

SOFA: a modular yet efficient physical simulation architecture

Francois.Faure@imag.fr



Outline

Motivation

Simple bodies

Layered bodies

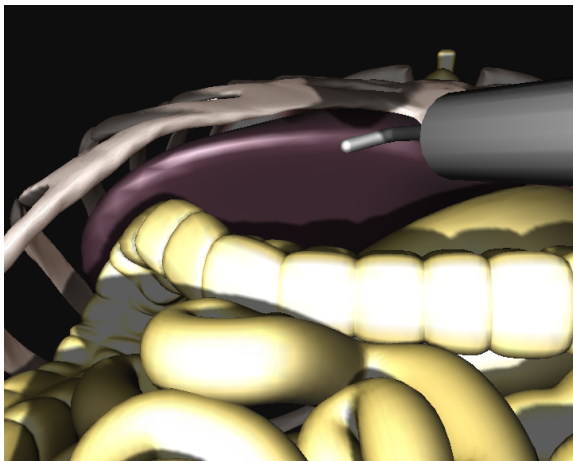
Mappings

Interacting bodies

Data processing

Conclusion

A complex physical simulation



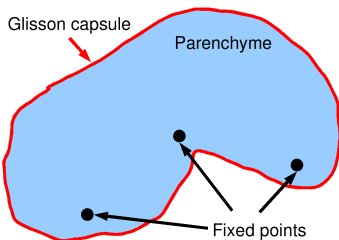
Material, internal forces, constraints, contact detection and modeling, ODE solution, visualization, interaction, etc.

Simulation platforms

- ▶ Current platforms (ODE, Havok, Novodex, etc.) provide :
 - ▶ limited number of material types
 - ▶ limited number of geometry types
 - ▶ no control on collision detection algorithms
 - ▶ no control on interaction modeling
 - ▶ few (if any) control of the numerical models and methods.
 - ▶ no control on the main loop
 - ▶ few (if any) parallelism
- ▶ We need much more !
 - ▶ models, algorithms, scheduling, visualization, etc.

Animation of a simple body

► a liver



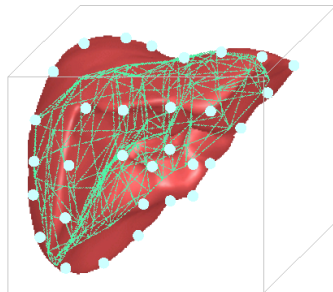
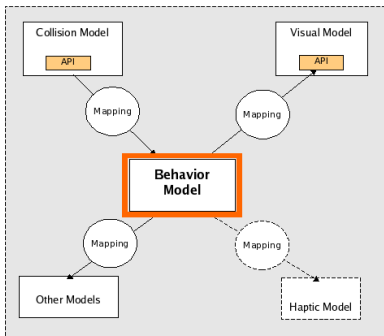
- inside : soft material
- surface : stiffer material

A specialized program :

```
f = M*g
f += F1(x,v)
f += F2(x,v)
a = f/M
a = C(a)
v += a * dt
x += v * dt
display(x)
```

A generic approach

- ▶ Behavior model : all internal laws
- ▶ Others : interaction with the world
- ▶ Mappings : relations between the models (uni- or bi-directional)



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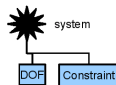
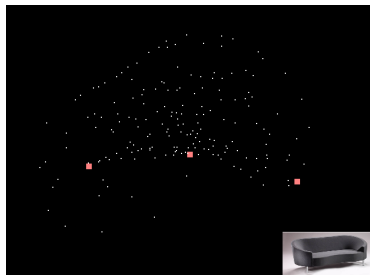
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Components

Data :

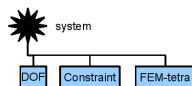
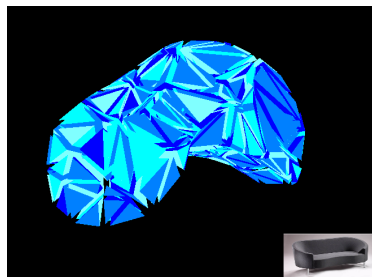
- ▶ sample points and associated values :
 x, v, a, f
- ▶ constraints : fixed points
other : oscillator, collision plane, etc.



