Go on GPU

Changkun Ou

changkun.de/s/gogpu

GopherChina 2023
Session “Foundational Toolchains”
2023 June 10

Agenda

- Basic knowledge for interacting with GPUs
- Accelerate Go programs using GPUs
- Challenges in Go when using GPUs
- Conclusion and outlooks

Agenda

- **Basic knowledge for interacting with GPUs**
    - Motivation
    - GPU Driver and Standards
    - Render and compute pipeline
    - Vulkan/Metal/DX12/OpenGL
- Accelerate Go programs using GPUs
- Challenges in Go when using GPUs
- Conclusion and outlooks

Motivation of GPU Acceleration

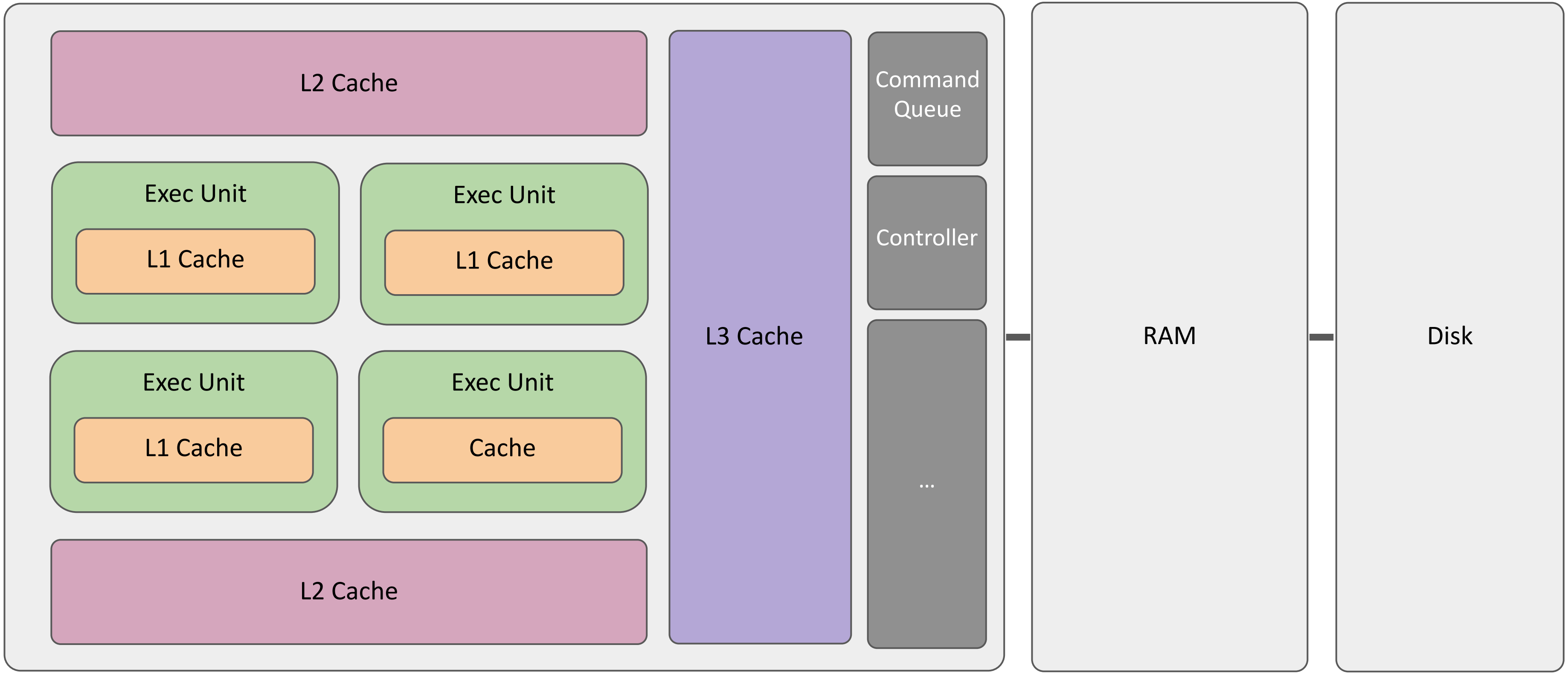
Improve system computation performance

Increase amount of concurrency

Processing large amount of data

Machine learning, deep learning, graphics rendering, etc.

CPU Architecture



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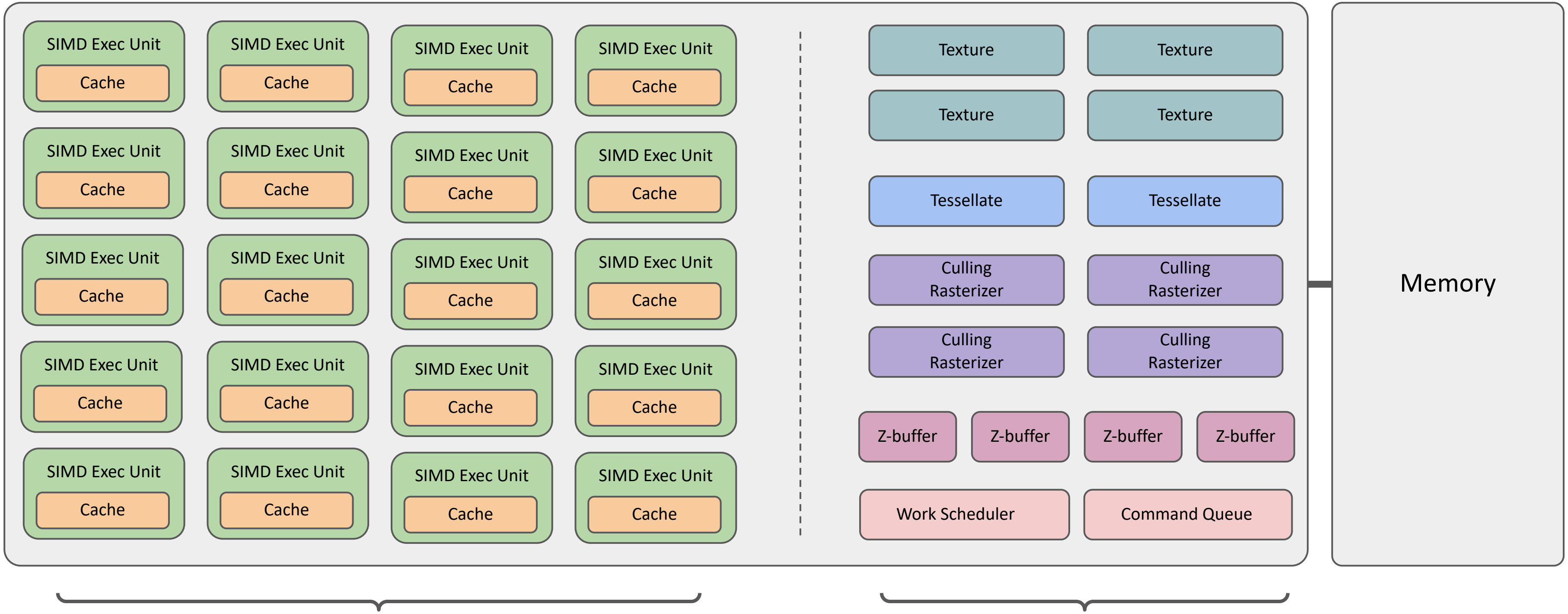
GPU Architecture



