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Simulation and Rendering Massive Crowds of Intelligent and Detailed Creatures on GPU

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Outline

- Motivation
- Crowd movement simulation on GPU
  - Global and local navigation and avoidance
- Lighting solution
- Crowd rendering and scene management on GPU
- Conclusions

Driving Visual Experience Frontiers

- Our task is to push the envelope for interactive visual experience
  - "What does it mean to have better interactive experiences?"
- Beyond just the pretty face
  - We know we can do that… We've done it!
  - Can we make them think?

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We Can Even Make Them Dream!

Motivation

- Making the gameplay more fun: A game is a series of choices...
  - It helps when choices are interesting!
- Artificial intelligence is ubiquitous in current games
  - Non-player and player characters require a form of AI
  - Path finding, obstacle avoidance, decisions, etc.

Motivation

- CPU can spend > 50% time on path finding computations alone in games
  - Limits possible decision complexity
  - Thus we frequently see “zombie-like” NPCs
  - Gameplay suffers
- Emergent behaviors improve any game with many characters
  - Making it more fun!

Top Level Overview

- *<u>Goal</u>:* Simulate and render massive crowds of characters on GPU at a scale that's both breathtaking and challenging
- Direct3D® 10.1
- Tessellation
- 4X MSAA
- HD resolution and HDR rendering

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A Smörgåsbord of Features

- Dynamic pathfinding AI computations on GPU
- Massive crowd rendering with LOD management
- Tessellation for high quality close-ups and stable performance
- HDR lighting and post-processing effects with gamma-correct rendering
- Terrain system
- Cascade shadows for large-range environments
- Advanced global illumination system

Introducing the Froblins

Outline

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- Crowd movement simulation on GPU
  – Global and local navigation and avoidance
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Motivation: Beware of Ghosts!!

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Dynamic and Engaging World Through AI

- Combine global path finding with local avoidance and individual decisions
- Crowd movement is more stable and realistic solved on a global scale
  - Crowd dynamics similar to fluids
  - Agents “flow” towards the closest goal, along the path of least resistance
  - Froblins follow correct paths and do not “get stuck”

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Global Path Finding

- Based on *Continuum Crowds* [TCP06]
- Convert motion planning into an optimization problem
  - Use continuum model
  - Computational algorithms from optics
- Smooth flow-like crowd movement
  - Congestion avoidance and emergent behavior

Pathfinding on GPU

- Numerically solve a 2nd order PDE on GPU with a computational iterative approach (eikonal solver)
  - Represent environment as a cost field
  - Through discretization of the eikonal equation
- Applicable to many general algorithms and areas

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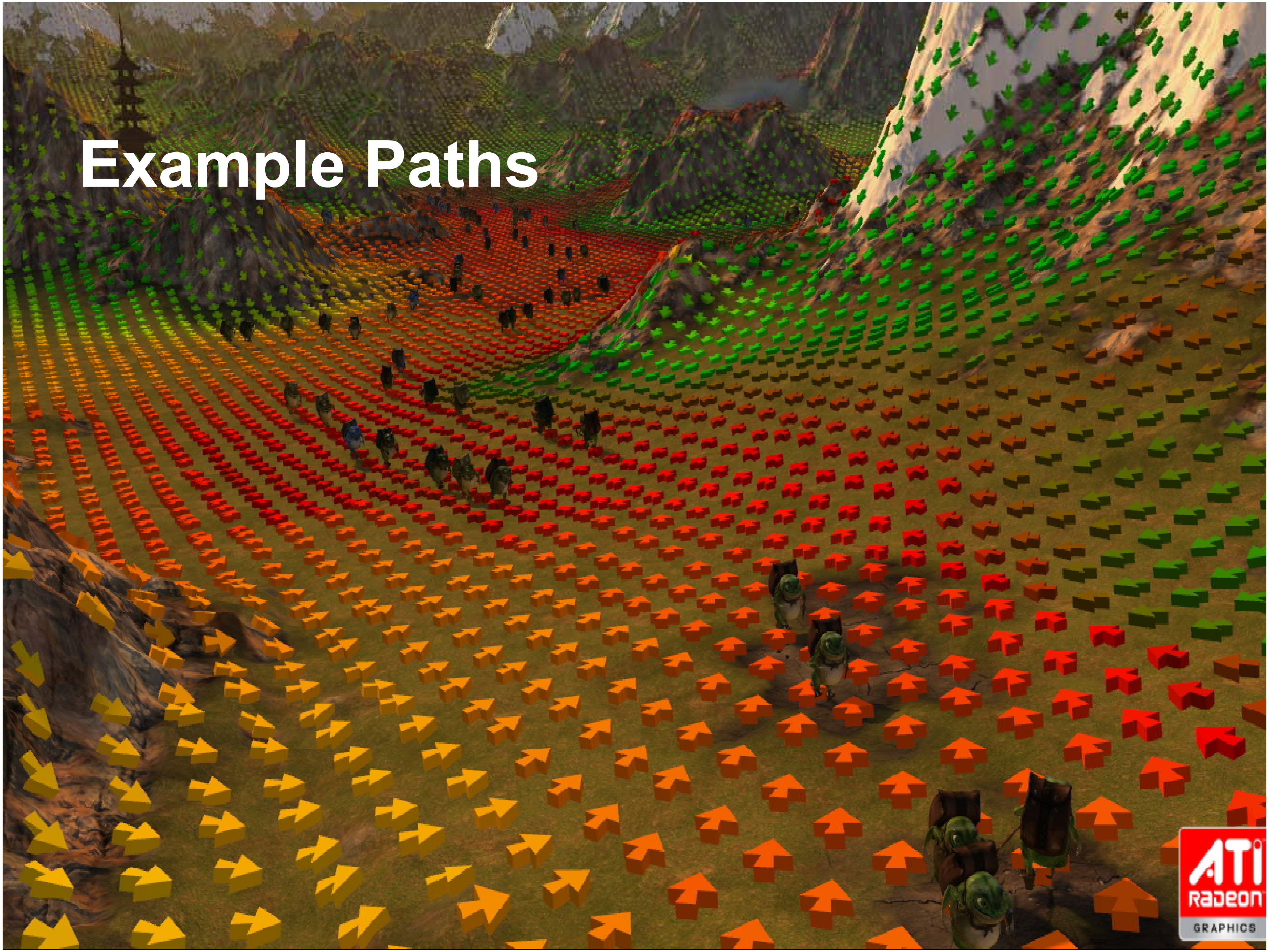
Example Paths



Solver: From Cost to Travel Time

- Solve for travel time as a function of potential
- *Potential φ* = integrated cost *F* along shortest path to goal
  - Follow negative gradient

$$\left\| \nabla \varphi(x) \right\| = F$$

- Set potential = 0 at goal, eikonal equation elsewhere
- Comes from optimization algorithms

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Eikonal Solver via Fast Marching Method

- Emulates Dijkstra's shortest path algorithm
- A finite difference approximation to the continuous eikonal equation
  - Start from known potential ($\varphi=0$ at goal) and propagate to neighbors until convergence
  - Compute potential for neighbor cells based on known cells
- Serial algorithm; requires an ordered data structure

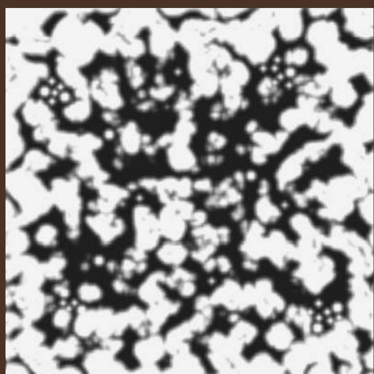
Parallel Eikonal Solver

- Using *Fast Iterative Method* [JW07]
- Use upwind finite difference approximation but no ordered data structures
- We use small grid resolutions (128^2 -256^2)
- Solve for four goals at once
  - Taking advantage of vectorization – use RGBA FP16 texture
- Convergence determined empirically

Environment As Cost Function

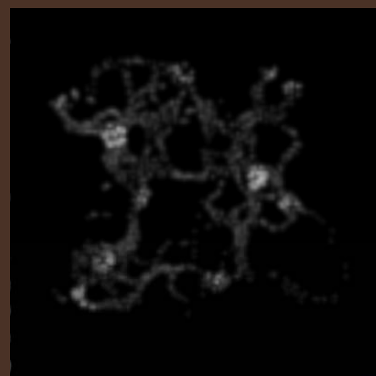
- Continuum Model models environment as *a positive cost function*
  - Can't be zero otherwise agents would move at infinite speed; add some small base amount
- Incorporate information about terrain and obstacles (static and dynamic)
  - Splat dynamic obstacles, including agents into the cost function

