SHAPE AND SEMANTICS FOR URBAN MODELLING

THE ROLE OF GEOMETRY IN CITY DIGITAL TWINS

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Consiglio Nazionale delle Ricerche

imati

LDAC Summer School 2023

OVERVIEW OF THE TALK

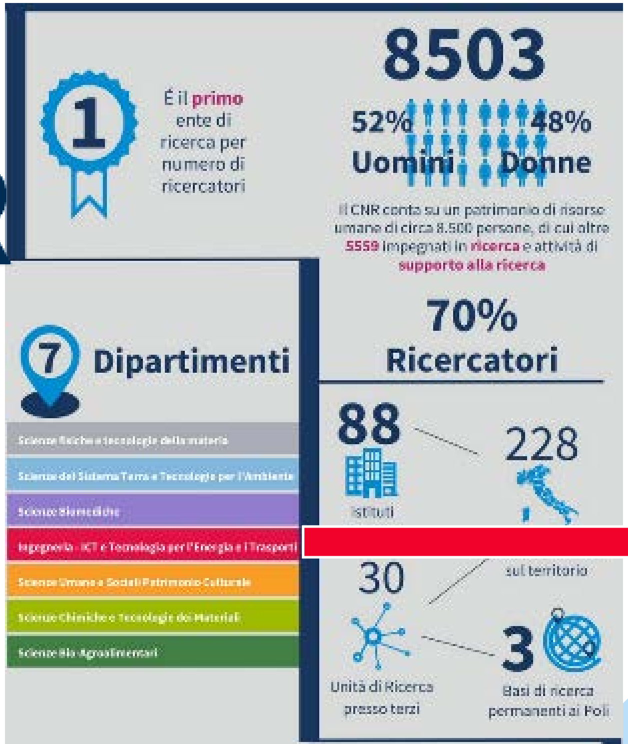
- Background and Context
  - CNR and IMATI
  - The DIITET Strategic **Urban Intelligence** project and its case studies

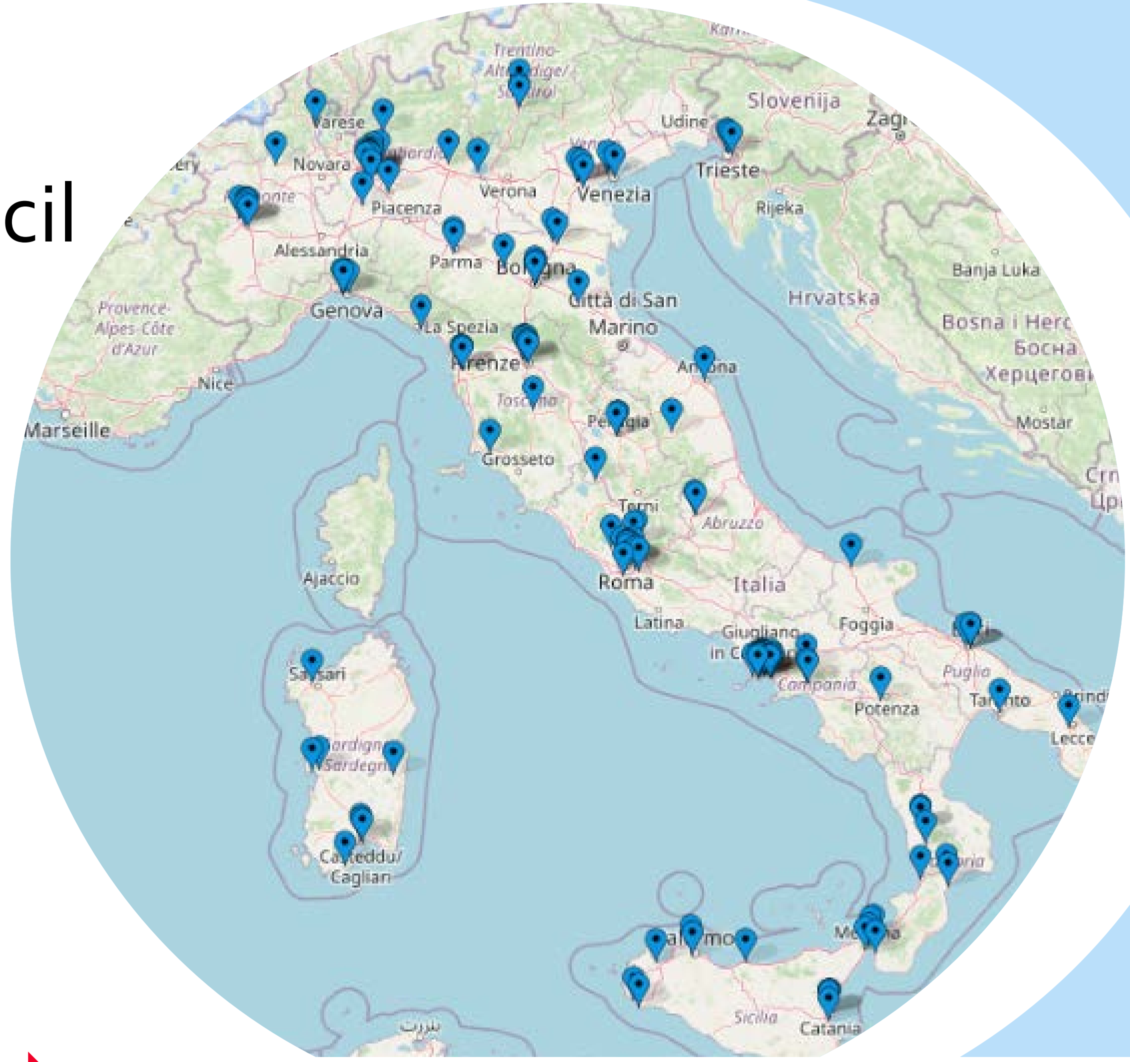
How to construct a digital 3D representation of the physical urban context from real data.

- Quick and dirty intro to shape modeling
  - Acquisition vs modeling; Representations and data structures
- Shape modeling for urban environments
  - Acquisition and reconstruction pipeline
  - … and semantics?
  - Examples from ongoing projects, especially in Matera (CTE Matera),
- Challenges and perspectives

BACKGROUND AND CONTEXT

CNR – National Research Council

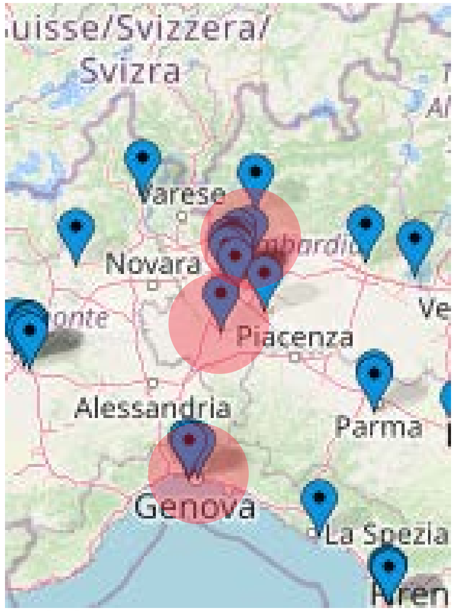




CNR | **Dipartimento Ingegneria - ICT e Tecnologia per l'Energia e i Trasporti**

15 institutes

IMATI – APPLIED MATHEMATICS & INFORMATION TECHNOLOGIES



PAVIA

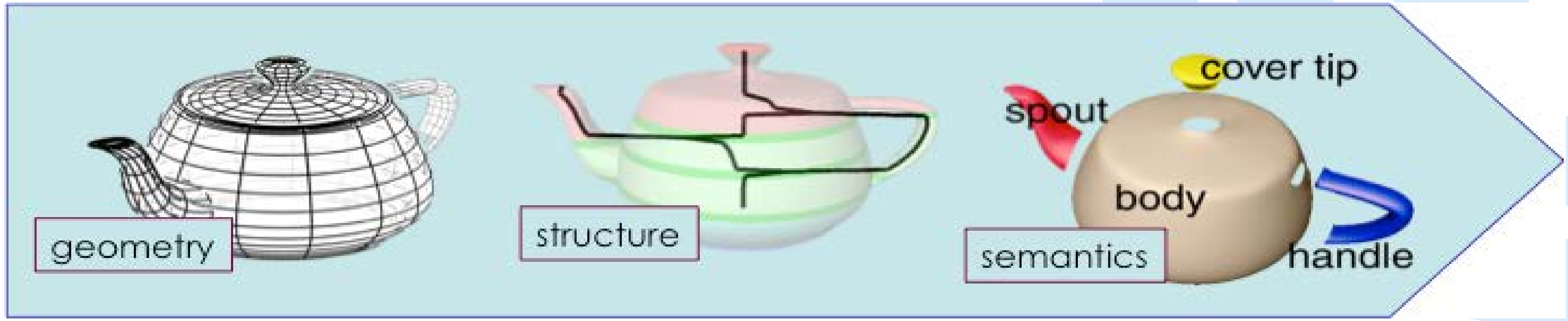
GENOVA

MILANO

- Theoretical study of PDEs
- Numerical methods for PDEs
- Uncertainty quantification
- Statistical and stochastic modelling
- Multimedia data analysis

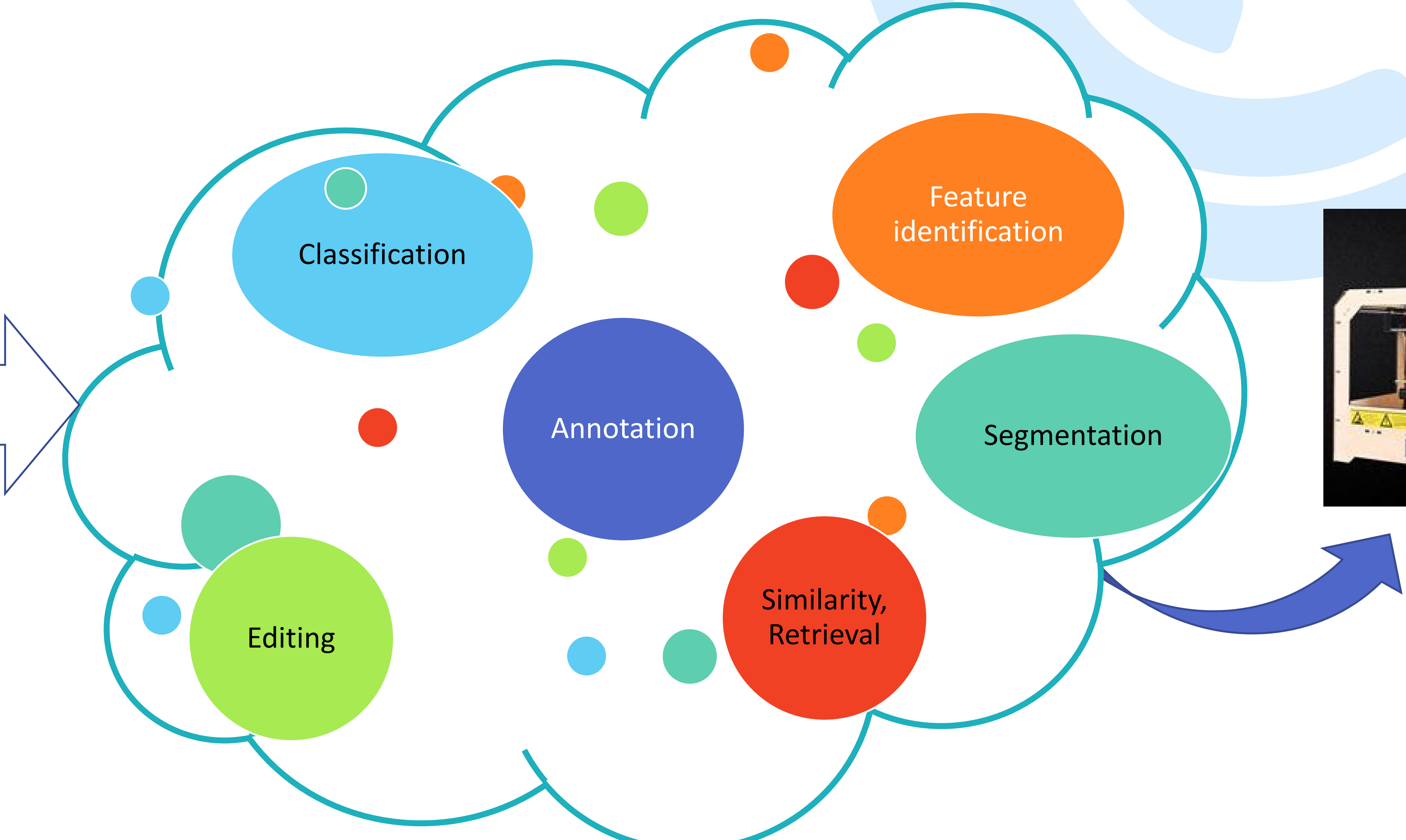
- Geometric Modelling & Computer Graphics
- Knowledge formalization
- Semantic annotation of visual data
- Computing Architectures
- High Performance Computing
- Cybersecurity

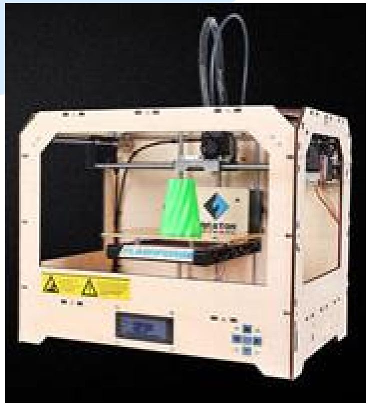
INNOVATION: SHAPE BEYOND GEOMETRY



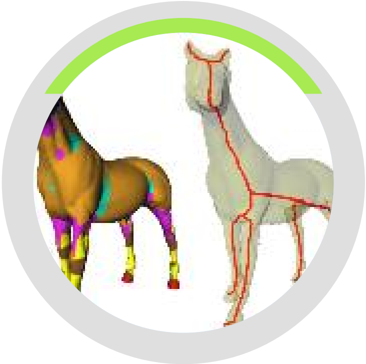
- **Network of Excellence AIM@SHAPE (FP6)**
  - A disruptive idea: 3D shape modelling and knowledge technologies
  - 4 years (2004-2008), 6. 5 Mio €, 13 partners, 150 researchers
  - tangible results: the DSW with its Repository
    - models with certified properties
    - documentation of models and tools via ontologies
    - promotion of benchmarking (SHREC events) and reproducibility

SHAPE AND SEMANTICS RESEARCH @IMATI





ME@CNR-IMATI: «SHAPE UNDERSTANDING»

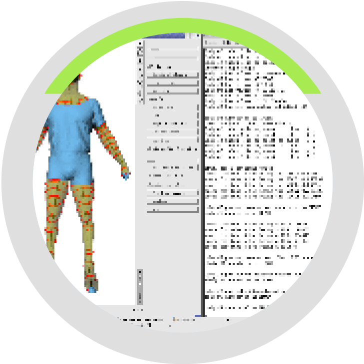


SHAPE ANALYSIS AND SYNTHESIS

analyse geometric properties of shapes

Identify salient regions

Build skeletons

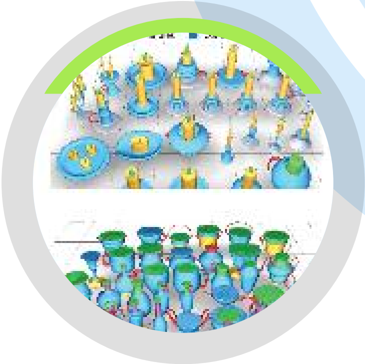


SEGMENTATION AND LABELING

Identify main components

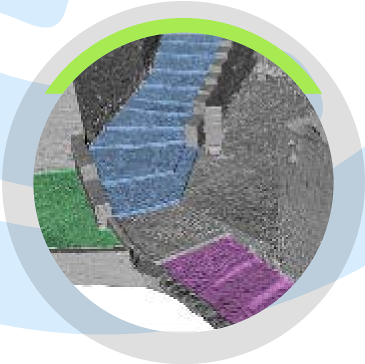
Characterize parts

Use contextual information to automatically label parts



ANNOTATION

Add semantics to geometry whole or parts, manually, semi-automatically, automatically



APPLICATIONS

Cultural Heritage

Serious games

Geoscience

Urban Intelligence

CONTEXT – URBAN DIGITAL TWINS

- The digital twin is a high-fidelity model of a system which can be used to emulate the actual system.
- The digital twin concept consists of three distinct parts: the **physical object or process** and its physical environment, the **digital representation** of the object or process, and the **communication channel** between the physical and virtual representations. The connections between the physical version and the digital version include physical sensor flows between the physical and virtual objects and environments.

GEOMETRIC MODELING PARADIGM

DIITET STRATEGIC PROJECT "URBAN INTELLIGENCE"

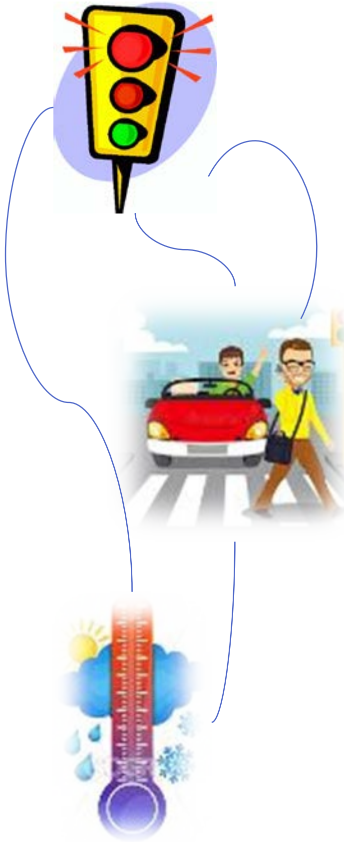
digital twins of urban spaces

Very complex systems!

...with a digital representation of the same physical reality...

Digitalization of the physical reality – «*built structures*»
Representation and modelling of events/processes – «*what happens in the real-world city*»
Capturing the status of the real-world city –«*immersed and connected sensors*»
Capturing data, feedback, suggestions of the urban space inhabitants – «*participatory approach*»

DIITET STRATEGIC PROJECT "URBAN INTELLIGENCE"



data access

Data-driven

behaviour and prediction learnt from observed data

Physics-based

governing physical laws are known and simulation models are tuned by observed data

Sensor network

Data

Digital Twins & AI

Usage scenarios

Castelli, Giordana, Amedeo Cesta, Matteo Diez, Marco Padula, Paolo Ravazzani, Giovanni Rinaldi, Stefano Savazzi et al. "Urban intelligence: a modular, fully integrated, and evolving model for cities digital twinning." In *2019 IEEE 16th International Conference on Smart Cities: Improving Quality of Life Using ICT & IoT and AI (HONET-ICT)*, pp. 033-037. IEEE, 2019.

