Things We Can’t Learn From Nature

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Nature’s Little Tricks

- It’s good to be inspired by Nature when designing new materials etc.
- But Nature has some tricks which we can’t imitate.
- Because of these tricks, Nature can use a material at higher stress levels than we can use the same material.

Some of Nature's Tricks:

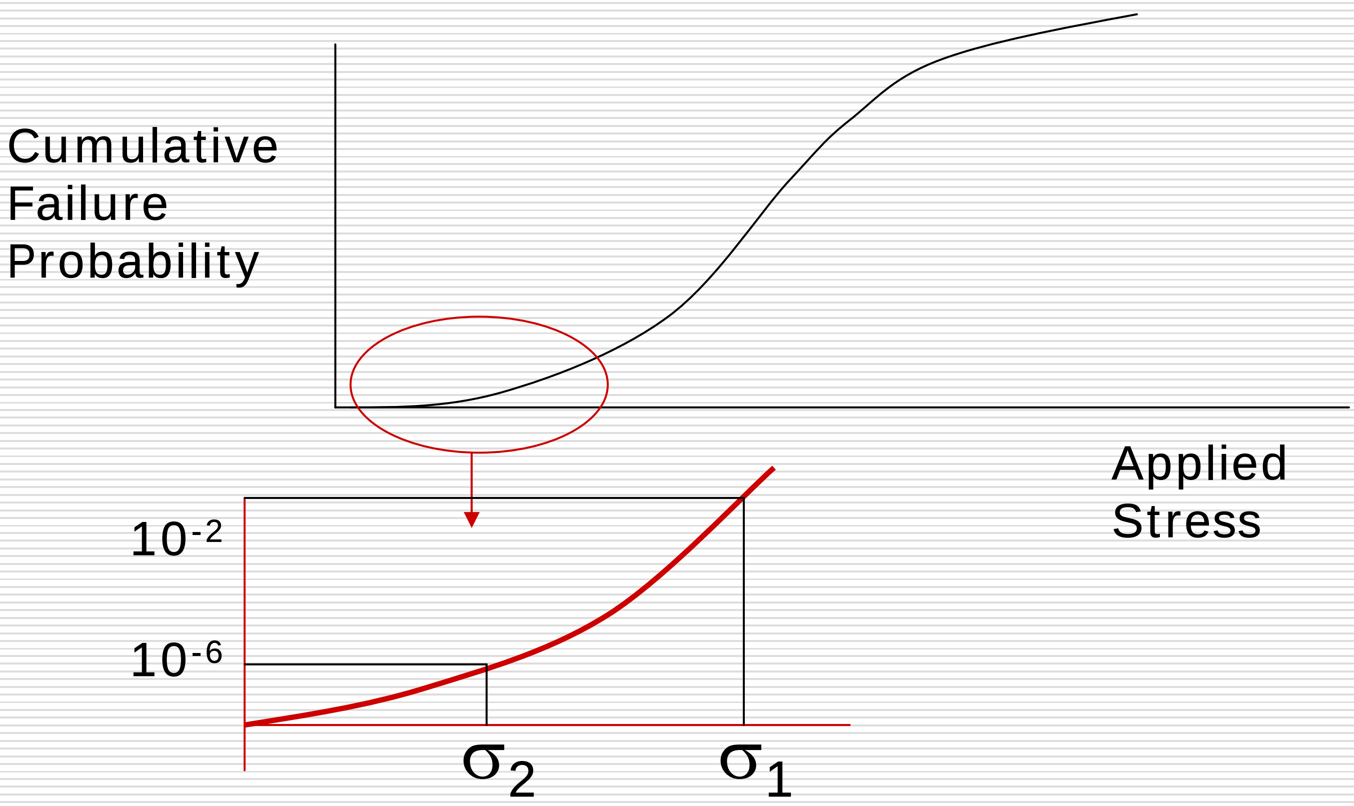
- High failure probabilities
- Continuous repair
- Pain
- Precisely tailored microstructures

In this talk I'm going to consider each of these tricks and try to quantify the advantage which they confer.