Cost Function Formulation



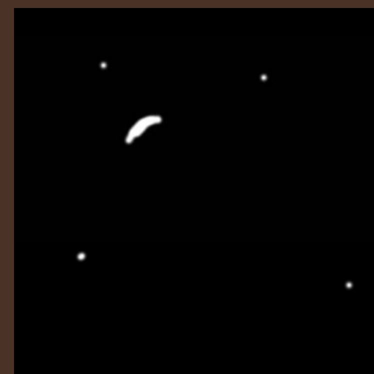
Static Cost

+



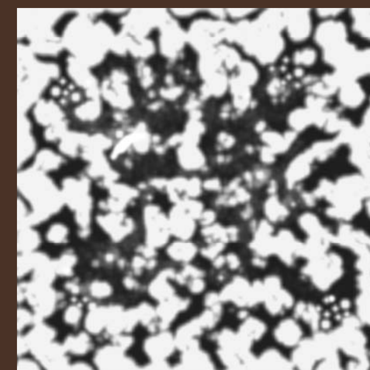
Agent Density

+

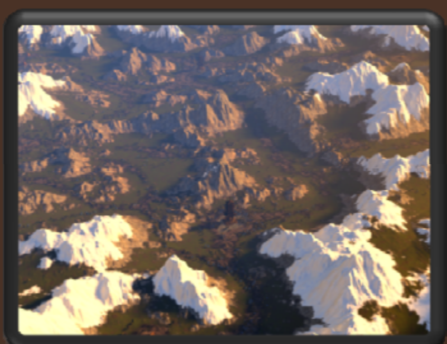


Hazards

=



Total Cost



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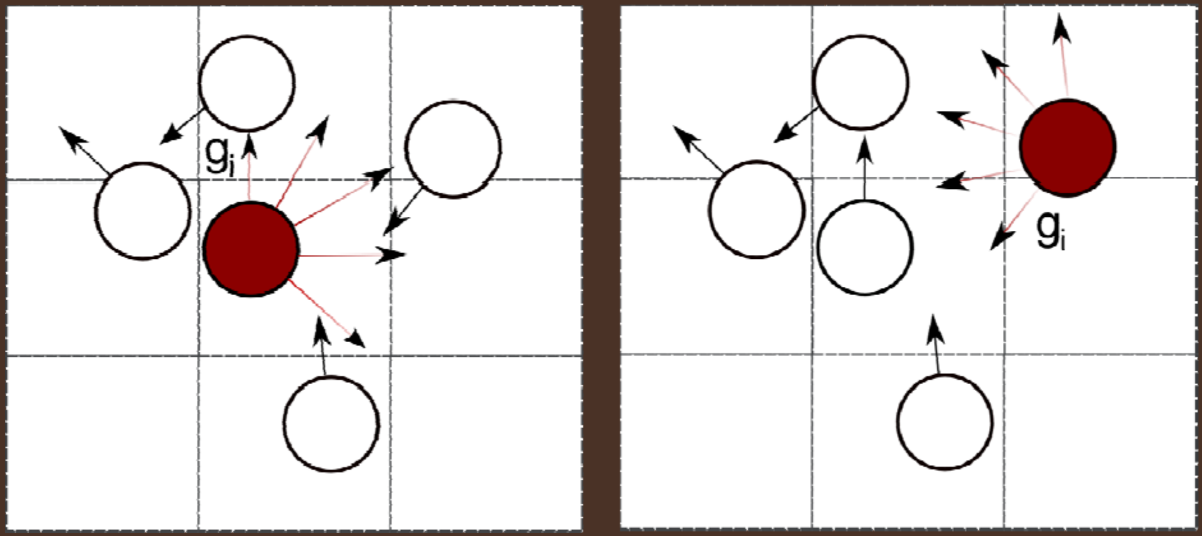
Local Navigation and Avoidance

- Global model not great for local obstacles
  - Performance & No need to avoid agent far away
- Update velocity based on positions and velocities of nearby agents/obstacles
  - Based on Velocity Obstacle formulation [Fiorini and Shiller 1998]
  - See course notes for more details & Jeremy Shopf's talk on in ***Beyond Programmable Shading: In Action*** course

Direction Determination

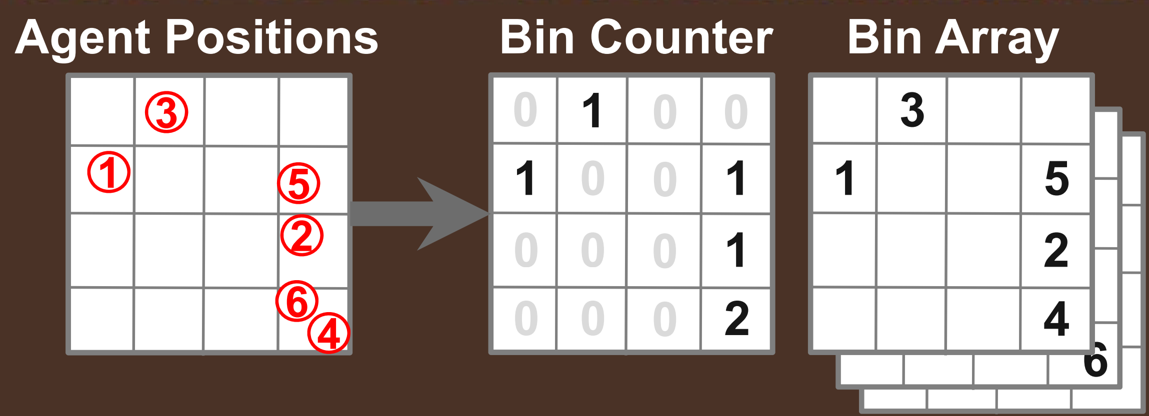
- Evaluate a fixed set of possible directions relative to global navigation direction



Spatial Queries

- Need to query nearby agent positions and velocities
- Spatial data structure
- Agents “binned” by position:
  - Bin Counter : Color buffer
  - Bin Array : Depth Buffer Array

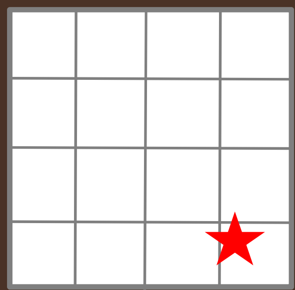
Spatial Data Structure: Bins



- World space position mapped to 2D index
- Bin Counter: color buffer, tracks bin loads
- ID Array: depth array, binned agent IDs