Components

Data :

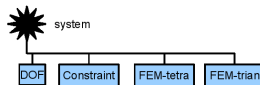
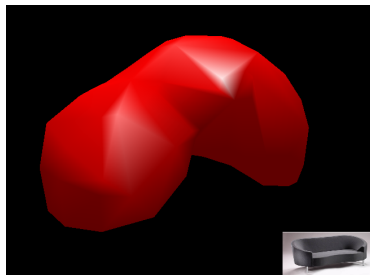
- ▶ sample points and associated values :
 x, v, a, f
- ▶ constraints : fixed points
- ▶ force field : tetrahedron FEM
other : triangle FEM, springs, Lennard-Jones, SPH, etc.



Components

Data :

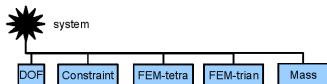
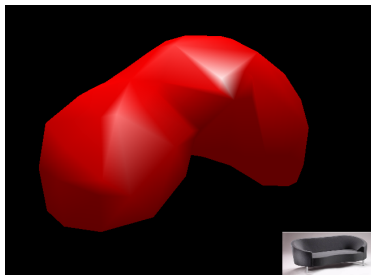
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- ▶ force field : triangle FEM



Components

Data :

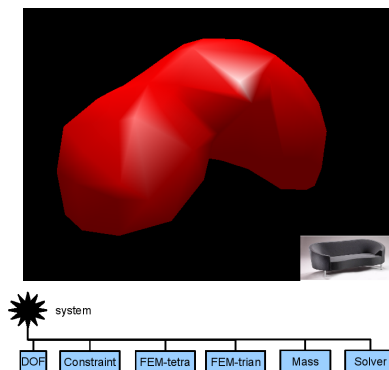
- ▶ sample points and associated values :
 x, v, a, f
- ▶ constraints : fixed points
- ▶ force field : tetrahedron FEM
- ▶ force field : triangle FEM
- ▶ mass : uniform
other : diagonal, sparse symmetric matrix



Components

Data :

- ▶ sample points and associated values :
 x, v, a, f
- ▶ constraints : fixed points
- ▶ force field : tetrahedron FEM
- ▶ force field : triangle FEM
- ▶ mass : uniform
- ▶ ODE solver : explicit Euler
other : Runge-Kutta, implicate Euler, static solution, etc.



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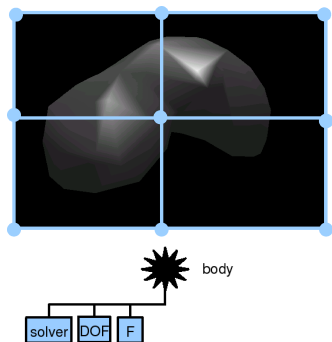
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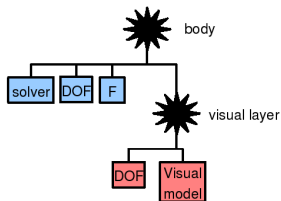
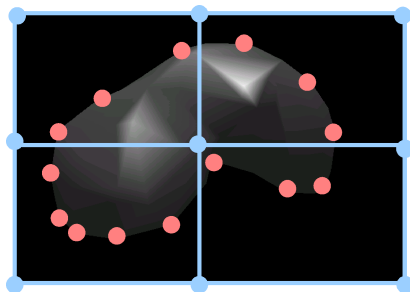
Layered body

- independent DOFs (blue)



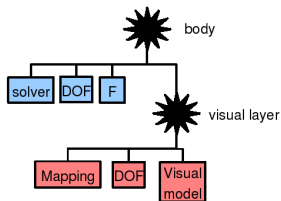
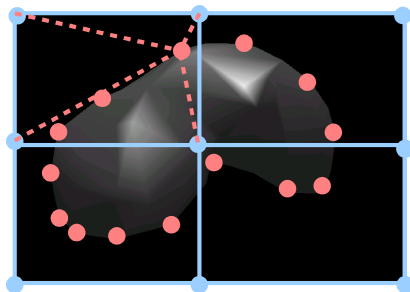
Layered body