CASE STUDIES

Emerging Technologies
Matera

CNR-DIITET Project
La Spezia

PON-POC Metro
Catania

UNIONE EUROPEA
FONDI STRUTTURALI E DI INVESTIMENTO EUROPEI

Agenzia per la Coesione Territoriale

MATERA

Matera – *European Capital of Culture 2019*

392 km² – 60K residents

- Mobility (pedestrian/vehicle)
- Cultural tourism
- Wellbeing
- Environment

- Optimization of paths under different constraints
  - Reduce/maximize fatigue /comfort
  - Accessibility – disabilities, limited abilities,..
- Monitoring occupation of POIs
  - Provide virtual visits in alternative

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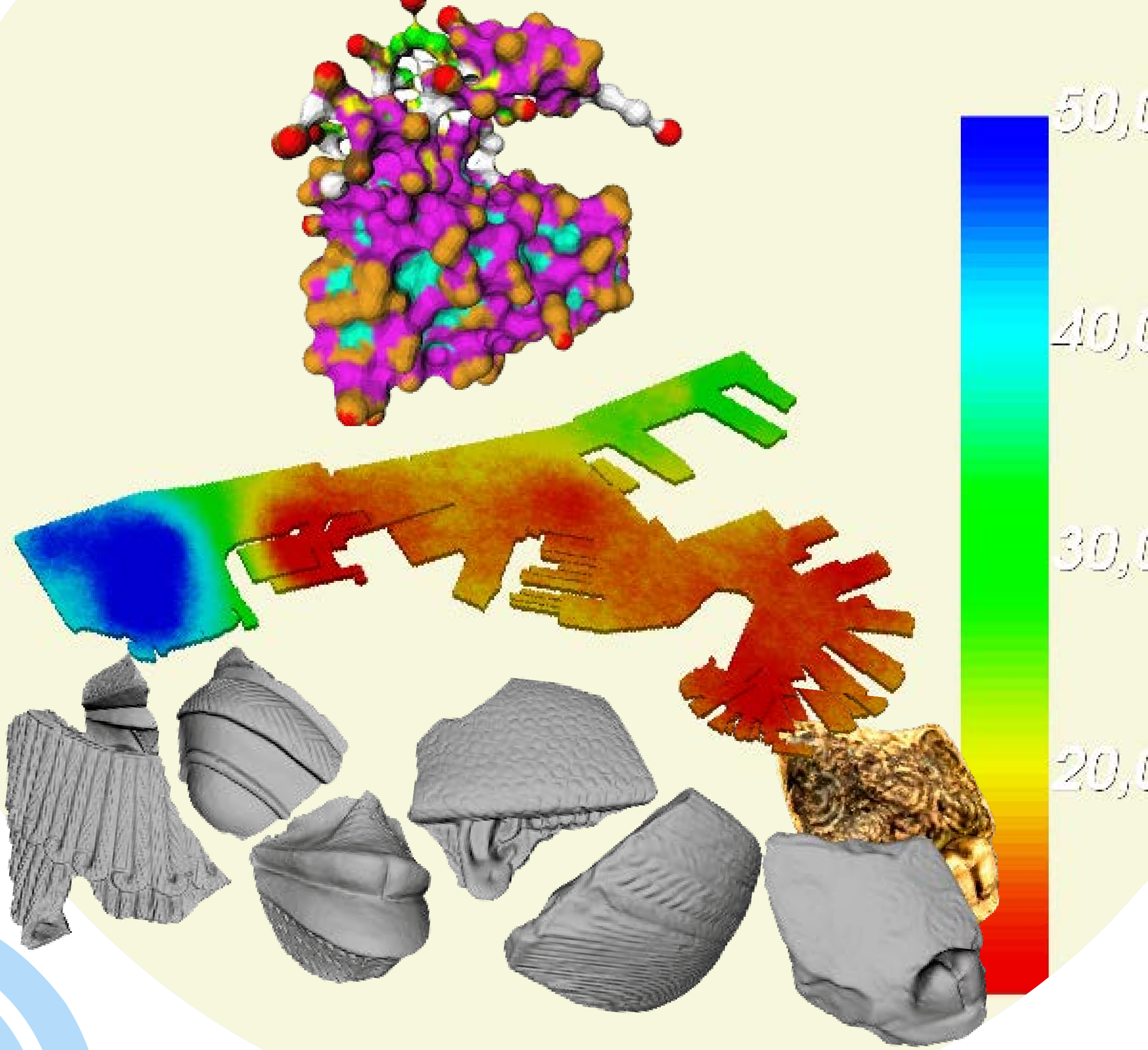
DIGITAL SHAPES

QUICK AND DIRTY INTRO TO GEOMETRIC MODELING

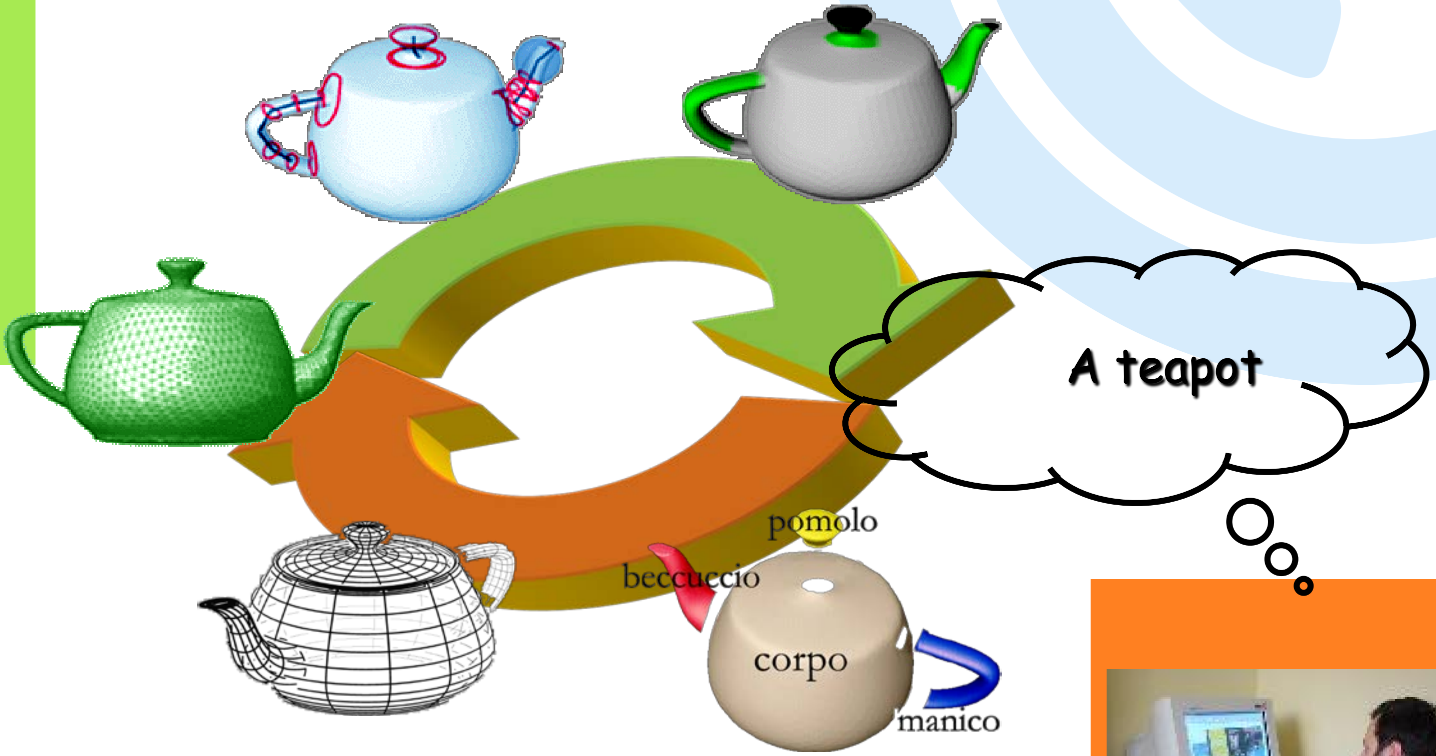
DIGITAL SHAPE

- Every object or phenomenon characterized by a spatial extent in 2, 3, … N dimensions which is digitally represented:
    - A curve / surface /volume
    - An animated character
    - The wind field
    - The distribution of pollutants in the water
    - The urban environment…



DIGITAL SHAPE LIFECYCLE

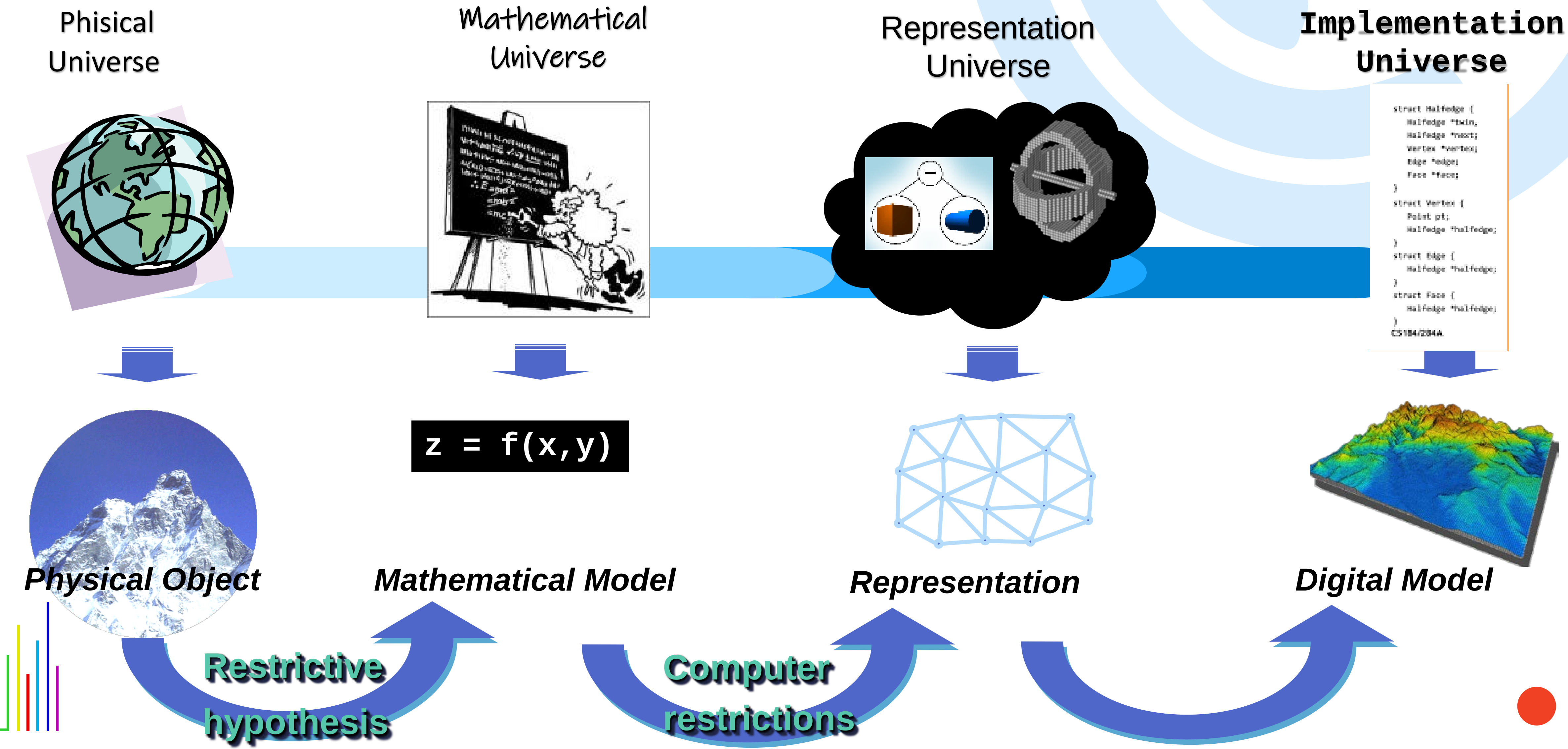
Real world



- Acquisition
- Reconstruction

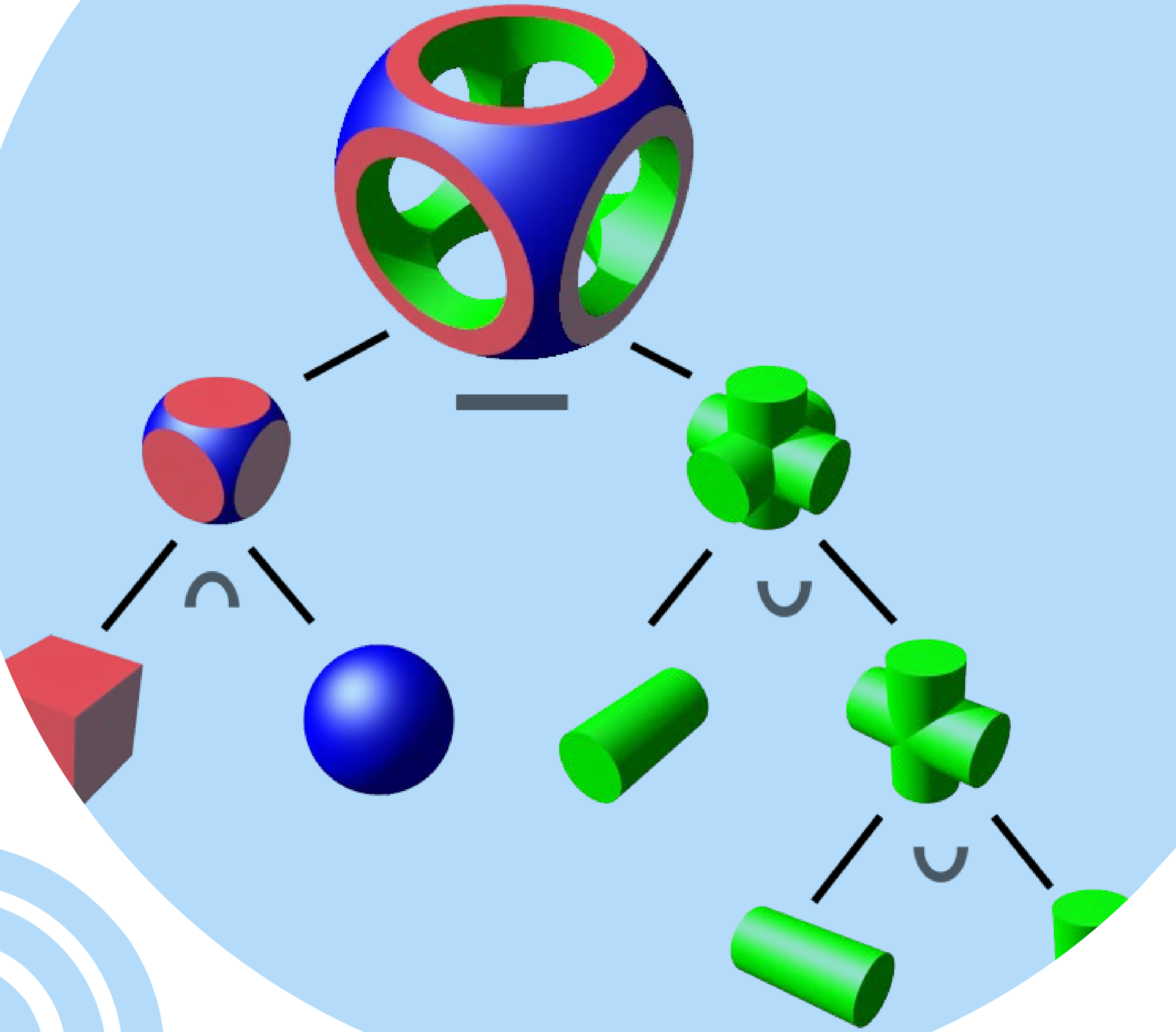
Conceptual world

GEOMETRIC MODELING PARADIGM (REQUICHA, 1980)



REPRESENTATION OF 3D SHAPES - METHODS

- **Constructive**
- Volume-based
- Boundary-based



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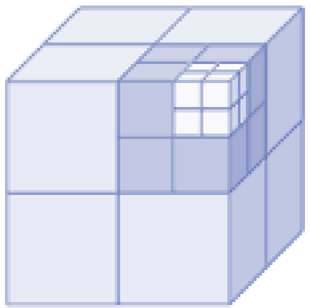

