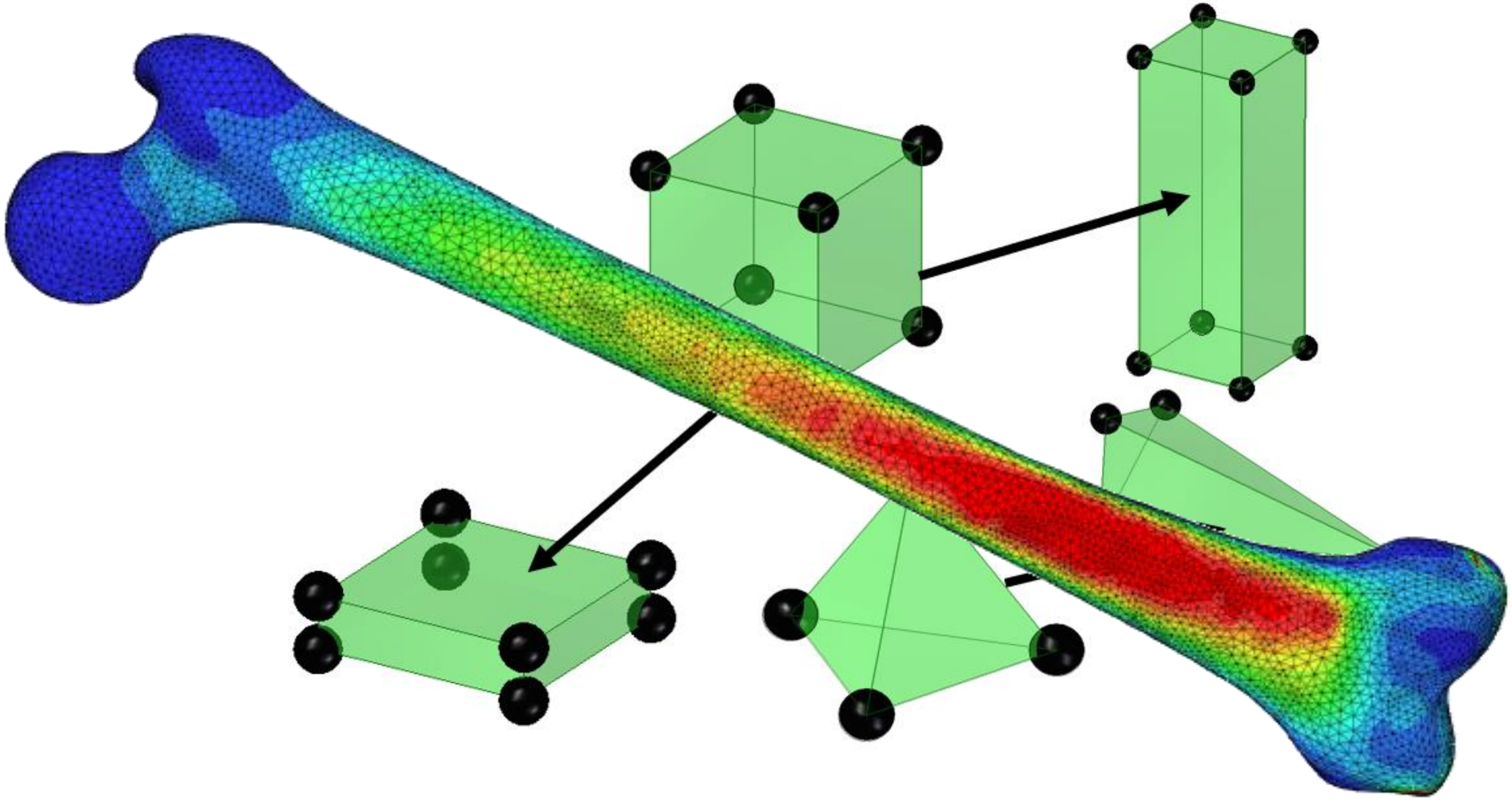
Computational Modelling in Biomechanical Systems



Laurence Marks

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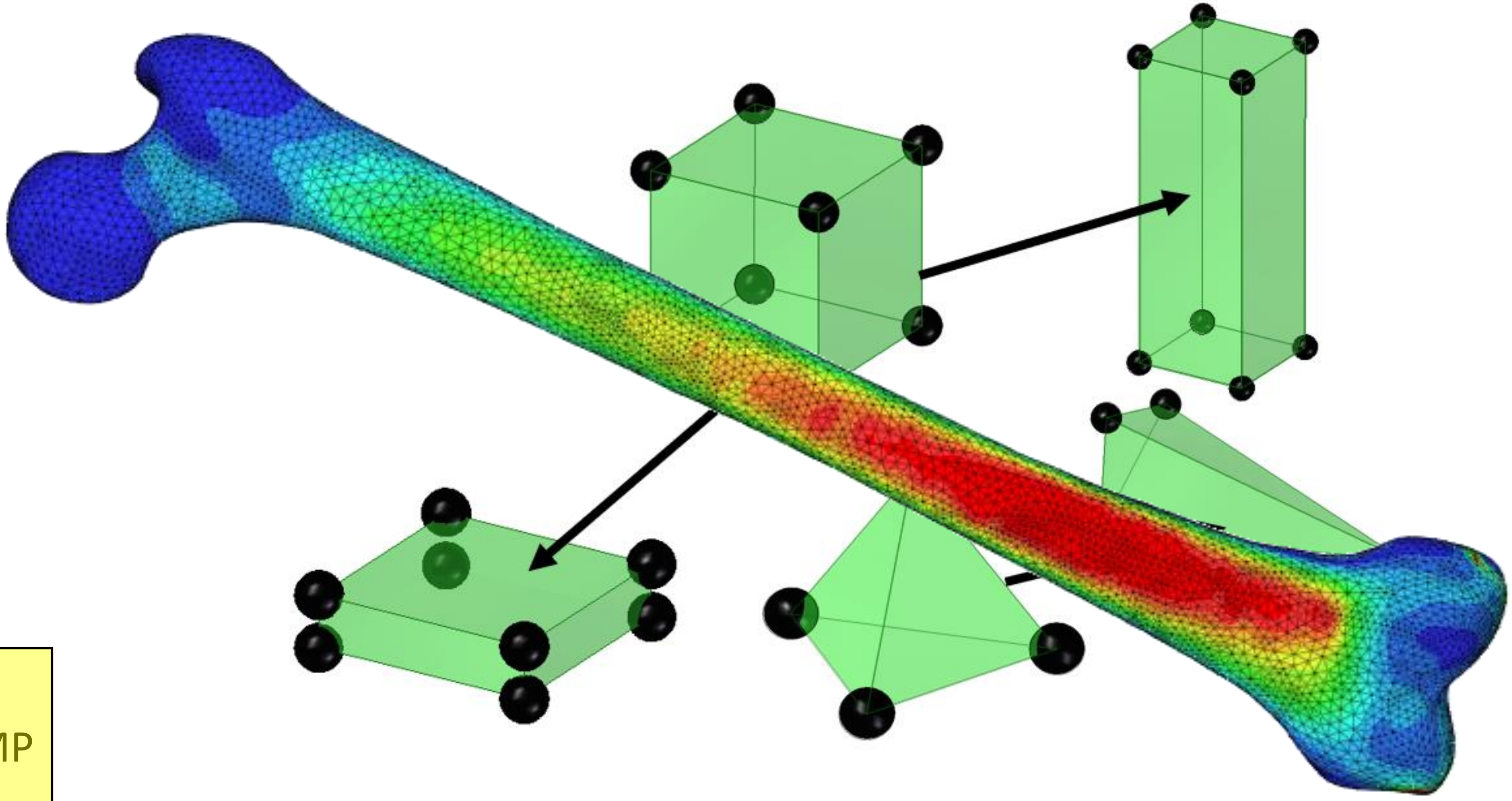
Computational Modelling in Biomechanical Systems



- About me..
- Finite Element Analysis in Biomechanics
- Finite Element Analysis
  - Basic concepts Meshing
  - Loads and boundary conditions
  - Interfaces
  - Non-linearity
  - Materials, biomaterials
  - Non-linearity
  - Model definition
- Explicit solutions and dynamics
- Multi-Body Dynamics, CFD and MP
- Implants and devices
- Defining the workflow.
- How do we know it’s right? Validation and Verification
- Summary

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About me..

- FEA and CFD engineer since the 1980's
- Founded and sold 3 simulation companies
- Published on fracture healing and tibial implant design
- Consultancy projects for surgeons and implant manufacturers
- PhD Examiner/DPhil Supervisor
- NAFEMS PSE
- Write for CAE publications
- And I'm an average racing driver.

TITLE	CITED BY	YEAR
The influence of mechanical stimulus on the pattern of tissue differentiation in a long bone fracture—an FEM study TN Gardnera, T Stoll, L Marks, S Mishra, MK Tate Journal of biomechanics 33 (4), 415-425	163	2000
The use of strain energy as a convergence criterion in the finite element modelling of bone and the effect of model geometry on stress convergence LW Marks, TN Gardner Journal of biomedical engineering 15 (6), 474-476	64	1993
Load transmission through a healing tibial fracture V Vijayakumar, L Marks, A Bremmer-Smith, J Hardy, T Gardner Clinical Biomechanics 21 (1), 49-53	36	2006
The role of osteogenic index, octahedral shear stress and dilatational stress in the ossification of a fracture callus TN Gardner, S Mishra, L Marks Medical engineering & physics 26 (6), 493-501	30	2004
Mathematical modelling of stress and strain in bone fracture repair tissue TN Gardner, T Stoll, L Marks, M Knothe-Tate Computer Methods in Biomechanics and Biomedical Engineering 2, 247-254	10	2020
Experimental characterisation of coefficient of friction at bone-implant interface X Min, D Heath, L Marks, DW Murray, SJ Mellon ORS 2024 Annual Meeting	2	2024
A finite element model for investigating the influence of keel design and position on unicompartmental knee replacement cementless tibial component fixation A MacAulay, A Rahman, L Marks, DW Murray, SJ Mellon Medical Engineering & Physics 125, 104119	1	2024
A finite element model of a human tibial fracture. Stress concentrations and mechanical failure in healing callus TN Gardner Journal of Biomechanics 31, 11	1	1998
Surgical factors that contribute to tibial periprosthetic fracture after cementless Oxford Unicompartmental Knee Replacement: a finite element analysis X Min, L Marks, S Mellon, T Hiranaka, D Murray Frontiers in Bioengineering and Biotechnology 13, 1543792		2025
Finite element analysis and experimental verification of press-fit peg push-in and pull-out in trabecular bone analogue X Min, D Heath, A Rahman, L Marks, D Murray, S Mellon Results in Engineering 25, 104029		2025
Image-based parametric finite element modelling for studying contact mechanics in human knee joints R Readioff, R Seil, C Mouton, L Marks, O Barrera bioRxiv, 2023.09. 07.556747		2023
Modelling the influence of the mechanical environment on healing human tibial fractures: a finite element study V Vijayakumar, L Marks, S Mishra, E Loveday, A Bremmer-Smith, J Hardy, ... ACTA OF BIOENGINEERING AND BIOMECHANICS 4, 317-318		2003

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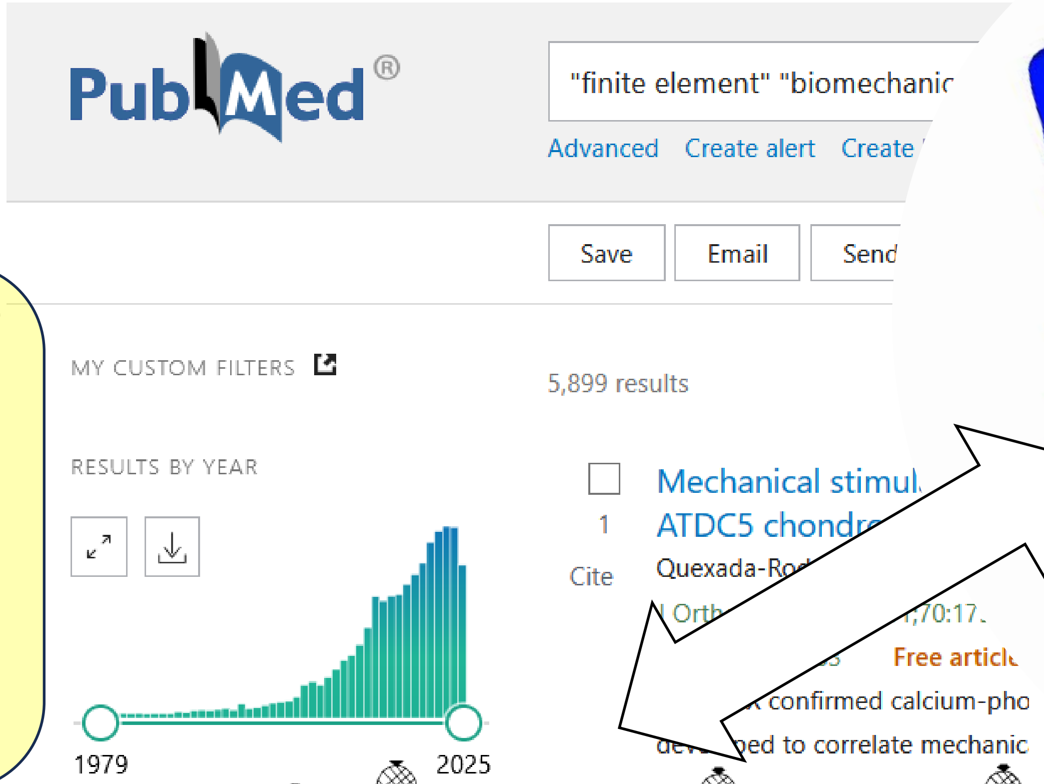
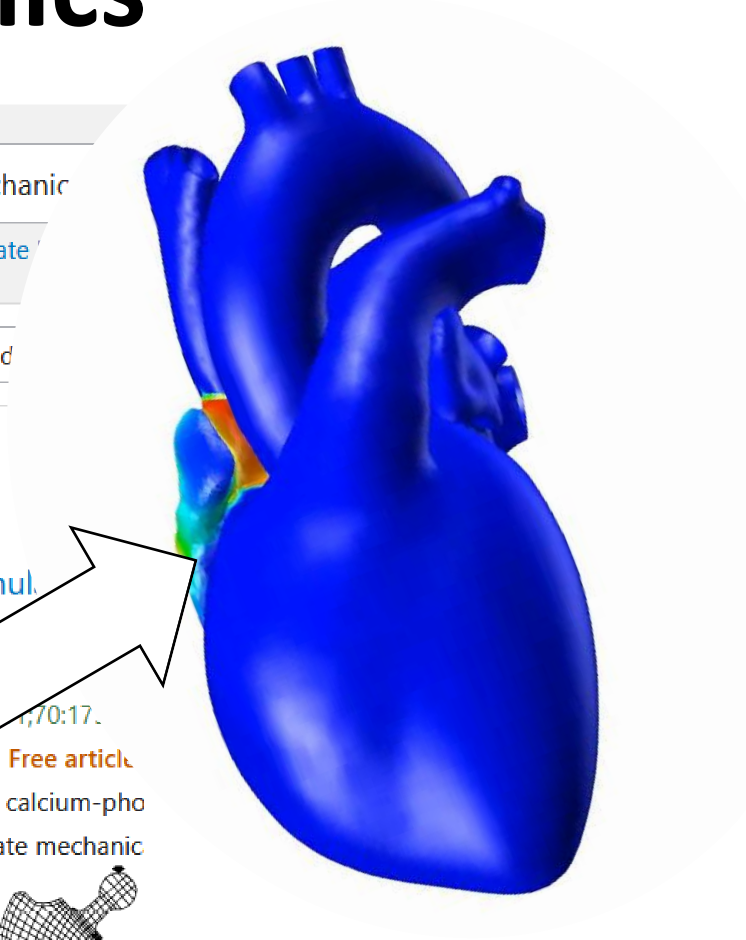
Finite Element Analysis in Biomechanics

- FEA is a popular tool in biomechanics research..
- Its use is growing.
- This session aims to provide you with a basic understanding of the technology and give you some reference points to judge the good the bad and the indifferent..
- Also a jumping off point if you want to become involved or even do FEA projects





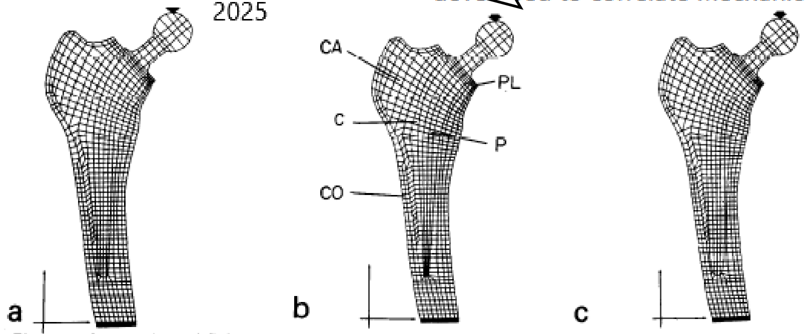


Figure 1 Geometries and finite element meshes for (a) standard prosthesis, (b) more tapered stem, (c) less tapered stem. P – prosthesis, CO – cortincal bone, CA – cancellous bone, C – cement, PL – plateau (if present).

282 J. Biomed. Engng. 1979, Vol. 1, October

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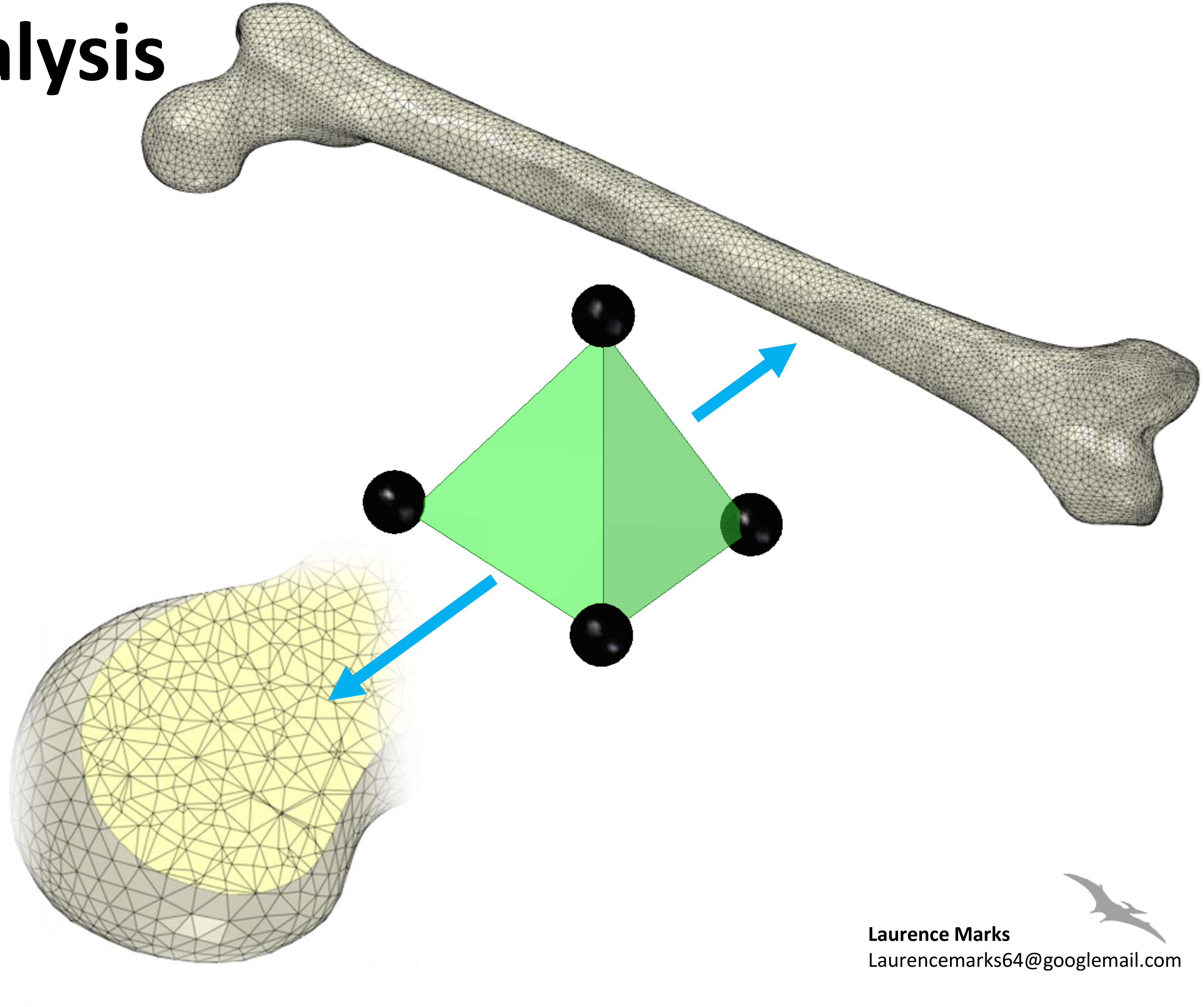
Finite Element Analysis

- Finite element analysis is the process of dividing structures and components into small subregions and calculating the behaviour of the whole by combining the behaviour of the parts.

- There's no magic and how the process works is easy to understand



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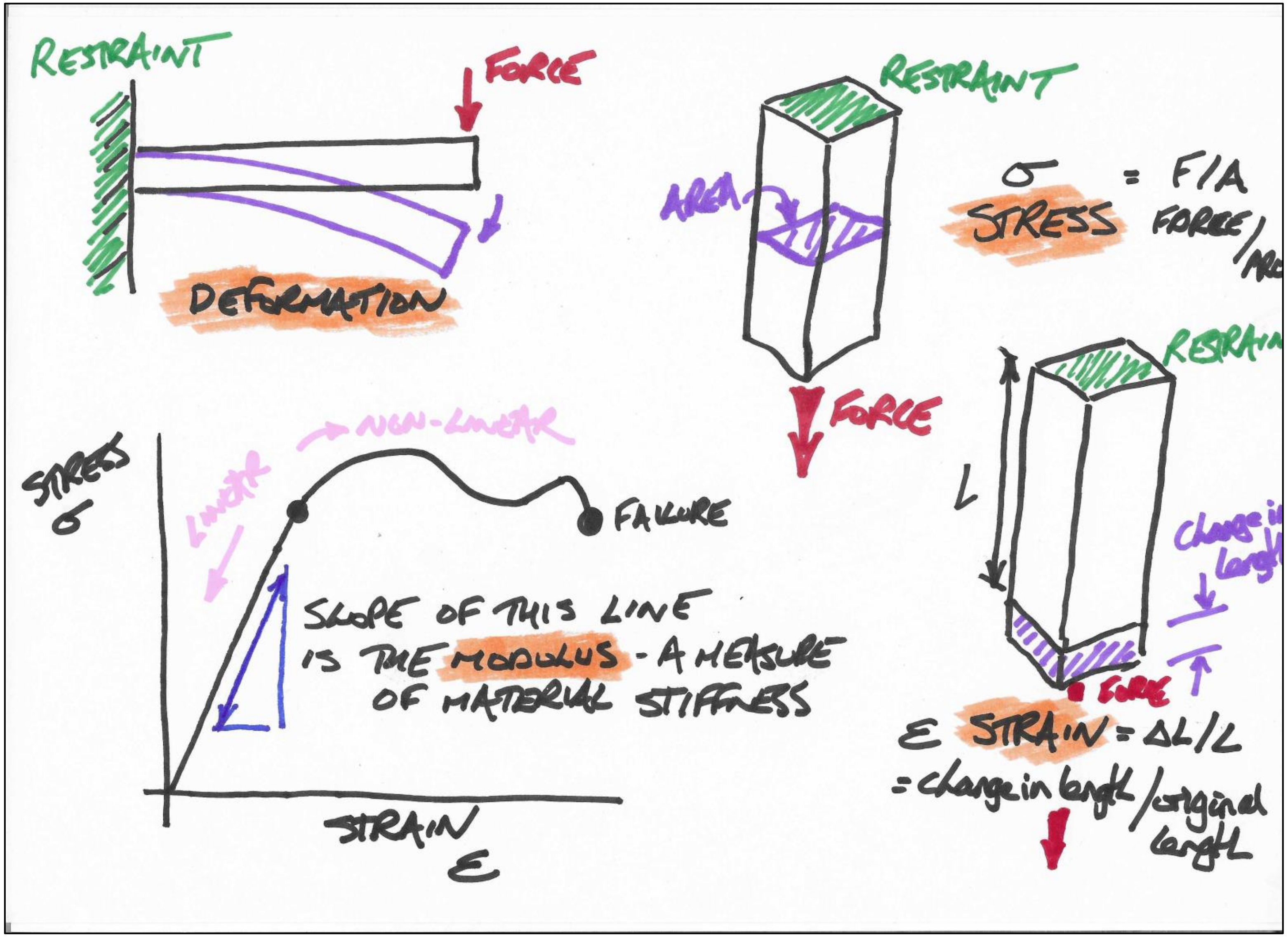
Some basic concepts that you need..

- To understand what a finite element model is working with..



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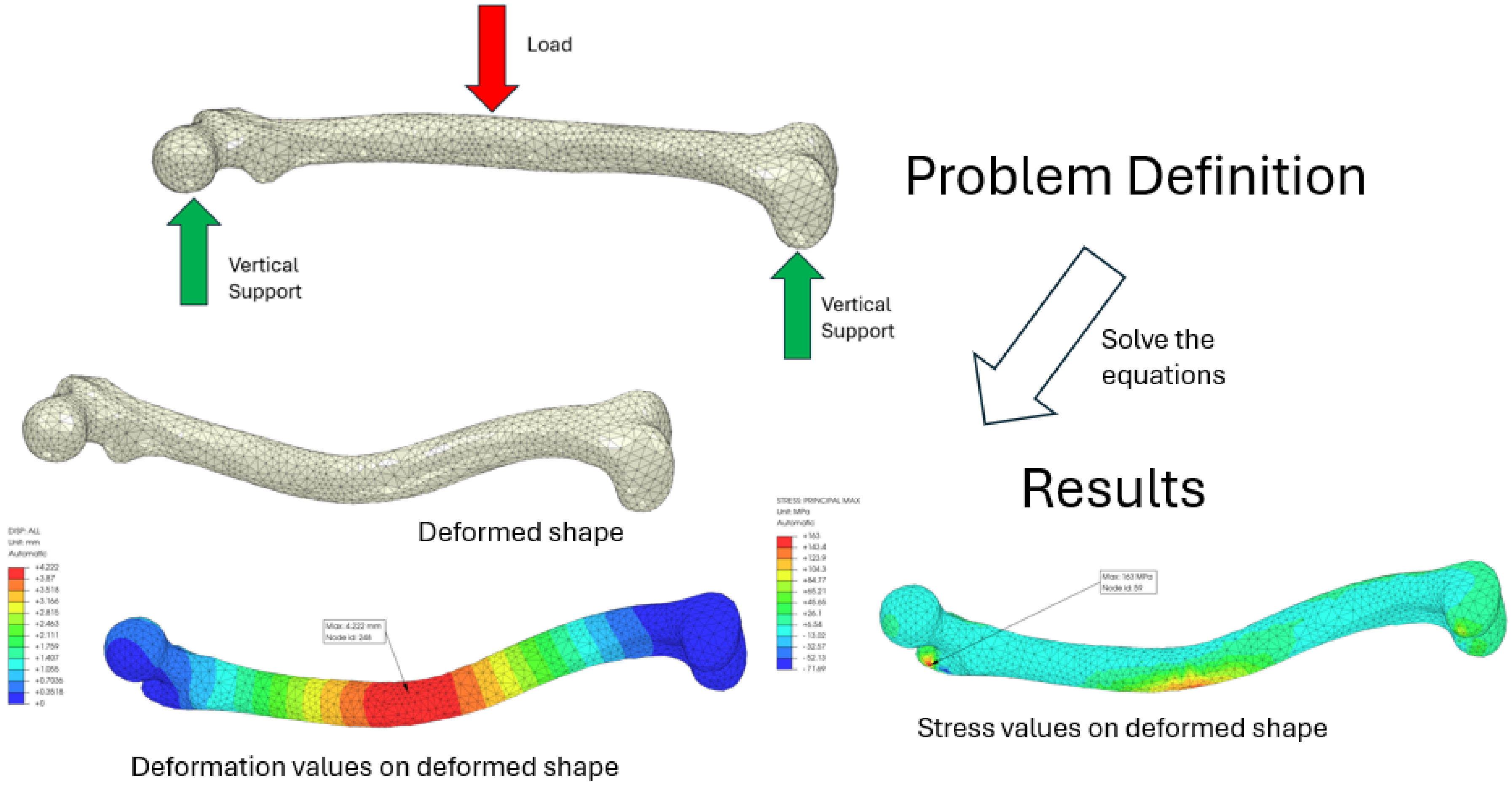
What will Finite Element Models tell you?

