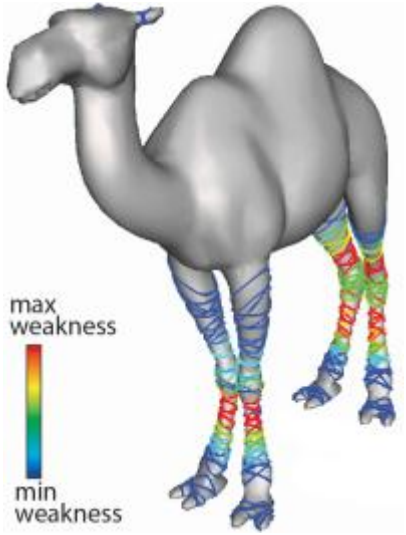
Cross-sectional Structural Analysis for 3D Printing Optimization

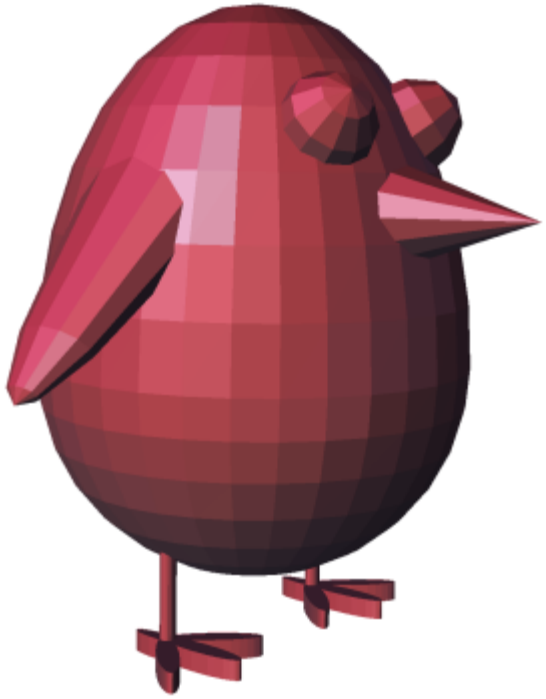
Nobuyuki Umetani Ryan Schmidt

AUTODESK. RESEARCH



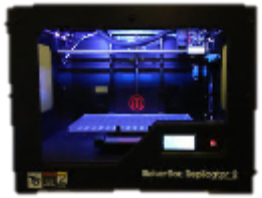
Shape Design for 3D Printing is Difficult

Beginners cannot design structurally sound shape



[source: DBrager14@Thingiverse]

3D printing



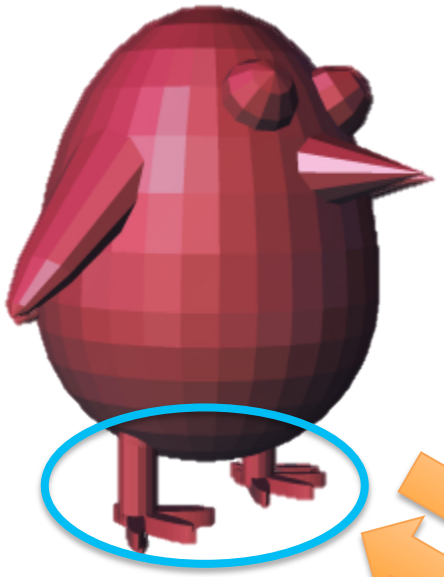
(1-2 hours)

shapeways

(1-3 weeks)

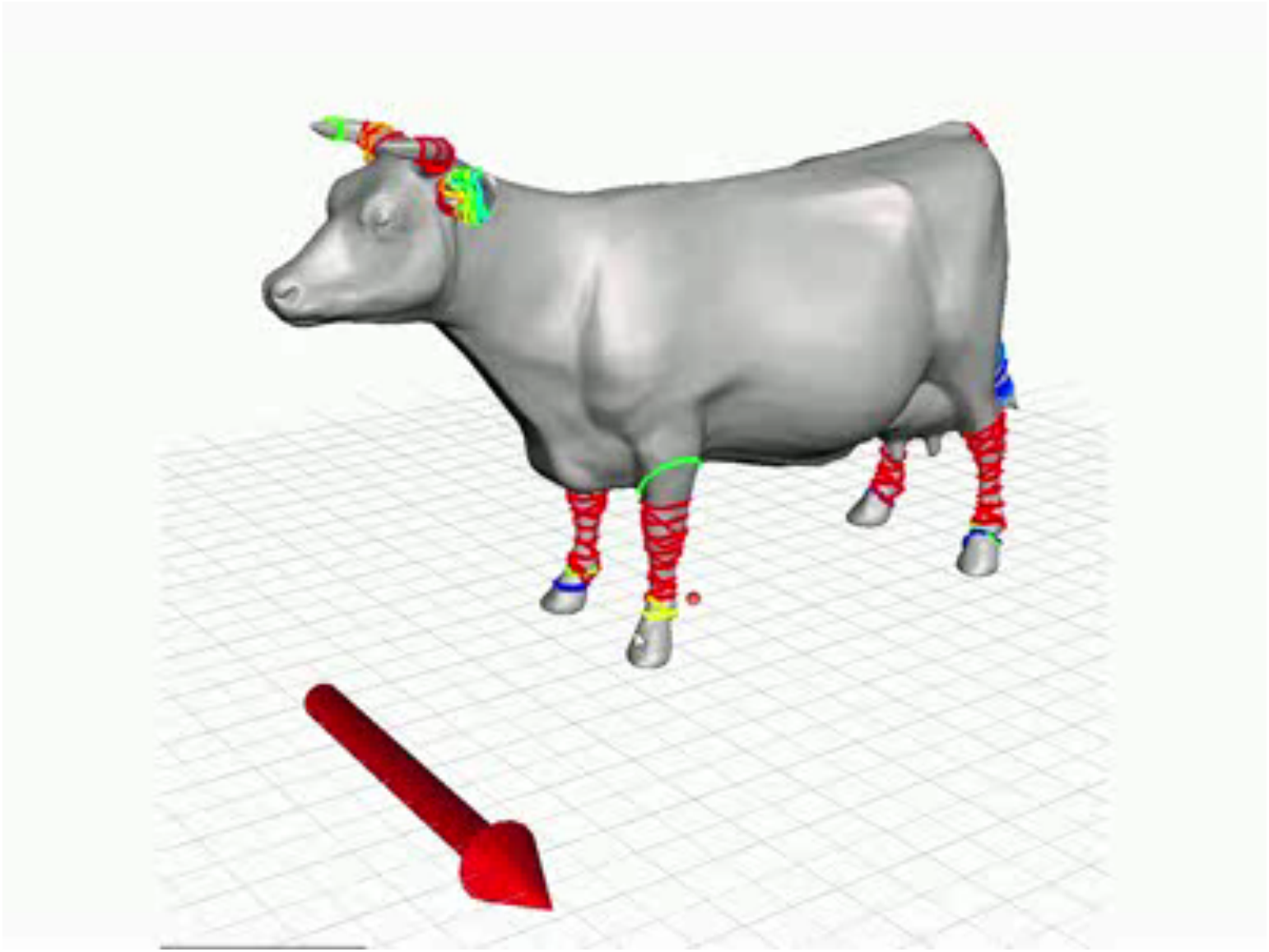
Goal: Real-time Weakness Detection During Design

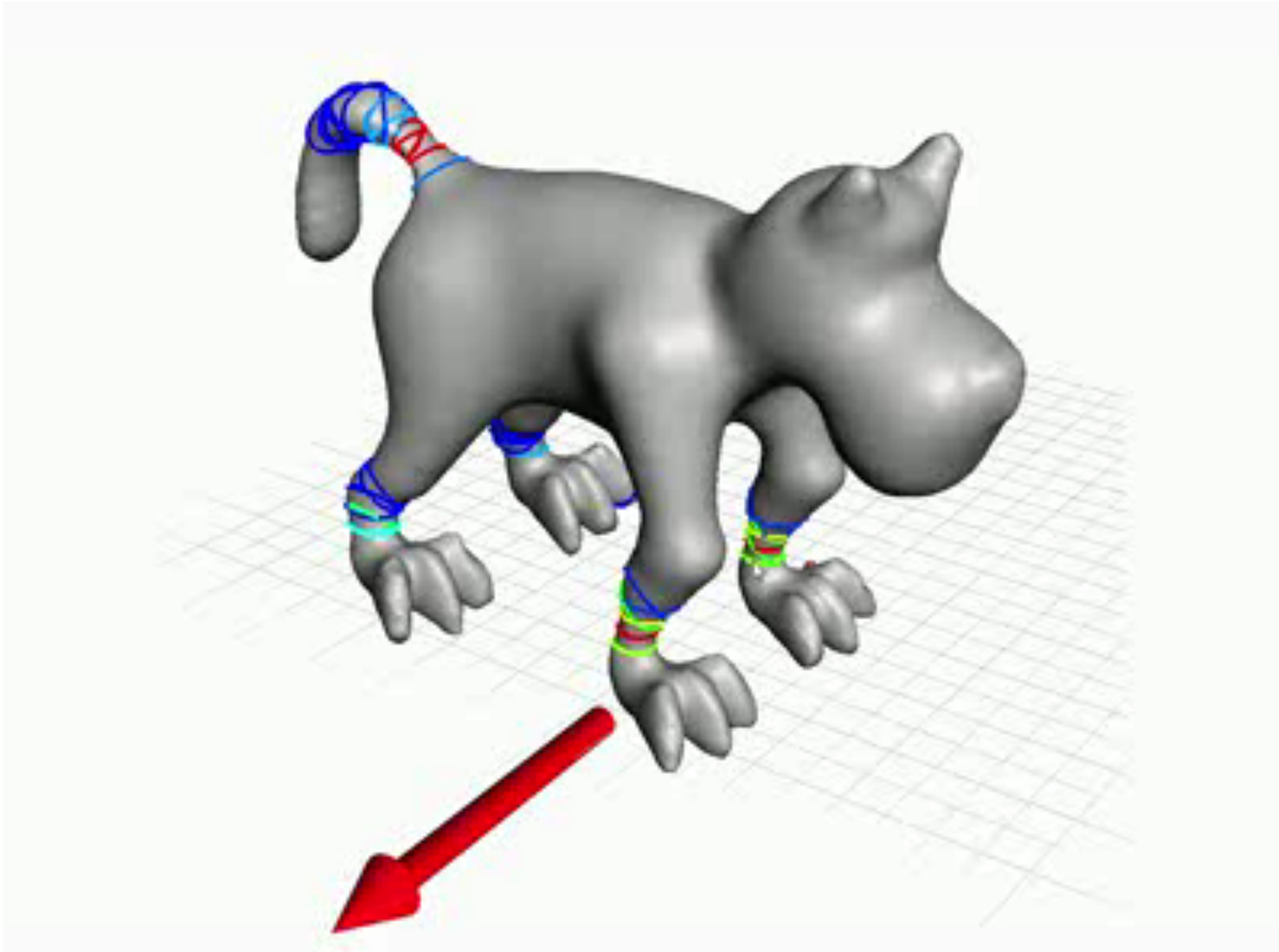
Design with interactive trial & error



The user thicken leg

3D printing





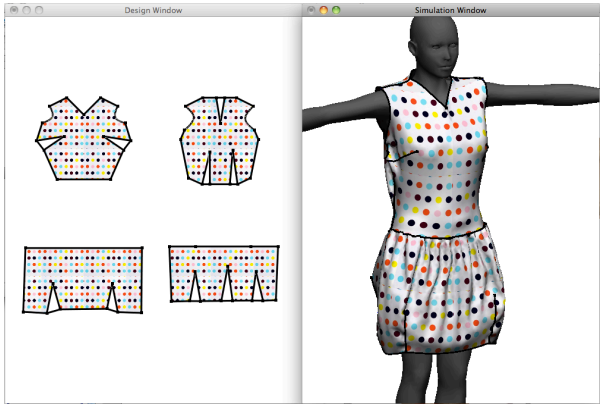
Related Works

Related Works: Simulation during Interactive Design

Structural analysis for solid 3D shape had been extremely difficult

[Umetani et al. NIME 2010]