Failure Probabilities

- Nature can live with high failure probabilities.
- Probability of a bone breaking during life: primates 0.01 – 0.03: birds 0.002-0.004 (Currey 2006).
- Engineering structures typical $P_f = 10^{-6}$

Quantifying Failure Probabilities



Quantifying the Effect of P_f

We showed that bone conformed to a Weibull distribution:

$$P_f = 1 - e^{-\left(\frac{\sigma}{\sigma_o}\right)^n}$$

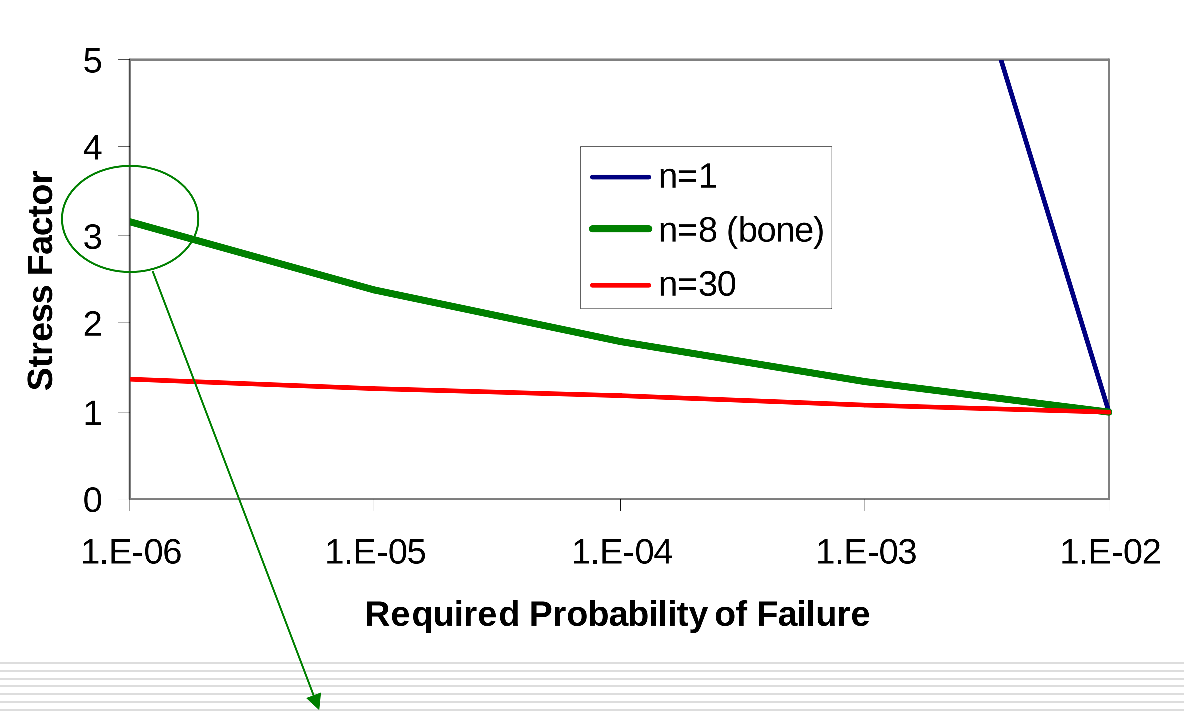
...with an exponent n = 8 (for high-cycle fatigue).

For simplicity, assume a constant applied stress.

To change from P_{f1} to P_{f2} requires a change in stress from σ_1 to σ_2 where:

$$\frac{\sigma_1}{\sigma_2} = \left(\frac{\ln(1-P_{f1})}{\ln(1-P_{f2})}\right)^{1/n}$$