Cores for executing shader programs (programmable), in parallel

Graphics-specific fixed functions (non-programmable)
and compute resources

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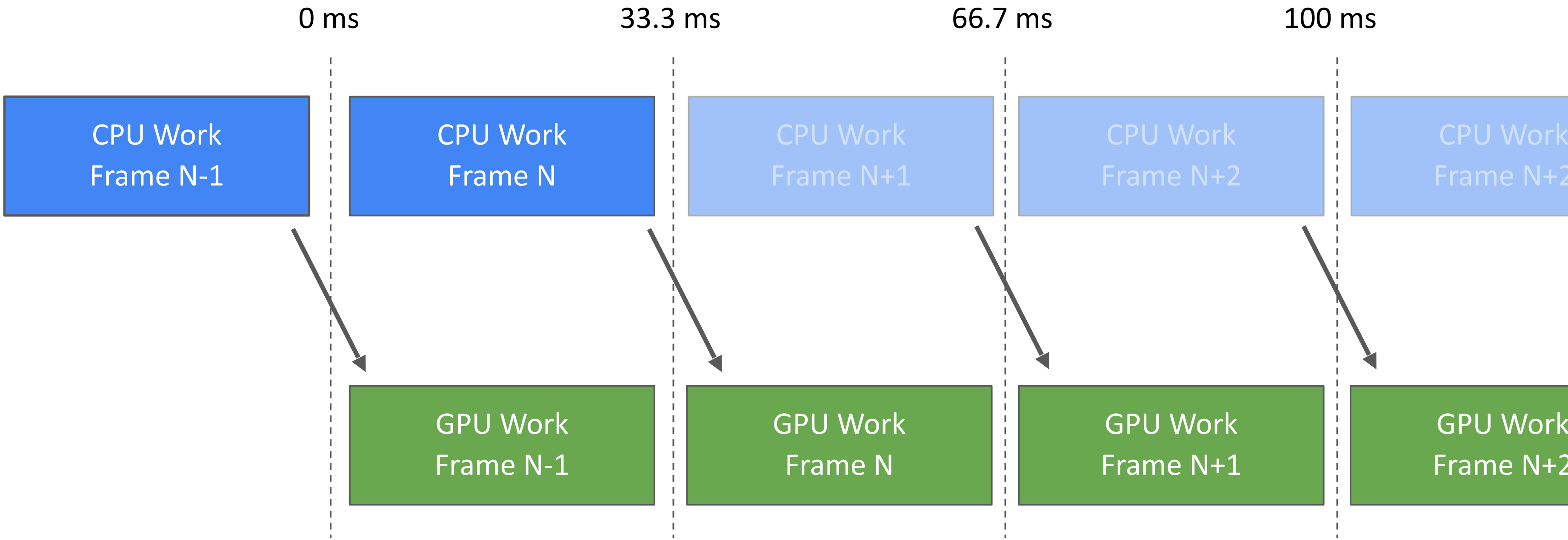
Collaboration between CPU and GPU: Render Scenario

CPU and GPU works together as a leader-follower relationship, CPU is responsible for preparing the GPU work and relevant resources, and GPU is responsible for the execution

For instance, in a gaming scenario, we often aim for 30 fps and GPU renders per 33.3ms



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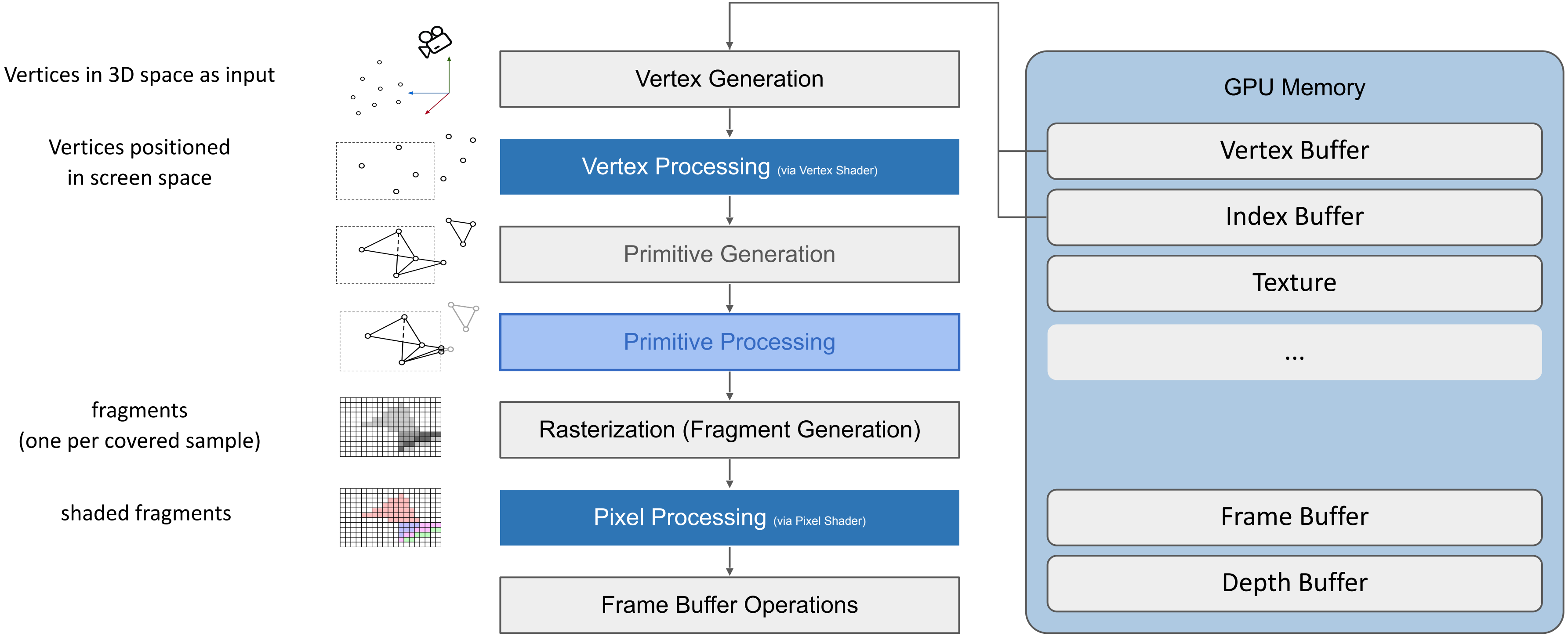
Graphics Rendering Pipeline

Rendering pipeline focuses on executing Render Passes. In each of the rendering pass, the associated render task can be customized using shaders. In GPU, except rasterizer unit, it also includes ray tracing unit.



Vertices in 3D space as input

Vertices positioned in screen space

fragments (one per covered sample)

shaded fragments

Vertex Generation

Vertex Processing (via Vertex Shader)

Primitive Generation

Primitive Processing

Rasterization (Fragment Generation)

Pixel Processing (via Pixel Shader)

Frame Buffer Operations

GPU Memory

- Vertex Buffer
- Index Buffer
- Texture
- ...
- Frame Buffer
- Depth Buffer

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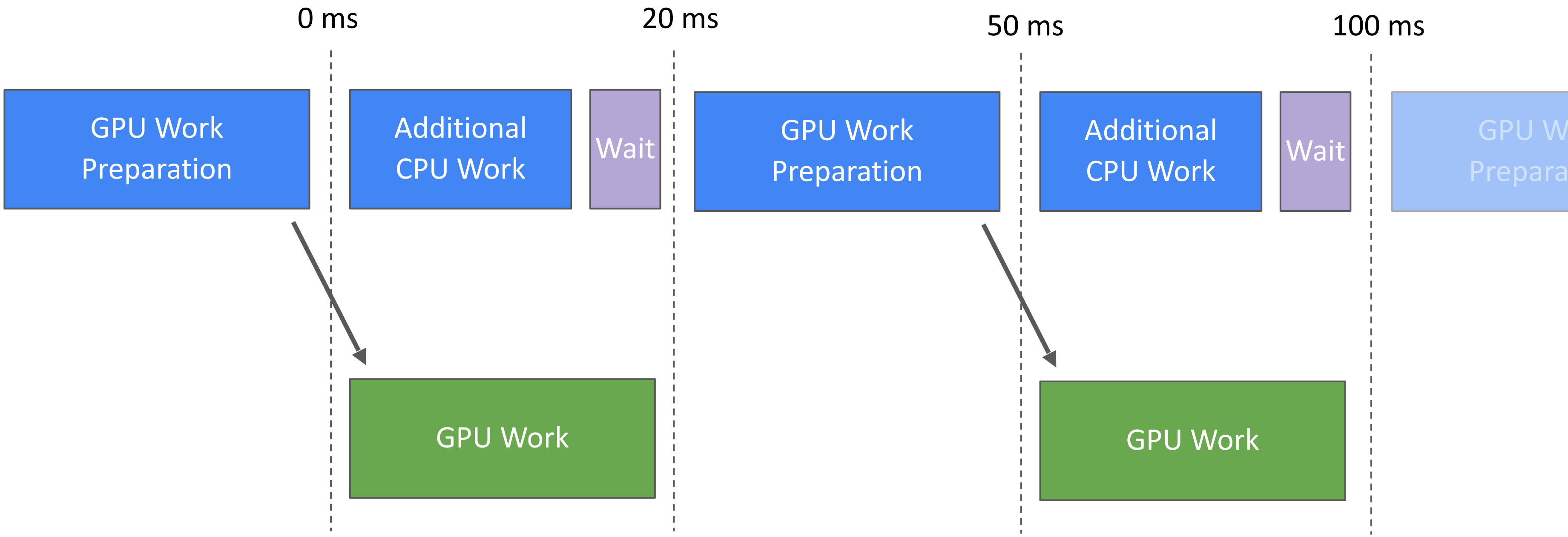
Collaboration between CPU and GPU: Compute Scenario

As general purpose computing involves, GPU starts to detach from rendering pipeline, and can be considered as an external computing resource. CPU can schedule compute tasks to GPU at any time.



