CS 378: Computer Game Technology

Spatial Partitioning, Visibility and Culling

Spring 2012

Spatial Data Structures

- Spatial data structures store data indexed in some way by their spatial location
  - For instance, store points according to their location, or polygons, …
  - Before graphics, used for queries like "Where is the nearest hotel?" or "Which stars are strong enough to influence the sun?"
- Multitude of uses in computer games
  - Visibility - What can I see?
  - Ray intersections - What did the player just shoot?
  - Collision detection - Did the player just hit a wall?
  - Proximity queries - Where is the nearest power-up?

Spatial Decompositions

- Focus on spatial data structures that partition space into regions, or *cells*, of some type
  - Generally, cut up space with planes that separate regions
  - Almost always based on tree structures (surprise, huh?)
- *Octrees (Quadtrees)*: Axis aligned, regularly spaced planes cut space into cubes (squares)
- *Kd-trees*: Axis aligned planes, in alternating directions, cut space into rectilinear regions
- *BSP Trees*: Arbitrarily aligned planes cut space into convex regions

Using Decompositions

- Many geometric queries are expensive to answer precisely
- The best way to reduce the cost is with fast, **approximate** queries that eliminate most objects quickly
  - Trees with a containment property allow us to do this
  - The cell of a parent completely contains all the cells of its children
  - If a query fails for the cell, we know it will fail for all its children
  - If the query succeeds, we try it for the children
  - If we get to a leaf, we do the expensive query for things in the cell
- Spatial decompositions are most frequently used in this way
  - For example, if we cannot see any part of a cell, we cannot see its children, if we see a leaf, use the Z-buffer to draw the contents

Octree

- Root node represents a cube containing the entire world
- Then, recursively, the eight children of each node represent the eight sub-cubes of the parent
- Quadtree is for 2D decompositions - root is square and four children are sub-squares
  - What sorts of games might use quadtrees instead of octrees?
- Objects can be assigned to nodes in one of two common ways:
  - All objects are in leaf nodes
  - Each object is in the smallest node that fully contains it
  - What are the benefits and problems with each approach?

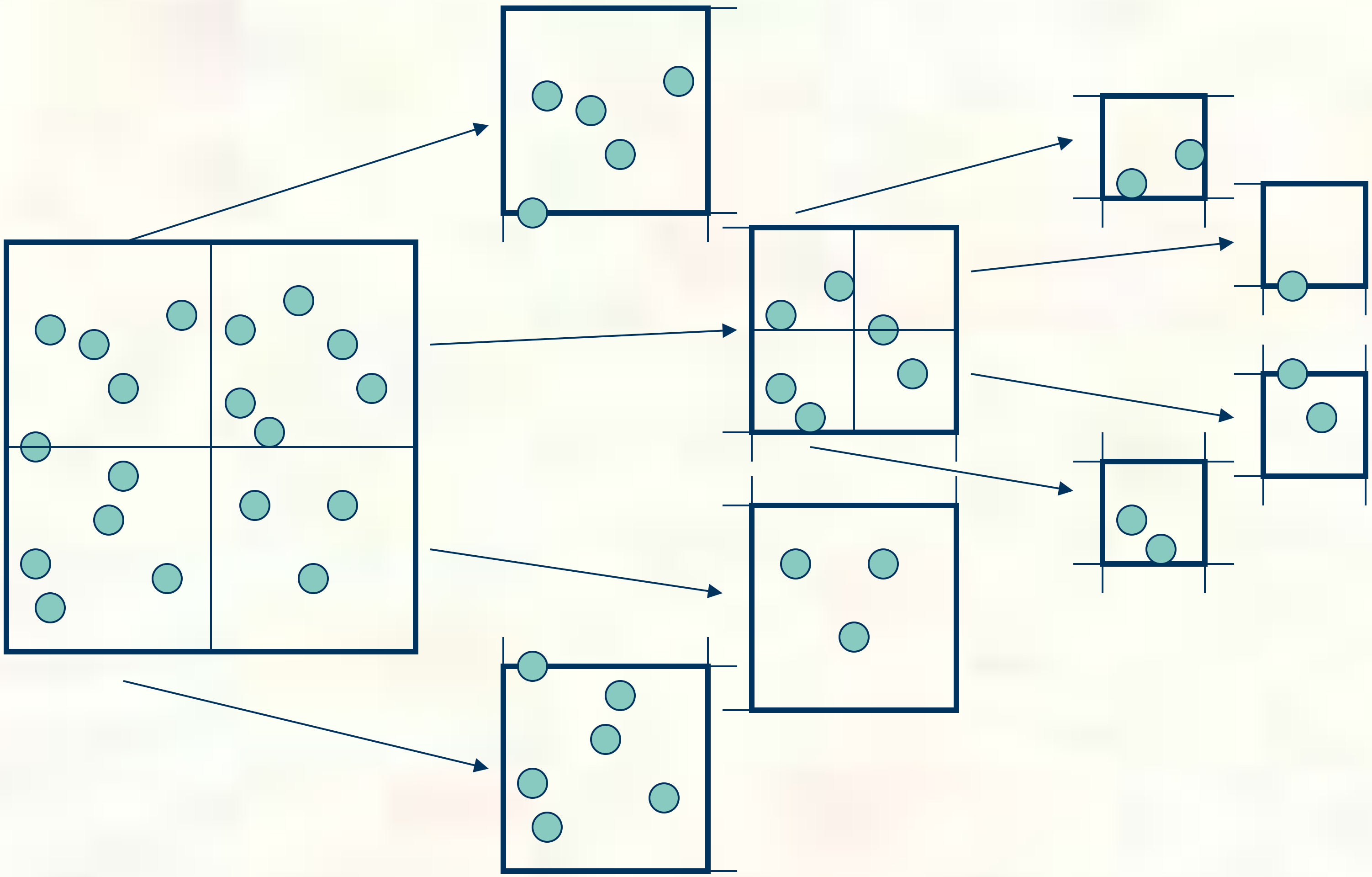
Octree Node Data Structure

- What needs to be stored in a node?
  - Children pointers (at most eight)
  - Parent pointer - useful for moving about the tree
  - Extents of cube - can be inferred from tree structure, but easier to just store it
  - Data associated with the contents of the cube
    - Contents might be whole objects or individual polygons, or even something else
  - Neighbors are useful in some algorithms (but not all)

Building an Octree

- Define a function, buildNode, that:
  - Takes a node with its cube set and a list of its contents
  - Creates the children nodes, divides the objects among the children, and recurses on the children, or
  - Sets the node to be a leaf node
- Find the root cube (how?), create the root node and call buildNode with all the objects
- When do we choose to stop creating children?
  - Is the tree necessarily balanced?
- What is the hard part in all this? Hint: It depends on how we store objects in the tree

Example Construction



Assignment of Objects to Cells

- Basic operation is to intersect an object with a cell
  - What can we exploit to make it faster for octrees?
- Fast algorithm for polygons (Graphics Gems V):
  - Test for trivial accept/reject with each cell face plane
    - Look at which side of which planes the polygon vertices lie
    - Note speedups: Vertices outside one plane must be inside the opposite plane
  - Test for trivial reject with edge and vertex planes
    - Planes through edges/vertices with normals like (1,1,1) and (0,1,1)
  - Test polygon edges against cell faces
  - Test a particular cell diagonal for intersection with the polygon
  - Information from one test informs the later tests. Code available online

Approximate Assignment

- Recall, we typically use spatial decompositions to answer **approximate** queries
  - Conservative approximation: We will sometimes answer yes for something that should be no, but we will never answer no for something that should be yes
- Observation 1: If one polygon of an object is inside a cell, most of its other polygons probably are also
  - Should we store lists of objects or polygons?
- Observation 2: If a bounding volume for an object intersects the cell, the object probably also does
  - Should we test objects or their bounding volumes? (There is more than one answer to this - the reasons are more interesting)

Objects in Multiple Cells

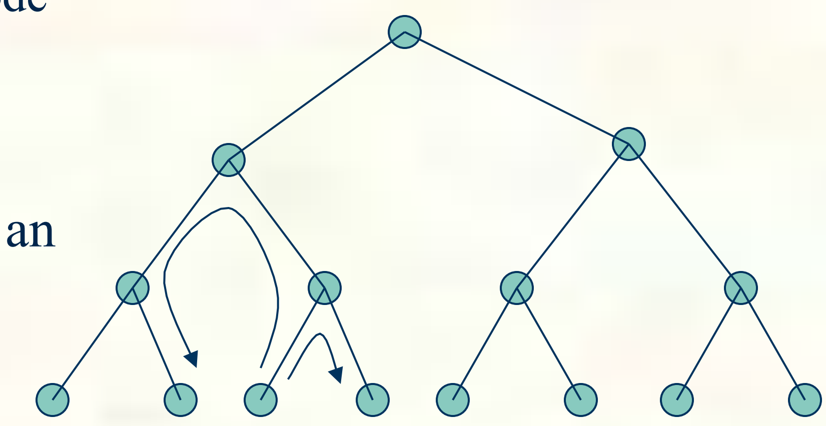
- Assume an object intersects more than one cell
- Typically store pointers to it in all the cells it intersects
  - Why can't we store it in just one cell? Consider the ray intersection test
- But it might be considered twice for some tests, and this might be a problem
  - One solution is to flag an object when it has been tested, and not consider it again until the next round of testing
    - Why is this inefficient?
  - Better solution is to tag it with the frame number it was last tested
    - Subtle point: How long before the frame counter overflows?

Neighboring Cells

- Sometimes it helps if a cell knows it neighbors
  - How far away might they be in the tree? (How many links to reach them?)
  - How does neighbor information help with ray intersection?
- Neighbors of cell A are cells that:
  - Share a face plane with A
  - Have all of A's vertices contained within the neighbor's part of the common plane
  - Have no child with the same property

Finding Neighbors

- Your right neighbor in a binary tree is the leftmost node of the first sub-tree on your right
  - Go up to find first rightmost sub-tree
  - Go down and left to find leftmost node (but don't go down further than you went up)
  - Symmetric case for left neighbor
- Find all neighbors for all nodes with an in-order traversal
- Natural extensions for quadtrees and octrees



Frustum Culling With Octrees

- We wish to eliminate objects that do not intersect the view frustum
- Which node/cell do we test first? What is the test?
- If the test succeeds, what do we know?
- If the test fails, what do we know? What do we do?

Frustum Culling With Octrees

- We wish to eliminate objects that do not intersect the view frustum
- Have a test that succeeds if a cell may be visible
  - Test the corners of the cell against each clip plane. If all the corners are outside one clip plane, the cell is not visible
  - Otherwise, is the cell itself definitely visible?
- Starting with the root node cell, perform the test
  - If it fails, nothing inside the cell is visible
  - If it succeeds, something inside the cell might be visible
  - Recurse for each of the children of a visible cell
- This algorithm with quadtrees is particularly effective for a certain style of game. What style?

Interference Testing

- Consider the problem of finding out which cells an object interferes with (collides with)
  - When do we need to answer such questions?
- Consider a sphere and an octree
  - Which octree node do we start at?
  - What question do we ask at each node?
  - What action do we take at each node?

Ray Intersection Testing

- Consider the problem of finding which cells a ray intersects
  - Why might we care?
- Consider a ray (start and direction) and an octree
  - Which cell do we start at?
  - How does the algorithm proceed?
  - What information must be readily accessible for this algorithm?

Octree Problems

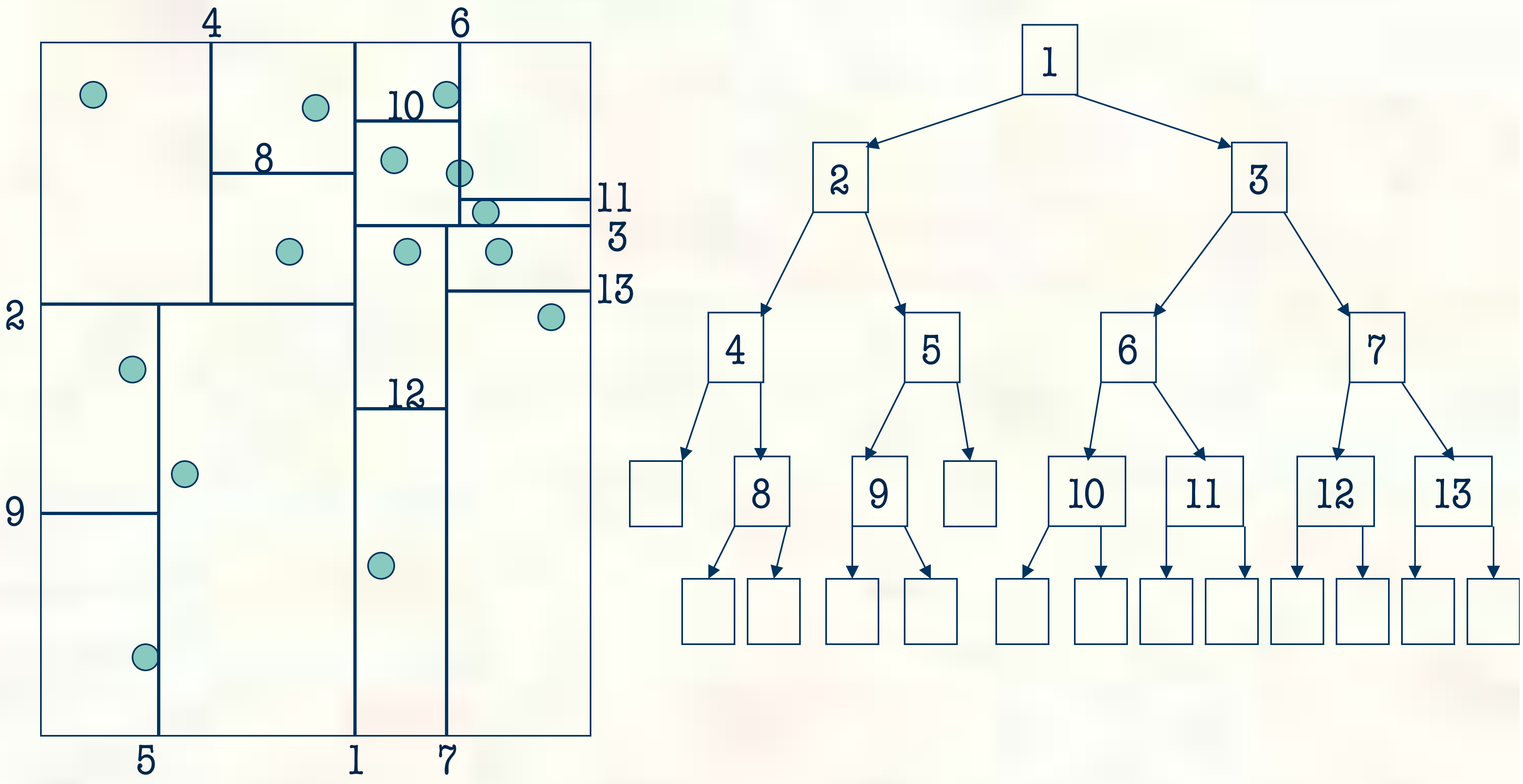
- Octrees become very unbalanced if the objects are far from a uniform distribution
  - Many nodes could contain no objects
- The problem is the requirement that cube always be equally split amongst children

