Game Developer's Perspective on OpenCL

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Motivation

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- **Supports a variety of compute resources**
  - CPUs, GPUs, SPUs, accelerators
  - Unifies programming for devices that have very different environments
  - Provides uniform interface to non-fixed platforms (e.g. PC/Mac)

Motivation

- **Open standard**
  - Many vendors will support directly
  - Potential for 3rd party implementations if no vendor support
  - Embedded platform support in spec

Motivation

- **Concurrent programming model**
  - Command queue(s) per device with support for dependencies across queues
  - Data parallel and SIMD support in a portable notation,
  - superior to intrinsics
  - Low-level programming model, minimalist abstractions

How to apply OpenCL to games

How to apply OpenCL to games

- **Don't try speed up everything**
  - Create new content/features that use the excess compute capacity
- **Some cases are easy**
  - We already parallelize them
- **Some cases are harder**
  - But with OpenCL it will be easier to try them.

Dodging Amdahl's Law

- **Amdahl's Law**
  - "The speedup of a program using multiple processors is limited by the sequential fraction of the program"
- **So, massively parallel hardware has limited benefit?**
- **No**
  - The game already runs on today's hardware.
  - More compute power => add more content/features.
  - Games have 100's or 1000's of algorithms to target.
- **OpenCL makes the coding easier**

The “Easy” cases

- **Rendering**
  - Rasterization / shading already runs on graphics hardware
  - Visibility culling
  - Procedural geometry
- **Codec decompression**
  - Animation, audio, video, etc.
- **Animation blending**
- **Audio mixing**
- **Rigid body physics integration**
- **Some collision calculations**
- **Etc.**

Then it gets harder...

- **AI**
  - Path finding
  - Search
  - Pattern matching
  - Fuzzy logic / neural nets for AI
  - Massive scale AI behavior on multiple actors
  - Speculative AI paths
- **Animation**
  - High level motion planning
  - Detailed crowd simulation with individual behaviors
- **Physics**
  - Broad phase collision systems
  - Character to character interaction
  - High quality liquid/smoke.
- **Asset creation**
  - Landscape, vegetation, architecture, etc.

Early Experiences

Early Experiences

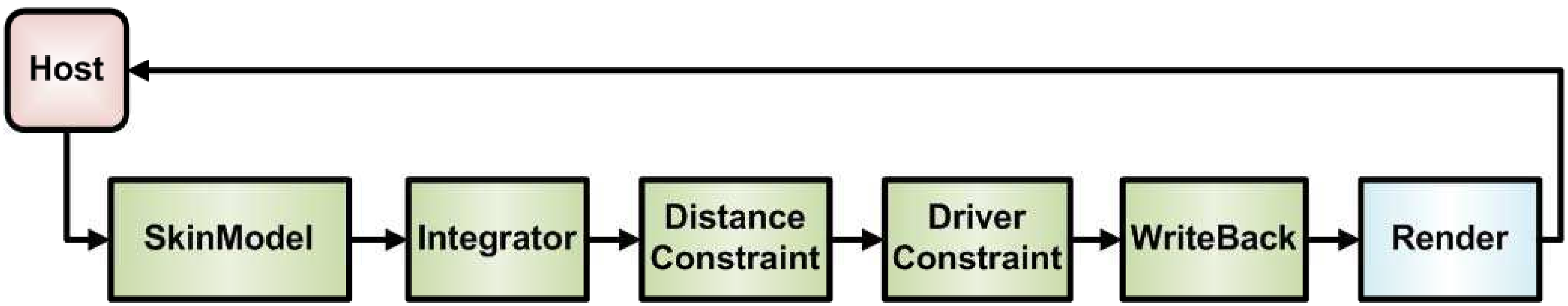
- **Too early to tell you about shipped game code**
- **We have done some feasibility experiments**
- **Skate 2 Cloth Experiment**
  - Pulls the character skinning and cloth physics out of EA's Skate 2 and embeds it into a stand alone demo
- **Goal:**
  - Exercise OpenCL on "real" code
  - Extract game subsystem and port key algorithms to OpenCL
  - Leave intact as much original code and API as possible

What does it do?

- **Play back recorded skeleton poses**
- **Skin character model to pose**
- **Apply cloth physics to portion of the skinned model**
  - Integrator for gravity
  - Particle-to-particle spring system
  - Constrained to underlying skinned model
- **Render via OpenGL**

Demo Task Graph

- Simple sequential execution graph
- In-order, data parallel tasks
- Render inputs are double buffered to OpenCL tasks could, in theory, begin prior to render completion



Enqueue Instead of Execute

- **In original code each box represents a function call**
- **Demo abstracts OpenCL kernel invocations as functors**
  - Functors take an event parameter to be dependent on, and return their own event
  - Functors enqueue a kernel—upon return the kernel may not have completed or even begun

Enqueue Instead of Execute

- A function like this

```
this->TCVIntegrate(dt, deltaPos);
```

- Became an enqueue functor call like this

```
if (mIntegratorFunc != NULL)
  event = (*mIntegratorFunc)(event, dt, deltaPos);
```

