Gmsh

C. Geuzaine and J.-F. Remacle

Université de Liège and Université catholique de Louvain

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Some background

- I am a professor at the University of Liège in Belgium, where I lead a team of about 15 people in the Montefiore Institute (EECS Dept.), at the intersection of applied math, scientific computing and engineering physics
- Our research interests include modeling, analysis, algorithm development, and simulation for problems arising in various areas of engineering and science
- Current applications: low- and high-frequency electromagnetics, geophysics, biomedical problems
- We write quite a lot of codes, some released as open source software: https://gmsh.info, https://getdp.info, https://onelab.info

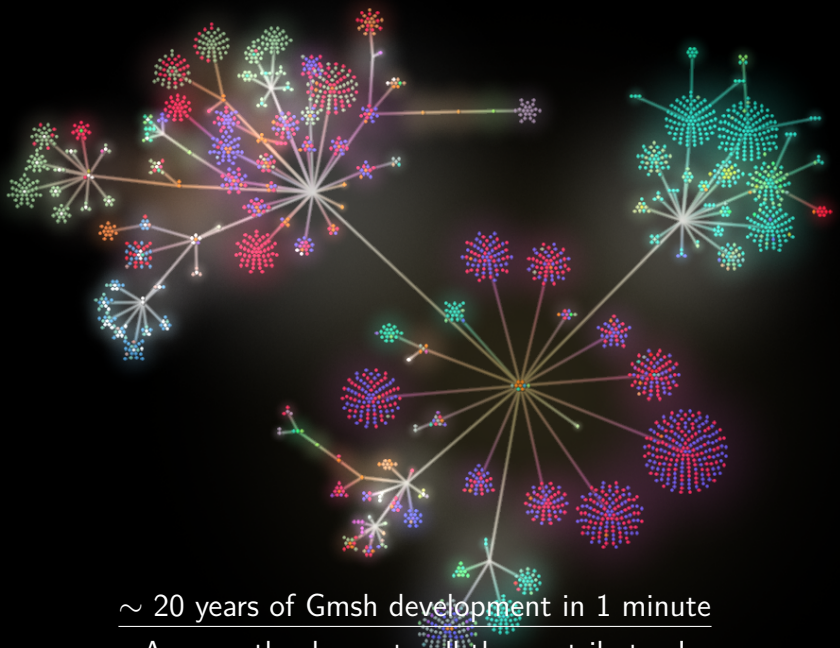
UCLouvain

Some background

- I am a professor at the Université catholique de Louvain in Belgium, where I lead a team of a dozen researchers in the Institute of Mechanics, Materials and Civil Engineering
- We work mainly on mesh generation and high-order methods for PDEs
- Our current main research topic is hex meshing, both unstructured and structured
- I have been co-operating with Christophe for more than 20 years, a fruitful collaboration that has led to the creation of Gmsh

What is Gmsh?

- Gmsh (https://gmsh.info) is an open source 3D finite element mesh generator with a built-in CAD engine and post-processor
- Includes a graphical user interface (GUI) and can drive any simulation code through ONELAB
- Today, Gmsh represents about 400k lines of C++ code
  - still same 2 core developers; about 100 with ≥ 1 commit
  - about 1,200 registered users on the development site https://gitlab.onelab.info
  - about 15,000 downloads per month (70% Windows)
  - about 700 citations per year – the Gmsh paper is cited about 5,000 times
  - Gmsh has probably become one of the most popular (open source) finite element mesh generators?



$\sim$ 20 years of Gmsh development in 1 minute

A warm thank you to all the contributors!

A little bit of history

- Gmsh was started in 1996, as a side project
- 1998: First public release
- 2003: Open Sourced under GNU GPL
- 2006: OpenCASCADE integration (Gmsh 2)
- 2009: IJNME paper and switch to CMake
- 2012: Curvilinear meshing and quad meshing
- 2013: Homology and ONELAB solver interface
- 2015: Multi-Threaded 1D and 2D meshing (coarse-grained)
- 2017: Boolean operations and switch to Git (Gmsh 3)
- 2018: C++, C, Python and Julia API (Gmsh 4)
- 2019: Multi-Threaded 3D meshing (fine-grained), robust STL remeshing
- 2021: GmshFEM, Quasi-structured quad meshing

Strategic choices

- Design goals: fast, light and user-friendly
  - Written in simple C++
  - GUIs: FLTK (desktop), UIKit (iOS), Android
  - OpenGL graphics
  - Highly portable (OSes & compilers)
  - Easy to distribute & install: zero dependencies on installation
- Handling of numerous third party libraries
  - Build system based on CMake – everything is optional
  - Some libs integrated and redistributed directly in gmsh/contrib (HXT, BAMG, Metis, Concorde, ...)
- Funding
  - Hobby until 2006, then industry, Wallonia, Belgium & EU

Strategic choices

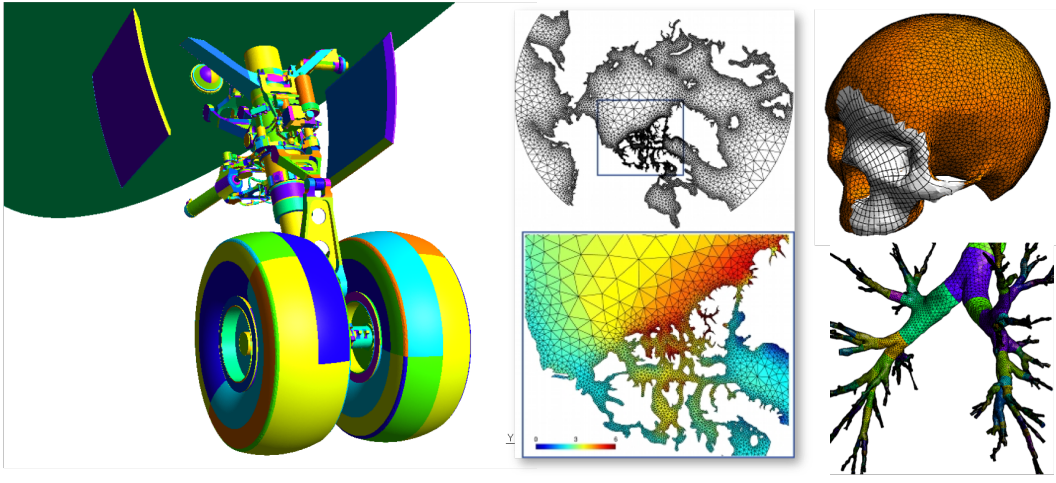
- Community infrastructure
  - Our own (using GitLab) to enable public/private parts (https://gitlab.onelab.info/gmsh/gmsh)
  - Continuous integration and delivery (CI/CD) of Gmsh app and Gmsh SDK on Windows, Linux and macOS
  - Web site (https://gmsh.info) with documentation, tutorials, etc.
  - Scientific aspects of algorithms detailed in journal papers
- Licensing
  - Gmsh is distributed under the GNU General Public License v2 or later, with exceptions to allow for easier linking with external libraries
  - We double-license to enable embedding in commercial codes

Basic concepts

- Gmsh is based around four modules: Geometry, Mesh, Solver and Post-processing
- Gmsh can be used at 3 levels
  - Through the GUI
  - Through the dedicated `.geo` language
  - Through the C++, C, Python and Julia API
- Main characteristics
  - All algorithms are written in terms of abstract model entities, using a Boundary REPresentation (BREP) approach
  - Gmsh never translates from one CAD format to another; it directly accesses each CAD kernel API (OpenCASCADE, Built-in, ...)