[Furuta et al. Eurographics 2010]

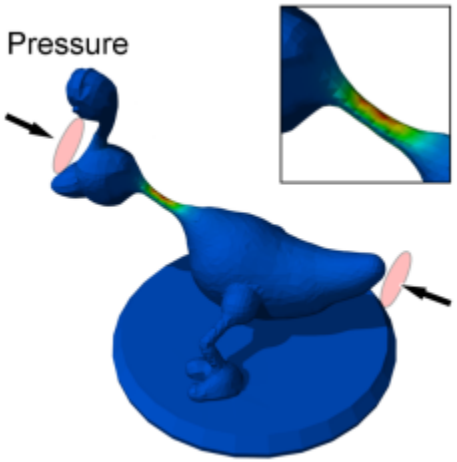


[Umetani et al. Siggraph 2011]

[Umetani et al. Siggraph 2012]

Related Works: Structural Weakness Detection

All previous works are based on Finite Element Method



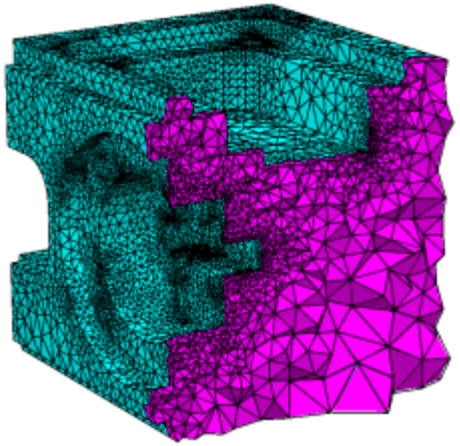
[Stava et al. Siggraph 2012]

[Luo et al. Siggraph Asia 2012]

[Zhou et al. Siggraph 2013]

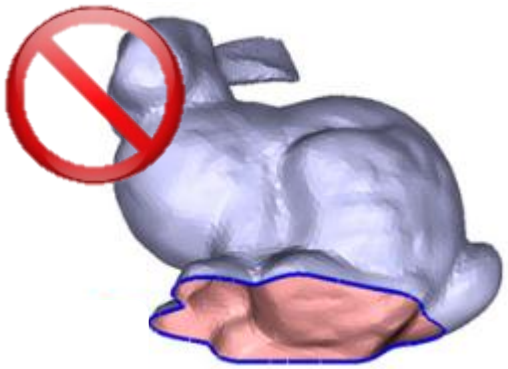
Drawbacks of Finite Element Method

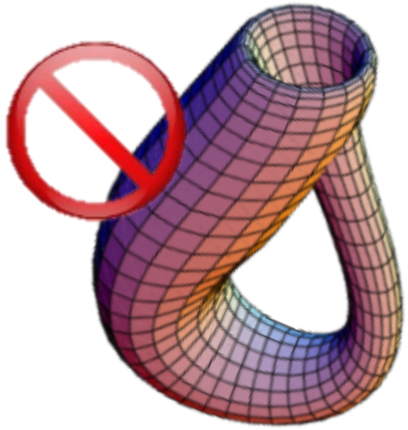
- Slow
  - Mesh construction
  - Linear solver



- FEM requires fair mesh
  - Without hole & intersection

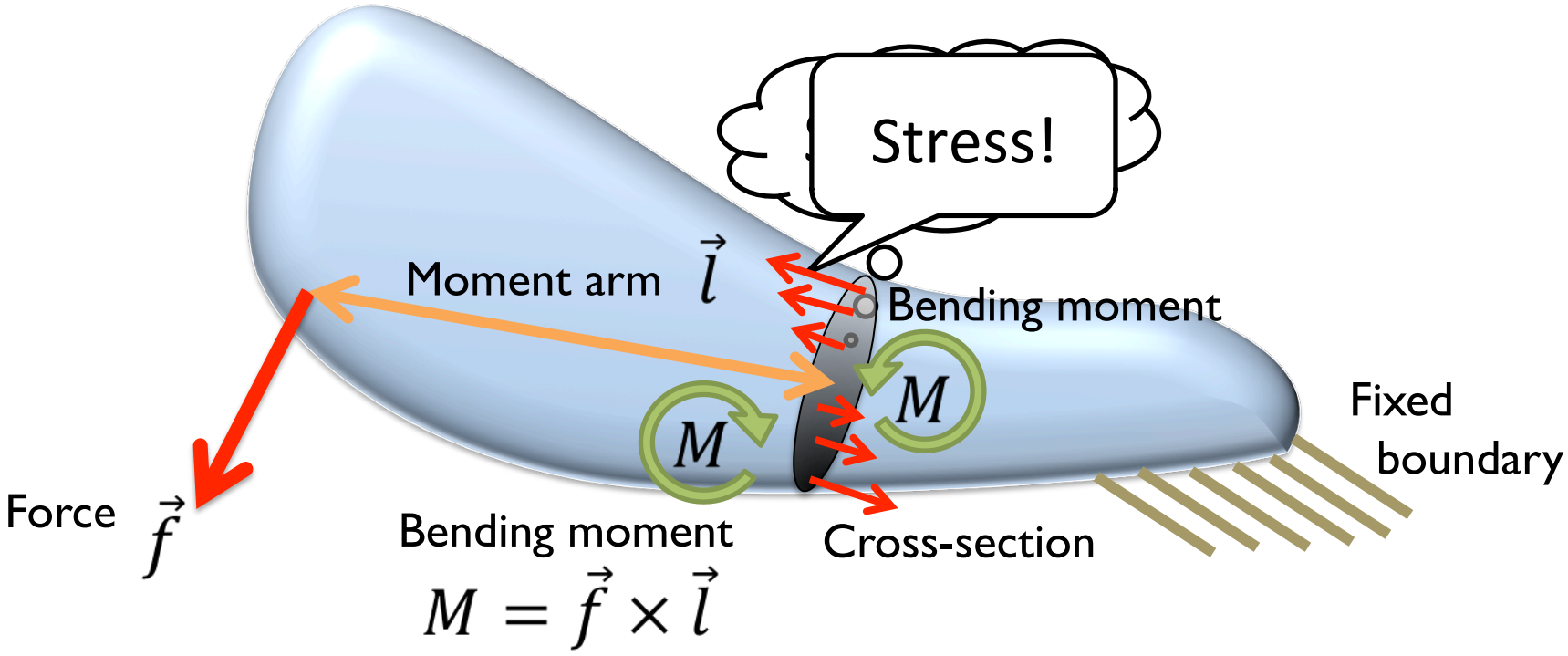
    (only less than 25% meshes are closed manifold, 90% are self-intersecting [Gilbert 2013])
  - Well-shaped triangle





Solution: Cross Sectional Structural Analysis

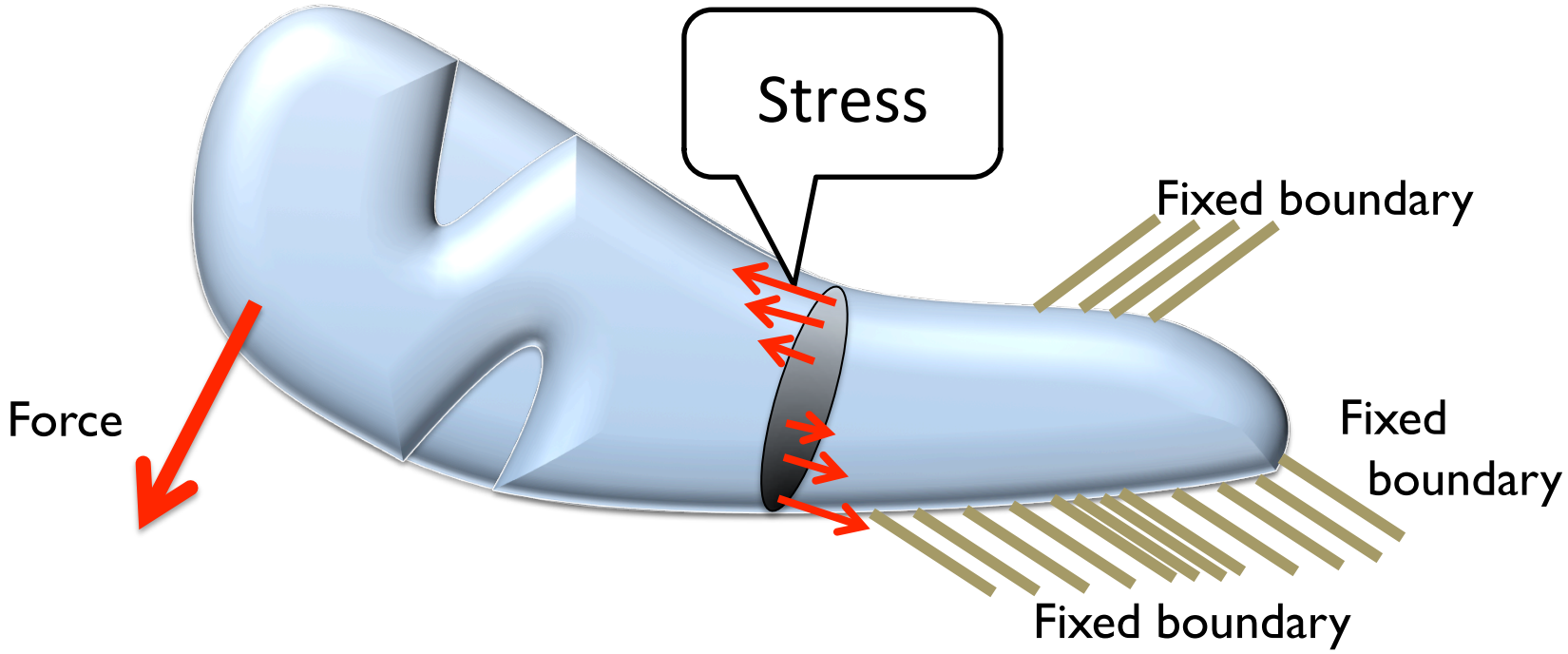
Key idea: bending momentum conservation



Problem is simplified very much

We don't care

- Location of fixed boundaries
- Object's in-between 3D shape



How the structure break ?

Structure breaks at **slender parts**

Structure breaks by **bending**

How a beam bends?

