Gmsh and GetDP in Academia and Industry

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OctConf 2015 - Darmstadt, September 23 2015

Some Background

- I am a professor of Electrical Engineering and Computer Science at the University of Liège in Belgium, where I lead the ACE research group
- Our research interests: modeling, analysis, algorithm development, and simulation for problems arising in various areas of engineering and science
- We write quite a lot of codes, mostly PDE solvers in C++/Python
- Two codes released under GNU GPL:
    - Gmsh mesh generator: http://gmsh.info
    - GetDP finite element solver: http://getdp.info
- These are long term efforts (both started in 1997)

Some Background

Today, Gmsh and GetDP represent

- half a million lines of (mostly C++) code
- still only 3 core devs; but about 100 with repo write access
- about 1000 people on mailing lists
- about 5000 binary downloads per week (80% Windows)
- about 400 (google scholar) citations per year

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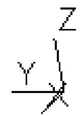
Let’s have a look!

Quick overview of Gmsh

- Gmsh is based around four modules: Geometry, Mesh, Solver and Post-processing; 3 levels of use:
  - Developper: through the (undocumented…) C++ or Python API
  - Advanced user: through the dedicated ".geo" language
  - Novice user: through the GUI (which translates most actions into ".geo" file commands)
- Main characteristic: all algorithms are written in terms of abstract CAD entities, using a "Boundary REPresentation" approach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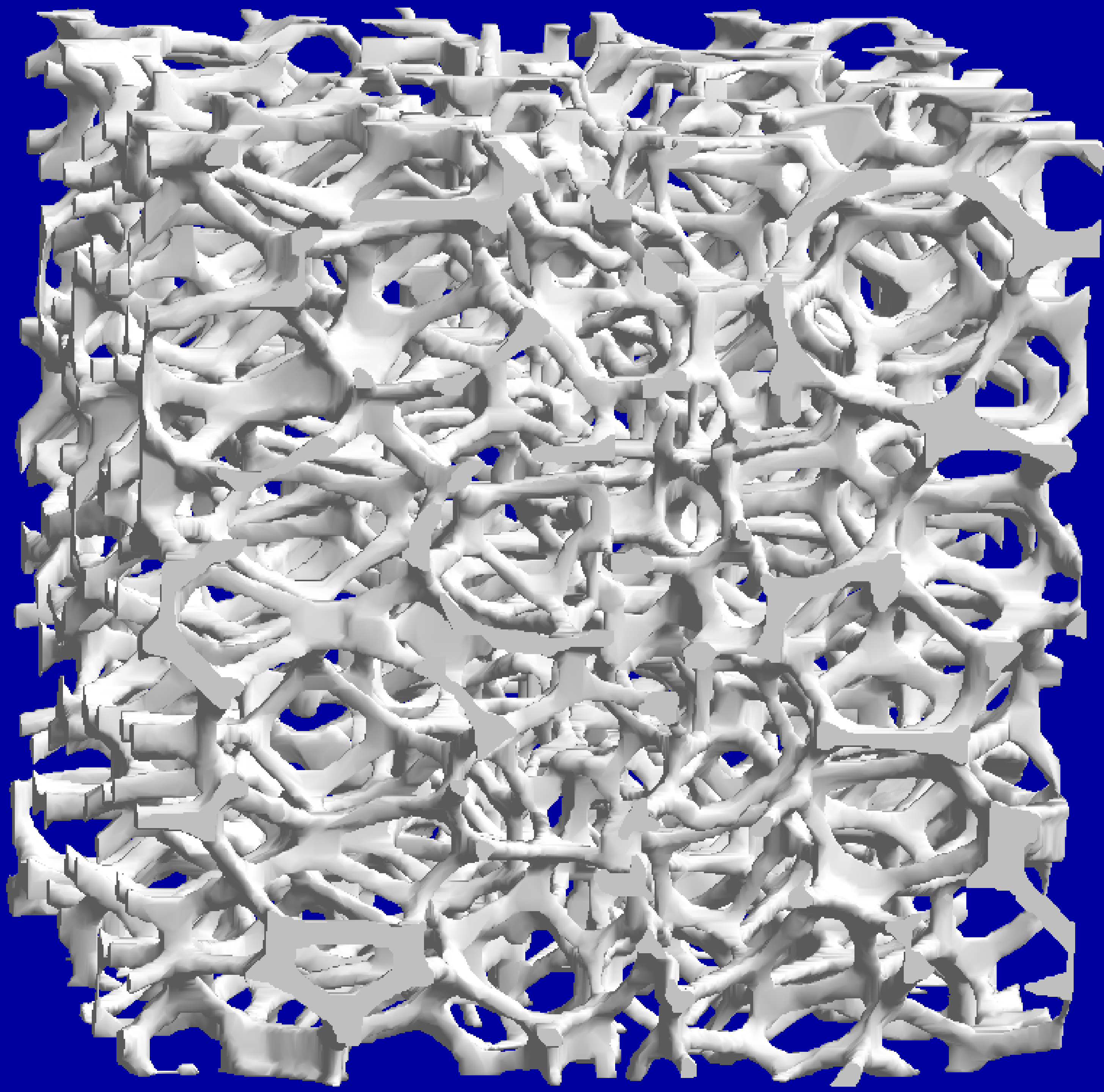