A bad octree case

Kd-trees

- A kd-tree is a tree with the following properties
  - Each node represents a rectilinear region (faces aligned with axes)
  - Each node is associated with an axis aligned plane that cuts its region into two, and it has a child for each sub-region
  - The directions of the cutting planes alternate with depth – height 0 cuts on x, height 1 cuts on *y*, height 2 cuts on *z*, height 3 cuts on *x*, …
- Kd-trees generalize octrees by allowing splitting planes at variable positions
  - Note that cut planes in different sub-trees at the same level need not be the same

Kd-tree Example



Kd-tree Node Data Structure

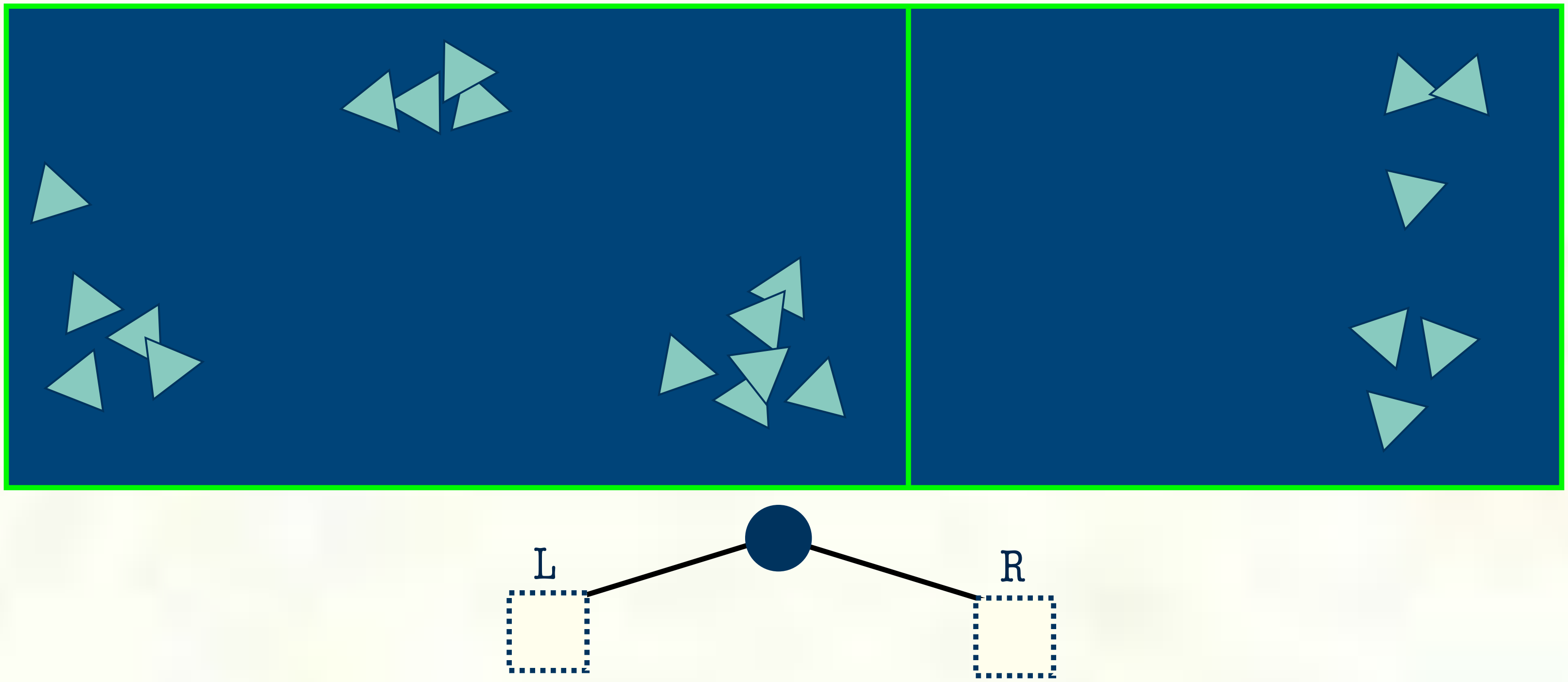
- What needs to be stored in a node?
  - Children pointers (always two)
  - Parent pointer - useful for moving about the tree
  - Extents of cell - x_{max}, x_{min}, y_{max}, y_{min}, z_{max}, z_{min}
  - List of pointers to the contents of the cell
  - Neighbors are complicated in kd-trees, so typically not stored

Building a Kd-tree

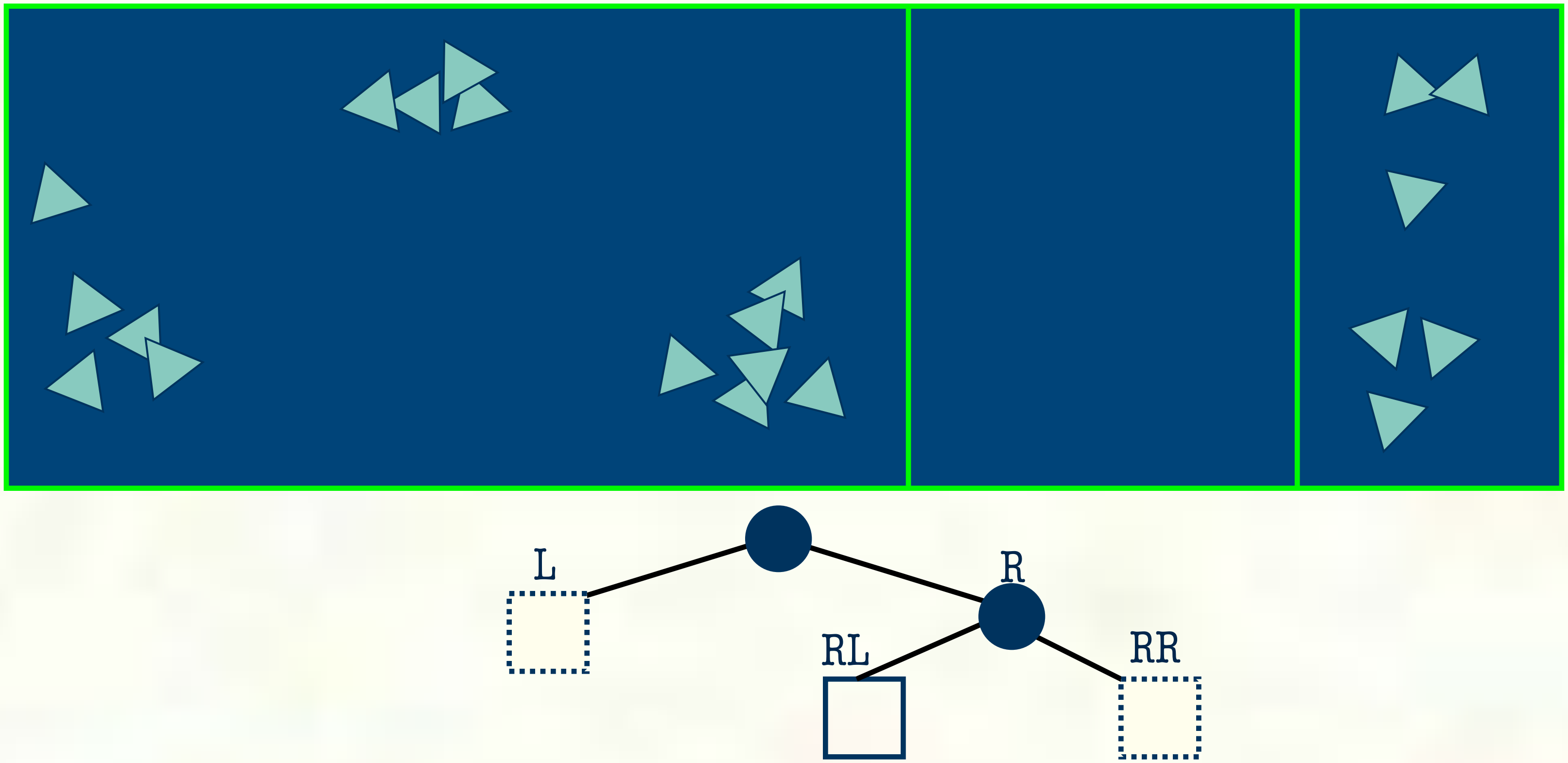
- Define a function, buildNode, that:
  - Takes a node with its cell defined and a list of its contents
  - Sets the splitting plane, creates the children nodes, divides the objects among the children, and recurses on the children, or
  - Sets the node to be a leaf node
- Find the root cell (how?), create the root node and call buildNode with all the objects
- When do we choose to stop creating children?
- What is the hard part?