- How much things will deform under load
- What sort of stresses the system will see across the part – and therefore how near breaking it is..
- What sort of strains it sees - this is sometimes more important than stress
- And lots of other stuff
- We have to tell them how much load is applied, how the parts are fixed, and what the material modulus is..



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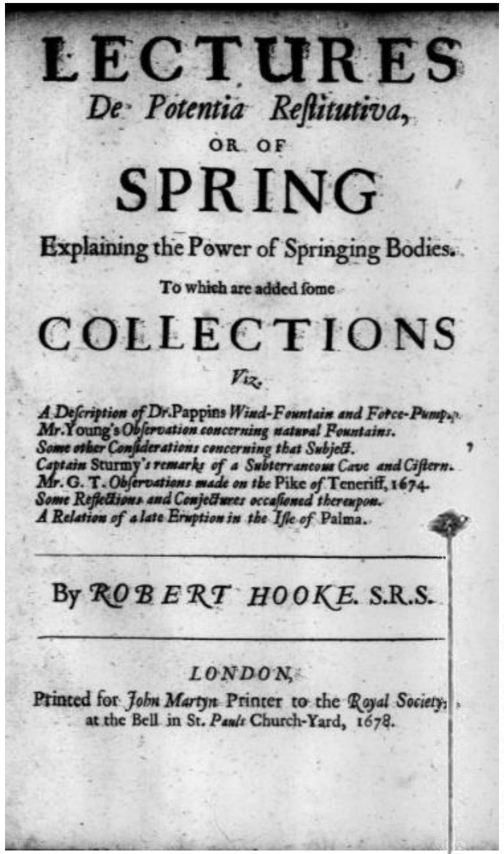
Basic concepts

- Finite element analysis can be used for many types of problem, but here we are going to concentrate on structural mechanics..

“ut tensio, sic vis”

“as the extension, so the force”



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To which are added some
COLLECTIONS
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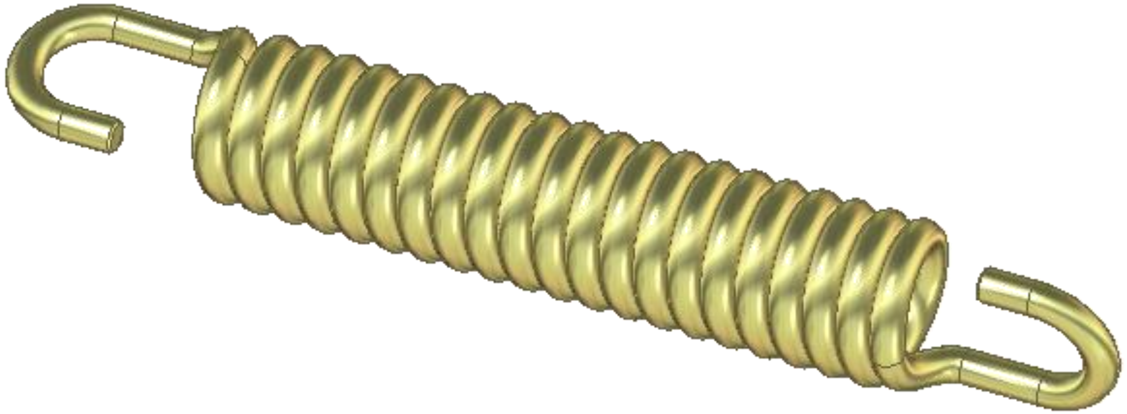

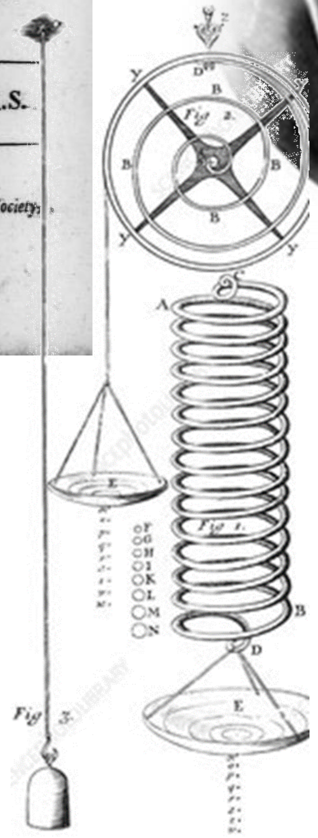

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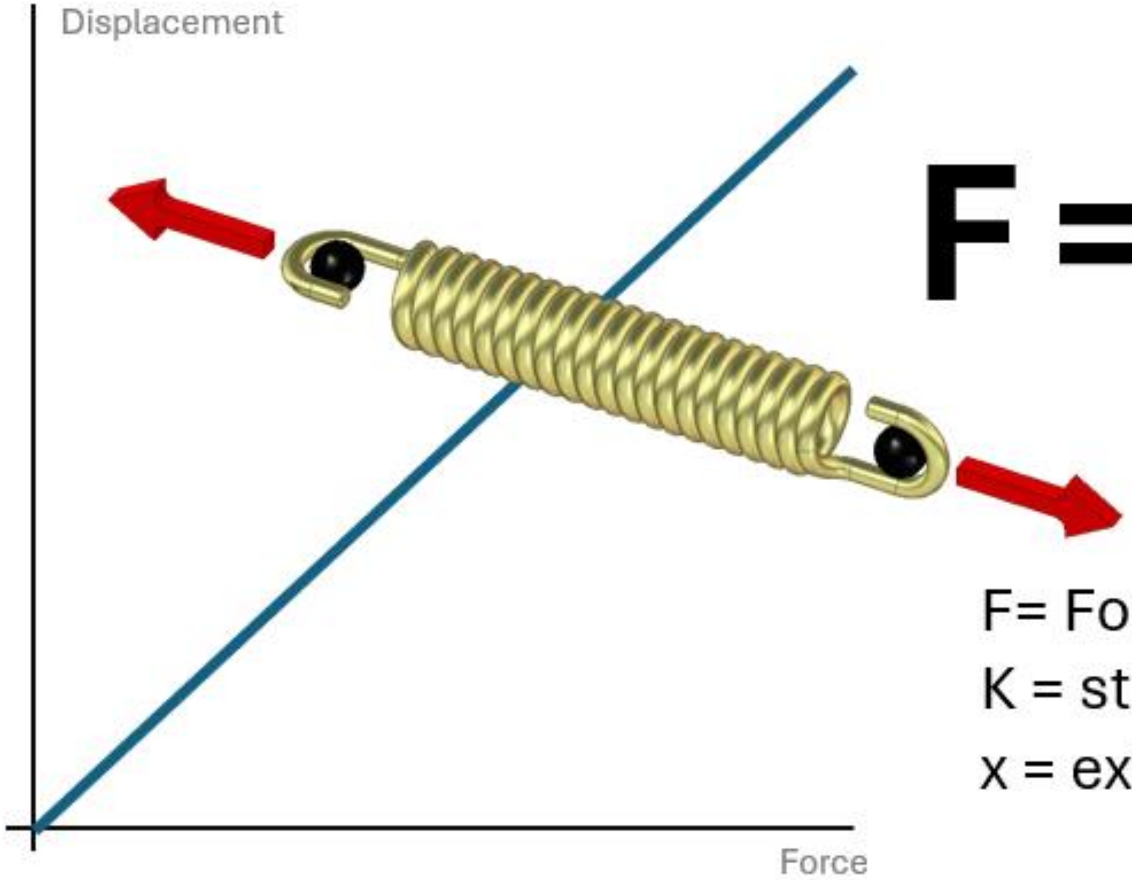
Basic concepts



$$F = K(x)$$

F= Force (N)
K = stiffness (N/m)
x = extension (m)

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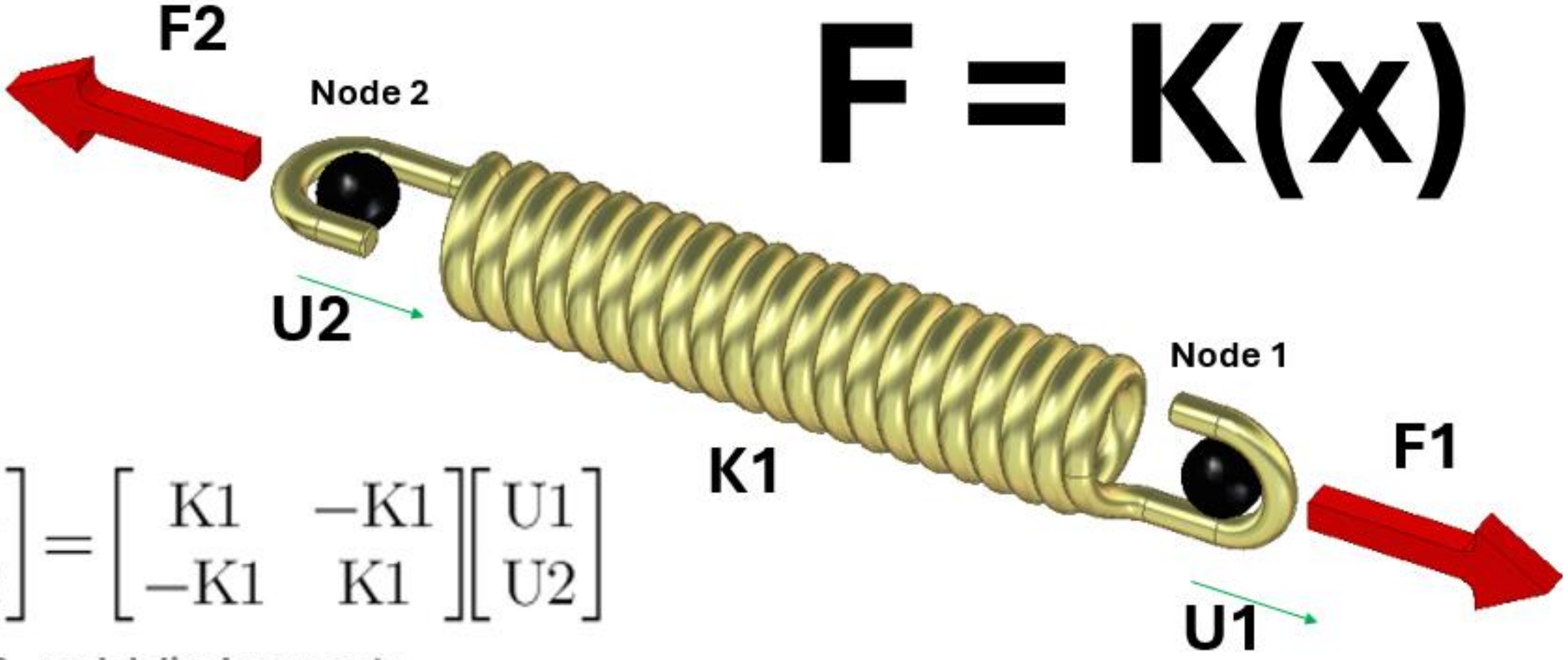
Basic concepts

$$F = K(x)$$



$$\begin{bmatrix} F1 \\ F2 \end{bmatrix} = \begin{bmatrix} K1 & -K1 \\ -K1 & K1 \end{bmatrix} \begin{bmatrix} U1 \\ U2 \end{bmatrix}$$

U1/U2 – nodal displacements
F1/F2 – nodal forces
K1 – element stiffness

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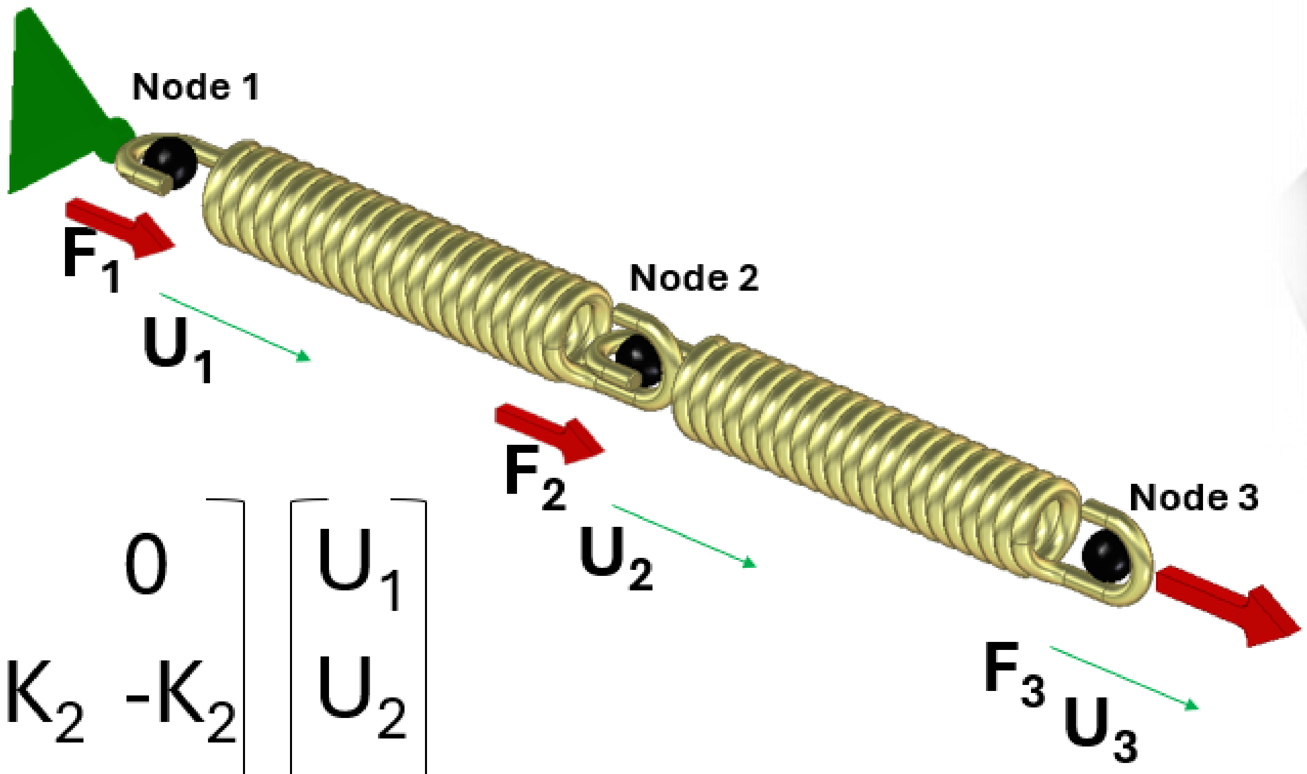
Basic concepts



Forces

$$\begin{bmatrix} F_1 \\ F_2 \\ F_3 \end{bmatrix} \quad \begin{bmatrix} K_1 & -K1 & 0 \\ -K_1 & K_1+K_2 & -K_2 \\ 0 & -K_2 & K_2 \end{bmatrix} \begin{bmatrix} U_1 \\ U_2 \\ U_3 \end{bmatrix}$$

Stiffnesses

Displacements

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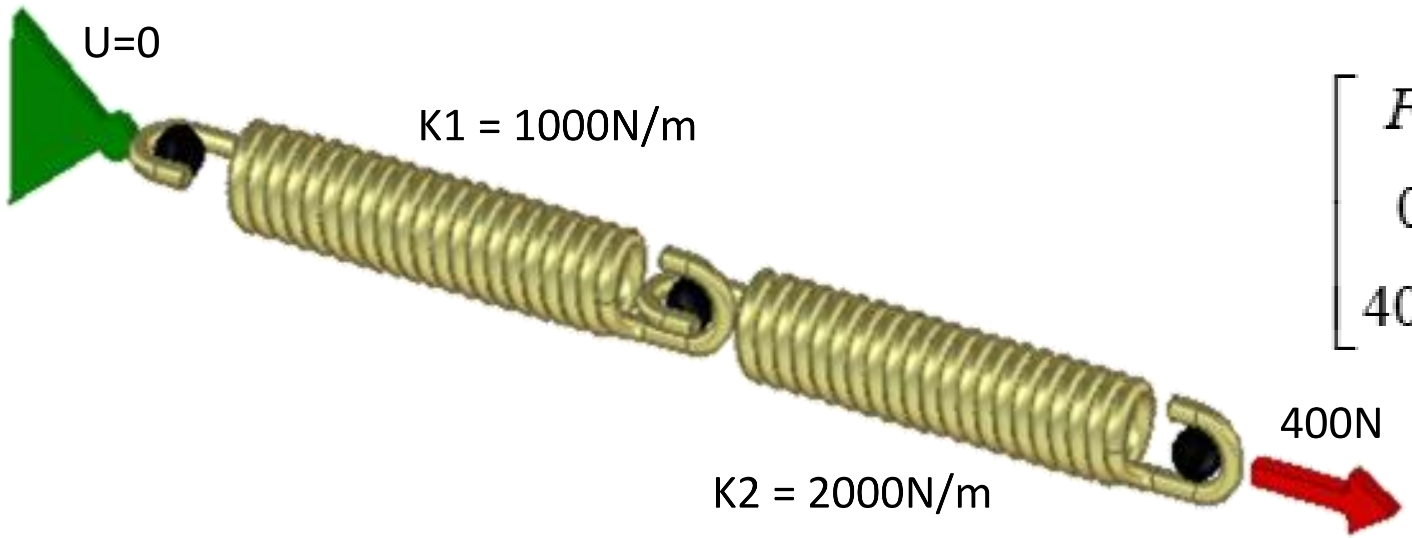
Basic concepts

- Adding some values



$$\begin{bmatrix} F_1 \\ F_2 \\ F_3 \end{bmatrix} = \begin{bmatrix} K_1 & -K_1 & 0 \\ -K_1 & K_1+K_2 & -K_2 \\ 0 & -K_2 & K_2 \end{bmatrix} \begin{Bmatrix} U_1 \\ U_2 \\ U_3 \end{Bmatrix}$$

$$\begin{bmatrix} F_1 \\ 0 \\ 400 \end{bmatrix} = \begin{bmatrix} 1000 & -1000 & 0 \\ -1000 & 3000 & -2000 \\ 0 & -2000 & 2000 \end{bmatrix} \begin{Bmatrix} U_1 \\ U_2 \\ U_3 \end{Bmatrix}$$

Removing the lines which represent the constrained freedom give

$$\begin{bmatrix} 0 \\ 400 \end{bmatrix} = \begin{bmatrix} 3000 & -2000 \\ -2000 & 2000 \end{bmatrix} \begin{Bmatrix} U_2 \\ U_3 \end{Bmatrix}$$

Which is the following set of simultaneous equations..

$3000U_2 \quad -2000U_3 \quad = \quad 0$

$-2000U_2 \quad + 2000U_3 \quad = \quad 400$

Solving them gives $U_2 = 0.4$m and $U_3 = 0.6$m

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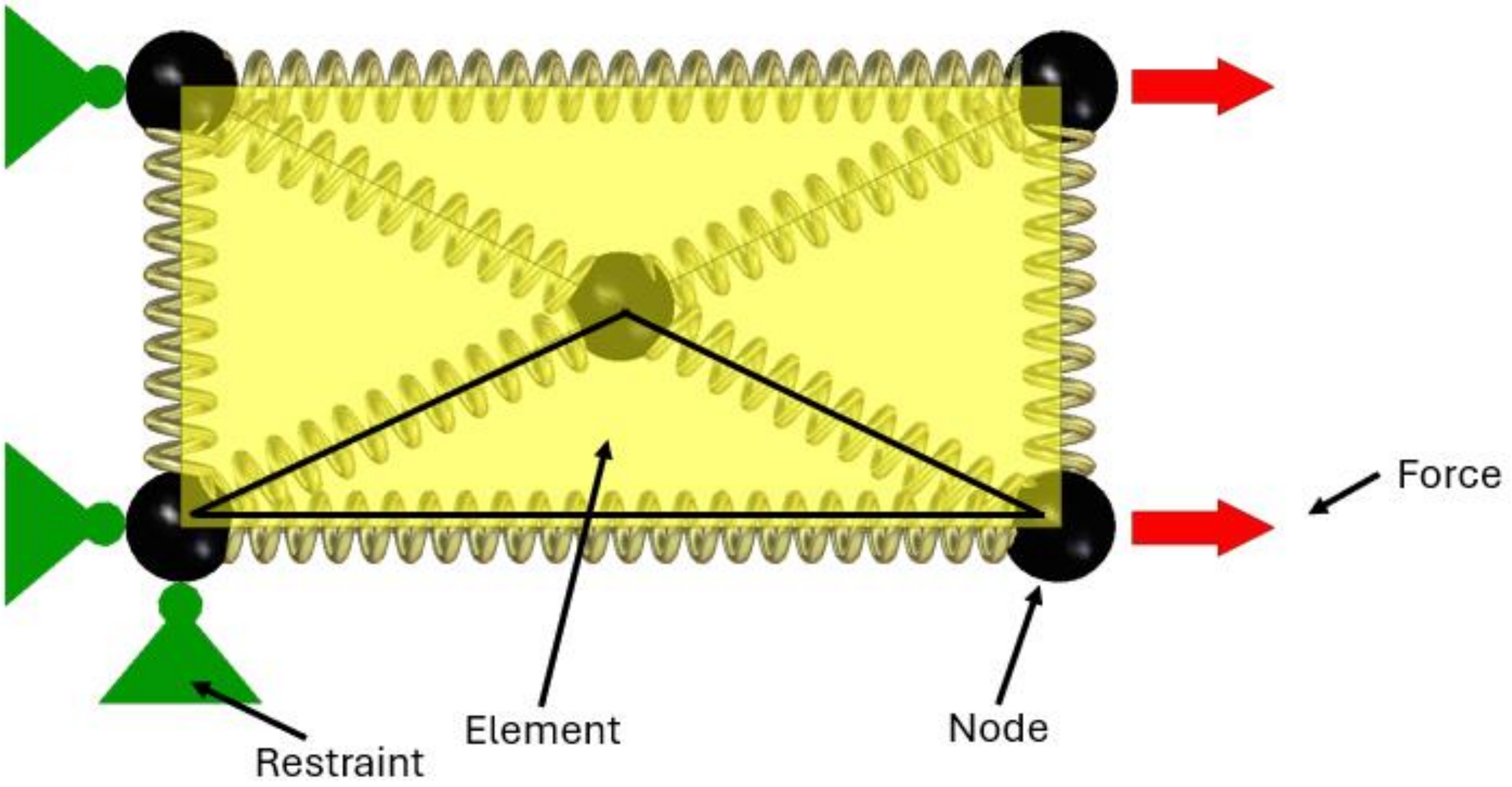
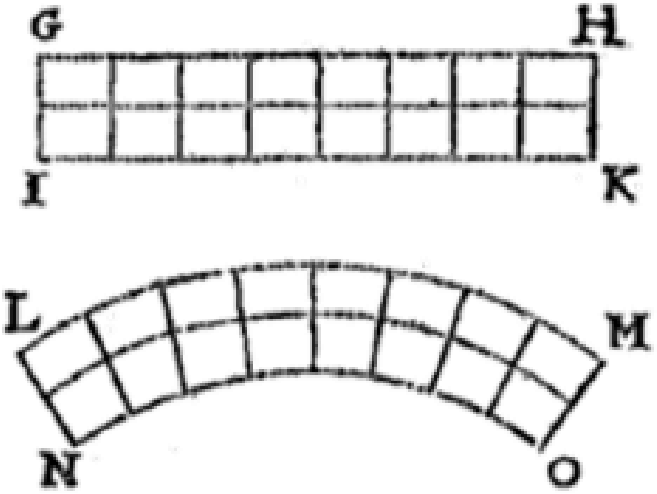
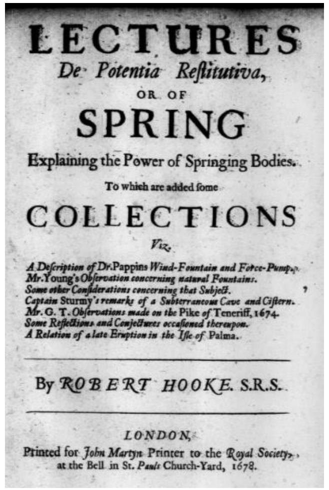
Basic concepts

- Modelling real structures







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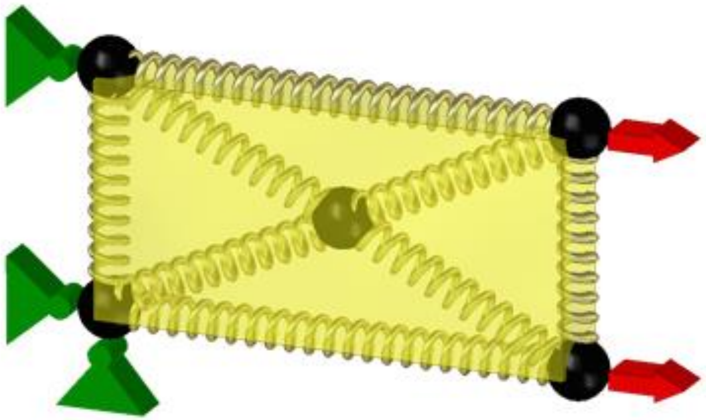

