High Performance Graphics and Text Rendering on the GPU

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Introduction

- Prologue
- Brief Introduction to Graphics
- Why Graphics Matters to <almost> Everyone
- Using Graphics in a C++ Application
- Graphics Demo
- Graphics Terminology
- Program/Data Flow
- Rendering Text as Graphics
- Roadmap

Who is CopperSpice

- Maintainers and Co-Founders
  - CopperSpice
    - set of cross platform C++ libraries *(linux, os x, windows)*
  - CsString
    - support for UTF-8 and UTF-16, extensible to other encodings
  - CsSignal
    - thread aware signal / slot library
  - libGuarded
    - library for managing access to data shared between threads
  - DoxyPress
    - documentation generator for C++ and various other languages to HTML, LaTeX, DocBook, and others

Who is CopperSpice

- Credentials
  - all libraries and applications are open source
  - developed using cutting edge C++ technology
  - source code hosted on github
  - prebuilt binaries available on our download site
  - documentation generated by DoxyPress

  - youtube channel for C++ with over 40 videos
  - speakers at multiple CppCon and CppNow conferences
  - speakers at emBO++ 2019
  - numerous presentations in the US and Europe

Existing Videos

- Additional Information
  - graphics timeline from 1989 through 2018
  - what drives the graphics industry
  - changes in GPU design
  - overview of the various API specifications

  - Evolution of Graphics Technology
    - https://www.youtube.com/watch?v=u5SNd9sKn94

  - GPU, Pipeline, and the Vector Graphics API
    - https://www.youtube.com/watch?v=CrKxMrLczis

  - Rendering 3D Graphics
    - https://www.youtube.com/watch?v=MXz2t0gvRxI

Graphics

- Brief Introduction to Graphics
  - graphics are responsible for displaying images and text in a way which is effective and meaningful to the consumer

  - classified into distinct categories
    - raster graphics
      - bitmap image rendered by addressing discrete pixels
      - typically processed on the CPU
      - resolution dependent, does not scale without loss of quality

    - vector graphics
      - an image defined by vertex coordinates
      - drawing commands are based on complicated mathematics
      - should be processed on the GPU
      - scaled to a larger size the image quality is not compromised

Graphics

- Image Quality
  - VGA
    - 307,000 pixels
    - 640 x 480
  - 1080p, Full HD
    - 2.07 million pixels
    - 1920 x 1080
  - 4k, UHD
    - 8.2 million pixels
    - 3840 x 2160
  - 8k, 8k UHD
    - 33.1 million pixels
    - 7680 x 4320

Graphics

- Processors
  - CPU
    - average around 4-8 cores
    - high end around 10-20 cores
    - typically 1 or 2 threads run on each core
  - GPU
    - average around 1000 cores
    - high end around 3000 cores
    - many are hyperthreaded which means there are typically 5-60 threads running on each core

Graphics

- Using Graphics in a C++ Application
  - gaming industry has the biggest influence over changes in graphics
  - changes in the GPU design require new programming tools
  - graphics are more than just explosions, robots, and lightsabers
  - are graphics important to the user of my desktop program

  - graphics for the GUI developer
    - high dpi support for free
    - responsive user interface
    - smooth scrolling of text
    - clean colors and edges
    - scalable charts, graphs, animations

Graphics

- Demo Dependencies
  - C++17
  - CMake version 3.8 or newer
  - SDL2 library for window management
    - handles user input like keyboard and mouse events
    - open source answer to DirectX
    - cross platform
    - lots of games leverage this library
    - similar to GLUT, GLEW, or GLFW
  - <insert demo here>

Graphics

- Structure of our Demo Program
  - demo.cpp
    - setup, main event loop (60 lines)
  - demo.h
    - two structures, function declarations (60 lines)
  - data.cpp
    - transform calculations (200 lines)
  - resources
    - mesh files, font image, shaders
  - links with SDL and one other library

