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Extended Morton Codes for High Performance Bounding Volume Hierarchy Construction

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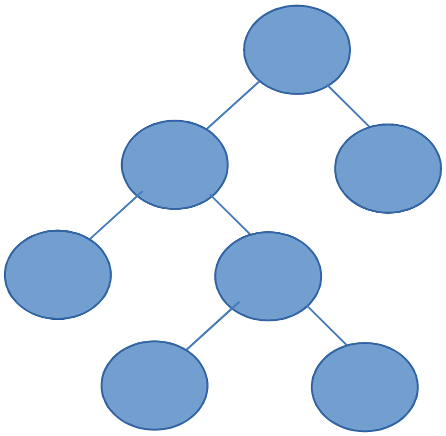
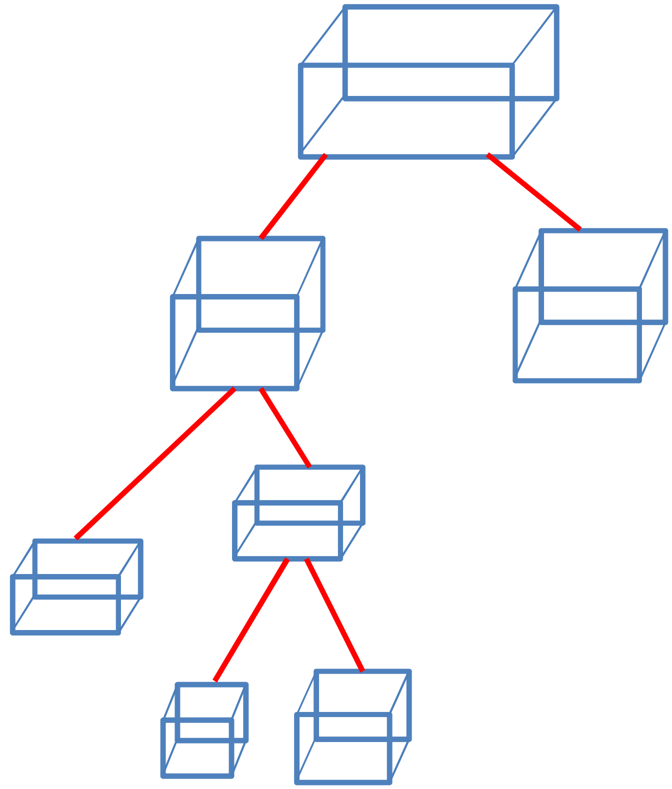
BVH – Old but Good Concept of Hierarchy

