CS354P

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# MULTITHREADING AND THE GPU PIPELINE

# WHAT IS MULTITHREADING?

- Occurs on a single processing unit
  - Multiple virtual threads executed concurrently using shared resources
- Not the same thing as parallel execution (i.e. multiple cores/multiple processing units execute their tasks in parallel)
- Note: hyper-threading is where the OS sees CPU as two logical cores increasing independent instructions

# TYPES OF PARALLELISM

- Task parallelism
  - Distributes multiple tasks (jobs) across cores to be performed in parallel
- Data parallelism
  - Distributes data across cores to have sub-operations performed on that data to facilitate parallelism of a single task
- Note: Parallelism is frequently accompanied by concurrency (i.e. multiple cores still have multiple threads operating on the data)
  - We will conflate these two concepts for simplicity in the remaining slides

# EMBARRASSINGLY PARALLEL WORKLOADS

- Workloads that can be easily separated into parallel subtasks are called “embarrassingly parallel”
- Some examples:
    - Monte Carlo analysis
    - Numerical integration
    - Graphics rendering
    - Discrete Fourier transforms
    - etc…
- What makes a problem easy to parallelize?

# COMMUNICATION AND DEPENDENCIES

- Any workload that is not embarrassingly parallel will have associated overhead
  - Threads need to communicate
  - Threads need to wait on other threads to complete
- Thread management is additional overhead
  - Creating and destroying threads is expensive
- Naive parallelization can increase, rather than decrease, execution time

# RACE CONDITIONS

- Occur when program behavior is dependent on timing of multiple threads or processes
  - Outcome of execution is non-deterministic
- Hard to identify and debug
  - Requires parallel thinking
  - Behavior is only reproducible some of the time
- Thread-safety indicates that access patterns by threads will not result in a race condition
  - Naive implementation can increase, rather than decrease, execution time

# MULTITHREADING FOR DEVELOPMENT

- Many development operations in a game engine can be highly parallelized
  - Light building
  - Level of detail generation
  - Code Compilation
  - Package building
  - etc…
- Build times **extremely** important in development
  - Full builds of large games can easily take overnight or multiple days

# NOT JUST COMPILING…

- C++ compilation is a slow process (particularly if .h files modified) but hardly the bulk of build times
- Working with geometry is extremely time consuming
    - Pre-baking global illumination
    - Performing mesh decimation
- Fortunately these operations can be offloaded to render farms and efficiently parallelized

# MULTITHREADING FOR GAMEPLAY

- Many operations within a game can be parallelized
- Some built-in Unreal threads:
    - Gameplay thread manages objects
    - Rendering thread handles graphics (always a frame or two behind the gameplay thread)
    - Audio and audio mixer threads handle playing of audio and mixing of audio respectively (note that they are two separate threads)
    - Physics substepping handled on its own thread
- These are notably task parallel, making them easier to distribute across cores/threads
- What is we want data parallelism?

# POOLS AND SCHEDULERS

- Thread pools manage threads to reduce the destruction and creation of workers
- Job schedulers allocate tasks or subtasks to worker threads to reduce under-utilization of threads
- At least some thought must be put into both of these to effectively parallelize a job

