Osseous biomaterials: When your bone needs help healing

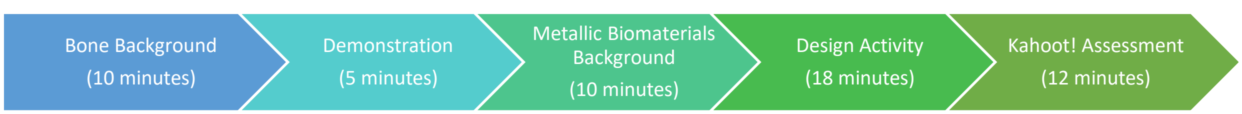
University of Florida Society For Biomaterials Student Chapter

Statement of Purpose

Current K-12 curricula lack significant depth in materials science yet has tremendous room for its incorporation [1]. In fact, middle school curricula are especially positioned for the inclusion of biomaterials concepts when students study the different organ systems of the body [1]. Our lesson is specifically designed as a companion lesson to those that teach the structure and function of bone. For our lesson, we reframe the study of bone through the lens of a materials engineer to focus on its structure-property-function relationships and the use of metallic biomaterials for orthopedic applications giving specific focus to their interactions. This lesson is targeted at 6^{th} and 7^{th} grade students with classroom sizes of 20 – 30 students. Nonetheless, it is scalable to older and younger students by incorporating more or less higher-level concepts. The learning objectives for the lesson are:

1. Identify that bone,
    a. is a composite material
    b. has a hierarchical structure
    c. is a living material composed of cells
2. Identify that metallic implants,
    a. are made from different metals for specific reasons
    b. can lead to stress shielding
3. Define stiffness, strength, and fracture
4. Compare material classes
5. Relate material properties to implant performance
6. Design stiff, stable composite structures

The lesson describes the properties of bone and metallic biomaterials with the aid of demonstrations, a hands-on engineering design challenge, and an interactive, web-enabled student assessment.



Description of activity methods including materials and budget

Specifically, the properties of bone related to its strength are presented to students including that bone 1) is a composite material, 2) has a hierarchical structure, and 3) is a living/dynamic material consisting of a cellular component. In (1) students learn about the properties of *elasticity* and *fracture* as they relate to soft and stiff materials. Marshmallows (soft, ductile material) and ceramic mugs (stiff, brittle material) are used to convey the differences in material properties and relate to the two main components of bone being a composite of a collagen (soft gel material) and hydroxyapatite (stiff ceramic material). This leads into (2) which describes how these two components are organized in a hierarchical structure. An analogy to an office building is used to explain the concept of hierarchy (**Figure 1**). Lastly, in (3) the cellular component of bone is discussed to introduce that bone has three general cell types: osteocytes, osteoblasts, and osteoclasts, and their specific functions in remodeling.

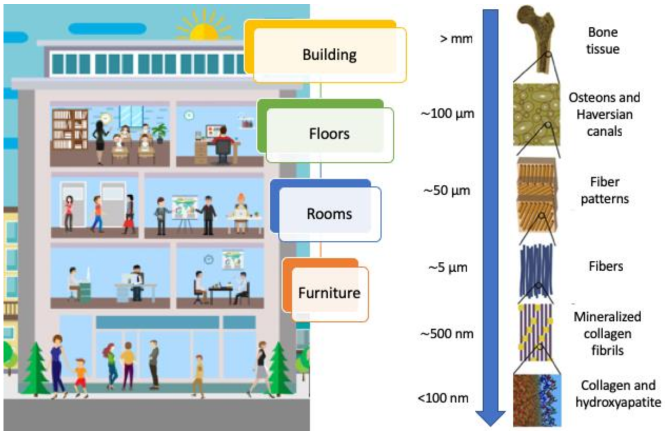


Figure 1: Diagram of hierarchical structure using the example of a building's hierarchical organization being analogous to that of bone's hierarchical structure.

As for metallic biomaterials, a short video titled, "'Smart implants' dissolve after healing," produced by the National Science Foundation for the *Science Nation* series is played to introduce the use of metals for orthopedic applications. Not only is this video pertinent to the topic, it also highlights traditionally underrepresented minorities in STEM fields in the role of the biomaterials engineer. Afterwards, several different metallic biomaterials are discussed including, steel, titanium, aluminum, and cobalt-chromium. During this time, students learn about stress shielding with a hands-on demonstration and materials selection.

All of these concepts are presented using a multitude of approaches: lecture, demonstration, and activity. General content is presented using a PowerPoint presentation. Throughout, students are engaged with questions posed on the slides such as, "Have you ever broken a bone?" and, "What do you think bone is made from?" To further reinforce the material property concepts of elasticity and fracture, in-class demonstrations of squeezing marshmallows and dropping ceramic mugs are employed. Students are especially excited to see the ceramic mug shatter. Likewise, a simple demonstration to convey the concept of stress shielding is conducted using a roll of toilet paper and a heavy textbook (**Figure 2**). For this the students are grouped into teams of 3-4 students to compete to see which team can unroll the entire toilet paper roll while keeping the textbook balanced on top of it (**Figure 2**). At the end, the students are asked which component of the toilet paper roll was actually supporting the weight of the textbook. *Was it the tissue paper or the cardboard tube?* Then the analogy is explained. In this case, the tube is analogous to the metallic implant and the tissue paper is analogous to bone. As the students unraveled the toilet paper, they were like the osteoclasts degrading the bone (tissue paper) surrounding the implant (tube). This demonstration is used to reiterate the concepts of elasticity/stiffness, stress shielding, and bone remodeling by cells. Together these demonstrations reinforce the content by activating the different learning modes for the students and help to break up the tedium of lectured content.

See companion PowerPoint file for presentation slides and script for lesson instructions.