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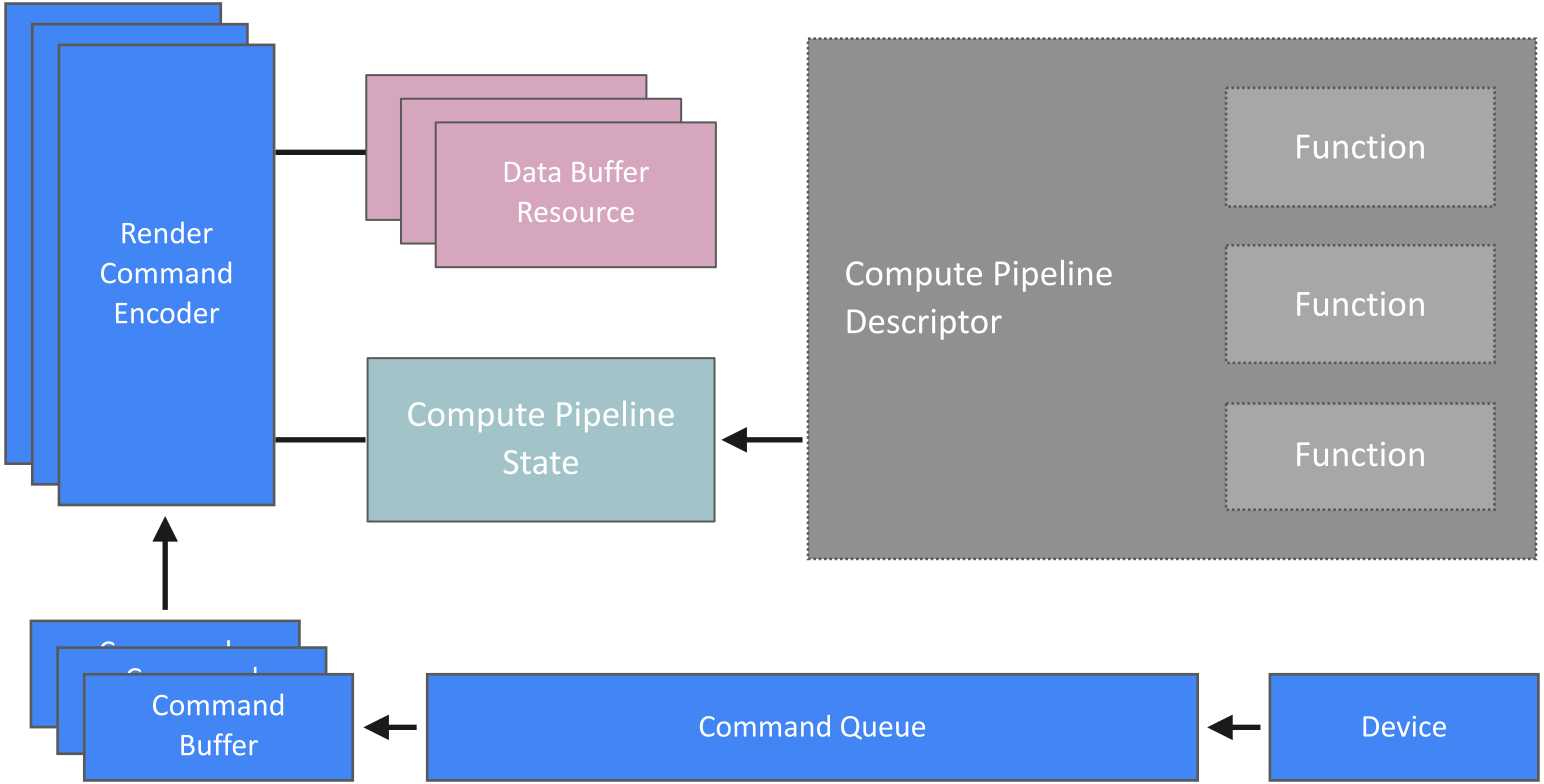
Compute Pipeline



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Command Submission Model

Command encoders convert API commands into hardware commands

Hardware commands stored in command buffers

Depending on the task, there are different types of command encoders (render, compute, blit)

Command buffer can be created on different threads, they are explicitly and concurrently submitted to command queue

Graphics Standards

Conventional Gold Standards: OpenGL series

A successor: Vulkan

Khronos Groups cannot consider all realistic requirements in all manufactures

OS designers starts to customize and design their own standards

Web platform builds standard on top them

WebGPU

WebGL™

OpenGL®

OpenGL® ES™

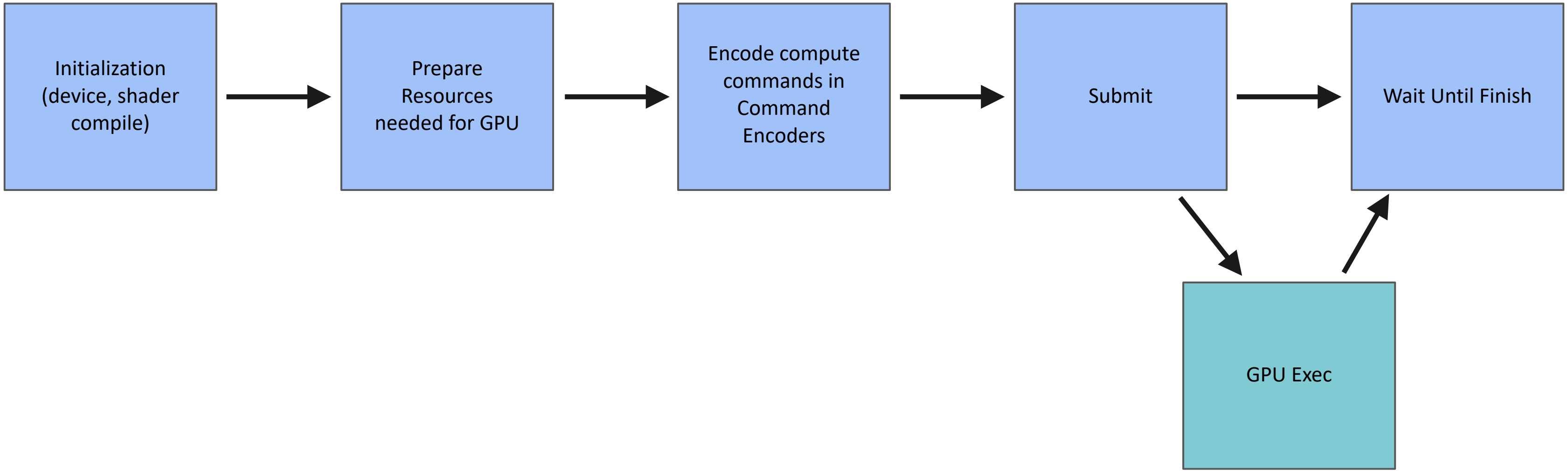
Microsoft® DirectX®

Vulkan®

Agenda

- Basic knowledge for interacting with GPUs
- **Accelerate Go programs using GPUs**
  - Overall workflow of GPU acceleration
  - Two examples
  - Design Questions to Consider
- Challenges in Go when using GPUs
- Conclusion and outlooks

Basic Workflow to Add GPU Acceleration in Go Program



Initialization (device, shader compile)

