HPCSE 2026
High Performance Computing in Science and Engineering

Multi-Resolution Grid Reconstruction for Efficient Volume Rendering of Large-Scale Simulation Data

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VISUAL QUALITY COMPARISON

Visual comparison of the dataset from OpenGADGET simulation of SPH gas particles at resolution 512^3 using compression rate ≈3.7 %

MOTIVATION

- Simulations, e.g. from astrophysics and cosmology, generate massive volumetric datasets.
- Datasets are difficult to store, analyze, and render in standard VFX tools.
- Uniform grids waste memory by sampling empty regions.
- This work introduces an adaptive multi-resolution representation designed for high-quality volume rendering in Blender/Cycles.

KEY IDEA

- Fractal dimension computation.
- Use it to find out how much the values change in a given area.
- Compute the fractal dimension using the box-counting technique.
- Use the fractal dimension values to steer the number of cell divisions in the respective spatial area.

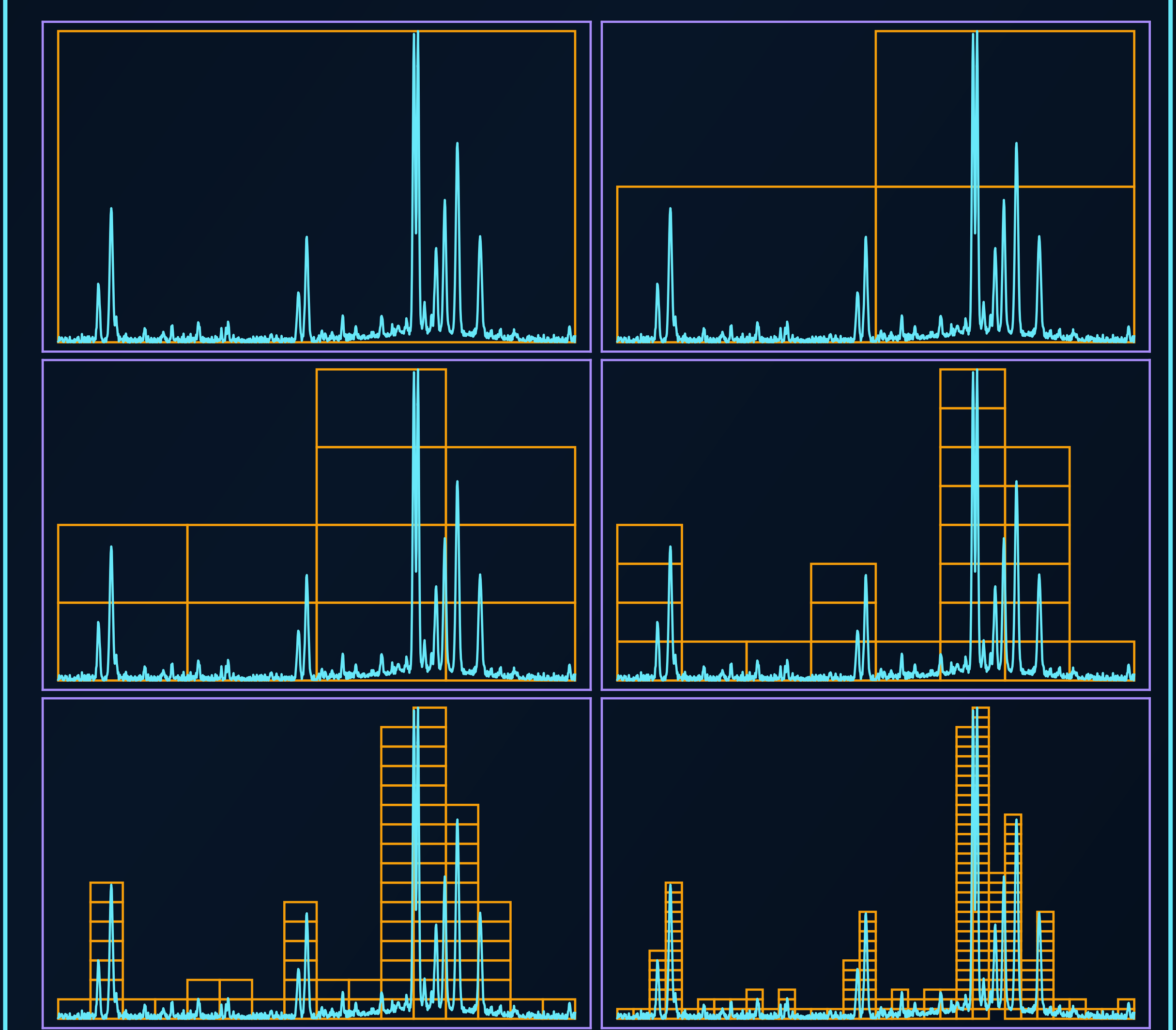
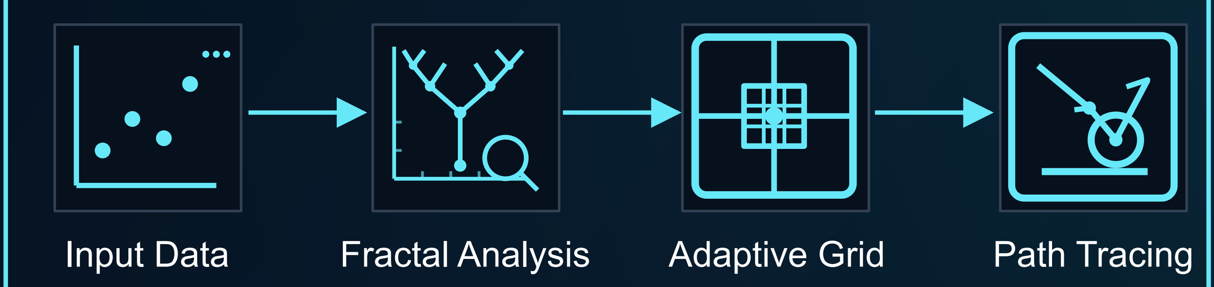