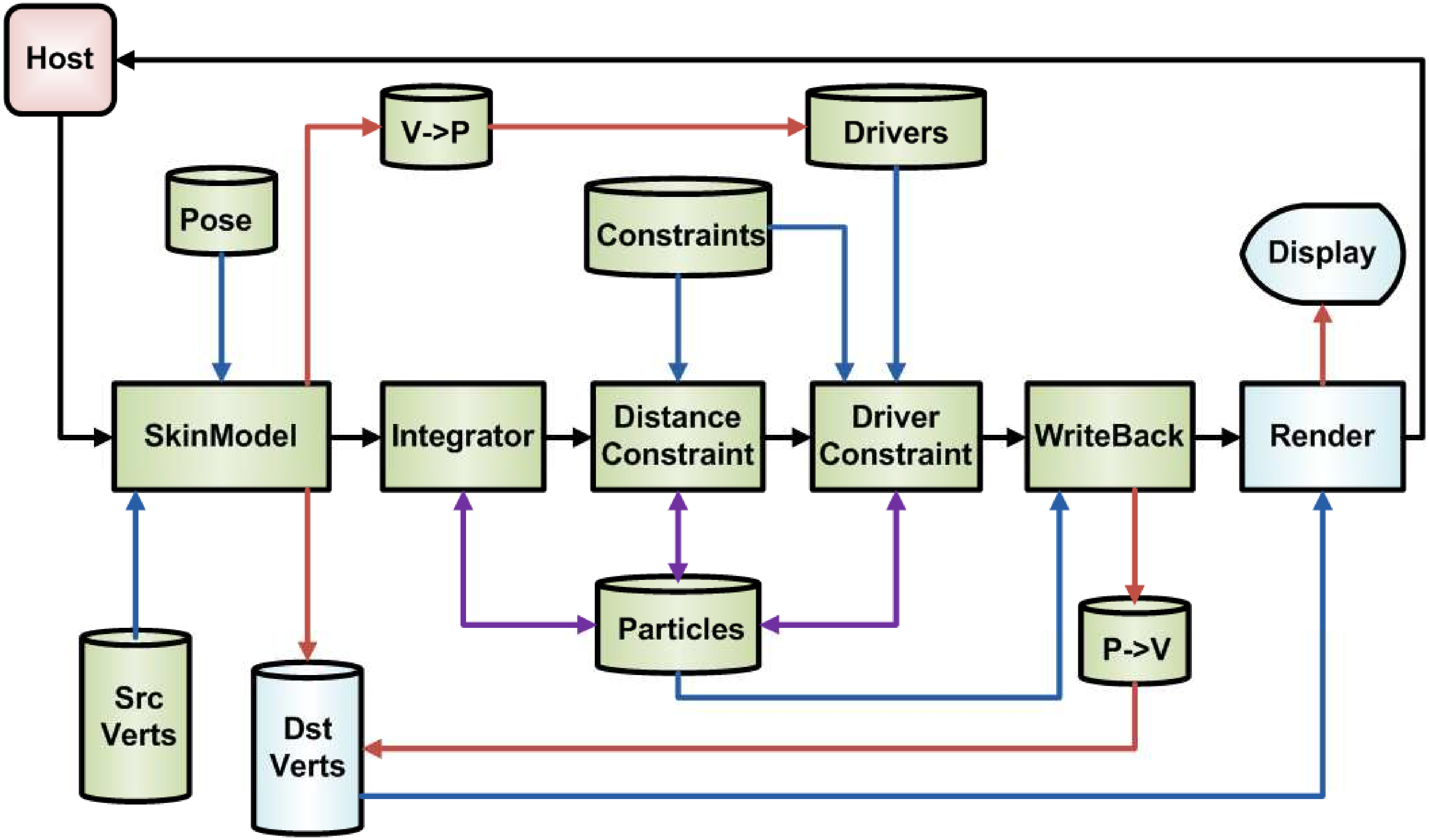
- The original code remains as a fallback, slightly modified

```
else {
   this->LockBuffers();
   this->TCVIntegrate(dt, deltaPos);
   this->UnlockBuffers();
}
```

Memory Objects

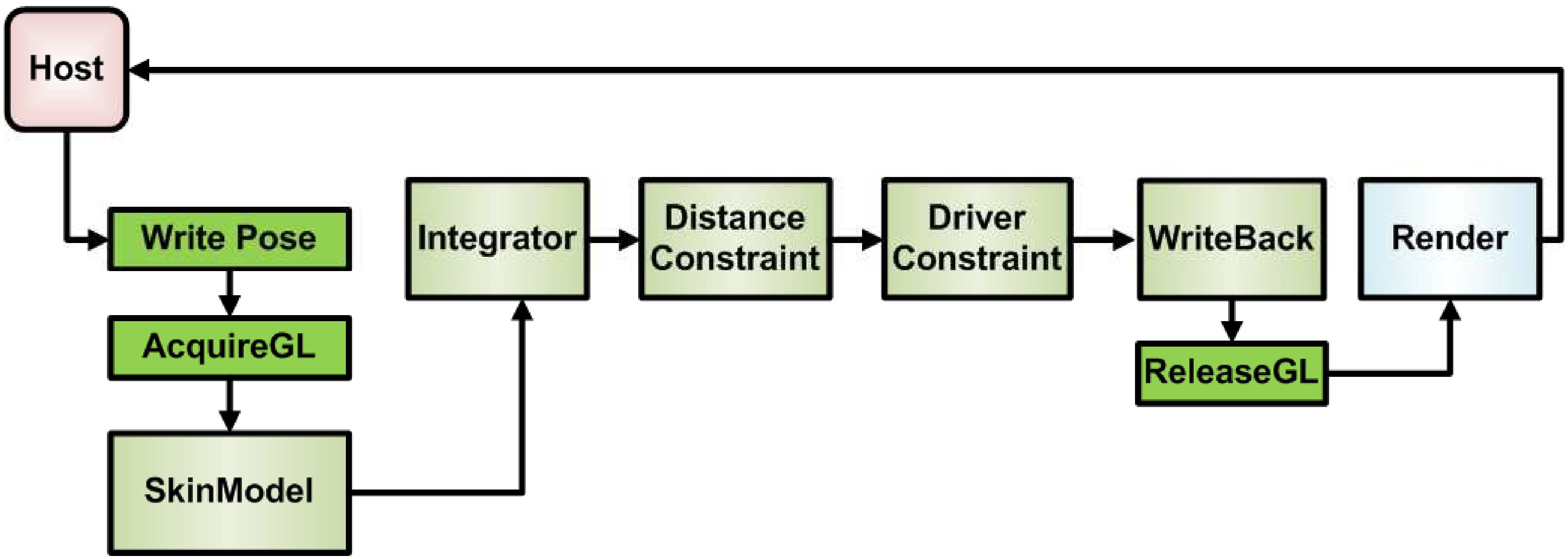
- **Original data was organized in aligned arrays of structs**
- **cl_mem objects were created for each array**
  - CL_MEM_USE_HOST_PTR to avoid additional allocations and copying (when using CPU device)
  - OpenGL vertex buffers allocated by GL and bound to OpenCL via GL/CL interop

