SIGGRAPH2005

Ray Tracing Performance

Zero to Millions in 45 Minutes

Gordon Stoll, Intel

Goals for this talk

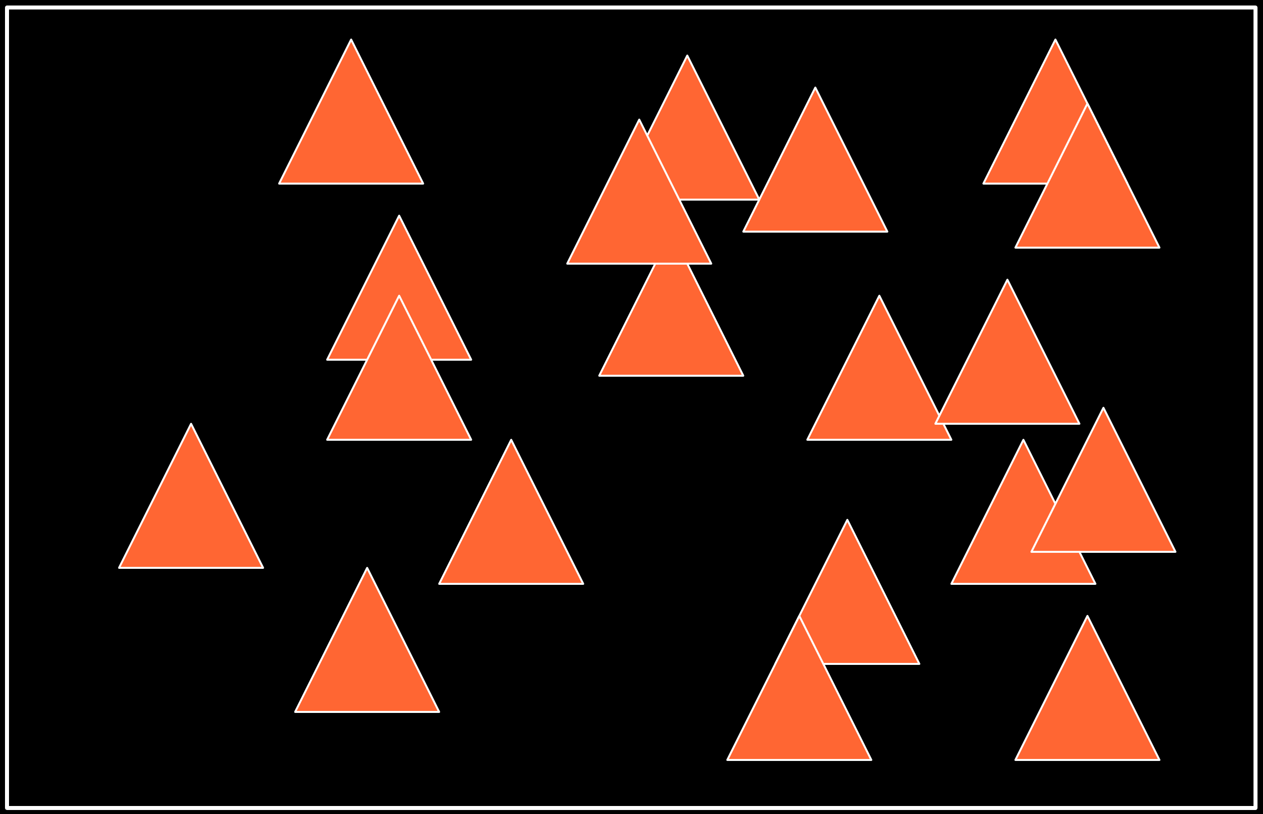
SIGGRAPH2005

- Goals
  - point you toward the current state-of-the-art (“BKM”)
    - for non-researchers: off-the-shelf performance
    - for researchers: baseline for comparison
  - get you interested in poking at the problem
- Non-Goals
  - present lowest-level details of kernels
  - present “the one true way”

Acceleration Structures

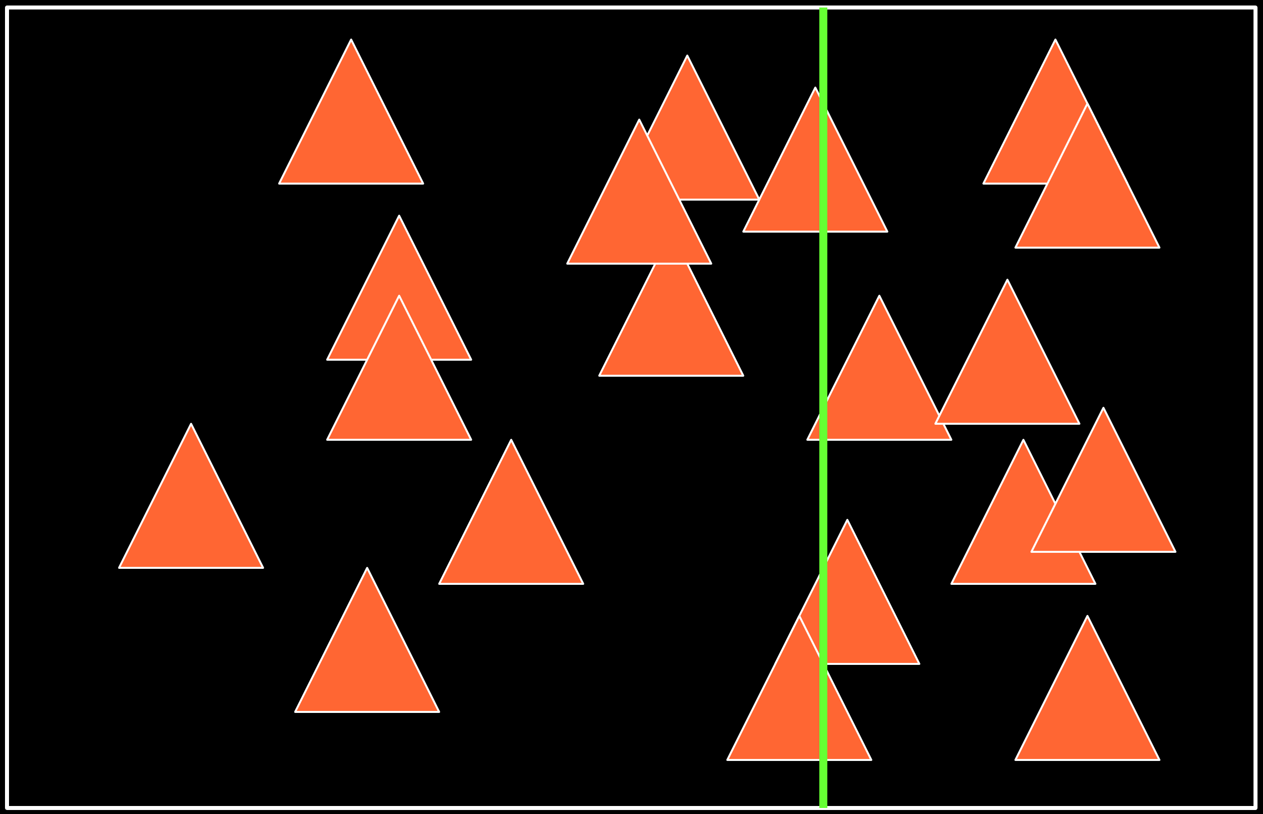
- BKM is to use a kD-tree (AA BSP)
- Previous BKM was to use a uniform grid
  - Only scheme with comparable speed
  - Performance is not robust
  - No packet tracing algorithm
- Other grids, octrees, etc…just use a kD-tree.
- *Don't use bounding volume hierarchies.*