Basic concepts

The goal is to deal with very different underlying data representations in a transparent manner



Geometry module

Under the hood, 4 types of model entities are defined:

1. Model points G_i^0 that are topological entities of dimension 0
2. Model curves G_i^1 that are topological entities of dimension 1
3. Model surfaces G_i^2 that are topological entities of dimension 2
4. Model volumes G_i^3 that are topological entities of dimension 3

Geometry module

- Model entities are topological entities, i.e., they only deal with adjacencies in the model; a bi-directional data structure represents the graph of adjacencies

$$G_i^0 \rightleftharpoons G_i^1 \rightleftharpoons G_i^2 \rightleftharpoons G_i^3$$

- Any model is able to build its list of adjacencies of any dimension using local operations
- The BRep is extended with non-manifold features: adjacent entities, and *embedded* (internal) entities
- Model entities can be either CAD entities (e.g. from the built-in or OpenCASCADE kernel) or *discrete* entities (defined by a mesh, e.g. STL)

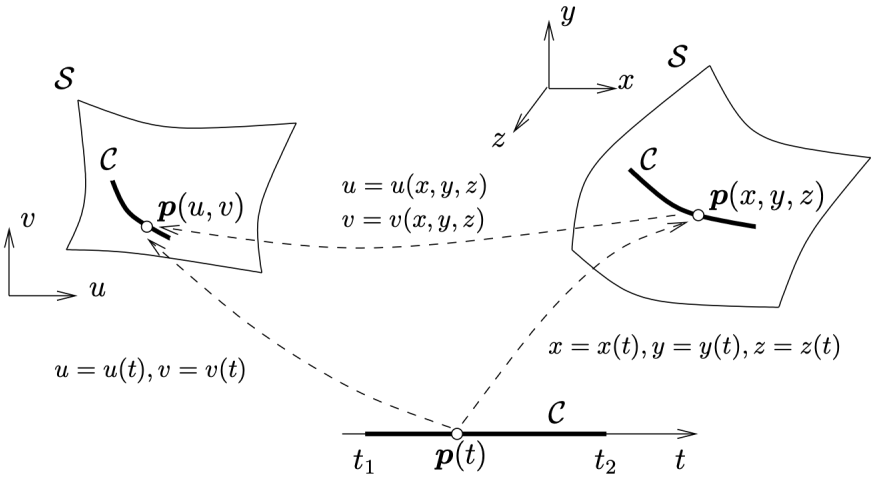
Geometry module

The geometry of a CAD model entity depends on the solid modeler kernel for its underlying representation. Solid modelers usually provide a parametrization of the shapes, i.e., a mapping:

$$\mathbf{p} \in R^d \mapsto \mathbf{x} \in R^3$$

1. The geometry of a model point G_i^0 is simply its 3-D location $\mathbf{x}_i = (x_i, y_i, z_i)$
2. The geometry of a model curve G_i^1 is its underlying curve $\mathcal{C}_i$ with its parametrization $\mathbf{p}(t) \in \mathcal{C}_i$, $t \in [t_1, t_2]$
3. The geometry of a model surface G_i^2 is its underlying surface $\mathcal{S}_i$ with its parametrization $\mathbf{p}(u, v) \in \mathcal{S}_i$
4. The geometry associated to a model volume is R^3

Geometry module

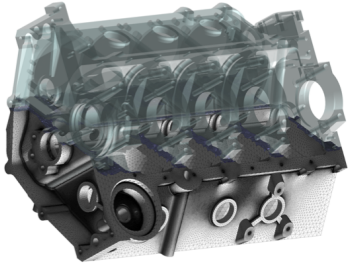


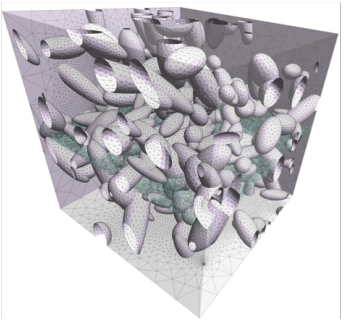
Point $\mathbf{p}$ located on a curve $\mathcal{C}$ that is itself embedded in a surface $\mathcal{S}$

Geometry module

Operations on CAD model entities are performed directly within their respective CAD kernels:

- There is no common internal geometrical representation
- Rather, Gmsh directly performs the operations (translation, rotation, intersection, union, fragments, ...) on the native geometrical representation using each CAD kernel's own API

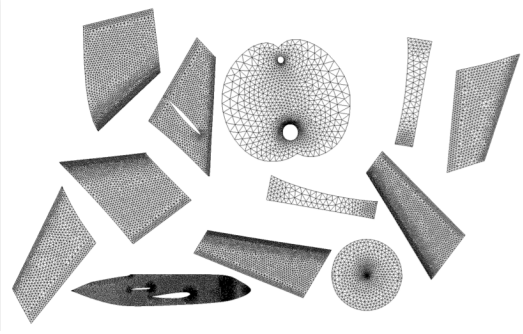


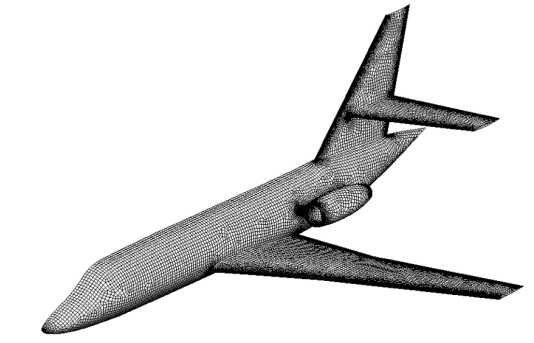


Geometry module

Discrete model entities are defined by a mesh (e.g. STL):

- They can be equipped with a geometry through a *reparametrization* procedure
- The parametrization is then used for meshing, in exactly the same way as for CAD entities