Graphics

- What is behind the Demo
  - CsPaint library
    - open source BSD license
    - encapsulates the Vulkan API exposing a higher level API
    - works on any GPU which supports Vulkan 1.1
    - uses vulkan.hpp which is the C++ interface
    - currently 38 source files

    - GLM
      - used for matrix math / linear algebra
      - provides buffer containers like the class glm::vec3
      - bundled with CsPaint
      - MIT license

Graphics

- CsPaint
  - platform independent
    - windows and linux have native drivers
    - android native drivers available since version 7
    - MoltenVK is a Vulkan wrapper on OS X and iOS
  - using the CsPaint library allows you to render graphics without having to focus on the tedious and repetitive sections
  - instead you are free to concentrate on writing your shaders and modeling 3D images or simply displaying text

Graphics

- Why Vulkan
  - Khronos Group took OpenGL and brought it closer to the metal
  - OpenGL is unable to send multiple commands
    - GPU sits idle too much of the time
    - CPU spends too much time waiting for the GPU

  - burden is now on the developer
  - no built in memory management, must be implemented and controlled by the developer
  - fixed function pipeline does not exist so developers must supply their own shader implementations
  - more configuration is required with fewer defaults supplied
  - same API for Linux, Windows, and Android
  - well supported translation layer for OS X and iOS

- Demo Source Code (set up, demo.cpp)

```
auto window              = init_window();
auto [context, surface] = init_vulkan(window);

auto device              = surface->graphicsDevice();
auto vertexShader        = device->createShader(vertexShaderData);
auto fragmentShader      = device->createShader(fragmentShaderData);
auto textFragmentShader = device->createShader(textFragmentShaderData);

auto graphicsQueue       = device->graphicsQueue();
auto transferQueue       = device->transferQueue();
auto renderPass          = device->createRenderPass();
auto commandpool         = device->graphicsCommandPool();
auto commandbuffer       = commandpool->createCommandBuffer();

init_render(device, surface, commandpool, vertexShader, fragmentShader,
            textFragmentShader, renderPass);
```

Graphics

- Demo Source Code (event loop, demo.cpp)

```
while (run) {
  SDL_Event evt;

  while (SDL_PollEvent(&evt)) {
    if (evt.type == SDL_QUIT) {
      run = 0;

    } else if (evt.type == SDL_KEYDOWN) {
      // process key events like the arrow keys to rotate the copper pot

    }
  }

  draw_frame(device, surface, renderPass,
       transform_matrix(glm::vec3(x_rotation, y_rotation, 0.0)), zoom_factor);
}
```

- Demo Data (fragment shader, shader.frag)

```
layout(location = 0) in  vec3 inNormal;
layout(location = 1) in  vec3 inColor;
layout(location = 2) in  vec3 inEyePos;
layout(location = 3) in  vec3 inLightVec;
layout(location = 0) out vec4 outColor;

void main() {
  vec3 Eye       = normalize(-inEyePos);
  vec3 Reflected = normalize(reflect(-inLightVec, inNormal));

  vec4 IAmbient  = vec4(0.4, 0.4, 0.4, 1.0);
  vec4 IDiffuse  = vec4(0.5, 0.5, 0.5, 0.5) * max(dot(inNormal, inLightVec),0.0);
  vec4 ISpecular = vec4(0.9, 0.9, 0.9, 1.0) * pow(max(dot(Reflected, Eye), 0.0),
                        1.5) * 0.50;

  outColor = vec4((IAmbient + IDiffuse) * vec4(inColor, 1.0) + ISpecular);
}
```

Terminology

- Graphics Terminology
  - instance, context, surface
  - memory heap
  - vertex buffer, uniform buffer
  - shaders (vertex, tessellation, geometry, fragment)
  - pipeline
  - command buffer
  - textures
  - frame buffer, depth buffer, render pass
  - swapchain
  - queues (graphics, present, transfer, compute)
  - fences, semaphores
  - face culling, winding
  - push constants, scissor, extent, viewport