kD-Trees

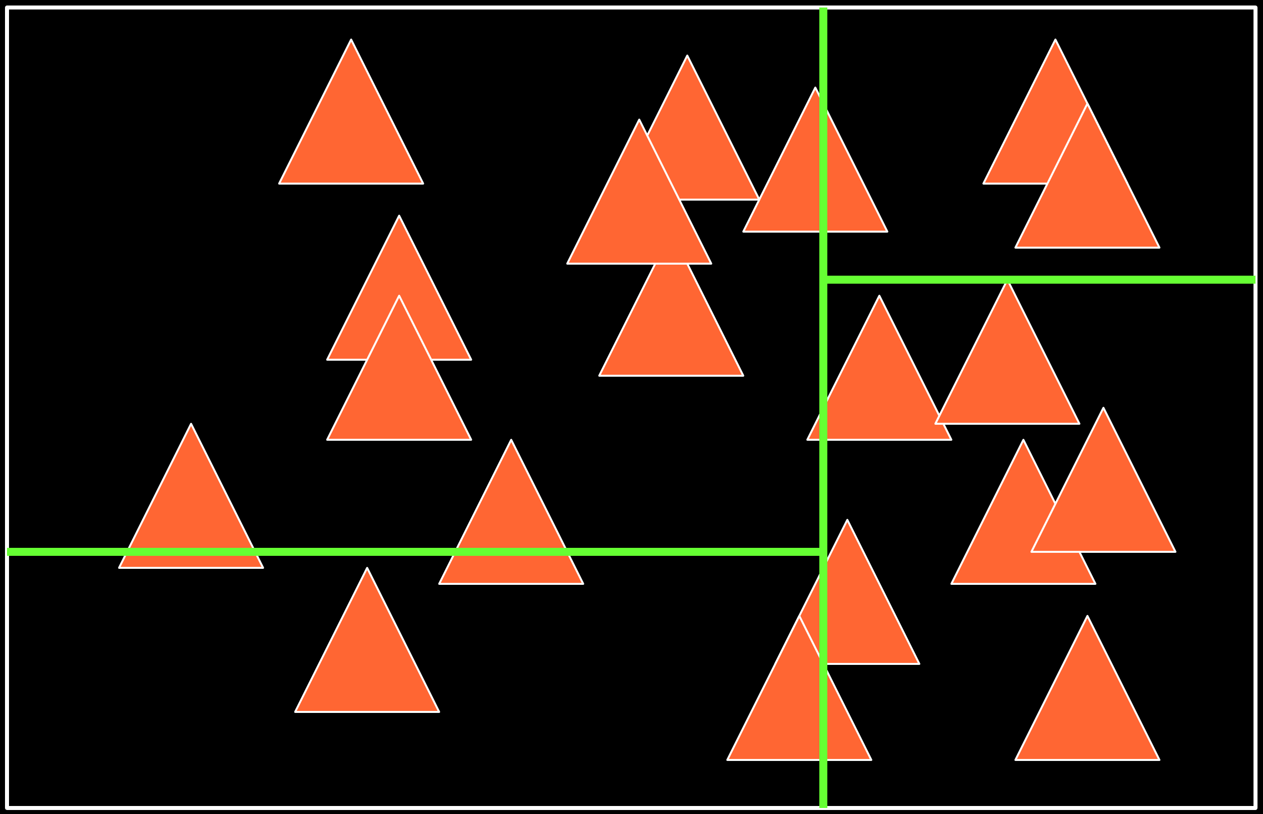


kD-Trees

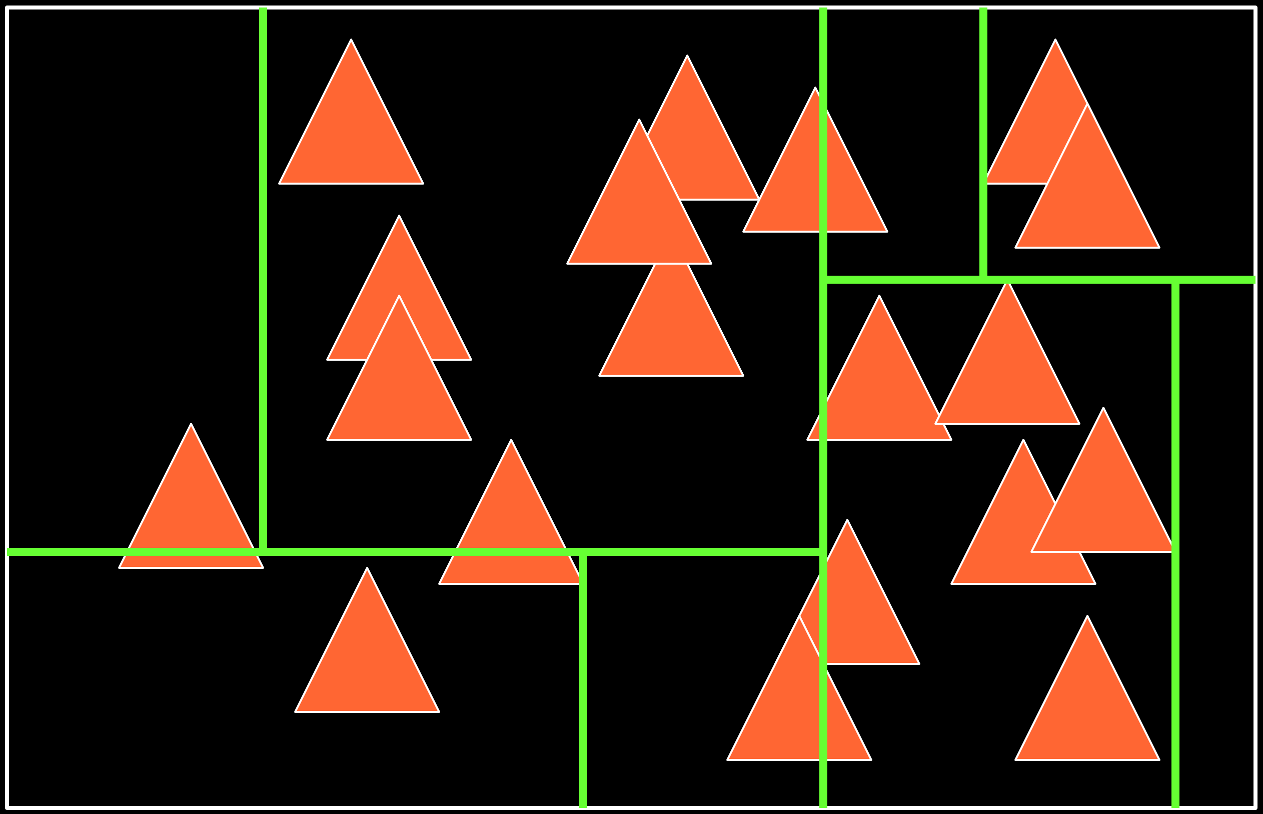
SIGGRAPH2005



kD-Trees



kD-Trees



Advantages of kD-Trees

SIGGRAPH2005

- Adaptive
  - Can handle the “Teapot in a Stadium”
- Compact
  - Relatively little memory overhead
- Cheap Traversal
  - One FP subtract, one FP multiply

Take advantage of advantages

SIGGRAPH2005

- Adaptive
  - You have to build a good tree
- Compact
  - At least use the compact node representation (8-byte)
  - You can’t be fetching whole cache lines every time
- Cheap traversal
  - No sloppy inner loops! (one subtract, one multiply!)

“Bang for the Buck” (!/$)

SIGGRAPH2005

A basic kD-tree implementation will go pretty fast…

…but extra effort will pay off *big.*

Fast Ray Tracing w/ kD-Trees

- Adaptive
- Compact
- Cheap traversal

Building kD-trees

SIGGRAPH2005

- Given:
  - axis-aligned bounding box (“cell”)
  - list of geometric primitives (triangles?) touching cell
- Core operation:
  - pick an axis-aligned plane to split the cell into two parts
  - sift geometry into two batches (some redundancy)
  - recurse

Building kD-trees

SIGGRAPH2005

- Given:
  - axis-aligned bounding box (“cell”)
  - list of geometric primitives (triangles?) touching cell
- Core operation:
  - pick an axis-aligned plane to split the cell into two parts
  - sift geometry into two batches (some redundancy)
  - recurse
  - termination criteria!

“Intuitive” kD-Tree Building

SIGGRAPH2005

- Split Axis
  - Round-robin; largest extent
- Split Location
  - Middle of extent; median of geometry (balanced tree)
- Termination
  - Target # of primitives, limited tree depth

“Hack” kD-Tree Building

SIGGRAPH2005

- Split Axis
  - Round-robin; largest extent
- Split Location
  - Middle of extent; median of geometry (balanced tree)
- Termination
  - Target # of primitives, limited tree depth
- All of these techniques stink.

“Hack” kD-Tree Building

SIGGRAPH2005

- Split Axis
  - Round-robin; largest extent
- Split Location
  - Middle of extent; median of geometry (balanced tree)
- Termination
  - Target # of primitives, limited tree depth
- All of these techniques stink. Don’t use them.

“Hack” kD-Tree Building

- Split Axis
  - Round-robin; largest extent
- Split Location
  - Middle of extent; median of geometry (balanced tree)
- Termination
  - Target # of primitives, limited tree depth
- All of these techniques stink. Don’t use them.
  - I mean it.