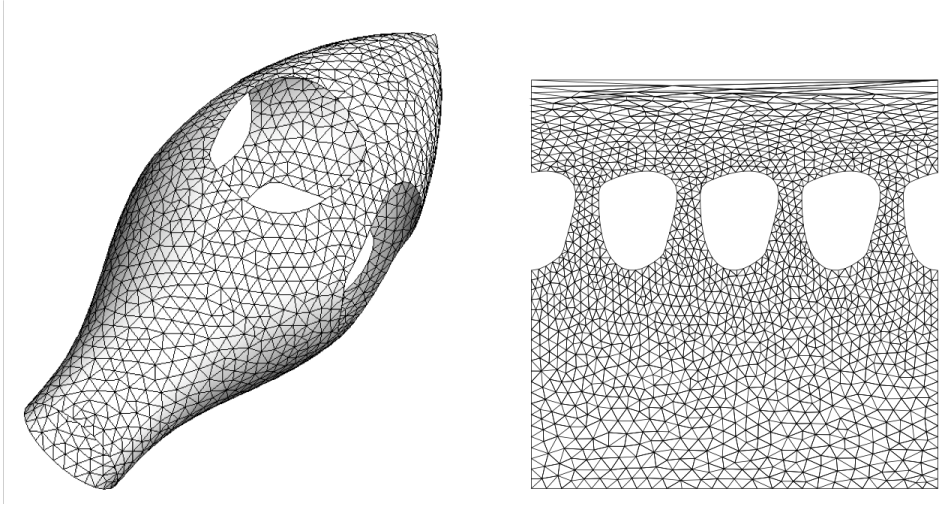




Mesh module

- Gmsh implements several meshing algorithms with specific characteristics
  - 1D, 2D and 3D
  - Structured, unstructured and hybrid
  - Isotropic and anisotropic
  - Straight-sided and curved
  - From standard CAD data or from STL through reparametrization
- Built-in interfaces to external mesh generators (BAMG, MMG3D, Netgen)

Mesh module



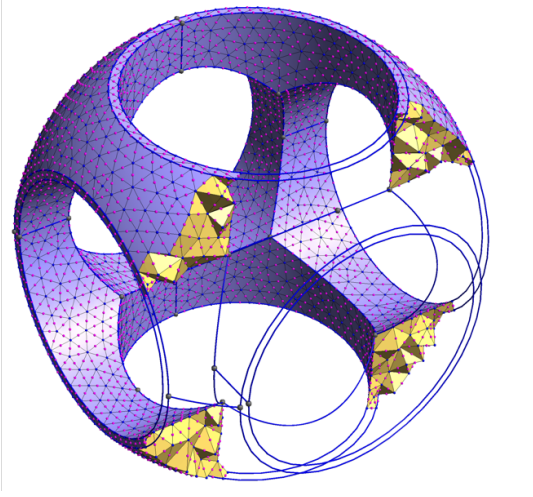
Typical CAD kernel idiosyncrasies: seam edges and degenerated edges

Mesh module

- Mesh data is made of *elements* (points, lines, triangles, quadrangles, tetrahedra, hexahedra, ...) defined by an ordered list of their *nodes*
- Elements and nodes are stored (*classified*) in the model entity they discretize:
  - A model point will thus contain a mesh element of type point, as well as a mesh node
  - A model curve will contain line elements as well as its interior nodes, while its boundary nodes will be stored in the bounding model points
  - A model surface will contain triangular and/or quadrangular elements and all the nodes not classified on its boundary or on its embedded entities (curves and points)
  - A model volume will contain tetrahedra, hexahedra, etc. and all the nodes not classified on its boundary or on its embedded entities (surfaces, curves and points)

Mesh module

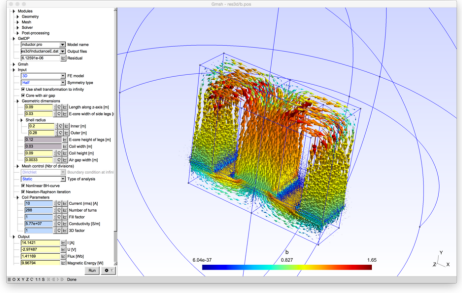
This mesh data structure allows to easily and efficiently handle the creation, modification and destruction of conformal finite element meshes



Solver module

- Gmsh implements a ONELAB (https://onelab.info) server to pilot external solvers, called "clients"
- Example client: GetDP finite element solver (https://getdp.info)

  - The ONELAB interface allows to call such clients and have them share parameters and modeling information
  - Parameters are directly controllable from the GUI



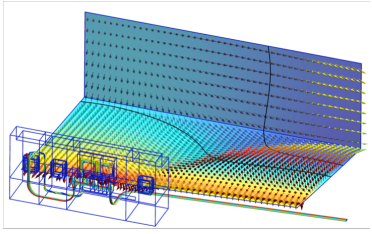
Solver module

- The implementation is based on a client-server model, with a server-side database and local or remote clients communicating in-memory or through TCP/IP sockets
  - Contrary to most solver interfaces, the ONELAB server has no a priori knowledge about any specifics (input file format, syntax, ...) of the clients
  - This is made possible by having any simulation preceded by an analysis phase, during which the clients are asked to upload their parameter set to the server
  - The issues of completeness and consistency of the parameter sets are completely dealt with on the client side: the role of ONELAB is limited to data centralization, modification and re-dispatching

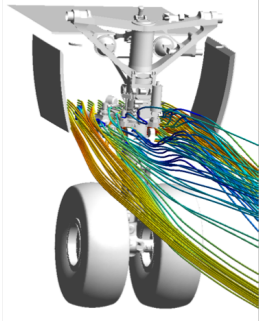
Post-processing module

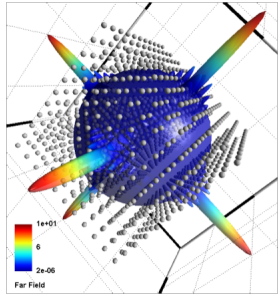
- Post-processing data is made of *views*
- A view stores both display *options* and *data* (unless the view is an *alias* of another view)
- View data can contain several *steps* (e.g. to store time series) and can be either linked to one or more models (*mesh-based* data, as stored in `.msh` or `.med` files) or independent from any model (*list-based* data, as stored in parsed `.pos` files)
- Data is interpolated through arbitrary polynomial interpolation schemes; automatic mesh refinement is used for adaptive visualization of high-order views
- Various *plugins* exist to create and modify views

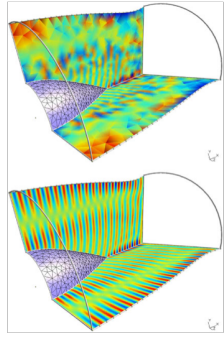
Post-processing module



- Cuts, iso-curves and vectors
- Elevation maps
- Streamlines
- Adaptive high-order visualization



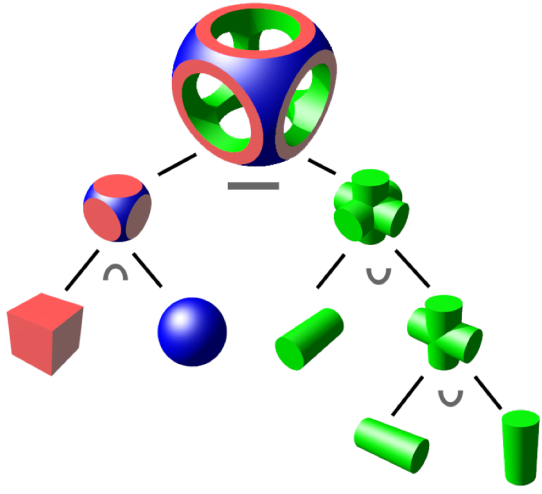




Recent developments

- Constructive Solid Geometry
- Application Programming Interface (API)
- Multi-Threaded meshing
- Robust STL remeshing based on parametrizations
- Quasi-structured quad meshing