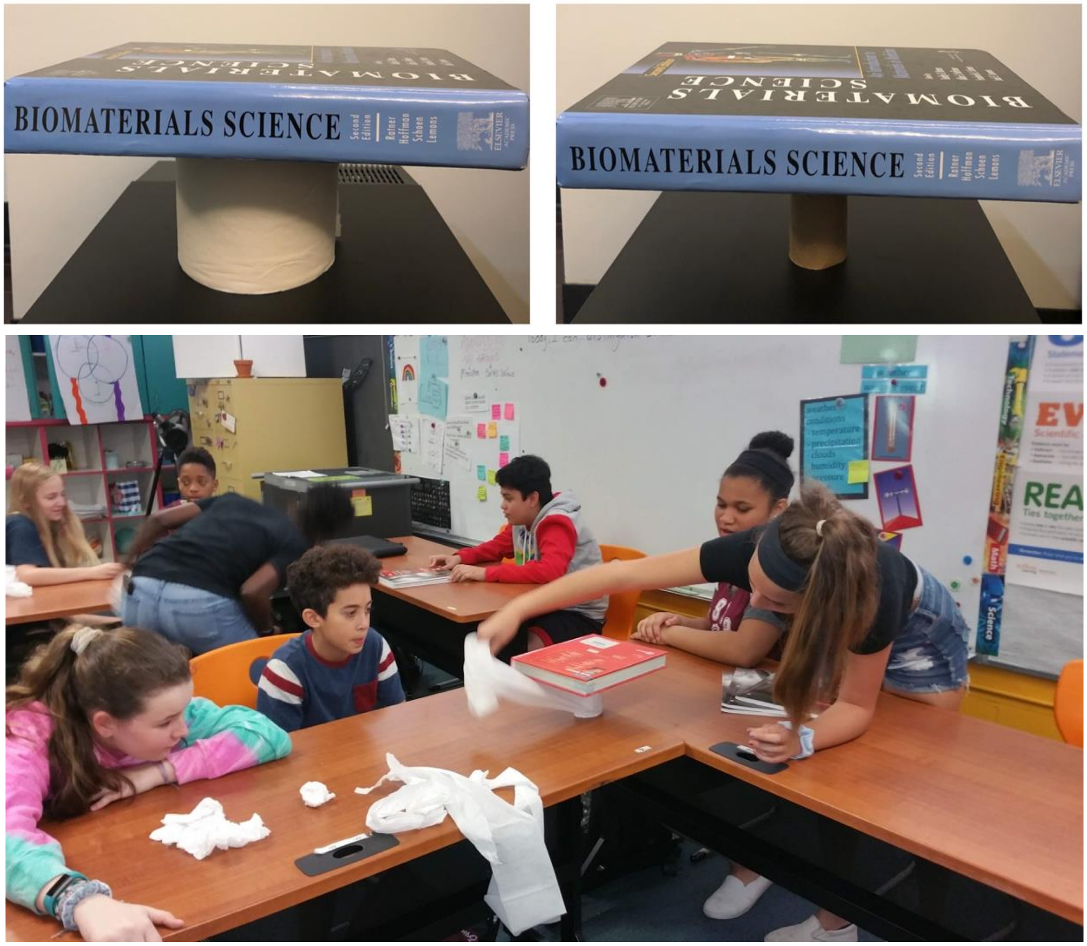


Figure 2: Stress shielding demonstration using a toilet paper roll and textbook. In the top left image, the *Biomaterials Science* textbook is supported by the full roll of toilet paper. In the top right image, the same textbook is supported only by the cardboard tube of the toilet paper roll. 7th grade student at PK Yonge Developmental Research School completing the demonstration.

The next part of the lesson is a design challenge activity. Students are asked to create a structure using only a single sheet of paper and Elmer's glue capable of supporting the weight of as many textbooks as possible on their desk. The only constraint for this activity is for the design to elevate the textbook an inch or more off of their desk. Students are free to cut, fold, and reshape the piece of paper in any way they see fit and to work individually or in teams (**Figure 3**). Students are encouraged to use the concepts they discussed throughout the beginning of the class in their designs namely those related to structure and composite materials. During this time, the teacher is able to go around the classroom and probe students as they formulate and build their designs. Throughout this period, students are able to quickly test their design and iterate on it using a new sheet of paper, if necessary. At the end of the activity, a brief classroom discussion is held to ask the students: *What designs worked? Which were crushed? Did your design use a composite material? How did you approach the challenge?*

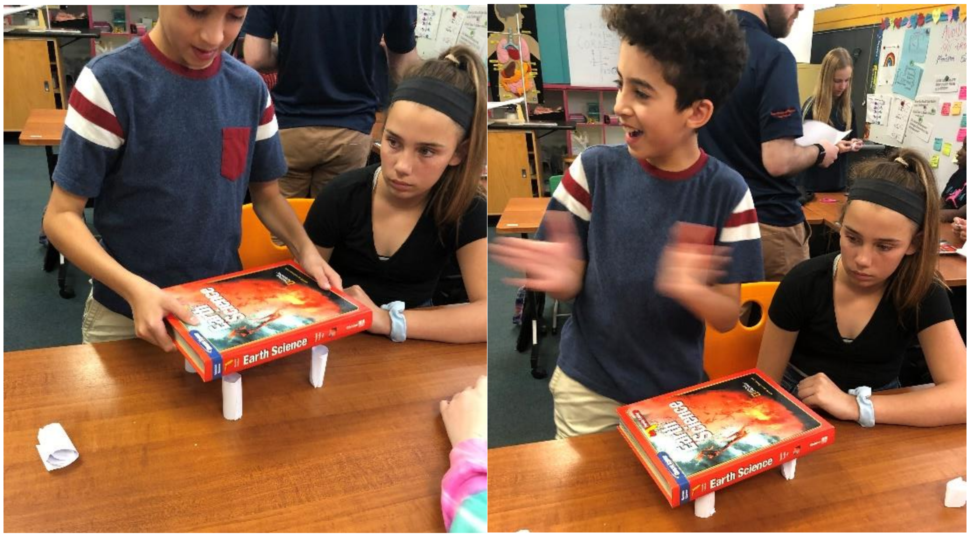


Figure 3: 7th grade students at PK Yonge Developmental Research School testing their paper structures during the design challenge activity.

To conclude the lesson, students are assessed using the web-enabled quizzing platform, Kahoot! Students are able to access Kahoot! through a free cellphone application or web browser interface. If these resources are unavailable, the assessment can be administered by traditional means as a classroom poll or paper handout. The assessment consists of eight questions related to the content of the lesson. The Kahoot! platform allows the questions to be timed, giving students only 20-30 seconds to answer. After the timer a histogram of responses for each answer choice is displayed on the screen, at this time the teacher is able to address the class to reiterate concepts related to the question.

