Modern Graphics Engine Design

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Overview

- Modern Engine Features
- Modern Engine Challenges
- Scene Management
  - Culling & Batching
- Geometry Management
  - Collision Structures
- Shader Systems
- Example Engine Design

Modern Graphics Engine Features

- High polygon count for added visual complexity
  - Not just to make things ‘smoother’
- Some form of bump mapping for more surface detail
  - From single-light dot3
  - To general diffuse / specular / aniso per-pixel lighting
- Some form of shadows
  - From simple blobby discs under characters
  - To full shadow map or shadow volume for each light

More Features

- Particle system for splashes, sparks, etc
- Decal System for blood, scorch marks, etc.
- Performance & Visual Scalability
  - Game should look good on the newer cards
    - 1280x1024 x 4X AA + 4X Aniso
  - Game should look ‘ok’ on the older cards
    - 800x600 x 2X AA
  - And run well on both at the appropriate resolution and Anti-Aliasing settings

Challenges

- To get achieve visually rich scenes, there must be several visually interesting objects
- To get acceptable frame rates, the number of draw calls in a frame should be low
  - < 500 per frame for good frame rates
  - This is a CPU limitation
    - The API & Driver must do a little work every time you make a render call to draw something
    - Many calls doing a little CPU work add up to a lot of CPU work

Challenges

- Complexity
  - Modern engines are able to lose some complexity compared to engines a few years ago
    - Software Transform
    - Software Rasterization
  - But, there are plenty of new things to worry about
    - High poly-count worlds in low memory
    - Realistic characters & animation
    - Shader Management
    - High Framerates

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Scene Mangement

- There are about 5 different game engine sections that need access to the geometry in the scene
- Culling
- Rendering
- Collision
- Decals
- AI

Scene Management

- Culling – View Frustum Culling
  - Also from light's point of view for some shadow approaches
- Rendering
  - May need to render from multiple points of view for radar, shadows, etc.
- Collision
  - May be simplified version of the rendered geometry
- Decals
  - If these are done by re-rendering scene triangles, need per-triangle collision
- AI
  - The computer needs some spatial awareness
  - For path-finding, tactical understanding, etc.

Scene Management - Culling

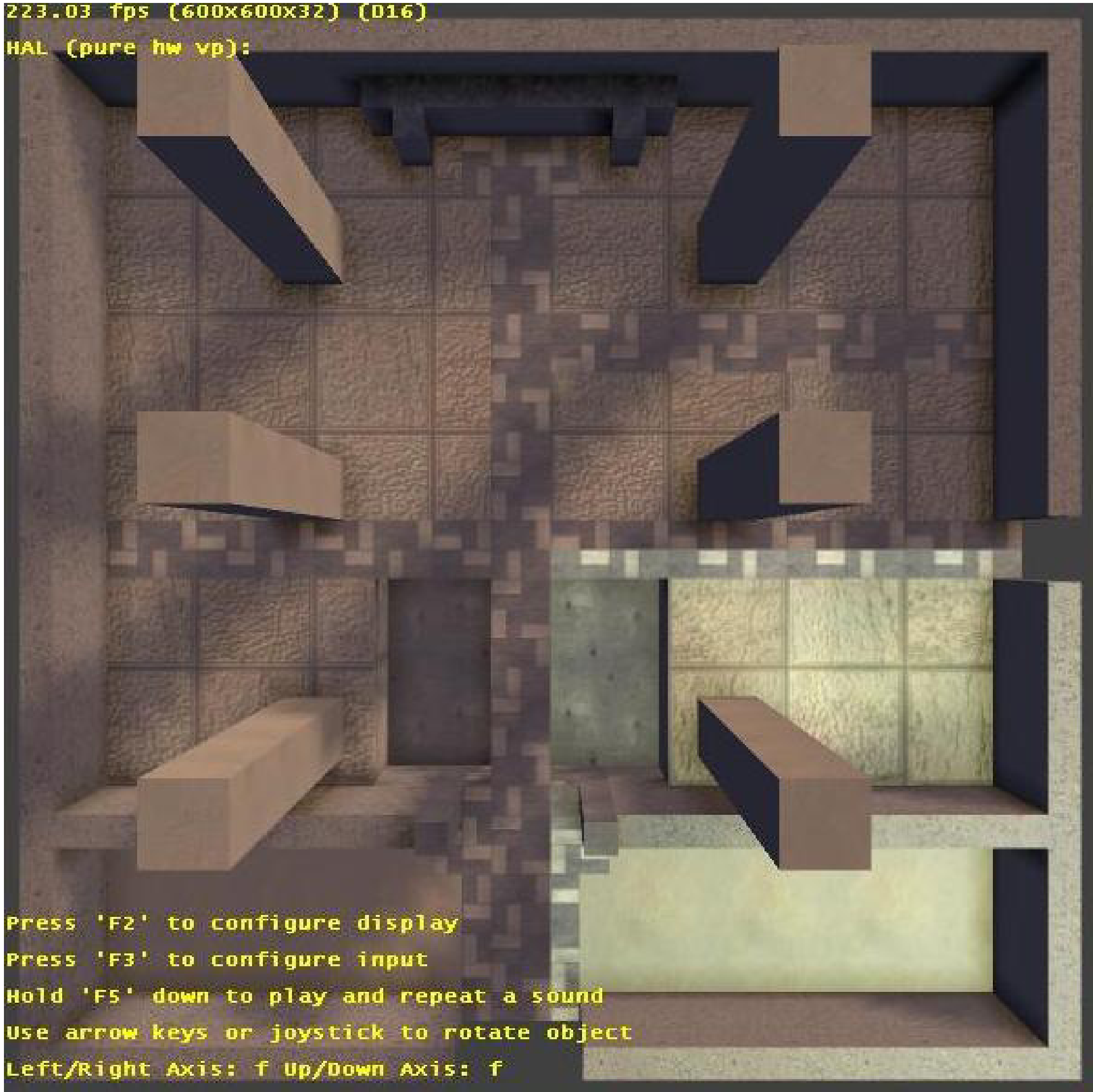
- Goal : To quickly identify groups of triangles that can be culled out efficiently
  - Typically inside a bounding volume
    - BSP Leaf, Sphere, Bounding Box

