Vulkan®

DEVELOPER DAY

Vulkan Subgroup Explained

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UBISOFT

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Agenda

- **Motivation**
- **Subgroup overview**
- **Vulkan 1.1 Subgroup Operations**
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  - Vote operations
  - Arithmetic operations
  - Ballot operations
  - Shuffle operations
  - Shuffle relative operations
  - Clustered operations
  - Quad operations
- **Partitioned Subgroup Operations**
- **NV Implementation**
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- **Mapping to HLSL**

Motivation

- **Vulkan 1.0**
  - supports sharing data between invocations in the local workgroup
    - via ***shared memory***
    - faster to access than buffer or image memory
  - Supports synchronizing between all invocations in the local workgroup
  - Only available in compute shaders
- **Vulkan 1.1**
  - Adds ability to share data and synchronize between invocations in a ***subgroup***
    - that run in parallel for a single shader stage
- **Benefits**
  - Avoids shared memory, effectively reducing latency and increasing bandwidth
  - Accelerates algorithms such as reductions, list building, and sorting
  - Allowed in all stages

What are Subgroups?

- **Set of shader invocations (threads)**
  - ***Efficiently*** synchronize and share data with each other
  - In compute shaders, a subset of the local workgroup
  - Exposed **"as if"** running concurrently (they may not actually be!)
    - AKA: warp, wave, or wavefront
    - But not necessarily a full wave/warp
    - Implementation *can* advertise smaller subgroup size
- **Invocations in a subgroup may be *active* or *inactive***
  - Active -> execution is being performed
  - Inactive -> not being executed
    - Non-uniform flow control
    - Insufficient work to fully pack a subgroup
      - Graphics shader – implementation dependent reasons
        - (e.g. end of a Draw call before state change, etc.)
      - Compute shader – local workgroup size not a multiple of subgroup size
  - Can change throughout shader execution as control flow diverges and re-converges

Vulkan 1.1 API: Subgroup Properties

- **A new structure to query subgroup support on a physical device**
  - subgroupSize – number of invocations in each subgroup
    - ***must be at least 1 (and <= 128)***
  - supportedStages – which shader stages support subgroup operations
    - ***VK_SHADER_STAGE_COMPUTE_BIT is required***
  - supportedOperations – which subgroup operations are supported
    - ***VK_SUBGROUP_FEATURE_BASIC_BIT is required***
  - quadOperationsInAllStages – do quads ops work in all stages or only fragment and compute

```
typedef struct VkPhysicalDeviceSubgroupProperties {
    VkStructureType           sType;
    void*                     pNext;
    uint32_t                  subgroupSize;
    VkShaderStageFlags        supportedStages;
    VkSubgroupFeatureFlags    supportedOperations;
    VkBool32                  quadOperationsInAllStages;
} VkPhysicalDeviceSubgroupProperties;
```

```
typedef enum VkSubgroupFeatureFlagBits {
    VK_SUBGROUP_FEATURE_BASIC_BIT = 0x00000001,
    VK_SUBGROUP_FEATURE_VOTE_BIT = 0x00000002,
    VK_SUBGROUP_FEATURE_ARITHMETIC_BIT = 0x00000004,
    VK_SUBGROUP_FEATURE_BALLOT_BIT = 0x00000008,
    VK_SUBGROUP_FEATURE_SHUFFLE_BIT = 0x00000010,
    VK_SUBGROUP_FEATURE_SHUFFLE_RELATIVE_BIT = 0x00000020,
    VK_SUBGROUP_FEATURE_CLUSTERED_BIT = 0x00000040,
    VK_SUBGROUP_FEATURE_QUAD_BIT = 0x00000080,
    VK_SUBGROUP_FEATURE_PARTITIONED_BIT_NV = 0x00000100,
} VkSubgroupFeatureFlagBits;
```

Subgroup Basic Operations

- **All supported stages Builtins**
  - gl_SubgroupSize – size of the subgroup – matches the API property
  - gl_SubgroupInvocationID – ID of the invocation within the subgroup, [0..gl_SubgroupSize)
- **Compute Builtins**
  - gl_NumSubgroups – number of subgroups in local workgroup
  - gl_SubgroupID – ID of subgroup within local workgroup, [0..gl_NumSubgroups)
- **Functions**
  - void subgroupBarrier() - Full memory and execution barrier
    - All active invocations sync and memory stores to ***coherent*** memory locations are completed
  - void subgroupMemoryBarrier()
    - Enforces ordering of all memory transactions by an invocation, as seen by other invocations in the subgroup
  - void subgroupMemoryBarrier{Buffer,Image,Shared}()
    - Enforces ordering on buffer, image, or shared (compute only) memory operations, respectively
  - bool subgroupElect()
    - Pick one active invocation, always the one with lowest gl_SubgroupInvocationID
    - Used for executing work on only one invocation