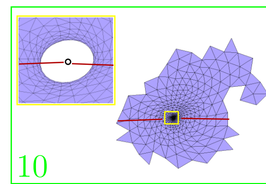
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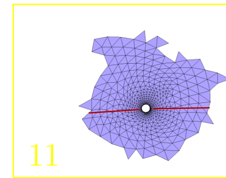
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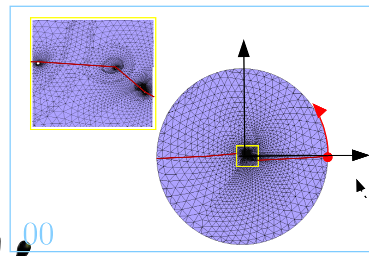
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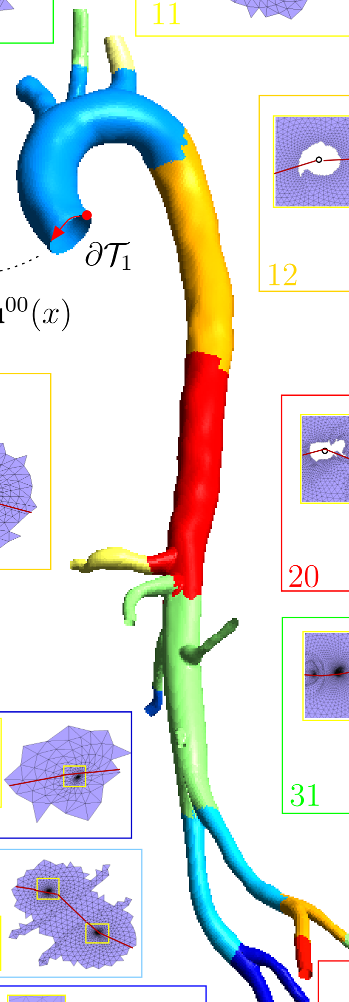
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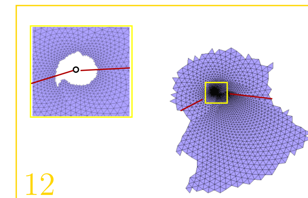
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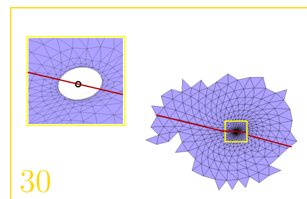
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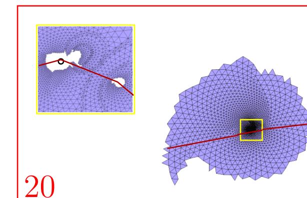
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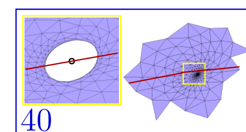
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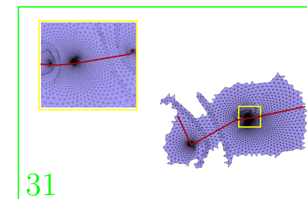
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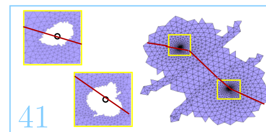
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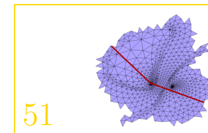
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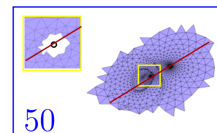
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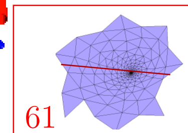
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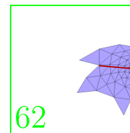
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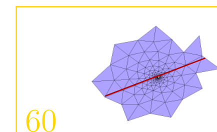
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Quick overview of Gmsh