Terminology

- Graphics Definitions
  - instance
    - connection between your application and the Vulkan library
    - typically your application will only create one
    - every other Vulkan call relies on passing this instance or some data associated with this instance
  - context
    - Vulkan instance is similar to an OpenGL context
    - not a term used in the Vulkan API
  - surface
    - a term for the window region where images are rendered
    - native window support is not handled directly in the API, implemented in platform extensions

Terminology

- Graphics Definitions
  - memory heap
    - provides storage for buffers which will be accessed by the GPU
    - every buffer must be created and managed by the user
    - memory is allocated from a memory heap
    - the buffer is then bound to the allocated memory
    - any memory which is visible to the GPU will be in the list of all memory heaps
    - there are usually multiple heaps available
    - certain heaps can only be used for specific types of buffers

Terminology

- Buffers
  - vertex buffer
    - coordinates of all vertices which describes the geometry for the image being rendered
    - triangles are the most widely used shape
    - there can be as few as three vertices, typically thousands for a given image
  - uniform buffer
    - contains data which is applied to every vertex
    - for example, transformations can be used to shift the geometry and render the image somewhere other than the center

Graphics

- What is a Shader
  - a program which is written in a specialized language
  - shaders are intended to be run on the GPU

  - OpenGL shaders are written in GLSL (OpenGL Shading Language)
  - Direct3D shaders are written in HLSL
  - Vulkan shaders are typically written in GLSL or HLSL and must be compiled to the SPIR-V binary format

  - there are various categories of shaders
  - each is responsible for a different aspect of image rendering
  - some shaders are required others are optional
  - ability to provide your own shader programs is considered one of the largest and most valuable graphics API advancements

Terminology

- Shader Categories
  - vertex shader
    - transforms a 3D position into 2D coordinates
    - executes once per vertex
  - tessellation shader
    - decompose shapes into smaller components, optional
  - geometry shader
    - alters the vertex shader output, optional
  - fragment shader
    - uses lighting and textures to calculate colors
    - executes at least once per pixel or fragment (partial pixel)

Terminology

- Graphics Definitions
  - pipeline
    - before a draw command is added to a command buffer you must create a pipeline object which sets a whole lot of options
    - shader handles, descriptor sets, push constants, depth buffer
    - winding direction, culling options, viewport
    - stencil, scissor, blending

  - command buffer
    - accumulates draw commands which are executed on the GPU at a later time
    - only way to synchronize these commands is by using a barrier
      - set semaphore, query semaphore
      - wait for pipeline stage (such as wait for a vertex shader to finish)

Terminology

- Graphics Definitions
  - frame buffer
    - no default buffer exists since displaying an image is optional
    - typically contains one image
    - not required if no images are displayed
  - depth buffer
    - a 3D mesh has perspective and to draw it realistically some triangles must appear in front of other triangles
    - a depth buffer is used to determine what part of the mesh is closer to the camera
    - misconfiguring this buffer will result in far away objects being rendered on top of closer objects

Terminology

- Graphics Definitions
  - render pass
    - added for improved performance on mobile
      - OpenGL and DirectX 12 do not have a render pass equivalent
    - for tile based GPU support
      - common in mobile, uncommon on desktop computers
    - a pipeline needs information about color channels, the depth buffer, possible image sampling, etc
    - all of this information is split into one or more render passes
    - begin command buffer, begin render pass
    - add commands for this one pass
    - end render pass, end command buffer

Terminology

- Graphics Definitions
  - swapchain
    - a set of buffers where the GPU can render
    - in Vulkan there is no default frame buffer
    - creating a swapchain is the only way to create an empty frame buffer
    - each frame buffer will hold a single image which is waiting to be presented on the surface
    - a single swap chain can contain many frame buffers
    - platform specific, supplied through “extensions” which are requested when you create the Vulkan instance

