SOFA: a modular yet efficient physical simulation architecture

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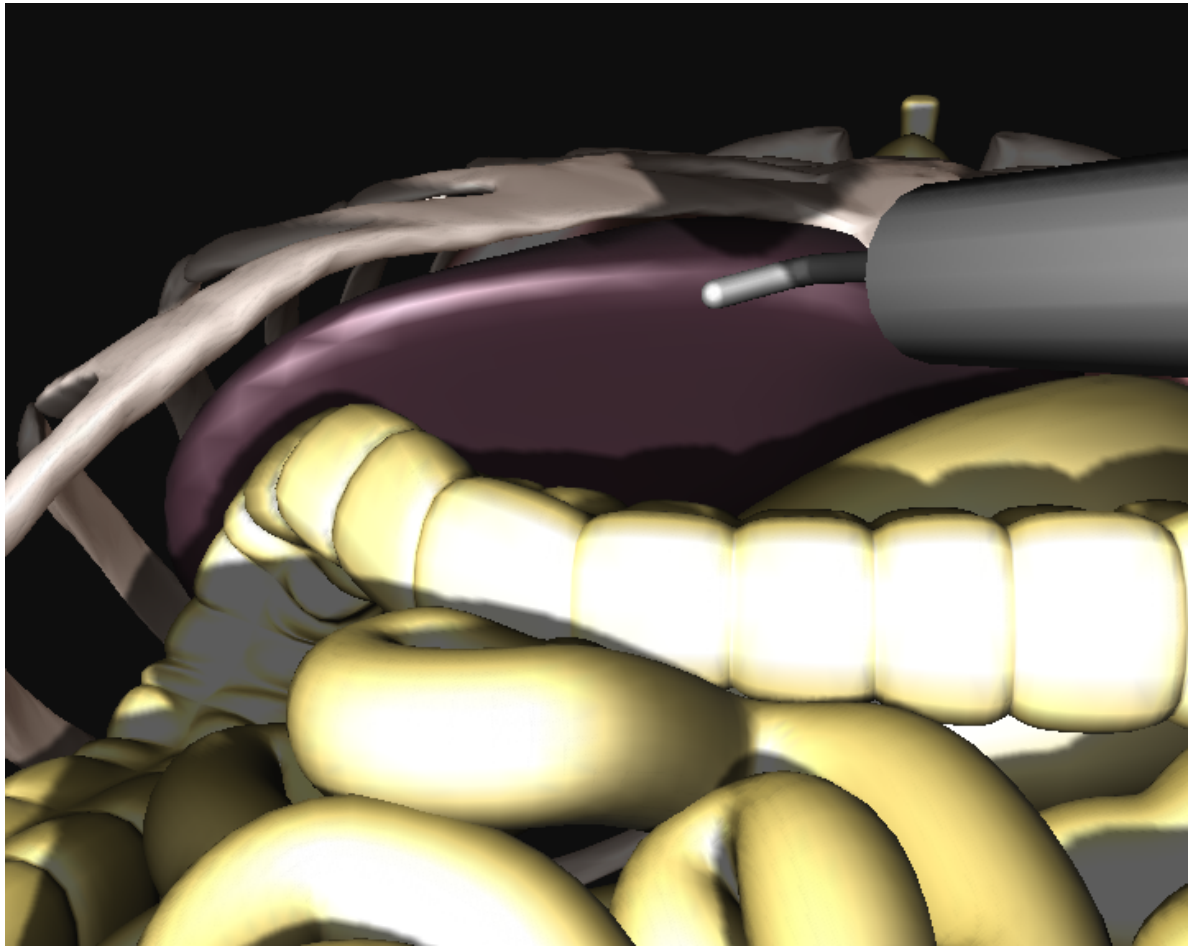
Evasion

MOAIS

Outline

A complex physical simulation



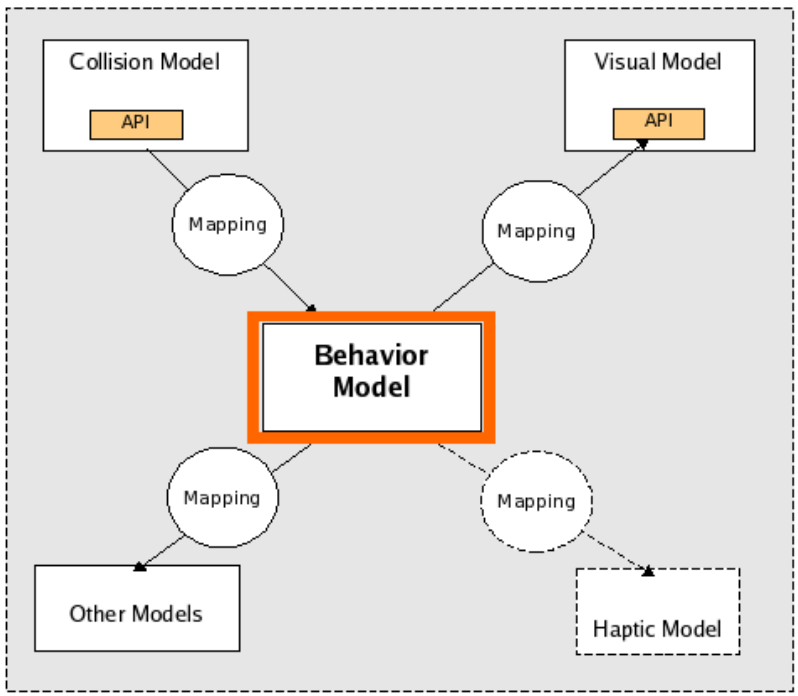
Material, internal forces, contraints, contact detection and modeling, ODE solution, visualization, interaction, etc.

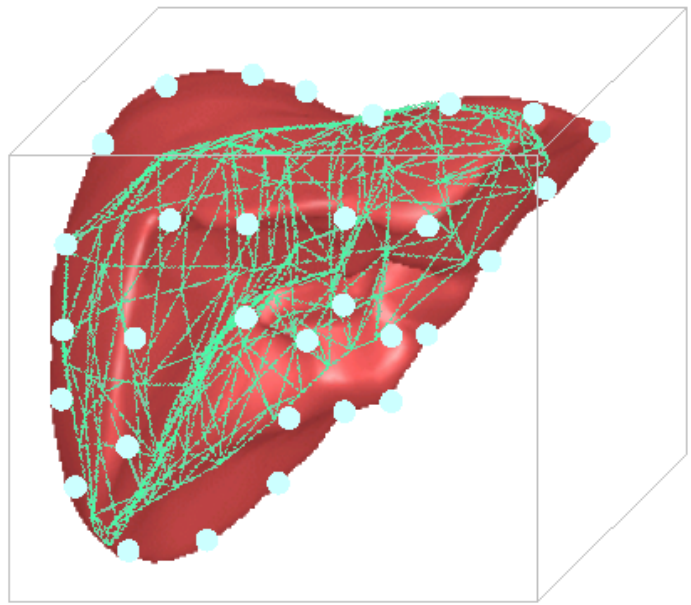
Simulation platforms

- Current platforms (ODE, Havok, PhysX, 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
- We need much more !
  - models, algorithms, scheduling, visualization, etc.

A generic approach

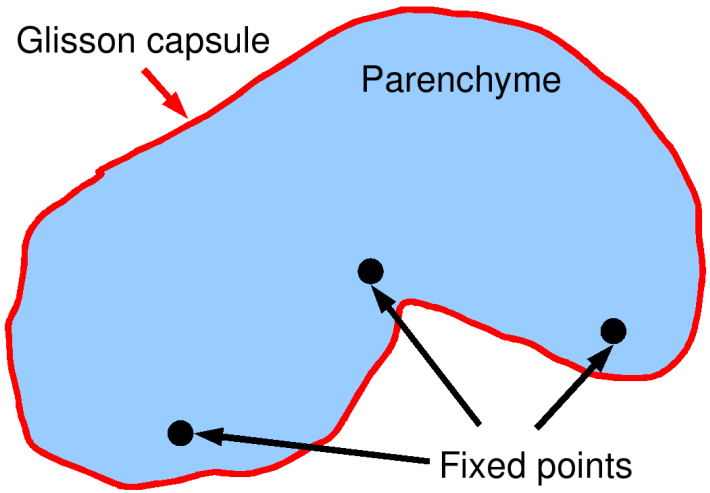
- Behavior model : all internal laws
- Others : interaction with the world
- Mappings : relations between the models (uni- or bi-directional)





Animation of a simple body

- a liver



- inside : soft material
- surface : stiffer material

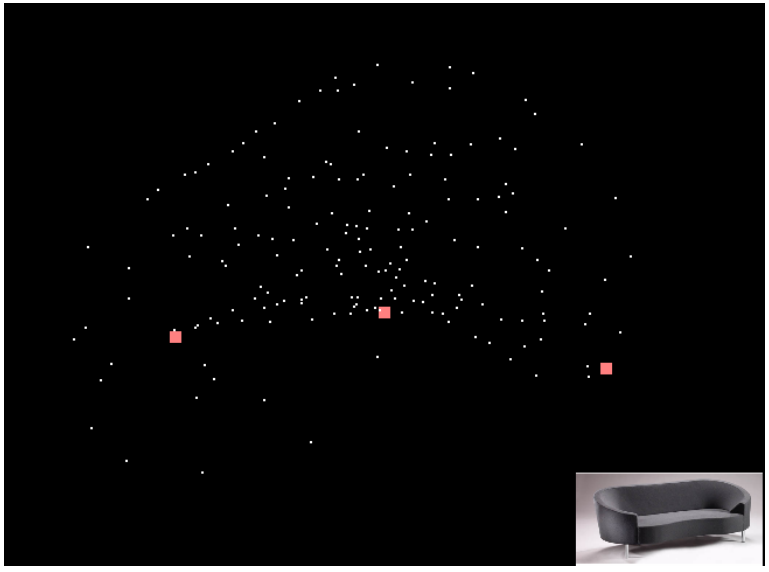
A specialized program :

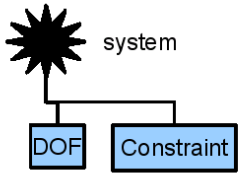
```
f = M*g
f += F1(x,v)
f += F2(x,v)
a = f/M
a = C(a)
v += a * dt
x += v * dt
display(x)
```

Outline

Components

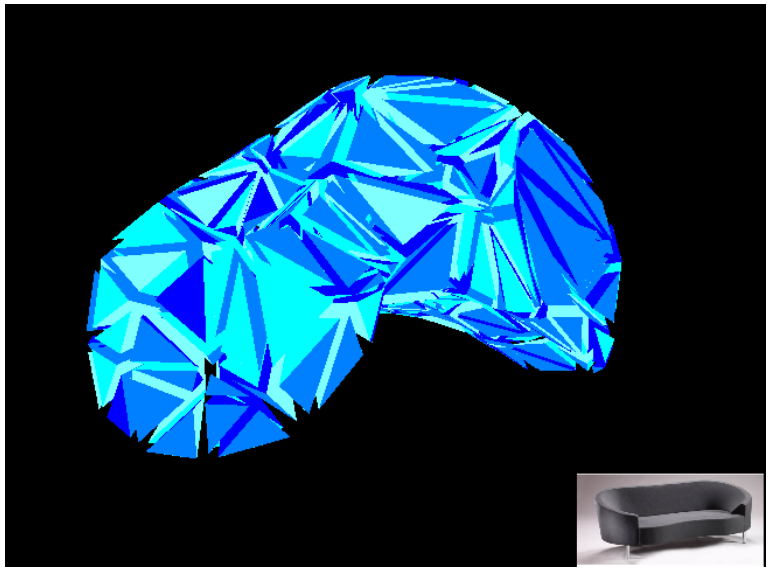
- state vectors (DOF) : x, v, a, f
- constraints : fixed points
  other : oscillator, collision plane, etc.