The Kahoot! quiz is available at the following link: https://create.kahoot.it/share/biomaterials-education-challenge/3148bbe6-dc36-4e60-b810-dcfdb4f13865

This lesson was designed from the ground up for inclusion in middle school science curriculums to address biomaterials concepts. To complete the lesson requires a minimum of supplies that are inexpensive and readily available (**Figure 4**). The lesson has a capital cost of $45.61 after sales tax, which includes the initial purchase of paint brushes, scissors, glue containers, Elmer's glue, a ream of copy paper, and a bag of jumbo marshmallows. The last two items are considered capital costs because their typical retail quantity can be used across several lesson repetitions. The consumables for the lesson cost $8.00 after tax, which includes the purchase of a ceramic mug and toilet paper rolls. Costs are based on item sales prices as sold by Target and a Florida state sales tax of 7%. In conclusion, this is a very affordable and accessible lesson for implementation in middle school curricula.

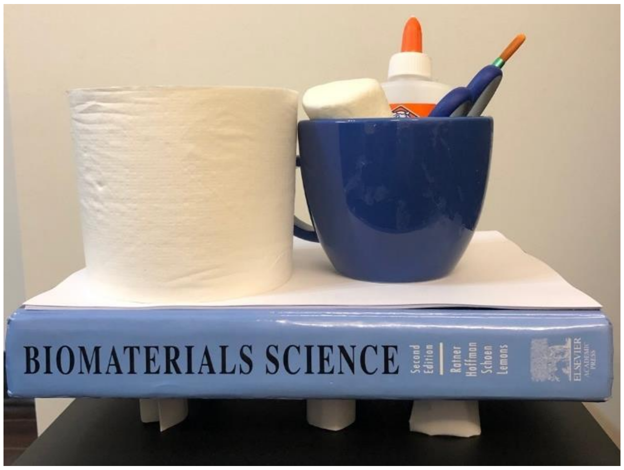


Figure 4: All of the materials necessary to complete the lesson's several demonstrations and design challenge activity.

Assessment method and results

To evaluate the effectiveness of the lesson, the development team partnered with Dr. Mayra Cordero, University School Assistant Professor and Instructor of Secondary Science, at the PK Yonge Developmental Research School at the University of Florida. Dr. Cordero says of the experience,

> "This lesson gave my students insights into biomaterials at an early stage of their education. The lesson was inclusive and interactive as it included various activities to engage students in the learning about biomaterials, such as a short video, an online game, and hands-on activities. The students were motivated by the challenge of designing a model of a structure made out of biomaterials. The lesson also allowed my students to engage in the 21st century scientific and engineering practices that will prepare them for the workforce in the future."

The lesson was given to 104 7^{th} grade students over 5 class periods (~20 per period). Content retention was assessed using the Kahoot platform and showed tremendous promise. Based on the compiled Kahoot results from the end of the lesson:

- 94% of students correctly identified that the composition, the structure, and the cells in bone contribute to its properties.
- 86% of students correctly identified that bone is a living, lightweight, strong material.
- 79% of students recalled that bone is a composite material.
- 61% of students correctly identified that stiffness is related to bending. 29% of students incorrectly identified that stiffness is related to fracture.
- Only 36% of students correctly identified that elasticity/stiffness is related to stress shielding. 22% incorrectly associated it to strength and 28% incorrectly associated it to fracture.

The assessment indicated that students were able to grasp the content related to bone; however, they had much more difficulty retaining the materials science content. We attribute this to the instruction in terms of guiding students to discriminate the difference between strength and stiffness. To rectify this, we intend to make sure to explicitly stress their difference. We also attribute this to the difference in language commonly used in daily life and by materials engineers; as these nuanced definitions can be challenging even for undergraduate students. On the other hand, students readily identified differences in properties between material types when asked about them abstractly. For instance, during the background instruction on bone, students were asked, "What if your bones were only made of ceramic?" They answered by saying that our bones would break much more readily. And then when asked, "What if our bones were only made of materials similar to marshmallows?" The class answered by saying that our bones would not be able to support our weight. This observation makes us hopeful much of the materials science content is being understood. From the group discussion held after the design challenge activity, students independently recognized that short, wide posts were better at supporting the load of the textbook as compared to long, skinny posts. Likewise, they identified that glue reinforced the paper after it dried resulted in a stiff composite material. At the beginning of the lesson, students were unaware of biomaterials; however, by the end students were interested in learning more about other types of biomaterials such as those related to cartilage or to the cardiovascular system. Most importantly, the students showed great interest and excitement to further learn about biomaterials!

References

[1] NGSS Lead States, *Next Generation Science Standards: For States, By States*, Washington, DC: The National Academies Press, 2013.

Lesson Script

1. (Slide 1) Introduction
    a. (Slide 2) ASK STUDENTS: Have any of you broken a bone? – Yes/No, place for student stories
    b. (Slide 3) ASK STUDENTS: When do bones break? – Force of impact
        i. Break a wishbone
    c. (Slide 4) ASK STUDENTS: What gives bone its strength? – Its properties, lightweight, strong, composite, LIVING material
        i. Go over Slides 5 – 9
            1. (Slide 5) ASK STUDENTS: What makes bone so special? – The structure! Bone is a composite material, which means it's a material made from a mixture of different materials. Bone is a combination of a ceramic (show a coffee mug), hydroxyapatite, and a soft gel (show a marshmallow), collagen. Coffee mugs are made of from a ceramic, porcelain. Marshmallows are made from gelatin, a form of collagen.
                a. Pass around the coffee mug and marshmallow
            2. (Slide 6) Stiffness is a material property. A stiff material is a popsicle stick. It doesn't bend very easily while Jell-O is a soft material. It wiggles and jiggles without much effort. In this case, the ceramic is stiff and the gel is soft.
            3. (Slide 7) Fracture is another material property. This is a measure of how easy it is to break a material. Ceramics are brittle and easily break upon impact whereas gels are ductile and can be stretched and deformed before finally breaking.
            4. (Slide 8) Discuss the structure of bone. It is HIERARCHICAL. Collagen triple helix with hydroxyapatite crystals. Then collagen fibrils. Then collagen bundles. Then suprastructures of bone.
            5. (Slide 9) Our bone has 3 main types of cells: Osteocytes which sense forces, osteoblasts which form new bone, and osteoclasts which consume bone. The osteocytes communicate forces to the osteoblasts and osteoclasts telling them whether they need to reinforce your bone to make it stronger to support greater loads or if they can resorb some of your bone to use those materials elsewhere in the body. This is a big problem for astronauts. Because there is no gravity their osteocytes don't really feel any force and so these cells continuously are telling the osteoclasts to degrade and thin their bones. This makes the astronaut's bone very brittle and prone to fracture.
    d. Ceramics are brittle and break easily (drop the coffee mug in a bin to have it break). Soft gels are squishy (squish the marshmallow)
        i.
    e. (Slide 10) ASK STUDENTS: But what happens with a bad break, if a cast isn't enough? – Metals are used: bone screws and plates, hip implants, knee implants
        i. (Slide 11) Play one or both videos
        ii. "Today we are going to learn about the materials used for assisting our body to heal when we have a bad break and the special properties of bone!"
2. Stress Shielding Demonstration
    a. Teacher takes out a roll of toilet paper and places a textbook on top of it. Then asks each student to unroll as much of it as they want.
        i. NOTE: Let students do this as teams