# CREATING YOUR OWN THREADS

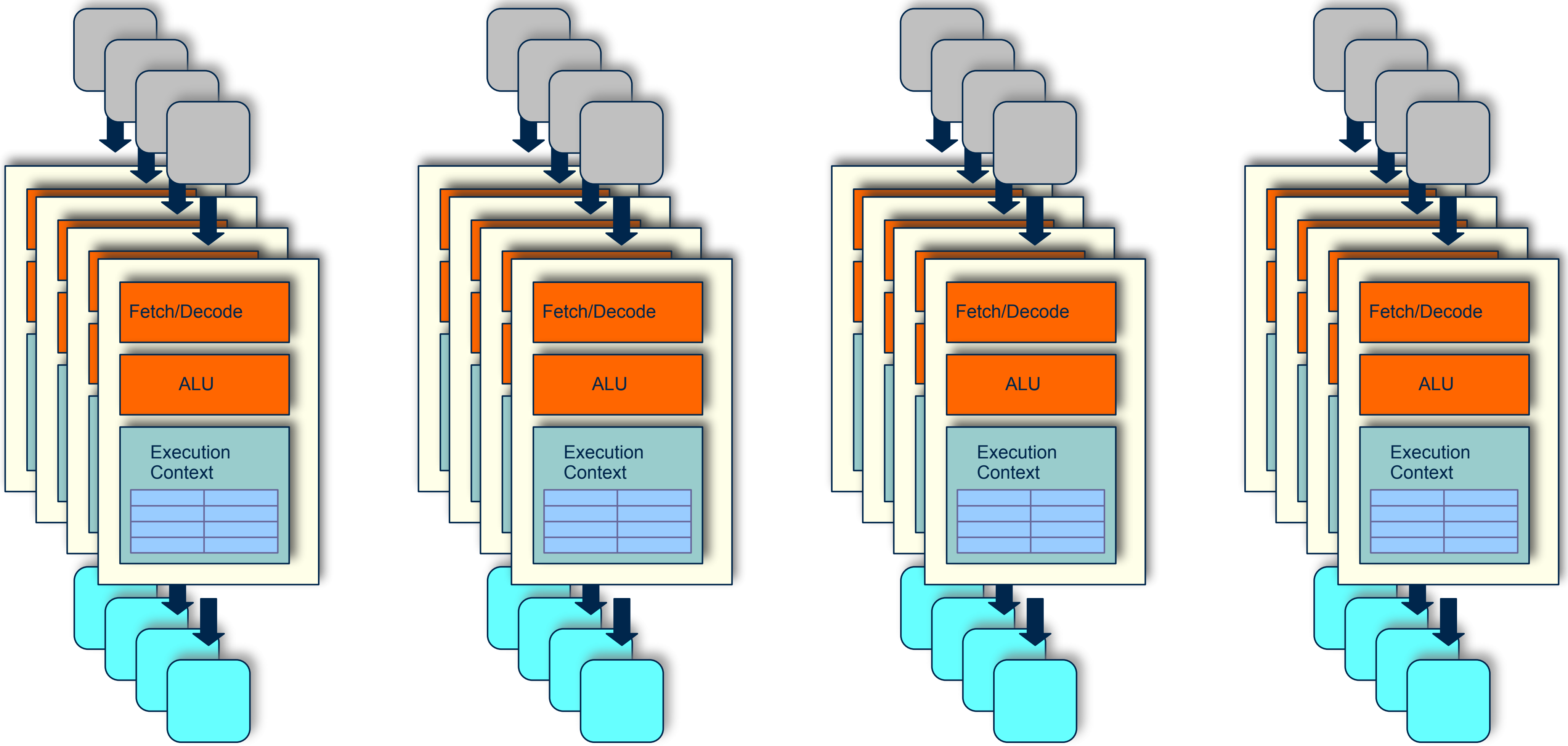
- `FRunnable` is an interface for objects that are run on an arbitrary thread
  - Implement `Init()`, `Run()`, and `Stop()`
  - Use in conjunction with `FQueuedThreadPool` to determine number of threads needed for the task
- `FNonAbandonableTask` used for running non-blocking, asynchronous tasks that cannot be abandoned
  - Other flavors of asynchronous tasks available

# WHEN TO THREAD?

- When you are not performant
  - Avoid premature optimization
  - And remember: poor parallelization is worse than no parallelization
- Tasks that are well-suited:
  - Asynchronous loading of assets
  - Calculations that are readily parallelizable
  - Tasks that can be pulled off the main game loop safely