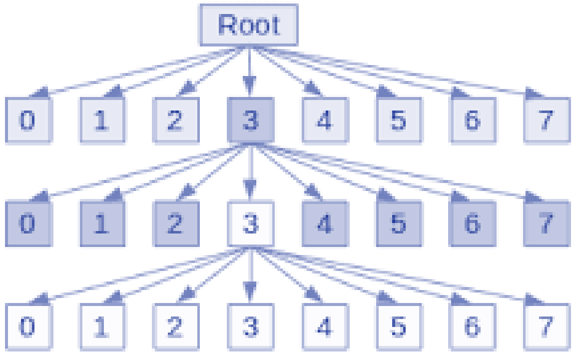

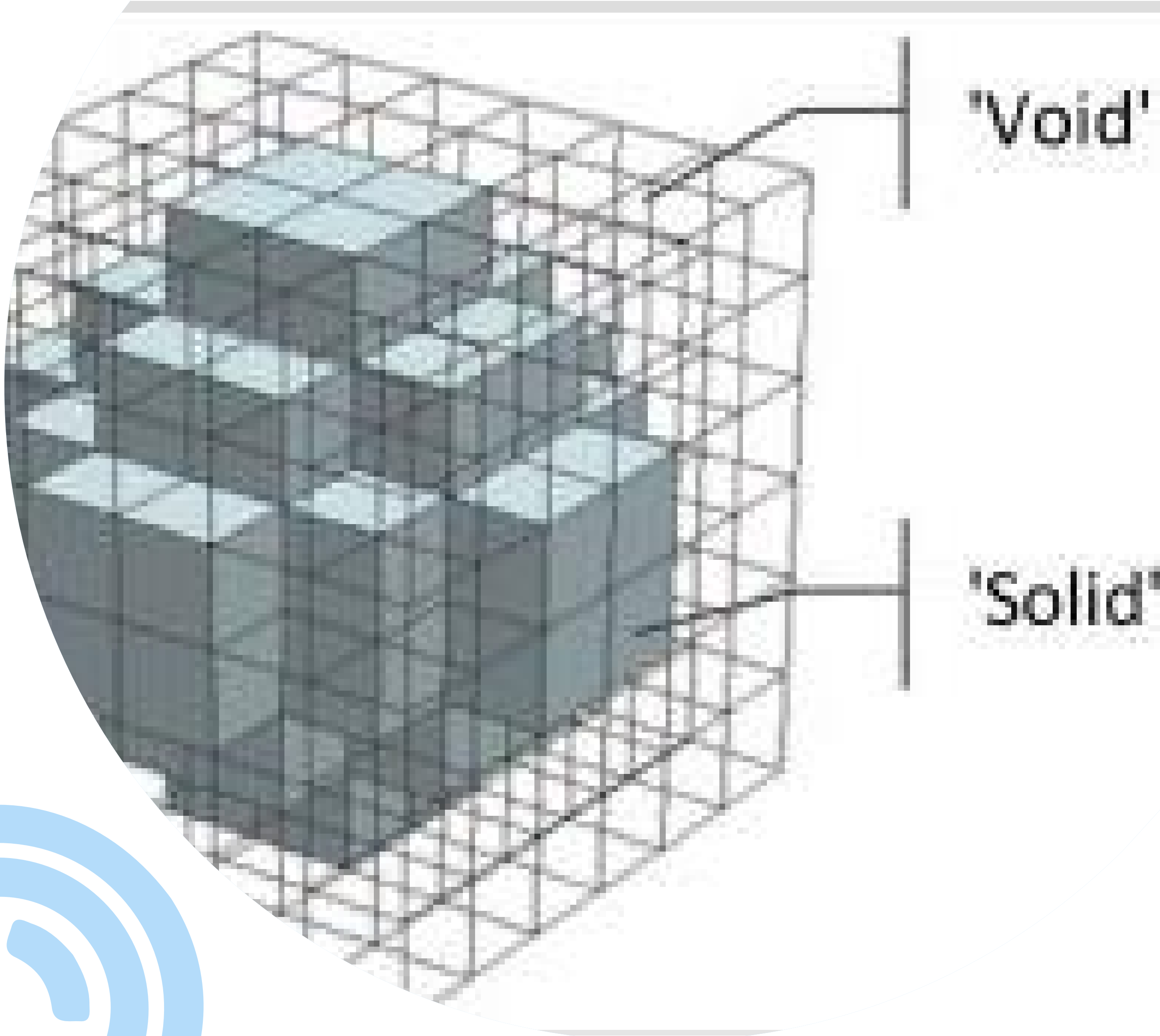

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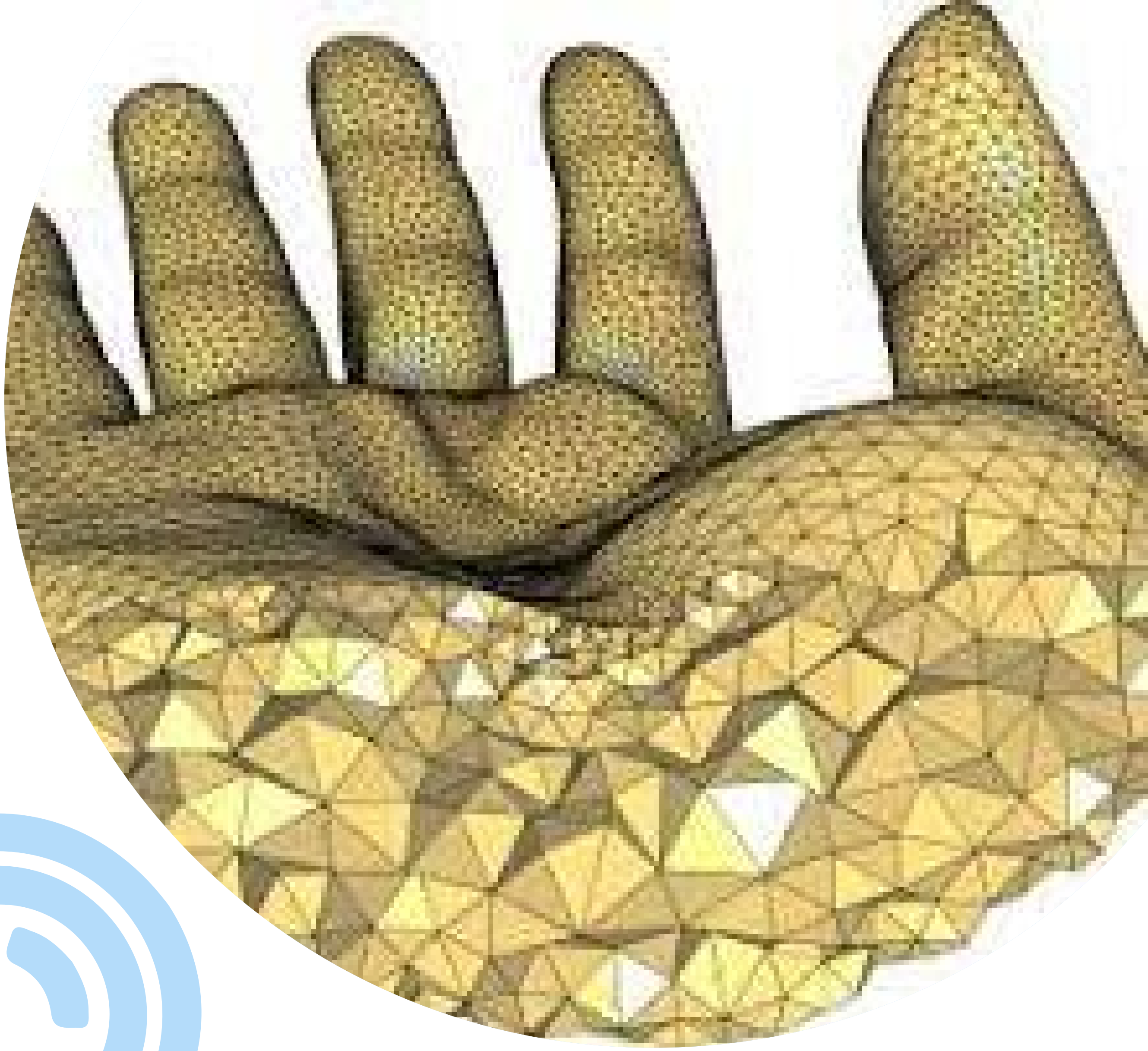
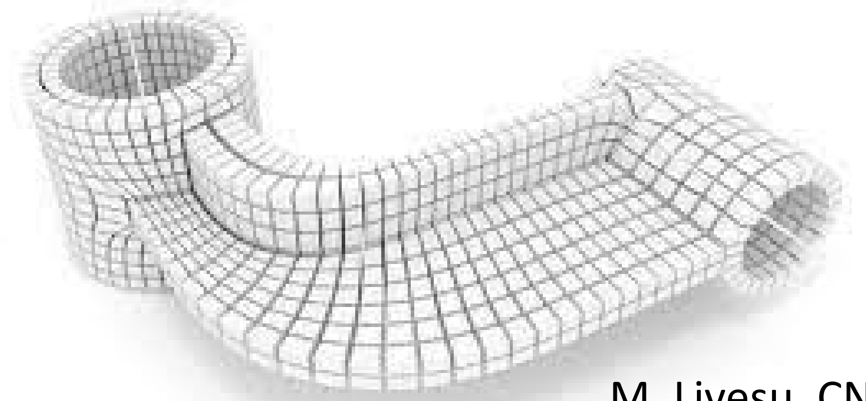
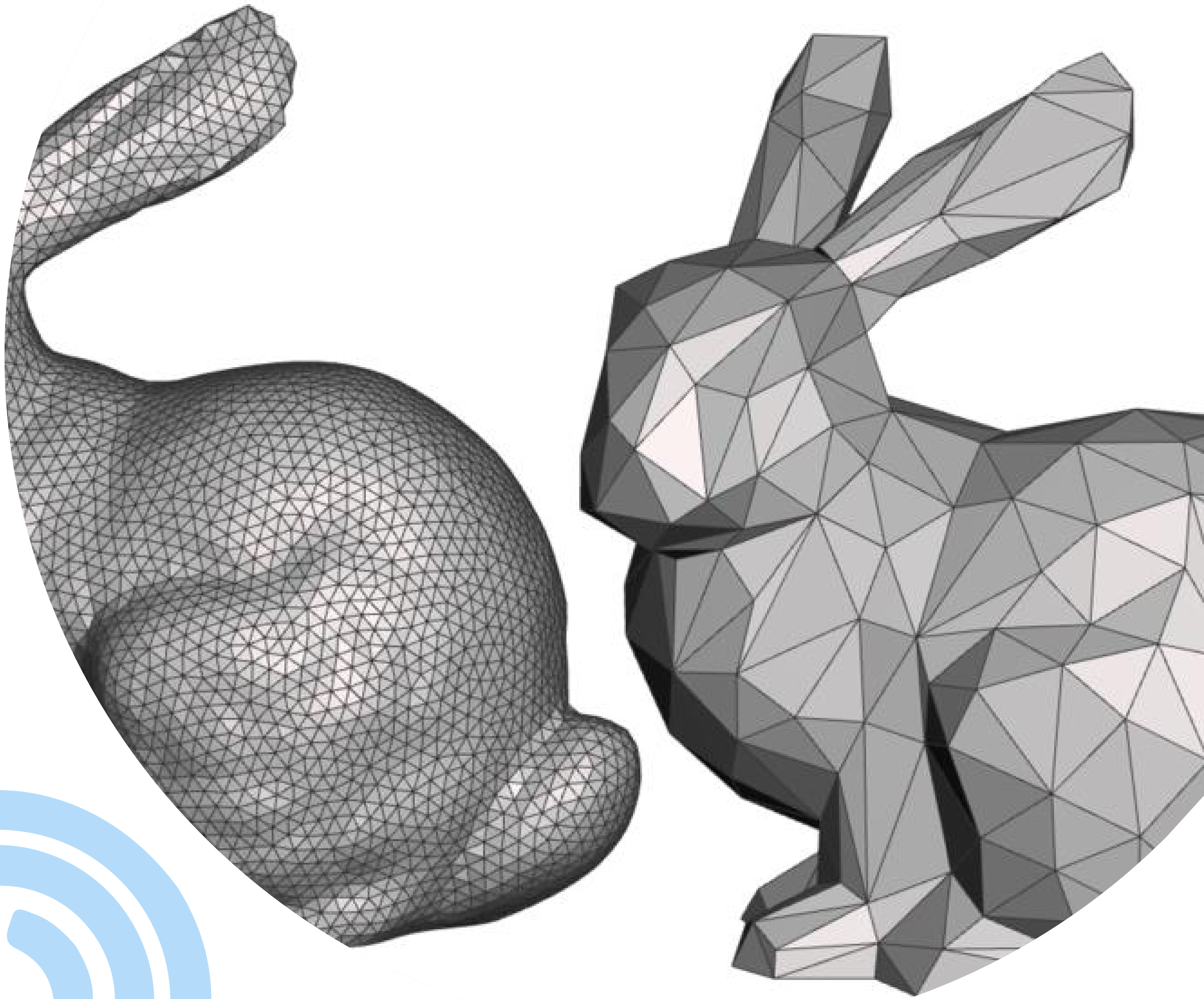




M. Livesu, CNR-IMATI, hex meshes

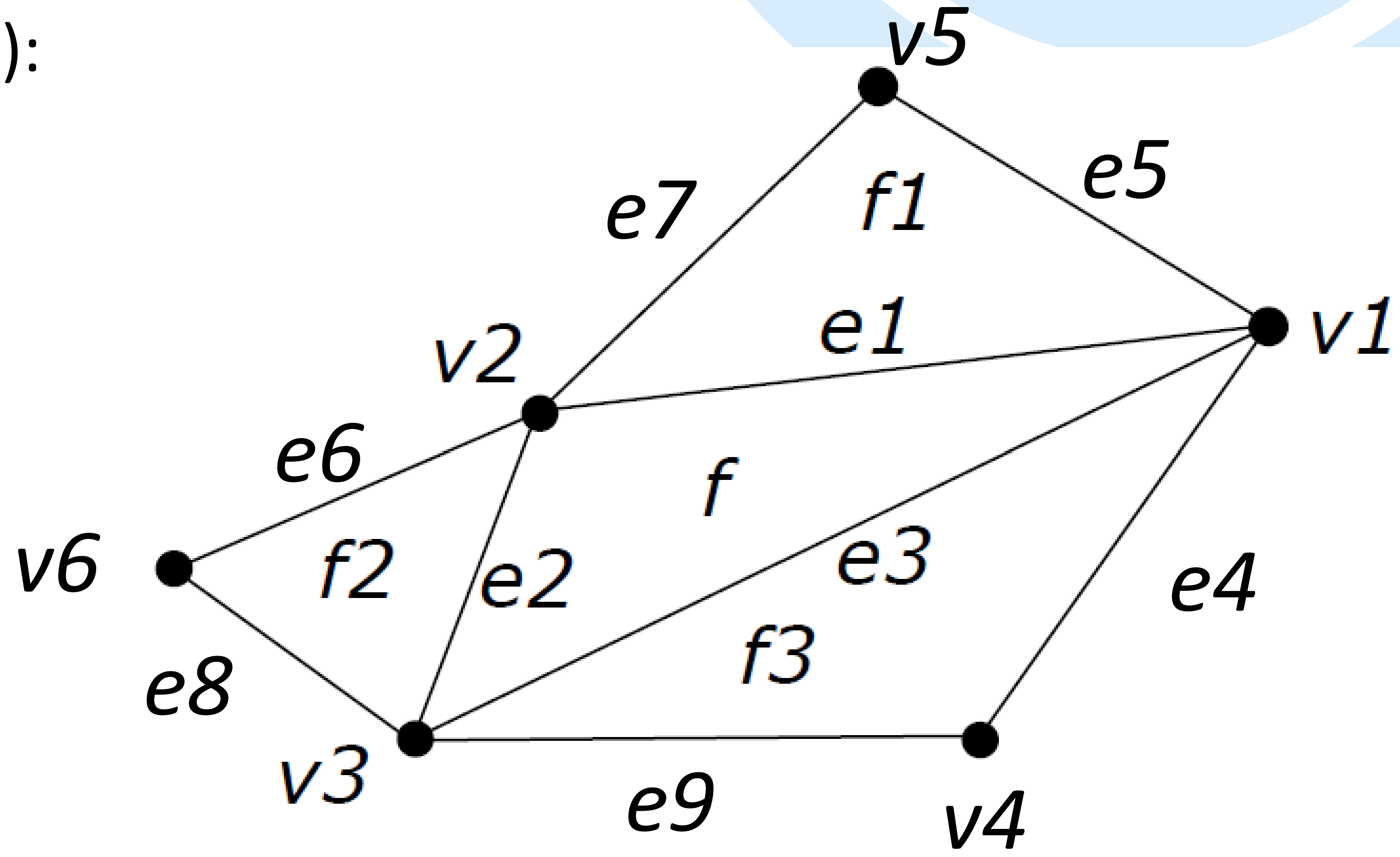
REPRESENTATION OF 3D SHAPES - METHODS

- Constructive
- Volume-based
- **Boundary-based**
  - Implicit surfaces f(x,y,z)=0
  - **Meshes**



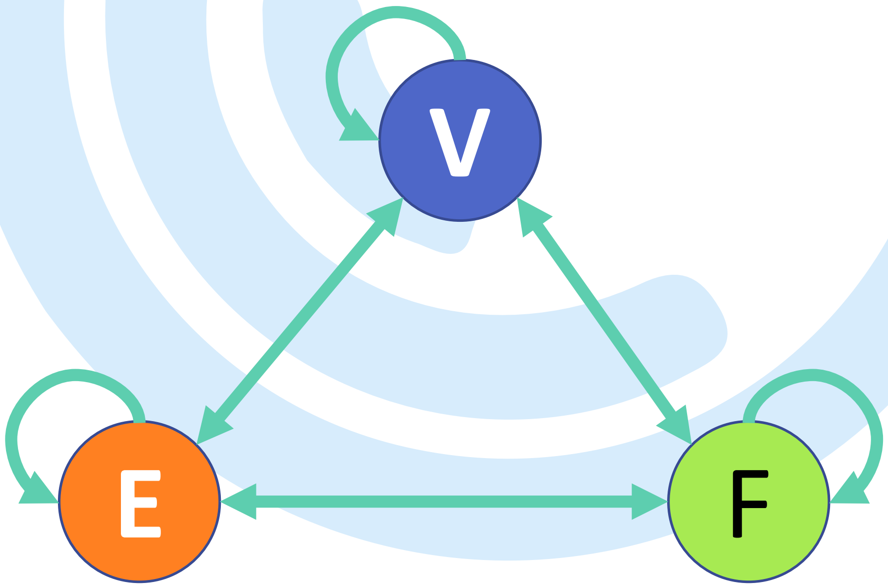
(TRIANGLE) MESHES

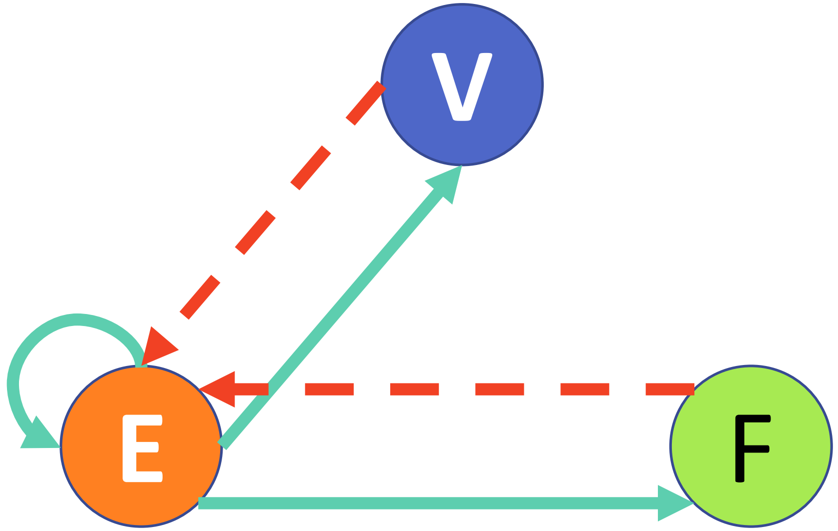
- Entities: vertices V, edges E, Faces F (Triangles T)
- Relations (constant/not):
  - VV, VE, VF
  - EV, EE, EF
  - FV, FE, FF