- There is a tradeoff between culling efficiency and CPU efficiency :
  - The ultimate culling efficiency would cull each triangle individually
  - The ultimate CPU efficiency would draw the entire world in one draw call

- The trick is to group most of your scene in large, easy-to-cull chunks

Scene Management - Culling

- In this scene, a world section is broken into a grid with ~300 triangle cells
- Highlighted area represents one such 3D Cell
- Probably too few tris for CPU batch efficiency

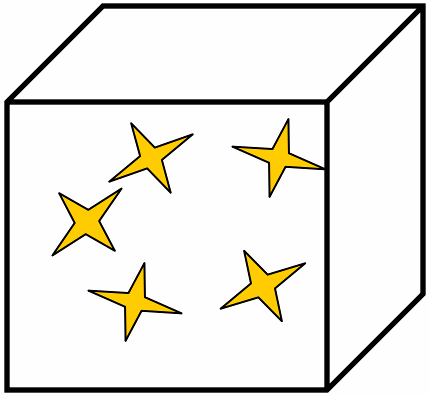
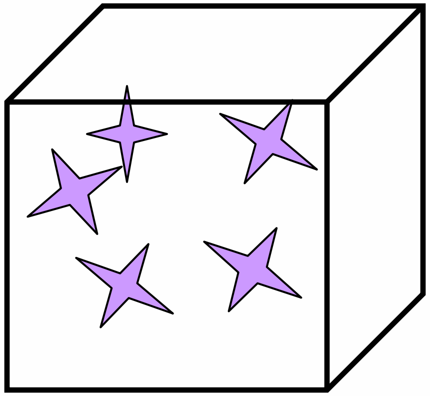


Scene Management - Culling

- Make bounding boxes too small, and clipping creates many extra triangles & vertices
- Make bounding boxes too large, and you end up sending down too much off-screen geometry
  - Can also create per-material AABoxes
- Instanced Geometry
  - Store a Axis-Aligned Bounding box, AA Cylinder or Sphere for each Instance for culling
  - Don't cull individual bone groups except for very expensive and close-to-camera characters

Scene Management - Culling

- Particle Systems
  - Store a bounding volume for each group of particles
  - Cull entire group as a unit
  - Also try to draw as a unit for efficiency
  - If particles don't affect gameplay, can also avoid calculating off-screen systems

Scene Management - Decals

- There are several popular approaches for creating decals for bullet holes, scorch marks, blood drops, etc.
- One approach renders little pieces of geometry to represent the bullet hole, etc.
  - Upside : Low fillrate for small decals
  - Downside : Needs to be clipped so that it doesn't hang over a corner
  - Downside : May Z fight with geometry, need bias

Scene Management - Decals

- Another method uses texture mapping to apply the decal by re-rendering scene polygons with the texture applied
- Upside : No need to clip to corners
- Upside : No depth fighting if you use the exact same geometry as used for rendering
- Downside : Large polygons cost fillrate for many decals

Scene Management - Decals

- Either approach requires finding the exact triangles the decal touches
  - Either for clipping the geometry decals to the scene geometry
  - Or re-rendering them with the decal texture
- Therefore, the engine must support being able to quickly find a group of nearby polygons on which to apply the decal
- This has implications for the collision system…