History of the Beam Theory

[Galileo 1638]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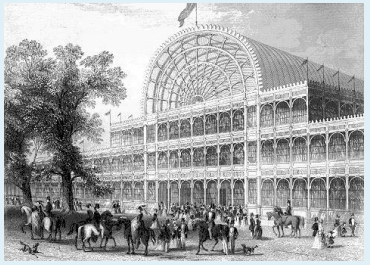
fin quì dichiarate, non farà difficile l'intender la ragione, onde auuenga, che un Prisma, ò Cilindro solido di vetro, acciaio, legno, ò altra materia frangibile, che sostenuto per lungo sostenerà gravissima peso, che gli sia attaccato, mà in trauerso (come poco fà dicevamo) da minor peso assai potrà tal volta essere spezzato, secondo che la sua lunghezza eccederà la sua grossezza. Imperò che figuriamoci il Prisma solido AB, CD fitto in un muro dalla parte AB, e nell'altra estremità s'intenda la forza del Peso E, (intendendo sempre il muro esser eretto all'Orizonte, & il Prisma, ò Cilindro fitto nel muro ad angoli retti) è manifesto che douendosi spezzare si romperà nel luogo B, dove il taglio del muro serue per sostegno, e la BC per la parte della Leua, dove si pone la forza, e la grossezza del solido BA e l'altra parte della Leua, nella quale è posta la resistenza, che consiste nello staccamento, che s'hà da fare della parte del solido BD, che è fuor del muro, da quella che è dentro, e per le cose dichiarate il momento della forza posta in C al momento della resistenza che sà nella

[source:The Stillman Drake Collection]

[Euler 1750]

[source: wikipedia]

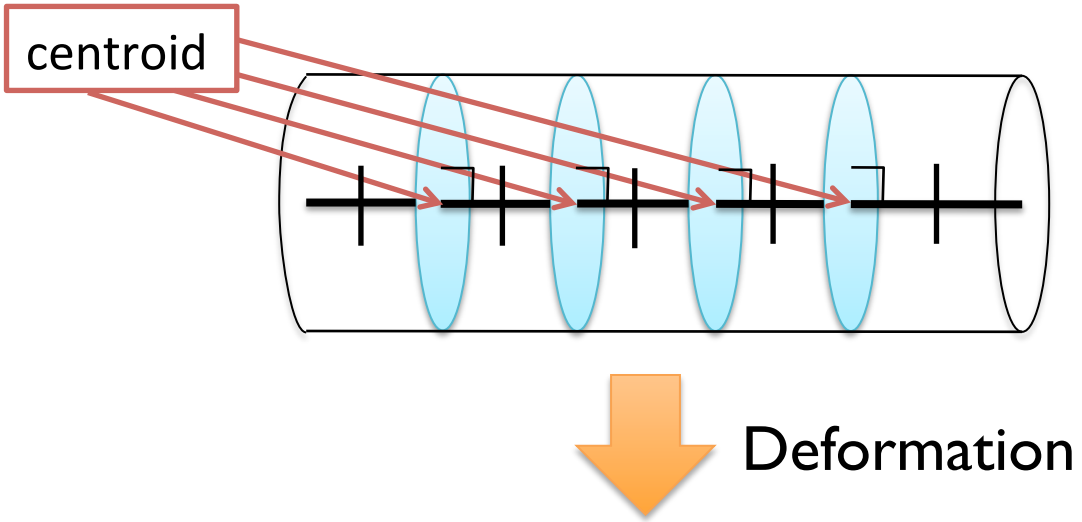
2nd industrial revolution



[source:wikipedia]

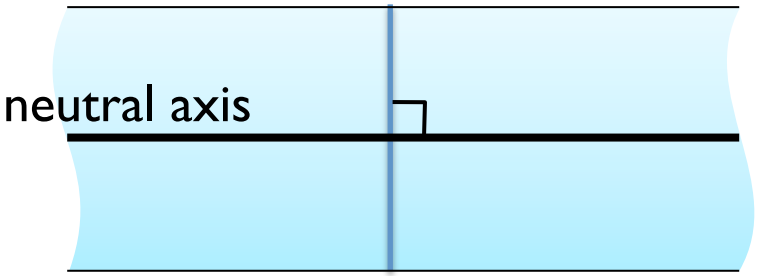
Euler-Bernoulli Assumption

- Neutral axis



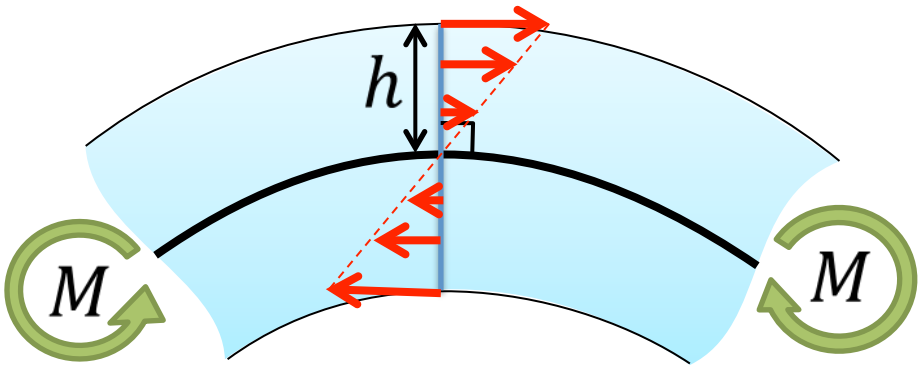
- Cross sections do not deform
- Neutral axis does not stretch
- Cross sections remain orthogonal to neutral axis

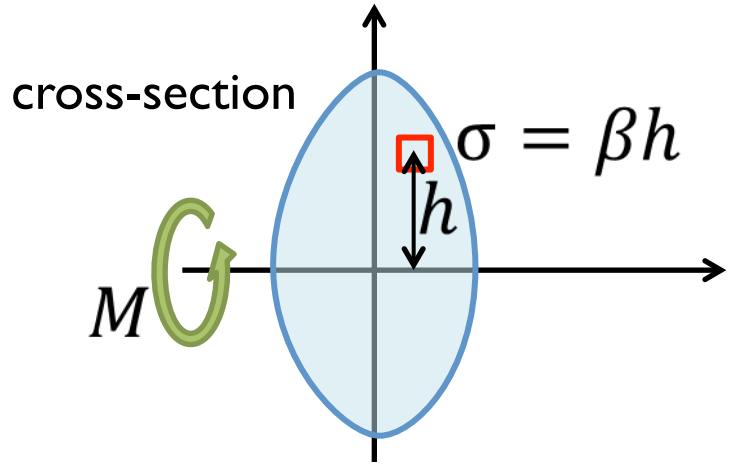
Stress on a Cross-Section



Deformation

$\sigma = \beta h$





$$M = \int_\Omega \sigma h d\Omega = \int_\Omega \beta h^2 d\Omega$$

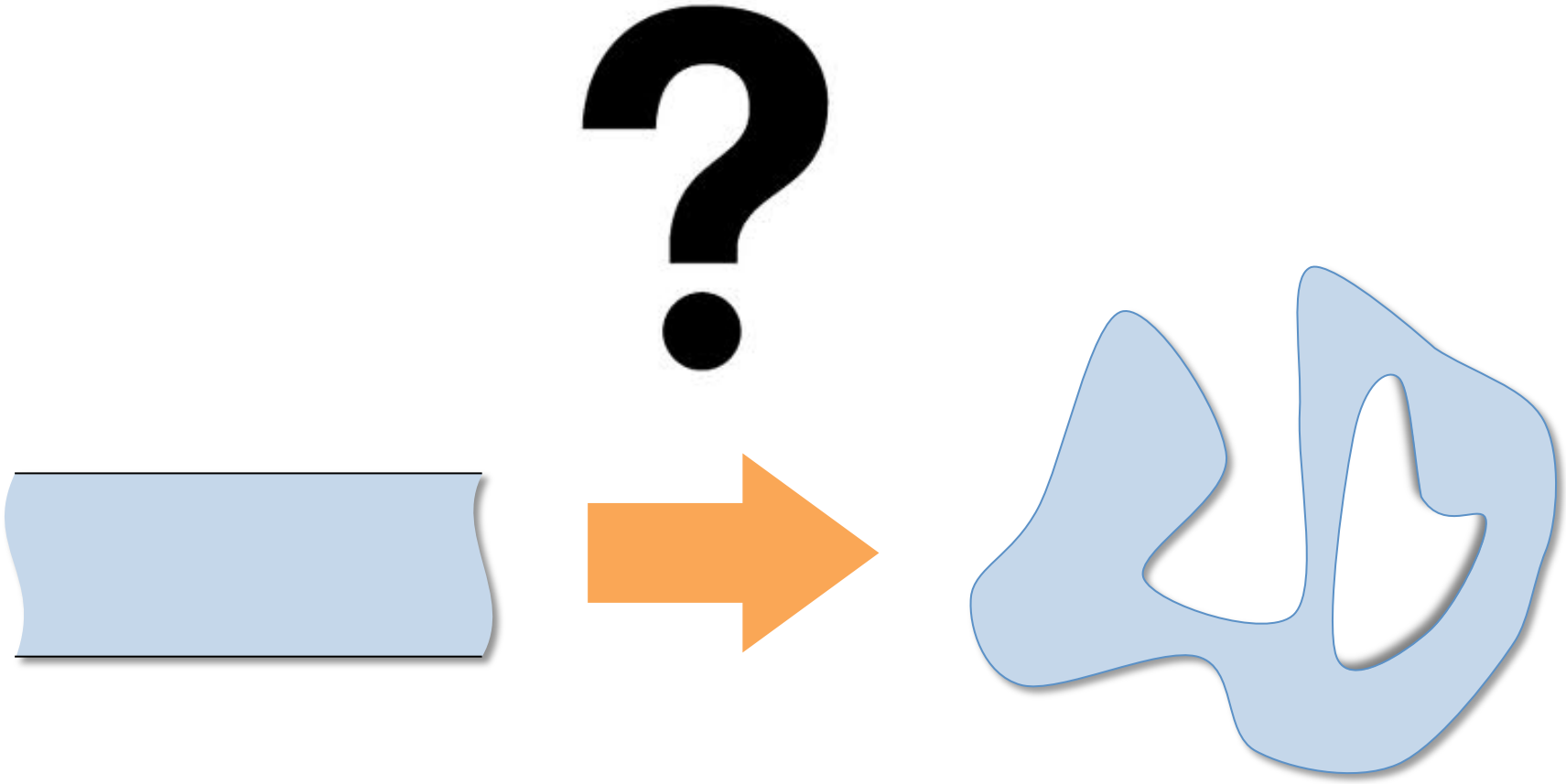
$$\beta = \frac{M}{\int_\Omega h^2 d\Omega}$$