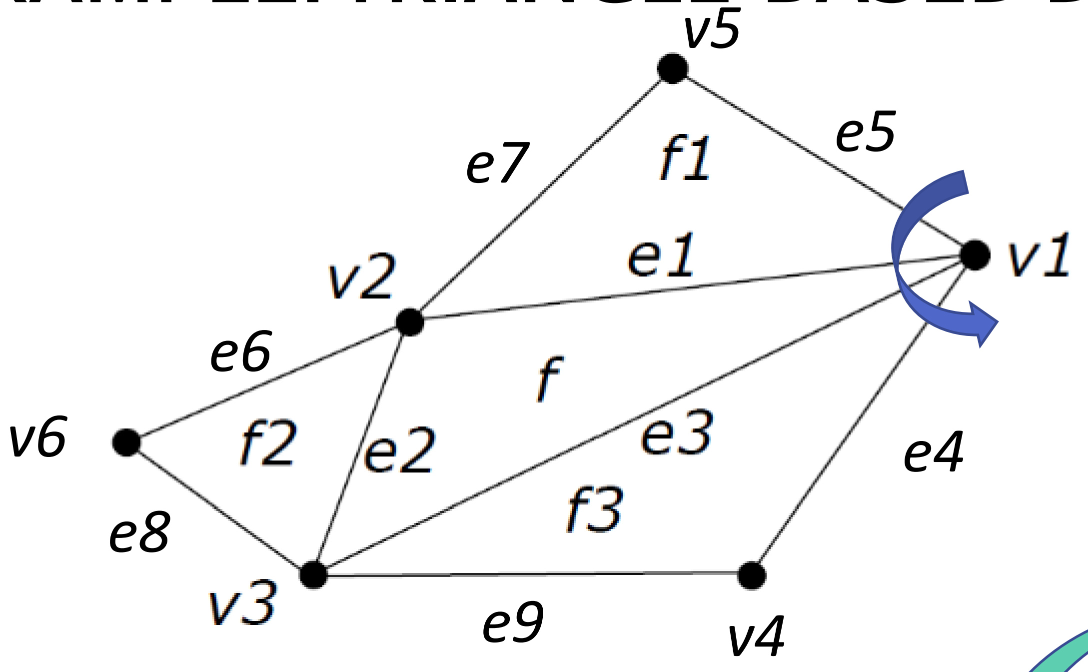
DATA STRUCTURES

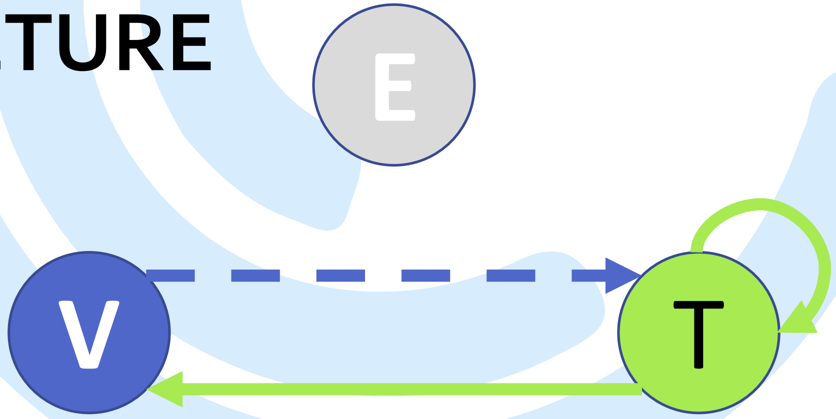
- 9 topological relations are redundant
- Data structures differ for which relations are explicitly encoded. Trade-off:
  - Efficiency of extracting not encoded relations: O(output)
  - Required memory
- Tricks:
  - partial relations, esp. for non constant relations (e.g., winged edge data structure)
  - Conventional orientation! (CCW)





EXAMPLE: TRIANGLE-BASED DATA STRUCTURE





V:

	x0	y0	z0	f6
v1:	x1	y1	z1	f1
v2:	x2	y2	z2	f2

T:

f:	v1	v2	v3	f1	f2	f3
f1:	v1	v5	v2	-1	-1	f
f2:	v3	v2	v6	f	-1	-1

OK, SOOOOO.....

- Now I know how to define a data structure to encode a mesh, but...

  Where do I find a triangle mesh?

- Please give me a nice file like...

```
ply
format ascii 1.0
element vertex 1335
property float32 x
property float32 y
property float32 z
element face 2452
property list uint8 int32 vertex_indices
end_header
896.994 48.7601 82.2656
906.593 48.7601 80.7452
907.539 55.4902 83.6581
896.994 55.4902 85.3283
896.994 42.8477 77.825
905.221 42.8477 76.522
```

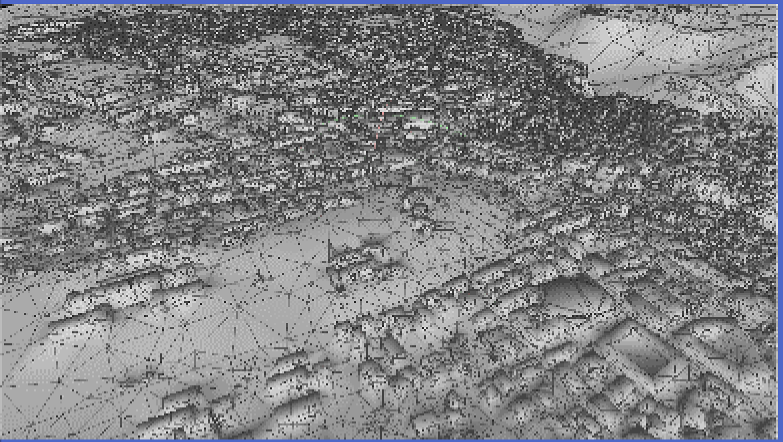
```
#vertri
NumVertices
12.345 45.872 2.654   123
43.21  13.72  51.7    012
…
NumTriangles
0      1      2       12     13     1
0      3      2       14     13     2
…
```

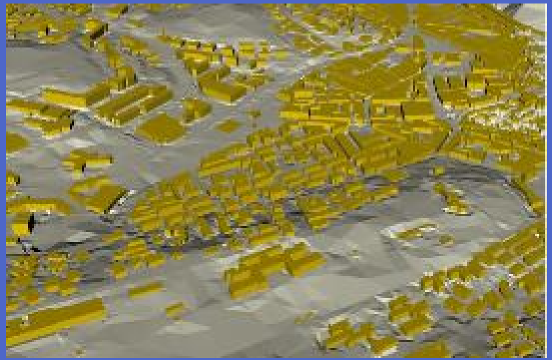
```
OFF
8 12 0
0 0 0
1 0 0
1 1 0
0 1 0
0 0 1
1 0 1
1 1 1
0 1 1
3 0 2 1
3 0 3 2
3 0 1 4
3 1 5 4
…
```

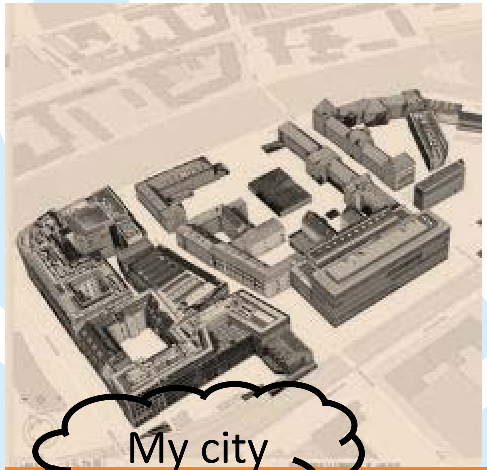
REMINDER

- Acquisition
- Reconstruction

Real world







My city

Conceptual world

- Modeling

- This is what we are going to do!

…But the best would be bridging the two worlds!
-> annotation

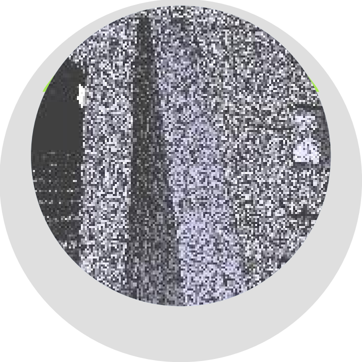
ACQUISITION & RECONSTRUCTION PIPELINE

FOR THE CITY

ACQUISITION&RECONSTRUCTION PIPELINE

ACQUISITION

Collect the data about the morphology of the urban environment

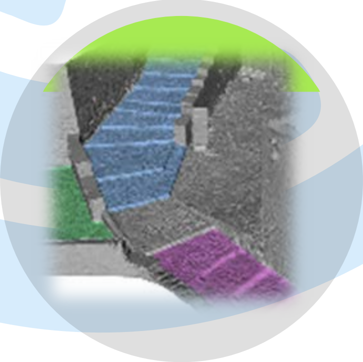


RECONSTRUCTION

Generate one (or more) meshes (or other reps) of a good quality for the application/s

ANALYSIS

Apply geometric processing algorithms to the model to extract new knowledge, implicitly encoded in the geometry



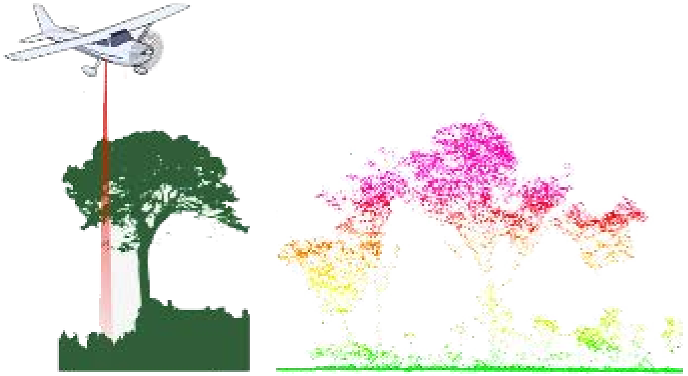
ANNOTATION

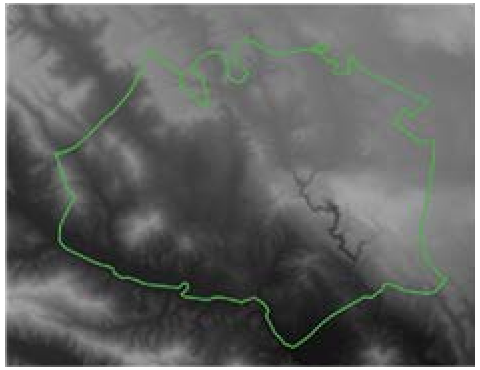
Add contextual knowledge explicitly to (portions of) geometry, so that it can be automatically processed

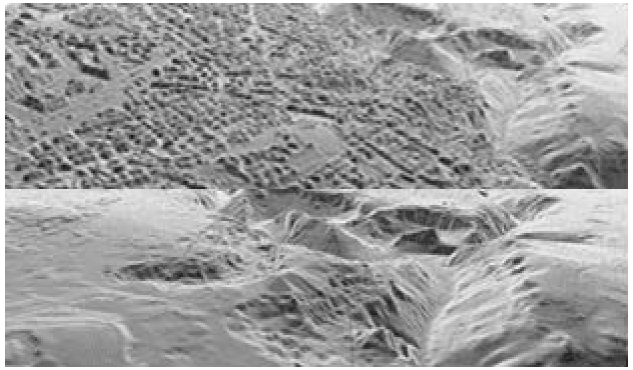
- **Acquisition COSTS!!! What data are already available? Are they sufficient? Are they too many????**
- **If acquisition is needed, which tools are appropriate?**
- **What geometries? Urban scenarios may be very complicated and heterogeneous… not only facades and blocks!**
- **What applications for the model?**

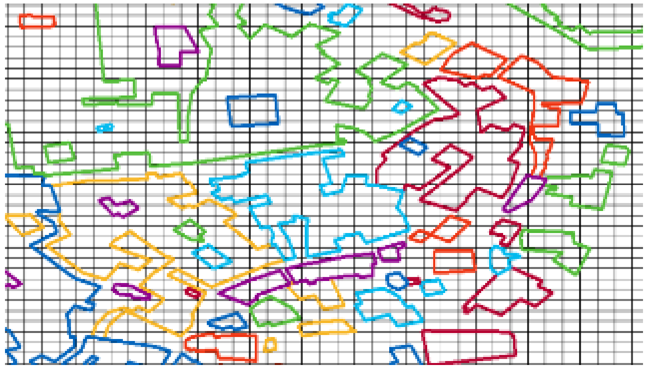
RECONSTRUCTION FROM LOW RES DATA

- Geoportale Nazionale: survey one point every 5 meters
- DSM, DTM (greyscale image)
- Building footprint from OpenStreetMap









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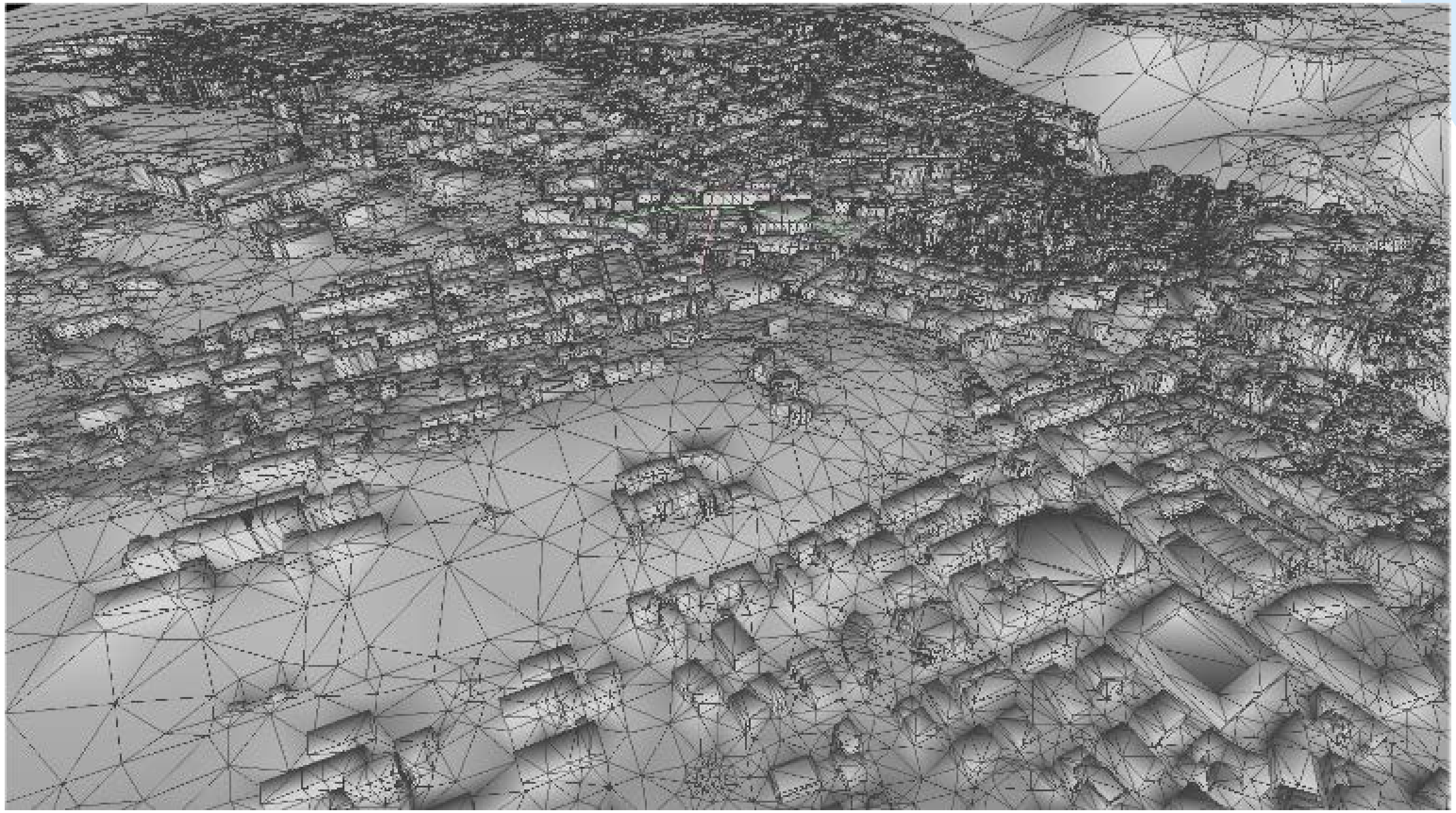
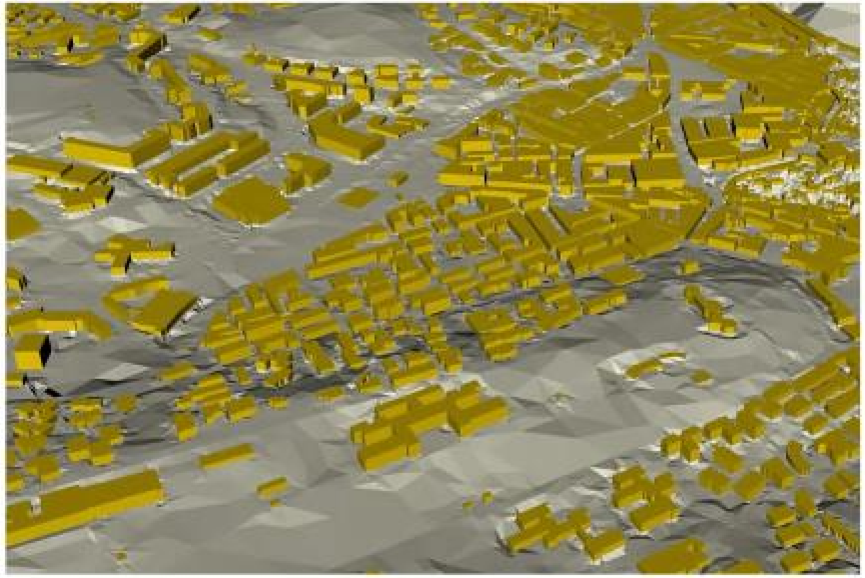




A. Scalas, D. Cabiddu, M. Mortara, M. Spagnuolo **Potential of the Geometric Layer in Urban Digital Twins.** *ISPRS Int. J. Geo-Inf.* **2022**, *11*(6), 343;
https://doi.org/10.3390/ijgi11060343

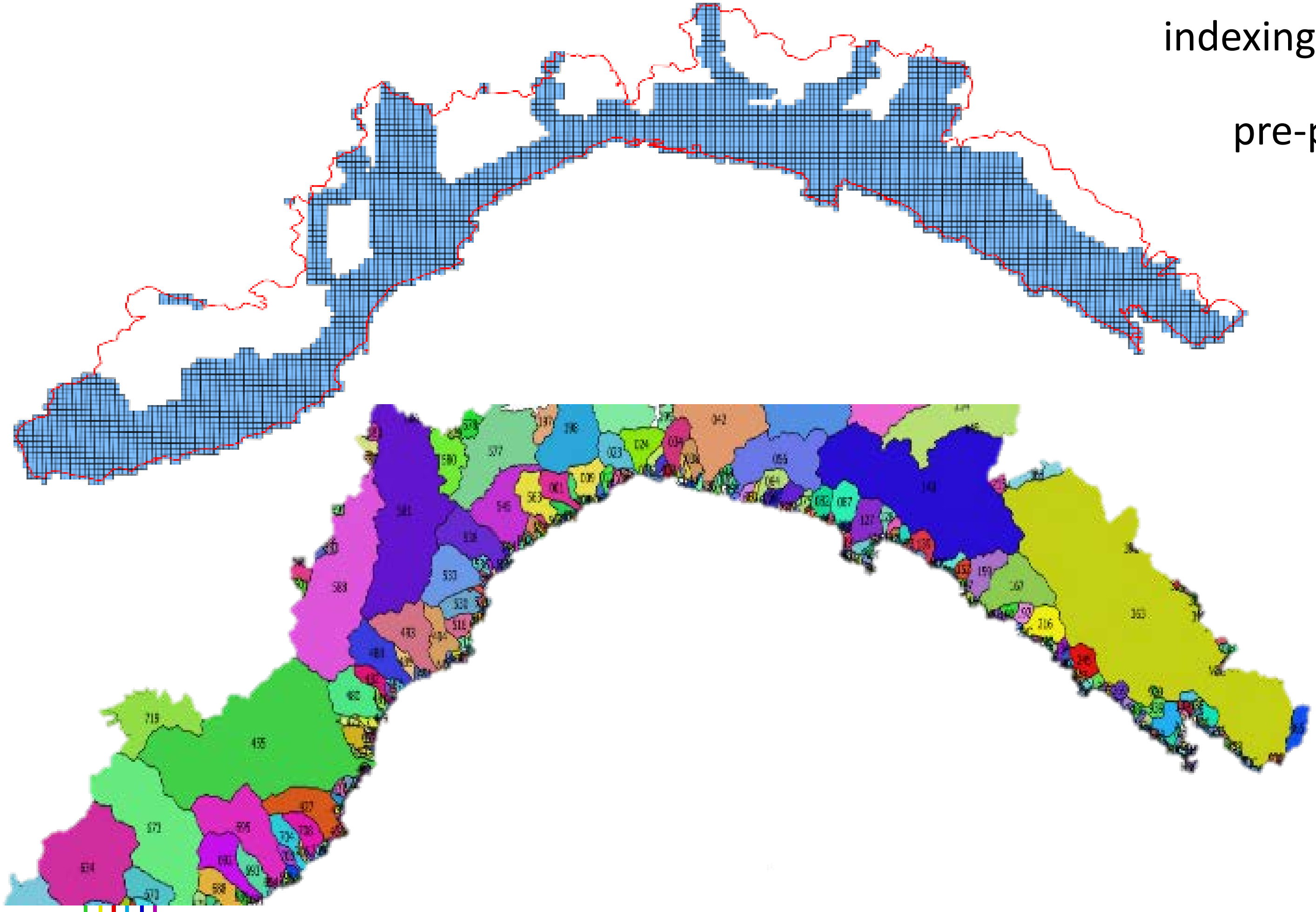
EFFICIENT MANAGEMENT OF LARGE LIDAR COLLECTIONS

handling large collections of large LiDAR data

- 48 folders, 925 files, average file size 0.85GB, 791 GB total size
- indexing based on geographical coverage and flight date

pre-processed and re-organized in regular tiles

- 1780 tiles, indexing based on ordering of the lower-left corner



high resolution data, but exploiting them is difficult

is there another way to store/index LAS so that can be accessed and processed more efficiently?

is the maximum resolution available always needed everywhere?