BVH = bounding volume hierarchy





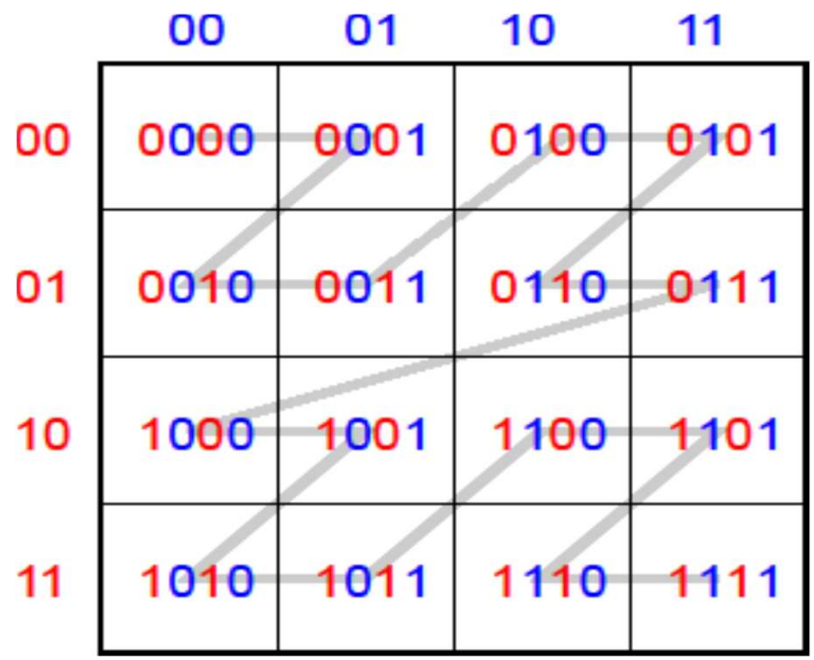
Selected Related Work on BVHs

- [Rubin and Whitted 1980] – first paper, top-down method
- 1980-2005 not so many papers e.g. [Goldsmith/Salmon 87]
- [Havran et al. 2006] – BVH binning+LSD trees
- [Wald 2007] – vertical/horizontal parallel BVH build
- [Walter et al. 2008] – agglomerative BVH build
- [Kensler 2008] – BVH optimization by rotations
- [Lauterbarch et al. 2009] – LBVH - fast build with Morton code
- [Pantaleoni and Luebke 2010] – hierarchical LBVH (HLBVH)
- [Garanzha et al. 2011] – another improvement HLBVH
- [Karras 2012] – faster parallel LBVH build
- [Gu et al. 2013] – efficient approx. agglomerative clustering
- [Bittner et al. 2013] – BVH optimization by insertion
- [Apetrei 2014] – Agglomerative LBVH construction
- [Domingues and Pedrini 2015] – optimization by treelet restructuring
- Etc.

Morton Codes

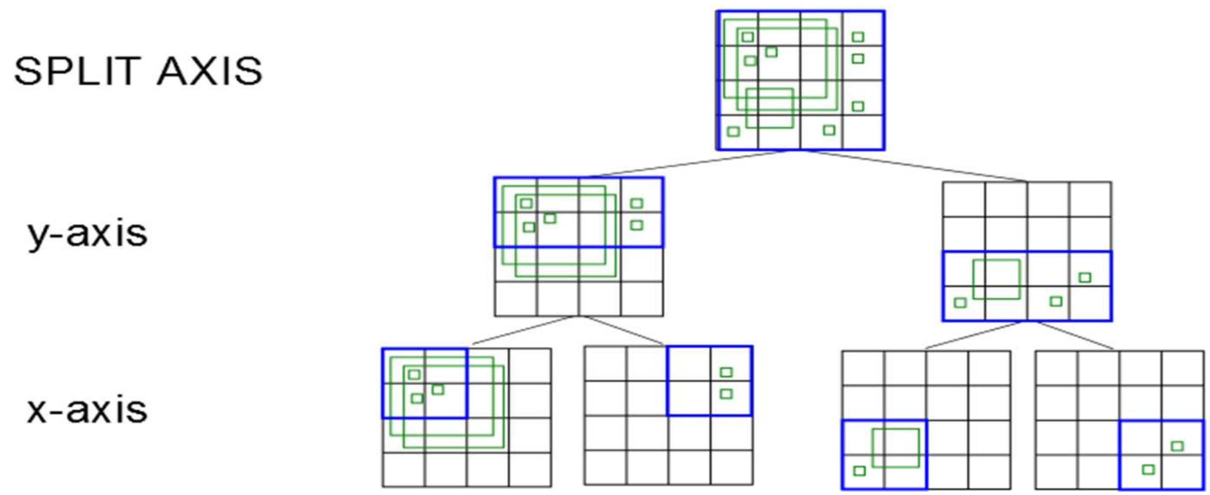
- [G.M. Morton 1966] – A Computer Oriented Geodetic Data Base: and a New Technique in File Sequencing, Research Report IBM Ltd., Ottawa, ON, Canada
- Simply regularly interleaving bits of spatial coordinates
- 2D example:

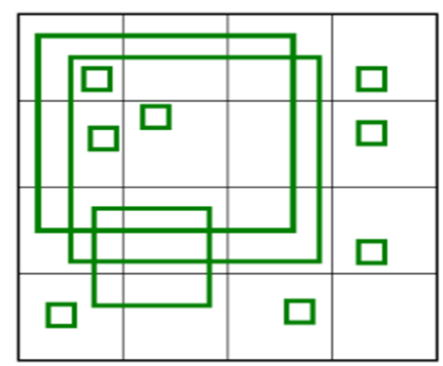
$\color{red}{y_2}\color{blue}{x_2}\color{red}{y_1}\color{blue}{x_1}\color{red}{y_0}\color{blue}{x_0}$