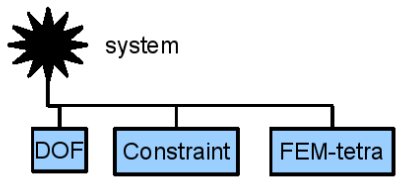




Components

- state vectors (DOF) : x, v, a, f
- constraints : fixed points
- force field : tetrahedron FEM
  other : triangle FEM, springs, Lennard-Jones, SPH, etc.





Components

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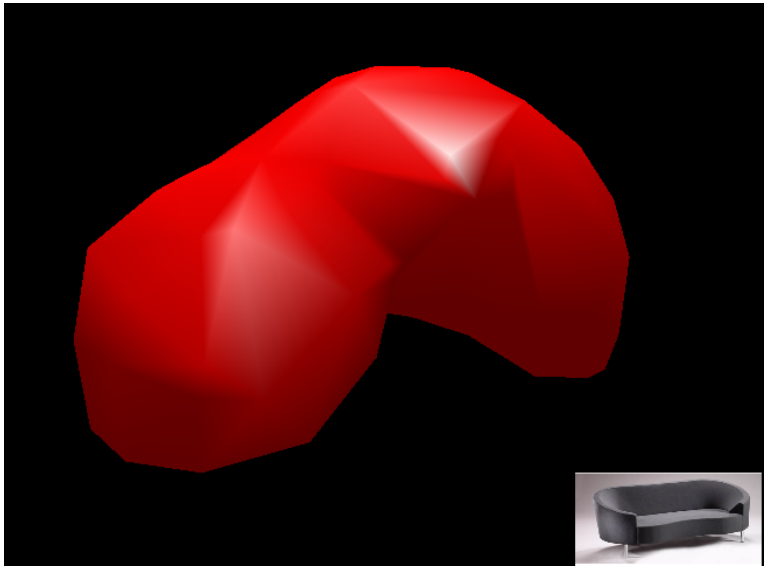
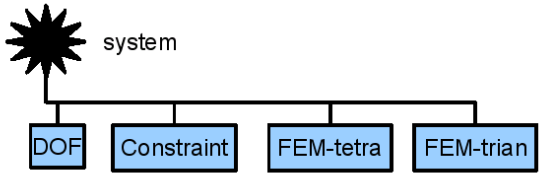
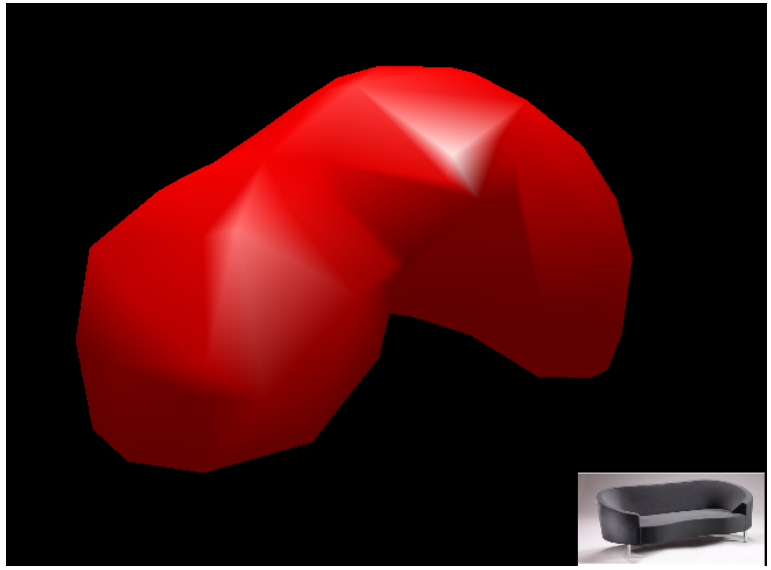
- force field : triangle FEM

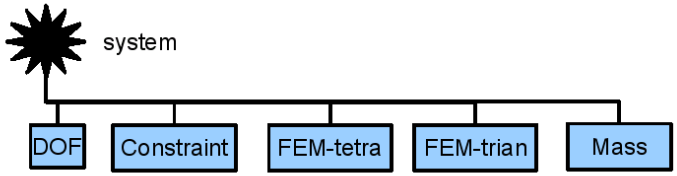




Components

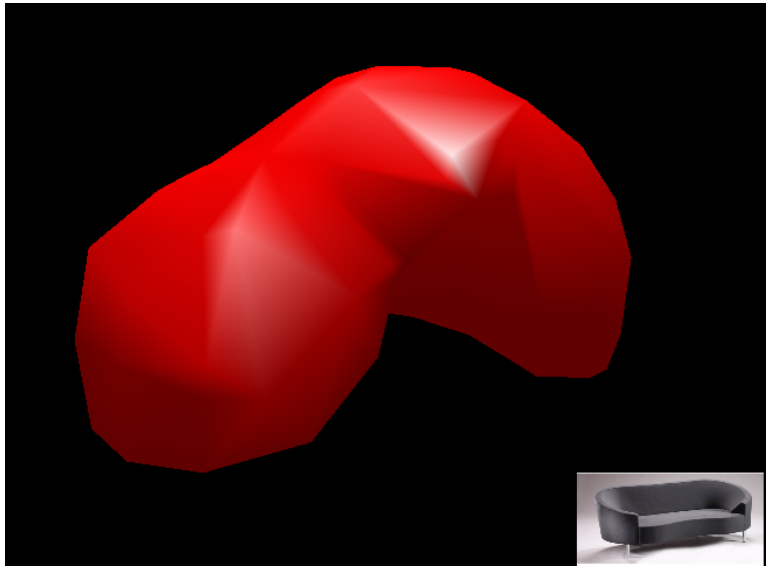
- state vectors (DOF) : x, v, a, f
- constraints : fixed points
- force field : tetrahedron FEM
- force field : triangle FEM
- mass : uniform
  other : diagonal, sparse symmetric matrix

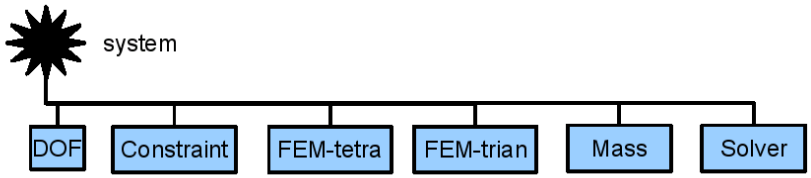




Components

- state vectors (DOF) : x, v, a, f
- constraints : fixed points
- force field : tetrahedron FEM
- force field : triangle FEM
- mass : uniform
- ODE solver : explicit Euler
  other : Runge-Kutta, implicite Euler, static solution, etc.





Operations

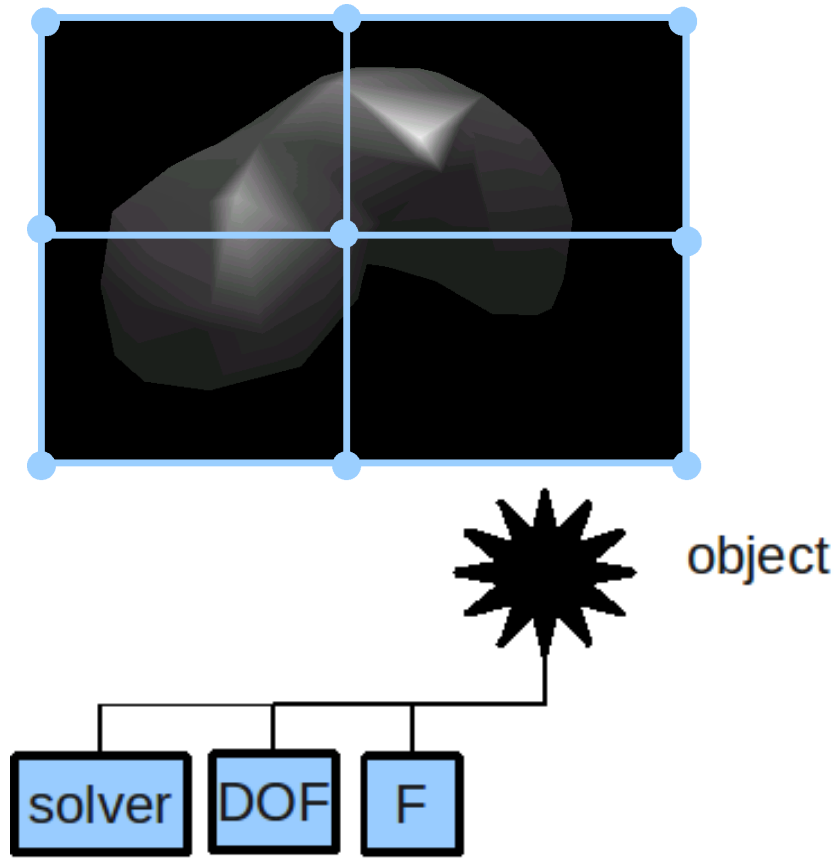
- The ODE solver sends visitors to apply operations
- The visitors traverse the scene and apply virtual methods to the components
- The methods read and write state vectors (identified by symbolic constants) in the DOF component
- Example : accumulate force
  - A `ResetForceVisitor` recursively traverses the nodes of the scene (only one node here)
    - All the `DOF` objects apply their `resetForce()` method
  - An `AccumulateForceVisitor` recursively traverses the nodes of the scene
    - All the `ForceField` objects apply their `addForce( Forces, const Positions, const Velocities )` method
  - the final value of f is weight + tetra fem force + trian fem force

Outline

Layered object

Object embedded in a deformable grid

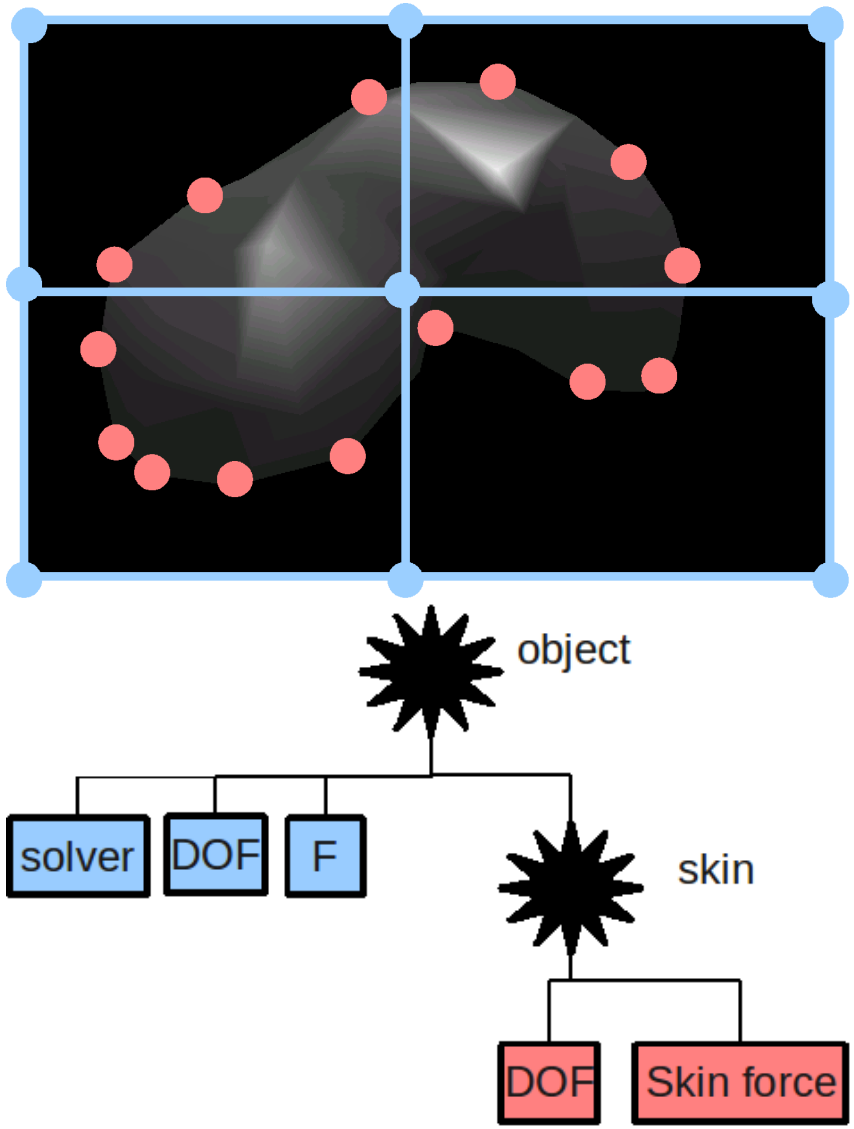
- independent DOFs (blue)