Scene Management - Decals

- Highlighted area indicates triangles possibly covered by decal shadow
- Amount of extra fillrate burned is more for less-tessellated geometry
- So, more vertices can save fillrate on decals

Scene Management - Collision

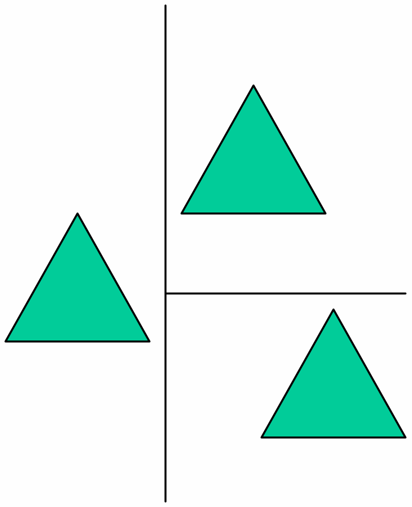
- Efficient collision with world & mesh data is a challenge in a modern engine
  - Many more polygons for required visual richness
- Standard BSP approaches won’t cut it
  - Only for very simple walls & floors will a leaf-based BSP suffice
  - The more polygons in the scene, the greater the penalty for splits

Scene Management - Collision

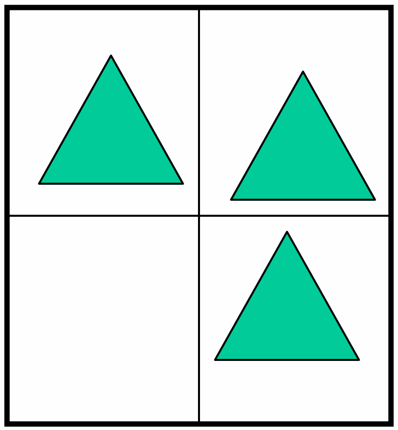
- One of the main problems with a standard BSP or KD-Tree (axis aligned BSP) is the depth of the tree
- Consider every time you follow a pointer, you can assume a CPU cache miss
  - The deeper your tree, the more cache misses you will take
  - Cache misses can be more expensive than intersection tests
  - Therefore, shallower tree types will perform better on high-polygon-count scenes
- Two ways to make a tree shallow :
  - High Branching Factor – QuadTree, Octree
    - More children per node
  - Store multiple items in one Leaf