Data Flow Through Kernels



Complete Command Queue

- Buffer write used to move data into pose buffer
- Acquire / release to give OpenCL access to GL buffers



Kernels

- **Skinning**
  - Generates vertex buffer and drivers from pose
- **Integrator**
  - Acceleration due to gravity
- **Distance constraint**
  - Springs between cloth particles
- **Driver constraint**
  - Keeps cloth near underlying ‘skin’
- **Writeback**
  - Output cloth positions to vertex buffer

Vectorization

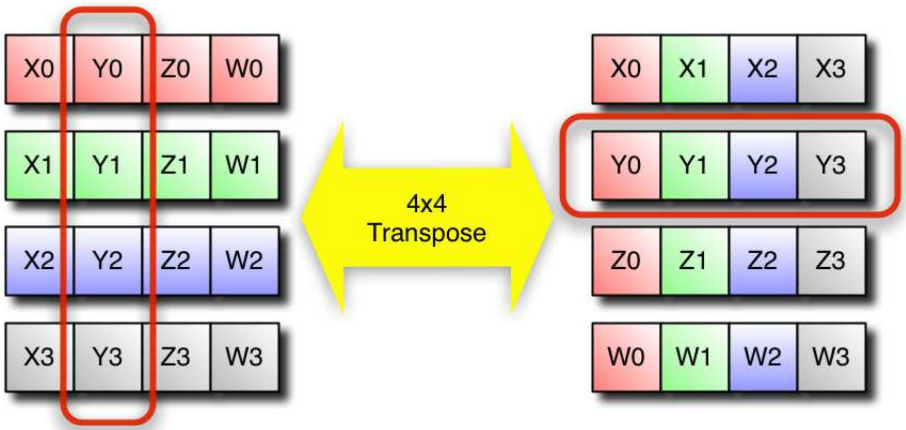
- **Wrote two variants of each kernel: Scalar and vector**
  - Some hardware does much better with SIMD code

- **“Structure of Arrays” (SoA) style math**
  - Memory data layout unchanged, rearranged at load/store
  - AoS float4 contains “xyzw”; SoA float4 contains “xxxx”

- **Two key techniques employed: Transpose and select**

4x4 Transpose

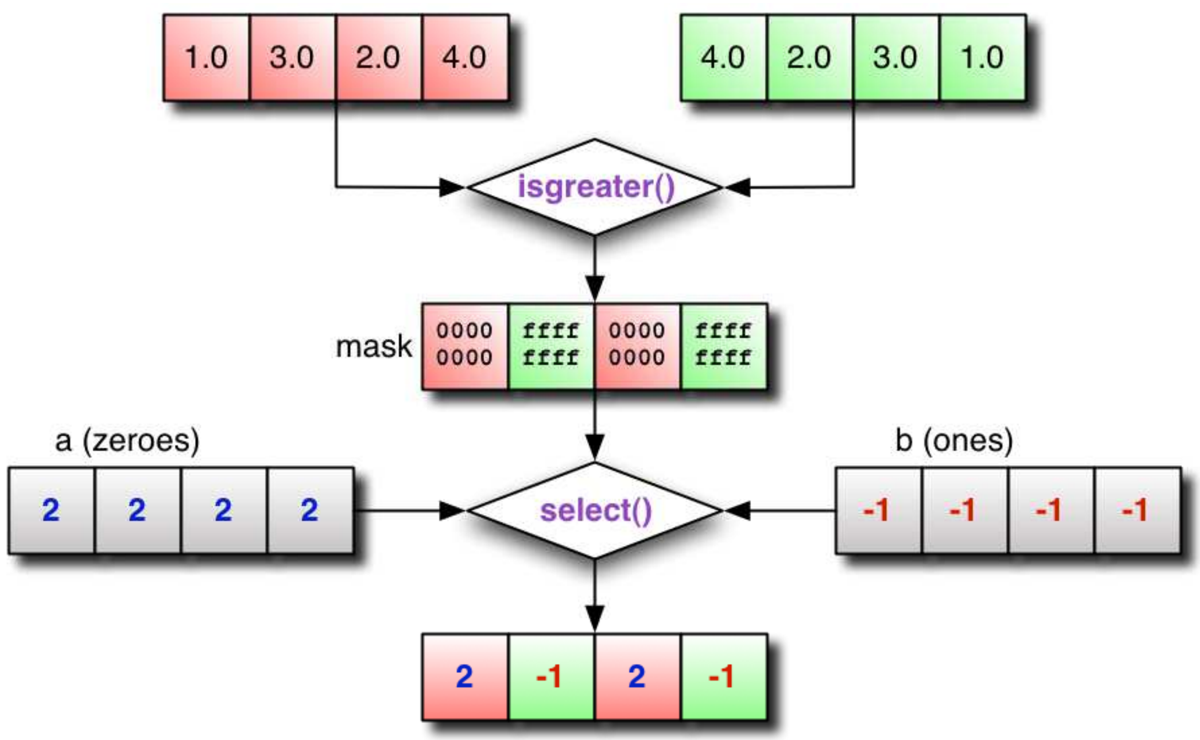
- Used to convert between AoS and SoA
- Four float4 AoS values loaded into one float16
- Post transpose the four float4 parts are SoA




```
float16 transpose (float16 m)
{
  float16 t;
  t.even = m.lo;  t.odd = m.hi;
  m.even = t.lo;  m.odd = t.hi;
  return m;
}
```