Building good kD-trees

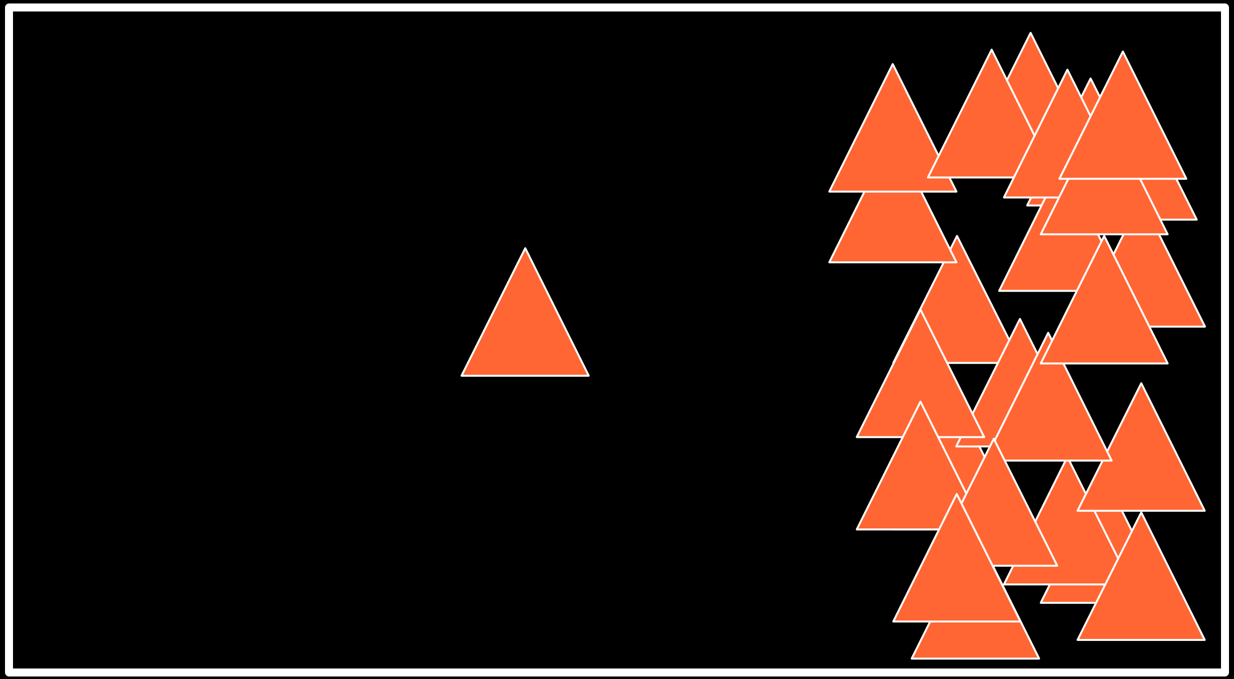
SIGGRAPH2005

- What split do we really want?
  - Clever Idea: The one that makes ray tracing cheap
  - Write down an expression of cost and minimize it
  - *Cost Optimization*
- What is the cost of tracing a ray through a cell?

Cost(cell) = C_trav + Prob(hit L) * Cost(L) + Prob(hit R) * Cost(R)