Scene Management - Collision

- This KD-Tree or BSP has 2 levels, the leftmost root and the rightmost children

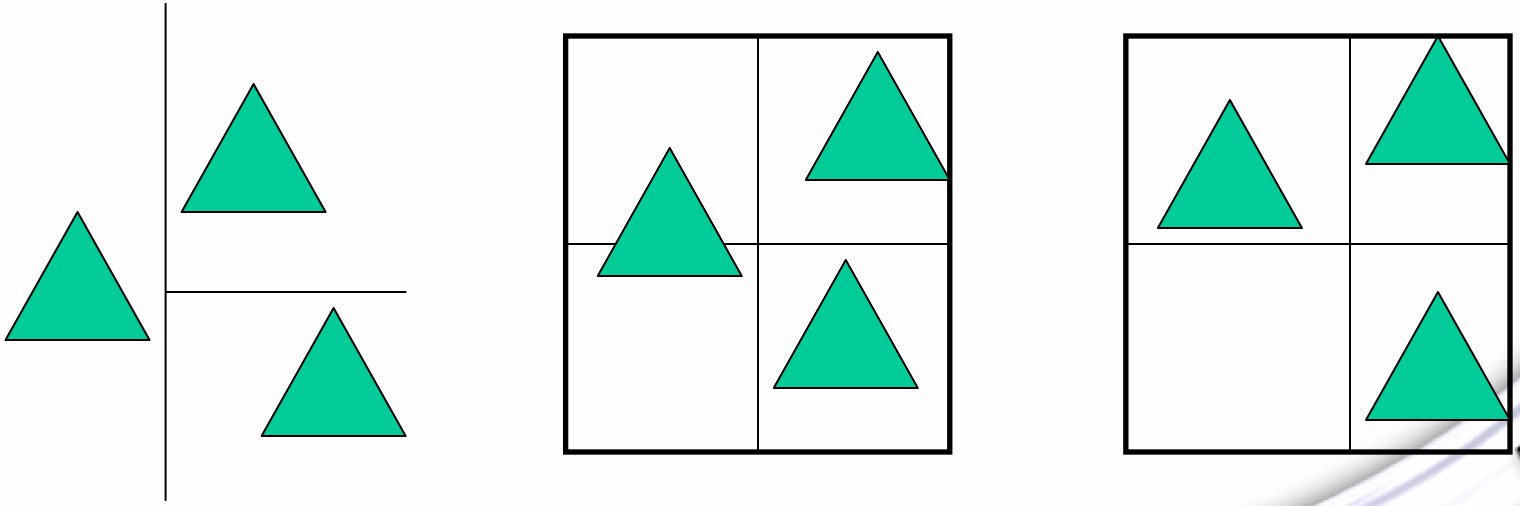


- The Quadtree only also needs 2 levels for this scene



Scene Management - Collision

- Of course, if the scene is arranged differently, the KD tree or BSP tree can cope better by adjusting where the split planes go.
- Standard Quadtrees and Octrees don't do this, so require more levels. Variations with rectilinear cells, as on the right, can cope better



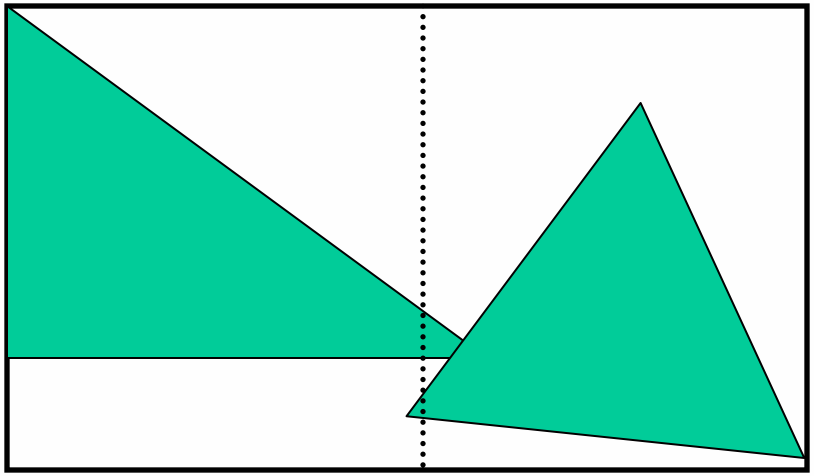
Scene Management - Collision

- An alternative is the Axis-Aligned Bounding Box Tree
  - Good example in Game Programming Gems 2
  - Also Short Tutorial on FlipCode
- This Tree contains a hierarchy of AA Bounding Boxes which contain all of the geometry
- The AABox Tree is not meant to represent empty space like a grid, but instead to just tightly contain the triangles

Scene Management - Collision

- The basic idea is to somehow divide the # of triangles in a node in half at each step, but without clipping them to the Split Plane

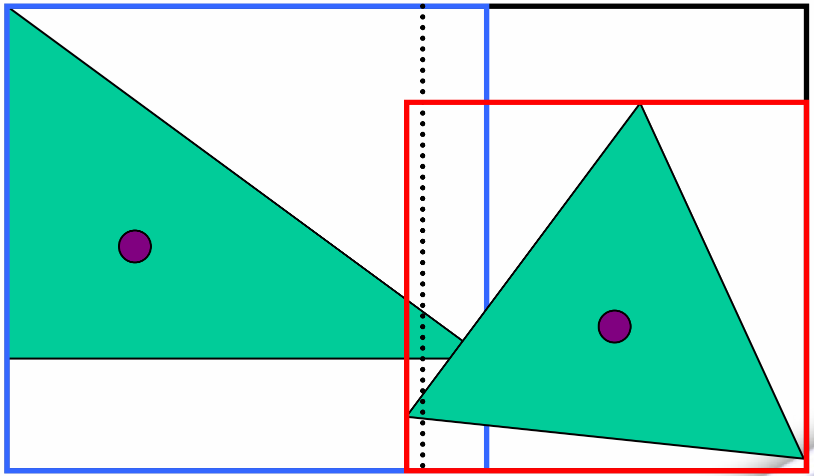
  - Root Node
  - Dashed line is Split Plane



Scene Management - Collision

- The triangle centroid is compared to the ‘Split Plane’
- This way each triangle only lives in one node
- No clipping to increase polycounts
  - Important for collision more than for rendering

- Left Child in Blue
- Right Child in Red
- Dots are Triangle Centroids



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Scene Management - Collision

- Each node in tree contains a Axis-Aligned Bounding box, and two children
- Each child may be a Node or a Leaf
- Leafs contain the triangle data or triangle ids
- Can create tree down to individual triangle level
  - Requires compression of nodes & bounding boxes to avoid too much memory – see GPG2
- Alternatively create down to a small # of triangles per leaf, like 8 – 20
  - All triangles in leaf will be nearby in memory
  - Argues against storing tri ids, and just vertex indices

Scene Management - Collision

- The 'Split Plane' must be intelligently chosen to create a nicely balanced tree
- One approach is to create the AABB tree top-down
  - Create a parent node and find the AABox containing all triangles
  - Split the node somehow into two children
  - Each child gets some of the triangles
  - Each child's AABox may overlap its sibling
  - Recurse into each child until
    - The # of triangles is small enough
    - Or the volume of the AABox is small enough

How To A Node Split into 2 Children?