ii. NOTE: Unroll toilet paper a bit before lesson to save time if necessary
iii. ASK STUDENTS: Which part of the toilet paper roll is supporting the weight of the textbook? The paper or the roll? – The roll!
iv. "This is what happens with a metal implant and your bone. The metal is much stiffer and stronger than your bone and so your body needs less bone because the metal can support the different forces acting on your body. "
v. "This is called STRESS SHIELDING. It is the loss of bone mass because the metal is stiffer than bone."

b. (Slide 12) ASK STUDENTS: Which metals do they think are used? Steel? Aluminum? Titanium? Cobalt-Chromium? – All of them, write the Young's Modulus of each metal and of bone.
   i. (Slide 13) ASK STUDENTS: But which is the best? – Titanium, because it has the closest stiffness to bone!

3. (Slide 14) Composite Demonstration
   a. Now we're going to make our own composites. Teacher hands out a piece of paper and Elmer's glue. Directs the students to make a structure to support the load of a textbook. Let student's structures dry.
   b. (Slide 15) Go over discussion questions – Test student's structures (warn that their structures might get crushed). Show a structure that does work and point out the hierarchical structure of it. Rolled tubes bundled together. A single tube cannot work, but several together do!

Osseous biomaterials

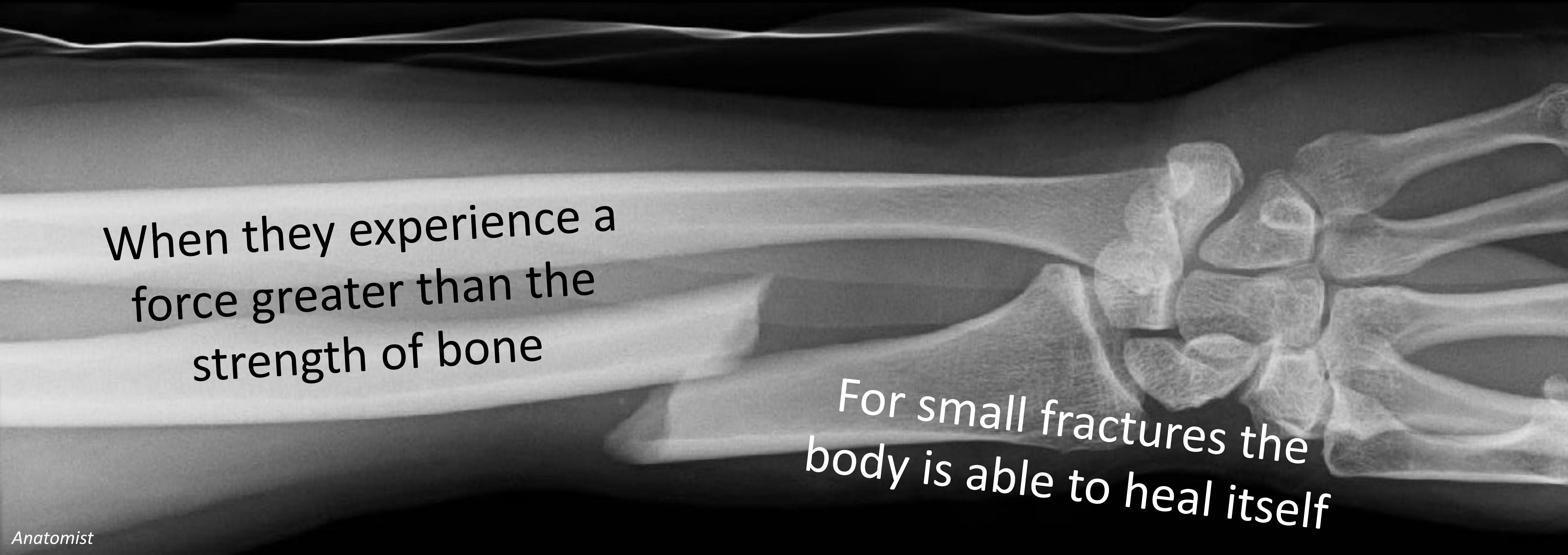
When your bones need help healing

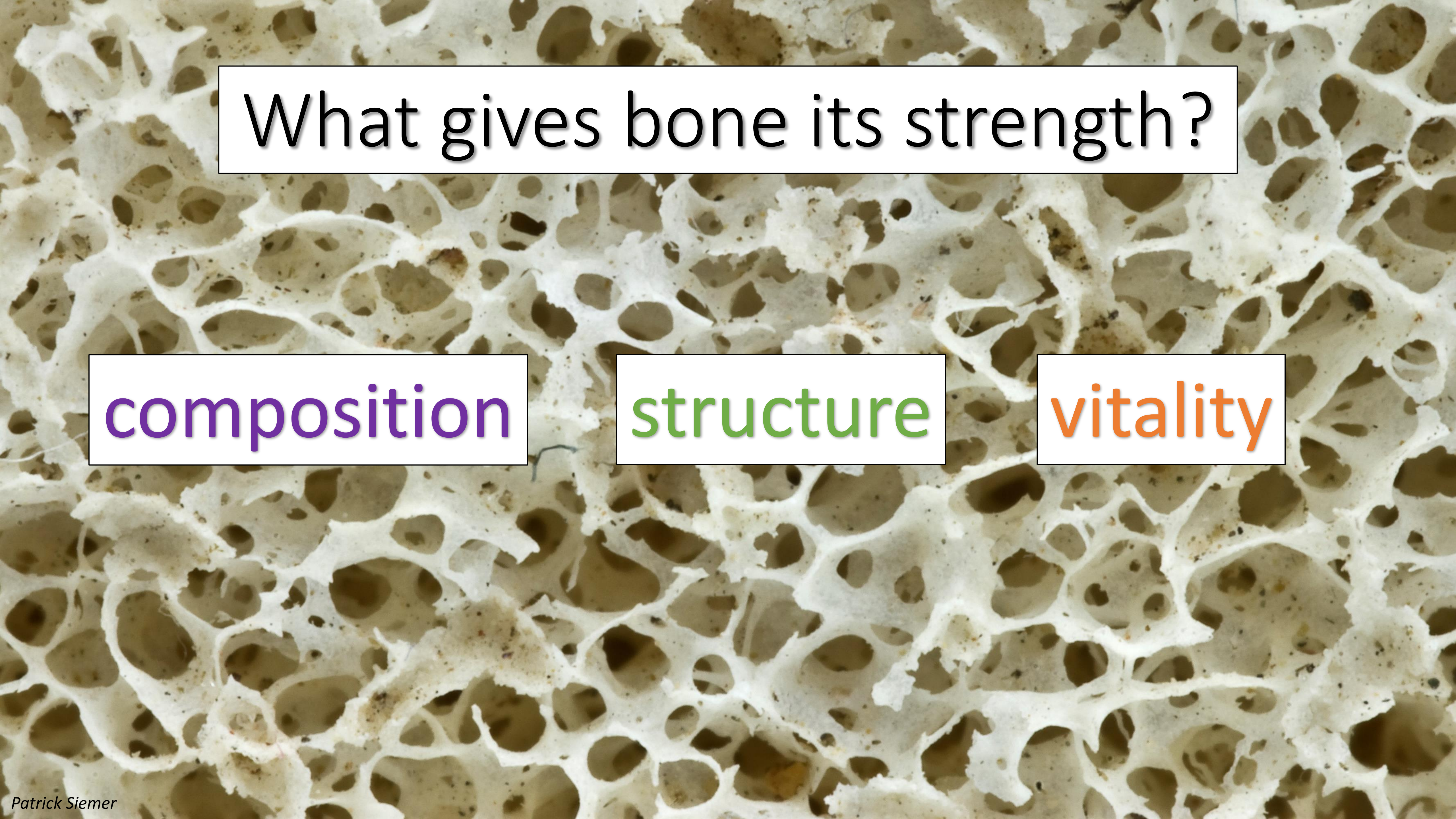
Wellcome Images

Have any of you broken a bone?

Wellcome Images

When do bones break?