Quantifying the Effect of P_f

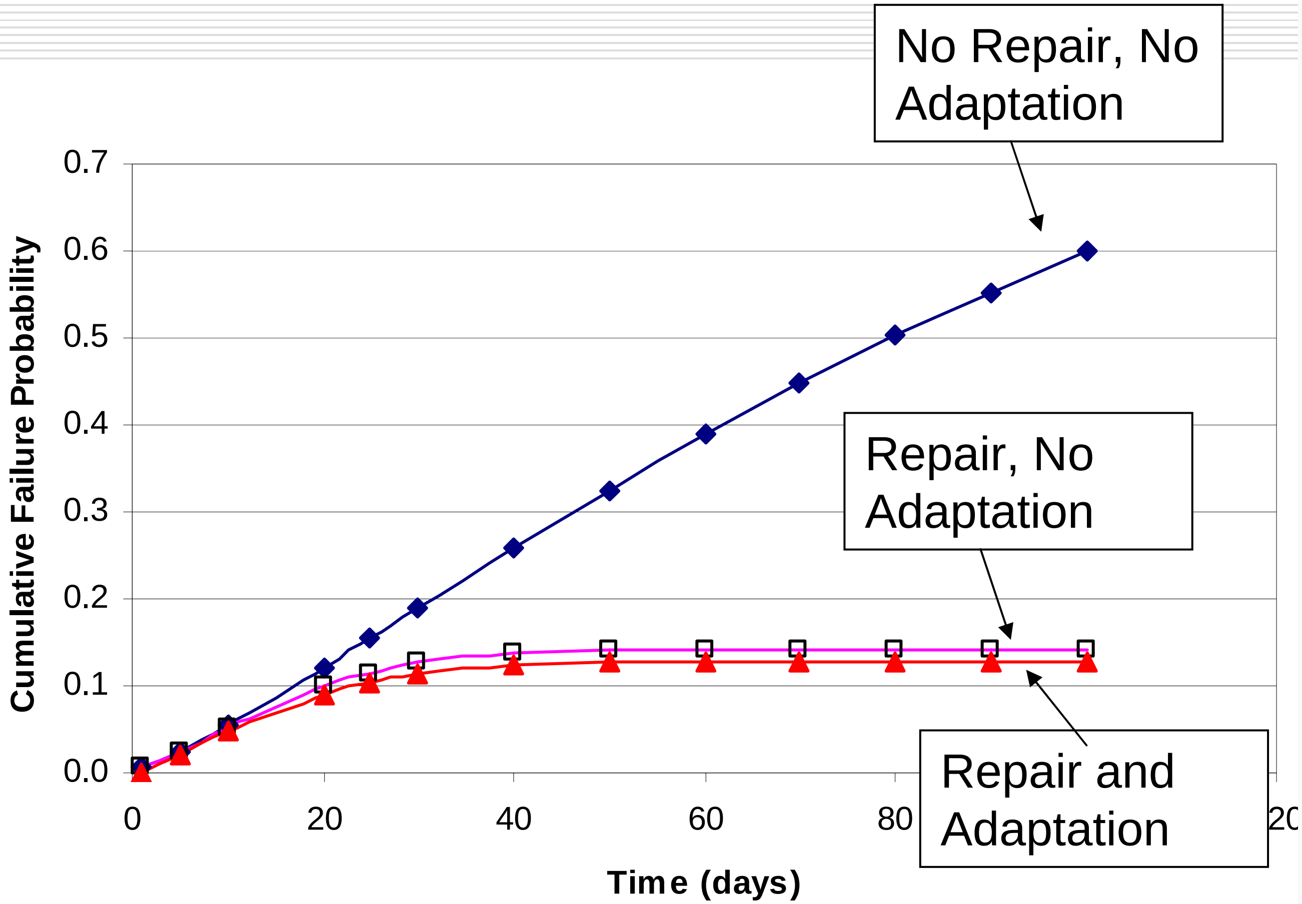


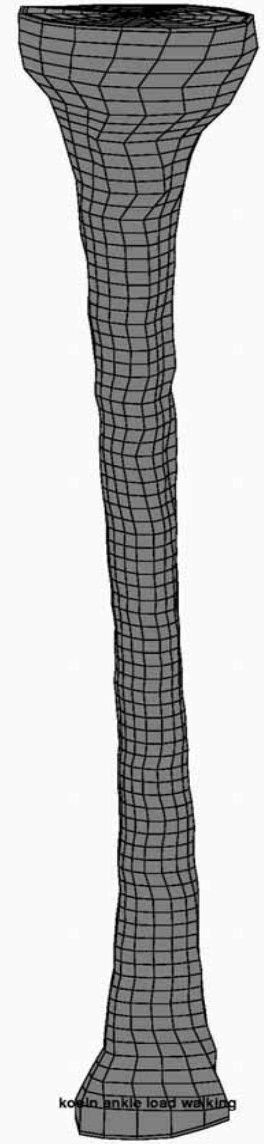
To reduce P_f to 10^{-6} you would need to reduce stress by a factor of **3.2**

Self-Repair

- Bone cells can detect cracks 100μm long
- They can be repaired within days
- This allows bone to live dangerously!
- Self-repair exists in some biological materials, but not all.