ACQUISITION – & THE CITY

(geometric data of the urban environment)

LASER SCANNING

- Active method
- terrestrial / aerial
- fixed / mobile
- Triangulation / time of flight
- precision, accuracy, resolution depending on the tool
- Point classification (LiDAR)
- Color?
- Expensive instrumentation
- Experts typically required

Which morphology? Which application requirements?

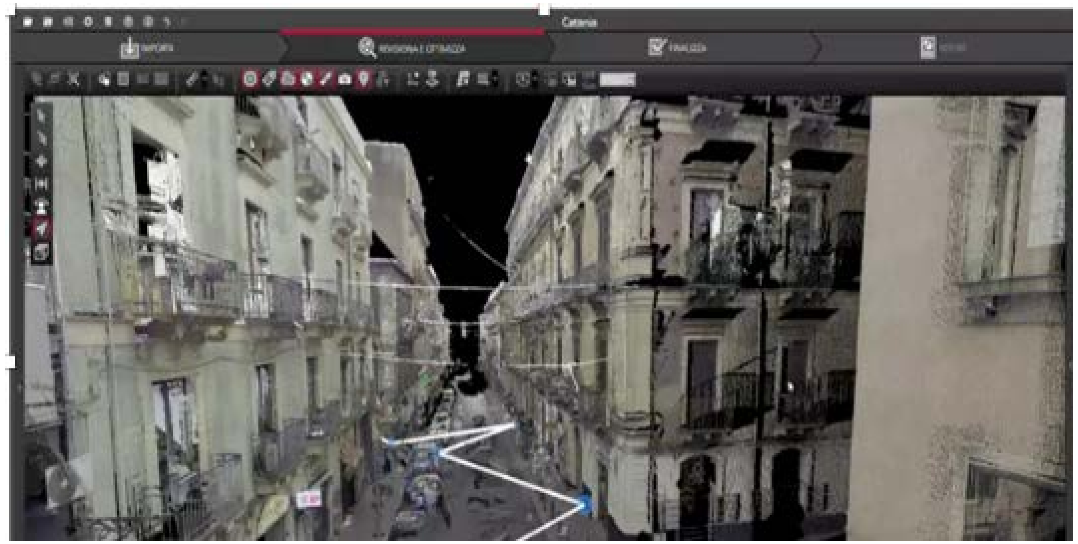
PHOTOGRAMMETRY

- Set of images
- Passive method
- terrestrial / aerial
- ~~fixed /~~ mobile
- No classification?
- Color
- Resolution depending on the camera, overall quality depending on external conditions (lighting, focus, depth-of-field, amount of photos, point-of-view
- Cheaper
- Some expertise required, nonetheless

CATANIA

- Aerophotogrammetry
- Terrestrial mobile acquisition
- Hi-res capturing of POIs

Case study area 2,5 Km²



courtesy of START4.0

ACQUISITION DEVICES

- Performant 3D acquisition technologies
  - Photogrammetry, aerial/terrestrial LiDAR, geo-radar,..
- START4.0 – MiSE Centre of Competence
  - Focus on safety and security of infrastructures
  - **Scan & Survey Laboratory** – Leica and Hexagon

Terrestrial mid range Laser Scanner
Leica RTC360

Leica Pegasus:Two Ultimate

START4.0

https://www.start4-0.it

Workstations and Software

portable handheld Laser
Leica BLK2Go

Terrestrial long range Laser Scanner
Leica RTC360

MATERA

- Optimization of paths under different constraints
  - Reduce/maximize fatigue
  - Accessibility – disabilities, limited abilities,..
- Virtual Visits of CH sites

- Highly heterogeneous shapes in the “Sassi” – *key area of the historical centre*
- Surface and sub-surface sites – *hypogeum*
- Highly valuable historical sites, potentially endangered by tourism and not accessible for all!

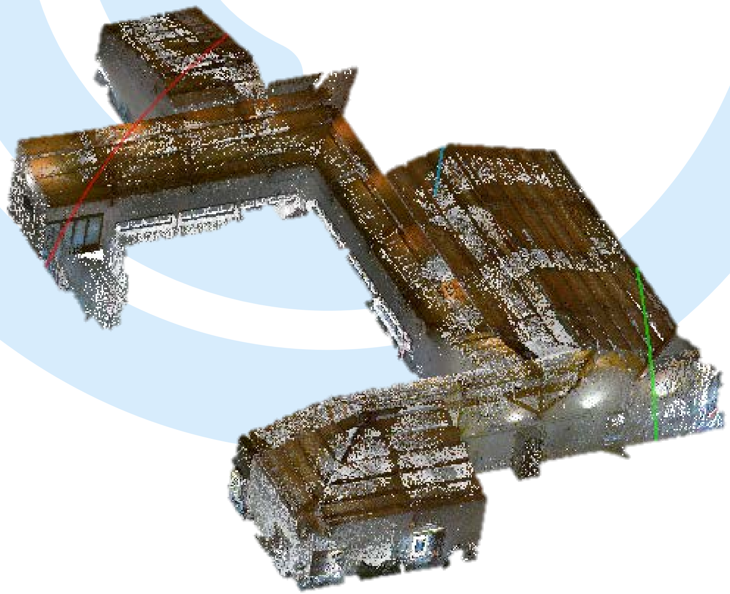
ACQUISITION AND RECONSTRUCTION OF POIS IN MATERA

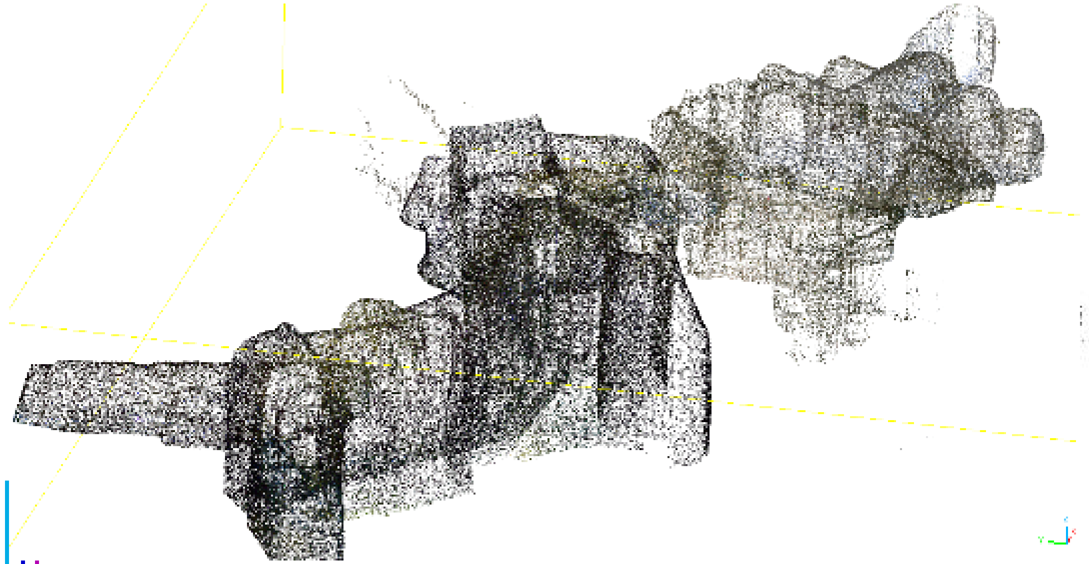
- Device: Leica BLK2GO
  - 420.000 points per second
  - field of view of 360° horizontal and 270° vertical
  - Precision range ± 3mm, global accuracy ± 10mm.
  - 3 cameras capture near-spherical photographs to get colour.

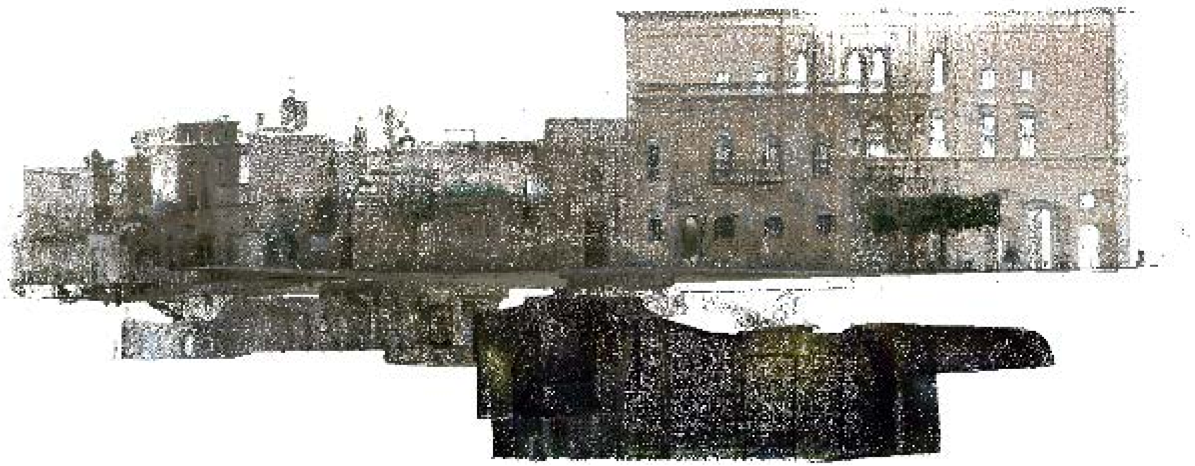
A. Scalas, D. Cabiddu , M. Mortara, S. Pittaluga and M. Spagnuolo
Mobile laser scanning of challenging urban sites: a case study in Matera
EUROGRAPHICS Workshop on Graphics and Cultural Heritage (2022) Short Papers

ACQUISITION AND RECONSTRUCTION OF POIS IN MATERA

- Piazza Vittorio Veneto
  - Palombaro Lungo (1)
  - Hypogeum (2)
- Vicinato Fondazione Sassi
- Vicinato Malve
- S. Rocco 4°th floor

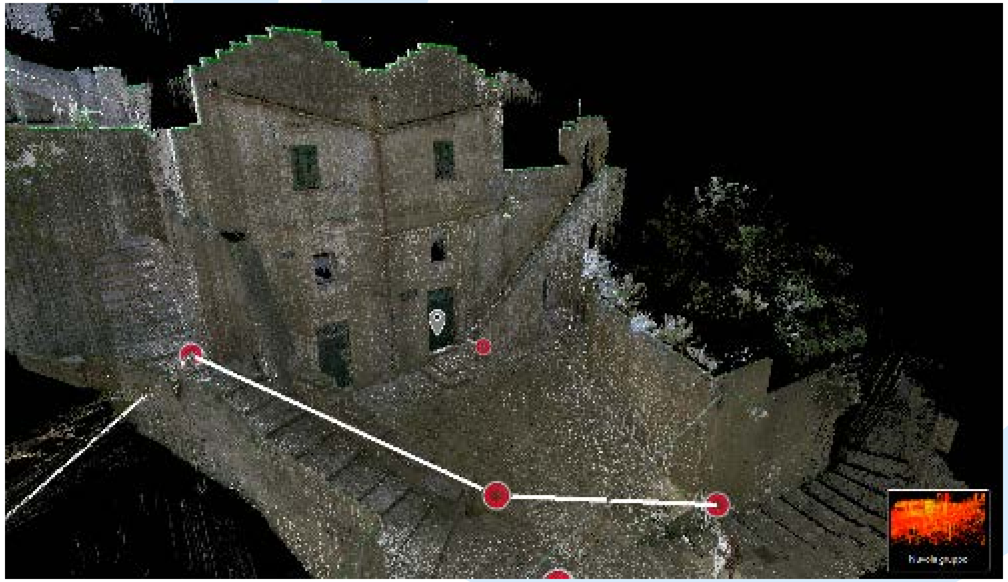


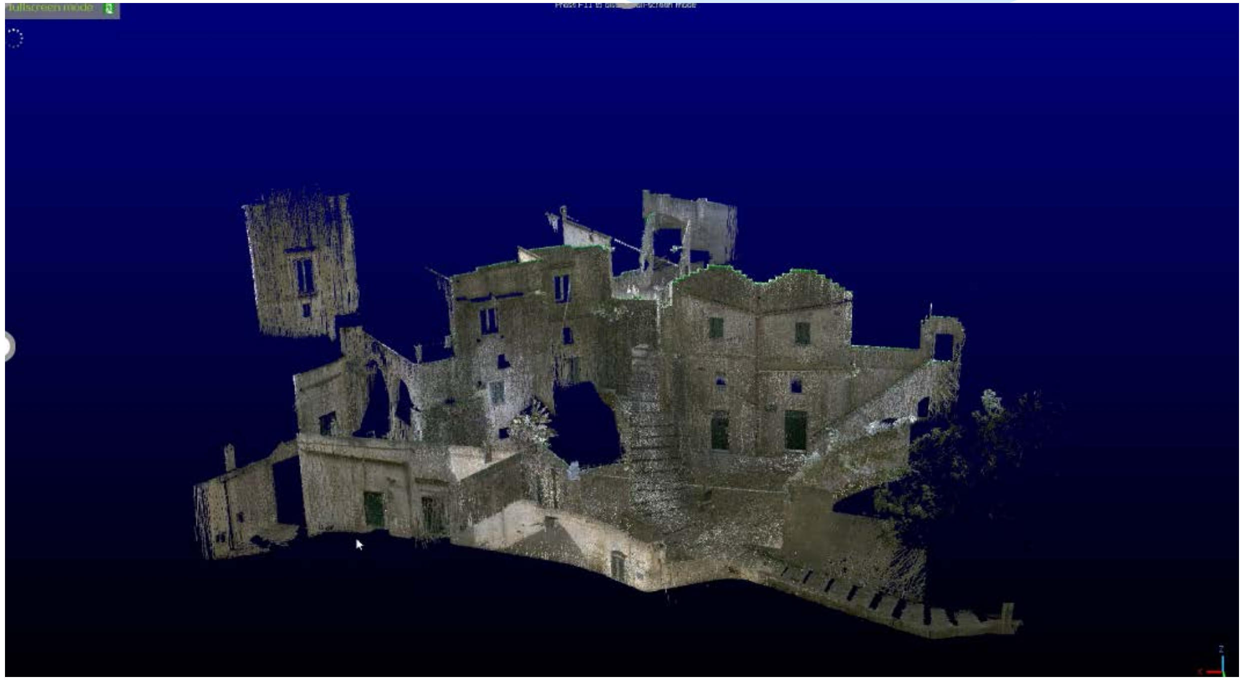




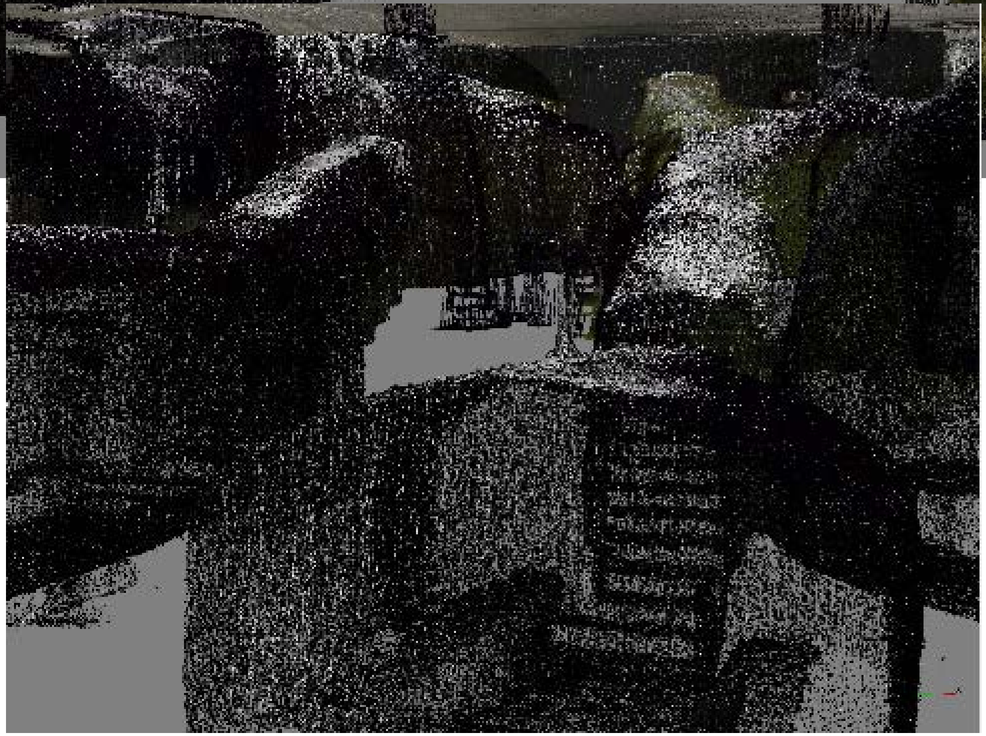
ACQUISITION WITH BLK2GO

- Plan several «walks»
- Significant overlap
- Passer-by create «traces»
- Post-processing:
- Cleaning (remove traces, outliers)
- Alignment (semi-automatic)
  -> a single, HUGE point cloud
- Simplification





