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Out-Of-Core Construction of Sparse Voxel Octrees

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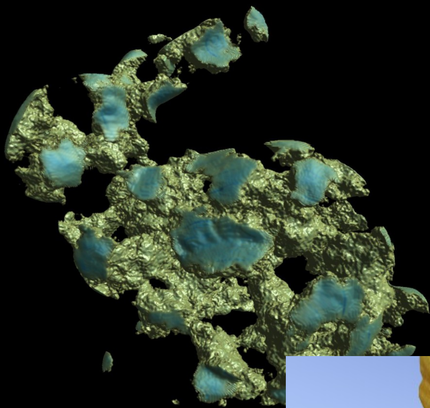
Voxel-related research

- Voxel Ray Casting
  - Gigavoxels (Crassin, 2009-...)
  - Efficient SVO's (Laine, Karras, 2010)
- Voxel Cone Tracing
  - Indirect Illumination (Crassin, 2011)
- Voxel-based Visibility
  - Voxelized Shadow Volumes (Wyman, 2013, later today!)
- ...



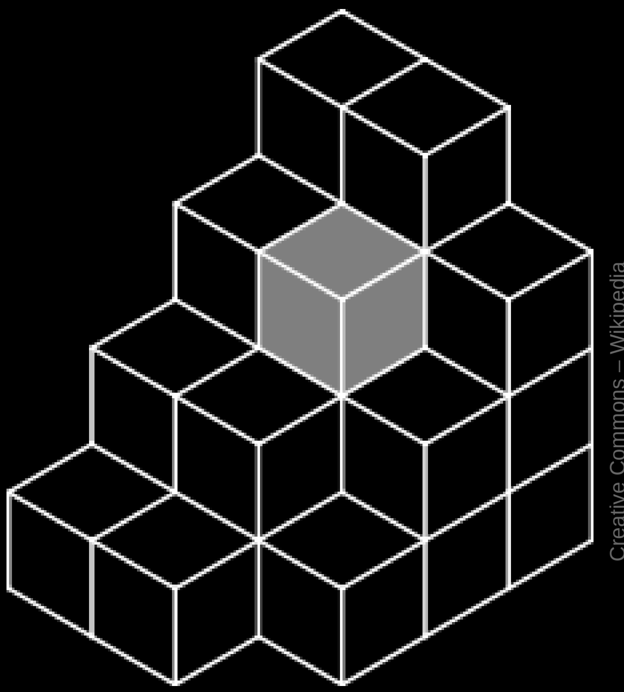
Crassin 2009

Laine / Karras 2010

Crassin 2011

Why voxels?

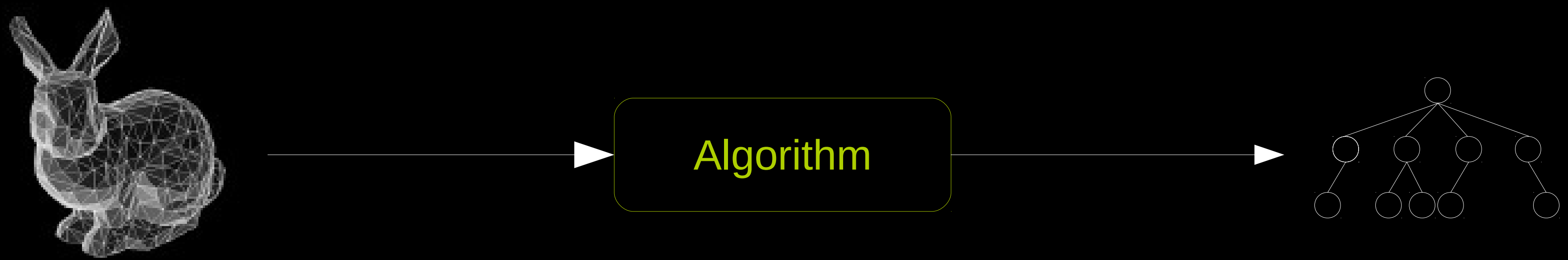
- Regular structure
- Hierarchical representation in **S**parse **V**oxel **O**ctrees (SVO's)
  - Level of Detail / Filtering
- Generic representation for geometry **and** appearance
  - In *a single* data structure



Polygon mesh to SVO

- We want large, highly detailed SVO scenes
- Where do we find content?
- Let's voxelize massive polygon meshes
  - Majority of current content pipelines is polygon-based

What do we want?

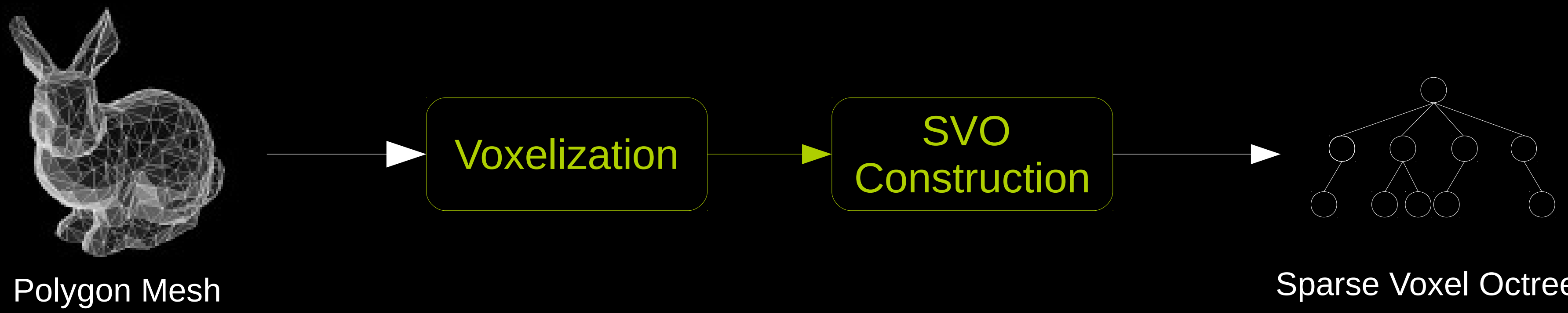


Polygon Mesh

Sparse Voxel Octree

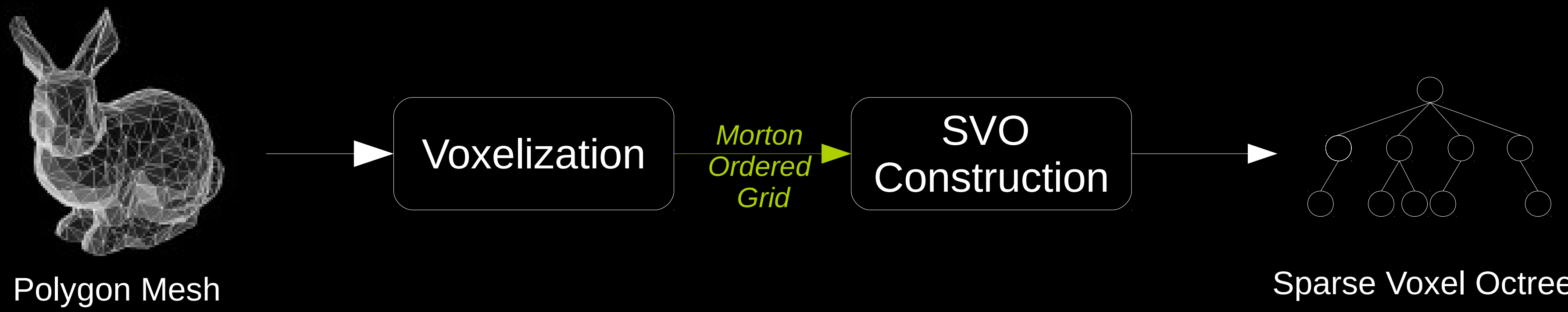
- Algorithm requirements:
  - Need an **out-of-core** method
    - Because polygon mesh &
      intermediary structures could be >> system memory
  - Data should be streamed in/out
    - from disk / network / other process
  - Ideally: out-of-core as fast as in-core

