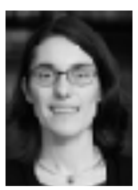
The committee

M. Stéphane Cotin
Directeur de Recherche (Rapporteur) - **Inria Nancy - Grand Est**

M. Hervé Delingette
Directeur de Recherche (Rapporteur) - **Inria Sophia Antipolis - Méditerranée**

M. Bernhard Thomaszewski
Associate Professor (Rapporteur, invité) - **Université de Montréal - Dept. I.R.O.**



Mme Maud Marchal
Maître de Conférences HDR (Examinatrice) - **INSA Rennes - IRISA**

Mme Marie-Paule Cani
Professeur des Universités (Examinatrice) - **Ecole Polytechnique - LIX**

M. François Faure
Professeur des Universités (Examinateur) - **Univ. Grenoble Alpes - Inria Grenoble -RA -LJK**

M. Fabrice Jaillet
Maître de Conférences HDR (Examinateur) - **Université Lyon 1 — LIRIS**

M. Tanneguy Redarce
Professeur des Universités (Examinateur) - **INSA Lyon — Laboratoire Ampère**

Simulation interactive d'objets déformables pour la conception de simulateurs d'apprentissage aux gestes médicaux-chirurgicaux

Florence Zara

Université Lyon 1, LIRIS, SAARA-ORIGAMI

Habilitation à Diriger les Recherches

Lundi 19 octobre 2020

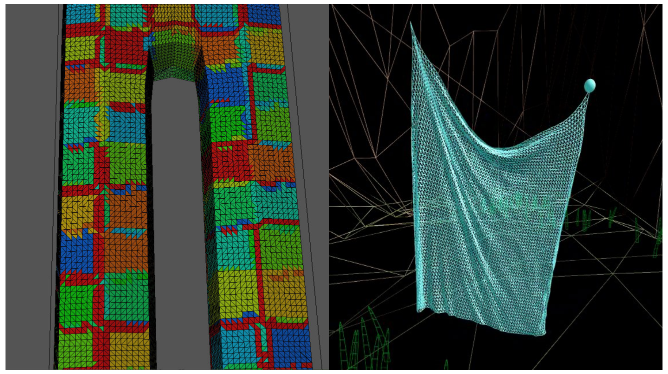
Who am I?

Grenoble — **Strasbourg** — **Lyon**

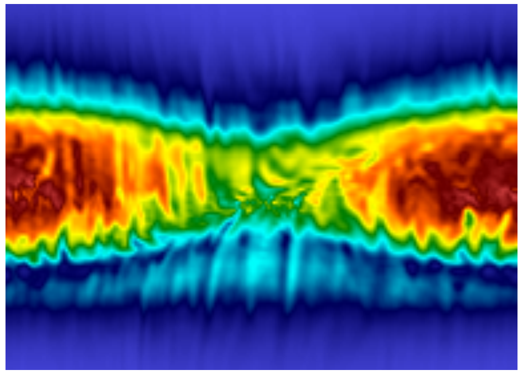
INPG PhD
2000-2003
ID-IMAG, INRIA
Grenoble 2

ATER
2003-2005
LSIIT, ULP

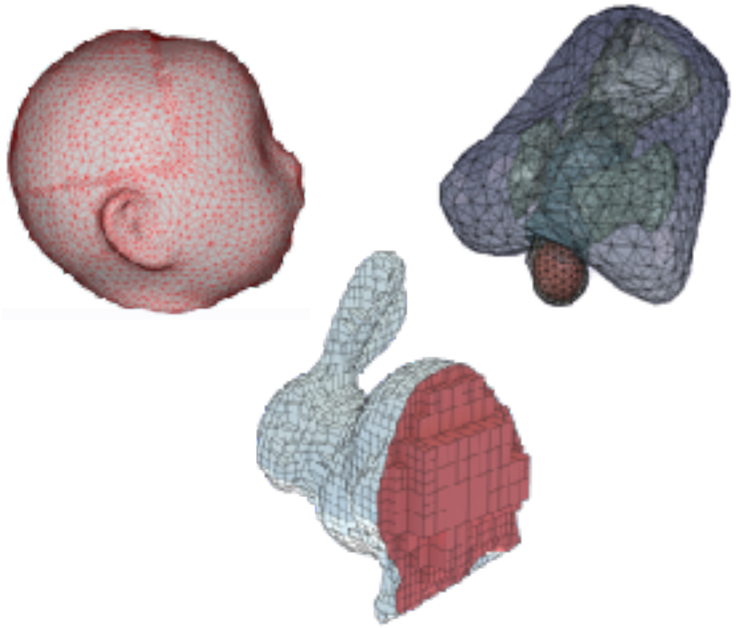
Since sept. 2005
Associate Professor
LIRIS, Lyon 1



Parallel computing
Computer Graphics



Parallel computing
High performance visualization



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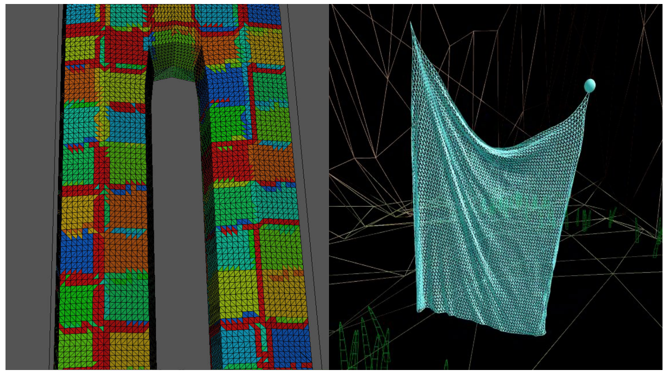

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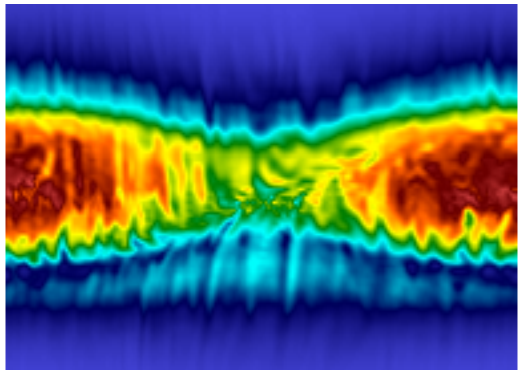

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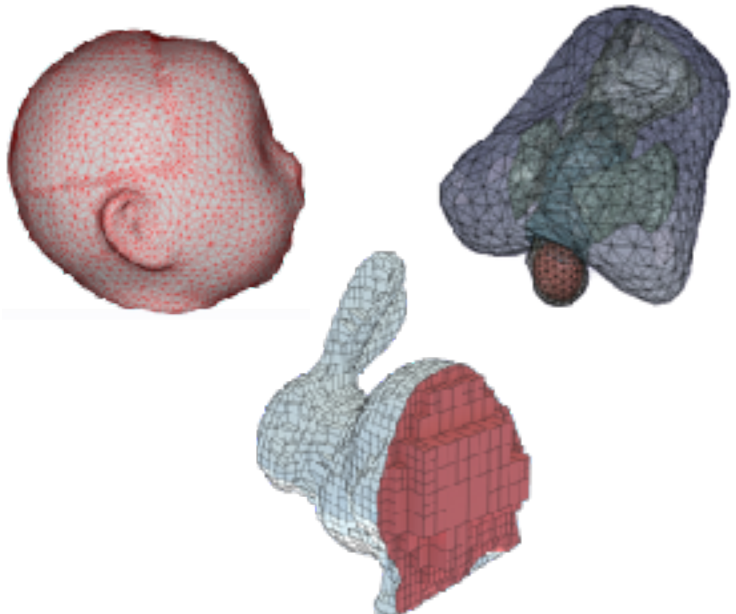
High performance visualization



Involvement in the scientific community

Scientific animation

- **National:**
  - **GTAS 2007**
  - **Theme F of GdR STIC-Santé (7 years):** 10 thematic days,1 thematic school
- **Eurographics workshop:**
  - **VRIPHYS 2015, VRIPHYS 2017**

24 Publications

- **in Computer Graphics:** **Pattern Recognition Letters, Visual Computer, VRIPHYS, GRAPP**
- **in Biomechanics:** **CMBBE, EMBC, Book's chap.**

Scientific responsibilities

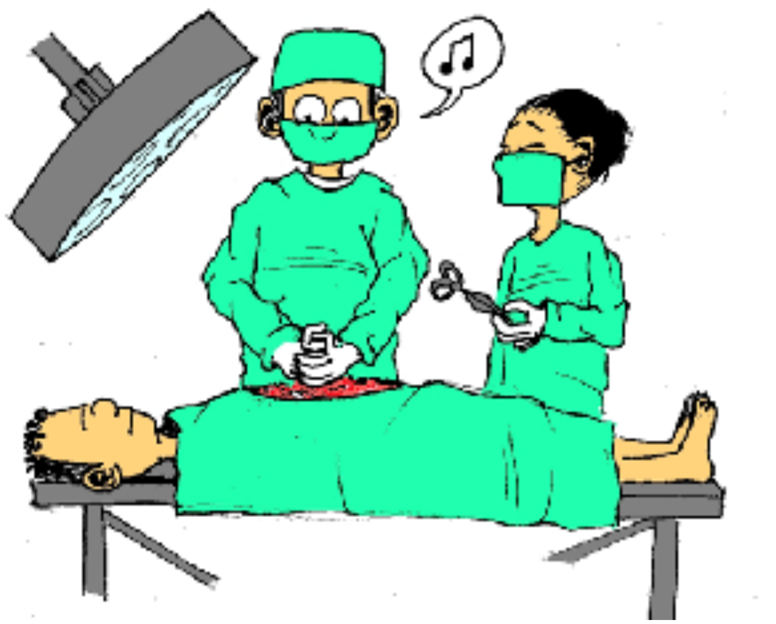
- **Member of the LIRIS council since 2011**
- **Co-superviser of ORIGAMI team since sept. 2020**
- **7 selection committees for associate professors**
- **6 PhD committees outside of the co-supervision**

Motivation - Context of medical training

"Never the first time on the patient"

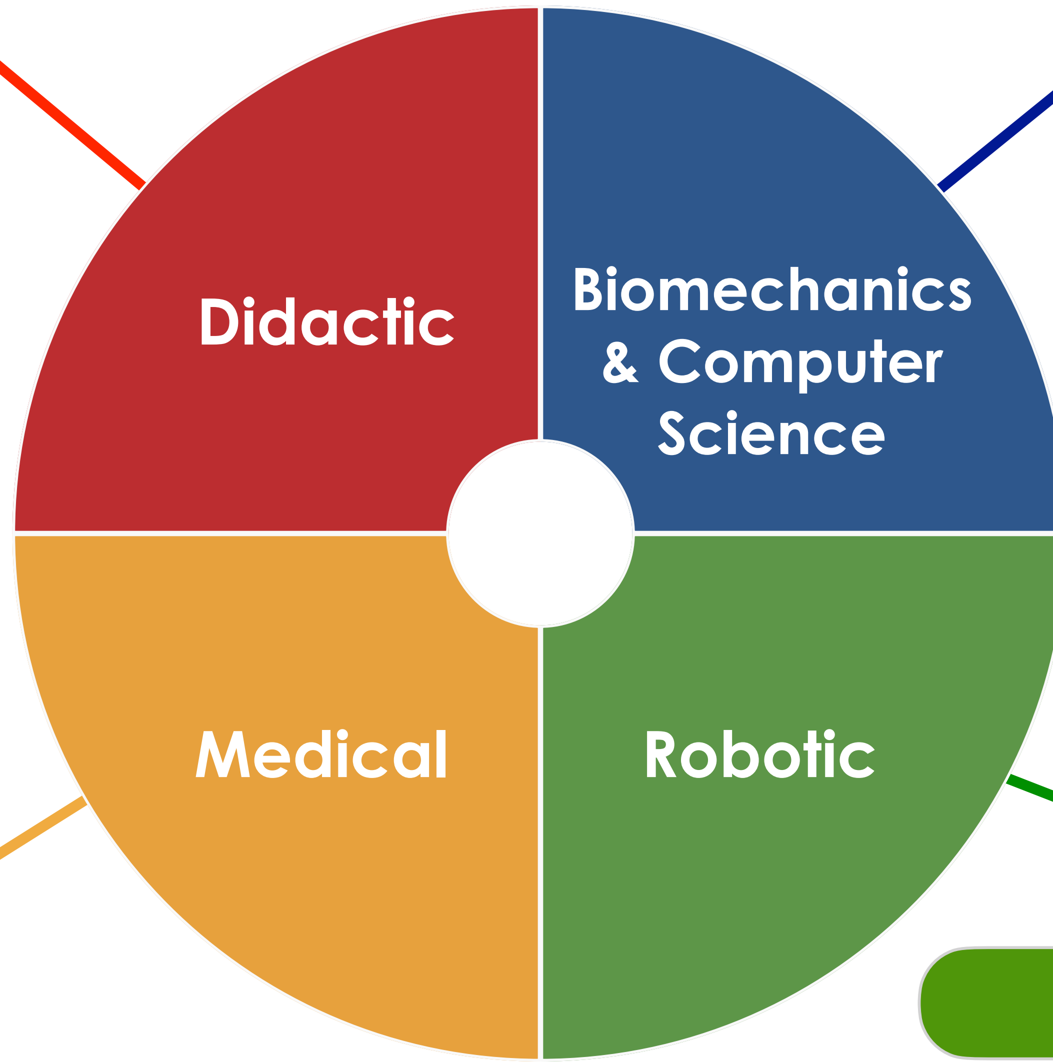
French High Authority of Health (HAS), 2012.

How to learn medical gestures without any risk for the patient?



LEMI Dessins de Presse

New training simulators based on Virtual Reality



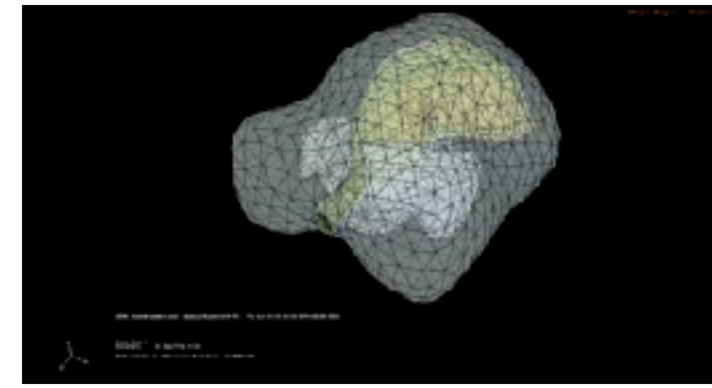
Didactic software

Analyze, understand the gesture and its learning

Elaborate scenarii

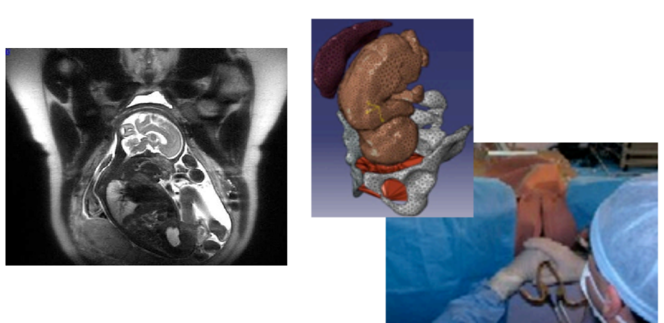
Evaluate the simulator

Numerical simulation



Simulate the organs behavior

Validation



Validate the components

Haptic device

Provide tactile feelings

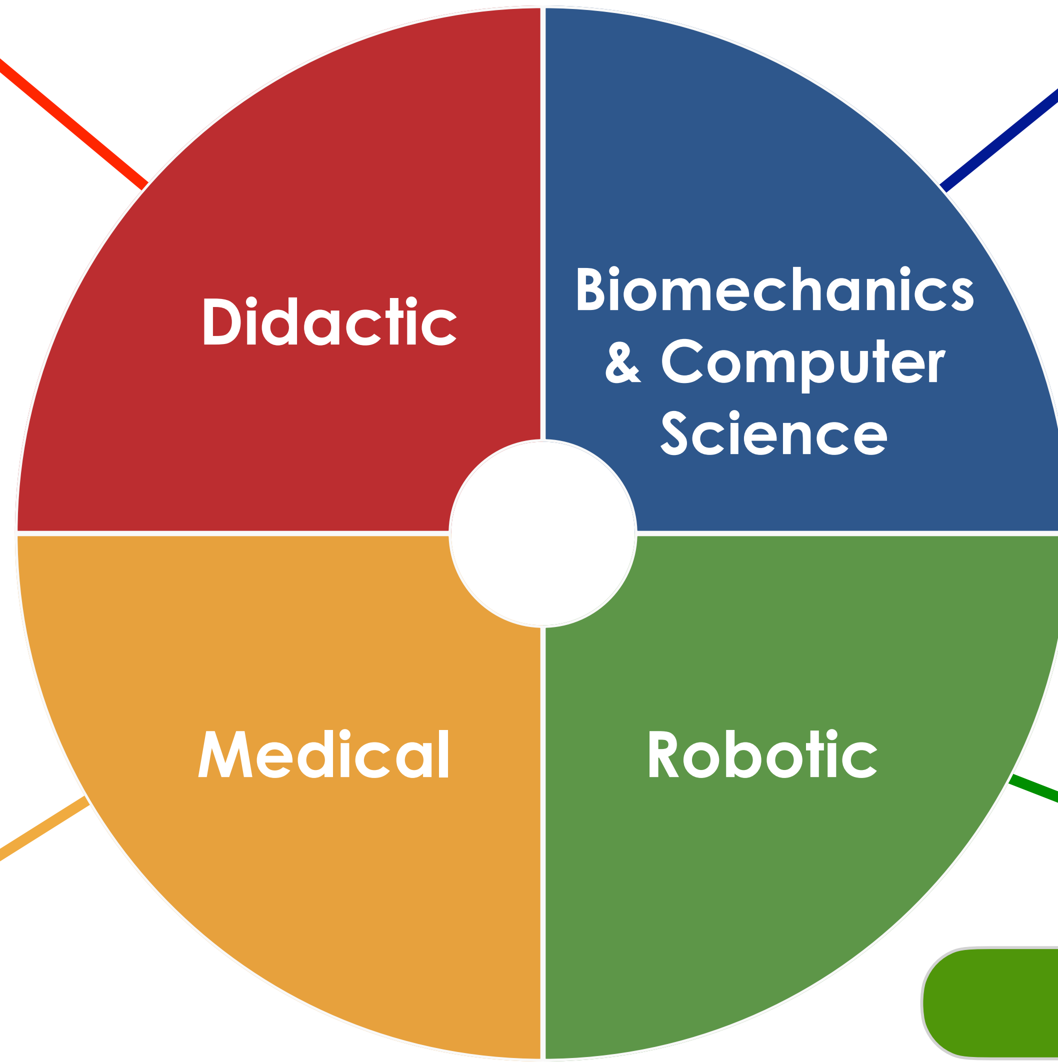
New training simulators based on Virtual Reality

Didactic software

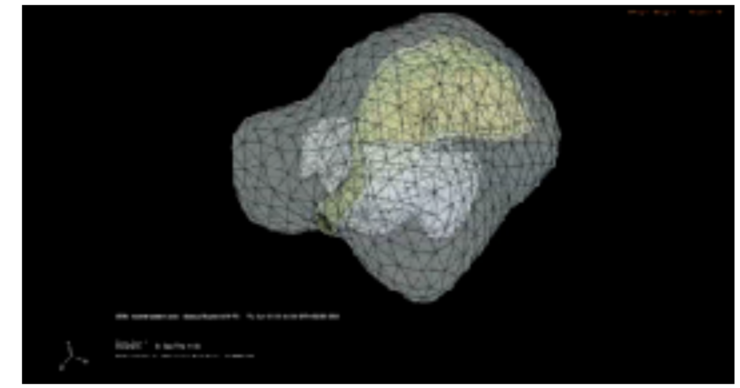
Analyze, understand the gesture and its learning

Elaborate scenarii

Evaluate the simulator



Numerical simulation



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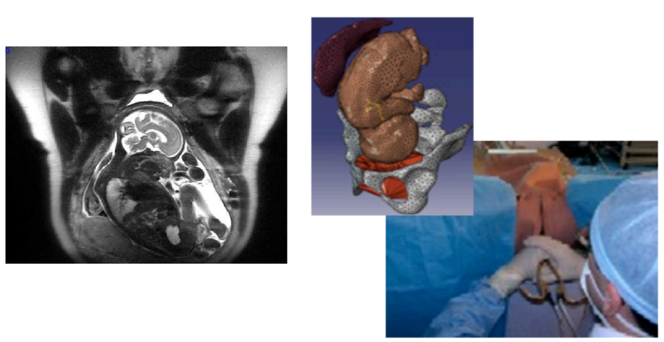

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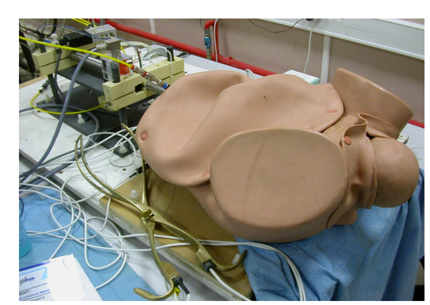

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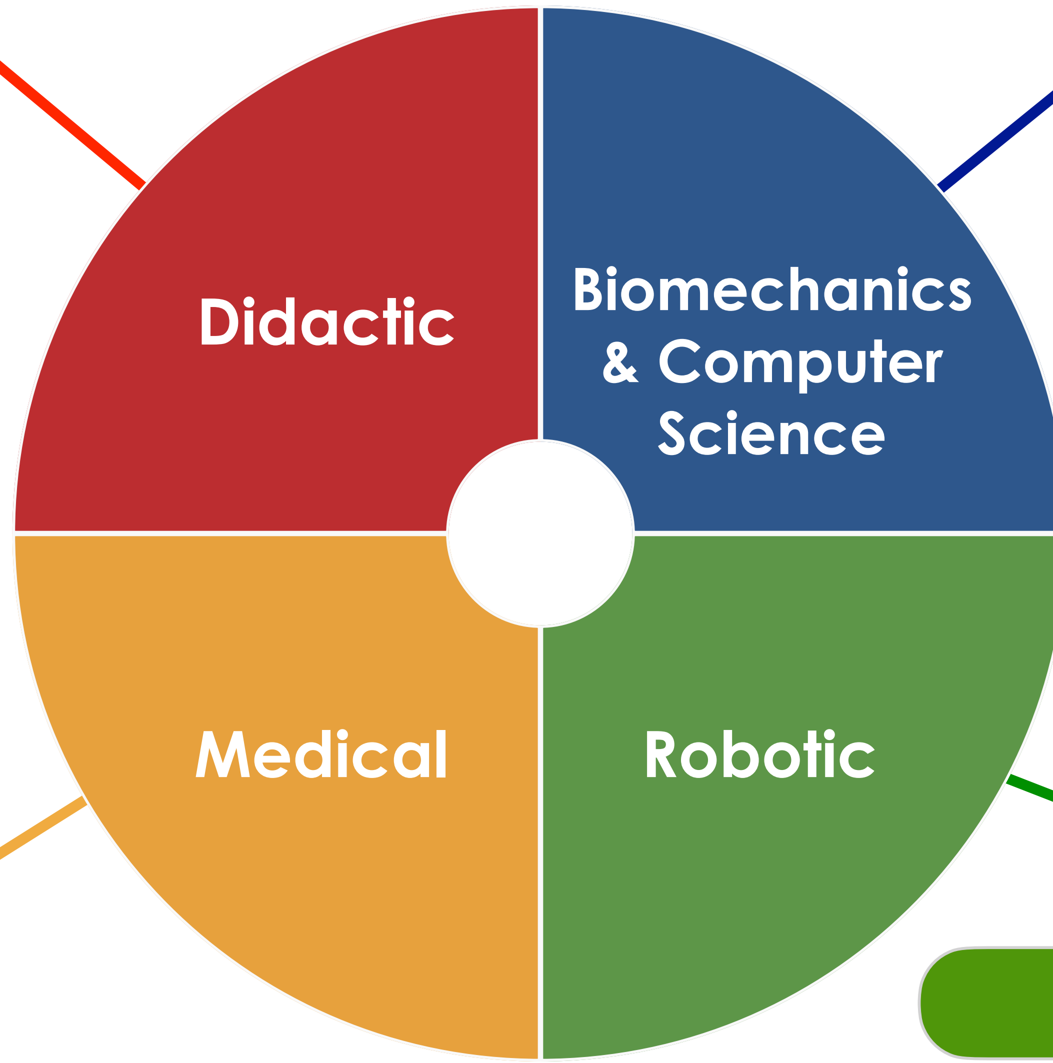

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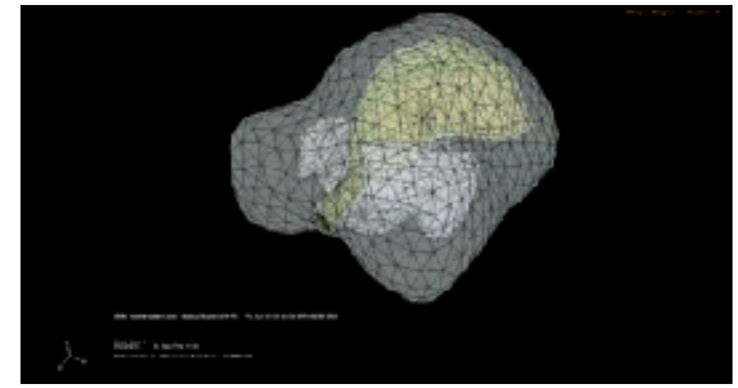
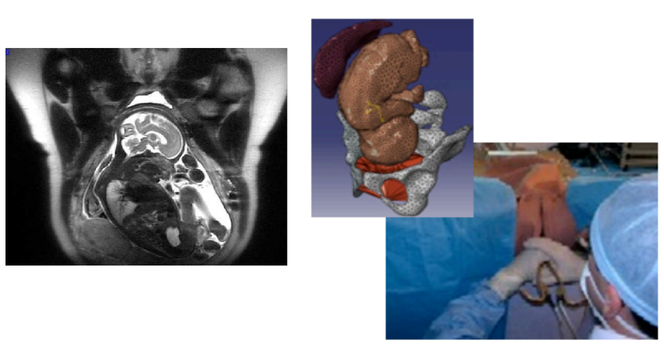


My topic of research

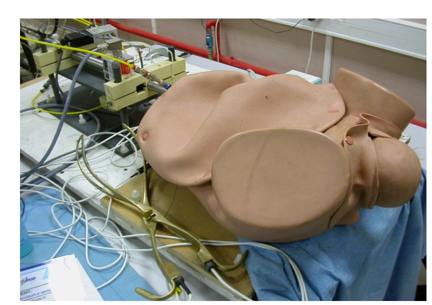
Simulate the organs behavior

Validation



Validate the components

Haptic device



Provide tactile feelings

Collaborations

Didactic

LSE
LABORATOIRE DES SCIENCES DE L'EDUCATION


libm

Robotic

Ampère



Biomechanics & Computer Science

LIRIS

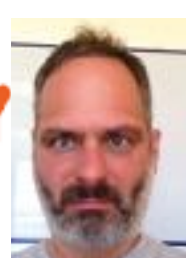




TIMC

ARMINES


LBMC




Lab PHYS
ENS de LYON

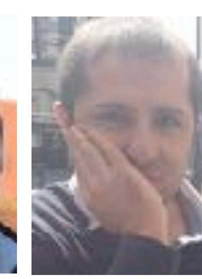
Medical

Hospices Civils de Lyon


Industrial

HRV





Thanks!