Bin Queries

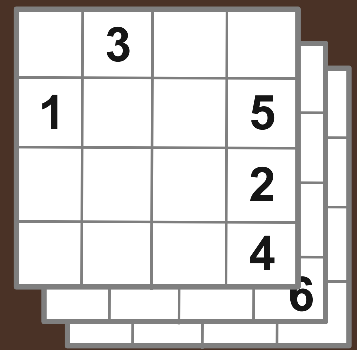
Agent Positions



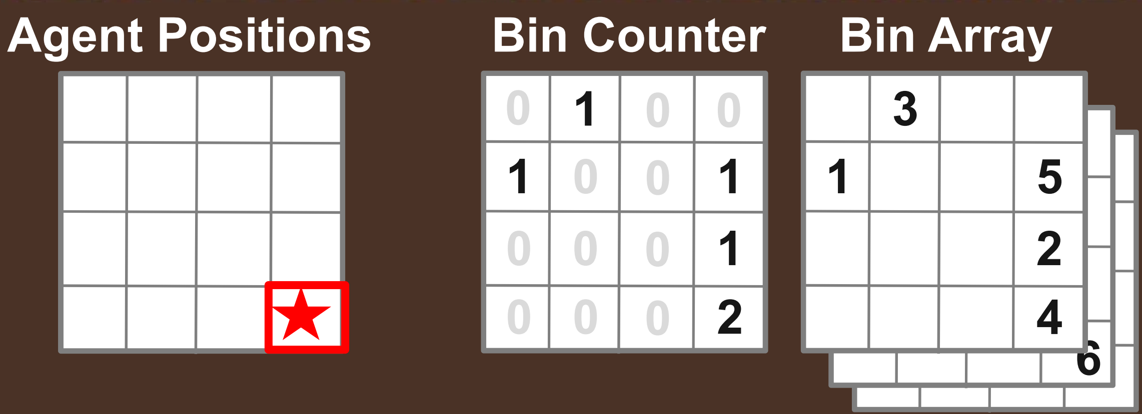
Bin Counter

0	1	0	0
1	0	0	1
0	0	0	1
0	0	0	2

Bin Array

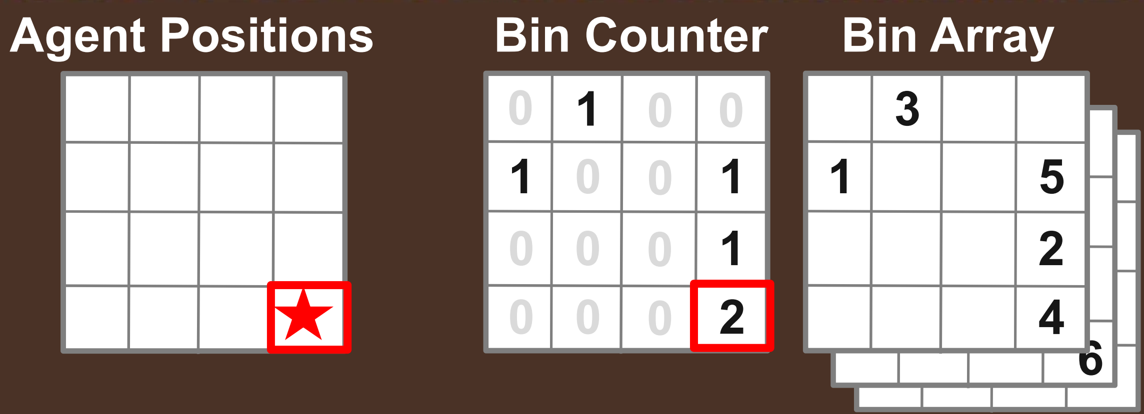


Bin Queries



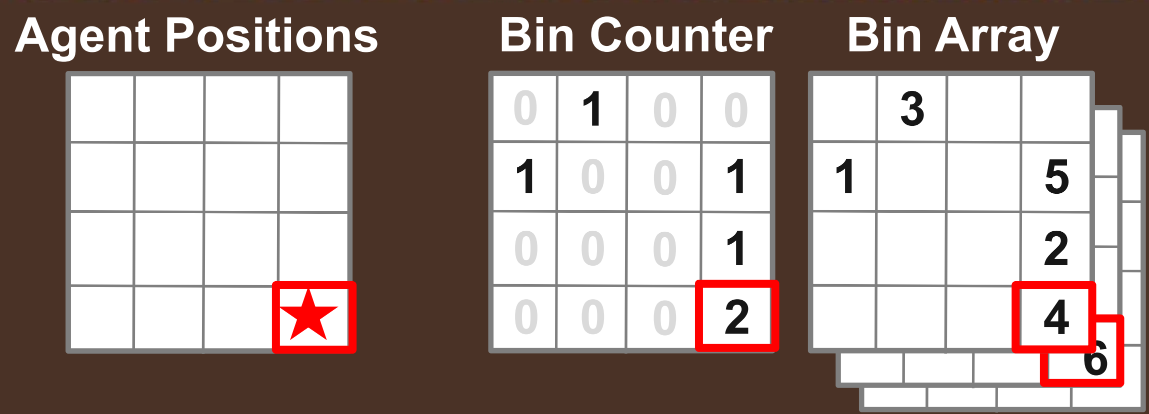
- Translate position to 2D index

Bin Queries



- Translate position to 2D index
- Fetch load from *Bin Counter* (color buffer)

Bin Queries



- Translate position to 2D index
- Fetch load from *Bin Counter* (color buffer)
- Fetch agent IDs from *Bin Array* (depth array)
  – Efficient: *known number* of *sorted* agents

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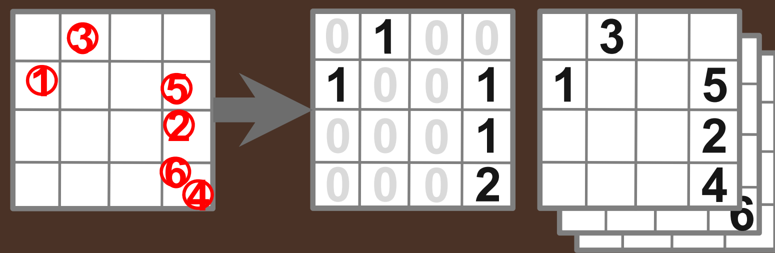
Data Structure Updates: Overview



- Binning is a multi-pass algorithm
  - Update one slice of *Bin Array* per pass
  - Once binned, agents removed from working set
  - Algorithm repeats until working set is empty
  - Overflow is possible & detectable

Data Structure Updates: Initialization

- Initialize data structure
  - Clear bin counter (color buffer) to 0
  - Clear bin array (depth array) to **`MAX_DEPTH`**
  - Working set is array of ***all*** agent IDs
    - No VB necessary

Data Structure Updates: Pass 1

- Bind bin counter & first slice of bin array
- Draw working set as point primitives
- Vertex shader:
  - Map agent position to 2D bin array index
  - Set point's depth to normalized agent ID
- Pixel shader: output "1"
- Depth test: **LESS_THAN**

Data Structure Updates: Pass 2…n

- Next slice of bin array bound as depth buffer
- VS: Sample ID from previous slice of bin array
  - Reject points less than or equal to previous
- GS: stream out non-rejected points
- PS: write pass number
- Depth test: **LESS_THAN**

Results of Pass 2..n

- VS test ensures only points that haven't yet been binned get streamed-out and rasterized
- Depth test ensures the point with lowest ID gets binned
- Results in points binned in sorted order
  - Like depth peeling
- Stream-out buffer becomes new working set

Early Termination

- We want to halt the algorithm once all points are binned
  - Do not query size of stream out buffer each pass
  - CPU/GPU synchronization results in pipeline stalls
- Would like to hand the whole thing off to the GPU to control execution

Avoiding Synchronization Stalls

- We know max number of iterations
  - Number of bin array slices
- Make all the draw calls for the max number of iterations
  - Use cascading predicated draw calls
  - Use along with "`DrawAuto`" to issue draws
  - Predicate on number of stream-out elements

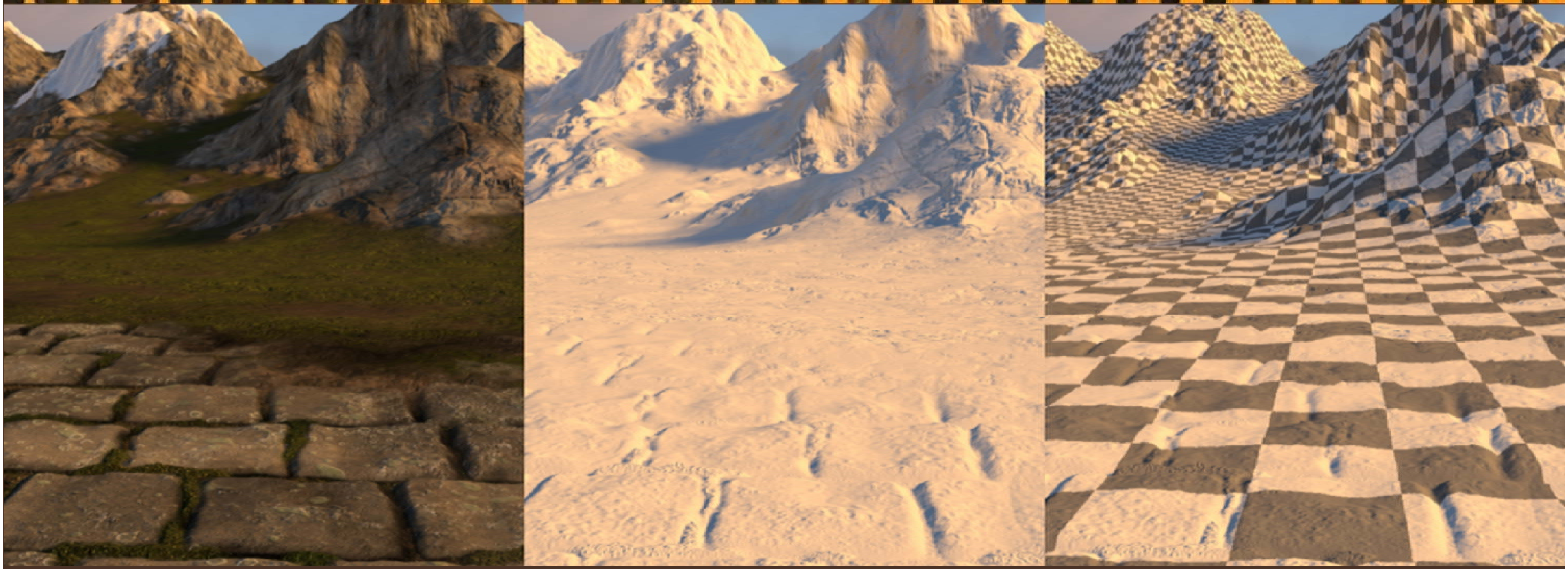
Avoiding Synchronization Stalls

- GPU terminates algorithm once all agents are binned
  - Once working set (stream out buffer) goes to 0
  - Remaining draw calls are skipped
- The algorithm either terminates or overflows