Morton Codes+Ray Tracing $y_2 x_2 y_1 x_1 y_0 x_0$

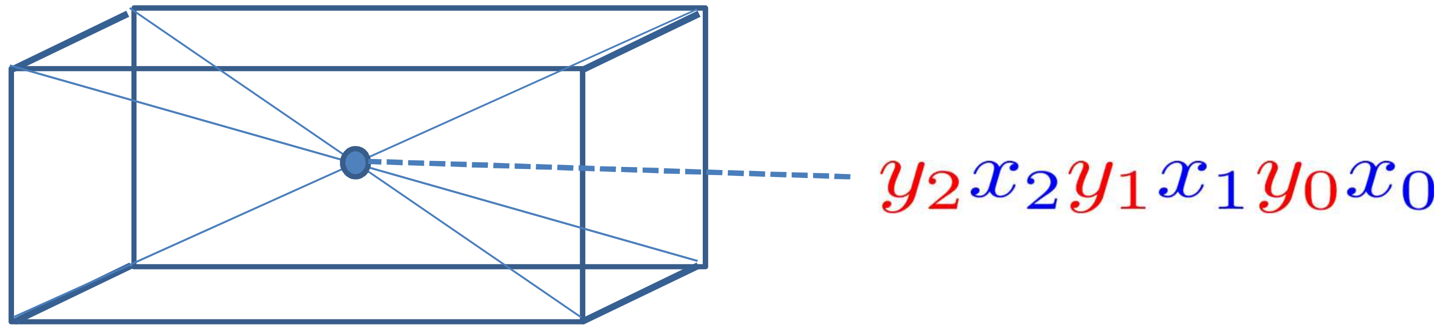
- Direct implementation paper by [Lauterbach et al. 2009]





Morton Codes+Ray Tracing $y_2x_2y_1x_1y_0x_0$

- Algorithm summary – direct build up
  - For each primitive assign the code according to the spatial coordinates of the center of the box around the primitive



  - Sort the primitives according to their Morton Codes
  - Build the BVH by the changes in the bits of the code from root to the leaves
  - Possibly postprocess BVH (e.g. more primitives in a leaf)