- A good approach is to pick the largest axis of the AAbox containing all triangles in the parent node
- Then sort the triangles by their centroid with respect to the AABox's largest axis
  - A tall AABox would have its triangles sorted by centroid.y
- Now you can go through exactly half the triangles in the sorted list and give them to the left child, and the assign the rest to the right child

- This gives a median distribution, which guarantees a O(log n) search time

Scene Management - Collision

- Modern engines will increasingly use non-splitting, looser trees with larger numbers of triangles per leaf
- Looser trees, like AABB Trees, and loose Octrees don't split, so they don't increase collision polys needlessly
- A dozen or so triangles per leaf reduce cache misses and amortize the memory cost of the bounding box and node information

Scene Management - AI

- The AI also needs some view of the scene
  - But it should be probably be separate from the rendering & collision views of the world
  - Should probably a simpler, more symbolic view of the world than a collision structure
- The AI will use raycasting and other spatial queries, so this should be fast
  - Line Of Sight
  - Enemies In Range

Scene Management - Rendering

- **Question : What is the most expensive render state change?**

Scene Management - Rendering

- **Question : What is the most expensive render state change?**
- **Answer : The one that caused you to make more draw calls.**

Scene Management - Rendering

- Question : What is the most expensive render state change?
- Answer : The one that caused you to make more draw calls.
- In general, sort by the item with the most useful coherency.

Scene Management - Rendering

- You can use the GPU to reduce the number of draw calls needed for your scene.
- Use per-vertex data to encode shading parameters
  - Reduces need to set vertex shader constants
  - Reduces need to switch vertex shaders
  - Example : Indexed Palette Skinning
  - Idea : Apply per-vertex index to other things like lighting, occlusion, etc.

Scene Management - Rendering

- Use textures to encode shading parameters
  - Reduces need to set pixel shader constants
  - Reduces need to switch pixel shaders
  - Example : Put gloss into the alpha of your normal map, instead of setting it via SetPixelShaderConstant()
  - Idea : Encode 4 light occlusion terms into a lightmap, and draw all 4 shadowed lights in one pass

Lighting and Shadows

- Your choices for Lighting and Shadowing will largely dictate the look and speed of your game
- How dynamic is your lighting?
  - Totally Static
    - Precompute per-vertex or lightmaps
  - Partially Dynamic
    - Lights can change color & intensity, but can't move
    - Build per-light occlusion term into vertex or texture
  - Totally Dynamic
    - Perform plenty of CPU raycasting for shadowing
    - Use GPU-assisted shadows like shadow maps or shadow volumes

Lighting Tradeoffs

Technique	CPU Cost	Vertex Cost	Pixel Cost	Comment
Static Lightmaps	Low, if using texture pages	Low	Low	Any # of lights and shadows free
Dynamic Lightmaps	High, at least when light changes	Low	Low	More lights cost during updates
Dynamic Lightmaps w/ Shadows	Prohibitive	Low	Low	Too many raycasts for CPU

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Lighting Tradeoffs

Technique	CPU Cost	Vertex Cost	Pixel Cost	Comment
Occlusion Maps	Low, if using texture pages	Low	Medium	Limits # of lights to 4 or so
Per-Vertex Occlusion	Low	Medium	Low	Lights Can only change color
Stencil Shadows on CPU	High, for batch count and silhouettes	Low	High	Limited to 3 lights per surface

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Lighting Tradeoffs

Technique	CPU Cost	Vertex Cost	Pixel Cost	Comment
Stencil Shadows on GPU	Medium for batch size	Very High	High	Limited to 3 lights per surface
Depth Shadow Maps	Low	Medium	Medium	Aliasing Artifacts
PRT via Spherical Harmonics	Low	Medium	Low	Only infinite lights & no animation