Repair and adaptation

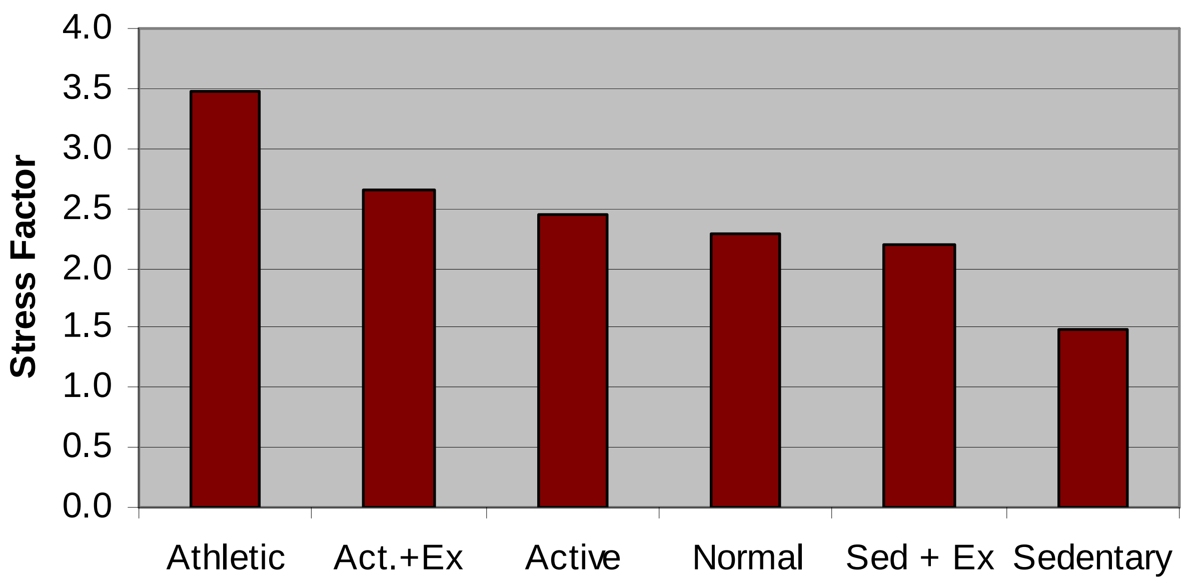




Predictions of stress fractures in athletes

LIVING WITHOUT REPAIR

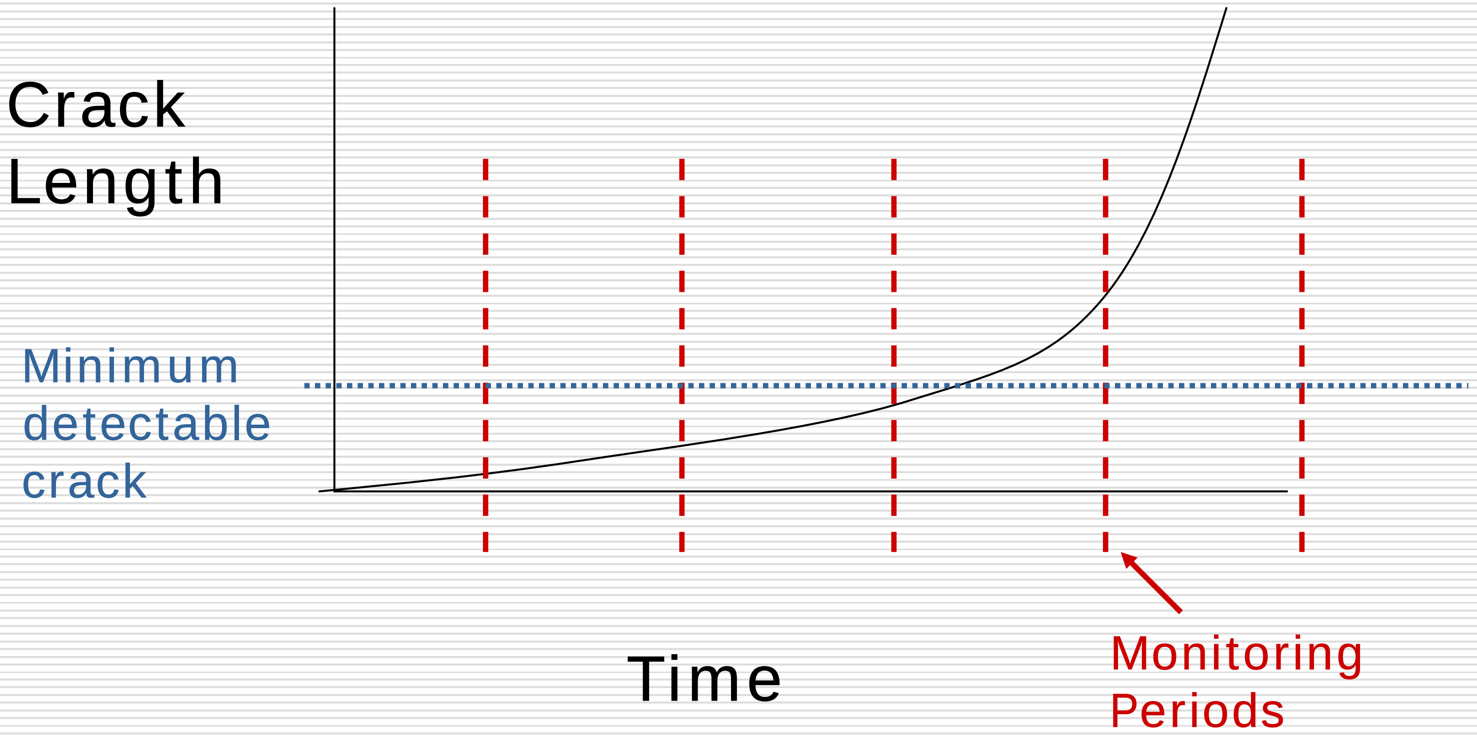
- To keep failure probability the same (1% per bone over lifetime)
- Bone's fatigue-life curve has an exponent of 6.6
- Need to reduce stresses by the following factor:



Pain

- Critical level of damage is detected…
- …and further loading effectively prevented…
- …instantaneously, thanks to continuous monitoring.