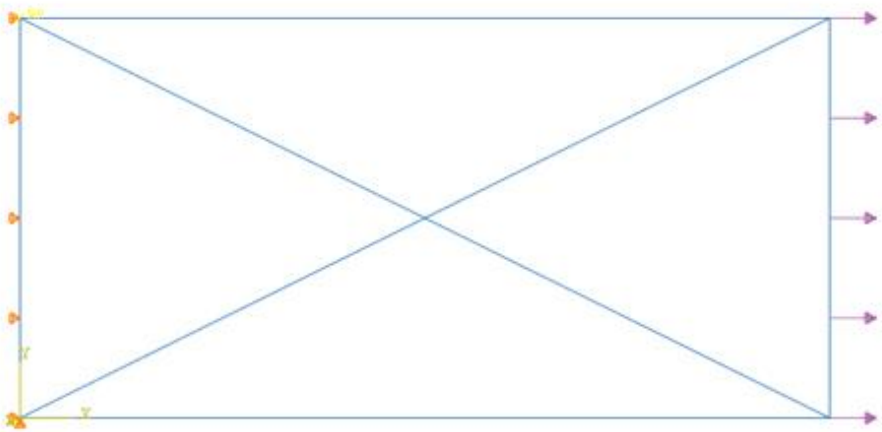

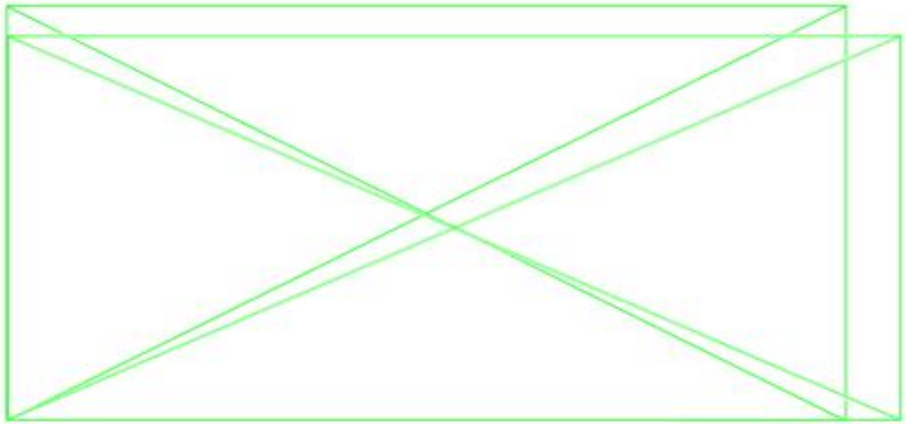

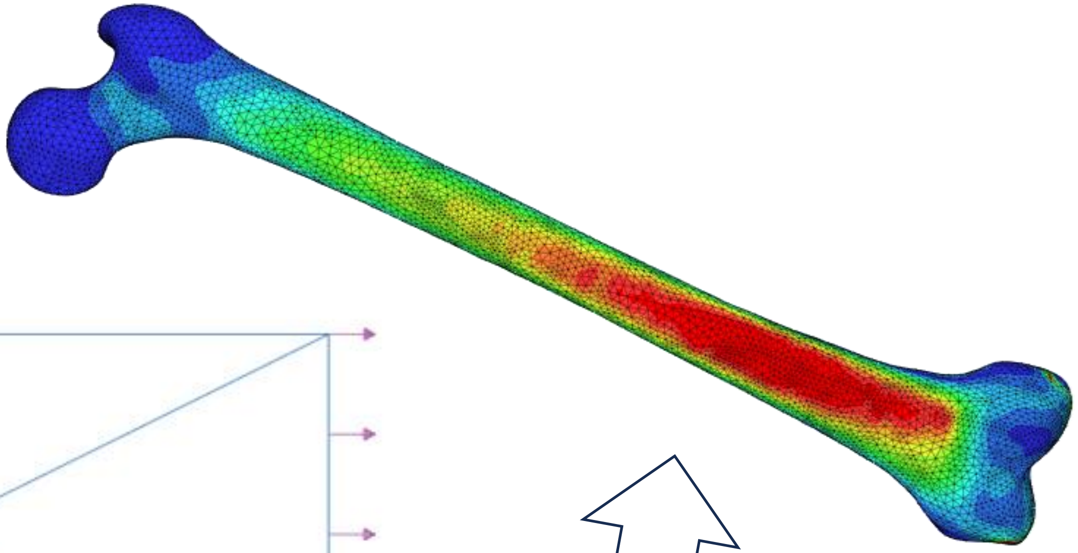

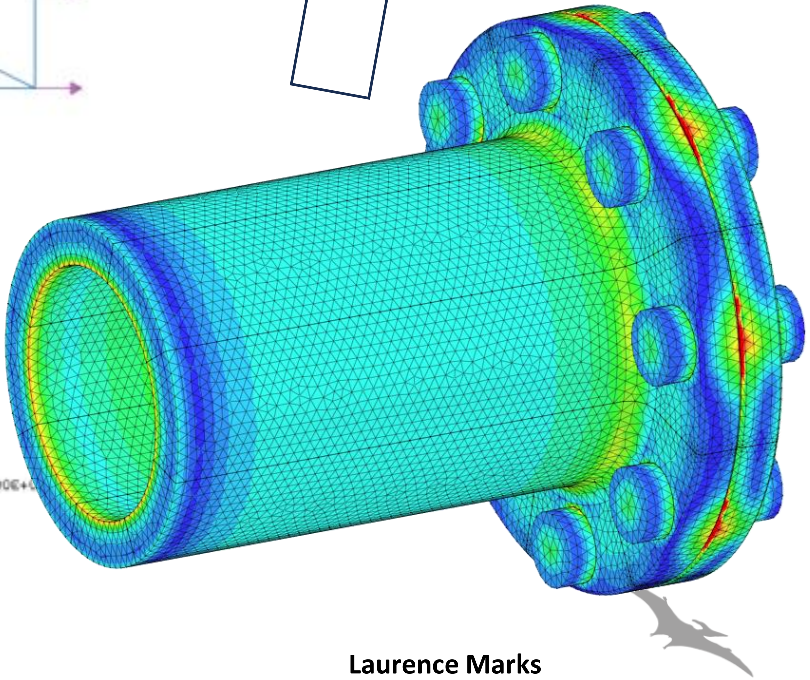

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S Y S T E M   S T I F F N E S S   M A T R I X
 BLOCK NUMBER           1
 FIRST EQUATION         1
 LAST EQUATION          7

    1           1
    0.25096E+07
    2           1           2
    0.55385E+07  0.75000E+06
    3           1           3
    0.10038E+08 -0.25096E+07
    4           1           2           3           4
    0.13846E+07 -0.75000E+06 -0.13846E+07 -0.28846E+05
    5           1           2           3           4           5
    0.25096E+07  0.75000E+06 -0.25096E+07 -0.75000E+06  0.10529E+07
    6           1           2           3           4           5
    0.13846E+07 -0.28846E+05 -0.11538E+06  0.75000E+06 -0.13846E+07
    7           1           2           3           4           5
    0.25096E+07 -0.75000E+06 -0.10529E+07  0.28846E+05 -0.25096E+07  0.75000E+0

MAXIMUM DIAGONAL STIFFNESS MATRIX VALUE =  0.100385E+08 (        3)
MINIMUM DIAGONAL STIFFNESS MATRIX VALUE =  0.138462E+07 (        4)
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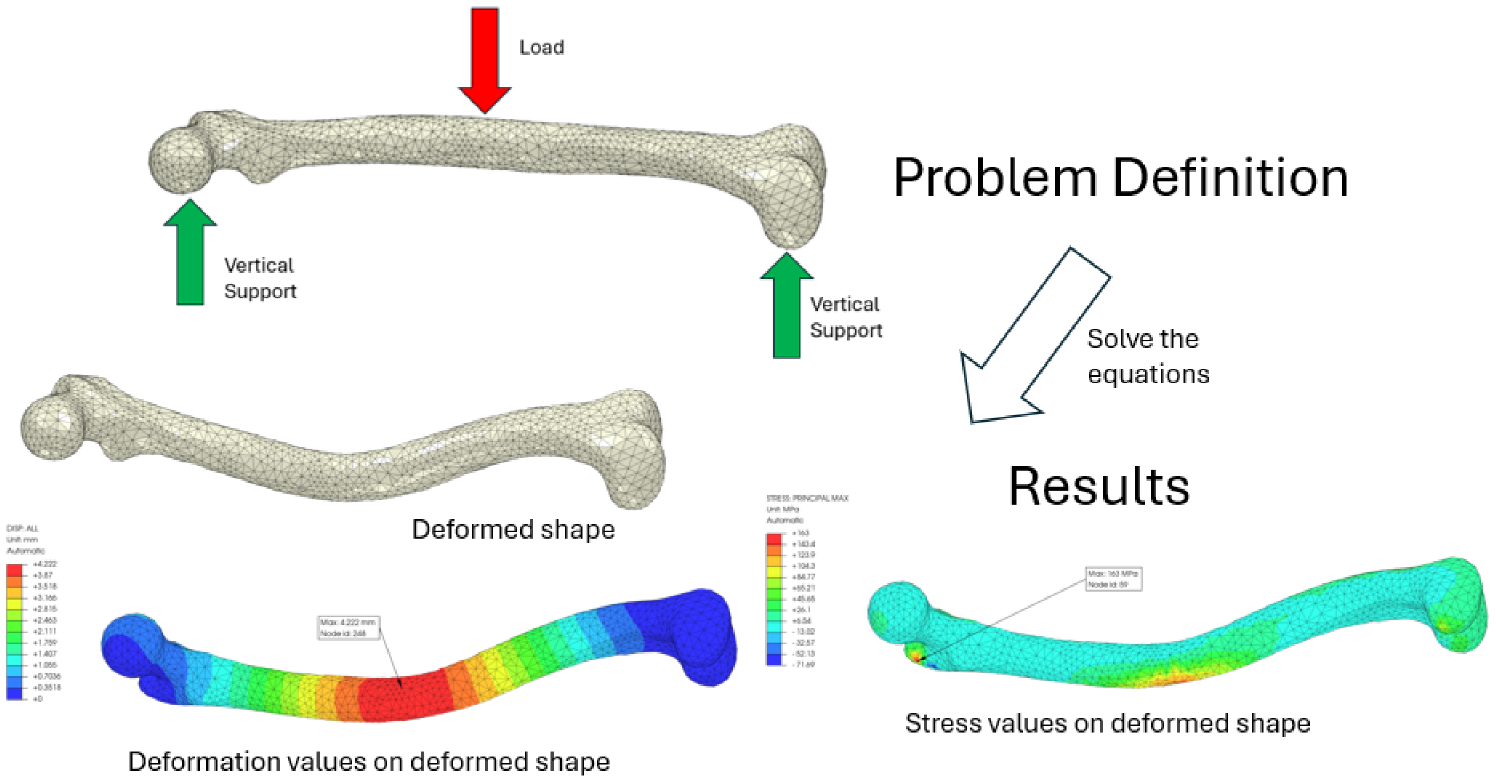
So…

- We have a methodology or process that will allow us to predict how structures react to external and internal loads in terms of deflection and stresses.
- We can apply this to traditional engineering components as well as biomechanical systems.
- If we mix traditional engineering components and biomechanical systems we can evaluate the effectiveness of designs and surgical interventions to a useful degree.



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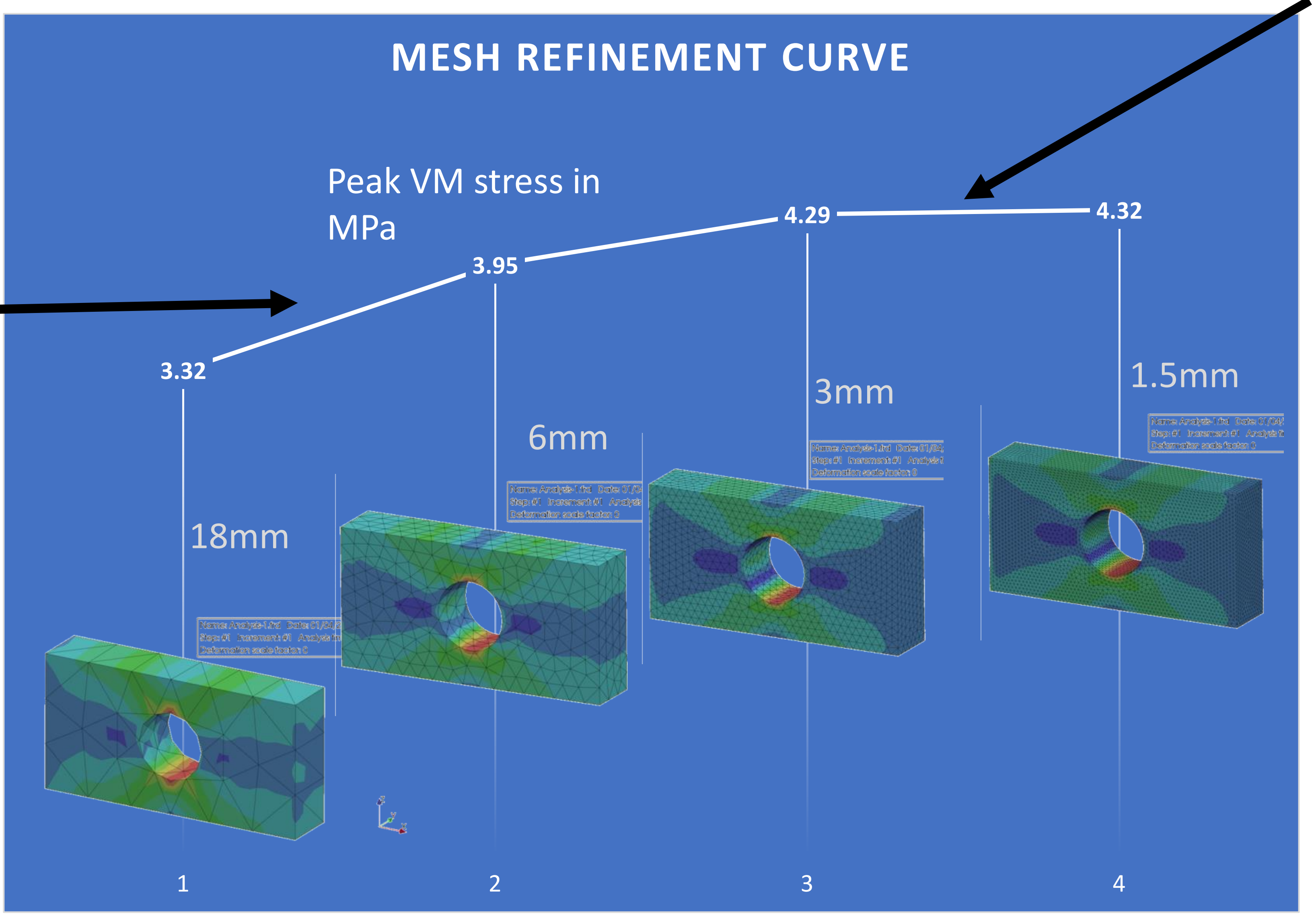
Mesh convergence

Here changes of element size change the answer

Here changes of element size don't change the answer



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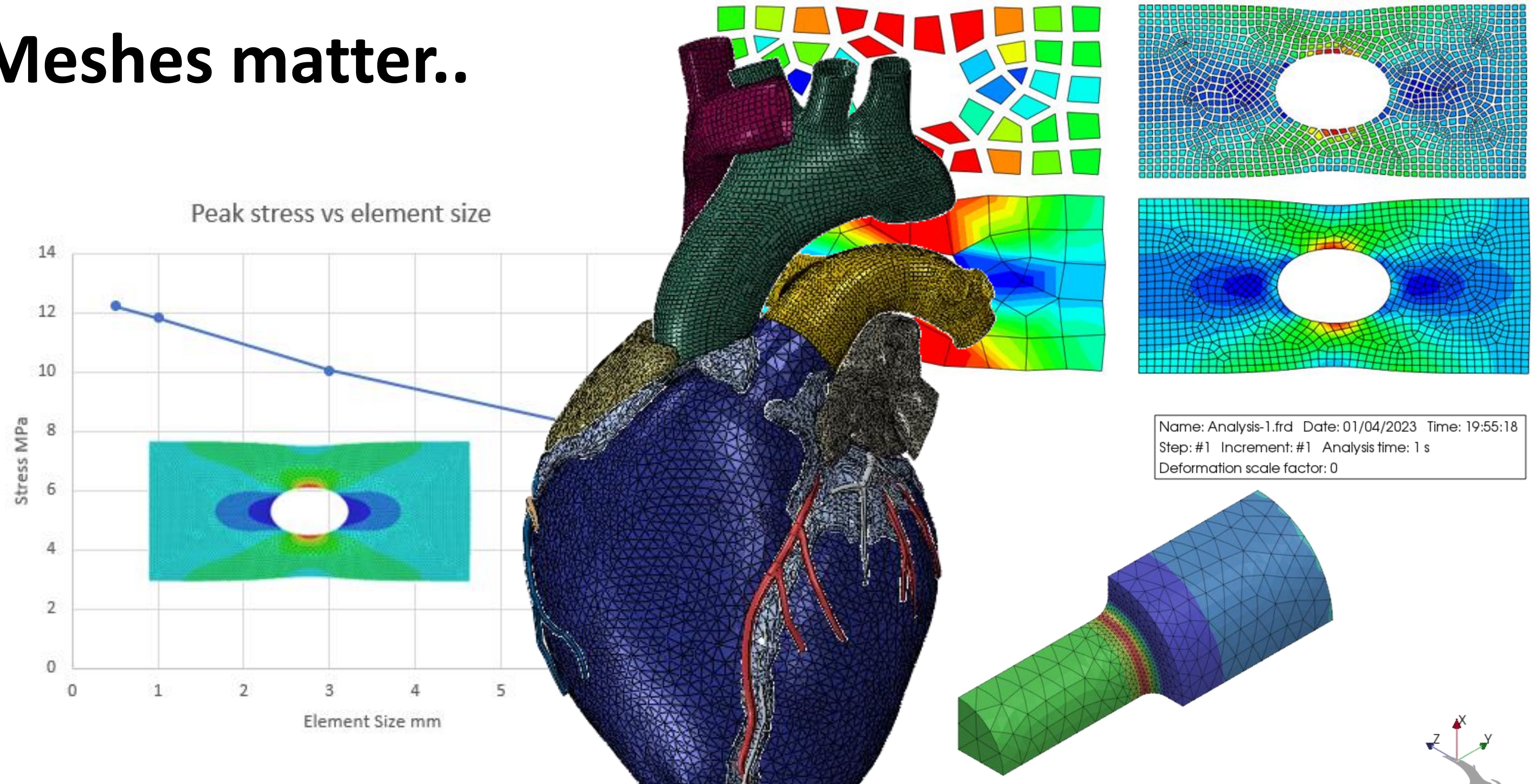
Meshes matter..



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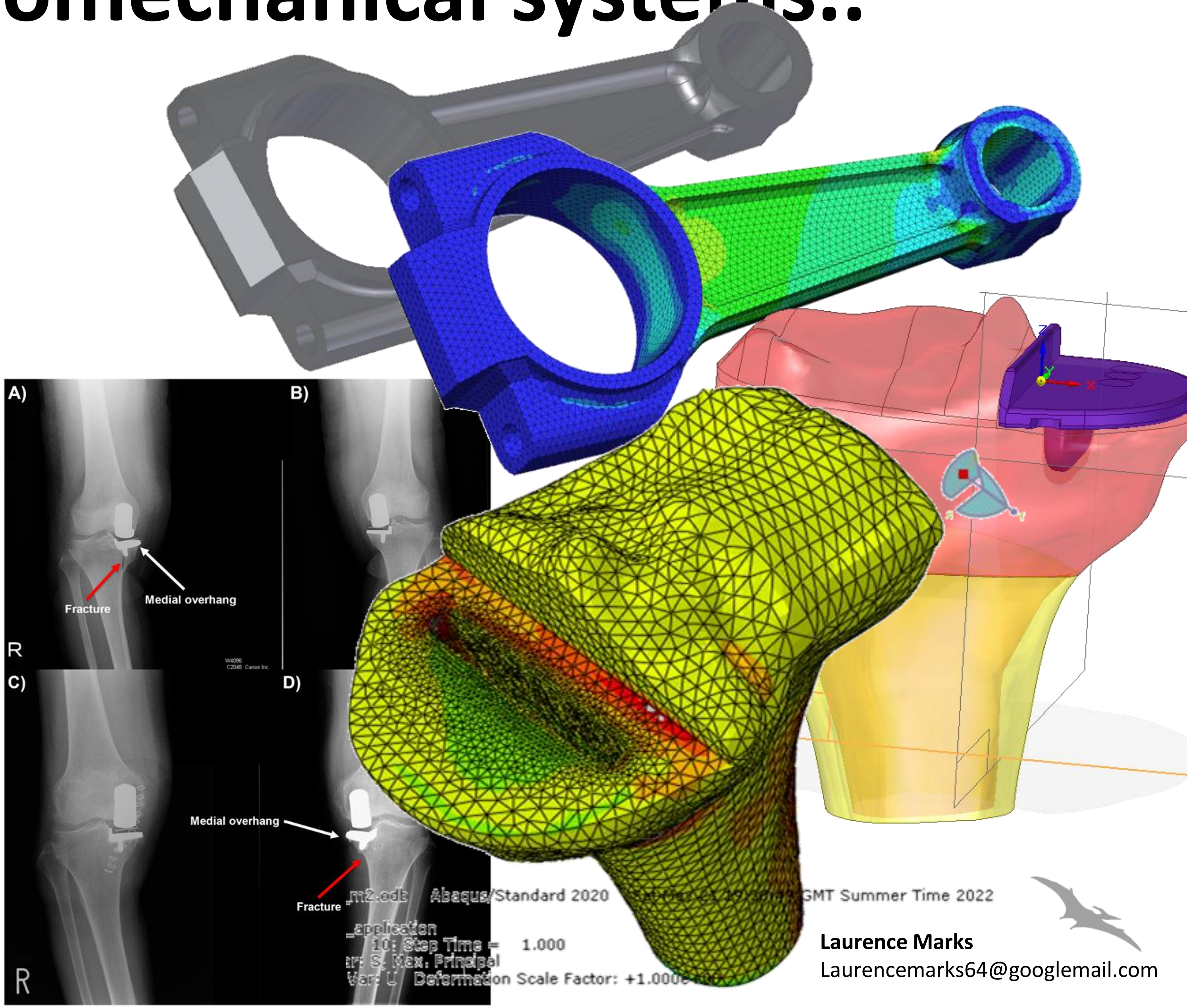
Creating meshes of biomechanical systems..

- Biomechanical systems present problems with mesh definition that don't happen with "engineering components"
- And mesh definition isn't trivial with engineering components..
- Scan to mesh technologies such as "Simpleware" automate the process of creating meshes from medical images
- We can also use more traditional CAD geometry approaches



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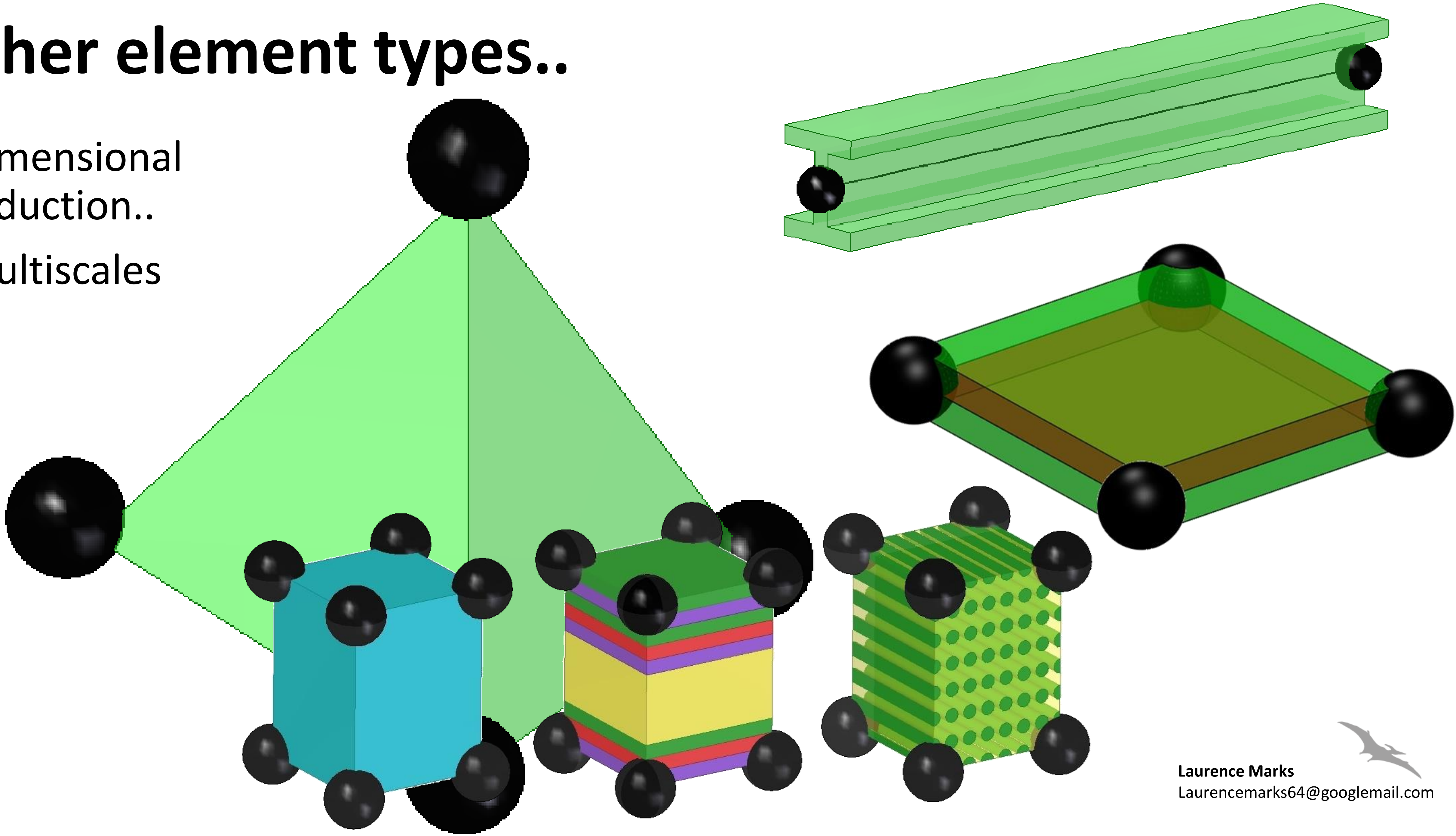
Other element types..