- ▶ independent DOFs (blue)
- ▶ visual samples (salmon)



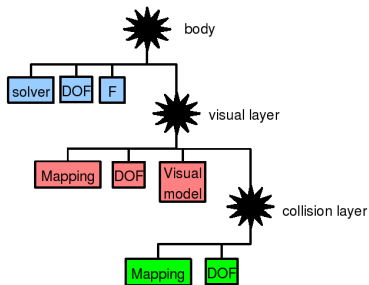
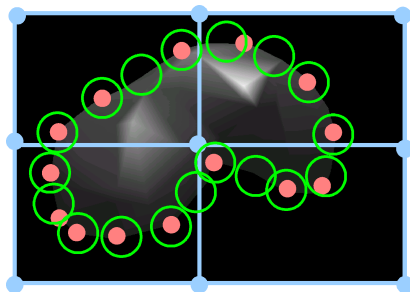
Layered body

- ▶ independent DOFs (blue)
- ▶ visual samples (salmon)
- ▶ visual mapping



Layered body

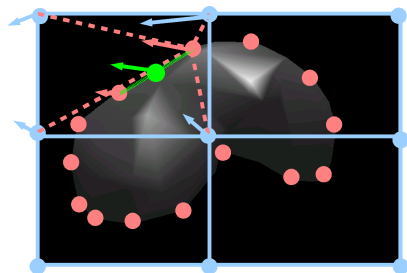
- ▶ independent DOFs (blue)
- ▶ visual samples (salmon)
- ▶ visual mapping
- ▶ collision samples (green)
- ▶ collision mapping



Layered body

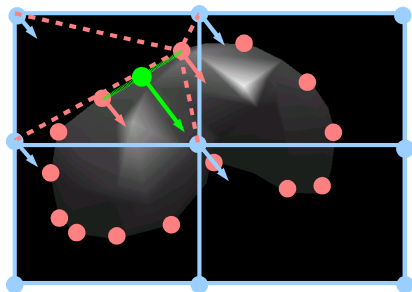
- ▶ independent DOFs (blue)
- ▶ visual samples (salmon)
- ▶ visual mapping
- ▶ collision samples (green)
- ▶ collision mapping
- ▶ apply displacements

1. $\mathbf{v}_{visual} = \mathbf{J}_{visual} \mathbf{v}$
2. $\mathbf{v}_{collision} = \mathbf{J}_{collision} \mathbf{v}_{visual}$



Layered body

- ▶ independent DOFs (blue)
- ▶ visual samples (salmon)
- ▶ visual mapping
- ▶ collision samples (green)
- ▶ collision mapping
- ▶ apply displacements
 1. $v_{visual} = J_{visual} v$
 2. $v_{collision} = J_{collision} v_{visual}$
- ▶ apply forces
 1. $f_{visual} = J_{collision}^T f_{collision}$
 2. $f = J_{visual}^T f_{visual}$



More on mappings

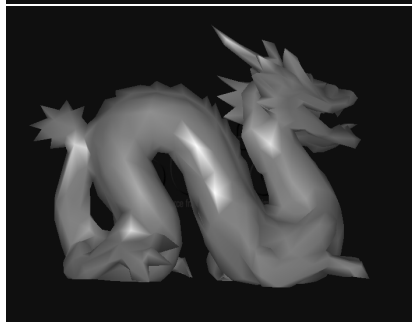
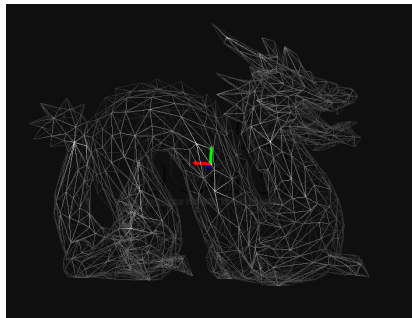
- ▶ Map a set of degrees of freedom (the parent) to another (the child).
- ▶ Typically used to attach a geometry to control points.
- ▶ Child degrees of freedom (DOF) are not independent : their positions are totally defined by their parent's.
- ▶ Displacements are propagated top-down (parent to child) :
$$v_{child} = Jv_{parent}$$
- ▶ Forces are propagated bottom-up