Layered object

Object embedded in a deformable grid

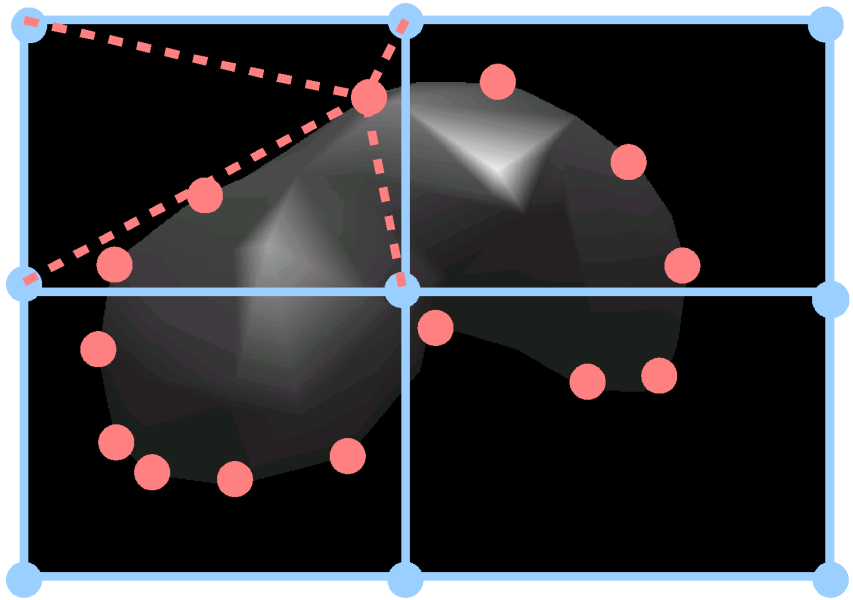
- independent DOFs (blue)
- skin vertices (salmon)

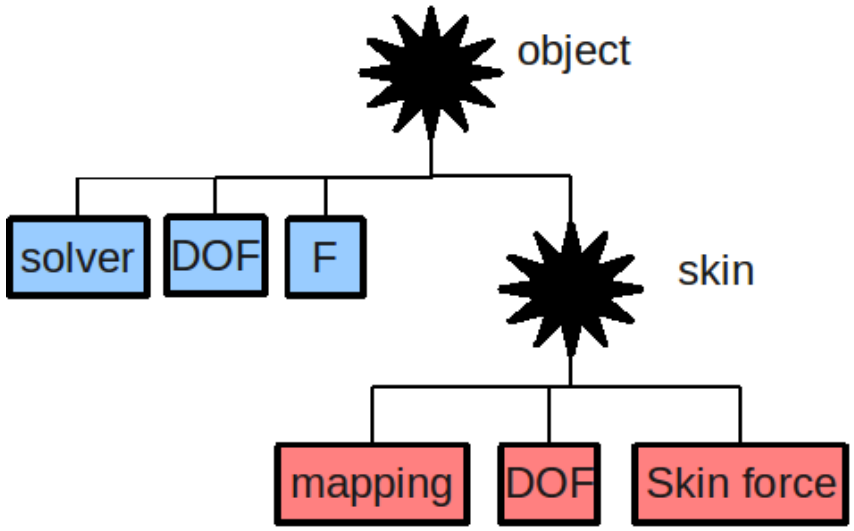


Layered object

Object embedded in a deformable grid

- independent DOFs (blue)
- skin vertices (salmon)
- mapping

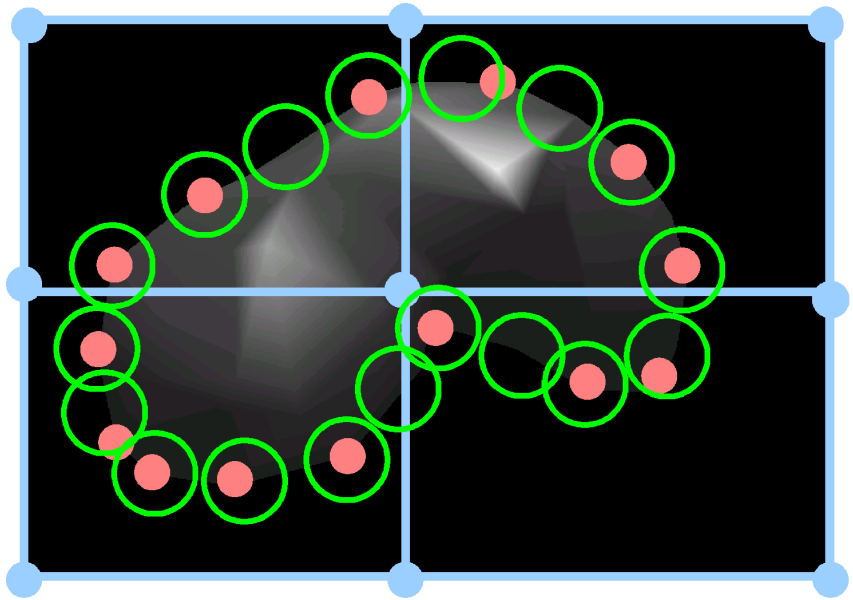


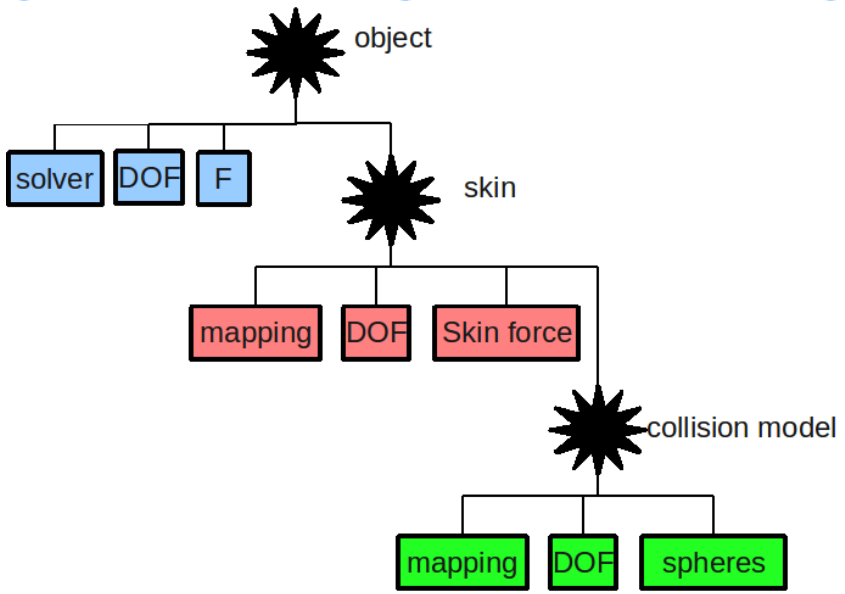


Layered object

Object embedded in a deformable grid

- independent DOFs (blue)
- skin vertices (salmon)
- mapping
- collision samples (green)
- collision mapping

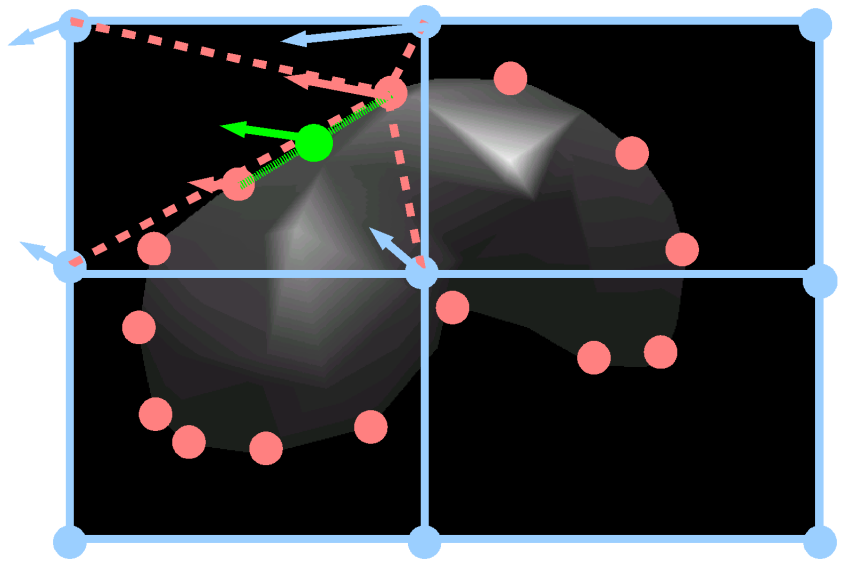




Layered object

Object embedded in a deformable grid

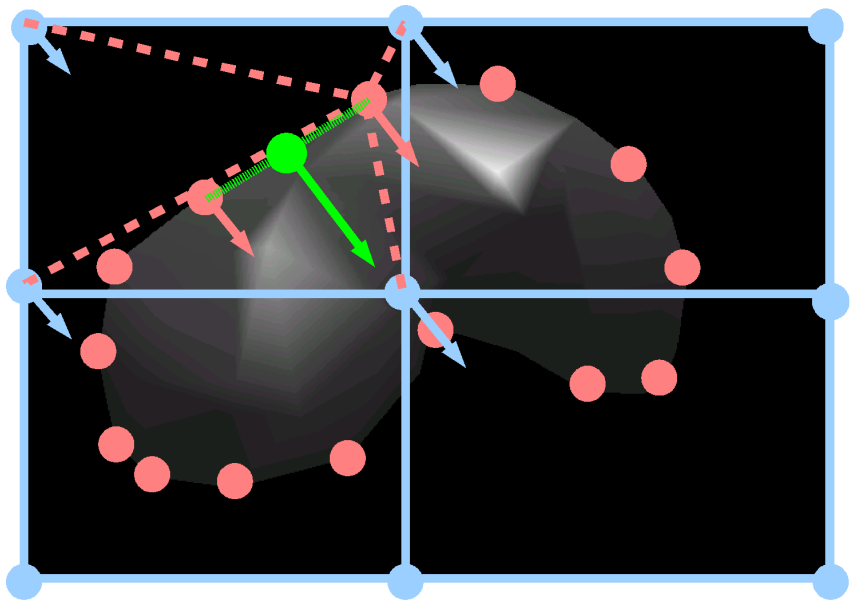
- independent DOFs (blue)
- skin vertices (salmon)
- mapping
- collision samples (green)
- collision mapping
- apply displacements
  1. $v_{skin} = J_{skin} v$
  2. $v_{collision} = J_{collision} v_{skin}$