Shader Management

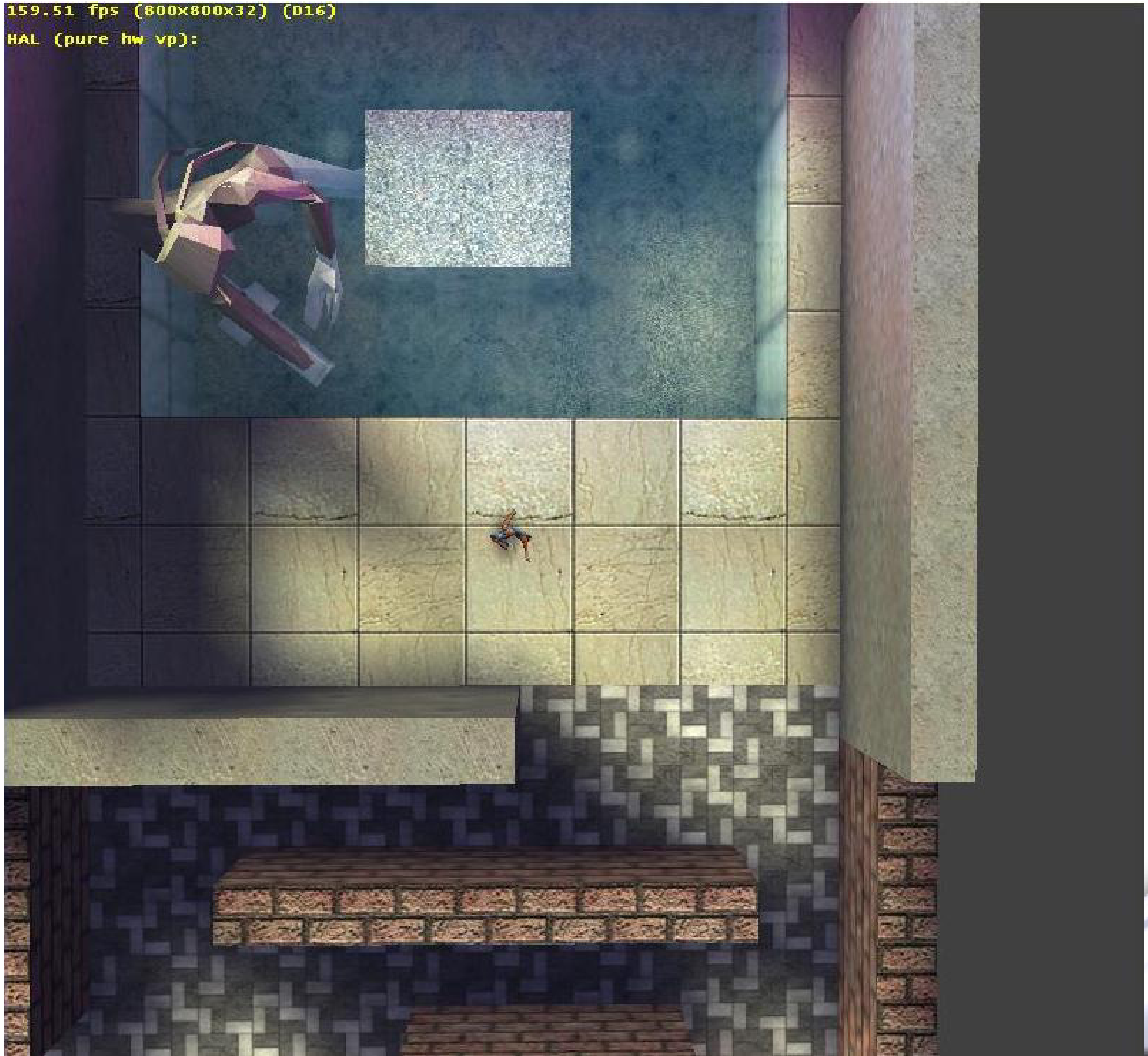
- There are two main ways to handle shaders, depending on your type of game
- Open-Ended - Artist-driven from within the level editor
  - Highly Flexible
  - Use HLSL / .FX files to manage complexity
  - Somewhat Complex to support many shader types
    - Use Annotations to identify shader parameters
  - Can create explosion of shaders if not careful
  - Switching shaders often is not good for reducing draw calls

Shader Management

- Unified Shader Model – Driven from the Engine Capabilites and/or Game Needs
  - Fewer, more specific, optimized shaders
  - Practical to do C++ coding to set up shaders
    - Can still use .fx files, but not needed as much
  - Shaders are from a more limited set of choices
  - Good for higher framerates by limiting maximum # of draw calls due to shader changes
  - Must build shader parameters into geometry & textures to get the speed benefit

Questions So Far?