Subgroup Vote Operations

- **Determine if a Boolean condition is met across the entire subgroup**
  - bool subgroupAll(bool value)
    - true if all invocations have <value> == true
  - bool subgroupAny(bool value)
    - true if any invocation has <value> == true
  - bool subgroupAllEqual(T value)
    - true if all invocations have the same value of <value>
- **Useful for code that has branching**
  - Can do more optimal calculations if certain conditions are met

```
void main() {
  bool condition = foo[gl_GlobalInvocationID.x] < bar[gl_GlobalInvocationID.x];

  if (subgroupAll(condition)) {
    // all invocations in the subgroup are performing x
  } else if (!subgroupAny(condition)) {
    // all invocations in the subgroup are performing y
  } else {
    // Invocations that get here are doing a mix of x & y so have a fallback
  }
}
```

Subgroup Basic and Vote Examples

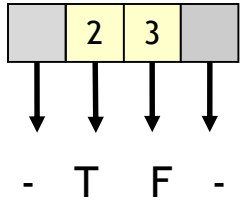
gl_SubgroupSize = 4

5	2	1	6

gl_SubgroupInvocationID:

0	1	2	3

subgroupElect():



Active Invocations

Inactive Invocations

bool condition = (value == 5);

5	5	5	5

5	2	1	6

2	2	2	2

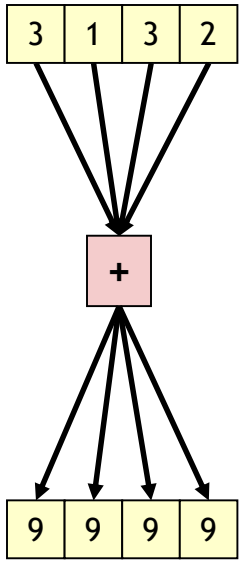
subgroupAll(condition);	true	false	false
subgroupAny(condition);	true	true	false
subgroupAllEqual(value);	true	false	true

Subgroup Arithmetic Operations

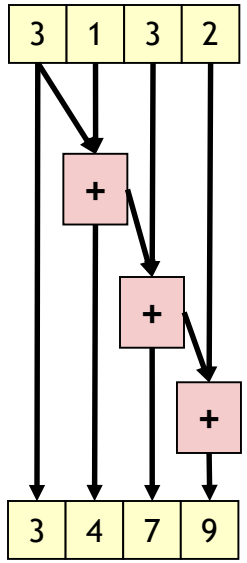
- **Operations across all active invocations in a subgroup**
  - T subgroup<op>(T value)
    - <op> = Add, Mul, Min, Max, And, Or, Xor
  - Reduction operations
    - Returns the result of the same calculation to each invocation
- **Operation on invocations with gl_SubgroupInvocationID less than self**
  - T subgroupInclusive<op>(T value)
    - Includes own value in operation
  - T subgroupExclusive<op>(T values)
    - Excludes own value from operation
  - Inclusive or exclusive scan
    - Returns the result of different calculation to each invocation
- **Useful for performing an operation across an entire dataset**
  - Step 1: use subgroup arithmetic across the subgroup
  - Step 2: use atomics to accumulate result from each subgroup to memory
  - Only requires (#data items)/gl_SubgroupSize atomics!

Subgroup Arithmetic Examples

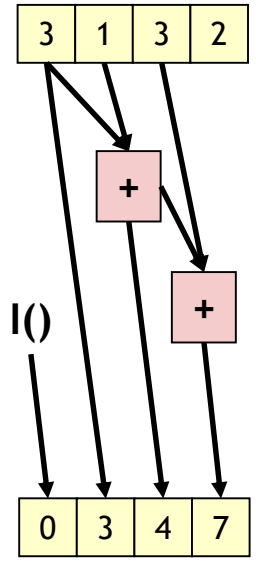
subgroupAdd



subgroupInclusiveAdd



subgroupExclusiveAdd



(same as inclusive but shifted by 1 invocation)

(exact order of operations is implementation dependent)