Constructive Solid Geometry

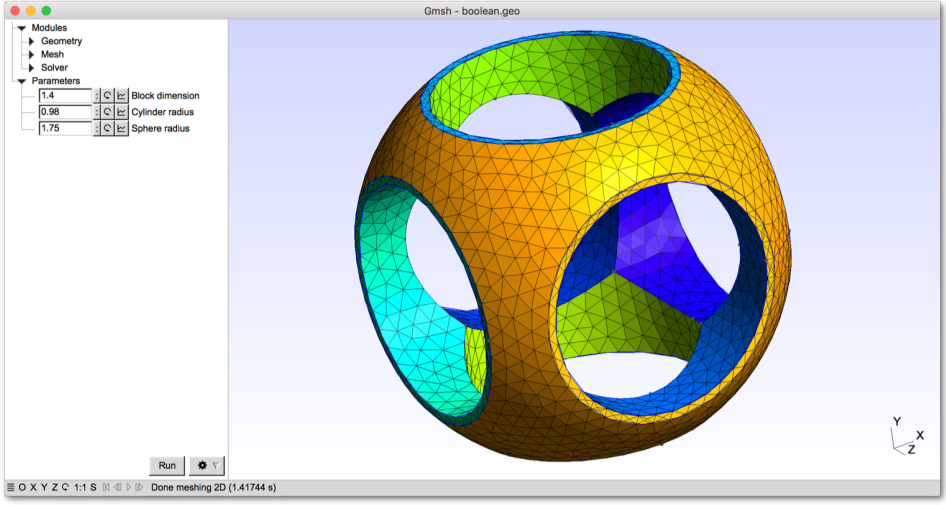


https://en.wikipedia.org/wiki/Constructive_solid_geometry

Constructive Solid Geometry

```
SetFactory("OpenCASCADE"); // use OpenCASCADE kernel

R = DefineNumber[ 1.4 , Min 0.1, Max 2, Step 0.01,
                  Name "Parameters/Box dimension" ];
Rs = DefineNumber[ R*.7 , Min 0.1, Max 2, Step 0.01,
                   Name "Parameters/Cylinder radius" ];
Rt = DefineNumber[ R*1.25, Min 0.1, Max 2, Step 0.01,
                   Name "Parameters/Sphere radius" ];

Box(1) = {-R,-R,-R, 2*R,2*R,2*R}; // explicit entity tag

Sphere(2) = {0,0,0, Rt};

BooleanIntersection(3) = { Volume{1}; Delete; }{ Volume{2}; Delete; };
                                      // delete object and tool
Cylinder(4) = {-2*R,0,0, 4*R,0,0, Rs};
Cylinder(5) = {0,-2*R,0, 0,4*R,0, Rs};
Cylinder(6) = {0,0,-2*R, 0,0,4*R, Rs};

BooleanUnion(7) = { Volume{4}; Delete; }{ Volume{5,6}; Delete; };
BooleanDifference(8) = { Volume{3}; Delete; }{ Volume{7}; Delete; };
```

Constructive Solid Geometry

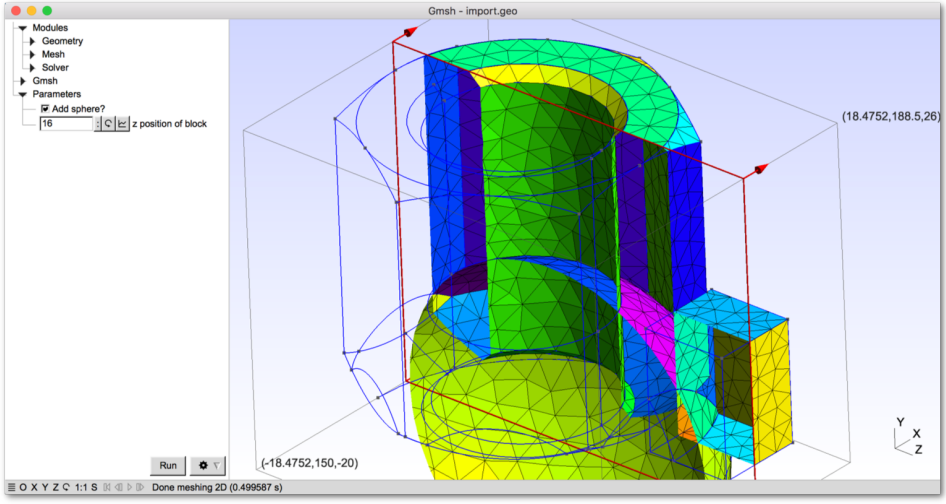


gmsh/demos/boolean/boolean.geo

Constructive Solid Geometry

```
SetFactory("OpenCASCADE");

DefineConstant[
  z = {16, Name "Parameters/z position of box"}
  sph = {0, Choices{0,1}, Name "Parameters/Add sphere?"}
];

a() = ShapeFromFile("component8.step"); // import STEP shape
b() = 2;
Box(b(0)) = {0,156,z, 10,170,z+10};

If(sph)
  b() += 3;
  Sphere(b(1)) = {0,150,0, 20};
EndIf

// fragmentation intersects everything
r() = BooleanFragments{ Volume{a()}; Delete; }{ Volume{b()}; Delete; };
Save "merged.brep"; // save into native OpenCASCADE format

Physical Volume("Combined volume", 1) = {r()};
Physical Surface("Combined boundary", 2) = CombinedBoundary{ Volume{r()}; }
```

Constructive Solid Geometry



gmsh/demos/boolean/import.geo

Constructive Solid Geometry

- All existing `.geo` commands are conserved
- New or modified `.geo` commands:
  - Shapes (with explicit numbering): `Circle`, `Ellipse`, `Wire`, `Surface`, `Sphere`, `Box`, `Torus`, `Rectangle`, `Disk`, `Cylinder`, `Cone`, `Wedge`, `ThickSolid`, `ThruSections`, `Ruled ThruSections`
  - Operations (implicit numbering): `ThruSections`, `Ruled ThruSections`, `Fillet`, `Extrude`
  - Boolean operations (explicit or implicit numbering): `BooleanUnion`, `BooleanIntersection`, `BooleanDifference`, `BooleanFragments`
  - Other: `ShapeFromFile`, `Recursive Delete`

Application Programming Interface

Gmsh 4 introduces a new stable Application Programming Interface (API) for C++, C, Python and Julia, with the following design goals:

- Allow to do everything that can be done in .geo files
  - ... and then much more!
- Be robust, in particular to wrong input data (i.e. "never crash")
- Be efficient; but still allow to do simple things, simply
- Be maintainable over the long run

Application Programming Interface

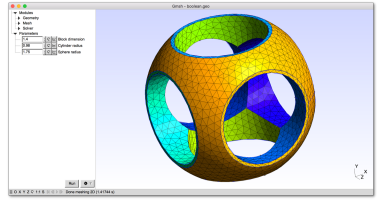
To achieve these goals the Gmsh API

- is purely functional
- only uses basic types from the target language (C++, C, Python or Julia)
- is automatically generated from a master API description file
- is fully documented