Layered object

Object embedded in a deformable grid

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



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

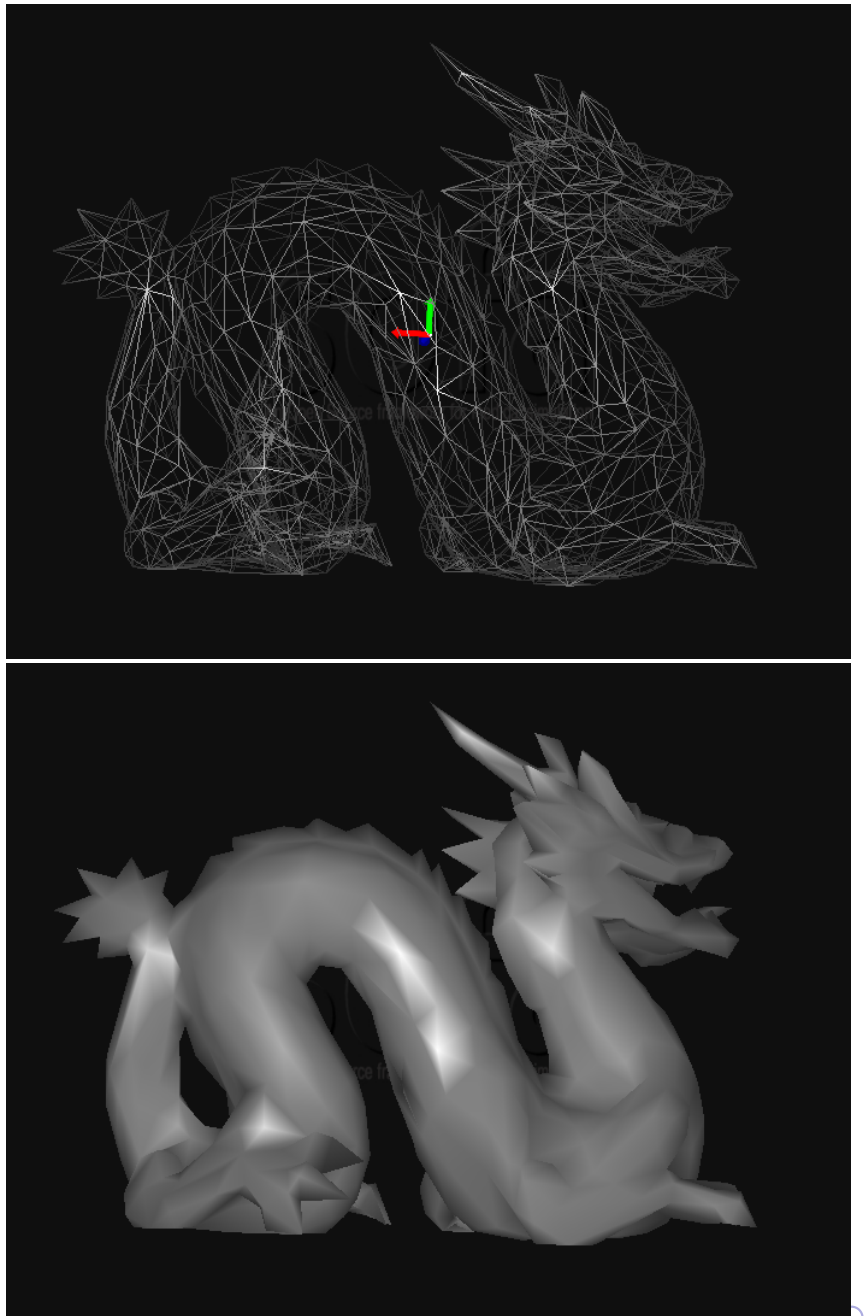
The physics of mappings

Example : line mapping

$$
\begin{aligned}
v = \begin{pmatrix} a & b \end{pmatrix} \begin{pmatrix} v_1 \\ v_2 \end{pmatrix} &= Jv \\
\begin{pmatrix} f_1 \\ f_2 \end{pmatrix} = \begin{pmatrix} a \\ b \end{pmatrix} f &= J^T f
\end{aligned}
$$

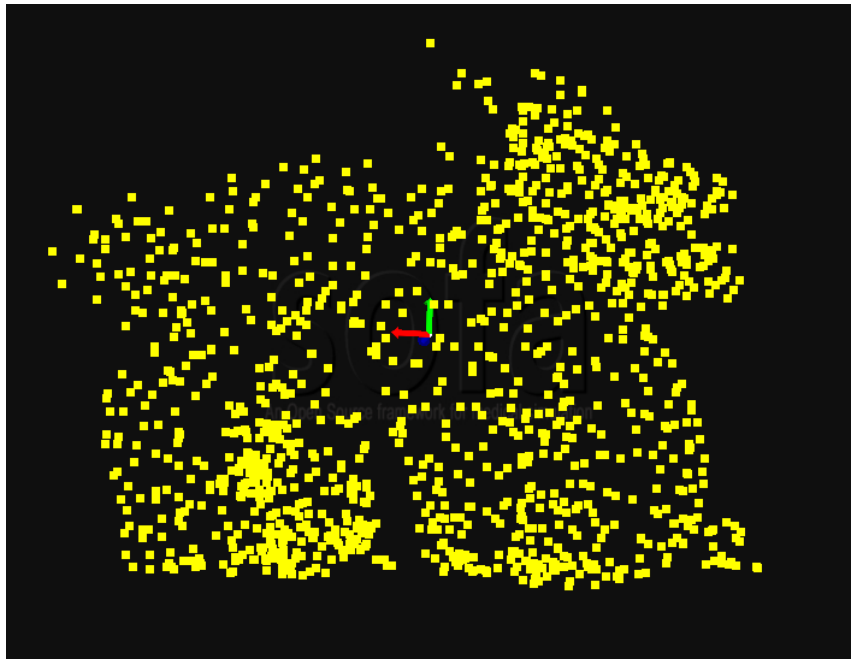
Examples of mappings

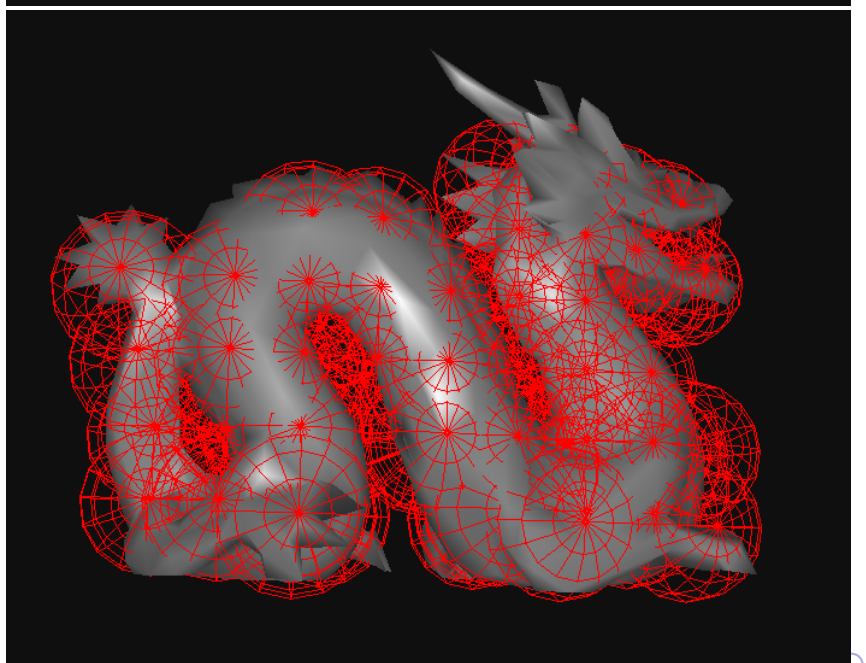
- RigidMapping can be used to attach points to a rigid body
  - to attach a visual model



Examples of mappings

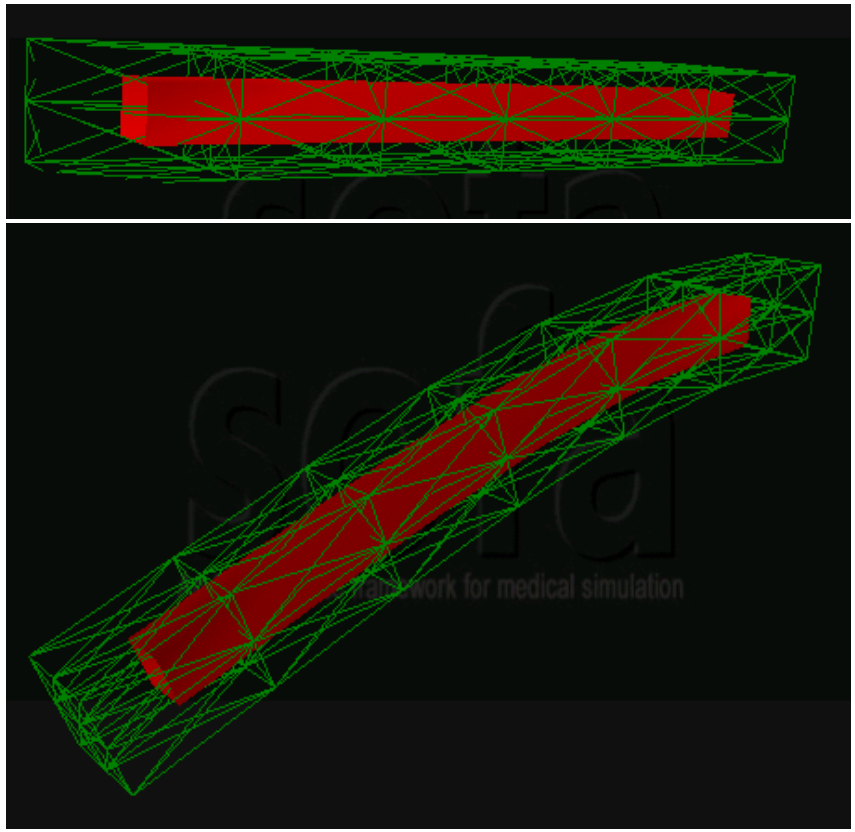
- RigidMapping can be used to attach points to a rigid body
  - to attach collision surfaces