Patrick Siemer

Bone is a composite material

A composite is a combination of more than one type of material

Bone has both a soft fibrous gel, collagen, a stiff ceramic, hydroxyapatite

Patrick Siemer

Stiffness (E) is a material property

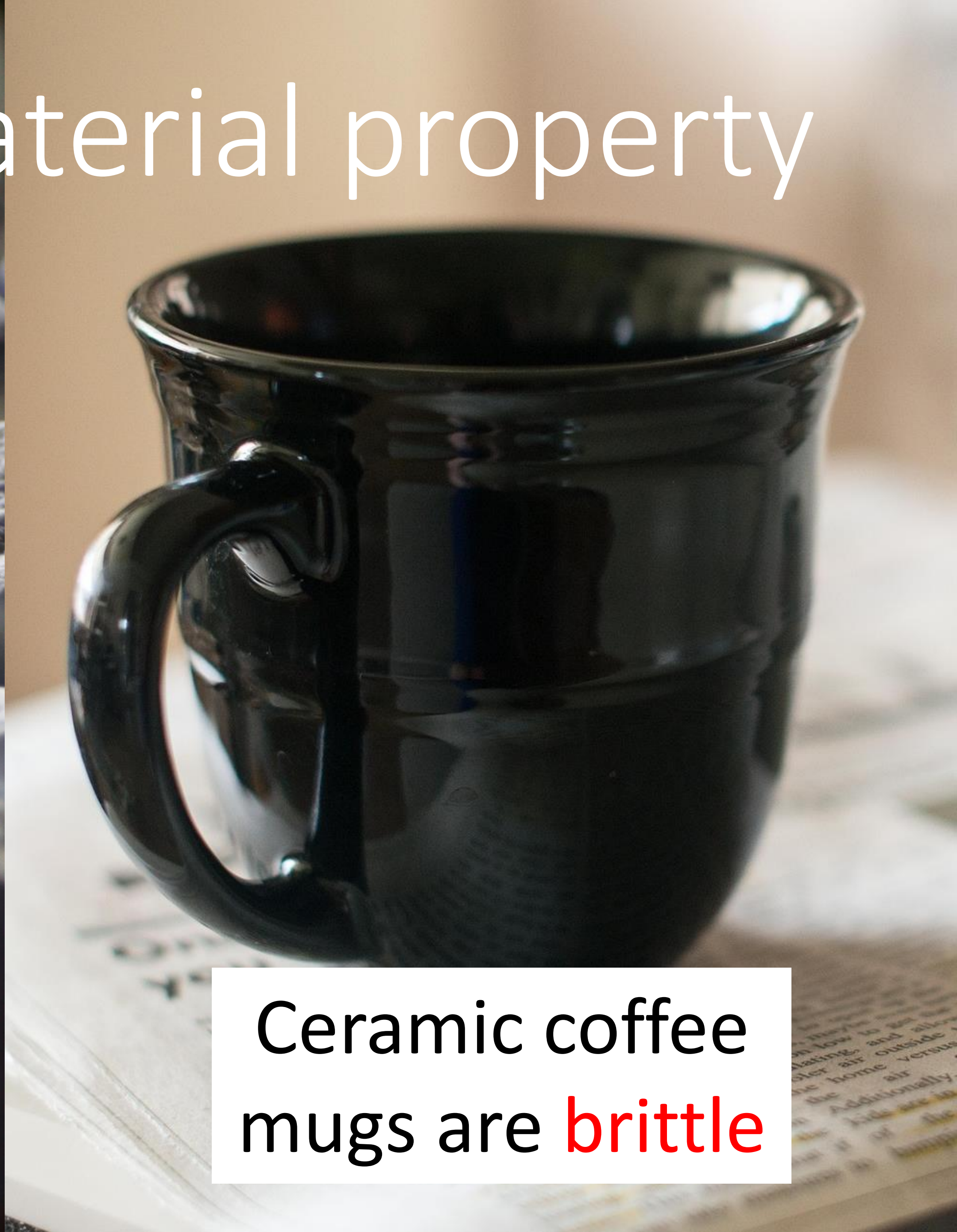
Marshmallows are soft

Ceramic coffee mugs are stiff

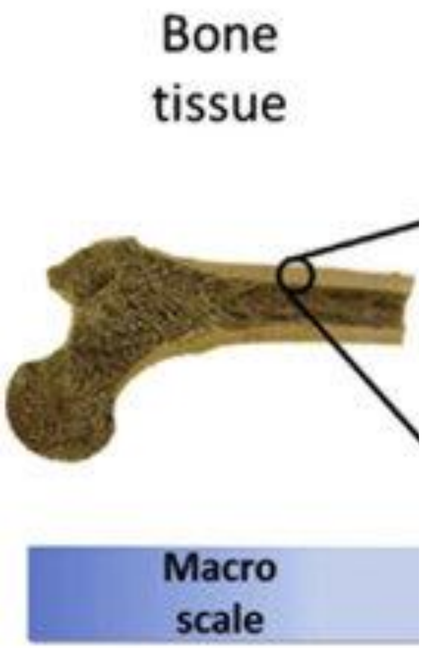
John Morgan

Fracture (K) is a material property

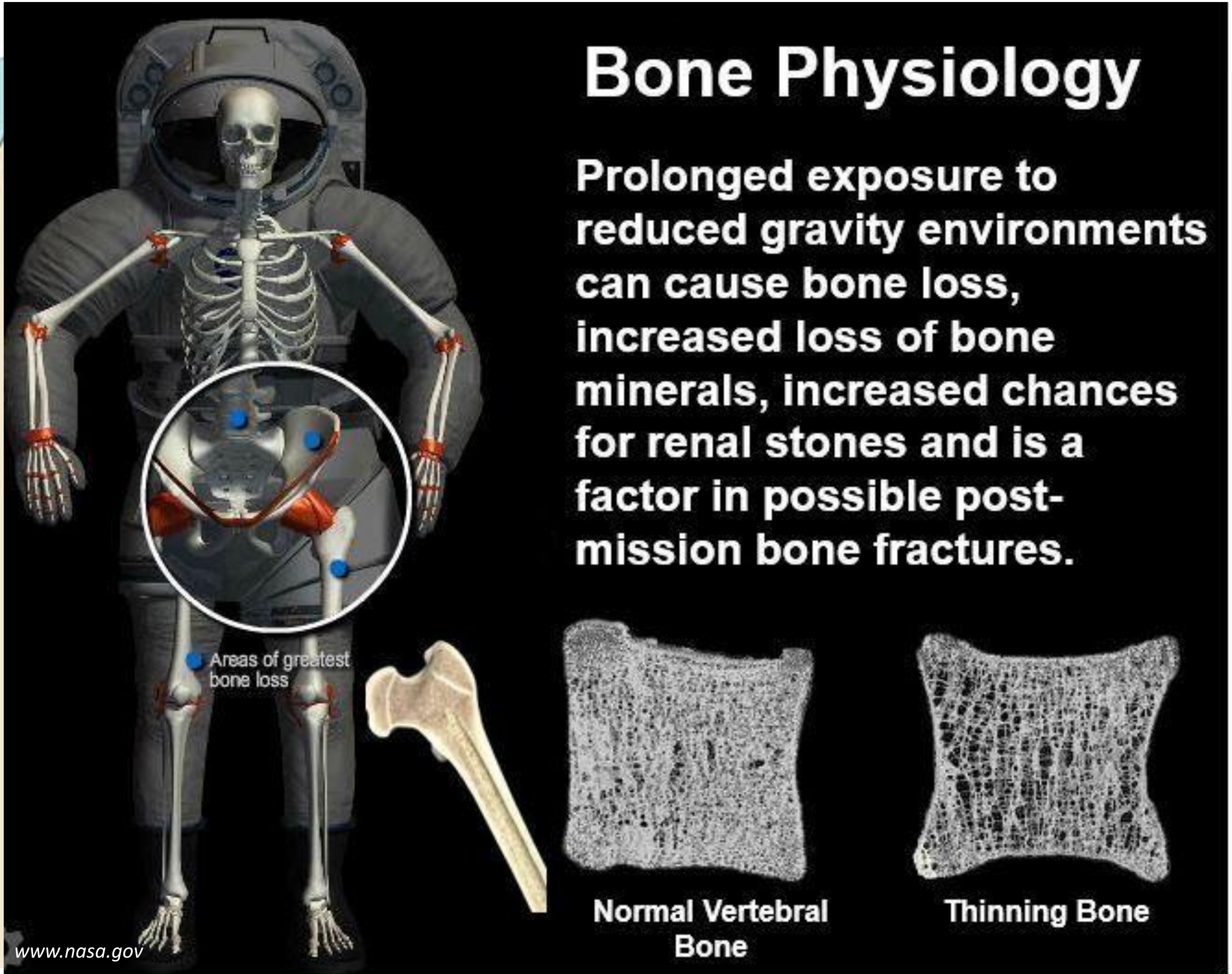
John Morgan