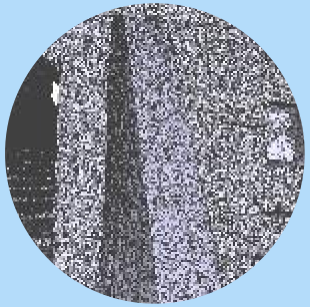
HYPOGEUM (2)



ACQUISITION&RECONSTRUCTION PIPELINE

ACQUISITION

Collect the data about the morphology of the urban environment

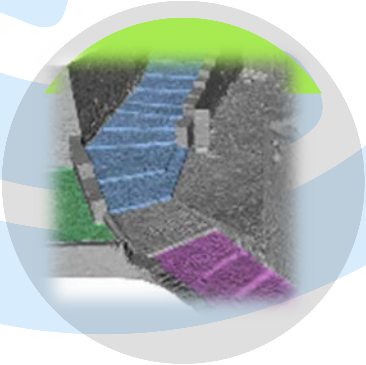


RECONSTRUCTION

Generate one (or more) meshes (or other reps) of a good quality for the application/s

ANALYSIS

Apply geometric processing algorithms to the model to extract new knowledge, implicitly encoded in the geometry

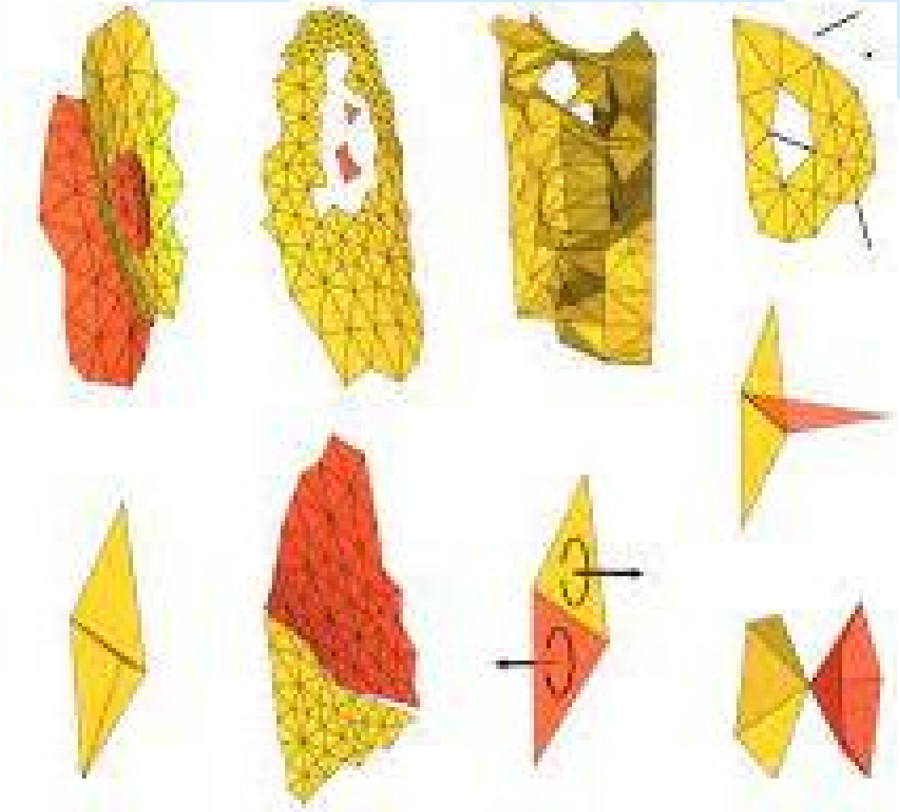


ANNOTATION

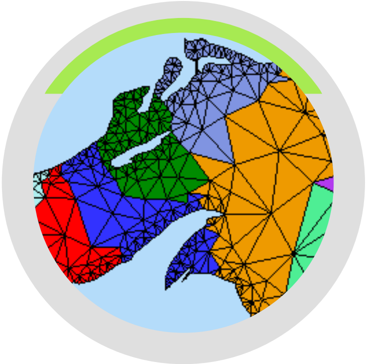
Add contextual knowledge explicitly to (portions of) geometry, so that it can be automatically processed

BUILD A MESH FROM A POINT CLOUD

- Plenty of methods to construct a mesh from a given set of points.
- Things are more complicated in 3D and many geometric and topological errors may occurr. However, there are more and more robust algorithms for reconstruction, fixing, denoising, fairing, remeshing ….



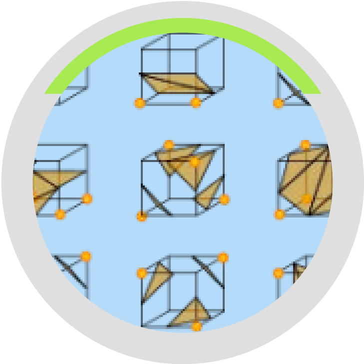
ONE OF THE MAJOR ISSUES IN GM! (INTERSECTING TWO LINES)



TRIANGLE

Schewchuk, 2003

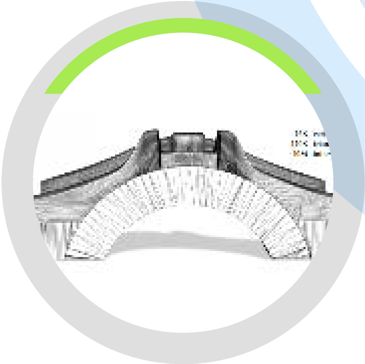
https://www.cs.cmu.edu/~quake/triangle.html



MARCHING CUBES

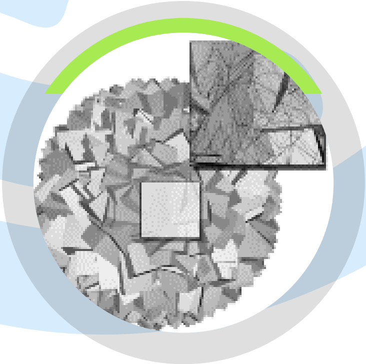
Lorensen and Cline, 1987

https://graphics.stanford.edu/~mdfisher/MarchingCubes.html



MESH ARRANGEMENT

Cherchi et al.,2020



POLIHEDRAL MESHING

Attene e Diazzi, 2022

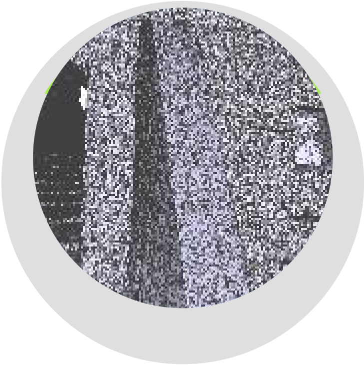
RECONSTRUCTION

- Academic products: Remesh (IMATI), MeshLab (ISTI), Triangle (Schewchuk), …
- Commercial products: Metashape (marching cubes), …
- Issues:
  - Model size
  - Geometric / topological errors, outliers, holes, many shells …
  - Thin surface with boundary
  - Visualization ok, but further processing might CRASH!
  - LOT of manual work for each specific case
- In these examples:
  - Agisoft Metashape for reconstruction
  - MeshFix (CNR-IMATI, Marco Attene) for fixing errors and add thickness
  - MeshLab (CNR-ISTI) for visualization and format conversion (and further simplification if needed)

ACQUISITION&RECONSTRUCTION PIPELINE

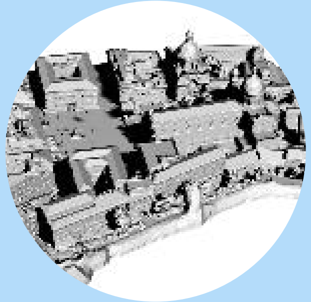
ACQUISITION

Collect the data about the morphology of the urban environment



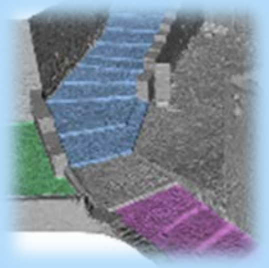
RECONSTRUCTION

Generate one (or more) meshes (or other reps) of a good quality for the application/s



ANALYSIS

Apply geometric processing algorithms to the model to extract new knowledge, implicitly encoded in the geometry

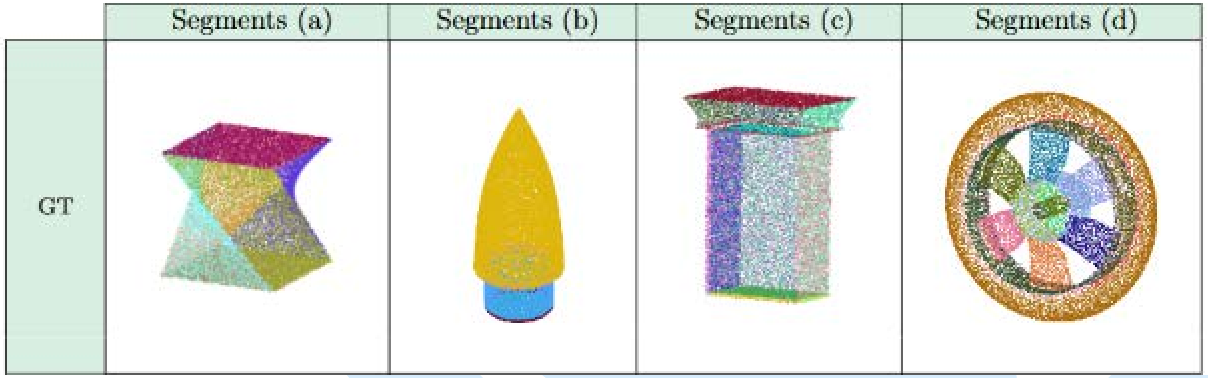


ANNOTATION

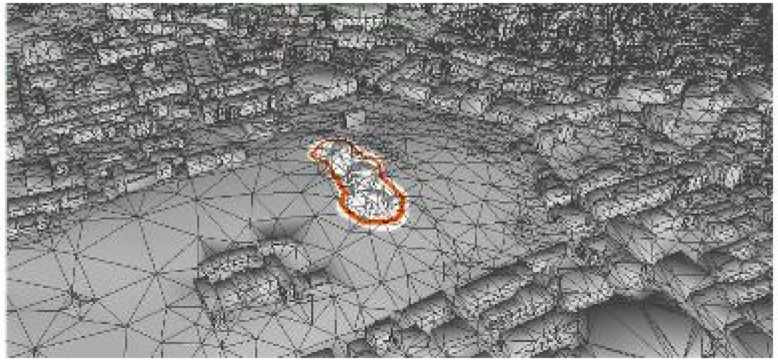
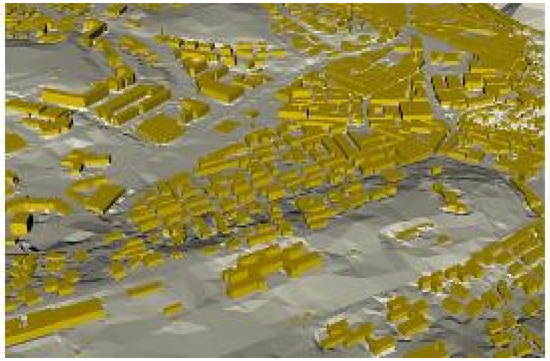
Add contextual knowledge explicitly to (portions of) geometry, so that it can be automatically processed

ANNOTATION / ANALYSIS

- Triangles are indifferentiated
- Which are Buildings? Streets? Parks? Windows? …
  - Manual / automatic **annotation**
    - **part of geometry**
    - **information to add**

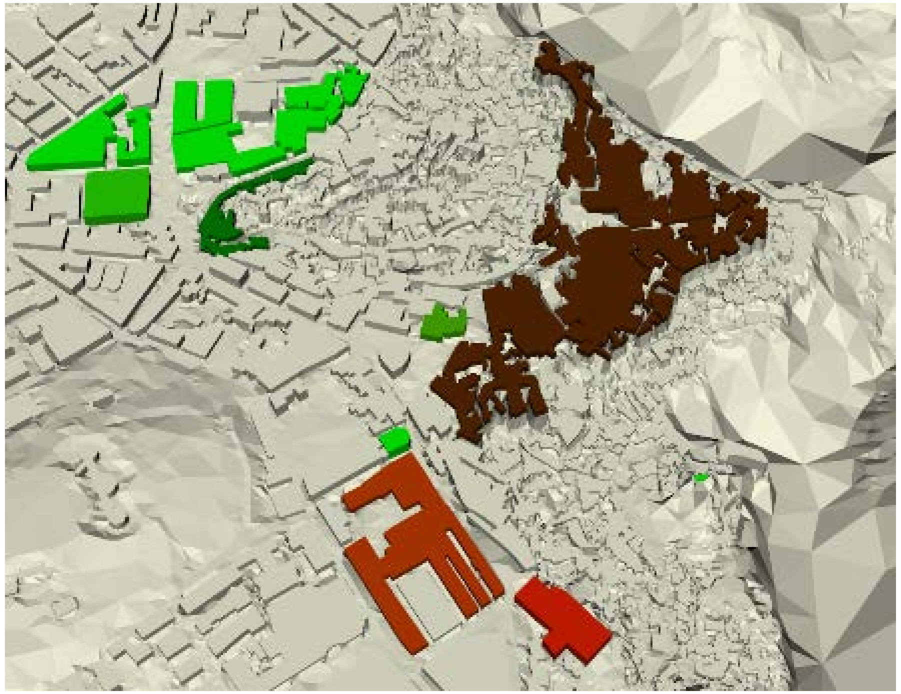


Romanengo C., Raffo A., Biasotti S., Falcidieno B.
[Recognizing geometric primitives in 3D point clouds of mechanical CAD objects]
Computer Aided Design 157 pp.tot 16

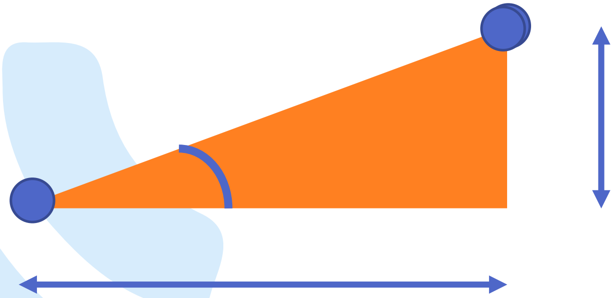

ANNOTATION / **ANALYSIS**

- Elements need characterization
  - What is the area of this window? How high is this step? How steep is this street? Will my path to the museum be in shadow tomorrow morning? How many people are now at the museum? Can my dog enter?