Terminology

- Queues
  - similar to a CPU thread, fixed number of queues on the GPU
  - each queue is intended to execute a certain kind of operation
  - a mechanism to send commands to the GPU for processing

  - graphics queue
    - used to generate an image
  - present queue
    - used to copy images to the screen
  - computation queue
    - used to run general purpose computations
  - transfer queue
    - used to copy data between CPU memory and GPU memory

Terminology

- Synchronization
  - draw_frame() is a function you write which puts a sequence of commands in a queue
  - this function is responsible for the following operations
    - retrieve an inactive frame buffer from the swapchain
    - build a command buffer
    - submit the command buffer to the graphics queue
    - submit the frame buffer to the presentation queue
  - some of these operations are executed asynchronously
  - unfortunately some tasks must wait until prior ones have completed
  - additional constraints are required for operations which have dependencies and these must be provided by the programmer

Terminology

- Graphics Definitions
  - there are two ways to synchronize these operations
  - fence
    - used to synchronize work between the CPU and the GPU
    - status of a fence can be accessed from your program
  - semaphore
    - used to synchronize work occurring on the GPU
    - semaphore dependencies are set up in your program however they are observed only on the GPU
    - not visible to the CPU nor can you query their status

Terminology

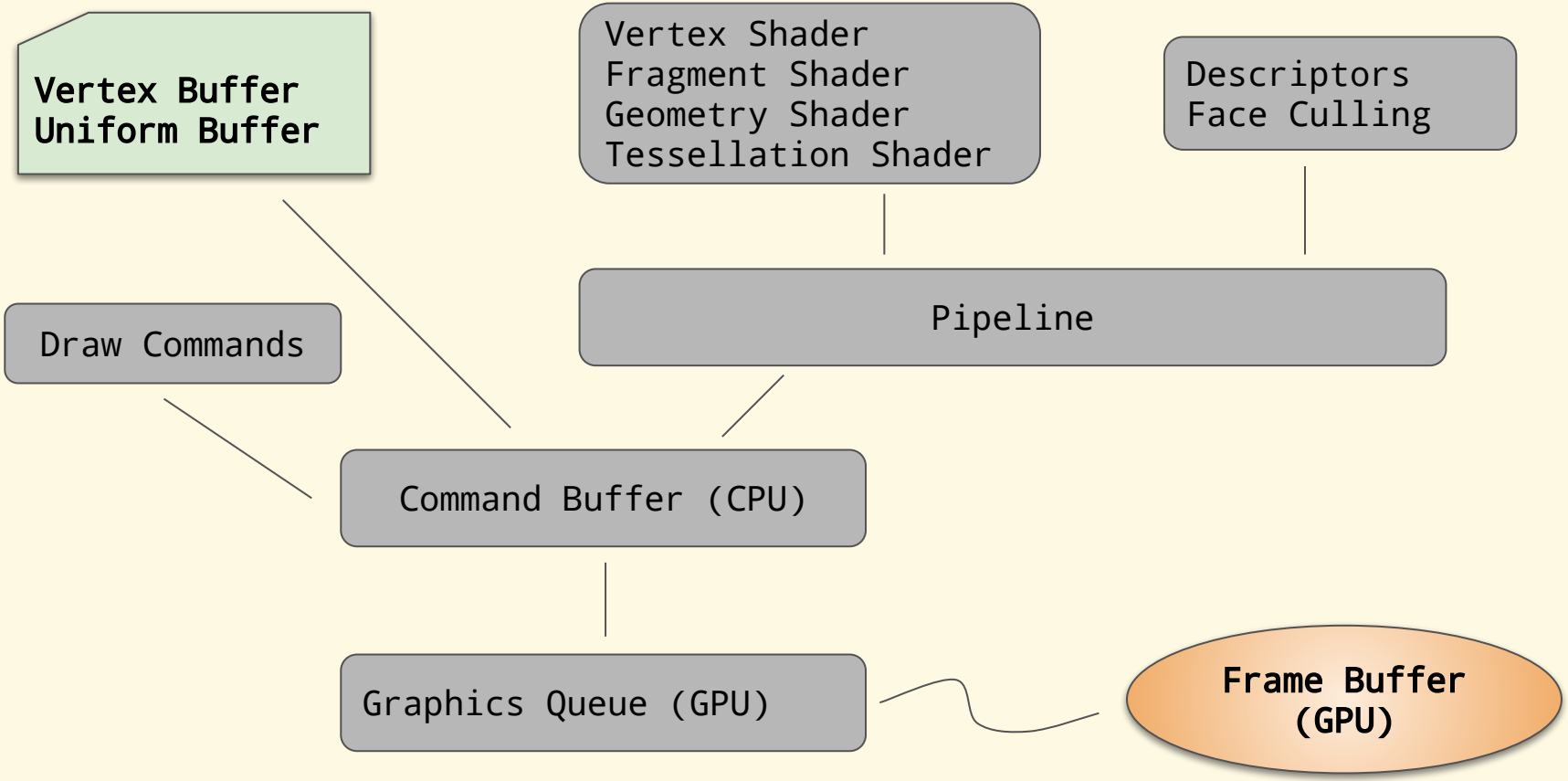
- Graphics Definitions
  - winding direction
    - must be specified as part of the pipeline
    - conventionally clockwise winding is used
    - the direction is used to determine whether a given triangle is facing the camera (front facing) or facing away (back facing)

