

Massive Geometric Algebra

Requirements and Applications for dealing with Big Data

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AHM Software GmbH / Louisiana State University



Background: Cutting-Edge Astrophysics

- Application: *Numerical Relativity*
 - Simulation of General Relativity via numerical means in the computer
 - Computationally intensive
 - Requires high performance computing (HPC)
 - Requires handling big data
 - Requires support of generic mathematical concepts
 - Differential geometry, Riemannian Geometry, Curved Space, Tensor Algebra

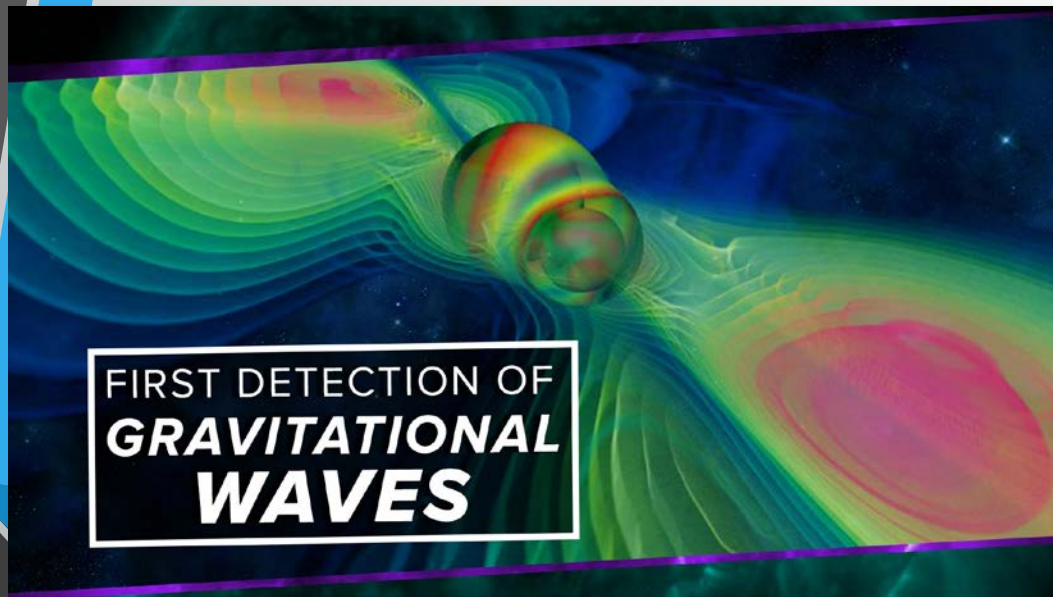
Max-Planck Institute for Gravitational Physics (Albert-Einstein Institute), Potsdam, Germany
National Center for Supercomputing Applications (NCSA), Champaign, Illinois, USA

Gravitational Waves

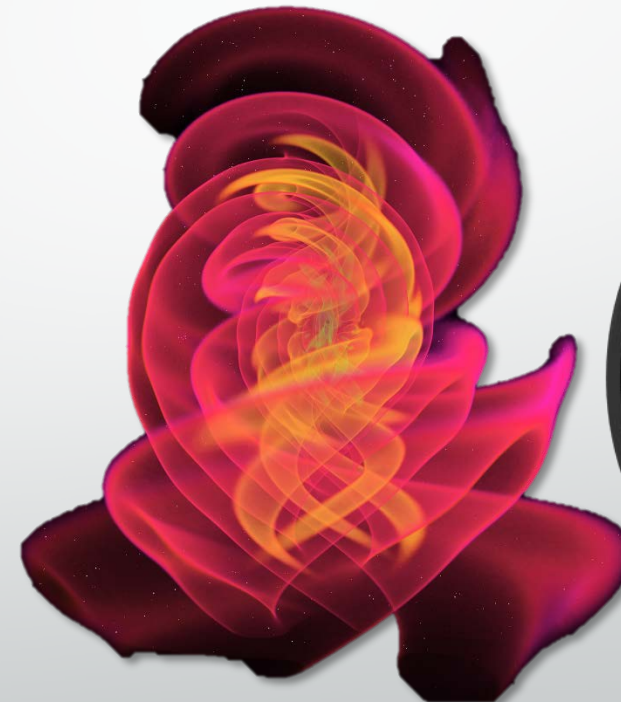
US National Science Foundation
LIGO International Consortium



16. Feb 2015



12GB raw data, 1999

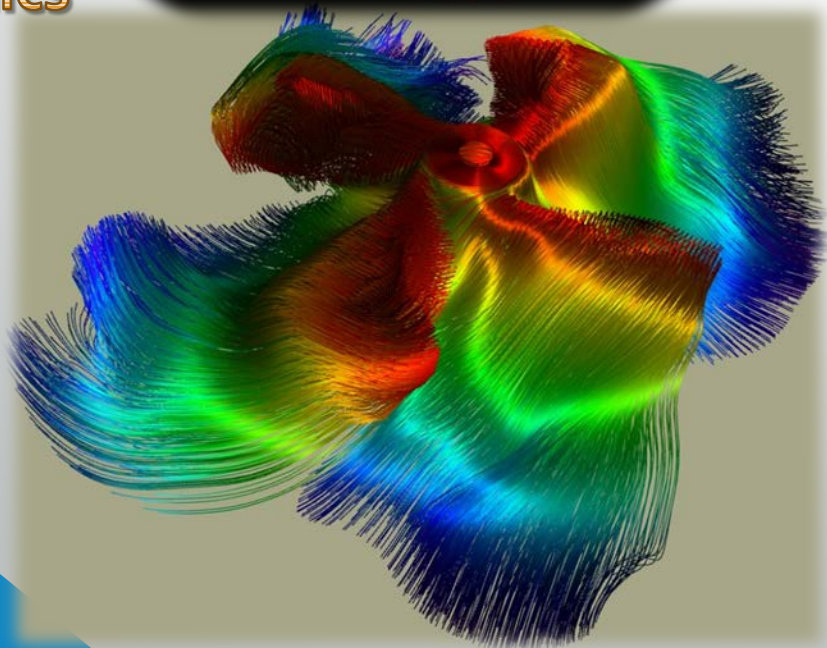
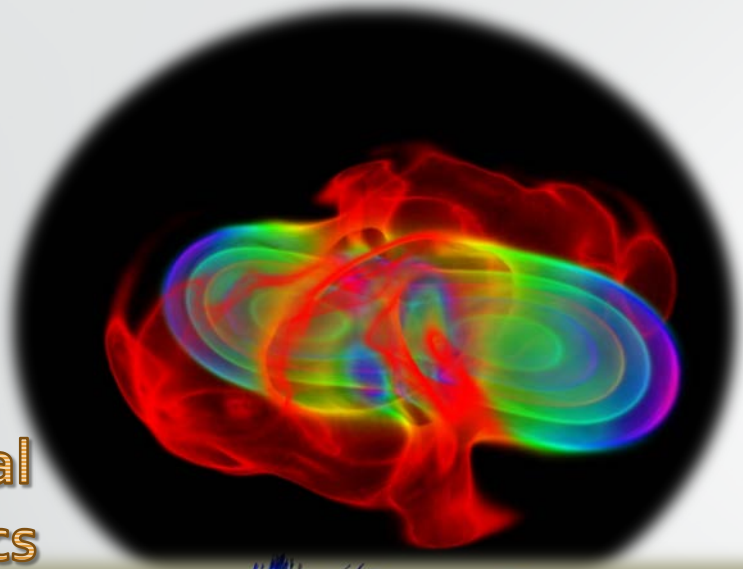


450GB raw data, 2016

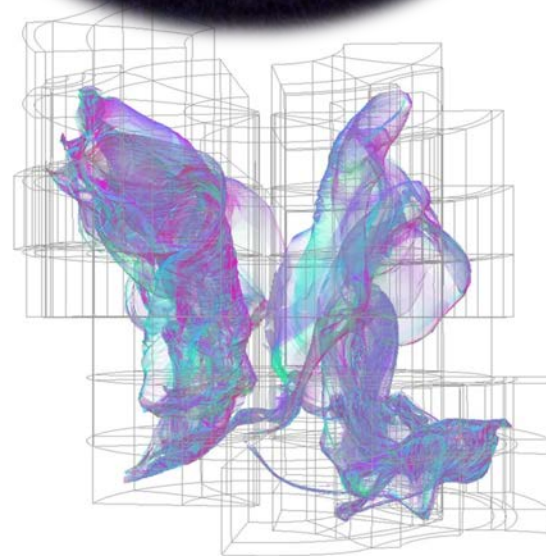


Background: Big Data in Big Flavors in HPC

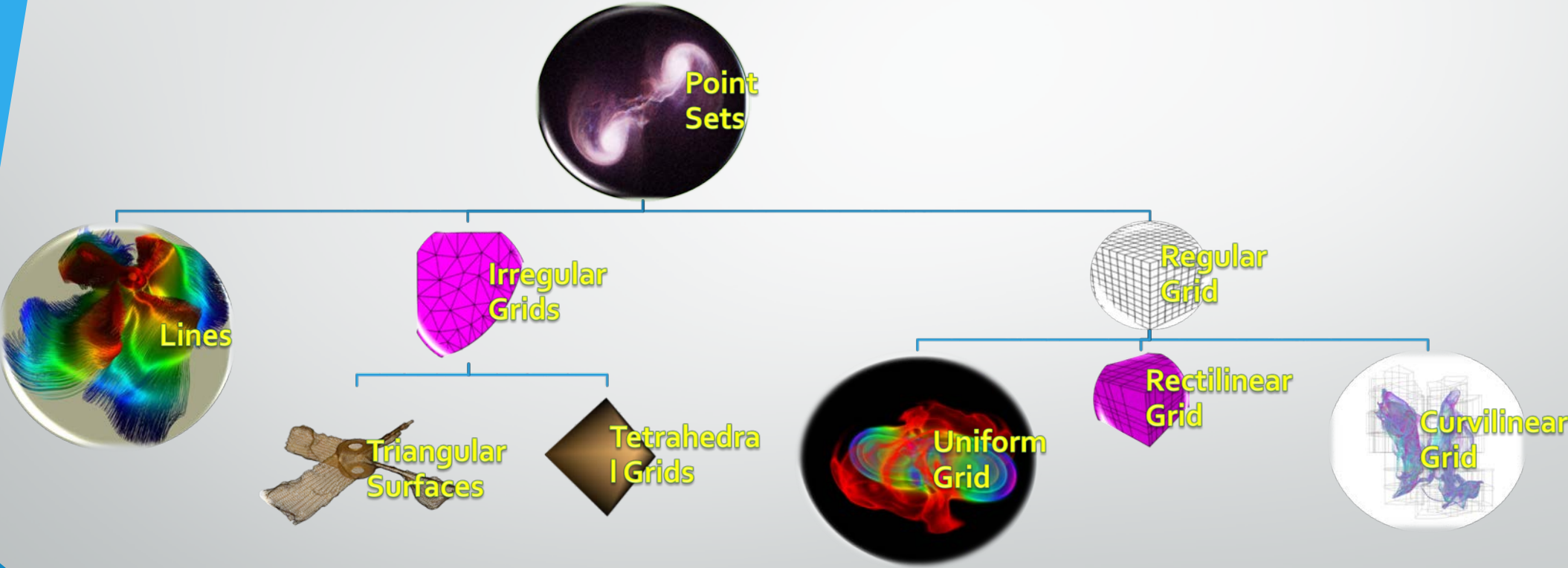
Computational
Fluid Dynamics



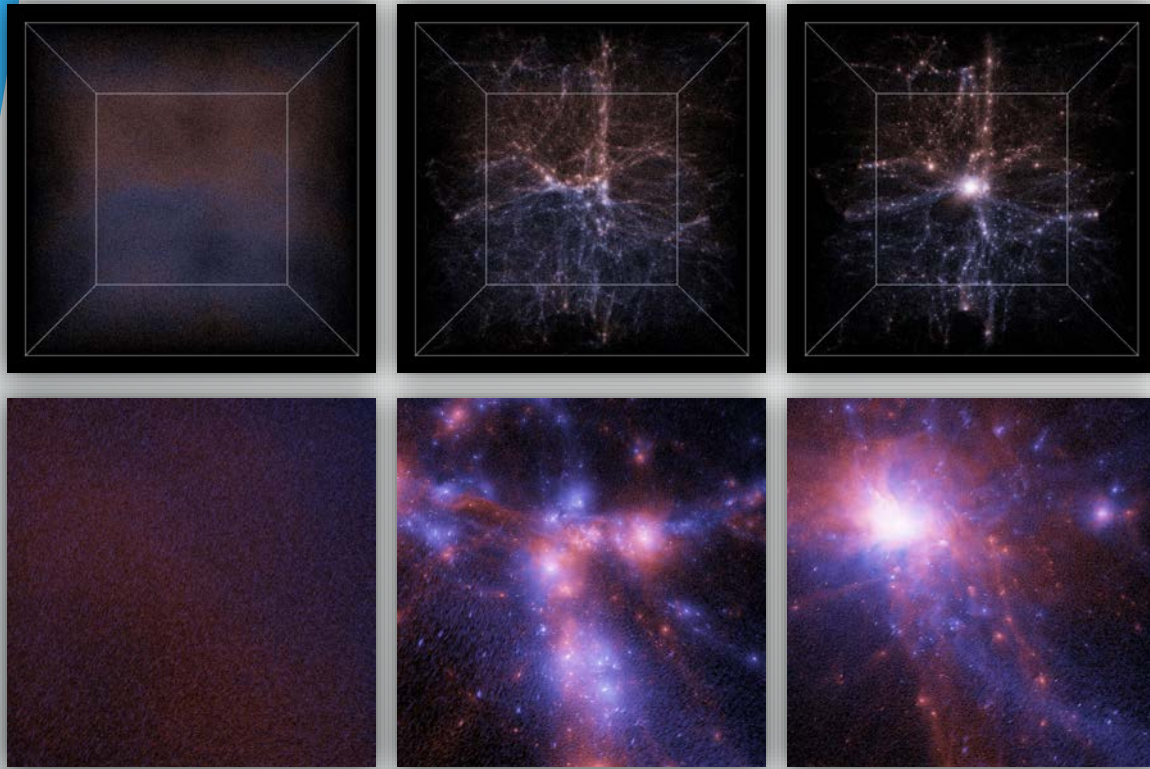
Particle
Systems



Background: Points as Common Base



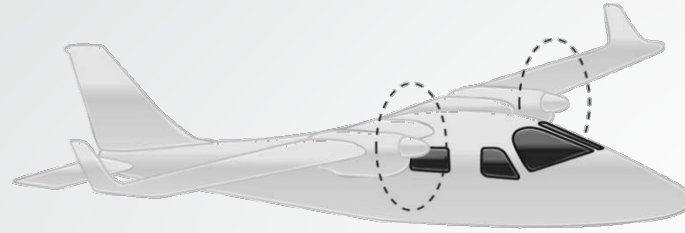
Application: Evolving Galaxies



- 16 Million particles, each representing one dust/darkmatter/newly formed stars
- Cosmological evolution over several billion years
- 280GB of binary data
- Velocity given for each particle

2011, University of Innsbruck, Austria

Background: What does AHM do?



AHM

AIRBORNE HYDROMAPPING

- Software HYDROVISH -

LIDAR, which stands for *Light Detection and Ranging*, is a [remote sensing](#) method that uses light in the form of a pulsed laser to measure ranges (variable distances) to the Earth. These light pulses—combined with other data recorded by the airborne system— generate precise, three-dimensional information about the shape of the Earth and its surface characteristics.

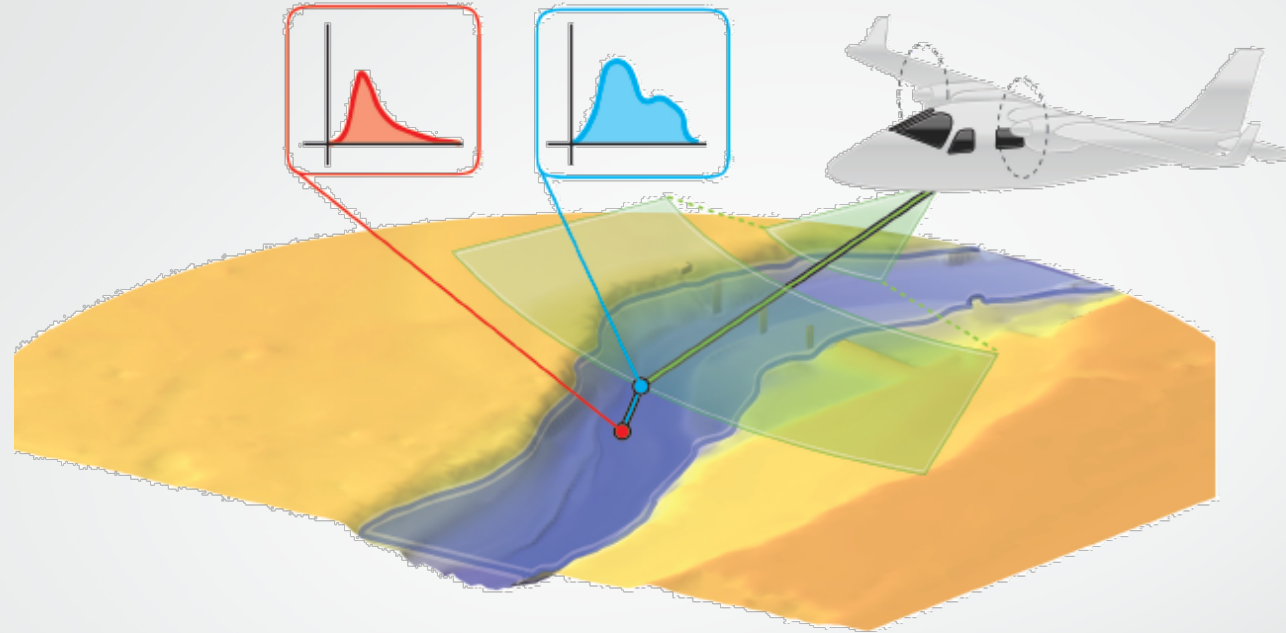
AM
AIRBORNE
HYDRO
MAPPING

AM
AIRBORNE
LAND
MAPPING

AM
AIRBORNE
NATURE
MAPPING

AM
AIRBORNE
ICE&SNOW
MAPPING

Airborne HydroMapping



What is Hydro Mapping?

Airborne Hydromapping is a new technology for the very detailed survey of rivers, lakes and reservoirs. This airborne-operated, ***water-penetrating laser system*** is considered as a technical revolution for the comprehensive and simultaneous monitoring of shallow water bodies (depths down to 8 m), and the adjacent foreland with an **accuracy of less than 10 cm**.

The hydromapping concept and HydroVISH

Fixed wing and helicopter survey platform concepts



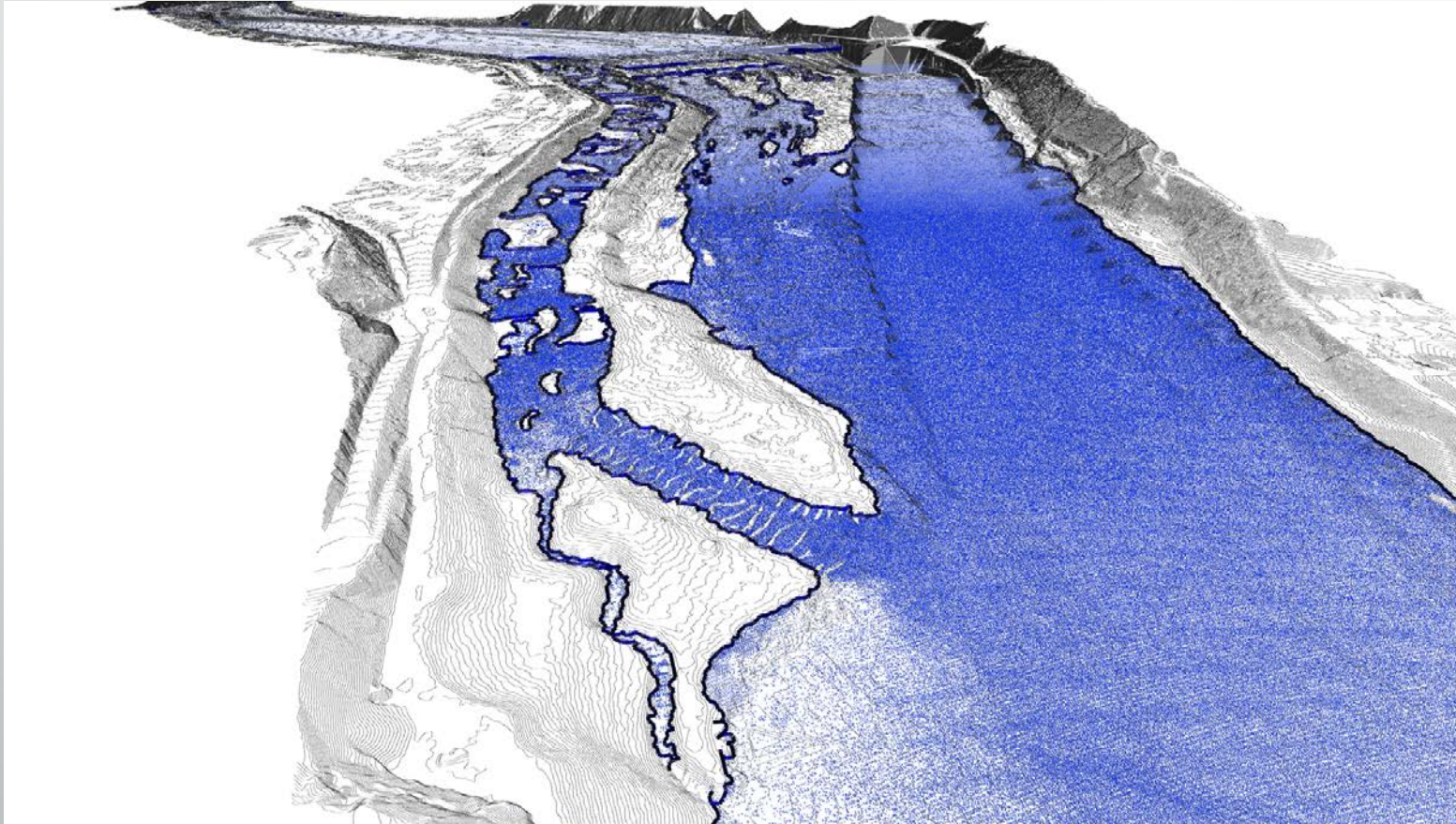
- Lightweight scanner
- Compact layout
- Low energy consuming
- Easy installation handling



Bathymetric survey projects Rheinfelden

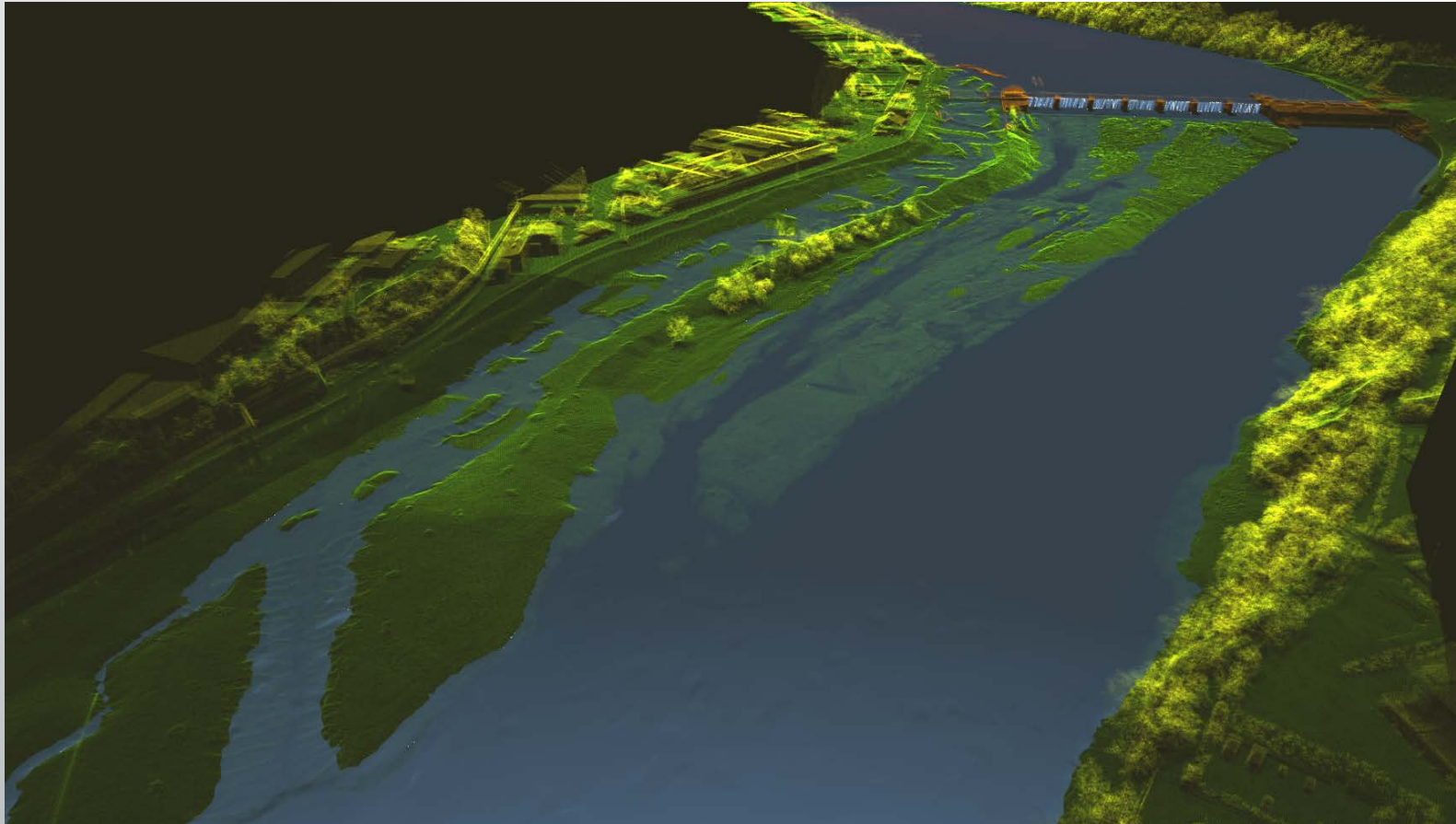


Bathymetric survey projects Rheinfelden

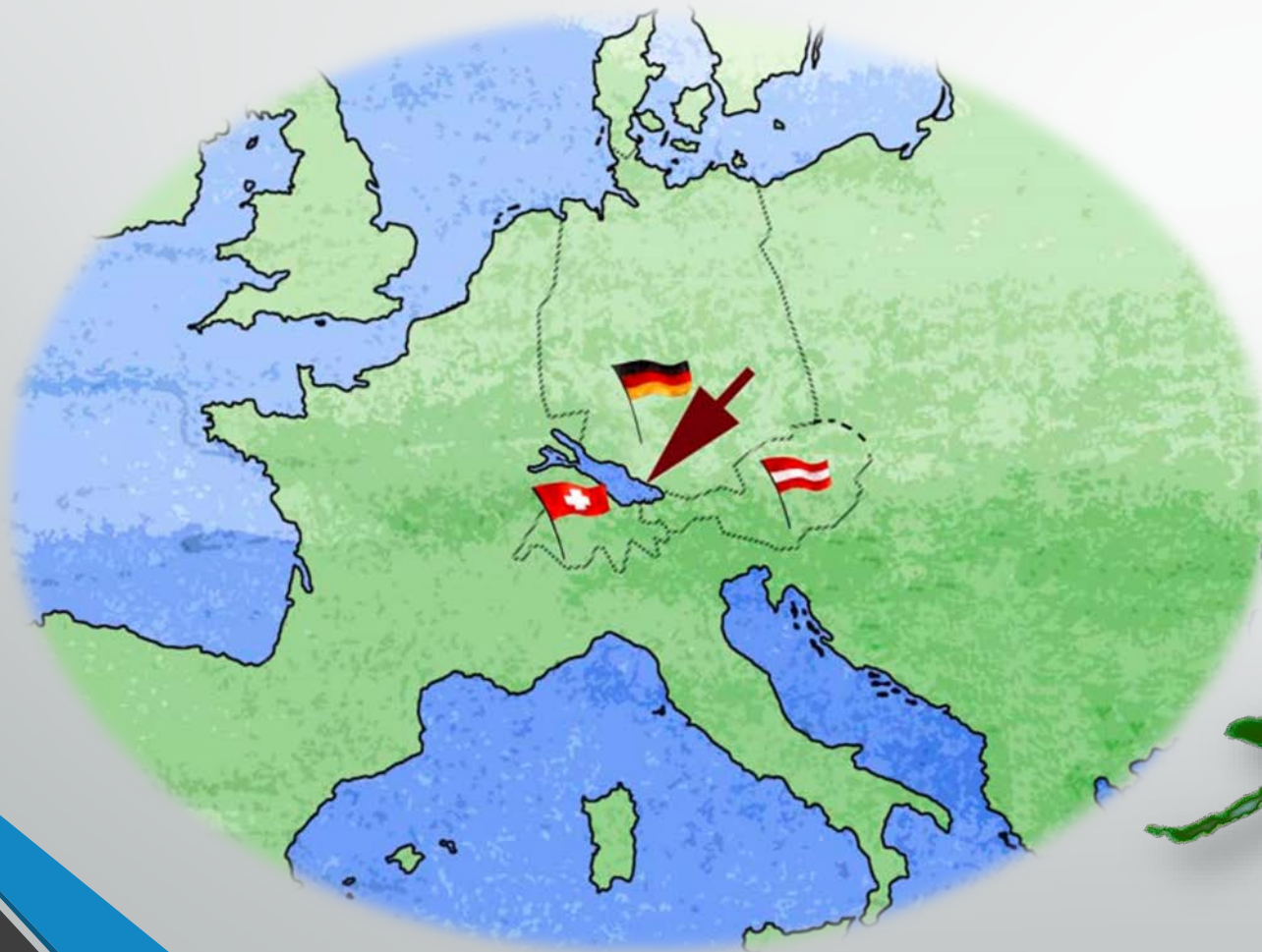


Bathymetric survey projects Rheinfelden

Shading of the water surface:



Application: Lake Constance, 2015



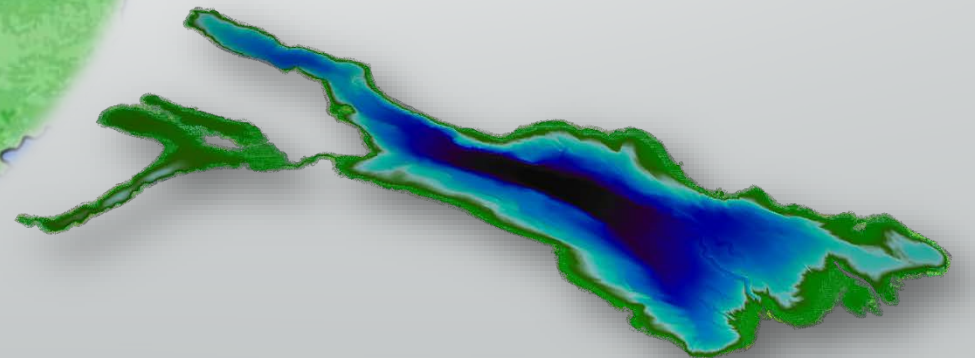
Europe's 3rd Largest Lake
Bordering Austria, Germany, Switzerland

11,500 km²

63km (max) x 14 km (max) –

LIDAR resolution at 80 points / m²

→ 600GB binary raw data



Project: Lake Constance, 2015

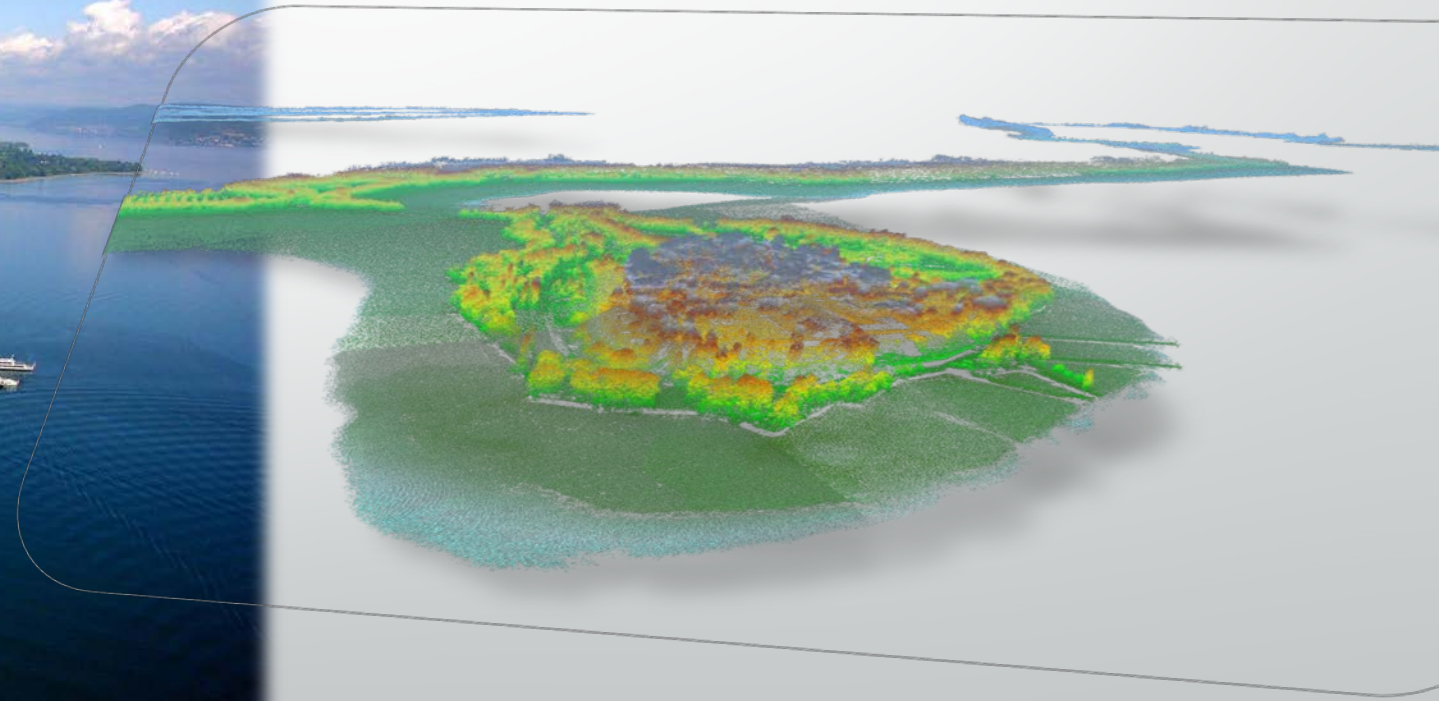


Large Lake at border of Austria,
Germany, Switzerland
11,500 km²
63km (max) x 14 km (max) –

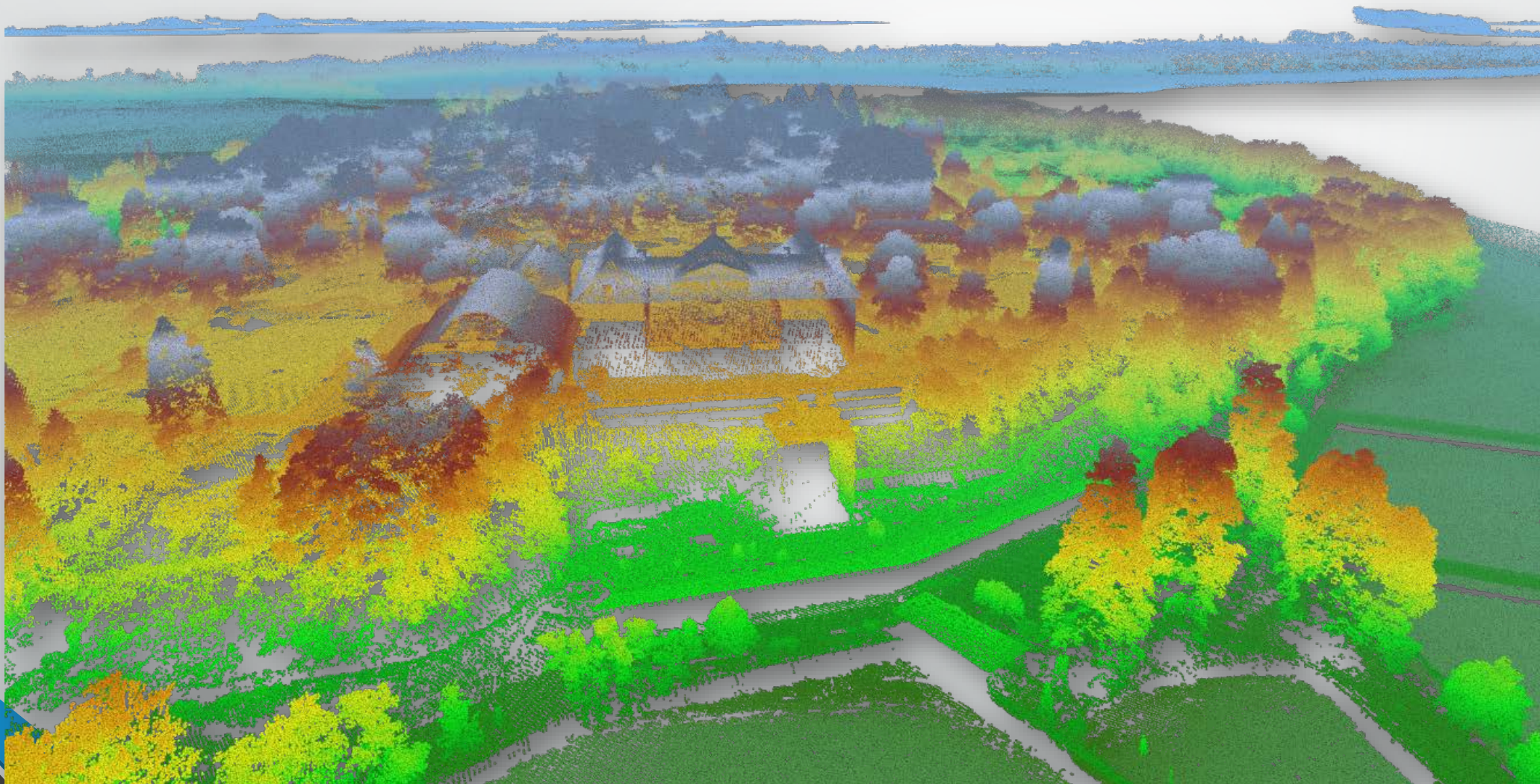
LIDAR resolution at 80 points /
m²

→ 600GB binary raw data

Detail: Mainau Island



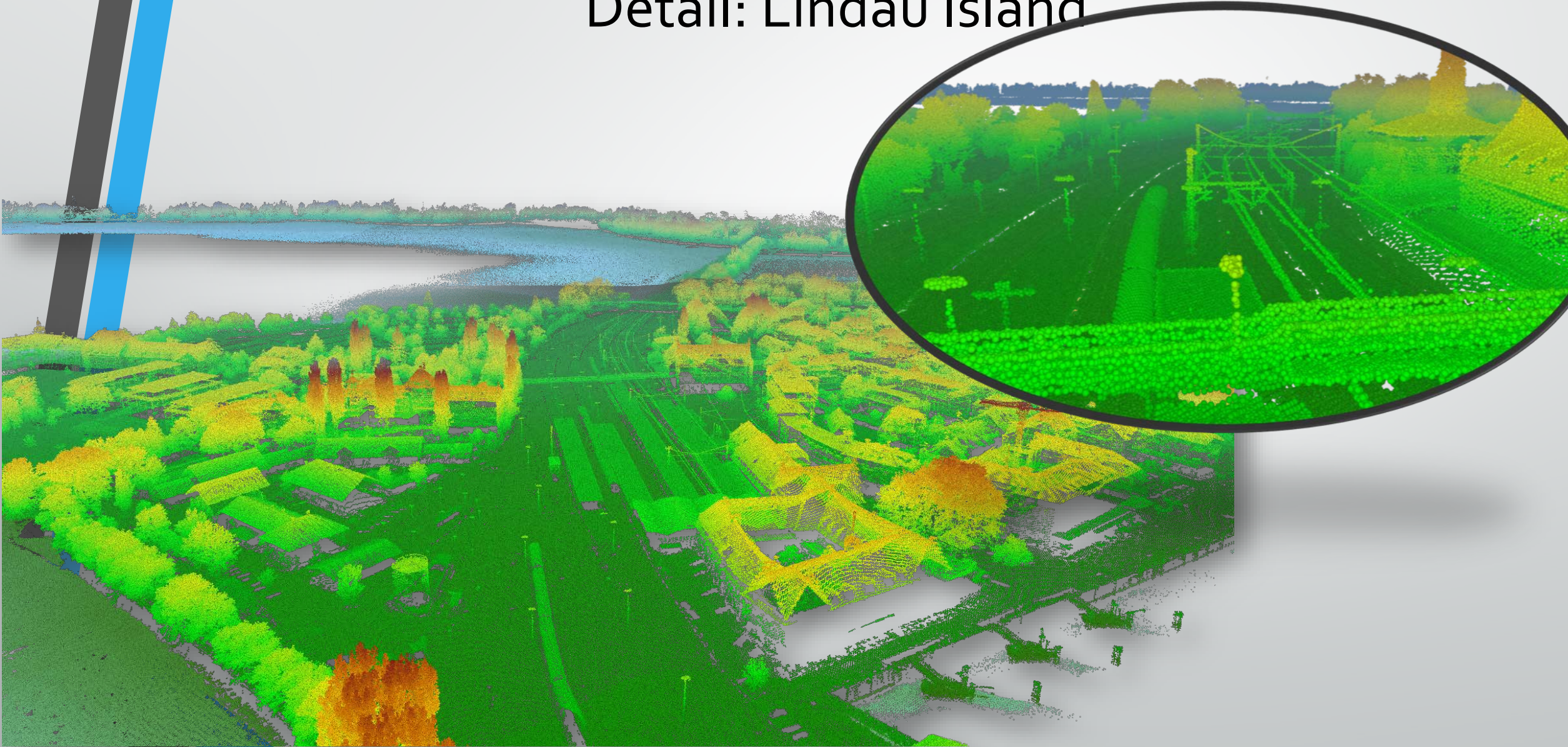
80 points / m²



Detail: Lindau Island



Detail: Lindau Island



Application: Bavaria, 2016 – 4TB



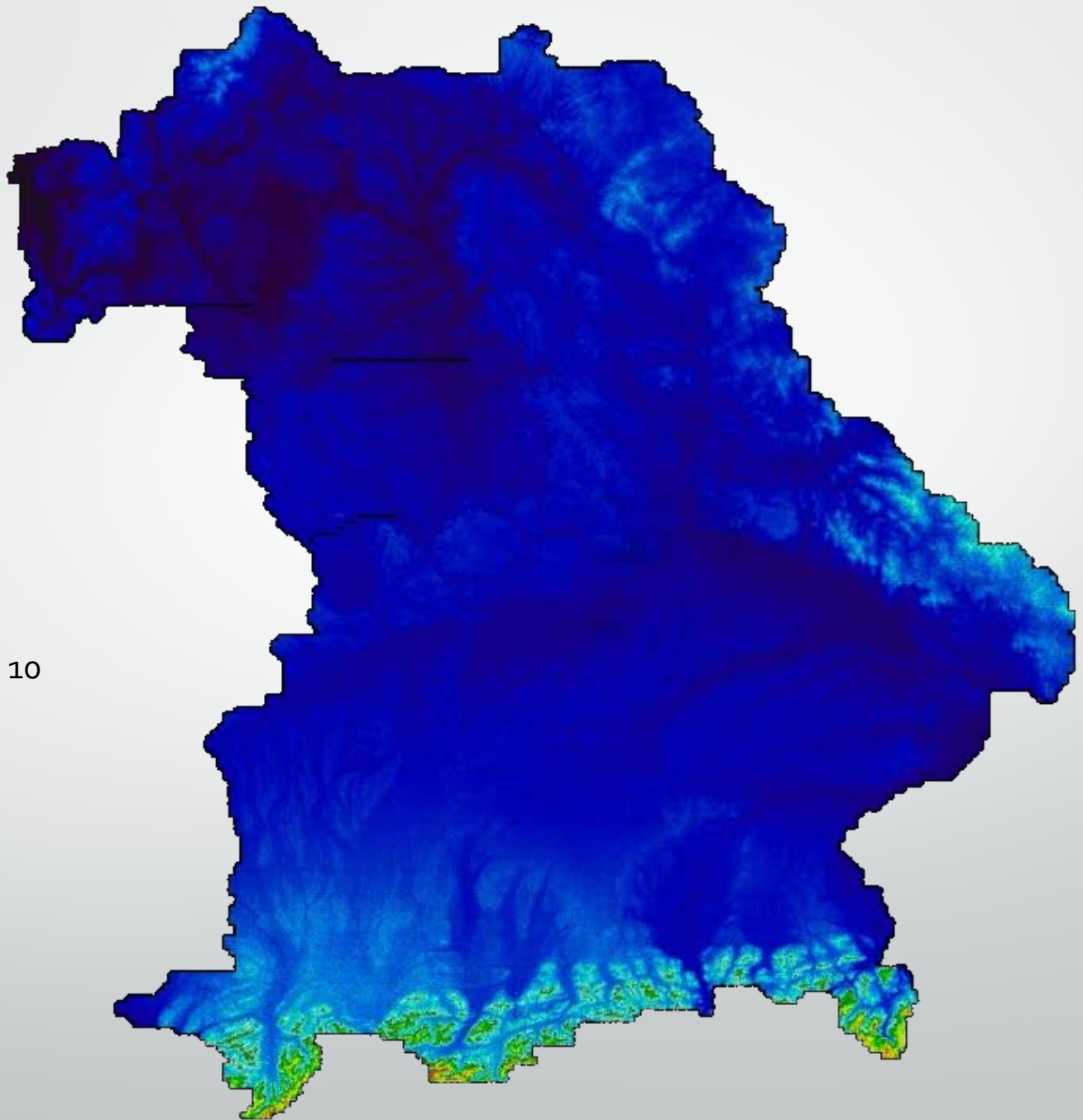
- Largest State of Germany, 70,549.44 km²
- Data resolution: 1m²
- > 73000 files of 1 km²

- Faces limitations in OS: Windows max 2048 files openable at the same time
- Faces limitations in hard disk space
- Work in progress

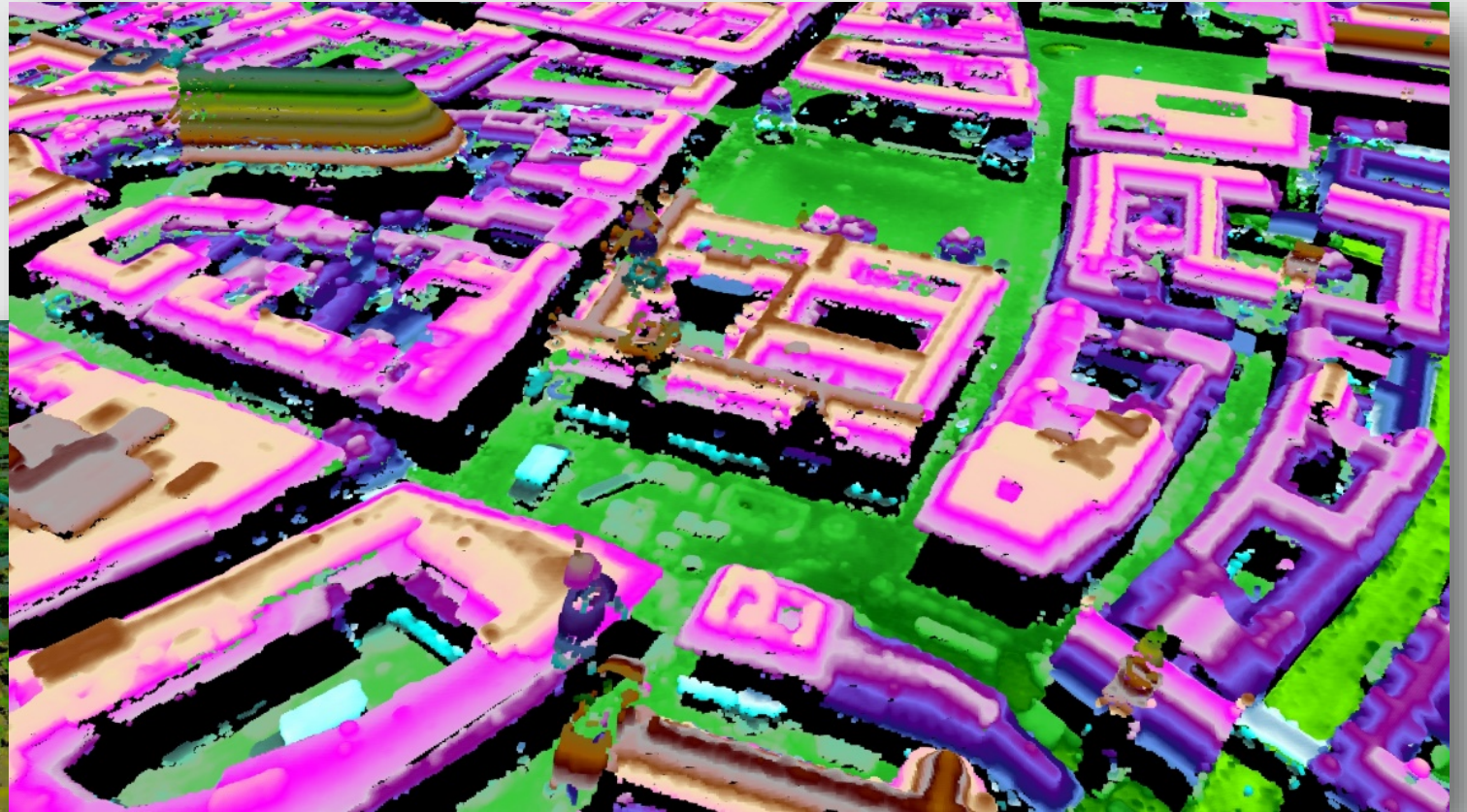
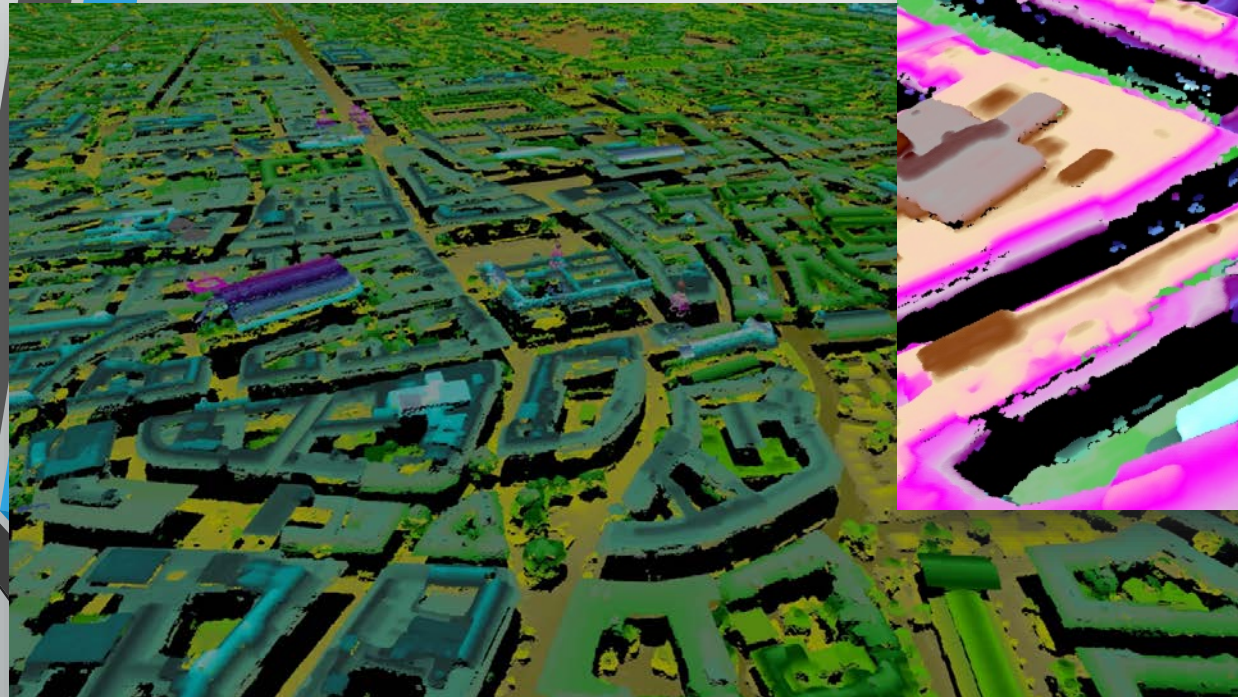
Bavaria, First Results

2TB Finest Resolution at 1m

2TB Hierarchical representation in 10
levels, Refinement factor 4



Bayern Detail (Munich, City Hall)

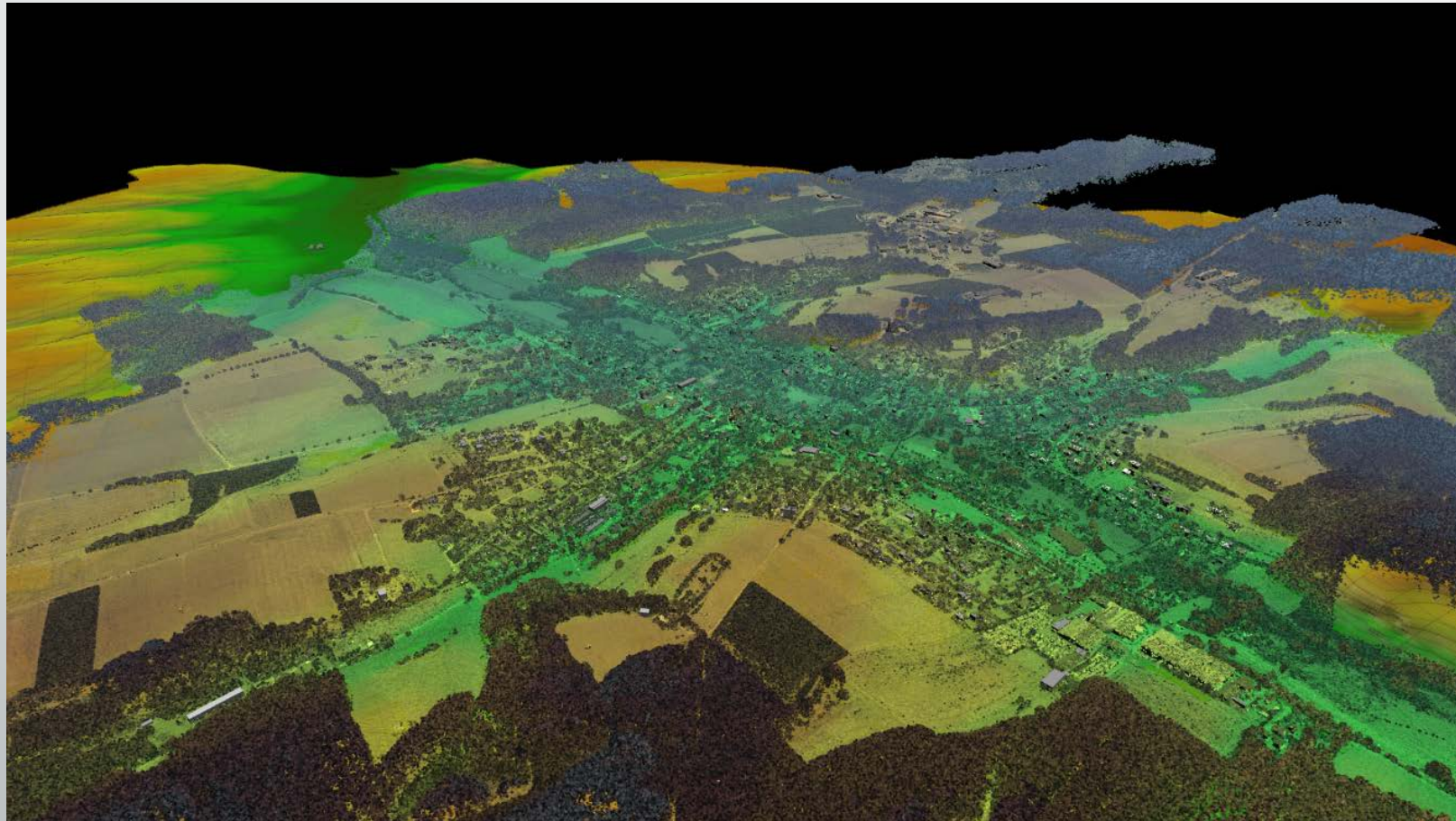




LIDAR Point Clouds & GIS data

Visualizing and Analysing massive point clouds

Massive Point Clouds – 10GB, 100GB, 10TB... (LIDAR observations)