Bone’s structure is hierarchical



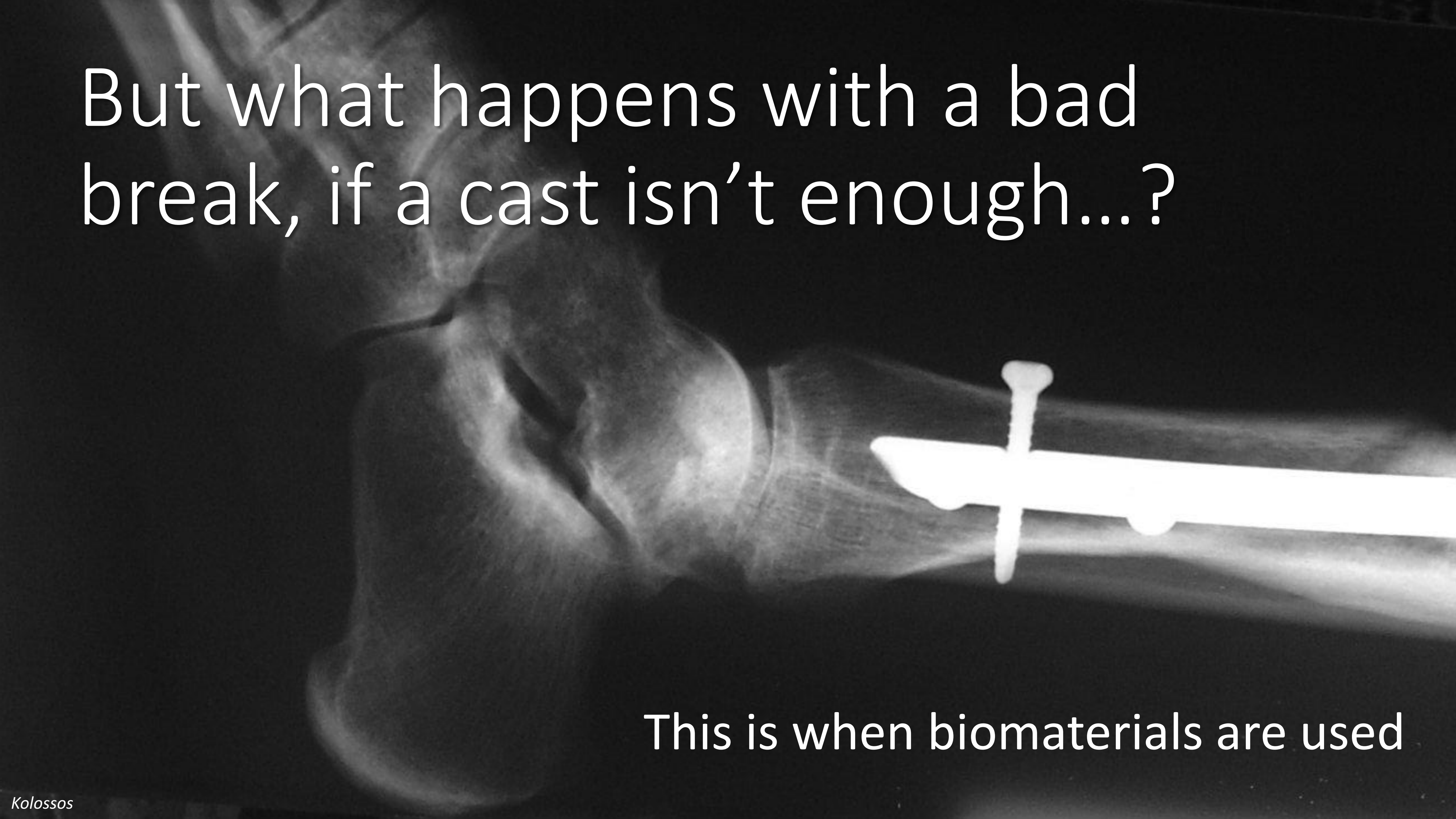
https://www.nature.com/articles/ncomms2720



www.nasa.gov

Smal

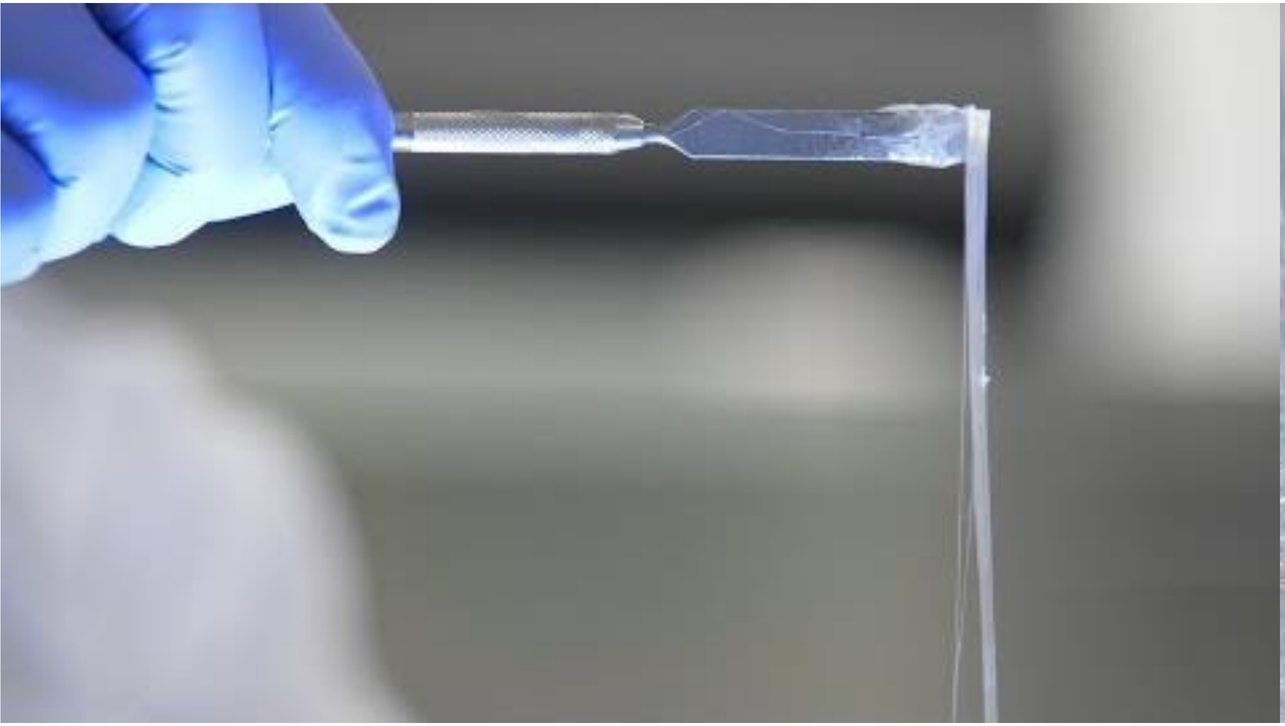
But what happens with a bad break, if a cast isn't enough…?