Kd-tree - Build

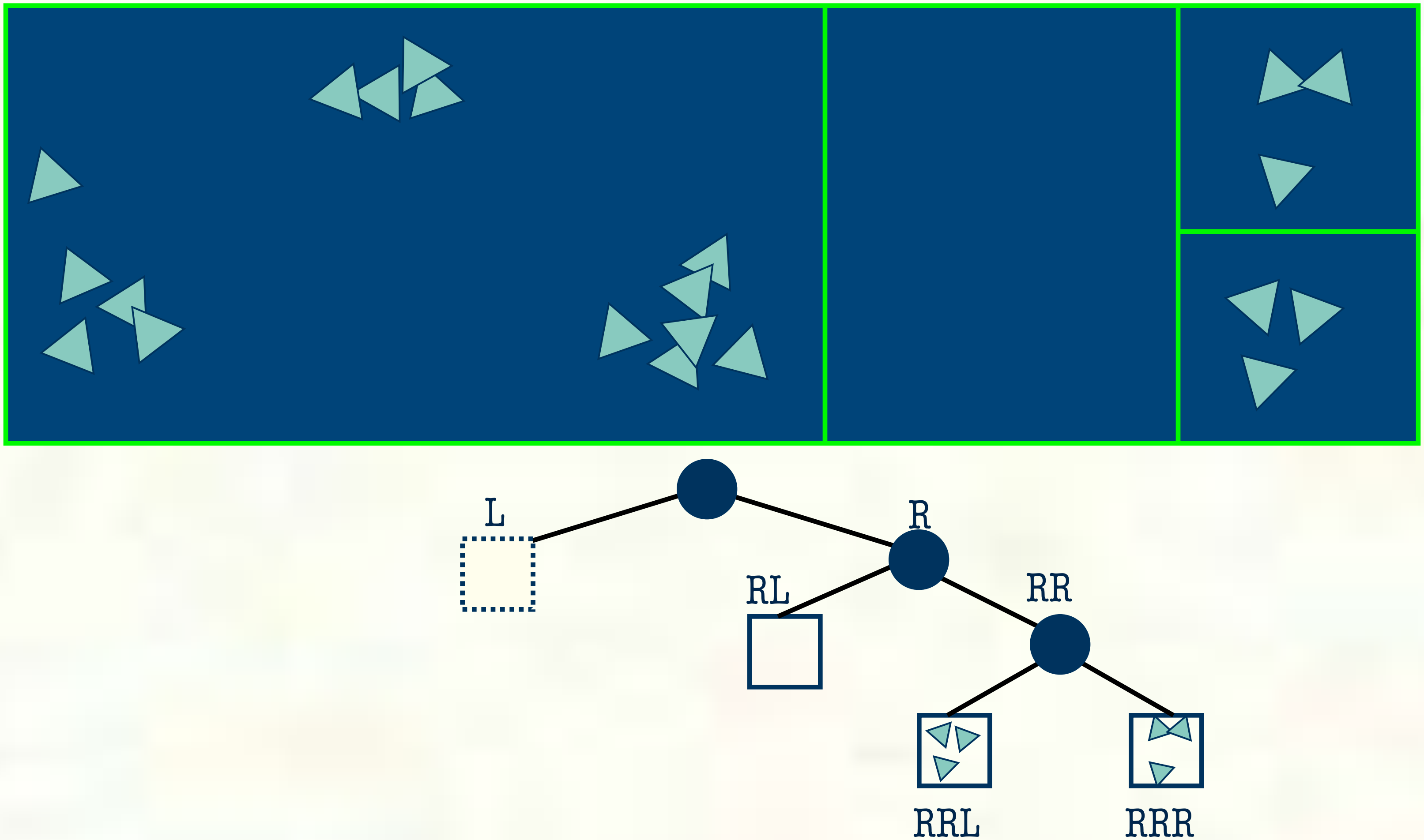
Kd-tree



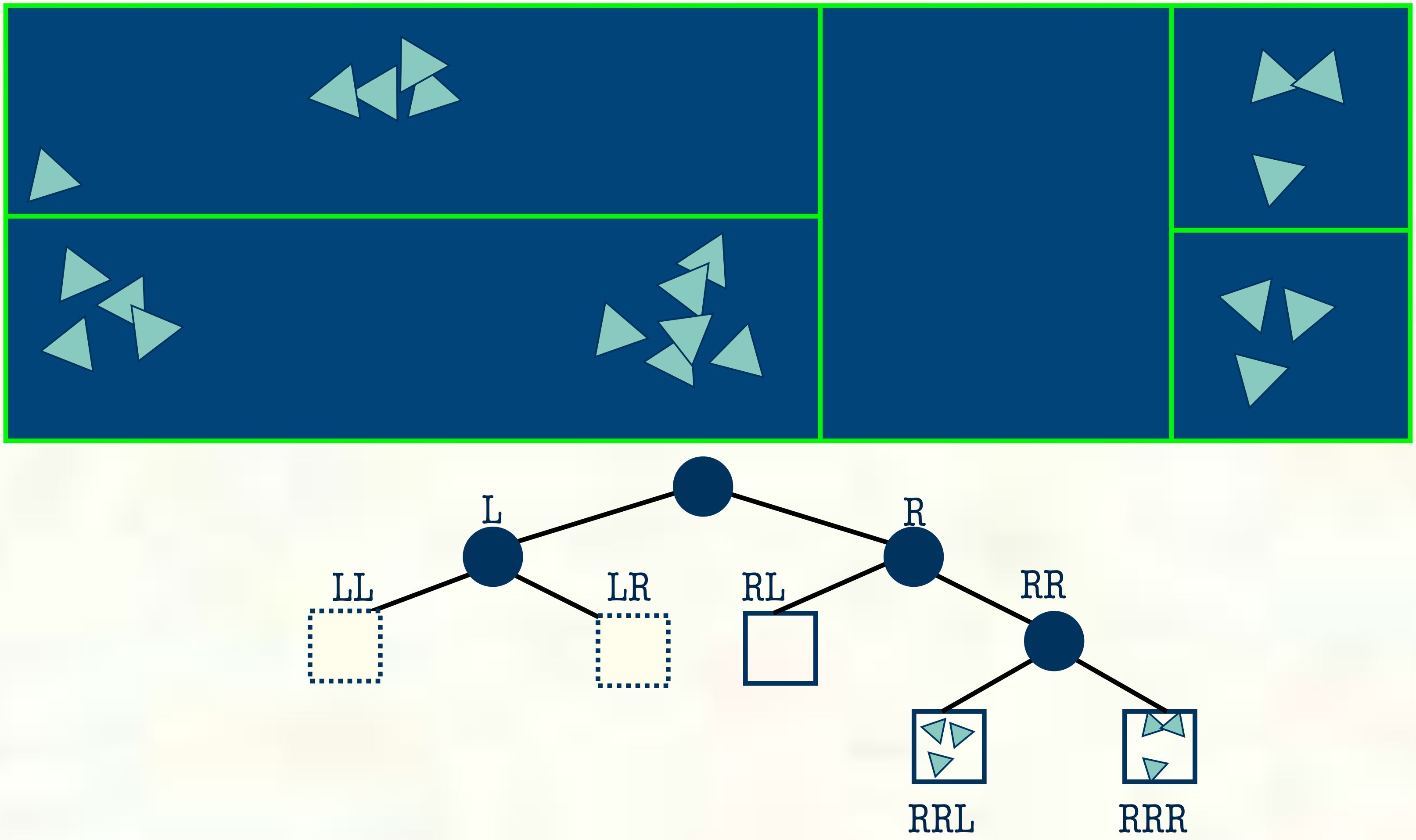
Kd-tree



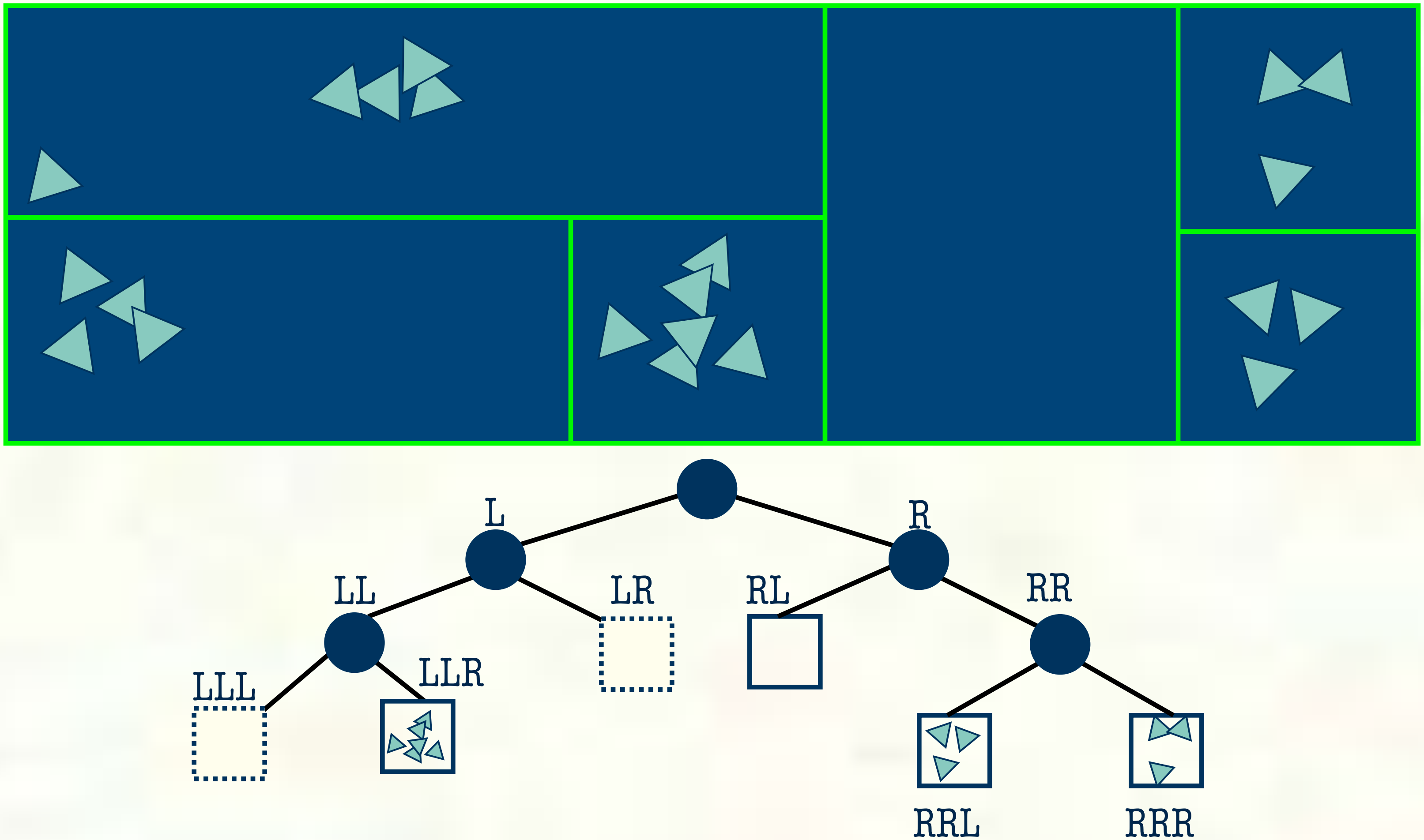
Kd-tree



Kd-tree



Kd-tree



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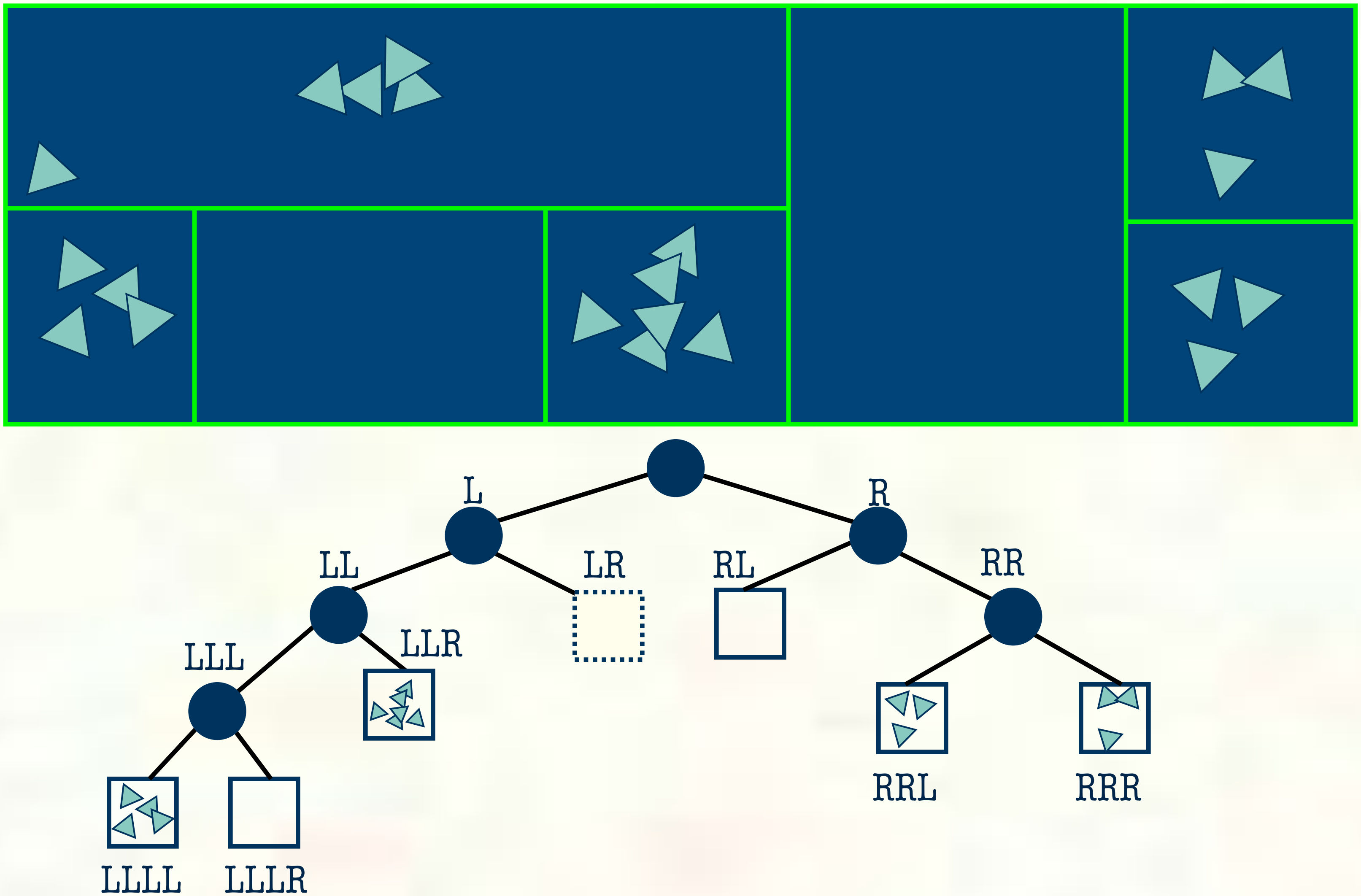

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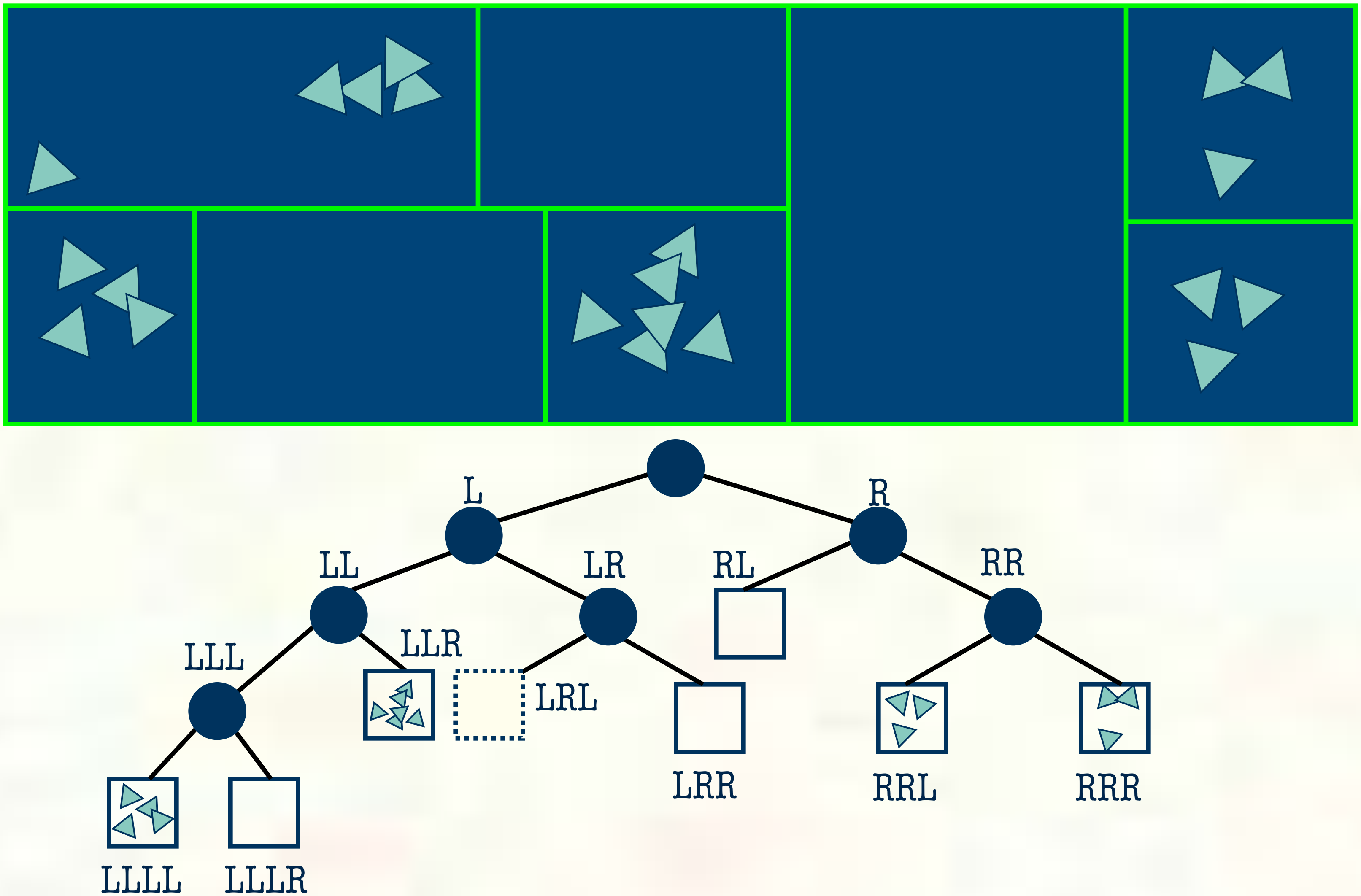