Subgroup Ballot Operations

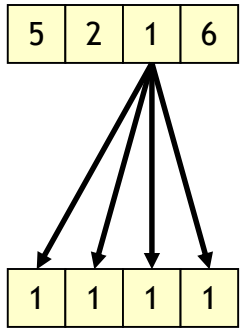
- **Allow invocations to do limited data sharing across a subgroup**
  - Potentially faster than shared memory
- **Broadcast – value from one invocation to all invocations**
  - T subgroupBroadcast(T value, uint id)
    - Broadcasts <value> from the invocation with gl_SubgroupInvocationID == id
    - <id> must be compile time constant
  - T subgroupBroadcastFirst(T value)
    - Broadcasts <value> from the invocation with lowest active gl_SubgroupInvocationID
- **More powerful form of voting**
  - uvec4 subgroupBallot(bool value)
    - Returns bitfield ***ballot*** with result of evaluating <value> in each invocation
    - Bit <i> == 1 means expression evaluated to true for gl_SubgroupInvocationID == i
    - Bit <i> == 0 means expression evaluated to false, or invocation inactive
    - uvec4 used in ballots is treated as a bitfield with gl_SubgroupSize significant bits
    - First invocation is in bit 0 of first vector component (.x), 32nd invocation in bit 0 of .y, etc.
    - Bits beyond gl_SubgroupSize are ignored
    - subgroupBallot(true) gives a bitfield of all the active invocations

Subgroup Ballot Operations

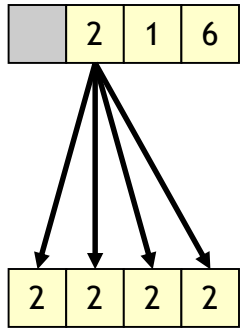
- **Ballot helper functions - to simplify working with uvec4 bitfield**
  - bool subgroupInverseBallot(uvec4 value)
    - Returns true if current invocation bit in <value> is set
    - like doing (value & (1<<gl_SubgroupInvocationID)) != 0 but handles uvec4
  - bool subgroupBallotBitExtract(uvec4 value, uint index)
    - Returns true if bit in <value> that corresponds to <index> is 1
  - uint subgroupBallotBitCount(uvec4 value)
    - Returns the count of bits set to 1 in <value>
  - uint subgroupBallot{Exclusive,Inclusive}BitCount(uvec4 value)
    - Returns the exclusive/inclusive count of bits set to 1 in <value>
    - For bits with invocation ID **<** or **<=** the current invocation ID
  - uint subgroupBallotFind{LSB,MSB}(uvec4 value)
    - Returns the lowest/highest bit set in <value>
- **New builtins**
  - gl_Subgroup{Eq,Ge,Gt,Le,Lt}Mask
    - bitmask of all invocations as compared to the gl_SubgroupInvocationID of current invocation
    - Useful for working with subgroupBallot results

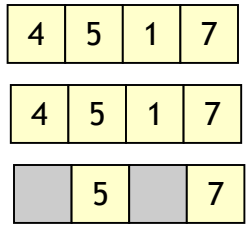
Subgroup Ballot Examples

subgroupBroadcast(x,2)



subgroupBroadcastFirst





subgroupBallot(val > 4) → 0b1010

subgroupBallot(true) → 0b1111

subgroupBallot(true) → 0b1010

subgroupInverseBallot(0b1010) → F T F T

subgroupBallotBitCount(0b1101) → 3 3 3 3

subgroupBallotInclusiveBitCount(0b1101) → 1 1 2 3

== subgroupBallotBitCount(val & **gl_SubgroupLeMask**)

subgroupBallotExclusiveBitCount(0b1101) → 0 1 1 2

== subgroupBallotBitCount(val & **gl_SubgroupLtMask**)

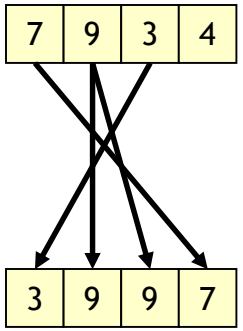
Subgroup Shuffle Operations

- **More extensive data sharing across the subgroup**
  - Invocations can read values from other invocations in the subgroup
- **Shuffle**
  - T subgroupShuffle(T value, uint id)
    - Returns <value> from the invocation with gl_SubgroupInvocationID == id
    - Like subgroupBroadcast, but <id> can be determined dynamically
- **ShuffleXor**
  - T subgroupShuffleXor(T value, uint mask)
    - Returns <value> from the invocation with gl_SubgroupInvocationID == (mask ^ current)
    - Every invocation trades value with exactly one other invocation
    - Specialization of general shuffle
    - <mask> must be constant integral expression
    - Special conditions for using in a loop (basically needs to be unrollable)