Pipeline construction (1)



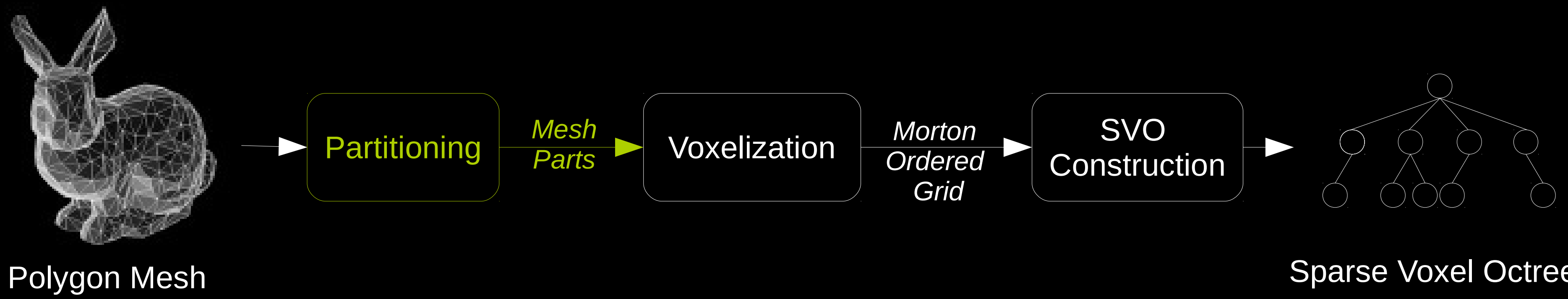
- Voxelization step
  - Polygon mesh → Voxel grid
- Followed by SVO construction step
  - Voxel grid → Sparse Voxel Octree

Pipeline construction (2)

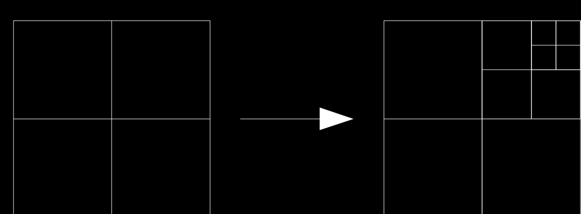


- Key insight:
  - If voxel grid is Morton-ordered
  - SVO construction can be done **out-of-core**
    - Logarithmic in memory usage ~ octree size
    - In a streaming manner
  - So voxelization step should deliver ordered voxels

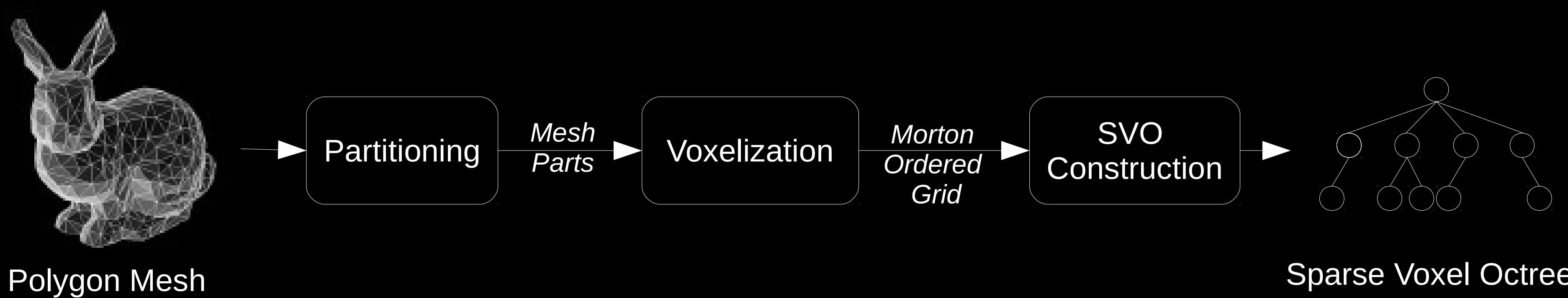
Pipeline construction (3)



- High-resolution 3D voxel grid may be **>>** system memory
  - So partitioning step (into subgrids) is needed
  - Seperate triangle streams for each subgrid



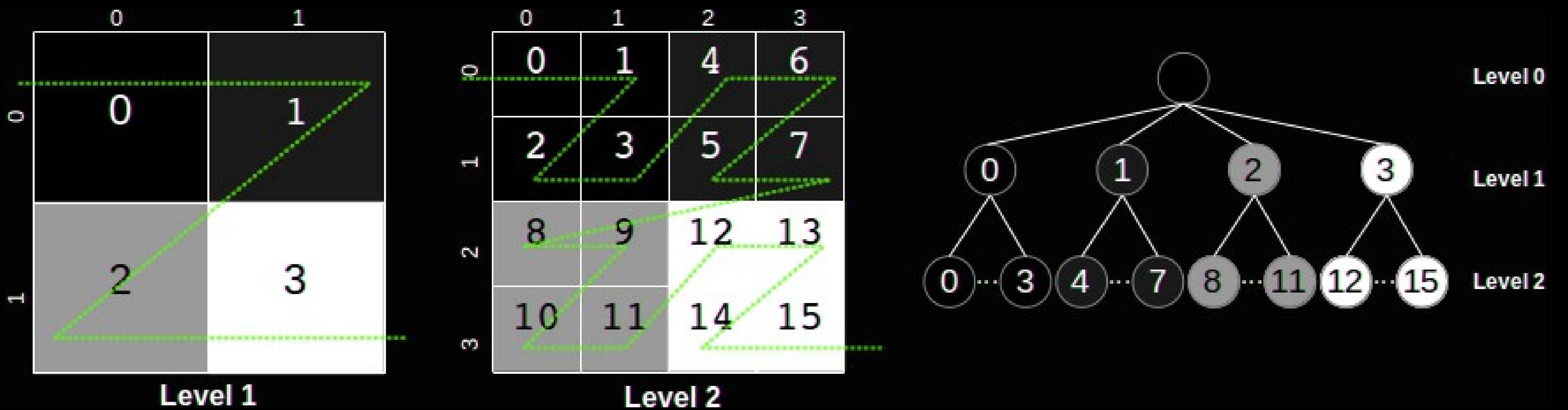
Final Pipeline



- Now, every step in detail ...