Second moment of area

Fracture condition

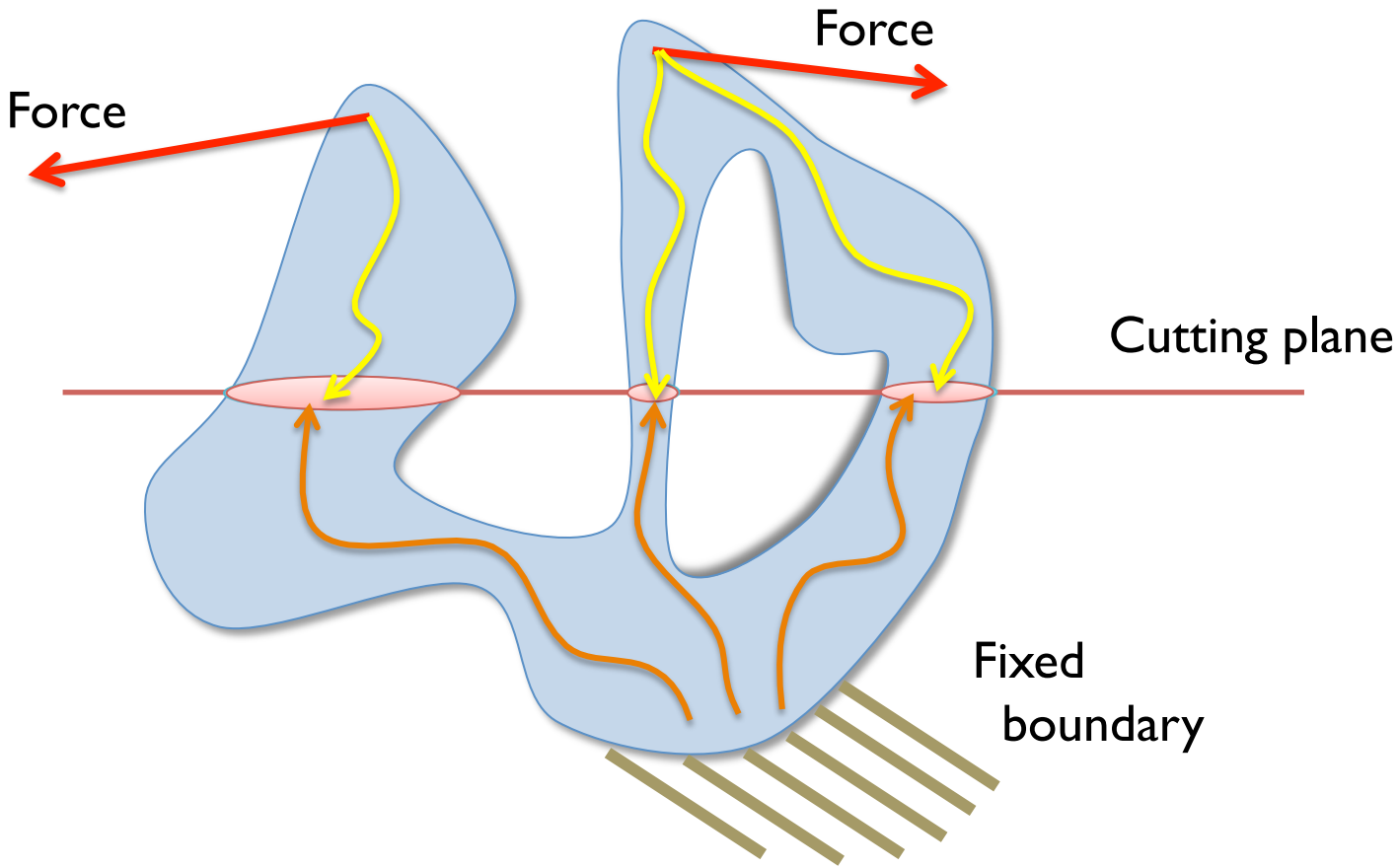
$$\sigma_{max} = \beta h_{max} > \sigma_{break}$$

How we can extend beam theory into 3D shape?



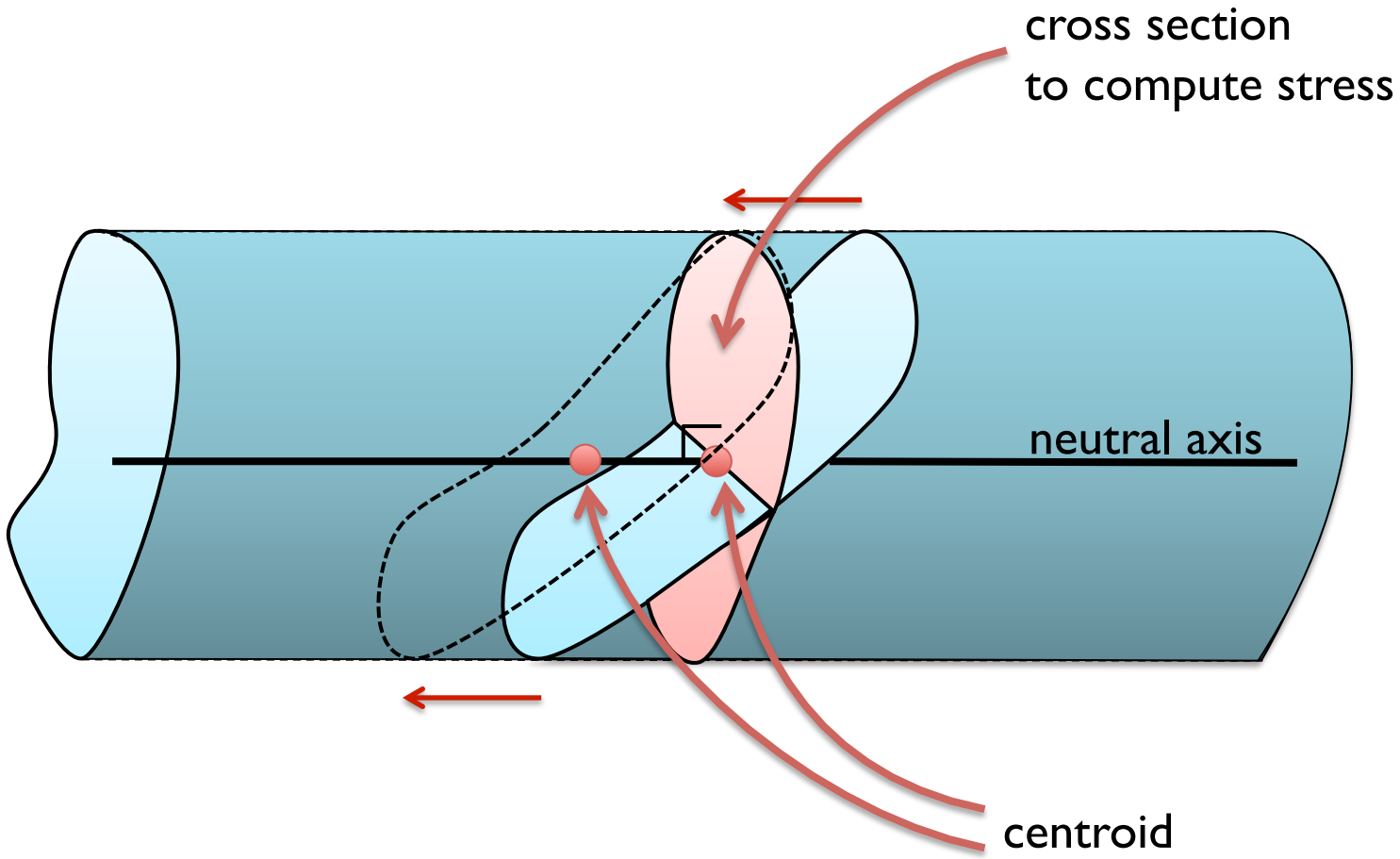
Extension to 3D Shape

- Topology analysis of cross sections



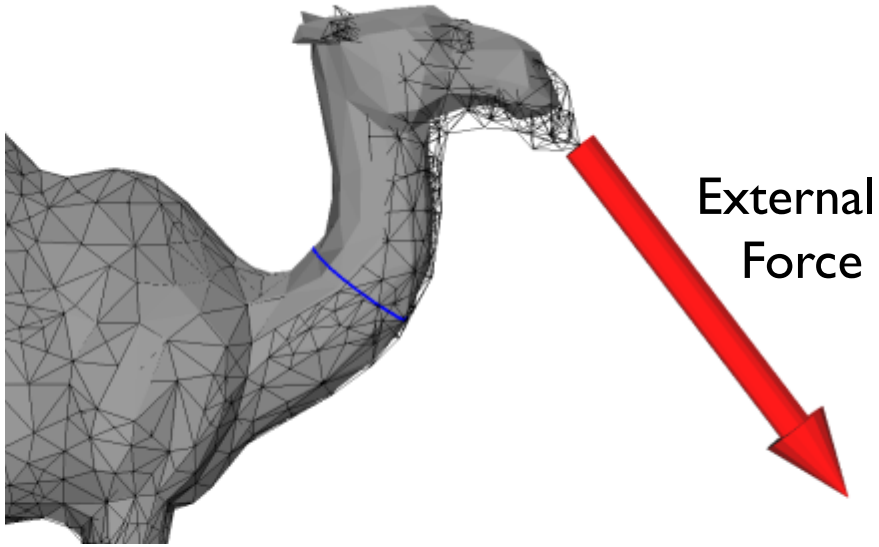
Neutral Axis Detection

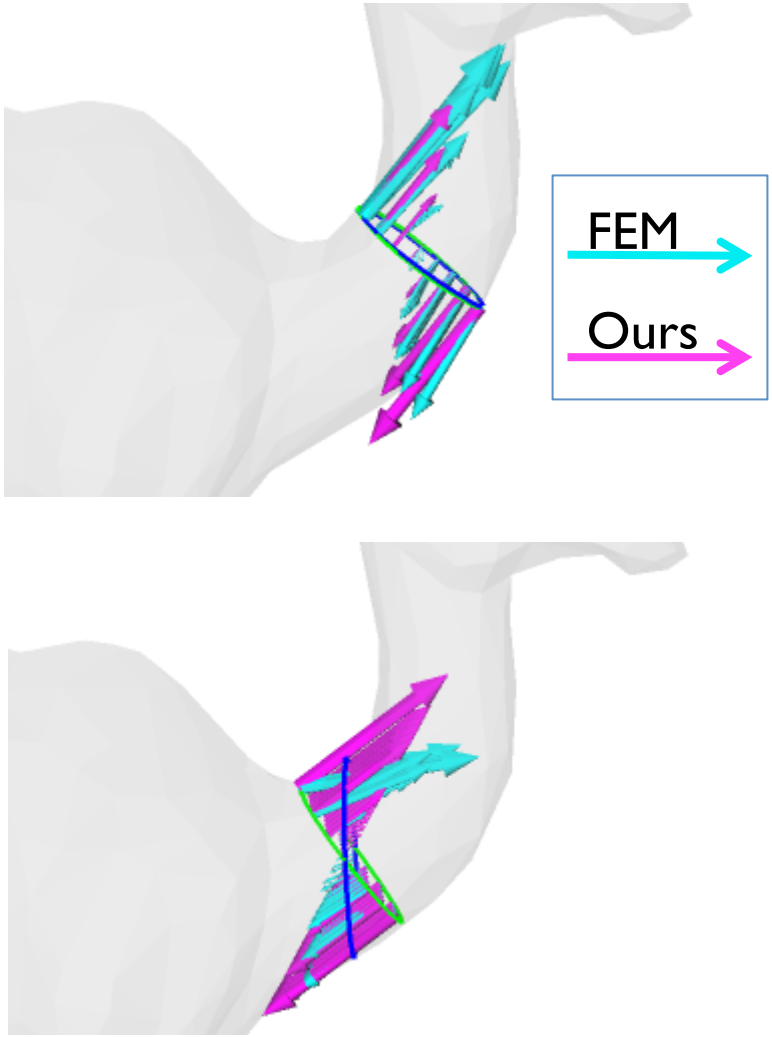
- Stress computation from arbitrary cross section