Select vs. Branch

- Branching is bad, for many reasons
- select(a,b,c) efficiently chooses between “a” and “b” based on “c” element-wise fashion
- Comparisons like isgreater(a,b) are set up to output to “c”



Scalar Integrator

```
void perform_integrator (int pIdx, float4 vsr, float4 acc,
 float dt, __global Particle* particles,
 __global short* indices, __global IntegratorState *iState)
{
    float4 curPos, curPrevPos, nextPos;
    curPos = particles[pIdx].mPos;
    curPrevPos = particles[pIdx].mPrevPos;
    float vsr = (1.0f - ctp->mVerticalSpeedDampening);
    // TIME CORRECTED VERLET
    // xi+1 = xi + (xi - xi-1)*(dti/dti-1) + a*dti* dti
    if ((indices[pIdx]) >= 0 && (curPrevPos.w > 0.0f)) {
        nextPos = curPos;
        nextPos -= curPrevPos;
        nextPos *= dt / iState->mLastDT;
        nextPos.y *= vsr;
        nextPos += acc;
        particles[pIdx].mPrevPos = curPos;
        particles[pIdx].mPos = curPos + nextPos;
    }
}
```

Vector Integrator

```
void perform_vector_integrator (
    float4 vdt_ratio,
    float4 acc,
    int numparticles,
    int pIdx,
    __global Particle *ptrParticle,
    __global uint *mapped)
{
    // load 4 particle positions and previous positions
    // transpose particles from Aos -> SoA
    // extract locked flags for particles
    // TIME CORRECTED VERLET:
    //     xi+1 = xi + (xi - xi-1) * (dti / dti-1)
    //          + a * dti * dti
    // select between unchanged (if locked)
    //     and new location (if not locked)
    // transpose SoA -> AoS
    // store particles back
}
```

Vector Integrator

```
// load particle position and previous position
float16 curPos, curPrevPos;
curPos.s0123 = ptrParticle[0].mPos;
curPrevPos.s0123 = ptrParticle[0].mPrevPos;
curPos.s4567 = ptrParticle[1].mPos;
curPrevPos.s4567 = ptrParticle[1].mPrevPos;
curPos.s89ab = ptrParticle[2].mPos;
curPrevPos.s89ab = ptrParticle[2].mPrevPos;
curPos.scdef = ptrParticle[3].mPos;
curPrevPos.scdef = ptrParticle[3].mPrevPos;

// transpose particles from Aos -> SoA
curPos = transpose(curPos);
curPrevPos = transpose(curPrevPos);

// extract locked flags for particles
uint4 mask = (uint4)isgreater(curPrevPos.scdef,
    (float4)0.0f) & ~ComputeMappedMask(mapped);
```

Vector Integrator

```
// TIME CORRECTED VERLET
float4 next_x = ((curPos.s0123 - curPrevPos.s0123) *
    vdt_ratio + (curPos.s0123 + acc.x));
float4 next_y = ((curPos.s4567 - curPrevPos.s4567) *
    vdt_ratio + (curPos.s4567 + acc.y));
float4 next_z = ((curPos.s89ab - curPrevPos.s89ab) *
    vdt_ratio + (curPos.s89ab + acc.z));

// select between unchanged (if locked)
// and new location (if not locked)
curPrevPos.s0123 = select(
     curPrevPos.s0123, curPos.s0123, mask);
curPrevPos.s4567 = select(
      curPrevPos.s4567, curPos.s4567, mask);
curPrevPos.s89ab = select(
      curPrevPos.s89ab, curPos.s89ab, mask);
curPos.s0123 = select(curPos.s0123, next_x, mask);
curPos.s4567 = select(curPos.s4567, next_y, mask);
curPos.s89ab = select(curPos.s89ab, next_z, mask);
```