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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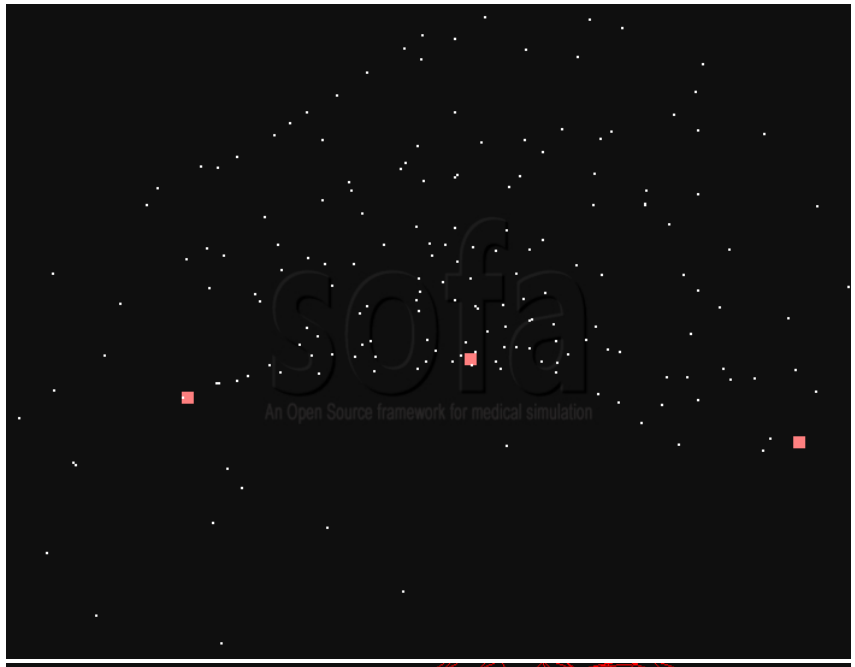
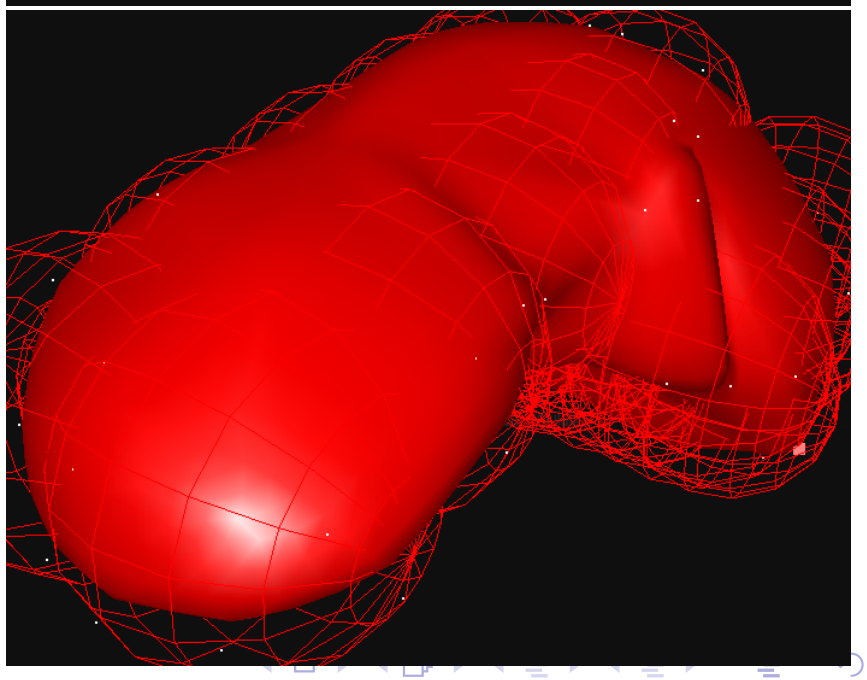
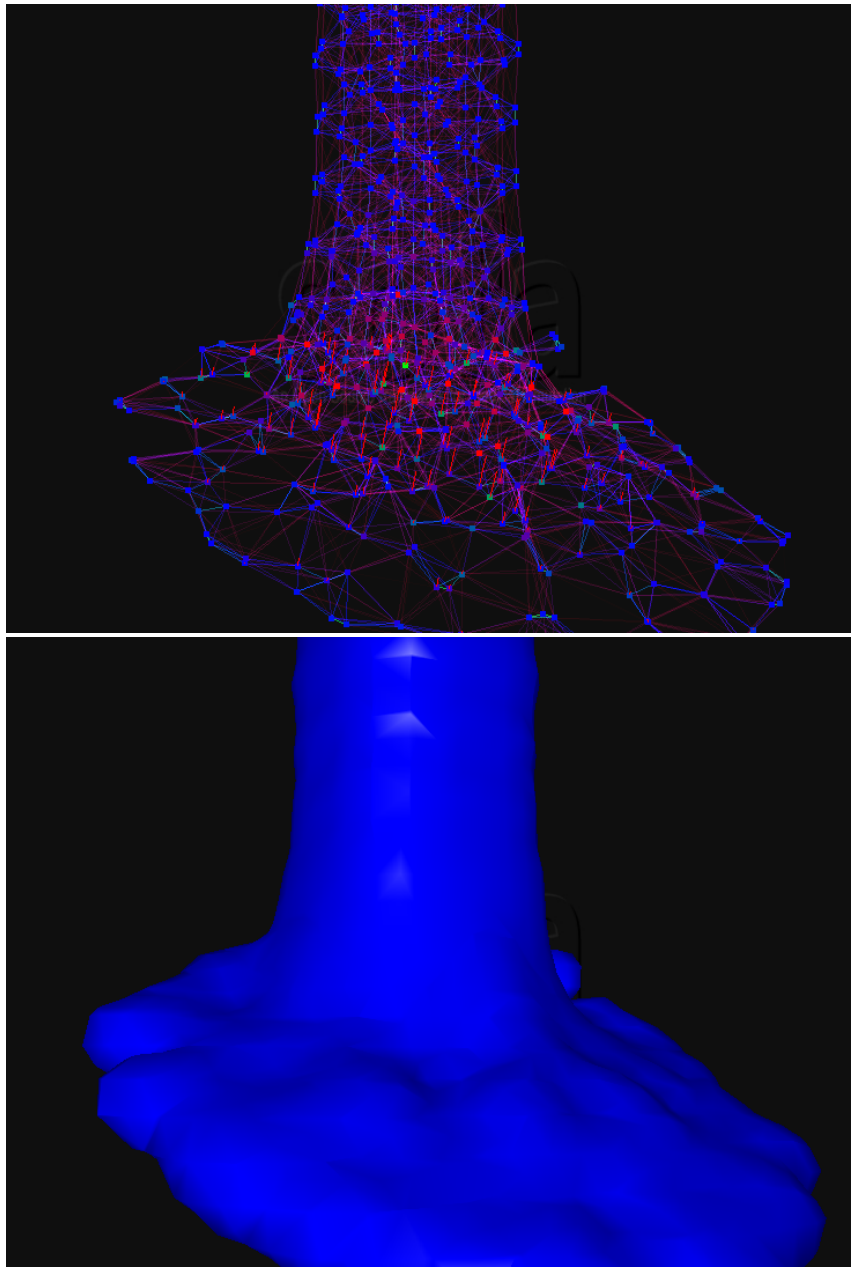




Examples of mappings

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



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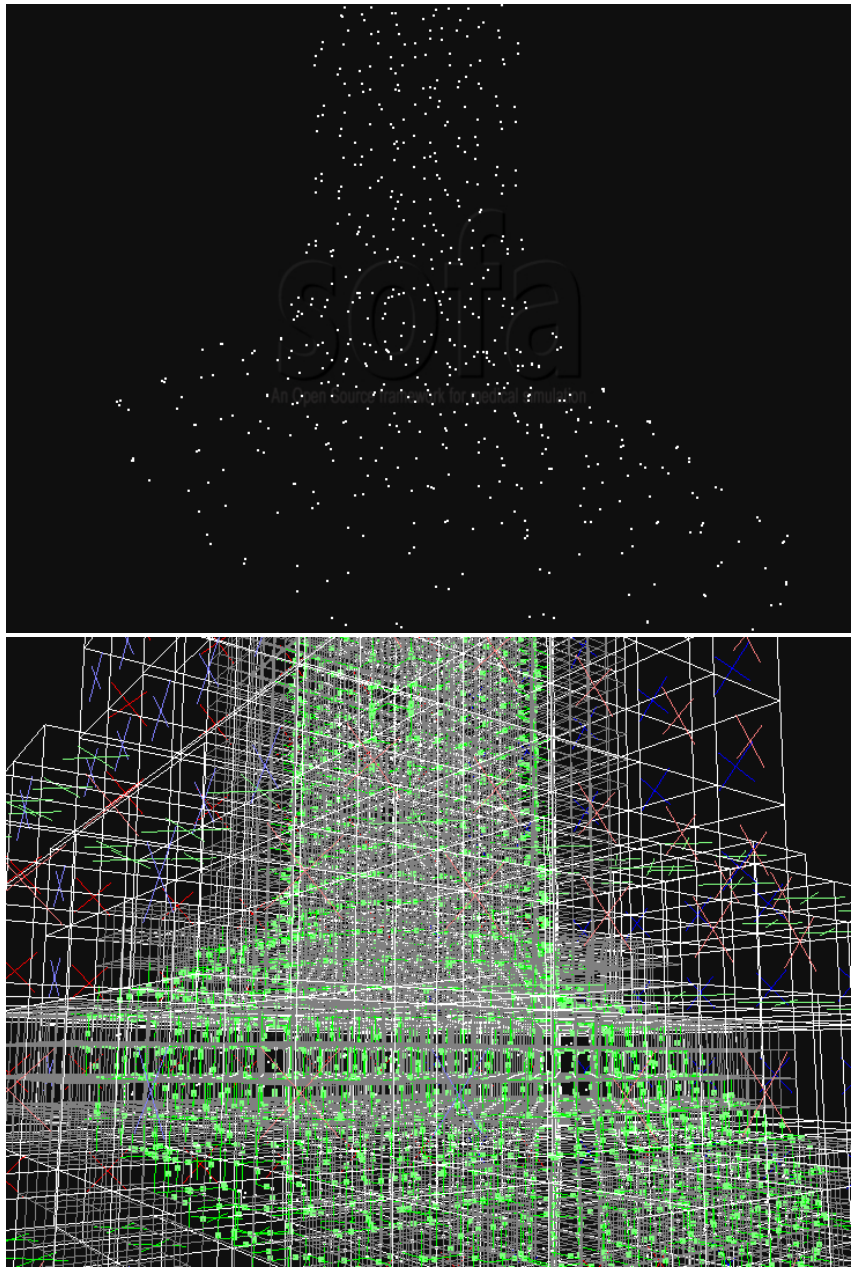


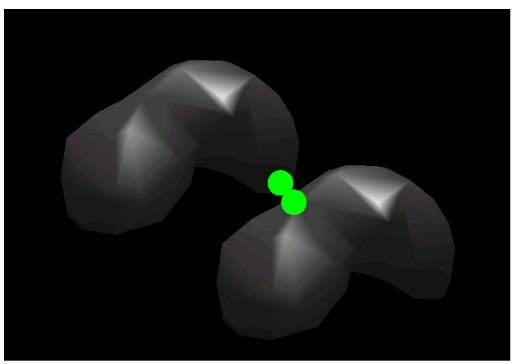
On the physical consistency of mappings

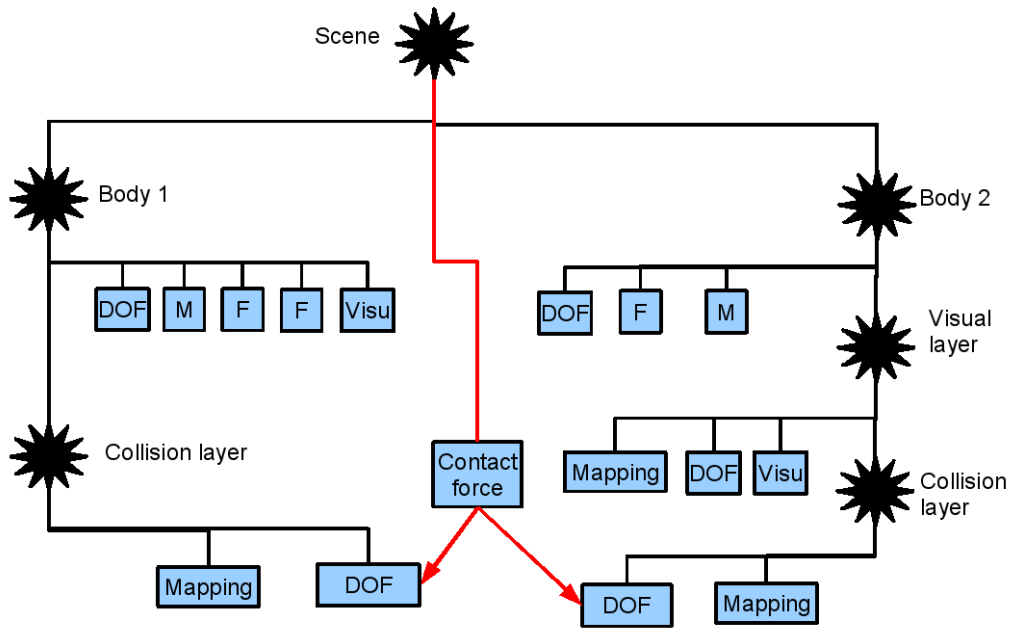
- Conservation of energy :
  Necessary condition : $v_{child} = J v_{parent} \Rightarrow f_{parent} += J^T f_{child}$
- Conservation of momentum :
  Mass is modeled at one level only. There is no transfer of momentum.
- Constraints on displacements (e.g. incompressibility, fixed points) are not easily applied *at the child level*