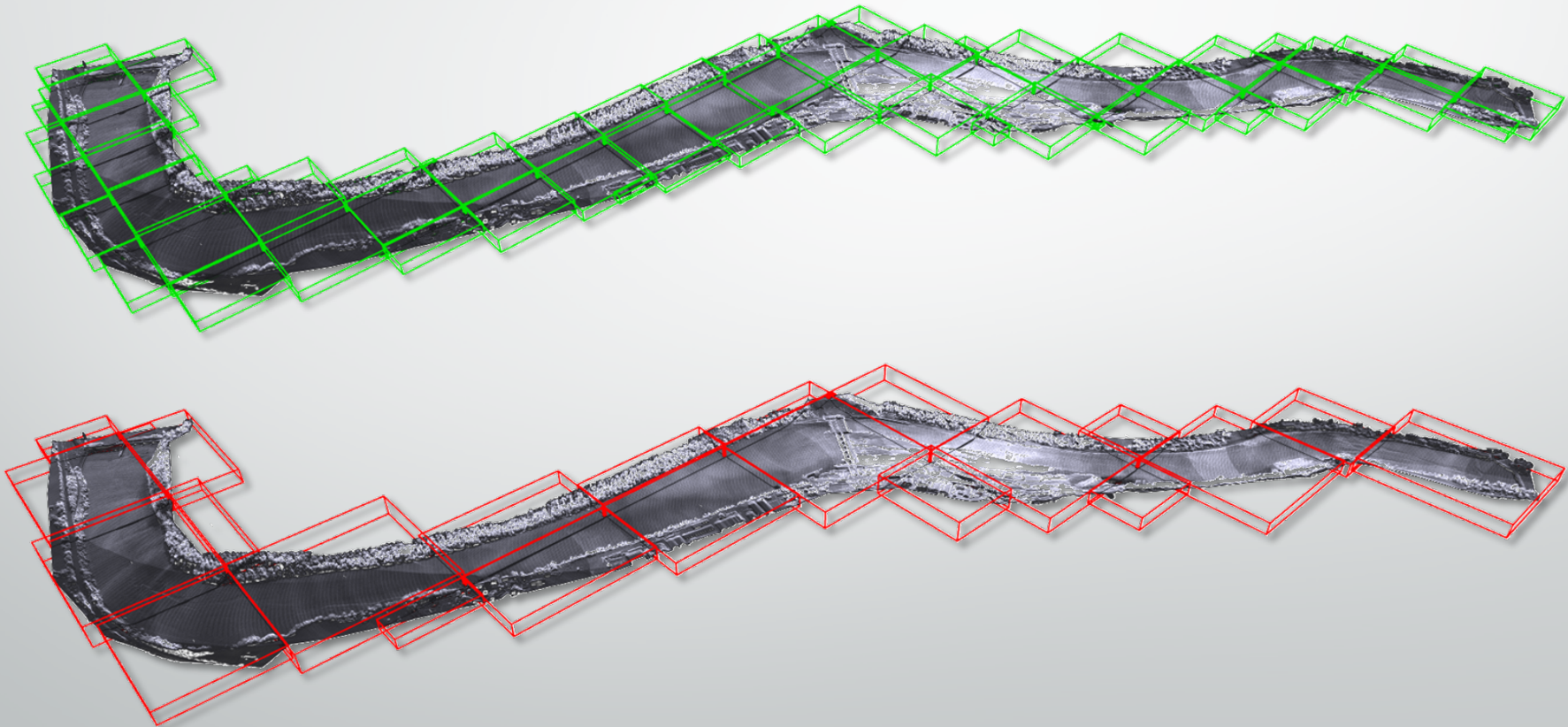


Objects are known via Point Coordinates

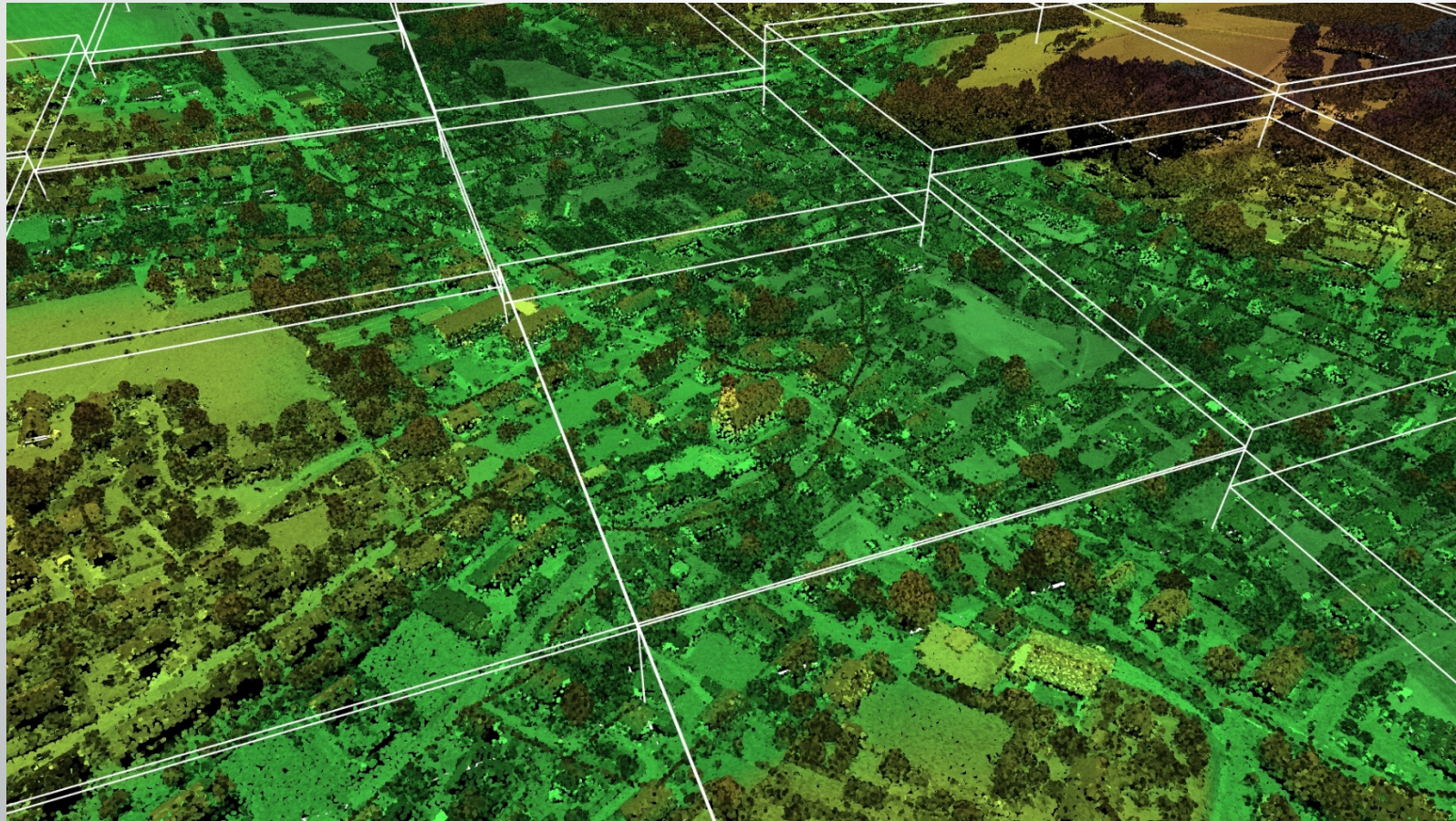


Data Handling #1: Fragmentation

Arbitrary fragment sizes to optimize performance (no requirement to be uniform):



Point Cloud is Fragmented

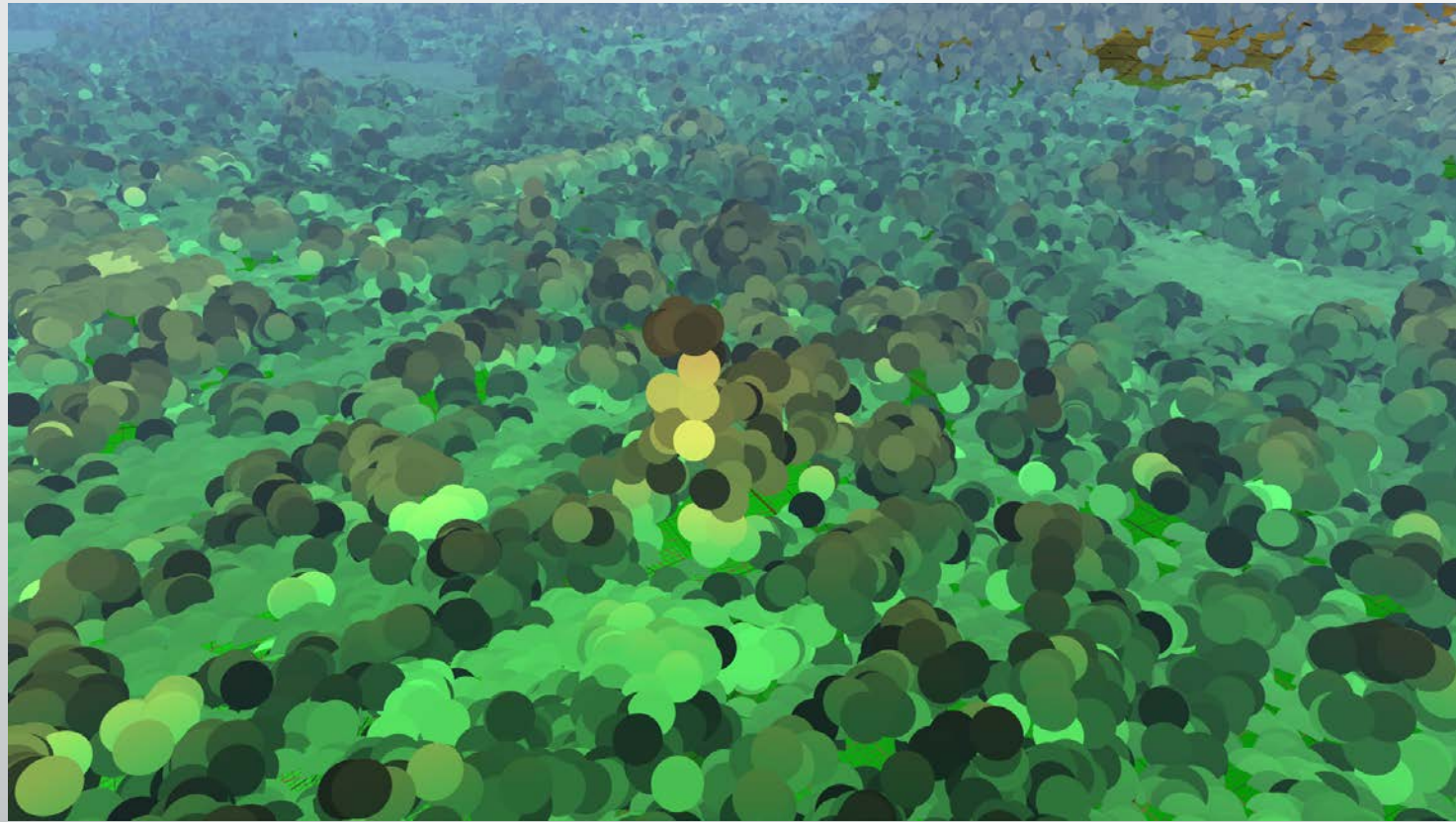


Data Handling #2: Hierarchy – Level of Detail

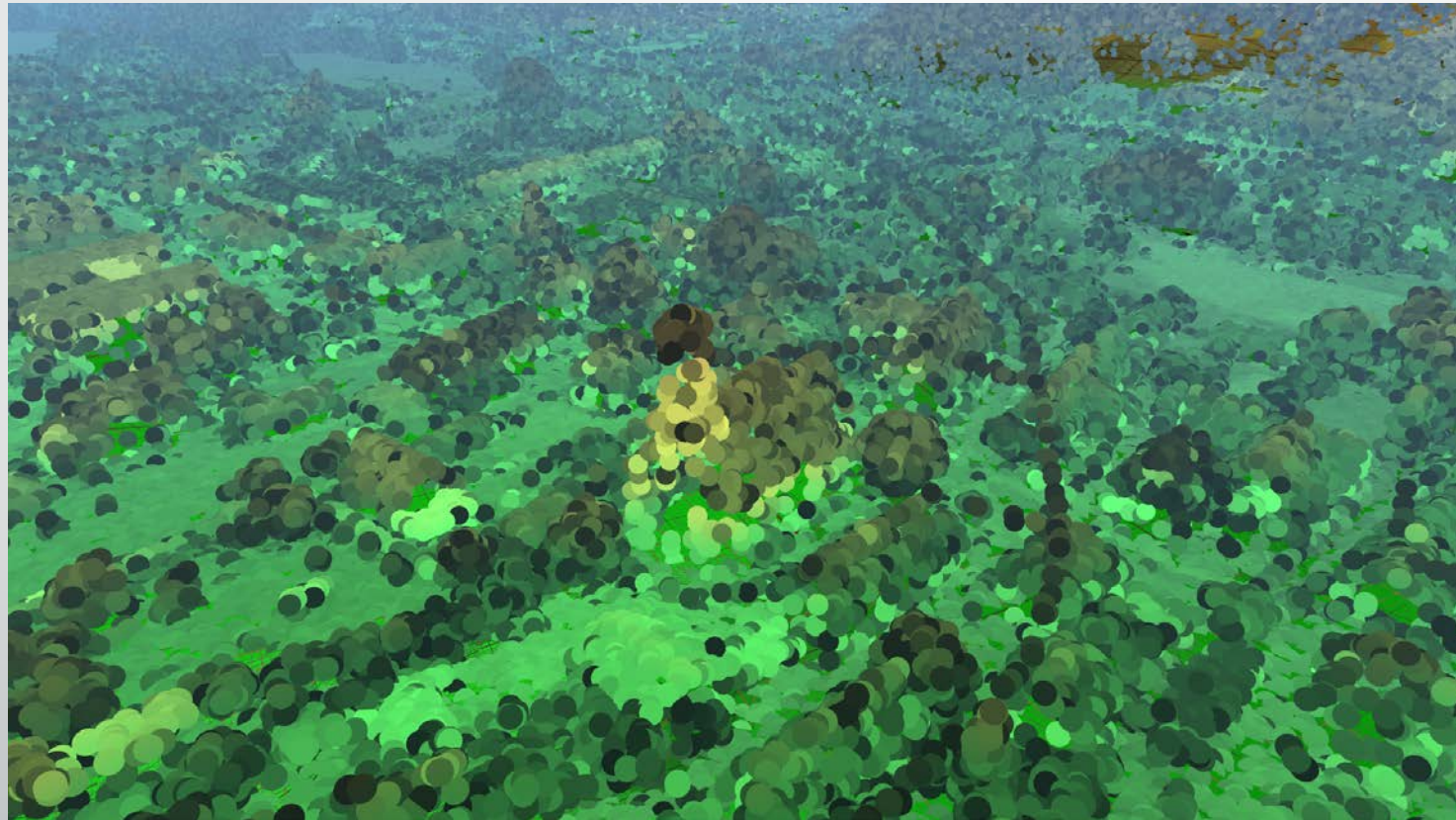
Hierarchy – Level 1



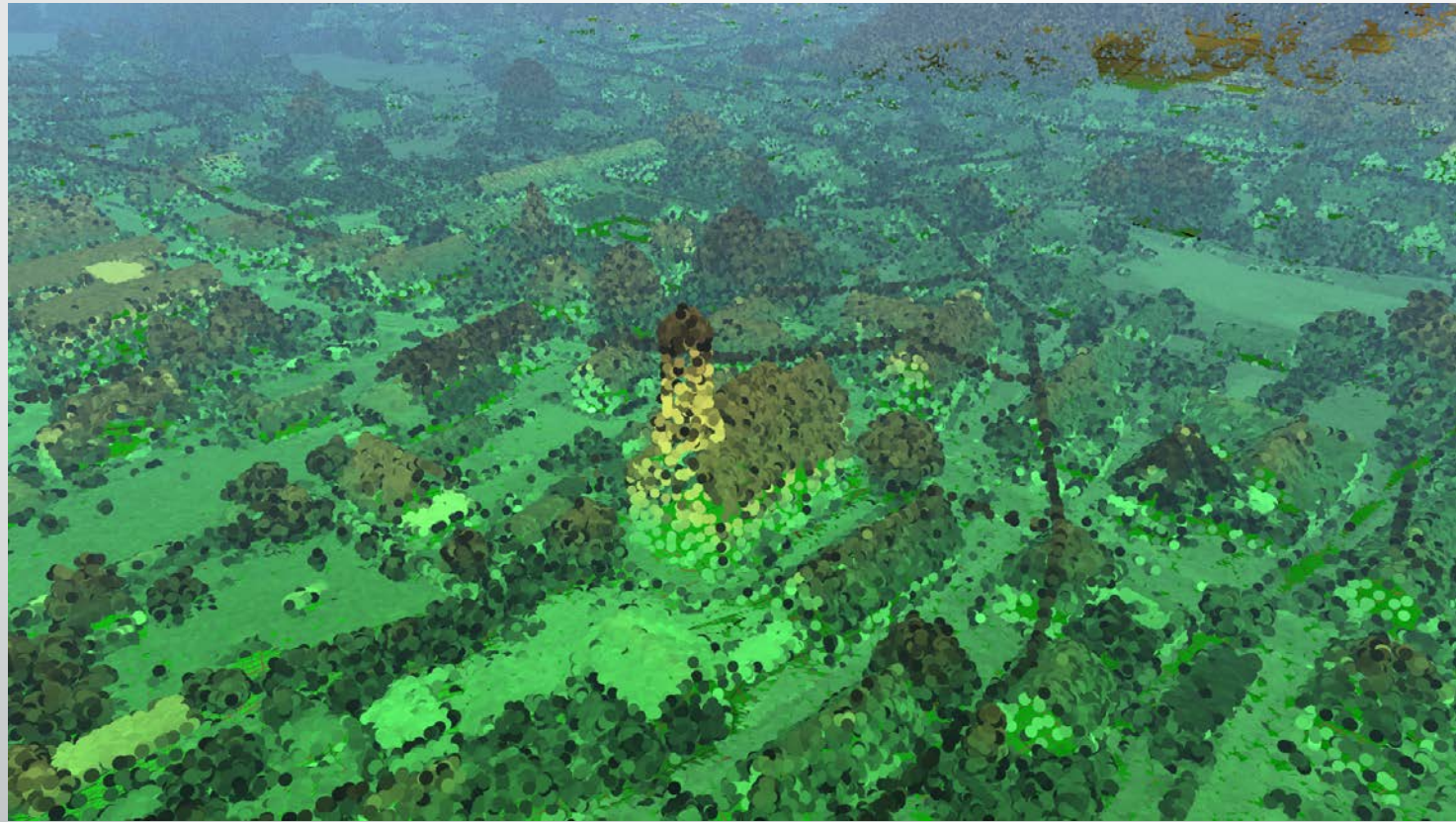
Hierarchy – Level 2



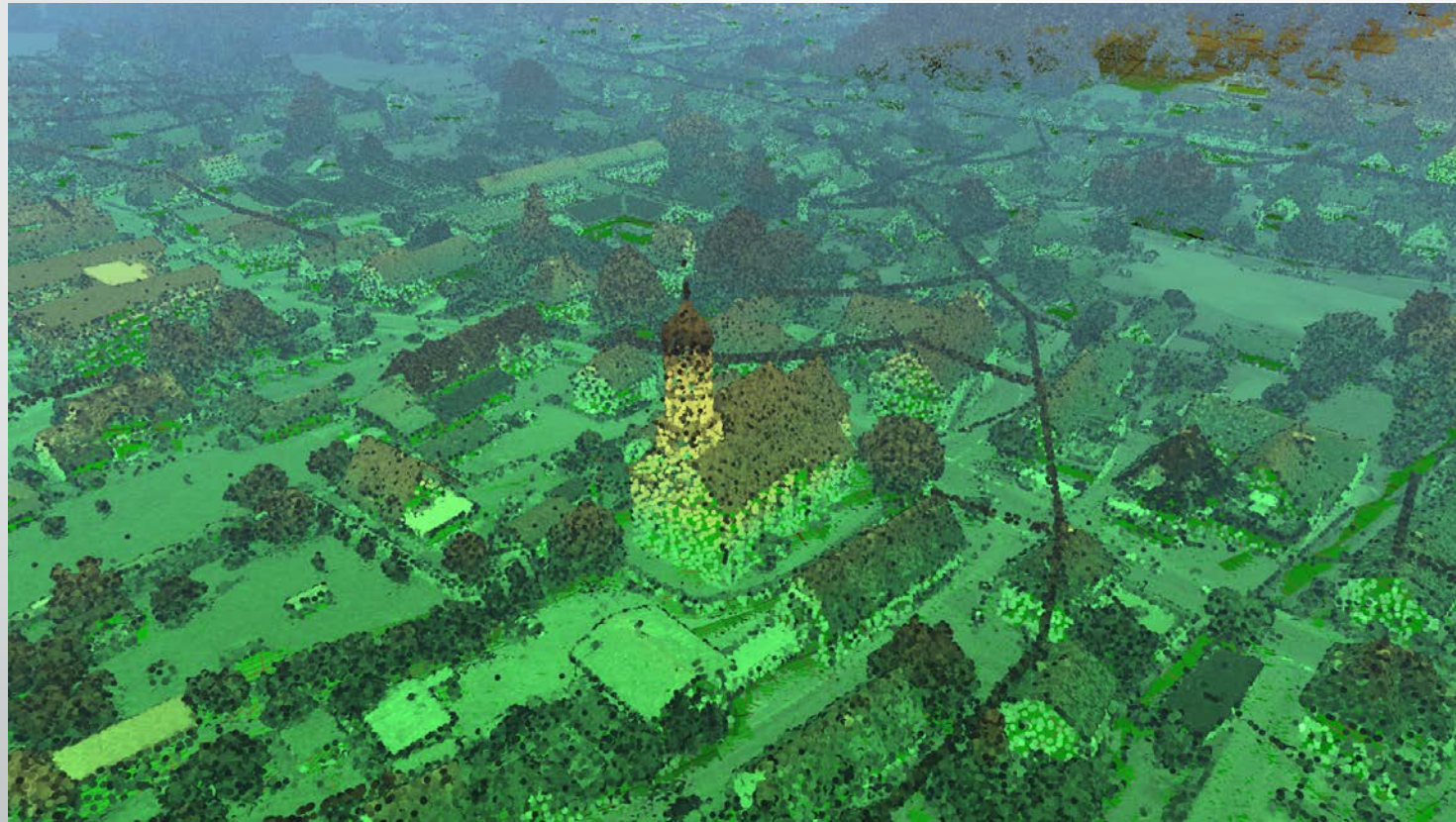
Hierarchy – Level 3



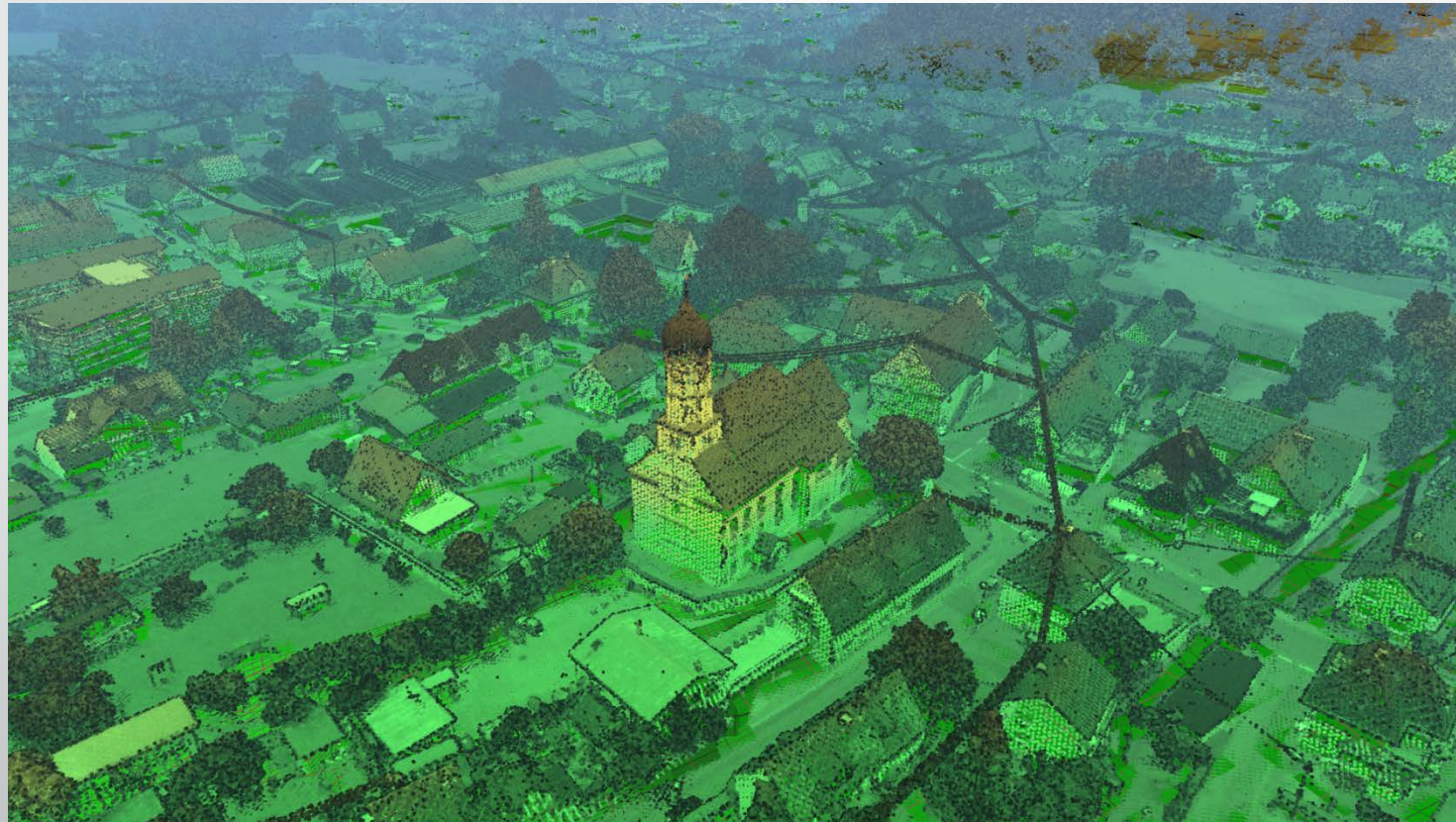
Hierarchy – Level 4



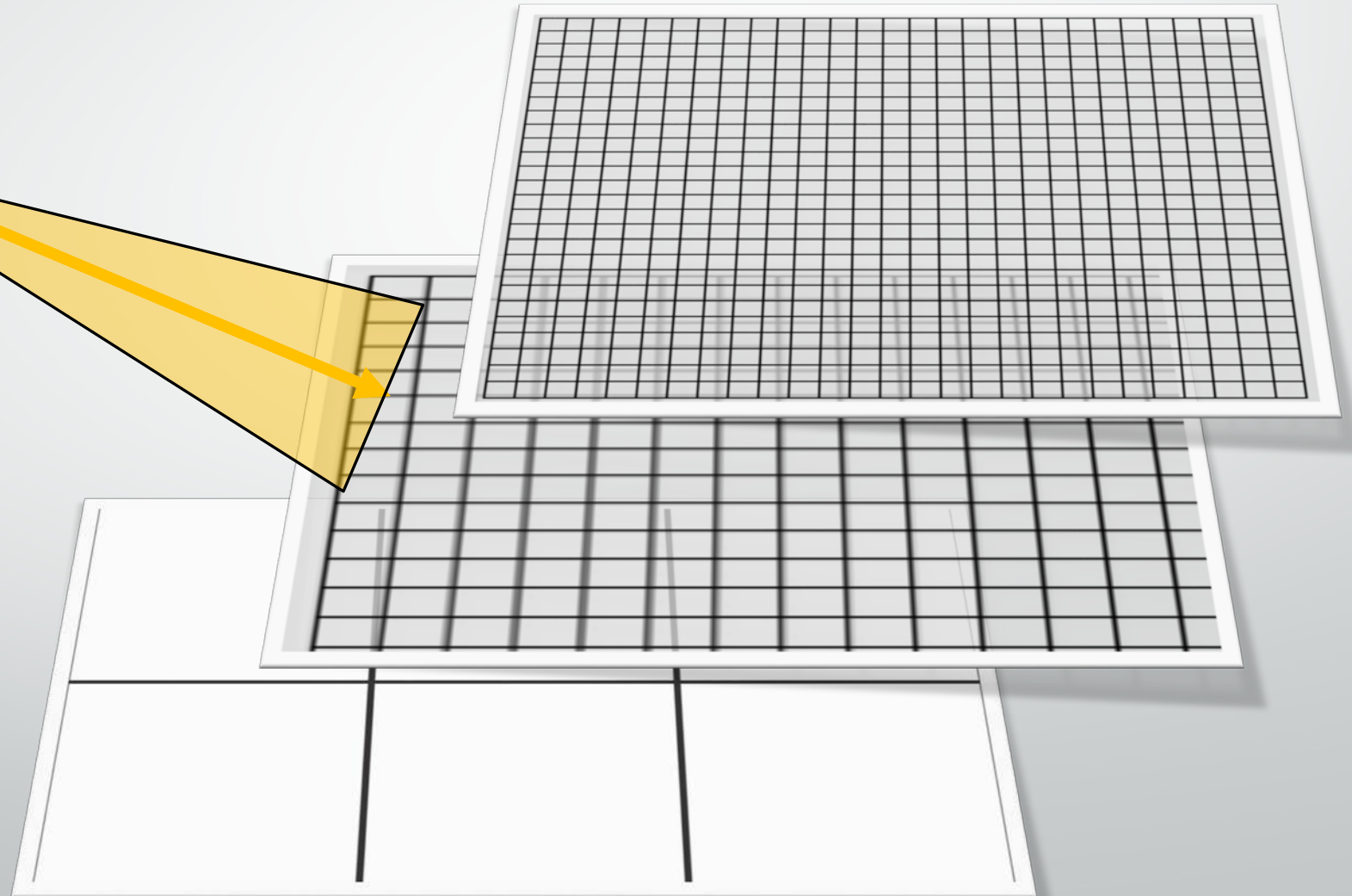
Hierarchy – Level 5



Hierarchy – Level 6



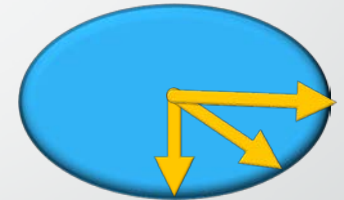
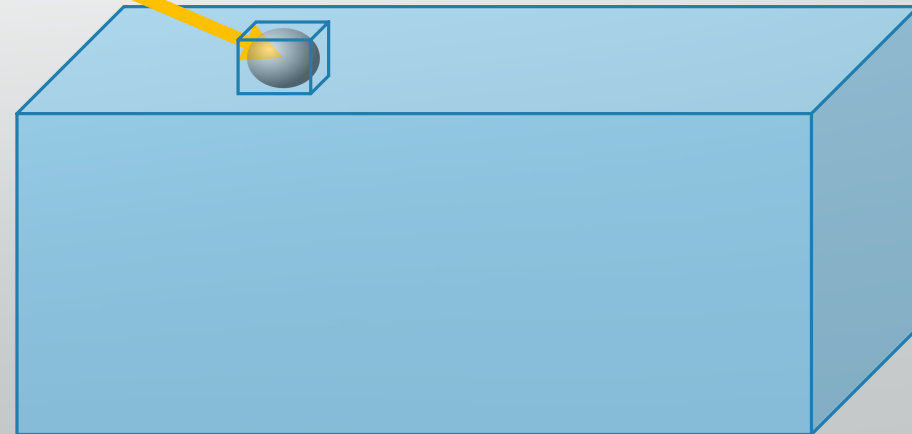
Performance Objective:
Number of Visible Points is constant



Anisotropic Apparent Cell Size The „Cell Tensor“

Measuring the
extent of a cell along
the ray of sight

$$s = \frac{1}{\sqrt{C(v, v)}}$$



Visibility Criteria



Compute Apparent
Cell Size of Next
Level

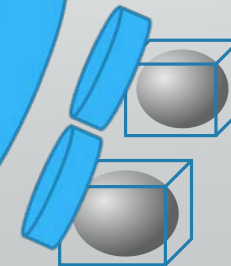
Is the visible
size of a cell
too small?

