The OpenGL Framebuffer Object Extension

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Overview

- Why render to texture?
- P-buffer / ARB render texture review
- Framebuffer object extension
- Examples
- Future directions

Why Render To Texture?

- Allows results of rendering to framebuffer to be directly read as texture
- Better performance
  - avoids copy from framebuffer to texture (`glCopyTexSubImage2D`)
  - uses less memory – only one copy of image
  - but driver may sometimes have to do copy internally
    - some hardware has separate texture and FB memory
    - different internal representations
- Applications
  - dynamic textures – procedurals, reflections
  - multi-pass techniques – anti-aliasing, motion blur, depth of field
  - image processing effects (blurs etc.)
  - GPGPU – provides feedback loop

WGL_ARB_pbuffer

- Pixel buffers
- Designed for off-screen rendering
  - Similar to windows, but non-visible
- Window system specific extension
- Select from an enumerated list of available pixel formats using
  - `ChoosePixelFormat()`
  - `DescribePixelFormat()`

Problems with PBuffers

- Each pbuffer usually has its own OpenGL context
  - (Assuming they have different pixel formats)
  - Can share texture objects, display lists between pbuffers using `wglShareLists()`
  - Painful to manage, causes lots of bugs
- Switching between pbuffers is expensive
  - `wglMakeCurrent()` causes context switch
- Each pbuffer has its own depth, stencil, aux buffers
  - Cannot share depth buffers between pbuffers

WGL_ARB_render_texture

- Allows the color or depth buffer of a pbuffer to be bound as a texture
  - `BOOL wglBindTexImageARB(HPBUFFERARB hPbuffer, int iBuffer`
  - `BOOL wglReleaseTexImageARB(HPBUFFERARB hPbuffer, int iBuffer)`
- Window system specific
  - GLX version of specification was never defined
  - MacOS X - APPLE_pixel_buffer
- Texture format is determined by pixel format of pbuffer
- Portable applications need to create a separate pbuffer for each renderable texture

Pbuffer Tricks

- The front and back buffers of a double-buffered pbuffer can be bound as separate textures

```
glDrawBuffer(GL_FRONT); // draw to front
glDrawBuffer(GL_BACK);  // draw to back
// bind front and back buffers as textures
wglBindTexImageARB(pbuffer, WGL_FRONT_LEFT_ARB);
wglBindTexImageARB(pbuffer, WGL_BACK_LEFT_ARB);
```

- This gives you two buffers that you can switch between without incurring context switching cost
- On systems that support multiple render targets (ARB_draw_buffers) you can also use AUX buffers

Render To Texture And Anti-Aliasing

- Render to texture doesn't work with multi-sample anti-aliasing
  - current texture hardware isn't capable of reading from a multi-sampled buffer
  - could be implemented in driver using copy
- Common problem with post-processing effects in games
- Solution: create a normal multi-sampled pbuffer, and use `glCopyTexImage2D` to copy from this to a texture
  - the copy performs the down-sampling automatically
- Also possible to do your own super-sample anti-aliasing in the application
  - much more expensive than multi-sampling

Anti-Aliasing with Post Processing

Without AA

With AA

The Framebuffer Object Extension

- Specification finally published!
- Available in beta drivers from NVIDIA
- http://developer.nvidia.com