Application Programming Interface

Same boolean example as before, but using the Python API:

```
import gmsh

gmsh.initialize()
gmsh.model.add("boolean")

R = 1.4; Rs = R*.7; Rt = R*1.25

gmsh.model.occ.addBox(-R,-R,-R, 2*R,2*R,2*R, 1)
gmsh.model.occ.addSphere(0,0,0,Rt, 2)
gmsh.model.occ.intersect([(3, 1)], [(3, 2)], 3)
gmsh.model.occ.addCylinder(-2*R,0,0, 4*R,0,0, Rs, 4)
gmsh.model.occ.addCylinder(0,-2*R,0, 0,4*R,0, Rs, 5)
gmsh.model.occ.addCylinder(0,0,-2*R, 0,0,4*R, Rs, 6)
gmsh.model.occ.fuse([(3, 4), (3, 5)], [(3, 6)], 7)
gmsh.model.occ.cut([(3, 3)], [(3, 7)], 8)

gmsh.model.occ.synchronize()
gmsh.model.mesh.generate(3)
gmsh.fltk.run()
gmsh.finalize()
```

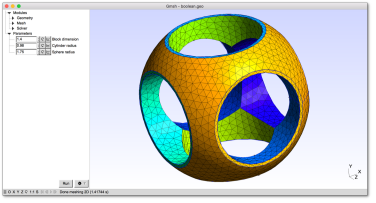


gmsh/demos/api/boolean.py

Application Programming Interface

... or using the C++ API:

```
#include <gmsh.h>

int main(int argc, char **argv)
{
  gmsh::initialize(argc, argv);
  gmsh::model::add("boolean");

  double R = 1.4, Rs = R*.7, Rt = R*1.25;

  std::vector<std::pair<int, int> > ov;
  std::vector<std::vector<std::pair<int, int> > > ovv;
  gmsh::model::occ::addBox(-R,-R,-R, 2*R,2*R,2*R, 1);
  gmsh::model::occ::addSphere(0,0,0,Rt, 2);
  gmsh::model::occ::intersect({{3, 1}}, {{3, 2}}, ov, ovv, 3);
  gmsh::model::occ::addCylinder(-2*R,0,0, 4*R,0,0, Rs, 4);
  gmsh::model::occ::addCylinder(0,-2*R,0, 0,4*R,0, Rs, 5);
  gmsh::model::occ::addCylinder(0,0,-2*R, 0,0,4*R, Rs, 6);
  gmsh::model::occ::fuse({{3, 4}, {3, 5}}, {{3, 6}}, ov, ovv, 7);
  gmsh::model::occ::cut({{3, 3}}, {{3, 7}}, ov, ovv, 8);

  gmsh::model::occ::synchronize();

  gmsh::model::mesh::generate(3);
  gmsh::fltk::run();
  gmsh::finalize();
  return 0;
}
```



gmsh/demos/api/boolean.cpp

Application Programming Interface

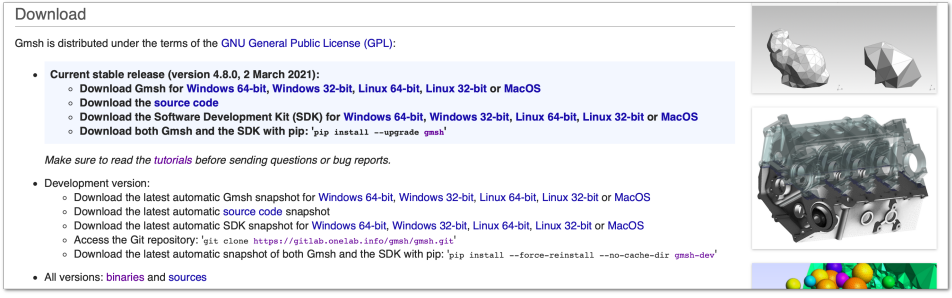
In addition to CAD creation and meshing, the API can be used to

- Access mesh data (`getNodes`, `getElements`)
- Generate interpolation (`getBasisFunctions`) and integration (`getJacobians`) data to build Finite Element and related solvers (see e.g. `gmsh/demos/api/poisson.py`)
- Create post-processing views
- Run the graphical user-interface
- Build custom graphical user-interfaces, e.g. for domain-specific codes (see `gmsh/demos/api/prepro.py` or `gmsh/demos/api/custom_gui.py`) or co-post-processing via ONELAB

Application Programming Interface

In order to make this API easy to use, we publish a binary Software Development Toolkit (SDK):

- Continuously delivered (for each commit in master), like the Gmsh app
- Contains the dynamic Gmsh library together with the corresponding C++/C header files, and Python and Julia modules



Multi-Threaded meshing

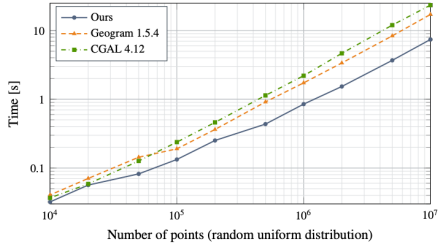
Most meshing algorithms are now multi-threaded using OpenMP:

- 1D and 2D algorithms are multithreaded using coarse-grained approach, i.e. several curves/surfaces are meshed concurrently
- The new 3D Delaunay-based algorithm is multi-threaded using a fine-grained approach. It currently lacks several features (embedded entities, hybrid meshes, ...), which will eventually be supported

You need to recompile Gmsh with `-DENABLE_OPENMP=1` to enable this; then e.g.

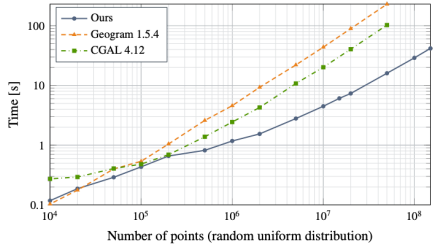
```
gmsh file.geo -3 -nt 8 -algo hxt
```

Multi-Threaded meshing



# vertices	10^4	10^5	10^6	10^7
Ours	0.032	0.13	0.85	7.40
Geogram	0.041	0.19	1.73	17.11
CGAL	0.037	0.24	2.20	23.37

(a) 4-core Intel® Core™ i7-6700HQ CPU.



# vertices	10^4	10^5	10^6	10^7	10^8
Ours	0.11	0.43	1.17	4.48	28.95
Geogram	0.10	0.54	4.58	43.70	/
CGAL	0.27	0.48	2.44	20.15	/

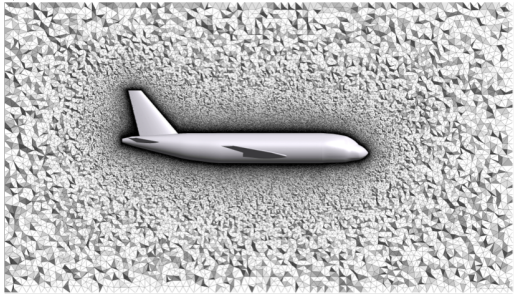
(b) 64-core Intel® Xeon Phi™ 7210 CPU.