Subgroup Shuffle Examples

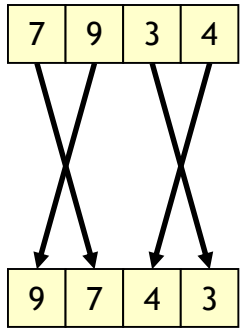
subgroupShuffle(x, index)

index = 2, 1, 1, 0

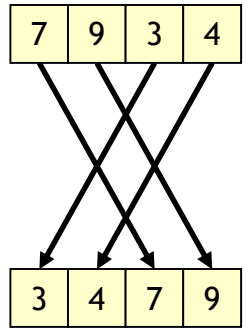


(index can be different for each invocation)

subgroupShuffleXor(x, 1)



subgroupShuffleXor(x, 2)

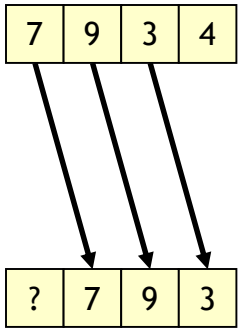


Subgroup Shuffle Relative Operations

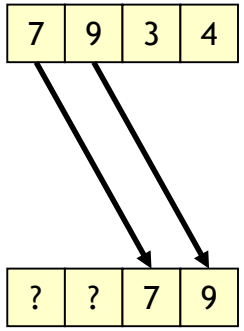
- **Enable invocations to perform shifted data sharing between subgroup invocations**
- **Shuffle up**
  - T subgroupShuffleUp(T value, uint delta)
    - Returns <value> from the invocation with gl_SubgroupInvocationID == (**current - delta**)
- **Shuffle down**
  - T subgroupShuffleDown(T value, uint delta)
    - Returns <values> from the invocation with gl_SubgroupInvocationID == (**current + delta**)
- **Useful to construct your own scan operations**
  - Strided scan (e.g. even or odd invocations, etc.)
  - Reverse scan (highest to lowest)
    - Although using builtins is likely more efficient than rolling your own.
    - In this case, do a shuffle and subgroupInclusive*

Subgroup Shuffle Relative Examples

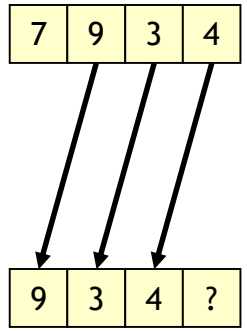
subgroupShuffleUp(x, 1)



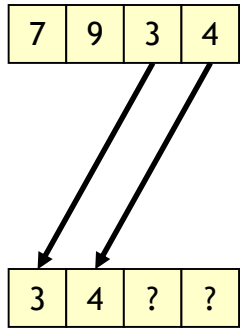
subgroupShuffleUp(x, 2)



subgroupShuffleDown (x, 1)



subgroupShuffleDown (x, 2)