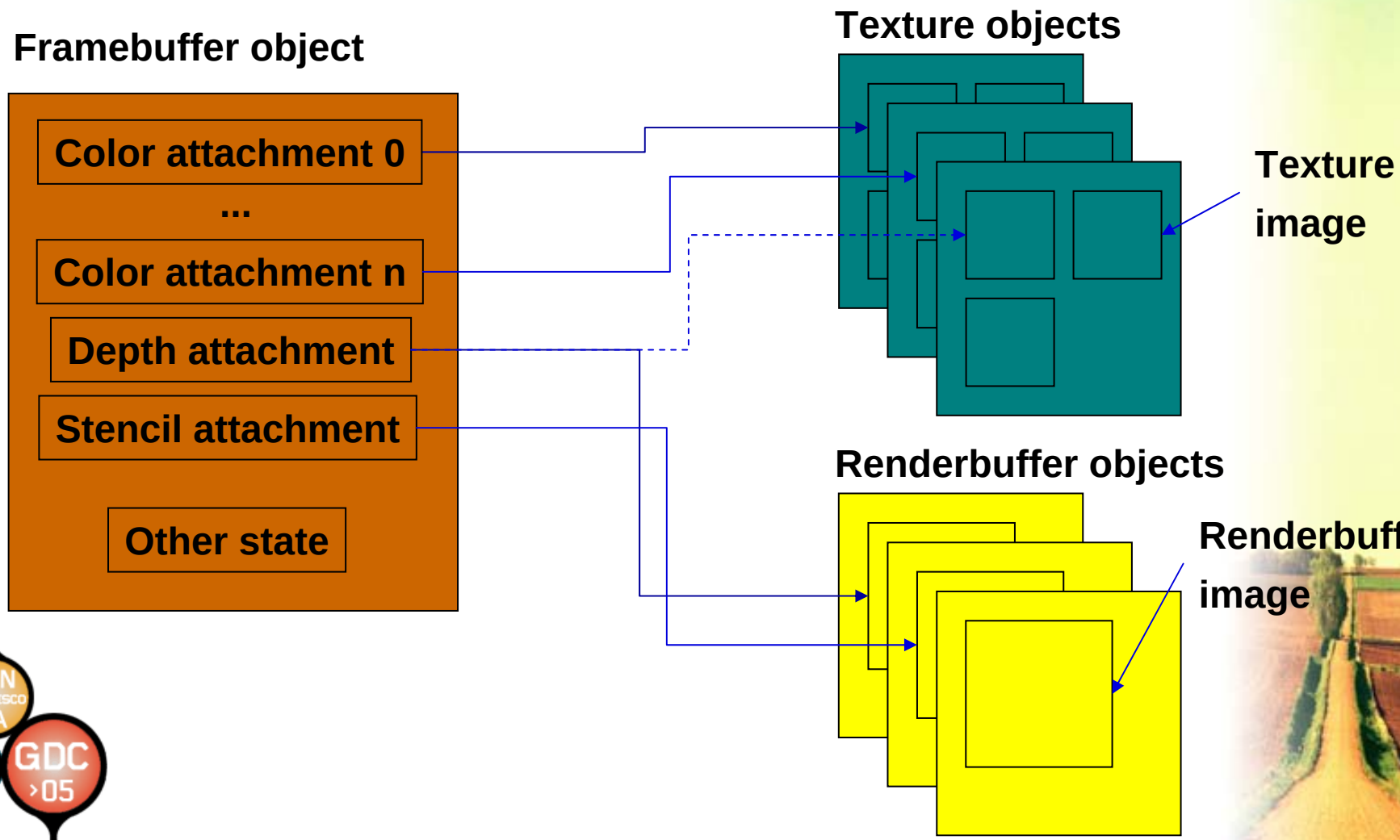
Framebuffer Object Advantages

- **Only requires a single OpenGL context**
  - switching between framebuffers is faster than switching between pbuffers (`wglMakeCurrent`)
- **No need for complicated pixel format selection**
  - format of framebuffer is determined by texture or renderbuffer format
  - puts burden of finding compatible formats on developer
- **More similar to Direct3D render target model**
  - makes porting code easier
- **Renderbuffer images and texture images can be shared among framebuffers**
  - e.g. share depth buffers between color targets
  - saves memory

EXT_framebuffer_object

- OpenGL framebuffer is a collection of logical buffers
  - color, depth, stencil, accumulation
- Framebuffer object extension provides a new mechanism for rendering to destinations other than those provided by the window system
  - window system independent
- Destinations known as “framebuffer-attachable images”. Can be:
  - off-screen buffers (Renderbuffers)
  - textures