[C. Marot et al., IJNME 2019]

Multi-Threaded meshing

Truck tire

# threads	# tetrahedra	Timings (s)		
		BR	Refine	Total
1	123 640 429	75.9	259.7	364.7
2	123 593 913	74.5	166.8	267.1
4	123 625 696	74.2	107.4	203.6
8	123 452 318	74.2	95.5	190.0

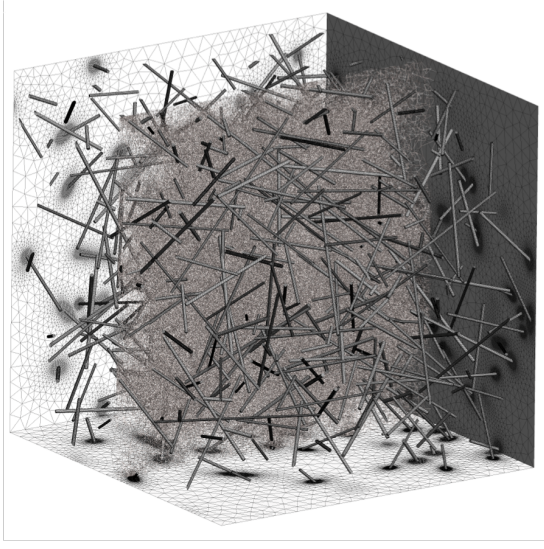


Aircraft

# threads	# tetrahedra	Timings (s)		
		BR	Refine	Total
1	672 209 630	45.2	1348.5	1418.3
2	671 432 038	42.1	1148.9	1211.5
8	665 826 109	39.6	714.8	774.8
64	664 587 093	38.7	322.3	380.9
127	663 921 974	38.1	255.0	313.3

AMD EPYC 2x 64-core

Multi-Threaded meshing



100 thin fibers

# threads	# tetrahedra	Timings (s)		
		BR	Refine	Total
1	325 611 841	3.1	492.1	497.2
2	325 786 170	2.9	329.7	334.3
4	325 691 796	2.8	229.5	233.9
8	325 211 989	2.7	154.6	158.7
16	324 897 471	2.8	96.8	100.9
32	325 221 244	2.7	71.7	75.8
64	324 701 883	2.8	55.8	60.1
127	324 190 447	2.9	47.6	52.0

500 thin fibers

# threads	# tetrahedra	Timings (s)		
		BR	Refine	Total
1	723 208 595	18.9	1205.8	1234.4
2	723 098 577	16.0	780.3	804.8
4	722 664 991	86.6	567.1	659.8
8	722 329 174	15.8	349.1	370.1
16	723 093 143	15.6	216.2	236.5
32	722 013 476	15.6	149.7	169.8
64	721 572 235	15.9	119.7	140.4
127	721 591 846	15.9	114.2	135.2

AMD EPYC 2x 64-core

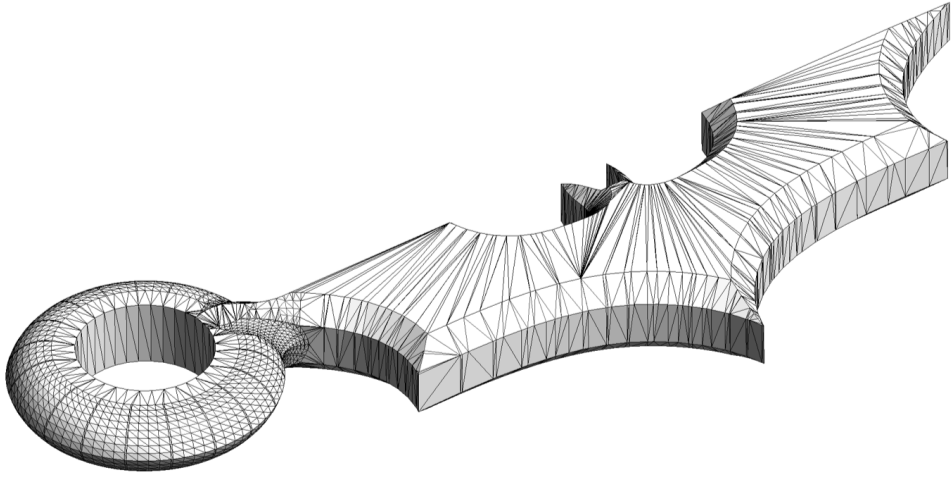
Robust STL remeshing

New pipeline to remesh discrete surfaces (represented by triangulations):

- Automatic construction of a set of parametrizations that form an atlas of the model
- Each parametrization is guaranteed to be one-to-one, amenable to meshing using existing algorithms
- New nodes are guaranteed to be on the input triangulation ("no modelling")
- Optional pre-processing (i.e. edge detection) to color sub-patches if sharp features need to be preserved

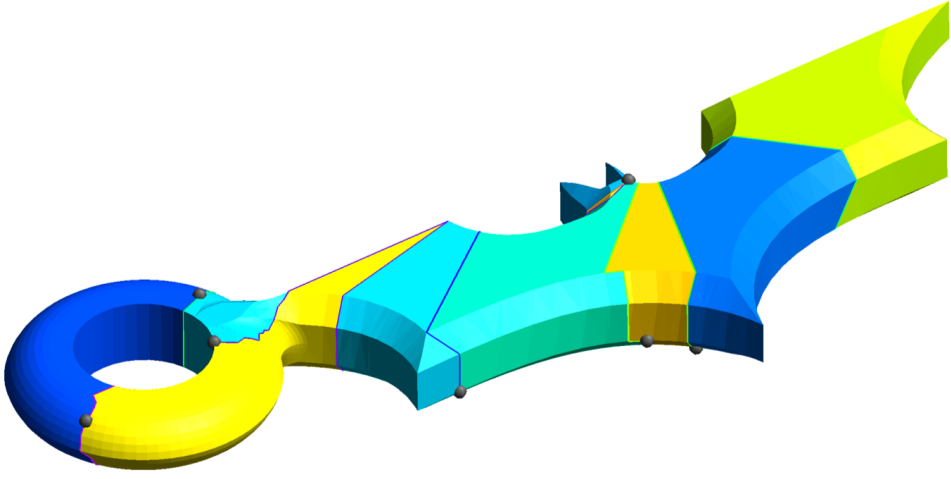
[P. A. Beaufort et al., JCP 2020]

Robust STL remeshing



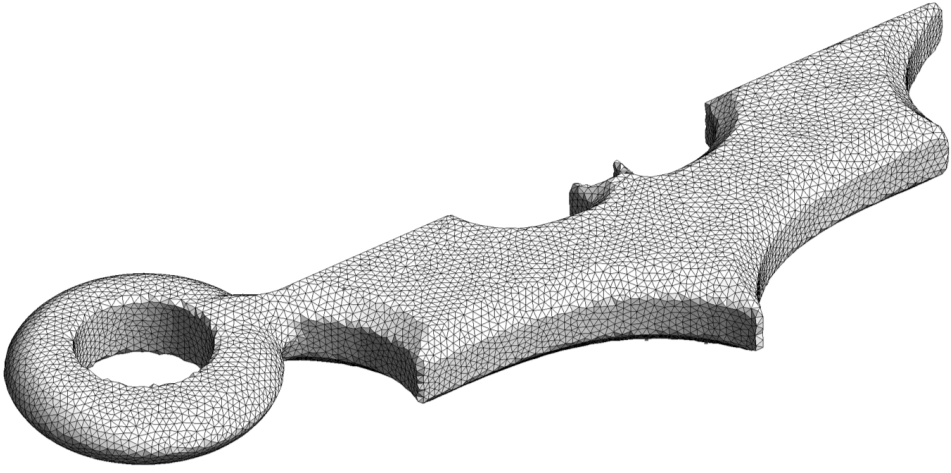
Batman STL mesh

Robust STL remeshing



Automatic atlas creation: each patch is provably parametrizable by solving a linear PDE, using mean value coordinates