- Dimensional reduction..
- Multiscales



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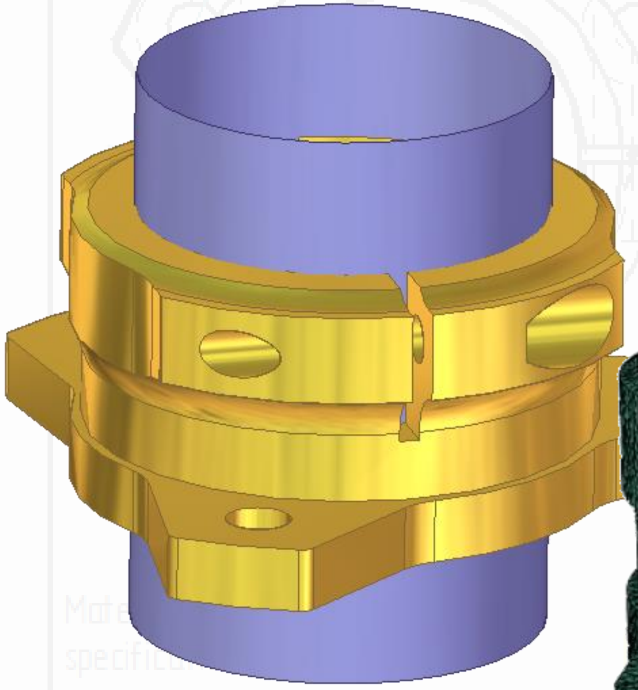
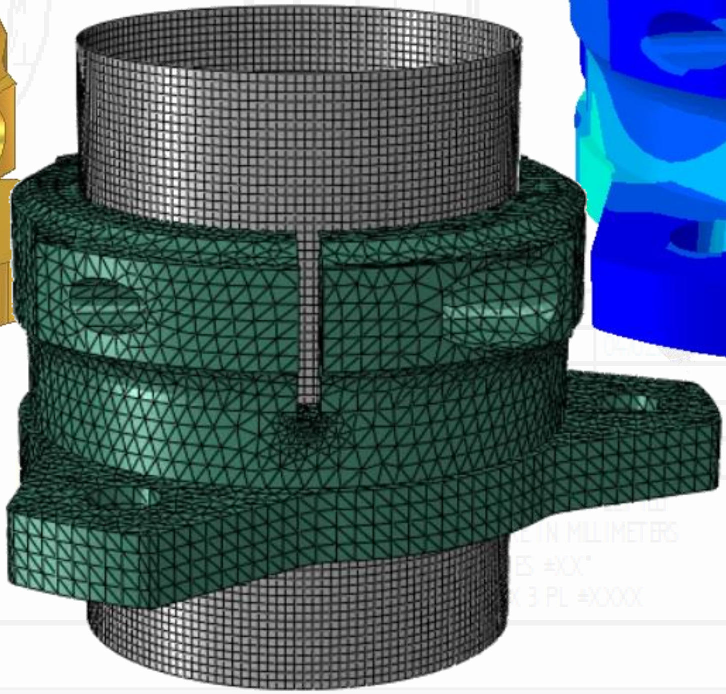
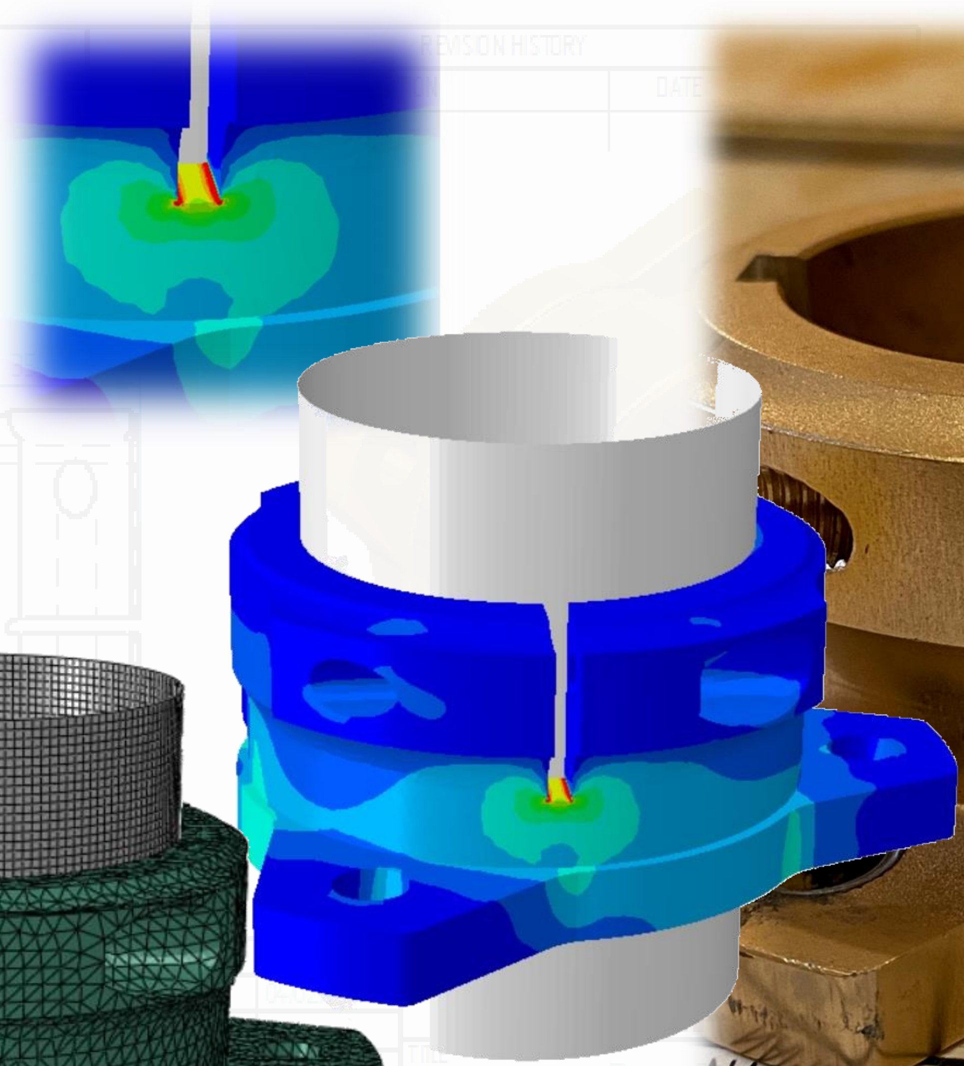
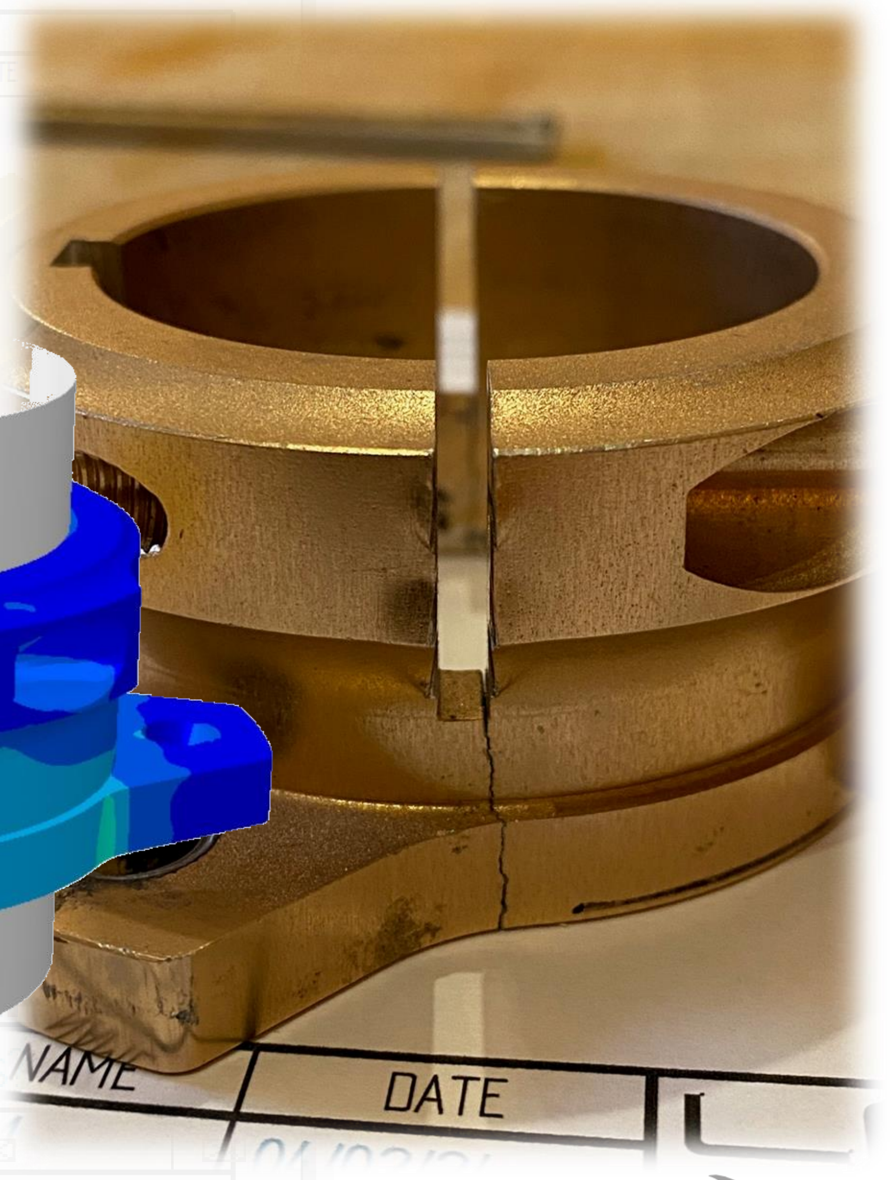
Sharp Corners

Sharp corners are challenging from a stress calculation point of view and are very bad from a durability point of view. Which this Karting disc carrier example shows very well.









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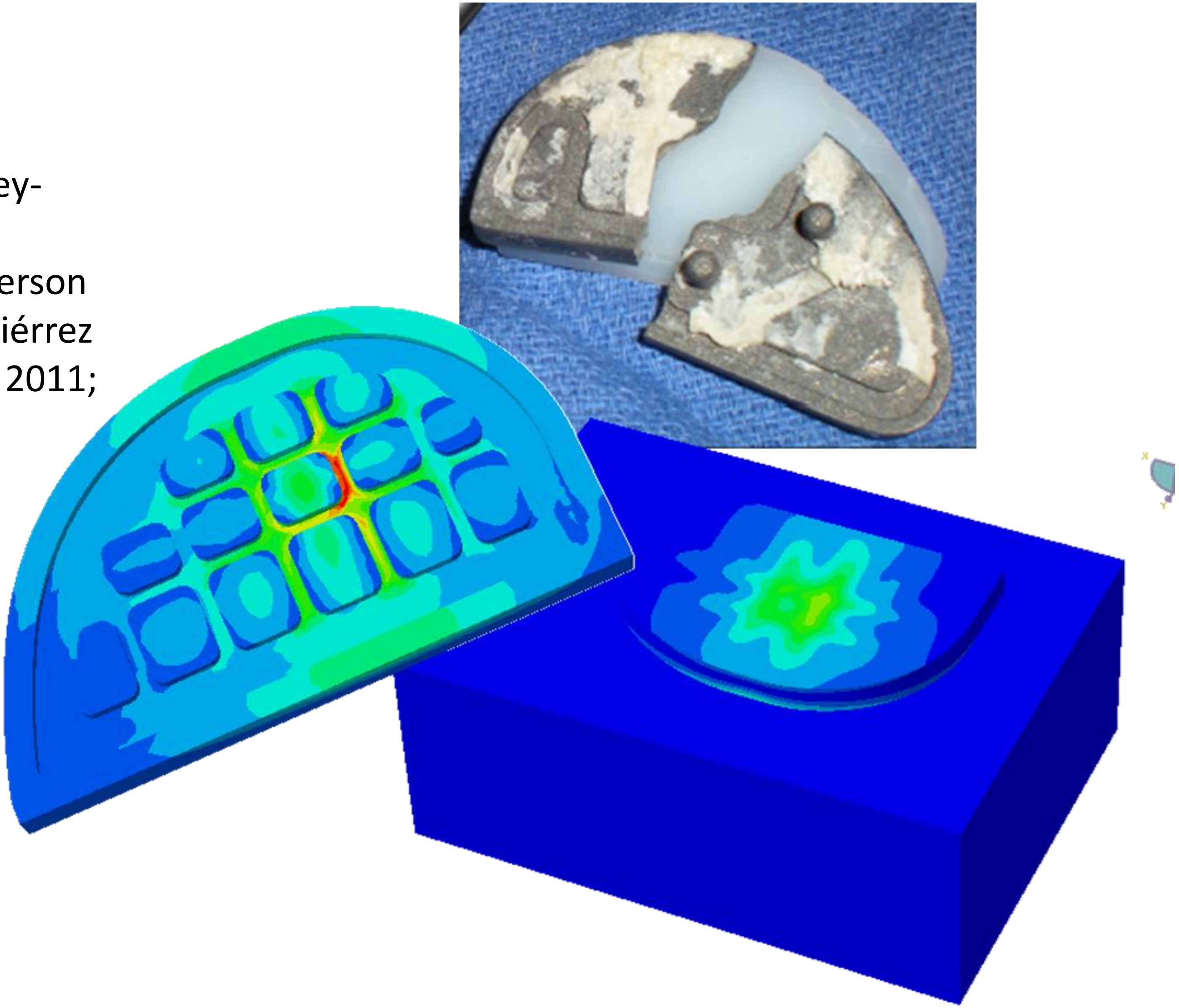
Nobody would do that in an implant…

- Really..

Initial experience of the Journey-Deuce bicompartmental knee prosthesis. Palumbo BT, Henderson ER, Edwards PK, Burris RB, Gutiérrez S, Raterman SJ. *J Arthroplasty* 2011; 26 (6) Suppl 1: 40-45.



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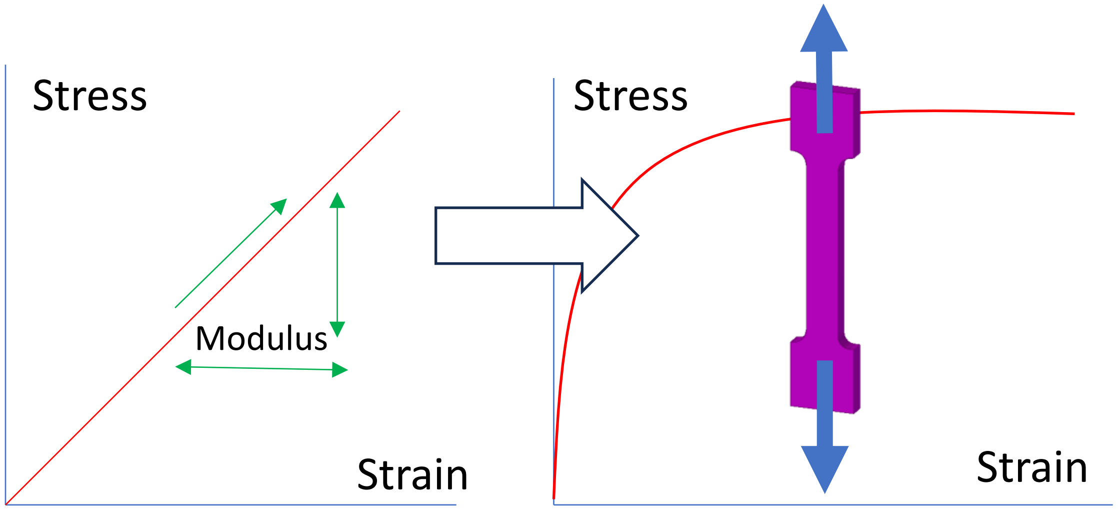
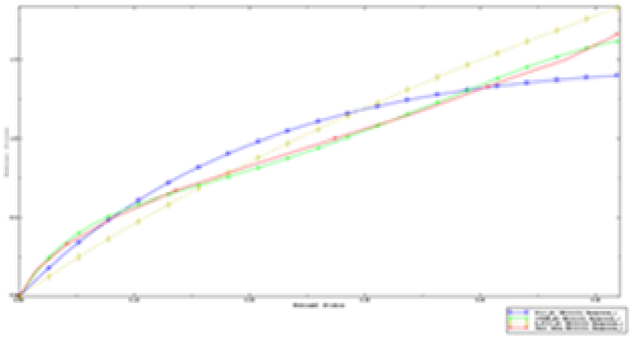
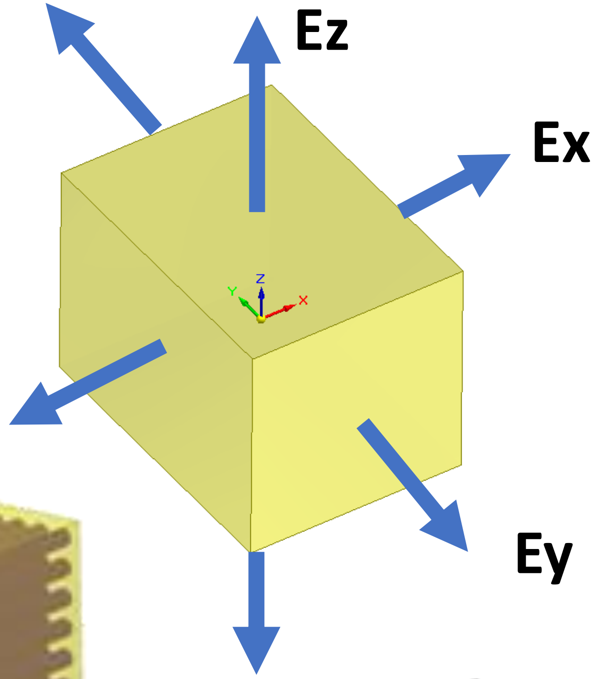
Modelling Biomaterials

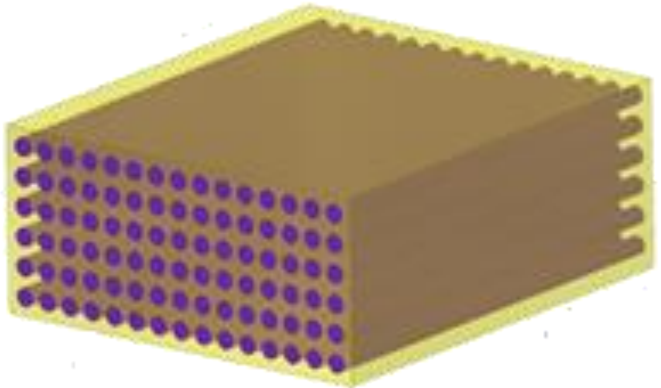
- Often we treat materials as linear elastic
- But materials can be..
  - **Non-linear** – properties are a function of stress level
  - **Anisotropic** – properties are a function of direction
  - **Non-heterogeneous** – properties are a function of spatial position
  - **Rate dependent** – properties are a function of loading speed
  - **Hyper-elastic** – properties are a function of strain energy density..

- And biomaterials are generally most or all of the above..









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Modelling Biomaterials - Bone

- We have properties which vary by position – cancellous vs cortical
- FEA models often use mappings taken from scans. Image density>material properties

A mechano-chemo-biological model for bone remodeling with a new mechano-chemo-transduction approach

December 2020 · Biomechanics and Modeling in Mechanobiology
DOI:10.1007/s10237-020-01353-0

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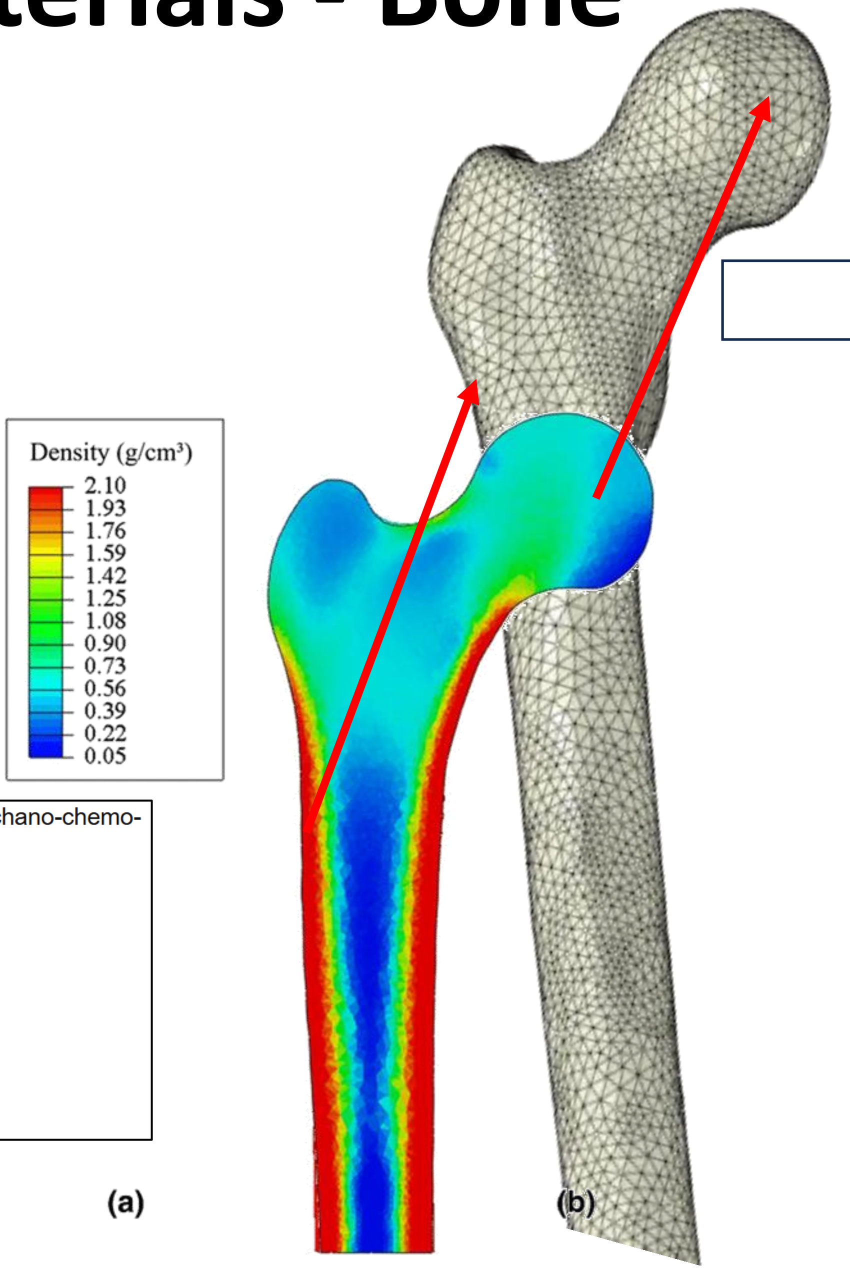
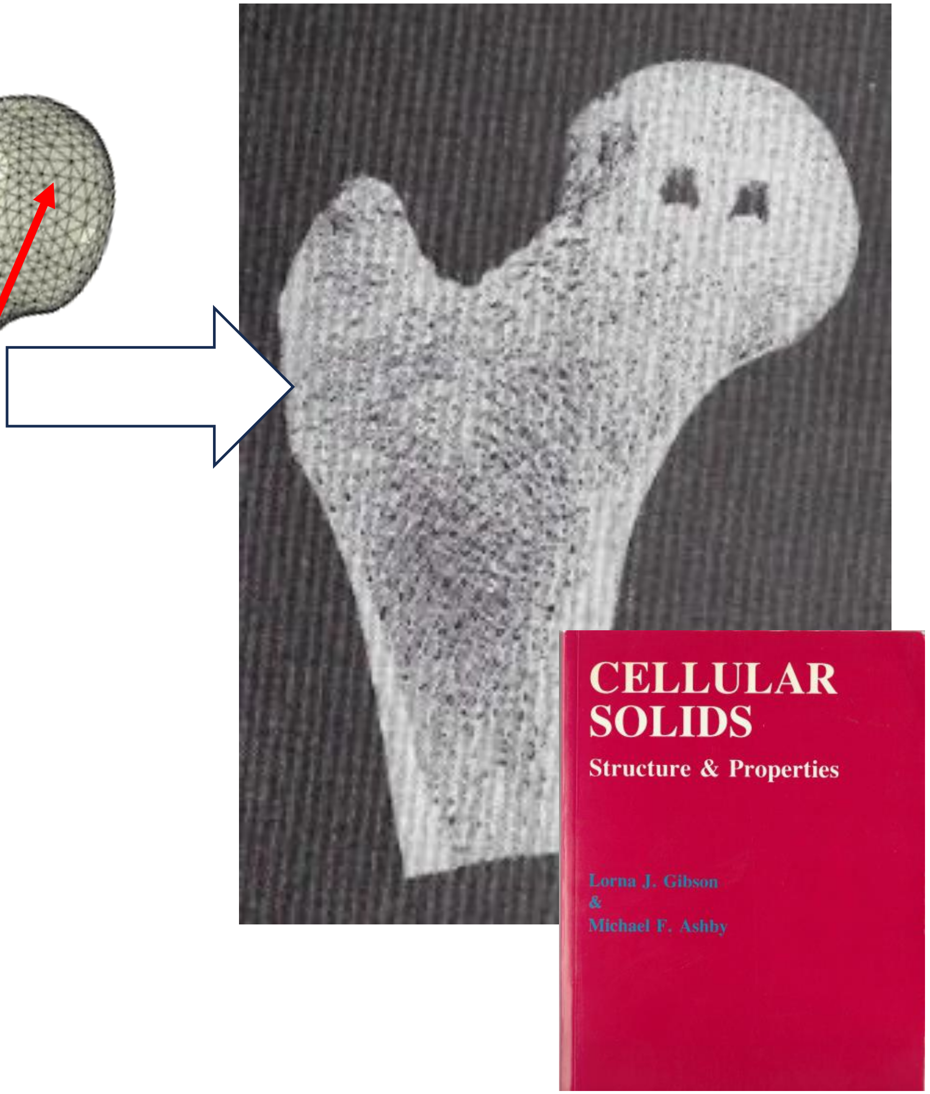
Jucelio Tomás Pereira, Federal University of Paraná
Farzan Gahlichi