Binning on the GPU

- GPU Binning
  - Efficient queries
    - Early-out on empty bins, known bin load, sorted order
  - Overflow detection
  - Stream-out reduction of working set
  - GPU termination control
- Many applications beyond local avoidance

Spherical Harmonic Light Map



Diffuse lighting with Shadow Map

- Extracted dominant directional light: L_d
  - Dominant directional light color: L_c
- Left over residual lighting environment: L_e
- Dynamic shadow term: V_s
- Surface normal: N

$$\max(N \cdot L_d, 0) * L_c * V_s + \mathrm{SH\_Eval}(N, L_e)$$

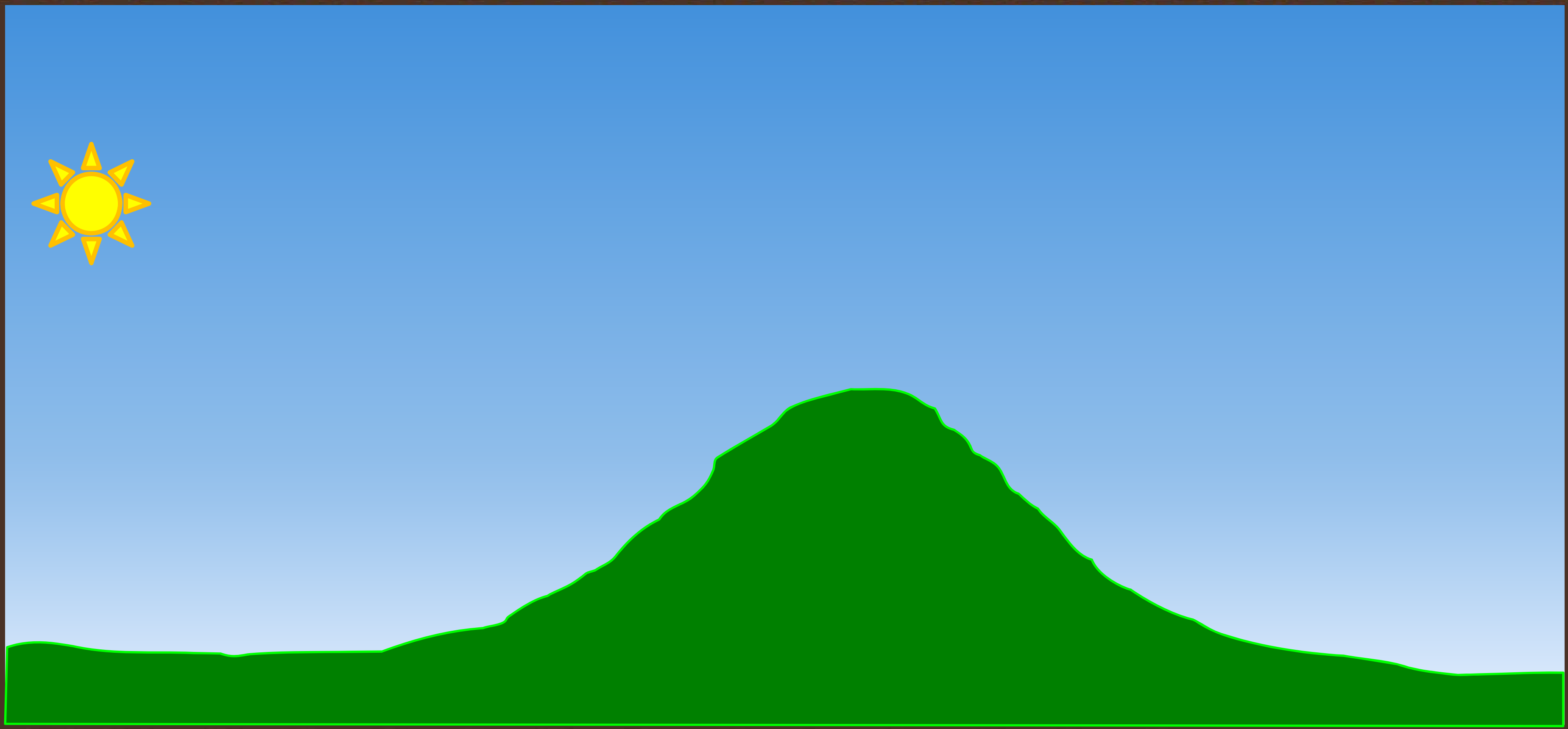
Dynamic Shadows Cast on Terrain

- Dynamic characters cast shadows on terrain
  - Shadow map shadows mingle with SHLM shadows
  - Shadow map attenuates *dominant* lighting term