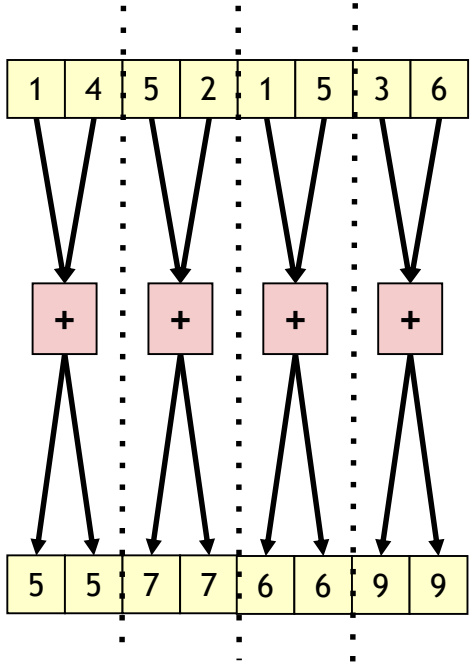


Subgroup Clustered Operations

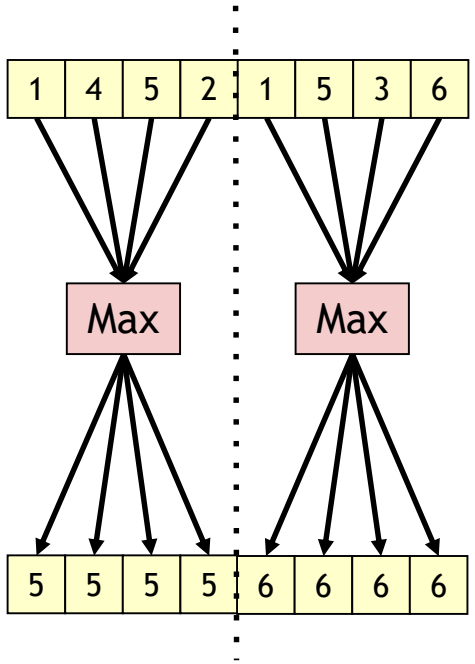
- **Perform arithmetic operations across a fixed partition of a subgroup**
  - T subgroupClustered<op>(T value, uint clusterSize)
    - <op> = Add, Mul, Min, Max, And, Or, Xor
    - clusterSize – size of partition
      - compile-time constant
      - power of 2
      - at least 1
    - Only active invocations in the partition participate
- **Sharing data only with a selection of your closest neighbors**
  - An algorithm that relies on a fixed size grid < gl_SubgroupSize
  - Eg: Convolution neural network – max pooling
    - Take large data set and compress to a smaller one
    - Divide data into NxN grid – N=clusterSize
    - Output maximum for each cluster

Subgroup Clustered Examples

subgroupClusteredAdd(x, 2)



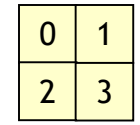
subgroupClusteredMax(x, 4)

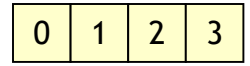


(gl_SubgroupSize = 8)

Subgroup Quad Operations

- **Subgroup quad is a cluster of size 4**
  - Neighboring pixels in a 2x2 grid in fragment shaders (ie derivative group)
  - Not restricted to fragment shaders,
  - Just a cluster of 4 in other stages (no defined layout)
    - Remember to check for support (quadOperationsInAllStages property)

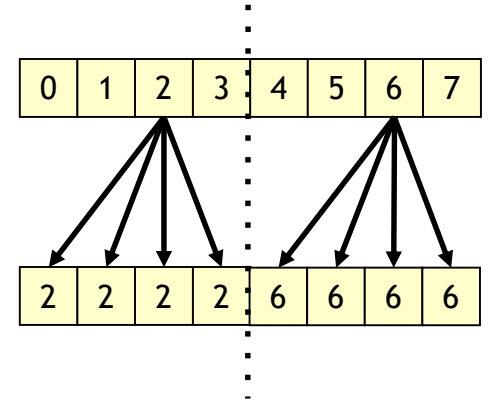


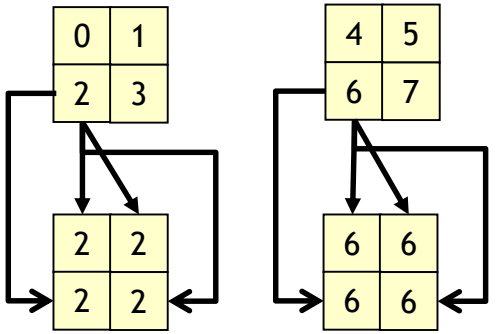


- **Broadcast**
  - T subgroupQuadBroadcast(T value, uint id)
    - Returns <value> from the invocation where gl_SubgroupInvocationID % 4 = <id>
- **Swap**
  - T subgroupQuadSwapHorizontal(T value)
    - Swap values horizontally in the quad
  - T subgroupQuadSwapVertical(T value)
    - Swap values vertically in the quad
  - T subgroupQuadSwapDiagonal(T value)
    - Swap values diagonally in the quad
- **Can easily construct a lower resolution image (2x2 filter)**
  - See subgroup tutorial for details

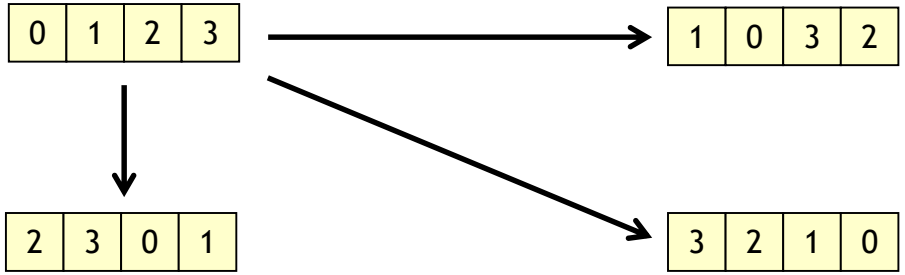
Subgroup Quad Examples

subgroupQuadBroadcast(x, 2)