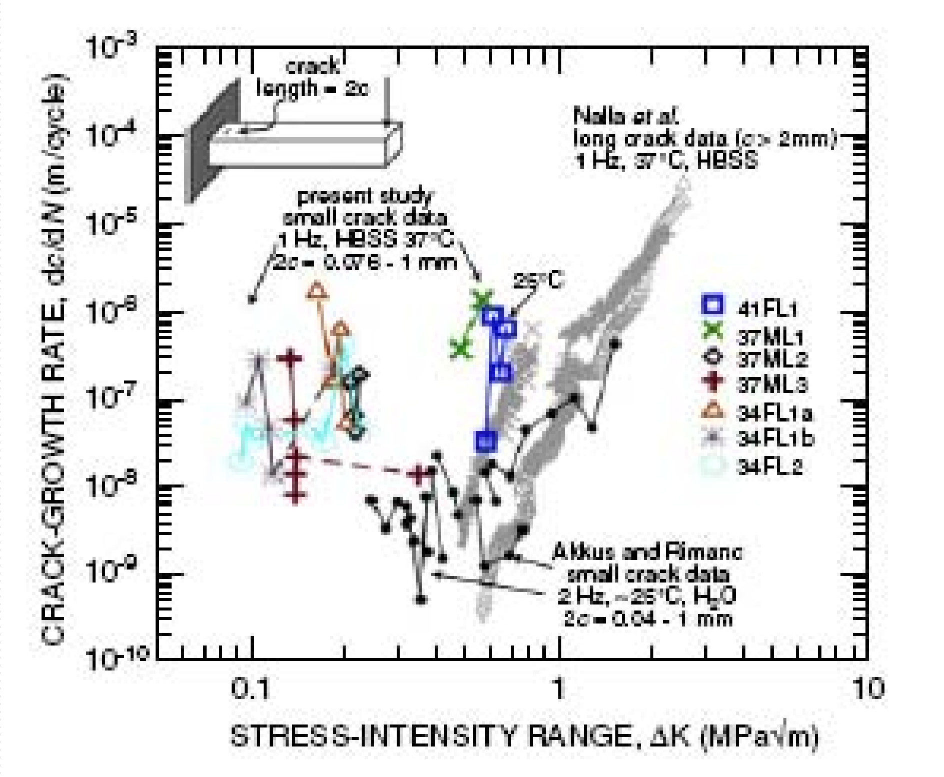
Quantifying the effect of pain



Quantifying the effect of pain

- Some approximate figures:
- Pain occurs when crack length is about 1mm
- Fracture occurs at a critical crack length of about 4mm (given bone's $K_c = 4MPa(m)^{1/2}$ and a max stress of 40MPa)

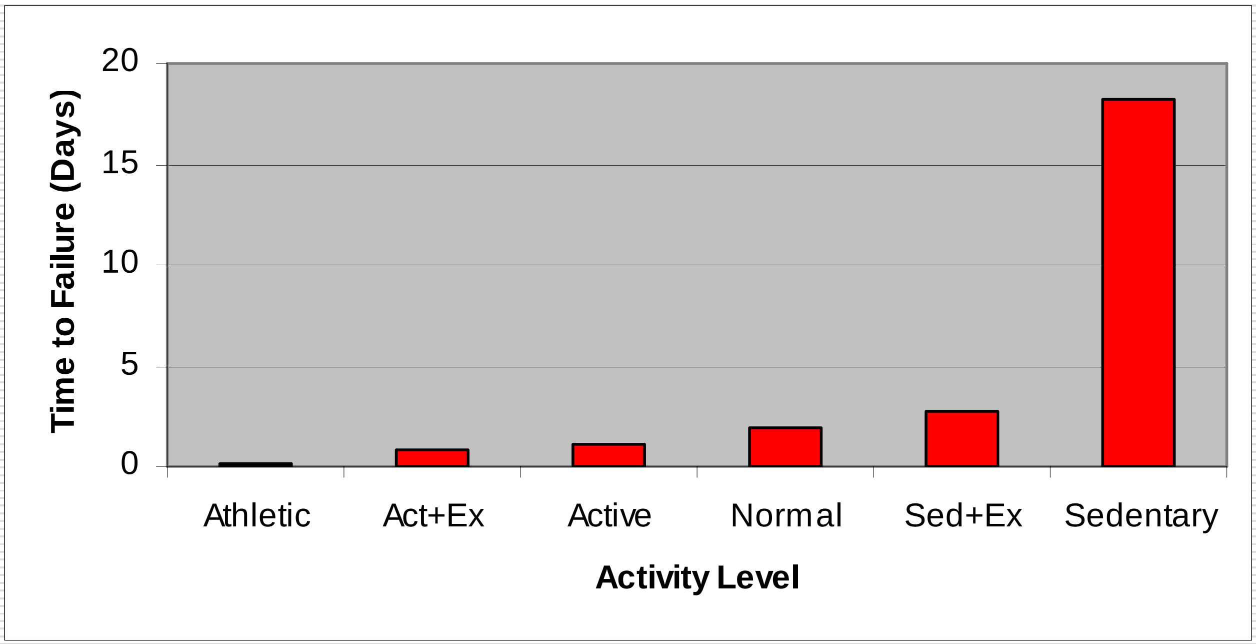
Fatigue Crack Growth in Bone



Kruzic et al 2006

Predicted Time to Failure

- Assuming you go on using the bone after pain starts
- Depends on your activity level
- Anyway time is short!



Standard activity levels defined by Whalen et al

Effect on allowable stress

- Can be estimated by re-running the above simulations with reduced stress.
- The effect of stress on life is given by the exponent in the Paris curve, which is 4.5 for bone.
- Assume we have monitoring once a year, instead of continuously.
- For normal or active people, stress would have to reduce by a factor of 3-4.