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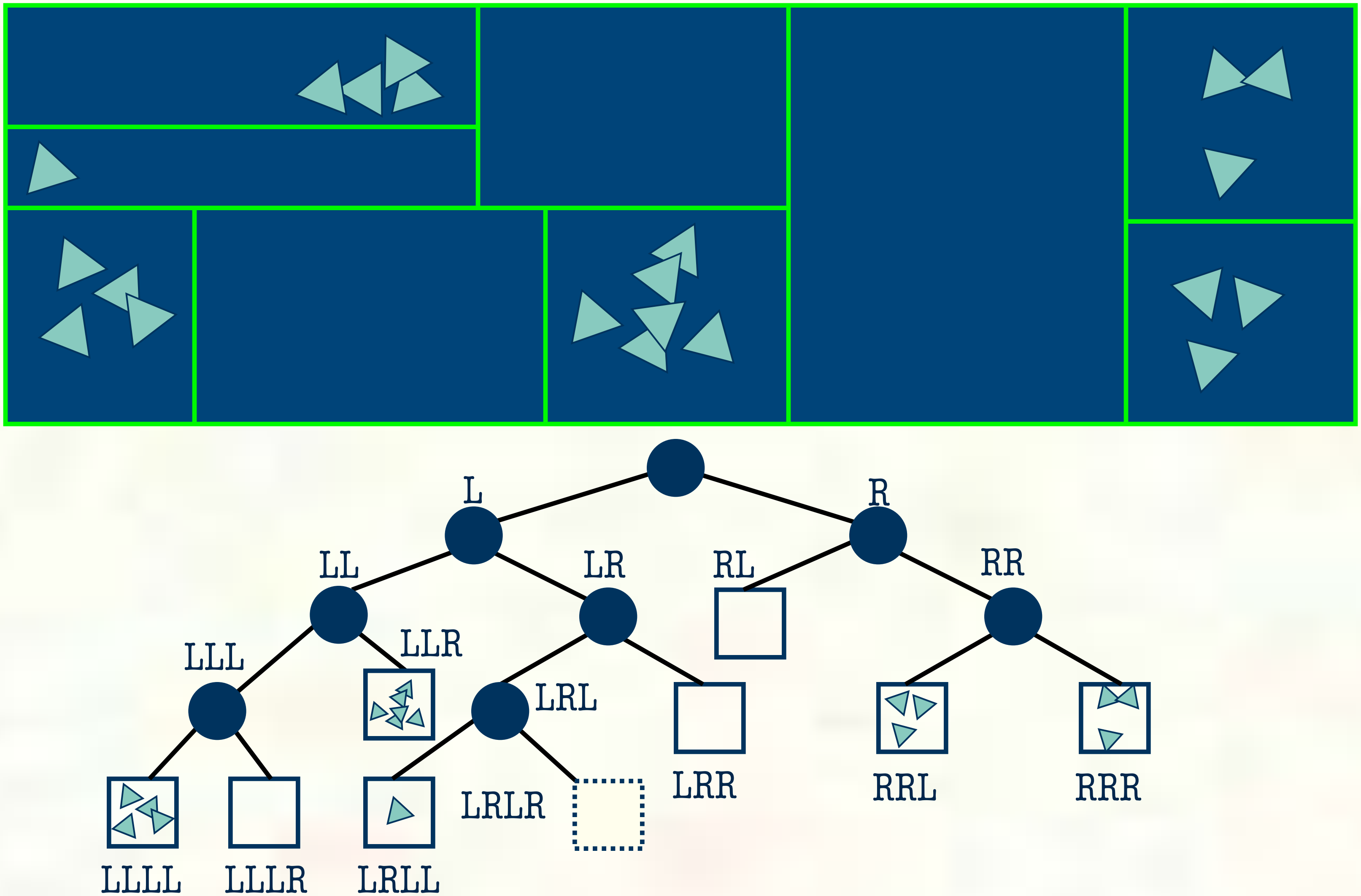
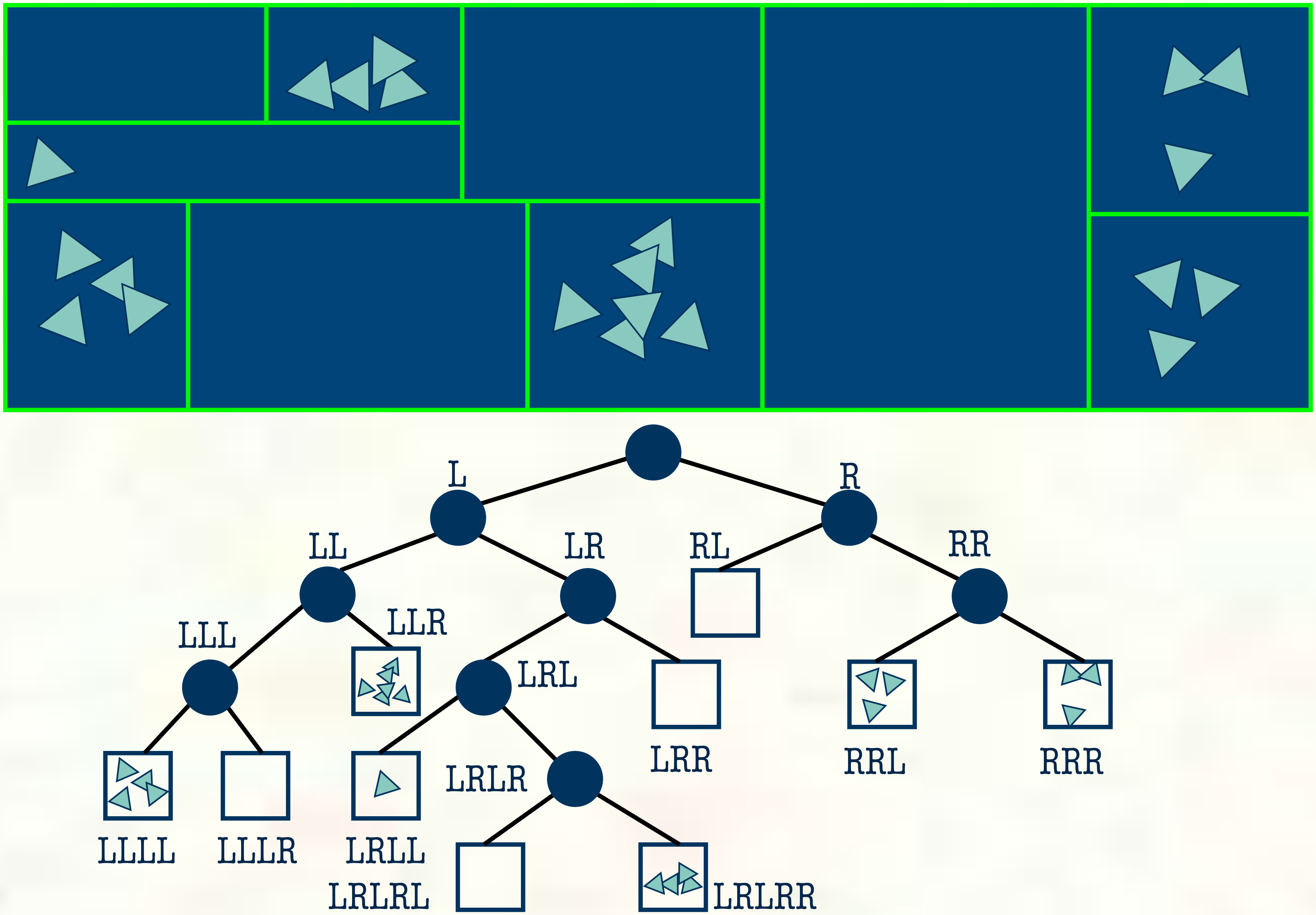


Kd-tree



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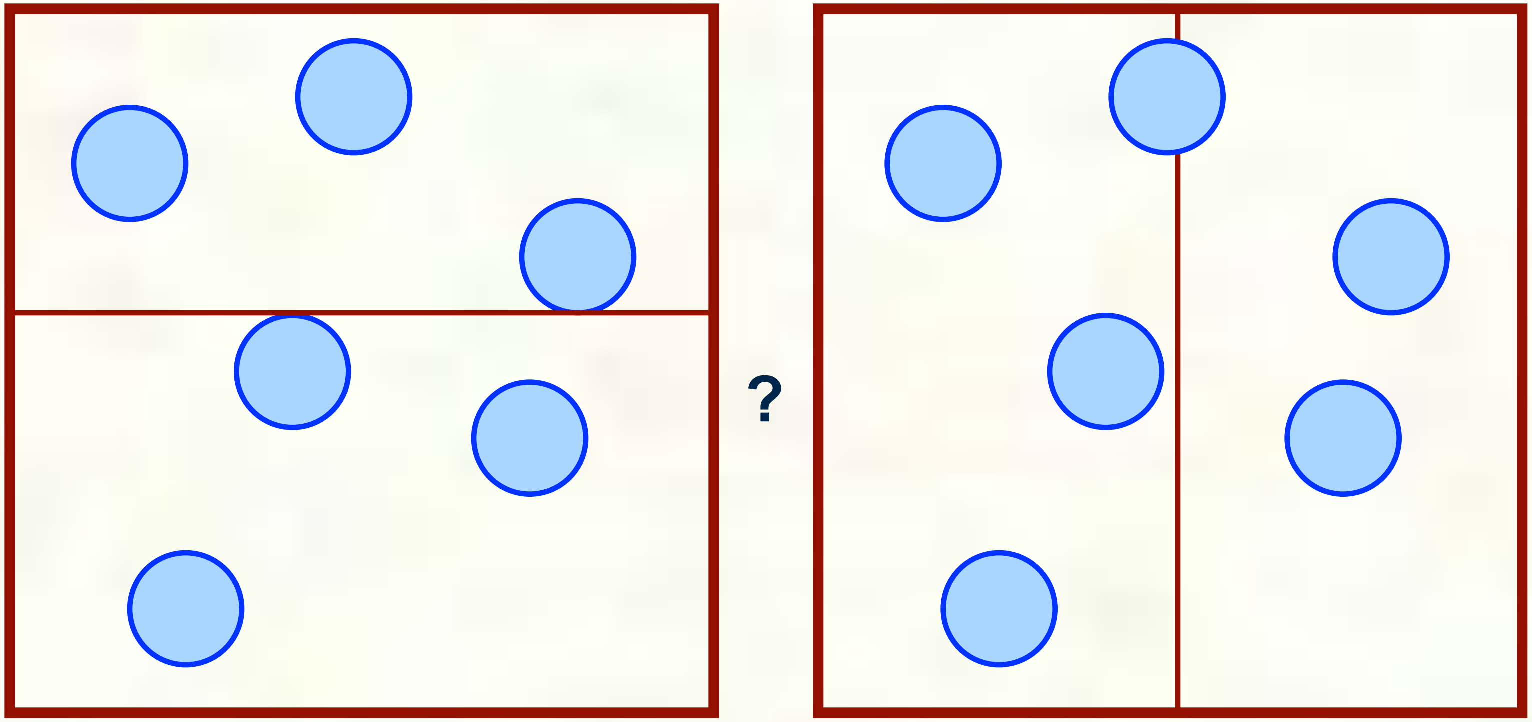
Choosing a Split Plane

- Two common goals in selecting a splitting plane for each cell
  - Minimize the number of objects cut by the plane
  - Balance the tree: Use the plane that equally divides the objects into two sets (the *median cut* plane)
  - One possible global goal is to minimize the number of objects cut throughout the entire tree (intractable)