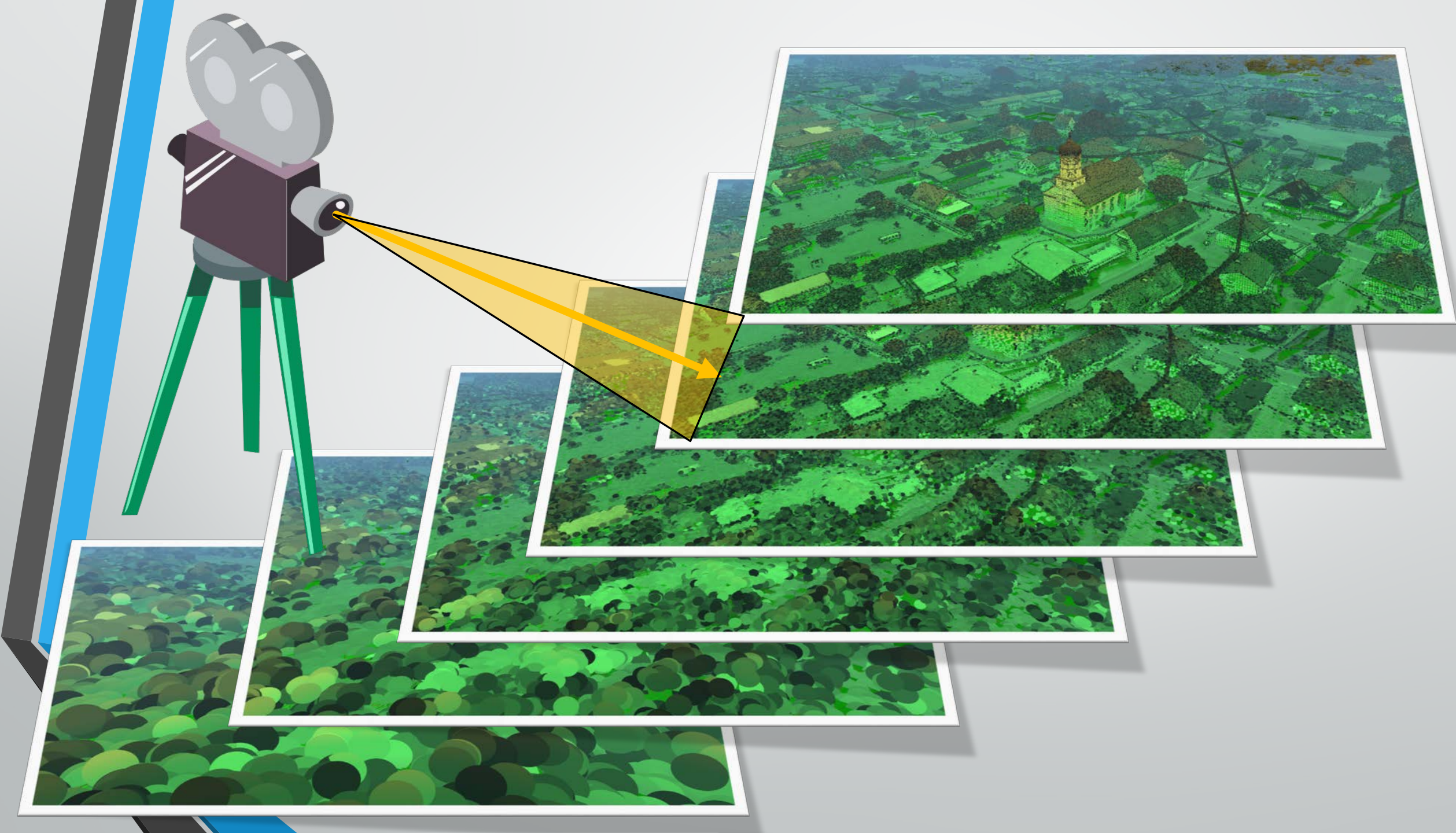
No

Check
next
level

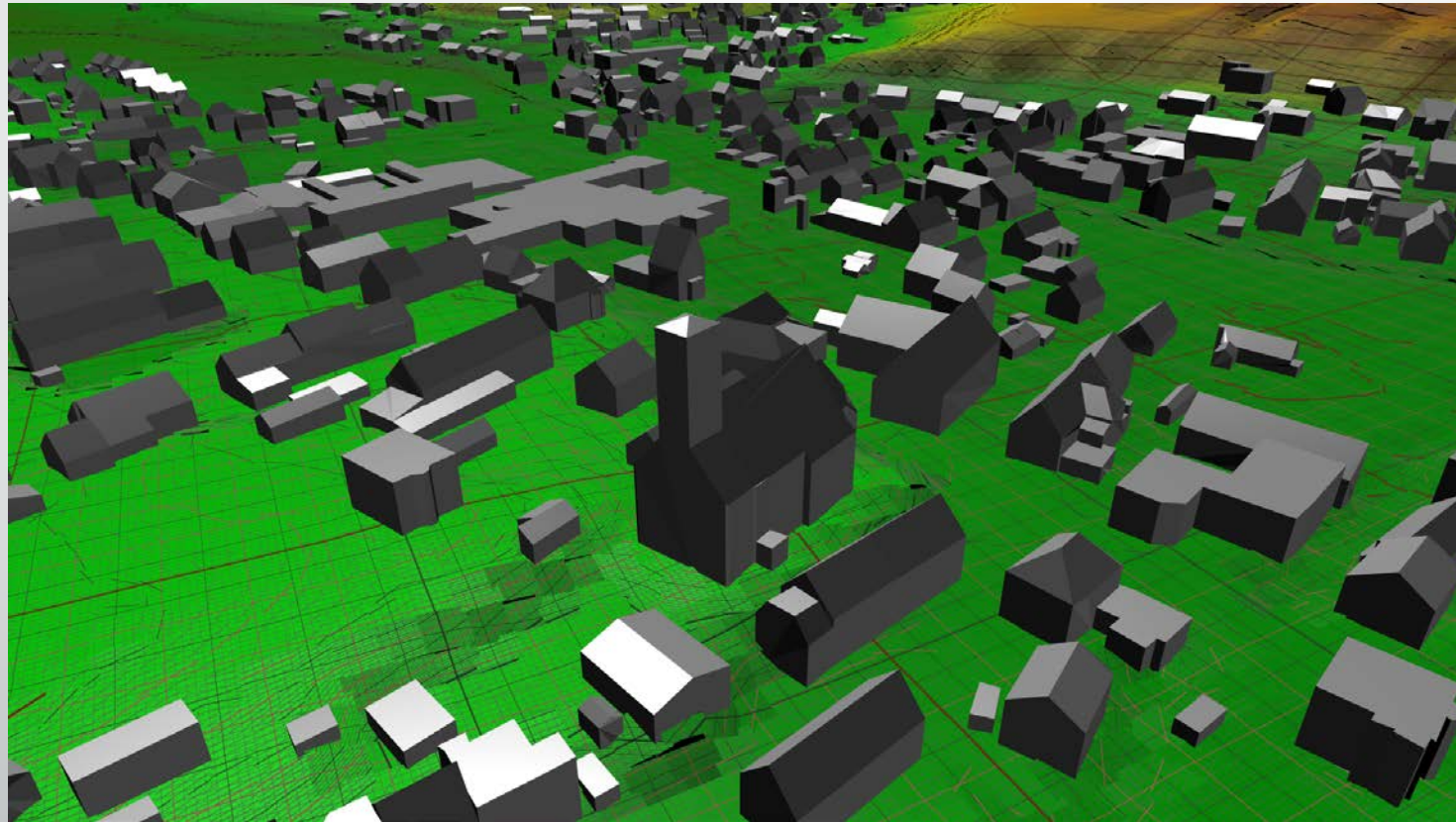
Yes

Keep at
Coarse
Level

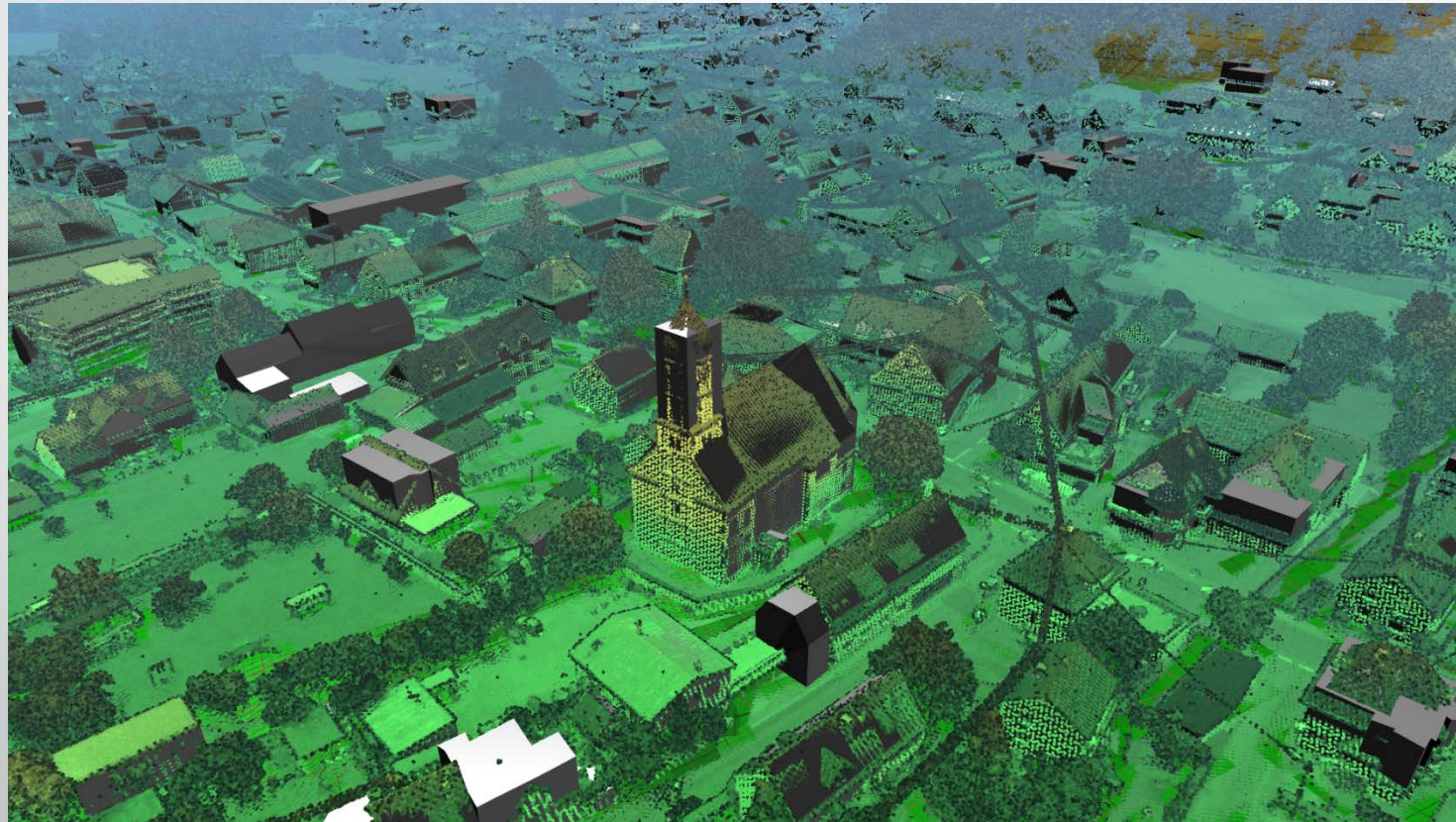




Integrate with Geometries (e.g. Triangular Surfaces)

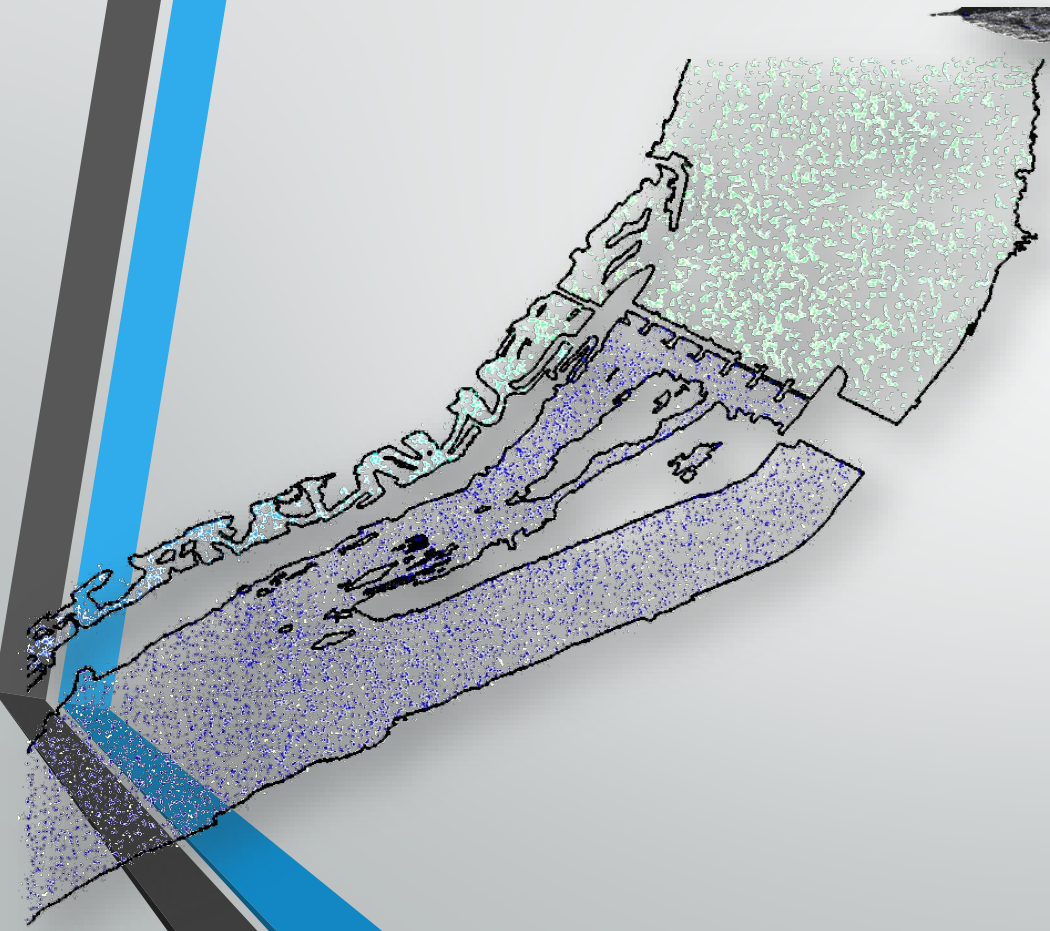


Integrate with Geometries (e.g. Triangular Surfaces)

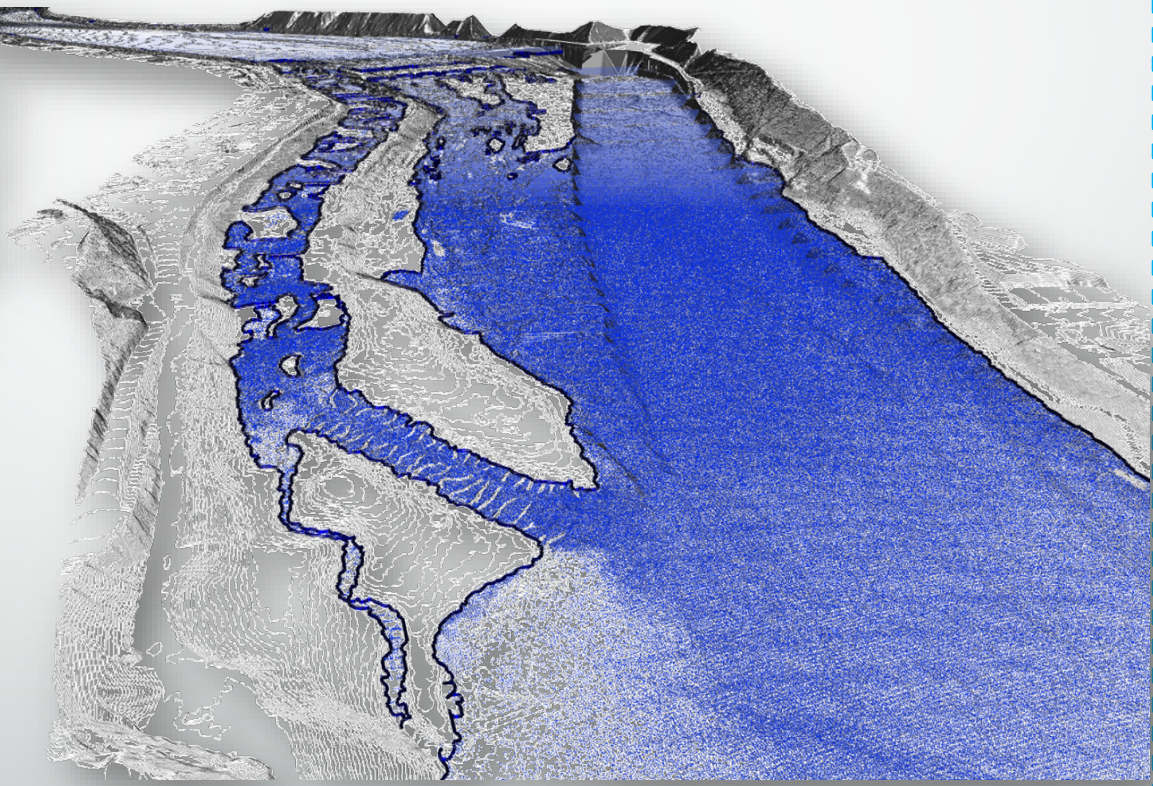


Data & Visualization fusion: 1D, 2D, 3D, ...

Extraction of boundarywater-surface



Explicit LinesContour



The Tool Approach

“Specific Problems need specific Solutions”

Point Cloud Data



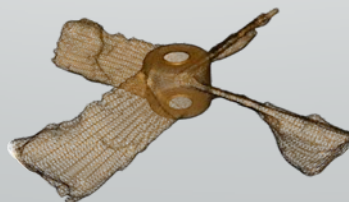
Display as Points



Triangular Mesh



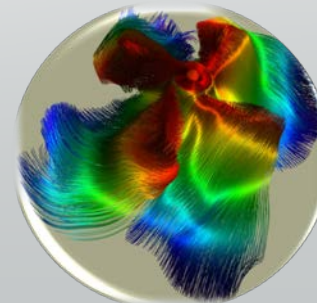
Display as Surface



Lines



Display as Lines



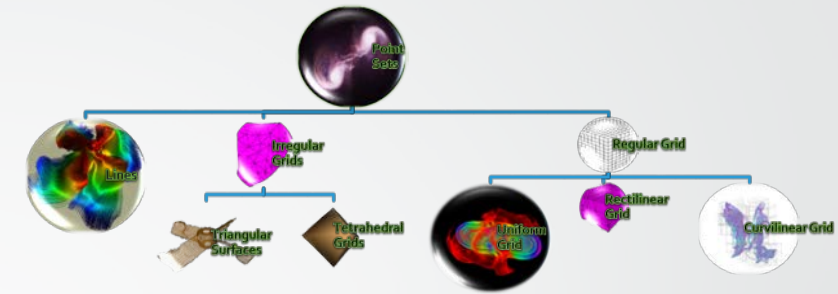
?



Display as ??

The Framework Approach

Generic Methods to avoid reinventing the wheel

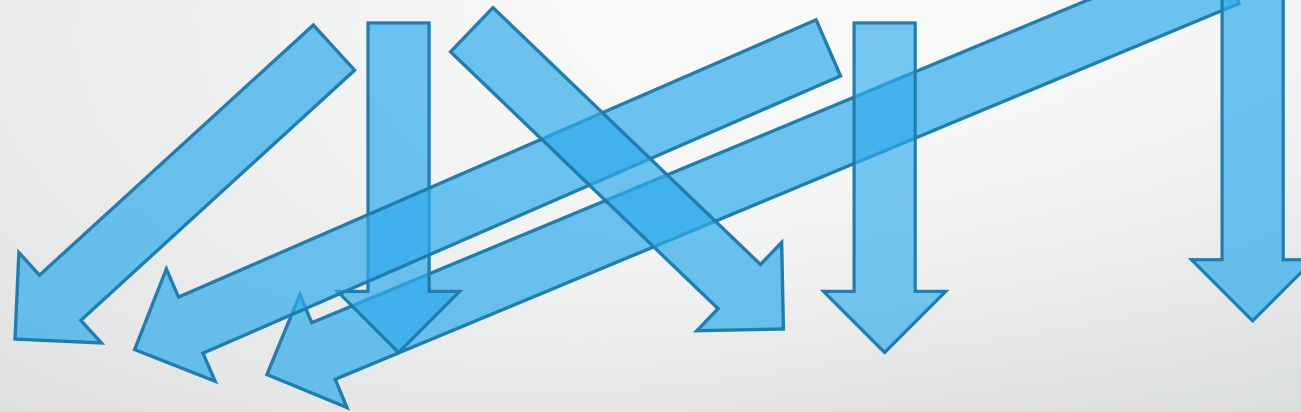


Point Cloud Data

Triangular Mesh

Lines

?

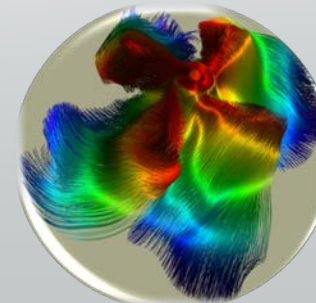
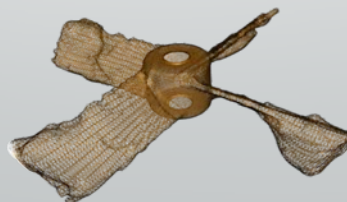


Display as Points

Display as Surface

Display as Lines

Display as ??





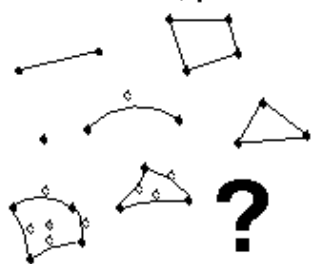
Unifying Application Cases as Fiber Bundles

Organising Data for Massive Amounts of data, fast processing and visualization

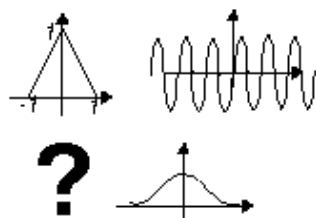
Inspired by: Differential Geometry, Topology, Geometric Algebra

Describing Data Is Challenging

Element Types



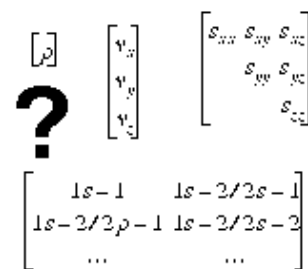
Basis Functions and Interpolation Schemes



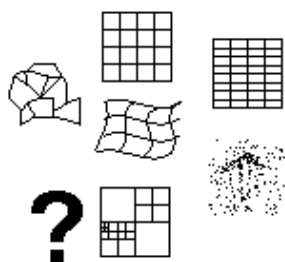
sparse and dense fields



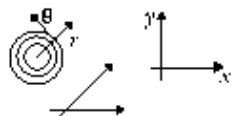
Field value types



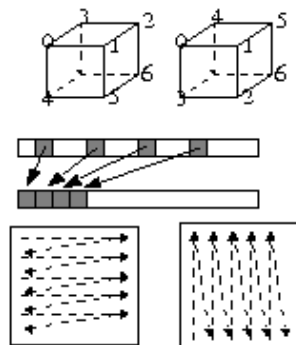
Mesh Types



Coordinate Systems



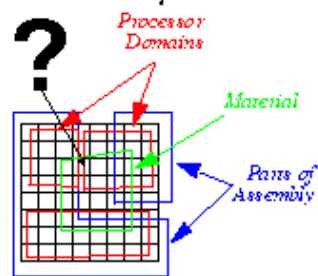
Storage Conventions And Data Structures



Compression



Mesh Decompositions



Challenge of a Common Data Model

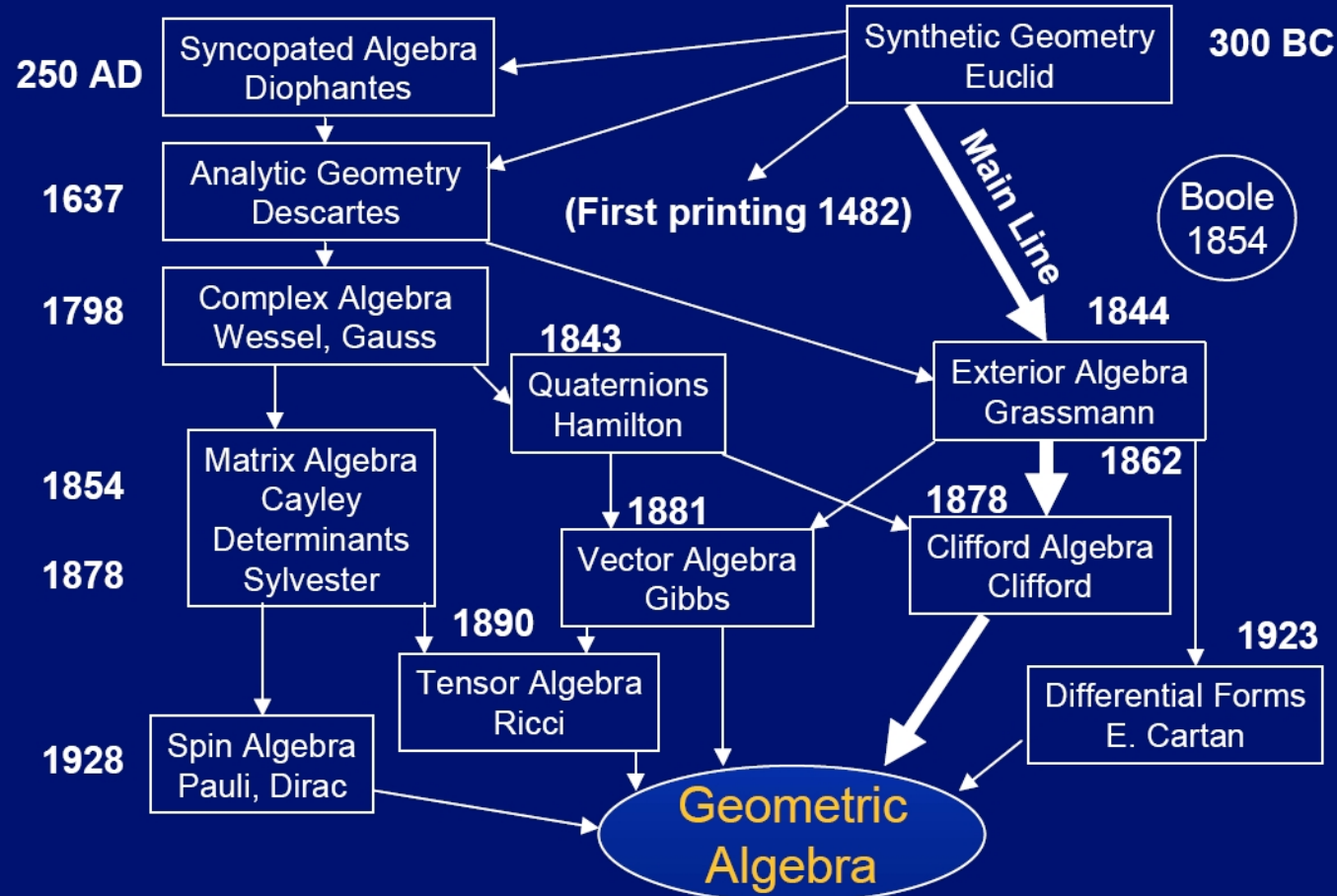
"The proper abstractions for scientific data are known. We just have to use them."