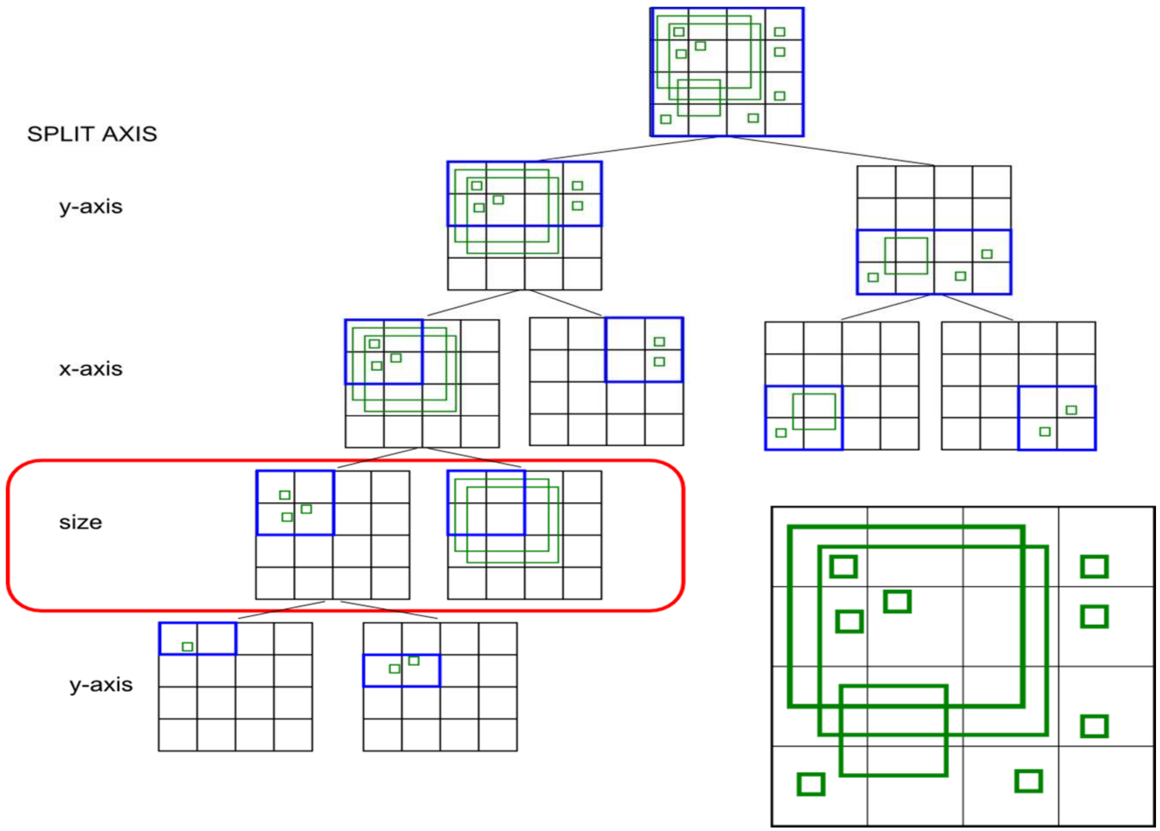
Morton Code (MC) Properties

- Relatively efficient for fast build
- Simple and clear
- Quality is the problem for scenes with non-uniform distribution
- Useful for ray tracing data structures

- **Question:** can we improve on the properties of BVH built with the Morton Code?

1st Idea – Encode Object Size $yxsy$

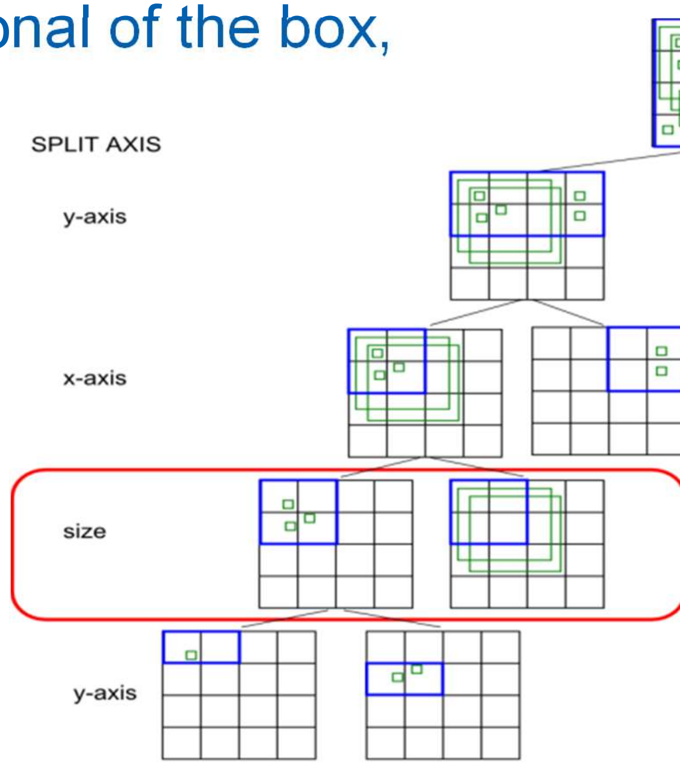
- Morton code designed to interleave bits of spatial coordinates X,Y … Z, we can however encode other properties than only spatial coordinates
- **Separate objects by their SIZE**

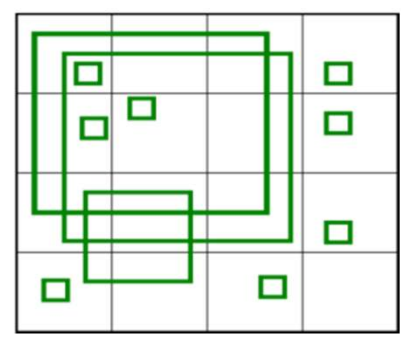


$yxsy$

1st Idea – Encode Object Size $yxsy$

- Size of object and spatial coordinates have to be related!
- Coordinates are normalized for MC before encoding
- We encode the diagonal of the box, its square root





2^{nd} Idea – Fewer Bits for Size $yxsyxyx$

- We can distribute the bit unevenly between coordinates and size, e.g. put less bits to the encoding of size
  - 3 times X
  - 3 times Y
  - 1 times SIZE

- Spatial size encoding the box is not that important as the spatial coordinates

$$yxsyxyx$$

- This allows to use also 32 bit long EMC codes for scenes with up to 200k primitives

3rd Idea – Adaptive Axis Order in 3D

- We can start with another axis than just with x-axis, according to the longest side of the box, the second longest side, only six possibilities: xyz, yzx, zxy, xzy, zyx, yxz

- Note: motivation comes from observation of fast SAH build kd-trees algorithms, use the longest side axis in X% cases and otherwise continue round robin, here globally for the whole tree.