27 Master's students & 6 PhDs co-supervised with

Ampère · TIMC · LBMC · Lab PHYS ENS de LYON

Projects

Europe: ENVISION

France: IDEFI SAMSEI, LabEx PRIMES

Rhône-Alpes: cluster ISLE

Mathieu Bailet

2011 – 2014

Elsa Fléchon

2011 – 2014

Charles Barnouin

2016 – 2020

Romain Buttin

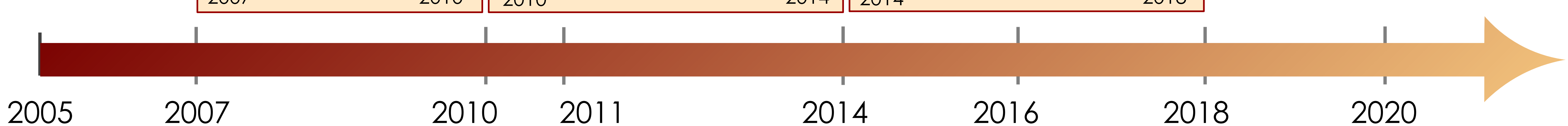
2007 – 2010

Xavier Faure

2010 – 2014

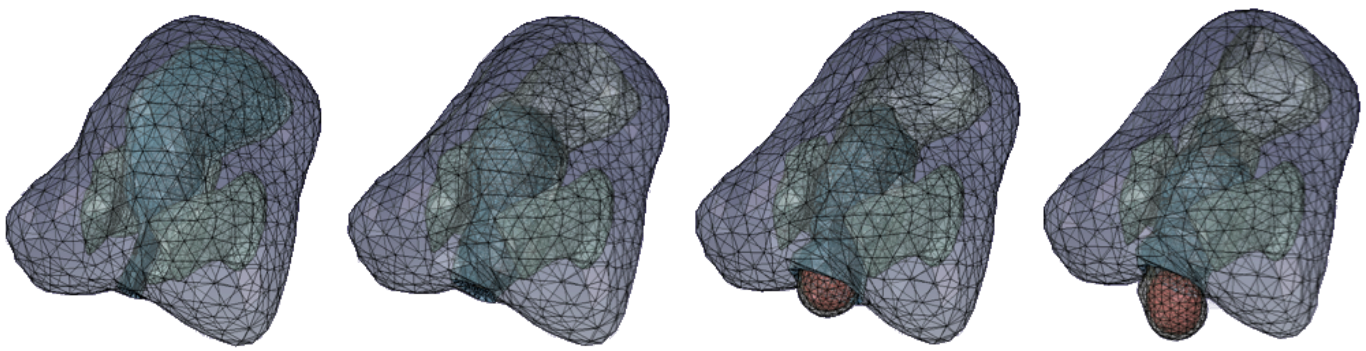
Karolina Golec

2014 – 2018



My topic of research

Numerical simulation for medical training simulators



Outline of the talk

- Challenges of interactive medical simulation
- Strategy: towards a generic model
- Contributions
- Application
- Conclusion & Research program

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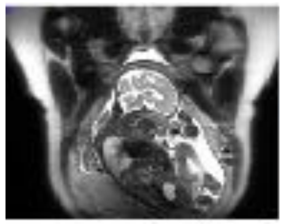
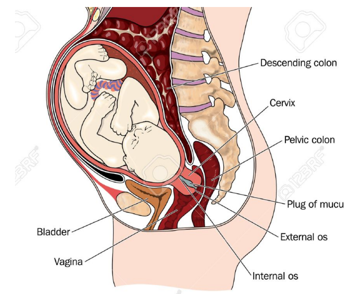
The usual pipeline for medical simulations

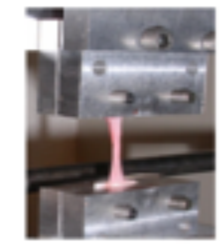
Medical images
MRI, scan



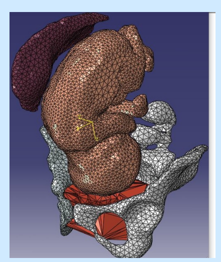
Anatomy



Mechanical tests on organs



Geometrical models
with high resolution



Constitutive laws
Mechanical properties
E, ν

Numerical simulations

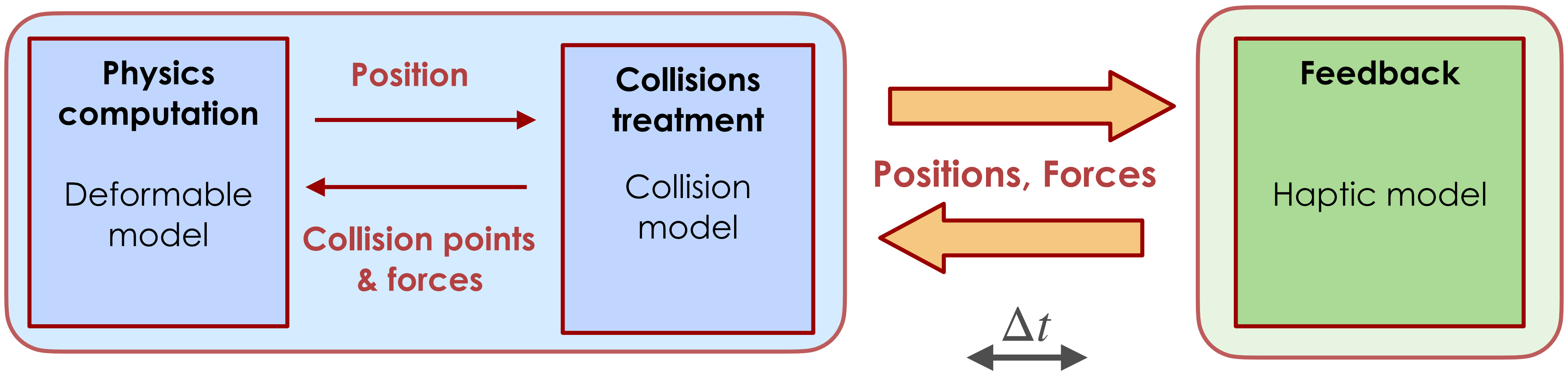
Solving of Partial Differential Equations with Boundary Conditions

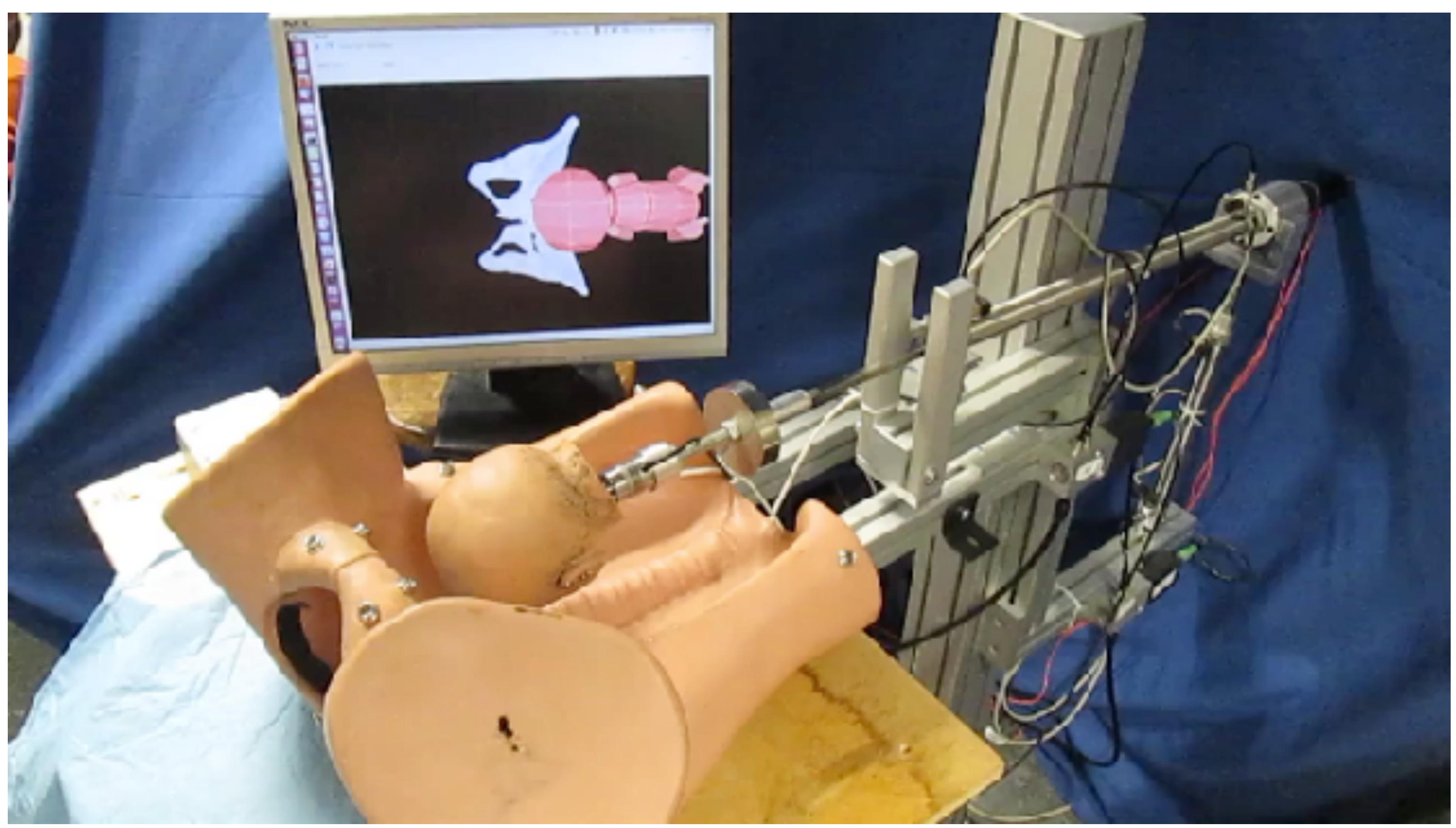
Forces accumulation

Numerical integration

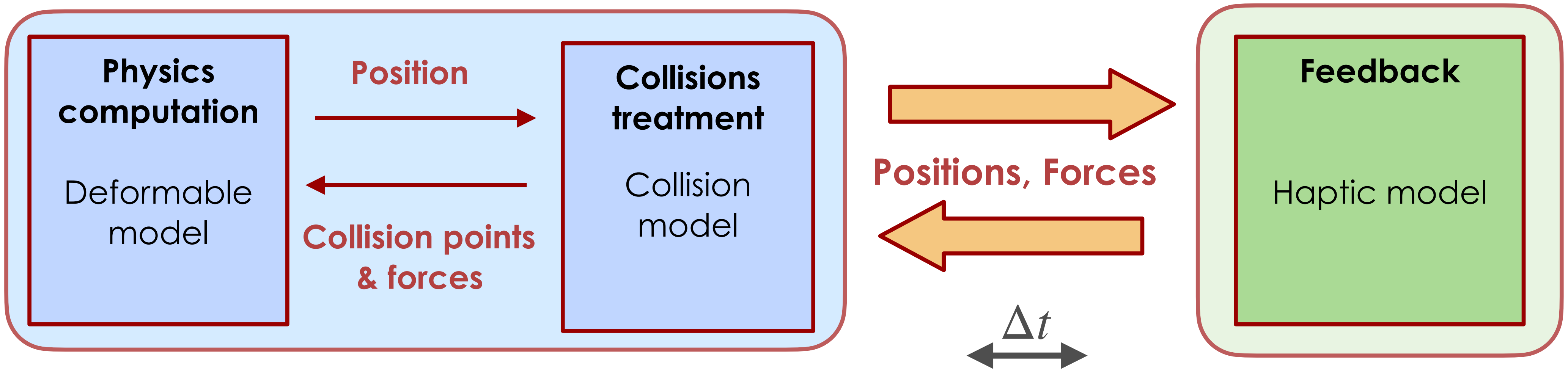
Collision

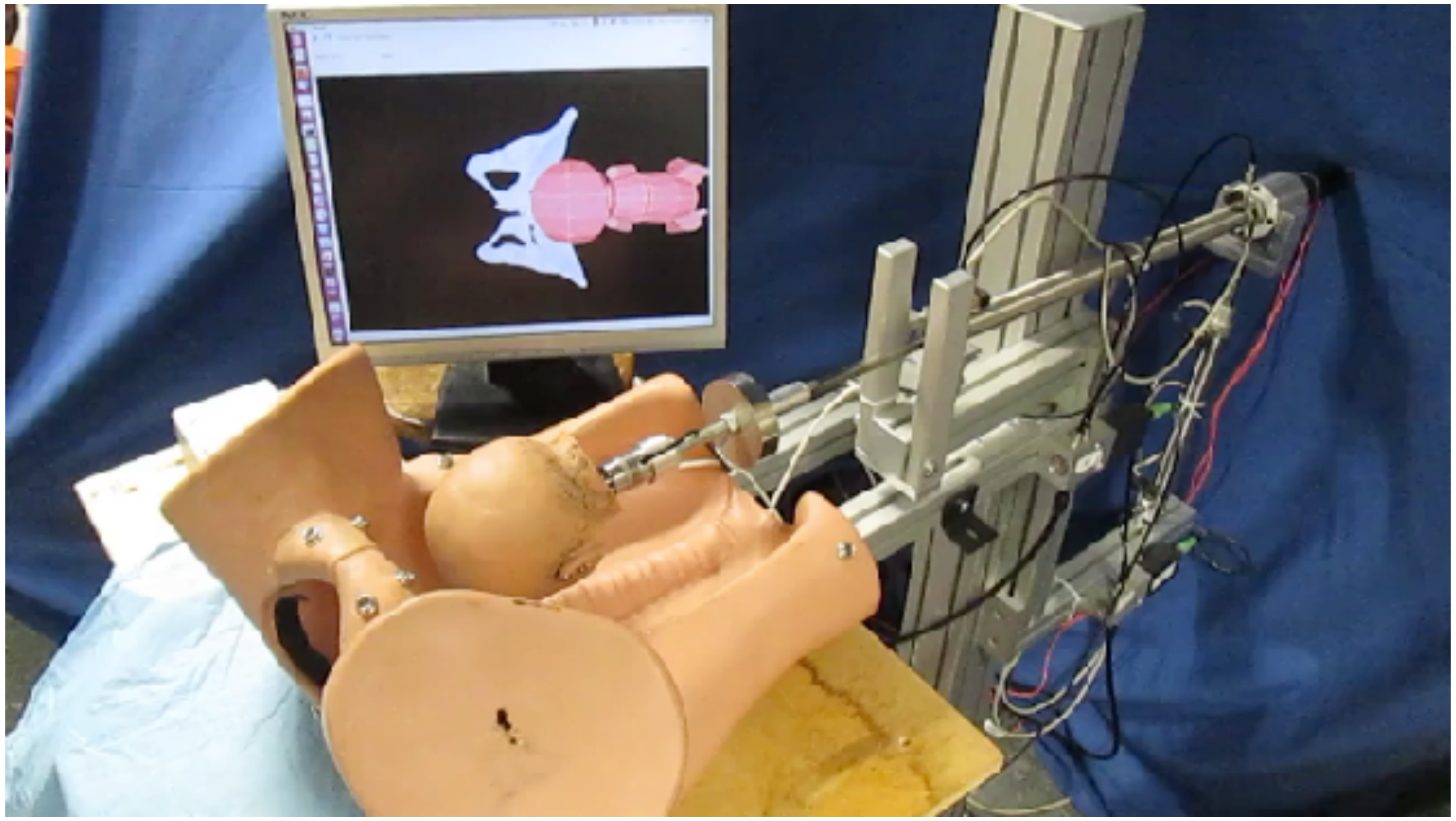
First challenge - Stability & time





First challenge - Stability & time

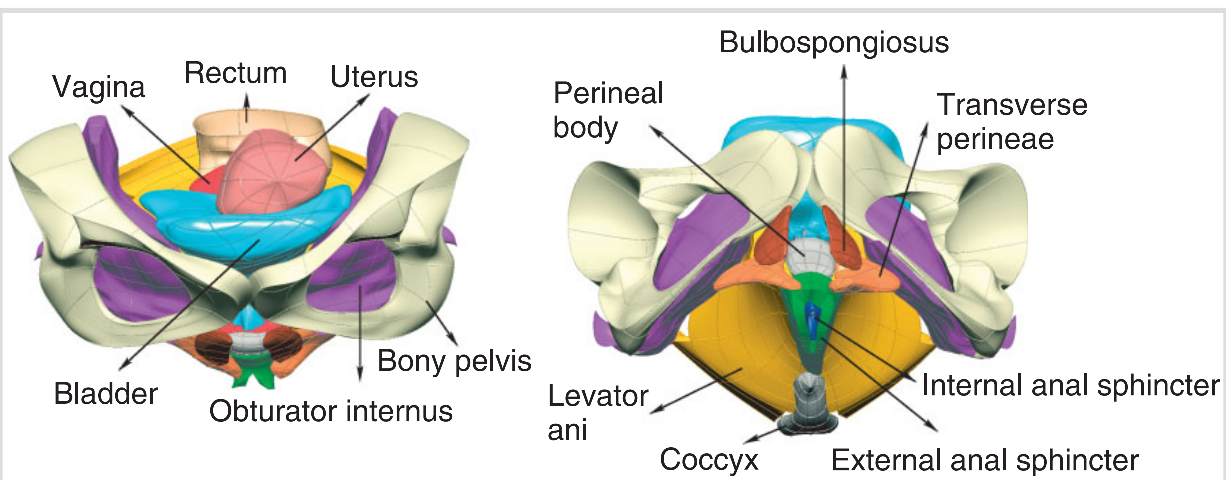




Second challenge -
A globally realistic behavior

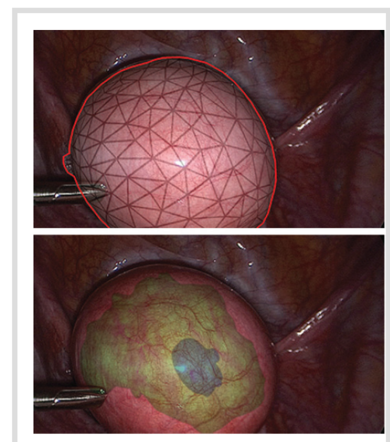
Complex simulations — *accuracy of biomechanical behavior* — **Simplified simulations**

Physiology



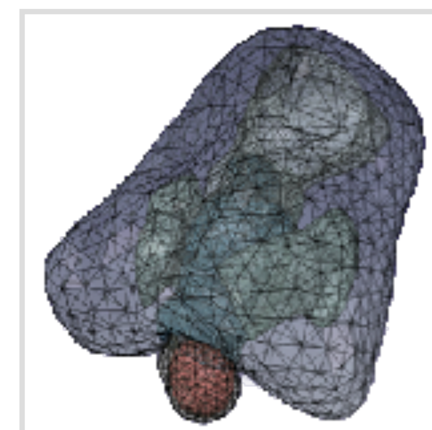
[Li 2008]

Operations planification



[Collins 2014]

Training simulators



[Buttin 2013]

Several hours — *execution time* — **Interactive time**

Outline of the talk

- Challenges of interactive medical simulation
- Strategy: towards a generic model
- Contributions
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Dynamic adaptation