Prepare Resources needed for GPU

Encode compute commands in Command Encoders

Submit

Wait Until Finish

GPU Exec

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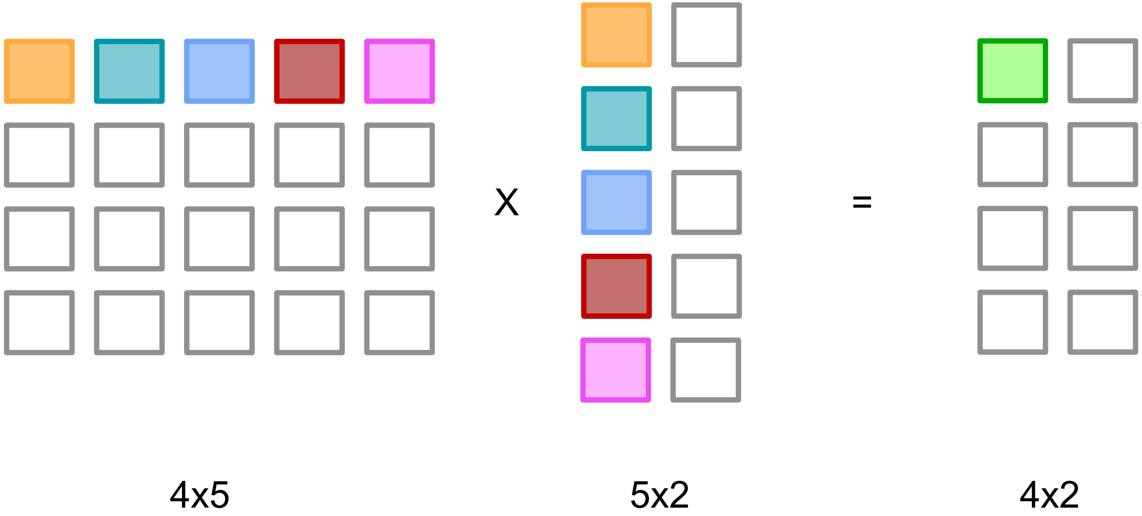
Preparation: Driver - Metal as Example

```
package mtl // import "changkun.de/x/gopherchina2023gogpu/gpu/mtl"

/*
#cgo CFLAGS: -Werror -fmodules -x objective-c
#cgo LDFLAGS: -framework Metal -framework CoreGraphics
#include "mtl.h"
*/
import "C"

type Device struct
func (d Device) MakeCommandQueue() CommandQueue

@import Metal;
#include "mtl.h"
void * Device_MakeCommandQueue(void * device) {
    return [(id<MTLDevice>)device newCommandQueue];
}
...
```

Example 1: Matrix Multiplication

Matrix multiplication is almost the fundamental compute unit for many modern scientific computation, it is also a classic performance improvement problem to solve.

Example: Feedforward propagation in neural network is done via matrix multiplication; many other linear solvers rely on matrices, etc



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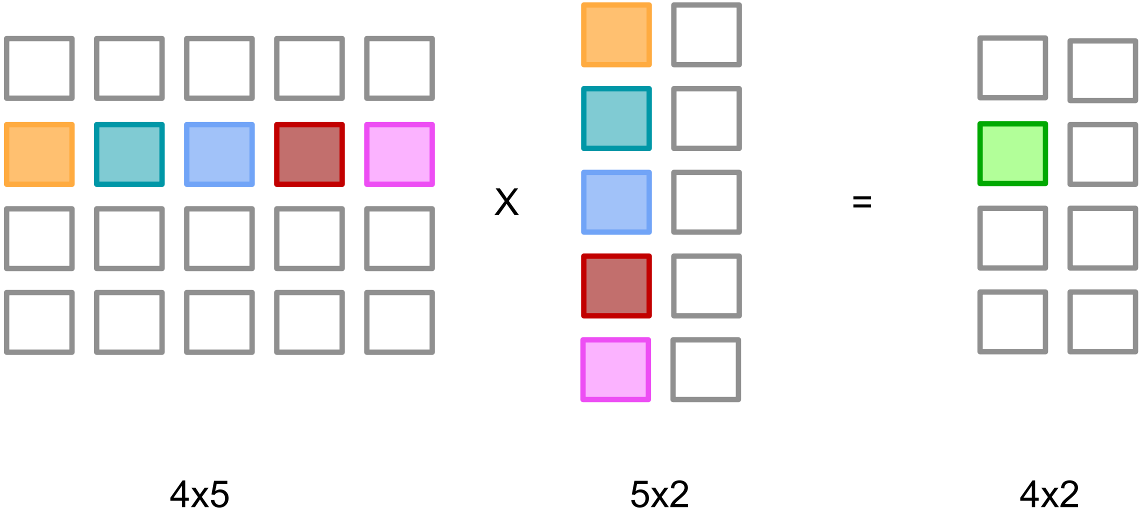

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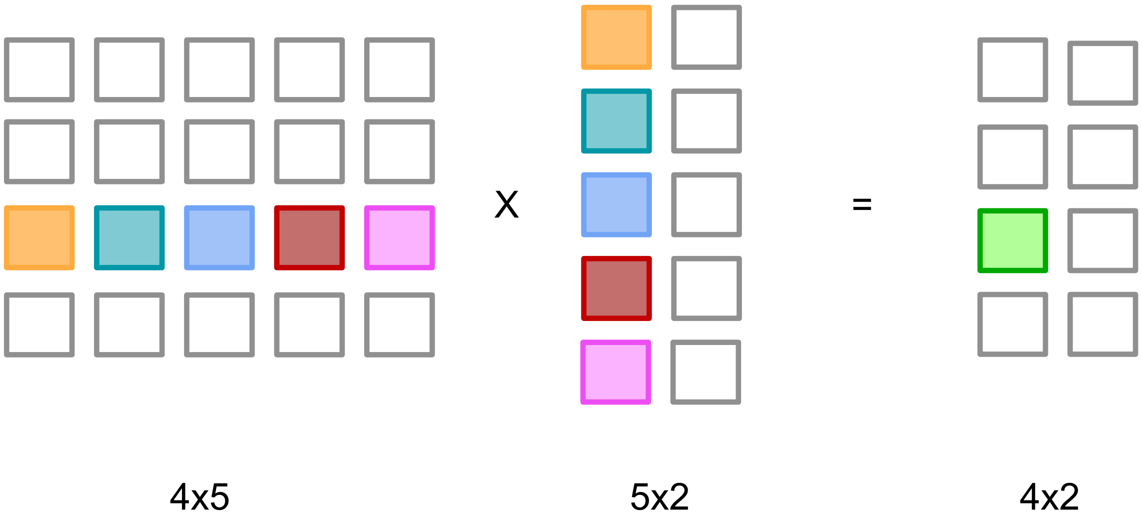

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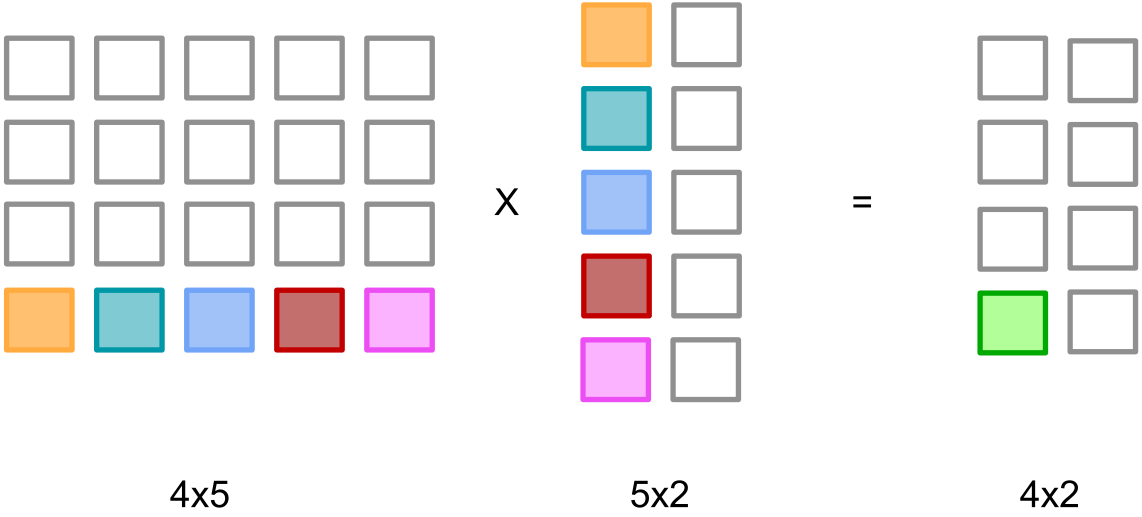