Any 3-D model can be defined using its Boundary Representation (BRep): a volume is bounded by a set of surfaces, and a surface is bounded by a series of curves; a curve is bounded by two end points.

Therefore, four kinds of *model entities* are defined:

1. Model Vertices G_i^0 that are topological entities of dimension 0,
2. Model Edges G_i^1 that are topological entities of dimension 1,
3. Model Faces G_i^2 that are topological entities of dimension 2,
4. Model Regions G_i^3 that are topological entities of dimension 3.

Quick overview of Gmsh

Model entities are topological entities, i.e., they only deal with adjacencies in the model, and we use a bi-directional data structure for representing the graph of adjacencies.

Schematically, we have

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

Any model entity is able to build its list of adjacencies using local operations.

Quick overview of Gmsh

The geometry of a model entity depends on the solid modeler for its underlying representation. Solid modelers usually provide a parametrization of the shapes, i.e., a mapping $\boldsymbol{p} \in R^d \mapsto \boldsymbol{x} \in R^3$:

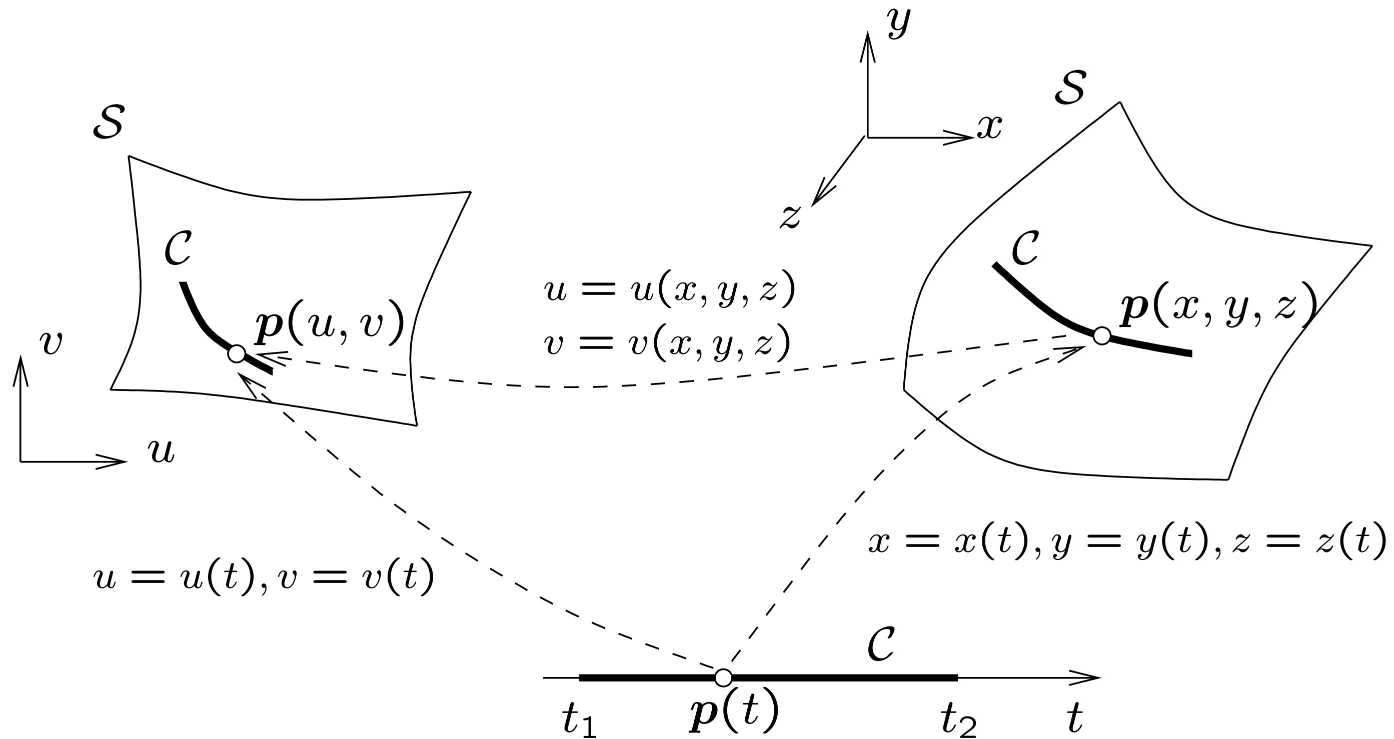
1. The geometry of a model vertex G_i^0 is simply its 3-D location $\boldsymbol{x}_i = (x_i, y_i, z_i)$.