Model

Topological model

Constitutive law

Physical model

Collision model

Dynamic adaptation

Model

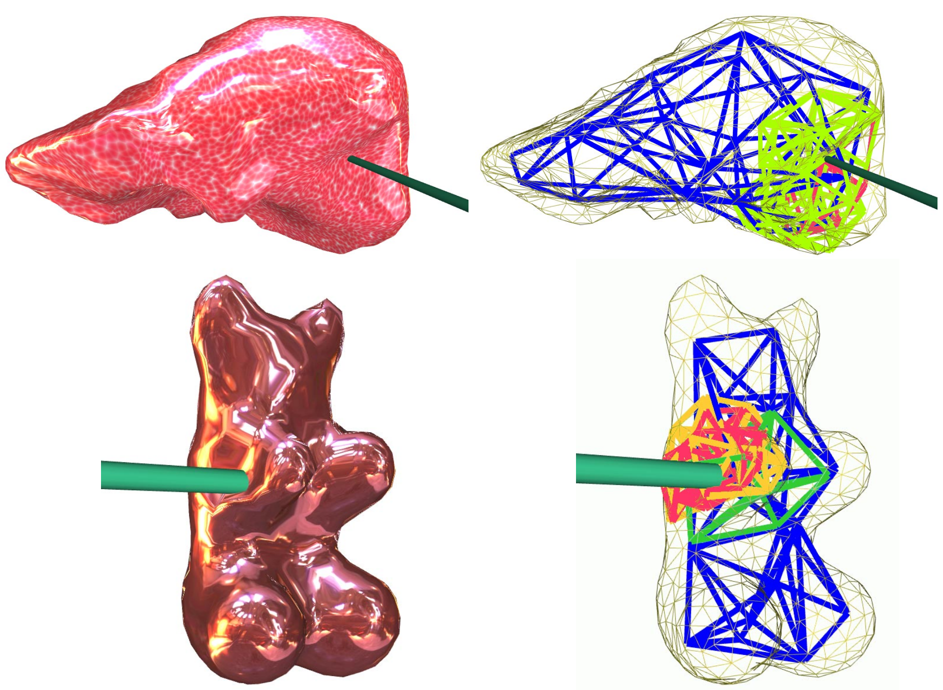
Topological model

- Refinement/merging
- Cutting
- Piercing

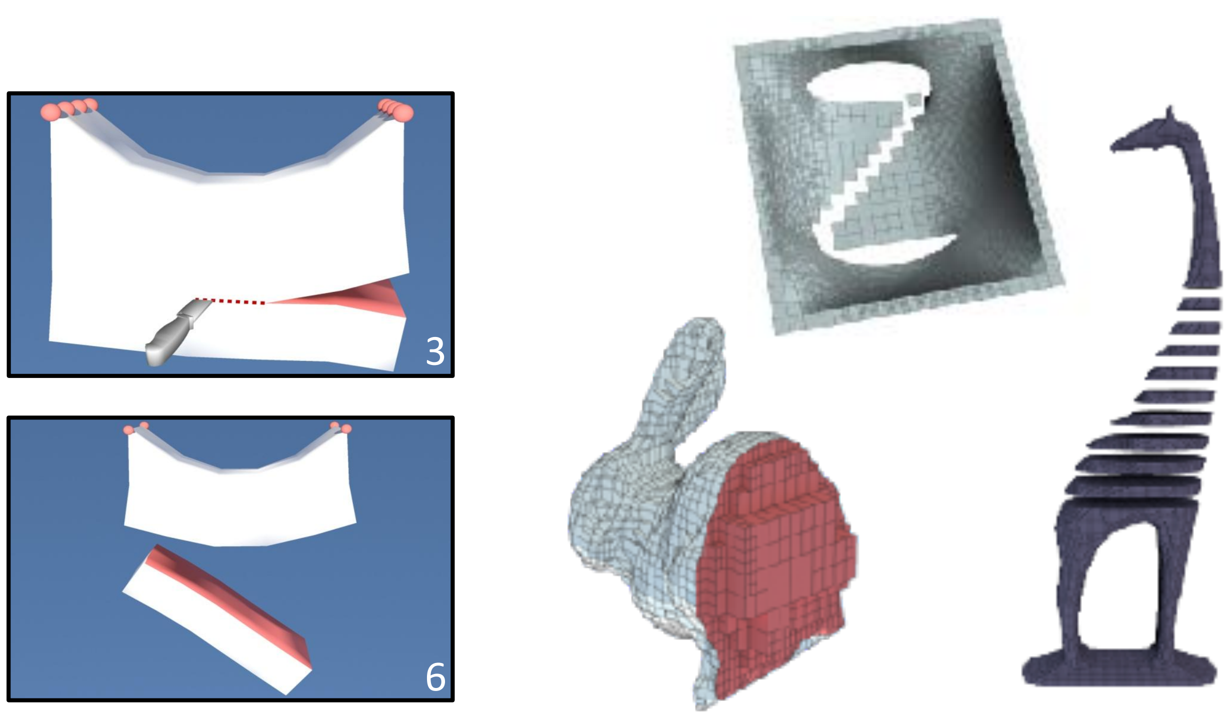
Constitutive law

Physical model

Collision model



[Debunne 2009]



[Fléchon 2014]

Dynamic adaptation

Model

Topological model

- Refinement/merging
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Constitutive law

- Linear
- Non-linear

Physical model

Collision model

Dynamic adaptation

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Topological model
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Constitutive law
- Linear
- Non-linear

Physical model
- 3D FEM
- 2D FEM - Shell
- Mass-tensor
- Mass-spring system

Collision model

3D Finite Element

\+ Accuracy

\- Computation time

2D FE - Shell

\+ Less time consuming

\- No volume

Mass-tensor approach

\+ Optimization for time

\+ Accuracy

\+ Force on nodes

\- Formulation not so easy

Mass-spring system

\+ Computation time

\+ Easy to implement

\- Accuracy

\- E, ν

Dynamic adaptation

Model

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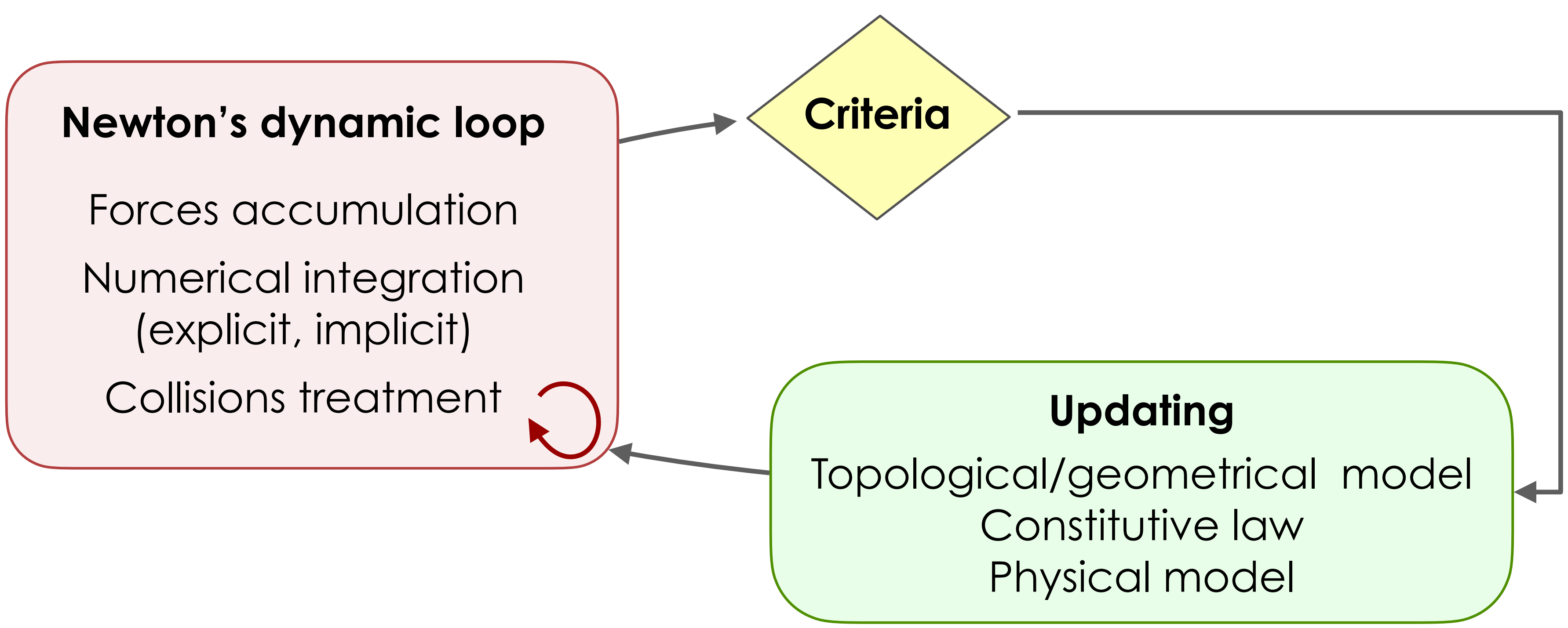
Collision model

Simulation



Contributions overview

Model

1 - A unified data structure

Topological model	Physical model

Forces computation

2 - Generation of mass-tensor force code

3 - Extension of mass-spring system

4 - A surface physical model

Simulation

Simulation's loop

Forces accumulation

Numerical integration (explicit, implicit)

Criteria

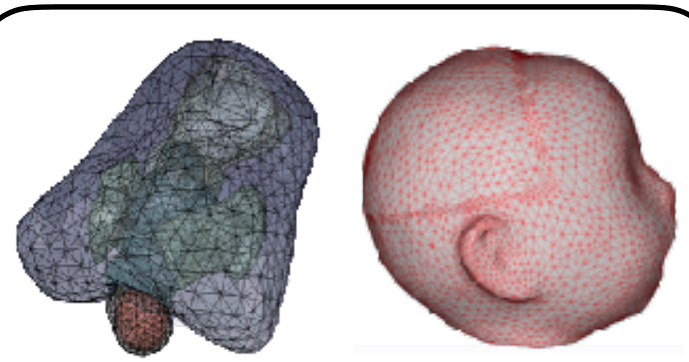
Updating

Topological/geometrical model

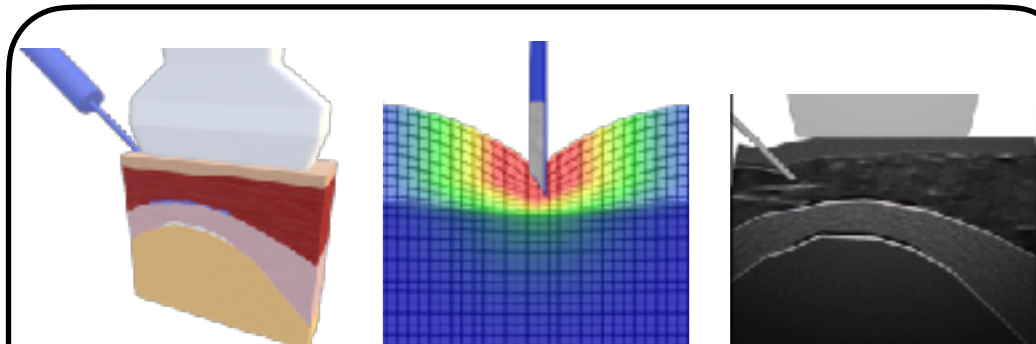
Constitutive law

Physical model

Couplage to haptic devices



Childbirth simulator



Puncture simulator

Contributions overview

Model

1 - A unified data structure

Topological model	Physical model

Forces computation

- **2 - Generation of mass-tensor force code**
- **3 - Extension of mass-spring system**
- **4 - A surface physical model**

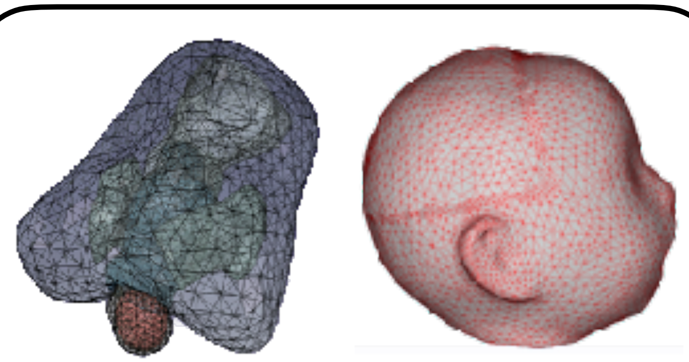
Simulation

Simulation's loop
- Forces accumulation
- Numerical integration (explicit, implicit)

Criteria

Updating
- Topological/geometrical model
- Constitutive law
- Physical model

Couplage to haptic devices



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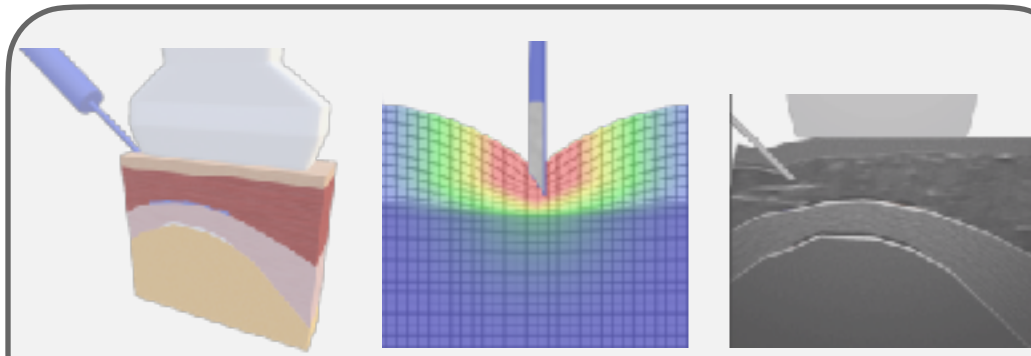

Puncture simulator

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  2. Generation of mass-tensor force code
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1 - A unified data structure

Topological model | **Physical model**

2 - Generation of mass-tensor force code

3 - Extension of mass-spring system

2011 2014

PhD Thesis of Elsa Fléchon

LIRIS

Project: **Bourse ministérielle & LIRIS projects**

MINISTÈRE DE L'ENSEIGNEMENT SUPÉRIEUR, DE LA RECHERCHE ET DE L'INNOVATION

Liberté Égalité Fraternité

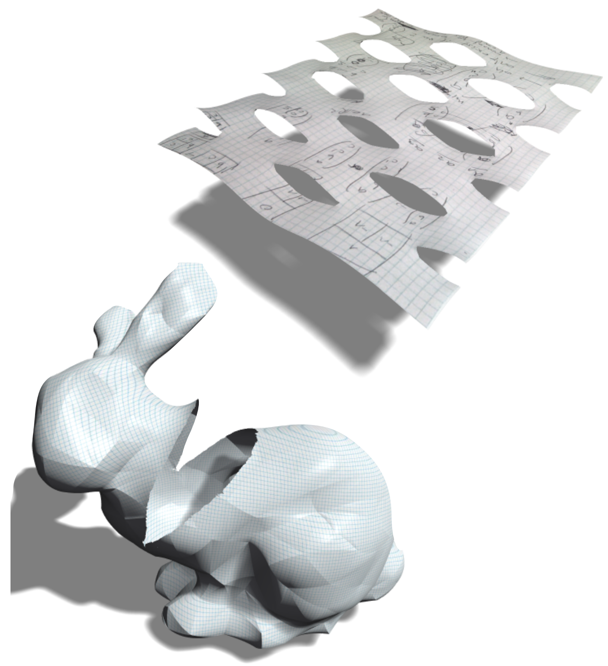
LIRIS

State of the art

Cloth in 2D

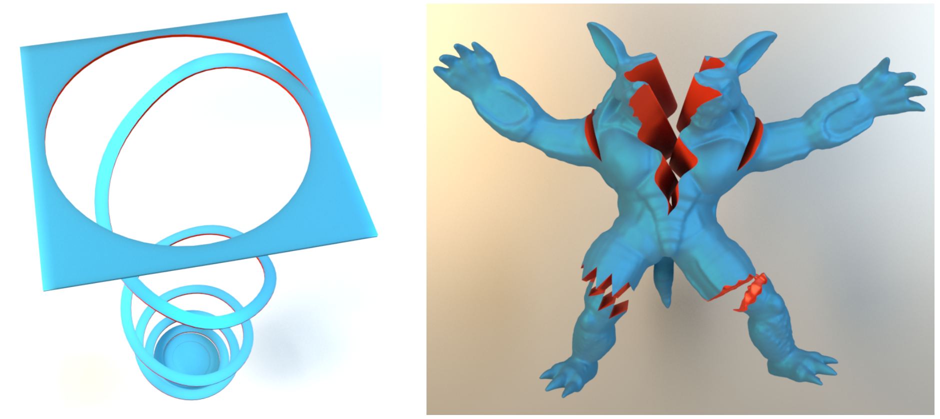
[Narain 2012]

Shell in 2D

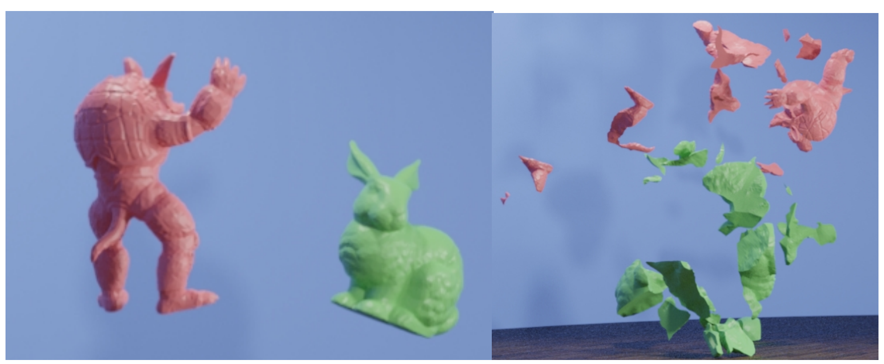


[Kaufmann 2009]

Cutting based on eXtended Finite Elements

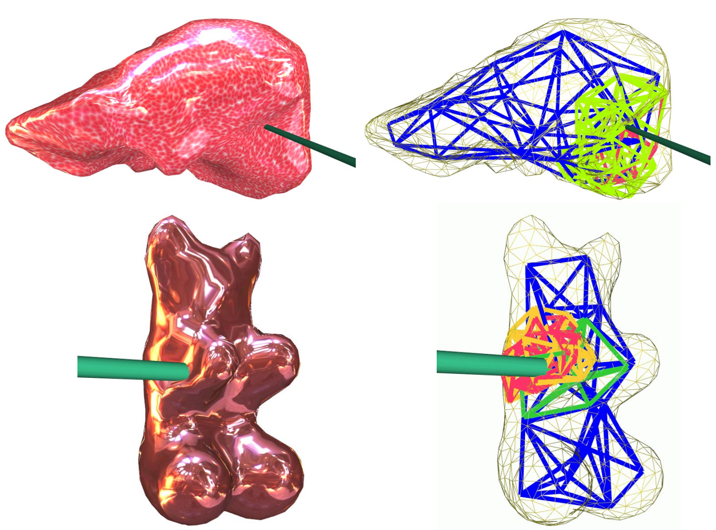


[Koschier 2017]



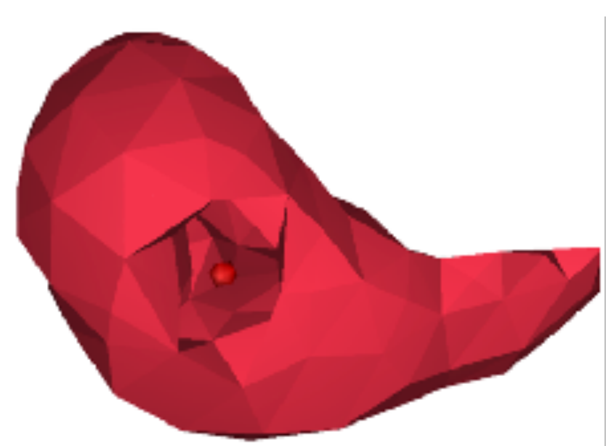
[Chitalu 2020]

Adaptative level of detail



[Debunne 2009]

Topological model



[Meseure 2010]

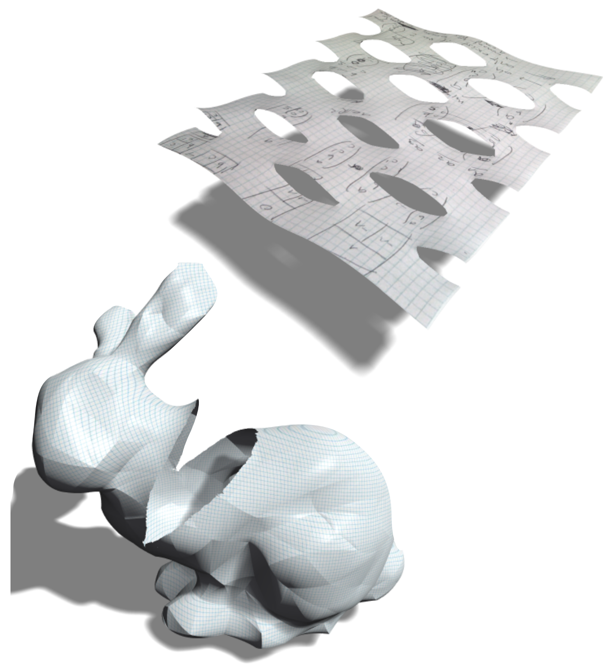
State of the art

Cloth in 2D

Images copyright Rahul Narain, Armin Samii, and James F. O'Brien

[Narain 2012]

Shell in 2D



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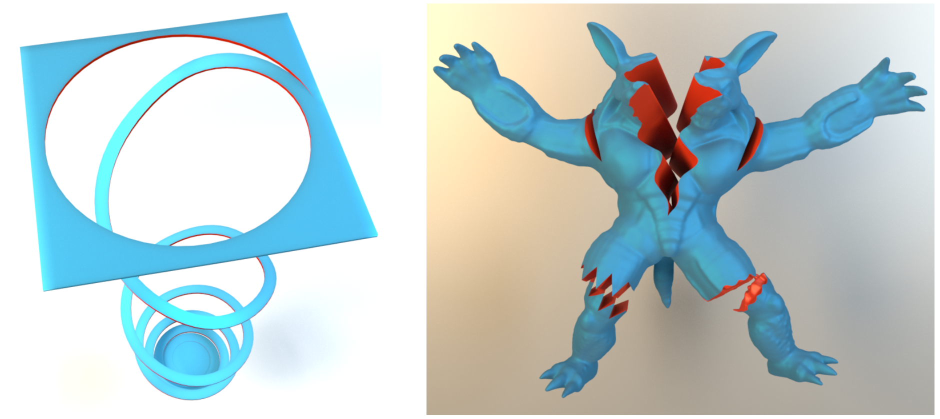
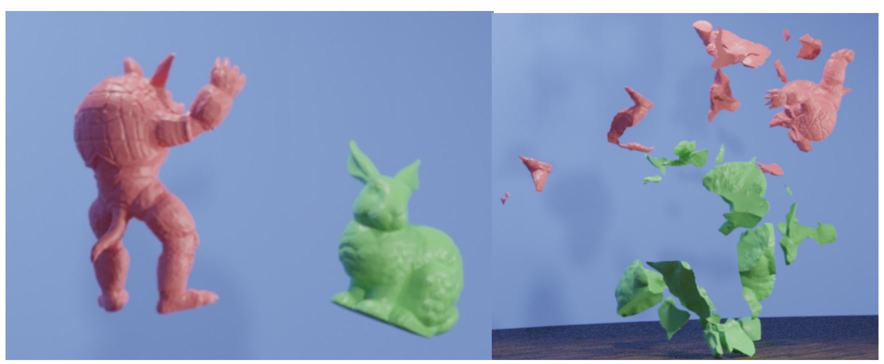
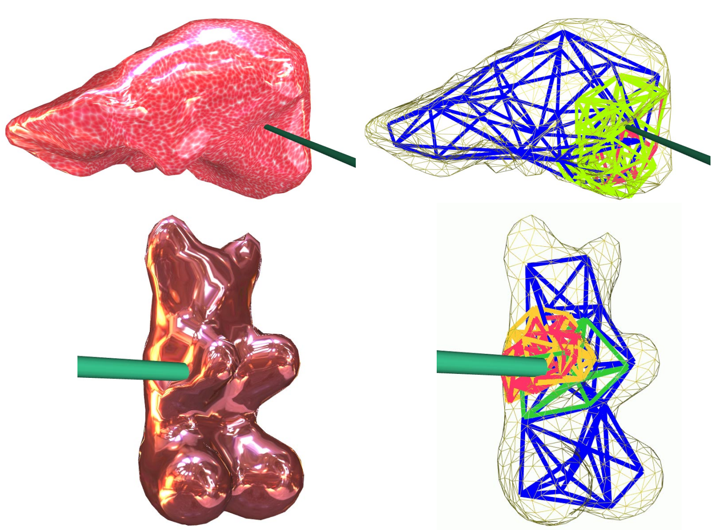


[Koschier 2017]



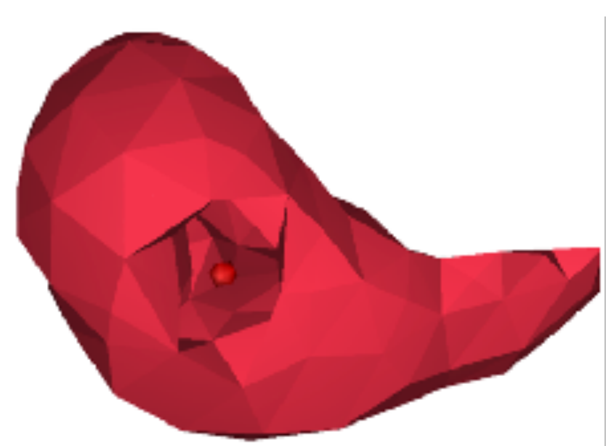
[Chitalu 2020]

Adaptative level of detail



[Debunne 2009]

Topological model



[Meseure 2010]

Our aim:

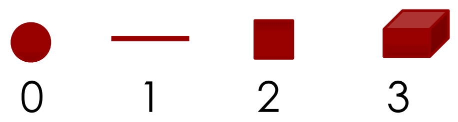
A single description for topology / geometry / physics / in 2D & 3D