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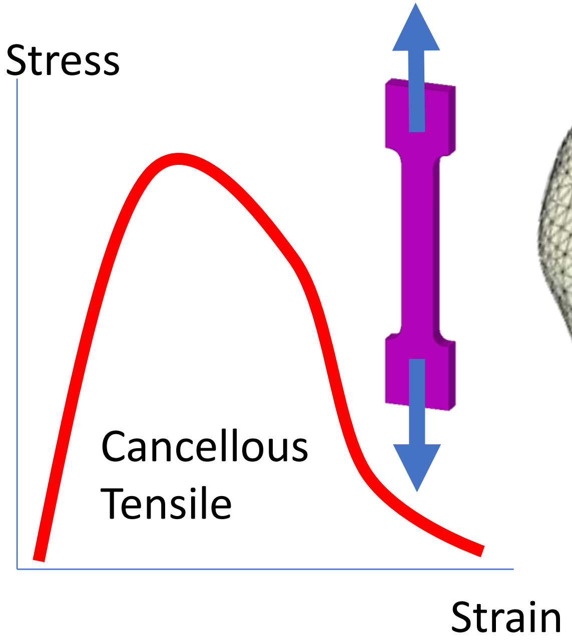
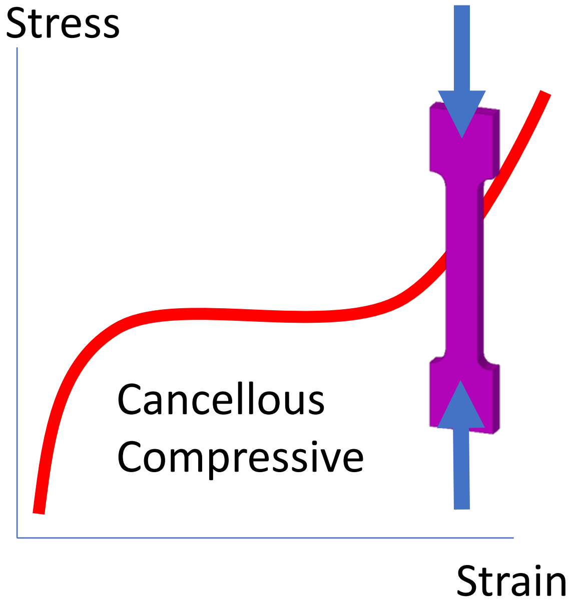
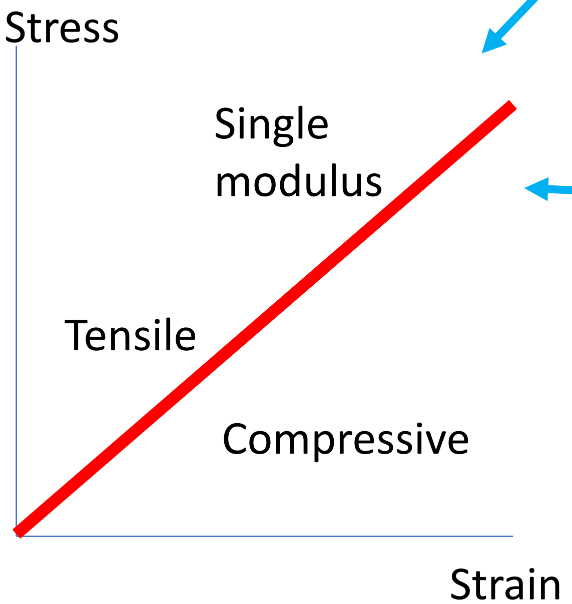
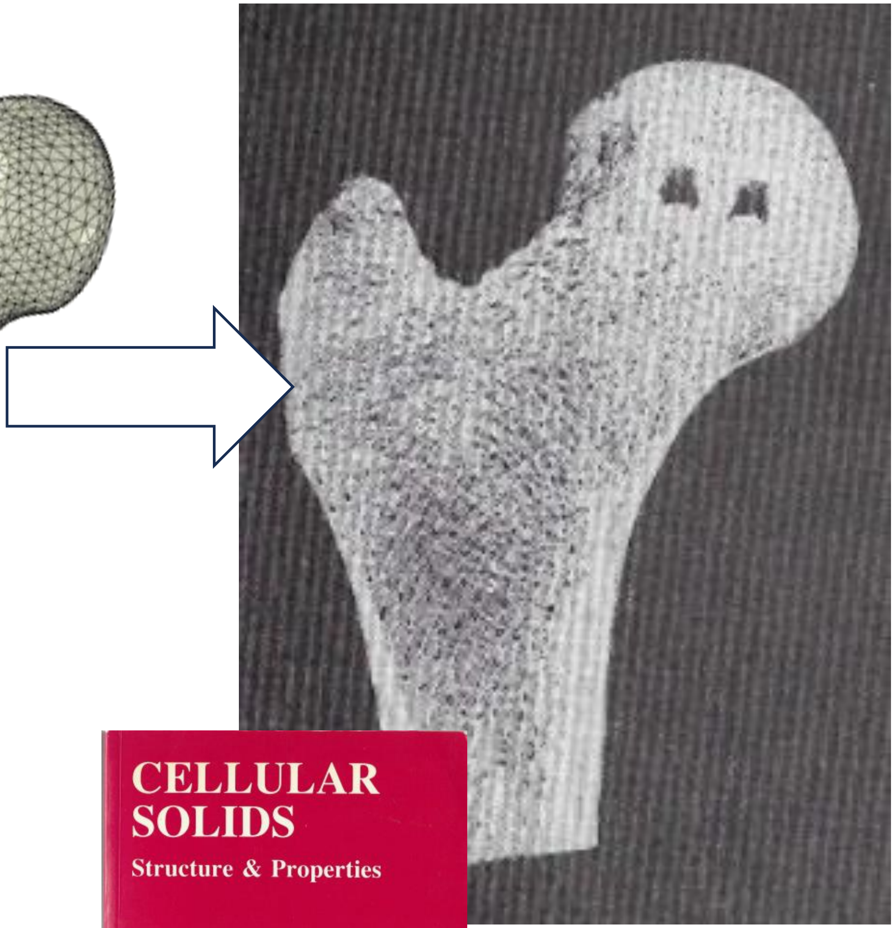
Modelling Biomaterials - Bone

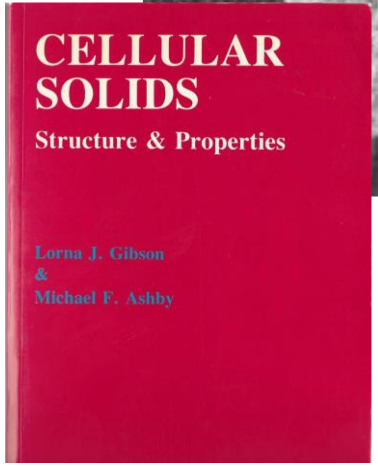
- We have properties which vary by position and we have non-linearity
- In most studies spatially varying linear properties are used.











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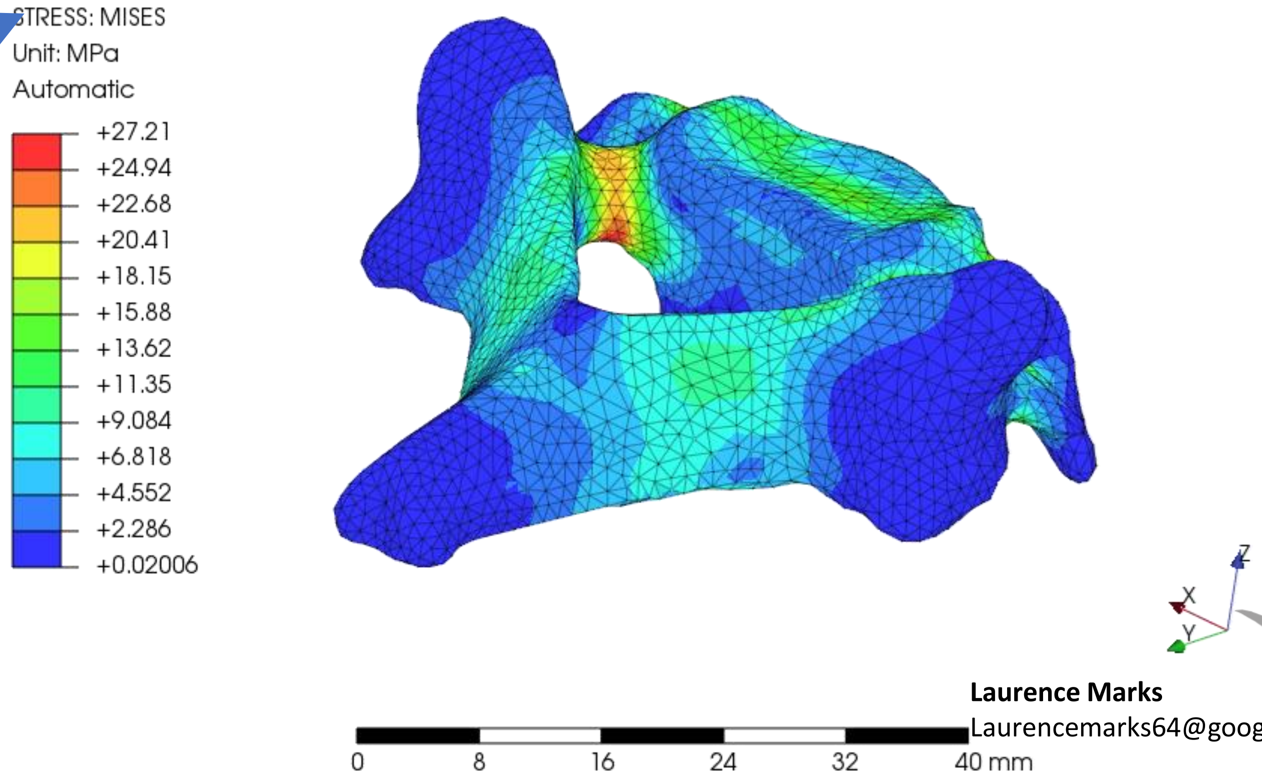
Modelling Biomaterials - Bone

- Post processing bone models.. A common mistake..

- When you plot results plot something that's relevant to the material of interest…

Von Mises stress is a stress combination used to establish if a metal has yielded. Never use it in assessing the state of stress in bone..



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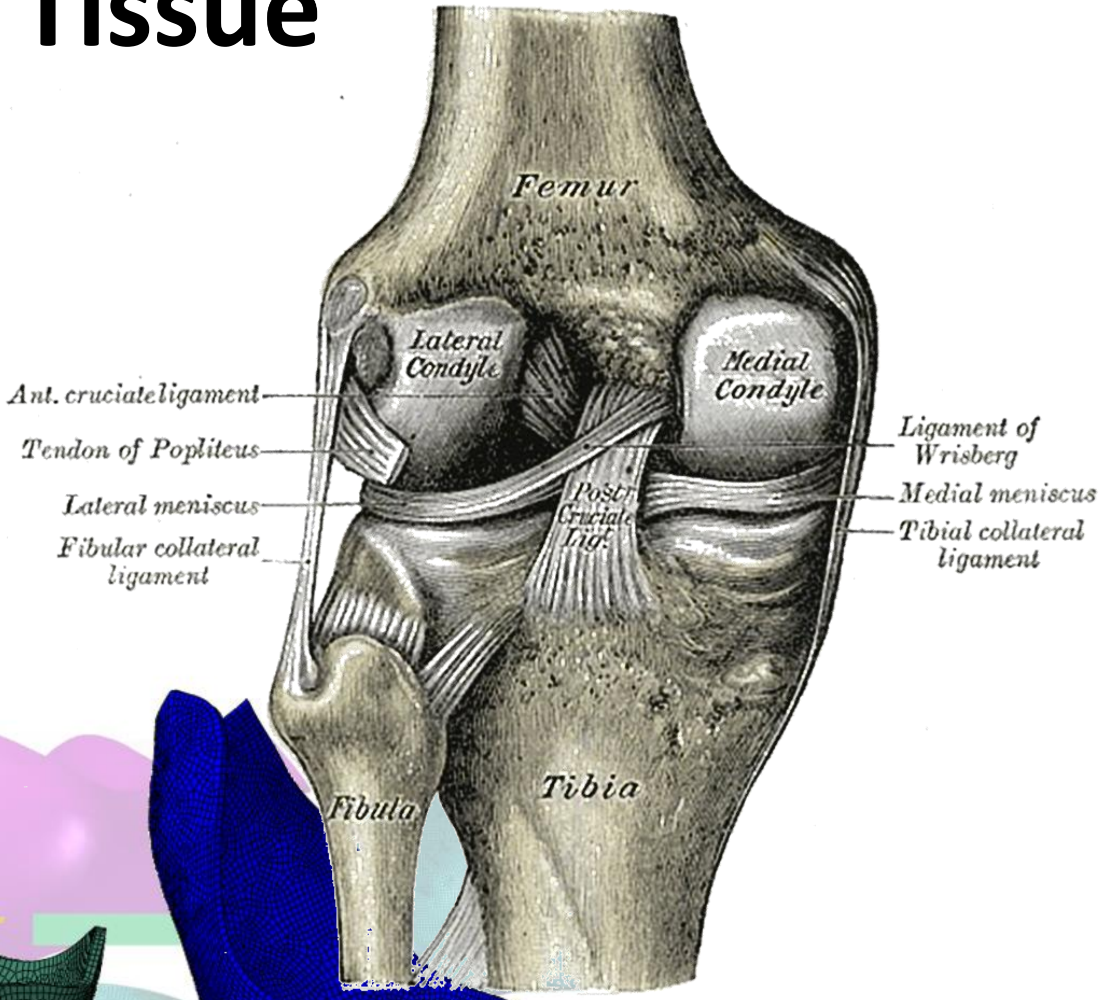
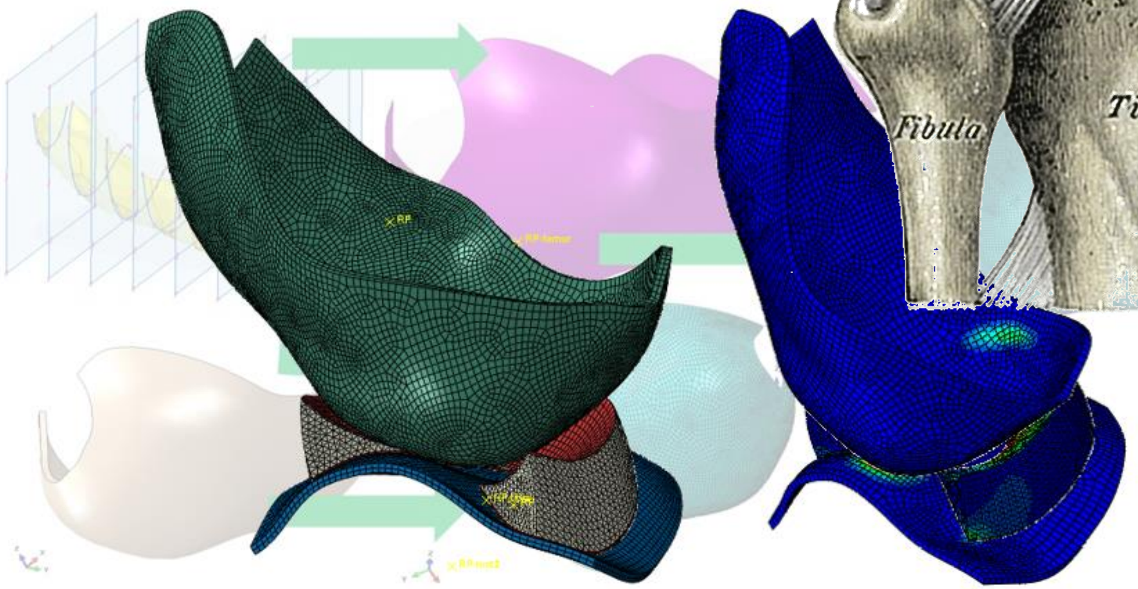
Materials/biomaterials – Soft Tissue

- Where we can obtain useful results by using simplified material responses for bone, we need to consider phenomena such as time dependency and hyperelasticity.. and possibly porosity..





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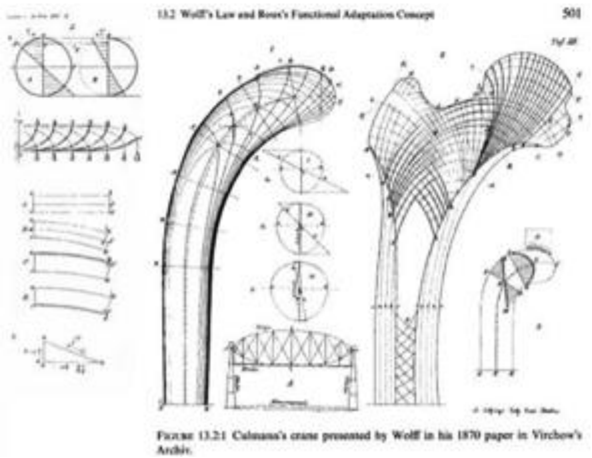
Bone remodelling



Julius Woolf

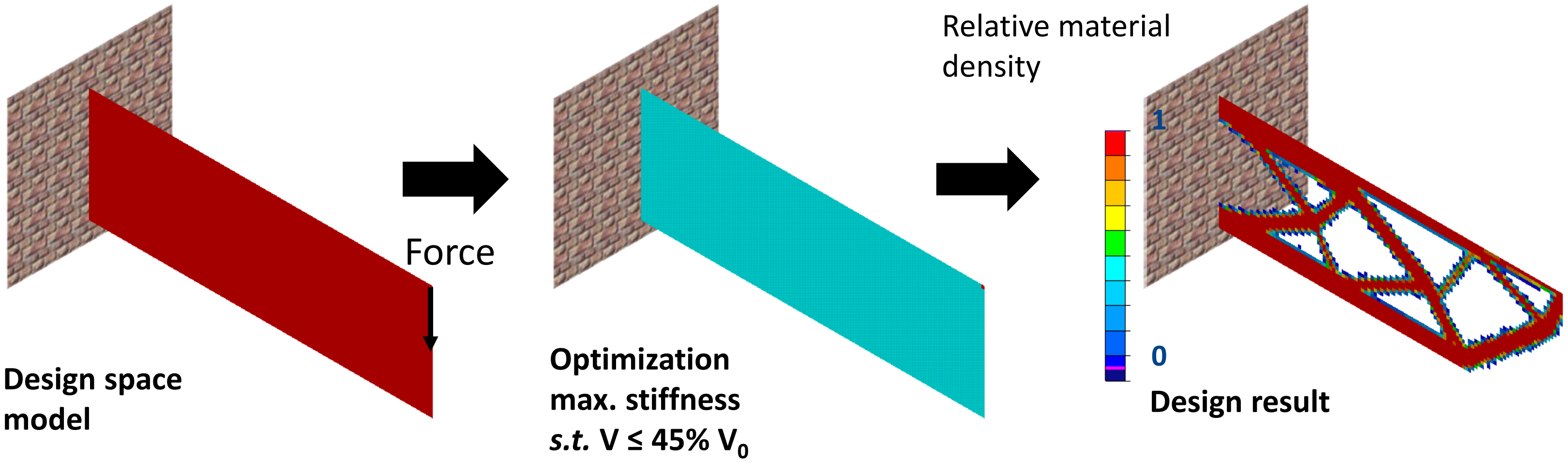
- Change density of elements within design space ("design variables / DV") considering:

Objective function
Minimize/maximize quantity

Constraints
Physical bounds

DV constraints
Manufacturing, symmetry

- Best material distribution for given optimization problem



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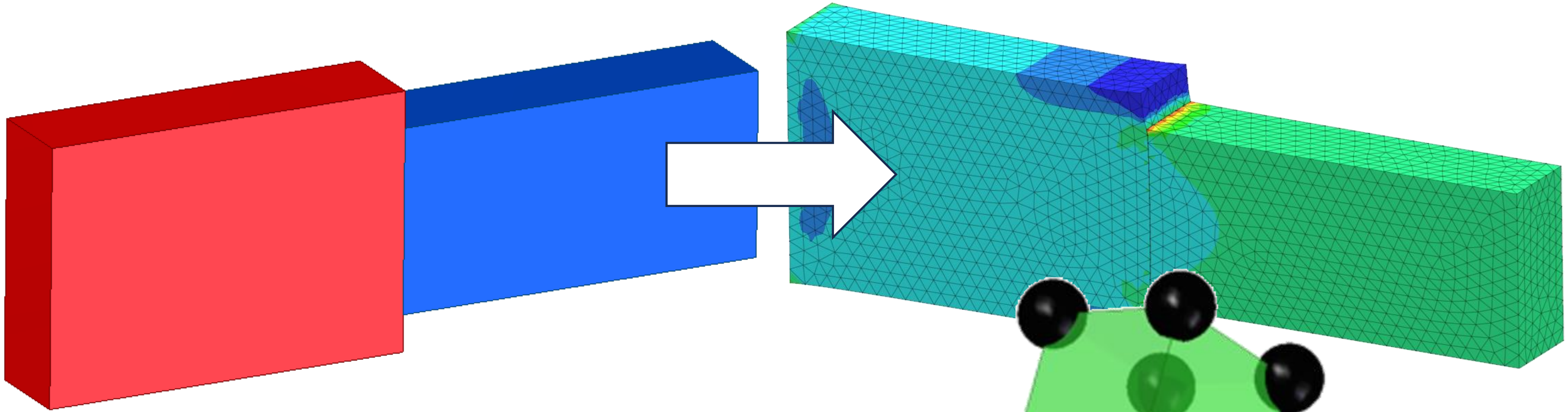
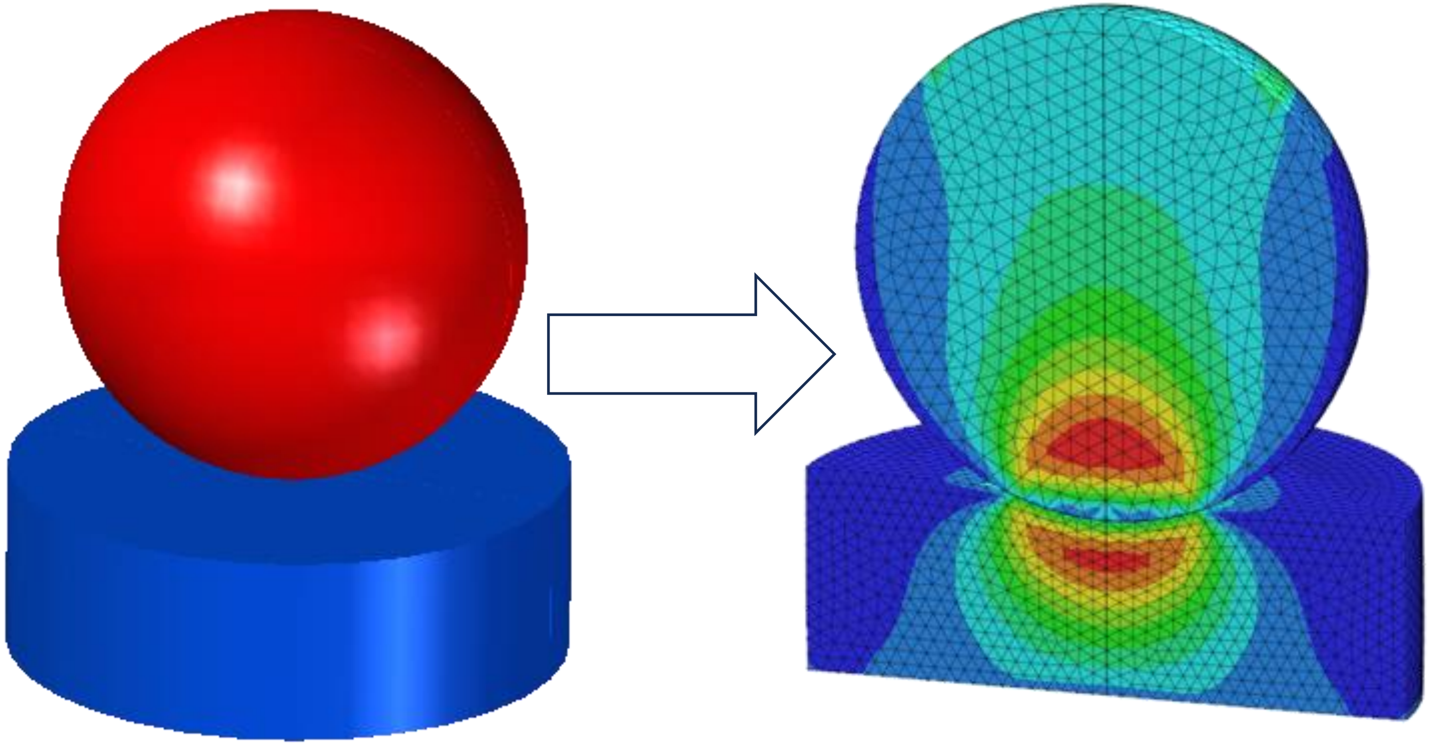
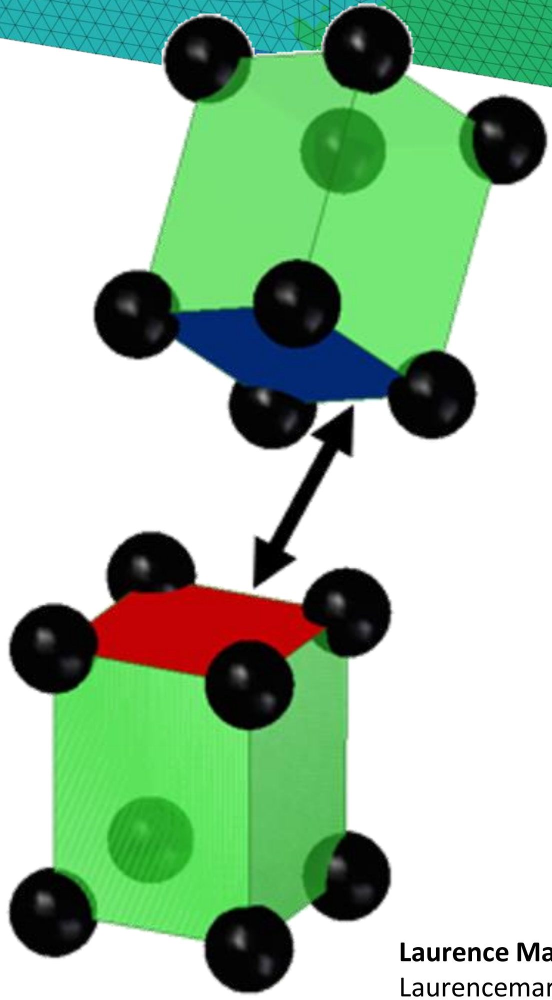
Interfaces

- How we define the interactions between parts and components.