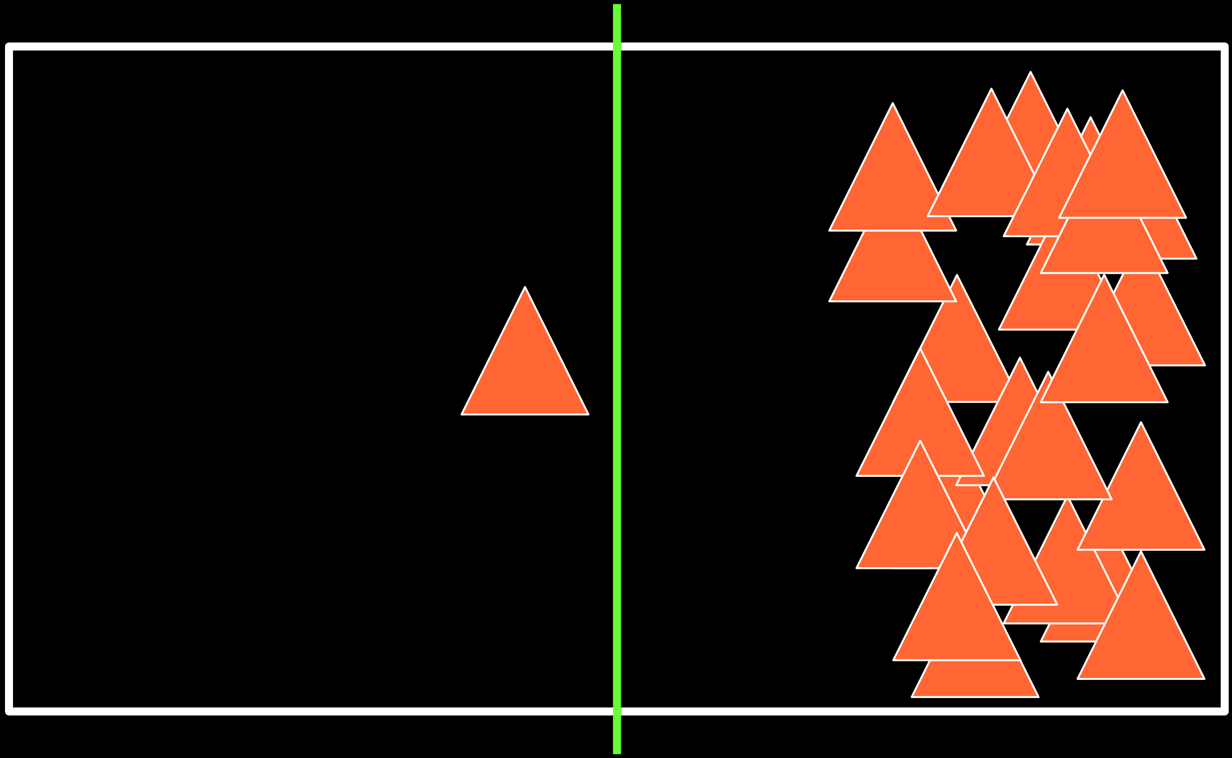
Splitting with Cost in Mind

SIGGRAPH2005



Split in the middle

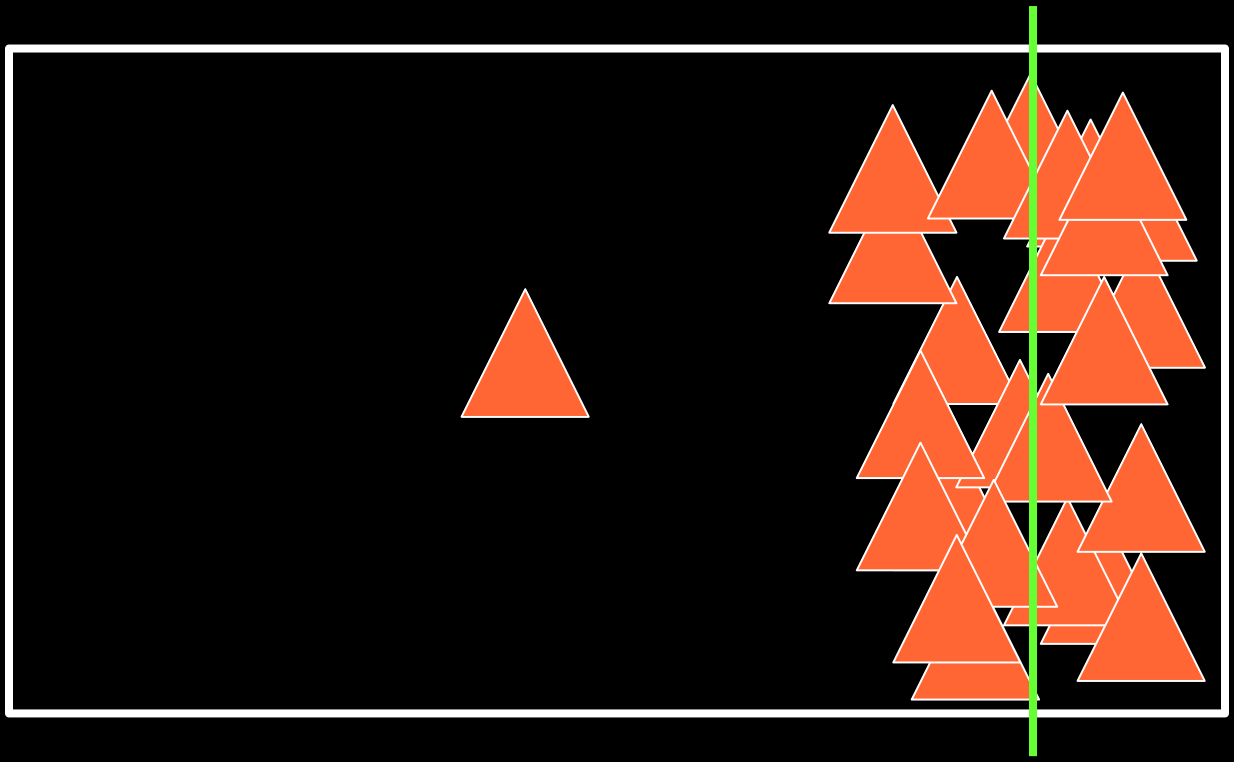
SIGGRAPH2005



- Makes the L & R probabilities equal
- Pays no attention to the L & R costs

Split at the Median

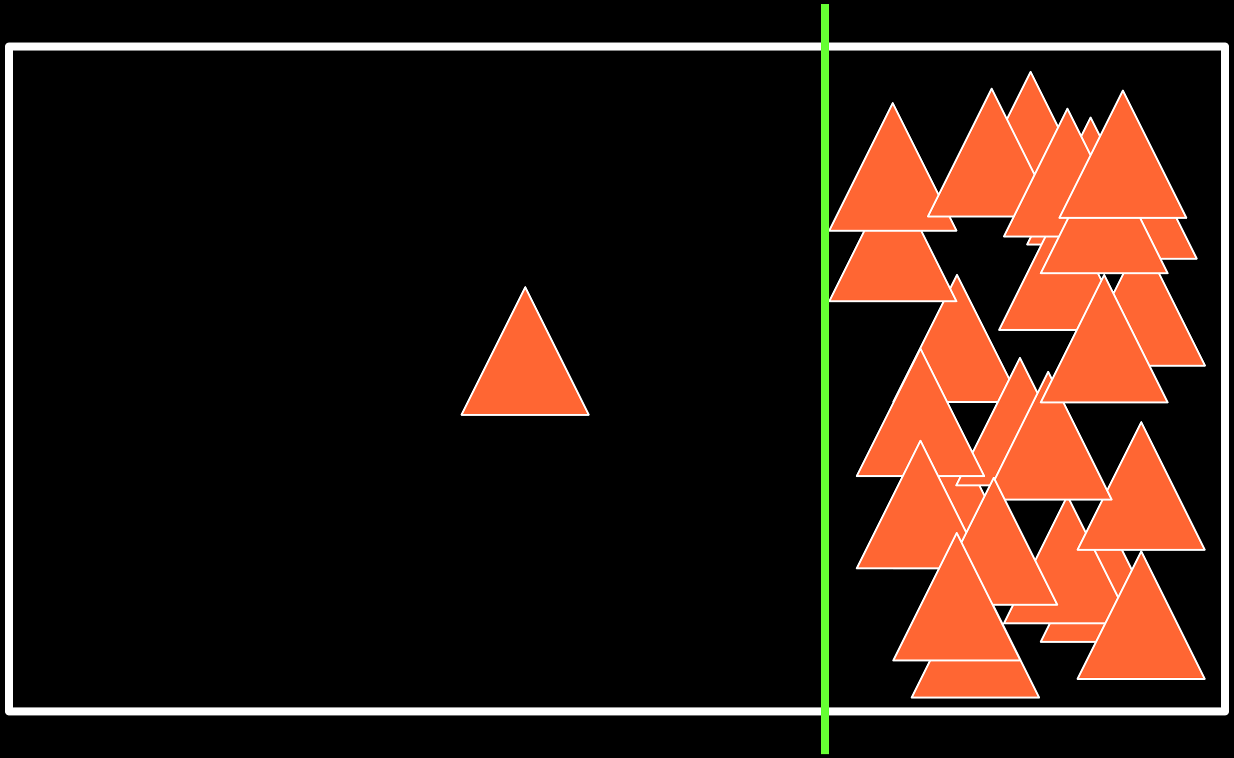
SIGGRAPH2005



- Makes the L & R costs equal
- Pays no attention to the L & R probabilities

Cost-Optimized Split

SIGGRAPH2005



- Automatically and rapidly isolates complexity
- Produces large chunks of empty space

Building good kD-trees

SIGGRAPH2005

- Need the probabilities
  - Turns out to be proportional to surface area
- Need the child cell costs
  - Simple triangle count works great (very rough approx.)