Test Engine Overview



Test Engine - Overview

- Top level of the scene is a 3d Grid of 16x16x16 meter cells
  - Triangles are clipped to the grid
  - Each Cell has a Vertex and an Index Buffer
  - AABBTree of collision triangles matching the tessellation of the rendering triangles
  - Also a vector of material records
    - Contains Index Buffer range for triangles
    - Contains AABox for triangles with material
  - List of Moving Entities
    - Contains AABox
    - Contains reference to mesh data for rendering only

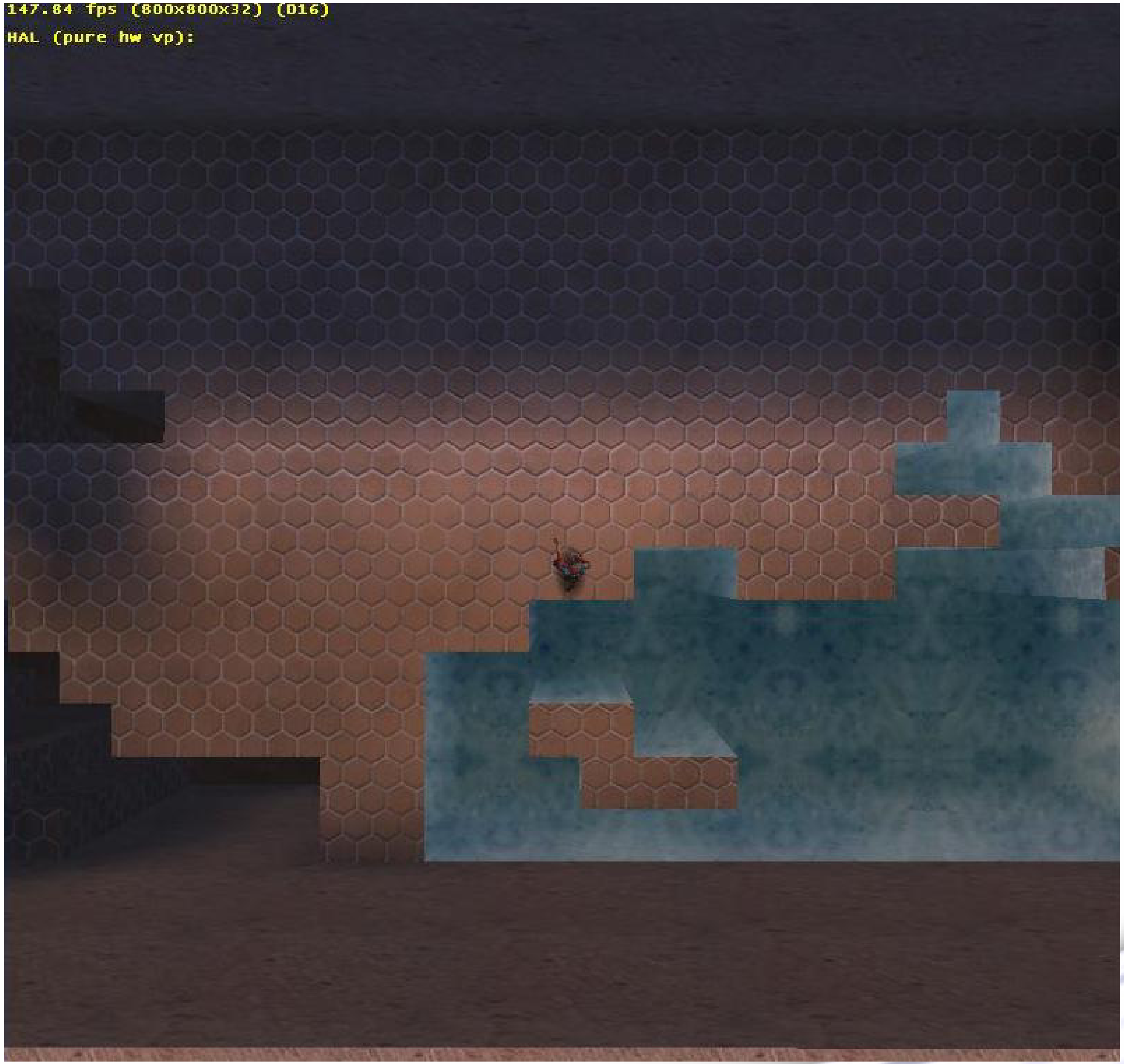
Test Engine - Overview

- Advantage to breaking the world into large cells
  - Efficient for culling
  - Can share same VB and IB without going over 65K vertex or triangle limits
    - Can use 16-bit indices for IB
    - Can use 16-bit indices for AABB tree
  - Can compress AABB boxes in tree to 16 or 8 byte per axis and still have good precision
  - Can more quickly reject moving entities in other cells
  - Can restrict lighting to only 7 lights per tile

Many Features, Few Draw Calls

- An entire world cell is drawn in one draw call
  - Up to 7 Lights
  - Diffuse & Specular Bump Mapping
  - Soft shadows
  - Gloss-Mapped, Color Shifted Specular
  - Masked Emissive
  - Water or Fog Depth stored in Dest Alpha
- Fog, Mist and Water are a partial alpha pass
  - Blend in fog layer colors based on dest alpha