Robust STL remeshing

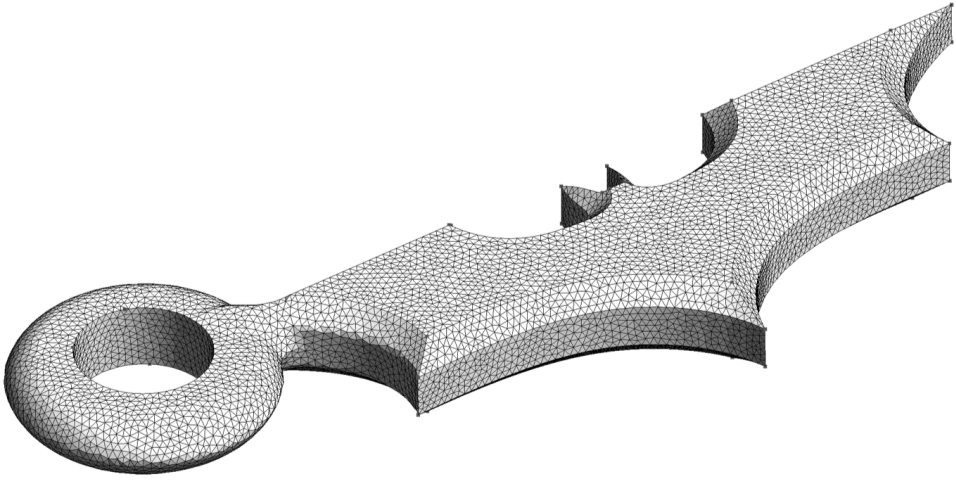


Remeshing

Robust STL remeshing

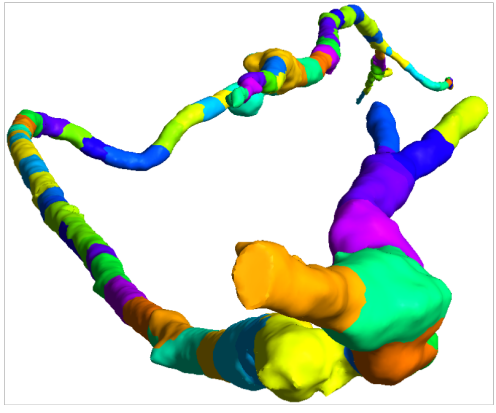
Automatic atlas creation, this time with feature edge detection

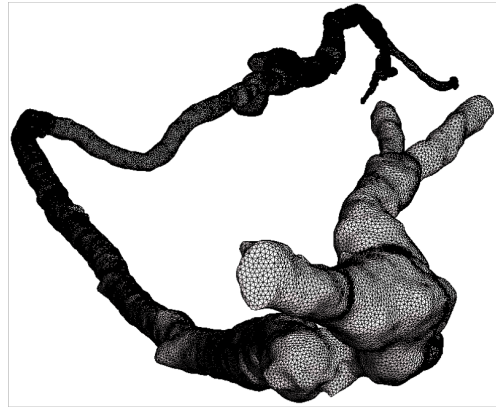
Robust STL remeshing



Remeshing with feature edge detection

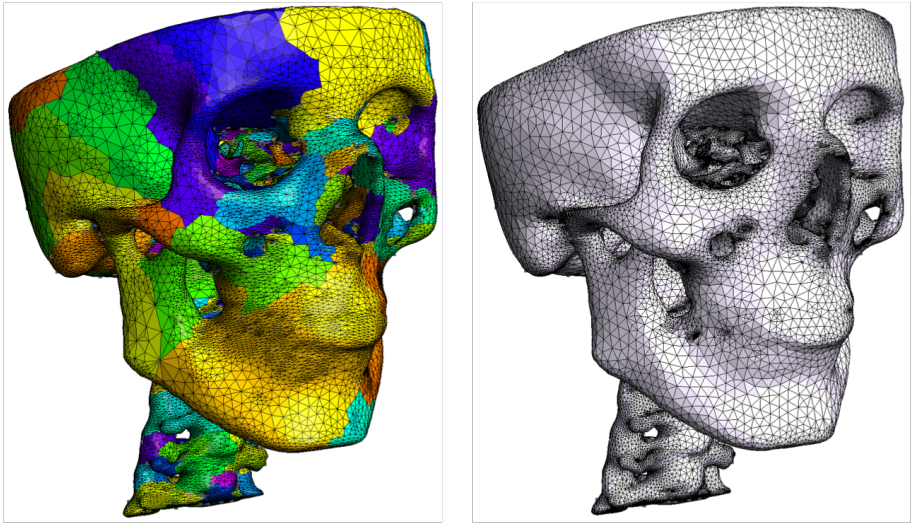
Robust STL remeshing





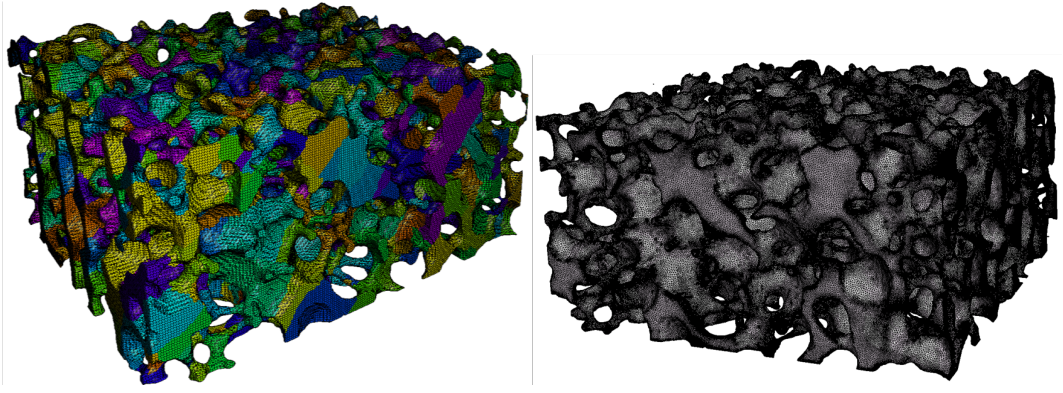
CT scan of an artery: 101 patches created, most because of the large aspect ratio

Robust STL remeshing



Remeshing of a skull: 715 patches created for reparametrization; mesh adapted to curvature