2. The geometry of a model edge G_i^1 is its underlying curve $\mathcal{C}_i$ with its parametrization $\boldsymbol{p}(t) \in \mathcal{C}_i$, $t \in [t_1, t_2]$.

3. The geometry of a model face G_i^2 is its underlying surface $\mathcal{S}_i$ with its parametrization $\boldsymbol{p}(u, v) \in \mathcal{S}_i$.

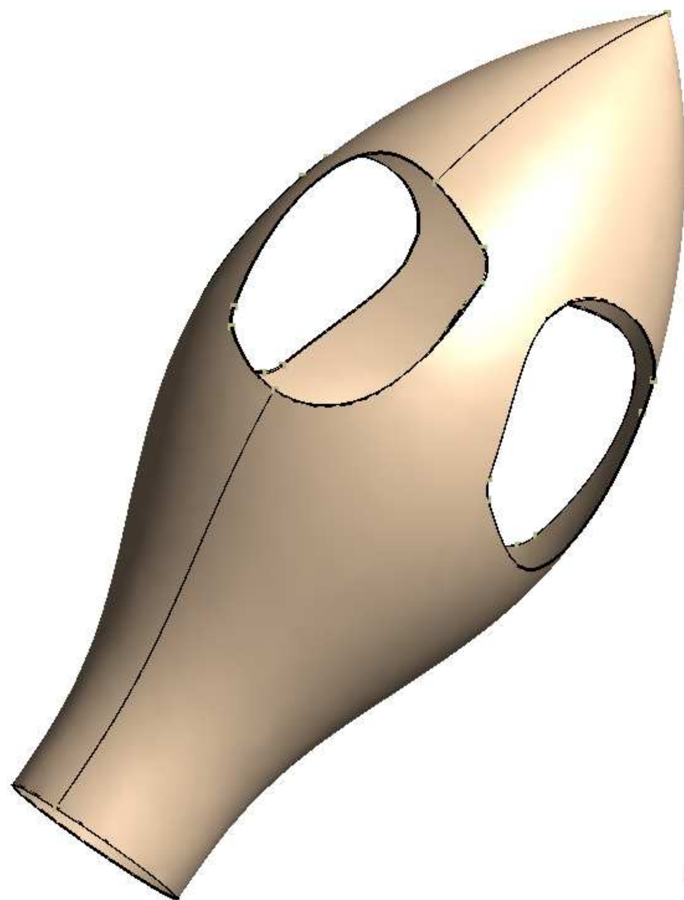
4. The geometry associated to a model region is R^3.