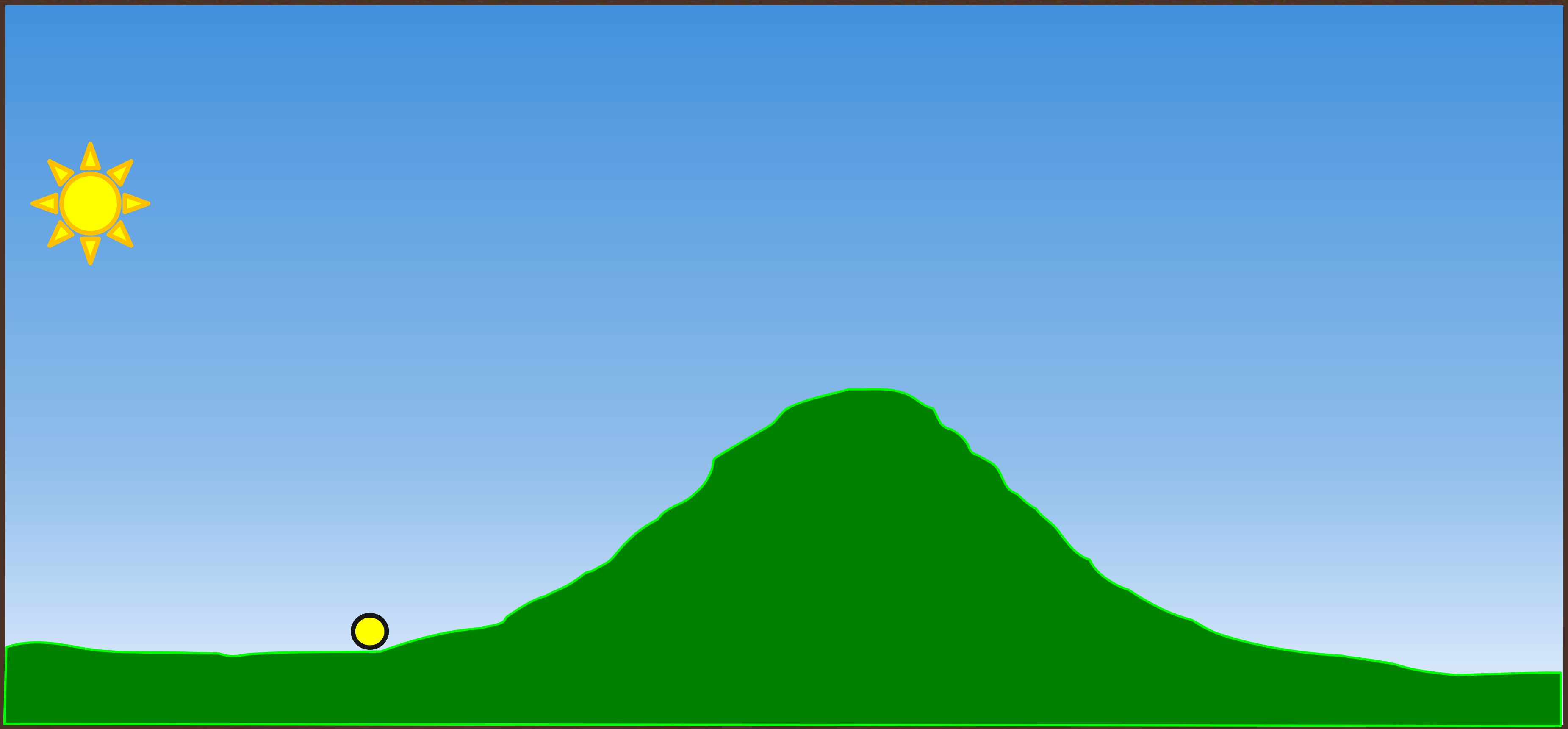
Double Shadows

- Results in double shadows…
  - Characters in shadow still cast shadows

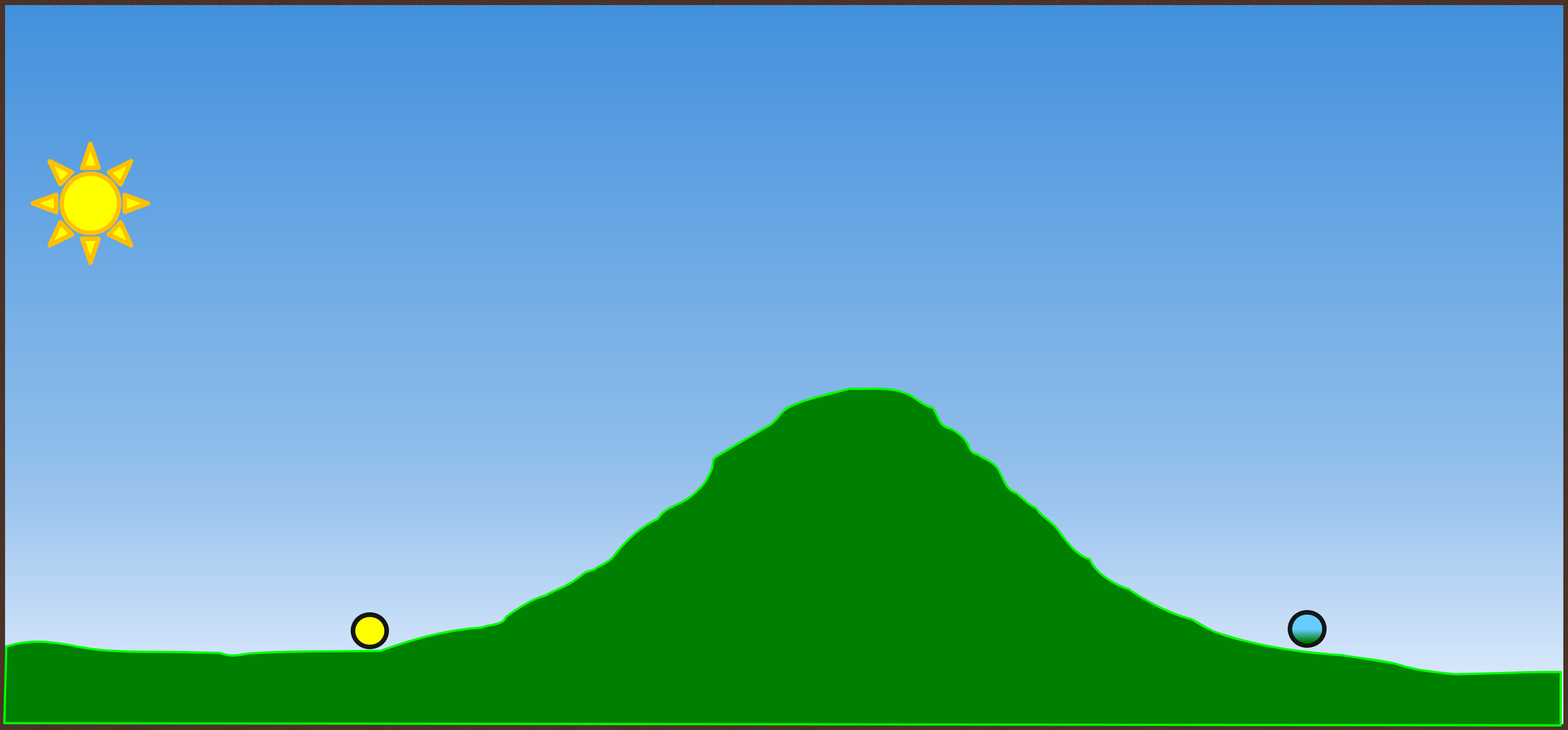
Detecting Direct Sun Light



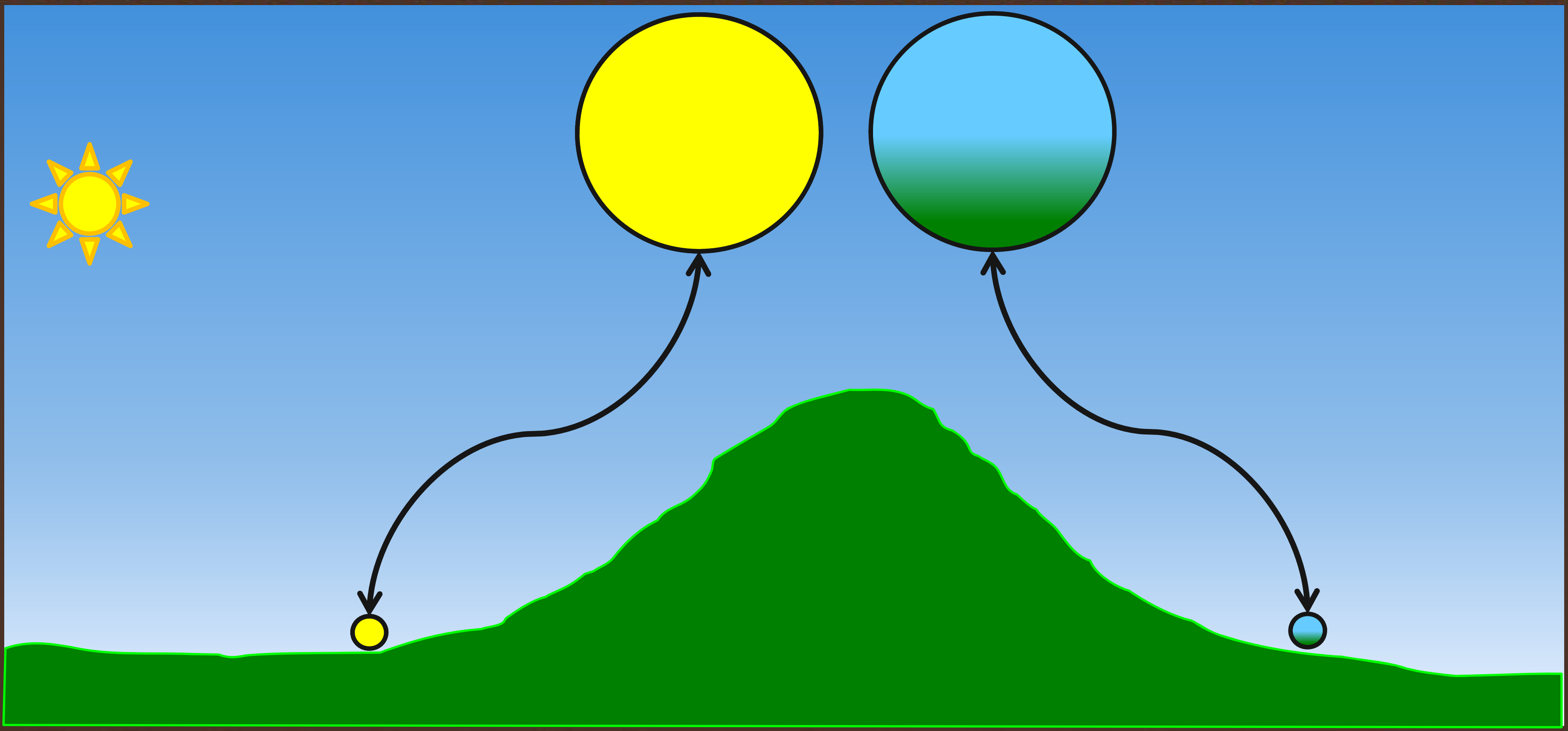
Detecting Direct Sun Light