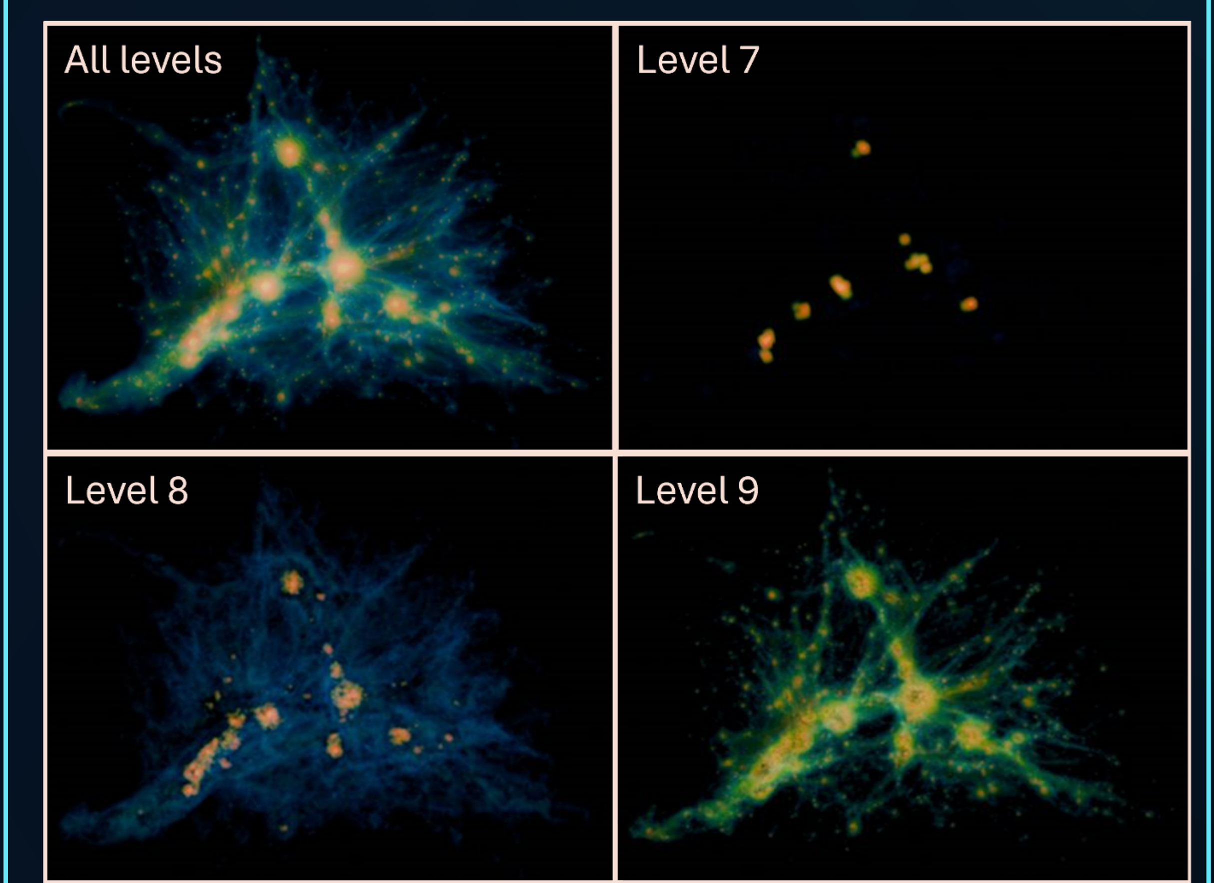
Illustration of box size reduction and computation of box count

METHOD WORKFLOW



MULTI-RESOLUTION HIERARCHY

- Individual finest levels (Level 7, 8, 9).
- Demonstrating how these levels contribute to the overall representation.