Framebuffer Object Architecture



Terminology

- Renderbuffer image – 2D array of pixels. Part of a renderbuffer object.
- Framebuffer-attachable image – 2D array of pixels that can be attached to a framebuffer. Texture images and renderbuffer images are examples.
- Attachment point – State that references a framebuffer-attachable image. One each for color, depth and stencil buffer of a framebuffer.
- Attach – the act of connecting one object to another. Similar to “bind”.
- Framebuffer attachment completeness
- Framebuffer completeness

Framebuffers and Renderbuffers

- Introduces two new OpenGL objects:
- “Framebuffer” (FBO)
  - collection of framebuffer-attachable images (e.g. color, depth, stencil)
  - plus state defining where output of GL rendering is directed
  - equivalent to window system “drawable”
- “Renderbuffer” (RB)
  - contains a simple 2D image
    - no mipmaps, cubemap faces etc.
  - stores pixel data resulting from rendering
  - cannot be used as textures

Framebuffer Objects

- When a framebuffer object is bound its attached images are the source and destination for fragment operations
  - Color and depth textures
    - Supports multiple color attachments for MRT
  - Color, depth or stencil renderbuffers

Framebuffer Object API

```
void GenFramebuffersEXT(sizei n, uint *framebuffers);
void DeleteFramebuffersEXT(sizei n,
                           const uint *framebuffers);
boolean IsFramebufferEXT(uint framebuffer);

void BindFramebufferEXT(enum target, uint framebuffer);

enum CheckFramebufferStatusEXT(enum target);
```

Framebuffer Object API

```
void FramebufferTexture1DEXT(enum target, enum attachment,
   enum textarget, uint texture, int level);
void FramebufferTexture2DEXT(enum target, enum attachment,
   enum textarget, uint texture, int level);
void FramebufferTexture3DEXT(enum target, enum attachment,
   enum textarget, uint texture, int level, int zoffset);

void FramebufferRenderbufferEXT(enum target, enum
   attachment, enum renderbuffertarget, uint
   renderbuffer);

void GetFramebufferAttachmentParameterivEXT(enum target,
   enum attachment, enum pname, int *params);

void GenerateMipmapEXT(enum target);
```

Managing FBOs and Renderbuffers

- **Creating and destroying FBOs (and Renderbuffers) is easy - similar to texture objects**

```
void GenFramebuffersEXT(sizei n, uint *framebuffers);
void DeleteFramebuffersEXT(sizei n,
                           const uint *framebuffers);
void BindFramebufferEXT(enum target, uint
   framebuffer);
```

- **Can also check if a given identifier is a framebuffer object (rarely used)**

```
boolean IsFramebufferEXT(uint framebuffer);
```

Binding an FBO

```
void BindFramebufferEXT(enum target, uint framebuffer);
```

- **Makes given FBO current**
  - **all GL operations occur on attached images**
- ***target* must be FRAMEBUFFER_EXT**
- ***framebuffer* is FBO identifier**
  - **if *framebuffer*==0, GL operations operate on window-system provided framebuffer (i.e. the window). This is the default state.**
- **Set of state that can change on a framebuffer bind:**
  - **AUX_BUFFERS, MAX_DRAW_BUFFERS, STEREO, SAMPLES, X_BITS, DOUBLE_BUFFER and a few more**

Attaching Textures to a Framebuffer

```
void FramebufferTexture2DEXT(enum target, enum
   attachment, enum textarget, uint texture, int
   level);
```