Detecting Direct Sun Light



Detecting Direct Sun Light



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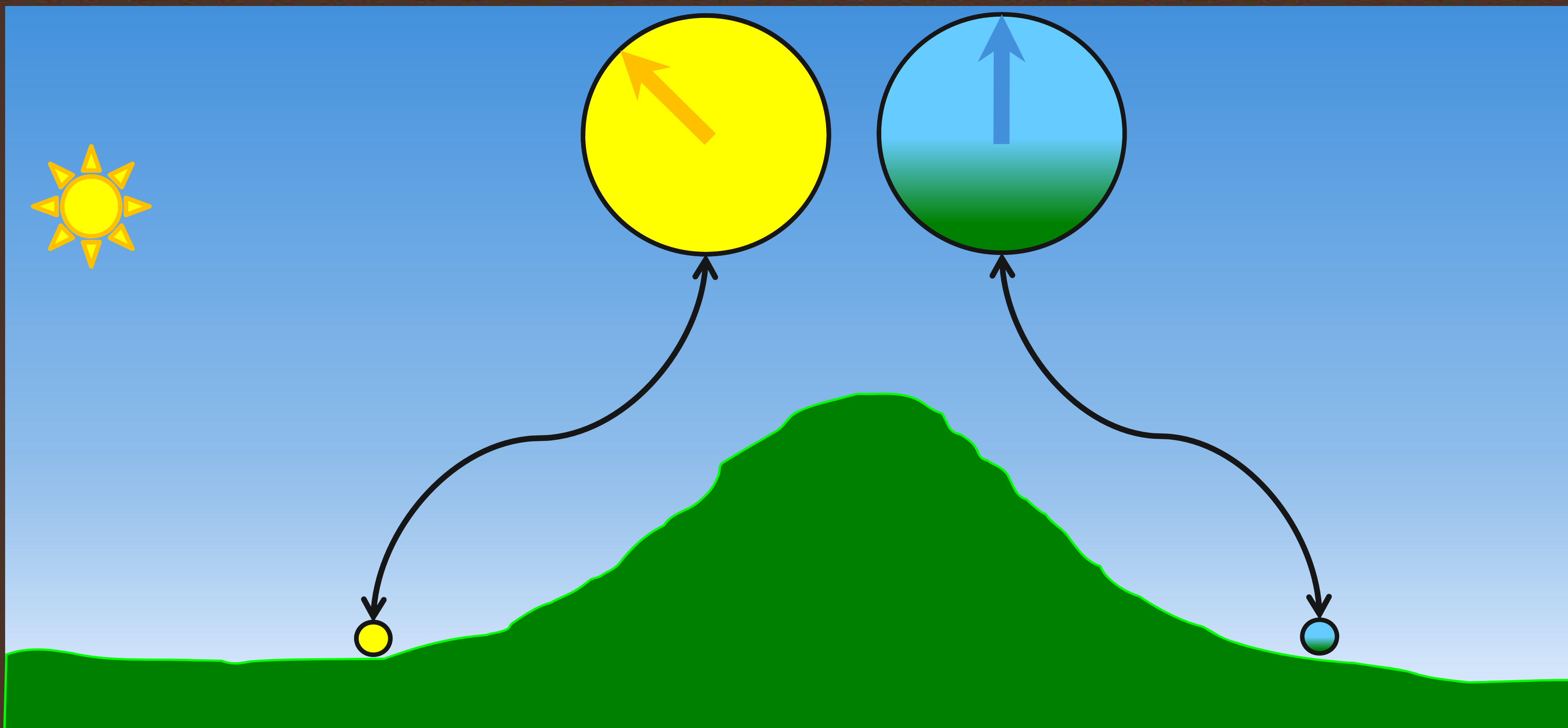
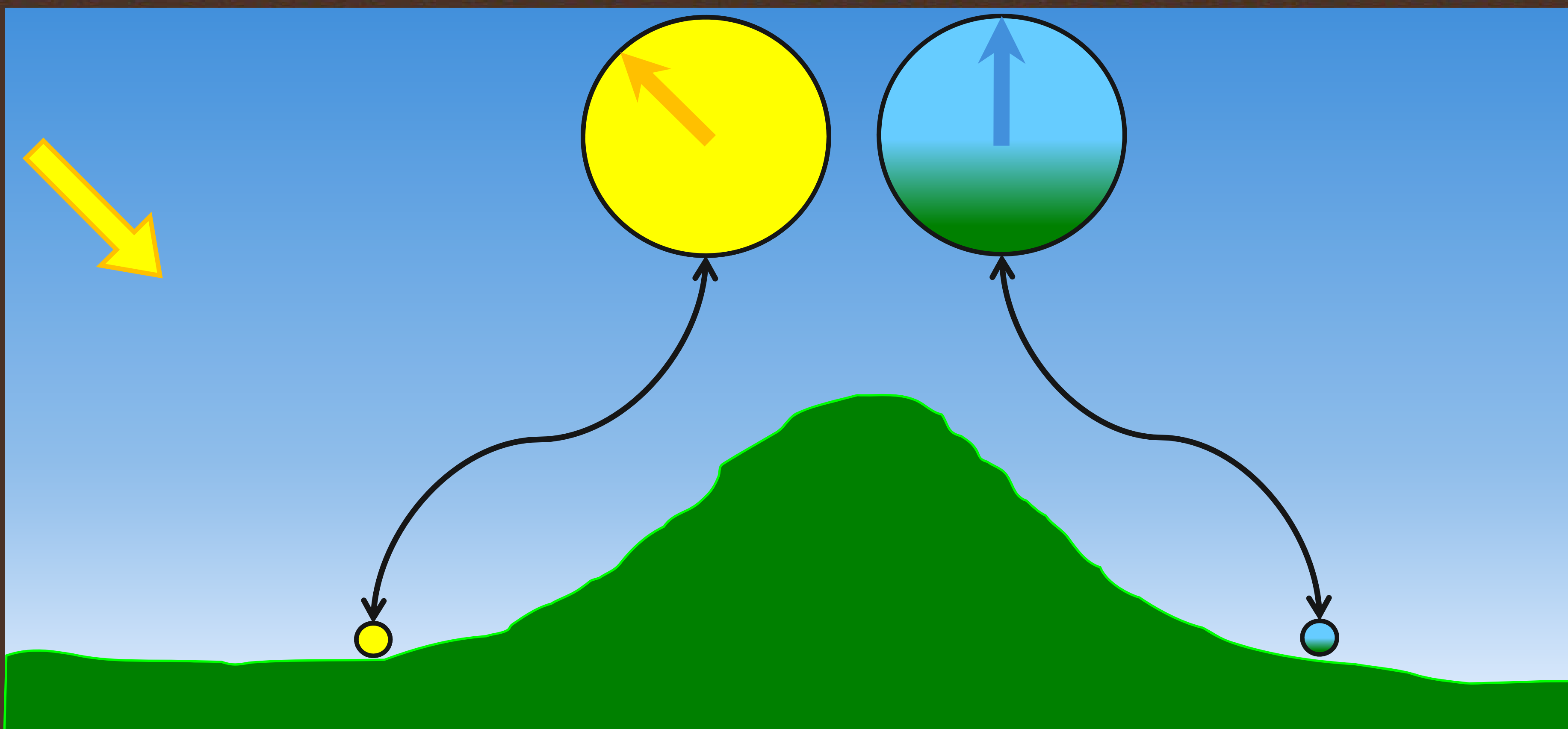
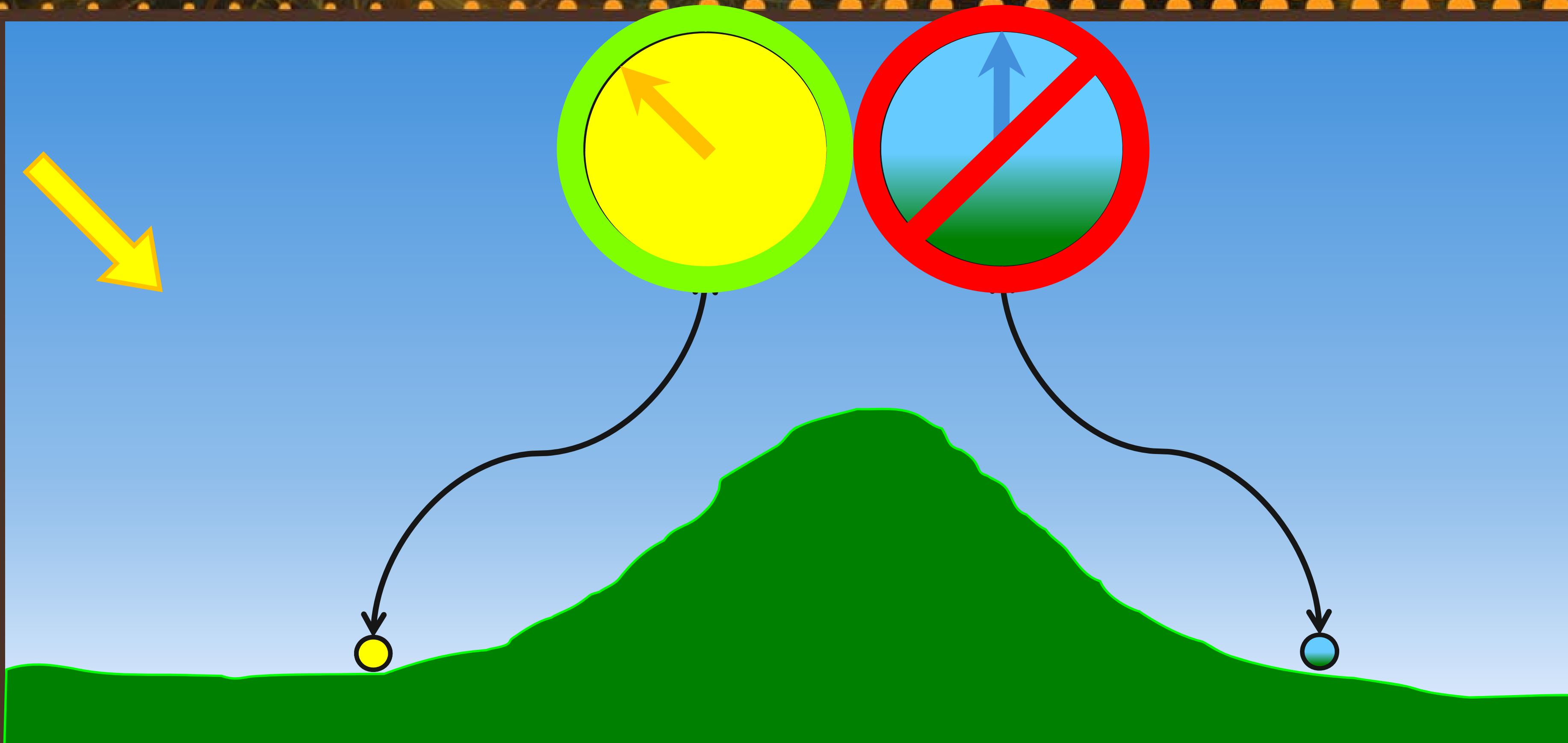
Detecting Direct Sun Light