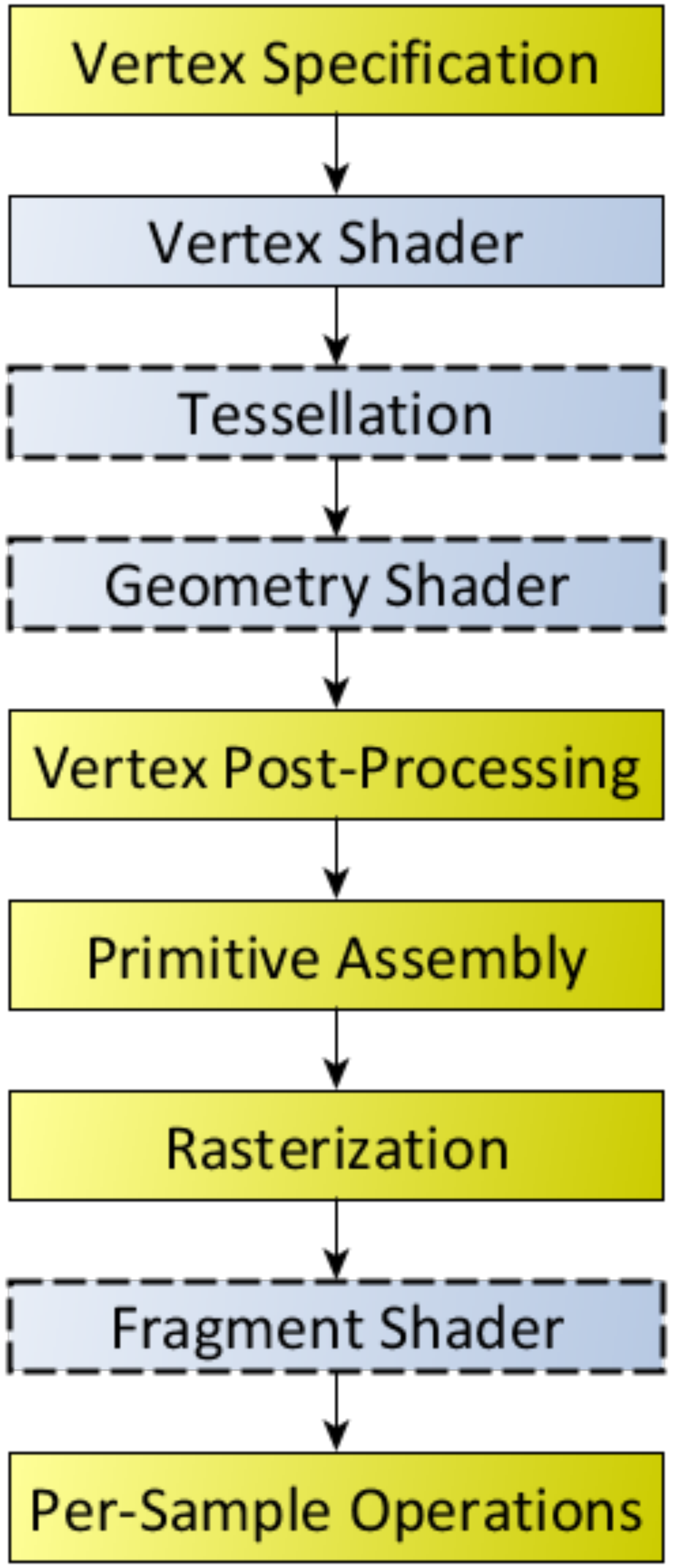
# GPUS AND PARALLELISM

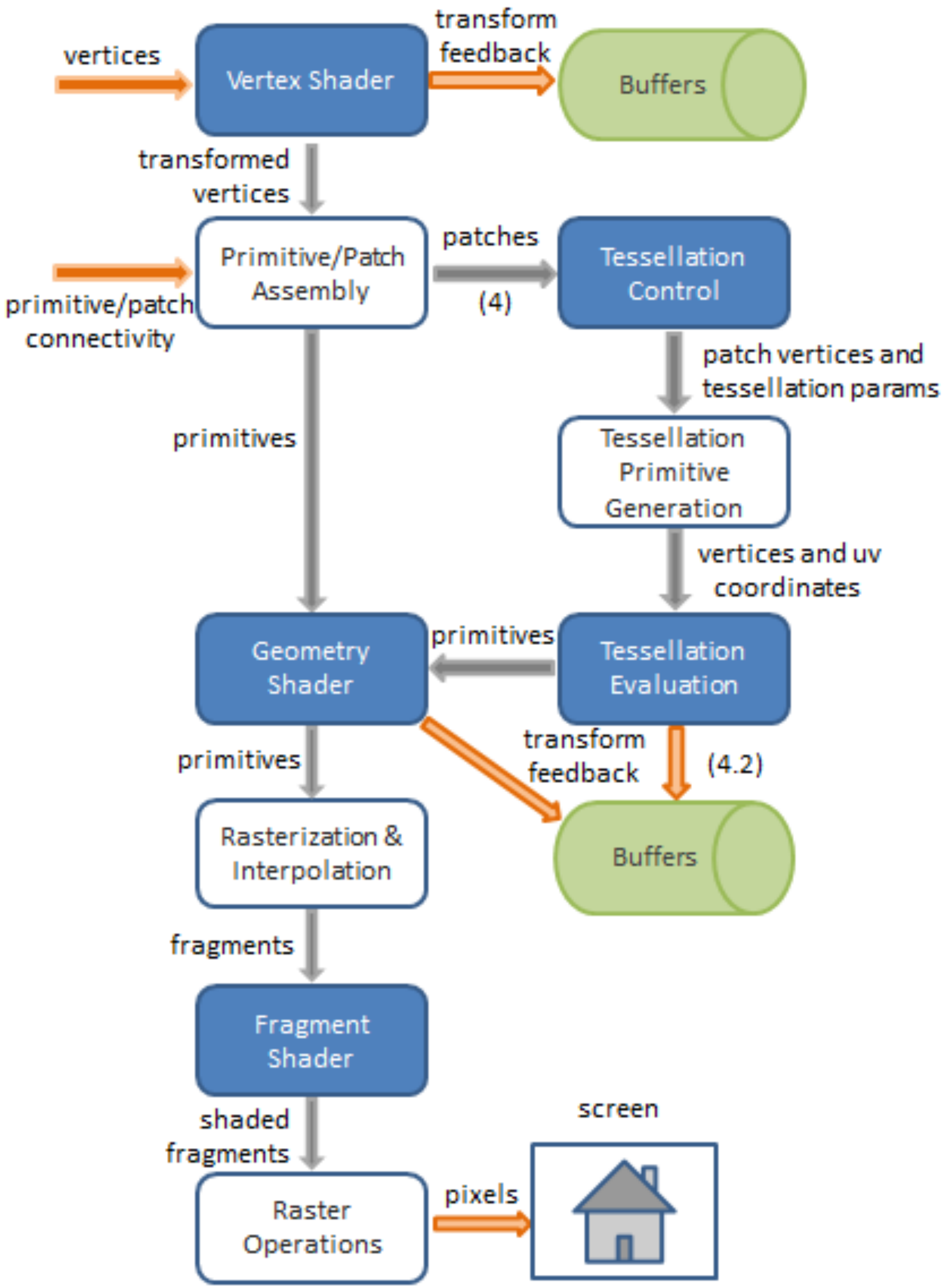
- GPUs (Graphical Processing Units) are designed for **throughput architecture**
- Relatively simple cores but a lot of them in parallel!