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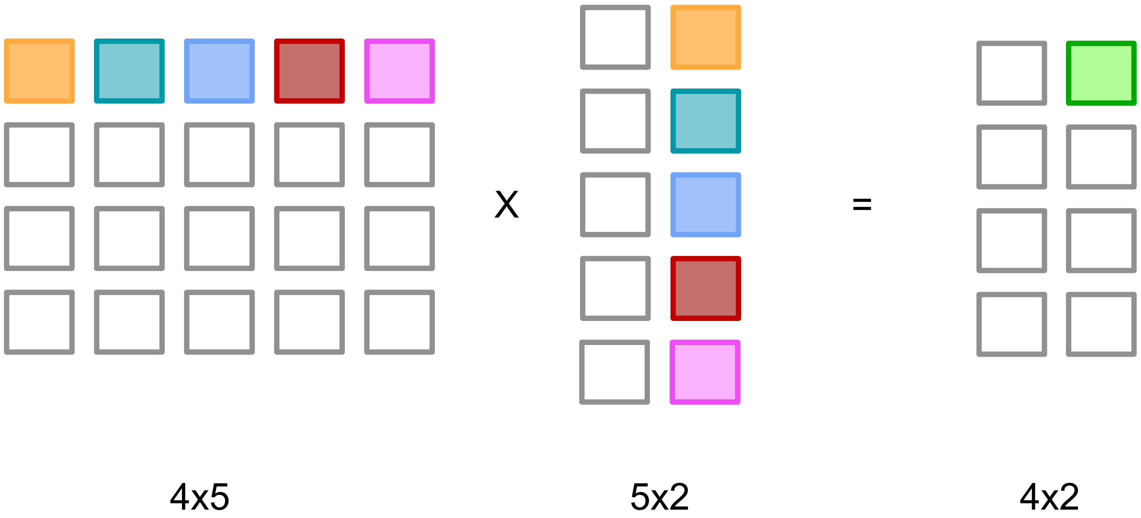

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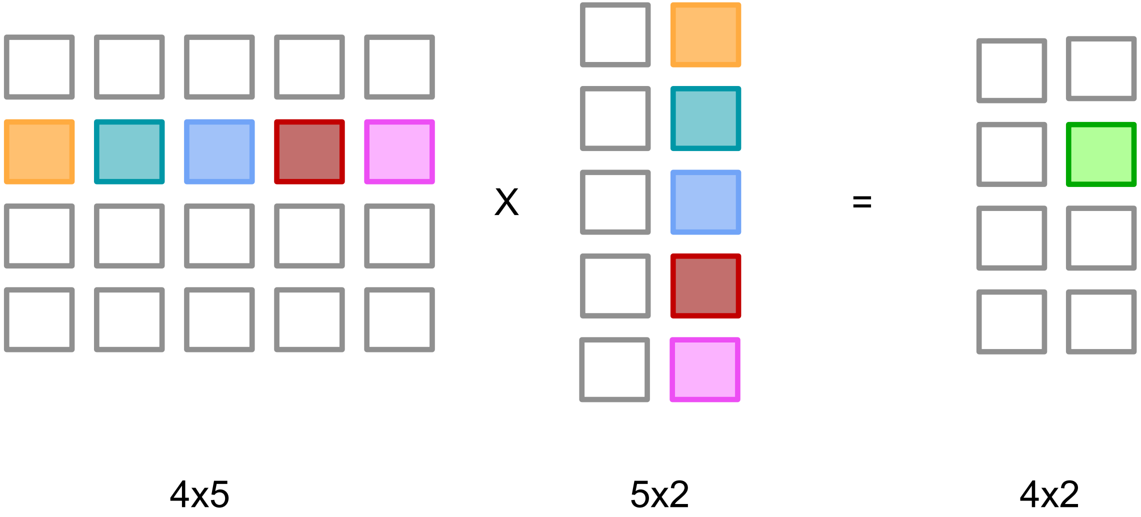

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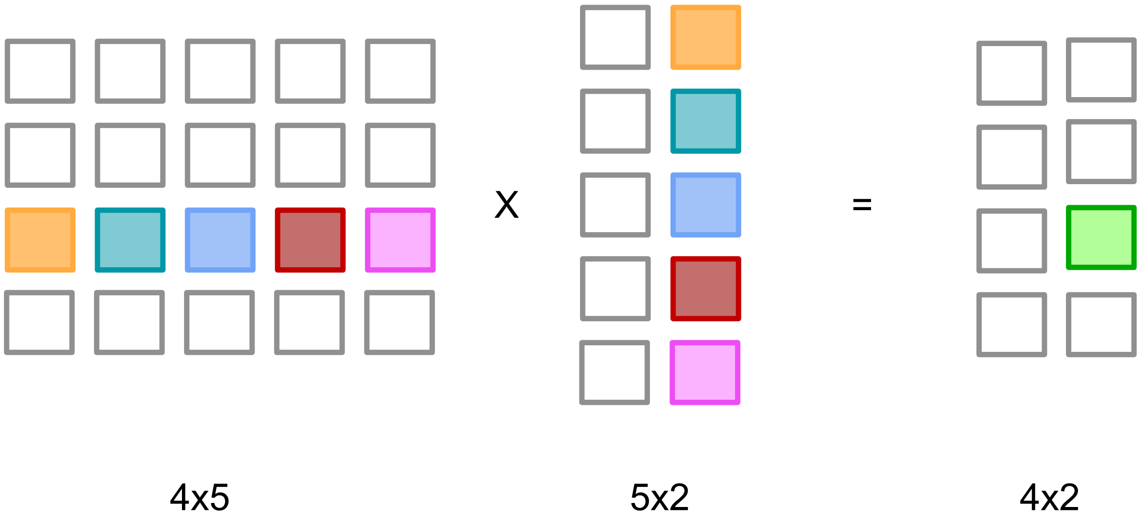

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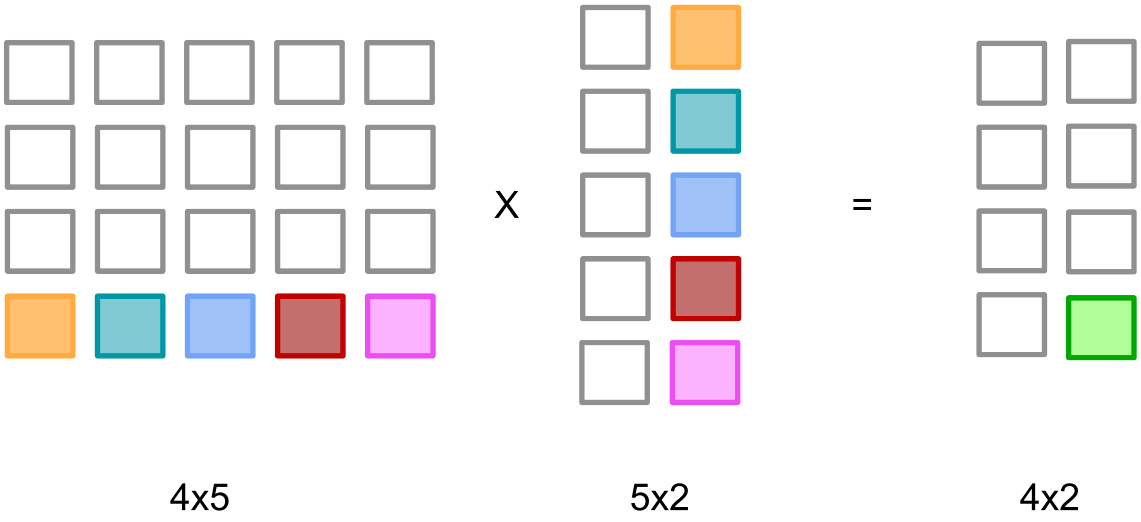

Example 1: Matrix Multiplication

```go
// Mat represents a Row x Col matrix.
type Mat[T Type] struct {
    Row  int
    Col  int
    Data []T
}

// MulNaive applies matrix multiplication of two given matrix, and returns
// the resulting matrix: r = m*n. This is a O(n^3) implementation.
func (m Mat[T]) MulNaive(n Mat[T]) Mat[T] {
    r := Mat[T]{Row:  m.Row, Col:  n.Col, Data: make([]T, m.Row*n.Col)}
    for i := 0; i < m.Row; i++ {
        for j := 0; j < n.Col; j++ {
            sum := T(0)
            for k := 0; k < m.Col; k++ {
                sum += m.Get(i, k) * n.Get(k, j)
            }
            r.Set(i, j, sum)
        }
    }
    return r
}
```