Cost(cell) = C_trav + Prob(hit L) * Cost(L) + Prob(hit R) * Cost(R)

= C_trav + SA(L) * TriCount(L) + SA(R) * TriCount(R)

Termination Criteria

- When should we stop splitting?
  - Another Clever idea: When splitting isn't helping any more.
  - Use the cost estimates in your termination criteria
- Threshold of cost improvement
  - Stretch over multiple levels
- Threshold of cell size
  - Absolute probability so small there's no point

Building good kD-trees

- Basic build algorithm
  - Pick an axis, or optimize across all three
  - Build a set of “candidates” (split locations)
    - BBox edges or exact triangle intersections
  - Sort them or bin them
  - Walk through candidates or bins to find minimum cost split
- Characteristics you’re looking for
  - “stringy”, depth 50-100, ~2 triangle leaves, big empty cells

Just Do It

- Benefits of a good tree are *not* small
  - not 10%, 20%, 30%...
  - several *times* faster than a mediocre tree

Building kD-trees quickly

SIGGRAPH2005

- Very important to build good trees first
  - otherwise you have no basis for comparison
- Don’t give up cost optimization!
  - Use the math, Luke…
- Luckily, *lots* of flexibility…
  - axis picking (“hack” pick vs. full optimization)
  - candidate picking (bboxes, exact; binning, sorting)
  - termination criteria (“knob” controlling tradeoff)

Building kD-trees quickly

- Remember, profile first! Where's the time going?
  - split personality
    - memory traffic all at the top (NO cache misses at bottom)
      - sifting through bajillion triangles to pick one split (!)
      - hierarchical building?
    - computation mostly at the bottom
      - lots of leaves, need more exact candidate info
      - lazy building?
    - change criteria during the build?

Fast Ray Tracing w/ kD-Trees

SIGGRAPH2005

- adaptive
  - build a cost-optimized kD-tree w/ the surface area heuristic
- compact
- cheap traversal

What’s in a node?

- A kD-tree internal node needs:
  - Am I a leaf?
  - Split axis
  - Split location
  - Pointers to children

Compact (8-byte) nodes

SIGGRAPH2005

- kD-Tree node can be packed into 8 bytes
  - Leaf flag + Split axis
    - 2 bits
  - Split location
    - 32 bit float
  - Always two children, put them side-by-side
    - One 32-bit pointer

Compact (8-byte) nodes

SIGGRAPH2005

- kD-Tree node can be packed into 8 bytes
  - Leaf flag + Split axis
    - 2 bits
  - Split location
    - 32 bit float
  - Always two children, put them side-by-side
    - One 32-bit pointer
- So close! Sweep those 2 bits under the rug…

No Bounding Box!

SIGGRAPH2005

- kD-Tree node corresponds to an AABB
- Doesn’t mean it has to *contain* one
  - 24 bytes
  - 4X explosion (!)

Memory Layout

- Cache lines are much bigger than 8 bytes!
  - advantage of compactness lost with poor layout
- Pretty easy to do something reasonable
  - Building depth first, watching memory allocator

Other Data

SIGGRAPH2005

- Memory should be separated by rate of access
  - Frames
  - << Pixels
  - << Samples [Ray Trees]
  - << Rays [Shading (not quite)]
  - << Triangle intersections
  - << Tree traversal steps
- Example: pre-processed triangle, shading info…

