw
MultiDraw

Where we came from



Render Target
Program
ROP
Texture
UBO Binding
Vertex Format
Uniform Updates
Draw

Conclusion

- Go forth and work magnify.

Questions?

- jmcdonald at nvidia dot com
- cass at nvidia dot com