- Attaches image from a texture object to one of the logical buffers of the currently bound framebuffer
- *target* must be FRAMEBUFFER_EXT
- *attachment* is one of:
  - COLOR_ATTACHMENT0_EXT ... COLOR_ATTACHMENTn_EXT, DEPTH_ATTACHMENT_EXT, STENCIL_ATTACHMENT_EXT
- *textarget* must be one of:
  - TEXTURE_2D, TEXTURE_RECTANGLE, TEXTURE_CUBE_MAP_POSITIVE_X etc.
- *level* is the mipmap level of the texture to attach
- *texture* is the texture object to attach
  - if *texture*==0, the image is detached from the framebuffer
- Other texture dimensions are similar
  - for 3D textures, *z-offset* specifies slice

Renderbuffer API

```
void GenRenderbuffersEXT(sizei n, uint *renderbuffers);
void DeleteRenderbuffersEXT(sizei n,
   const uint *renderbuffers);
boolean IsRenderbufferEXT(uint renderbuffer);

void BindRenderbufferEXT(enum target, uint renderbuffer);

void RenderbufferStorageEXT(enum target,
   enum internalformat, sizei width, sizei height);
void GetRenderbufferParameterivEXT(enum target,
   enum pname, int* params);
```

Defining RenderBuffer Storage

```
void RenderbufferStorageEXT(enum target,
   enum internalformat, sizei width, sizei height);
```

- **Defines format and dimensions of a Renderbuffer**
  - **similar to TexImage call, but without image data**
  - **can read and write data using Read/DrawPixels etc.**
- ***target* must be RENDERBUFFER_EXT**
- ***internalformat* can be normal texture format (e.g. GL_RGBA8, GL_DEPTH_COMPONENT24) or:**
  - **STENCIL_INDEX1_EXT**
  - **STENCIL_INDEX4_EXT**
  - **STENCIL_INDEX8_EXT**
  - **STENCIL_INDEX16_EXT**

Attaching Renderbuffers to a Framebuffer

```
void FramebufferRenderbufferEXT(enum target,
   enum attachment, enum renderbuffertarget,
   uint renderbuffer);
```

- **Attaches given renderbuffer as one of the logical buffers of the currently bound framebuffer**
- *target* **must be FRAMEBUFFER_EXT**
- *attachment* **is one of:**
  - **COLOR_ATTACHMENT0_EXT ... COLOR_ATTACHMENTn_EXT**
    - **Maximum number of color attachments implementation dependent - query MAX_COLOR_ATTACHMENTS_EXT**
  - **DEPTH_ATTACHMENT_EXT**
  - **STENCIL_ATTACHMENT_EXT**
- *renderbuffertarget* **must be RENDERBUFFER_EXT**
- *renderbuffer* **is a renderbuffer id**

Generating Mipmaps

```
void GenerateMipmapEXT(enum target);
```

- **Automatically generates mipmaps for texture image attached to *target***
- **Generates same images as GL_SGIS_generate_mipmap extension**
  - **filtering is undefined, most likely simple 2x2 box filter**
- **Implemented as new entry point for complicated reasons (see spec).**

Framebuffer Completeness

- **Framebuffer is complete if all attachments are consistent**
  - **texture formats make sense for attachment points**
    - **i.e. don't try and attach a depth texture to a color attachment**
  - **all attached images must have the same width and height**
  - **all images attached to COLOR_ATTACHMENT0_EXT - COLOR_ATTACHMENTn_EXT must have same format**
- **If not complete, glBegin will generate error INVALID_FRAMEBUFFER_OPERATION**

Checking Framebuffer Status

```
enum CheckFramebufferStatusEXT(enum target);
```

- Should always be called after setting up FBOs
- Returns enum indicating why framebuffer is incomplete:
  - FRAMEBUFFER_COMPLETE
  - FRAMEBUFFER_INCOMPLETE_ATTACHMENT
  - FRAMEBUFFER_INCOMPLETE_MISSING_ATTACHMENT
  - FRAMEBUFFER_INCOMPLETE_DUPLICATE_ATTACHMENT
  - FRAMEBUFFER_INCOMPLETE_DIMENSIONS_EXT
  - FRAMEBUFFER_INCOMPLETE_FORMATS_EXT
  - FRAMEBUFFER_INCOMPLETE_DRAW_BUFFER_EXT
  - FRAMEBUFFER_INCOMPLETE_READ_BUFFER_EXT
  - FRAMEBUFFER_UNSUPPORTED
  - FRAMEBUFFER_STATUS_ERROR
- Completeness is implementation-dependent
  - if result is “FRAMEBUFFER_UNSUPPORTED”, application should try different format combinations until one succeeds

FBO Performance Tips

- Don’t create and destroy FBOs every frame
- Try to avoid modifying textures used as rendering destinations using TexImage, CopyTexImage etc.