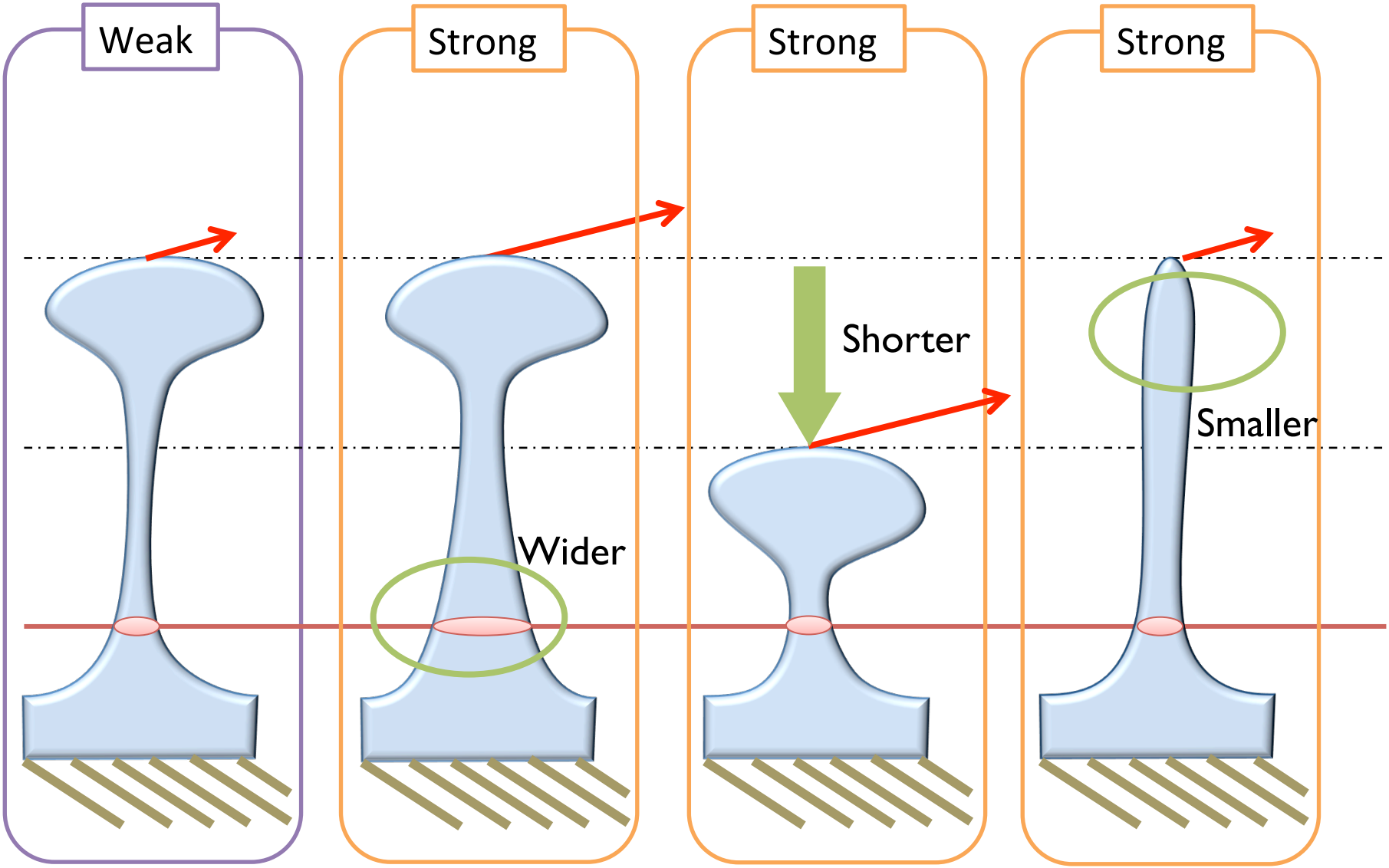
Comparison with FEM

Linear solid material analysis
with 2nd–order finite element method



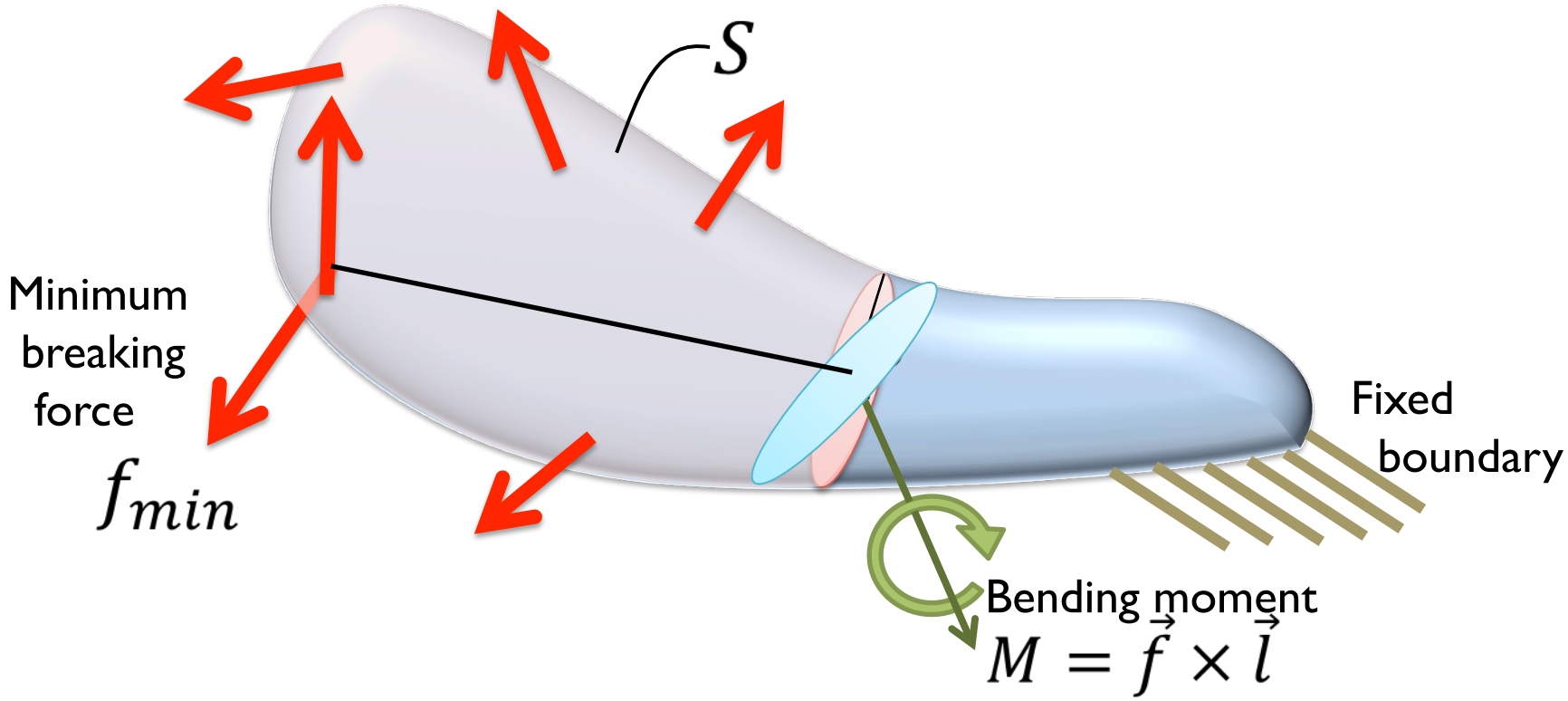


Structural Weakness is Both Local and Global

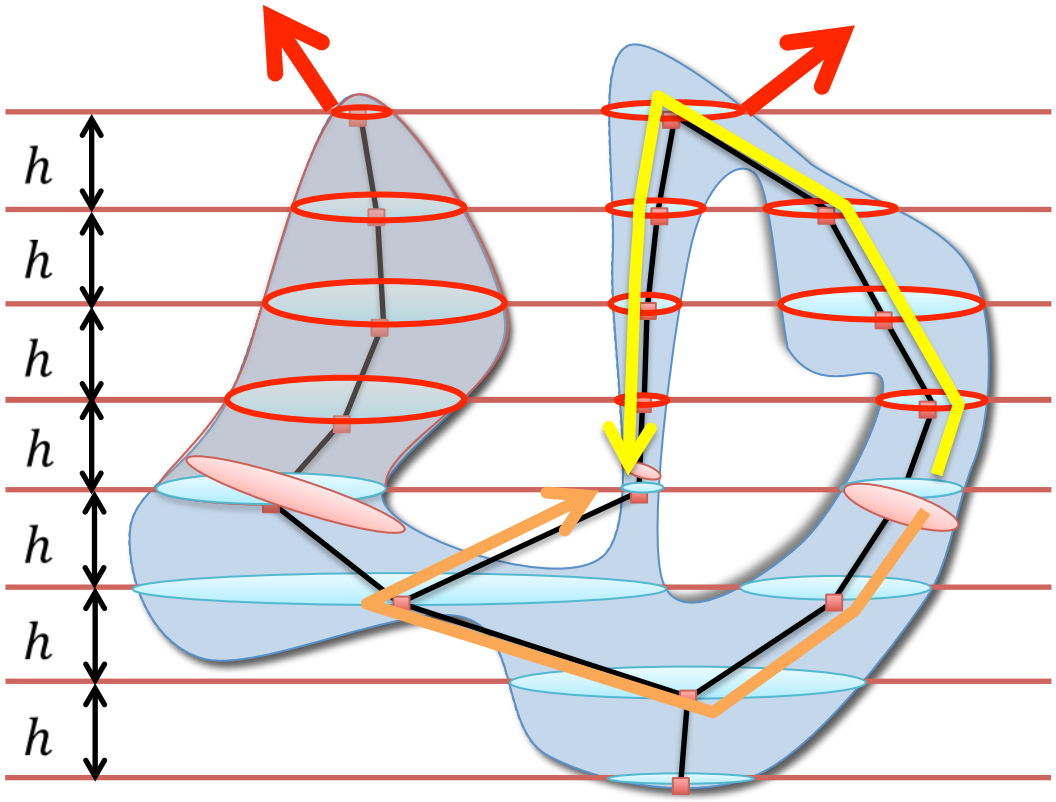


Weakness of a Cross-Section

$$weakness = \int_S \int_{2\pi} \frac{1}{f_{min}} \, d\theta \, ds$$



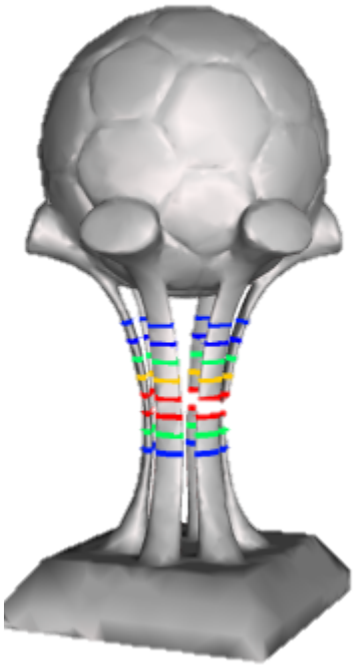
Acceleration of Weakness Computation



Weak Cross Sections Performance

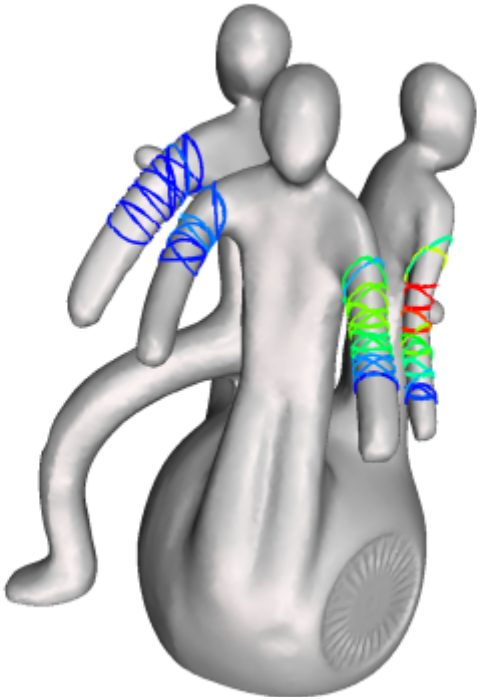
- 13 directions of cross section, 32 slices in each direction