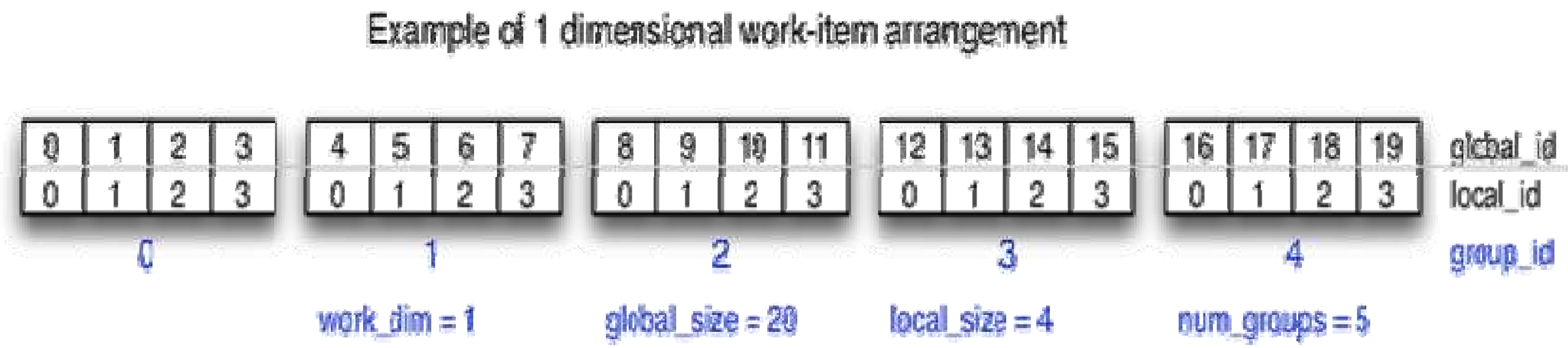
Vector Integrator

```
// transpose SoA -> AoS
curPos = transpose(curPos);
curPrevPos = transpose(curPrevPos);

// store particles back
ptrParticle[0].mPos = curPos.s0123;
     ptrParticle[0].mPrevPos =
curPrevPos.s0123;
ptrParticle[1].mPos = curPos.s4567;
     ptrParticle[1].mPrevPos =
curPrevPos.s4567;
ptrParticle[2].mPos = curPos.s89ab;
     ptrParticle[2].mPrevPos =
curPrevPos.s89ab;
ptrParticle[3].mPos = curPos.scdef;
     ptrParticle[3].mPrevPos =
curPrevPos.scdef;
```

Work-Items and Workgroups

- **Data parallel model in OpenCL is based on work-items**
  - Each work-item is given its own index (in up to three dimensions)
  - Work-items are organized into uniformly sized “workgroups”
  - Workgroup size is limited by device and kernel
- **Work-items in a workgroup execute in parallel and share**
  - Local memory
  - Barriers
  - Fences



Per Kernel Index Space

- **This demo's kernels are all in one-dimensional spaces**
- **Each kernel uses its own space**
  - Skinning: Complete vertex array
  - Integrator: Particle array
  - Driver constraint: Driver array
  - Distance constraint: Constraints array
  - Writeback: Clothed portion of vertex array

Distance Constraint: Limited Parallelism

- **Each distance constraint modifies two particles**
  - Modifying a particle from multiple constraints concurrently gives incorrect results
- **Original constraints organized into "octets"**
  - Eight-at-once is far too few to keep GPU busy

CPU Device Performance

	Host	Scalar Task	Scalar DP (8 Cores)	Vector DP (8 Cores)
Overall	1.00	2.72	17.03	17.27

Skinning	1.00	2.98	20.98	20.98*
Integrator	1.00	1.53	1.48	1.10
Distance	1.00	1.34	2.54	2.69
Driver	1.00	1.14	5.58	8.83
WriteBack	1.00	1.01	7.26	7.26*

*No vector version available

GPU Device Performance

	Host	Best CPU (8 Cores)	Unoptimized GTX285
Overall	1.00	17.27	4.11

Skinning	1.00	20.98	4.39
Integrator	1.00	1.53	1.10
Distance	1.00	2.69	0.74
Driver	1.00	8.83	3.24
WriteBack	1.00	7.26	17.69

Optimizations – Algorithmic

- **Each distance constraint modifies two particles**
  - Modifying a particle from multiple constraints concurrently gives incorrect results.
  - Original algorithm allows for at most eight particles in a work-group. This cripples GPU performance.
- **Reordering constraints to maximize the workgroup size (7x) improved kernel performance dramatically**
- **Limited by algorithm,**
  - Alternatives should be investigated

Optimizations – Work per Task

- **Larger simultaneous data set sizes provide the GPU with substantially more work**
  - CPU benefits as well, but drops off with larger data sets
- **Real game: Process all characters as a single batch**
- **Demo: Simple geometry replication (25x)**

Optimizations – Bandwidth

- Memory access is crucial in bandwidth limited kernels (and most will be bandwidth limited)