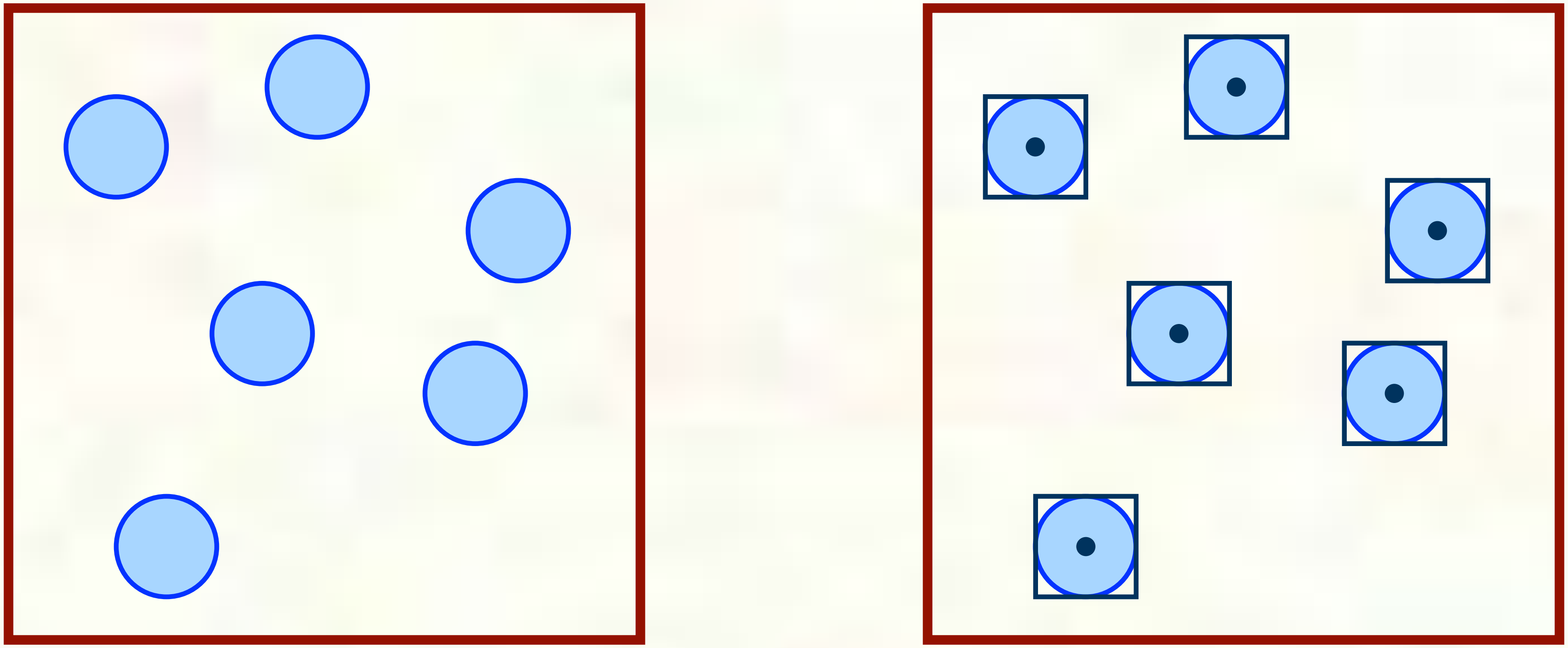
Choosing Split Planes



Generally NP-complete

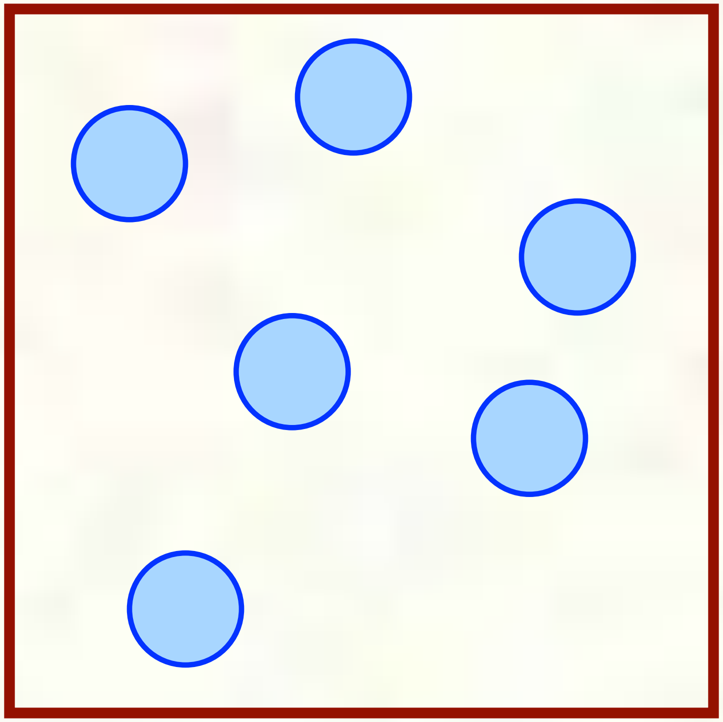
- Use some heuristic
- Minimize split objects?
- Balance - median split?

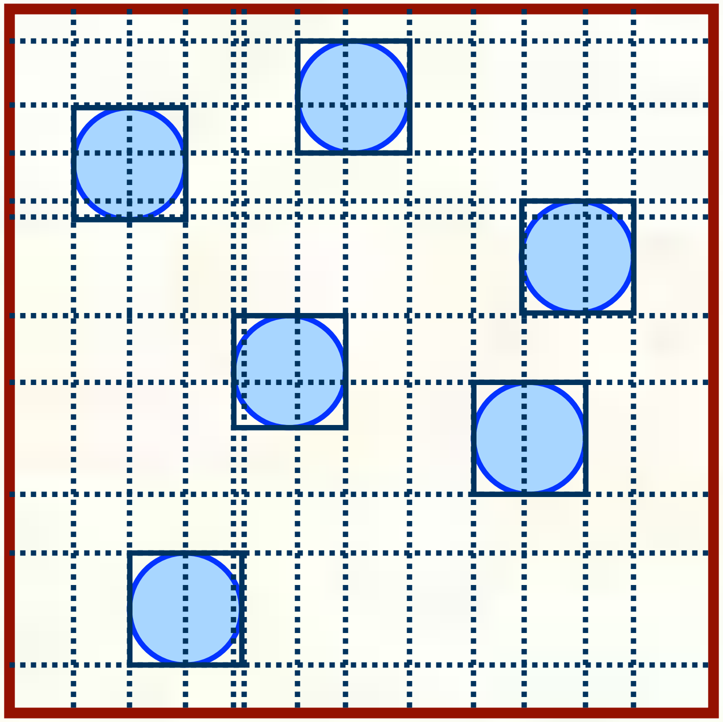
AABBs and Barycenters



- For many operations, it's convenient to simplify objects to "fat points"
  - Compute axis-aligned bounding box
  - For each coordinate, compute the mean of the bounds

Candidate Split Planes

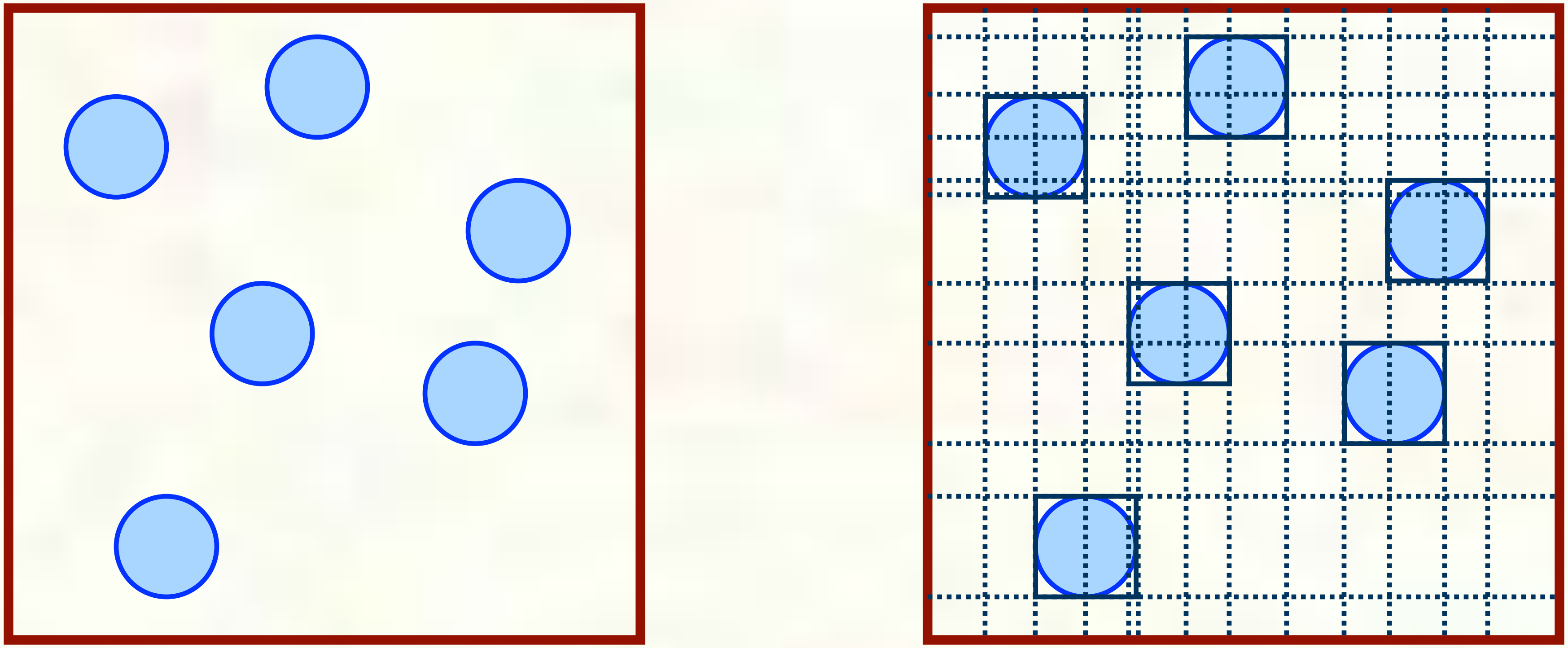




Infinite number of choices:

- Which planes to choose from?
- Axis-aligned?
- Use AABBs to define candidate planes

Choosing Split Planes

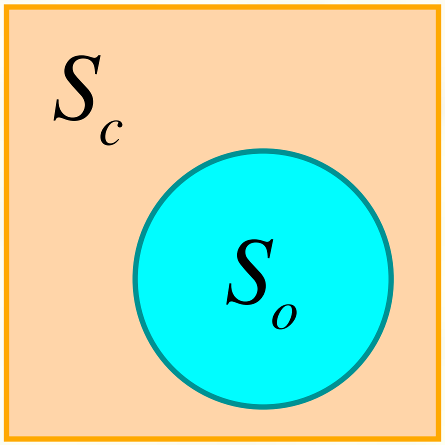


Generally NP-complete

- Use some heuristic
- Minimize split objects?
- Balance?
- Just split at midpoint of range?

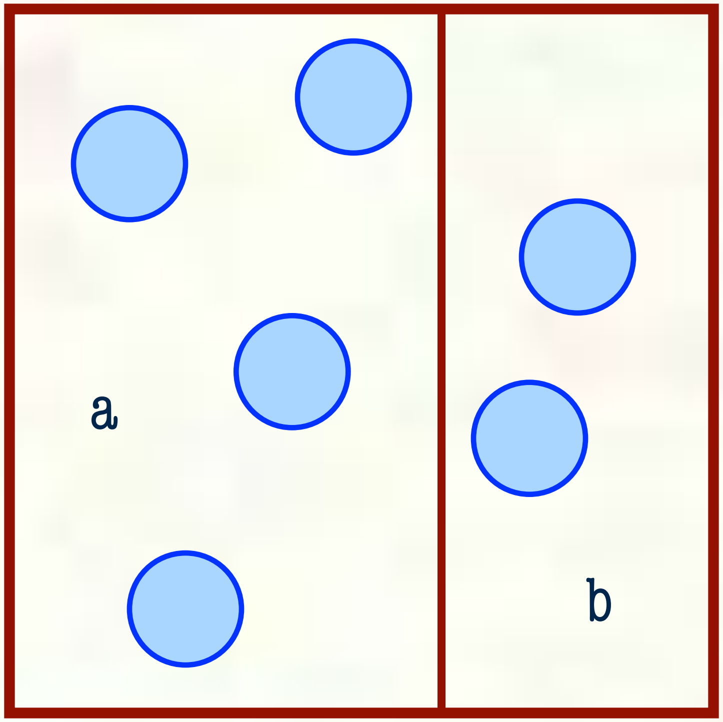
Surface Area and Rays

- The probability of a ray hitting a convex shape that is completely inside a convex cell equals