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    for i := 0; i < m.Row; i++ {
        for j := 0; j < n.Col; j++ {
            sum := T(0)
            for k := 0; k < m.Col; k++ {
                sum += m.Get(i, k) * n.Get(k, j)
            }
            r.Set(i, j, sum)
        }
    }
    return r
}
```

①

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Example 1: Matrix Multiplication

```go
import "changkun.de/x/gopherchina2023gogpu/gpu/mtl" // Metal driver
var (
    //go:embed mul.metal
    mulMetal string
    device      mtl.Device
    cq          mtl.CommandQueue
    lib         mtl.Library
    funcMul     mtl.Function
    funcMulCPS mtl.ComputePipelineState
)
func init() {
    // 0. Initialization
    device = try(mtl.CreateSystemDefaultDevice())
    cq = device.MakeCommandQueue()
```

①

```go

    lib = try(device.MakeLibrary(mulMetal, mtl.CompileOptions{
        LanguageVersion: mtl.LanguageVersion2_4,
    }))
    funcMul = try(lib.MakeFunction("mul"))
    funcMulCPS = try(device.MakeComputePipelineState(funcMul))
}
```

②

Example 1: Matrix Multiplication

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import "changkun.de/x/gopherchina2023gogpu/gpu/mtl" // Metal driver
var (
    //go:embed mul.metal
    mulMetal string
    device     mtl.Device
    cq         mtl.CommandQueue
    lib        mtl.Library
    funcMul    mtl.Function
    funcMulCPS mtl.ComputePipelineState
)
func init() {
    // 0. Initialization
    device = try(mtl.CreateSystemDefaultDevice()) ①
    cq = device.MakeCommandQueue()

    lib = try(device.MakeLibrary(mulMetal, mtl.CompileOptions{
        LanguageVersion: mtl.LanguageVersion2_4,
    }))
    funcMul = try(lib.MakeFunction("mul"))
    funcMulCPS = try(device.MakeComputePipelineState(funcMul)) ②
}
```

Example 1: Matrix Multiplication

```go
// Mul is a GPU version of math.Mat[T].Mul method and it multiplies
// two matrices m1 and m2 and returns the result.
func Mul[T math.Type](m1, m2 math.Mat[T]) math.Mat[T] {

    // 1. Allocate GPU buffers
    a := device.MakeBuffer(unsafe.Pointer(&m1.Data[0]), uintptr(math.TypeSize[T]
()*len(m1.Data)), mtl.ResourceStorageModeShared)
    defer a.Release()
    b := device.MakeBuffer(unsafe.Pointer(&m2.Data[0]), uintptr(math.TypeSize[T]
()*len(m2.Data)), mtl.ResourceStorageModeShared)
    defer b.Release()
    out := device.MakeBuffer(nil, uintptr(math.TypeSize[T]()*m1.Row*m2.Col),
mtl.ResourceStorageModeShared)
    defer out.Release()
    dp := device.MakeBuffer(unsafe.Pointer(&params{
        ColA: int32(m1.Col),
        ColB: int32(m2.Col),
    }), unsafe.Sizeof(params[T]{}), mtl.ResourceStorageModeShared)
    defer dp.Release()
    …
}
```

①

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Example 1: Matrix Multiplication

```
#include <metal_stdlib>
using namespace metal;

struct params { uint colA; uint colB; };

kernel void mul(device const float*  inA     [[ buffer(0) ]],   ①
                device const float*  inB     [[ buffer(1) ]],
                device       float*  out     [[ buffer(2) ]],
                device const params& params  [[ buffer(3) ]],
                uint                 index   [[thread_position_in_grid]]) {   ②

    uint i = index / uint(params.colB);
    uint j = index % uint(params.colB);
    float sum = 0.0;
    for (uint k = 0; k < params.colA; k++) {
        float a = inA[i * int(params.colA) + k];
        float b = inB[k * int(params.colB) + j];   ③
        sum += a * b;
    }
    out[index] = sum;
}
```

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// two matrices m1 and m2 and returns the result.
func Mul[T math.Type](m1, m2 math.Mat[T]) math.Mat[T] {
    …
    // 2. Create command buffer, command encoder, and set buffer
    cb := cq.MakeCommandBuffer()
    defer cb.Release()

    ce := cb.MakeComputeCommandEncoder()
    ce.SetComputePipelineState(fn.funcMul.cps)
    ce.SetBuffer(a, 0, 0)
    ce.SetBuffer(b, 0, 1)
    ce.SetBuffer(out, 0, 2)
    ce.SetBuffer(dp, 0, 3)
    …
}
```

①

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// two matrices m1 and m2 and returns the result.
func Mul[T math.Type](m1, m2 math.Mat[T]) math.Mat[T] {
    …
    // 2. Create command buffer, command encoder, and set buffer
    cb := cq.MakeCommandBuffer()
    defer cb.Release()
    …


    // 3.Dispatch threads and commit command encoders in the command buffer
    ce.DispatchThreads(
        mtl.Size{Width: m1.Row * m2.Col, Height: 1, Depth: 1},
        mtl.Size{Width: 1, Height: 1, Depth: 1})
    ce.EndEncoding()
    cb.Commit()
    cb.WaitUntilCompleted()
    …
}
```

❶

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// two matrices m1 and m2 and returns the result.
func Mul[T math.Type](m1, m2 math.Mat[T]) math.Mat[T] {
    …
    out := device.MakeBuffer(nil, uintptr(math.TypeSize[T]()*m1.Row*m2.Col),
mtl.ResourceStorageModeShared)                                              ①
    …