# SHADERS

- Small arbitrary programs that run on GPU
- Massively parallel
- Four kinds: vertex, geometry, tessellation, fragment





vertices

Vertex Shader

transform feedback

Buffers

transformed vertices

Primitive/Patch Assembly

primitive/patch connectivity

patches

(4)

Tessellation Control

patch vertices and tessellation params

Tessellation Primitive Generation

vertices and uv coordinates

primitives

Tessellation Evaluation

primitives

Geometry Shader

transform feedback

(4.2)

Buffers

primitives

Rasterization & Interpolation

fragments

Fragment Shader

shaded fragments

Raster Operations

pixels

screen

# VERTEX SHADER

- Runs in parallel on every **vertex**
  - No access to triangles or other vertices
- Performs operations such as vertex transformations
  - e.g. apply 4x4 matrices to each vertex

# TESSELLATION SHADER

- Controls amount of **tessellation** per patch
  - Lower poly models can be subdivided into higher resolution models
  - Values calculated for generated vertices
  - Level of detail (LOD) controllable within the shader pipeline
  - Optional

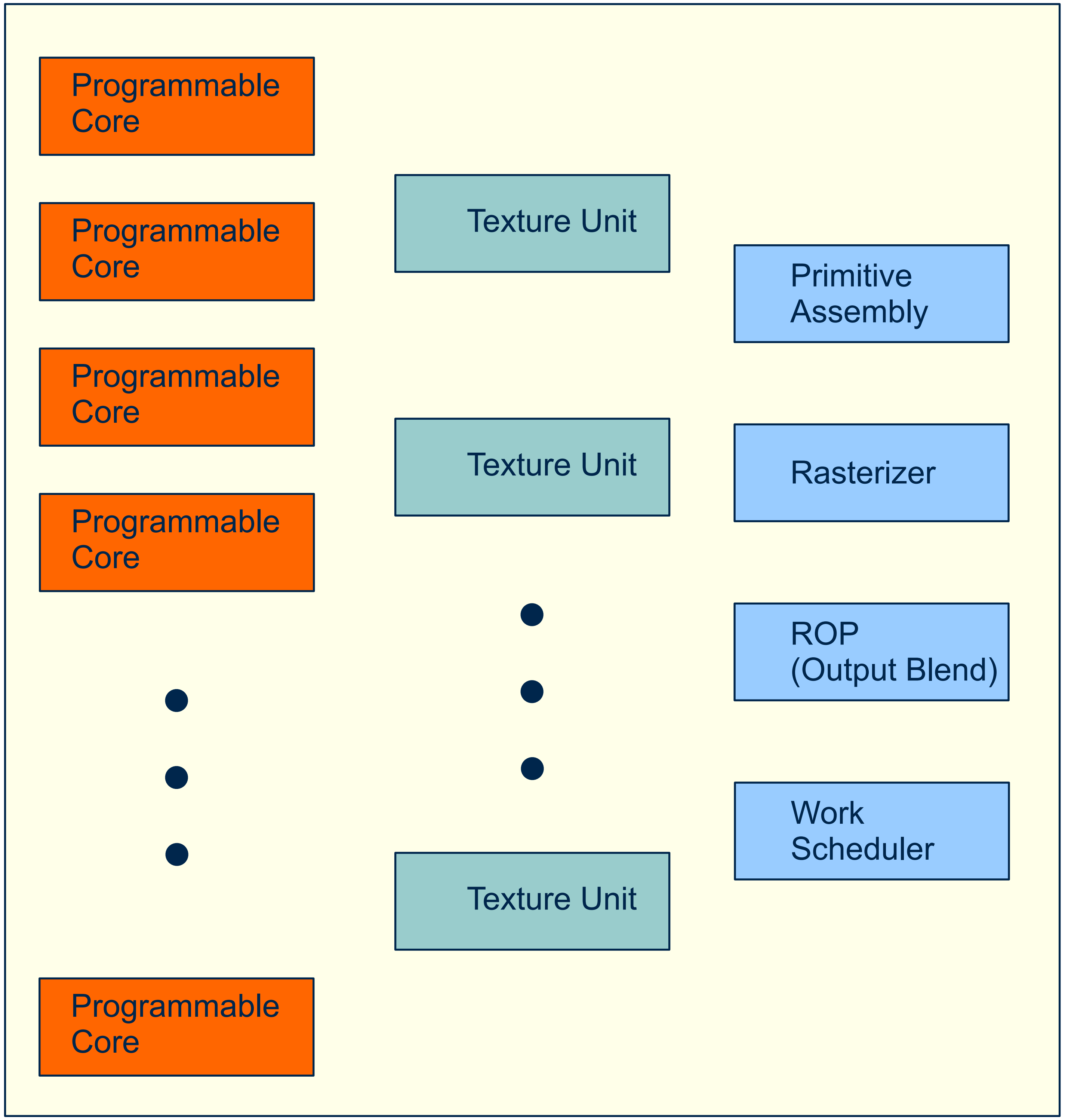
# GEOMETRY SHADER

- Takes a primitive and outputs multiple **primitives**
    - Not optimized for subdivision (tessellation shader’s job)
    - Ability to work on entire primitive
    - Optional

# FRAGMENT SHADER

- Runs in parallel on each fragment (**pixel**) of the rasterized data
  - Can only access neighboring pixel values via textures
- Writes color and depth values per pixel
  - Finalizes appearance of pixels