4th Idea – Variable Bit Count $xxyszxxyz$

- We can distribute the bit unevenly between coordinates, e.g.
  - 4 times X
  - 2 times Y
  - 2 times Z
  - 1 times S

$$xxyszxxyz$$

Algorithm Example for EMC

```
function INIT(scene)
    a0 = x, a1 = y, a2 = z, a3 = size ▷ default axis order
    ▷ descending axis order using scene dimensions
    sort(a0..2)
    ▷ Compute quantization scales
    s0 = 2^16/scene.box.size[a0]
    s1 = 2^16/scene.box.size[a1]
    s2 = 2^16/scene.box.size[a2]
    s3 = 2^16/scene.box.diagonal.length
end function
function EXPAND((integer X))
    integer v=0, mask=1
    for i=0 to 15 step 1 do
        v = v | ((X & mask) ≪(3.i))
        mask = mask ≪1
    end for
    return v
end function
function CODE(triangle)
    v = triangle.box.center-scene.box.min
    size = triangle.box.diagonal.length
    integer v0* = s0 · v[a0]
    integer v1* = s1 · v[a1]
    integer v2* = s2 · v[a2]
    integer v3* = s3 · size
    return ((Expand(v0*) ≪ 3 ) |  (Expand(v1*) ≪ 2)
              | (Expand(v2*) ≪ 1 ) |  Expand(v3*))
end function
```

More complete pseudocode in the paper and project webpage contains real code

http://dcgi.fel.cvut.cz/projects/emc

Extended Morton Code – Ideas Summary

- Standard Morton Code – interleaving bits regularly

$$xyzxyzxyzxyz$$

- Extended Morton Code – break of regularity assumption

$$xxyszyxxyszx$$

  - Encoding size of the object
  - Variable bit count for each dimension, including size of box
  - Variable bit count and dimensions order, considering the shape of original scene box