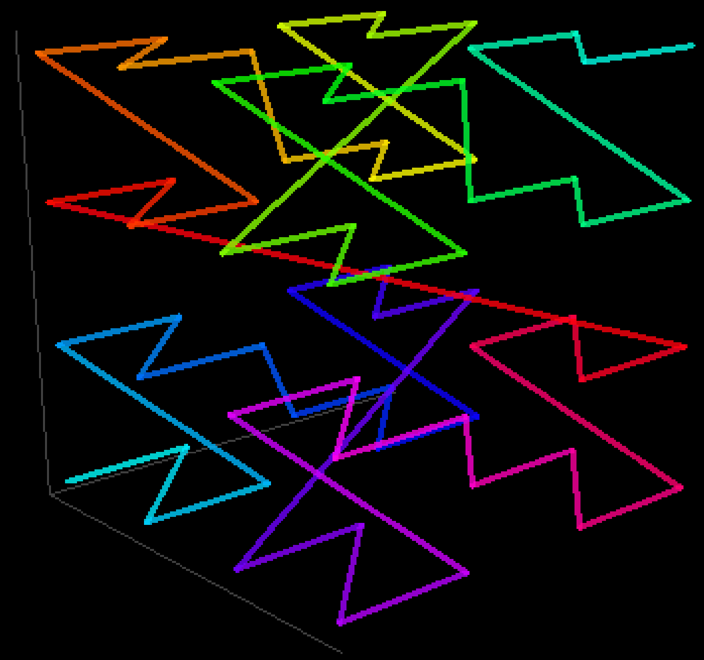
Morton order / Z-order

- Linearization of n-dimensional grid
  - Post-order depth-first traversal of 2^n-tree
- Space-filling curve, Z-shaped

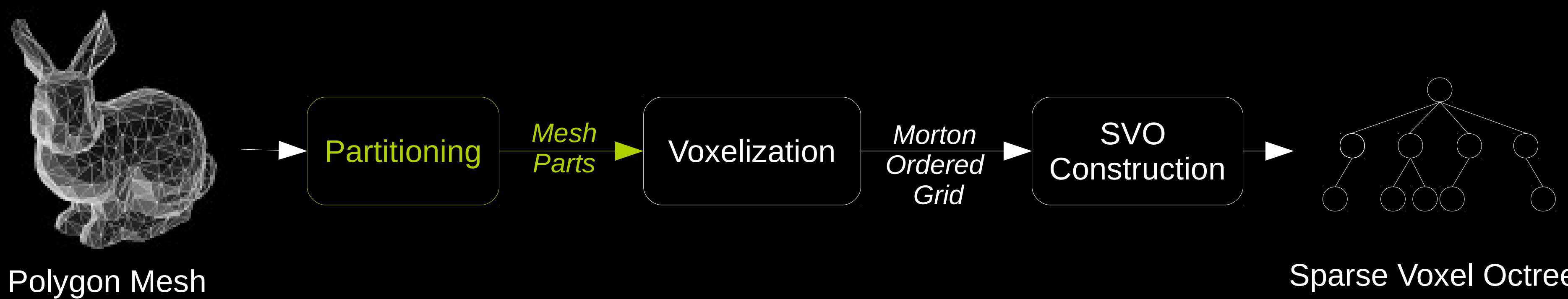


Morton order / Z-order

- Hierarchical in nature
- Cell at position (x,y)
  → Morton code
  - Efficiently computed
  - (x,y,z) = (5,9,1)
    → (0101,1001,0001)
    → 010001000111
    → 1095[th] cell along Z-curve

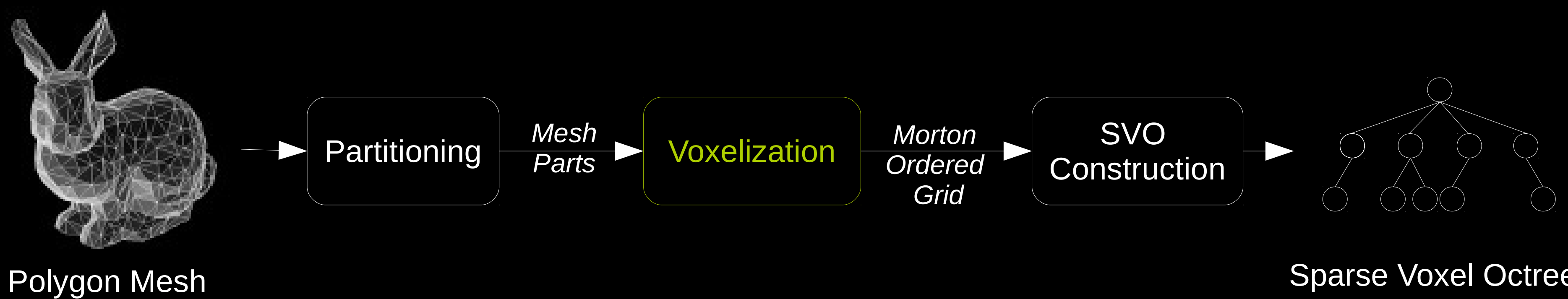


Partitioning subprocess



- Partitioning (1 linear pass)
  - Into power-of-2 subgrids until it fits in memory
  - Subgrids temporarily stored on disk
  - Subgrids correspond to contiguous range in Morton order
- If we voxelize subgrids in Morton order, output will be Morton-ordered

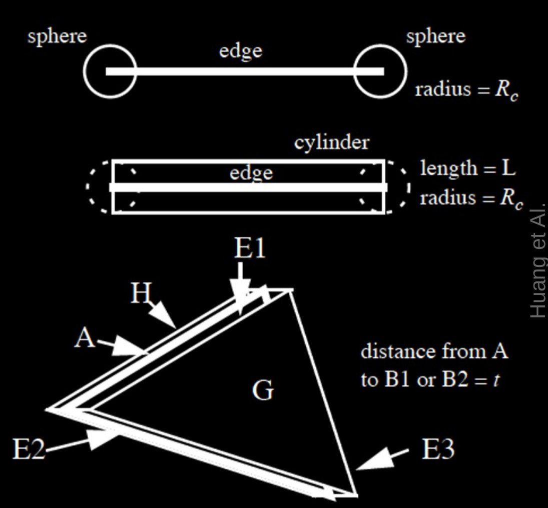
Voxelization subprocess (1)

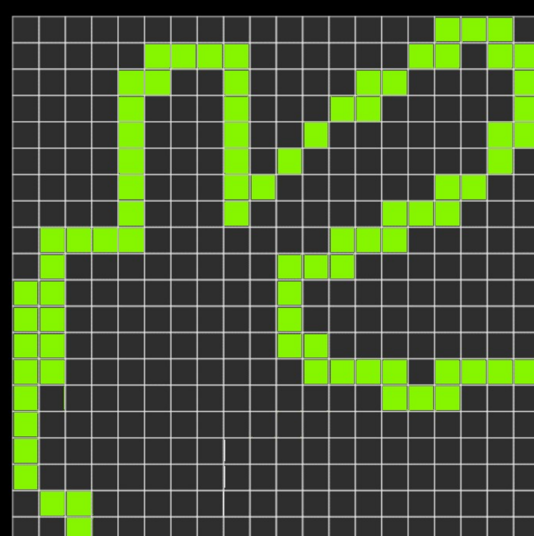


- Voxelize each subgrid in Morton order
  - **Input:** Subgrid triangle stream
    - Each triangle voxelized independently
  - **Output:** Morton codes of non-empty cells
    - Typically, majority of grid is empty

Voxelization subprocess (2)

- We use a simple voxelization method
  - But any method that works one triangle at a time will do

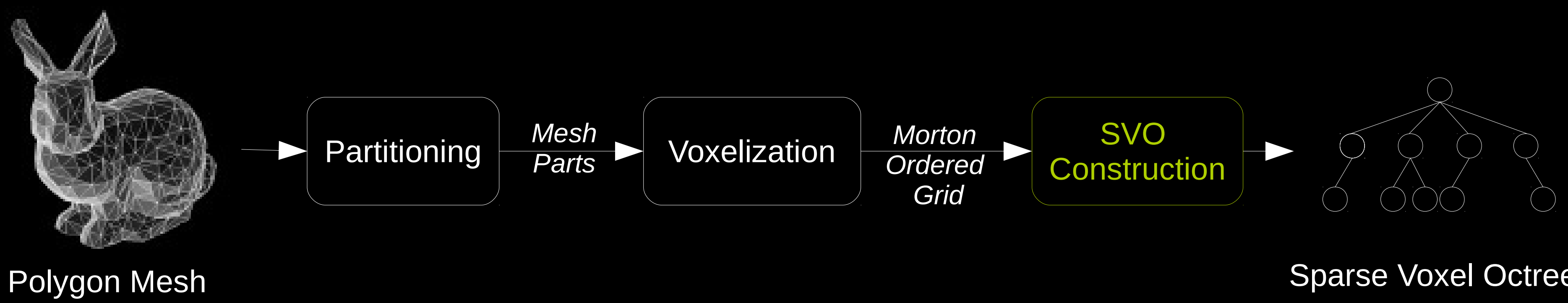




1110110101000
1011110101111
...