An approach suitable for several physical models

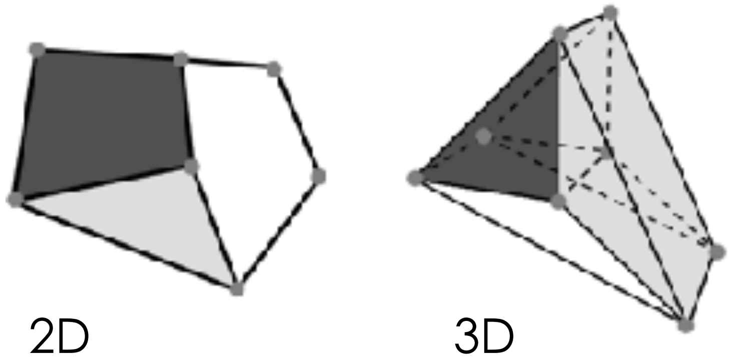
Definition of the data structure

Definition of the data structure

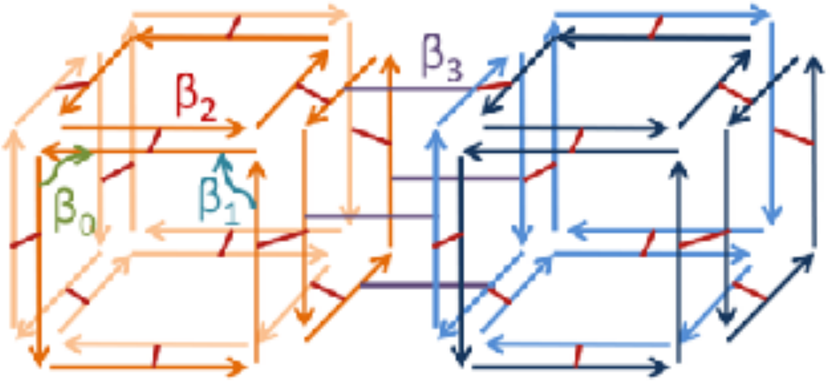
1) <u>Topology = **combinatorial maps** [Lienhardt 1991, Damiand 2012]</u>



object = set of i-cells



need incidence & adjacency relationships



darts and pointers

Definition of the data structure

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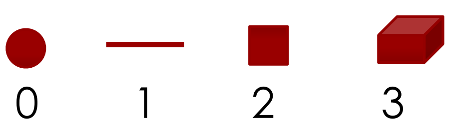

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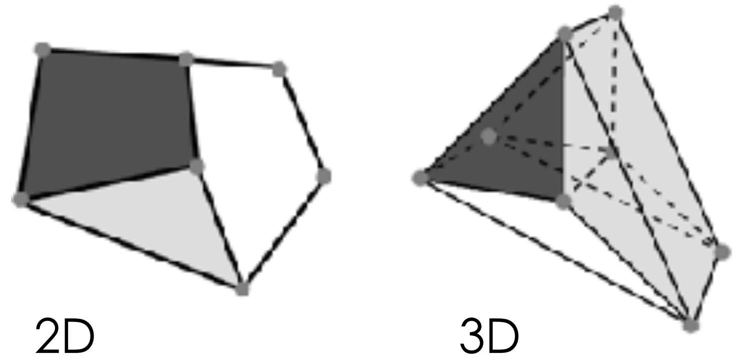

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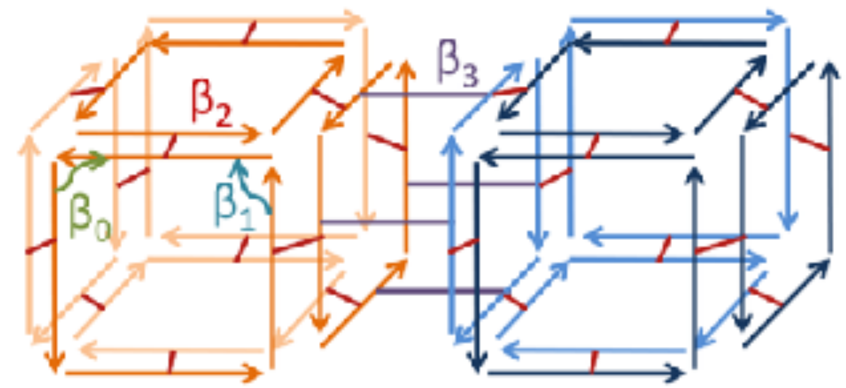
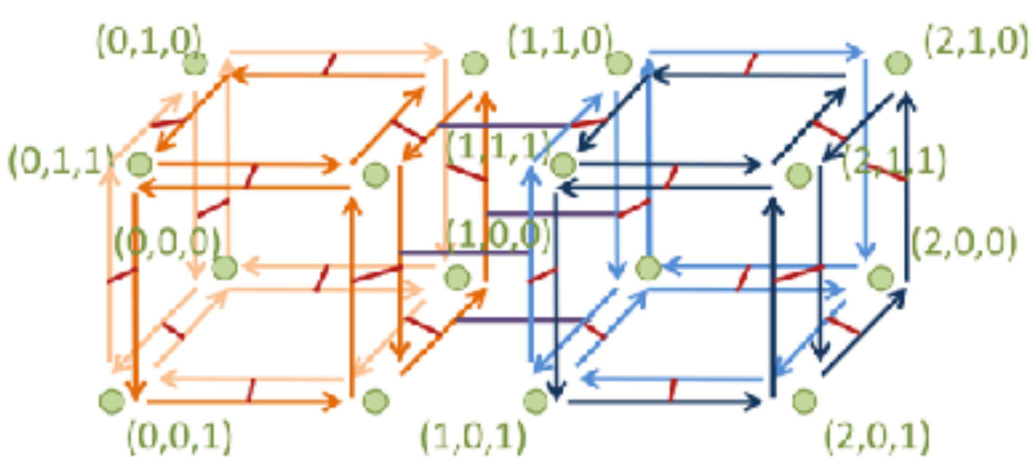


darts and pointers

2) Geometry = **Linear Cell Complex** [Lienhardt 1991, Damiand 2012]



geometry embedded in 0-cells

Definition of the data structure

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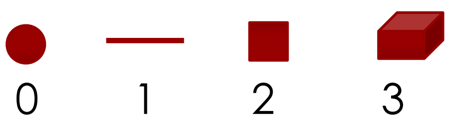

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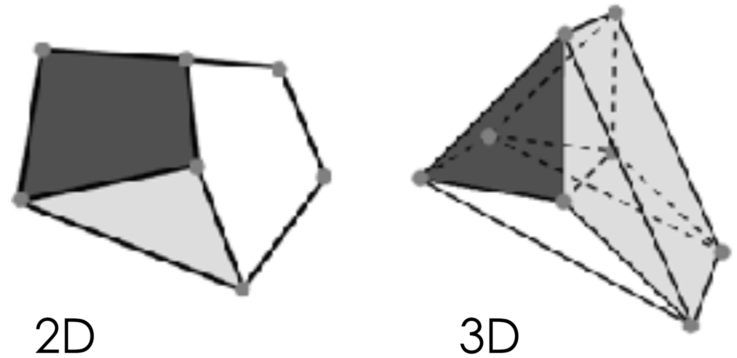

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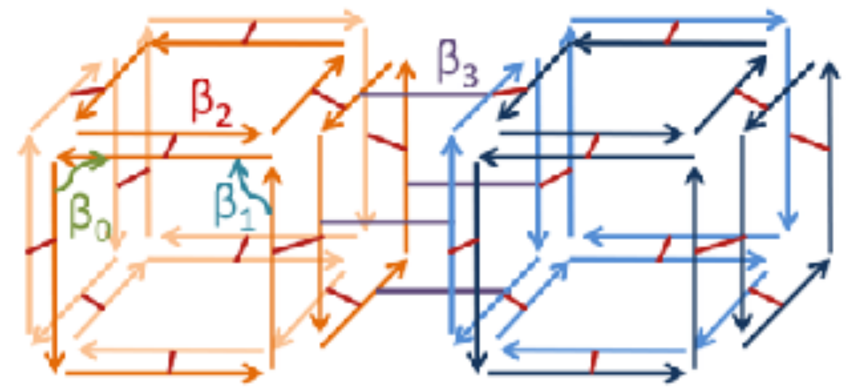

darts and pointers

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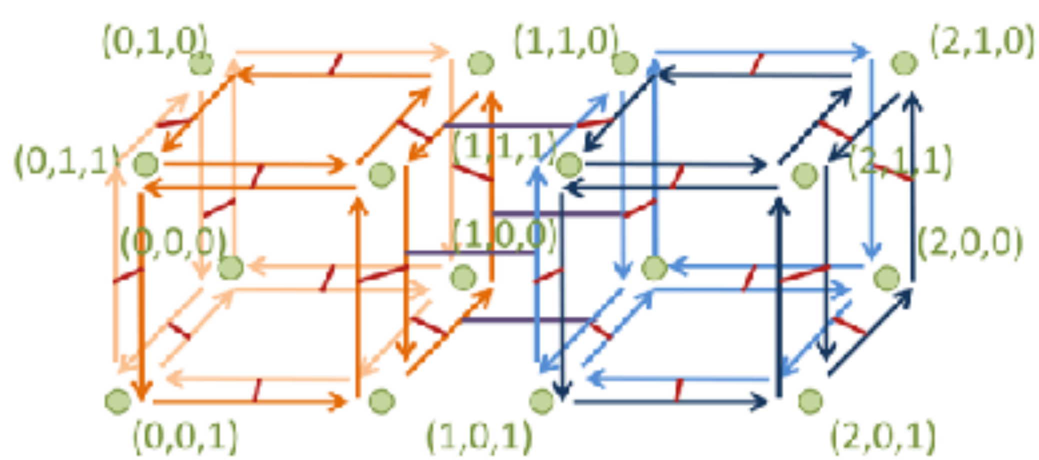


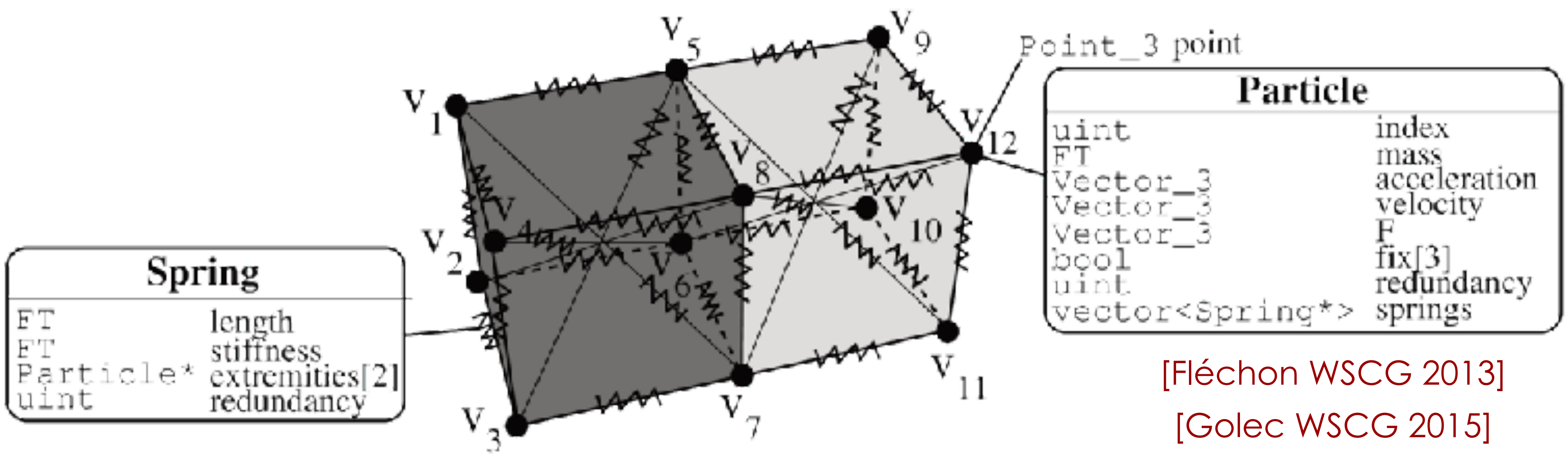
geometry embedded in 0-cells

We can mix several topologies of 2-cells or 3-cells inside the same object

Definition of the data structure

3) Physics = **add mechanical properties into i-cells**

For mass-spring system: *0-cells: particles; 1-cells: springs; 3-cells: internal springs*



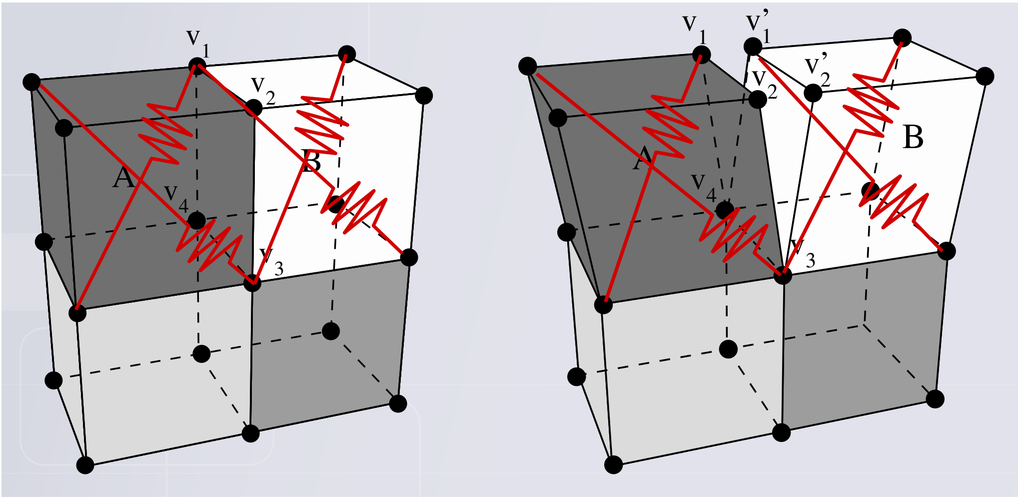
[Fléchon WSCG 2013]
[Golec WSCG 2015]

For mass-tensor: *0-cells: nodes; 3-cells: forces*

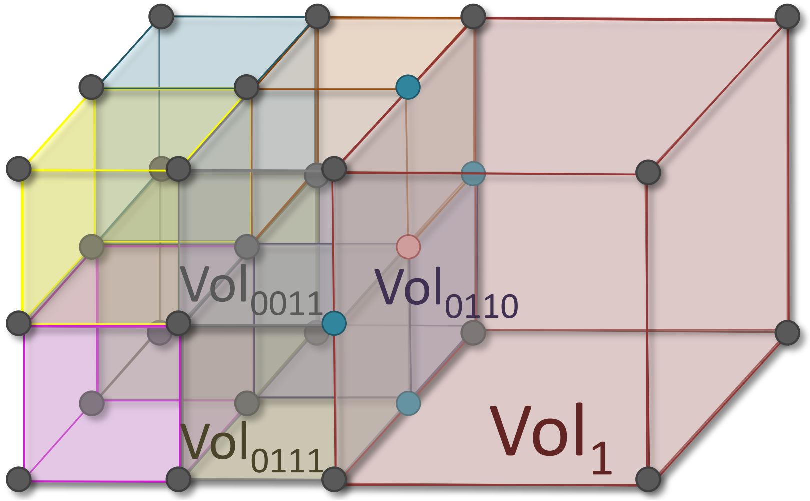
+ Direct access to information for simulation
+ Same approach for any physical model & topology / in any dimension

Topological operations

4) Topological changes = **used combinatorial maps operations**



Cutting



Refinement

Cutting is based on `unsew` operator of the combinatorial map

- Delete the β_3 link
- Some 2-cells and 1-cells are split into two
- Information is copied (naturally done by the combinatorial map)

We have to update mechanical properties

For mass-spring: springs, particles

[Fléchon WSCG 2013]

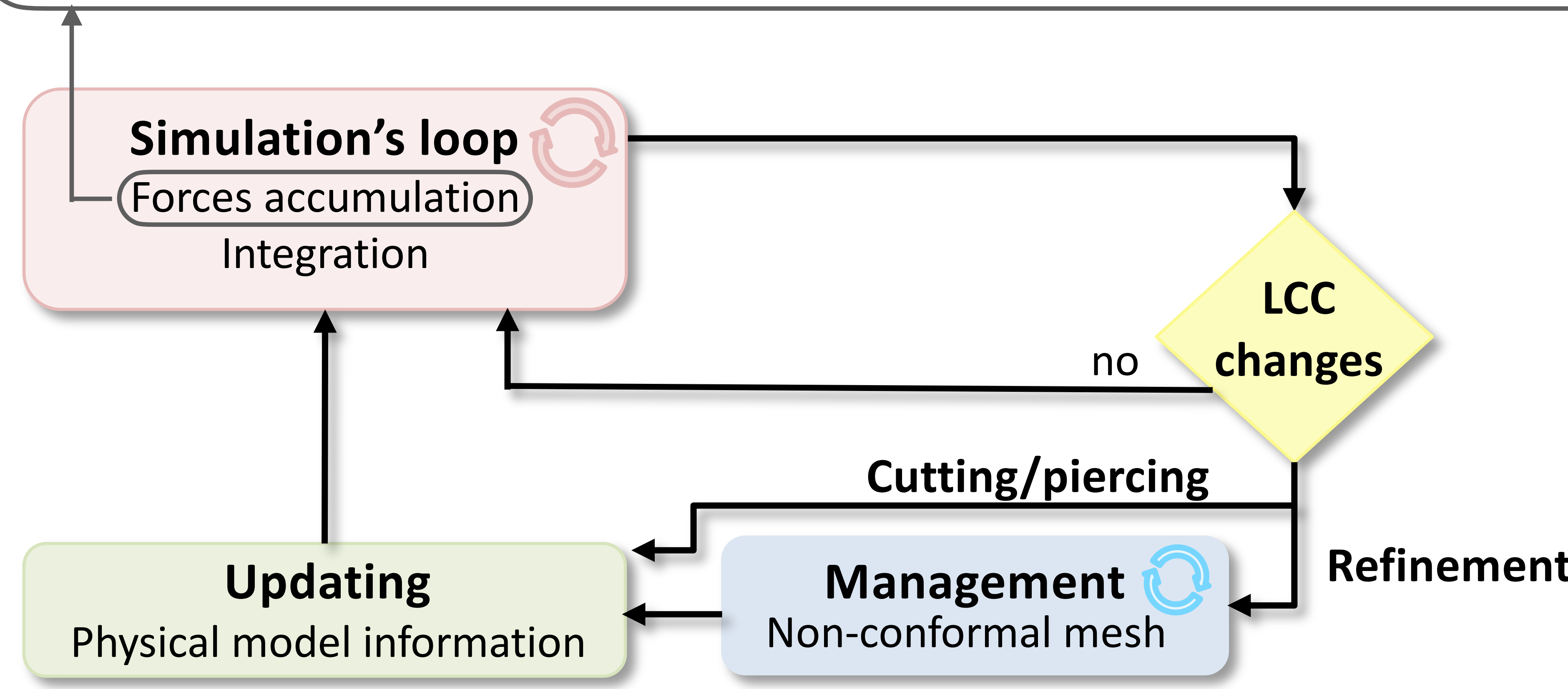
[Damiand PRL 2020]

+ Topological operations: managed by combinatorial maps

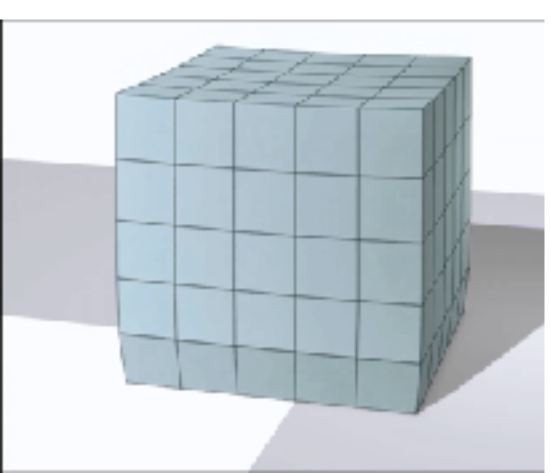
Simulation with topological changes

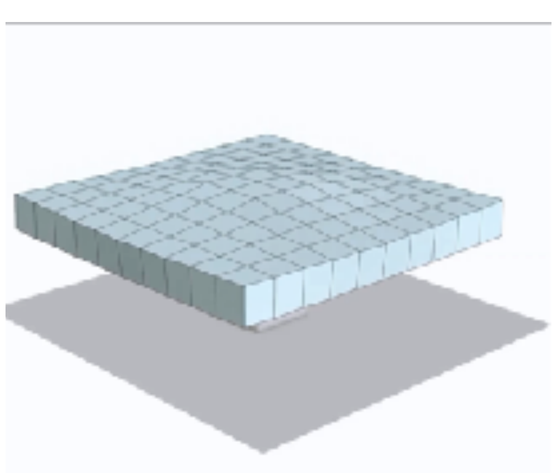
Forces computation: call appropriate `addForce()` function into appropriate i-cells

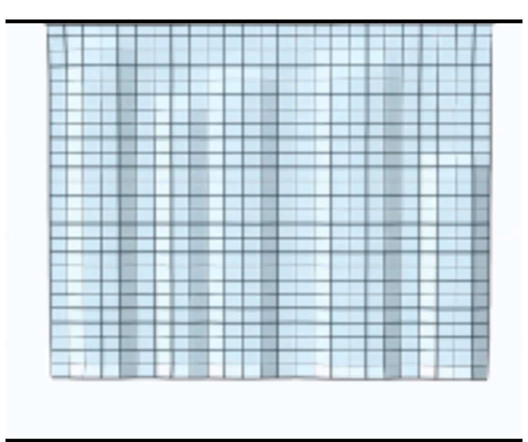
For mass-spring: *spring's force* ***For mass-tensor:*** *force code*

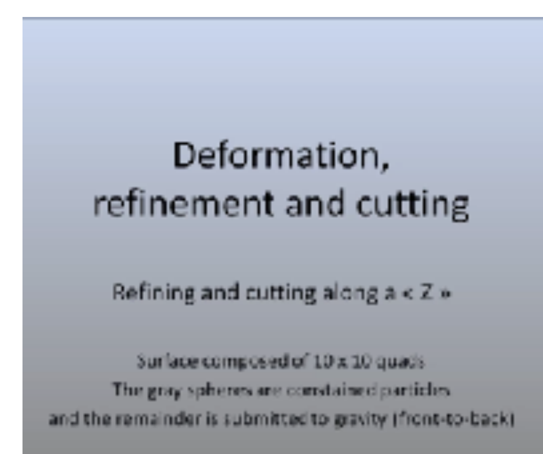


[Fléchon WSCG 2014]