# MODERN GPU CHARACTERISTICS

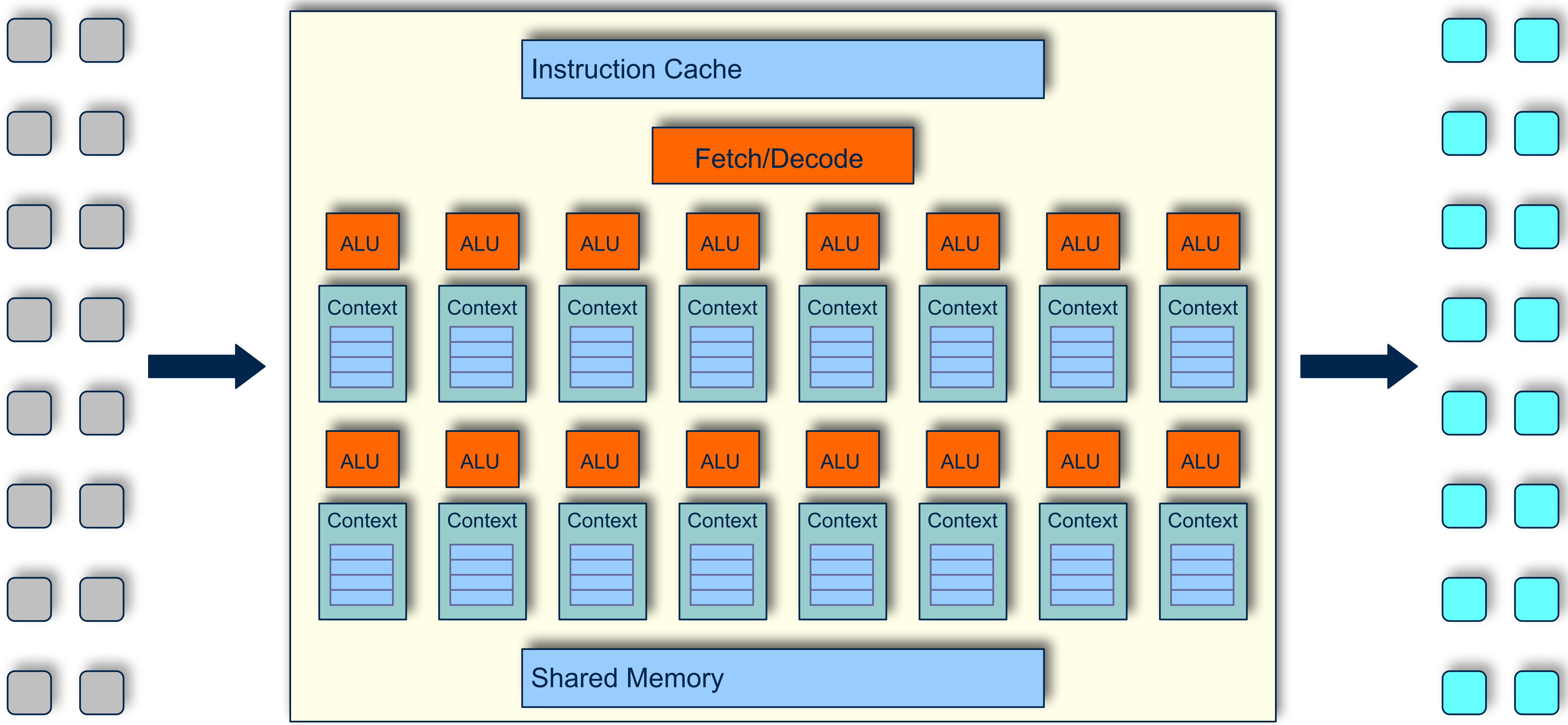


- Homogeneous programmable cores for all programmable stages
- Relatively few special purpose texture units
- Even fewer fixed function units
- Task parallel at pipeline level

# SIMD

- Single instruction, multiple data
- Large vectors of data that have the same operation applied to individual elements in parallel
- Based on old super computing techniques but has regained popularity in modern architectures (both CPU and GPU)