The physics of mappings

Example : line mapping

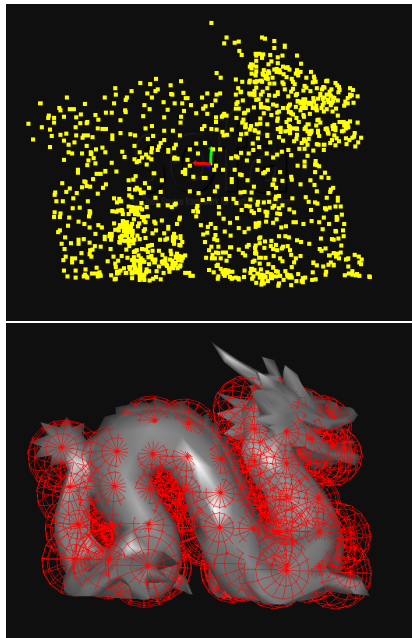
Examples of mappings

- ▶ RigidMapping can be used to attach points to a rigid body
 - ▶ to attach a visual model



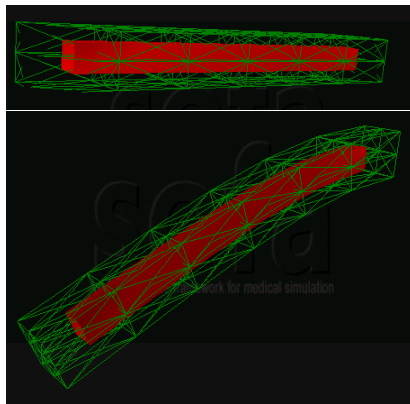
Examples of mappings

- ▶ RigidMapping can be used to attach points to a rigid body
 - ▶ to attach collision surfaces



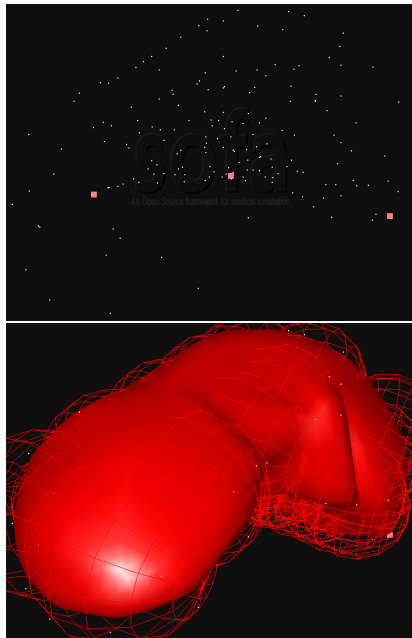
Examples of mappings

- ▶ RigidMapping can be used to attach points to a rigid body
- ▶ BarycentricMapping can be used to attach points to a deformable body
 - ▶ to attach a visual model



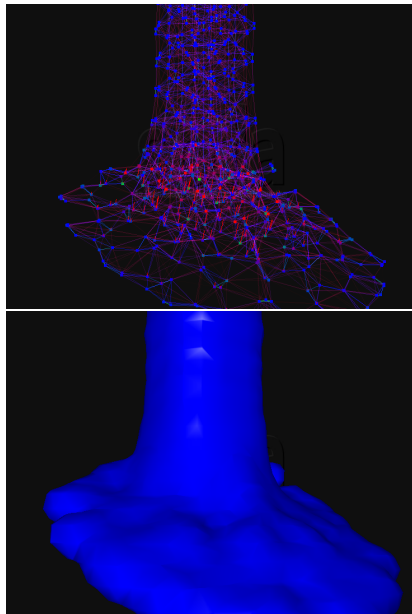
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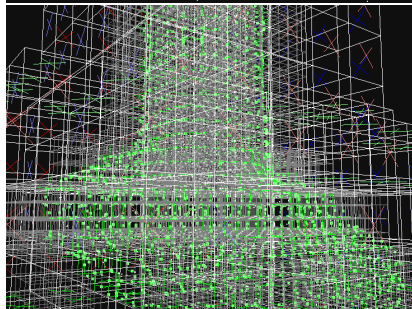
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- ▶ More advanced mapping can be applied to fluids