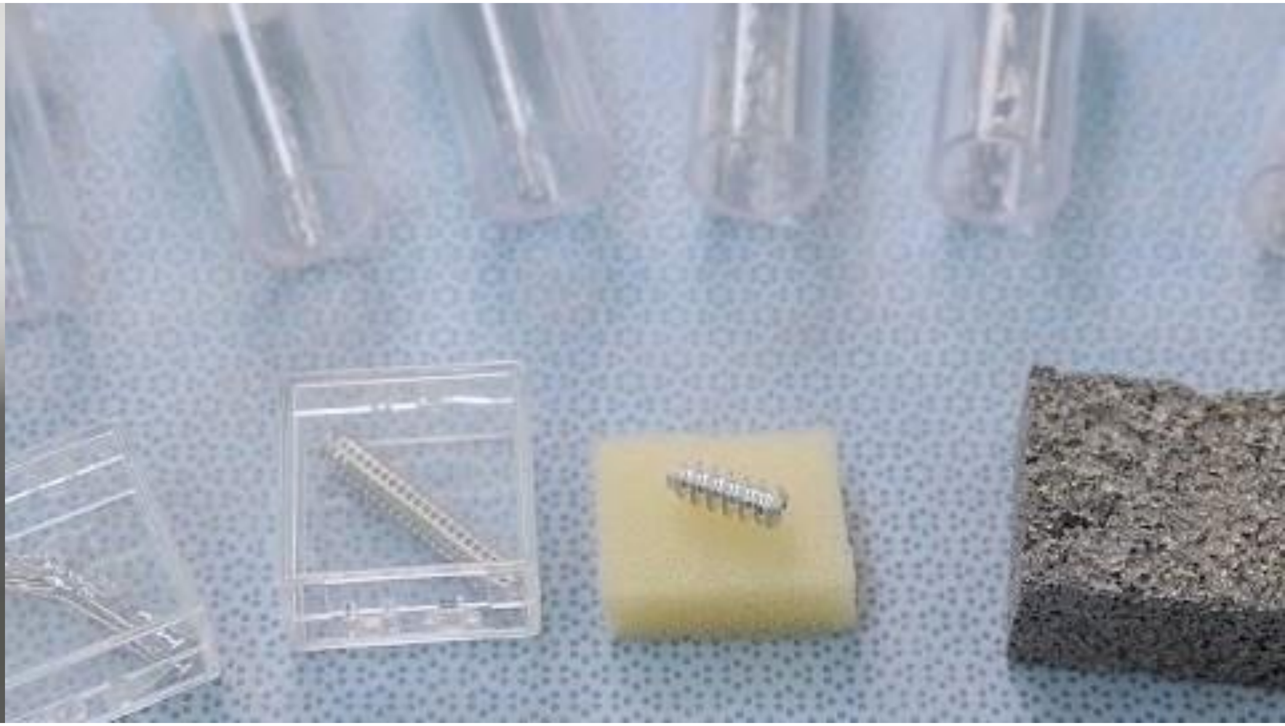


This is when biomaterials are used

Kolossos

What are biomaterials?





Which metals do you think are used?

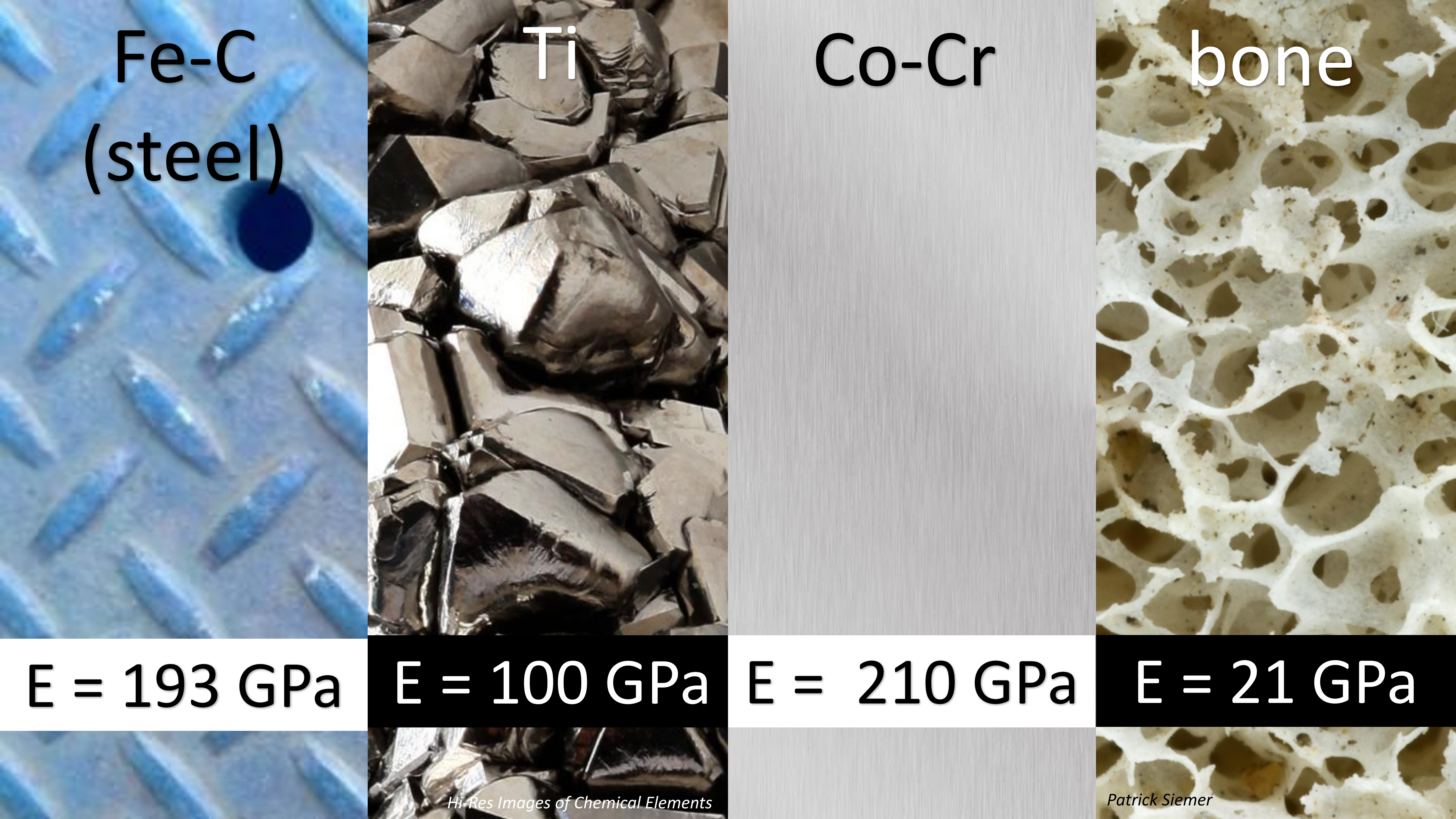
steel?

titanium?

aluminum?

cobalt-chromium?

DanR



Fe-C
(steel)
Ti
Co-Cr
bone
E = 193 GPa
E = 100 GPa
E = 210 GPa
E = 21 GPa
Hi-Res Images of Chemical Elements
Patrick Siemer

Design Challenge Activity!

Using only a single sheet of paper and Elmer's glue make something to support…

1 textbook, 5 textbooks, a person (is that possible?!)

Think about the properties of bone and use those ideas to inspire your solutions!

- Does your design have a special structure?
- Does it use a composite material?

Post-activity questions

- What designs supported the most weight?
- Which designs were crushed?
- What properties of bone did you use?
- How did you try to solve the problem?