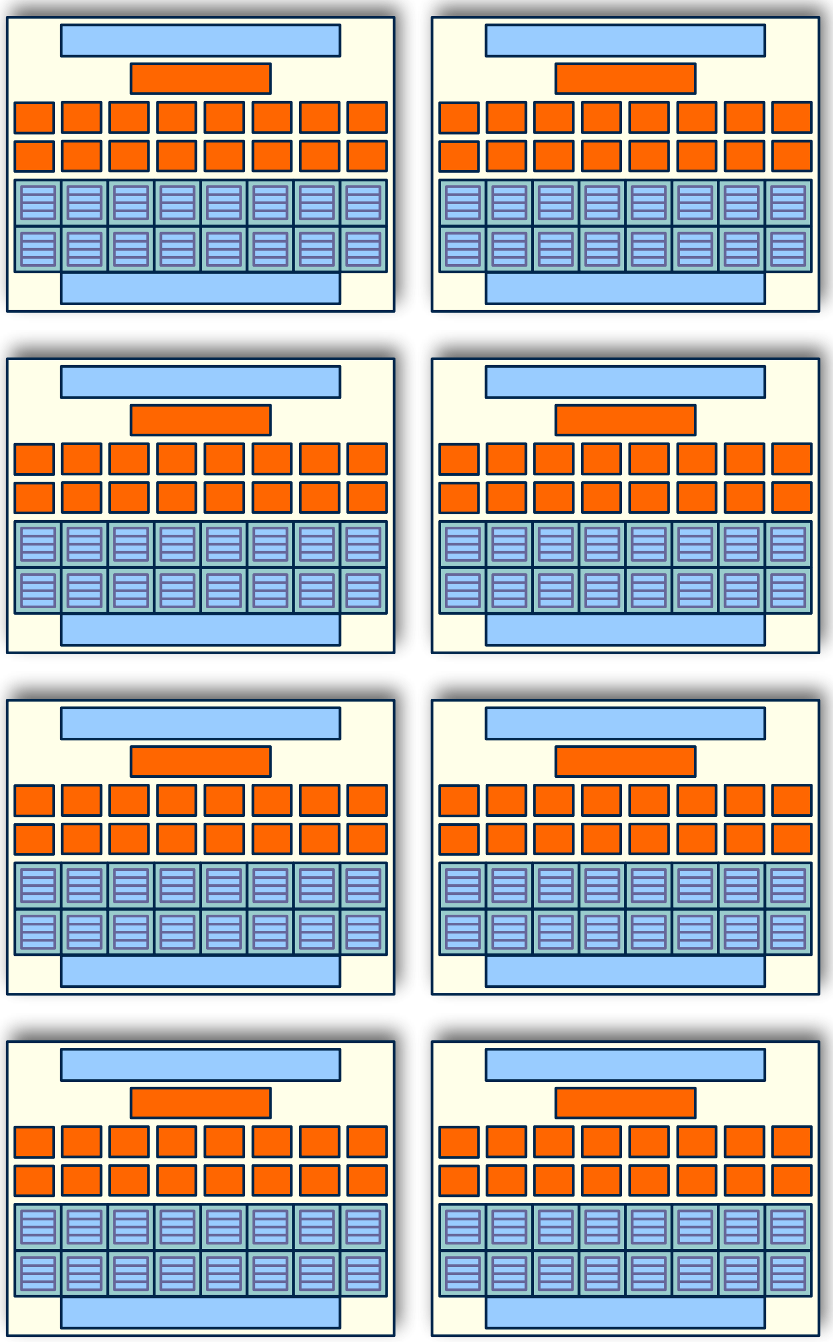
# SHARED INSTRUCTIONS



- Same thing is done in parallel for all fragments/verts/etc
- SIMD **amortizes** instruction handling over multiple ALUs

# MULTIPLE TYPES OF PROCESSING

- GPUs do more than shading
  - Allow execution of more than one program
- Replicate SIMD processors for different SIMD computations in parallel