  - back face culling
    - is the process of discarding triangles which are back facing since these are not normally visible to the viewer
    - there is no default so it must be set on or off in the pipeline
    - triangles are "culled" early in the rendering pipeline
    - increases efficiency by reducing the number of fragments which are processed

Terminology

- Graphics Definitions
  - push constants
    - a way to provide a small amount of uniform data to shaders
  - scissor
    - scissor test restricts drawing to the specified rectangle
    - test is always enabled and can not be turned off
  - extent
    - structure containing width and height
    - defines things like the size of the screen or the render area
  - viewport
    - specifies a region of the frame buffer which should be refreshed, potentially complicated to determine

Program / Data Flow



When the frame buffer is ready, a previously configured semaphore is triggered which presents the output

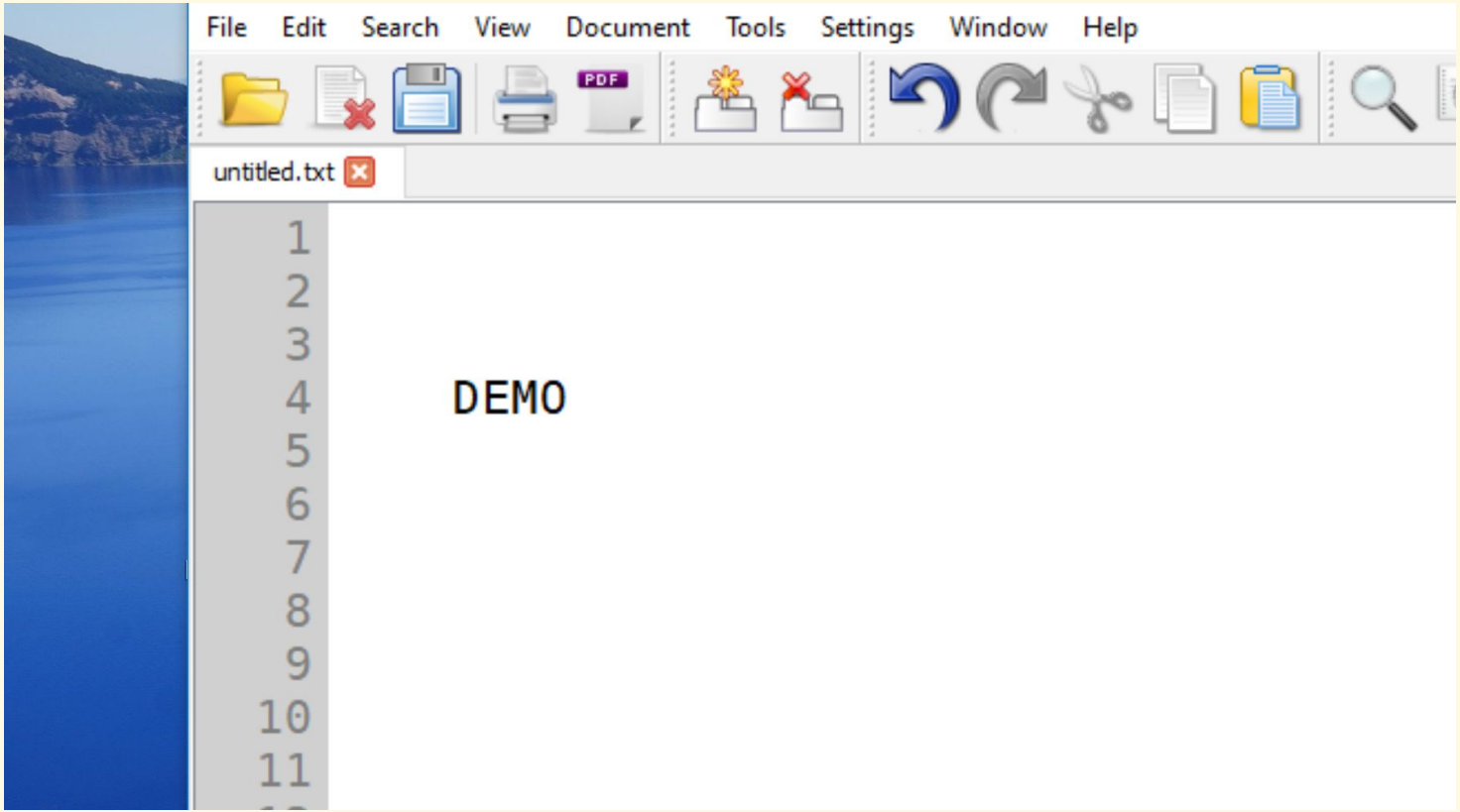
Graphics User Interface

- Putting the Graphics back in GUI
  - intent of a GUI is to present a graphical interface
  - graphics have traditionally been rendered on the CPU
  - most GUI libraries still use software rendering

  - why not use the GPU for all types of graphics
  - text is graphics too

  - CsPaint can render text as graphics on the GPU
  - more efficient
  - infinitely scalable