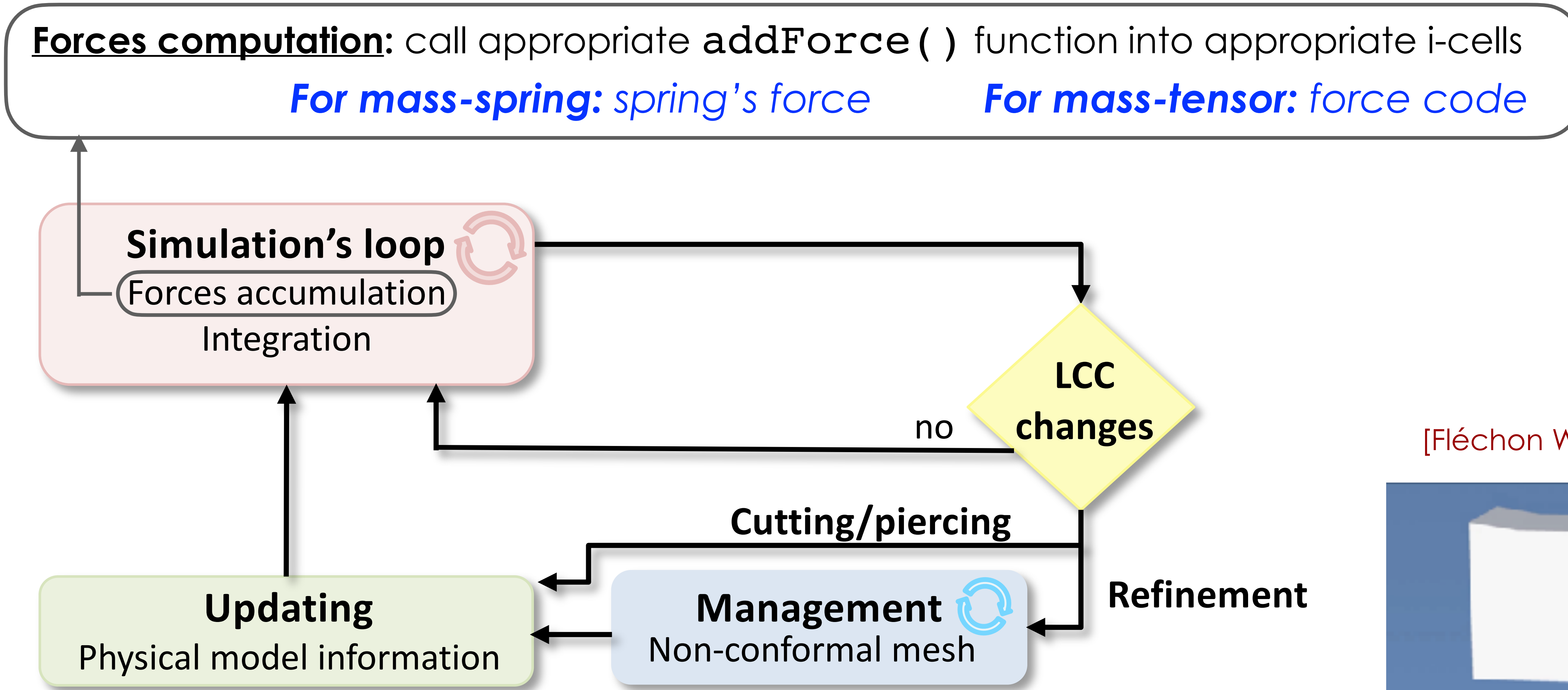




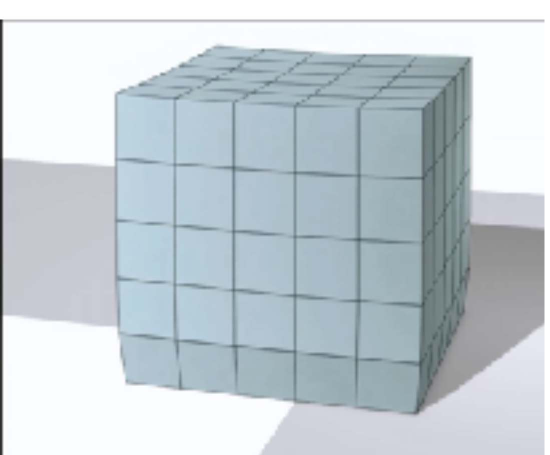


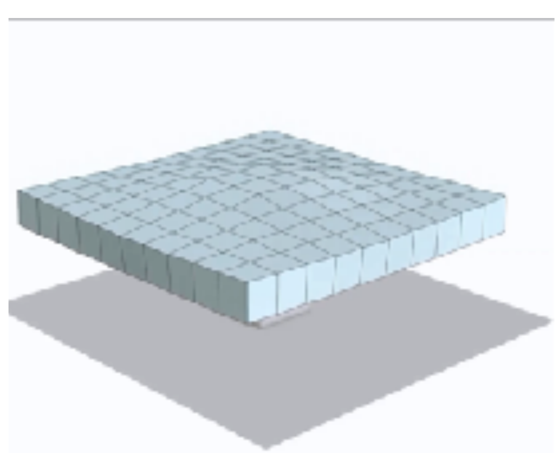


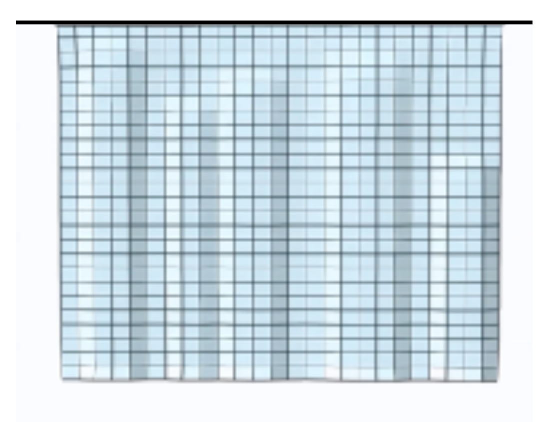
Simulation with topological changes

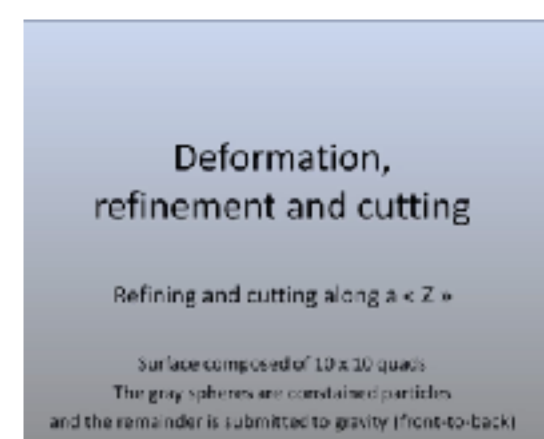


[Fléchon WSCG 2014]









Our contribution: a generic approach

- **Description of an object = a single data representation**
  - combinaison of elements (2 or 3-cells)
  - with different topologies, with different physical models
- **Easy to add new physical model**
- **During simulation: refinement, merging, cutting, piercing, etc.**
  - mathematically robust thanks to combinatorial maps

What's next?

Addition of subdivision schemes / other topological operations

Improvement of mesh cutting in 3D

Integration of collision model inside our representation?

Outline of the talk

- Challenges of interactive medical simulation
- Strategy: towards a generic model
- Contributions
  1. A unified data structure
  2. Generation of mass-tensor force code
  3. Extension of mass-spring system
- Application
- Conclusion & Research program

1 - A unified data structure

Topological model	Physical model

2 - Generation of mass-tensor force code

3 - Extension of mass-spring system

2010 2014

PhD Thesis of Xavier Faure

LIRIS

Project: **European ENVISION project (European NoVel Imaging Systems for ION therapy)**

ENVISION

COOPERATION

Motivation - Mass-tensor approach

[Cotin97, Pincinbono2003, Schwartz 2005]

Motivation - Mass-tensor approach

1. Discretization of displacement's field on an element

$\overrightarrow{u_E}(x,y,z) \simeq \sum_{i=0}^{n-1} \Lambda_i(x,y,z)\ u_i$ according displacement of nodes Pi

Parameters chosen according to element's topology

2. Computation of the deformation energy on an element

$$\begin{cases} \epsilon_{Hooke} = \frac{1}{2}(\mathbb{U}^T + \mathbb{U}) \\ \epsilon_{svk} = \frac{1}{2}(\mathbb{U}^T + \mathbb{U}) + \frac{1}{2}(\mathbb{U}^T \cdot \mathbb{U}) \end{cases}$$ strain tensor

$$W_{law}(x,y,z) = \frac{\lambda}{2}\left(\text{Tr}\ \epsilon(x,y,z)\right)^2 + \mu\ \text{Tr}\left(\epsilon(x,y,z)^2\right)$$ constitutive law

$$W_E = \int_E W_{law}(x,y,z)\ dx\ dy\ dz$$ Integration using Gauss points

Parameters chosen according to soft tissue's mechanical behavior

[Cotin97, Pincinbono2003, Schwartz 2005]

Motivation - Mass-tensor approach

3. Computation of the force applied on any node Pi of an element

$$\overrightarrow{F_E}(P_i) = -\frac{\partial W_E(P_i)}{\partial u_i}$$

+ A formulation for each node of element

- Complex for non-linear laws / some topologies / implicit integration scheme

In [Cotin97, Pincinbono2003, Schwartz 2005]:

- **formulation for: Hooke / Saint-Venant Kirchhoff / non-linear visco-elastic**
- **Euler's explicit integration scheme**
- **triangles / tetrahedra**

Deriving code of F, dF/du, dF/dv

1. C++ code to derive symbolic code of strain energy

Algorithme 2 : Algorithme du code C++ pour le calcul du déplacement.

1: **Pour** chaque nœud i de l'élément **Faire**
2: $L_i := \Lambda_i(\overrightarrow{R})$; *// Fonctions de forme en fonction de la géométrie*

3: **Pour** chaque nœud i de l'élément **Faire**
4: $U_i(R) := L_i * U_i$;

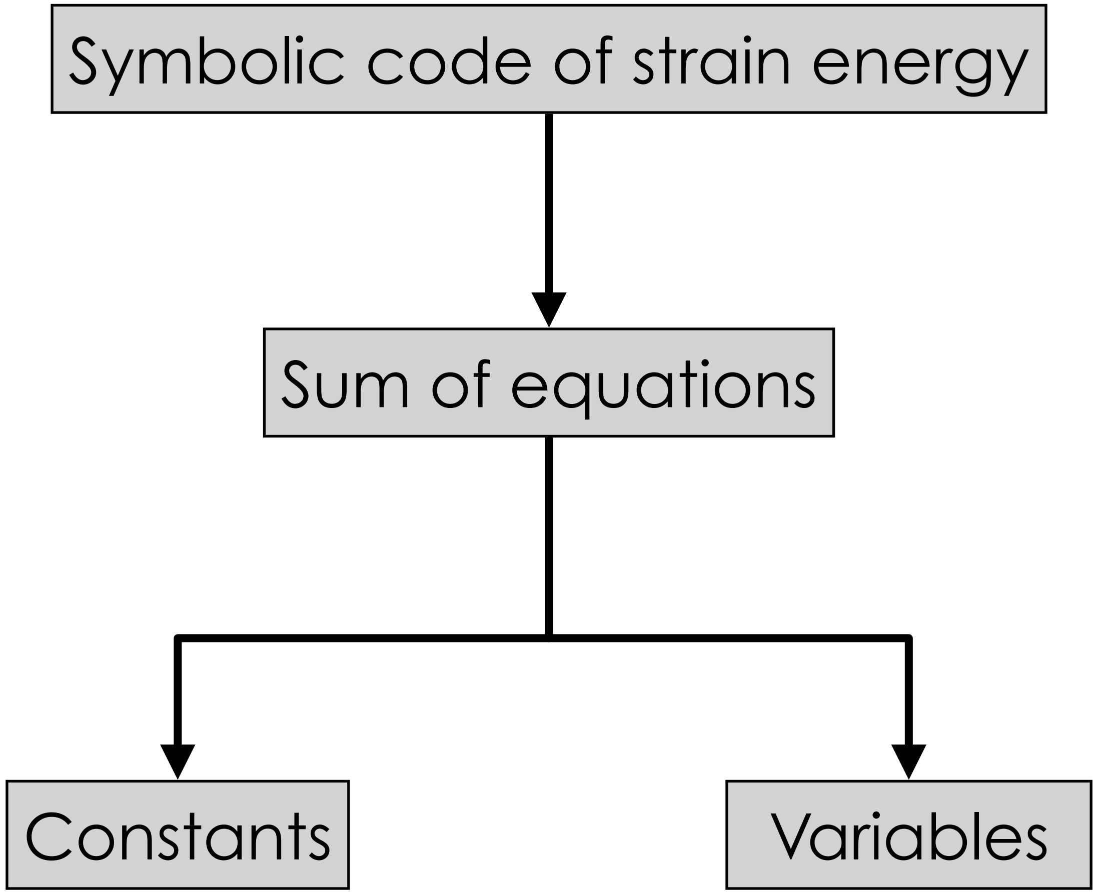
5: **Pour** chaque nœud i de l'élément **Faire**
6: $U(R) := U(R) + U_i(R)$;

```
// Fonctions de forme avec R = (R0, R1, R2)
L0:=1-R0-R1; L1:=R0;  L2:=R1;

// Deplacement
U0:=[L0*U0x,L0*U0y]; U1:=[L1*U1x,L1*U1y]; U2:=[L2*U2x,L2*U2y

U:=U0+U1+U2;

// Gradient du deplacement
JT := matrix([diff((1-R0-R1)*P0x+(R0)*P1x+(R1)*P2x,R0),
        diff((1-R0-R1)*P0y+(R0)*P1y+(R1)*P2y,R0)],
        [diff((1-R0-R1)*P0x+(R0)*P1x+(R1)*P2x,R1),
        diff((1-R0-R1)*P0y+(R0)*P1y+(R1)*P2y,R1)]);

GradU:=JT^(-1)matrix([diff(U,R0),diff(U,R1)]);

GradUT:=matrix(transpose(GradU));
```

```
// Code Maxima genere pour un element triangulaire ave
E:=1/2 * (GradU + GradUT);

//  p0 et p1 les coefficients de Lame
W0:=p0/2 * trace(E)^2;
W1:=p1 * trace(E^2);

// Integration analytique
WE :=integrate(integrate(W0(R0,R1)*det(JT(R0,R1)),R1,0

// Integration en utilisant des points de Gauss
// a = 1/6, b = 2/3, omega = 1/6 (par exemple)
intW0_0:=omega * W0(a,a) * det(JT(a,a));
intW1_0:=omega * W1(a,a) * det(JT(a,a));
intW0_1:=omega * W0(b,a) * det(JT(b,a));
intW1_1:=omega * W1(b,a) * det(JT(b,a));
intW0_2:=omega * W0(a,b) * det(JT(a,b));
```

Deriving code of F, dF/du, dF/dv

2. Grouping of constant data for pre-processing purpose



+ Grouping performed at this step as any other variables are next introduced

Deriving code of F, dF/du, dF/dv

3. C++ code to derive symbolic code of F and its derivatives

Algorithm 3 Generation of the symbolic formulation of the forces and their differentials for each node of an element.

{**Reformulation of the total strain energy**}
$IW = \mathcal{P}(U_i \in [0..n-1], D_j \in [0..m-1])$

{**Computation of the forces**}
for each node i **do**
  $F_i = -\frac{\partial IW}{\partial U_i}$

{**Computation of the forces differentials**}
for each node i **do**
  for each dimension k **do**
    for each node j **do**
      for each dimension l **do**
        $dF_{ik,jl} = \frac{\partial F_i[k]}{\partial U_{jl}}$

{**Multiplication of** $\frac{\partial F}{\partial U}$ **by a vector** V}
for $i = 0$ to $n-1$ **do**
  for $k = 0$ to $dim - 1$**do**
    for $j = 0$ to $n-1$ **do**
      for $l = 0$ to $dim - 1$ **do**
        $dF_i[k] += dF_{ik,jl} * V_j[l]$

```
// Maxima's code generated for the triangle's nodes
F0x: -diff(WE,U0x); F0y: -diff(WE,U0y);
F0:[F0x,F0y];

F1x: -diff(WE,U1x); F1y: -diff(WE,U1y);
F1:[F1x,F1y];

F2x: -diff(WE,U2x); F2y: -diff(WE,U2y);
F2:[F2x,F2y];

dF00 := diff(F0,U0);
dF01 := diff(F0,U1);
dF02 := diff(F0,U2);

dF10 := diff(F1,U0);
dF11 := diff(F1,U1);
dF12 := diff(F1,U2);

dF20 := diff(F2,U0);
dF21 := diff(F2,U1);
dF22 := diff(F2,U2);
```

Deriving code of F, dF/du, dF/dv

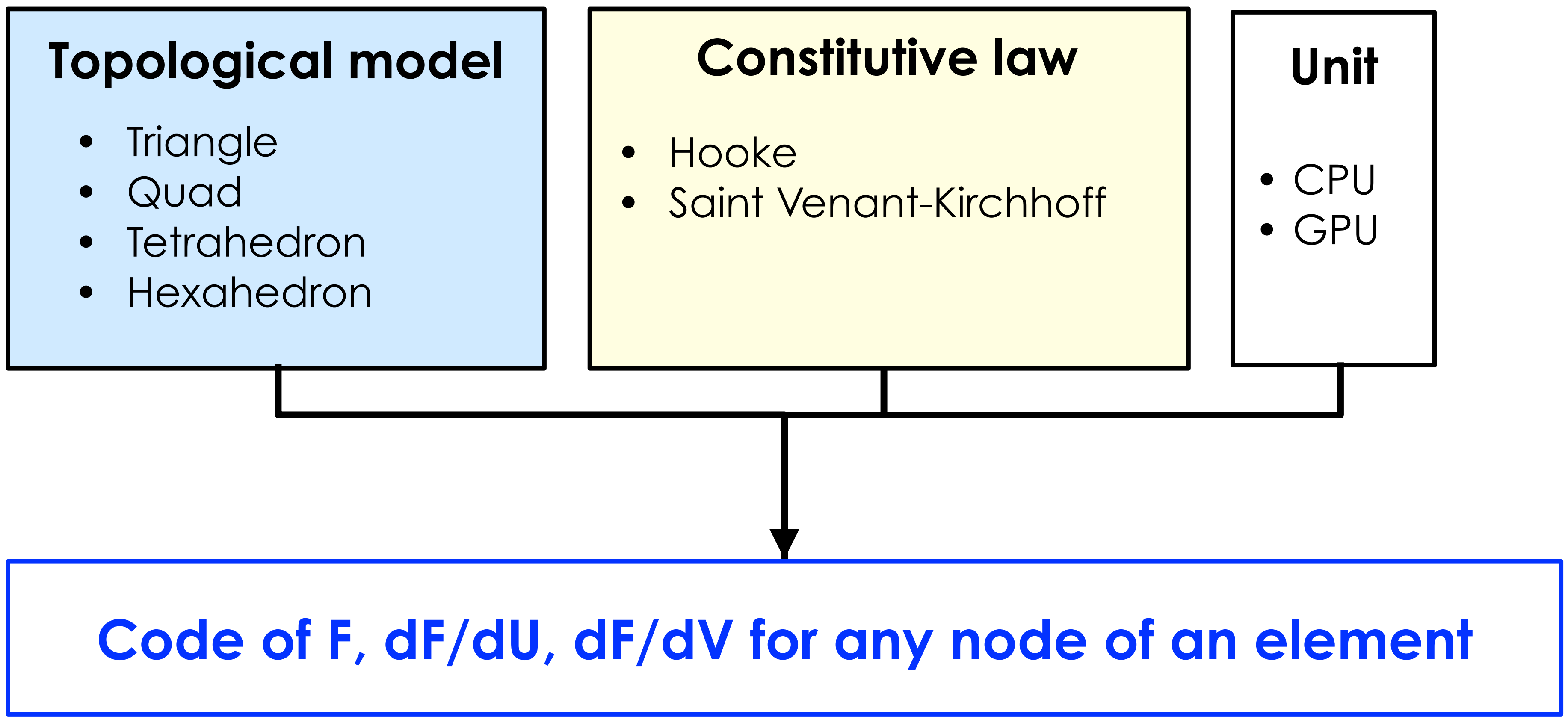
4. Split of equations for compilation purpose

```
1.0*1.0/(2.0)*D[1]*((-1.0)*1.0*1.0/(4.0)*u[3][0]+1.0*1.0/(4.0)*u[2][0]+(-1.0)*1.0*1.0/
(4.0)*u[1][0]+1.0*1.0/(4.0)*u[0][0])+(-1.0)*1.0*1.0/(2.0)*D[2]*(D[3]*((-1.0)*1.0*1.0/
(4.0)*u[3][0]+1.0*1.0/(4.0)*u[2][0]+1.0*1.0/(4.0)*u[1][0]+(-1.0)*1.0*1.0/(4.0)*u[0][0])
+D[4]*(1.0*1.0/(4.0)*u[3][1]+1.0*1.0/(4.0)*u[2][1]+(-1.0)*1.0*1.0/(4.0)*u[1][1]+
(-1.0)*1.0*1.0/(4.0)*u[0][1]))*D[3]+1.0*1.0/(4.0)*D[5]*D[6]*((-1.0)*1.0*1.0/(4.0)*u[3]
[0]+1.0*1.0/(4.0)*u[2][0]+(-1.0)*1.0*1.0/(4.0)*u[1][0]+1.0*1.0/(4.0)*u[0][0])+1.0*1.0/
(2.0)*D[5]*D[8]*((-1.0)*1.0*1.0/(4.0)*u[3][0]+1.0*1.0/(4.0)*u[2][0]+(-1.0)*1.0*1.0/
(4.0)*u[1][0]+1.0*1.0/(4.0)*u[0][0])+D[9]*((-1.0)*1.0*1.0/(2.0)*D[8]*((-1.0)*1.0*1.0/
(4.0)*u[3][0]+1.0*1.0/(4.0)*u[2][0]+1.0*1.0/(4.0)*u[1][0]+(-1.0)*1.0*1.0/(4.0)*u[0][0])+
(-1.0)*1.0*1.0/(2.0)*(1.0*1.0/(2.0)*D[3]*((-1.0)*1.0*1.0/(4.0)*u[3][1]+1.0*1.0/(4.0)*u[2]
[1]+1.0*1.0/(4.0)*u[1][1]+(-1.0)*1.0*1.0/(4.0)*u[0][1])+1.0*1.0/(2.0)*D[4]*(1.0*1.0/
(4.0)*u[3][0]+1.0*1.0/(4.0)*u[2][0]+(-1.0)*1.0*1.0/(4.0)*u[1][0]+(-1.0)*1.0*1.0/(4.0)*u[0]
[0]))*D[4])
```

5. Sofa's plugin: CPU & GPU

```
addForce(): uses generated code of F
addDForce(): uses generated code of dF
```

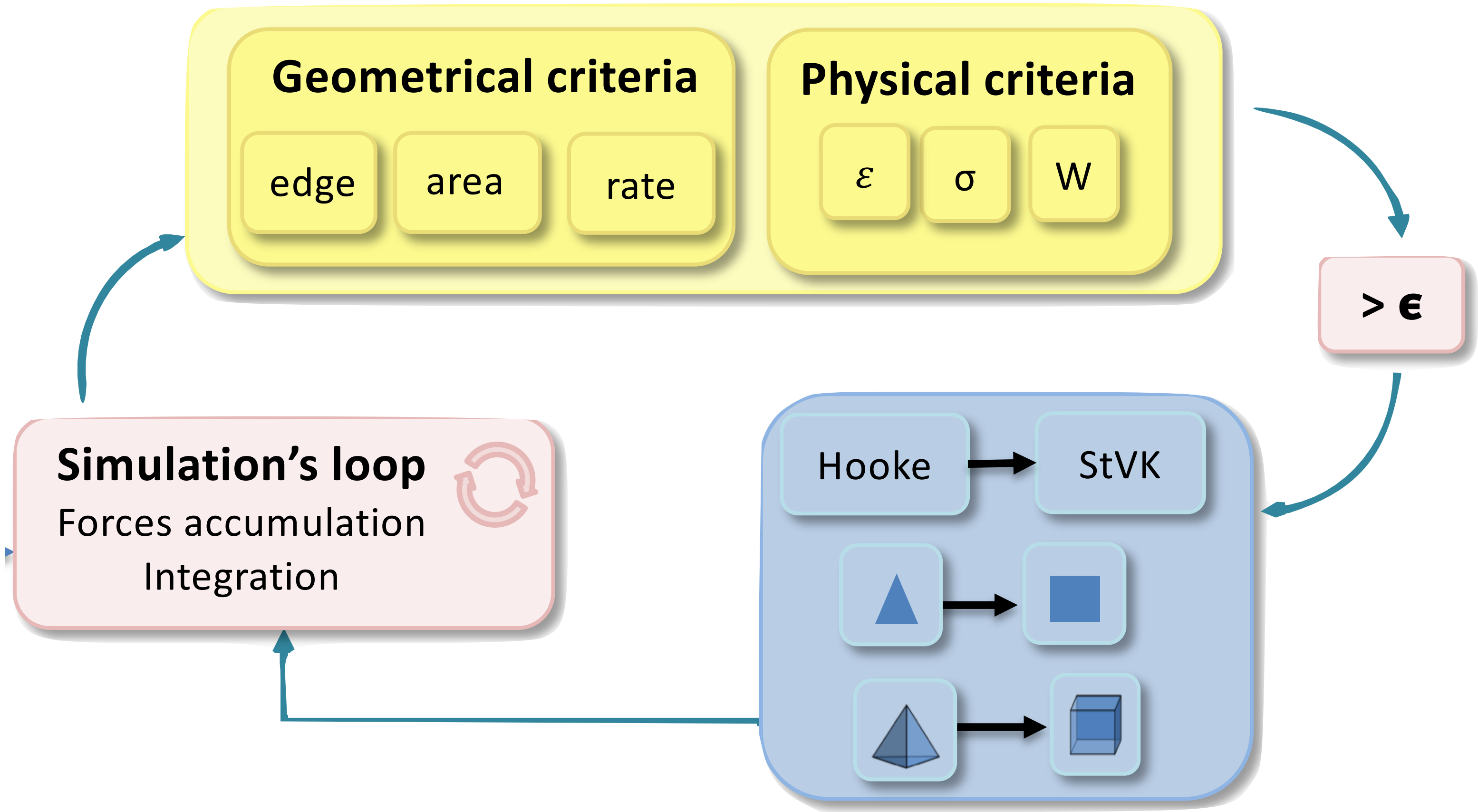
Our contribution: a generic approach to derive code of F, dF/dU, dF/dV