Outline

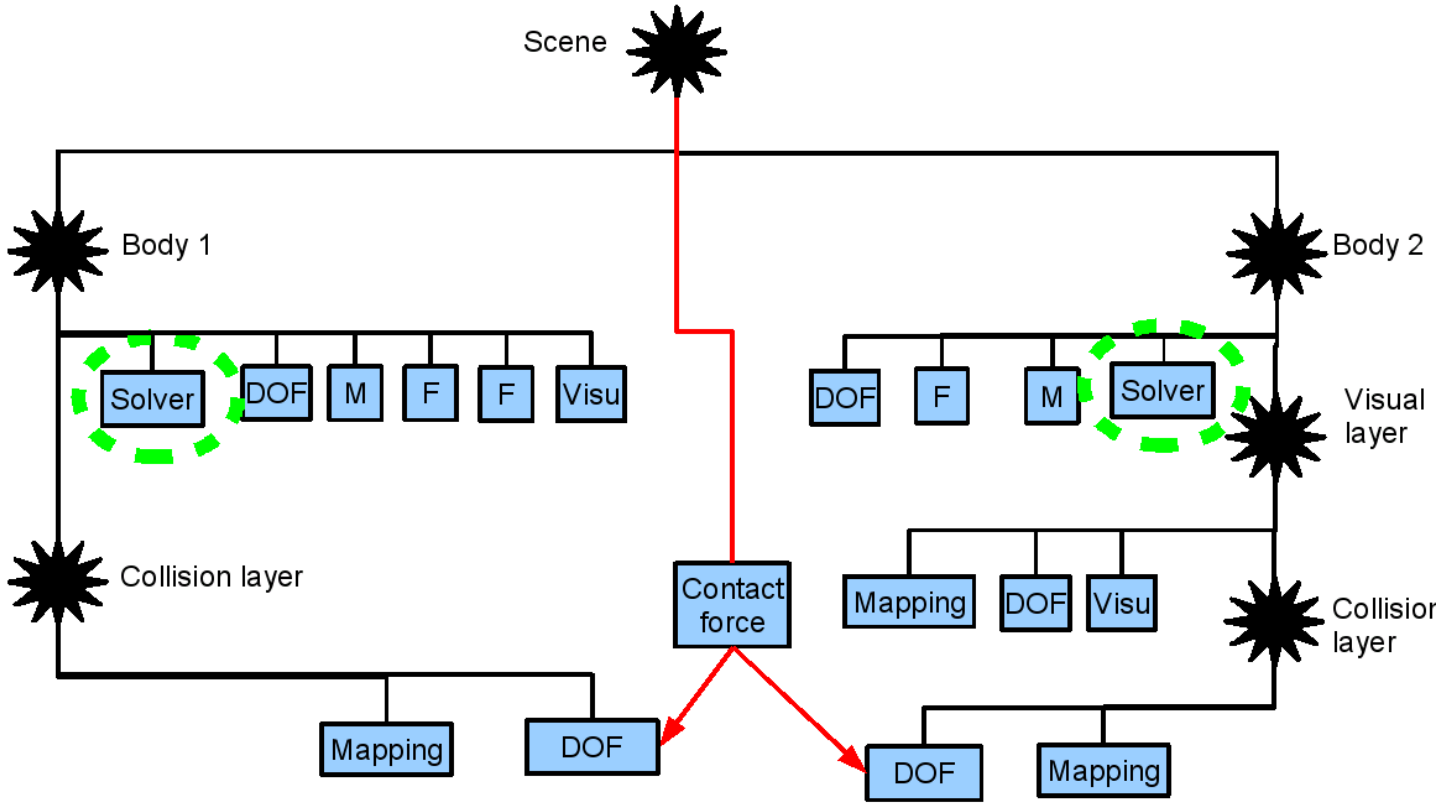
Two bodies in contact

Example : 2-layer liver against 3-layer liver using a contact force.
Use extended trees (Directed Acyclic Graphs) to model trees with loops.



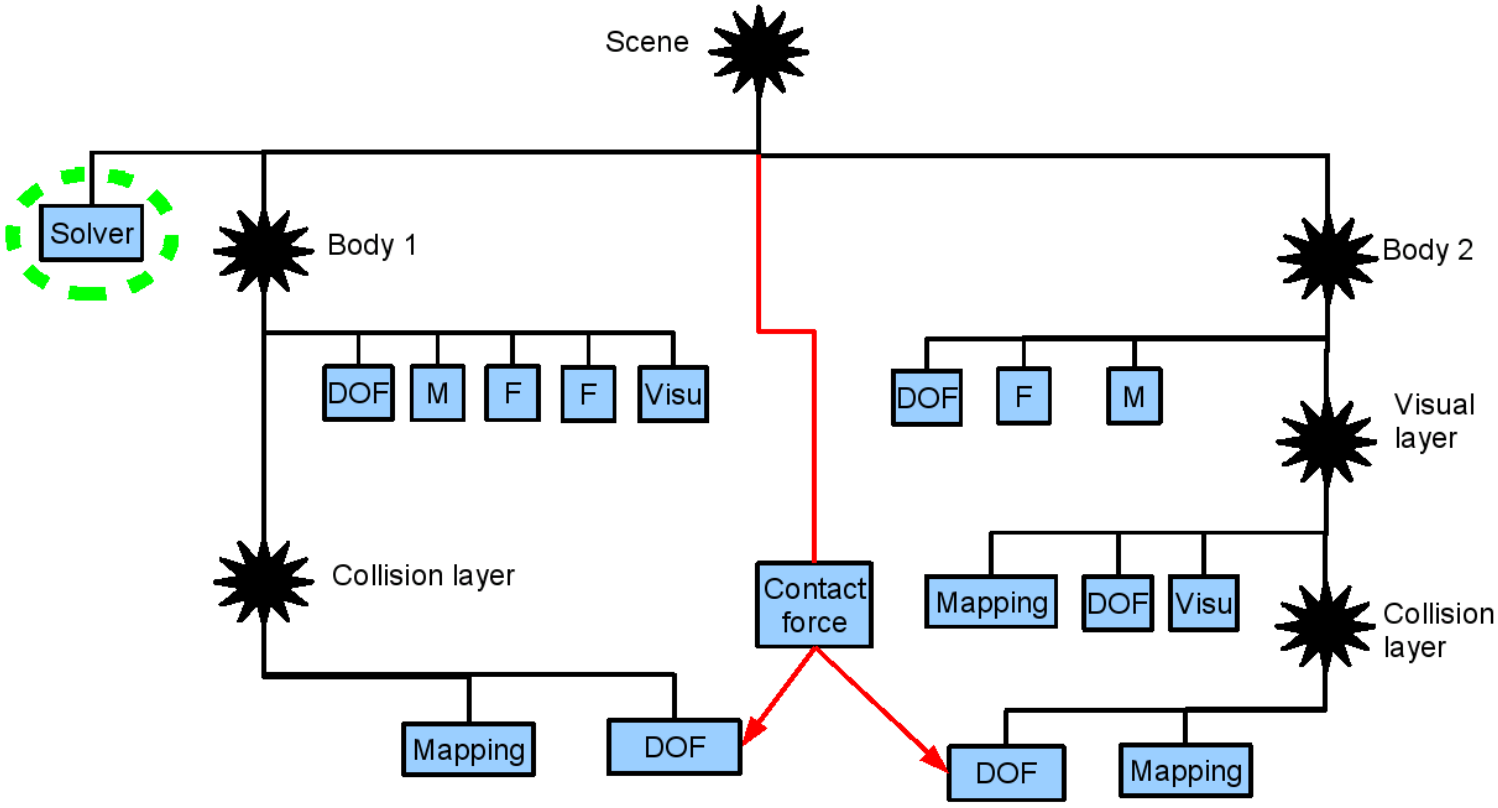


ODE solution of interacting bodies



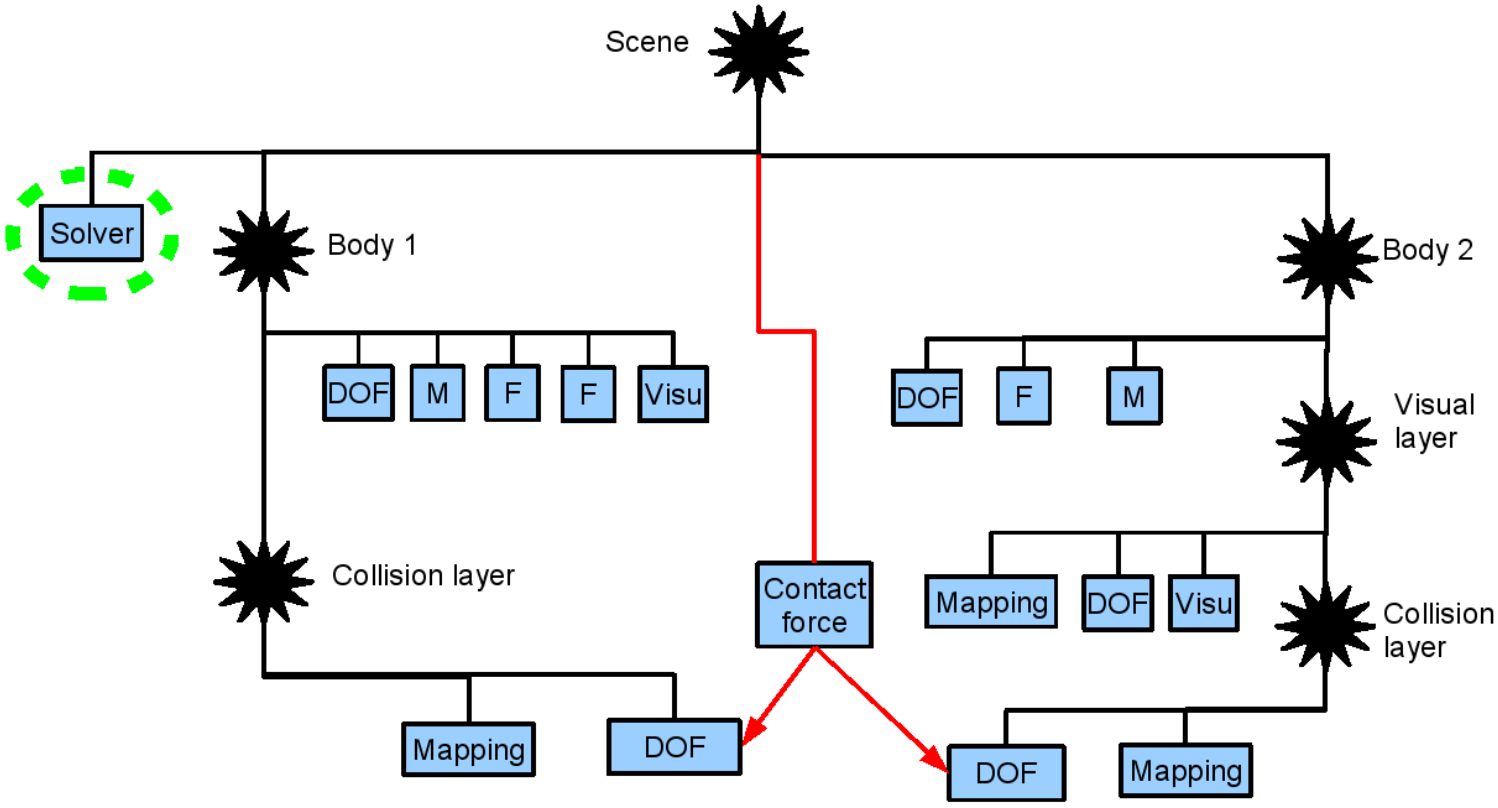
- Soft interactions : independent processing, no synchronization required