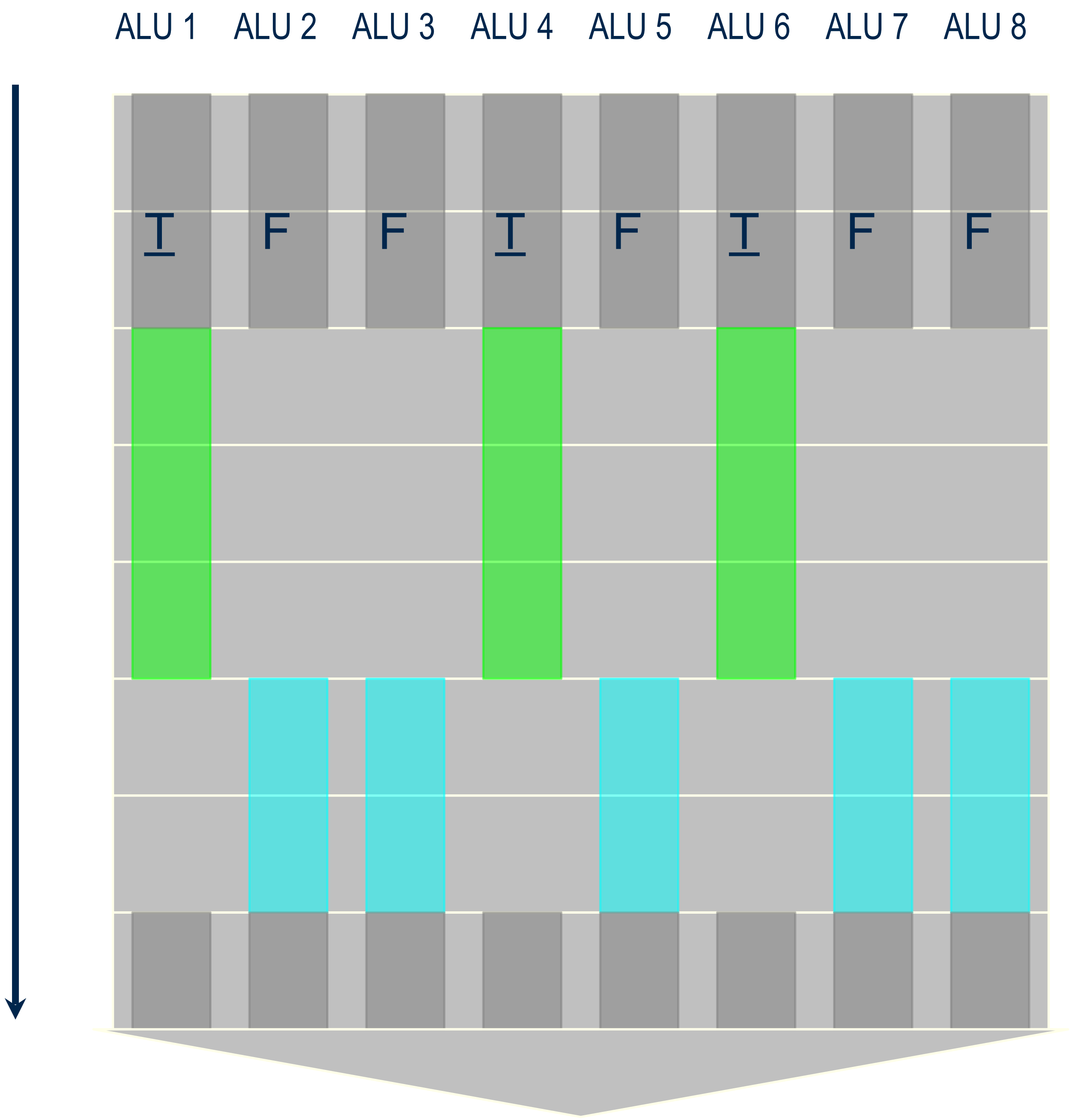


8 programs running in parallel, 128 threads in parallel

# PROBLEMS?

- What situations does this throughput style of architecture not handle well?

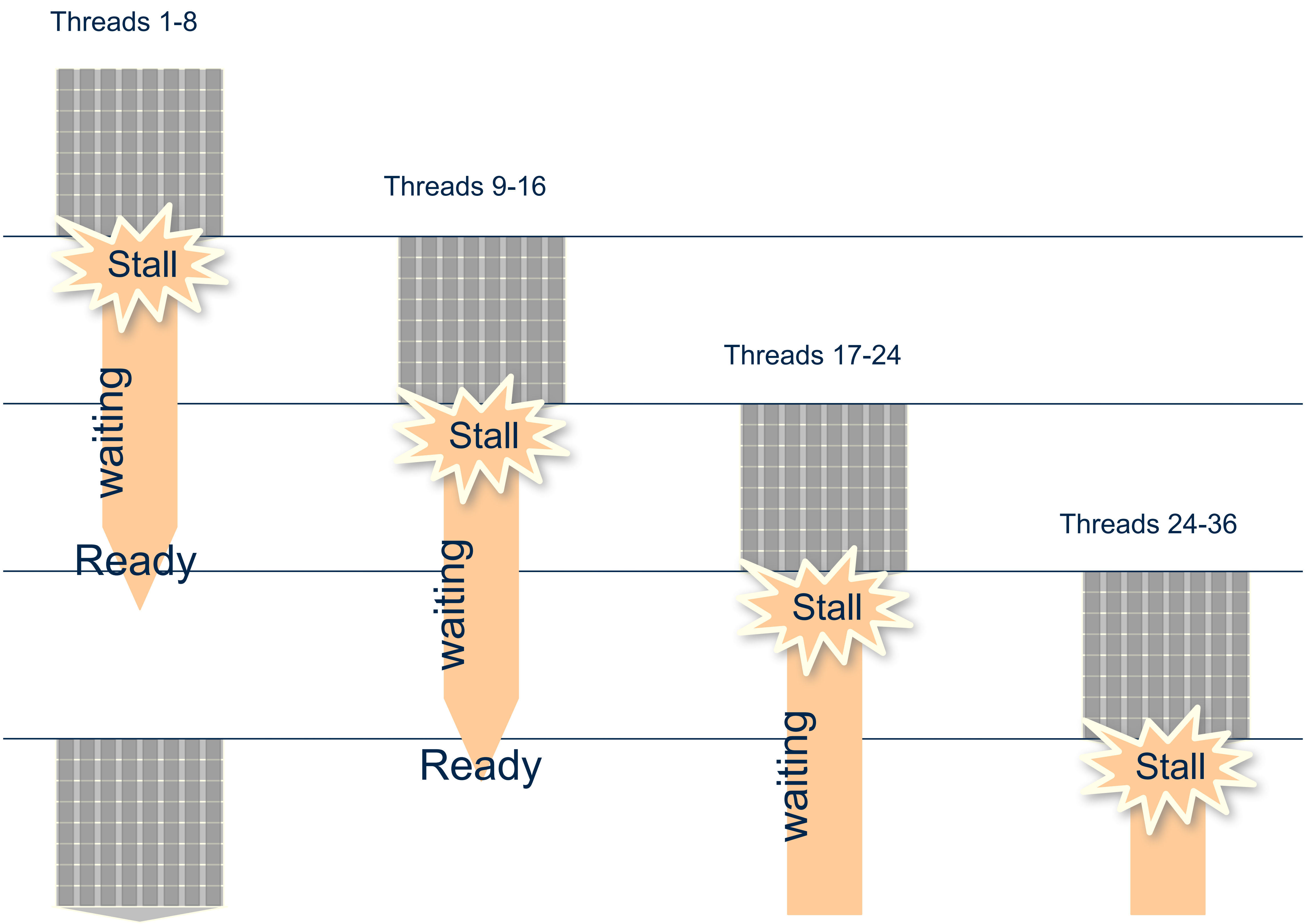
# BRANCHING AND STALLING



- Threads stall when next instruction depends on previous instruction's result
    - Pipeline dependencies
    - Memory latency
- How to handle these?