Visualization of the multi-resolution grid hierarchy

RENDERING PIPELINE

- Input: OpenVDB volumetric grids
- Convert: OpenVDB → compact NanoVDB format
- Store: Sequential compressed multi-grid layout
- Modify renderer: Extend Blender Cycles to use multi-grid data
- Sampling: Query grids in order, take first non-zero value
- Render: Path tracing with Cycles
- Result: Lower memory usage + high-quality rendering

RESULTS

Quantitative evaluation

- Quantitatively evaluating multi-resolution grid generation method and ZFP compression algorithm against original uniform grid.
- We used the ZFP compressor in fixed-rate mode, which guarantees a predictable compression ratio.

Set.	Meth.	Vox. [%]	Size [MB]	Compr. Rate [%]	PSNR [dB]	SNR [dB]	SSIM	NMSE
1	Multi	2.31	13.60	3.78	132.62	60.82	0.9999	5.47e−14
	ZFP	–	19.92	3.71	73.89	1.34	0.9983	4.08e−8
2	Multi	1.65	10.11	2.81	86.83	15.03	0.9999	2.08e−9
	ZFP	–	14.68	2.73	71.89	−0.20	0.9991	6.47e−8
3	Multi	1.17	7.50	2.08	82.80	11.00	0.9999	5.24e−9
	ZFP	–	11.53	2.15	71.69	−0.11	0.9953	6.77e−8
4	Multi	0.79	5.30	1.47	76.60	4.80	0.9999	2.19e−8
	ZFP	–	NA	NA	NA	NA	NA	NA
5	Multi	0.48	3.42	0.95	74.86	3.06	0.9999	3.26e−8
	ZFP	–	NA	NA	NA	NA	NA	NA

Dataset at resolution 512^3 (input VDB size: 360.27 MB)

Set.	Meth.	Vox. [%]	Size [MB]	Compr. Rate [%]	PSNR [dB]	SNR [dB]	SSIM	NMSE
1	Multi	1.79	79.05	5.47	142.33	64.15	0.9999	5.84e−15
	ZFP	–	234.88	5.47	83.60	3.78	0.9993	4.37e−9
2	Multi	1.13	51.66	3.58	135.43	57.24	0.9999	2.86e−14
	ZFP	–	150.99	3.52	80.49	1.98	0.9999	8.94e−9
3	Multi	0.80	37.71	2.61	131.19	53.00	0.9999	7.60e−14
	ZFP	–	109.05	2.54	78.15	−0.09	0.9999	1.53e−8
4	Multi	0.64	30.72	2.13	94.48	16.30	0.9999	3.56e−10
	ZFP	–	92.27	2.15	77.51	−0.67	0.9986	1.77e−8
5	Multi	0.26	13.42	0.93	82.98	4.79	0.9999	5.03e−9
	ZFP	–	NA	NA	NA	NA	NA	NA

Dataset at resolution 1024^3 (input VDB size: 1.44 GB)

Rendering Performance

- Evaluating rendering performance of original uniform grid and the proposed multi-resolution representation.

Dataset	Grid Type	Memory [MB]	FPS (CPU)	FPS (GPU)
512^3	Uniform grid	421.1	0.3	10.3
	Multi-resolution	33.3	0.6	14.0
1024^3	Uniform grid	4 304.8	0.2	9.7
	Multi-resolution	170.8	0.4	13.3

Rendering comparison for dataset at 512^3 and 1024^3 resolution for setting 1

CONCLUSION

1-5 % compressed data size

>0.99 SSIM visual structure

12x-25x lower render memory

74+ dB PSNR fidelity range

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ACKNOWLEDGEMENTS · This work has been produced with the financial support of the European Union under the REFRESH Research Excellence For REgion Sustainability and High tech Industries project number CZ.10.03.01/00/22_003/0000048 via the Operational Programme Just Transition. This work was also supported by the Ministry of Education, Youth and Sports of the Czech Republic through the e-INFRA CZ (ID:90254). This work was also supported by the SPACE project under grant agreement No 101093441. The project is supported by the European High-Performance Computing Joint Undertaking and its members (including top-up funding by the Ministry of Education, Youth and Sports of the Czech Republic ID: MC2304).

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