Morton codes of non-empty cells

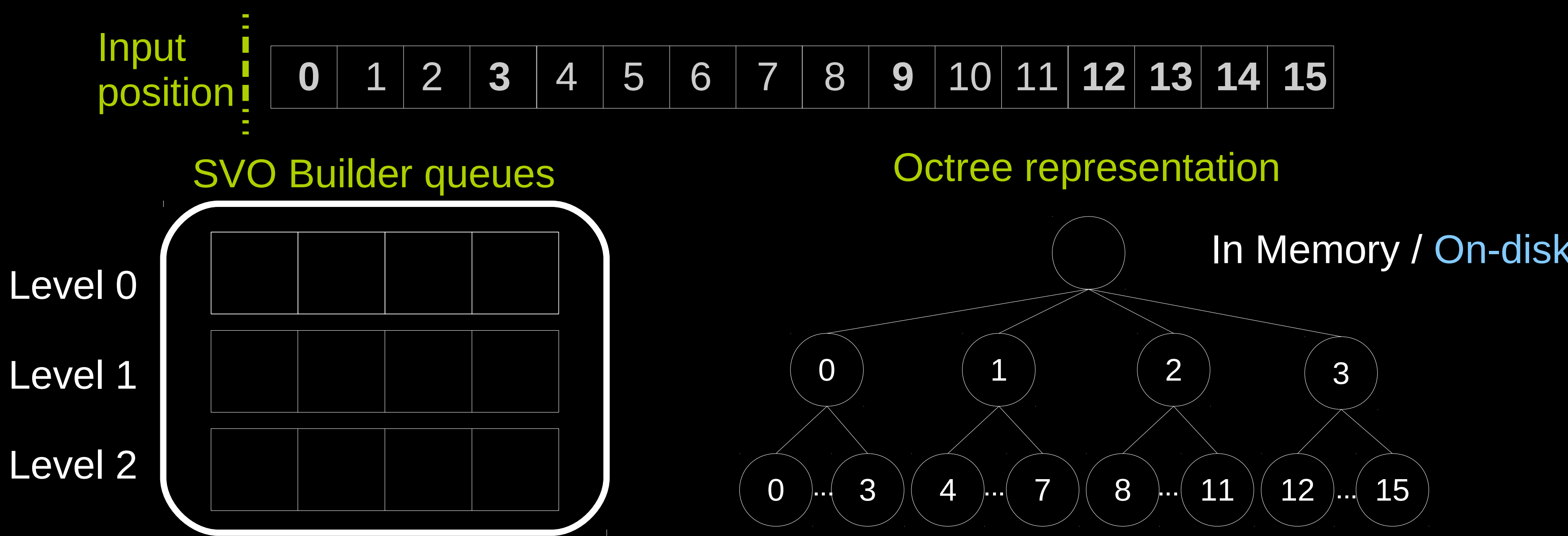
Out-of-core SVO Construction



- **Input:** Morton-ordered voxel grid
- **Output:** SVO nodes + referenced data

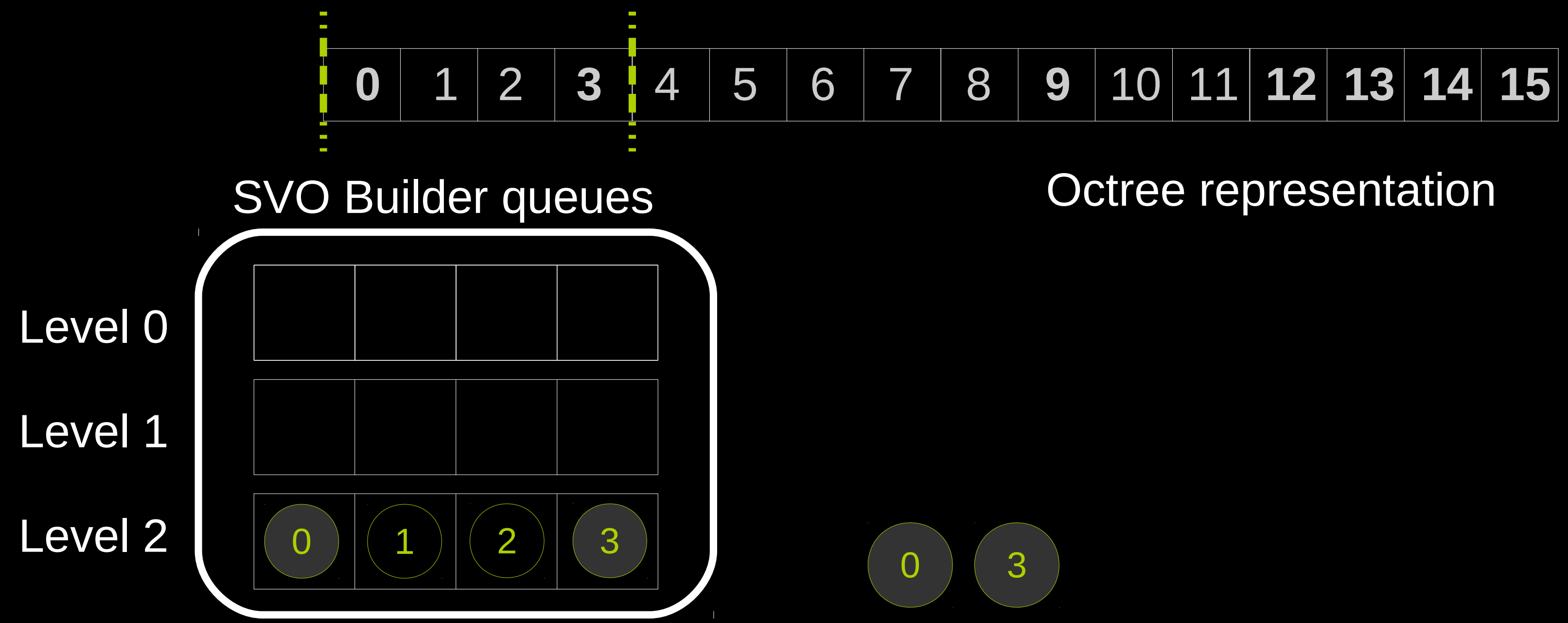
SVO Construction algorithm in 2D

- Required: queues of 2^d nodes / octree level
  - Ex: 2048^3 grid → 11 * 8 octree nodes-l