# MULTITHREADING

- We can assume there are more threads (scheduled computations) than processors
- Threads with similar code executed in “warps” to maintain minimal divergence
- Interleaving warp execution keeps hardware busy when an individual warp stalls



Threads 1-8

Stall

waiting

Ready

Threads 9-16

Stall

waiting

Ready

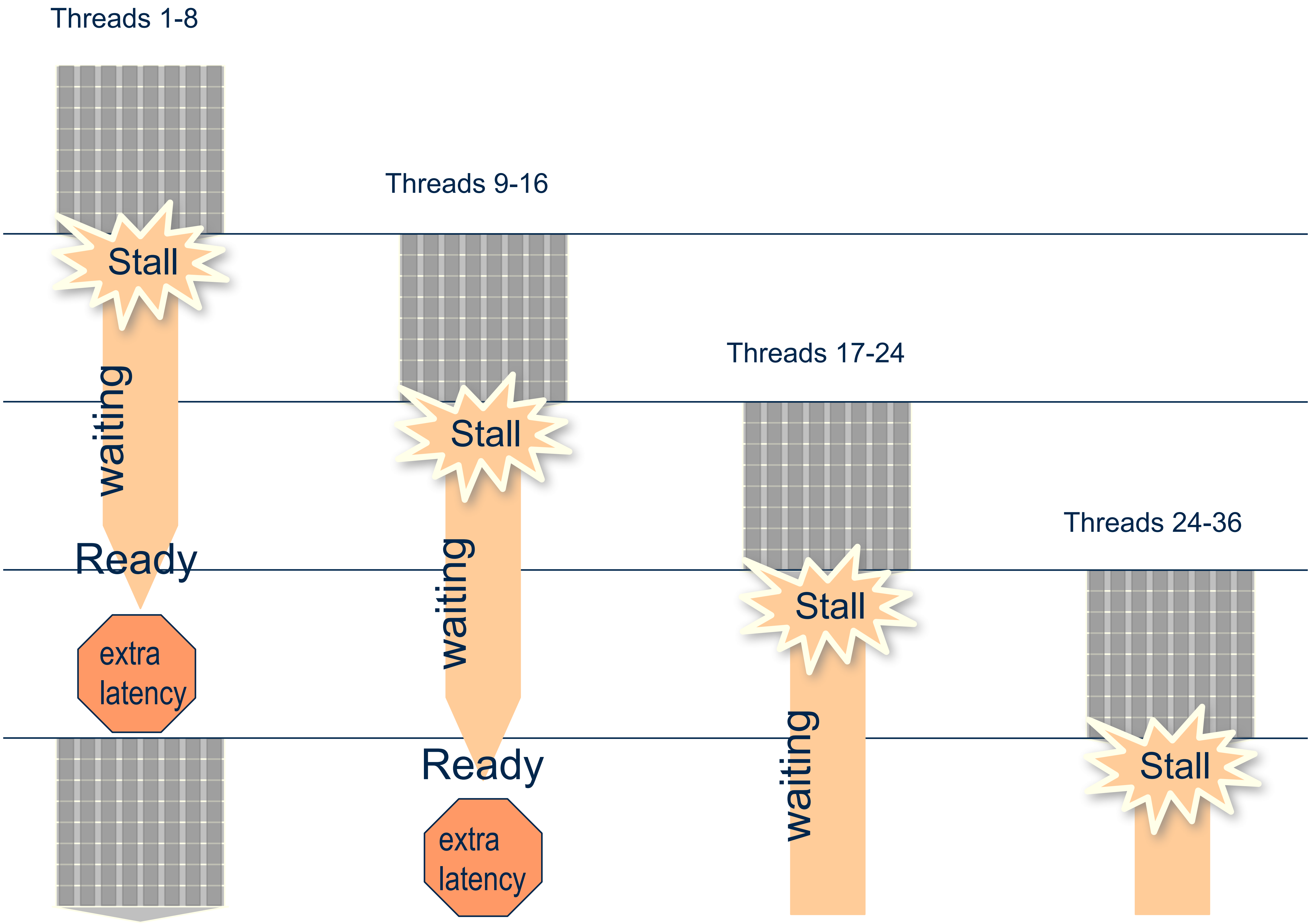
Threads 17-24

Stall

waiting

Threads 24-36

Stall



Threads 1-8

Stall

waiting

Ready

extra latency

Threads 9-16

Stall

waiting

Ready

extra latency

Threads 17-24

Stall

waiting

Threads 24-36

Stall

# GPGPU

- Can do operations on the GPU besides graphics
  - Heavily used in scientific computing and machine learning
- Potentially useful in games for highly parallel calculations (e.g. physics and AI)
  - Depends on the graphical demands of the game
  - Upfront versus amortized costs of sending data between cpu and gpu