|T| = 17k
n-sample=60k
time = 0.18sec



|T| = 34k
n-sample=200k
time = 0.31sec

|T| = 600k
n-sample=414k
time = 3.8sec



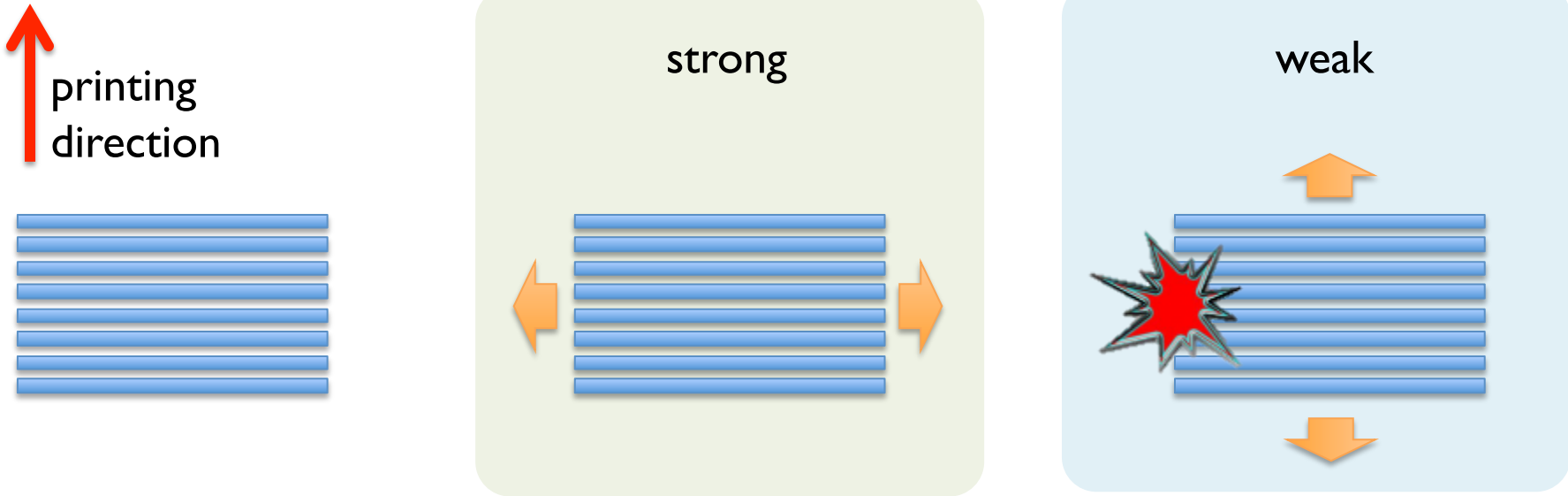
Live Demo with

Please download and check it out !

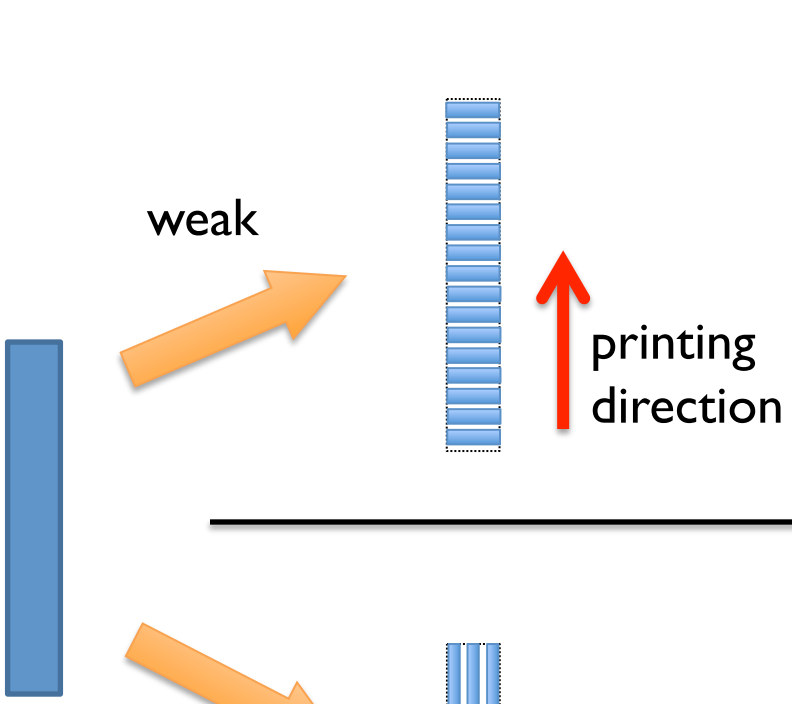
http://www.meshmixer.com/

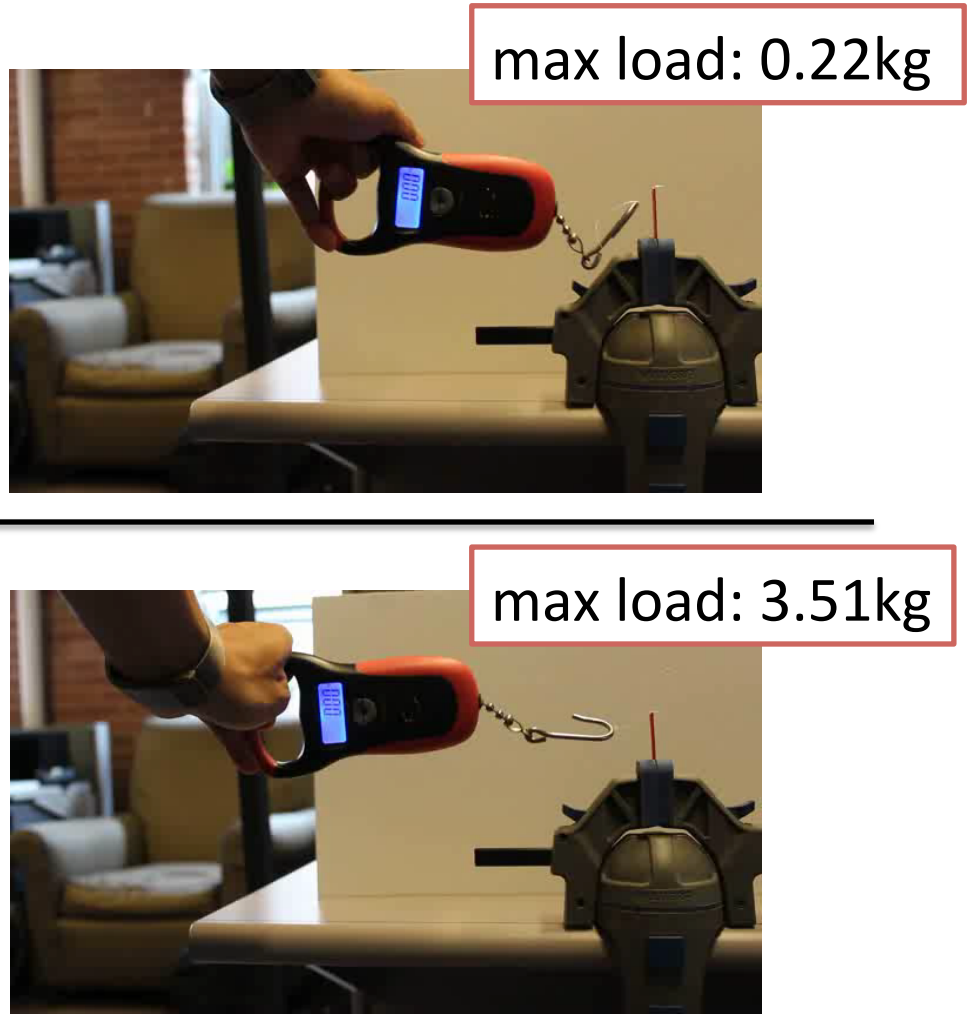
Application: 3D printing optimization

Printed Objects Have Large An-isotropy



Printing Direction Determines Strength

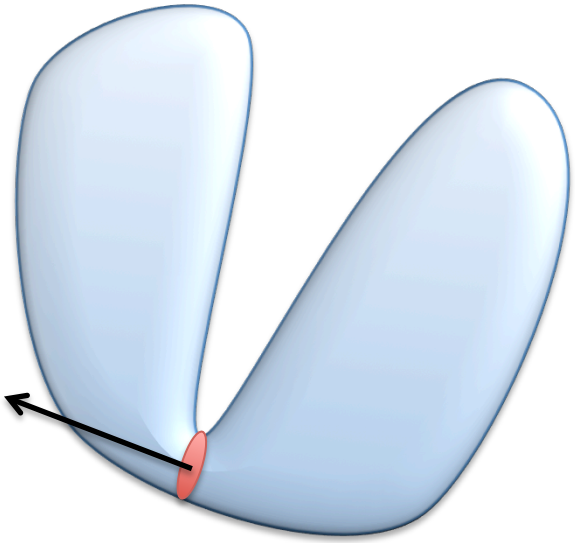


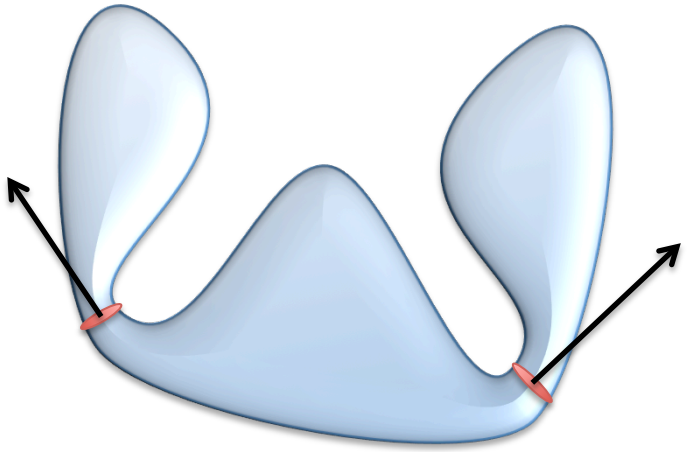


Printing Optimization

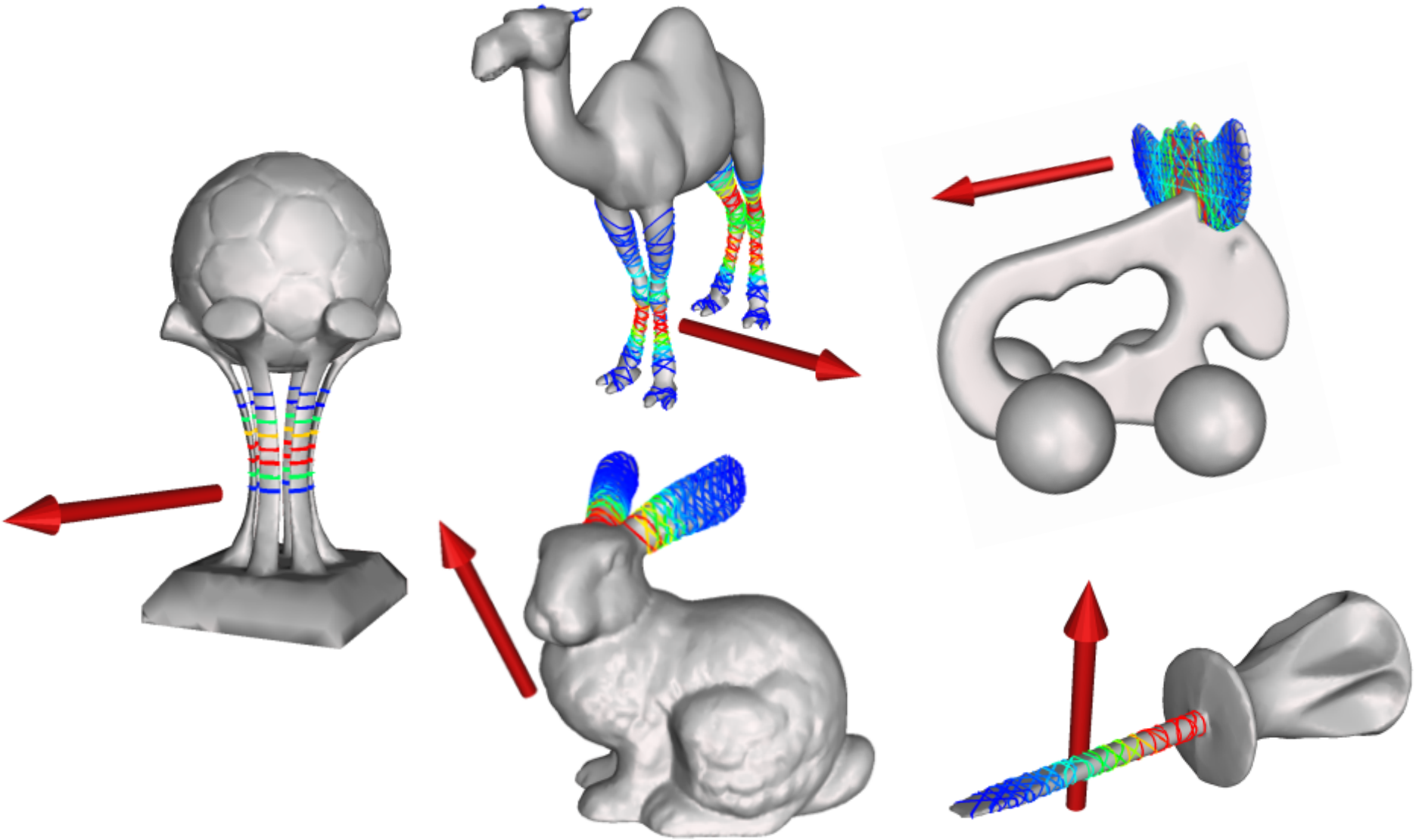
- Filament should goes through weak cross section