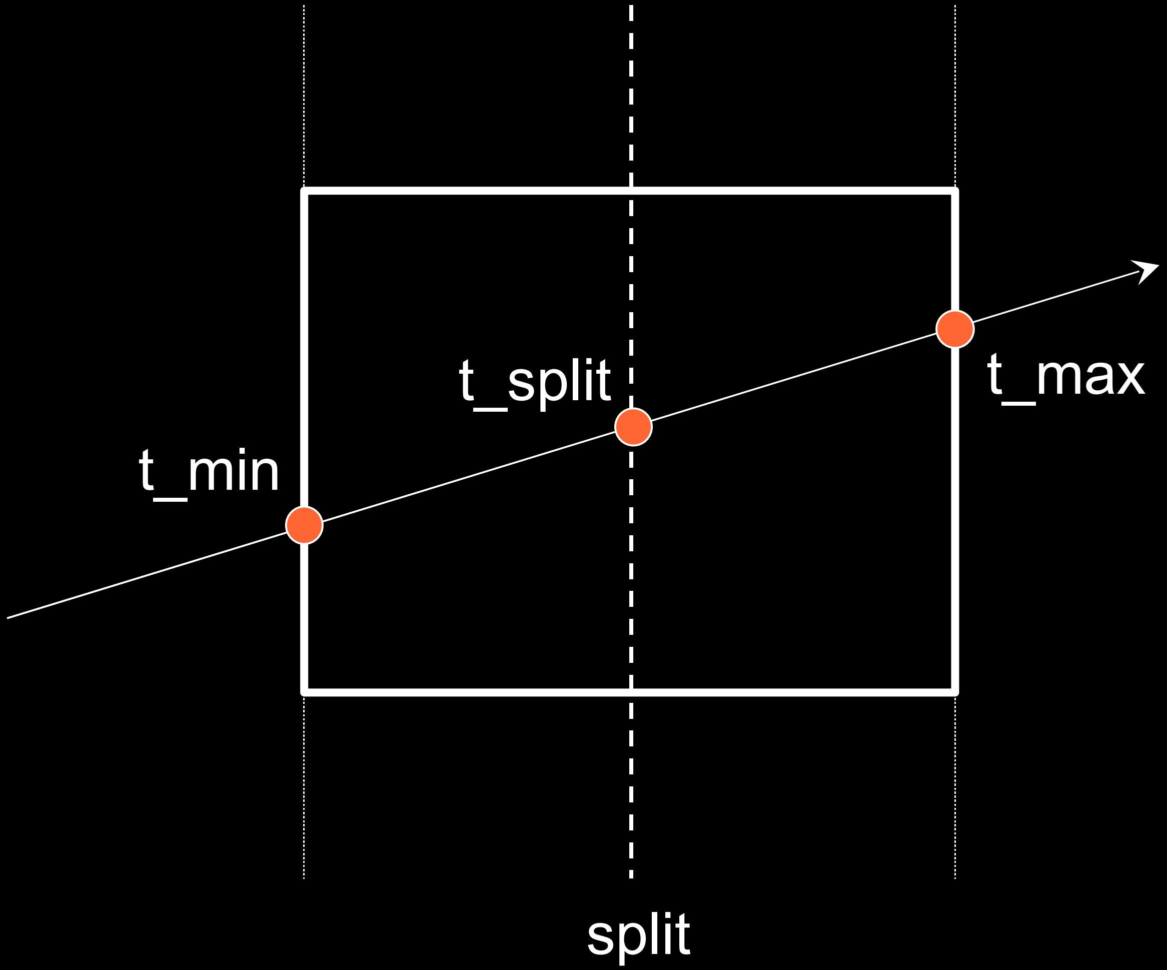
Fast Ray Tracing w/ kD-Trees

SIGGRAPH2005

- adaptive
  - build a cost-optimized kD-tree w/ the surface area heuristic
- compact
  - use an 8-byte node
  - lay out your memory in a cache-friendly way
- cheap traversal