Scenes of Various Size – 100k to 13M

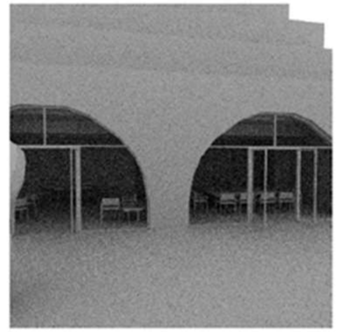
SC1
sponza

76k

SC2
conference

331k

SC3
sodahall

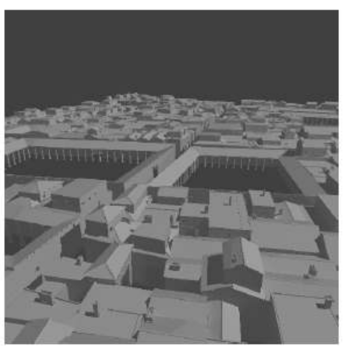


2,169k

SC4
hairball

2,880k

SC5
pompeii



5,646k

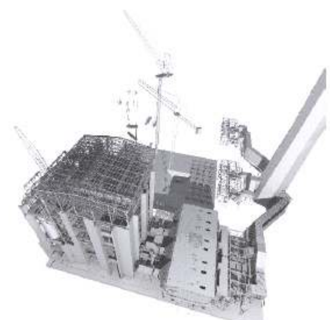
SC6
san-miguel

7,880k

SC7
city

8,737k

SC8
powerplant



12,759k

Results – Example Codes for 8 Scenes

Bit 63 Bit 32 Bit 0

#bits
x/ y/ z/ s

SC1 20/19/19/6
SC2 20/18/20/6
SC3 19/20/19/6
SC4 19/20/19/6
SC5 21/16/21/6
SC6 20/18/20/6
SC7 21/16/21/6
SC8 20/19/19/6

```
6666555555555544444444443333333333222222222211111111110000000000
3210987654321098765432109876543210987654321098765432109876543210
----------------------------------------------------------------
xxyzxySzxyzxySzxyzxySzxyzxySzxyzxySzxyzxySzxyzxyzxyzxyzxyzxyzxyz
xzxzxySzxyzxySzxyzxySzxyzxySzxyzxySzxyzxySzxyzxyzxyzxyzxyzxyzxyz
yxzyxzSyxzyxzSyxzyxzSyxzyxzSyxzyxzSyxzyxzSyxzyxzyxzyxzyxzyxzyxzy
yzxyzxSyzxyzxSyzxyzxSyzxyzxSyzxyzxSyzxyzxSyzxyzxyzxyzxyzxyzxyzxy
xzxzxzSxzxzxzSyxzyxzSyxzyxzSyxzyxzSyxzyxzSyxzyxzyxzyxzyxzyxzyxzy
zxzxzxSyzxyzxSyzxyzxSyzxyzxSyzxyzxSyzxyzxSyzxyzxyzxyzxyzxyzxyzxy
```

EMC-64-var code

Numbers for LBVH (lower quality), GPU

- reference – standard Morton code, rendering time/cost
- EMC-64 against MC-64, two variants

	76k	331k	2169k	2880k	5646k	7880k	8737k	12759k	
	SC1	SC2	SC3	SC4	SC5	SC6	SC7	SC8	
Build	5.1	13.0	65.3	88.5	158.5	234.4	261.4	355.3	[ms]
sort									**AVG**
cost	-13%	-22%	-9%	-1%	-16%	-13%	-17%	-10%	**-12%**
Mrays/s	+1%	+17%	+1%	+2%	+11%	+12%	+18%	+13%	**+7.5%**
var									
cost	-4%	-22%	-6%	+0%	-47%	-18%	-52%	-9%	**-27%**
Mrays/s	-5%	+23%	-1%	+1%	+47%	+17%	+101%	+9%	**+19%**

Numbers for ATRBVH (higher quality), GPU

- reference – standard Morton code, rendering time/cost
- EMC-64 against MC-64, two variants

	76k	331k	2169k	2880k	5646k	7880k	8737k	12759k	
	SC1	SC2	SC3	SC4	SC5	SC6	SC7	SC8	
Build	10.7	31.9	184.3	242.1	478.5	669.3	750.6	1029.0	[ms]
sort									**AVG**
cost	+0%	-2%	+0%	+0%	-7%	+1%	-8%	-2%	**-2%**
Mrays/s	+2%	+2%	-11%	+1%	+4%	+2%	+7%	+5%	**+1%**
var									
cost	+2%	-2%	+0%	+0%	-25%	+0%	-26%	-1%	**-7%**
Mrays/s	-4%	-2%	+3%	+0%	+23%	+4%	+31%	+3%	**+7%**

Conclusions on Extended Morton Code

- Useful anywhere Morton Code is used for spatial objects (CPU, GPU, …)
- Requires only to change the code, the rest of algorithm the same as it was (LBVH, HLBVH, AAC, ATRBVH …)
- It is a **heuristic**, does not guarantee the improvement for more sophisticated build algorithms
- Reviewer #4 reimplemented the method in 2 hours with similar results
- Extension on Morton Code summary
  - uses spatial size of object – e.g. box diagonal
  - variable bit count for each axis
  - irregular structure of the code
- Improvement for 8 scenes on GPU +7% for free
- Possible HW implementation perhaps easy

Acknowledgments

- Thanks for scenes: M. Dabrovic (Sponza model), G. Ward (conference model), Prof. Sequin (Sodahall), S. Laine and T. Karras (Hairball scene), G. Llaguno (San Miguel), UNC (Powerplant model),
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- L. Dominges and H. Pedrini for 2nd GPU ray tracing framework,
- Samsung Electronics Co. Ltd. for financial motivation and support, patent pending U.S. Application No. 15/403,612 filed on January 11, 2017

- Project webpage including essential source code

  http://dcgi.fel.cvut.cz/projects/emc

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