  - cleaner edges
  - textured, reflective, shadowing . . .

CPU Text vs GPU Rendering



This text is a 16 point monospace font.
Generated screenshot was taken from a Windows GUI application.

CPU Text vs GPU Rendering

Increased the previous image size by 1400 percent.

CPU Text vs GPU Rendering

In the “Graphics Demo” moved the camera closer to the text.
Generated a screenshot with no alterations.

Text

- Rendering Text on the GPU
  - walk the string and create a “rectangle” for each letter
  - uses a process similar to applying a standard texture to a model

  - texture for text does not contain a color or pattern
  - contains a distorted font image generated from any normal font file
  - currently supports monospace fonts for Latin-1

  - fragment shader
    - computes a high resolution output using a multi channel (color) signed distance field algorithm

  - all the heavy lifting is part of CsPaint

Useful Links

- Vulkan API
  - LunarG is the organization which provides the main Vulkan SDK
  - key element is the loader which is responsible for the bridge between your program and the vendor supplied graphics drivers
    - supports various layers
    - supports multiple GPUs
  - tools for compiling shaders to SPIR-V binary output
  - other development tools
    - https://www.lunarg.com/vulkan-sdk

  - informative overview of LunarG
    - https://www.youtube.com/watch?v=wWYRFwIHdJc