$$\Pr[r \cap S_o \mid r \cap S_c] = \frac{S_o}{S_c}$$

Surface Area Heuristic



Intersection time

$$t_i$$

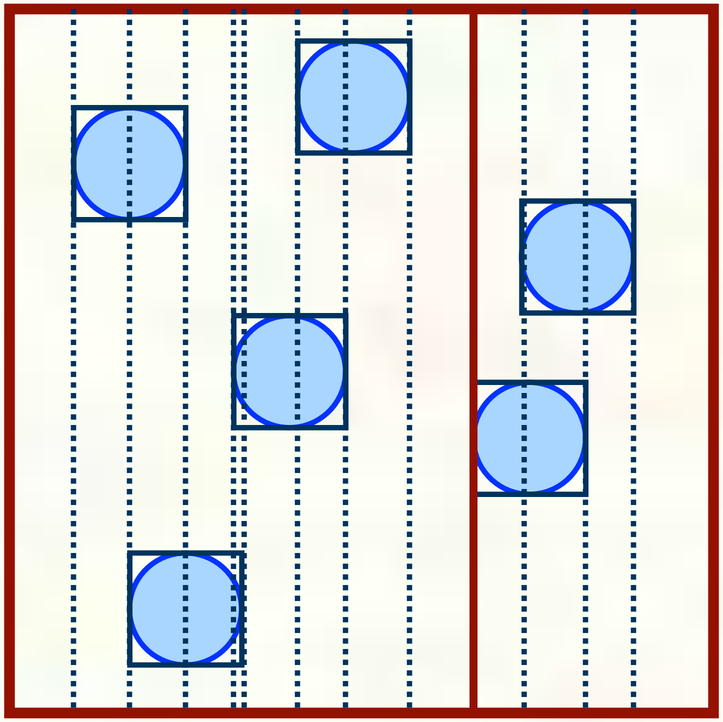
Traversal time

$$t_t$$

$$t_i = 80t_t$$

$$C = t_t + p_a N_a t_i + p_b N_b t_i$$

Surface Area Heuristic



2n splits

$$p_a = \frac{S_a}{S}$$

$$p_b = \frac{S_b}{S}$$

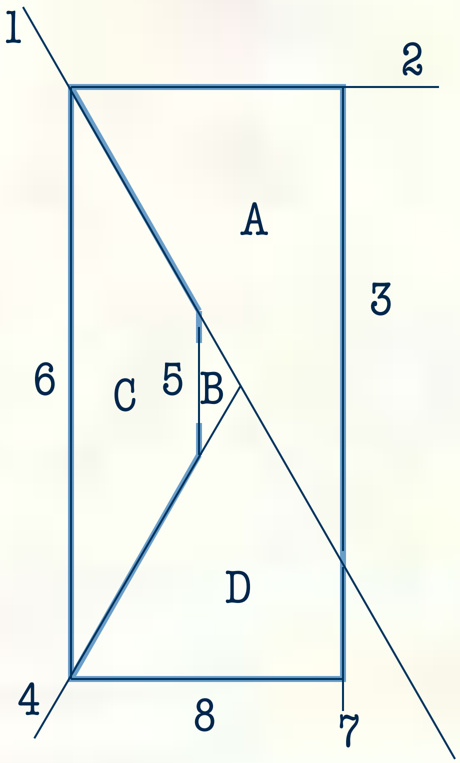
Kd-tree Applications

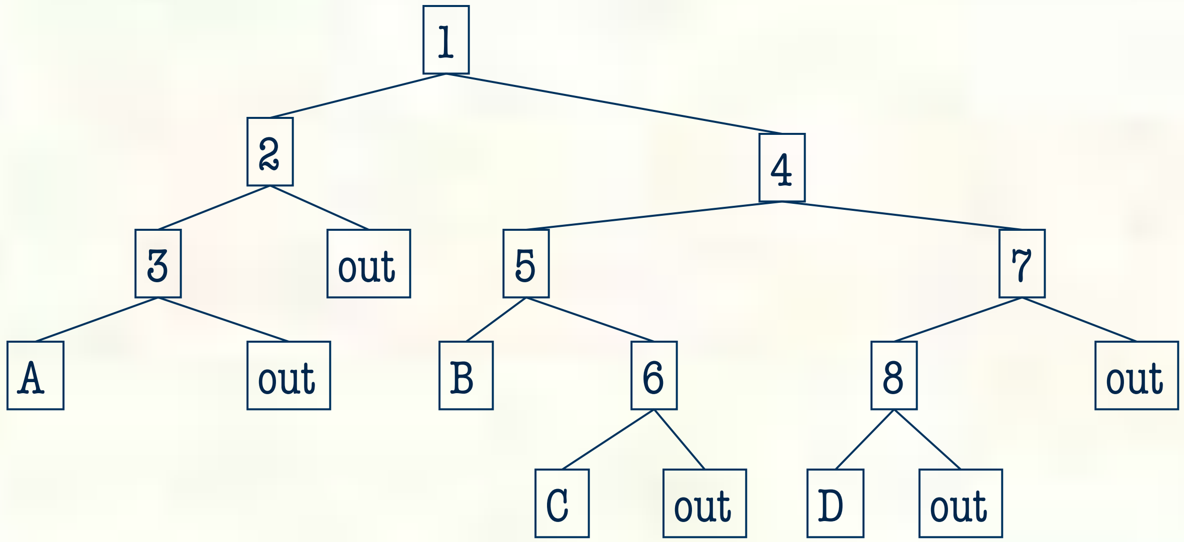
- Kd-trees work well when axis aligned planes cut things into meaningful cells
  - What are some common environments with rectilinear cells?
- View frustum culling extents trivially to kd-trees
- Kd-trees are frequently used as data structures for other algorithms – particularly in visibility
- Specific applications:
  - Soda Hall Walkthrough project (Teller and Sequin)
    - Splitting planes came from large walls and floors
  - Real-time Pedestrian Rendering (University College London)

BSP Trees

- *Binary Space Partition* trees
  - A sequence of cuts that divide a region of space into two
- Cutting planes can be of any orientation
  - A generalization of kd-trees, and sometimes a kd-tree is called an axis-aligned BSP tree
- Divides space into convex cells
- The industry standard for spatial subdivision in game environments
  - General enough to handle most common environments
  - Easy enough to manage and understand
  - Big performance gains

BSP Example





- Notes:
  - Splitting planes end when they intersect their parent node’s planes
  - Internal node labeled with planes, leaf nodes with regions

BSP Tree Node Data Structure

- What needs to be stored in a node?
  - Children pointers (always two)
  - Parent pointer - useful for moving about the tree
  - If a leaf node: Extents of cell
    - How might we store it?
  - If an internal node: The split plane
  - List of pointers to the contents of the cell
  - Neighbors are useful in many algorithms
    - Typically only store neighbors at leaf nodes
    - Cells can have many neighboring cells
  - Portals are also useful - holes that see into neighbors

Building a BSP Tree

- Define a function, buildNode, that:
  - Takes a node with its cell defined and a list of its contents
  - Sets the splitting plane, creates the children nodes, divides the objects among the children, and recurses on the children, or
  - Sets the node to be a leaf node
- Create the root node and call buildNode with all the objects
  - Do we need the root node's cell? What do we set it to?
- When do we choose to stop creating children?
- What is the hard part?

Choosing Splitting Planes

- Goals:
  - Trees with few cells
  - Planes that are mostly opaque (best for visibility calculations)
  - Objects not split across cells
- Some heuristics:
  - Choose planes that are also polygon planes
  - Choose large polygons first
  - Choose planes that don't split many polygons
  - Try to choose planes that evenly divide the data
  - Let the user select or otherwise guide the splitting process
  - Random choice of splitting planes doesn't do too badly

Drawing Order from BSP Trees

- BSP tress can be used to order polygons from back to front, or visa-versa
  - Descend tree with viewpoint
  - Things on the same side of a splitting plane as the viewpoint are always in front of things on the far side
- Can draw from back to front
  - Removes need for z-buffer, but few people care any more
  - Gives the correct order for rendering transparent objects with a z-buffer, and by far the best way to do it
- Can draw front to back
  - Use info from front polygons to avoid drawing back ones
  - Useful in software renderers

BSP in Games

- Use a BSP tree to partition space as you would with an octree or kd-tree
  - Leaf nodes are cells with lists of objects
  - Cells typically roughly correspond to "rooms", but don't have to
- The polygons to use in the partitioning are defined by the level designer as they build the space
  - A *brush* is a region of space that contributes planes to the BSP
  - Artists lay out brushes, then populate them with objects
  - Additional planes may also be specified
    - Sky planes for outdoor scenes, that dip down to touch the tops of trees and block off visibility
    - Planes specifically defined to block sight-lines, but not themselves visible

Dynamic Lights and BSPs

- Dynamic lights usually have a limited radius of influence to reduce the number of objects they light
- The problem is to find, using the BSP tree, the set of objects lit by the light (intersecting a sphere center (x,y,z) radius r)
- Solution: Find the distance of the center of the sphere from each split plane
  - What do we do if it's greater than r distance on the positive side of the plane?
  - What do we do if it's greater than r distance on the negative side of the plane?
  - What do we do if it's within distance r of the plane?
  - Any leaf nodes reached contain objects that might be lit

BSP and Frustum Culling

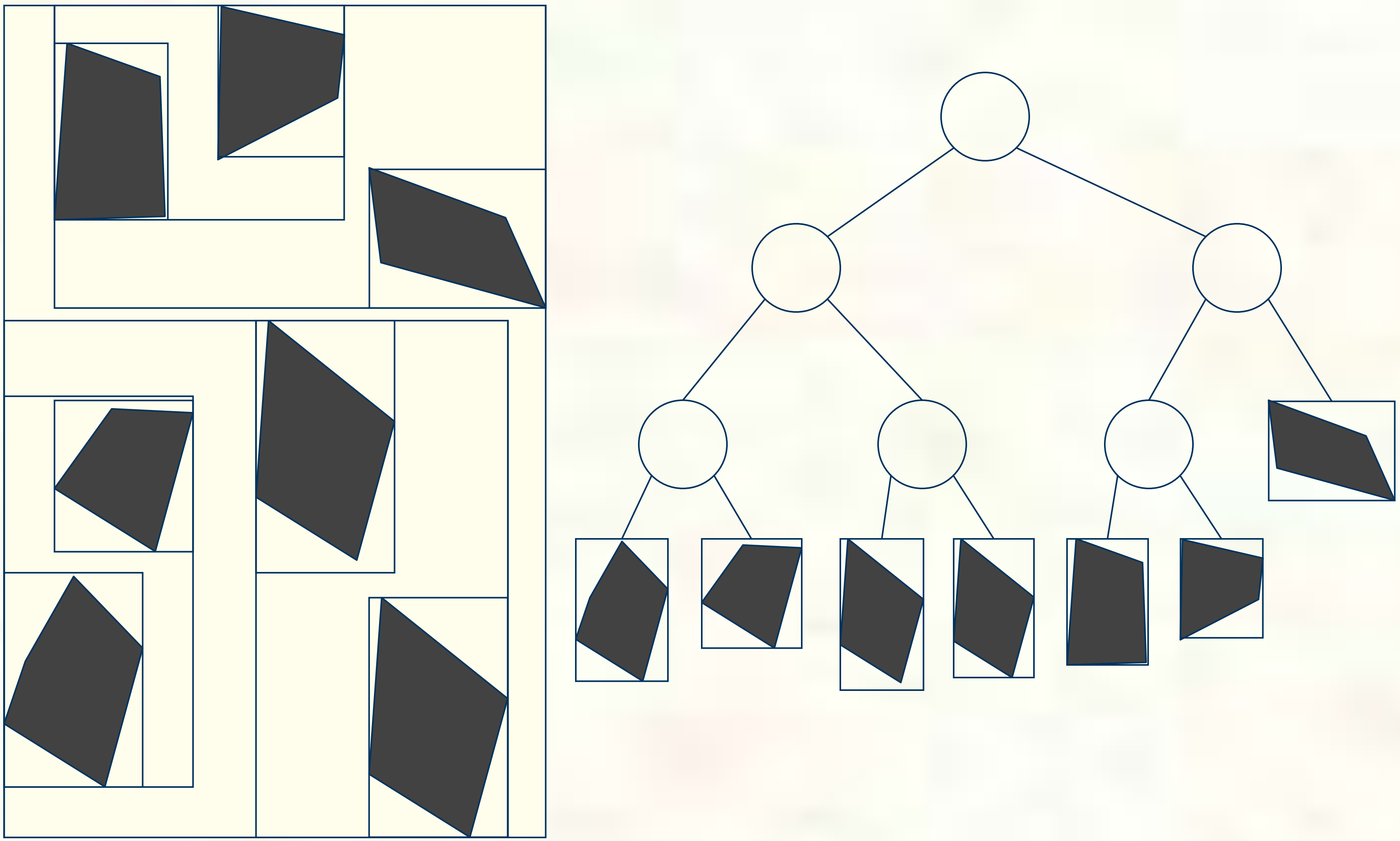
- You have a BSP tree, and a view frustum
  - With near and far clip planes
- At each splitting plane:
  - Test the boundaries of the frustum against the split plane
  - What if the entire frustum is on one side of the split plane?
  - What if the frustum intersects the split plane?

- What do you test in situations with no far plane?
- What do you do when you get to a leaf?

Bounding Volume Hierarchies

- So far, we have had subdivisions that break the world into cell
- General *Bounding Volume Hierarchies* (BVHs) start with a bounding volume for each object
  - Many possibilities: Spheres, AABBs, OBBs, k-dops, …
  - More on these later
- Parents have a bound that bounds their children's bounds
  - Typically, parent's bound is of the same type as the children's
  - Can use fixed or variable number of children per node
- No notion of cells in this structure

BVH Example



BVH Construction

- Simplest to build top-down
  - Bound everything
  - Choose a split plane (or more), divide objects into sets
  - Recurse on child sets
- Can also be built incrementally
  - Insert one bound at a time, growing as required
  - Good for environments where things are created dynamically
- Can also build bottom up
  - Bound individual objects, group them into sets, create parent, recurse
  - What's the hardest part about this?