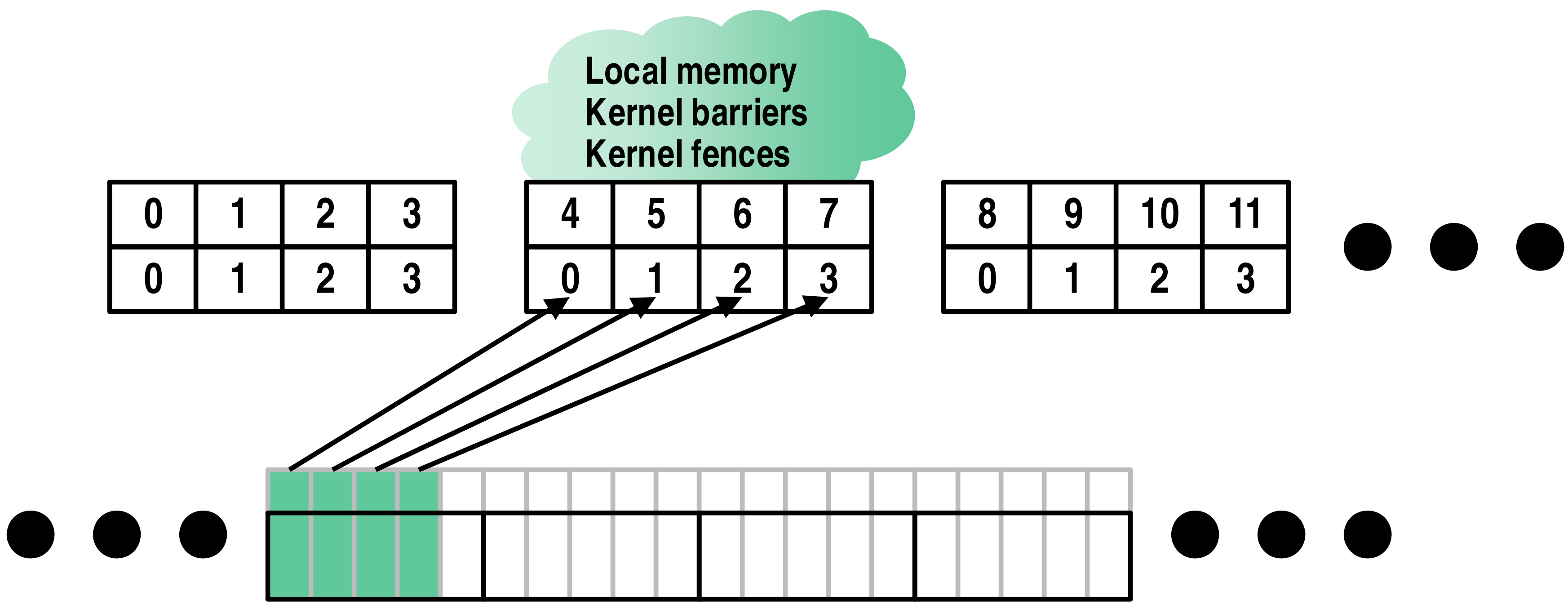
- GL/CL integration
- CL_MEM_COPY_HOST_PTR for GPU
- Current GPU memory controllers are optimized for a specific set of memory access patterns

GPU Memory and Execution Optimization

- Burst reads from memory are essential
- Bursts only happen on sequential accesses
- Bursts are created by coalescing smaller reads
- Can only coalesce 4-, 8-, or 16-byte reads
- Coalesces across work-items in a workgroup

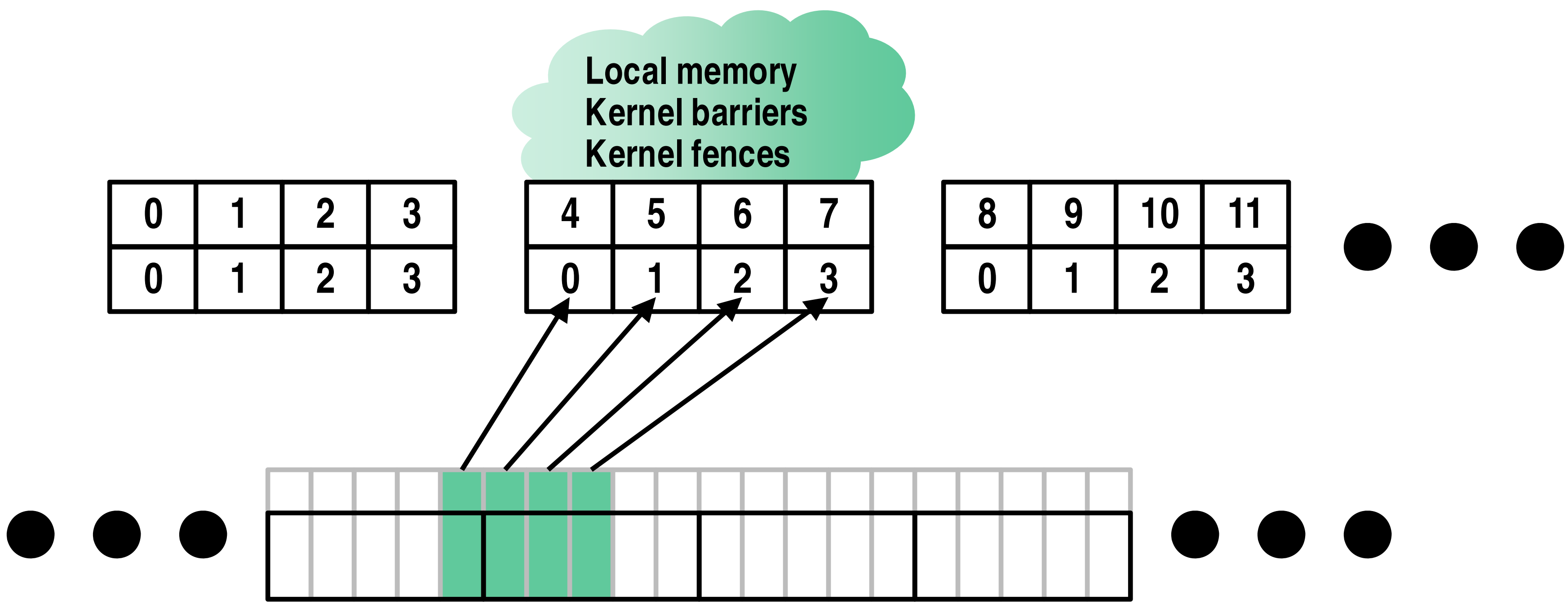
- Solution: Optimized transfer from global to local memory, then operate on local memory
- This pattern must currently be explicitly coded for