Detecting Direct Sun Light



Detecting Direct Sun Light



Double Shadow Fix

- Shadow map only used on non-occluded regions of terrain

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The Need for GPU Character Management

- Need scalability and stable performance
- Don’t want to render thousands million-poly characters
  – Wasteful if details are unseen
- CPU side character management is impractical when doing GPU simulation
  – Requires a read-back
- *Solution*: Perform GPU –side scene management

GPU Scene Management

GPU Scene Management

- We use Direct3D® 10.1 features for GPU scene management and level of detail management
- Render froblins as an army of instanced characters
- 3 discrete LODs
- Use tessellation to get maximum amount of details with stable performance for close-ups

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Geometry Shaders as *Filters*

- Act on instances
- A set of point primitives (instance data) as input
- Re-emit only points that pass a specific test
  - Discard the rest
  - Use *DrawAuto* for multiple tests or combine into a single GS invocation for efficiency

GPU Character Management Overview

1. Render the occluder geometry
2. Construct the Hi-Z map
3. Run all characters through the view frustum culling filter
4. Results are run through the occlusion culling
5. Run through a series of LOD selection filters
6. Render each LOD

View Frustum Culling

- Using the filtering GS perform view frustum culling
  - Using standard methods
- VS checks for intersection between character bounding volume and the view frustum
  - Regular methods apply
- If the test passes, the character is visible: emit it
  - Otherwise it's culled

Occlusion Culling

- Render all occluders prior to rendering characters
- Determine which characters are occluded by the environment or structures
  - Use resulting depth buffer
  - Cull against arbitrary, dynamic occluders
- Novel formulation: *Hi-Z map*

Hi-Z Map

- A hierarchical depth image
  - Uses the Z buffer information
- A mip-mapped, *screen-resolution* image
  - Each texel at level i = *max* (all texels at level i - 1)
- Does not require a separate depth pass

Occlusion Culling with Hi-Z Map

- Use constructed Hi-Z map
- Examine the depth information for pixels covered by the object's projected bounding sphere
  - Compare the max fetch depth to the projected depth of the point on the sphere closest to the camera
- Conservative culling
  - Does not result in false culling
- Details in the course notes

Hi-Z Map Construction

- Finest level – use the main depth buffer
  - DepthStencil view (with MS DB in Direct3D® 10.1)
- Generate the mip chain levels with *reduction* passes
  - Mind the dimensions – screen-space images don't mip well!
  - Use integer operations to avoid incorrect indexing

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Reduction Pass for Hi-Z Levels

- Render into one mip level while sampling the previous level
  - Rendering into smaller mip *reducing* the larger one
- Fetch 2×2 neighborhood and compute *max* value
- Fetch additional texels on the odd-sized boundary

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GS Filtering for LOD Selection

- Use a discrete LOD scheme
  - Each LOD is selected by character's distance to camera
- Three successive filtering passes
  - Separate the characters into three disjoint sets
  - LOD parameters easily specified for each set

GS Filtering for LOD Selection

- Compute LOD selection *post* culling
  - Only process visible characters
  - Culling results are only computed once and re-used
- Render closest LOD using tessellation and displacement
- Conventional rendering for middle LOD
- Simplified geometry and shaders for furthest LOD

Organize Draw Calls Around Queries

- Need instance count for issuing the draw call for each LOD
- This requires a stream out stats query
  - Can cause significant stall when results are used in the same frame issuing the query
- Re-organize the draw-calls to fill the gap between issuing the query and using the results
  - We perform AI simulation steps

CPU Animation Sampling

- Traditionally matrix palettes are computed on the CPU per character
  - Loaded into constant store
- Limitations on the number of characters handled in one draw-call with this approach
  - Large crowds of characters require numerous draw calls
- GPU character management makes this tricky

Froblin Character Animation

- Agents have a set number of actions with associated animation sequence

GPU Animation Sampling and Control

- At preprocessing time, bake animation data into texture arrays
  - Slice number = animation sequence
  - X and Y = key frame and bone index
- At rendering time, determine per-instance animation sequence index and time offset
  - During simulation in our case

GPU Animation Sampling and Control

- Sample and interpolate animation data when rendering the character
  - Sample the animation textures

Character Animation on GPU

- At preprocessing, flatten the transform hierarchy
- Compute bone transforms for each key frame transforming that bone into object space
- During simulation, assign an animation sequence to each character
  - Including a time offset into that sequence

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Animation Texture Layout

		Key 0	Key 1	…	→	…	Key N
Bone 1	Matrix Row 0						
	Matrix Row 1						
	Matrix Row 2						
Bone 2	Matrix Row 0						
	Matrix Row 1						
	Matrix Row 2						
	↓						

Character Animation on GPU

- During rendering VS fetches, interpolates, and blends the key frames for each bone
  - Using per-character information
- Each instanced character performs its skinning in object space
- Transforms the result using its position and orientation

Tessellation and Crowd Rendering

- Combine with Direct3D® 10 instancing support
- Render using interpolative planar tessellation
  - Fast evaluation
  - With displacement mapping for fine-scale detail
- Control tessellation level per-draw call
  - Use character location
- The same art assets as conventional rendering