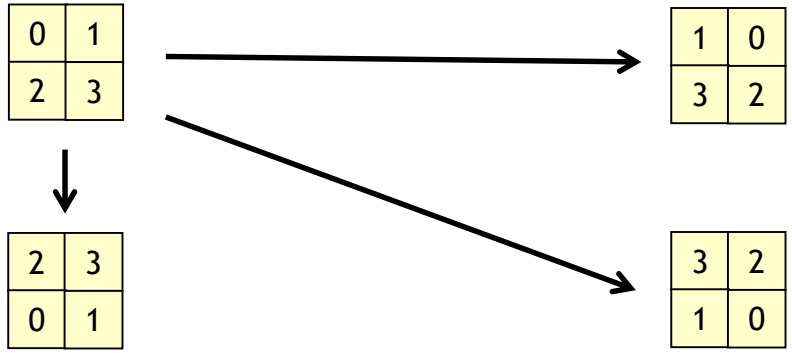
subgroupQuadSwapHorizontal



subgroupQuadSwapVertical

subgroupQuadSwapDiagonal

subgroupQuadSwapHorizontal



subgroupQuadSwapVertical

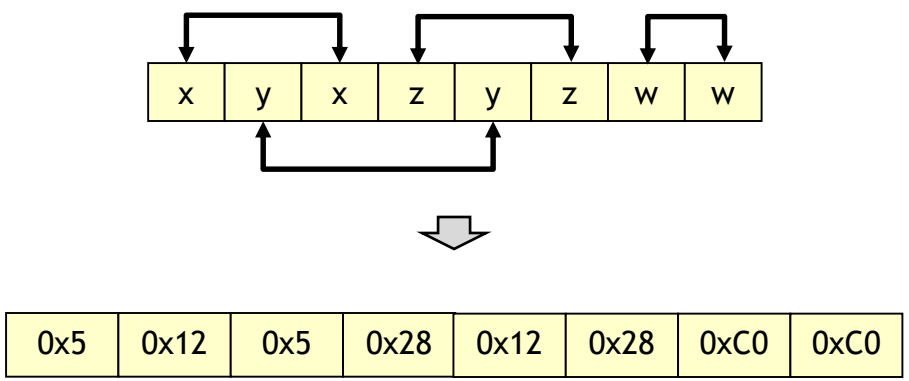
subgroupQuadSwapDiagonal

Subgroup Partitioned Operations (NV)

- **Perform arithmetic operations across a flexible set of invocations**
  - Generalization of clustering which does not need fixed-size clusters or offsets
  - VK_NV_shader_subgroup_partitioned /GL_NV_shader_subgroup_partitioned
- **Generate a partition**
  - uvec4 subgroupPartitionNV(T value)
    - Returns a ballot which is a partition of all invocations in the subgroup based on <value>
    - All invocations represented by the same ballot have the same <value>
    - All invocations in different ballots have different <value>
- **Operation on a partition**
  - T subgroupPartitionedInclusive<op>NV(T value, uvec4 ballot)
  - T subgroupPartitionedExclusive<op>NV(T value, uvec4 ballot)
  - T subgroupPartitioned<op>NV(T value, uvec4 ballot)
    - <op> is Add, Mul, Min, Max, And, Or, Xor
    - Inclusive scan, exclusive scan, reduction operate similar to clustered/arithmetic operations
    - <ballot> describes the partition – typically the result from subgroupPartitionNV
    - No restrictions on how the invocations are partitioned, except that the ballot values passed in must represent a “valid” partition

Subgroup Partitioned Examples

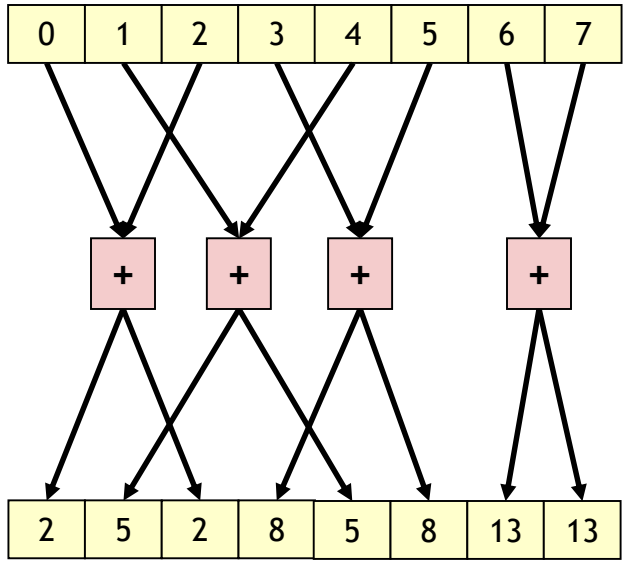
subgroupPartitionNV(value)



ballot = 0x5, 0x12, 0x28, 0xC0

subgroupPartitionedAddNV(values, ballot)

ballot = 0x5, 0x12, 0x28, 0xC0



(Partitions can be differing sizes, completely data determined!)