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- ▶ RigidMapping can be used to attach points to a rigid body
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- ▶ More advanced mapping can be applied to fluids



On the physical consistency of mappings

- ▶ Conservation of energy :

Necessary condition : $v_{child} = Jv_{parent} \Rightarrow f_{parent}^+ = J^T f_{child}$

- ▶ Conservation of momentum :

Mass is modeled at one level only. There is no transfer of momentum.

- ▶ Constraints on displacements (e.g. incompressibility, fixed points) are not easily applied *at the child level*

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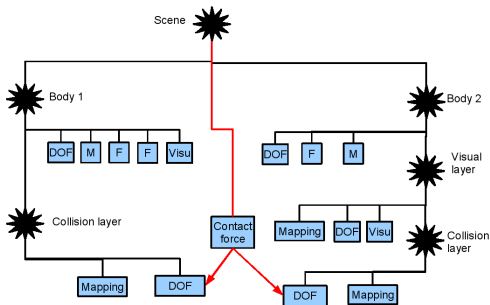
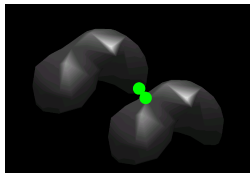
Interacting bodies

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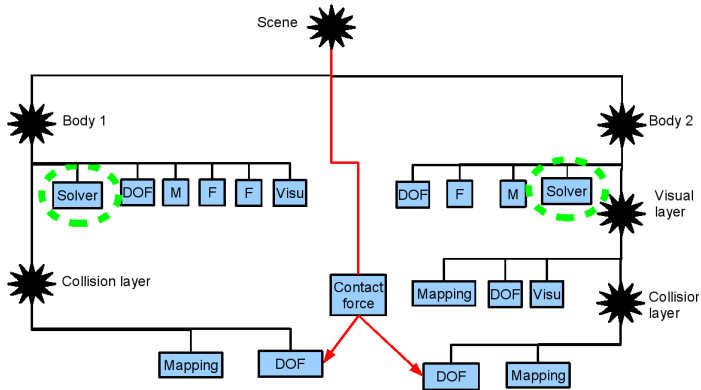
Conclusion

Two bodies in contact

Use extended trees (Directed Acyclic Graphs) to model trees with loops.