+ Useful to use an implicit integration scheme / to perform virtual prototyping

+ This process is usable for other physical model

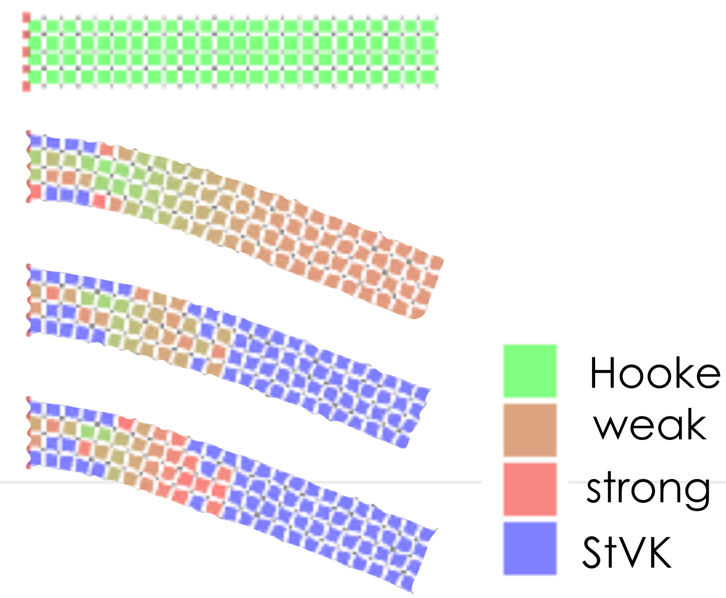
Criteria driven adaptative simulation

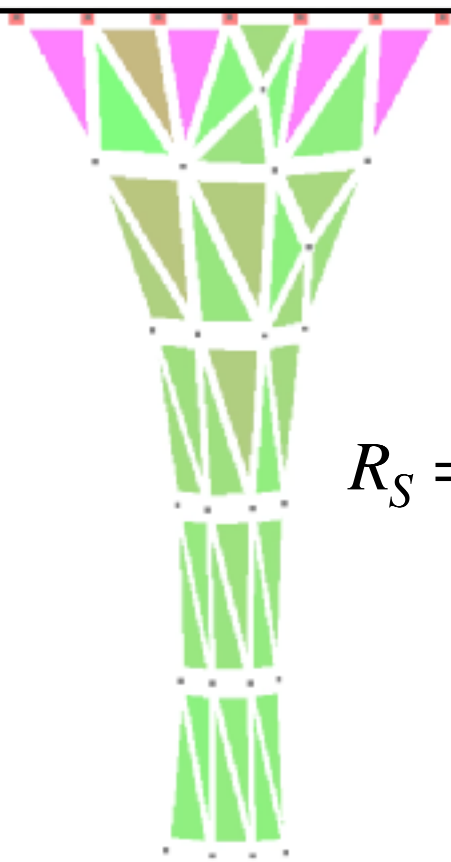


Geometrical criteria

$$R_L = max_{i \in [0,..,n_e]} \frac{|l_0^i - l_t^i|}{l_0^i}$$

$$R_A = \frac{|S_0 - S_t|}{S_0}$$

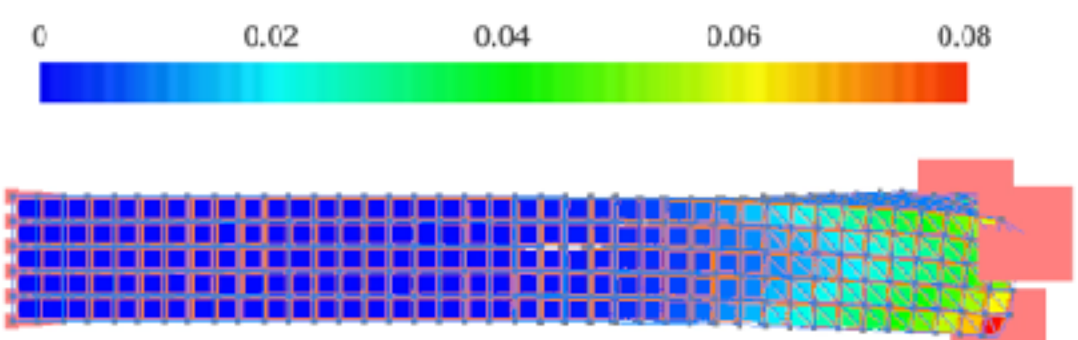




Physical criteria (σ)

Subdivision of triangles > 90% of max

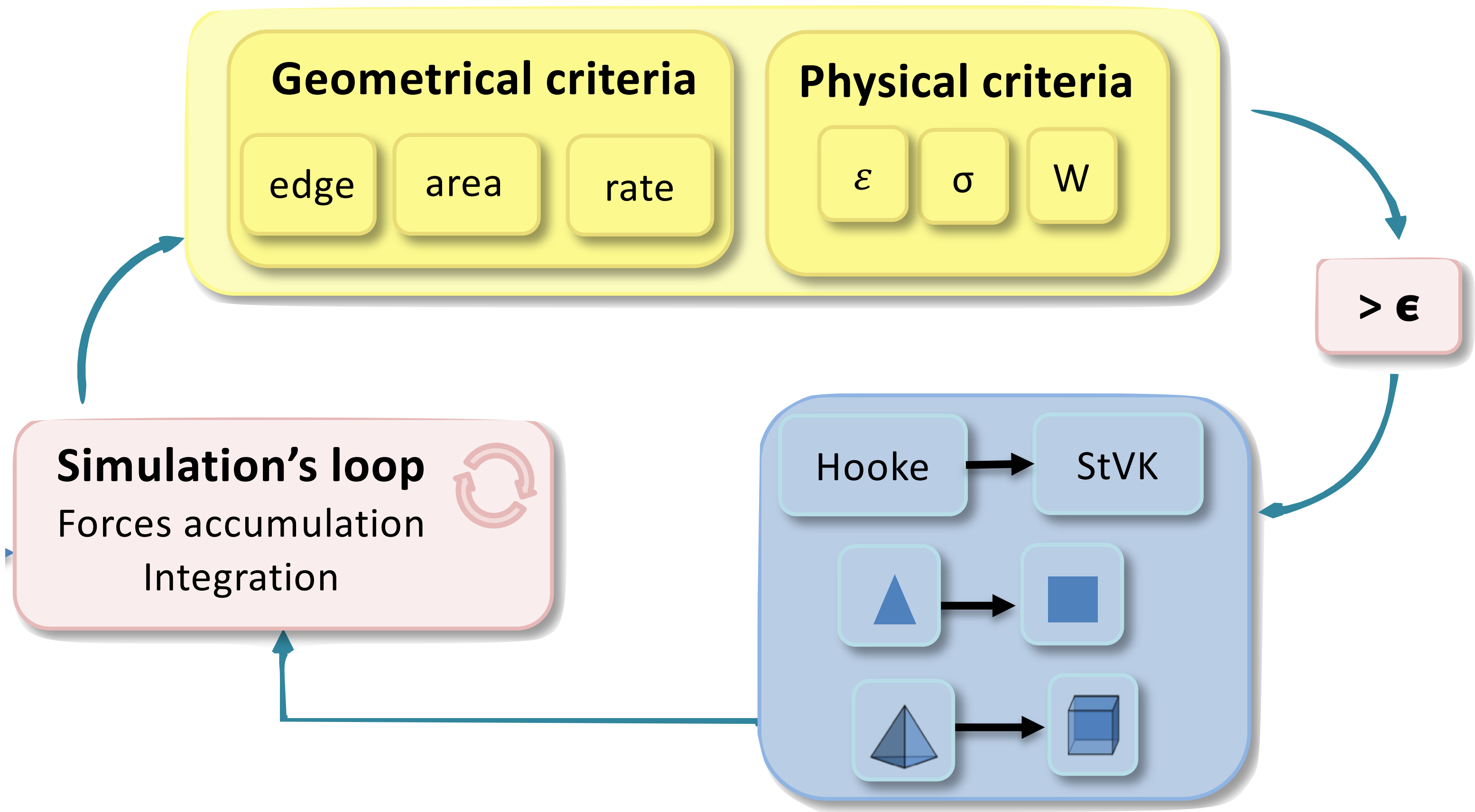
$$R_S = \frac{1}{A(t)} \sum_{i=0}^{n_g-1} w_i \sum_{j=0}^{n-1} \|\Lambda_j(g_i)\, \mathbf{F}_E(P_j)\|$$



Object = tetra + hexa + prism + pyr.
Saint-Venant Kirchhoff

[Faure VRIPHYS 2012] [Caillaud VRIPHYS 2013]

Criteria driven adaptative simulation



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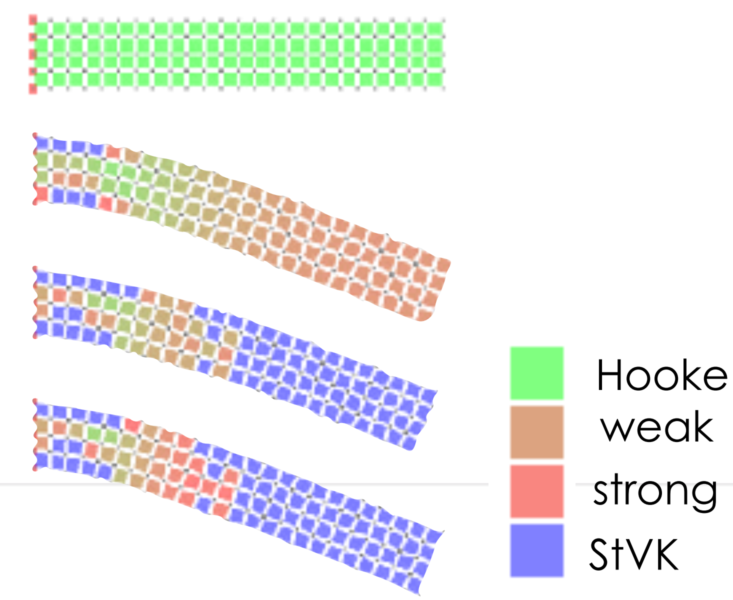

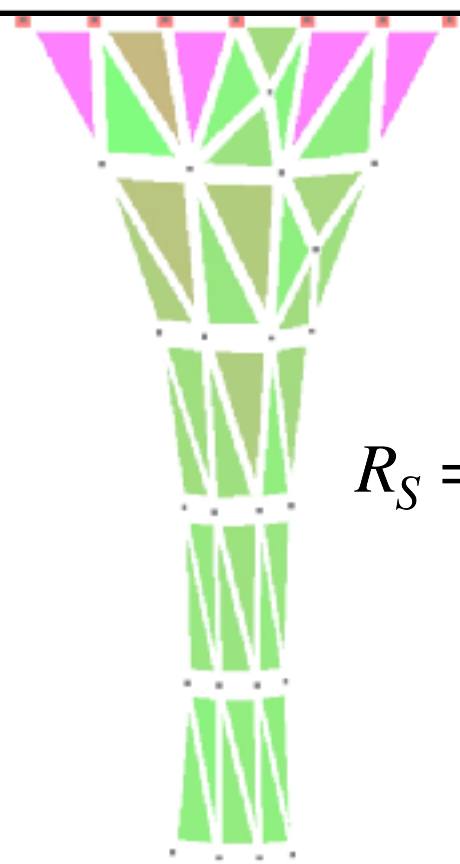

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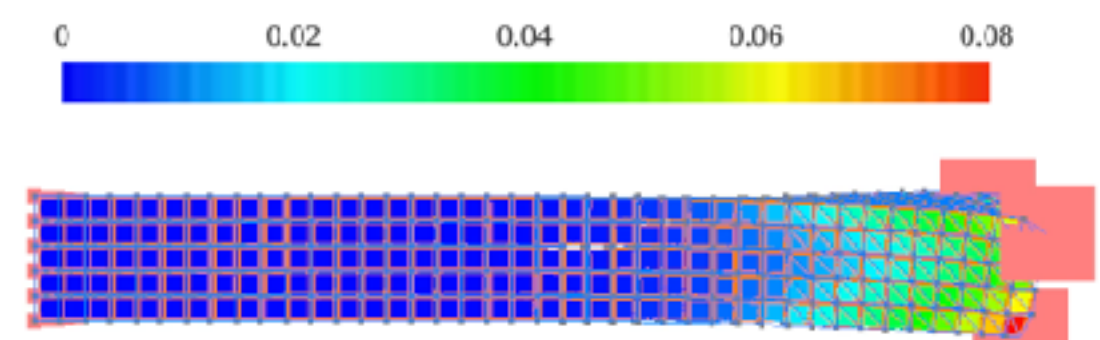


Object = tetra + hexa + prism + pyr.
Saint-Venant Kirchhoff

[Faure VRIPHYS 2012] [Caillaud VRIPHYS 2013]

What's next?

- Integration of other **constitutive laws / topologies / shape functions**

- Improvement of the process / optimization

Outline of the talk

- Challenges of interactive medical simulation
- Strategy: towards a generic model
- Contributions
  1. A unified data structure
  2. Generation of mass-tensor force code
  3. Extension of mass-spring system
- Application
- Conclusion & Research program

1 - A unified data structure

Topological model	Physical model

2 - Generation of forces formulation

3 - Extension of mass-spring system

2014	2018

PhD Thesis of Karolina Golec

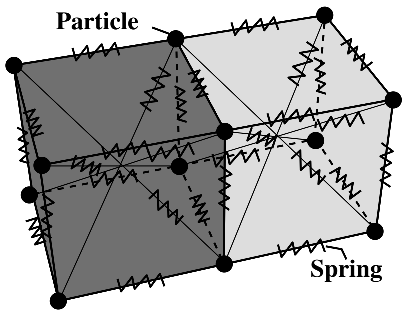
<u>Project:</u> WP5 of LabEx PRIMES (Physics, Radiobiology, Medical Imaging and Simulation)

LABEX PRIMES
UNIVERSITÉ DE LYON

PHYSIQUE, RADIOBIOLOGIE,
IMAGERIE MÉDICALE ET SIMULATION

Motivation - Mass-spring system

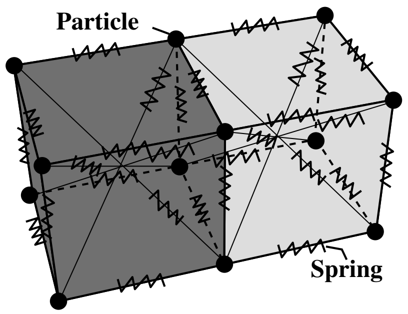
Motivation - Mass-spring system



$$\overrightarrow{F}^{e}_{ij}(t) = -\,k_{ij}\,\left(\|x_i(t) - x_j(t)\| - l_{ij}\right)\,\overrightarrow{u}_{ij}(t)$$

$$\overrightarrow{F}^{v}_{ij}(t) = -\,d_{ij}(x'_j(t) - x'_i(t))$$

Motivation - Mass-spring system



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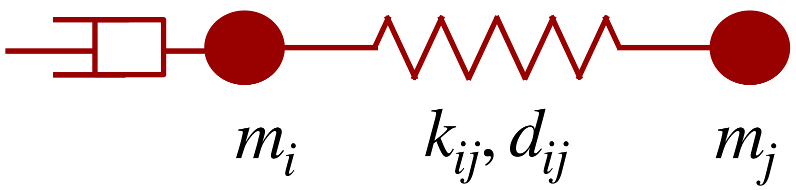
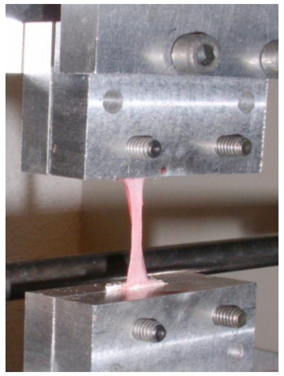
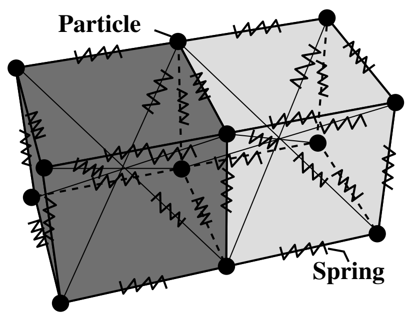




ρ, E, ν

Motivation - Mass-spring system



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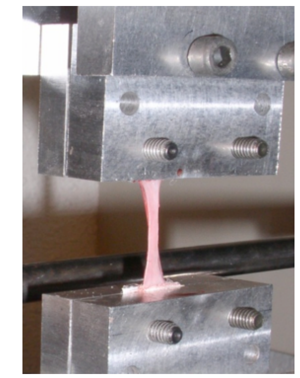
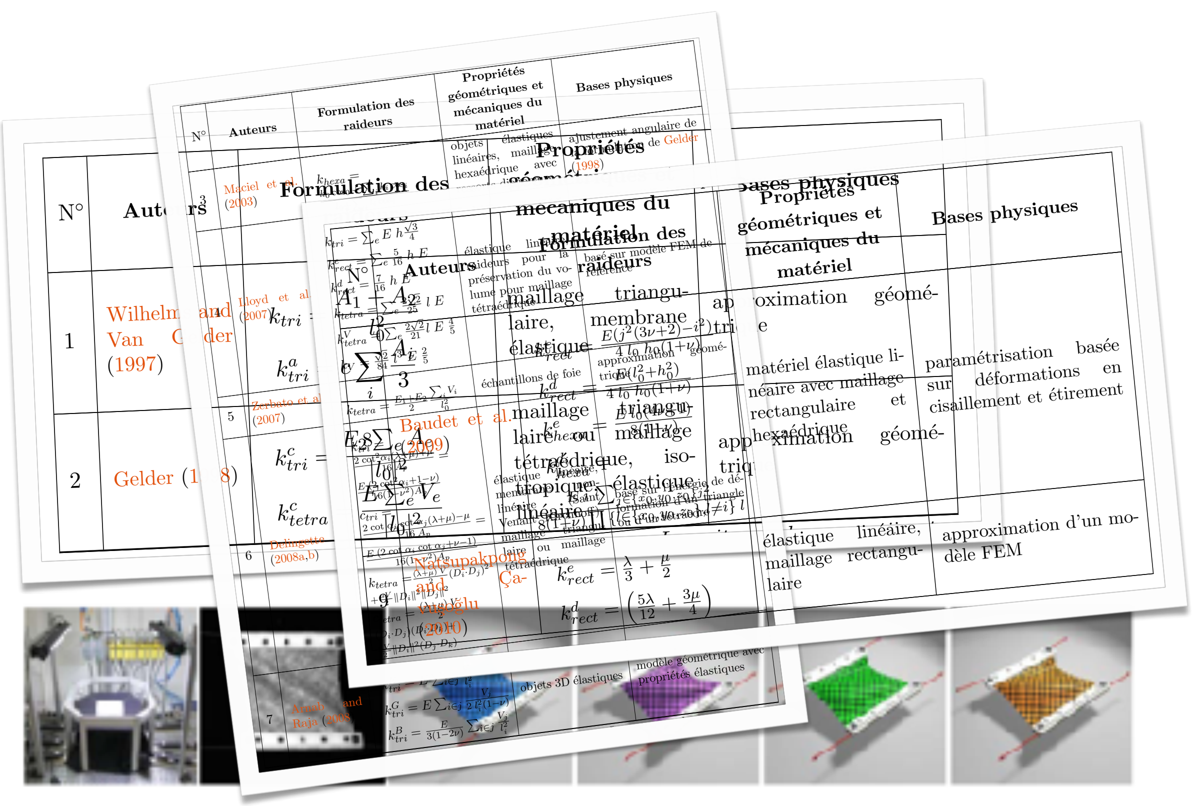


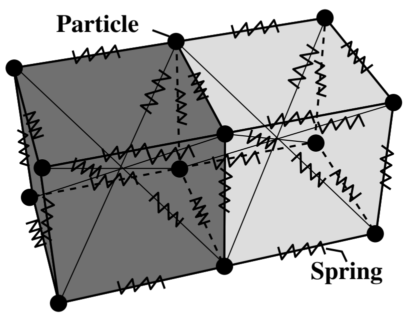
ρ, E, ν

Stiffness formulations & Additional forces to preserve volume



N°	Auteurs	Force ajoutée dans le système masses-ressorts
0	*Formulation initiale*	$F^j_{ressort} = -\left(k_s\,(\|x_j - x_i\| - l_0) + k_d \frac{(v_j - v_i)\cdot(x_j - x_i)}{\|x_j - x_i\|}\right) \frac{x_j - x_i}{\|x_j - x_i\|}$
1	Bourguignon and Cani (2000)	$F^j_{tetra} = -k_s \left(\sum_{i=0}^{3} \|x_i - x_B\| - \sum_{i=0}^{3} \|x_i - x_B\|_{t=0}\right) \frac{x_j - x_B}{\|x_j - x_B\|}$ $F^j_{hexa} = -\left(k_s\,(\|x_j - x_B\| - \|x_j - x_B\|_{t=0}) + k_d \frac{(v_j - v_B)\cdot(x_j - x_B)}{\|x_j - x_B\|}\right) \frac{x_j - x_B}{\|x_j - x_B\|}$
2	Mollemans et al. (2003)	$F^{vol^j}_{tetra} = \sum_t (V_t - V_t^0) \frac{x_j - x_{b_t}}{\|x_j - x_{b_t}\|},\ x_{b_t} = \frac{1}{4} \sum_{k=0}^{4} x_k,\ t$ indice des tétraèdres
3	Baudet et al. (2009)	$F^{\perp e}_{rect} = \frac{i\ F_i(1 - 3\,\nu)}{8\ j},\ (i, j) \in \{l_0, h_0\}, i \neq j$ $F^{\perp e}_{hexa} = -\frac{F_i(4\,\nu - 1)}{16},\ i \in \{x_0, y_0, z_0\}$
4	Jarrousse et al. (2010)	$W_v = W + \frac{1}{2}\,k\,(det(\mathbb{F}) - 1)^2 = W + \frac{1}{2}\,k \left(\frac{V - V_0}{V_0}\right)^2,\ k = 2 \times 10^6$
5	Kot and Nagahashi (2015, 2017); Kot et al. (2014)	$F^j = F^j_\mu + F^j_*,\ F^j_\mu = -\kappa^\mu\,(\|x_j - x_i\| - l_0)\,,\ F^j_* = -q\,\kappa^\mu\,(\|x_j - x_i\| - l_0)$
6	Arnab and Raja (2008)	$F^j = k^B_{tri}\,(V - V_0)\ \alpha\ N$

Motivation - Mass-spring system



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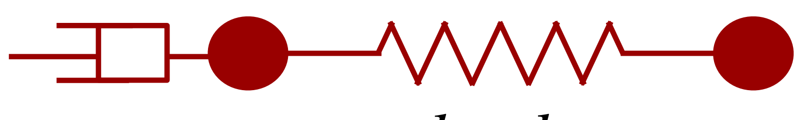
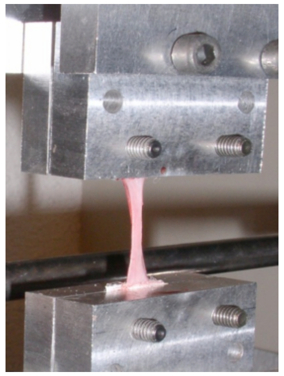
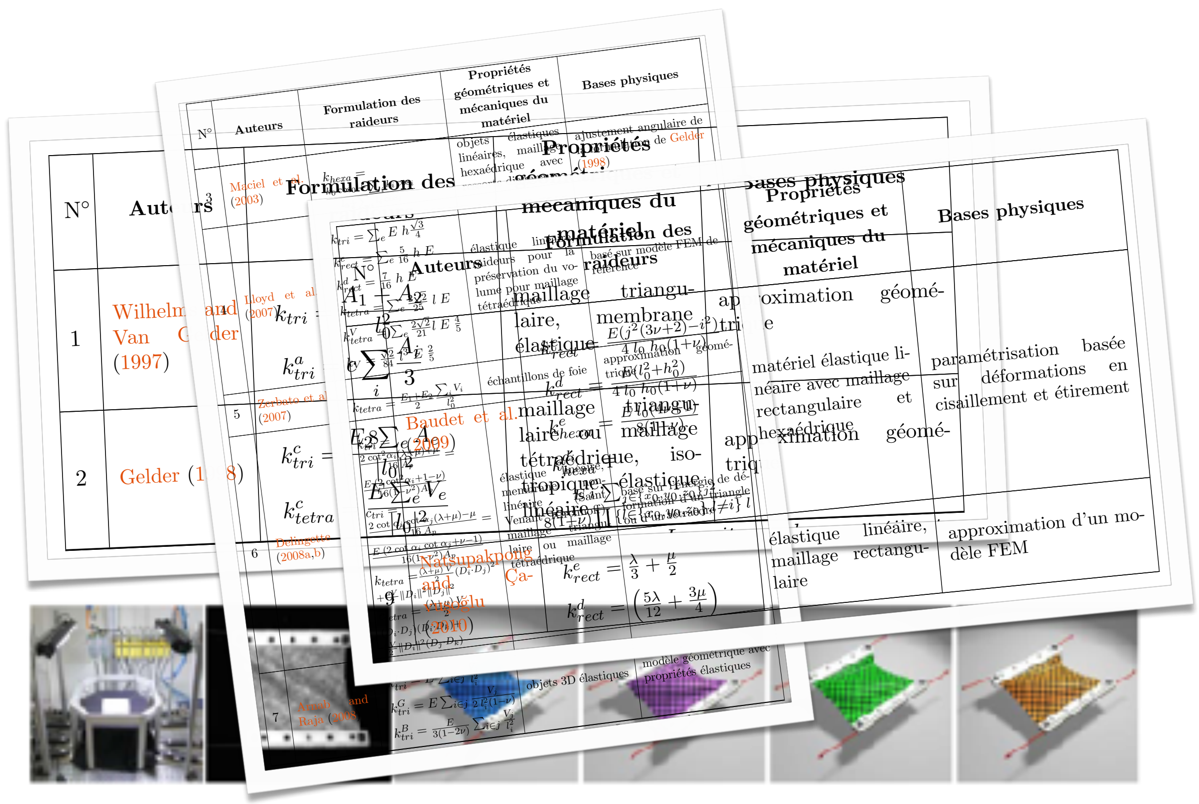




ρ, E, ν

Stiffness formulations & Additional forces to preserve volume



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Is it possible to have an analytical formulation integrating E , ν?