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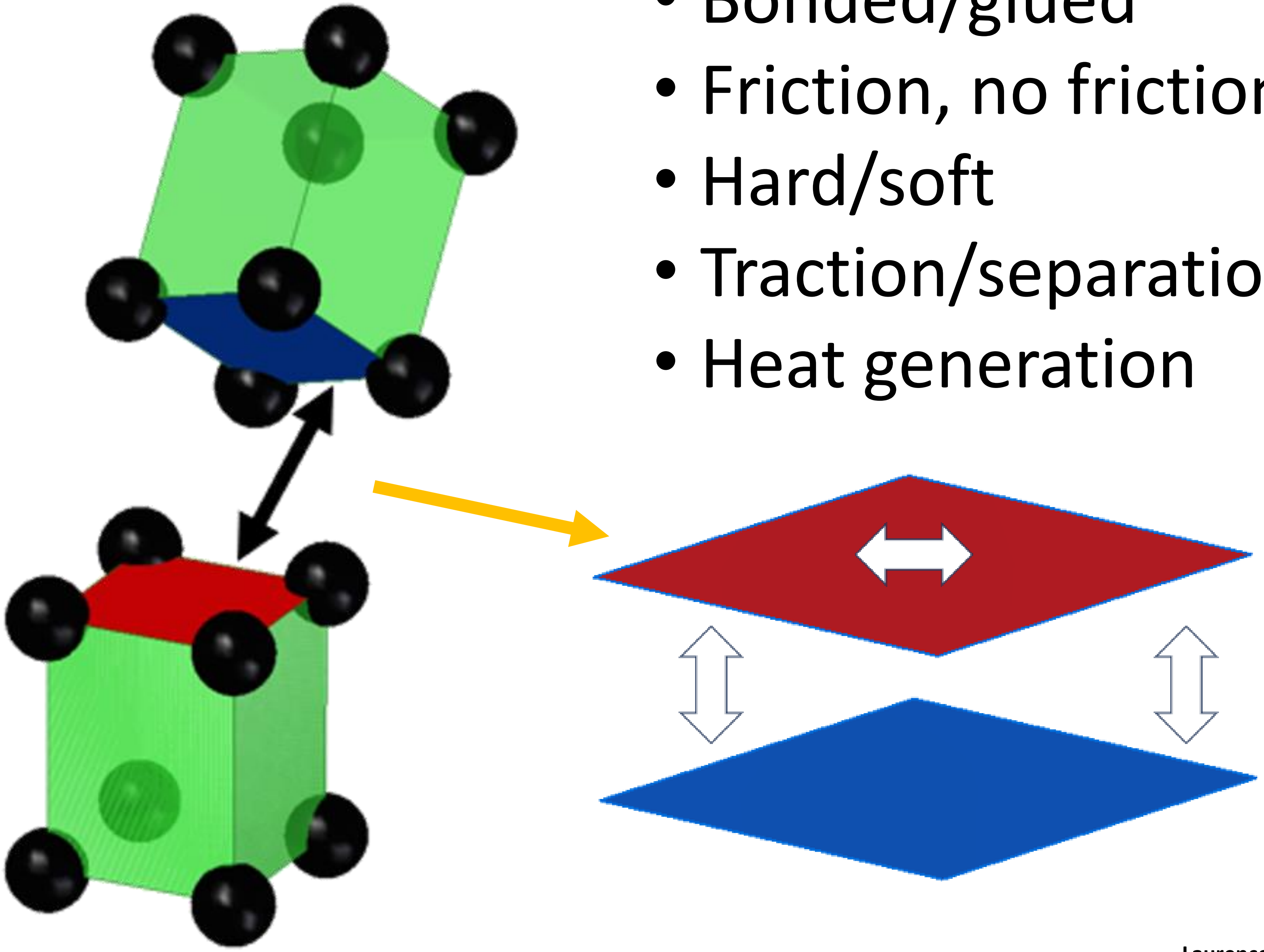
Interfaces

- How we define the interactions between parts and components.



- Bonded/glued
- Friction, no friction
- Hard/soft
- Traction/separation
- Heat generation

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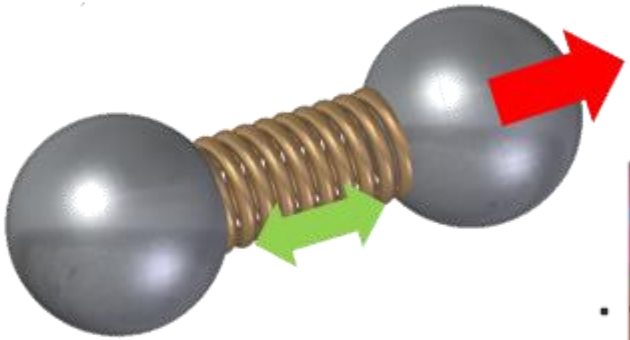
Explicit solutions and dynamics

- Sometimes the main event is dynamics – where kinetic energy dominates (or at least is a significant part of) the picture
- We can use a special type of solver for this sort of problem.
- These are widely employed in vehicle crash simulations. But are also used extensively in any biomechanics scenario where the event is rapid and energetic..

- You can use this technology for slow, quasi static events, with extreme care, but this should be justified carefully.



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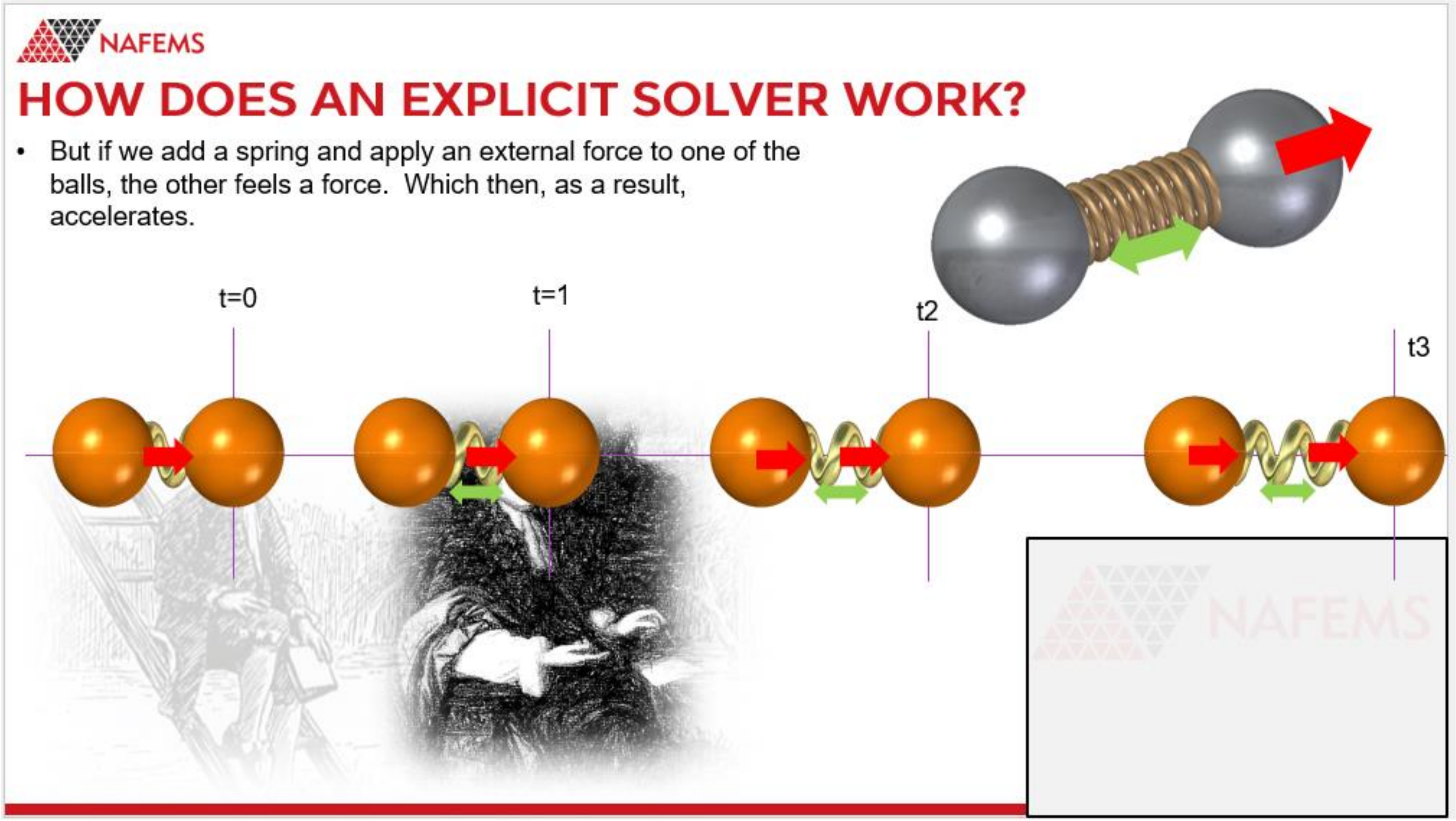
Explicit solutions and dynamics



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Explicit solutions and dynamics

NAFEMS

HOW DOES AN EXPLICIT SOLVER WORK?

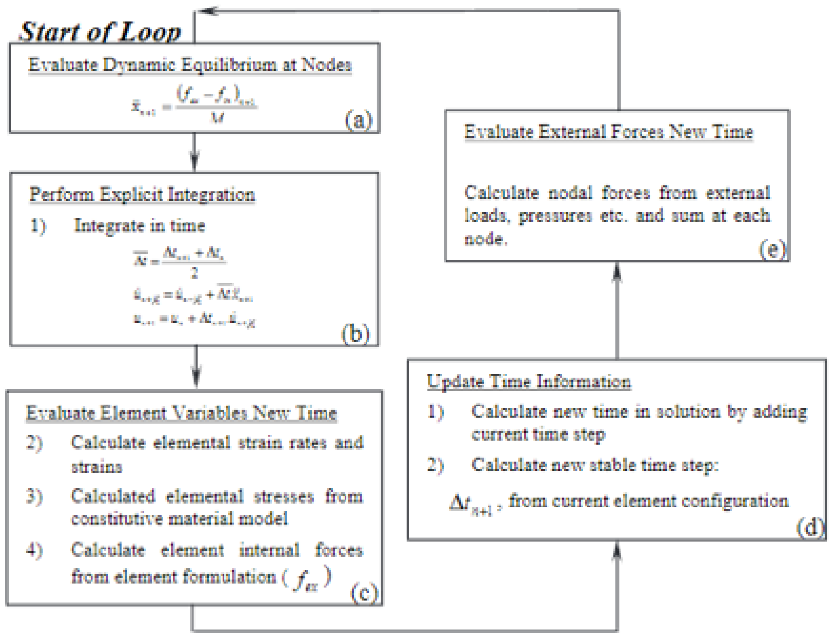
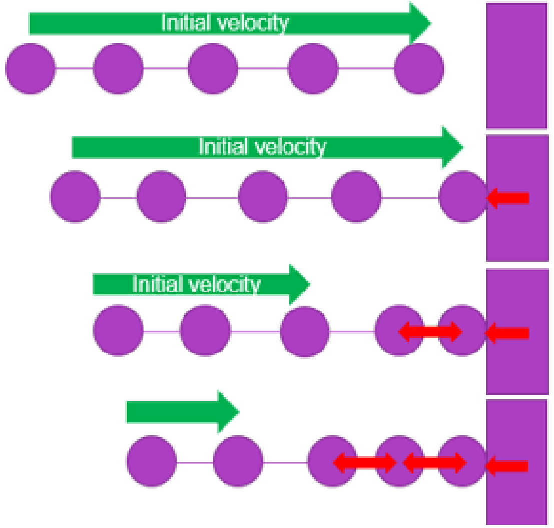


Figure 2.04: Basic Explicit Time Integration Loop



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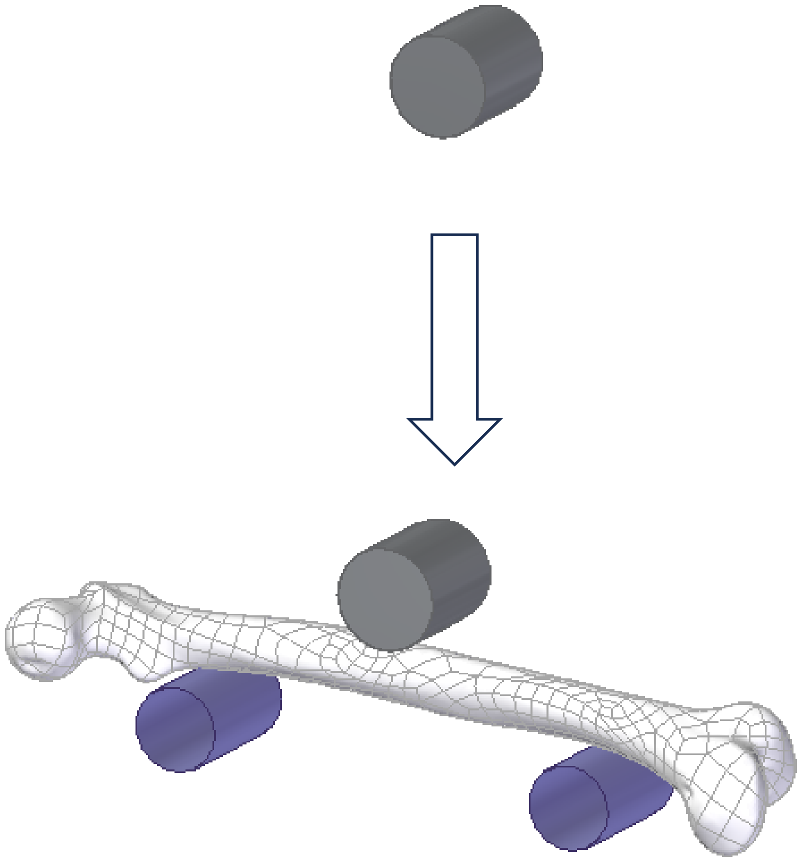
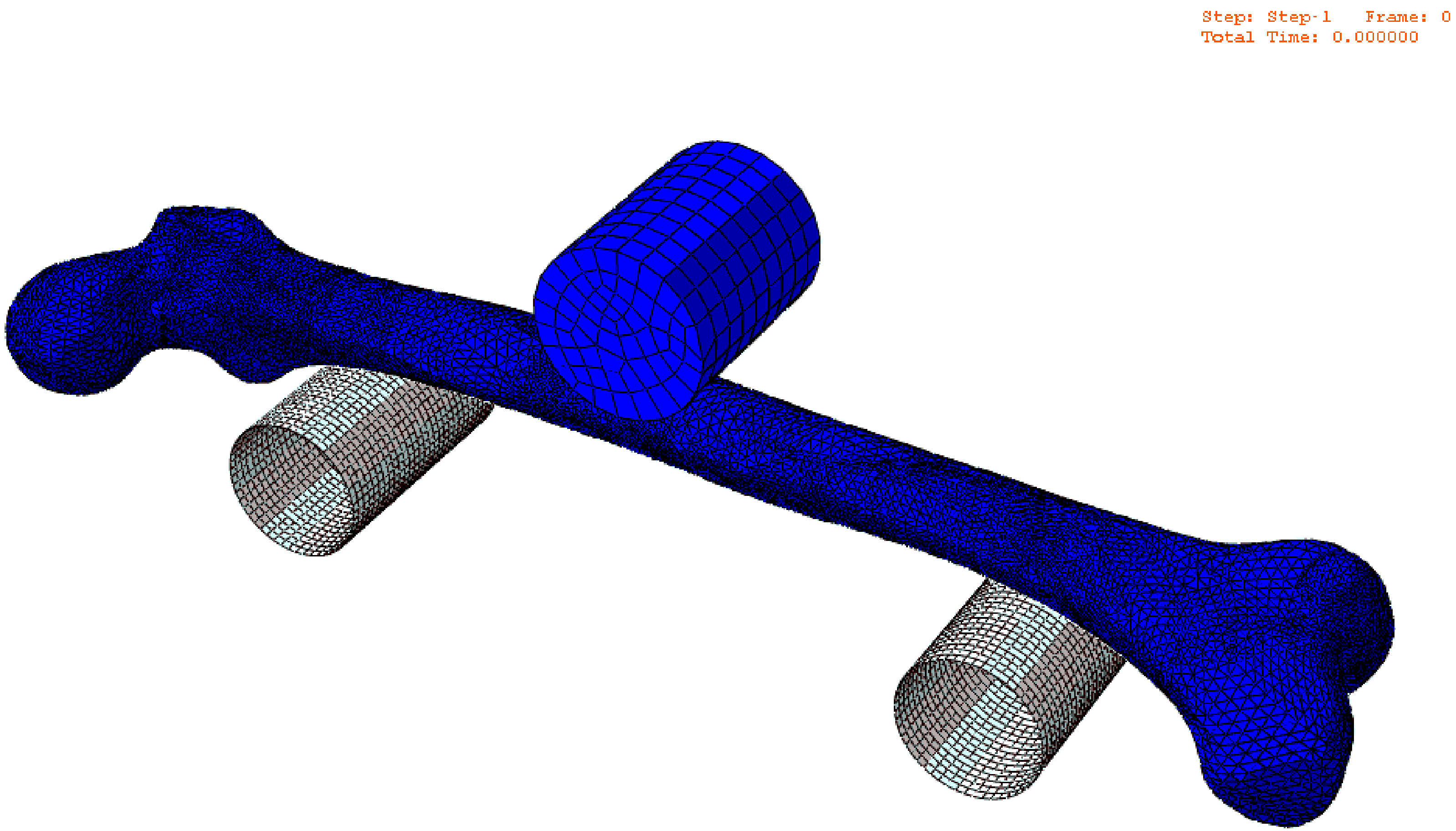
Explicit solutions and dynamics





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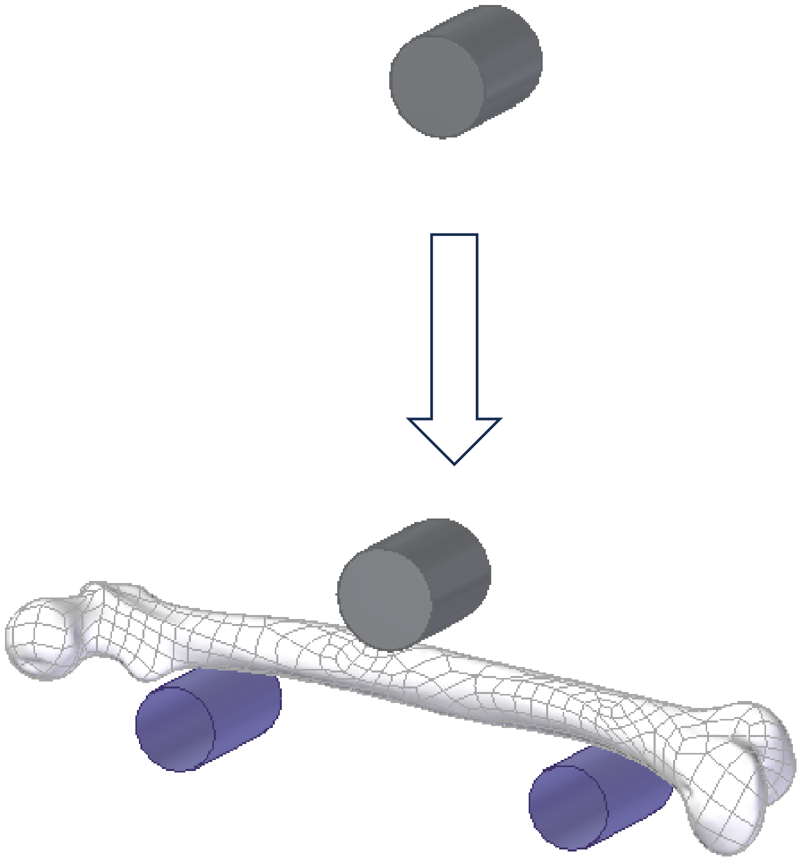
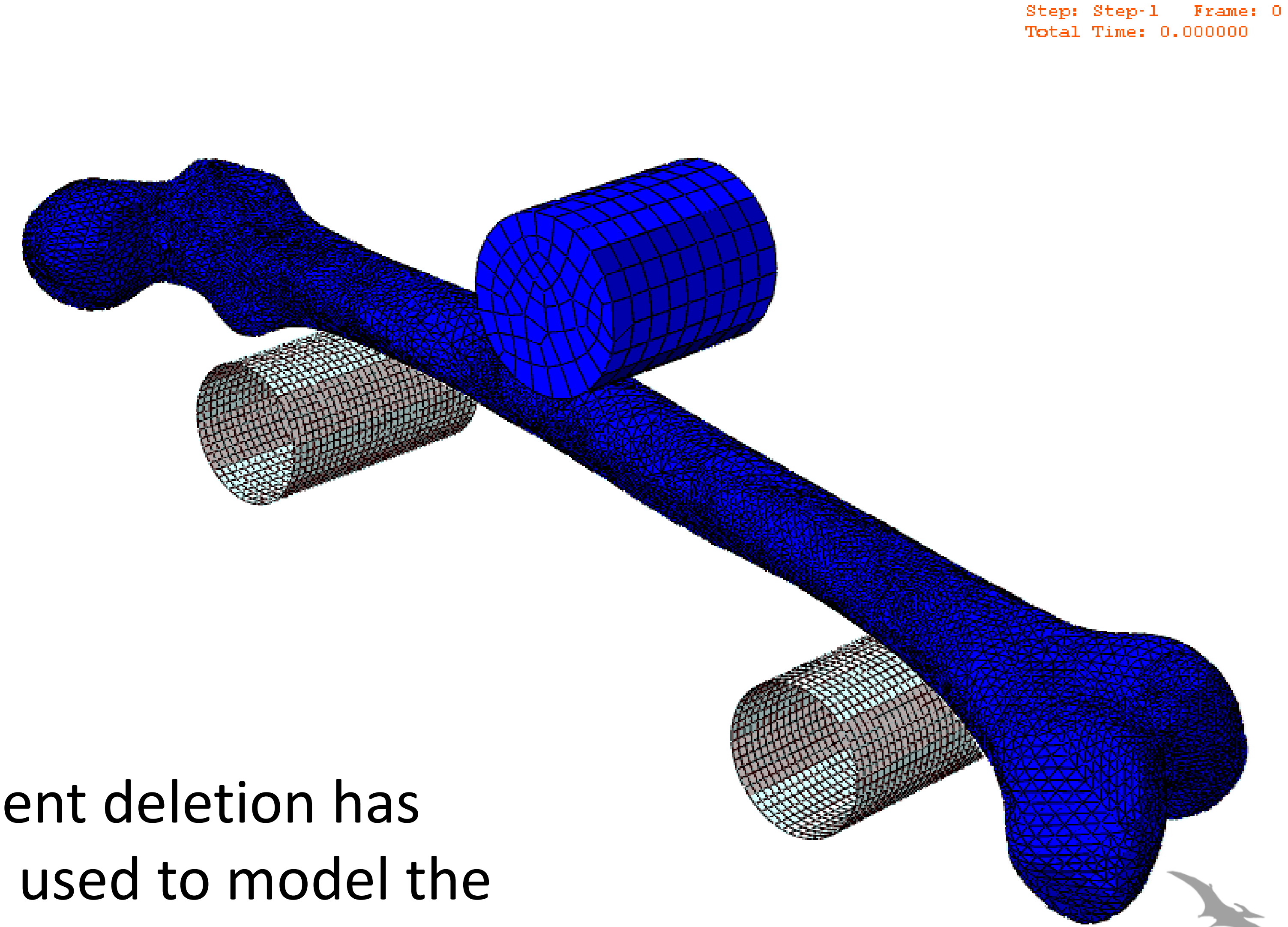
Explicit solutions and dynamics





Element deletion has been used to model the fracture process..

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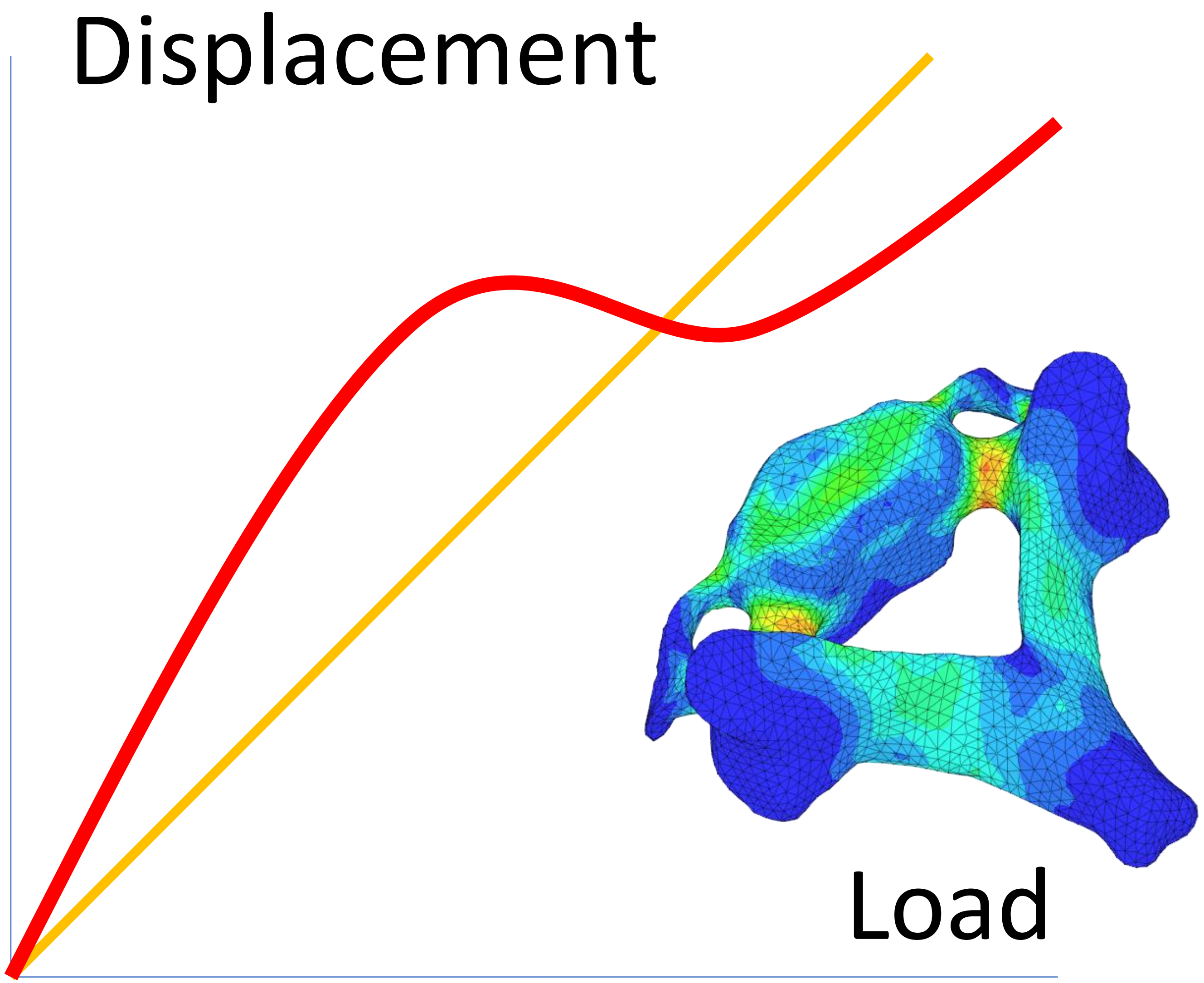
Non-linearity