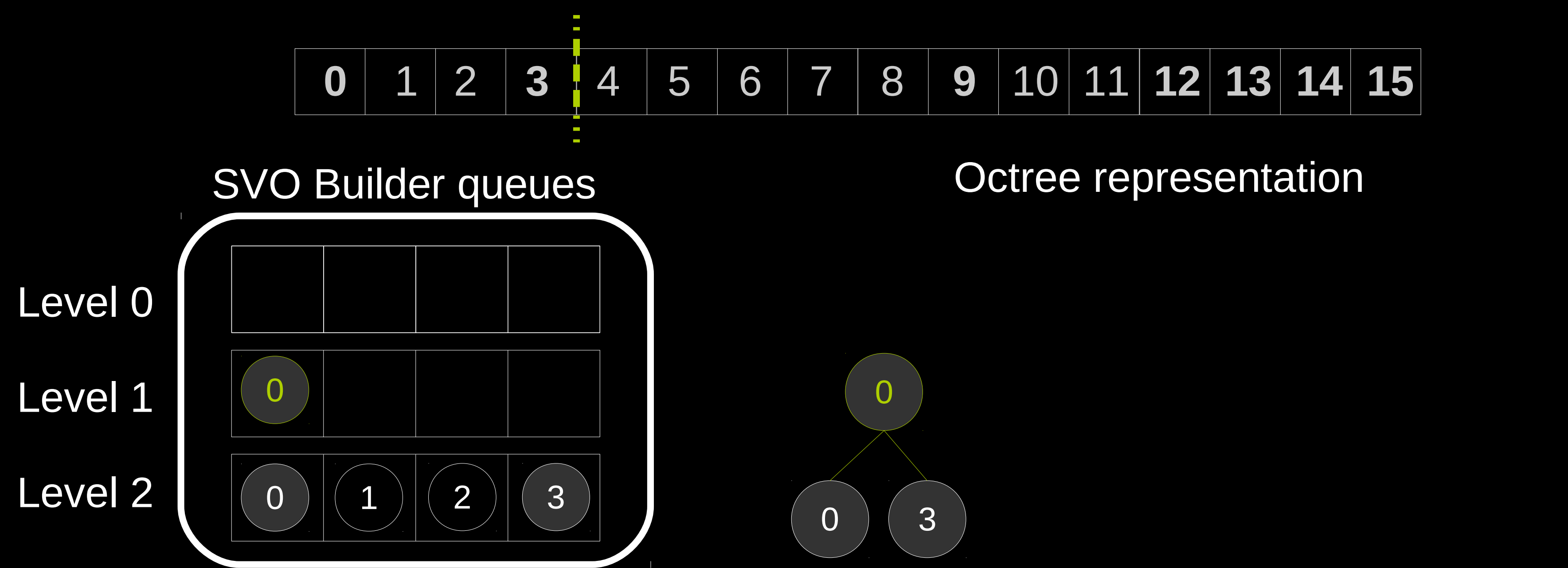
SVO Construction algorithm in 2D

- Read Morton codes **0 → 3** (+ voxel data)
  - Store them in level 2 queue
  - Level 2 queue = full



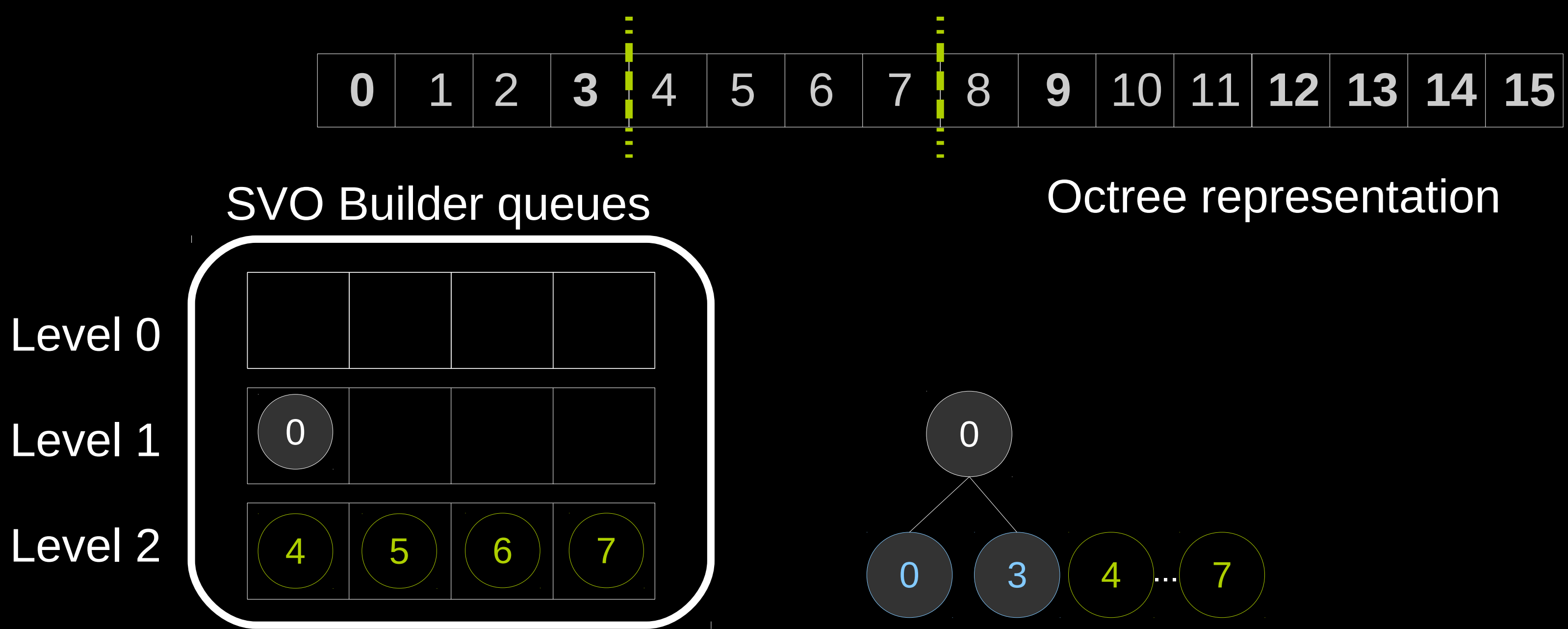
SVO Construction algorithm in 2D

- Create internal parent node
  - With level 1 Morton code **0**
  - Store parent-child relations
  - Write non-empty level 2 nodes to disk+clear level 2