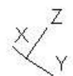
Quick overview of Gmsh

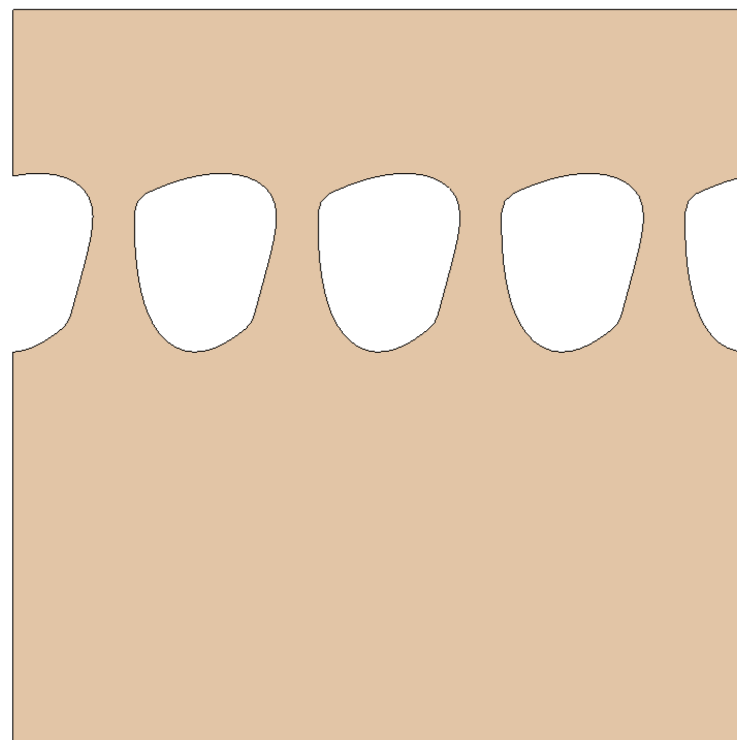


Point $\boldsymbol{p}$ located on the curve $\mathcal{C}$ that is itself embedded in surface $\mathcal{S}$

Quick overview of Gmsh







CAD kernel idiosyncrasies: *seam* edges and *degenerated* edges

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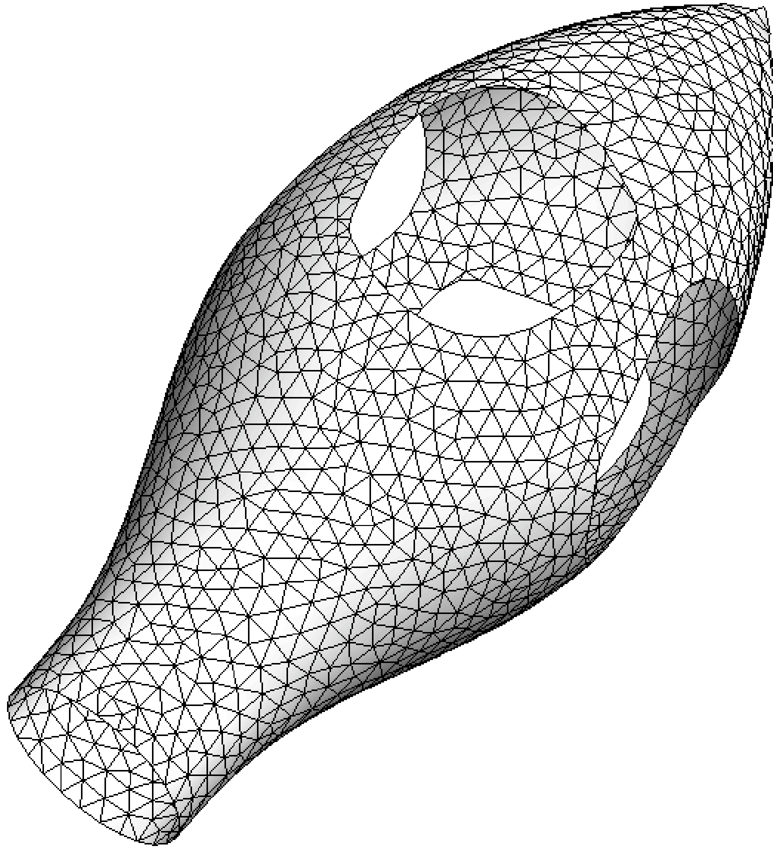