- Printing direction should be perpendicular to weak cross sections

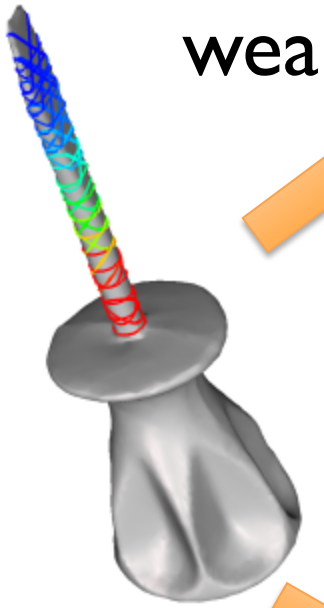




Results



Experiment #1



weak

printing direction

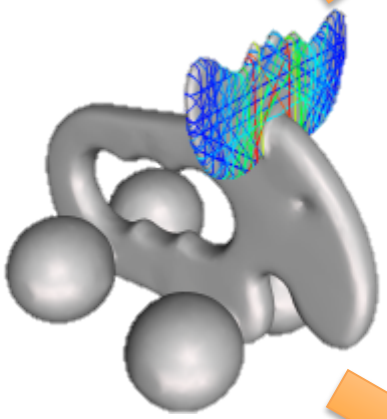
max load: 0.21kg

strong

printing direction

max load: 1.43kg

Experiment #2

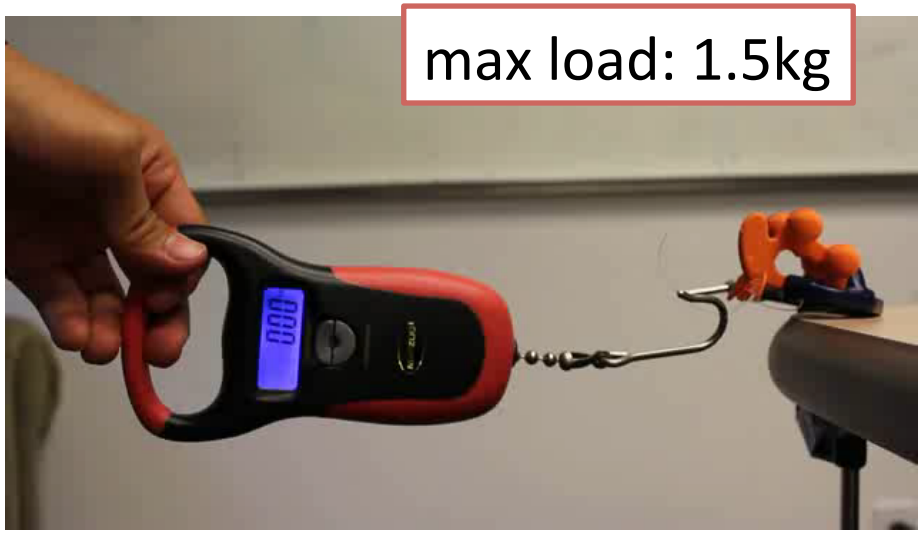


weak

printing direction

strong

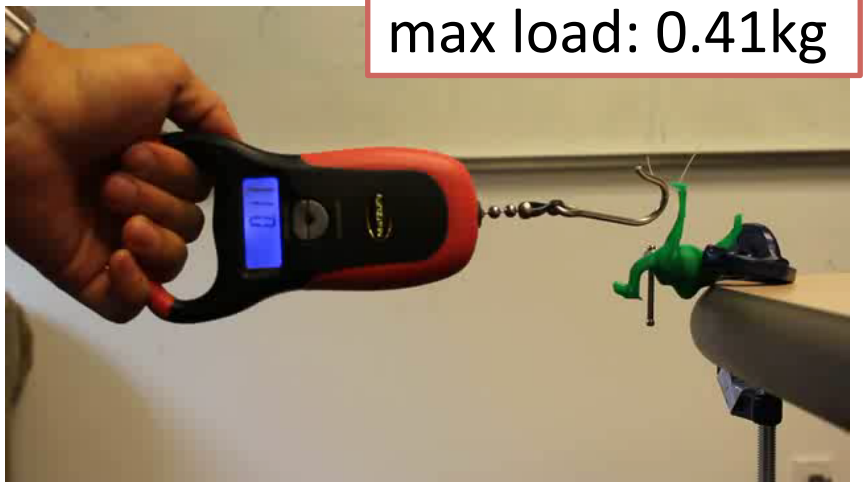
printing direction



Experiment #2

weak

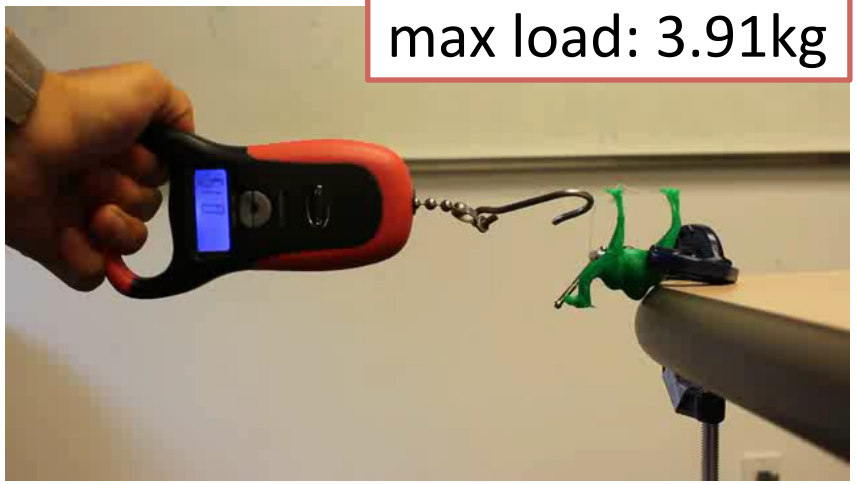
printing direction



max load: 0.41kg

strong

printing direction

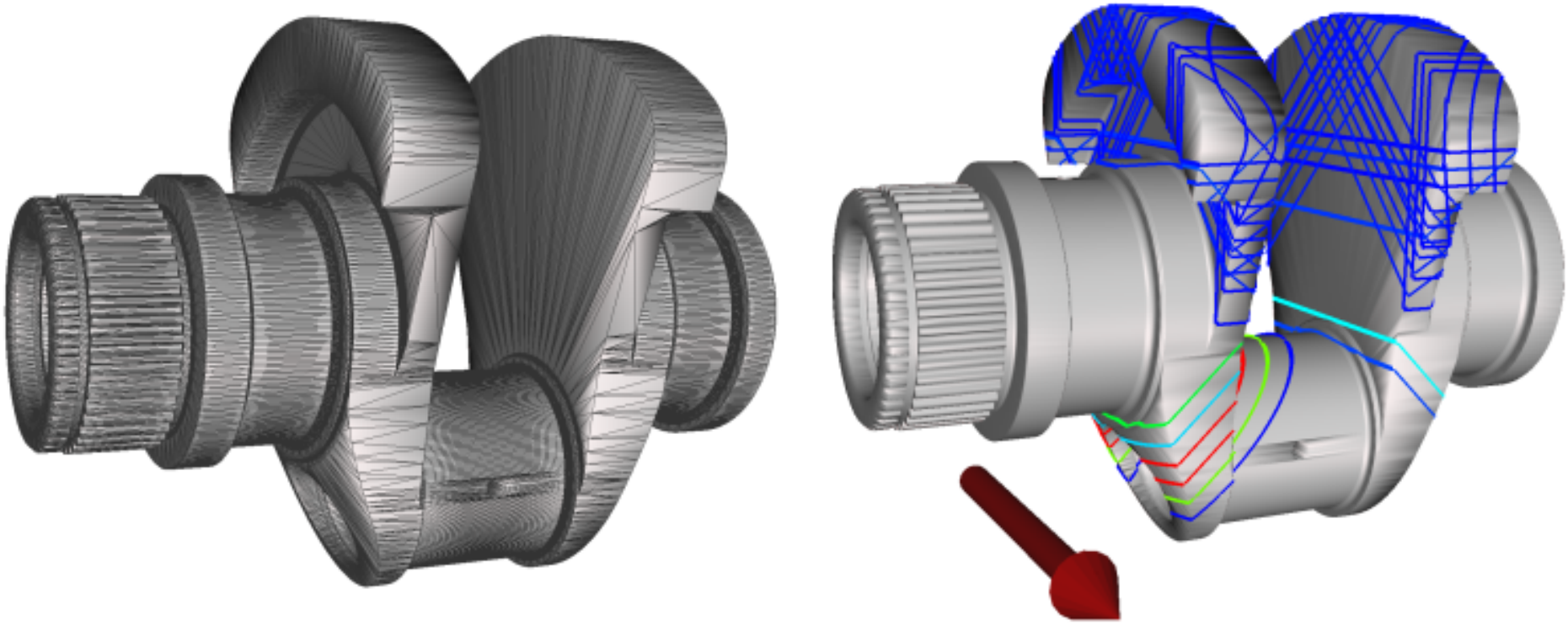


max load: 3.91kg

Discussion

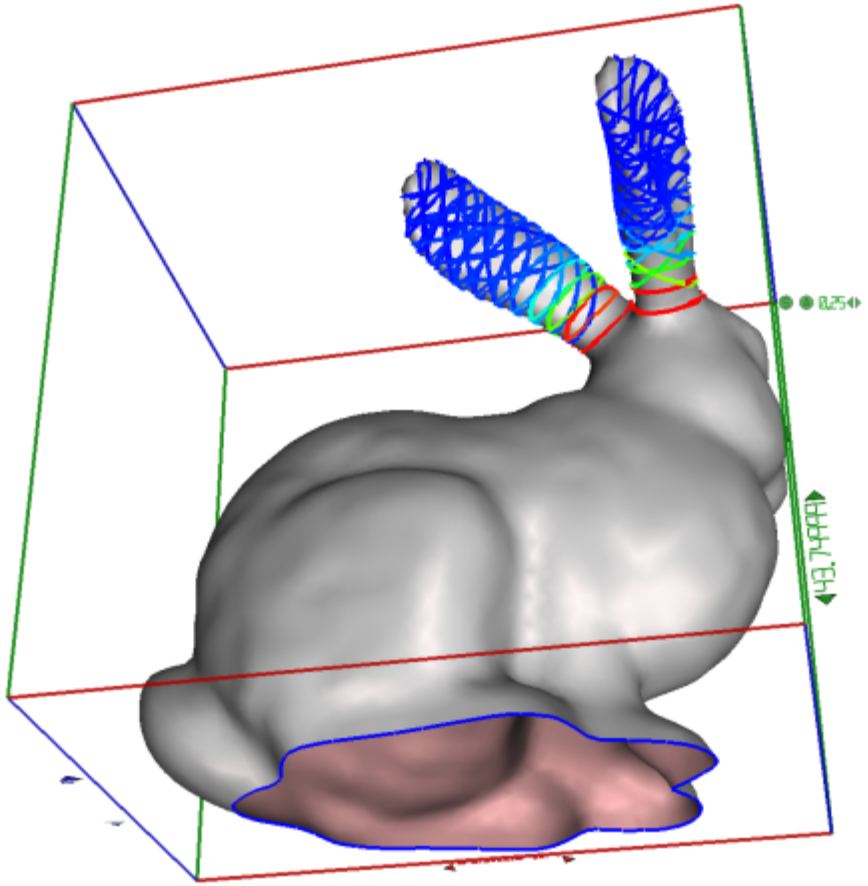
Analysis on Skinny Triangle Mesh