    // 4. Copy data from GPU buffer to CPU buffer
    data := make([]T, m1.Row*m2.Col)
    copy(data, unsafe.Slice((*T)(out.Content()), m1.Row*m2.Col))  ②
    return math.Mat[T]{
        Row:  m1.Row,
        Col:  m2.Col,
        Data: data,
    }
}
```

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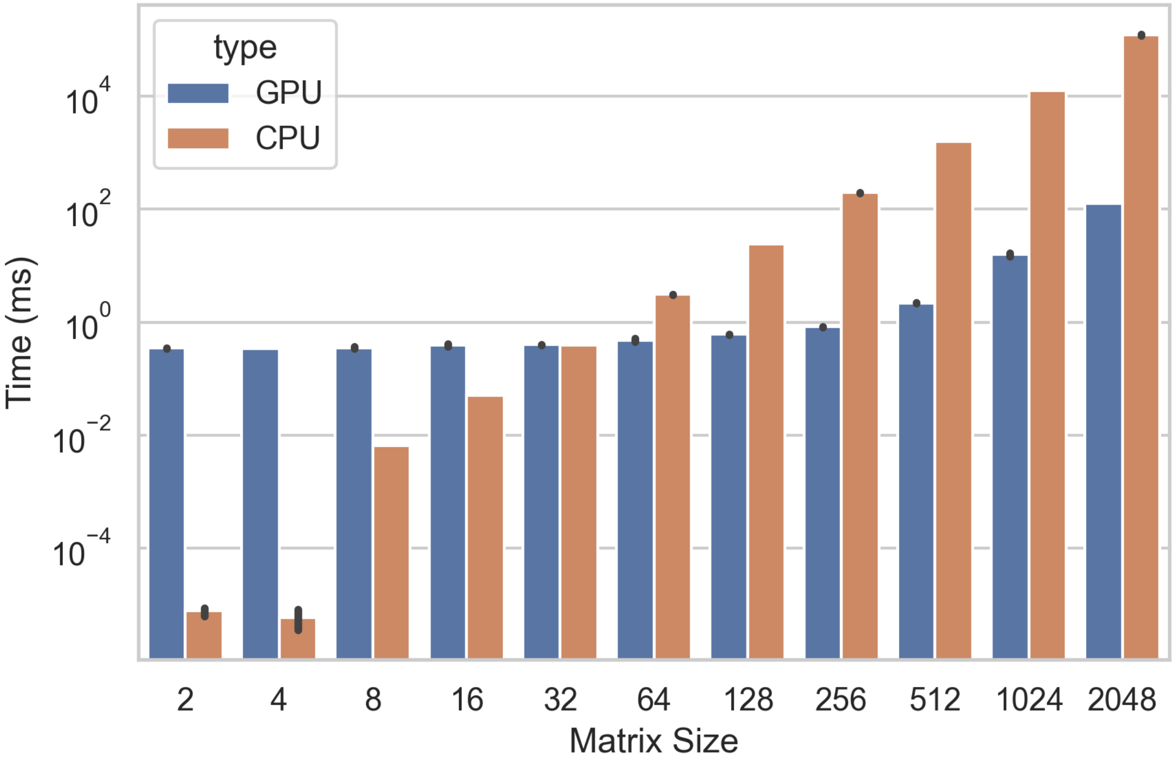
Example 1: Matrix Multiplication



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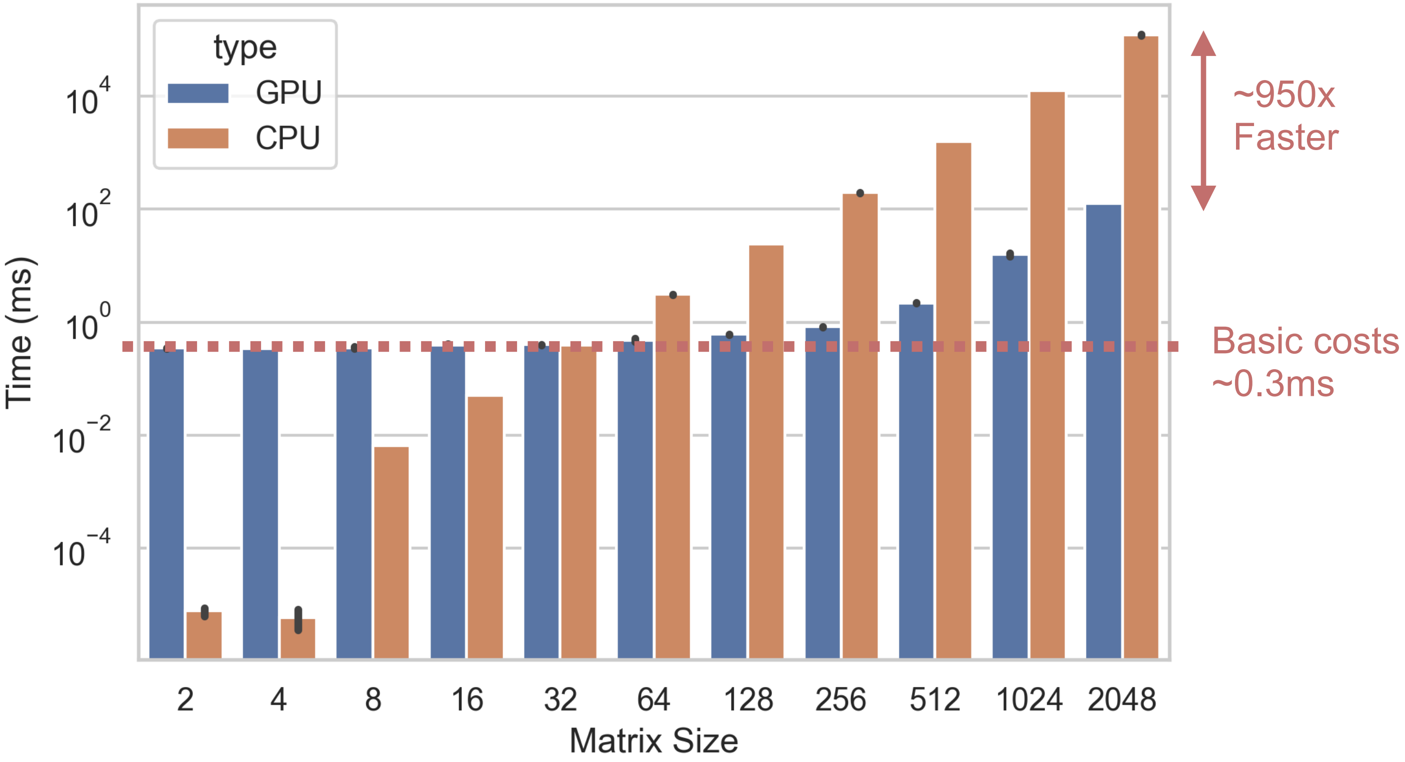

~950x Faster

Basic costs ~0.3ms

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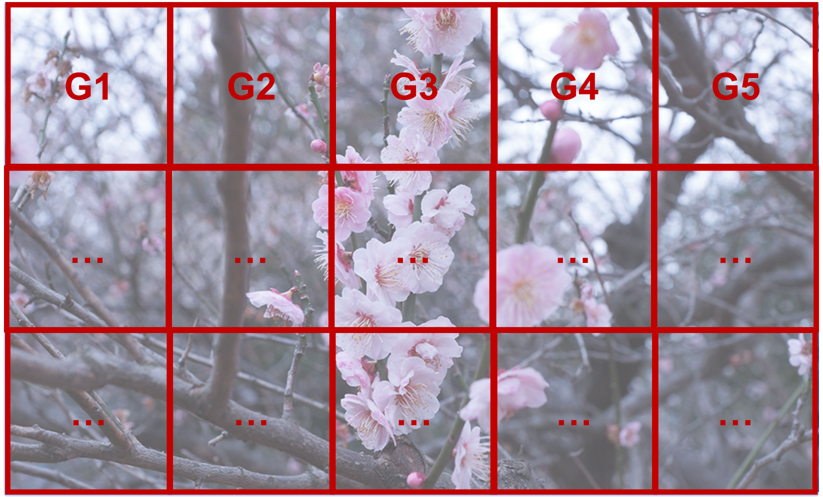
Example 2: Image Processing

Image source: Yuki Koyama

Original

After Processing

Example 2: Image Processing's Parallelization Granularity



Original

After Processing

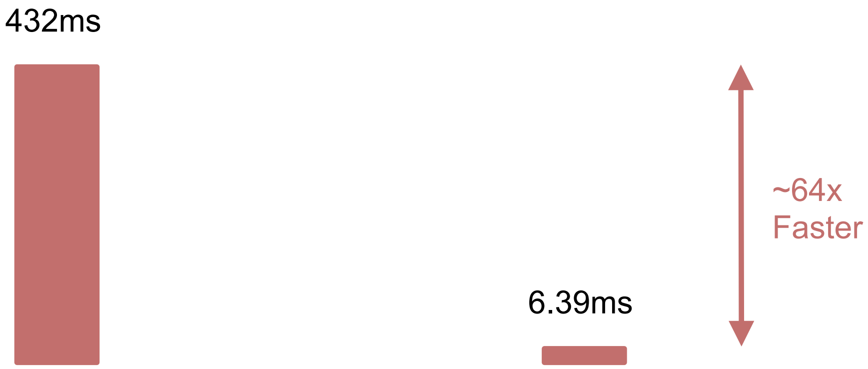
CPU Compute Granularity = Half of CPU Cache Line Size

GPU Compute Granularity = Pixel Level Parallelization

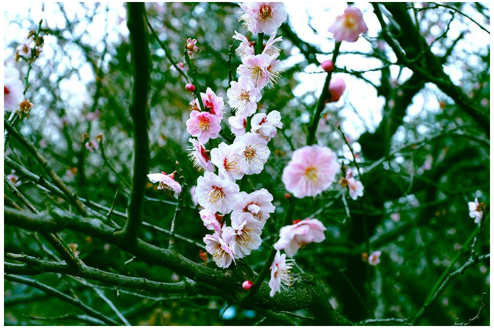
Example 2: Image Processing’ Kernel Function