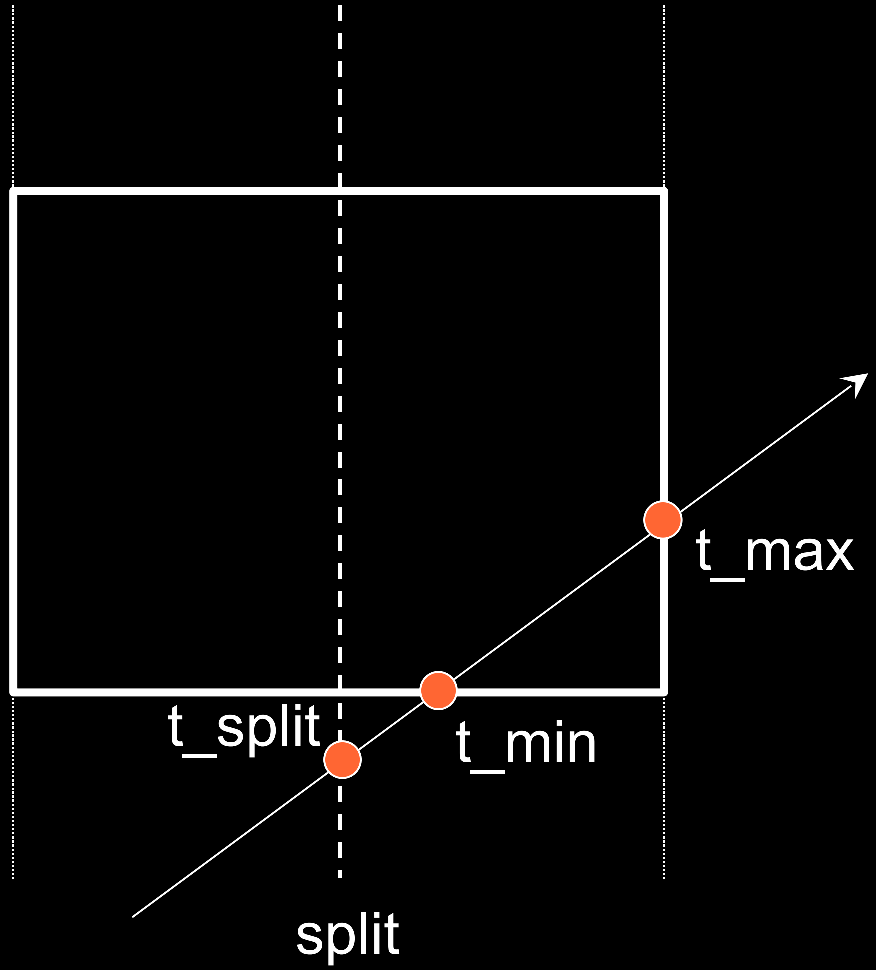
kD-Tree Traversal Step

SIGGRAPH2005



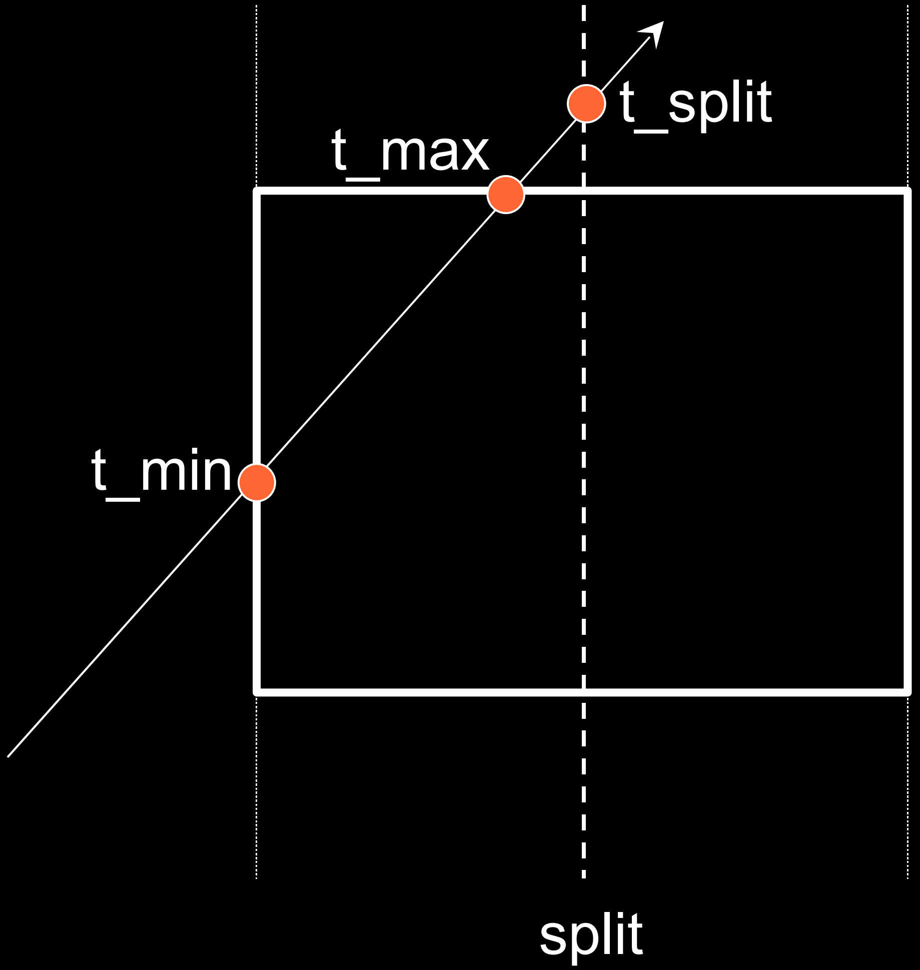
kD-Tree Traversal Step

SIGGRAPH2005



SIGGRAPH2005

kD-Tree Traversal Step



kD-Tree Traversal Step

SIGGRAPH2005

Given: ray P & iV (1/V), t_min, t_max, split_location, split_axis

```
t_at_split = ( split_location - ray->P[split_axis] ) * ray_iV[split_axis]

if t_at_split > t_min
    need to test against near child
If t_at_split < t_max
    need to test against far child
```

Optimize Your Inner Loop

SIGGRAPH2005

- kD-Tree traversal is the most critical kernel
  - It happens about a zillion times
  - It's tiny
  - Sloppy coding *will* show up
- Optimize, Optimize, Optimize
  - Remove recursion and minimize stack operations
  - Other standard tuning & tweaking

kD-Tree Traversal

SIGGRAPH2005

```
while ( not a leaf )
    t_at_split = ( split_location - ray->P[split_axis] ) * ray_iV[split_axis]
    if t_split <= t_min
        continue with far child        // hit either far child or none
    if t_split >= t_max
        continue with near child       // hit near child only
    // hit both children
    push (far child, t_split, t_max) onto stack
    continue with (near child, t_min, t_split)
```

Can it go faster?

- How do you make fast code go faster?
- Parallelize it!

Ray Tracing and Parallelism

SIGGRAPH2005

- Classic Answer: Ray-Tree parallelism
  - independent tasks
  - # of tasks = millions (at least)
  - size of tasks = thousands of instructions (at least)
- So this is wonderful, right?

Parallelism in CPUs

SIGGRAPH2005

- Instruction-Level Parallelism (ILP)
  - pipelining, superscalar, OOO, SIMD
  - fine granularity (~100 instruction “window” tops)
  - easily confounded by unpredictable control
  - easily confounded by unpredictable latencies
- So…what does ray tracing look like to a CPU?

No joy in ILP-ville

SIGGRAPH2005

- At <1000 instruction granularity, ray tracing is anything *but* “embarrassingly parallel”
- kD-Tree traversal (CPU view):

    1) fetch a tiny fraction of a cache line from who knows where

    2) do two piddling floating-point operations

    3) do a completely unpredictable branch, or two, or three

    4) repeat until frustrated

    PS: Each operation is dependent on the one before it.

    PPS: No SIMD for you! Ha!

Split Personality

- Coarse-Grained parallelism (TLP) is perfect
  - millions of independent tasks
  - thousands of instructions per task
- Fine-Grained parallelism (ILP) is *awful*
  - look at a scale <1000 of instructions
    - sequential dependencies
    - unpredictable control paths