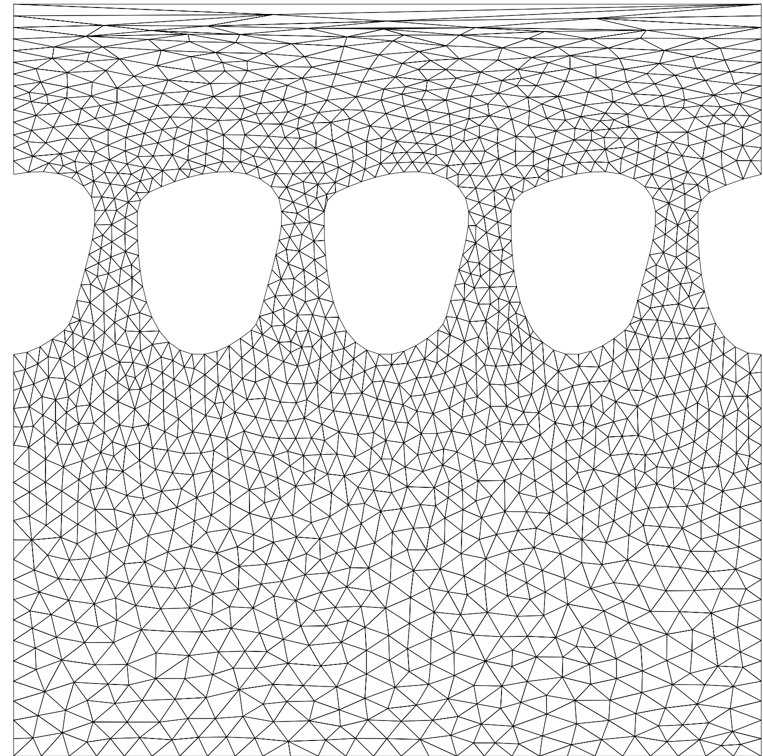

CAD kernel idiosyncrasies: *seam* edges and *degenerated* edges

Quick overview of Gmsh

- For the geometry:

```
GModel
  GVertex
  GEdge
  GFace
  GRegion
```

Concrete implementation for each CAD kernel (e.g. `gmshFace`, `OCCFace`, `parasolidFace`, `fourierFace`, `levelsetFace`, `discreteFace`).

Direct access via CAD kernel APIs: never translate/convert formats!

Quick overview of Gmsh

```
class GEdge : public GEntity {
  //bi-directional data structure
  GVertex *v1, *v2;
  std::list<GFace*> faces;
public:
  //pure virtual functions that have to be overloaded for every
  //solid modeler
  virtual std::pair<double> parRange() = 0;
  virtual Point3 point(double t) = 0;
  virtual Vector3 firstDer(double t) = 0;
  virtual Point2 reparam(GFace *f, double t, int dir) = 0;
  virtual bool isSeam(GFace *f) = 0;
  //other functions of the class are non pure virtual
  //..
};
```

Quick overview of Gmsh

```
class GFace : public GEntity {
  //bi-directional data structure
  GRegion *r1, *r2;
  std::list<GEdge*> edges;
public:
  //pure virtual functions that have to be overloaded for every
  //solid modeler
  virtual std::pair<double> parRange(int dir) const = 0;
  virtual Point3 point(double u, double v) const = 0;
  virtual std::pair<Vector3> firstDer(double u, double v) const = 0;
  //other functions of the class are non pure virtual
  virtual double curvature(double u, double v) const;
  //...
};
```

Quick overview of Gmsh

- For the mesh:

  `MElement`

  `MVertex`

Each `GEntity` stores its "internal" vertices. Parallel I/O through `GModel`.