GPU Memory and Execution Optimization



Buffer of 80-byte vertex structs
(5 x 16-byte float4)

GPU Memory and Execution Optimization



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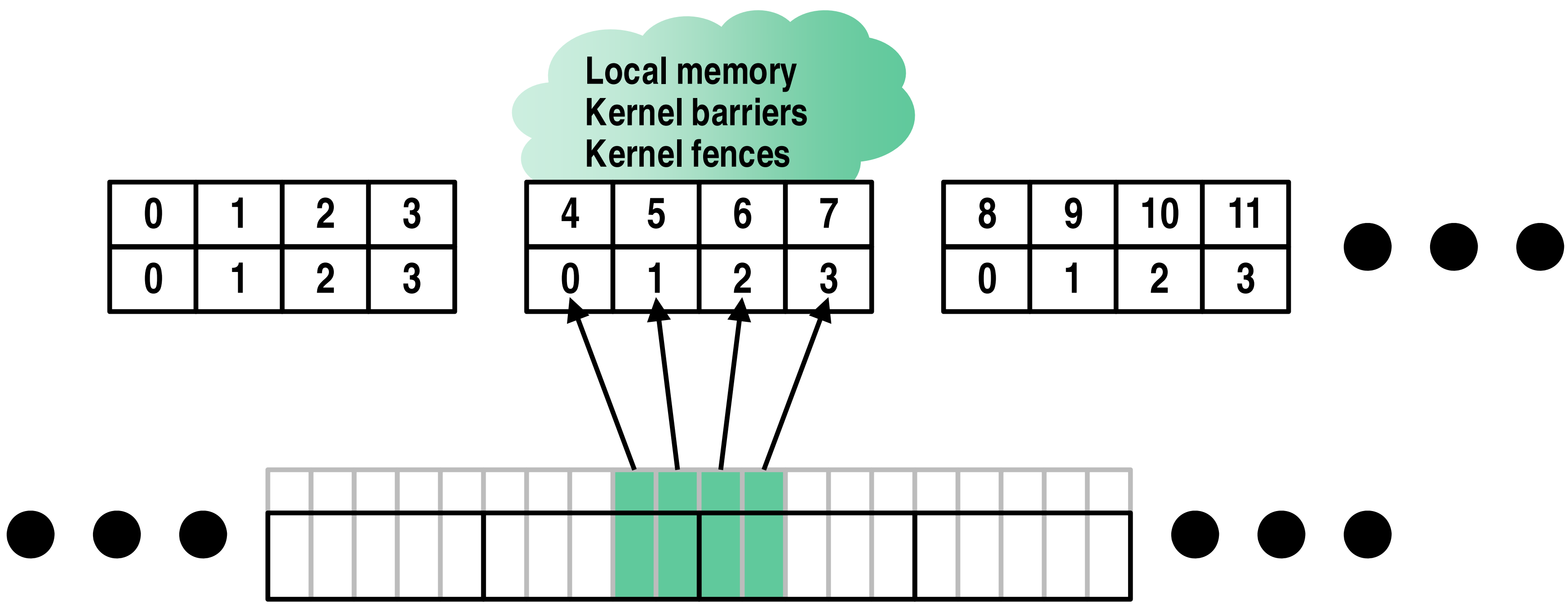