```
kernel void procPixel(device const float* img      [[ buffer(0) ]],
                      device       float* out      [[ buffer(1) ]],   ❶
                      device const params& params  [[ buffer(2) ]],
                      uint                 index   [[thread_position_in_grid]]) {
    float brightness = clamp(params.brightness) - 0.5;
    float contrast = clamp(params.contrast) - 0.5;
    float saturation = clamp(params.saturation) - 0.5;
    float temperature = clamp(params.temperature) - 0.5;
    float tint = clamp(params.tint) - 0.5;
    float r = srgb2linear(img[index * 4 + 0]);
    float g = srgb2linear(img[index * 4 + 1]);
    float b = srgb2linear(img[index * 4 + 2]);
    color c = color{r, g, b};
    c = apply_temperature_tint(c, temperature, tint);
    c = apply_brightness(c, brightness);
    c = apply_contrast(c, contrast);
    c = apply_saturation(c, saturation);
    out[index * 4 + 0] = clamp(linear2srgb(c.r));
    out[index * 4 + 1] = clamp(linear2srgb(c.g));   ❷
    out[index * 4 + 2] = clamp(linear2srgb(c.b));
    out[index * 4 + 3] = img[index * 4 + 3];
}
```

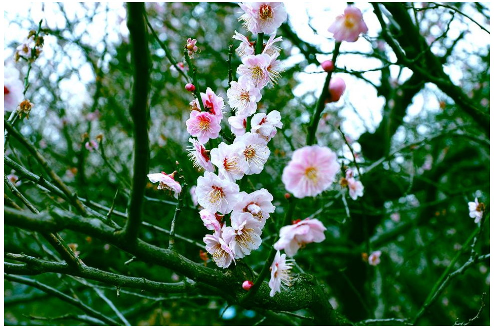
Example 2: Image Processing



Original



Before Processing (CPU)



After Processing (GPU)

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What to Consider When Adding GPU Acceleration?

When?	How Frequent?	Design Consideration
Initialization	Only once	Shader Compilation
Resource Loading	Less often	Memory Copy
Command Encoding	Frequent	Scheduling Strategy
Resource Sharing	Frequent	Sync Callback

Agenda

- Basic knowledge for interacting with GPUs
- Accelerate Go programs using GPUs
- **Challenges in Go when using GPUs**
  - Costs of Cgo
  - Fundamental infrastructure
  - Common abstraction
  - Writing and debugging shaders
- Conclusion and outlooks

Challenge 1: The cost of Cgo

Operations on GPU involves system calls, and easiest approach is to use Cgo:

```
/*
#cgo CFLAGS: -Werror -fmodules -x objective-c
#cgo LDFLAGS: -framework Metal -framework CoreGraphics
#include "mtl.h"
*/
import "C"
```

For other examples: https://github.com/go-gl/gl and https://github.com/go-gl/glfw

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#include "mtl.h"
*/
import "C"
```

For other examples: https://github.com/go-gl/gl and https://github.com/go-gl/glfw

However, the use of Cgo will cause more problems to solve:

1. Cannot easily do cross compilation

2. Call performance drops

3. Hard to maintain, non-reproducible build

Challenge 1: The cost of Cgo

Surprisingly Windows platform do not need use Cgo:

```
var (
    LibGLESv2       = syscall.NewLazyDLL("libGLESv2.dll")
    _glCreateShader = LibGLESv2.NewProc("glCreateShader")
    ...
)
```

Challenge 1: The cost of Cgo

Recently, there are work exist in the community starts to remove the need of ego, and start to use assembly to pass arguments to system call directly, the project is:

https://github.com/ebitengine/purego

```
libc, err := purego.Dlopen("/usr/lib/libSystem.B.dylib", purego.RTLD_NOW|purego.RTLD_GLOBAL)
if err != nil { panic(err) }
var puts func(string)
purego.RegisterLibFunc(&puts, libc, "puts")
```

Challenge 2: Lack of Foundational Infrastructure

~~Nearly~~ No mature framework*

There are well known GUI frameworks: Fyne, Ebitengine, GioUI and a 3D engine g3n/engine

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These frameworks have common limitations:

1. In Fyne, the underlying rendering depends on OpenGL/ES, and only support 2D rendering. No exposed APIs to users.
2. In Ebitengine, the underlying rendering uses OpenGL+DirectX+Metal but no exposed APIs to users.
3. GioUI is the most comprehensive approach but only designed 2D rendering abstraction. No exposed APIs to users.
4. g3n/engine is depending on OpenGL's rendering

*https://github.com/changkun/awesome-go-graphics

Challenge 3: Lack of Common Abstraction

There are no common abstractions in the Go world

Design an abstraction is as challenge as designing a new standard

Example 1: Fyne’s Graphics Driver Interface

```go
package fyne

// Driver defines an abstract concept of a Fyne render driver.
// Any implementation must provide at least these methods.
type Driver interface {
    // CanvasForObject returns the canvas that is associated with a given CanvasObject.
    CanvasForObject(CanvasObject) Canvas

    // Device returns the device that the application is currently running on.
    Device() Device
    // Run starts the main event loop of the driver.
    Run()

    // StartAnimation registers a new animation with this driver and requests it be started.
    StartAnimation(*Animation)
    // StopAnimation stops an animation and unregisters from this driver.
    StopAnimation(*Animation)

    …
}
```

Example 2: Ebitengine’s Graphics Driver Interface

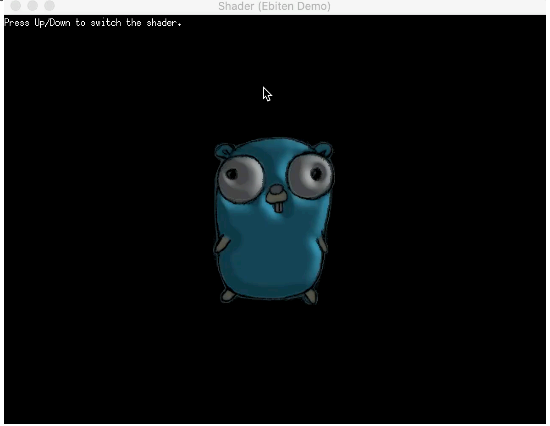
```
type Graphics interface {
    Initialize() error
    Begin() error
    End(present bool) error
    SetTransparent(transparent bool)
    SetVertices(vertices []float32, indices []uint16) error
    NewImage(width, height int) (Image, error)
    NewScreenFramebufferImage(width, height int) (Image, error)
    IsGL() bool
    IsDirectX() bool
    MaxImageSize() int

    NewShader(program *shaderir.Program) (Shader, error)

    // DrawTriangles draws an image onto another image with the given parameters.
    DrawTriangles(dst ImageID, srcs [graphics.ShaderImageCount]ImageID, shader ShaderID,
dstRegions []DstRegion, indexOffset int, blend Blend, uniforms []uint32, evenOdd bool) error
}
```

Example 3: GioUI’s Graphics Driver Interface

```go
type GPU interface {
    Release()
    // Frame draws the graphics operations from op into a viewport of target.
    Frame(frame *op.Ops, target RenderTarget, viewport image.Point) error
    …
}
// Device represents the abstraction of underlying GPU APIs such as OpenGL,
// Direct3D useful for rendering Gio operations.
type Device interface {
    BeginFrame(target RenderTarget, clear bool, viewport image.Point) Texture
    EndFrame()
    NewComputeProgram(shader shader.Sources) (Program, error)
    NewVertexShader(src shader.Sources) (VertexShader, error)
    NewFragmentShader(src shader.Sources) (FragmentShader, error)
    NewPipeline(desc PipelineDesc) (Pipeline, error)
    BeginCompute()
    EndCompute()
    DispatchCompute(x, y, z int)
    Release()
    …
}
```

Challenge 4: Writing and Debugging Shaders

Syntax of Shaders are based on variation of C/C++. It is not possible to debug in a regular manner



Press Up/Down to switch the shader.

The only community work that extends Go syntax to shader is Kage in Ebitengine

```go
package main

// Uniforms
var Time float
var Cursor vec2
var ScreenSize vec2

// Fragment is the entry point of the fragment shader.
func Fragment(position vec4, texCoord vec2, color vec4) vec4 {
    lightpos := vec3(Cursor, 50)
    lightdir := normalize(lightpos - position.xyz)
    normal := normalize(imageSrc1UnsafeAt(texCoord) - 0.5)
    ambient := 0.25
    diffuse := 0.75 * max(0.0, dot(normal.xyz, lightdir))

    return imageSrc0UnsafeAt(texCoord) * (ambient + diffuse)
}
```

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Agenda

- Basic knowledge for interacting with GPUs
- Accelerate Go programs using GPUs
- Challenges in Go when using GPUs
- **Conclusion and outlooks**

Conclusion and Outlook

- In Go, it is only possible to schedule and manage resources for GPU tasks
- The actual computation need to utilize shaders
- There is a little work in Go to extend its syntax for writing shaders
- There is a large gap and huge opportunity in Go to support GPU computation infra
  - Common abstraction: cross platform
  - Automatic inference for architecture selection depending on compute workload
  - Extend Go syntax to support shaders
    - E.g., using //go:gpu to mark a function that can be a shader function
    - E.g., Automatically analyze if a function can be used in shader
  - Debug and profiling toolchain

References

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https://github.com/changkun/gopherchina2023gogpu
https://github.com/polyred/polyred
https://git.sr.ht/~eliasnaur/gio
https://github.com/fyne-io/fyne
https://github.com/hajimehoshi/ebiten
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https://github.com/tinne26/kage-desk

Go on GPU

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changkun.de/s/gogpu

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