ODE solution of interacting bodies



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

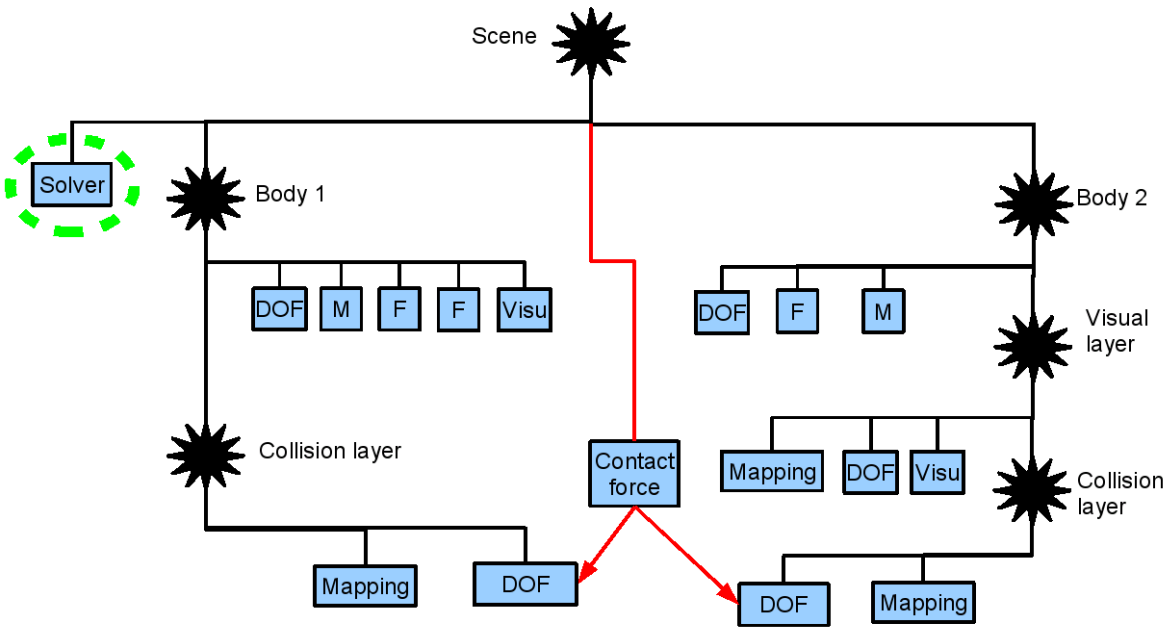
ODE solution of interacting bodies



- Soft interactions : independent processing, no synchronization required
- Stiff interactions : unified implicit solution with Conjugate Gradient, synchronized objects
- Hard interaction constraints : work in progress

Outline

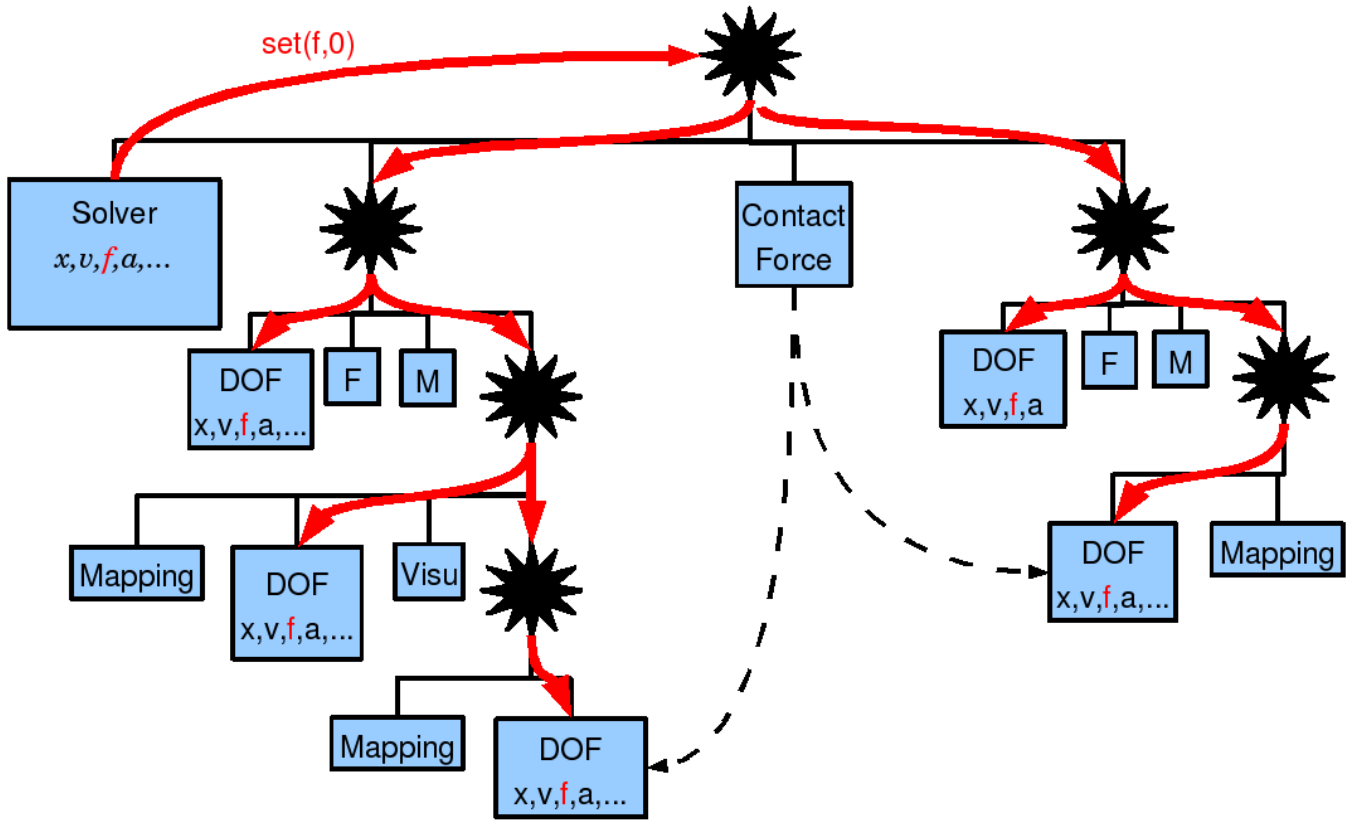
Actions



- No global state vector
- Operation = graph traversal + abstract methods + vector identificators

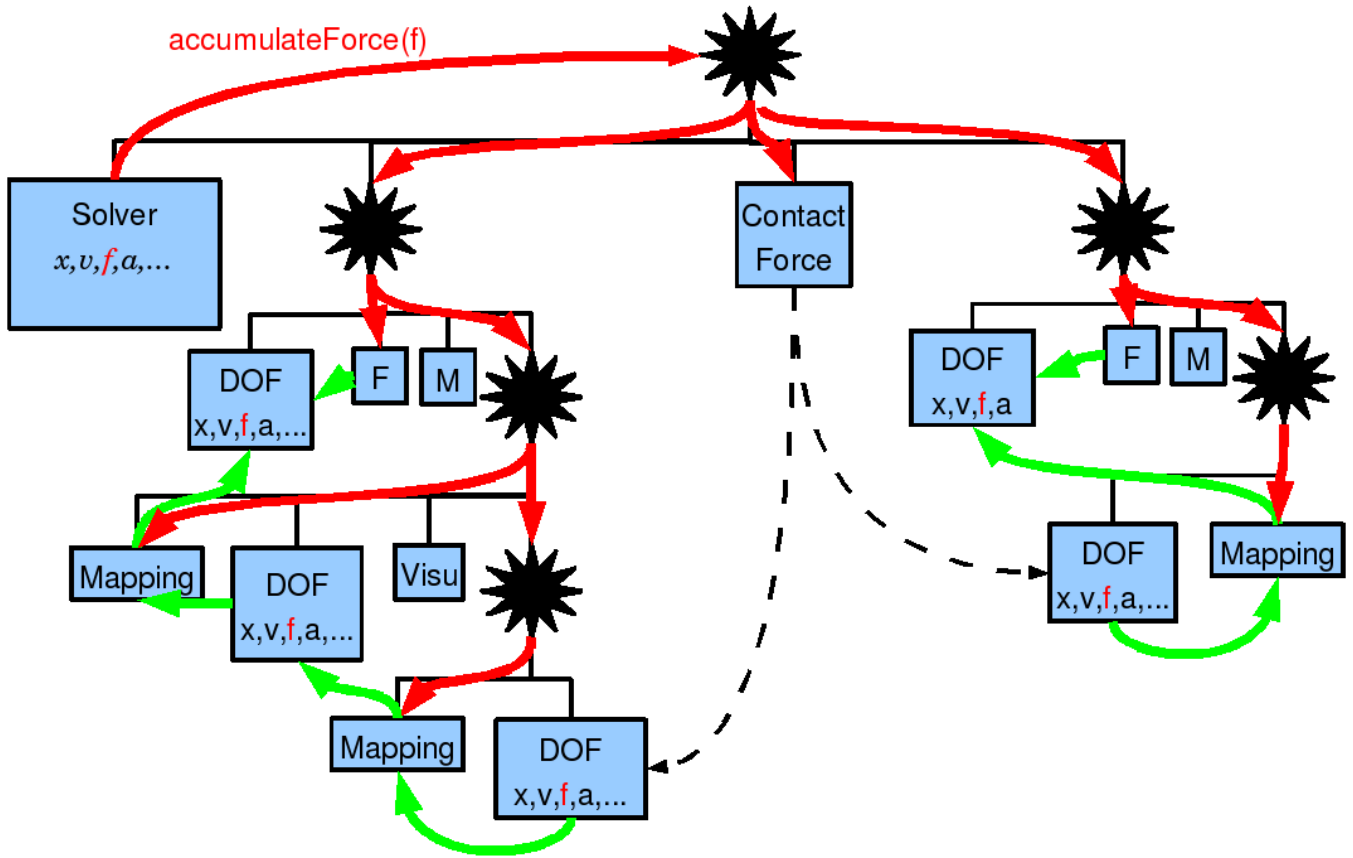
Example : clearing a global vector

- 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 : accumulating the forces

- The solver triggers the appropriate action
- the action is propagated through the graph and calls the appropriate (botom-up) methods at each Force and Mapping 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
  - virtual functions applied to components

Outline

Collision detection and response

CollisionPipeline component orchestrates specific components

- BroadPhase : bounding volume intersections
- NarrowPhase : geometric primitive intersections
- Reaction : what to do when collisions occur
- GroupManager : putting colliding objects under a common solver