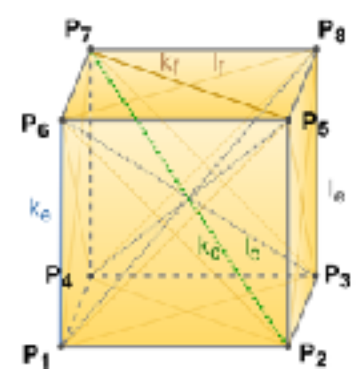
Cauchy's limitation
$\nu = 1/4$

An analytical stiffness formulation

Our proposition for a cubic Mass-Spring System

Springs: 12 edges (e), 12 faces (f), 4 cube (c), with: $l_e = \frac{l_f}{\sqrt{2}} = \frac{l_c}{\sqrt{3}}$

Masses: $m_i = \sum_{j \mid P_i \in E_j} \frac{\rho}{8} V^c_{E_j}$



Forces involved: springs forces

System's energy: $W_{springs}$

[Golec Visual Computer 2020]

An analytical stiffness formulation

Cauchy's limitation $\nu = 1/4$

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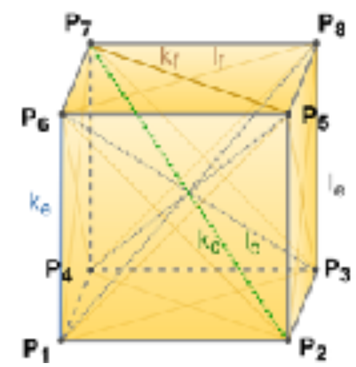

A geometrical constraint

$$A = \frac{k_f}{k_c}$$

$$A = 0$$

[Golec Visual Computer 2020]

An analytical stiffness formulation

Cauchy's limitation
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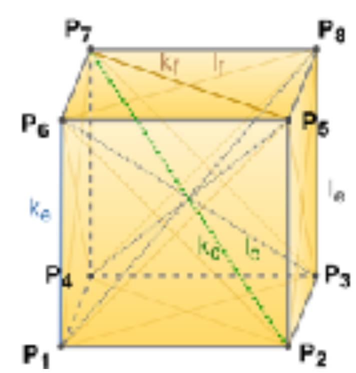

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A geometrical constraint

$$A = \frac{k_f}{k_c}$$

$$A = 0$$

$$k_c = \frac{3\, E\, l_c}{\sqrt{3}\,(10 + 7.5\, A)} = \frac{6}{5}\,\frac{E\, l_e}{4 + 3A}$$

$$k_e = k_f + \frac{8}{3}\, k_c = \frac{2\, E\, l_e}{5}\,\frac{8 + 3A}{4 + 3A}$$

[Golec Visual Computer 2020]

Additional forces to break Cauchy's limitation ($\nu = 1/4$)

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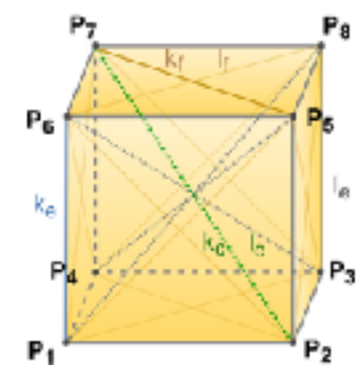

Forces involved: springs forces

System's energy: $W_{springs}$

[Golec Visual Computer 2020]

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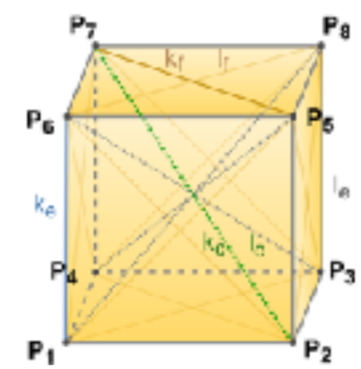

Forces involved: springs forces **+ additional forces**

System's energy: $W_{HybMSS} = W_{springs} + W_{vol}$

[Golec Visual Computer 2020]

Additional forces to break Cauchy's limitation ($\nu = 1/4$)

Our proposition for a cubic Mass-Spring System

Springs: 12 edges (e), 12 faces (f), 4 cube (c), with: $l_e = \frac{l_f}{\sqrt{2}} = \frac{l_c}{\sqrt{3}}$

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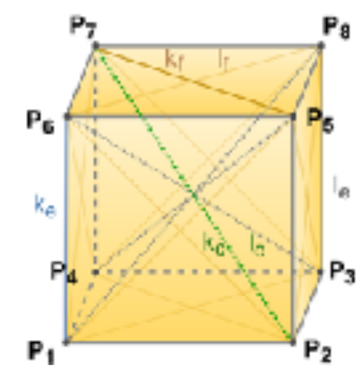


For an element: $W^c_{vol} = \frac{1}{2}\kappa \frac{(V^c - V^c_0)^2}{V_0}$ $\quad \overrightarrow{F_{P_i}} = \frac{\partial W^c_{vol}}{\partial P_i} = \kappa \frac{V^c - V^c_0}{V_0} \frac{\partial V^c}{\partial P_i}$

κ: material coefficient linked to volume variation

$$\kappa = \frac{1}{2}\frac{E\,(4\,\nu - 1)}{(1+\nu)(1-2\nu)}$$

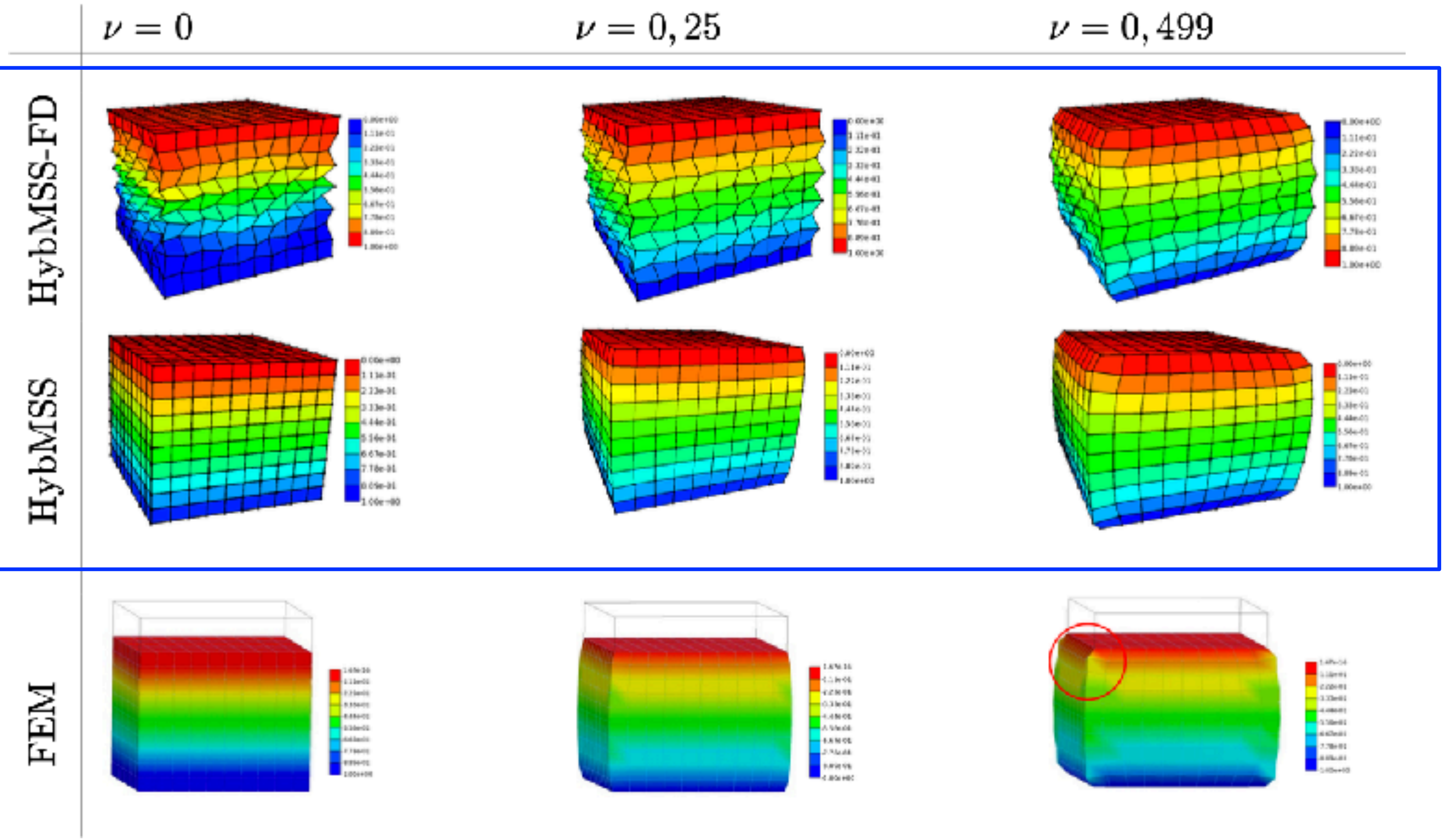
$\epsilon = \frac{1}{2}(\mathbb{U}^T + \mathbb{U})$

$Tr(\epsilon) = (V - V_0)/V_0$

[Golec Visual Computer 2020]

Stability improvement thanks to springs on faces

A = 0



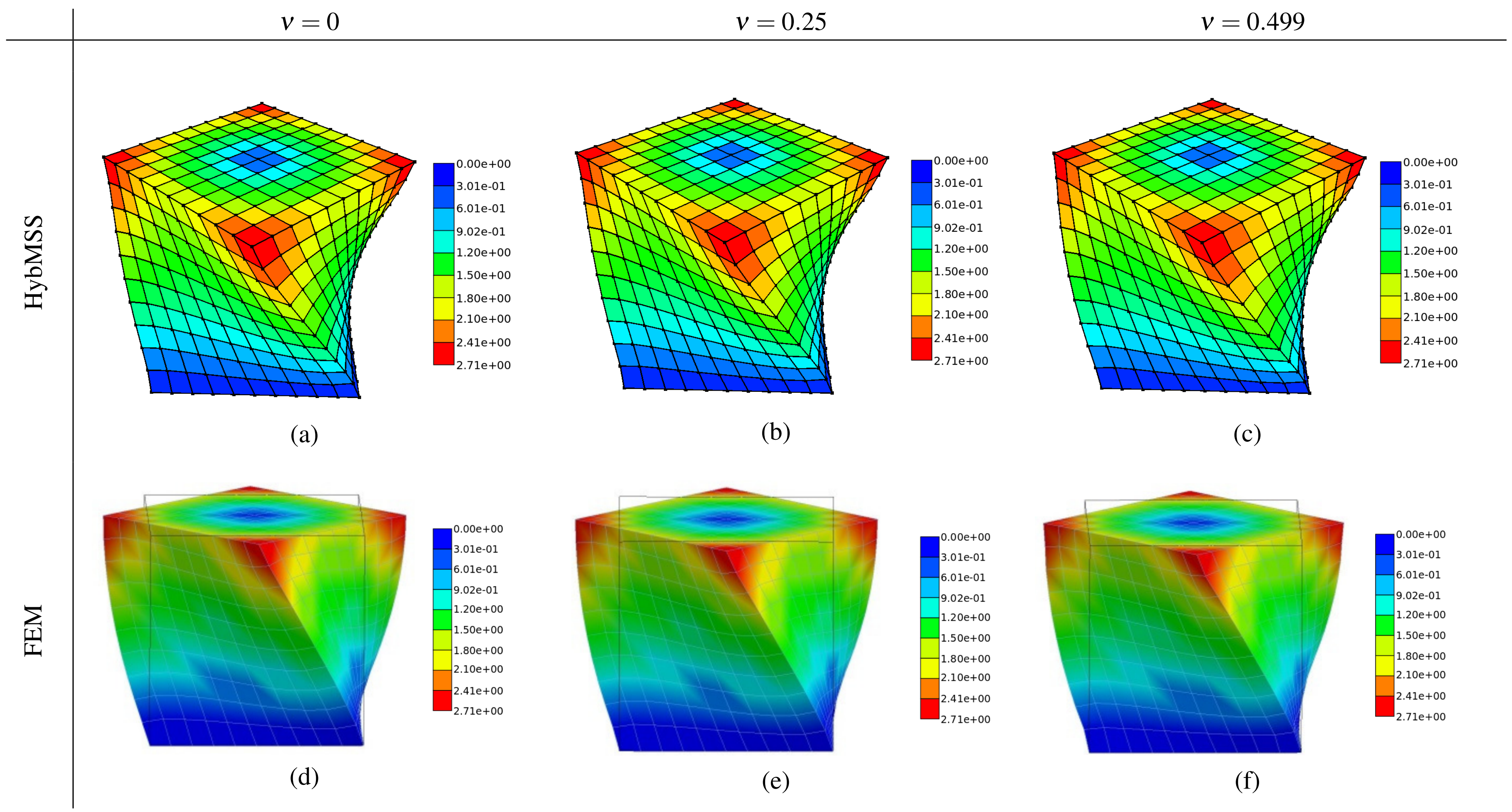
No more wrinkles in compression!

+ Results similar to those obtained using the FEM

[Golec Visual Computer 2020]

Breaking Cauchy's limitation thanks to additional forces

Results close to FEM results in shear, tension, torsion



+ Possibility to simulate any ν

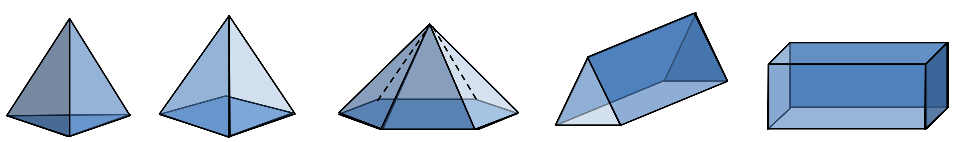
+ Stiffness formulations according to E, ν

[Golec Visual Computer 2020]

What's next?

Extension

$k = ?$



For

complex object (not with a cubic grid)
any refinement scheme
cutting without any constraint

Extension of **non-linear force formulation**

To be suitable to "any" constitutive law of soft tissues

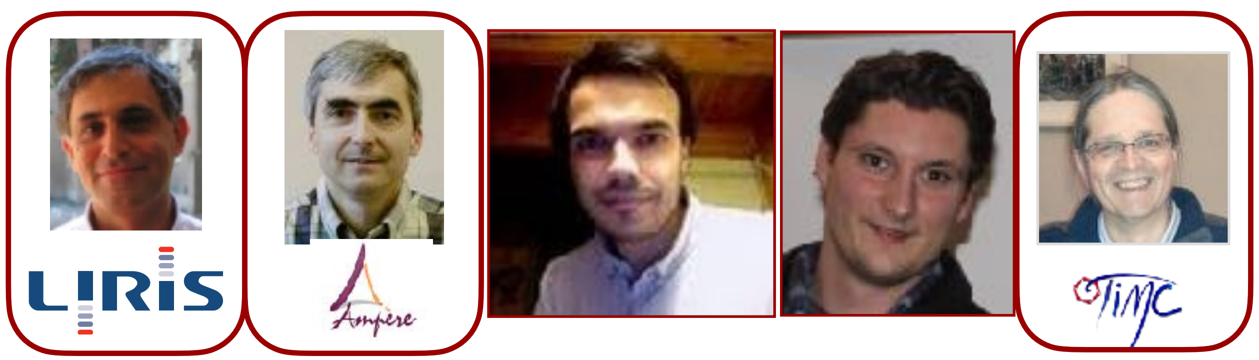
In collaboration with LBMC Lab PHYS ENS de LYON

Outline of the talk

- Challenges of interactive medical simulation
- Strategy: towards a generic model
- Contributions
- Application
- Conclusion & Research program

Outline of the talk

- Challenges of interactive medical simulation
- Strategy: towards a generic model
- Contributions
- Application: A childbirth simulator
- Conclusion & Research program

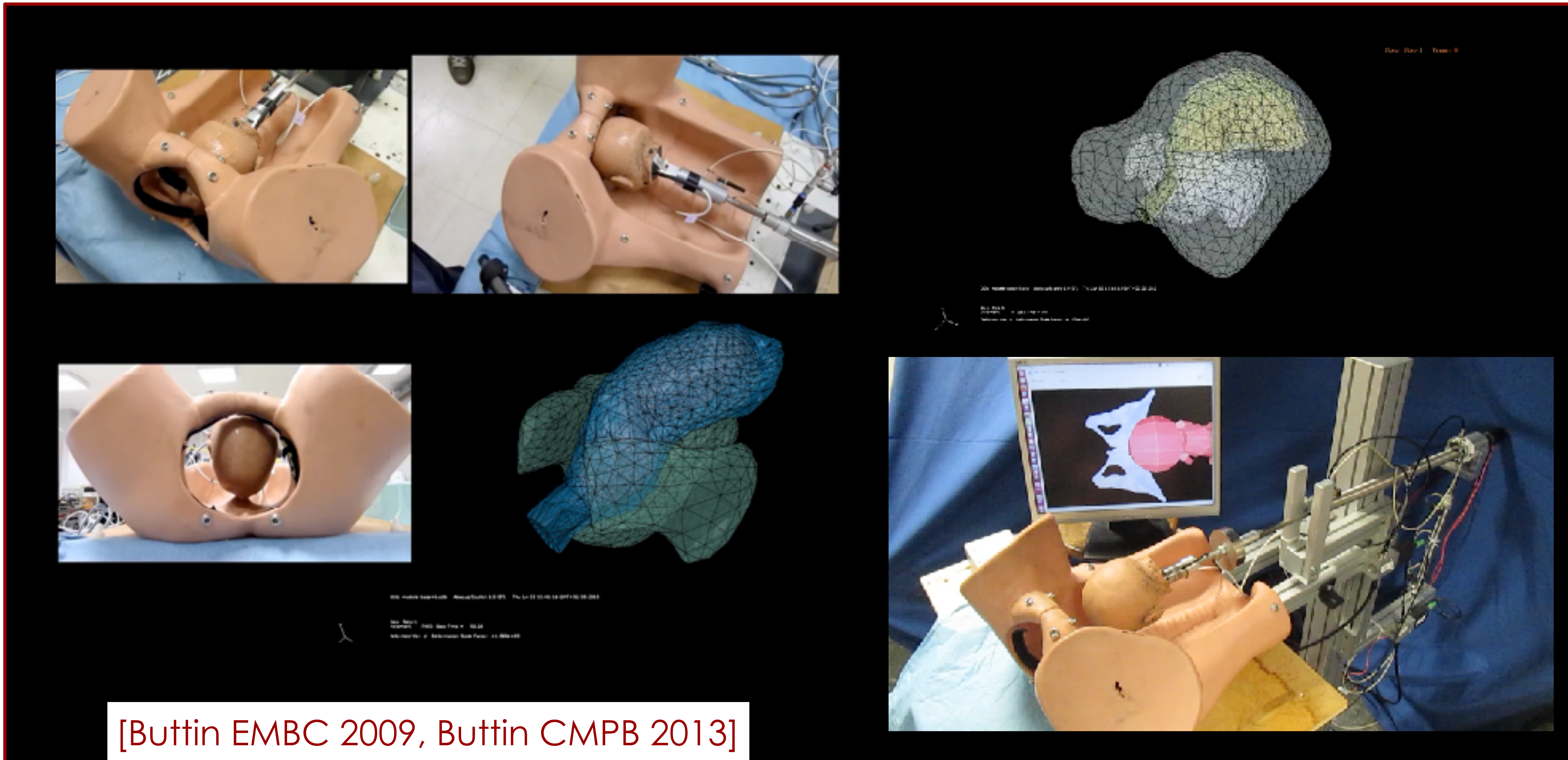


PhD Thesis of
Romain Buttin & Mathieu Bailet

Projects: GMCAO & SIMED, cluster ISLE (Informatique, signal, logiciel embarqués), Région Rhône-Alpes
SAGA project (ANR-12-MONU-0006)

Development of a childbirth simulator

midwifery school of Grenoble



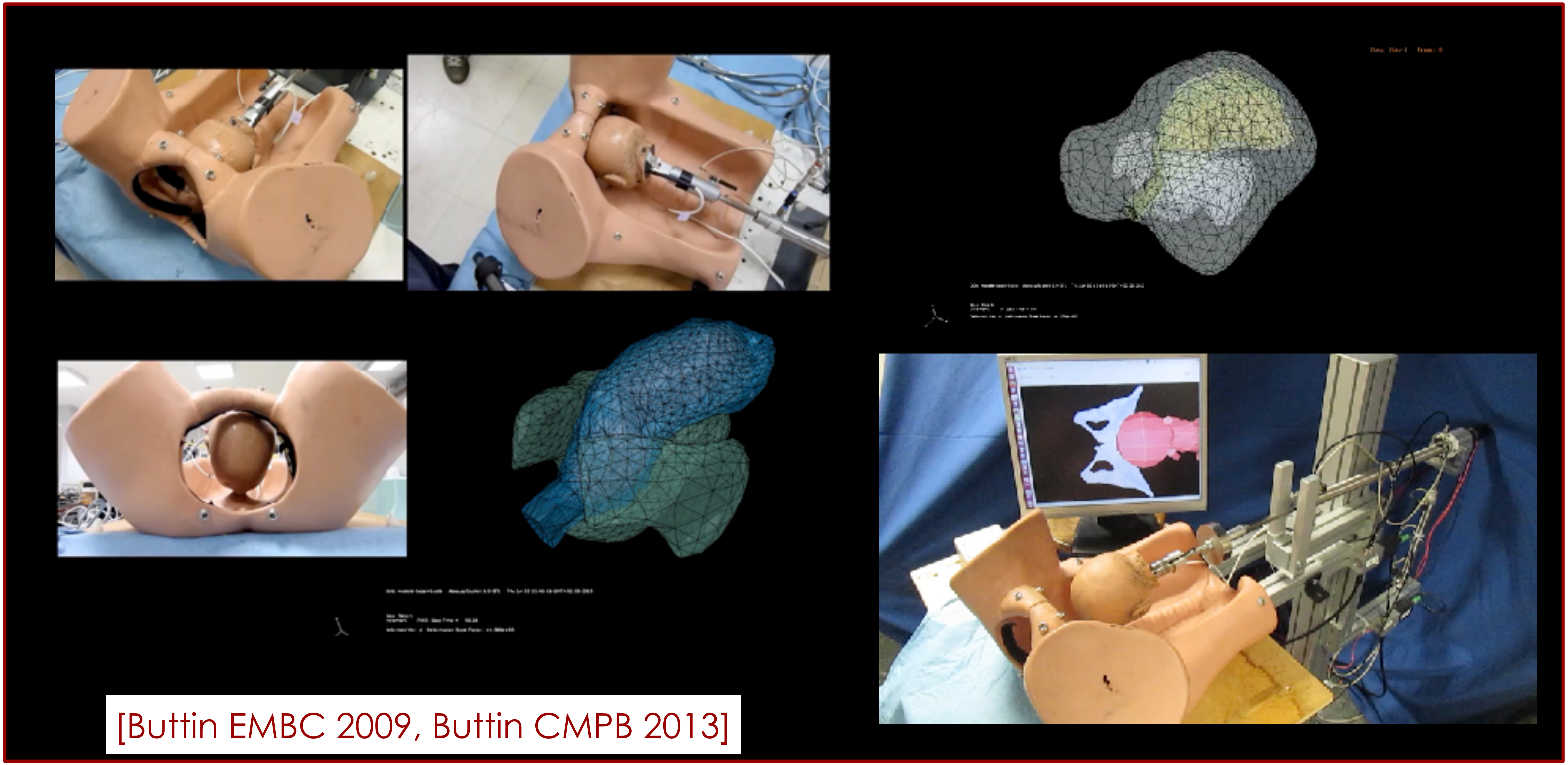
[Buttin EMBC 2009, Buttin CMPB 2013]

The first childbirth simulation without any trajectory imposed!