D. M. Butler & S. Bryson

Vector-Bundle Classes form Powerful Tool for Scientific Visualization

Computers in Physics, Vol. 6, No 6., Nov/Dec 1992

Family Tree for Geometric Algebra



Alyn Rockwood, Oct 1999

1966-2005: David Hestenes (Arizona State University) recovers geometrical interpretation of clifford algebra as "geometric algebra"

Mathematics for Visualization

Topology

- Discretization schemes, combinatorial structure, relational information

Differential Geometry

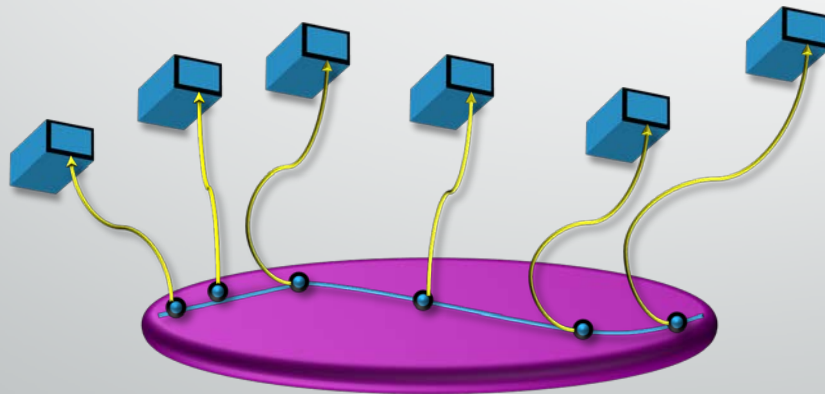
- Coordinate representations, transformations, differential operators, tensor algebra

Geometric Algebra

- N-dimensional Rotations, navigation, data analysis, feature extraction, spinor formalism, generalized quaternions, mimetic operators

Fiber Bundle Data Model

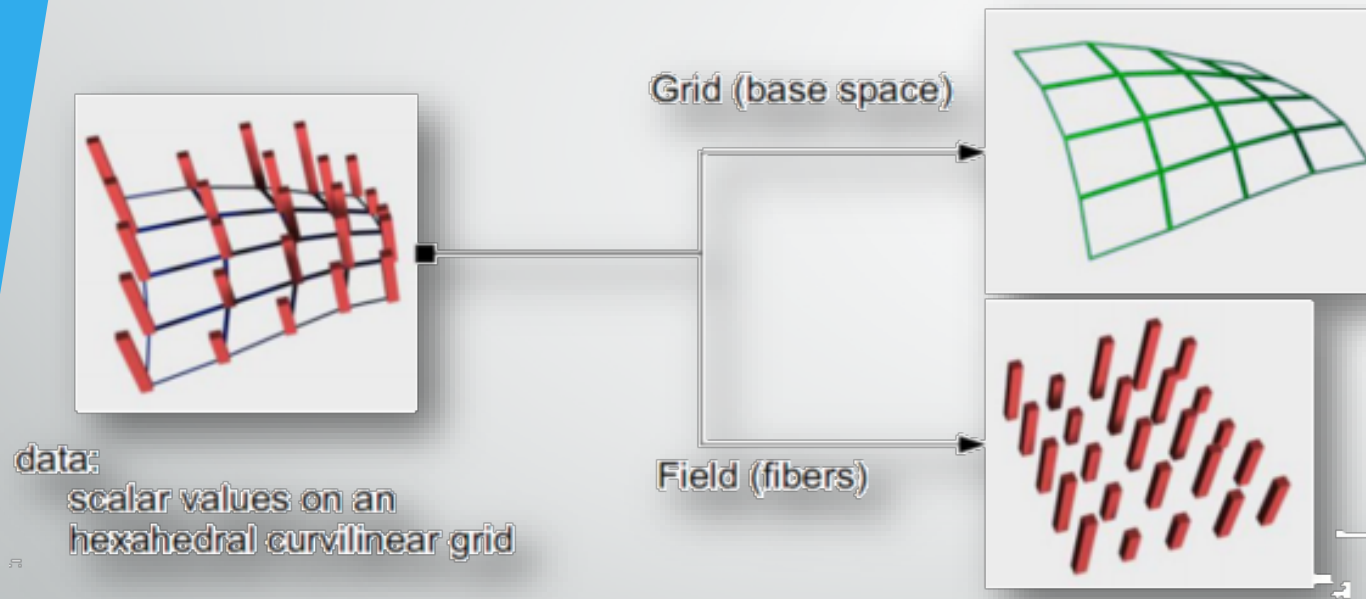
- Is a generic approach to handle a wide range of data types used for scientific visualization
- Basic concept: Base space maps to fibers



Fiber Space at each
point of Base Space

Base Space

Geometric Algebra in the Fiber Bundle



Base-Space operations:

- Dealing with large data
- Differential operators
- This is where Geometric Algebra „may life“.

→ Operations on the manifold (possibly a vector space)

Fiber-Space elements:

- This is where Geometric Algebra „lives“
- Zoo of multivectors and tensors

→ Operations on the tangential space and powers of it (always vector space)

Mathematical Notation

- Concept of a Manifold M with Tangential Spaces $T_p(M)$ at each point $p \in M$



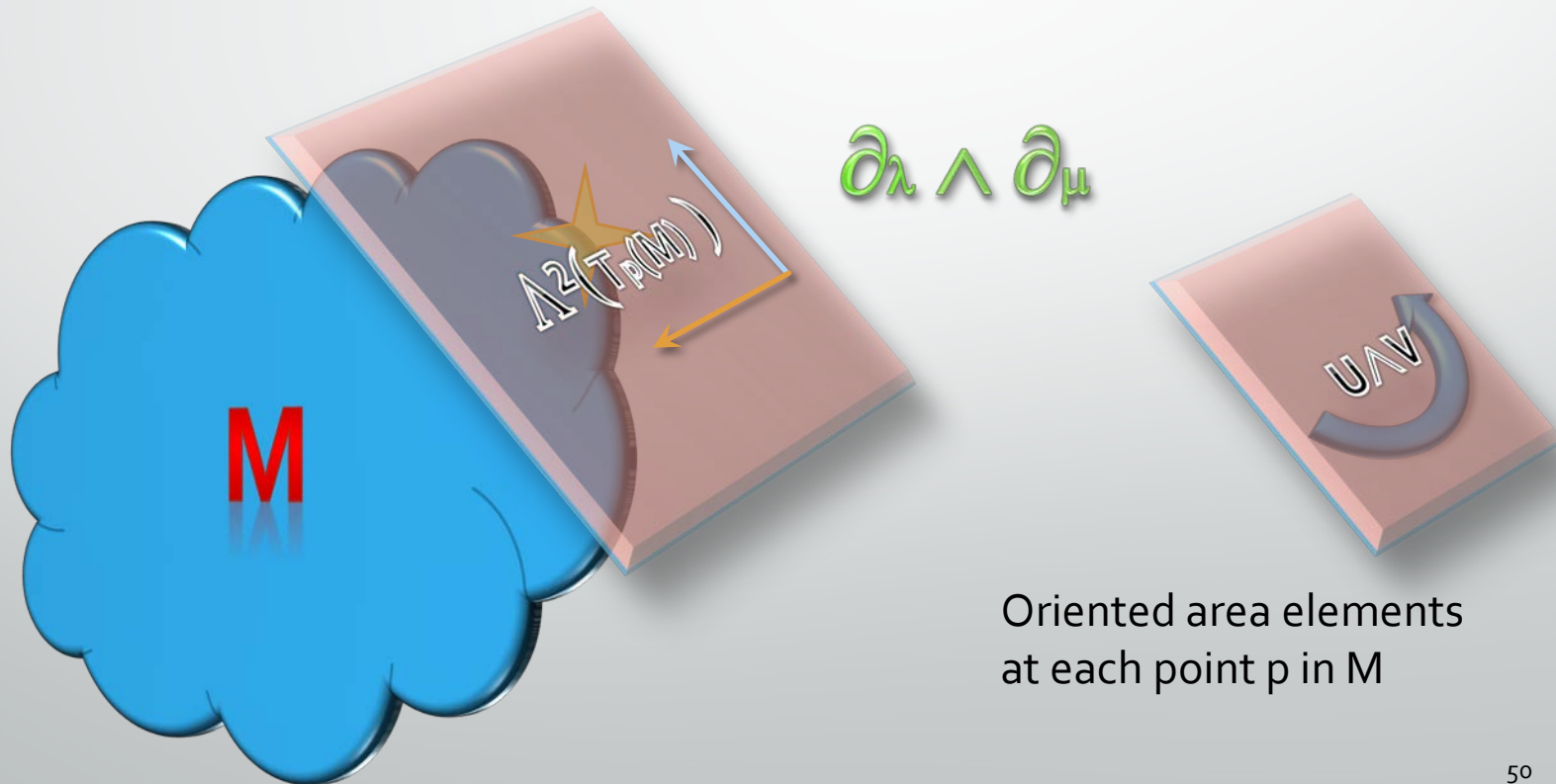
M is not a vector space
 T is a vector space
(at each point p of M)

Spun by derivatives $d/d\lambda$

Grassmann Algebra on $T_p(M)$

- $\wedge: T_p(M) \times T_p(M) \rightarrow \Lambda^2(T_p(M))$

$$u, v \Rightarrow u \wedge v \text{ where } u \wedge v = -v \wedge u$$



Data Type Classification

Base Space

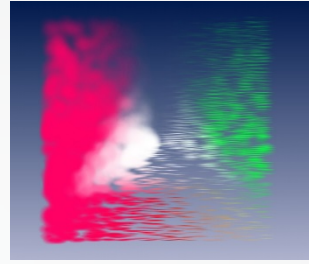
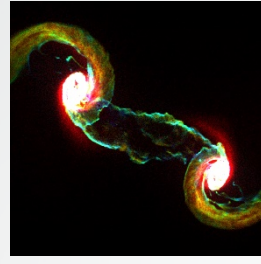
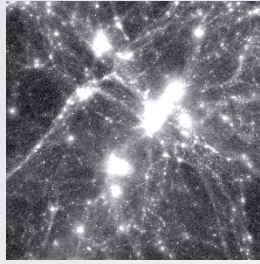
- “Structured” Grids
 - Uniform
 - Curvilinear
 - Multiblock
 - Refinement
- “Unstructured” Grids
 - Particle Sets
 - Surfaces
 - Line sets

Fiber Space

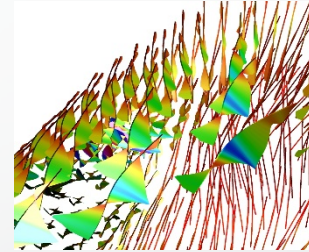
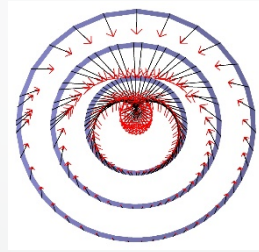
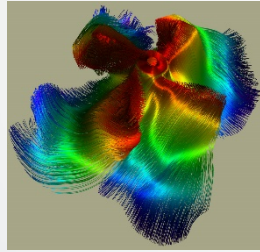
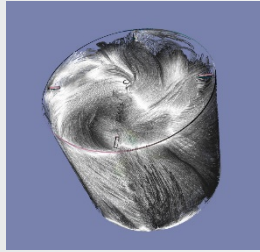
- Scalar Fields
- Vector Fields
 - Bivector fields
 - Co-vector fields
 - Multivector fields
- Tensor Fields
 - Symmetric / Asymmetric
 - 2nd order, 3rd order, 4th order...

Fiber: 0D 1D 3D 6D

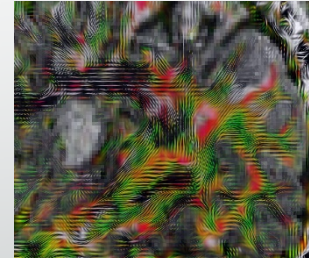
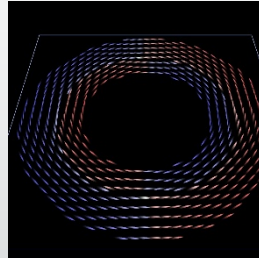
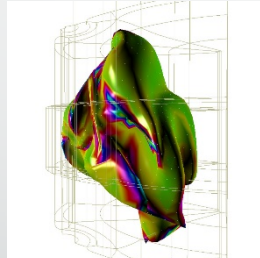
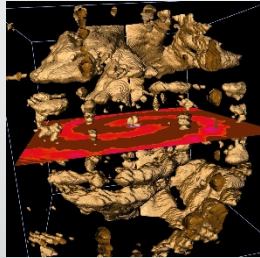
Base: 0D



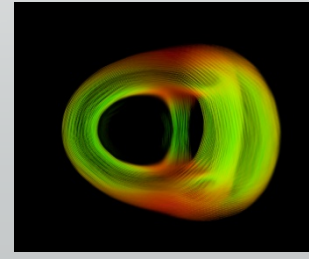
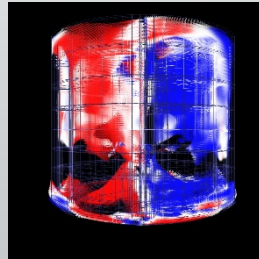
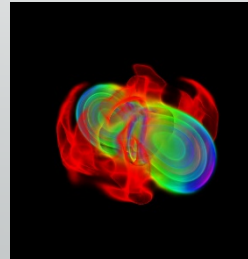
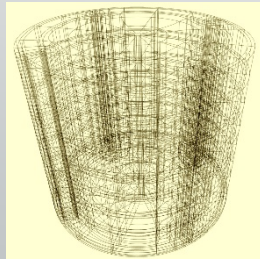
Base: 1D



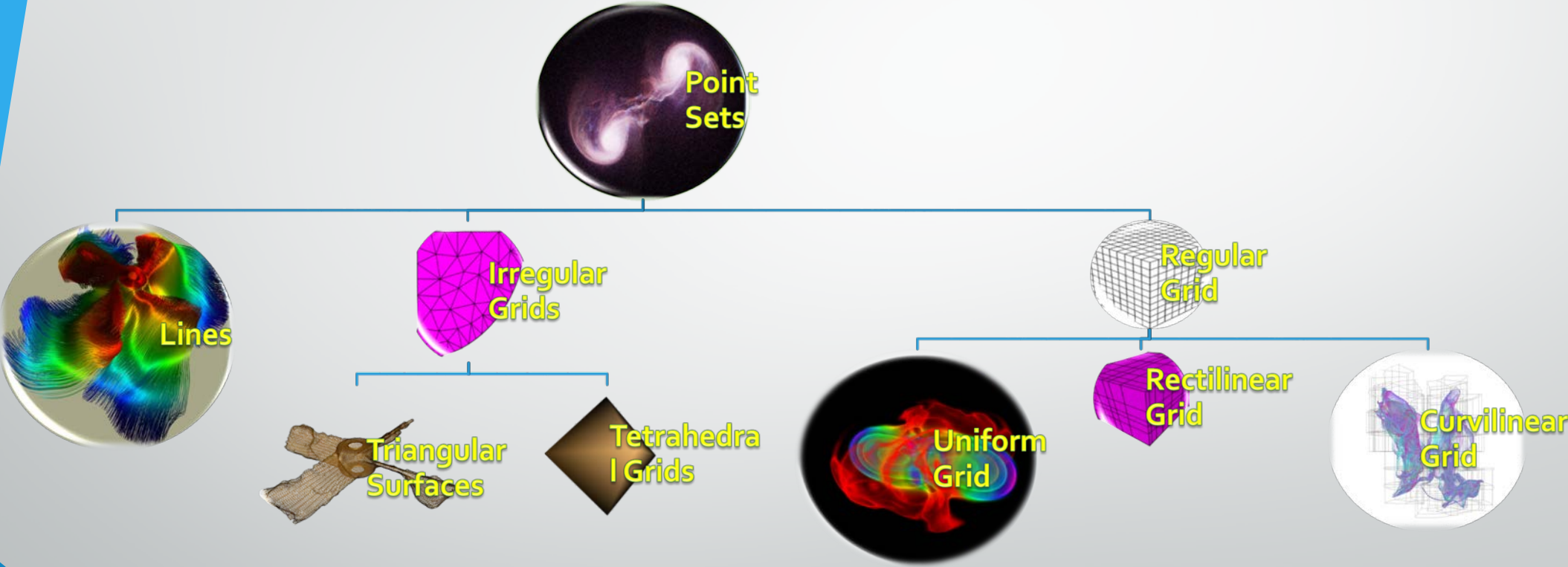
Base: 2D



Base: 3D

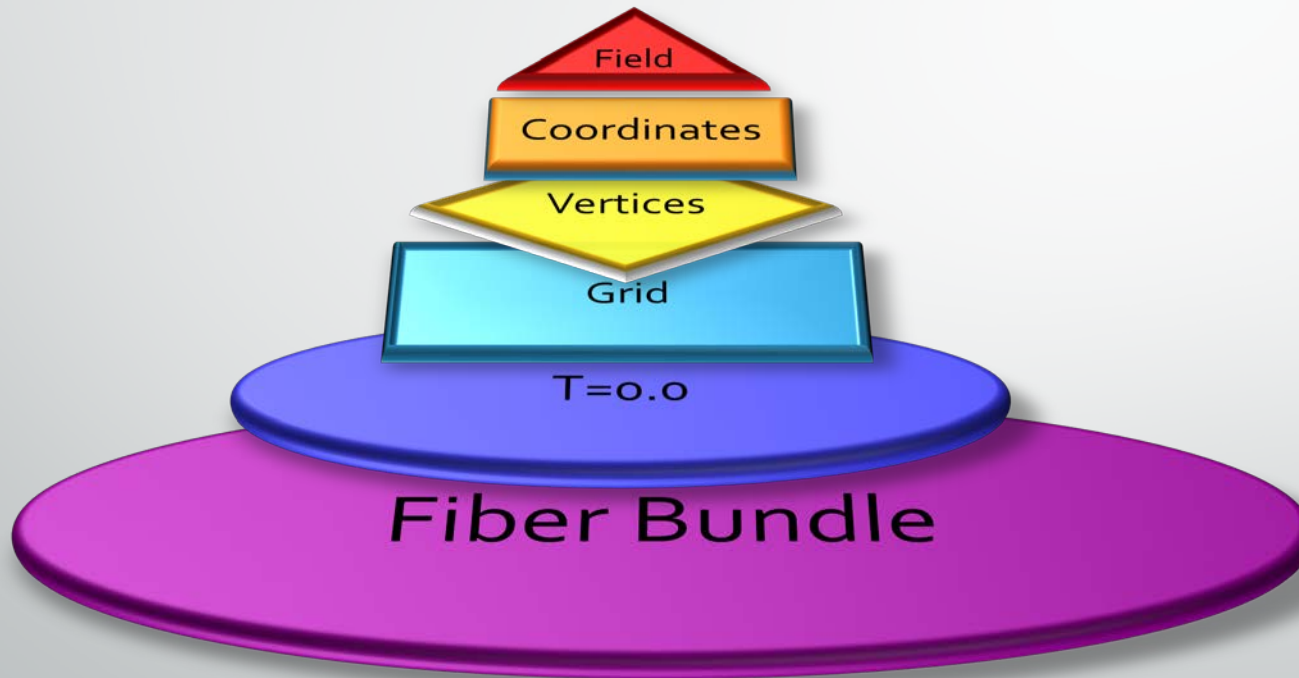


Hierarchy of Grid Types



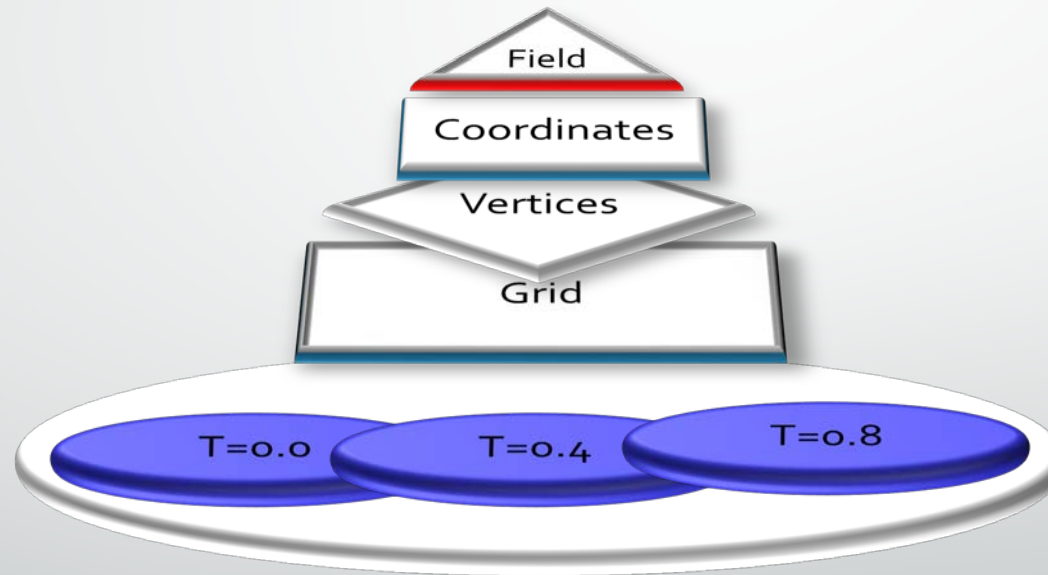
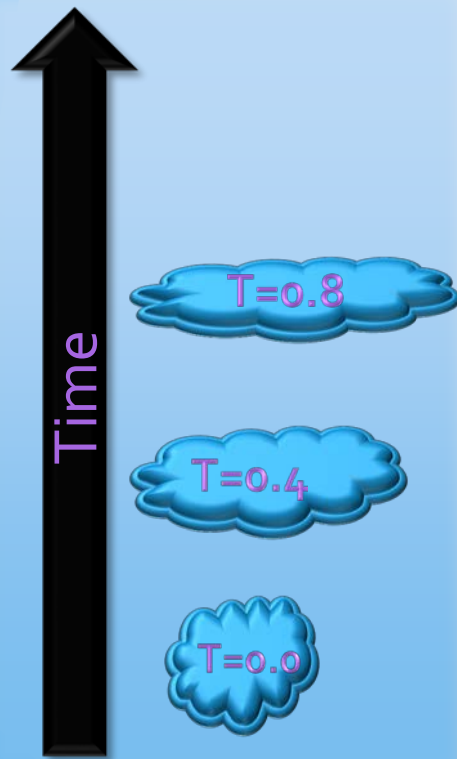
The F₅ Fiber Bundle Data Model

Casts data into hierarchy:



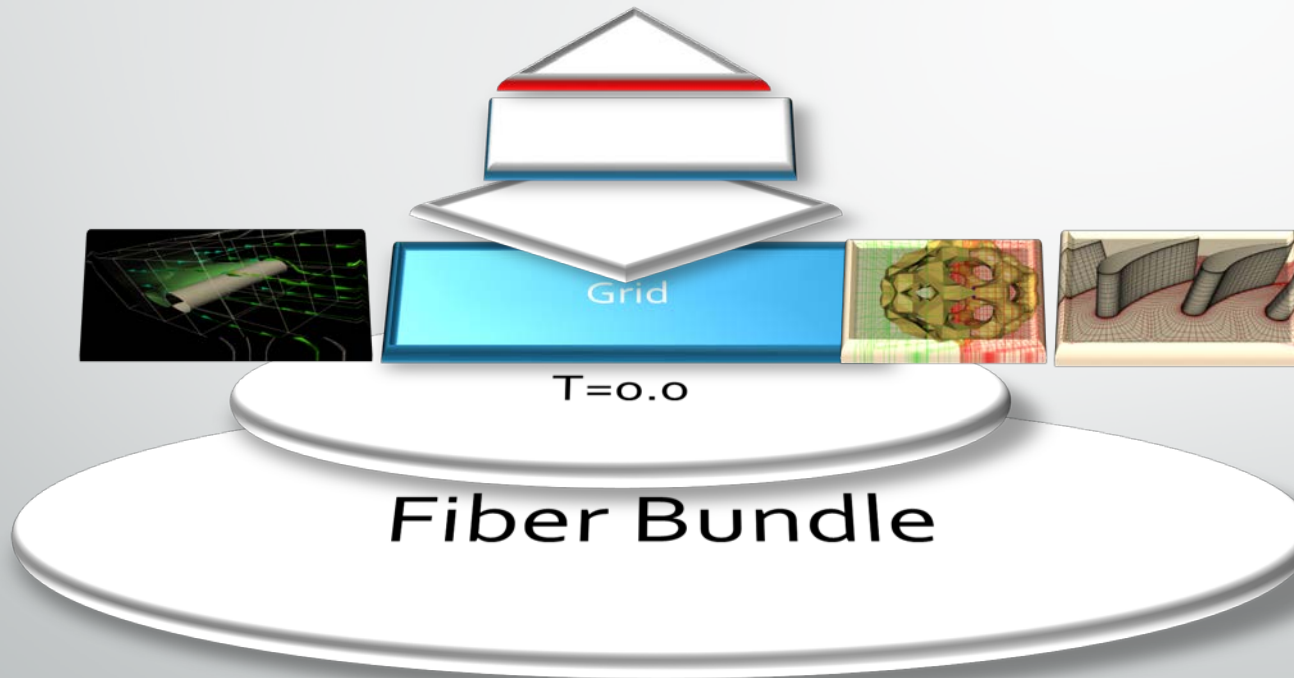
1. Field
2. Representation
3. Skeleton
4. Grid object
5. (Time) Slice
6. Bundle

Lowest Level: Fiber Bundle over a Parameter Space



1. Field
2. Representation
3. Skeleton
4. Grid object
5. (Time) Slice
6. Bundle

Grid: A geometric entity



1. Field
2. Representation
3. Skeleton
4. **Grid object**
5. (Time) Slice
6. Bundle

Topology: cw-Complex

- Discretized n-dimensional Manifold
- Concept of k-cells with adjacency
- Hierarchy of k-Skeletons, $k=0\dots N$



0-cell: Vertices



1-cell: Edges

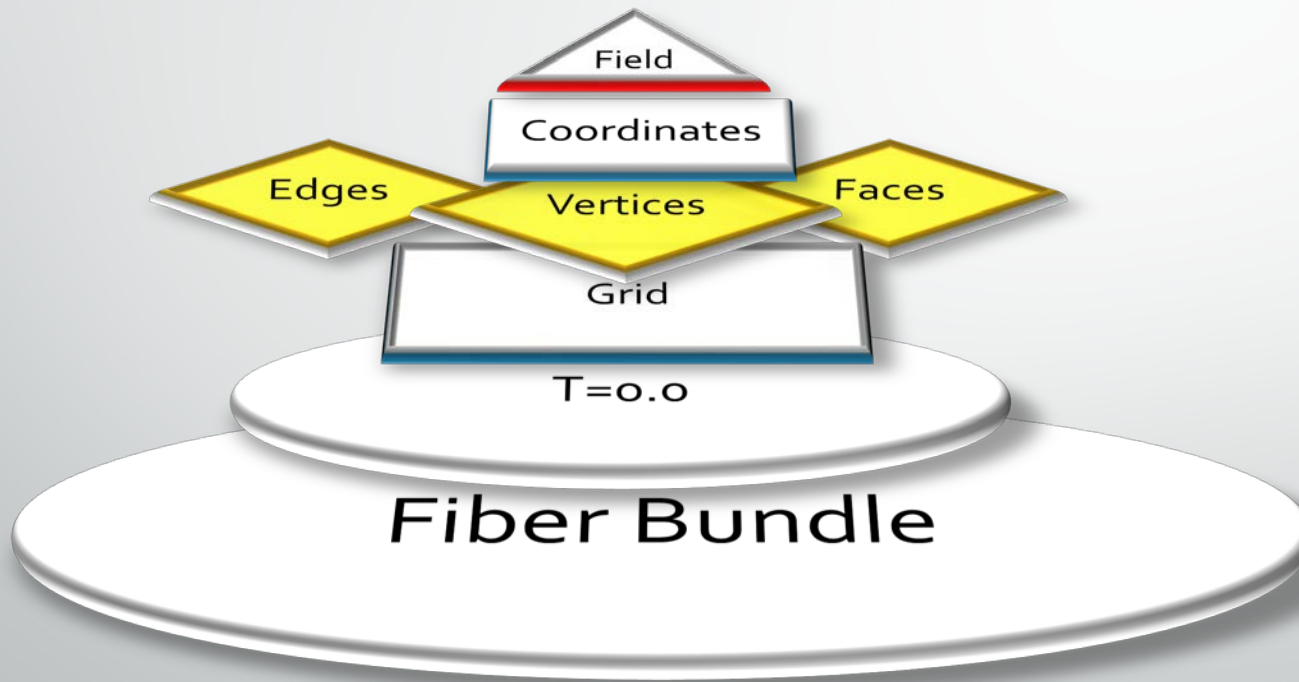


2-cell: Faces



3-cell: simplexes

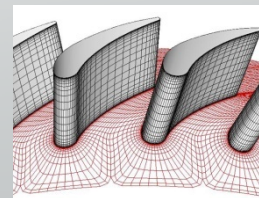
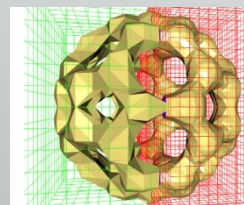
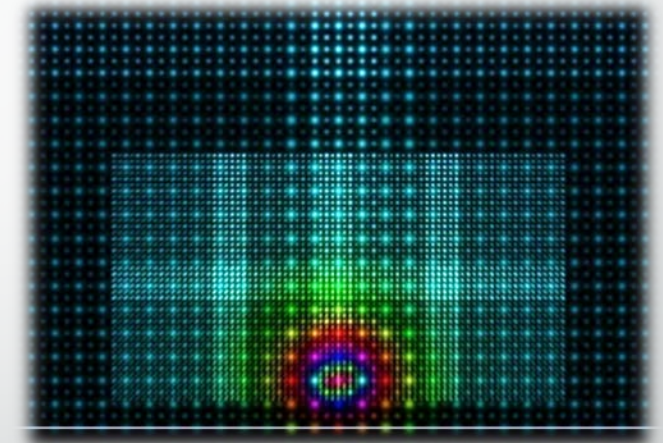
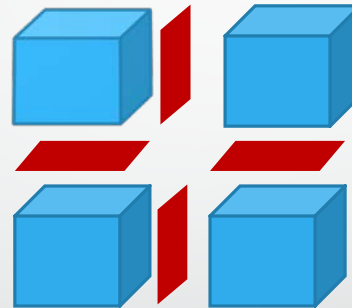
Topology: k-Skeletons