Precisely Tailored Structures

- Natural materials are almost always fibrous.
- The fibres are arranged to best advantage, following local stresses.

Examples

- Cartilage
- Tendon/bone attachments
- Tree branch/trunk attachments

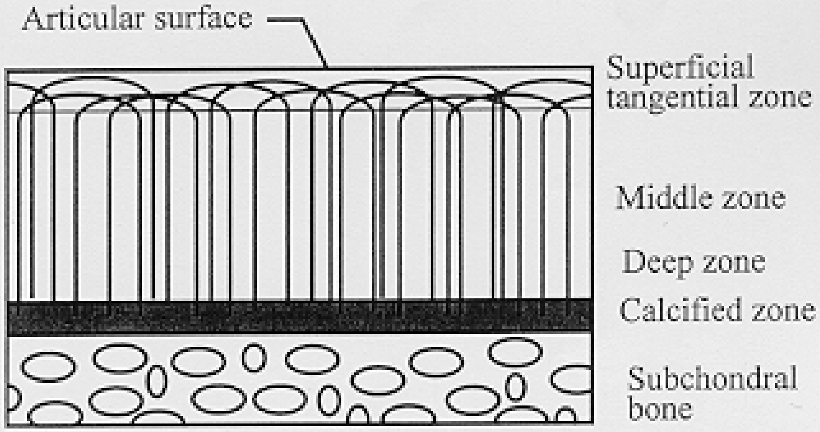
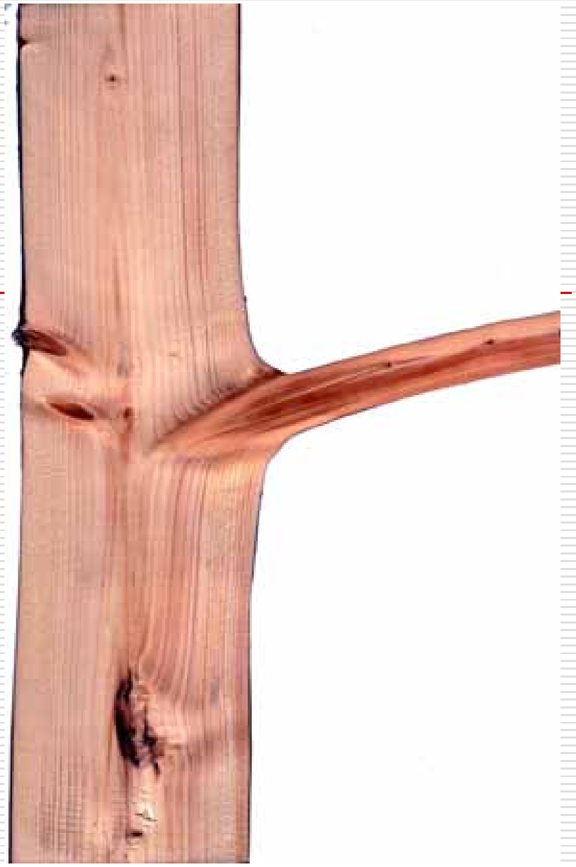


FIGURE 7.3. Schematic diagram of collagen fiber orientations in articular cartilage.