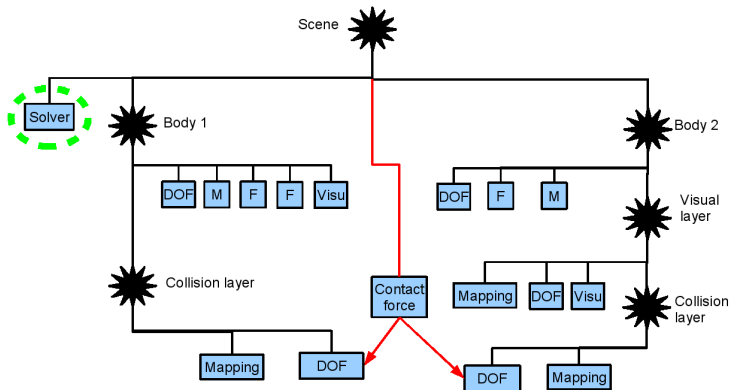


ODE solution of interacting bodies



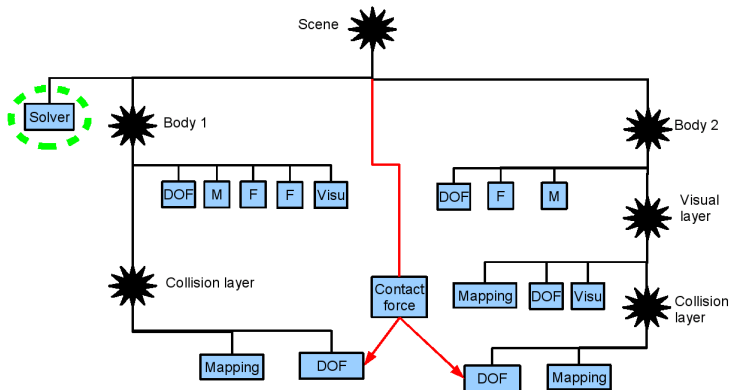
- Soft interactions : independent processing, no synchronization required

ODE solution of interacting bodies



- ▶ Soft interactions : independent processing, no synchronization required
- ▶ Stiff interactions : unified implicit solution, synchronized objects

ODE solution of interacting bodies



- ▶ Soft interactions : independent processing, no synchronization required
- ▶ Stiff interactions : unified implicit solution, synchronized objects
- ▶ Hard interaction constraints : work in progress (*Christian Duriez, ALCOVE*)

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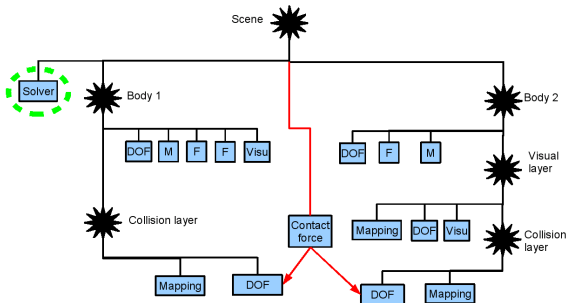
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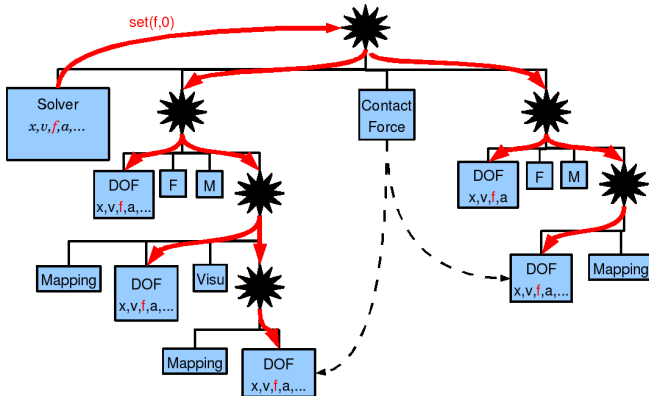
Actions



- ▶ No global state vector
- ▶ Action = graph traversal + global vector ids + call of abstract top-down and bottom up methods

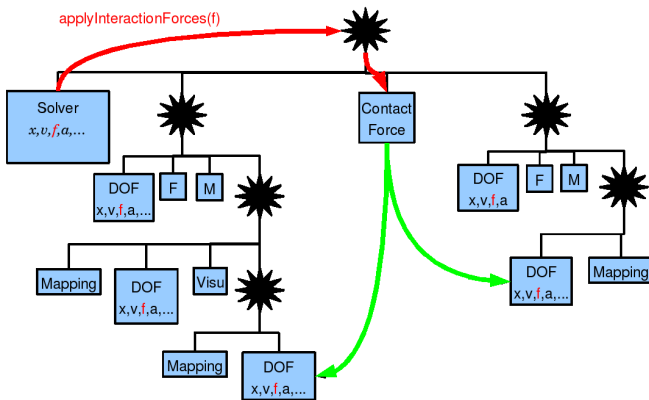
Example : clearing a global vector

- ▶ The solver triggers an action starting from its parent system and carrying the necessary symbolic information
- ▶ the action is propagated through the graph and calls the appropriate methods at each DOF node