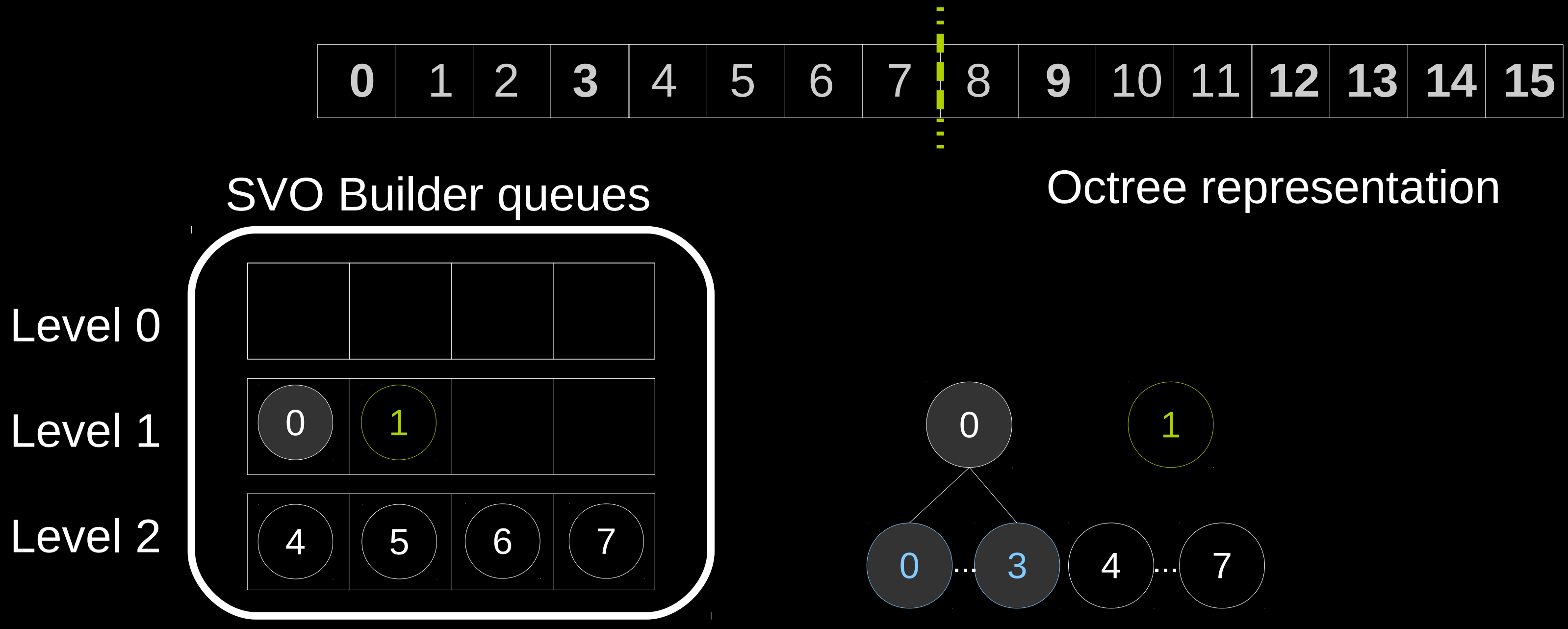
SVO Construction algorithm in 2D

- Read Morton codes 4 → **7** (+ voxel data)
  - Store them in level 2 queue



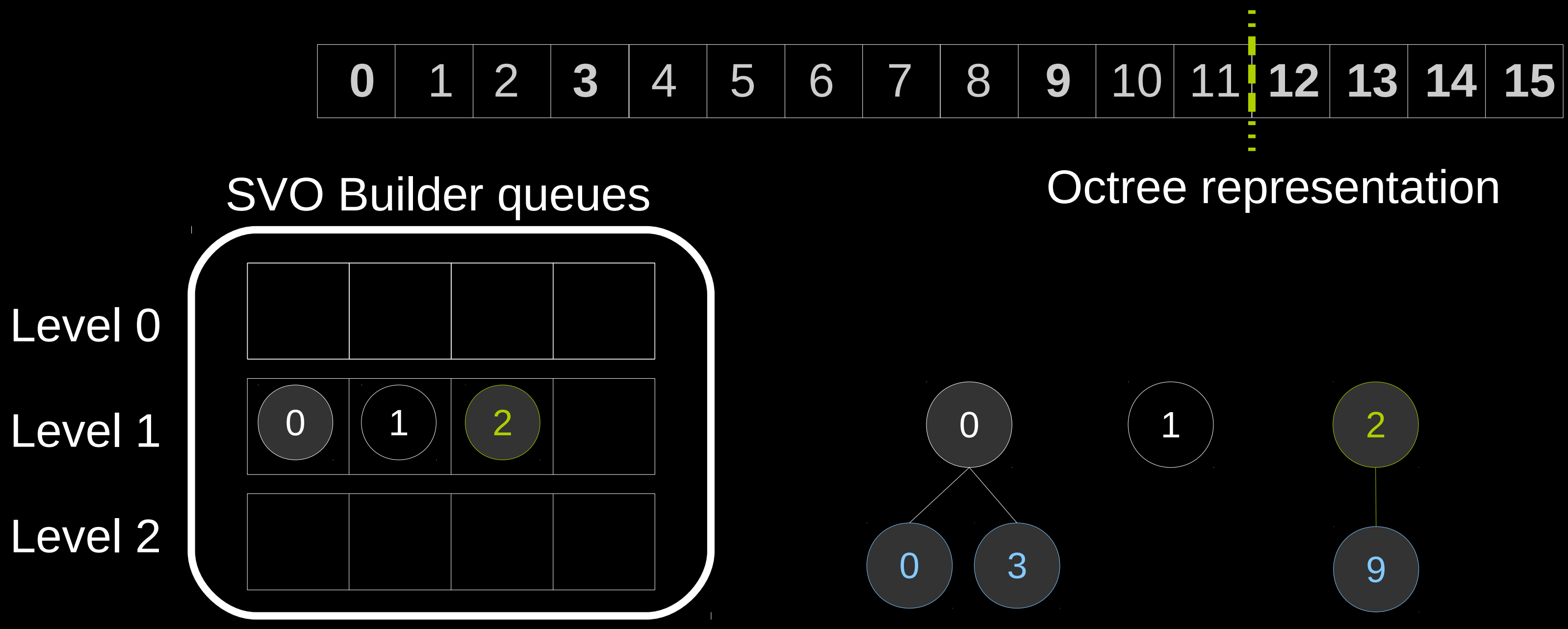
SVO Construction algorithm in 2D

- Create internal parent node
  - With level 1 Morton code **1**
  - Store parent-child relations (there are none)
  - Write non-empty level 2 nodes to disk+clear level 2