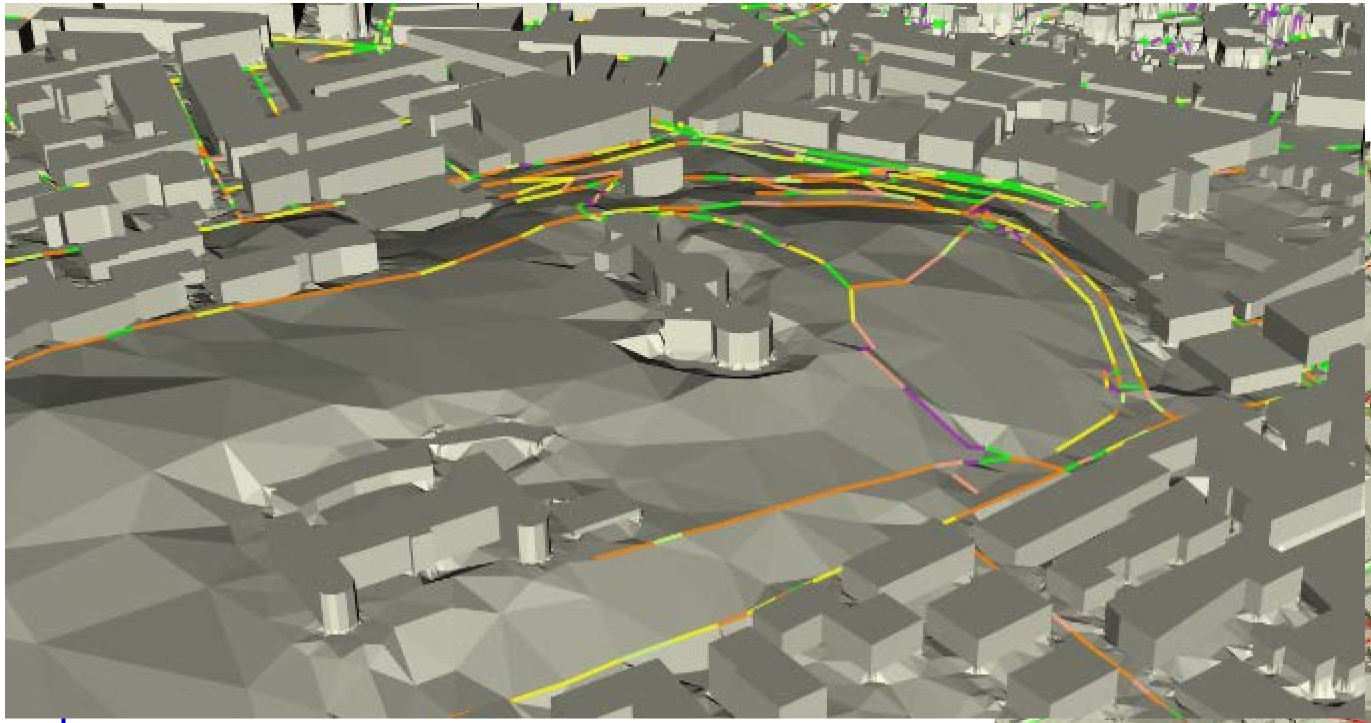


Prediction of POIs occupation by CNR-INM

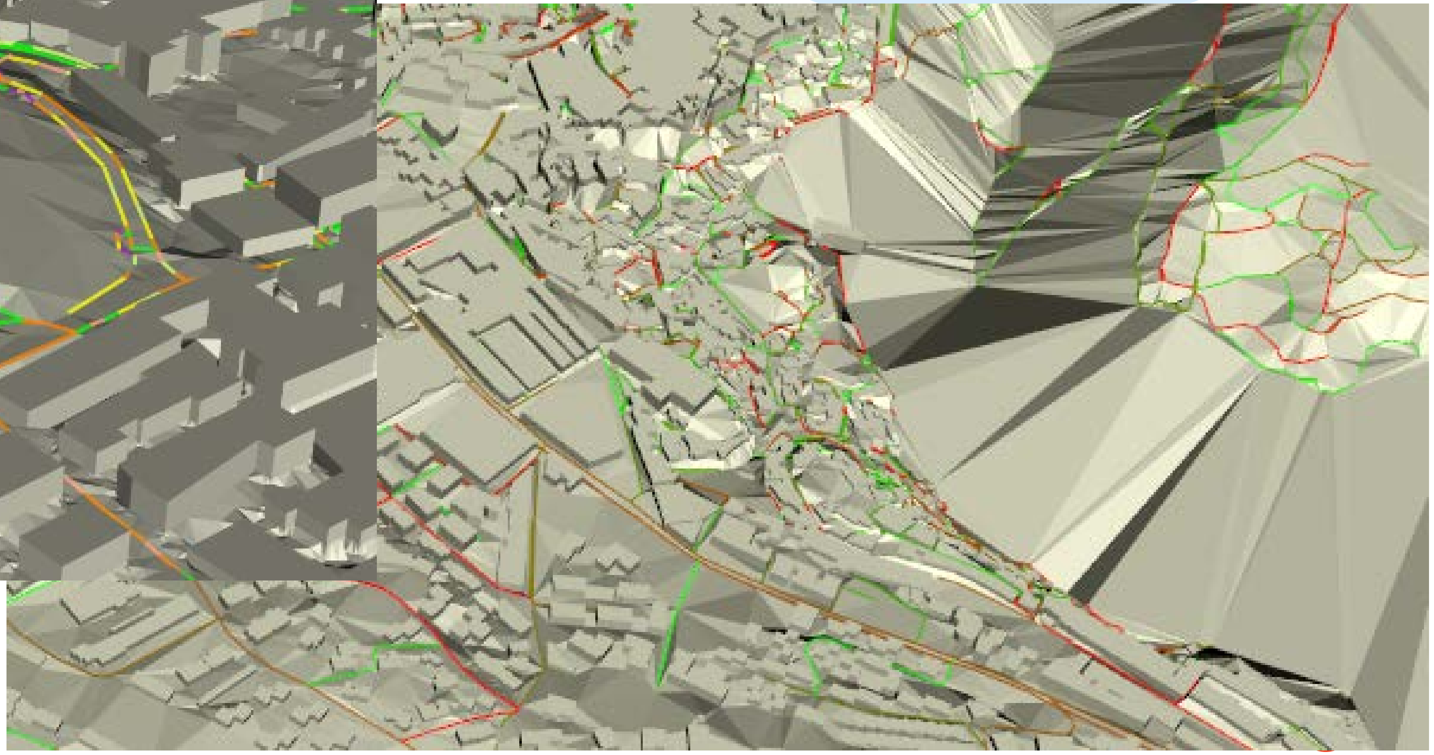
ANALYSIS



- Extract «geometric knowledge» that is implicit in the 3D model

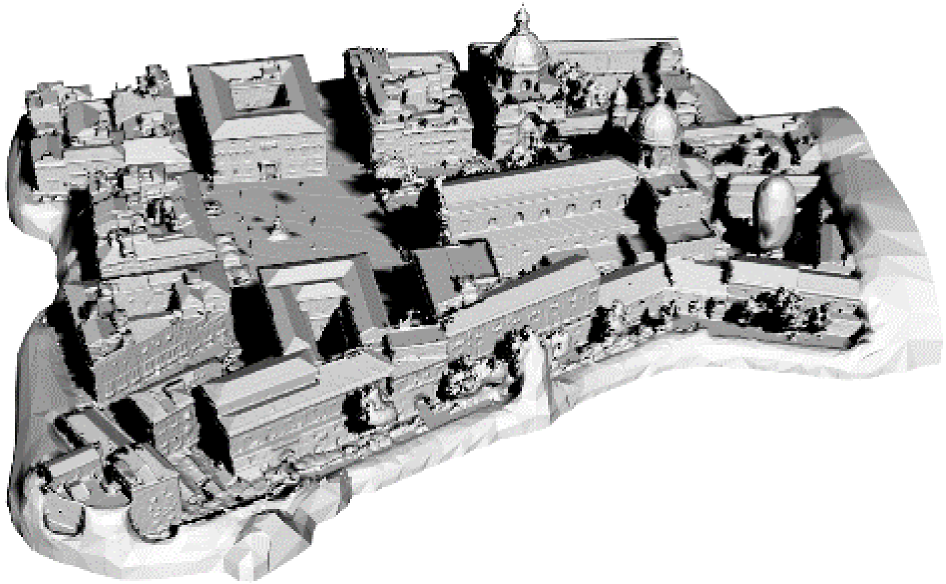


steepness



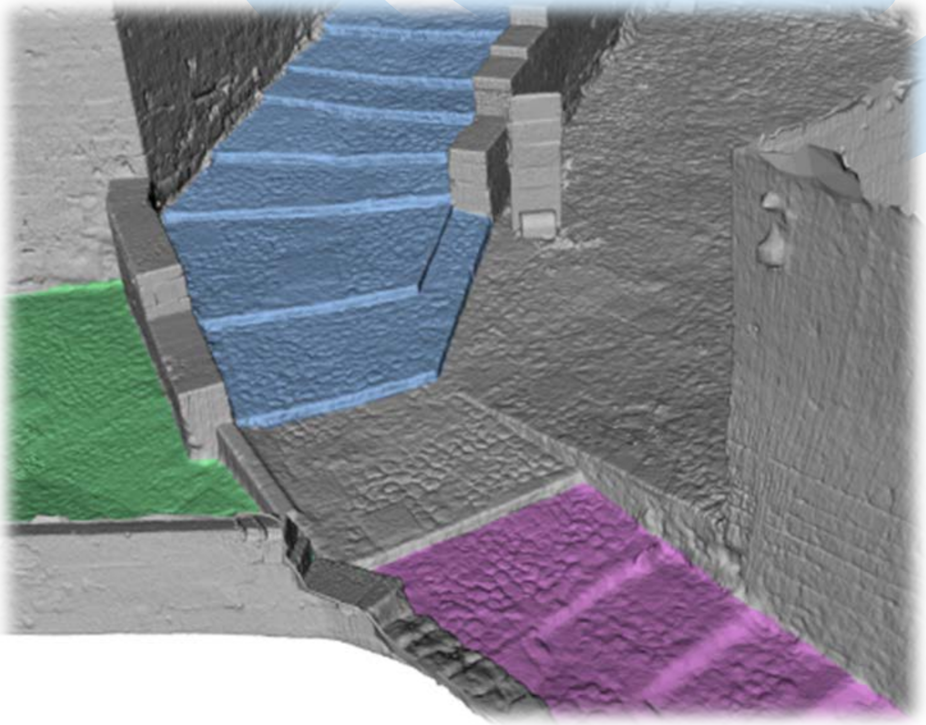
ANALYSIS

Shadow/light



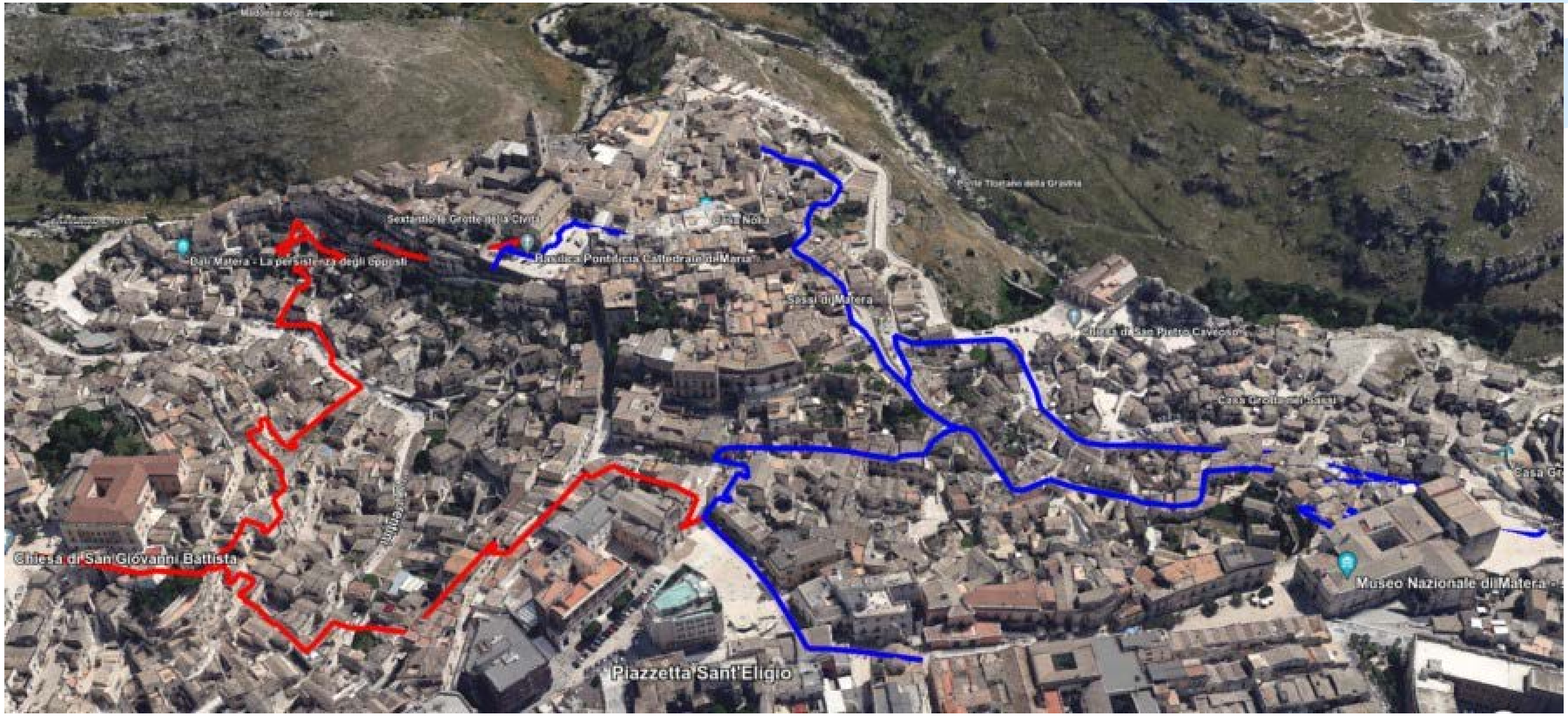
ACCESSIBILITY

- The proposed challenge



APPLICATION EXAMPLE: BEST TOUR

- Optimize path wrt interest / lenght / slope / comfort (sun/shadow) – CNR-IASI



CHALLENGES AND PERSPECTIVES

CHALLENGES

- Link geometric, “as-is” representations with designed, semantic representation
  - Automatic feature recognition - and change detection!
  - Documentation using standards (CityGML)
- Different processes may require different representations of the same physical object
  - Geometric Model = (Shape, Context, Usage)
- Ensure persistence of semantic annotation across different representations of the same object
  - Mapping across geometric models
- Efficient management of big ”geospatial” data

More geometric reps

- Different processes may require different representations of the same physical object
  - Geometric Model = (Shape, Context, Usage)

Path optimization to reduce/maximize fatigue, or tailor to accessibility level requires detailed geometric models

- Stairs, stair height and size, bumps..
- Shadow mapping – *very high temperature in summer*

…but…

for remote VR visits a much coarser geometric model would suffice

More geometric reps

- Different processes may require different representations of the same physical object
  - Geometric Model = (Shape, Context, Usage)

Monitoring the evolution of the shape for early detection of degradation requires detailed geometric/appearance models

…but…

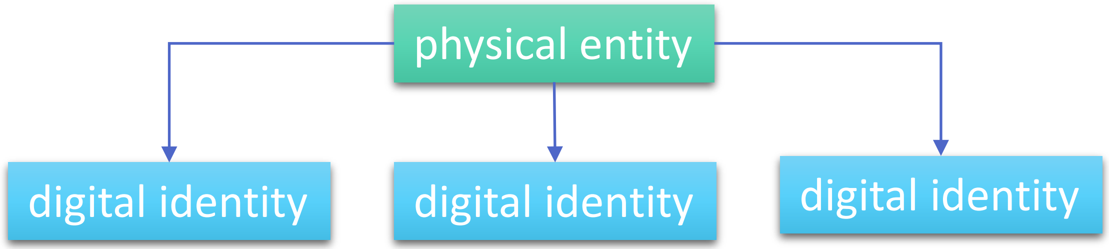
for remote VR visits a much coarser geometric model would suffice

More geometric reps

- Different processes may require different representations of the same physical object
  - Geometric Model = (Shape, Context, Usage)

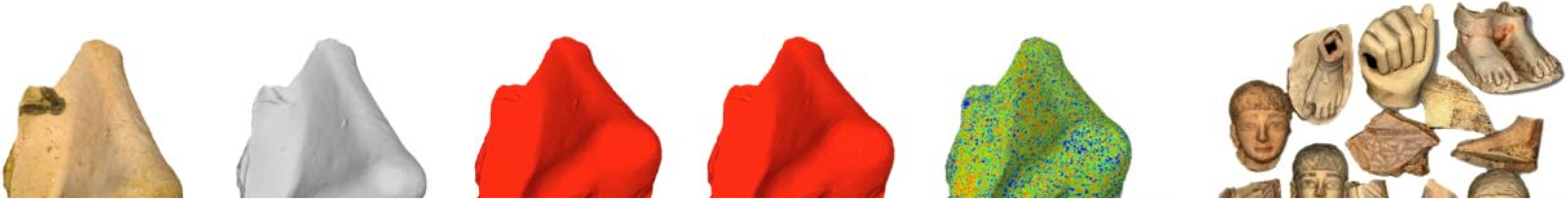
…but…

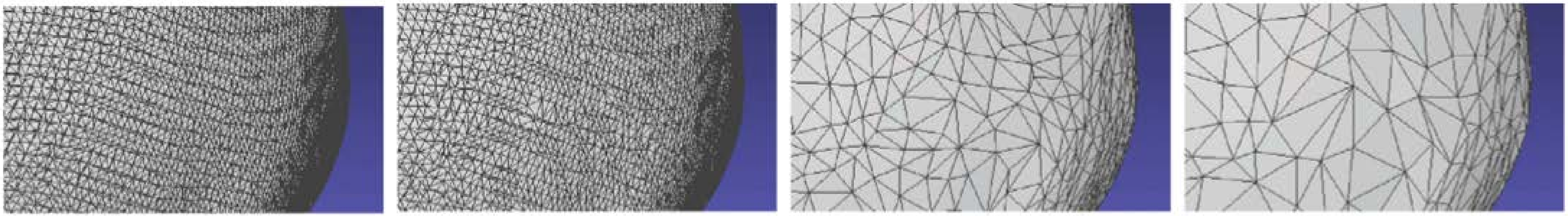
monitoring the structural condition of sub-surface construction requires FEM-oriented representations of the same physical entity

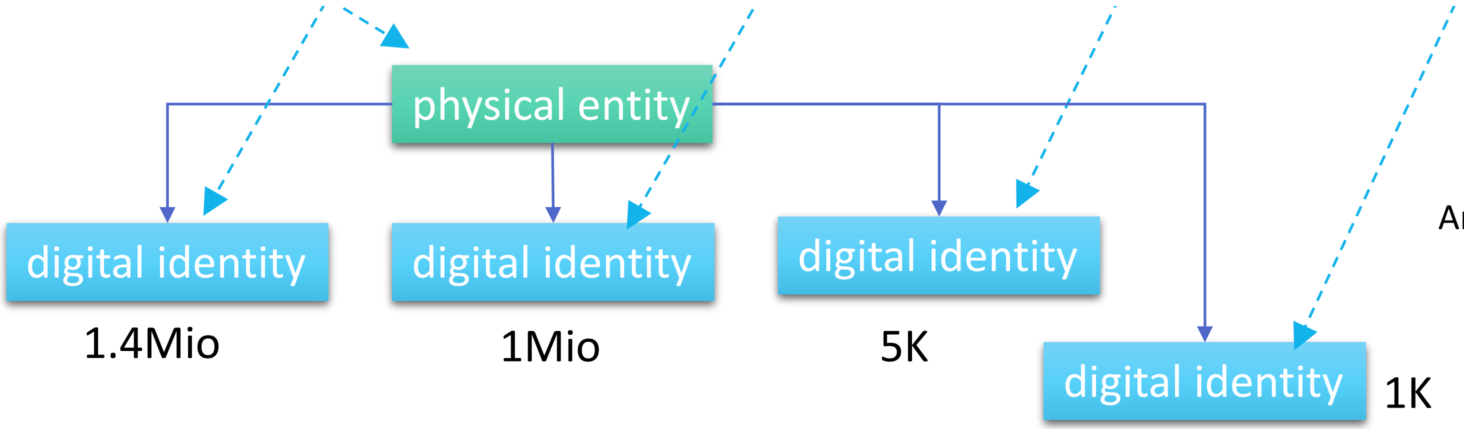


Annotation persistence - resolution

- An example in a slightly different domain – *Cultural Heritage*



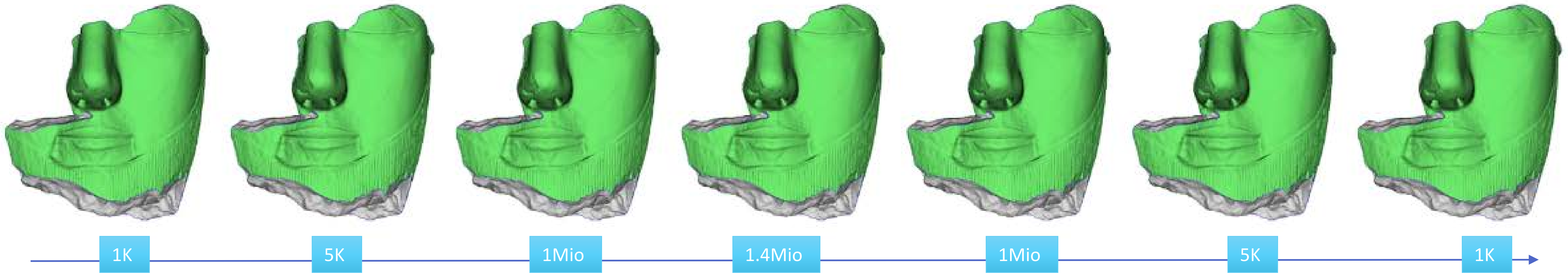




Andreas Scalas, Michela Mortara, Michela Spagnuolo. A pipeline for the preparation of artefacts that provides annotations persistence. Journal of Cultural Heritage, Vol. 41, 2020

Annotation persistence – *annotation transfer*

- An example in a slightly different domain – *Cultural Heritage*



automatic 3D annotation transfer across resolutions

physical entity

digital identity
1.4Mio

digital identity
1Mio

digital identity
5K

digital identity
1K

Andreas Scalas, Michela Mortara, Michela Spagnuolo. A pipeline for the preparation of artefacts that provides annotations persistence. Journal of Cultural Heritage, Vol. 41, 2020