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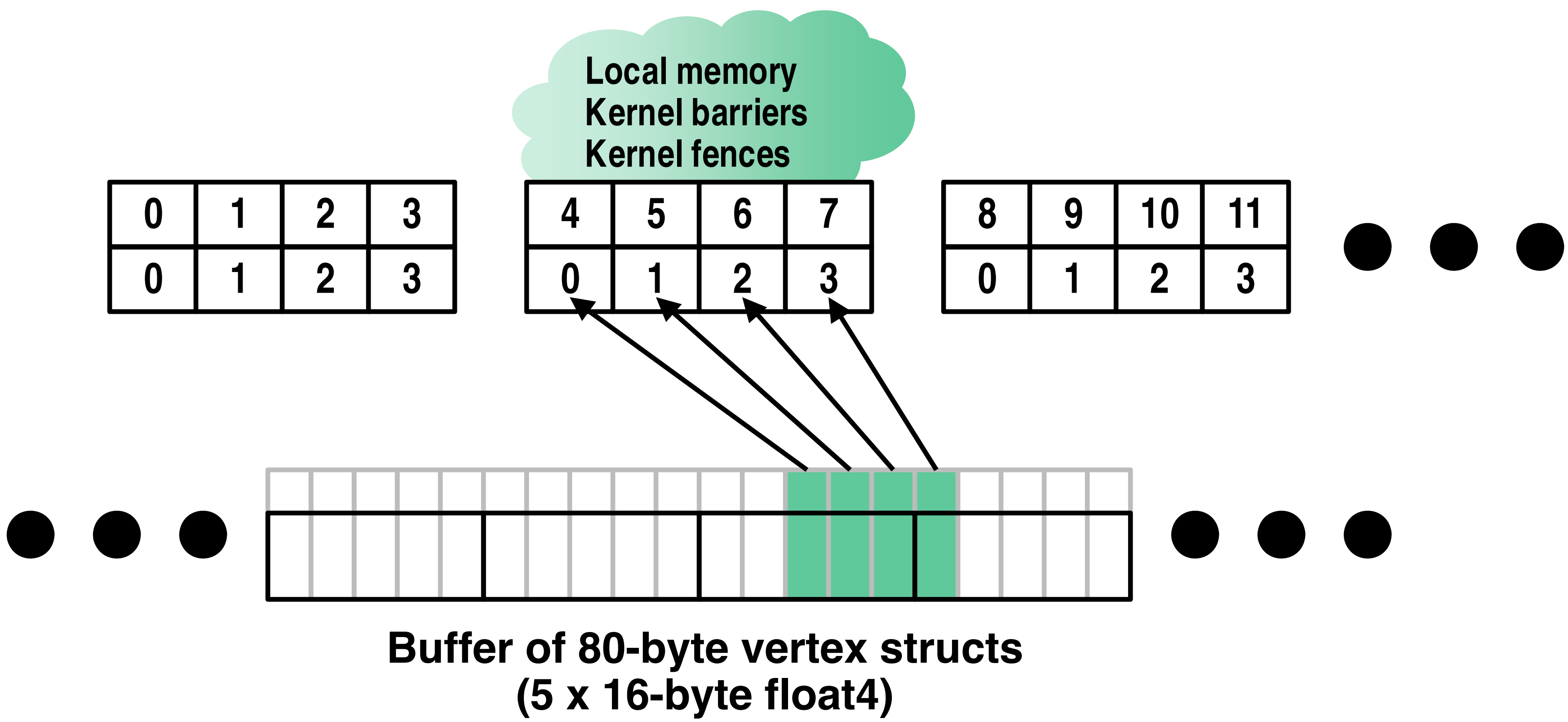
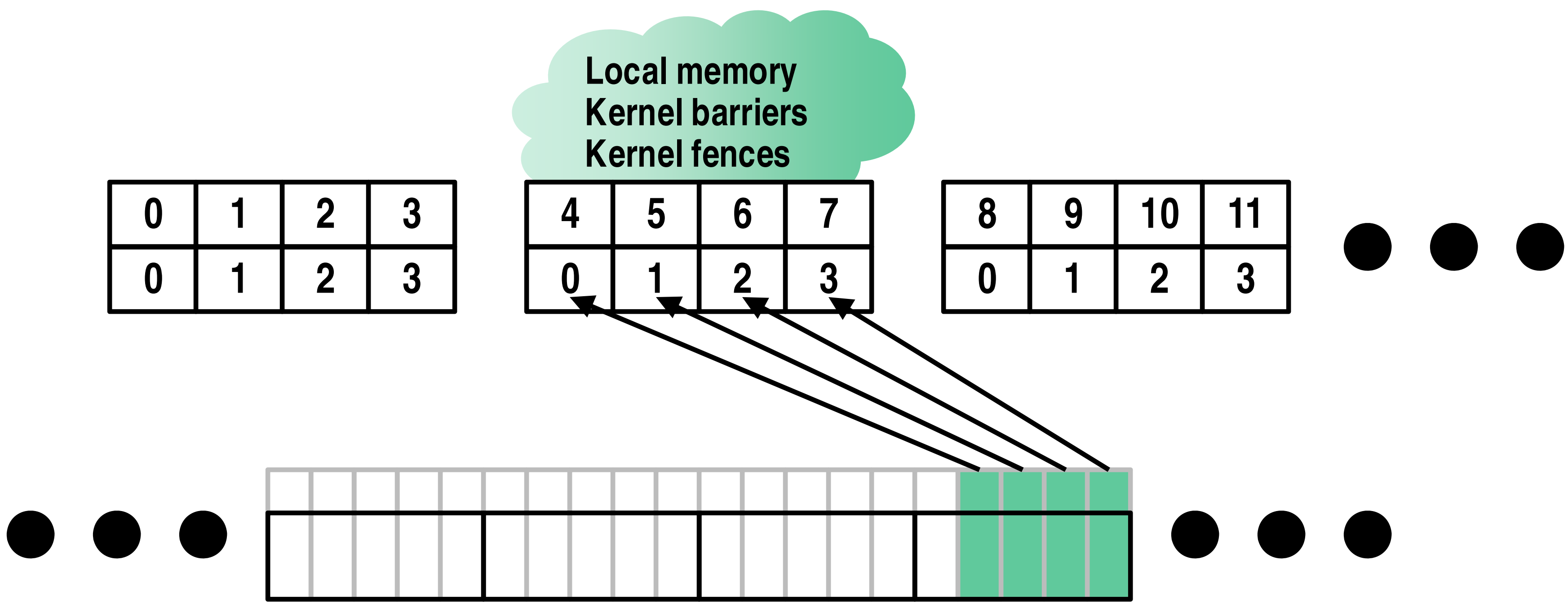


GPU Memory and Execution Optimization



Buffer of 80-byte vertex structs
(5 x 16-byte float4)

GPU Device Performance

	Host	Best CPU (8 Cores)	Unoptimized GTX285	Optimized GTX285
Overall	1	17.27	4.11	45.15

Skinning	1	20.98	4.39	83.56
Integrator	1	1.53	1.1	4.6
Distance	1	2.69	0.74	1.73
Driver	1	8.83	3.24	14.45
WriteBack	1	7.26	17.69	56.6

Performance Summary

- Performance tuning is essential
- Performance characteristics are not hidden by abstraction layer
- Expect to write multiple variations and choose empirically at runtime