Recent work uses the GPU

Outline

Parallelism in time integration

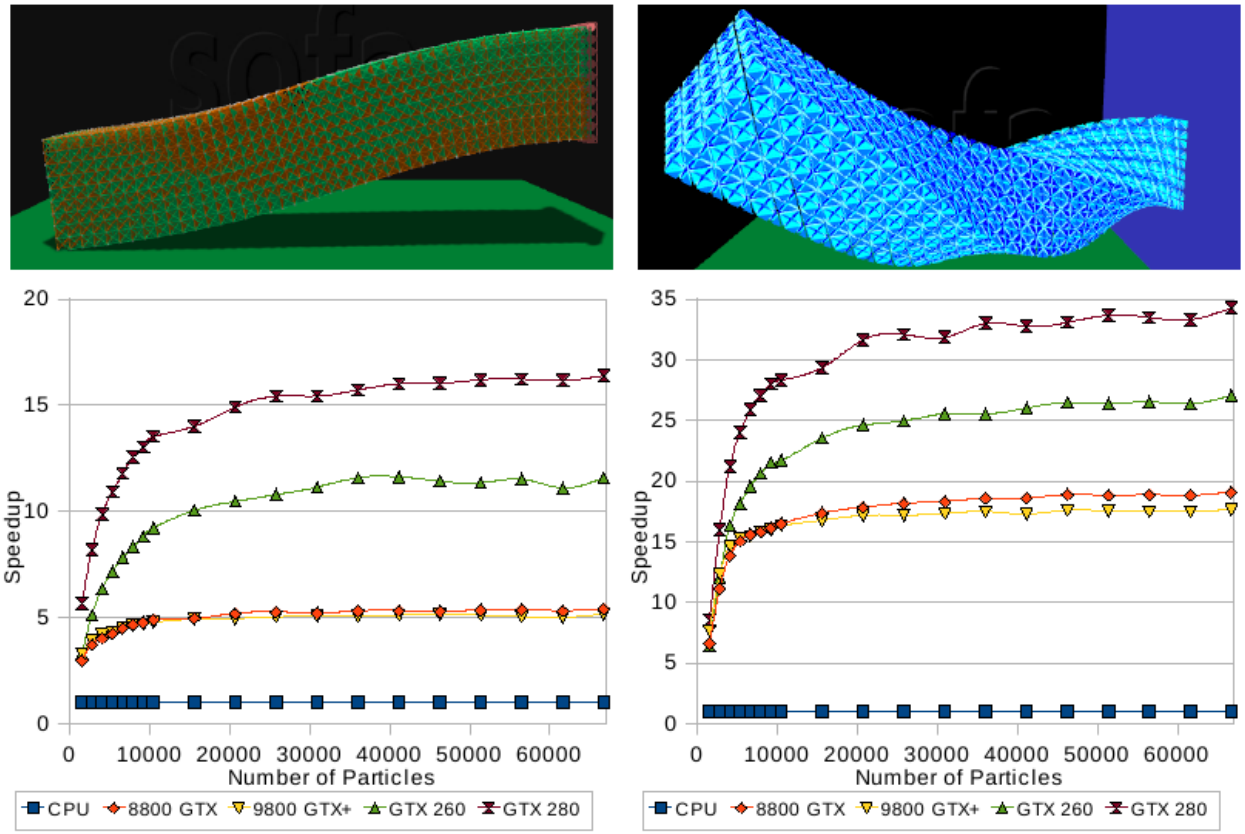
Two levels of parallelism :

- Low level : GPU implementations of components
- High level : task-based using data dependencies

We can combine them !

GPU Parallelism

- StiffSpringForceField, TetrahedronFEMForceField, HexahedronFEMForceField are implemented on the GPU
- The DOF component makes data transfer transparent
- CPU and GPU components can be used simultaneously
- Nice speedups

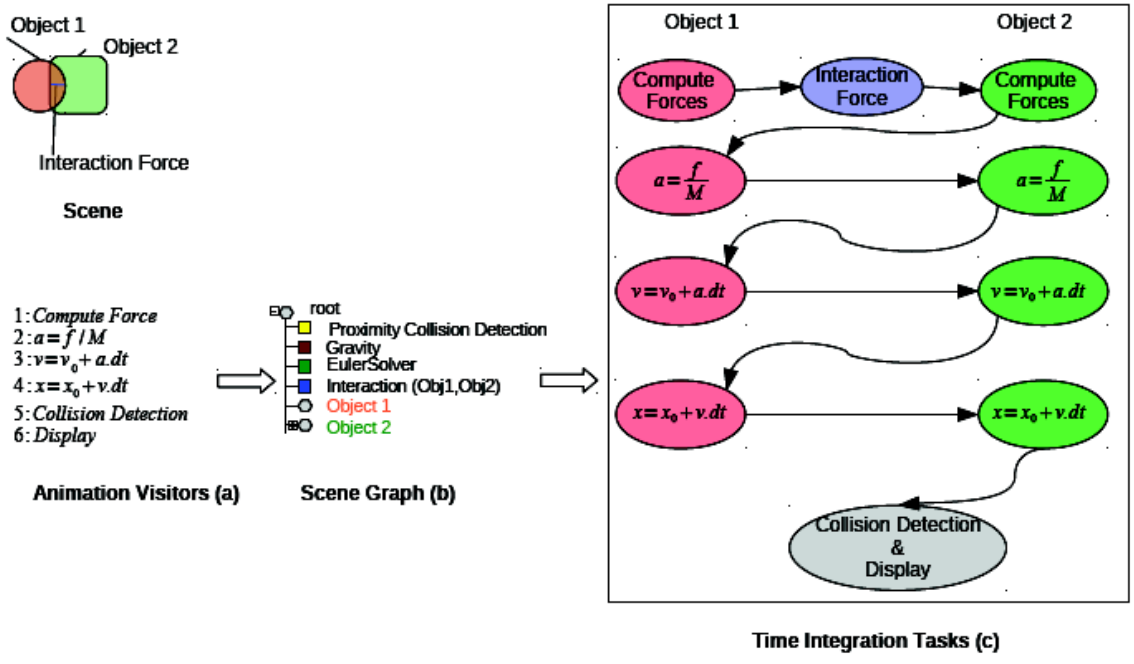


(a) Mass-Spring (b) Co-rotational FEM

High-level Parallelism

Everton Hermann's Ph.D. thesis (2007-2010) :

- analyses solver operations



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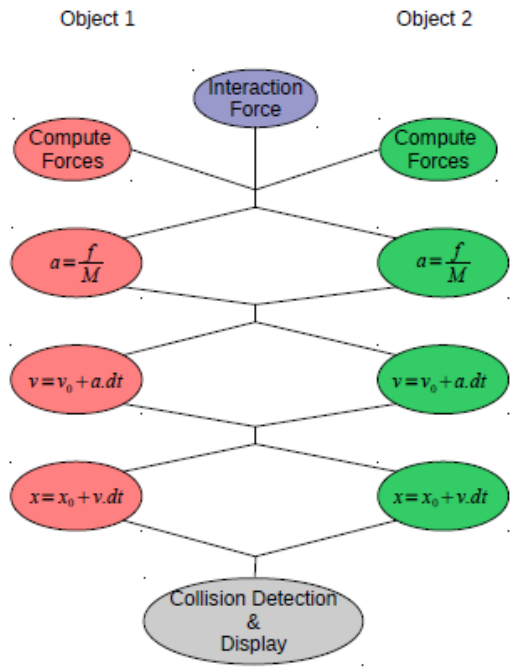
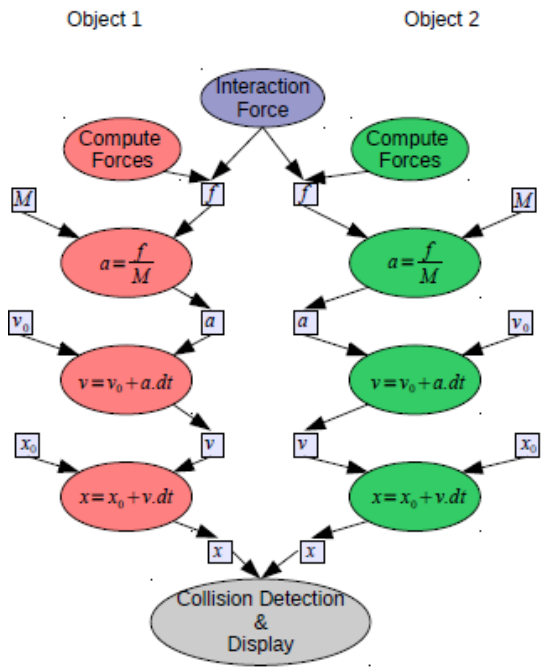
- analyses solver operations
- exploits scene graph branches



High-level Parallelism

Everton Hermann's Ph.D. thesis (2007-2010) :

- analyses solver operations
- exploits scene graph branches
- removes spurious synchronizations using data dependency analysis [Athapascan]
- efficiency ranges for 50% to 90%



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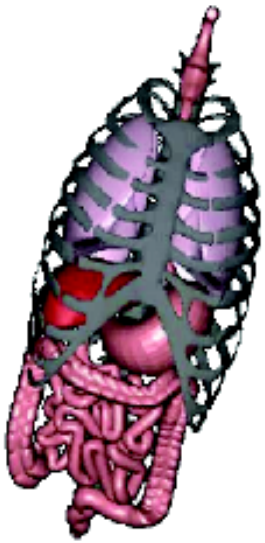
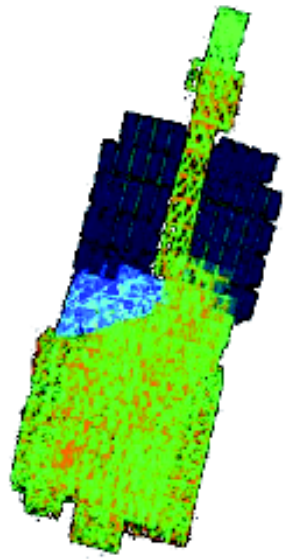
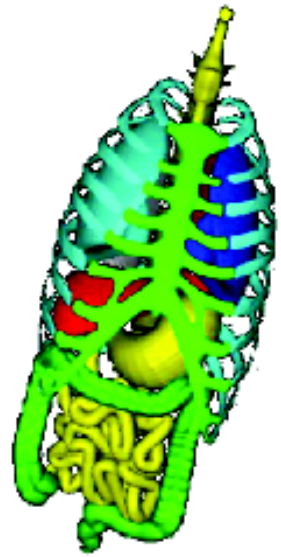


(a) Visual Model



(b) Behavior Model

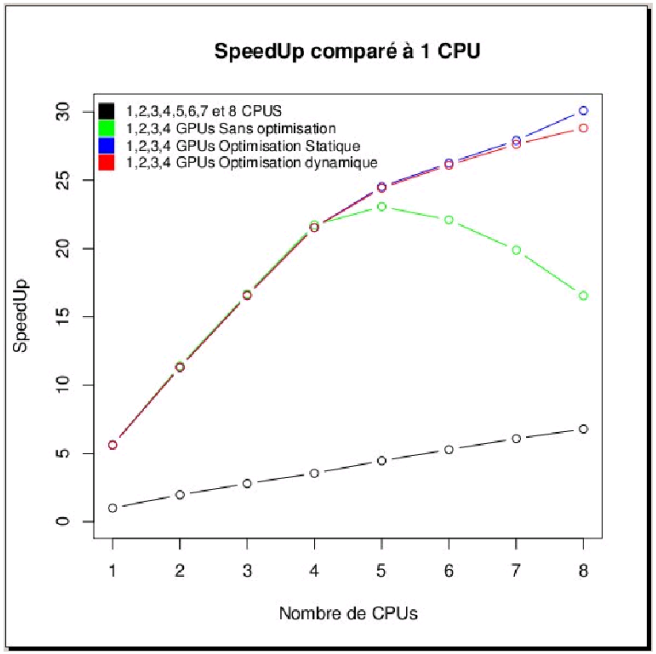


(c) Processor Distribution

Hybrid Parallelism

Work in progress

- Use high level and low level simultaneously
- Dynamically balance between multiple CPUs and GPUs



Outline

Conclusion - Features

High modularity :

- Abstract components : DOF, Force, Constraint, Solver, Topology, Mass, CollisionModel, VisualModel, etc.
- Multimodel simulations using mappings
- Explicit and implicit solvers, Lagrange multipliers

Efficiency :

- global vectors and matrices are avoided
- parallel implementations

Implementation :

- currently $450,000$ C++ lines
- Linux, MacOs, Windows

Ongoing work

- models and algorithms : better numerical solvers, cutting, haptics, Eulerian fluids...
- asynchronous simulation/rendering/haptic feedback
- multiphysics (electrical/mechanical)
- parallelism for everyone
- more documentation (release 1.0 this year ?)

www.sofa-framework.org