- Materials
- Dynamics
- Contact
- Large displacements



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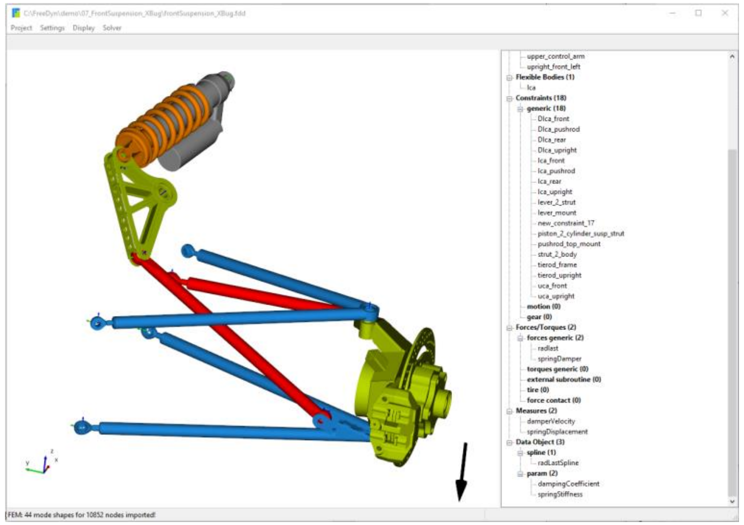
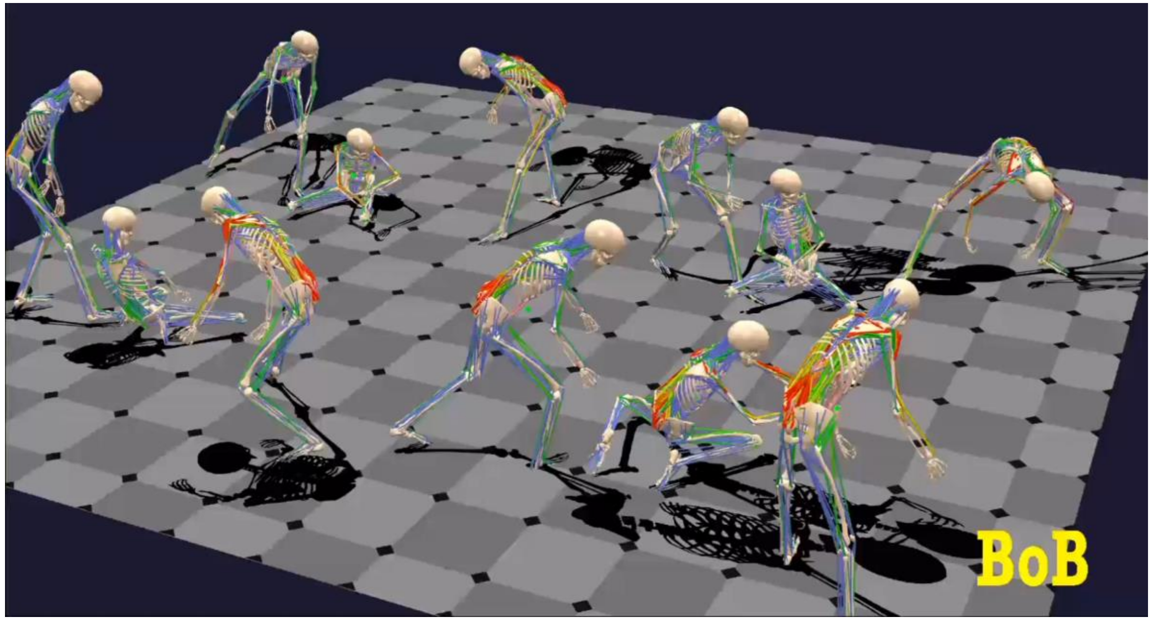
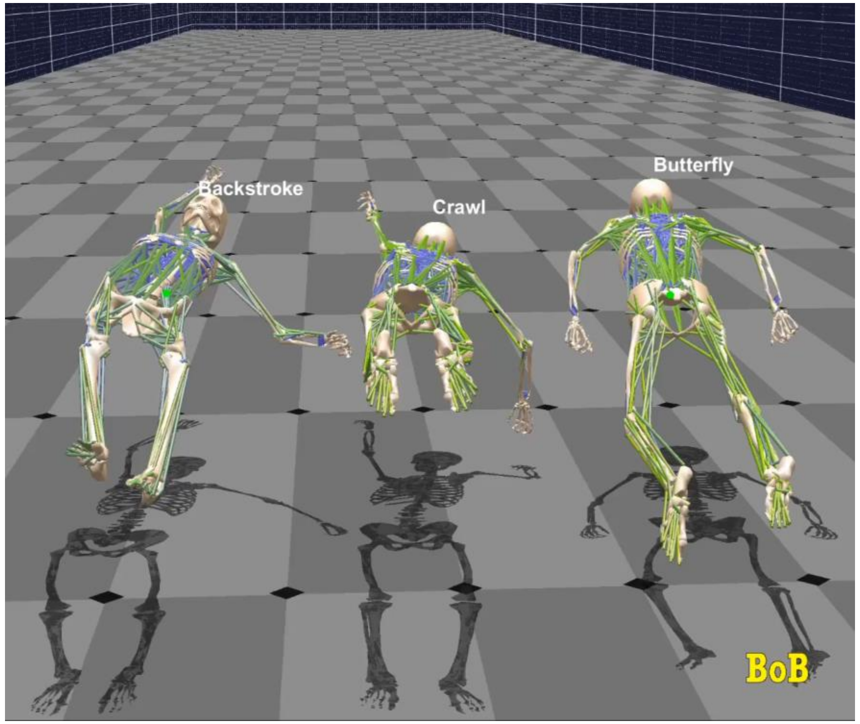
Multi-body Dynamics..

Key aspects of multibody dynamics

- **Systems:** MBD models systems of bodies connected by joints, such as pins or hinges.
- **Motion:** It analyzes the translational and rotational movements of these bodies under the influence of forces, torques, and constraints.
- **Rigid and flexible bodies:** Models can assume bodies are rigid, or they can include flexibility for more accurate simulations of components like chassis or landing gear.
- **Simulation:** It involves using software to solve the equations of motion over time to simulate the system's response.
- **Applications:** MBD is used across many industries, including aerospace, automotive, robotics, and biomechanics.







BoB Biomechanics

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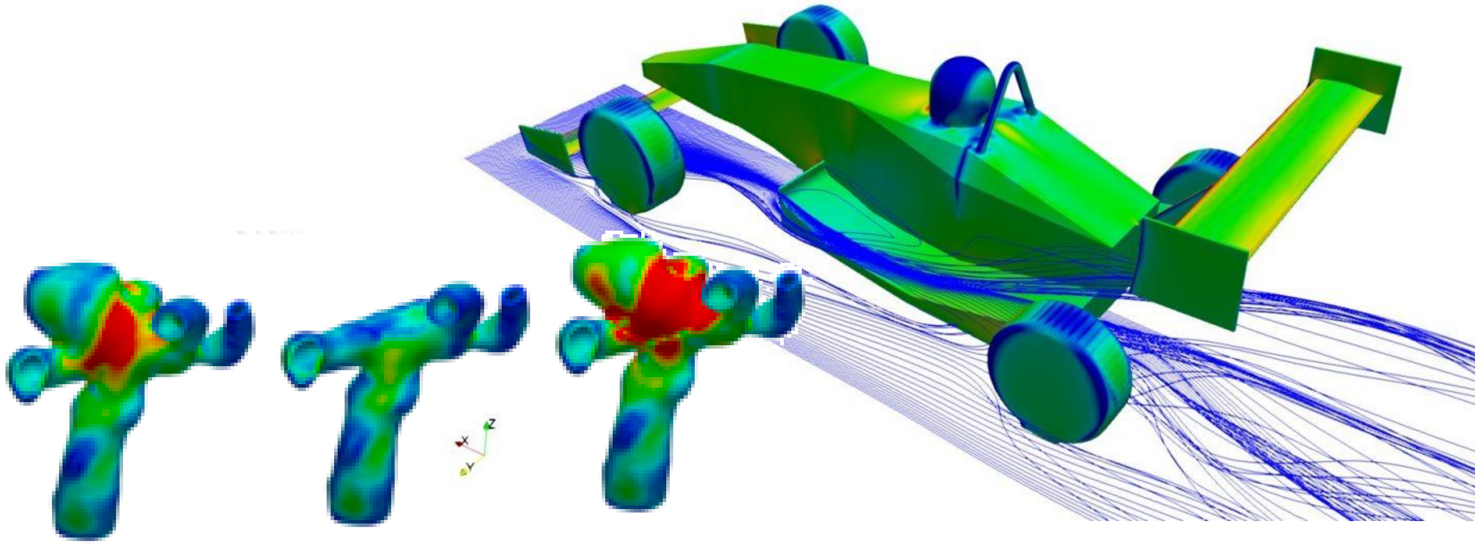
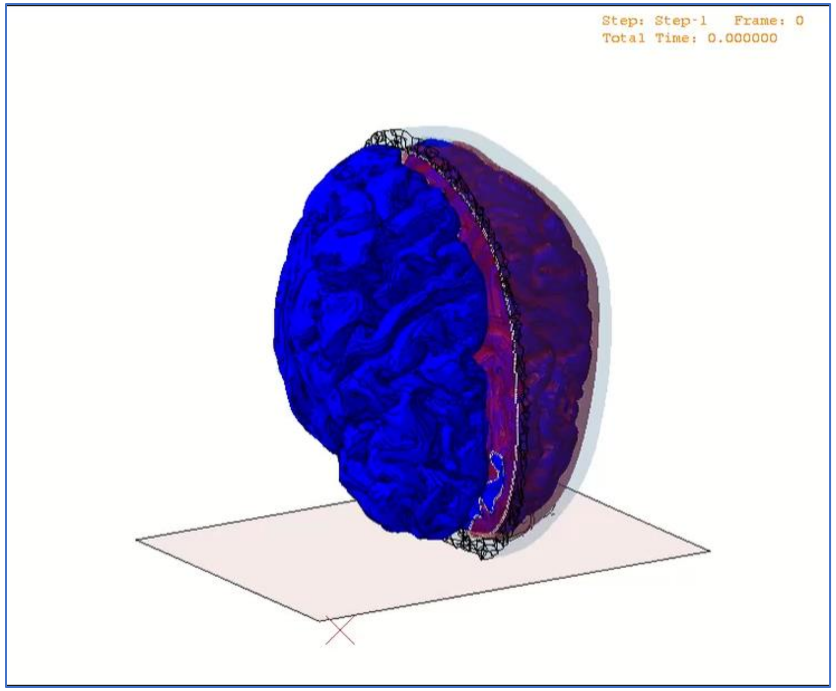
Computational Fluid Dynamics and Multi-physics

- **C**omputation **F**luid **D**ynamics models the motion of fluids
- Multi-physics
- **F**luid **S**tructural **I**nteraction





Skull/Brain Impact models by Sam Swift, Nottingham University

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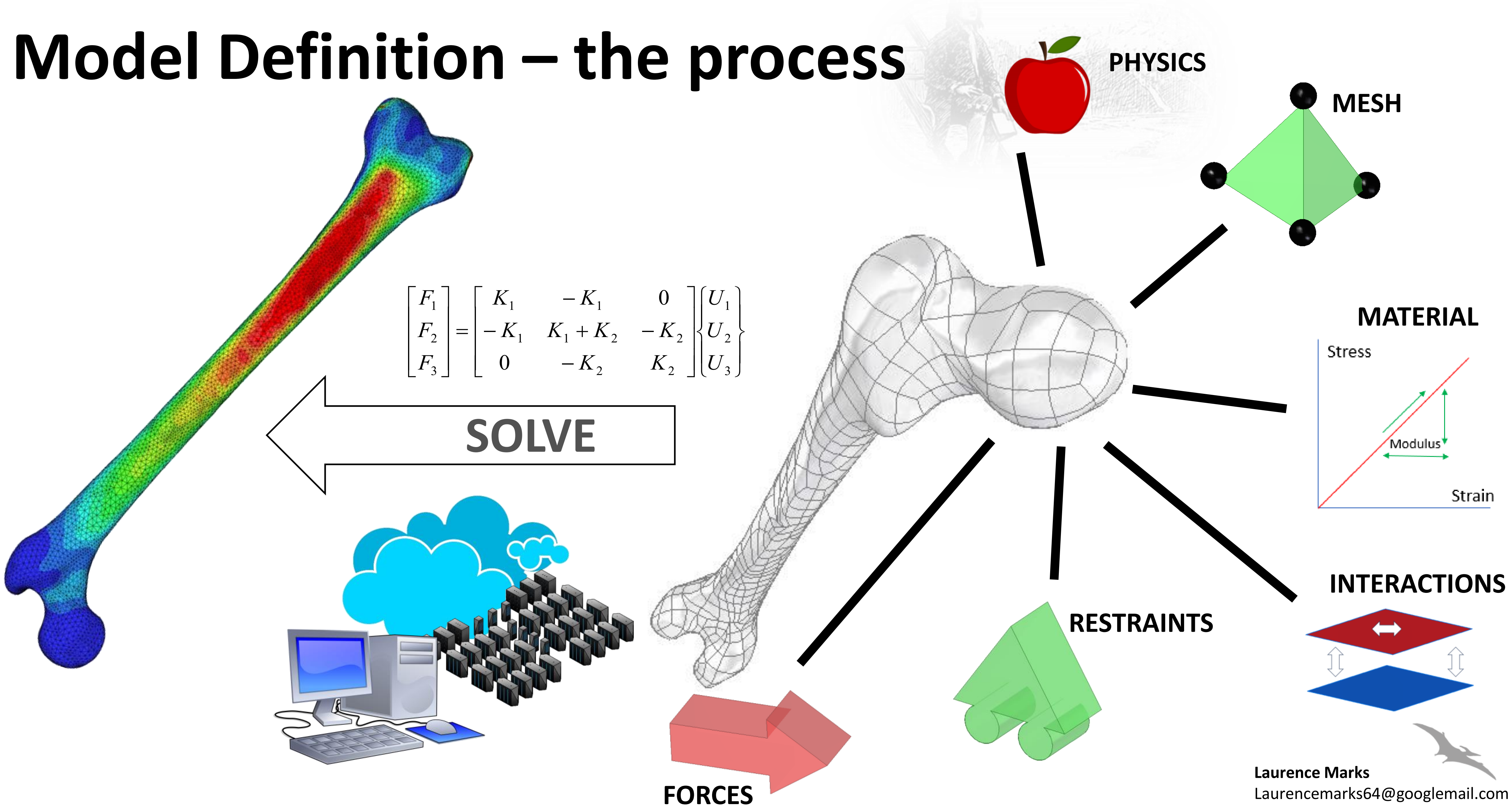
Model Definition – the process

$$\begin{bmatrix} F_1 \\ F_2 \\ F_3 \end{bmatrix} = \begin{bmatrix} K_1 & -K_1 & 0 \\ -K_1 & K_1 + K_2 & -K_2 \\ 0 & -K_2 & K_2 \end{bmatrix} \begin{Bmatrix} U_1 \\ U_2 \\ U_3 \end{Bmatrix}$$



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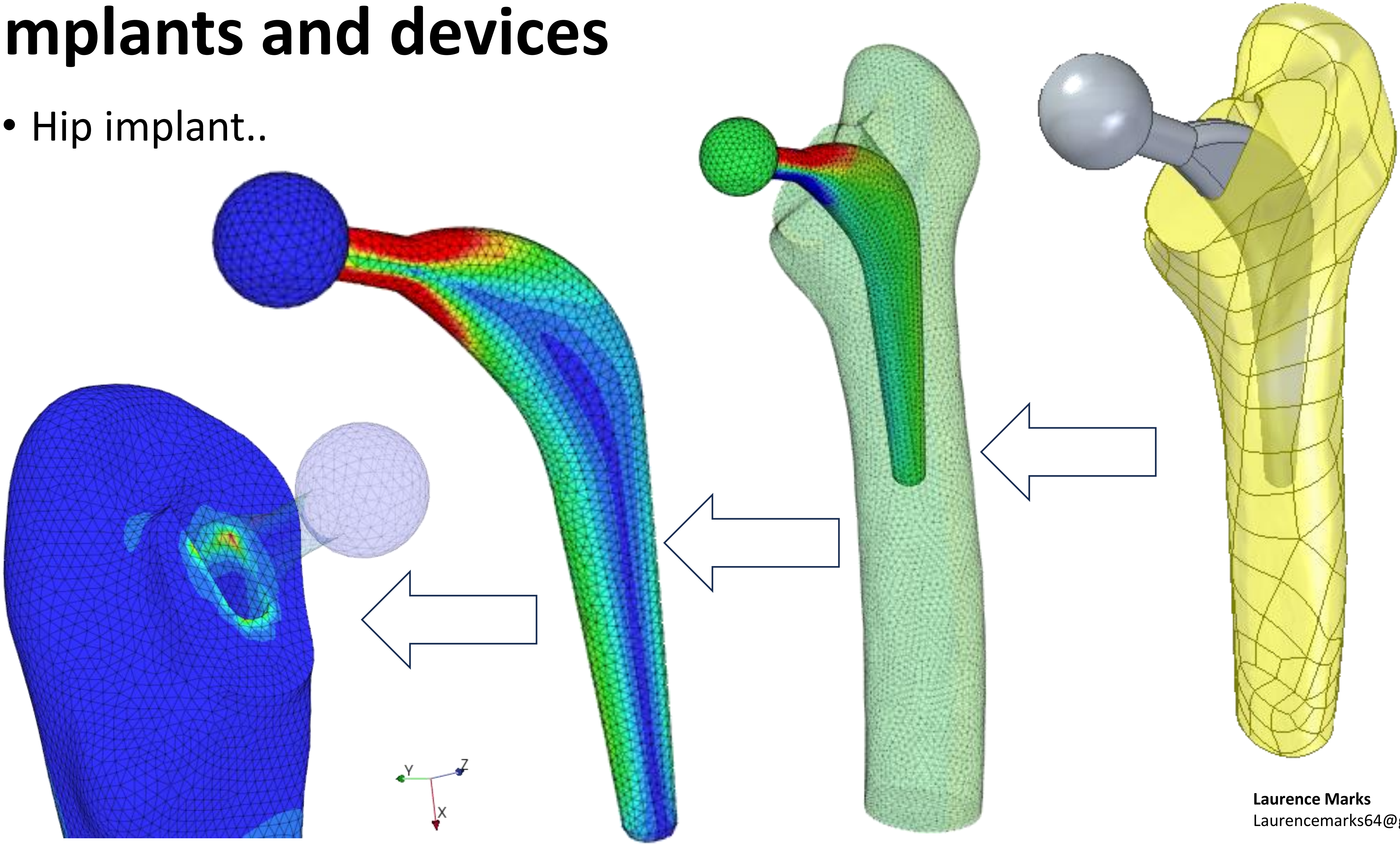
Implants and devices

- Hip implant..



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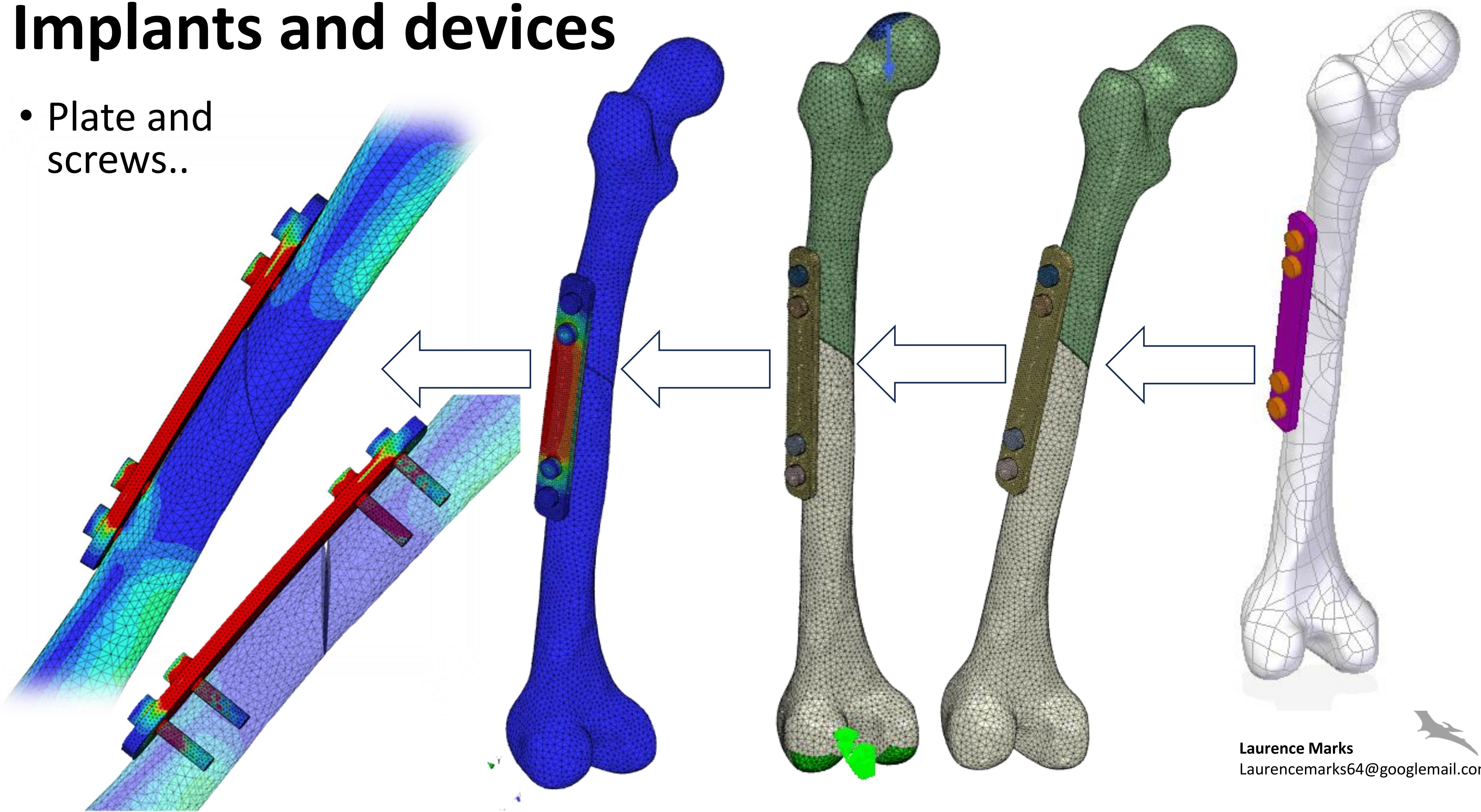
Implants and devices

- Plate and screws..



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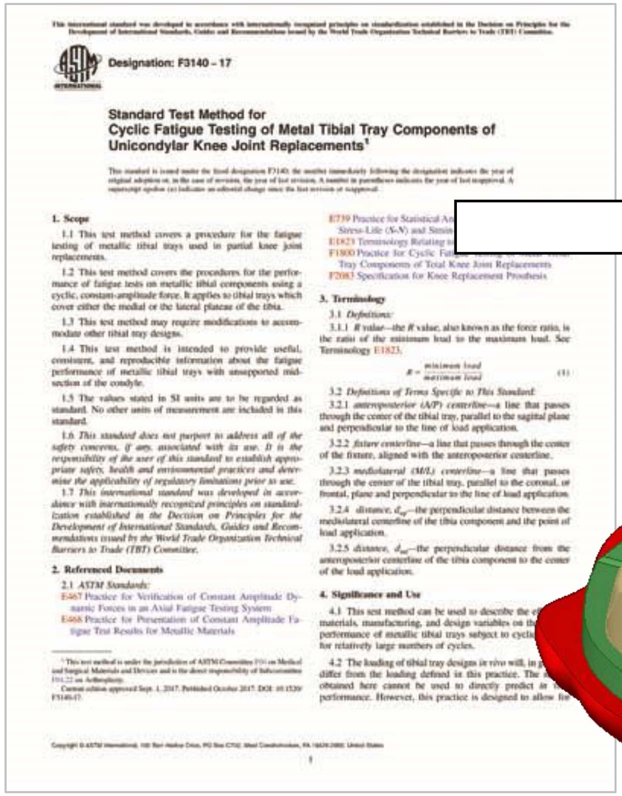
Implants and devices

- Design to standard…
- Test specification
  - Test vs real life vs simulation trichotomy
  - ASTM test doesn't replicate real world usage
  - Almost into codes based design here
  - But it's probably the best test case we can apply..



Designation: F3140 – 17

Standard Test Method for Cyclic Fatigue Testing of Metal Tibial Tray Components of Unicondylar Knee Joint Replacements[1]

1. Scope

1.1 This test method covers a procedure for the fatigue testing of metallic tibial trays used in partial knee joint replacements.

1.2 This test method covers the procedures for the performance of fatigue tests on metallic tibial components using a cyclic, constant-amplitude force. It applies to tibial trays which cover either the medial or the lateral plateau of the tibia.

1.3 This test method may require modifications to accommodate other tibial tray designs.

1.4 This test method is intended to provide useful, consistent, and reproducible information about the fatigue performance of metallic tibial trays with unsupported mid-section of the condyle.

1.5 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.6 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety, health and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.7 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*

E467 Practice for Verification of Constant Amplitude Dynamic Forces in an Axial Fatigue Testing System

E468 Practice for Presentation of Constant Amplitude Fatigue Test Results for Metallic Materials

E739 Practice for Statistical An…

Stress-Life (S-N) and Strain…

E1823 Terminology Relating to…

F1800 Practice for Cyclic Fatigue … Tray Components of Total Knee Joint Replacements

F2083 Specification for Knee Replacement Prosthesis

3. Terminology

3.1 *Definitions:*

3.1.1 *R value*—the *R* value, also known as the force ratio, is the ratio of the minimum load to the maximum load. See Terminology E1823.

$$R = \frac{\text{minimum load}}{\text{maximum load}} \quad (1)$$

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *anteroposterior (A/P) centerline*—a line that passes through the center of the tibial tray, parallel to the sagittal plane and perpendicular to the line of load application.

3.2.2 *fixture centerline*—a line that passes through the center of the fixture, aligned with the anteroposterior centerline.

3.2.3 *mediolateral (M/L) centerline*—a line that passes through the center of the tibial tray, parallel to the coronal, or frontal, plane and perpendicular to the line of load application.

3.2.4 *distance, d_{ap}*—the perpendicular distance between the mediolateral centerline of the tibia component and the point of load application.

3.2.5 *distance, d_{ml}*—the perpendicular distance from the anteroposterior centerline of the tibia component to the center of the load application.

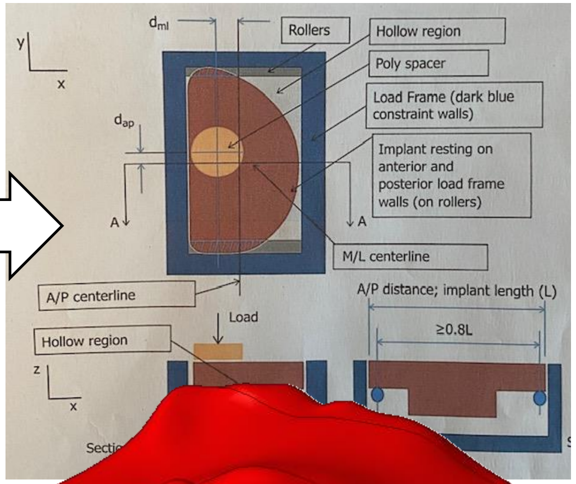
4. Significance and Use

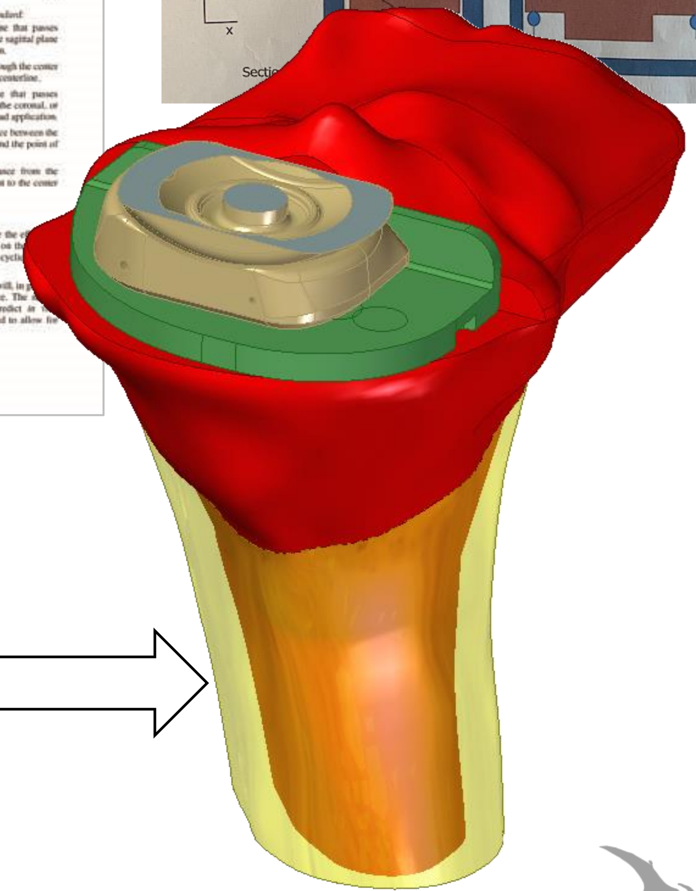
4.1 This test method can be used to describe the e… materials, manufacturing, and design variables on th… performance of metallic tibial trays subject to cycli… for relatively large numbers of cycles.