1. Field
2. Representation
3. Skeleton
4. Grid object
5. (Time) Slice
6. Bundle

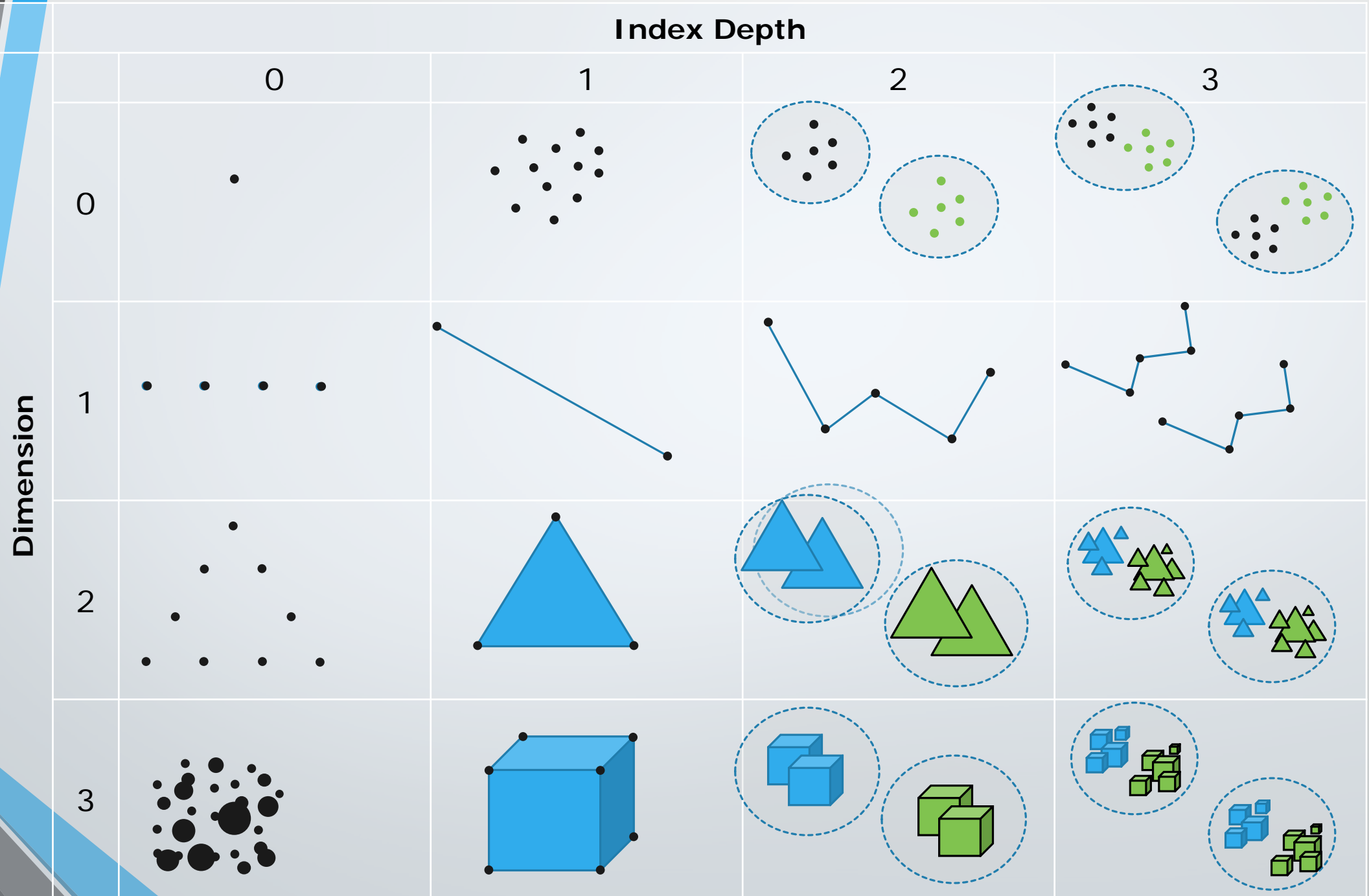
Extended Skeletons

- Refinement Levels - Multiresolution, Adaptive Mesh Refinement
- Cell Complex - Blocks, fragments
- Topological Relationships
 - Grid future/past
 - Intergrid Relationships

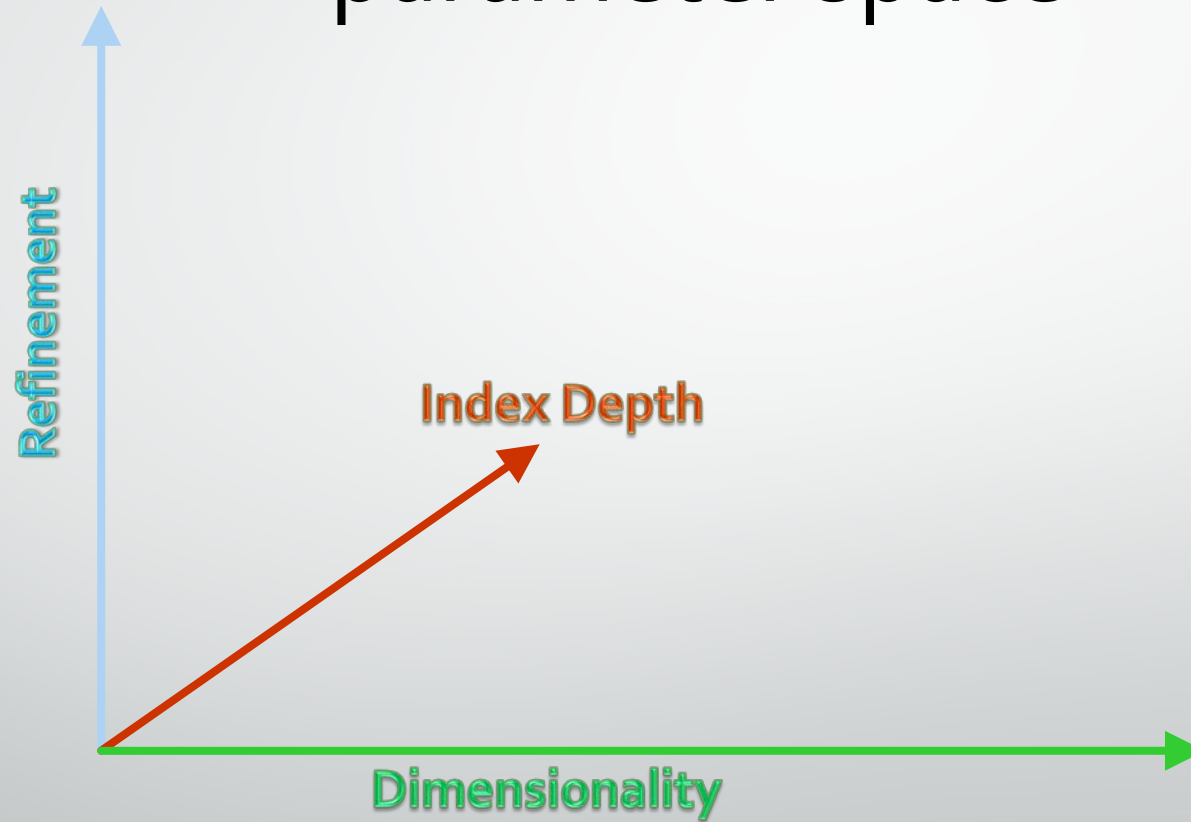


Concept of “Index Depth”

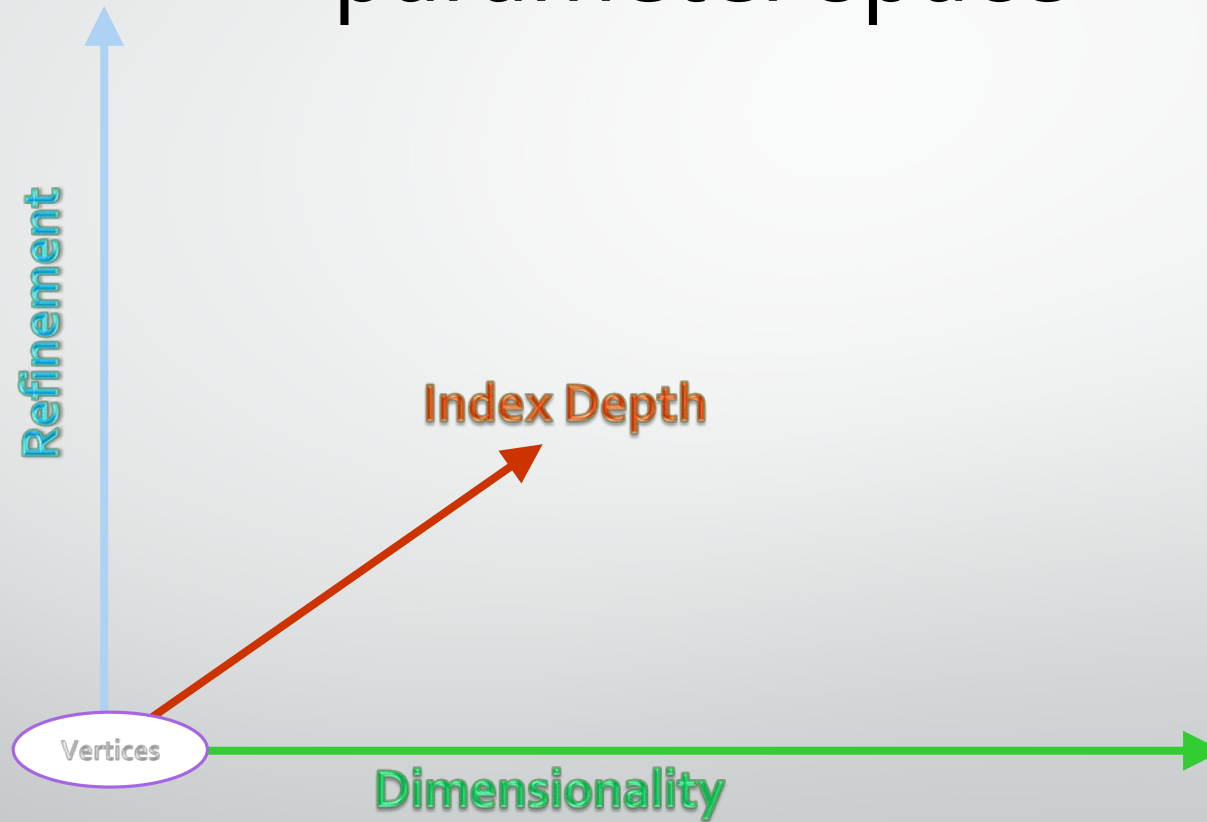
- An integer property of an index space (Skeleton object), similar to dimensionality
 - Dimensionality: intrinsic property
 - Index depth: extrinsic property
- Describes “how far” the index space is from the primary (mandatory) Vertex information of a Grid:
 - 0 → Vertices
 - 1 → Edges, Faces, Tetrahedrons, ...
 - 2 → Groups of edges, faces, tetrahedrons
 - 3 → Groups of elements of index depth 2
 - 4 → Groups of 3-elements
 - ...



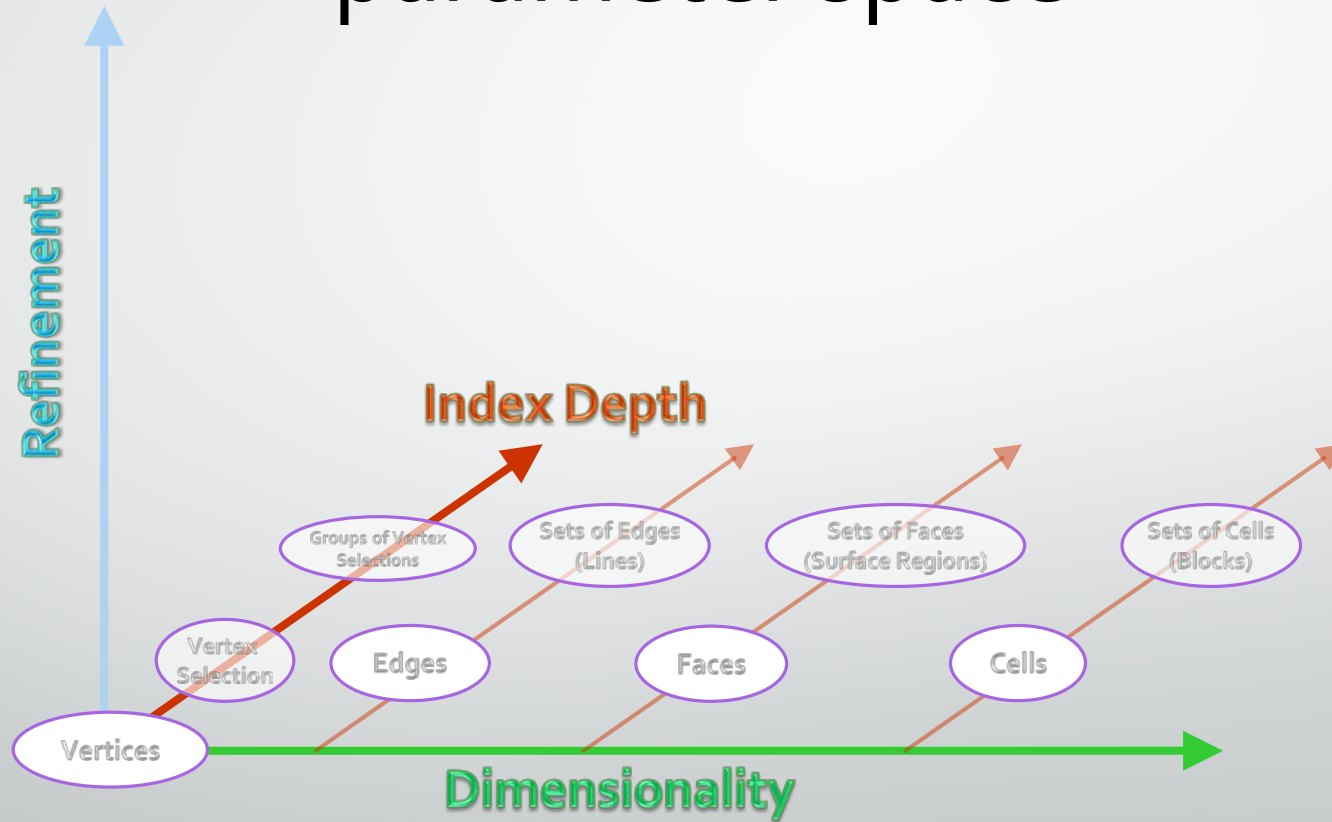
Skeletons as Fibers of a 3-dimensional parameter space



Skeletons as Fibers of a 3-dimensional parameter space

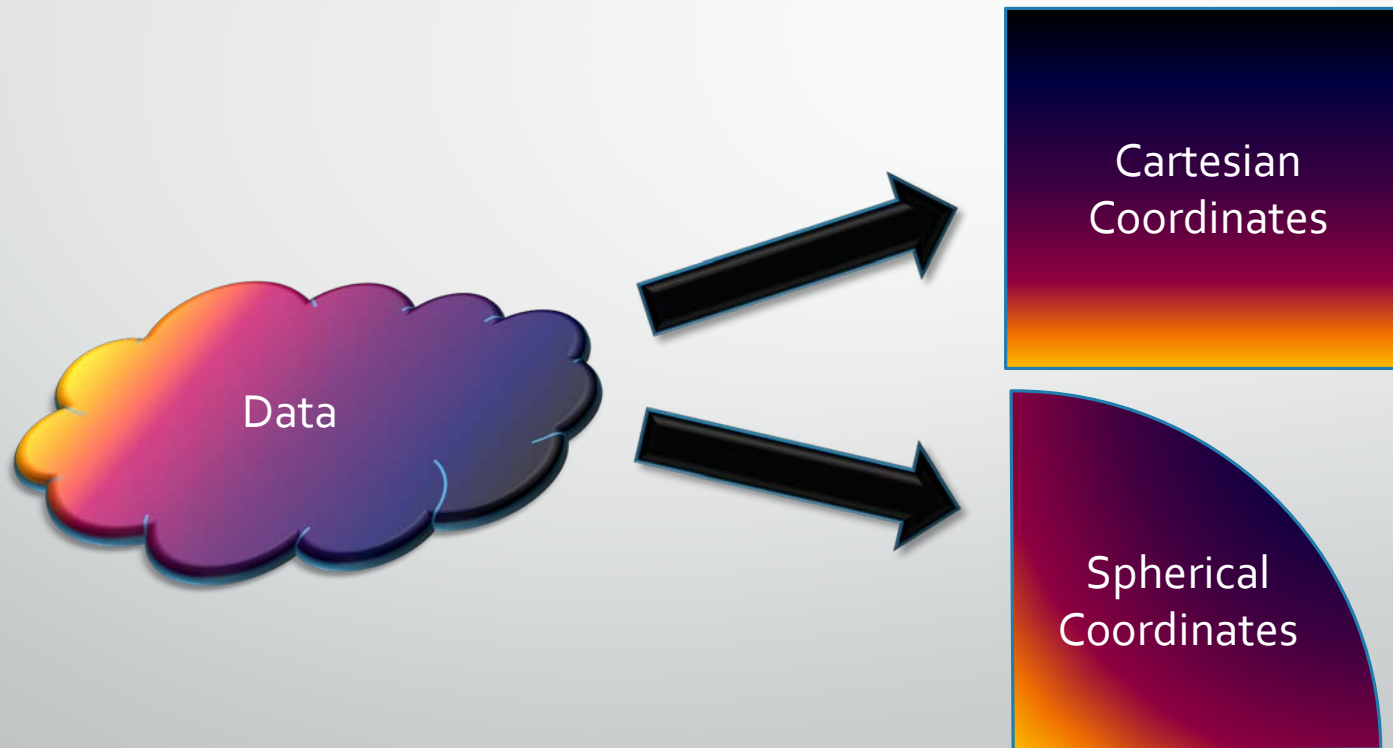


Skeletons as Fibers of a 3-dimensional parameter space

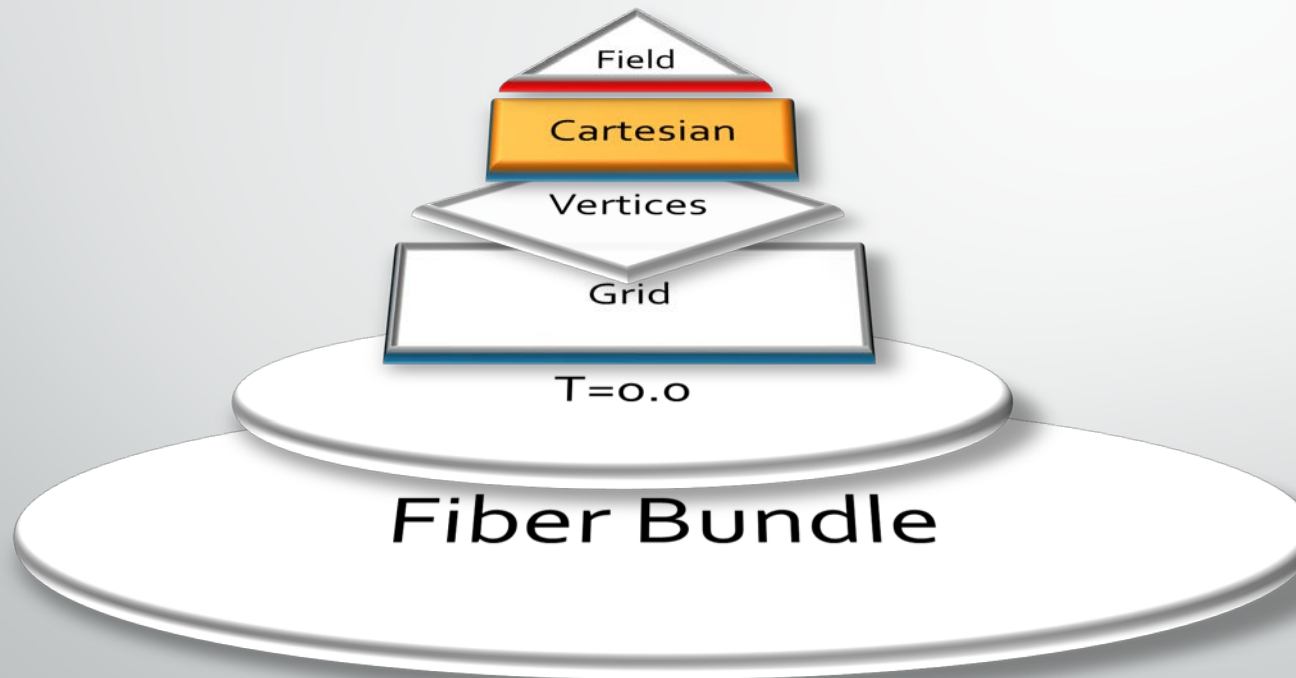


Differential Geometry

Concept of a manifold and charts – numerical data are coordinate-dependent



Multiple Representations

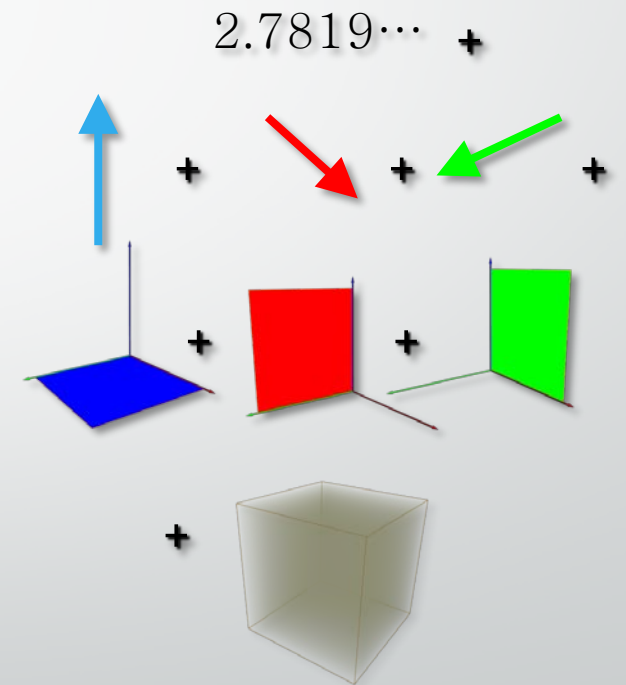
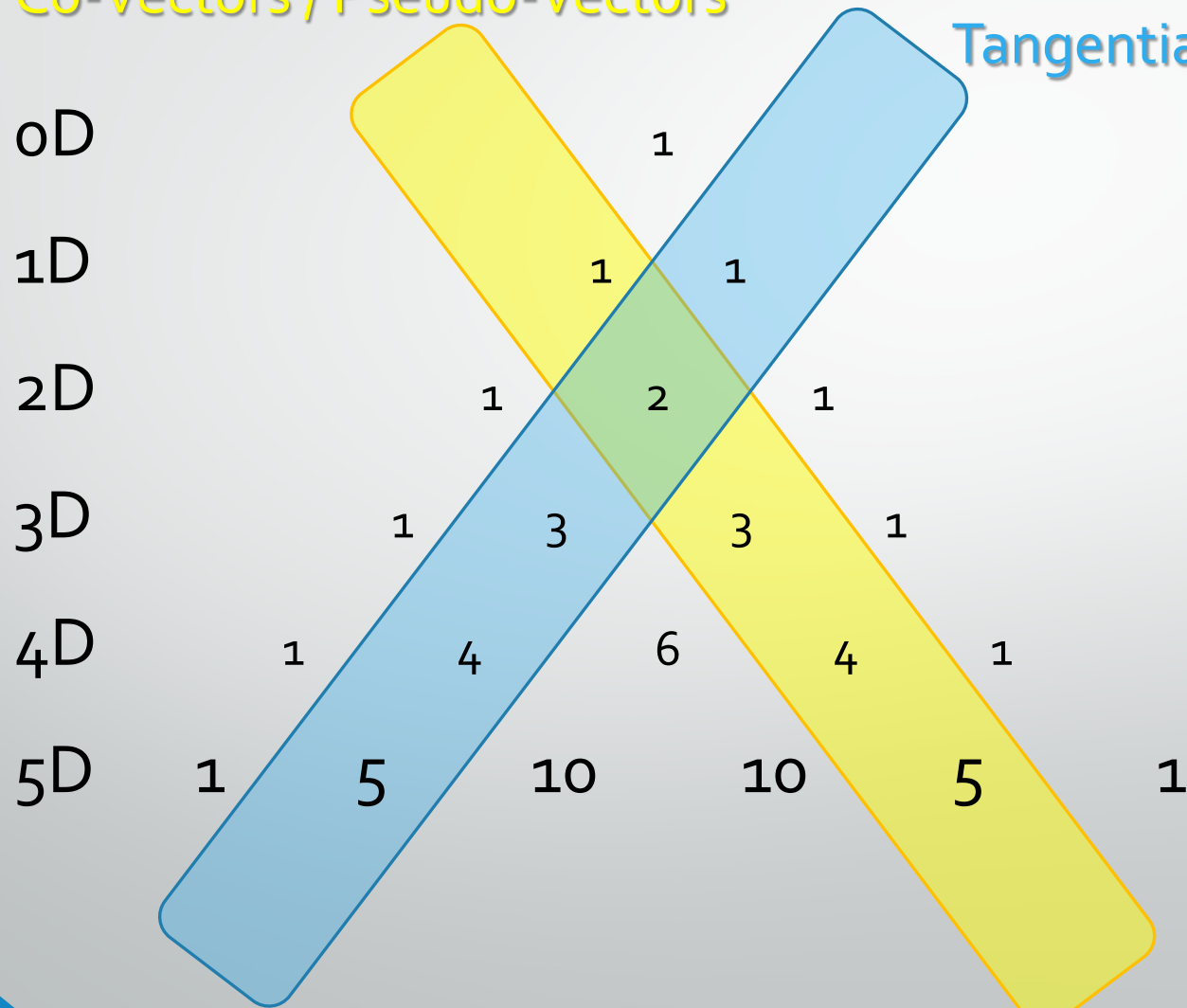


1. Field
2. Representation
3. Skeleton
4. Grid object
5. (Time) Slice
6. Bundle

Tangential / Co- / Bi-Vectors

Co-Vectors / Pseudo-Vectors

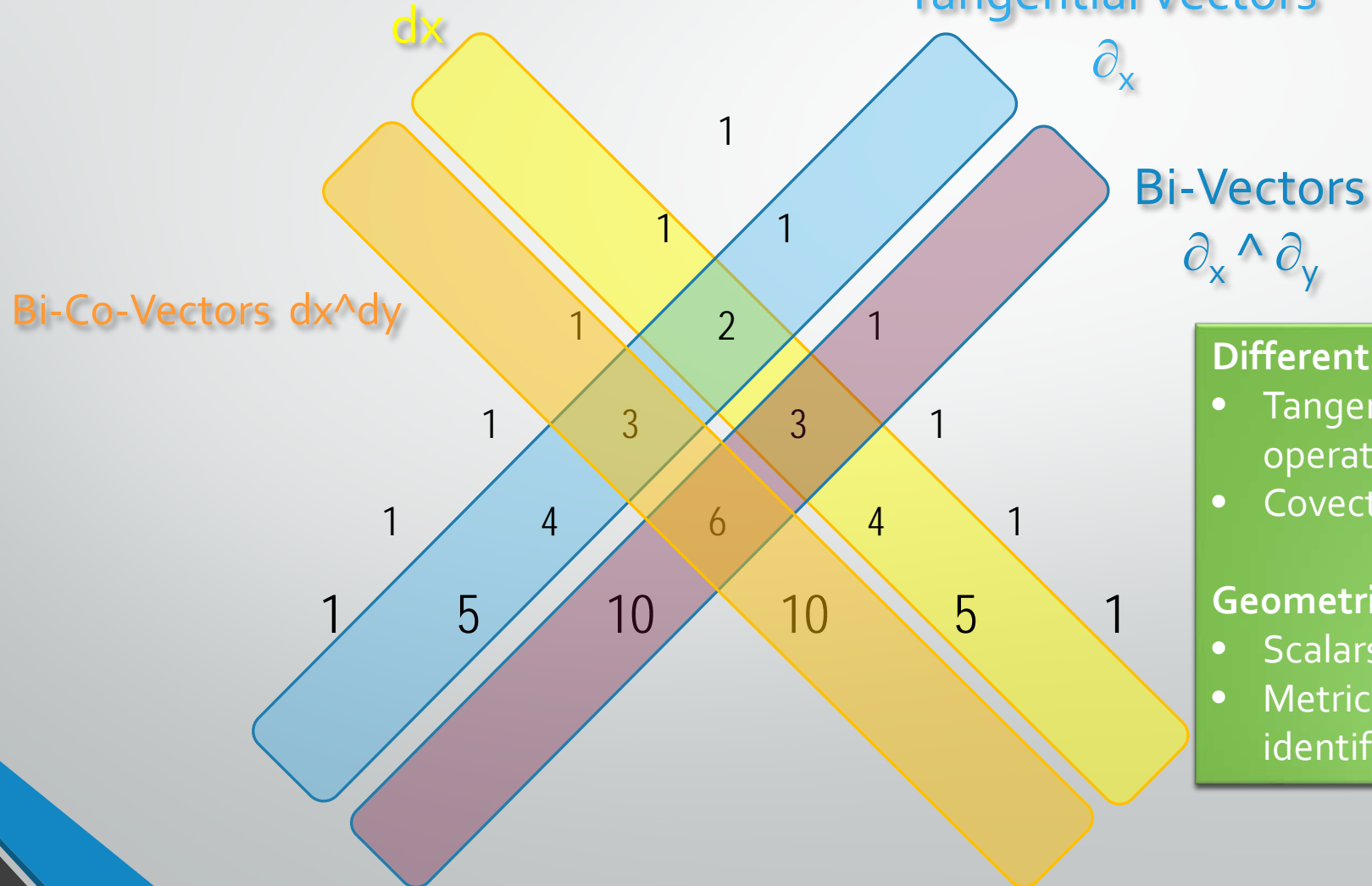
Tangential Vectors



Co-, Bi-, Pseudo- Vectors

Co-Vectors / Pseudo-Vectors

Tangential Vectors



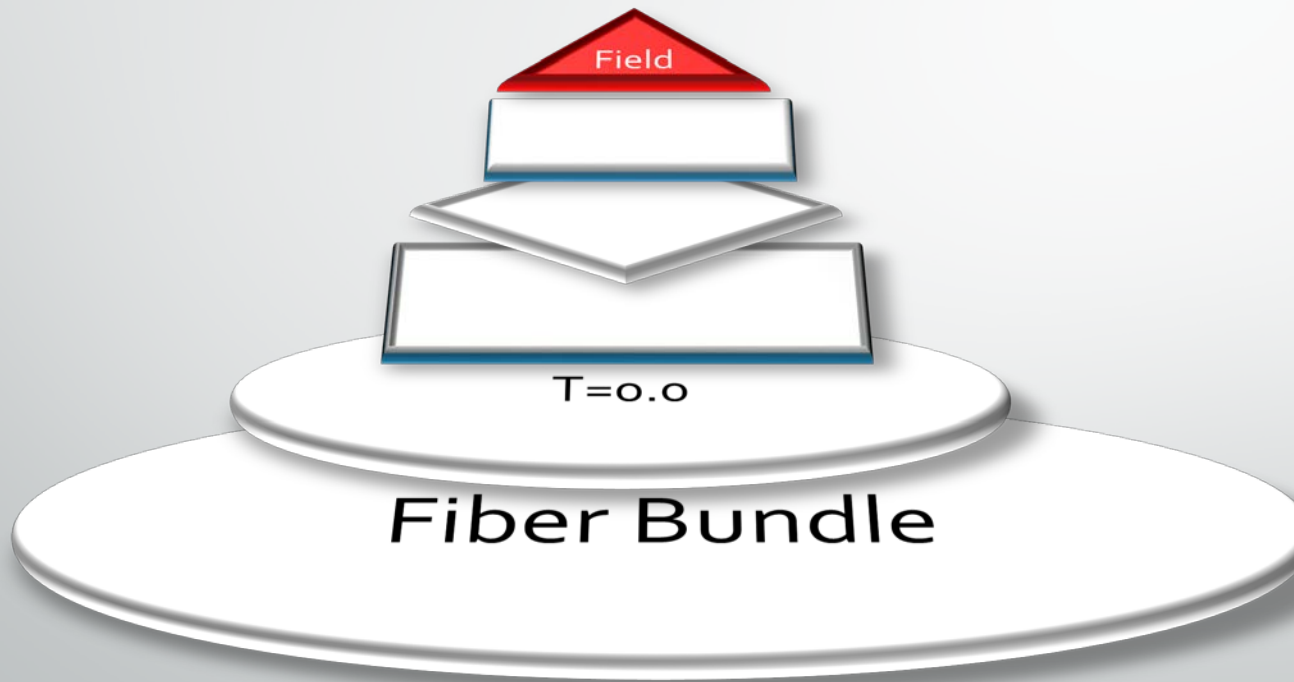
Differential Geometry:

- Tangential vectors as differential operators
- Covectors as integral elements

Geometric Algebra:

- Scalars, Vectors, Bivectors...
- Metric Tensor field allowing identification

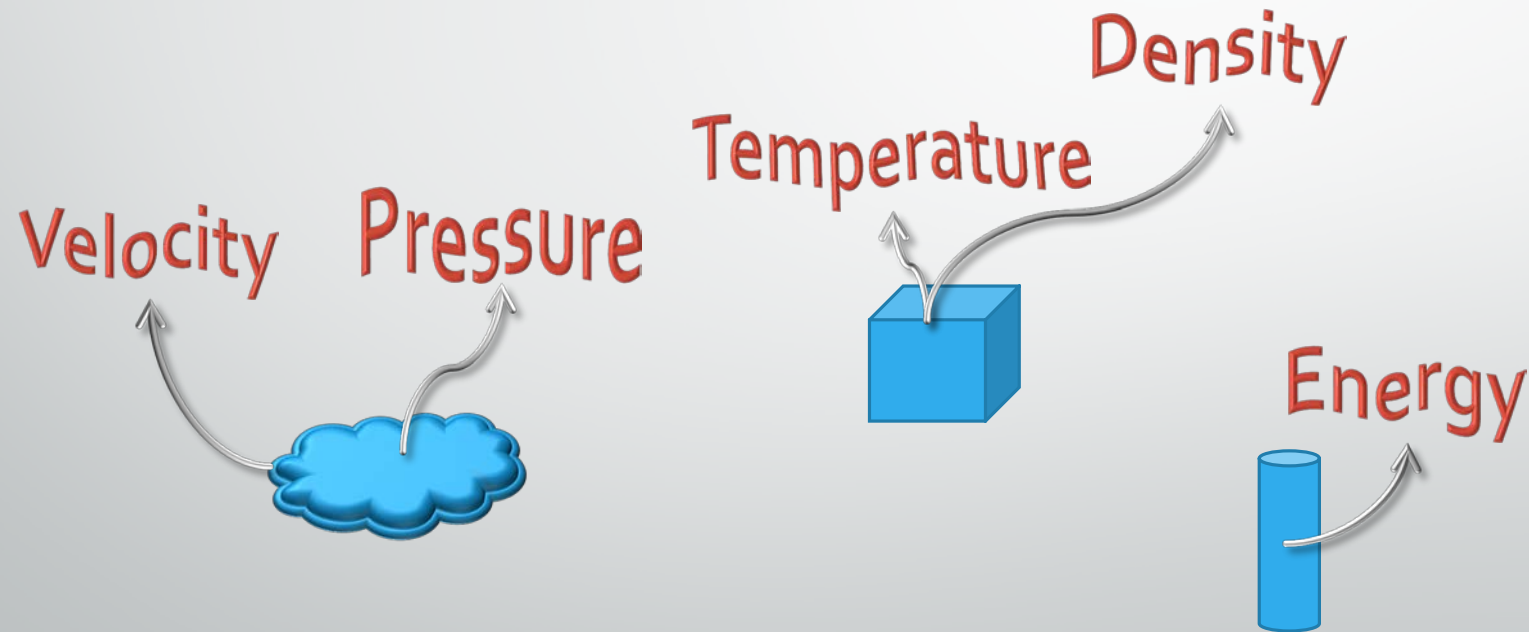
Geometric Algebra: Vectors, Tensors, Spinors, ...



1. Field
2. Representation
3. Skeleton
4. Grid object
5. (Time) Slice
6. Bundle

Grids and Fields

End-user operates only on Grid objects and Fields





Practice: The F₅ File Format

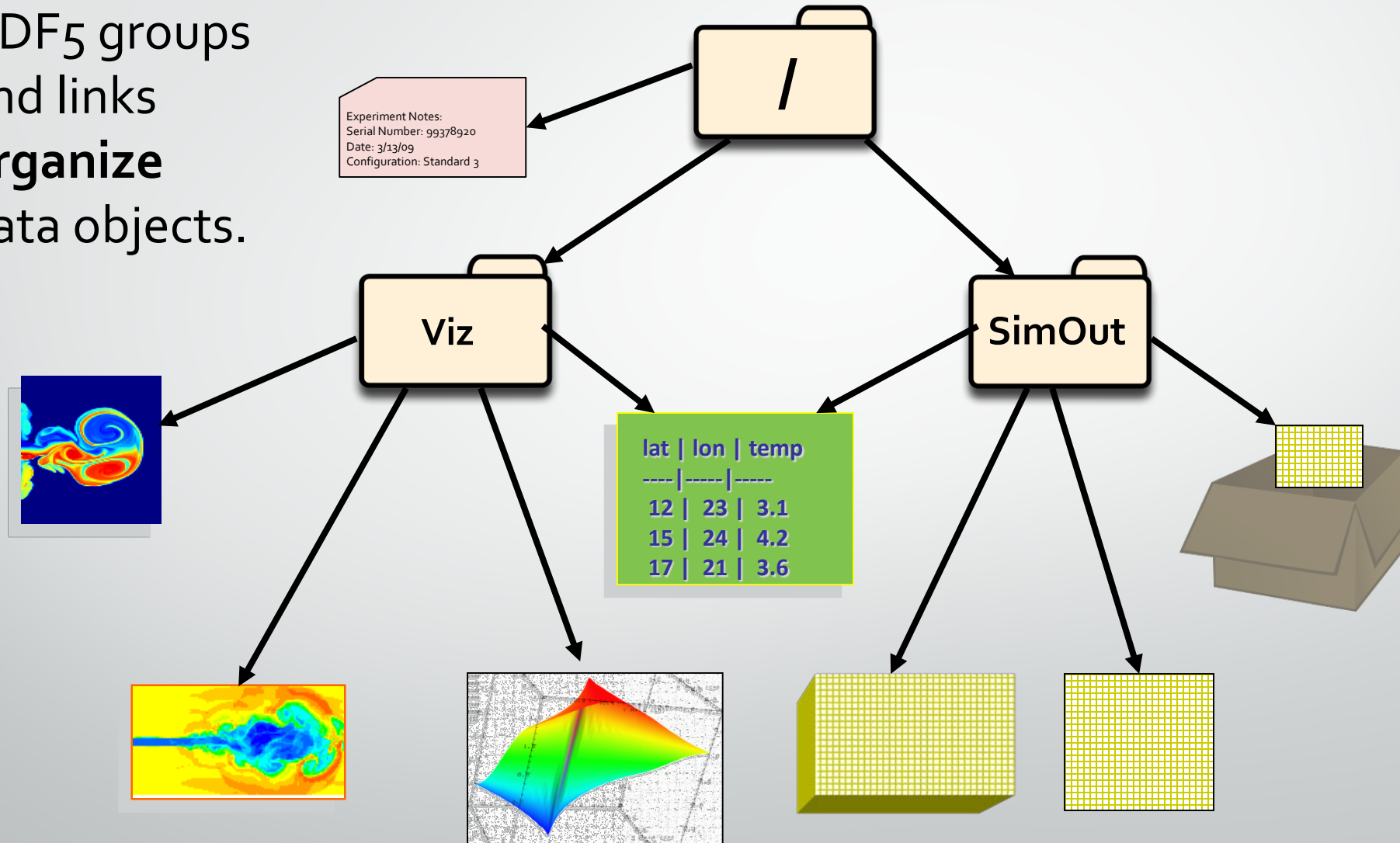
The F₅ data model in the Hierarchical Data Format HDF₅

HDF = Hierarchical Data Format

- HDF5 is the second HDF format
 - Development started in 1996
 - First release was in 1998
 - <http://www.hdfgroup.org>
- Designed for HPC simulations
- High-performance, large data, long-term data preservation (archival), portability

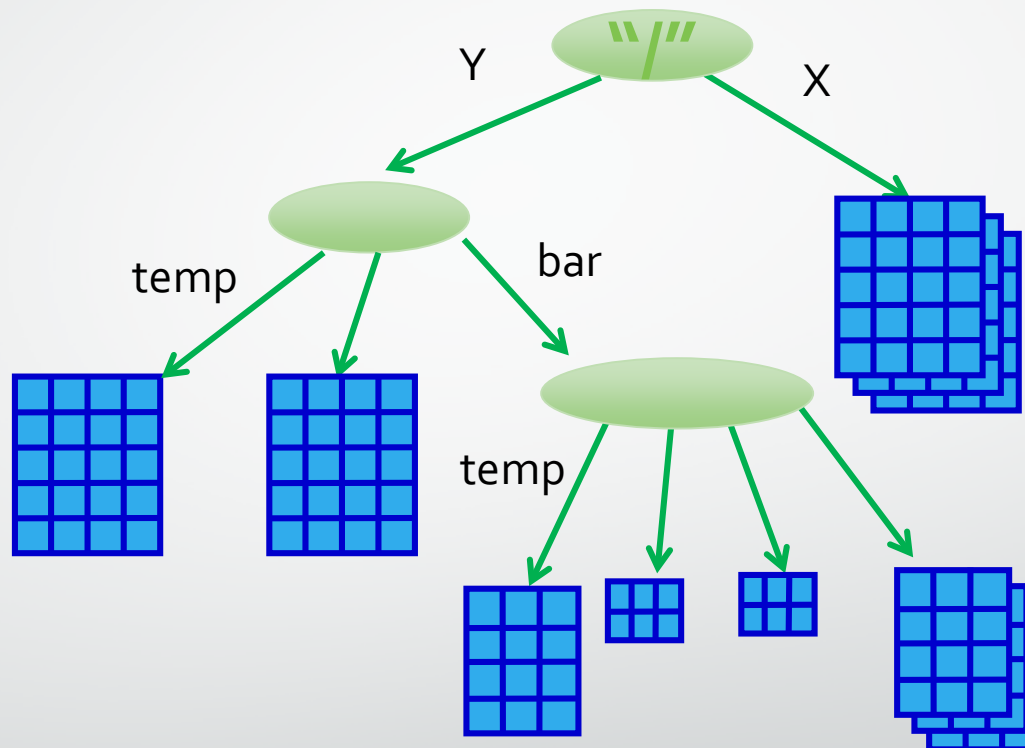
HDF5 Groups and Links

HDF5 groups and links **organize** data objects.



Path to HDF5 object in a file

/(root)
/X
/Y
/Y/temp
/Y/bar/temp



HDF5 is like a file system in a file, plus with additional meta-information (data type, dimensions, ...)

/Time/Grid/Top/Rep/Field/

```
h5ls -r minkowski-0000.f5
```

```
/T=0/minkowski/Points/StandardCartesianChart3D Group
/T=0/minkowski/Points/StandardCartesianChart3D/ADMBASE::CURV Group
/T=0/minkowski/Points/StandardCartesianChart3D/ADMBASE::CURV/gxx Dataset {43, 37, 19}
/T=0/minkowski/Points/StandardCartesianChart3D/ADMBASE::CURV/gxy Dataset {43, 37, 19}
/T=0/minkowski/Points/StandardCartesianChart3D/ADMBASE::CURV/gxz Dataset {43, 37, 19}
/T=0/minkowski/Points/StandardCartesianChart3D/ADMBASE::CURV/gyy Dataset {43, 37, 19}
/T=0/minkowski/Points/StandardCartesianChart3D/ADMBASE::CURV/gyz Dataset {43, 37, 19}
/T=0/minkowski/Points/StandardCartesianChart3D/ADMBASE::CURV/gzz Dataset {43, 37, 19}
/T=0/minkowski/Points/StandardCartesianChart3D/ADMBASE::LAPSE Dataset {43, 37, 19}
/T=0/minkowski/Points/StandardCartesianChart3D/ADMBASE::METRIC Group
/T=0/minkowski/Points/StandardCartesianChart3D/ADMBASE::METRIC/gxx Dataset {43, 37, 19}
/T=0/minkowski/Points/StandardCartesianChart3D/ADMBASE::METRIC/gxy Dataset {43, 37, 19}
/T=0/minkowski/Points/StandardCartesianChart3D/ADMBASE::METRIC/gxz Dataset {43, 37, 19}
/T=0/minkowski/Points/StandardCartesianChart3D/ADMBASE::METRIC/gyy Dataset {43, 37, 19}
/T=0/minkowski/Points/StandardCartesianChart3D/ADMBASE::METRIC/gyz Dataset {43, 37, 19}
/T=0/minkowski/Points/StandardCartesianChart3D/ADMBASE::METRIC/gzz Dataset {43, 37, 19}
/T=0/minkowski/Points/StandardCartesianChart3D/Positions Group
/T=0.119047619047619041010577234374 Group
/T=0.119047619047619041010577234374/minkowski Group
```

HDFView Browsing HDF5 Files

Fragmented Particles

Coordinates

The screenshot shows the HDFView 2.11 interface. The left pane displays a file tree for 'FragmentedParticles.h5'. The right pane shows a table of data for 'Frag0000', which is a 50x3 array of coordinates (x, y, z).

	x	y	z
0	-196.16998	-291.14	-299.223
1	-186.30	-288.73	-288.31
2	-197.89001	-296.32	-289.43298
3	190.70999	291.97998	299.578
4	-197.70999	-295.27	-299.279
5	-185.07	-294.74	-288.908
6	-196.95001	-290.75	-289.91602
7	198.76001	291.05	299.418
8	-199.13	-291.91998	-299.724
9	-180.68	-288.4	-288.324
10	-192.04999	-294.3	-299.566
11	193.48001	292.44	299.099
12	-195.6	-292.71	-299.869
13	-184.33002	-291.44	-288.503
14	-194.72	-291.29	-299.268
15	196.6	298.51	299.204
16	-196.20999	-295.12	-299.236
17	-180.76001	-290.06	-288.013
18	-195.68	-294.48	-288.563
19	199.70999	297.63	299.765
20	-192.23999	-295.96	-299.257
21	-180.72	-293.12	-288.63080
22	-195.1	-295.01	-299.228
23	193.31	299.18	299.468
24	-193.78	-291.72	-299.701
25	-193.95001	-291.99	-289.339
26	-194.78	-295.35	-299.292
27	194.0	299.64	299.548
28	-191.19	-290.7	-299.06702
29	190.41	-292.27	-289.107
30	-199.1	-293.16	-299.634
31	191.13	295.88	299.052
32	-197.94	-296.99	-299.287
33	-180.60999	-291.08	-289.06
34	-198.79999	-297.76	-299.578
35	193.28	291.5	299.375
36	-197.01999	-298.1	-299.476
37	-180.06	-288.86	-288.621
38	-194.20999	-291.16	-289.00702
39	196.73999	297.41	299.056
40	-194.72	-299.11	-299.128
41	-186.97	-286.66880	-288.067
42	-195.0	-298.54	-289.212
43	197.47	291.08002	299.314
44	-195.64001	-295.4	-299.286
45	-184.44	-290.97998	-288.206
46	-195.0	-293.19	-289.363
47	197.85	298.73	299.496
48	-188.23001	-291.0	-289.762
49	-182.57	-280.58	-288.171

HDFView Browsing HDF5 Files

Fragmented Particles

A Tensor Field
(six components)

The screenshot shows the HDFView 2.11 interface. The left pane displays a tree structure of the HDF5 file 'FragmentedParticles.h5'. The tree includes a 'MyTensor' object containing a series of 'Frag' objects (Frag0000 to Frag0009). The right pane shows a table view of the selected 'Frag0000' object, which is a 2D array of 50 rows and 6 columns. The columns are labeled 'gxx', 'gxy', 'gxz', 'gyy', 'gyz', and 'gzz'. The table contains numerical values for each component across the 50 rows.

	gxx	gxy	gxz	gyy	gyz	gzz
0	0.93	0.92	0.21	0.35	0.49	0.86
1	0.63	0.26	0.36	0.26	0.72	0.4
2	0.82	0.23	0.35	0.3	0.67	0.62
3	0.69	0.56	0.42	0.67	0.11	0.93
4	0.84	0.24	0.7	0.37	0.15	0.98
5	0.56	0.7	0.81	0.73	0.96	0.62
6	0.36	0.29	0.57	0.05	0.13	0.46
7	0.14	0.64	0.5	0.67	0.43	0.34
8	0.88	0.51	0.99	0.84	0.54	0.03
9	0.39	0.86	0.39	0.12	0.94	0.26
10	0.67	0.02	0.92	0.01	0.17	0.97
11	0.86	0.89	0.19	0.41	0.44	0.65
12	0.97	0.75	0.27	0.71	0.09	0.81
13	0.86	0.83	0.24	0.65	0.19	0.06
14	0.03	0.68	0.15	0.19	0.08	0.7
15	0.18	0.51	0.55	0.45	0.21	0.46
16	0.41	0.0	0.64	0.5	0.34	0.93
17	0.43	0.65	0.36	0.91	0.59	0.27
18	0.75	0.21	0.95	0.07	0.58	0.74
19	0.18	0.11	0.29	0.28	0.28	0.43
20	0.13	0.4	0.18	0.38	0.04	0.06
21	0.17	0.43	0.83	0.96	0.7	0.24
22	0.44	0.39	0.86	0.9	0.54	0.05
23	0.97	0.04	0.11	0.07	0.48	0.55
24	0.46	0.22	0.1	0.68	0.11	0.4
25	0.78	0.36	0.26	0.05	0.44	0.2
26	0.82	0.37	0.24	0.58	0.62	0.24
27	0.79	0.71	0.31	0.5	0.73	0.68
28	0.6	0.81	0.96	0.63	0.99	0.99
29	0.9	0.66	0.4	0.95	0.84	0.26
30	0.36	0.56	0.18	0.07	0.79	0.45
31	0.59	0.1	0.87	0.09	0.42	0.36
32	0.21	0.99	0.04	0.55	0.21	0.19
33	0.05	0.5	0.58	0.28	0.84	0.27
34	0.96	0.84	0.72	0.81	0.92	0.3
35	0.22	0.42	0.13	0.99	0.98	0.4
36	0.09	0.36	0.55	0.81	0.32	0.19
37	0.73	0.55	0.42	0.76	0.6	0.5
38	0.21	0.13	0.54	0.67	0.61	0.04
39	0.02	0.21	0.68	0.06	0.42	0.84
40	0.58	0.08	0.48	0.98	0.53	0.36
41	0.9	0.46	0.29	0.54	0.68	0.67
42	0.49	0.33	0.97	0.9	0.63	0.03
43	0.52	0.88	0.29	0.96	0.57	0.75
44	0.6	0.27	0.48	0.04	0.5	0.28
45	0.99	0.02	0.03	0.43	0.28	0.39
46	0.59	0.34	0.92	0.51	0.39	0.35
47	0.49	0.29	0.35	0.64	0.43	0.85
48	0.49	0.88	0.95	0.89	0.92	0.67
49	0.82	0.69	0.32	0.4	0.26	0.41

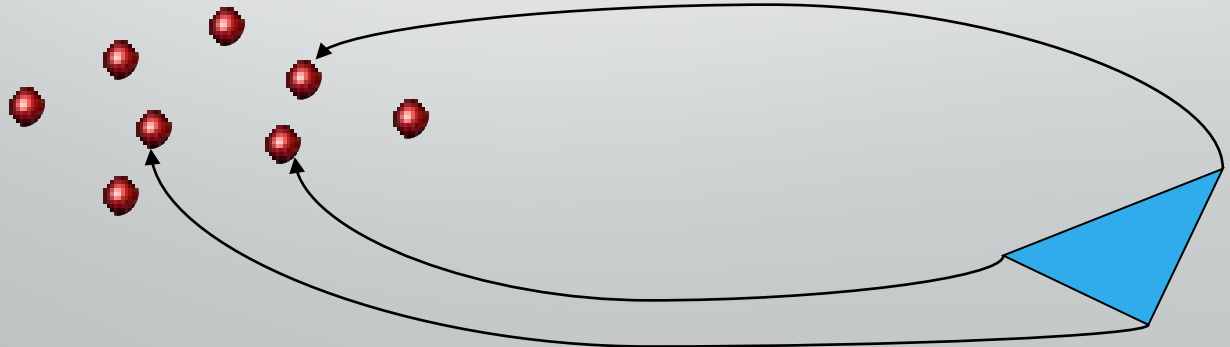
Relative Representations

Triangular Surface: 600331 Triangles, 314442 Points

```
/T=1          Group
/T=1/adcirc  Group
/T=1/adcirc/Points Group
/T=1/adcirc/Points/StandardCartesianChart3D Group
/T=1/adcirc/Points/StandardCartesianChart3D/Positions Dataset {314442}
/T=1/adcirc/Connectivity Group
/T=1/adcirc/Connectivity/Points Group
/T=1/adcirc/Connectivity/Points/Positions Dataset {600331}
```

Index Depth = 0

Index Depth = 1



HDFView Browsing HDF5 Files

Triangular Surface

- Coordinates
- Triangle Indices



LOD.f5

HDFView 2.11

File Window Tools Help

Recent Files C:\Private\Private Documents\My Presentations\2015\LOD.f5 Clear Text

LOD.f5

- Charts
- TableOfContents
- I=00000000.00000000
- BuildingsLOD
 - Charts
 - F5:TimeTable
 - Faces
 - Points
 - Positions
 - Points
 - StandardCartesian
 - Positions

Positions at I=00000000.00000000\BuildingsLOD\aces\Pointe [L...]

Table

0-based

	ii	U	1	U
0	3	0	1	U
1	3	1	2	
2	7	4	5	
3	7	5	6	
4	13	8	9	
5	13	8	10	
6	13	10	11	
7	13	11	12	
8	17	14	15	
9	17	15	16	
10	21	18	19	
11	21	19	20	
12	27	22	23	
13	27	23	24	
14	27	24	25	
15	27	25	26	
16	31	28	29	
17	31	29	30	
18	35	32	33	
19	35	33	34	
20	39	36	37	
21	39	37	38	
22	43	40	41	

Positions at I=00000000.00000000\BuildingsLOD\Points\Standar...

Table

0-based

	x	y	z
0	4397883.38	5358755.58	511.22
1	4397883.35	5358755.58	514.359
2	4397883.2	5358755.05	513.781
3	4397883.2	5358755.05	511.22
4	4397515.37	5358773.43	509.83
5	4397515.37	5358773.43	512.731
6	4397524.55	5358773.39	512.73
7	4397524.55	5358773.39	509.83
8	4397880.8	5358755.2	511.22
9	4397883.2	5358755.05	511.22
10	4397883.2	5358755.05	513.781
11	4397880.8	5358755.2	513.781
12	4397875.05	5358755.79	513.781
13	4397875.05	5358755.79	511.22
14	4397875.51	5358760.3	511.22
15	4397875.51	5358760.3	513.756
16	4397881.28	5358759.83	513.779
17	4397881.28	5358759.83	511.22
18	4397977.85	5358441.82	485.183
19	4397974.4	5358444.2	487.779
20	4397981.4	5358454.0	487.779
21	4397984.7	5358451.74	485.183
22	4397524.55	5358773.39	512.817
23	4397524.55	5358773.39	509.82
24	4397524.55	5358777.4	509.82
25	4397524.55	5358781.41	509.82
26	4397524.55	5358781.41	512.817
27	4397524.55	5358777.4	513.759
28	4397515.42	5358781.42	509.82
29	4397515.42	5358781.42	512.819
30	4397524.55	5358781.41	512.817
31	4397524.55	5358781.41	509.82

Positions (72750, 2)

CompoundView, 155921

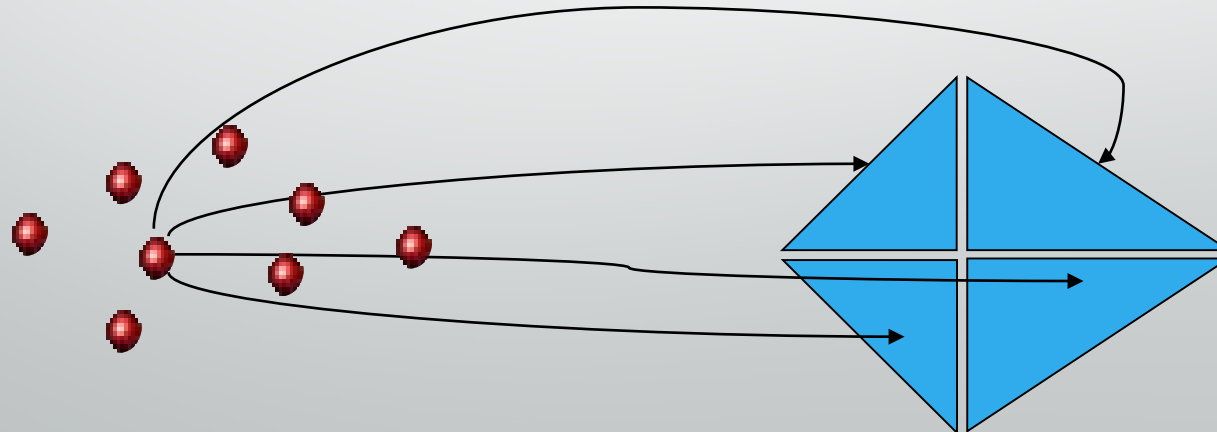
Log Info Metadata

Relative Representations

Inverse Information: Triangles per Vertex

```
/T=1 Group
/T=1/adcirc Group
/T=1/adcirc/Points Group
/T=1/adcirc/Points/StandardCartesianChart3D Group
/T=1/adcirc/Points/StandardCartesianChart3D/Positions Dataset {314442}
/T=1/adcirc/Points/Connectivity/Positions Dataset {314442}

/T=1/adcirc/Connectivity Group
/T=1/adcirc/Connectivity/Points Group
/T=1/adcirc/Connectivity/Points/Positions Dataset {600331}
```

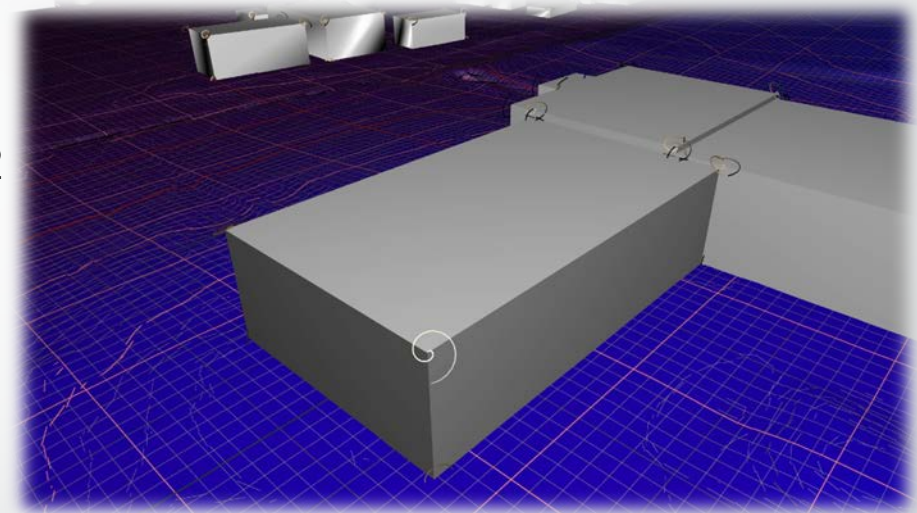


Fields on Relative Representations

Triangular Surface: 600331 Triangles, 414442 Points

plus **data** on the **vertices**

```
/T=1                               Group
/T=1/adcirc/Connectivity Group
/T=1/adcirc/Connectivity/Points Group
/T=1/adcirc/Connectivity/Points/Positions Dataset {600331}
/T=1/adcirc/Points                 Group
/T=1/adcirc/Points/StandardCartesianChart3D Group
/T=1/adcirc/Points/StandardCartesianChart3D/Positions Dataset {314442}
/T=1/adcirc/Points/StandardCartesianChart3D/elevation Dataset {314442}
/T=1/adcirc/Points/StandardCartesianChart3D/vector Dataset {314442}
```