+ Necessary to take into account user's mouvements

Development of a childbirth simulator

LSE Laboratoire des Sciences de l'Education · TIMC · Ampère · ARMINES · HRV · Hospices Civils de Lyon · CHU Grenoble Alpes · midwifery school of Grenoble



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What's next?

1. Dynamic adaptation
2. Parallel computing
3. Childbirth simulator
4. An optimal description?
5. Validation: towards medical simulators
6. Patient specific simulators

Assessment of my contributions

Model

A topological description by element	A physical model with a force formulation by node

Mass-tensor
- Formulation

Mass-spring system
- $\forall \nu, \forall E$, non-linear

Simulation

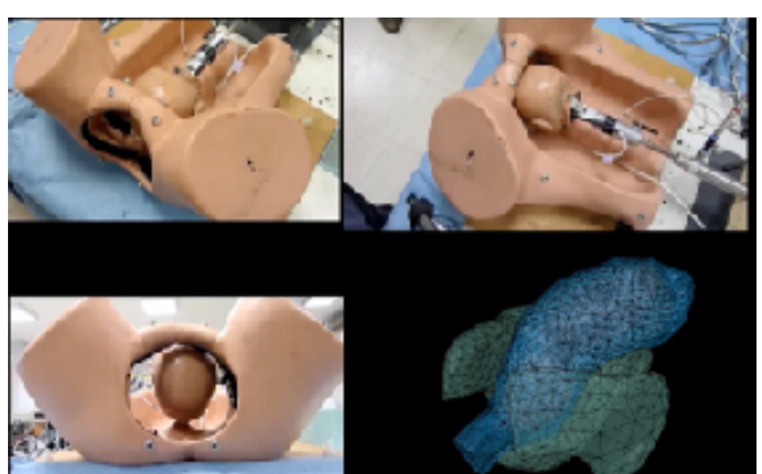
Simulation's loop
- Forces accumulation
- Numerical integration (explicit, implicit)

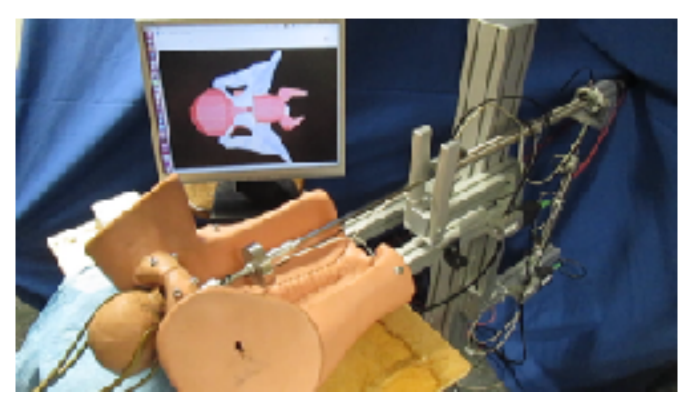
Criteria
- Topological one (shape)
- Physical one (stress, strain)

Dynamic adaptation

• Refinement • Merging • Cutting • Piercing	• Linear • Non-linear	• Mass-tensor • Mass-spring

Couplage to haptic devices





A generic model

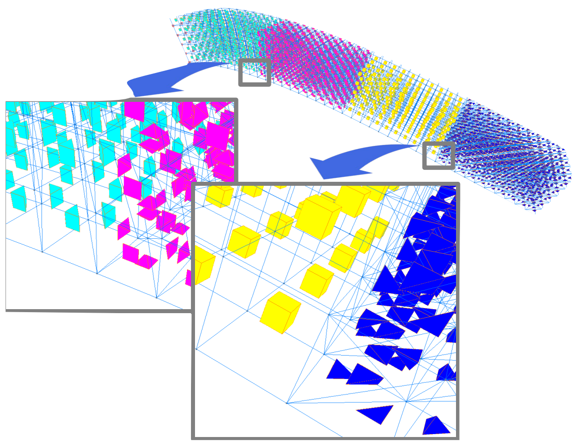
A lot of papers in Computer Graphics for 3D deformable objects

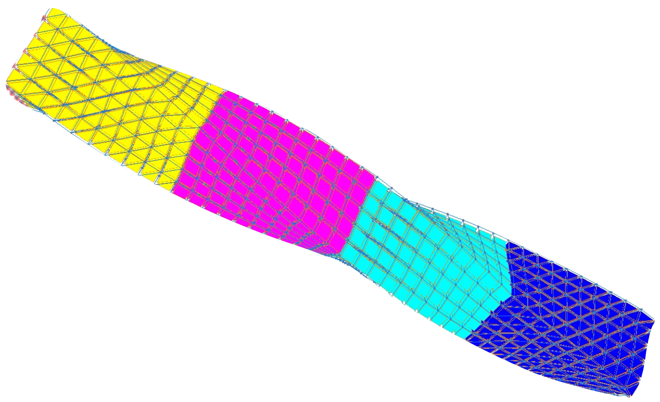
Our strategy:

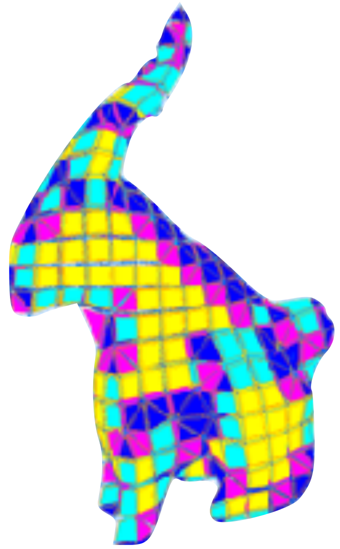
- A model suitable to the simulation of objects composed of several types of elements (topology, physics)
- A dynamic adaptation of these elements according to criteria

To meet the need of user's interaction

Dynamic adaptation of hybrid objects







Topology	Constitutive law	Physical model	Numerical integration
• Hexahedron • Tetrahedron • Prism • etc.	• Linear • Non-linear • etc.	• 3D FEM • 2D FEM Shell • Mass-tensor • Mass-spring system	• Implicit • Explicit **?**

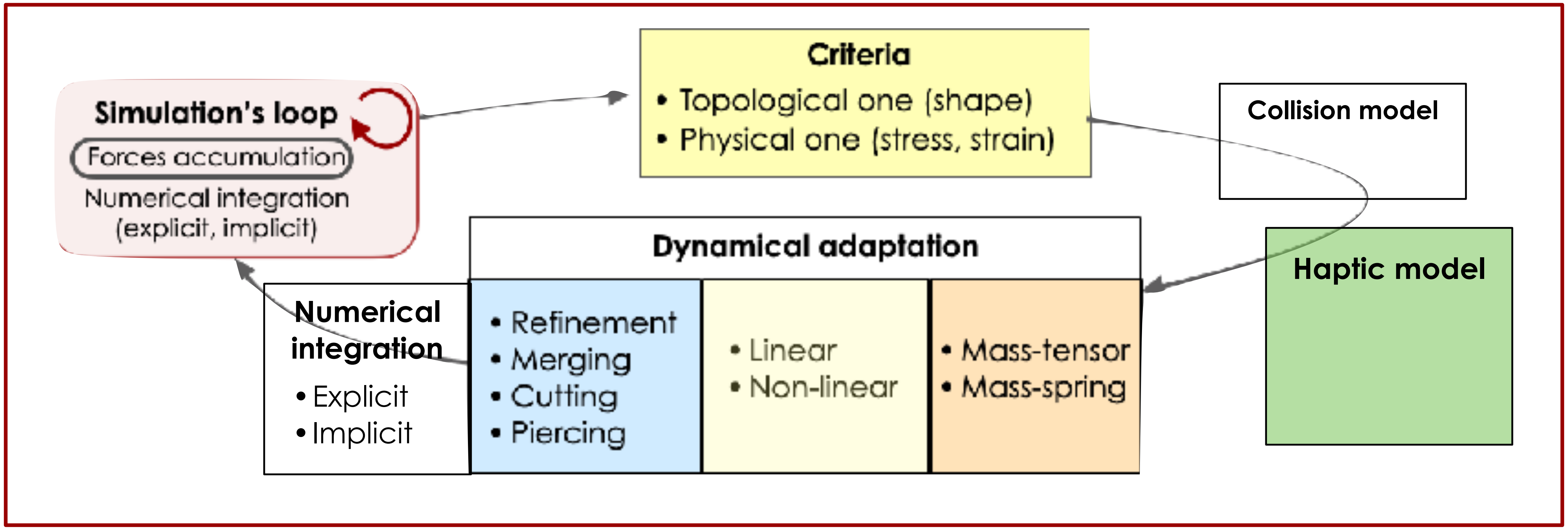
Border management between different elements (topology/physics)

Implication for **implicit integration scheme**

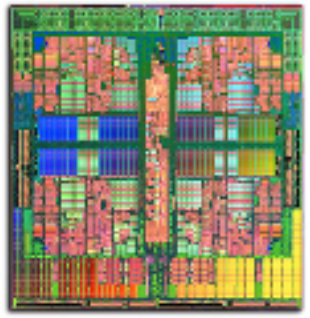
Implication for **stability** / **convergence**/ **mechanics** / **perception**

Parallel computing (GPU, multi-CPU)

To propose adequate data structure / algorithms



GPU: GeForce 6600GT Nvidia

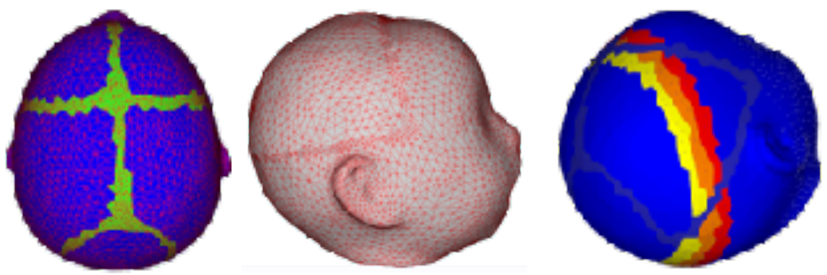


Processor: Quad-core AMD Opteron

Childbirth simulator

Combine several physical models:

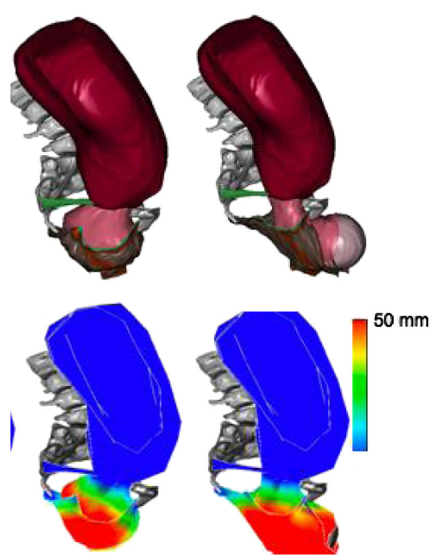
- Foetus's head
- Articulated body
- Pelvic floor
- Bony pelvis
- Parturient's abdomen



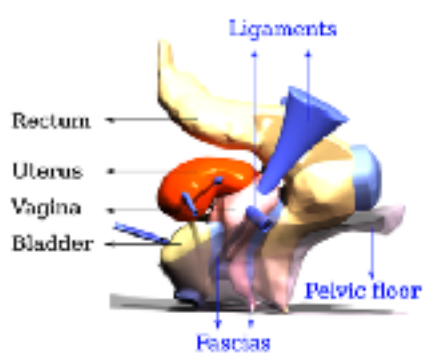
Integration of forceps with sensors into the simulator

In collaboration with

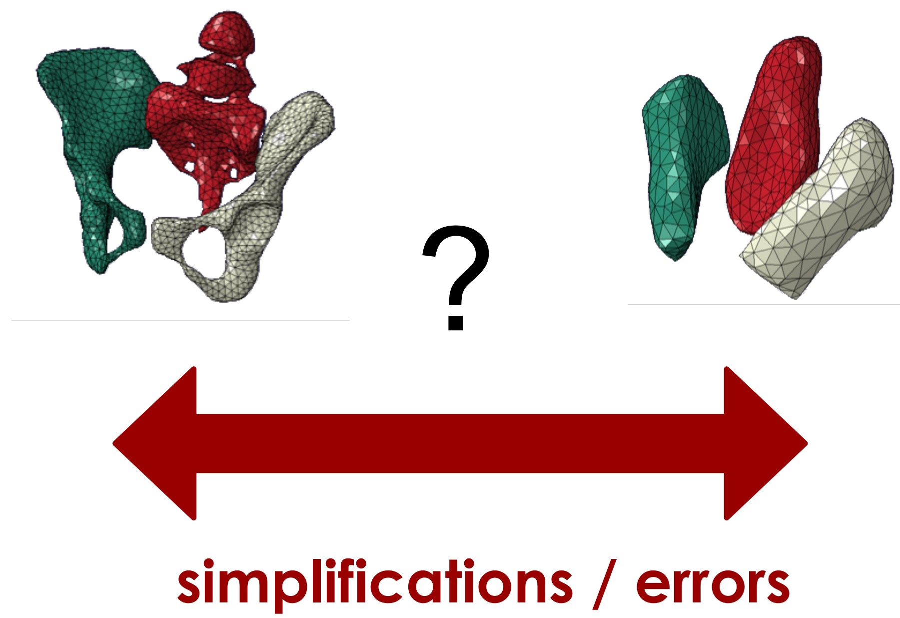
Towards an optimal description during simulation?

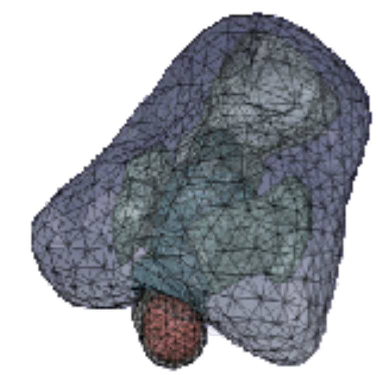


[Lepage 2014]



[Jiang 2019]





[Buttin 2009]

Automatic adjustment of elements properties (law, physical model, topology) in order to reach a description with an optimal trade-off between speed and precision/user interactions

Need to determine the validity limit of each physical model: machine learning?

Towards medical training simulators

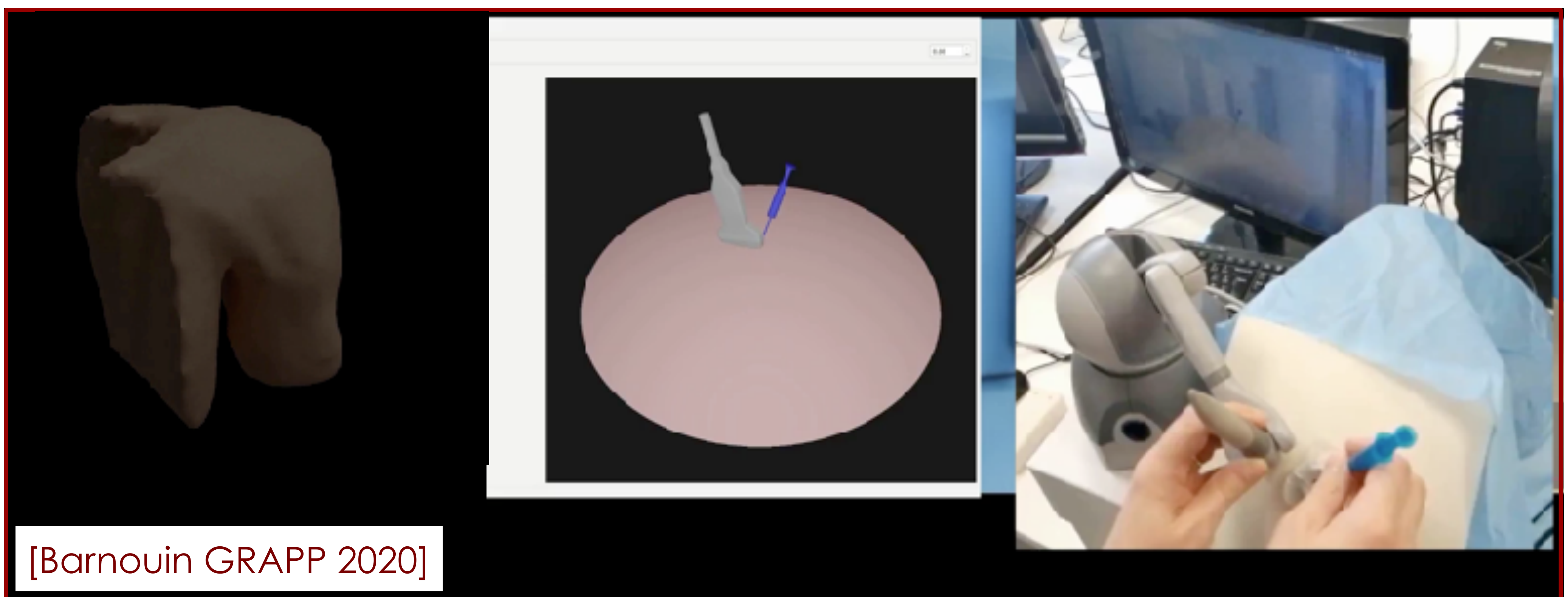
A long development process…
to provide a simulator which improves the learning gesture

- **An initial validation:** simulation & haptic & ultrasound rendering
- **A second validation** with the elaboration of relevant scenarii (morphology, pathology - usual & rare situations) for learning to reproduce
- **A third validation in regards of medical training:** tests campaign with practitioners

"We have to learn how to operate on a real patient and not learn to run the simulator. "

with

LBMC



[Barnouin GRAPP 2020]

SPARTE project (ANR-11-IDFI-0034, SAMSEI project of Université de Lyon)

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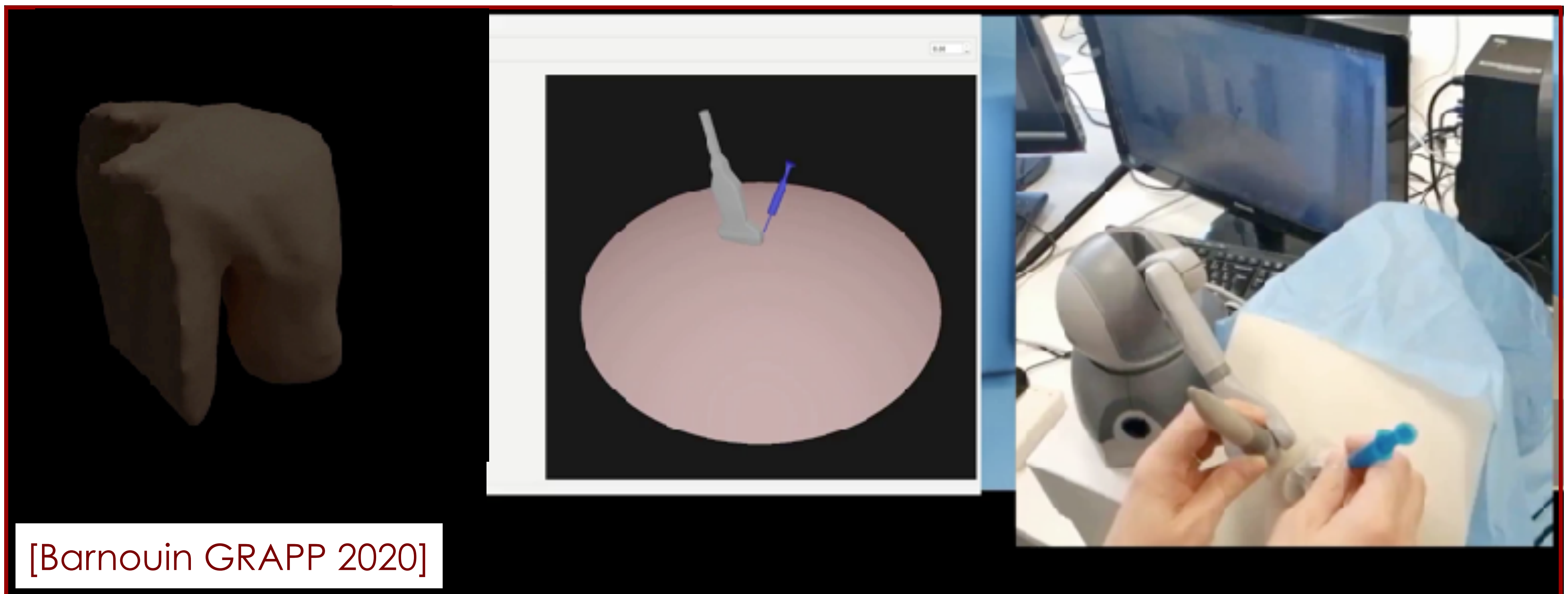
"We have to learn how to operate on a real patient and not learn to run the simulator. "

with



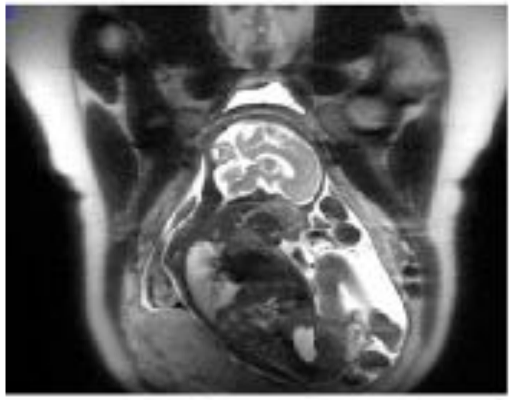
[Barnouin GRAPP 2020]

SPARTE project (ANR-11-IDFI-0034, SAMSEI project of Université de Lyon)

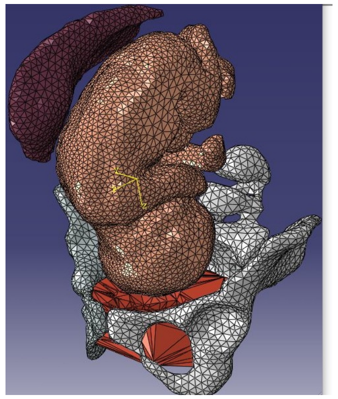
From medical training simulators… to patient specific simulators

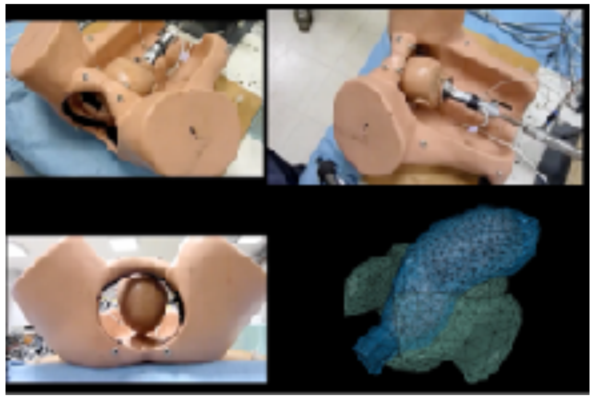
Even more challenges at each step of the simulation

- **Data** (3D mesh, mechanical parameters) from patient
- Need to **automate** the whole pipeline
- Need for **more accurate simulations**
- A robust **validation!**



[Charlotte 2011]





Thanks to my family

Simulation interactive d'objets déformables pour la conception de simulateurs d'apprentissage aux gestes médicaux-chirurgicaux

Florence Zara

Université Lyon 1, LIRIS, SAARA-ORIGAMI

Habilitation à Diriger les Recherches

Lundi 19 octobre 2020