Example : applying interaction forces

- ▶ The solver triggers the appropriate action
- ▶ the action is propagated through the graph and calls the appropriate methods at each Contact node



Efficient implicit integration

- ▶ Large time steps for stiff internal forces and interactions
- ▶ solve $(\alpha M + \beta h^2 K)\Delta v = h(f + hKv)$ Iteratively using a conjugate gradient solution

Actions :

- ▶ propagateDx
- ▶ computeDf
- ▶ vector operations
- ▶ dot product (only global value directly accessed by the solver)

Ongoing work : building global vectors and matrices also

Efficiency

- ▶ No global state vector
 - ▶ they are scattered over the DOF components
 - ▶ each DOF component can be based on its own types (e.g. Vec3, Frame, etc.)
 - ▶ symbolic values are used to represent global state vectors
- ▶ Action = graph traversal + global vector ids + call of abstract top-down and bottom up methods
 - ▶ Displacements are propagated top-down
 - ▶ Interactions forces are evaluated after displacement propagation
 - ▶ Forces are accumulated bottom-up
 - ▶ Branches can be processed in parallel
 - ▶ virtual functions applied to components

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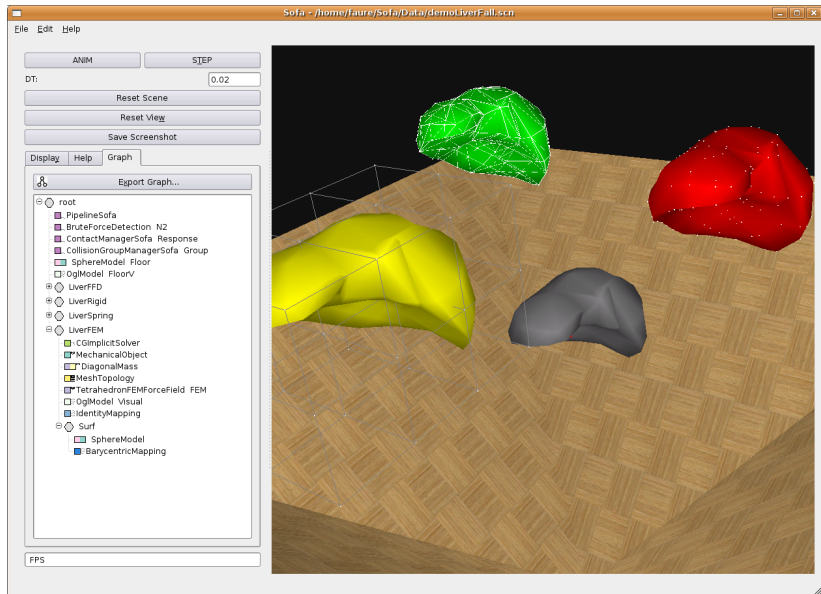
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Current stage

About 60 man.month, 20000 C++ code lines



Efficient coupling

High modularity :

- ▶ Abstract components : DOF, Force, Constraint, Solver, Topology, Mass, CollisionModel, VisualModel, etc.
- ▶ Arbitrary DOF types can coexist in the same scene

Efficiency :

- ▶ global vectors and matrices are avoided
- ▶ parallel processing is allowed

Implementation :

- ▶ currently 20000 C++ lines
- ▶ Windows, Linux
- ▶ Qt or FLTK user interfaces
- ▶ XML file format

Ongoing work

- ▶ More people : ETHZ, ...
- ▶ More algorithms : cutting (*Hervé Delingette, ASCLEPIOS*), interfaces (*François Faure, EVASION*),...
- ▶ More schedulers : asynchronous simulation/rendering/haptic feedback (*Jeremie Allard, Cimit*)
- ▶ More brute force : parallelization on PC cluster (*Everton Hermann, LIG/LJK*)
- ▶ More visual performance : coupling to a good render engine (*Pierre-Jean Bensusan, ALCOVE*)
- ▶ More documentation (*everybody...*)
- ▶ Licensing

www.sofa-framework.org