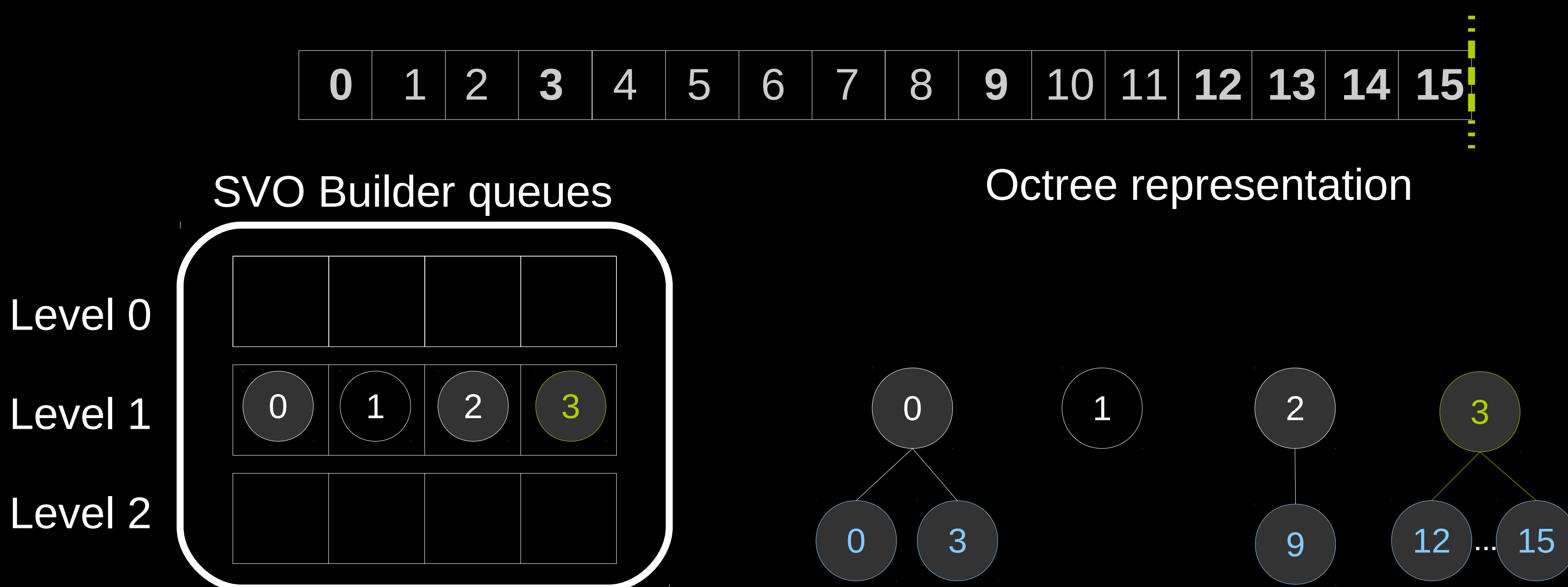
SVO Construction algorithm in 2D

- Same for Morton codes **8 → 11**



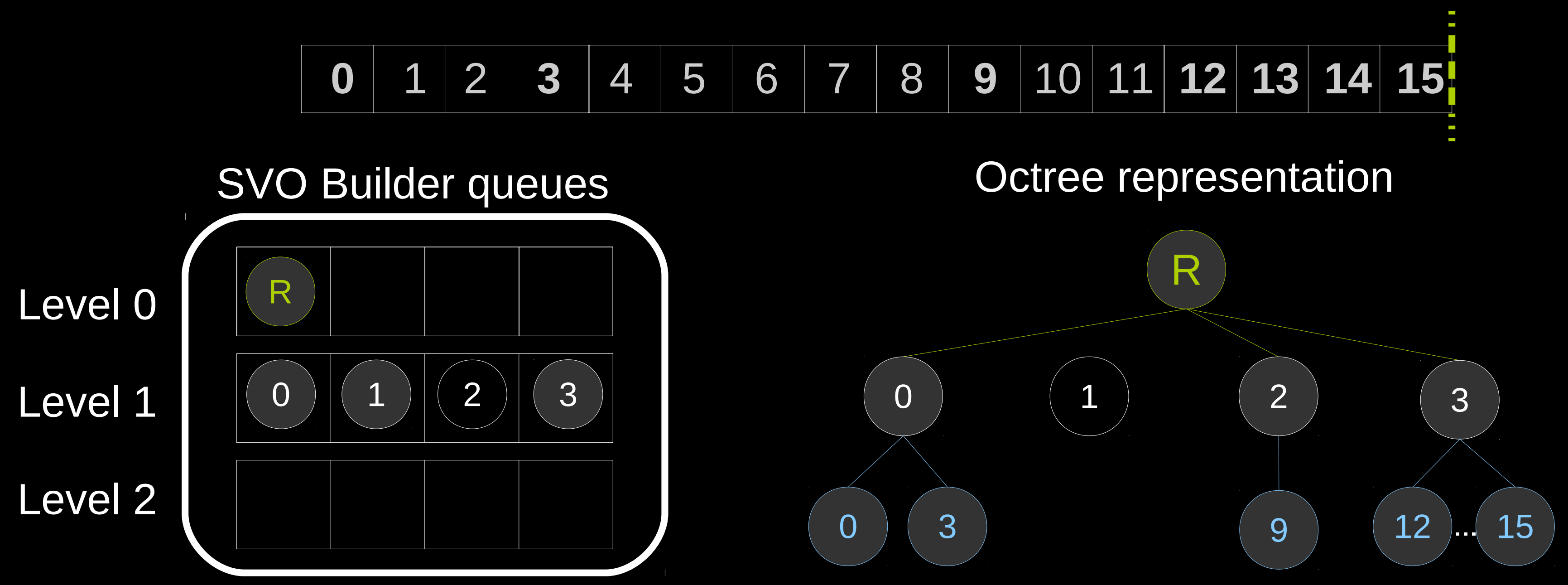
SVO Construction algorithm in 2D

- Same for Morton codes **12 → 15**



SVO Construction algorithm in 2D

- Now level 1 is full
  - Create parent node (root node)
  - Store parent-child relations
  - Write non-empty level 1 nodes to disk+clear level 1

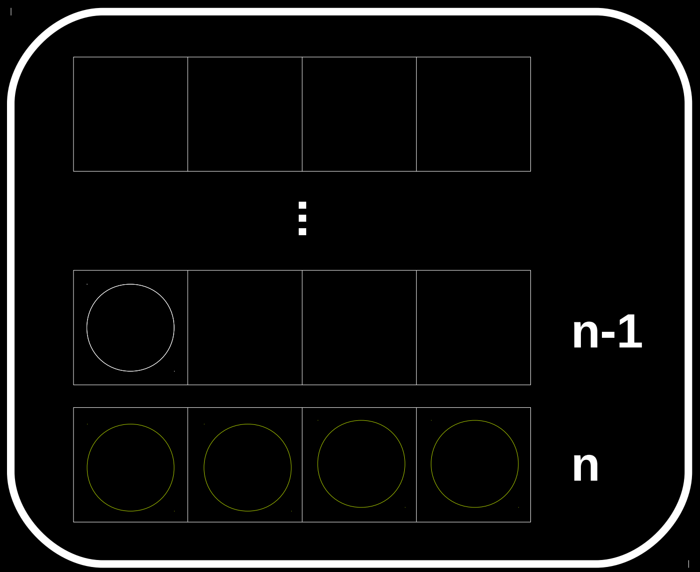


SVO Construction: optimization

- Lots of processing time for empty nodes
  - Sparseness = typical for high-res voxelized meshes

- Insight for optimization
  - Pushing back 2^d empty nodes in a queue at level n

    = Pushing back 1 empty node at level n-1



SVO Builder queues

SVO Construction: optimization

- Implementation details in paper
- Optimization exploits sparseness of voxelized meshes

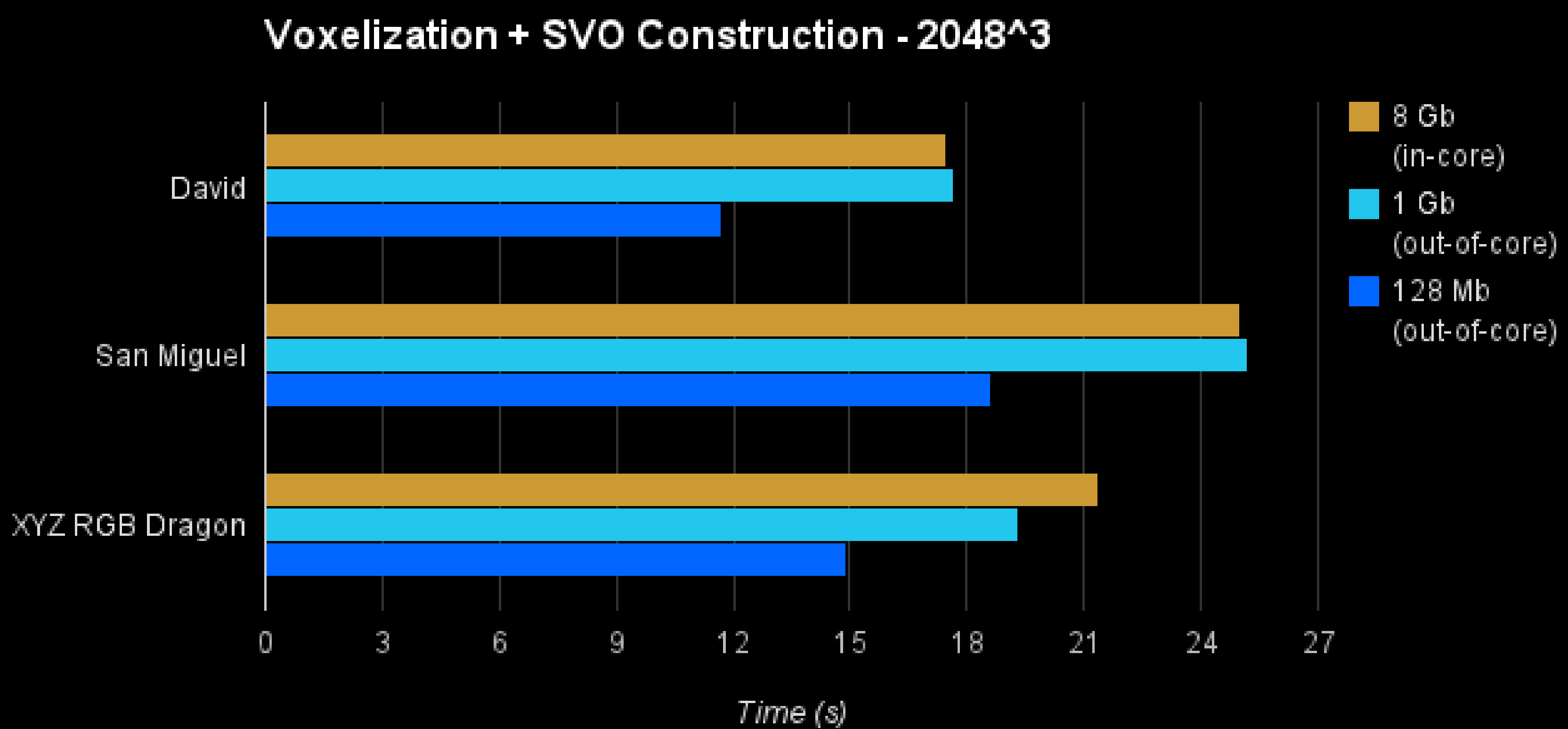
- Speedup: two orders of magnitude
  - Building SVO from grid:
    - David: 471 vs 0.55 seconds
    - San Miguel: 453 vs 1.69 seconds