Minimal storage:
- 44 bytes per vertex, 28 bytes per tetrahedron (12 Mtets/Gb)
- Enriched for specific algorithms
- `MEdge` and `MFace` created on demand

`MElement` provides access to mapping, Jacobian and integration

Quick overview of Gmsh

Recent features:

- Reparameterization of surfaces (“STL remeshing”)
- Coarse grained (distributed, via MPI) and fine-grained (shared memory, via OpenMP) parallel 3D Delaunay meshing algorithm
- Automatic quad and hex-dominant meshing
- Anisotropic meshes and boundary layers
- Homology and cohomology solver

Quick overview of GetDP

- GetDP language (".pro" files) for the natural expression of finite element problems (explicit function spaces and weak forms, ...)
- Solving $\nabla \cdot (a \nabla u) = f$ on domain Ω translates into:

```
Formulation{
  { Name F; Type FemEquation;
    Quantity {
      { Name u; Type Local; NameOfSpace H1_0; }
    }
    Equation {
      Galerkin { [ a[] * Dof{d u}, {d u} ] ; In Omega; … }
      Galerkin { [ f[], {u} ] ; In Omega; … }
    }
  }
}
```

i.e. a quite direct transcription of the weak form of the problem:
Find $u \in H_0^1(\Omega)$ such that $\int_\Omega a \nabla u \cdot \nabla u' \, \mathrm{d}\Omega + \int_\Omega f \, u' \, \mathrm{d}\Omega = 0$, $\forall u' \in H_0^1(\Omega)$

Quick overview of GetDP

- No distinction between 1D, 2D or 3D ; static, transient, time-(multi-)harmonic, eigenproblems
- Easy coupling of fields and formulations (physics), staggered or monolithic, e.g. for explicit Jacobian matrices/sensitivity analysis of strongly coupled nonlinear problems
- Natural handling of non-local (global, integral) quantities, e.g. for circuit coupling
- Linear algebra through PETSc/SLEPc and/or Sparksit/Arpack

Quick overview of GetDP

- Recent developments:
  - Use of Gmsh library for IO, post-processing, mesh-to-mesh interpolation
  - Large scale calculations through domain decomposition methods (> 1 billion DoFs on 10,000 CPUs for time-harmonic wave scattering)
  - High-order eigenvalue problems
  - Built-in Octave and Python interpreters

Gmsh and GetDP in academia and in industry

Actual use is difficult to assess, but today we estimate that

- Gmsh is probably the most popular *open source* mesh generator; it is used in hundreds of universities, research centers and commercial companies around the world
- GetDP is used intensively in a few dozens universities and companies

Several commercial tools use or integrate (with dual licensing) the codes, e.g. http://www.nxmagnetics.de

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Where do we go from here? The **ONELAB** project: http://onelab.info

Context of the ONELAB project

- **Economic**
  - Growing importance of numerical simulation in education and industry
  - Prohibitive cost of commercial packages for a significant subset of potential users (SMEs, education, occasional use)

- **Scientific**
  - High quality of free/open-source software developed in universities and research centers
  - Sometimes ahead of commercial equivalents

- **Practical**
  - No user-friendly interface and/or poor documentation for most open source Finite Element Analysis (FEA) codes

General goal of the ONELAB project

Develop a platform for **integrating free Finite Element Analysis** (FEA) software:

- allowing the integration (by co-simulation) of any open-source code, whatever their characteristics
- with an intuitive GUI allowing newbie users to get started and guided into the world of FE modeling — *but with the possibility to construct sophisticated, upgradable, multi-code, multi-platform scripts for the specialized user*
- and with the possibility to construct both education- and business-specific tools

General goal of the ONELAB project

The solution should overcome two difficulties associated with free FEA software :

(1) The heterogeneity of the tools

(2) The missing “expert layer”, top-down validation and documentation found in commercial offerings

State of the art

- Many closed, commercial tools (COMSOL, Ansys Workbench, …)
- More open tools, e.g. GiD (http://gid.cimne.upc.es), but not free
- Closest free software: SALOME (http://salome-platform.org), but *very* large project, not well suited for building "fast and light" domain-specific applications
- Other open source projects: "multi-physic" codes (Elmer, etc.) still mainly focused on a single domain (CFD, solids, E-M); the implementation of new physics leads to bare-bones features, far from the refinement of specialized codes; no easy-to-use interface and no driving of other codes