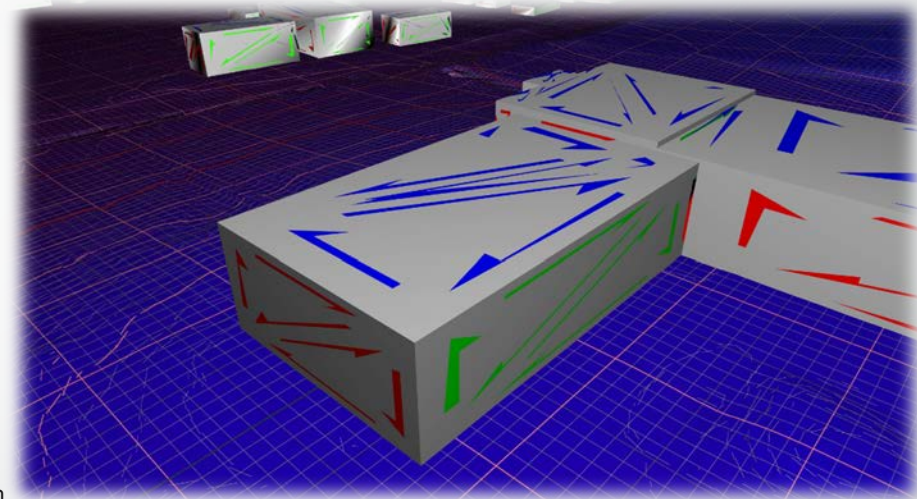


Fields on Relative Representations

Triangular Surface: 600331 Triangles, 414442 Points

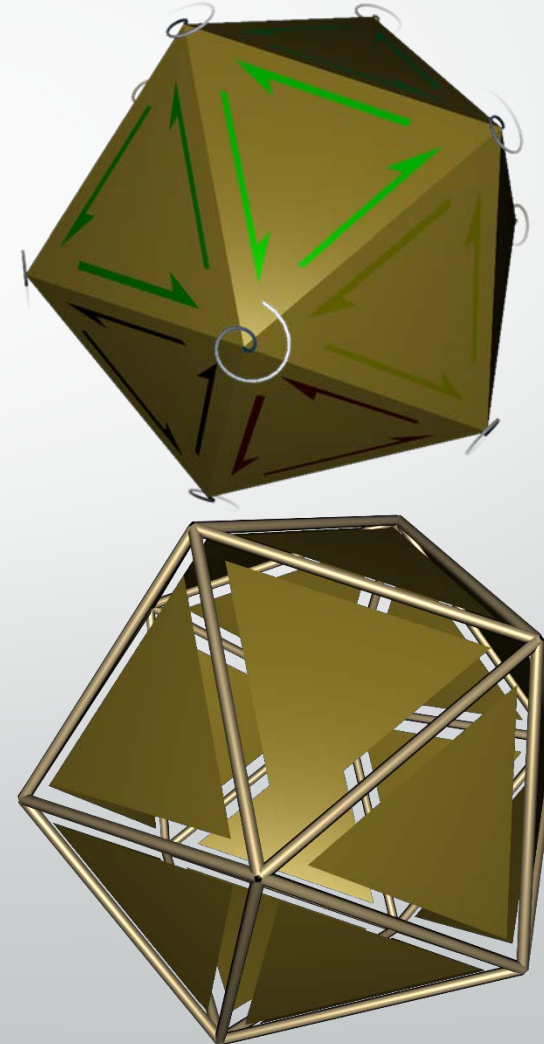
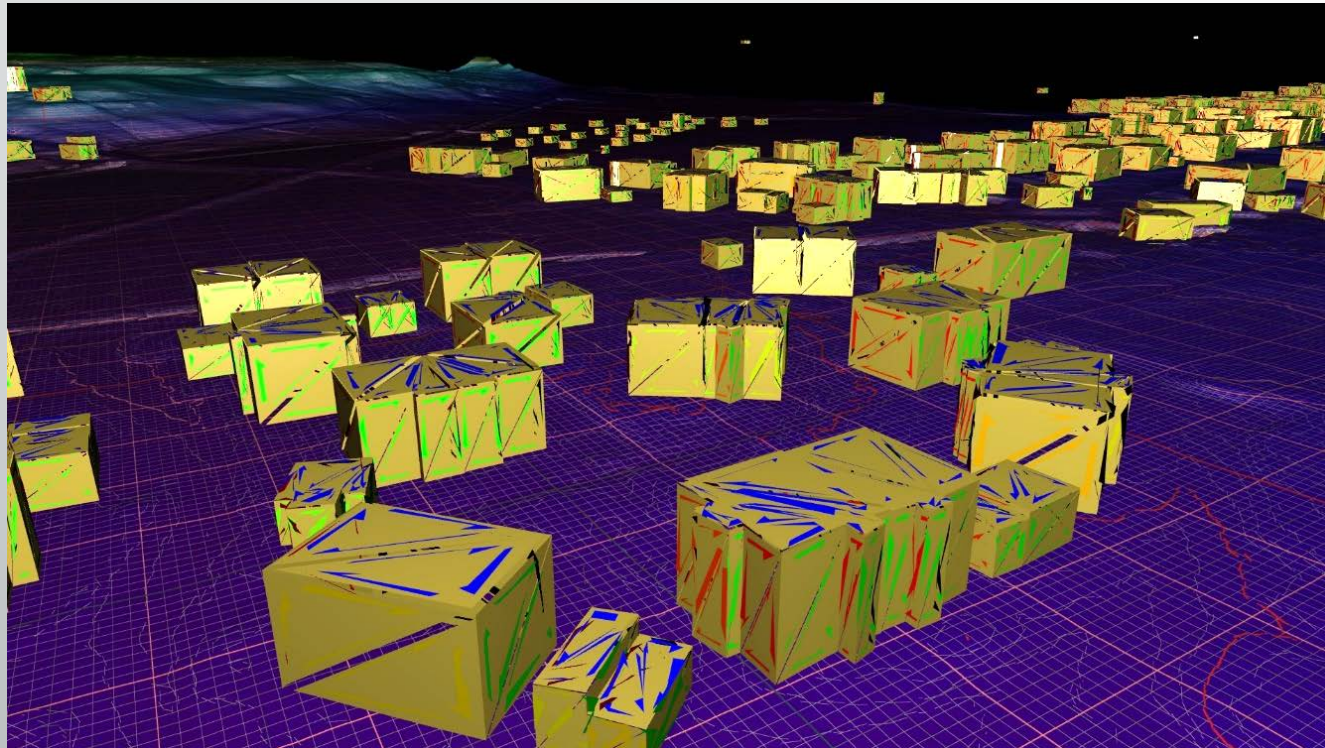
plus **data** on the **triangles**

```
/T=1          Group
/T=1/adcirc/Connectivity Group
/T=1/adcirc/Connectivity/Points Group
/T=1/adcirc/Connectivity/Points/Positions Dataset {600331}
/T=1/adcirc/Connectivity/StandardCartesianChart3D/elevation Dataset {600331}
/T=1/adcirc/Connectivity/StandardCartesianChart3D/vector Dataset {600331}
/T=1/adcirc/Points          Group
/T=1/adcirc/Points/StandardCartesianChart3D Group
/T=1/adcirc/Points/StandardCartesianChart3D/Positions Dataset {314442}
```



Data Fields on topological Skeletons

Vertices, Edges, Faces, Sets of Edges...



Unstructured Meshes

Skeletons and Primary Representations

Index
Depth 0

/T=1 Group
/T=1/adcirc Group
/T=1/adcirc/**Points** Group
/T=1/adcirc/**Points**/StandardCartesianChart3D Group
/T=1/adcirc/**Points**/StandardCartesianChart3D/Positions Dataset

Index
Depth = 1

/T=1/adcirc/**Edges** Group
/T=1/adcirc/**Edges**/**Points** Group
/T=1/adcirc/**Edges**/**Points**/Positions Dataset

/T=1/adcirc/**Faces** Group
/T=1/adcirc/**Faces**/**Points** Group
/T=1/adcirc/**Faces**/**Points**/Positions Dataset

/T=1/adcirc/**Connectivity** Group
/T=1/adcirc/**Connectivity**/**Points** Group
/T=1/adcirc/**Connectivity**/**Points**/Positions Dataset

Dimensionality 1

Dimensionality 2

Dimensionality 3

Unstructured Meshes

Skeletons and Secondary Representations

```
/T=1 Group
/T=1/adcirc Group
/T=1/adcirc/Points Group
/T=1/adcirc/Points/StandardCartesianChart3D Group
/T=1/adcirc/Points/StandardCartesianChart3D/Positions Dataset
/T=1/adcirc/Points/Faces Group
/T=1/adcirc/Points/Faces/Positions Dataset
```

```
/T=1/adcirc/Edges Group
/T=1/adcirc/Edges/Faces Group
/T=1/adcirc/Edges/Faces/Positions Dataset
```

```
/T=1/adcirc/Faces Group
/T=1/adcirc/Faces/Edges Group
/T=1/adcirc/Faces/Edges/Positions Dataset
```

```
/T=1/adcirc/Connectivity Group
/T=1/adcirc/Connectivity/Edges Group
/T=1/adcirc/Connectivity/Edges/Positions Dataset
```

Faces per Vertex

Faces per Edge

Edges per Face

Edges per Cell

Hierarchical Skeletons

- Third identification parameter on Skeletons:
 “refinement” (integer valued or n-dimensional set of integer valued group attribute)
- Allows to formulate “a grid within a grid”
- Replicates topological structure on different refinement levels

HDFView 2.11

File Window Tools Help

Recent Files C:\MinGW\msys1.0\home\ahm\AHM\Bayern\MergedBayern_0005_Refinement.f5 Clear Text

- MergedBayern_0005_Refinement.f5
 - Charts
 - TableOfContents
 - t=00000000.000000000
 - Bayern
 - CellsSet
 - Charts
 - F5::TimeTable
 - Points
 - PointsLevel10x10x10
 - PointsLevel2x2x2
 - PointsLevel3x3x3
 - PointsLevel4x4x4
 - PointsLevel5x5x5
 - PointsLevel6x6x6
 - PointsLevel7x7x7
 - PointsLevel8x8x8
 - PointsLevel9x9x9

j (48)
Group size = 3
Number of attributes = 0

Log Info Metadata

HDFView 2.11

File Window Tools Help

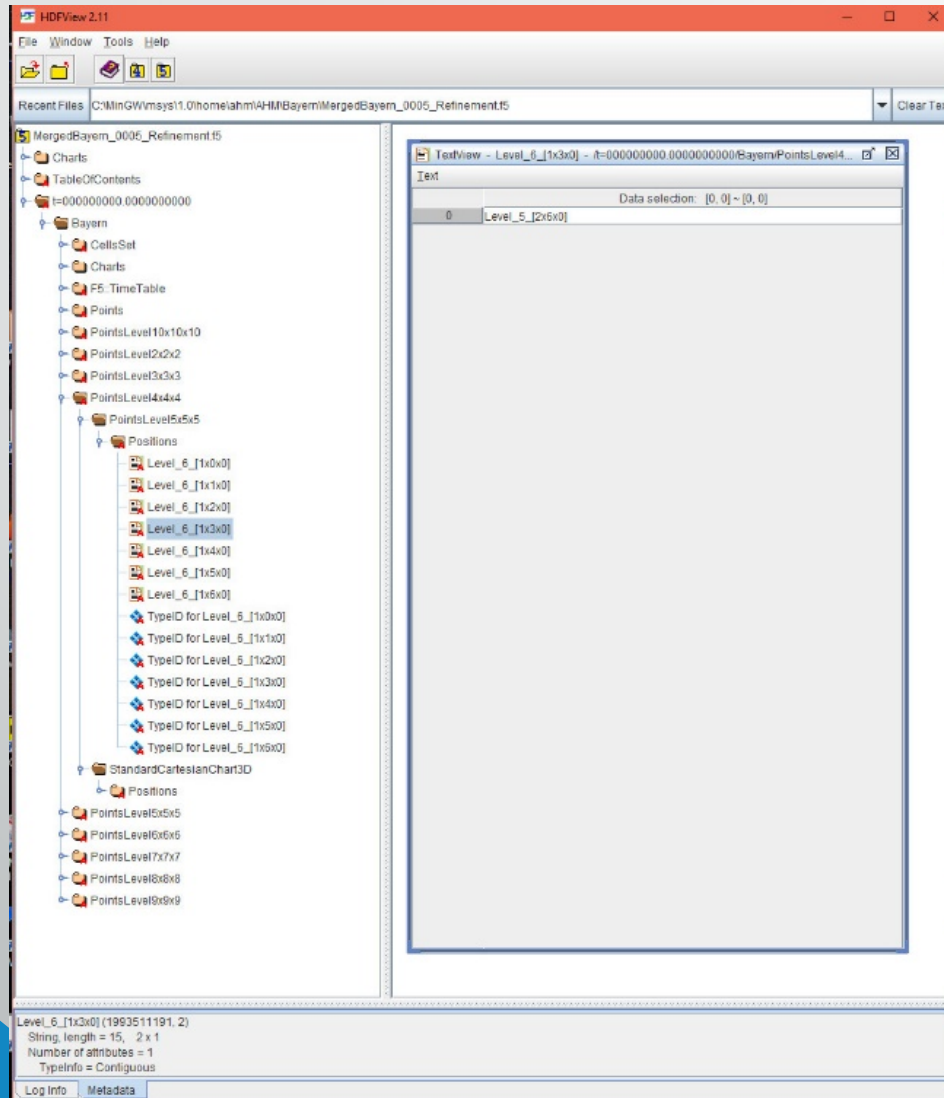
Recent Files C:\MinGW\msys1.0\home\ahm\AHM\Bayern\MergedBayern_0005_Refinement.f5 Clear Text

- MergedBayern_0005_Refinement.f5
 - Charts
 - TableOfContents
 - t=00000000.000000000
 - Bayern
 - CellsSet
 - Charts
 - F5::TimeTable
 - Points
 - PointsLevel10x10x10
 - PointsLevel2x2x2
 - PointsLevel3x3x3
 - PointsLevel4x4x4
 - PointsLevel5x5x5
 - Positions
 - StandardCartesianChart3D
 - Positions
 - PointsLevel5x5x5
 - PointsLevel6x6x6
 - PointsLevel7x7x7
 - PointsLevel8x8x8
 - PointsLevel9x9x9

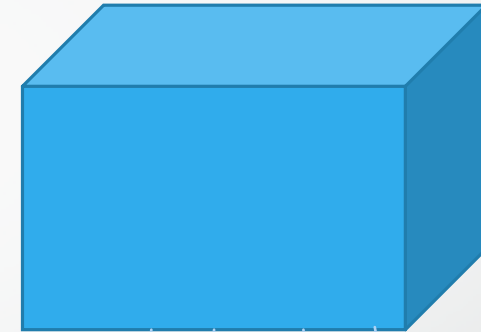
j (48)
Group size = 3
Number of attributes = 0

Log Info Metadata

Hierarchical References in F5



Level 4
FragmentID



Level 5
FragmentIDs

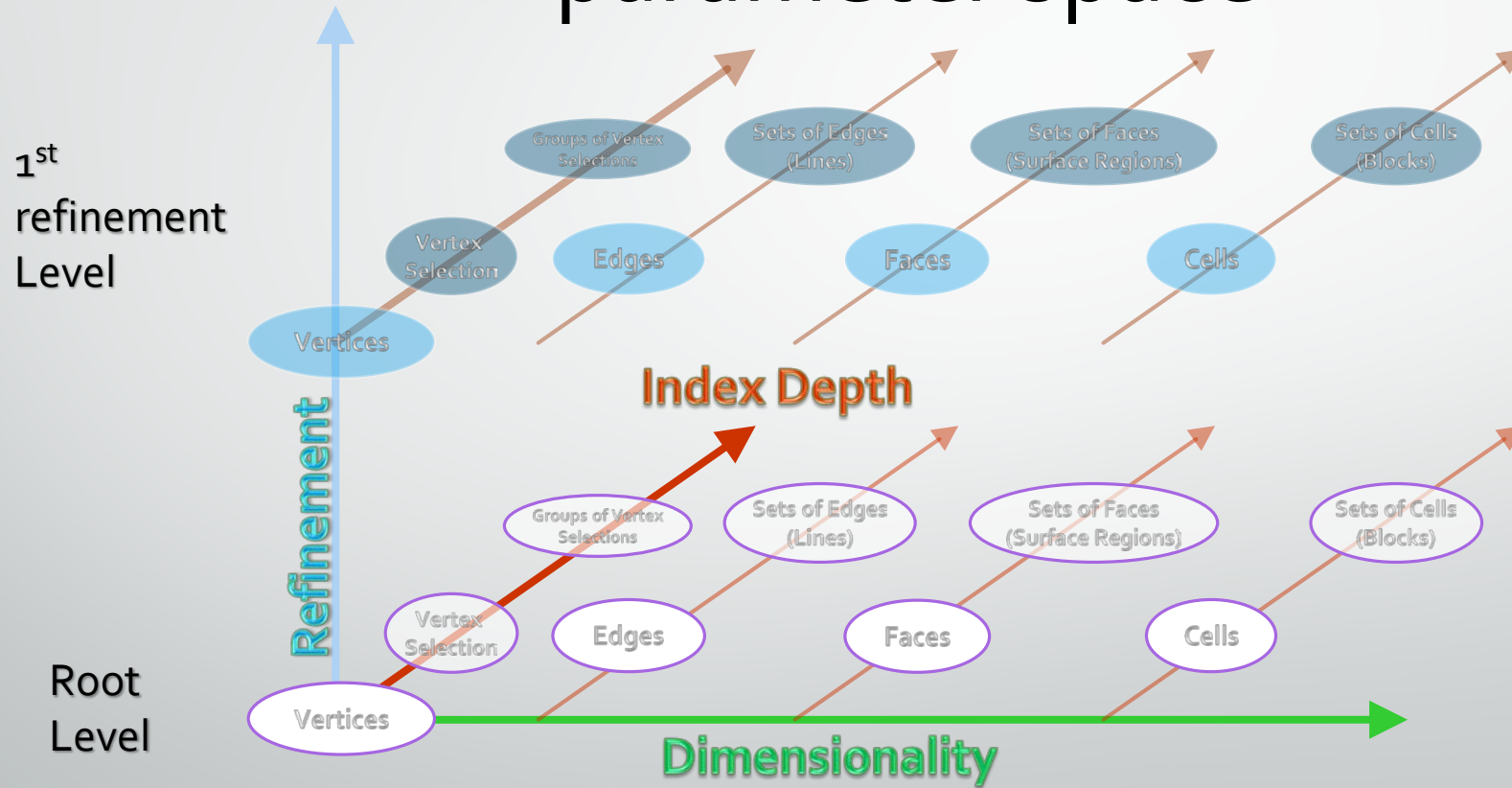


Data Processing – „Hierarchization“

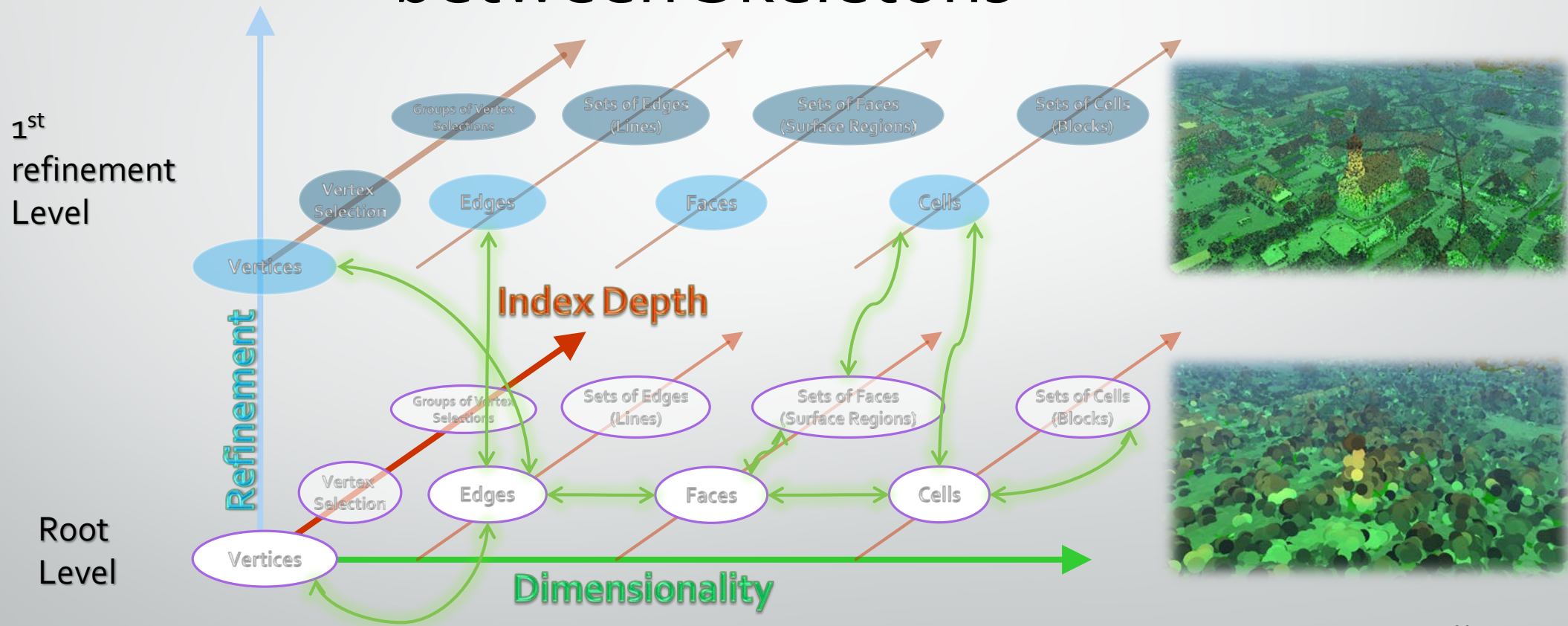
The screenshot displays a Windows desktop environment with three main windows:

- File Explorer (BayernMerged (F:)):** Shows a directory containing files like `AllOfBavaria_Refinement.f5`, `Makefile18`, and `Makefile`.
- Terminal Window:** Displays the output of an HDF5 application. The logs show the process of saving a grid, writing fragments, and scanning coordinates to compute bounding boxes. Key messages include: `RELEASE CANDIDATE: [Field:setPersistentData()]`, `INFO: SAVING Grid Bayern loaded from path AllOfBavaria.f5/...`, `HDF5 WRITING FRAGMENT DATA Bayern -> PointsLevel19x9x9 -> StandardCartesianChart3D -> Positions -> Level_1_1[40x26x0]`, and `Performance Warning: No Range attribute found or usage disabled, computing bounding box information from data.`
- Task Manager Performance:** Shows system resource usage for `Disk 3 (F:)`. The CPU is at 9% (3.29 GHz), Memory is at 6.8/63.9 GB (11%), and Disk 3 (F:) is at 0%. The active time graph shows significant spikes in disk activity. Below the graphs, the disk properties are listed: Capacity: 3.6 TB, Formatted: 3.6 TB, System disk: No, Page file: No, Read speed: 0 KB/s, Write speed: 0 KB/s.

Skeletons as Fibers of a 3-dimensional parameter space



Relative Representations as Connectors between Skeletons



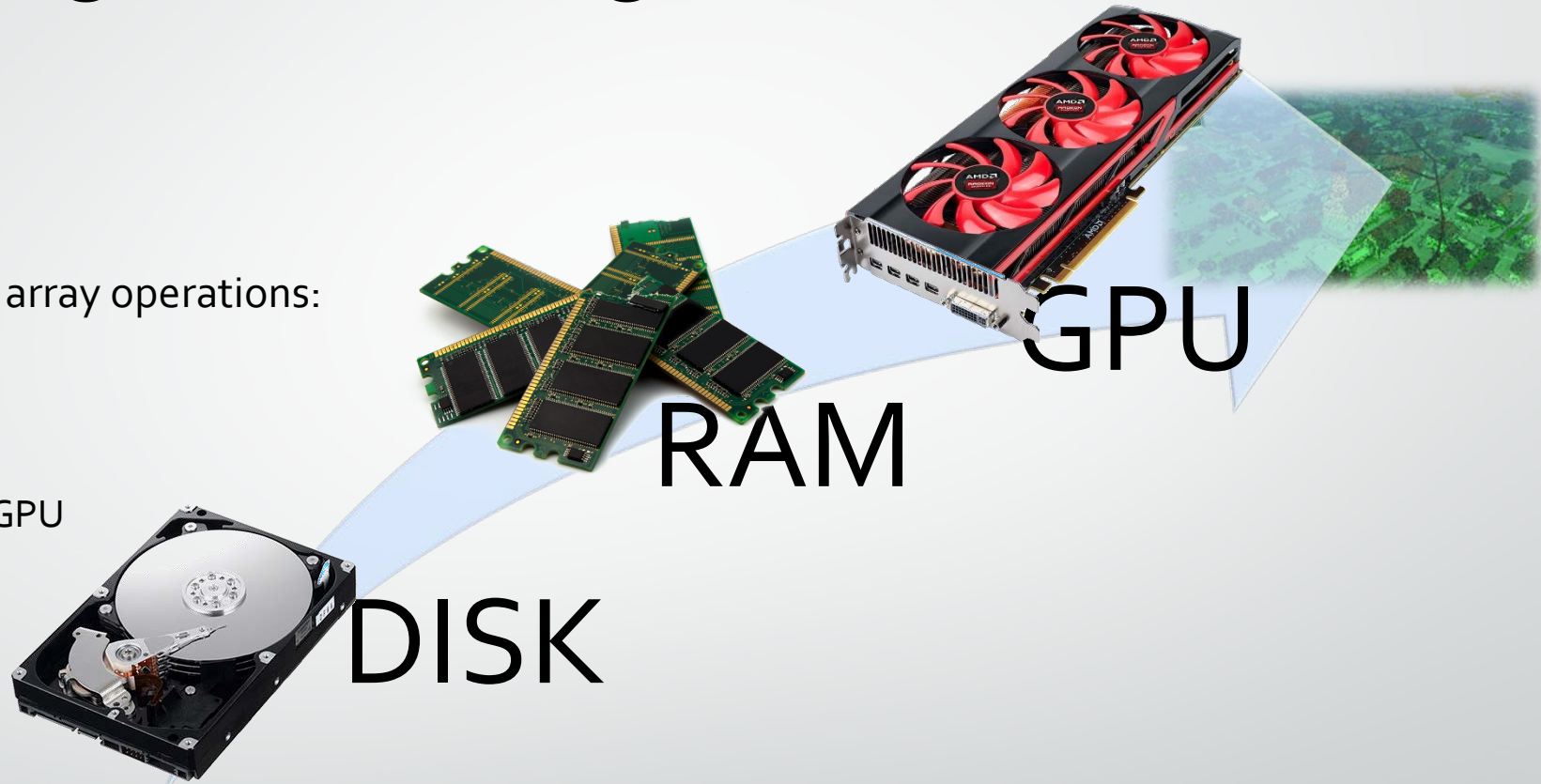
Arrays as High Performing Fiber Bundles

- Important: All operations are array operations:

- Parallelizable
- Fast I/O disk → RAM
- Fast data transfer RAM → GPU

- *No pointer data structures*

- Relative information via indices and arrays of indices
- Optimized for visualization and data processing, not so much for data modification requiring rebuilding of index lists (e.g. surface editing)



GA for Massive Data

- Alignment of Point Clouds / Geometries / Images
- Feature detection / Point Classification / Object Identification
- Clustering of points for hierarchy generation
- Camera navigation & animation control
- ...

“F5 Fiber Bundle Data Model”

- A property-based description of scientific data
- A specific data type is built from “construction blocks” (not enumerated case lists)
- Does not answer the question “*what is it?*” but answers the question(s) “*how is it?*”
- A specific data set can have properties of *many* data types
 - non-exclusive properties
 - eases/enhances interoperability
- Enables abstract operations independent of data type

Conclusion

- A data model for Unified Real-Time Visualization of Arbitrarily Massive Generic Scientific Data
- Commonalities across Grid types are not just enabled, they are unavoidable
- Simple data types have simple representations
- Complex data types are constructible from similar, reusable structures
- The F5 model does not cover *any* type of data, but a very wide range
- Geometric Algebra, Differential Geometry & Topology as foundation

Web References

- www.fiberbundle.net – The F₅ Data model
- vish.fiberbundle.net – The Vish Visualization Shell (based on the F₅ model)
- www.ahm.co.at – Airborne HydroMapping (LIDAR data acquisition & software development)
- www.aei.mpg.de – Max Planck Institute for Gravitational Physics



AHM

Demo: Lake Constance

www.ahm.co.at

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