Efficient management of big geospatial data

- Access to raw data by Semantic Level-of-Detail

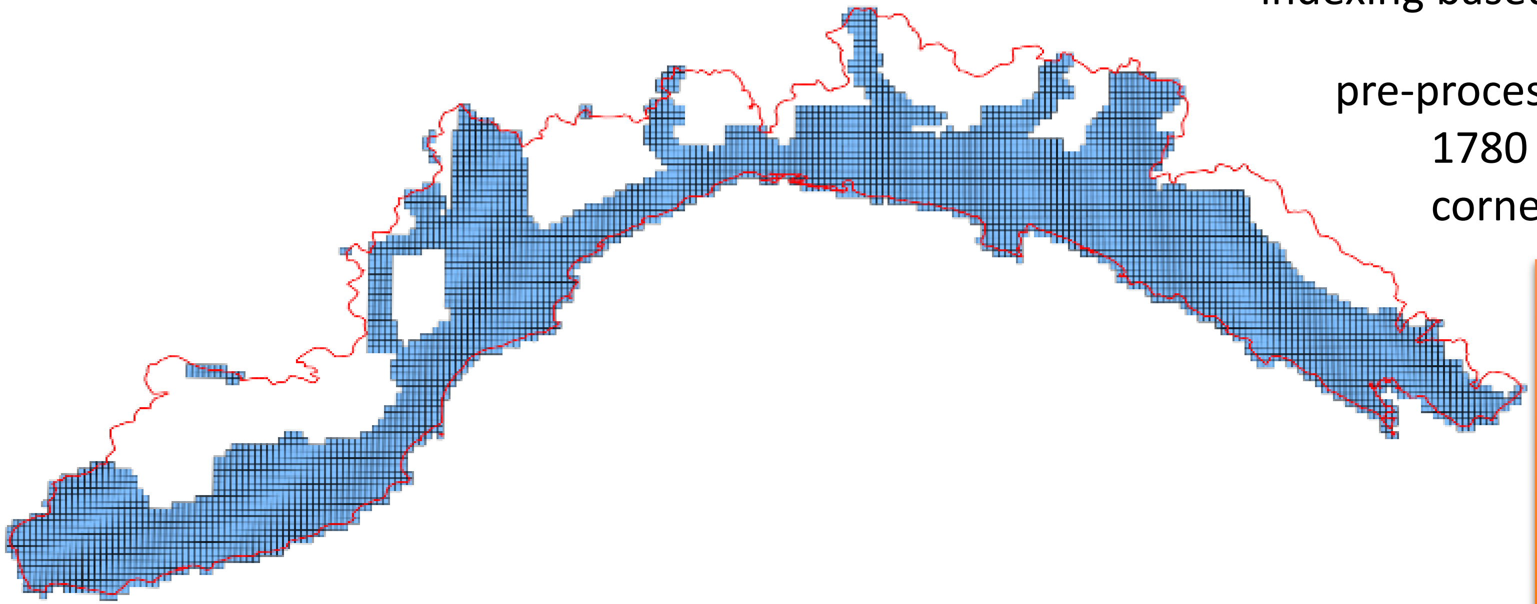
handling large collections of large LiDAR data

48 folders, 925 files, average file size 0.85GB, 791 GB total size

indexing based on geographical coverage and flight date

pre-processed and re-organized in regular tiles

1780 tiles, indexing based on ordering of the lower-left corner



LiDAR data coverage of the Liguria region, Italy

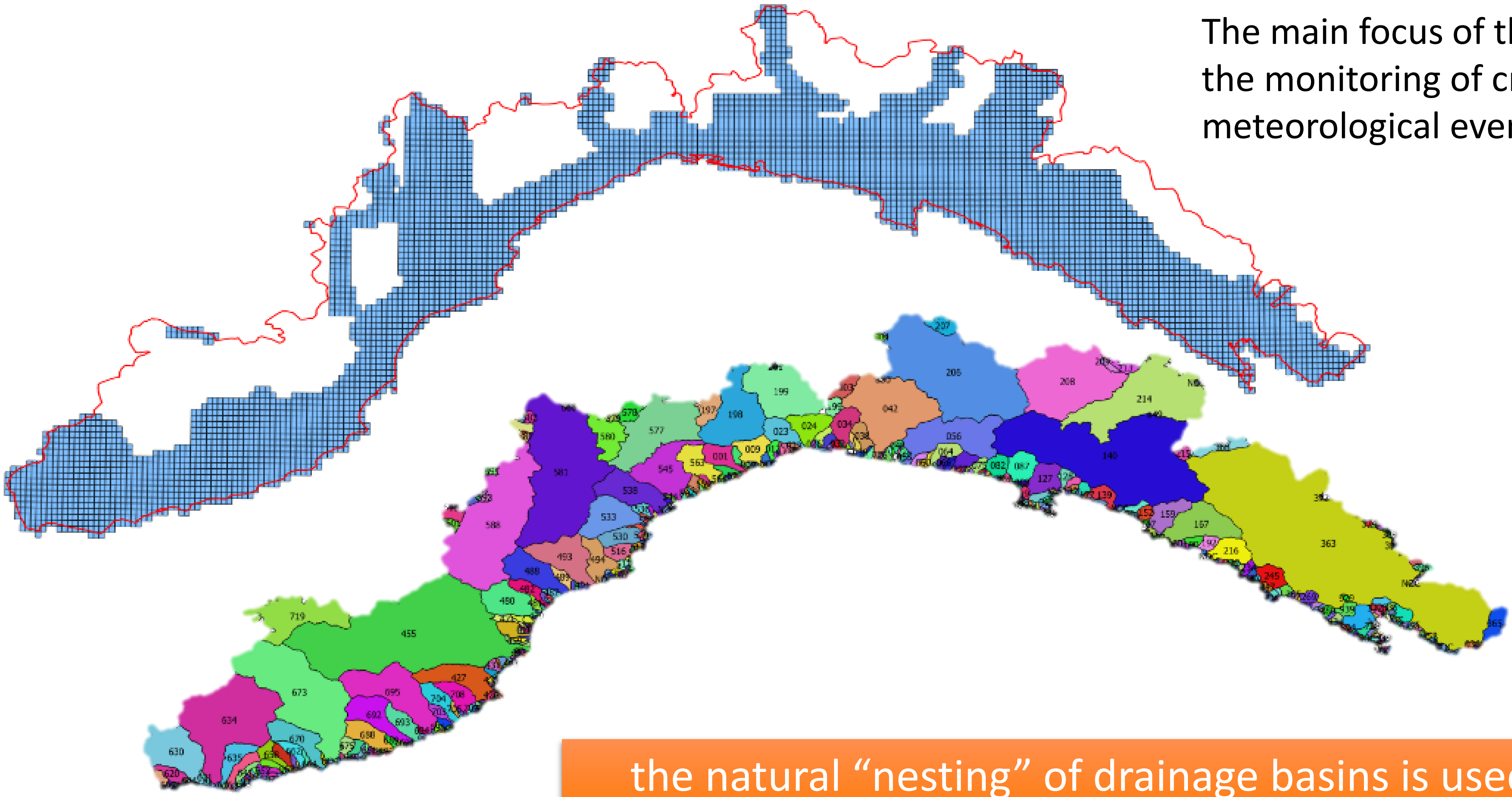
high resolution data, but exploiting them is difficult

is there another way to store/index LAS so that can be accessed and processed more efficiently?

is the maximum resolution available always needed everywhere?

IQmulus

LOD-based indexing of raw data for model extraction



The main focus of the project was on the monitoring of critical hydro-meteorological event - *flooding risks*

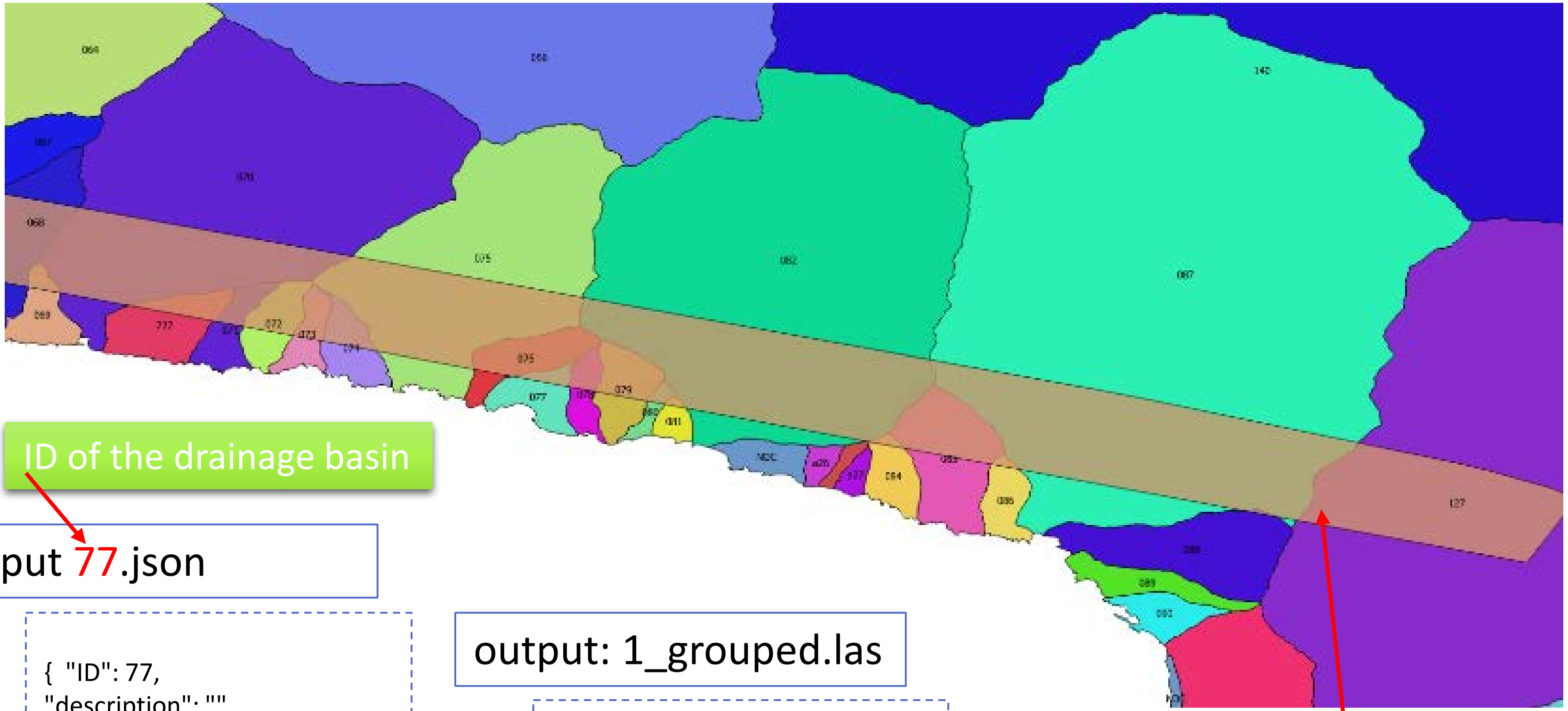
the natural “nesting” of drainage basins is used to re-order, index and eventually partition the original LAS files

IQmulus

Efficient management of big geospatial data

1.las

6.3421764 2.548937 6.5348957
6.5238579 2.534895 8.5375691
3.9654897 5.342847 9.4214729
6.5238579 2.534895 8.5375691
7.3421764 2.548937 6.5348957
6.5238579 2.534895 8.5375691
6.3421764 2.548937 6.5348957
6.5238579 2.534895 8.5375691
.....
....
7.3421764 2.548937 6.5348957
6.5238579 2.534895 8.5375691
....
6.3421764 2.548937 6.5348957
3.5984357 6.57847 8.5183784
6.3421764 2.548937 6.5348957
6.3421764 2.548937 6.5348957
6.5238579 2.534895 8.5375691
3.9654897 5.342847 9.4214729
6.5238579 2.534895 8.5375691
7.3421764 2.548937 6.5348957
6.5238579 2.534895 8.5375691
6.3421764 2.548937



ID of the drainage basin

output 77.json

```
{ "ID": 77,
"description": "",
"las_blocks": [
  {
   "file": "1_grouped.las",
   "start_record": 0,
   "num_records": 226325
  },
  {
   "file": ....
    .
    .
```

output: 1_grouped.las

0

3.9654897 5.3428473 9.4214729
5.3746372 8.3217643 4.5847395
.
.
6.3421764 2.548937 6.5348957
6.5238579 2.534895 8.5375691
3.5984357 6.57847 8.5183784

226325

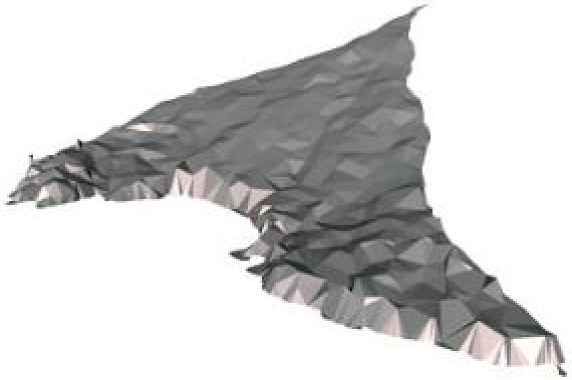
.
.
.

LiDAR «strip»

First step
indexing by drainage basin

IQmulus

Efficient management of big geospatial data



3.9654897 5.3428473 9.4214729
5.3746372 8.3217643 4.5847395
.
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6.3421764 2.548937 6.5348957
6.5238579 2.534895 8.5375691
3.5984357 6.57847 8.5183784
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226325

0

6.5238579 2.534895 8.5375691
4.6584967 3.384675 2.5348574
.
.
6.3421764 2.548937 6.5348957
5.3746372 8.3217643 4.584739
.
3.5984357 6.57847 8.5183784
3.9654897 5.3428473 9.421472
.
7.4325459 6.423462 3.34534548
.
.

34

104512

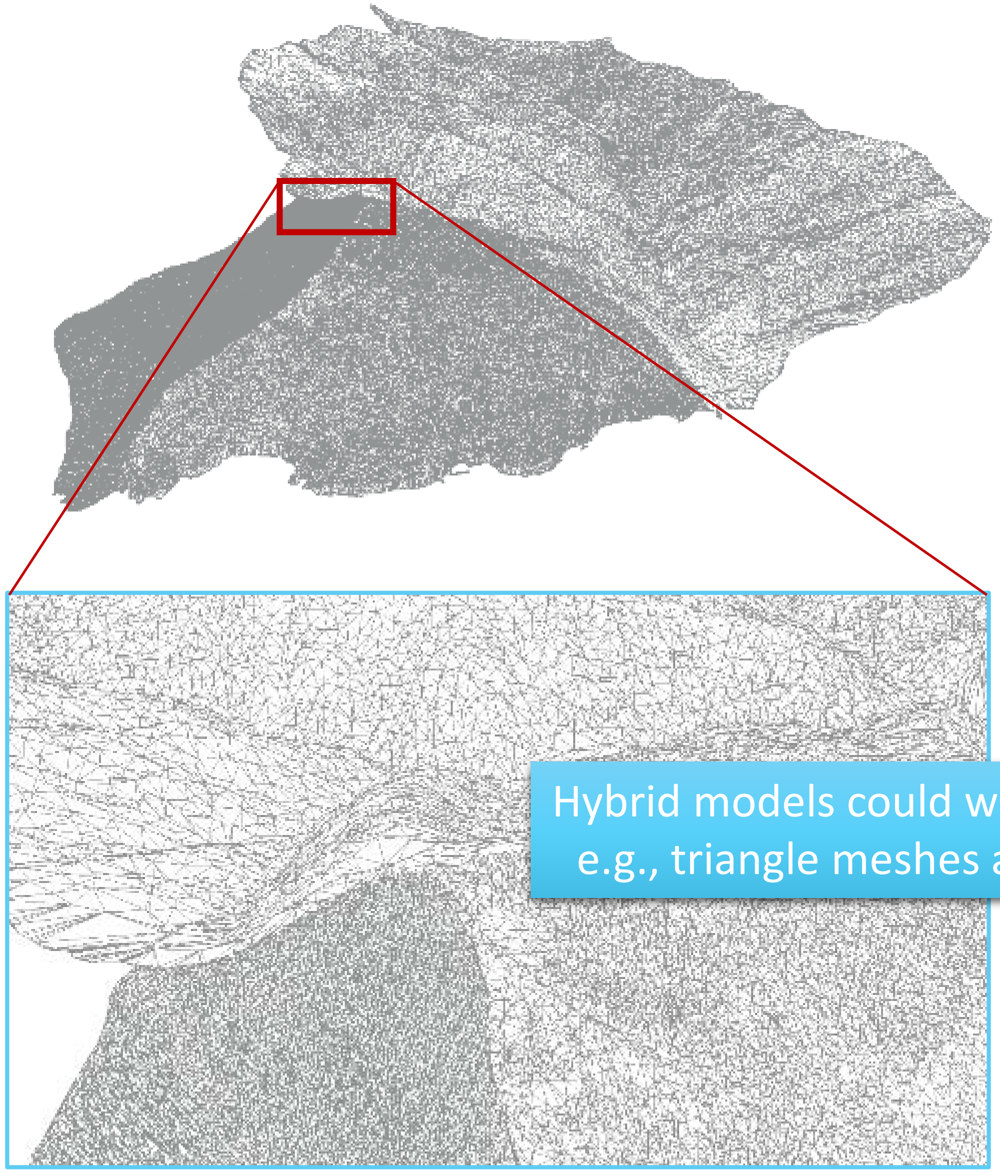
226325

second step
ordering LiDAR blocks by LOD

IQmulus

Efficient management of big geospatial data

- Basin #82 at low res (LOD 1)
- Basins #77-81 at mid res (LOD 5)
- Basin #76 at high res (LOD 10)



Hybrid models could work even better
e.g., triangle meshes and LR-Splines

URBAN DIGITAL TWIN

- Be careful to «technological utopia»
  - Data vs Information vs Intelligence
  - “Digital realities” should be always associated to a degree of confidence
  - Visualization should be effective and truly informative – AR/VR/XR
  - Documentation of assets and processes

- Models of Urban Realities should be tailored to the characteristics and needs of the urban spaces, territory and citizens
  - “Dynamic” change of scale for urban digital models – *3D Model-as-a-service*
  - Interoperability and suitability to interact with numerical models of phenomena and decision-making services

Thanks to the whole Shape Modelling Group@CNR-IMATI, and in particular:
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Marco Attene, Chiara Romanengo,
Silvia Biasotti, Bianca Falcidieno.

Projects:
DIITET Urban Intelligence
CTE Matera
UISH Pon Metro Catania

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imati

Ministero delle Imprese e del Made in Italy

FSC Fondo per lo Sviluppo e la Coesione

Politecnico di Bari