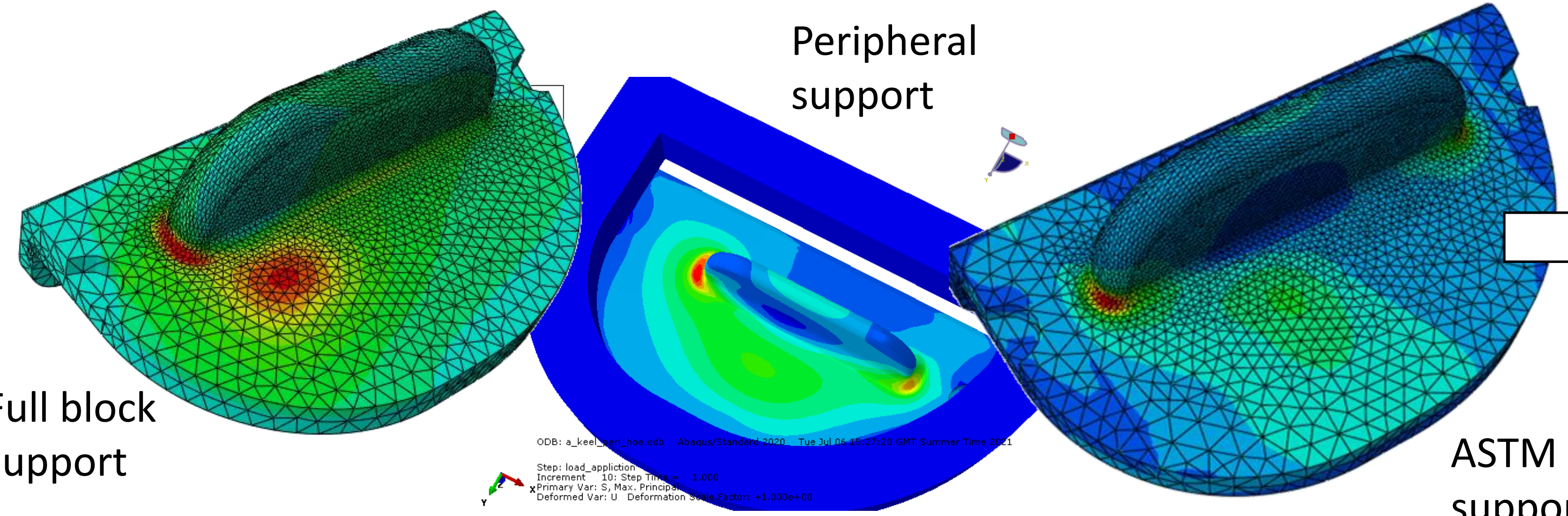
4.2 The loading of tibial tray designs *in vivo* will, in g… differ from the loading defined in this practice. The … obtained here cannot be used to directly predict *in* v… performance. However, this practice is designed to allow for

[1] This test method is under the jurisdiction of ASTM Committee F04 on Medical and Surgical Materials and Devices and is the direct responsibility of Subcommittee F04.22 on Arthroplasty.

Current edition approved Sept. 1, 2017. Published October 2017. DOI: 10.1520/F3140-17.







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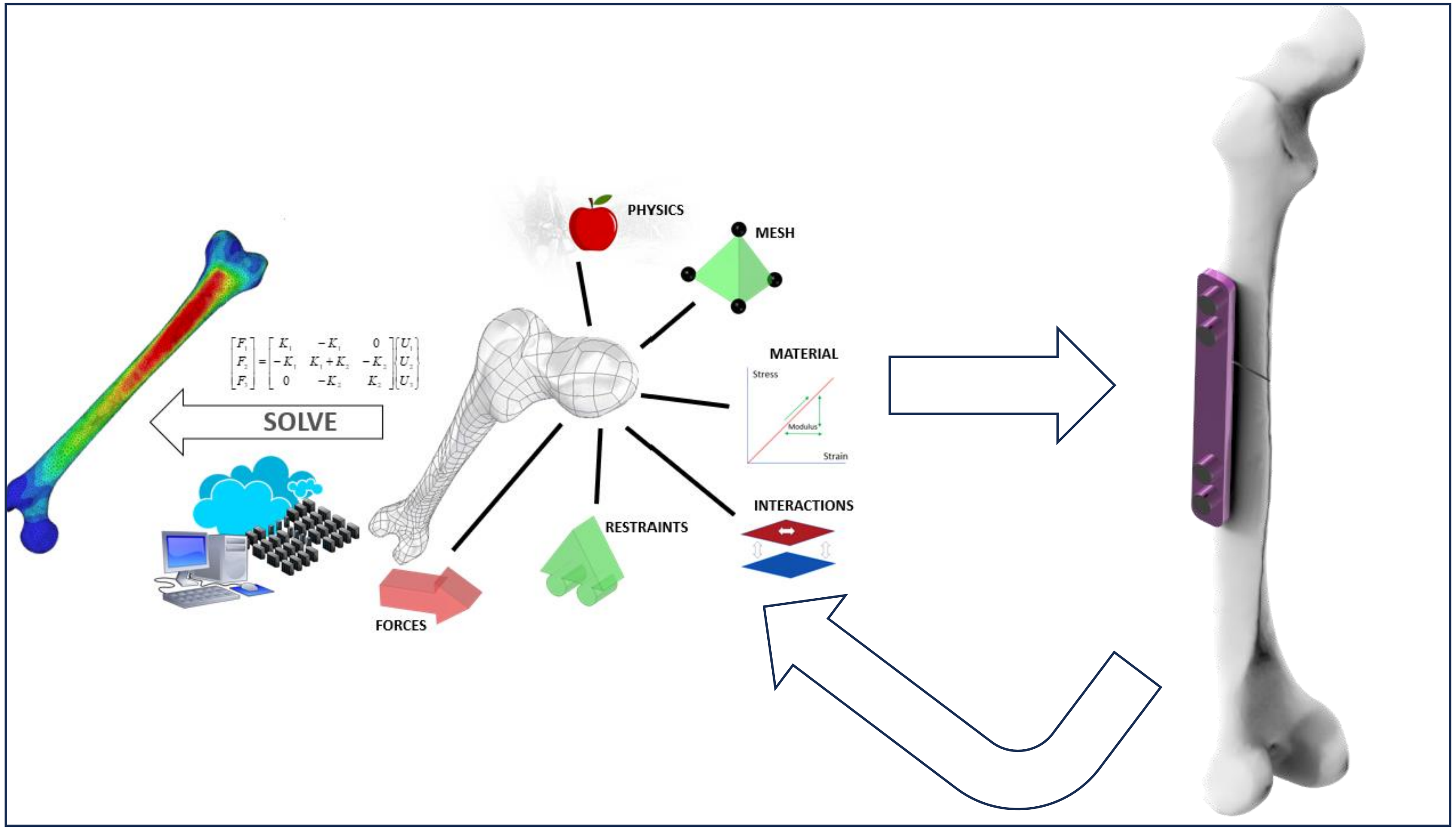
Defining the workflow…

- Once the model/validation loop has been established we can use the model to answer research questions or investigate design options

Research question or design challenge



IP and understanding reside in the workflows – much more than in the individual models

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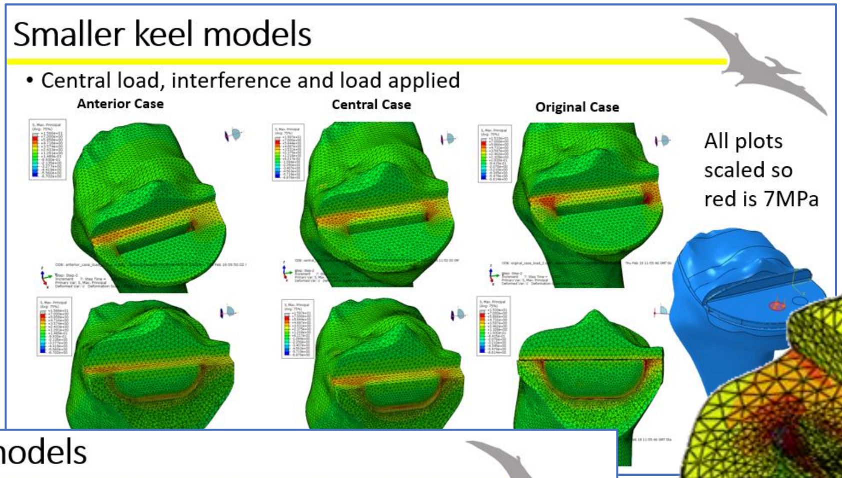
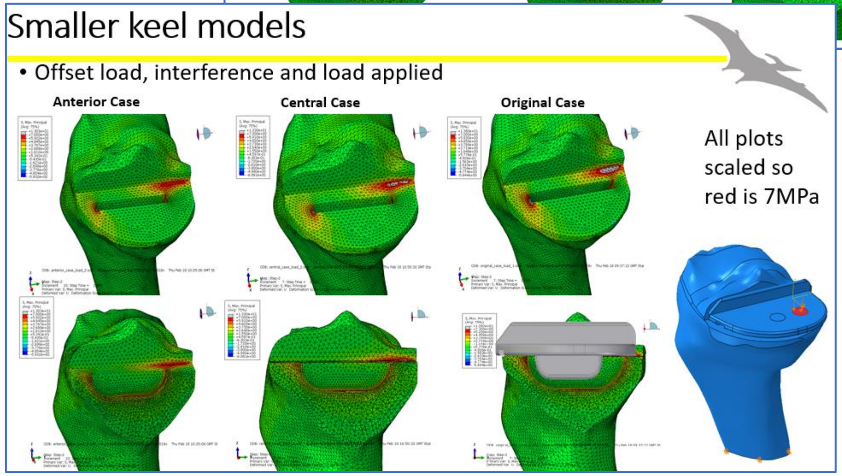
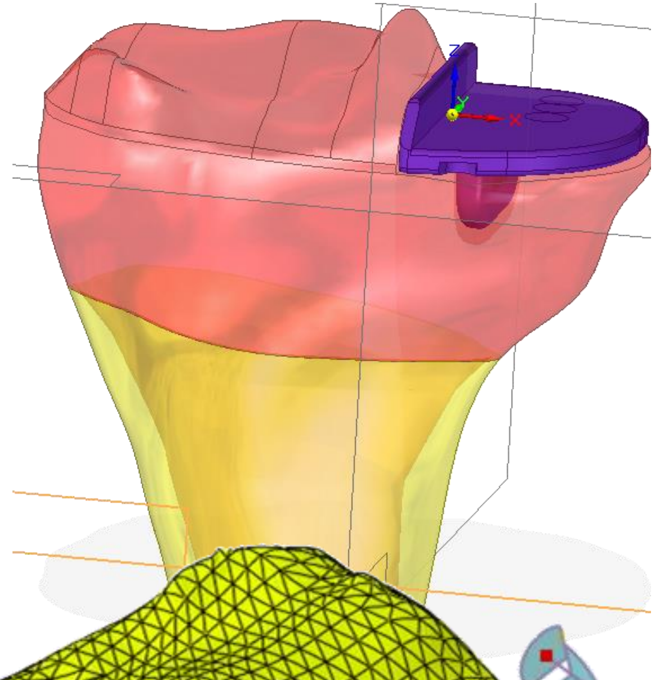
Exploring the designspace and AI…

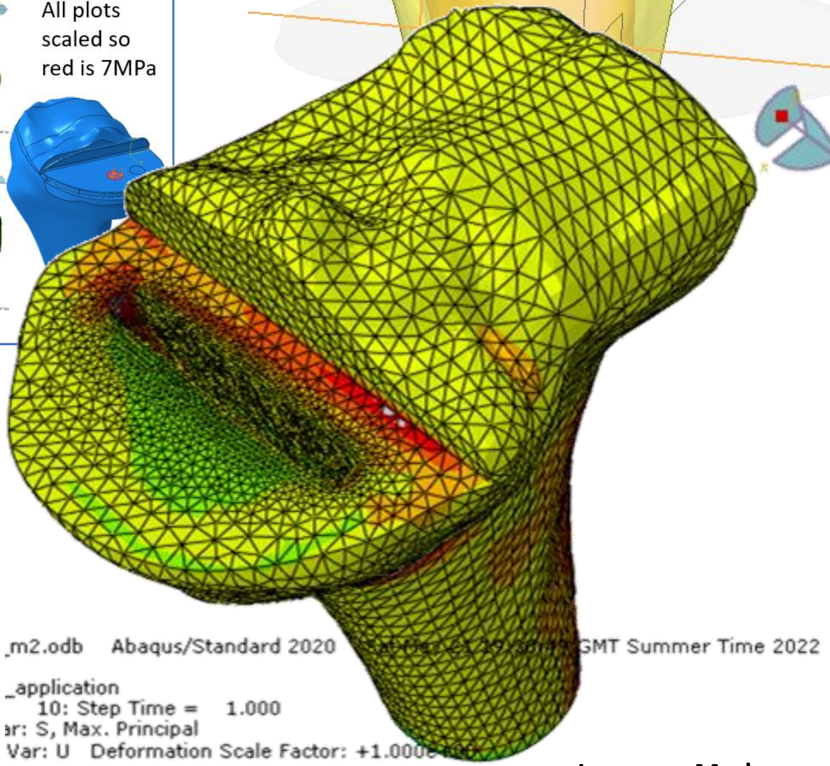
- Building a single model of a scenario probably isn't enough..

- Lots of models = automation =









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How do we know it's right? Validation and Verification

- So the results have got to be right right..
- There are two checks that need to be performed..

100% wrong

Verification – have the equations been solved correctly?

Validation – have the correct equations been solved?

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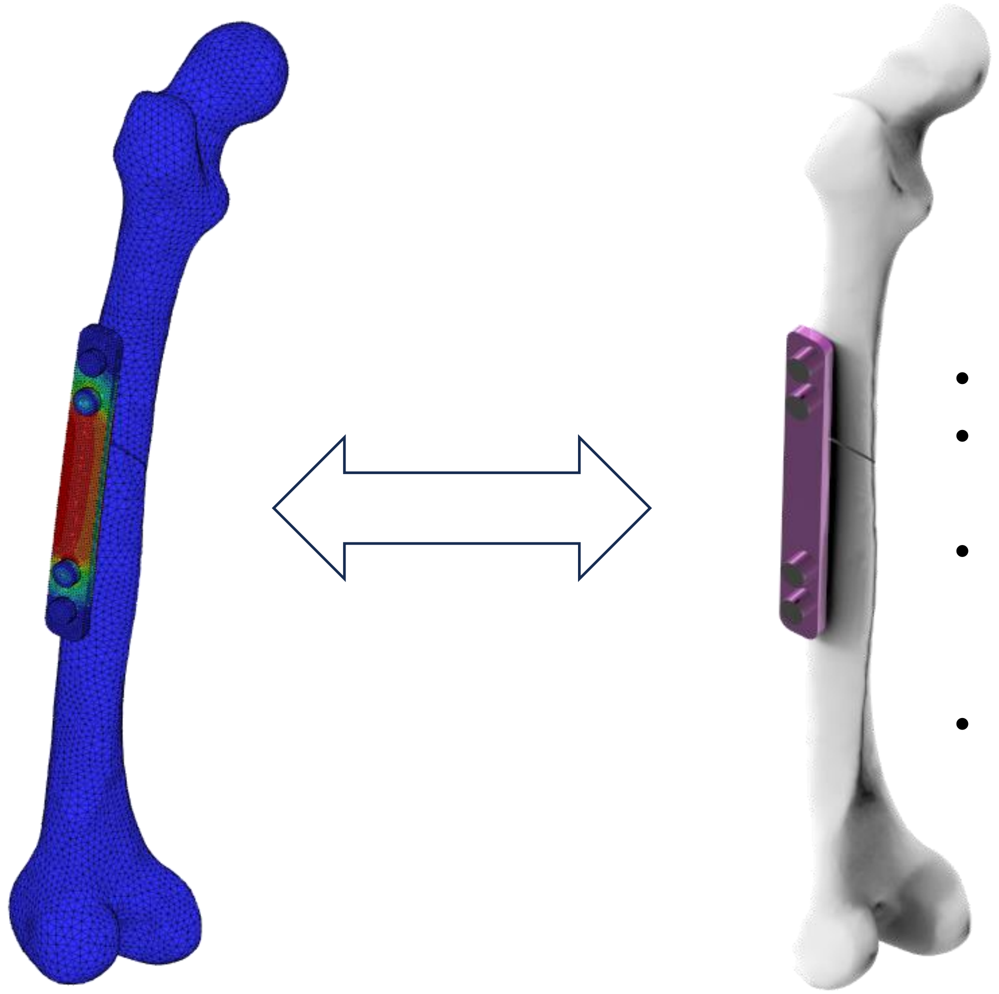
How do we know it’s right? Validation and Verification

- Verification is pretty much out of your control, its largely an activity for software authors..
- Validation is very much the engineers (doctors??) responsibility.
- When the real and digital worlds agree, and the reasons demonstrated or explained, we can say we understand (some of) what’s going on.
- There was a time when FEA was a discredit technology in biomechanics – because of a lack of attention to correlation

FEA “World” **Real World**



- Strain gauges
- Digital Image Correlation
- Digital volume correlation
- Direct load measurement

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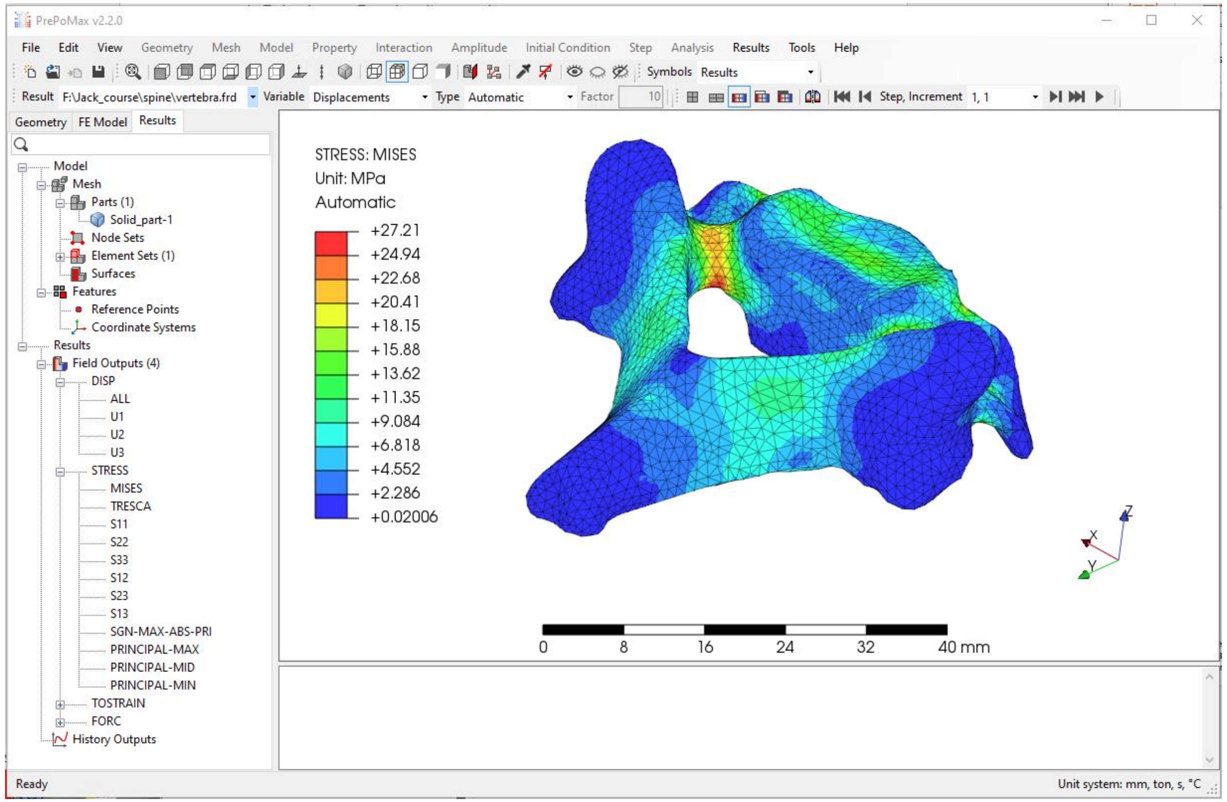
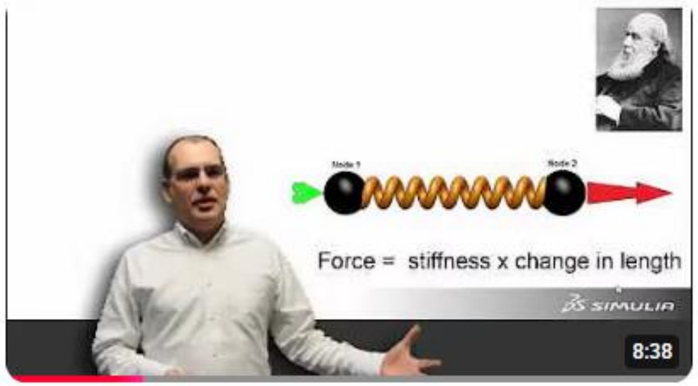
Learning to undertake FEA studies

- Get in there and have a go.. It's an accelerated learning program.
- Use free software – PrePoMax was used for most of the examples in this lecture.
- Talk to the experts.. We don't get out much generally..
- Online resources abound..





Introduction to Basics FEA

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7 chapters Introduction | Graphics | Hookes Law |...

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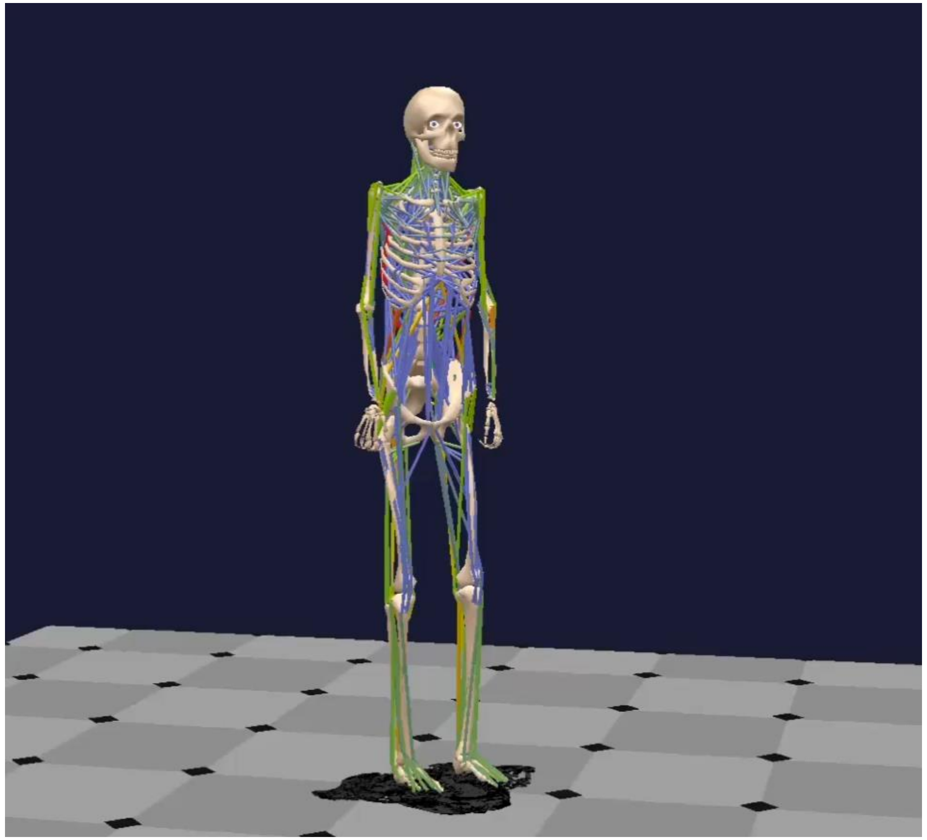
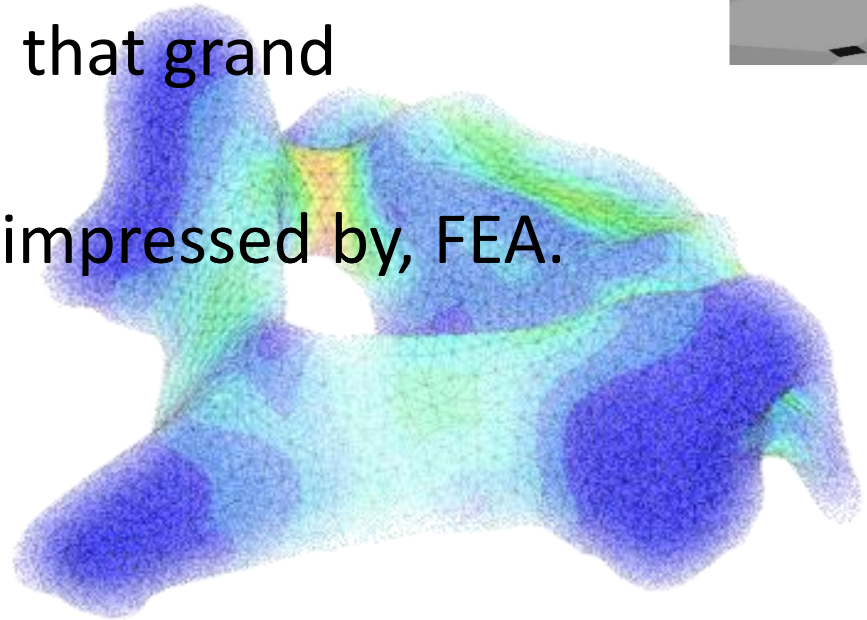
In summary..

- The quality of published FEA work is hugely variable. It pays to know what to look out for and maintain a sceptical attitude..
- The basics are easy to understand, and will take you a long way.
- Simple well planned and executed studies are often much more insightful that grand challenge projects
- Don't be scared of, or over impressed by, FEA.





BoB Biomechanics

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