Subgroup Partitioned Operations

- **Why partitions?**
  - Shaders can't really predict that consecutive invocations will have related values
  - More useful to "discover" (subgroupPartitionNV) those invocations that are related, and then do subgroup operations on related invocations
  - E.g. Deferred shading, detect pixels with the same material or light

- **Any implementation that supports VK_SUBGROUP_FEATURE_ARITHMETIC_BIT can trivially support partitioned ops**
  - Loop over unique partition subsets, compute each in flow control
  - Cost = NumSubsets * costof(SUBGROUP_FEATURE_ARITHMETIC)
- **Some implementations can compute all subsets in parallel**
  - Cost = costof(SUBGROUP_FEATURE_ARITHMETIC)
  - More useful generalization of clustering, and at the same cost
- **Most implementations can probably do better than the trivial looping**

NVIDIA Implementation Details

- **No NDA Required! ☺**
- **Native hw instructions are essentially what is exposed in**
  - GL_NV_shader_thread_shuffle and GL_NV_shader_thread_group
- **shuffle/shuffleUp/shuffleDown/shuffleXor are fast instructions**
  - Essentially our primitives
  - Most other instructions are built up from these using relatively simple transforms
  - Don't be afraid to use more general operations!
- **All the subgroup operations are similar cost**
  - E.g. a REDUCE operation (subgroup<op>) is basically:

```
x = op(x, shuffleXor(x, 1));
x = op(x, shuffleXor(x, 2));
x = op(x, shuffleXor(x, 4));
x = op(x, shuffleXor(x, 8));
x = op(x, shuffleXor(x, 16));
```

  - Slightly more expensive to handle inactive threads in some cases

Tips

- **Make local workgroup be at least the size of the subgroup (compute),**
  - ideally integer multiples
- **Common subgroup sizes: 32 (NVIDIA, Intel), 64 (AMD)**
- **Subgroup size of 1 isn't very useful, but makes a single code path possible**
- **Subgroup operations provide implicit subgroup execution barriers**
- **Operations only act on active invocations**
- **Be aware of inactive lanes or out of range invocation IDs**
  - Reading gives undefined values in most cases!
- **Helper invocations participate in subgroup operations**

HLSL SM 6.0 Wave Ops Comparison

D3D Wave Ops

- **Wave lane count: 4 - 128**
- **Required in pixel and compute shaders**
  - Not supported in any other stages
- **All or nothing functionality**
- **Types: half, float, double, int, uint, short, ushort, uint64 (as supported)**

Vulkan Subgroups

- **Subgroup size: 1 - 128**
- **Required in compute shaders**
  - Optional in Frag, Vert, Tess, Geom stages
- **Minimum functionality guaranteed, additional bundles of functionality**
- **Types: bool, float, double, int, uint**
  - Future: u/int8, u/int16, u/int64, fp16?
- **More complete set of intrinsics**
  - Inclusive scan, clustered ops, etc.
  - barriers
  - More helper routines

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HLSL / GLSL / SPIR-V Mappings

HLSL Intrinsic (Query)	GLSL Intrinsic	SPIR-V Op
WaveGetLaneCount() [4-128]	gl_SubgroupSize[1-128]	SubgroupSize decorated OpVariable
WaveGetLaneIndex	gl_SubgroupInvocationID	SubgroupId decorated OpVariable
WaveIsFirstLane()	subgroupElect()	OpGroupNonUniformElect

HLSL Intrinsic (Vote)	GLSL Intrinsic	SPIR-V Op
WaveActiveAnyTrue()	subgroupAny()	OpGroupNonUniformAny
WaveActiveAllTrue()	subgroupAll()	OpGroupNonUniformAll
WaveActiveBallot()	subgroupBallot()	OpGroupNonUniformBallot

HLSL Intrinsic (Broadcast)	GLSL Intrinsic	SPIR-V Op
WaveReadLaneAt()	subgroupBroadcast(const) / subgroupShuffle(dynamic)	OpGroupNonUniformBroadcast / OpGroupNonUniformShuffle
WaveReadLaneFirst()	subgroupBroadcastFirst()	OpGroupNonUniformBroadcastFirst