Useful Links

- Vulkan Tutorials
  - https://vulkan-tutorial.com/
  - https://vulkan.lunarg.com/doc/view/1.1.101.0/windows/tutorial/html/index.html
  - https://gpuopen.com/understanding-vulkan-objects/
  - https://developer.nvidia.com/transitioning-opengl-vulkan

3D Design

- Modeling
  - numerous open source and proprietary programs

  - selected Blender
    - open source 3D graphics modeling application
    - professional quality
    - version 2.8 released July 2019
    - several good youtube channels which use Blender

    - blender guru has a 9 part tutorial series
      - https://www.blenderguru.com/

Where is CsPaint Headed

- Roadmap
  - enhance the graphics demo
  - allow some of the defaulted parameters to be configured
  - add a slightly higher level API to CsPaint
  - provide sample fragment shaders
  - enhance 2D graphics support
  - create distance field textures on the fly for a given font
  - add text shaping using the Harfbuzz version 2 library
  - potentially link with CsString for Unicode support
  - enhance API documentation
  - incorporate user contributions

Integrating CopperSpice with CsPaint

- Roadmap
  - main application window will be a Vulkan surface
  - internal paint system redesigned to call CsPaint
  - all controls rendered using Vulkan

  - majority of controls will render on the GPU without modification
    - push button, radio button, check box, combo box
      table view, tree view, calendar, line edit, text edit

  - on Windows and Unix CopperSpice will use CsPaint directly
  - on OS X MoltenVK wrapper will be used to translate Vulkan

  - some level of fallback may be maintained for systems which do not have current Vulkan 1.1 support

Presentations

- ❏ Why CopperSpice
- ❏ Why DoxyPress
- ❏ Compile Time Counter
- ❏ Modern C++ Data Types (references)
- ❏ Modern C++ Data Types (value categories)
- ❏ Modern C++ Data Types (move semantics)
- ❏ CsString library (unicode)
- ❏ CsString library (library design)
- ❏ Multithreading in C++
- ❏ Multithreading using libGuarded
- ❏ Signals and Slots
- ❏ Build Systems
- ❏ Templates in the Real World
- ❏ Copyright Copyleft
- ❏ What's in a Container
- ❏ Modern C++ Threads
- ❏ C++ Undefined Behavior
- ❏ Regular Expressions
- ❏ Using DoxyPress
- ❏ Type Traits
- ❏ C++ Tapas (typedef, forward declarations)
- ❏ Lambdas in C++
- ❏ C++ Tapas (typename, virtual, pure virtual)
- ❏ Overload Resolution
- ❏ Futures & Promises
- ❏ Special Member Functions
- ❏ C++ in Review
- ❏ Thread Safety
- ❏ Constexpr Static Const
- ❏ When Your Codebase is Old Enough to Vote
- ❏ Sequencing
- ❏ Linkage
- ❏ Inheritance
- ❏ Evolution of Graphics Technology
- ❏ GPU, Pipeline, and the Vector Graphics API
- ❏ Rendering 3D Graphics
- ❏ Declarations and Type Conversions
- ❏ C++ ISO Standard
- ❏ Inline Namespaces
- ❏ Lambdas in Action
- ❏ Any Optional

Please subscribe to our YouTube Channel
https://www.youtube.com/copperspice

Libraries

- CopperSpice
  - libraries for developing GUI applications
- CsPaint Library
  - standalone C++ library for rendering graphics on the GPU
- CsSignal Library
  - standalone thread aware signal/slot library
- CsString Library
  - standalone unicode aware string library
- libGuarded
  - standalone multithreading library for shared data

Applications

- KitchenSink
  - contains 30 demos and links with almost every CopperSpice library
- Diamond
  - programmers editor which uses the CopperSpice libraries
- DoxyPress & DoxyPressApp
  - application for generating source code and API documentation

Where to find CopperSpice

- www.copperspice.com

- ansel@copperspice.com
- barbara@copperspice.com

- source, binaries, documentation files
  - download.copperspice.com

- source code repository
  - github.com/copperspice

- discussion
  - forum.copperspice.com