BVH Operations

- Some of the operations we've looked at so far work with BVHs
  - Frustum culling
  - Collision detection
- BVHs are good for moving objects
  - Updating the tree is easier than for other methods
  - Incremental construction also helps (don't need to rebuild the whole tree if something changes)
- But, BVHs lack some convenient properties
  - For example, not all space is filled, so algorithms that "walk" through cells won't work

Visibility

- Visibility algorithms aim to identify everything that will be visible, and not much more
- Trade off: Application-side time on visibility, vs. hardware time on processing invisible stuff
- *Conservative Visibility*: Identify more than what is visible and clean up remaining with a z-buffer
- The simplest are view-frustum algorithms that eliminate objects outside the view frustum
  - These algorithms don't do very well on scenes with *high depth complexity*, or many objects behind a single pixel
  - Buildings are a classic case of high depth complexity

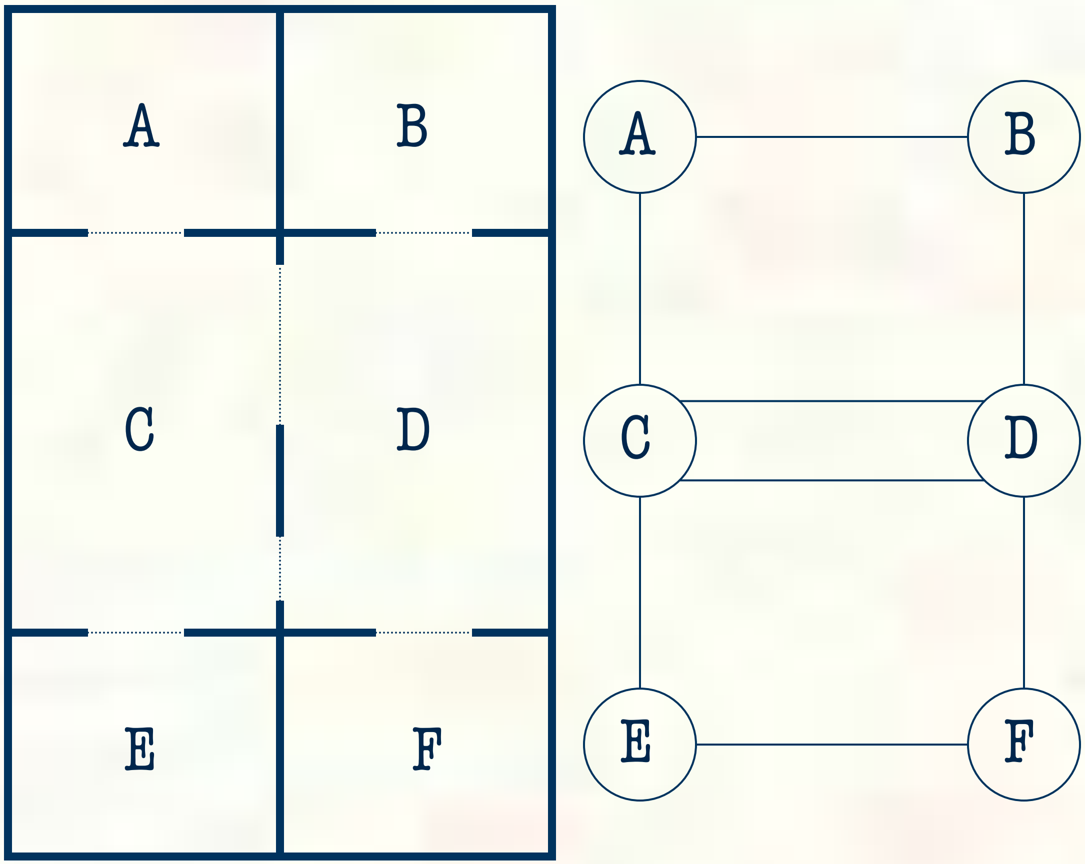
Point-based vs. Cell-based

- Point-based algorithms compute visibility from a specific point
  - Which point?
  - How often must you compute visibility?
- Cell-based algorithms compute visibility from an entire cell
  - Union of the stuff visible from each point in the cell
  - How often must you compute visibility?
- Which method has a smaller visible set?
- Which method is suitable for pre-computation?

Cell-Portal Structures

- Cell-Portal data structures dispense with the hierarchy and just store neighbor information
  - This make them graphs, not trees
- Cells are described by bounding polygons
- Portals are polygonal openings between cells
- Good for visibility culling algorithms, OK for collision detection and ray-casting
- Several ways to construct
  - By hand, as part of an authoring process
  - Automatically, starting with a BSP tree or kd-tree and extracting cells and portals
  - Explicitly, as part of an automated modeling process

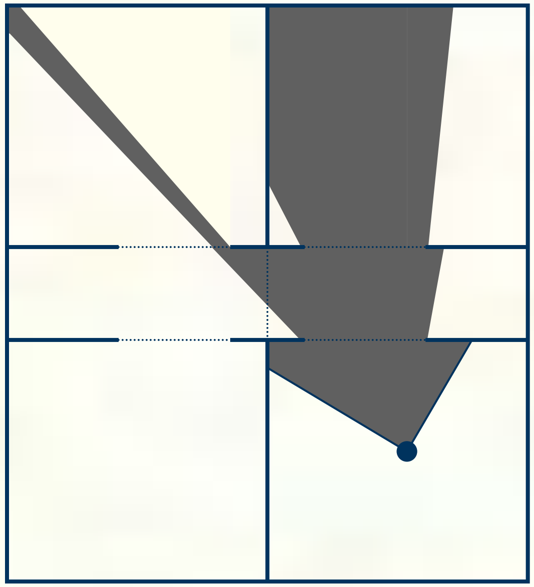
Cell Portal Example



- Portals can be one way (directed edges)
- Graph is normally stored in adjacency list format
  - Each cell stores the edges (portals) out of it

Cell-Portal Visibility

- Keep track of which cell the viewer is in
- Somehow walk the graph to enumerate all the visible regions
- Cell-based: Preprocess to identify the potentially visible set (PVS) for each cell
  - Set may contain whole cells or individual objects
- Point-based: Traverse the graph at runtime
  - Granularity can be whole cells, regions, or objects
- Trend is toward point-based, but cell-based is still very common
  - Why choose one over the other?

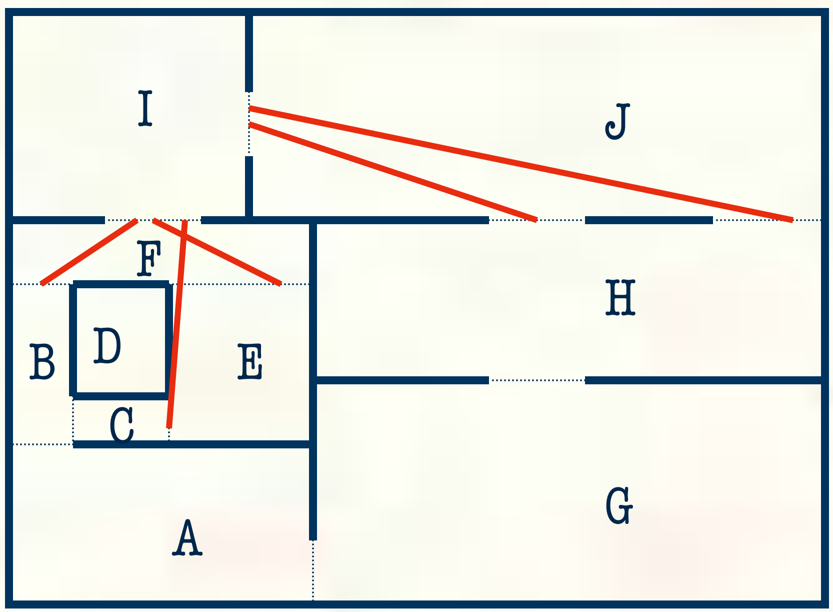


Potentially Visible Sets

- PVS: The set of cells/regions/objects/polygons that can be seen from a particular cell
  - Generally, choose to identify objects that can be seen
  - Trade-off is memory consumption vs. accurate visibility
- Computed as a pre-process
  - Have to have a strategy to manage dynamic objects
- Used in various ways:
  - As the only visibility computation - render everything in the PVS for the viewer's current cell
  - As a first step - identify regions that are of interest for more accurate run-time algorithms

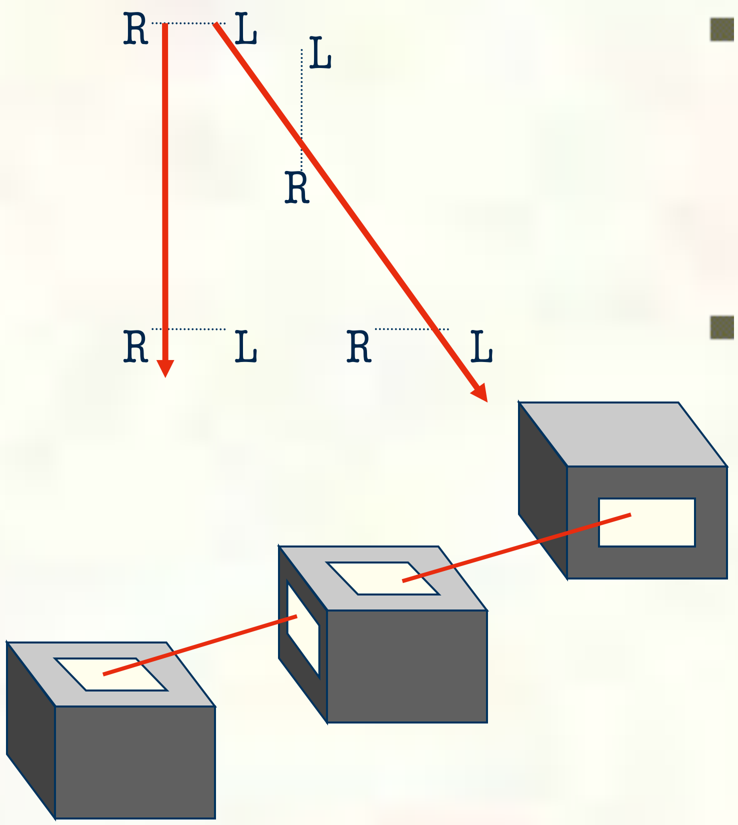
Cell-to-Cell PVS

- Cell A is in cell B's PVS if there exist a *stabbing line* that originates on a portal of B and reaches a portal of A
  - A *stabbing line* is a line segment intersecting only portals
  - Neighbor cells are trivially in the PVS



PVS for I contains:
B, C, E, F, H, J

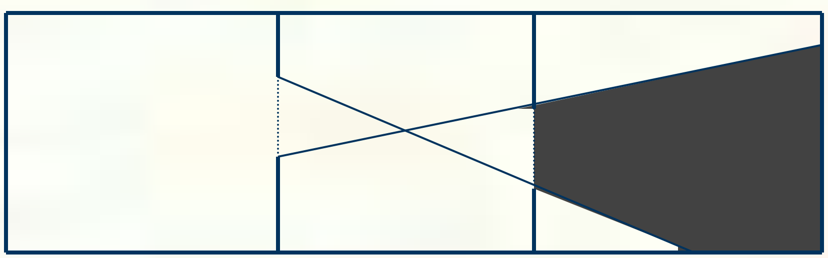
Finding Stabbing Lines



- In 2D, have to find a line that separates the left edges of the portals from the right edges
  - A linearly separable set problem solvable in *O(n)* where *n* is the number of portals
- In 3D, more complex because portals are now a sequence of arbitrarily aligned polygons
  - Put rectangular bounding boxes around each portal and stab those
  - *O(nlogn)* algorithm

Cell-To-Region PVS

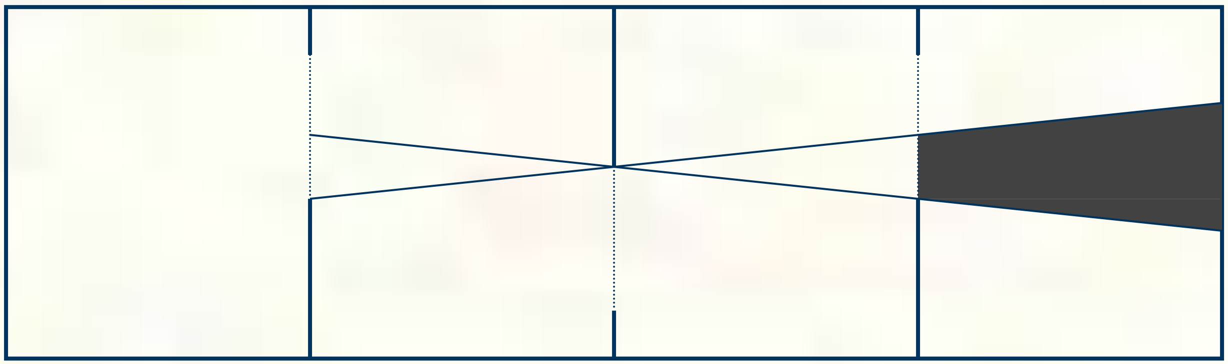
- Identify which *regions* are visible from a cell
  - Add objects within region to PVS for the cell
- Key idea is separating planes (or lines in 2D):
  - Lines going through left edge of one portal and right edge of the other, and vice versa
  - Potentially visible region is bounded by planes
  - In 3D, have to find maximal planes (those that make region biggest)



This picture should remind you of something (Hint: Think of the left portal as a light source)

Cell-To-Region (More)

- If the sequence has multiple portals, find maximal separating lines



- This work originates from many sources, including shadow computations and mesh generation for radiosity
- More applications of separating and supporting planes later
  - Is it OK to use portals that are larger than the actual opening?
  - Is it OK to use portals that are smaller than the actual opening?

Properties of PVSs?

- Almost all of the work is done as a preprocess
  - At run-time, simply traverse PVS and render contents
  - Can pre-compute display lists for each cell – fast rendering
- Most algorithms go further than just Cell-to-Cell PVS
  - It overestimates by quite a lot – PVS removes 90% of the model, 99.6% is actually invisible, and better visibility gets 98% (Teller 91)
- Cell-to-Cell PVS is good for dynamic objects
  - Associate moving objects with the cell they currently occupy
  - Draw a moving object if the cell it is in is visible

PVS Problems?