HLSL / GLSL / SPIR-V Mappings

HLSL Intrinsic (Reduction)	GLSL Intrinsic	SPIR-V Op
WaveActiveAllEqual()	subgroupAllEqual()	OpGroupNonUniformAllEqual
WaveActiveBitAnd()	subgroupAnd()	OpGroupNonUniformBitwiseAnd / OpGroupNonUniformLogicalAnd
WaveActiveBitOr()	subgroupOr()	OpGroupNonUniformBitwiseOr / OpGroupNonUniformLogicalOr
WaveActiveBitXor()	subgroupXor()	OpGroupNonUniformBitwiseXor / OpGroupNonUniformLogicalXor
WaveActiveCountBits()	subgroupBallotBitcount()	OpGroupNonUniformBallotBitCount
WaveActiveMax()	subgroupMax()	OpGroupNonUniform*Max
WaveActiveMin()	subgroupMin()	OpGroupNonUniform*Min
WaveActiveProduct()	subgroupMul()	OpGroupNonUniform*Mul
WaveActiveSum()	subgroupAdd()	OpGroupNonUniform*Add

HLSL / GLSL / SPIR-V Mappings

HLSL Intrinsic (Scan and Prefix)	GLSL Intrinsic	SPIR-V Op
WavePrefixCountBits()	subgroupBallotExclusiveBitCount()	OpGroupNonUniformBallotBitCount
WavePrefixSum()	subgroupExclusiveAdd()	OpGroupNonUniform*Add
WavePrefixProduct()	subgroupExclusiveMul()	OpGroupNonUniform*Mul

HLSL Intrinsic (Quad Shuffle)	GLSL Intrinsic	SPIR-V Op
QuadReadLaneAt()	subgroupQuadBroadcast()	OpGroupNonUniformQuadBroadcast
QuadReadAcrossDiagonal()	subgroupQuadSwapDiagonal()	OpGroupNonUniformQuadSwap
QuadReadAcrossX()	subgroupQuadSwapHorizontal()	OpGroupNonUniformQuadSwap
QuadReadAcrossY()	subgroupQuadSwapVertical()	OpGroupNonUniformQuadSwap

Availability

- **GLSL functionality**
  - Glslang - https://github.com/khronosgroup/glslang/
- **HLSL functionality**
  - Glslang - https://github.com/KhronosGroup/glslang
  - DXC - https://github.com/Microsoft/DirectXShaderCompiler/
- **SPIR-V 1.3**
- **Vulkan support**
  - https://vulkan.gpuinfo.org/ (under Device Properties)
  - NVIDIA Vulkan 1.1 drivers - http://www.nvidia.com/Download/index.aspx
  - AMD Vulkan 1.1 drivers
  - Intel Vulkan 1.1 drivers

References

- **Vulkan Subgroup Tutorial**
  - https://www.khronos.org/blog/vulkan-subgroup-tutorial
- **Vulkan 1.1 Specification (with extensions)**
  - https://www.khronos.org/registry/vulkan/specs/1.1-extensions/html/vkspec.html
- **GL_KHR_shader_subgroup GLSL extension**
  - https://github.com/KhronosGroup/GLSL/blob/master/extensions/khr/GL_KHR_shader_subgroup.txt
- **GL_NV_shader_subgroup_partitioned GLSL extension**
  - https://github.com/KhronosGroup/GLSL/blob/master/extensions/nv/GL_NV_shader_subgroup_partitioned.txt
- **SPIR-V 1.3 (Unified)**
  - https://www.khronos.org/registry/spir-v/specs/unified1/SPIRV.html
- **HLSL Shader Model 6.0 (MSDN)**
  - https://msdn.microsoft.com/en-us/library/windows/desktop/mt733232(v=vs.85).aspx
- **DirectXShaderCompiler Wave Intrinsics**
  - https://github.com/Microsoft/DirectXShaderCompiler/wiki/Wave-Intrinsics
- **Reading Between the Threads: Shader Intrinsics**
  - https://developer.nvidia.com/reading-between-threads-shader-intrinsics

Thank You

- Neil Henning (Codeplay) @sheredom
- Lei Zhang (Google)
- Jeff Bolz (NVIDIA)
- Piers Daniell (NVIDIA)

NVIDIA Vulkan Driver issues/questions?

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Email us to help make your Vulkan titles AWESOME!