The Benefits of Tessellation

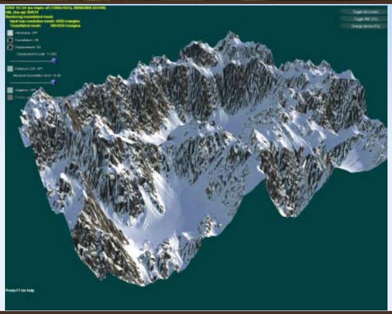
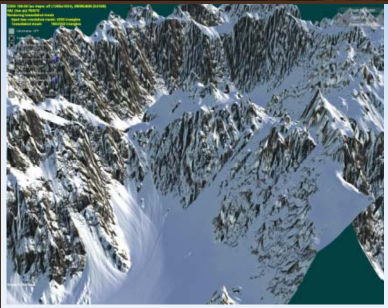
- Tessellation reduces memory footprint and bandwidth
  - Only store low resolution mesh
  - Always relevant, especially for consoles

	Polygons	Total Memory
Low resolution Froblin model	5160 polygons	VB/IB: 100K 2K x 2K 16 bit displacement map: 10MB
ZBrush High res Froblin model	>15M polygons	~270MB VB and 180MB IB storage

The Benefits of Tessellation

- Scalability
- Stable and predictable performance

Tessellation Performance Analysis

Rendering Mode	Num faces:	 Far away view		 Close-up view	
$N_T = 411 \times N_L$		ATI Radeon™ HD 4870	ATI Radeon™ HD 2900 XT	ATI Radeon™ HD 4870	ATI Radeon™ HD 2900 XT
Original **low res mesh (N_L)**	4,050 triangles	852 fps	359 fps	850 fps	275
Continuously tessellated mesh (N_T)	1.6 M triangles	232 fps	143 fps	213 fps	101
Adaptively tessellated mesh N_A	Dynamic, 1.6M > N_A > 4K triangles	845 fps	356 fps	574 fps	207

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*Configuration: AMD reference platform with AMD Athlon™ 64 X2 Dual-Core Processor 4600+, 2.40GHz, 2GB RAM. Motherboard: ASUSTek M2R32-MVP. Memory: DDR2-800 400 MHz. Operating System: Windows Vista® SP1."

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Tessellation Pre Direct3D® 11

- GPU tessellation already available
  - Supported on Xbox™ 360
  - ATI Radeon™ HD 2000 Series and beyond: supported on all models
    - *Even on the integrated chipsets!*
- Subset of Direct3D® 11 tessellation features
- Contact AMD ATI developer relations for details on accessing tessellation

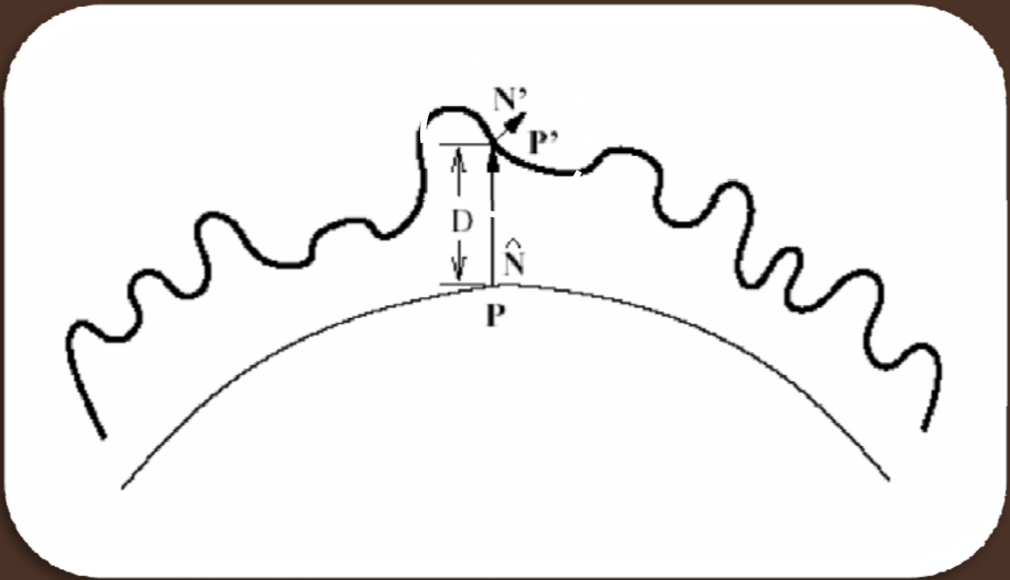
Preview and Prepare for Direct3D® 11

- Support across most APIs gives you best bang for the buck for this feature
  - Support on Microsoft® Windows® XP as well as Microsoft® Windows® Vista
  - PC versions can use Xbox™ 360 native features
  - Reach more players
- Developing artwork takes time
  - Integrating tessellation early gives you and your artists time to design and polish

Tessellation Process

Combining Normal Maps and Displacement Maps

- As we displace, we change the actual displayed normal



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Lighting with Displacement

- Use TS normal maps *even with displacement*
- Generate displacement and normal maps using the same tangent space
  - The same TS computations for preprocessing
  - The normal encoded in TS normal map will match the normal from displacement

Regularly drawn Froblin

No tessellation used

High Detail Froblin with Tessellation and Displacement Mapping

Froblin Close-up:

No tessellation

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Froblin With Tessellation and Displacement Mapping Close-up

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Tessellated Characters LOD Control

- Dynamic number of detailed characters in view
  - Simulation changes interactively, no a priori control
- Need stable frame rate in dense crowd simulations
- Compute tessellation level as a function of tessellated characters in view
  - Avoid polygonal count explosion

Tessellation Level Computation

$$T_l = \text{clamp}(\ M\ T_{max} / N, 1, T_{max})$$

- *N* characters rendered with tessellation
- Bound the number of amplified triangles
- Primitive count never exceeds than the cost of *M* fully tessellated characters

Control Cage Pre-Pass

- Perform animation and transformation on control cage in a *pre-pass*
  - Allows for more complex per-vertex operations
- Combine with vertex (de)compression for reducing bandwidth

Pass 1: Control cage animation and transforms

↓

Stream Out Buffer

↓

Pass 2: Tessellate the control cage

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PrePass and Vertex Compression

- Shader-based vertex compression / decompression
- Reduce stream out memory footprint between the pre-pass and tessellated pass
- Reduce fetch bandwidth for tessellated pass

PrePass and Vertex Compression

- Pack transformed vertex positions into 128 bit format
  - Lets us load each vertex with one fetch
  - Gives as much as 30% speedup
  - More details in the course notes

Froblin Land: Terrain Rendering

Froblin Land: Terrain Rendering

- Smooth, crack-free LOD without degenerates
- Tessellation and instancing
- Leverages Direct3D® 10.1 functionality to help minimize memory footprint
- Complex material system

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Froblins Performance Details*

- Staggering polygon count at interactive rates (>20fps)
  – From 900 polygons -> 6K -> 1.6M at the closest tessellated level of details
  – Up to 18M triangles per frame at fast interactive rates
  – 6M-8M triangles on average at 20-25 fps
- Full high quality lighting and shadowing solution
  – Rendering all objects into multiple shadow maps more than doubles polygon count per frame
- Rendering and simulating high quality detailed 3K froblins at 21 fps on average

*Configuration: AMD reference platform with AMD Athlon™ 64 X2 Dual-Core Processor 4600+, 2.40GHz, 2GB RAM. GPU: ATI Radeon™ HD 4870 Grahpics. Motherboard: ASUSTek M2R32-MVP. Memory: DDR2-800 400 MHz. Operating System: Windows Vista® SP1."

Simulation Performance Details*

- All modes render with 4X MSAA HDR and post-processing
- Simulate behavior and render > 65K agents at 30 fps
- AI simulation for 65K agents alone – 45 fps
- Rendering and simulating 65K agents – 31 fps
- Rendering 9,800,000 polygons each frame
- AI simulation executes with high efficiency resulting in ~1 *tera*flops!

*Configuration: AMD reference platform with AMD Athlon™ 64 X2 Dual-Core Processor 4600+, 2.40GHz, 2GB RAM. GPU: ATI Radeon™ HD 4870 Grahpics. Motherboard: ASUSTek M2R32-MVP. Memory: DDR2-800 400 MHz. Operating System: Windows Vista® SP1."

Conclusions

- Practical and efficient simulation and rendering of large crowds of characters on GPU
- New GPU algorithms for
  - Global and local navigation and spatial data structures
  - Scene management
  - etc
- And a number of other advanced techniques!

Learn More about Our Approaches

- All shaders are included in the course notes
- Course notes are available for download:
  - ACM Digital Library: http://portal.acm.org/dl.cfm
  - AMD Graphics Technical Publications webpage: http://ati.amd.com/developer/techreports.html

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Questions?

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