    - unpredictable latencies
    - no SIMD

Options

SIGGRAPH2005

- Option #1: Forget about ILP, go with TLP
  - improve low-ILP *efficiency* and use multiple CPU cores
- Option #2: Let TLP stand in for ILP
  - run multiple independent threads (ray trees) on one core
- Option #3: Improve the ILP situation directly
  - how?
- Option #4: …

…All of the above!

SIGGRAPH2005

- multi-core CPUs are already here (more coming)
  - better performance, better low-ILP performance
  - on the right performance curve
- multi-threaded CPUs are already here
  - improve well-written ray tracer by ~20-30%
- packet tracing
  - trace multiple rays together in a packet
  - bulk up the inner loop with ILP-friendly operations

Packet Tracing

SIGGRAPH2005

- Very, very old idea from vector/SIMD machines
  - Vector masks
- Old way
  - if the ray wants to go left, go left
  - if the ray wants to go right, go right
- New way
  - if *any* ray wants to go left, go left with mask
  - if *any* ray wants to go right, go right with mask

Key Observations

- Doesn’t add “bad” stuff
  - Traverses the same nodes
  - Adds no global fetches
  - Adds no unpredictable branches
- What it does add
  - SIMD-friendly floating-point operations
  - Some messing around with masks

Result: Very robust in relation to single rays

How many rays in a packet?

SIGGRAPH2005

- Packet tracing gives us a “knob” with which to adjust computational intensity.
- Do natural SIMD width first
- Real answer is potentially much more complex
  - diminishing returns due to per-ray costs
  - lack of coherence to support big packets
  - register pressure, L1 pressure
- Makes hardware much more likely/possible

Fast Ray Tracing w/ kD-Trees

SIGGRAPH2005

- Adaptive
  - build a cost-optimized tree (w/ surface area heuristic)
- Compact
  - use an 8-byte node
  - lay out your memory in a cache-friendly way
- Cheap traversal
  - optimize your inner loop
  - trace packets

Getting started…

SIGGRAPH2005

- Read PBRT (yeah, I know, it's 1300 pages)
  - great book, pretty decent kD-tree builder
- Read Ingo Wald's thesis
  - lots of coding details for this stuff
- Track down the interesting references
- Learn SIMD programming (e.g. SSE intrinsics)
- Use a profiler.

Getting started…

SIGGRAPH2005

- Read PBRT (yeah, I know, it's 1300 pages)
  - great book, pretty decent kD-tree builder
- Read Ingo Wald's thesis
  - lots of coding details for this stuff
- Track down the interesting references
- Learn SIMD programming (e.g. SSE intrinsics)
- Use a profiler. I mean it.

If you remember nothing else

SIGGRAPH2005

- “Rays per Second” is measured in *millions*.