Results: Tests

- Resolution: 2048^3
- Memory limits
  - 8 Gb (in-core)
  - 1 Gb (out-of-core)
  - 128 Mb (out-of-core)
- Models
  - David (8.25 M polys)
  - San Marco (7.88 M polys)
  - XYZRGB Dragon (7.2 M polys)

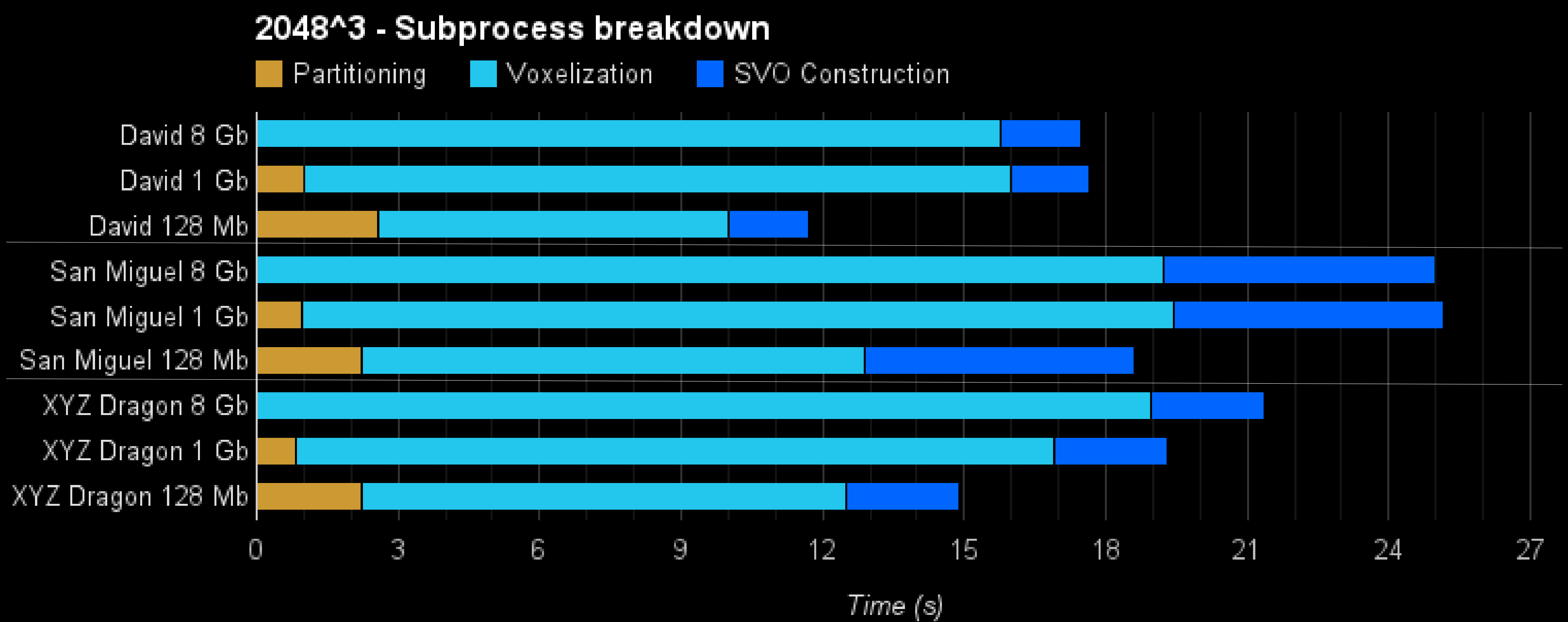
Results: Out-Of-Core performance

- Out-Of-Core method = ~ as fast as In-Core
  - Even when available memory is 1/64



Results: Time breakdown

- Partitioning speedup from skipping empty space



Results: Extremely large models

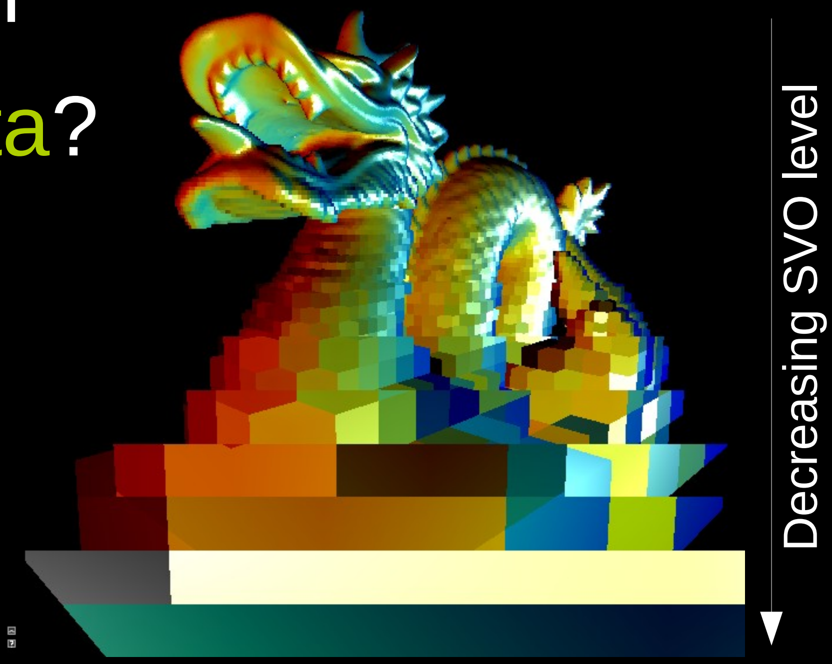
- 4096^3 – In-core: 64 Gb
- **Atlas** model
  - 17.42 Gb, 507 M tris
  - < 11 min at 1 Gb
- **St. Matthew** model
  - 13.1 Gb, 372 M tris
  - < 9 min at 1 Gb

Results: SVO Construction

- SVO output stream
  - Good locality of reference
    - Nonempty siblings on same level always stored next to each other
  - Nodes separated from data itself (separation hot/cold data)
    - Using data pointers + offsets as reference

Appearance

- Pipeline: **binary** voxelization
- Extend with appearance data?
  - Interpolate vertex attributes (color, normals, tex)
  - Propagate appearance data upwards



- Global data access ↔ Out-Of-Core algorithms
  - Multi-pass approach

Conclusion

- Voxelization and SVO construction algorithm
  - Out-of-core as fast as in-core
  - Support for extremely large meshes
- Future work
  - Combine with GPU method to speed up voxelization
  - Handle global appearance data

Thanks!

- Source code / binaries will be available at project page

- Contact
  - jeroen.baert @ cs.kuleuven.be
  - @jbaert

- Acknowledgements:

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