- Does not take into account the viewer's location, so reports things that the viewer cannot possibly see
- Not good at managing dynamic cells/portals
  - What do you do for doors that can be open or closed?
- Pre-processing time can be huge
  - Impacts development of game – turnaround time for changes is large
- Other algorithms address these things

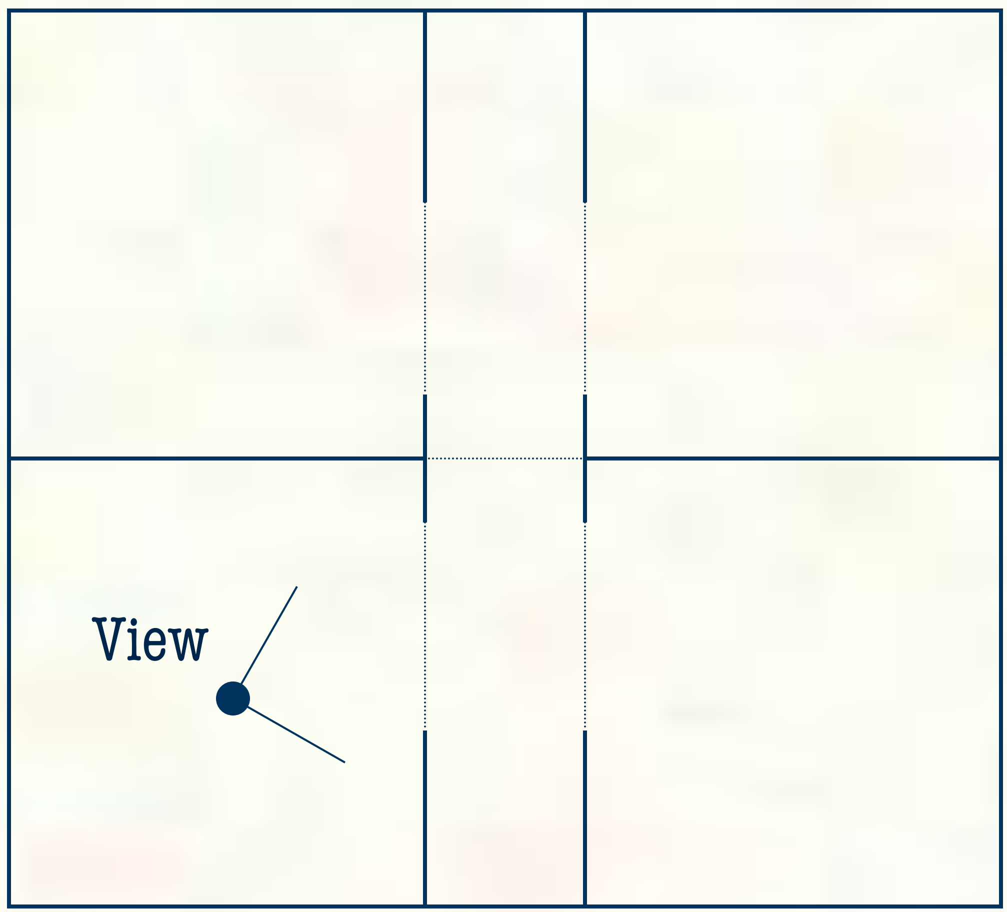
Enhancing Cell-to-Anything

- If the viewer cannot go everywhere in the cell, then cell-based visibility will be too pessimistic
- One solution is to add special cells that the viewer can see into, but can't see out of
  - Put them in places that the viewer cannot go, but can still see
    - Above a certain altitude in outdoor games
    - Below the player's minimum eye level
  - Basically implemented as one-way portals
    - The portals only exist in the direction into the cell
  - Note, doesn't work if the player should be able to see through a special cell into another cell beyond – why not?

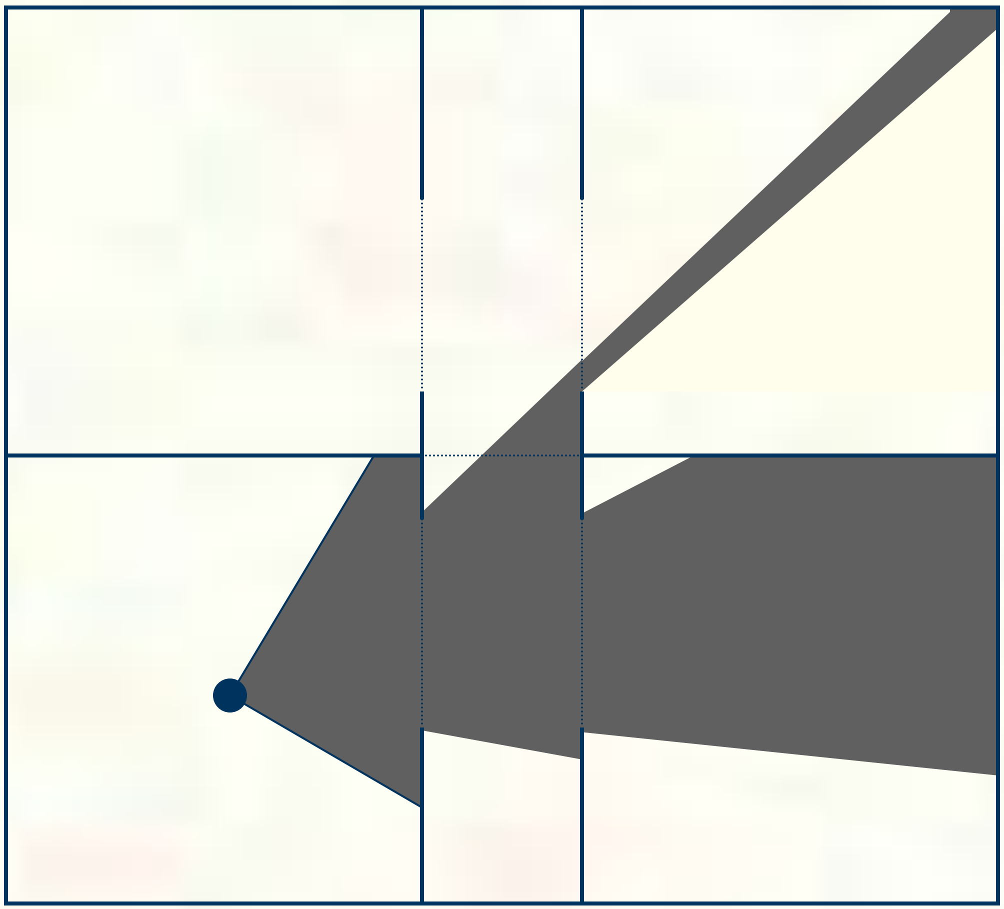
Runtime Portal Visibility

- Define a procedure renderCell:
  - Takes a view frustum and a cell
    - Viewer not necessarily in the cell
  - Draws the contents of the cell that are in the frustum
  - For each portal out of the cell, clips the frustum to that portal and recurses with the new frustum and the cell beyond the portal
    - Make sure not to go to the cell you entered
- Start in the cell containing the viewer, with the full viewing frustum
- Stop when no more portals intersect the view frustum

Eye-to-Region Example (1)



Eye-to-Region Example (2)



Implementation

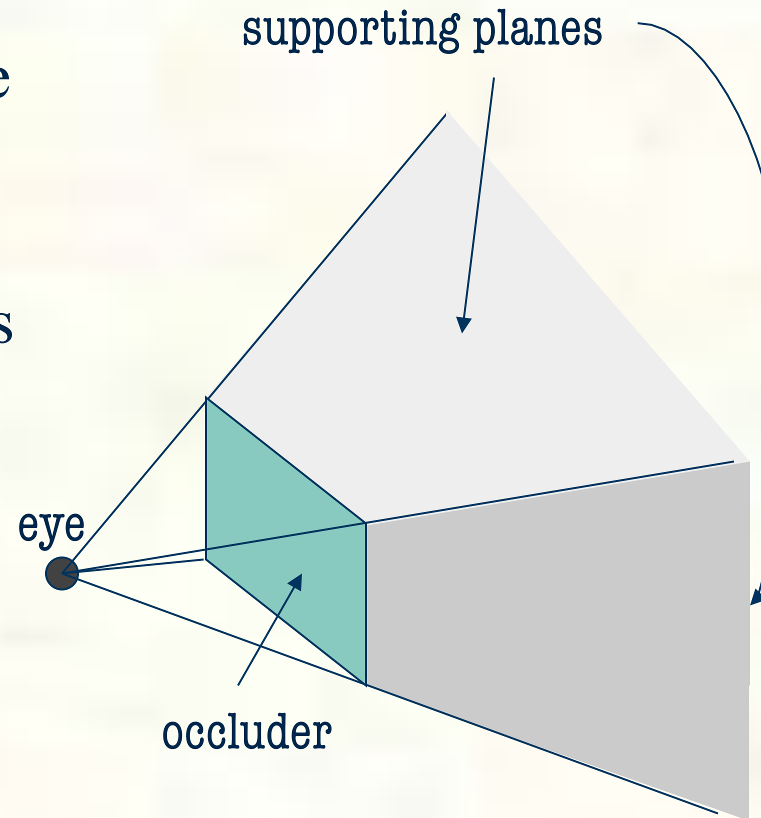
- Each portal that is passed through contributes some clipping planes to the frustum
  - If the hardware has enough planes, add them as hardware clipping planes
  - Or, clip object bounding volumes against them to determine which objects to draw
- Mirrors are reasonably easy to deal with
  - Flip the view frustum about the mirror
  - Add appropriate clipping planes to make sure the right things are drawn
- A very effective algorithm if the portals are simple
  - More complex portals can be bounded with screen-space rectangles

No Cell or Portals?

- Many scenes do not admit a good cell and portal structure
  - Scenes without large co-planar polygons to act as blockers or cell walls
  - Canonical example is a forest – you can't see through it, but no one leaf is responsible
- What can we do?
  - Find *occluders* and use them to cull geometry
  - Inverse of cells as portals: Assume all space is open and explicitly look at places where it is blocked

Using Occluders

- Assume the occluder is a polygon
- Form clipping planes using the eye point and the polygon edges
  - *Supporting planes*
- Objects inside all of the occluder's clipping planes are NOT visible
  - Occluder itself is a clipping plane
  - Can use tests similar to view frustum culling, but note that now we trivially accept as soon as the object is *outside* a clipping plane



Simple Occluder Finding

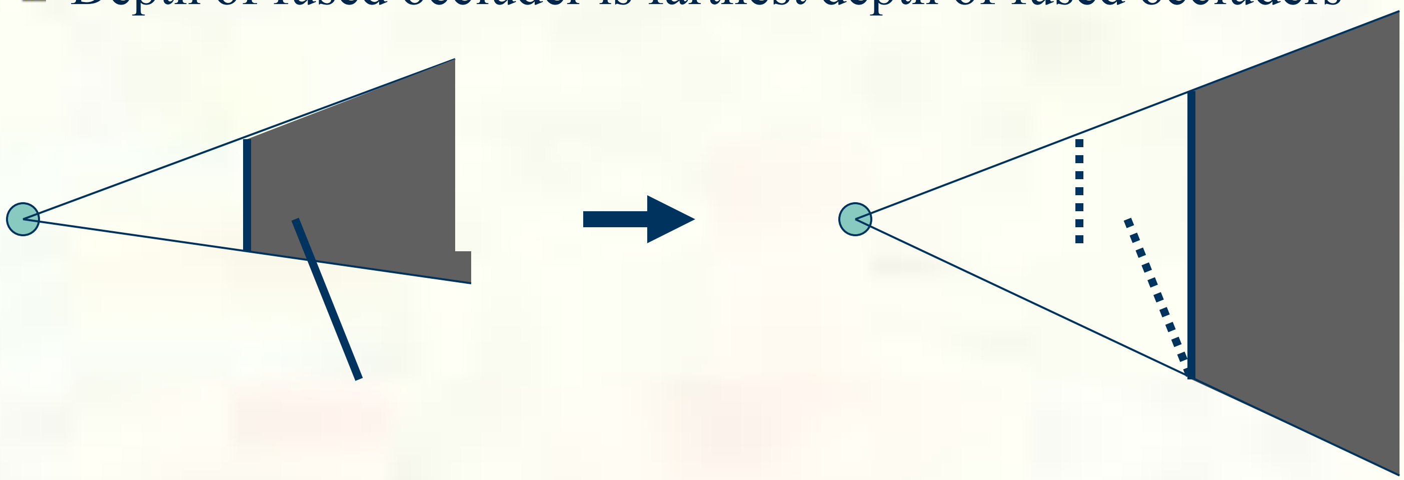
- Cell based approach
- Find good sets of occluders for each cell in a preprocess
  - At run time, use occluders from the viewer’ s region
- What makes a good occluder?
  - Things that occlude lots of stuff
  - What properties will a good occluder have?

Simple Occluder Issues

- Works best when there are large polygons close to the viewer
  - Dashboards are a good example
- For objects, how do you choose their “occlusion shape”?
- Level designers can add special polygons just to act as occluders
  - In what situation would you do this?
  - But should they be drawn?
- Cell size is clearly important
- Problem: If an object is partially hidden by one occluder, and partially by another, it is hard to determine whether the entire object is occluded

Occluder Fusion

- Small occluders can be merged to generate larger occluders
  - Level editors are essentially doing this by hand when they place special occluders
- Key insight: If a potential occluder intersects the occluded region of another, they can be fused
  - Depth of fused occluder is farthest depth of fused occluders



Algorithms for Combining Occluders

- *Occlusion Horizons* work for 2.5D scenes
  - Great for cities and the like
  - An extension exists for relatively simple 3D scenes (eg bridges)
- Green's *Hierarchical Z-Buffer* builds occluders in screen space and does occlusion tests in screen space
  - Requires special hardware or a software renderer
- Zhang et.al. *Hierarchical Occlusion Maps* render occluders into a texture map, then compare objects to the map
  - Uses existing hardware, but pay for texture creation operations at every frame
  - Allows for approximate visibility if desired (sometimes don't draw things that should be)
- Schaufler et.al. *Occluder Fusion* builds a spatial data structure of occluded regions