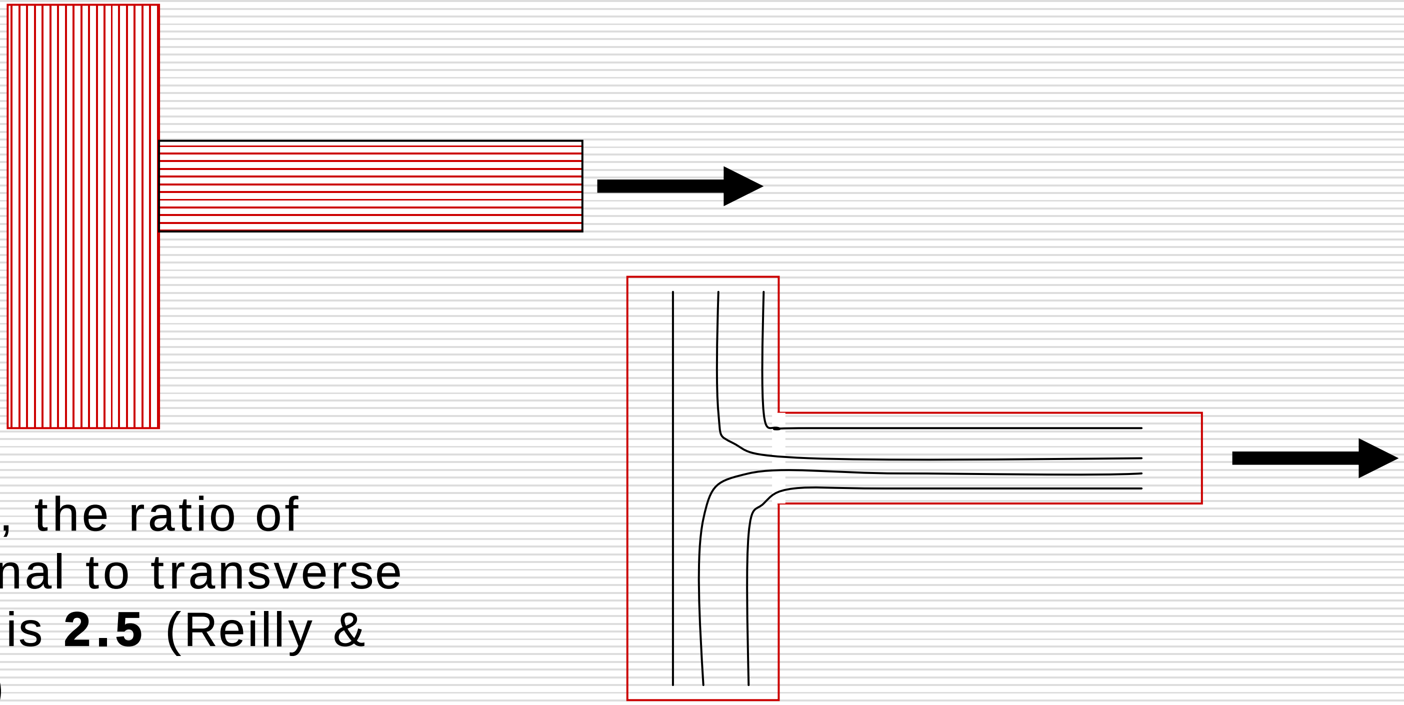


The arrangement of wood fibres at a trunk/branch junction. (Photo: Dr.Ulrich Muller, Linz, Austria)

Quantifying this Effect

- Obviously difficult
- Varies from case to case
- A simple estimate could be the ratio of strengths in the best and worst directions

Example: a joint (e.g. tree branch or tendon/bone insertion)



For bone, the ratio of longitudinal to transverse strength is **2.5** (Reilly & Burstein)

Summary of Factors for Bone

High Failure Probability	3.2
Self Repair	3.5
Pain	3.5
Tailored Micro-structures	2.5

Combining These Factors

- If each factor acts independently, we should multiply them together.
- But the Repair and Pain factors are not independent; they are both affected by the rate of damage.
- The factor estimated for Tailored Microstructures is an upper bound, 1.5 is probably more realistic for bone.
- So the overall factor is 3.2 x 3.5 x 1.5 = **16.8**

Lower Stress Means More Weight

- To reduce stress by x16.8 in a load-bearing member, without changing length, means increasing the cross section.
- Bones are loaded with a mixture of bending and compression. When these have similar magnitudes the weight increase will be $(16.8)^{5/6}$ = **10.5**.
- This tenfold increase in bone weight will itself add extra stress by increasing total body weight.
- Our bodies would probably become impossible!

In Conclusion

- It’s good to be inspired by Nature…
- …but useful to remember that Nature does things differently.
- Nature’s structural materials are poor, compared to modern engineering materials.
- They work because of some tricks which Nature can play.
- We can use some of those tricks (e.g. nano-structures) and we may learn to use others.
- But some of Nature’s tricks cannot be copied, either because we don’t have the technology or because the result would be unacceptable.