FBO Usage Scenarios

- FBO allows several ways of switching between rendering destinations
- In order of increasing performance:
  - Multiple FBOs
    - create a separate FBO for each texture you want to render to
    - switch using `BindFramebuffer()`
      - can be 2x faster than `wglMakeCurrent()` in beta NVIDIA drivers
  - Single FBO, multiple texture attachments
    - textures should have same format and dimensions
    - use `FramebufferTexture()` to switch between textures
  - Single FBO, multiple texture attachments
    - attach textures to different color attachments
    - use `glDrawBuffer()` to switch rendering to different color attachments

Simple FBO Example

```
#define CHECK_FRAMEBUFFER_STATUS() \
{ \
 GLenum status; \
 status = glCheckFramebufferStatusEXT(GL_FRAMEBUFFER_EXT); \
 switch(status) { \
 case GL_FRAMEBUFFER_COMPLETE_EXT: \
   break; \
 case GL_FRAMEBUFFER_UNSUPPORTED_EXT: \
    /* choose different formats */ \
   break; \
 default: \
   /* programming error; will fail on all hardware */ \
   assert(0); \
 } \
}
```

Simple FBO Example

```
GLuint fb, depth_rb, tex;

// create objects
glGenFramebuffersEXT(1, &fb);          // frame buffer
glGenRenderbuffersEXT(1, &depth_rb);   // render buffer
glGenTextures(1, &tex);                // texture
glBindFramebufferEXT(GL_FRAMEBUFFER_EXT, fb);

// initialize texture
glBindTexture(GL_TEXTURE_2D, tex);
glTexImage2D(GL_TEXTURE_2D, 0, GL_RGBA8, width, height, 0,
             GL_RGBA, GL_UNSIGNED_BYTE, NULL);
// (set texture parameters here)

// attach texture to framebuffer color buffer
glFramebufferTexture2DEXT(GL_FRAMEBUFFER_EXT,
    GL_COLOR_ATTACHMENT0_EXT, GL_TEXTURE_2D, tex, 0);
```

Simple FBO Example

```
// initialize depth renderbuffer
glBindRenderbufferEXT(GL_RENDERBUFFER_EXT, depth_rb);
glRenderbufferStorageEXT(GL_RENDERBUFFER_EXT,
   GL_DEPTH_COMPONENT24, width, height);

// attach renderbuffer to framebuffer depth buffer
glFramebufferRenderbufferEXT(GL_FRAMEBUFFER_EXT,
   GL_DEPTH_ATTACHMENT_EXT, GL_RENDERBUFFER_EXT,
   depth_rb);
CHECK_FRAMEBUFFER_STATUS();
...

// render to the FBO
glBindFramebufferEXT(GL_FRAMEBUFFER_EXT, fb);
// (draw something here, rendering to texture)

// render to the window, using the texture
glBindFramebufferEXT(GL_FRAMEBUFFER_EXT, 0);
glBindTexture(GL_TEXTURE_2D, tex);
```

Future Directions

- Currently an EXT extension
  - will be promoted to an ARB extension once the design is proven
- Got feedback?
  - Give it to the OpenGL ARB!
- Future extensions
  - Render to vertex attribute
    - likely built on top of Renderbuffers
  - Format groups
    - like pixel formats, defines groups of formats that work together for a given implementation
  - Multisampling, accumulation buffer support

Thanks

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