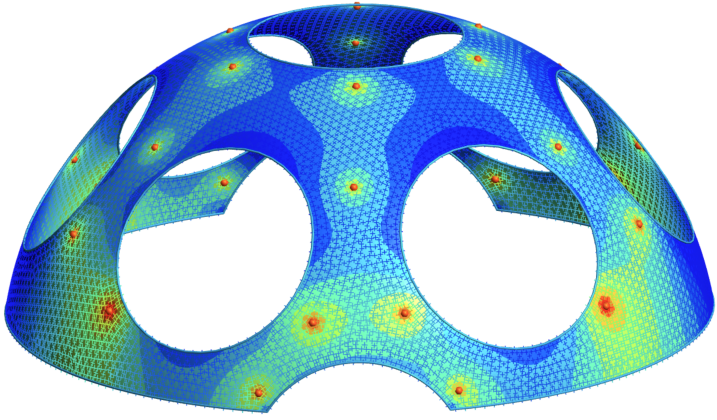
Robust STL remeshing



Remeshing of an X-ray tomography image of a silicon carbide foam by P. Duru, F. Muller and L. Selle (IMFT, ERC Advanced Grant SCIROCCO): 1,802 patches created for reparametrization

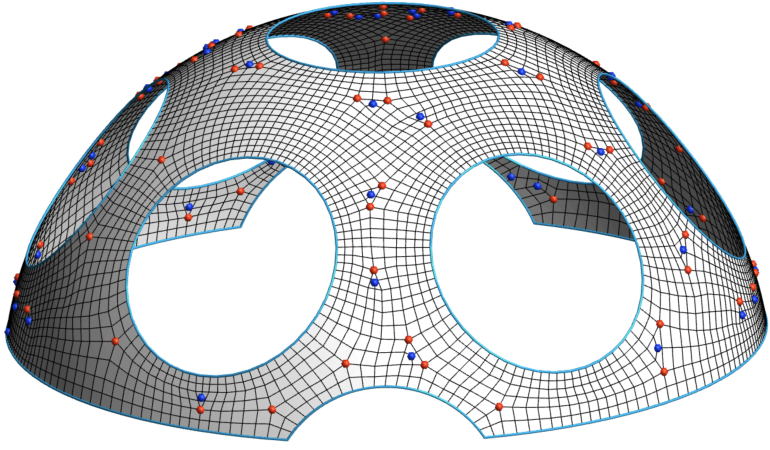
Quasi-structured quad meshing

New experimental algorithm by [M. Reberol et al. 2021] that has just landed in the development version



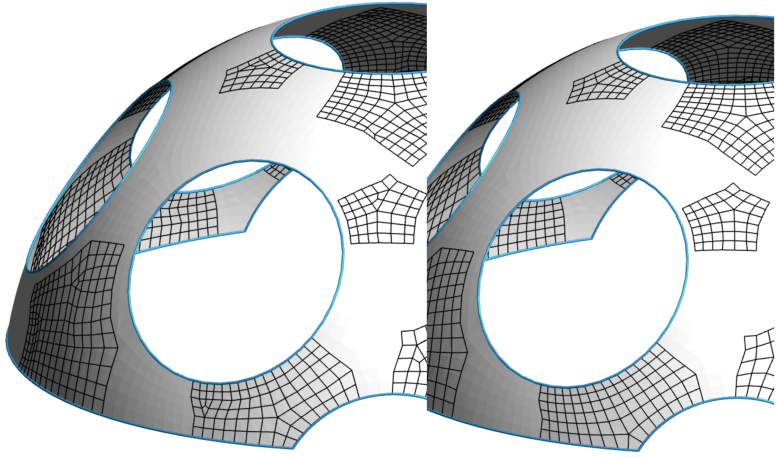
Compute a (scaled) cross-field with multilevel diffusion

Quasi-structured quad meshing



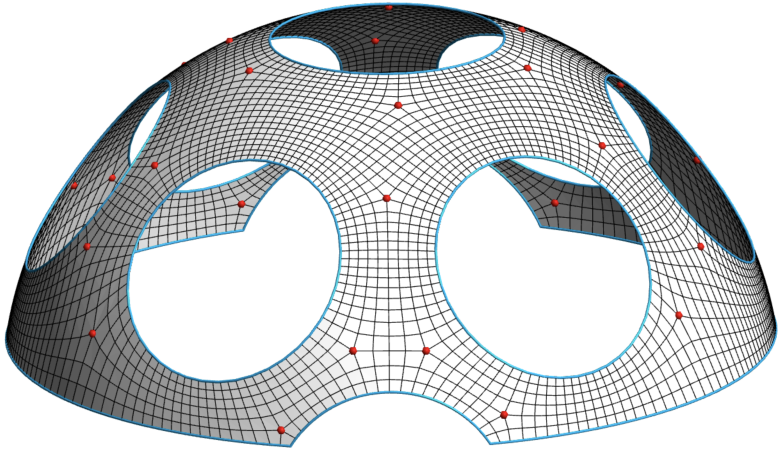
Build a unstructured quadrilateral mesh with a frontal approach guided by the scaled cross field

Quasi-structured quad meshing



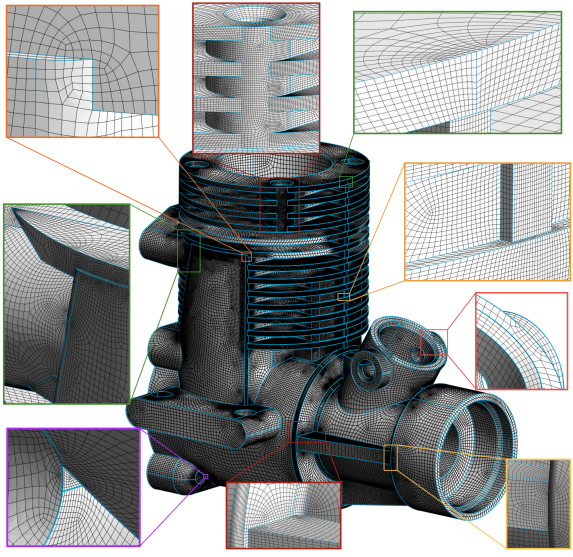
Pattern-based quadrilateral meshing and cavity remeshing to eliminate unnecessary irregular vertices while preserving the cross field singularities

Quasi-structured quad meshing



The final quad mesh is very similar to the one obtained with the global parametrization approach and has the same number of irregular vertices

Quasi-structured quad meshing



- "Block" model: 533 surfaces, 1584 curves, 261.5k vertices, 261.6k quads
- Average SICN quality: 0.87 (minimum: 0.11)
- 58 sec. (initial unstructured quad mesh) + 33 sec. (quasi-structured improvement) on Intel Core i7 4 cores
- Quasi-structured improvement reduces the number of irregular from 14.4k to 3.6k

Conclusions and perspectives

- Overview of Gmsh and recent developments:
  - Constructive Solid Geometry
  - Application Programming Interface
  - New multi-threaded algorithms
  - Robust STL remeshing based on parametrizations
  - Quasi-structured quad meshing
- Many exciting developments in the pipeline:
  - Improved high-order remeshing
  - Hex-dominant meshes
  - Boundary layers

Post-Scriptum

- To download Gmsh: https://gmsh.info
- For references, see https://gmsh.info/#References

- For fun, go to the
  - Google Play Store (if you are on Android)
  - Apple AppStore (if you are on iOS)

  and download the **ONELAB app**: it contains a full-featured version of Gmsh + the finite element solver GetDP

  ... so you can impress your friends by solving finite element models on your smartphone!