- Desirable for industrial design

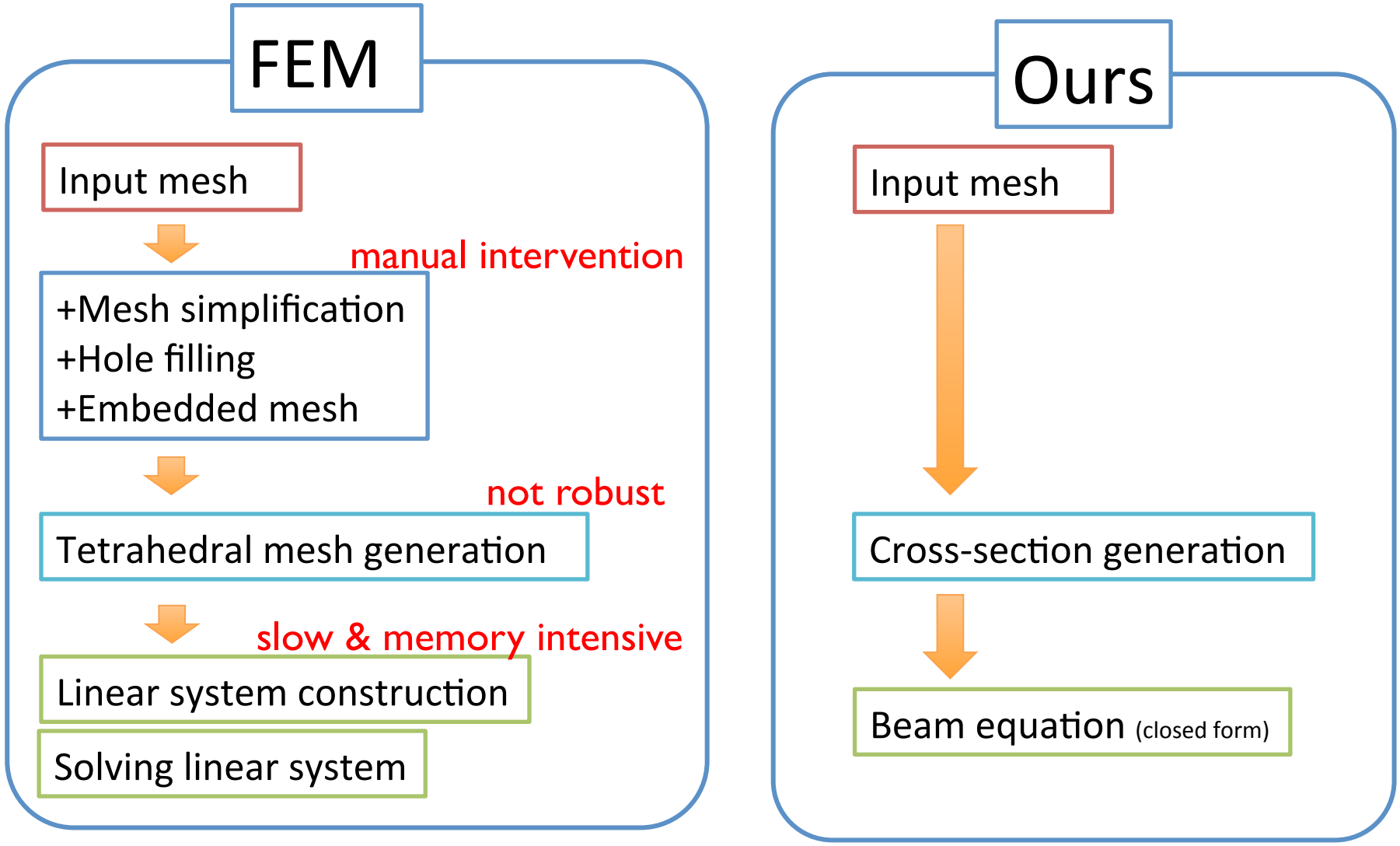


Analysis on Holey Mesh

- Skip the cross sections on the hole

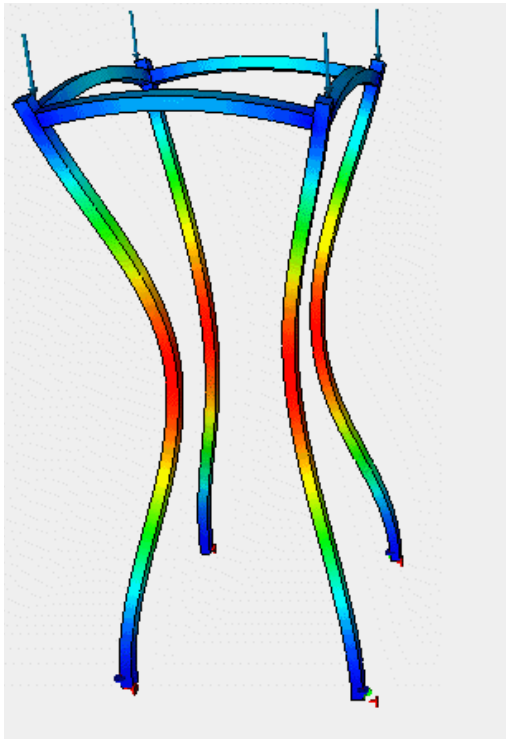


Comparison with a Typical Procedure of FEM

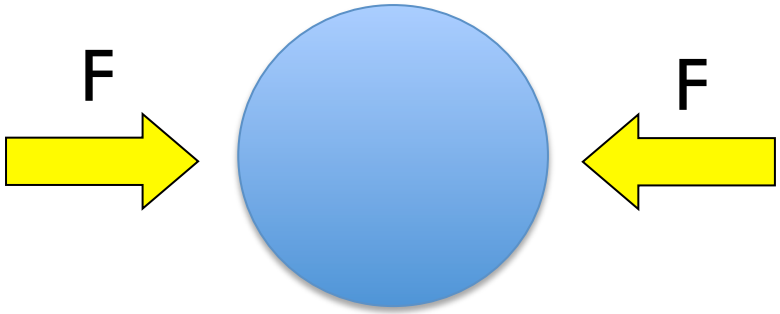


Limitations

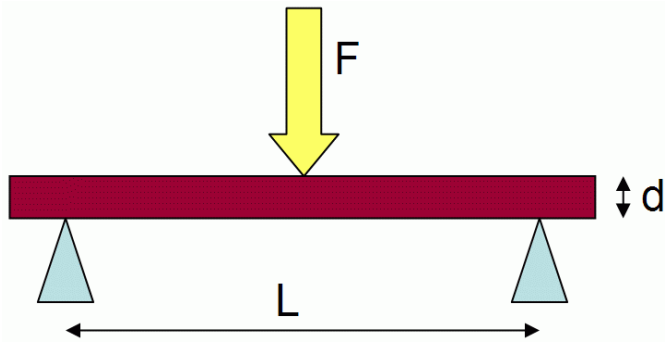
- Complex fracture is difficult
  (e.g. Buckling)



- Round object is difficult

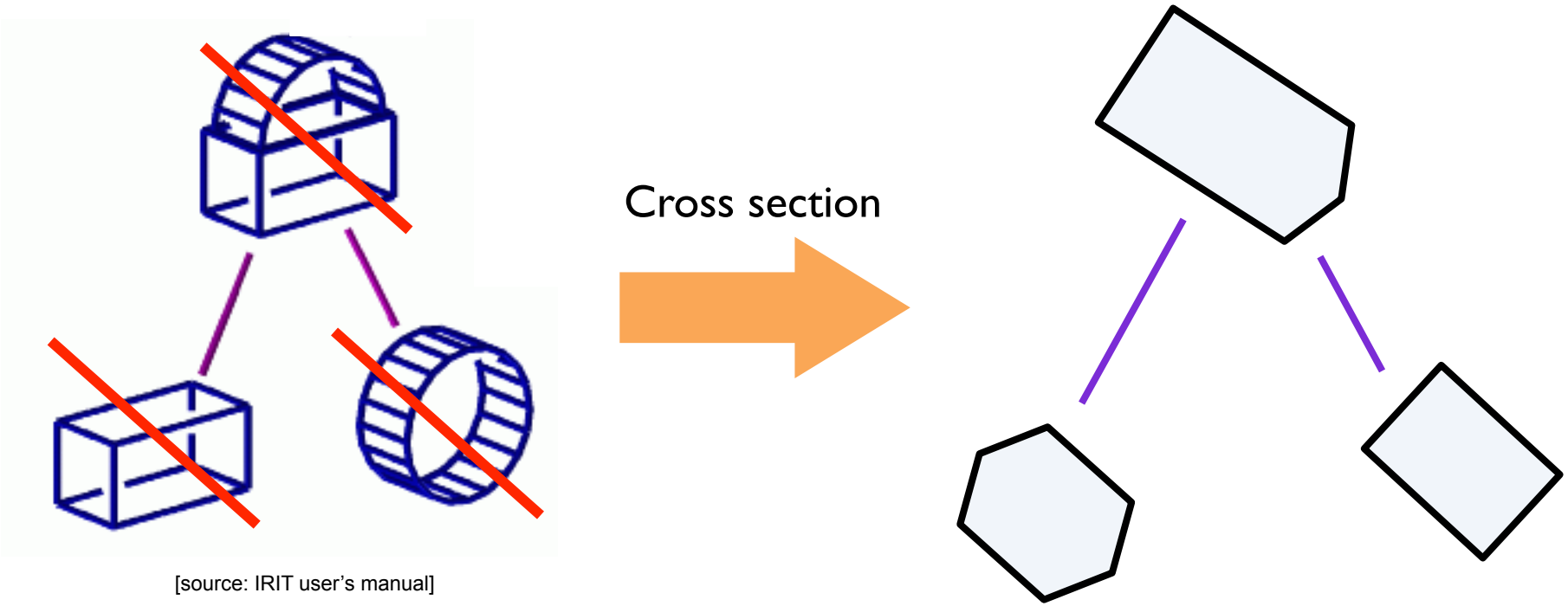


- Some boundary conditions are hard



Future Work: Direct Stress Analysis on CSG

- Real-time stress analysis for interactive CAD system



[source: IRIT user's manual]

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