Shadows & Deep Water



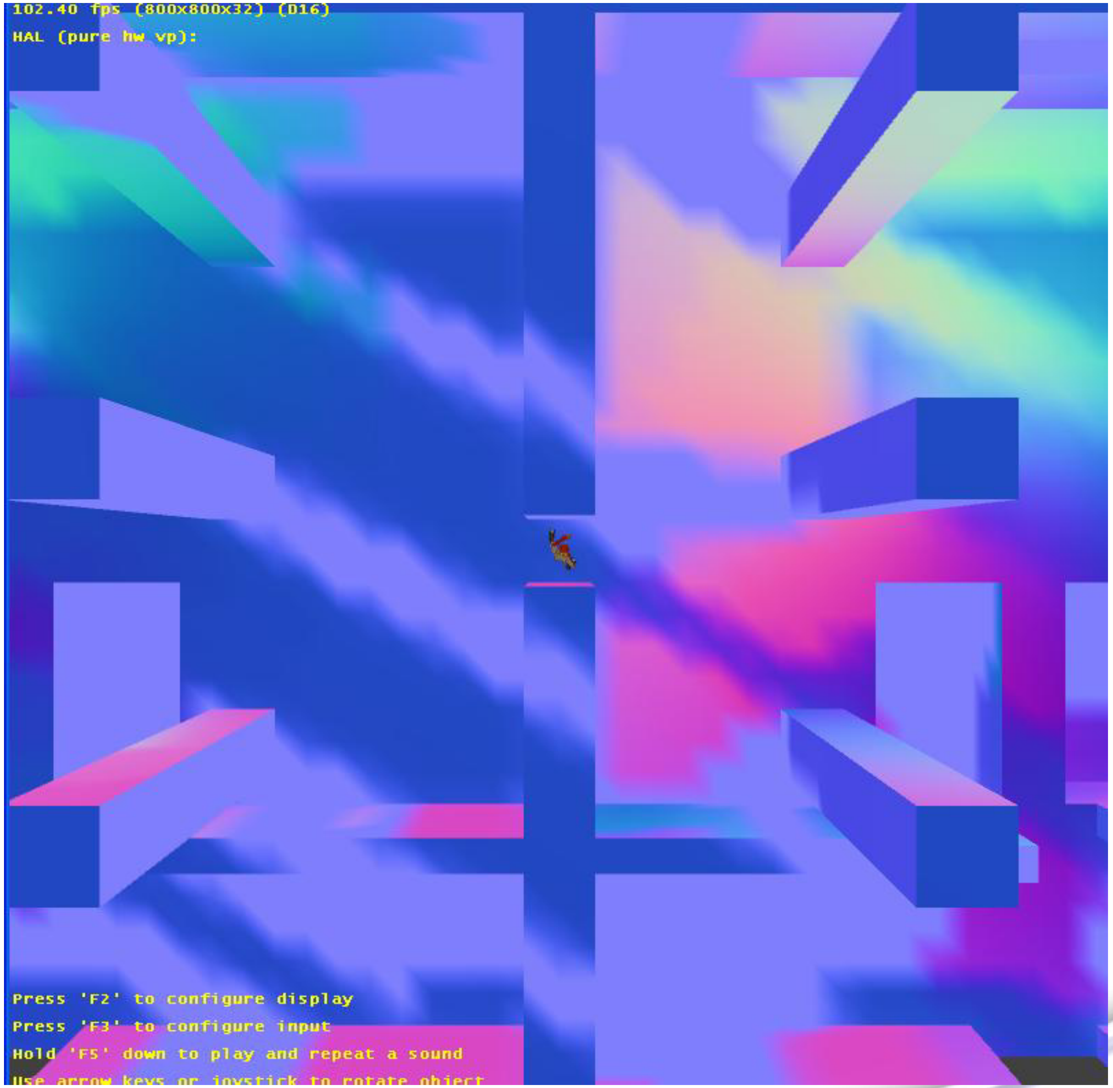
Test Engine - Lighting

- Shadows for world geometry are pre-calculated for up to 7 lights
- Per-Light occlusion terms are stored in diffuse.rgba and specular.rgb per vertex
- The vertex shader calculates the 7 L vectors
  - Scales the L vectors down by the occlusion & attenuation terms
  - Performs per-vertex N.L
  - Adds up scaled L vectors

Averaged L Bump Mapping

- The Pixel Shader uses this averaged L vector to perform bump mapping – 'Averaged L Bump Mapping'
- Bump mapping is nice, but not worth it to do for many lights
- This way, if lights change intensity or turn on and off, the bumps respond to the most intense lights
- The bump mapping still corresponds to the scene's lighting, but no need to do up to 7 rendering passes for 7 lights

Averaged L Vectors for "Averaged L Bump Mapping"



Metallic Specular

Questions?

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