ONELAB guiding principles

- Don’t reimplement, **interface** the existing!
- Make it as **small**, **lightweight** and as **easy to maintain** as possible (no solver-dependent code in the interface)
- Make it easy to provide **templates**, with interactive parameter modification
- ONELAB role = data **centralization**, (optional) **modification** and **redispatching**

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Issues of completeness and consistency of the parameter set are completely dealt with on the solver side

ONELAB features

(1) Heterogeneity of the tools

(2) Missing “expert” layer, top-down validation and documentation

ONELAB features

(1) Abstract interface to FEA codes

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- Model: blackbox, parameterizable via abstract interface

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(2) Development and documentation of templates ("meta-models")

- Model: blackbox, parameterizable via abstract interface
- Meta-model: set of models + selection logic

ONELAB implementation

Client-server:

- Clients: CAD kernels, meshers, solvers, post-processors
- Server: Gmsh (currently) + database

Abstract interface:

- The server **has no a priori knowledge of the clients** (no meta-language or exchange file format)
- The server **does not write input files for (native) clients**: the client communicates with the server to define what information should be exchanged

ONELAB implementation

Abstract interface to physical properties, constraints & code drivers:

- Library for parameter exchange:
    - Reference server in C++ for portability, e.g. on iOS/Android (`onelab::server`)
    - Clients in C++ (`onelab::client`) or Python
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  - Clients in C++ (`onelab::client`) or Python
  - Exchange parameters (`onelab::parameter`) through TCP/IP or Unix sockets, or in-memory
- "Native" clients use C++ or Python directly
- "Non-native" clients use Python, by instrumenting their input files
  - Currently: Elmer, OpenFOAM, Code_Aster, Abaqus, Gnuplot

ONELAB implementation

Native client: overloading of existing functions (GetDP)

```
...
DefineConstant[ Numstep = { 50, Name "Elmer/Number of time steps"} ];
DefineConstant[ TimeStep = { 0.1, Name "Elmer/Time step"} ];
...
```

Non-native clients: instrumentation the input files of the client (Elmer)

```
...
OL.line NumStep.number(50, Elmer/, Number of time steps);
OL.line TimeStep.number(0.1, Elmer/, Time step);
Simulation
Simulation Type = Transient
Timestep sizes = OL.get(TimeStep)
Timestep Intervals = OL.get(NumStep)
...
```

Preprocessing: conversion into a valid input file for the client (Elmer)

```
...
Simulation
Simulation Type = Transient
Timestep sizes = 0.1
Timestep Intervals = 50
...
```

ONELAB implementation

`onelab::parameter`

- name as '/'-separated path
- dynamic dependency list of clients and status change
- decorations (help, bounds, choices, ...)
- serialization and deserialization

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Example for native Gmsh & GetDP clients (in .geo or .pro files):

```
DefineConstant[ N = {32, Name "Number of slices"} ];
```

Example for Python client:

```
c = onelab.client()
N = c.defineNumber('Number of slices', value=32)
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ONELAB implementation

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Let’s have another look!

Conclusion

- Growing use of Gmsh and GetDP in academia and industry
- “Vulgarization” requires quite a bit of work, hence the ONELAB project:
  - A simple (trivial?) way to interface FEA solvers
  - Interactive, based on Gmsh, and free
  - And now available on iOS and Android
- Give it a try:

http://onelab.info

- Wishlist: we want an Octave server (and client)!

PS: Doing open source is rewarding!

Comment about Gmsh on http://www.fltk.org (sic):

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>From Anonymous, 20:33 May 18, 2004 (score=1)
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Translation (including misspellings!) for the non-french speaking:

```
>From Anonymous, 20:33 May 18, 2004 (score=1)
I am ashamed of the program for intelectuals you
should have more imagination you are the schame of
computer science
```

Thanks for your attention!

cgeuzaine@ulg.ac.be