On the relationship between indentation hardness and modulus, and the damage resistance of biological materials.

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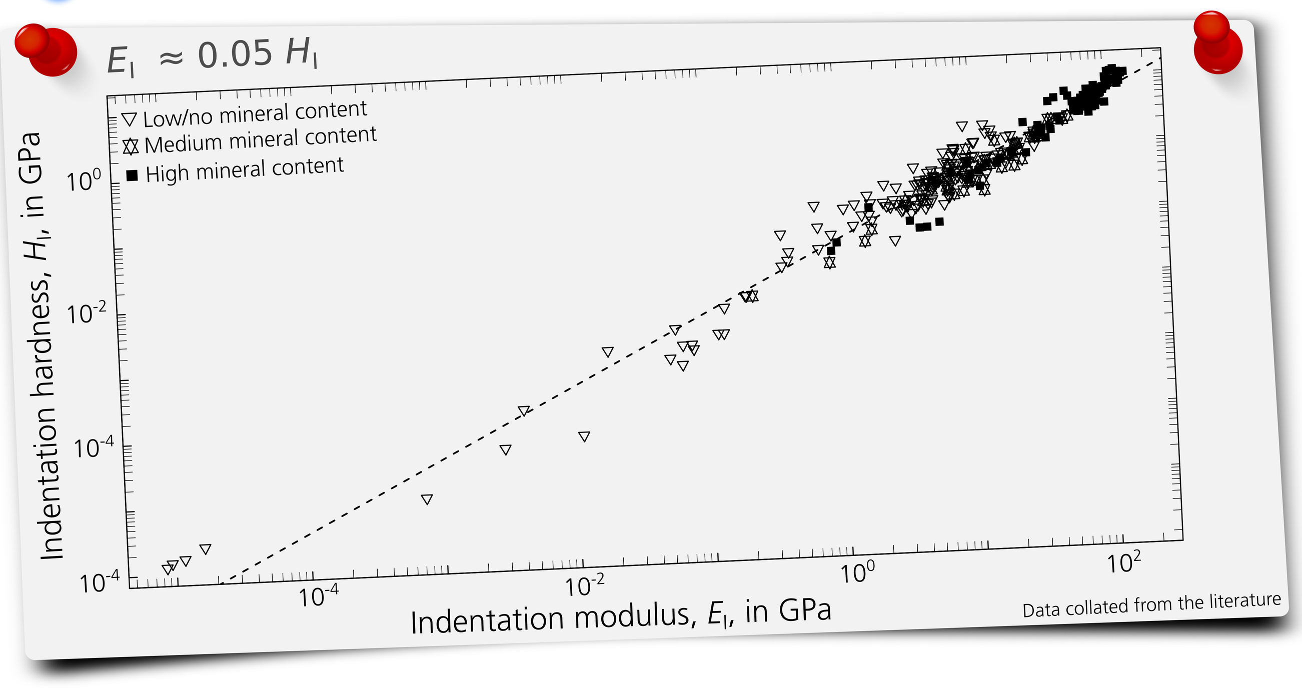
Nanoindentation has become the primary method for determining the mechanical properties of biological materials. However, most of our understanding of the measured parameters derives from 'classic' engineering materials such as metals. While elastic properties - characterised by a 'modulus' - are well understood, plastic properties - characterised by a 'hardness' - have been more elusive. What is the relevance and functional meaning of indentation hardness, H_I?

Indentation hardness is defined as the mean contact pressure:

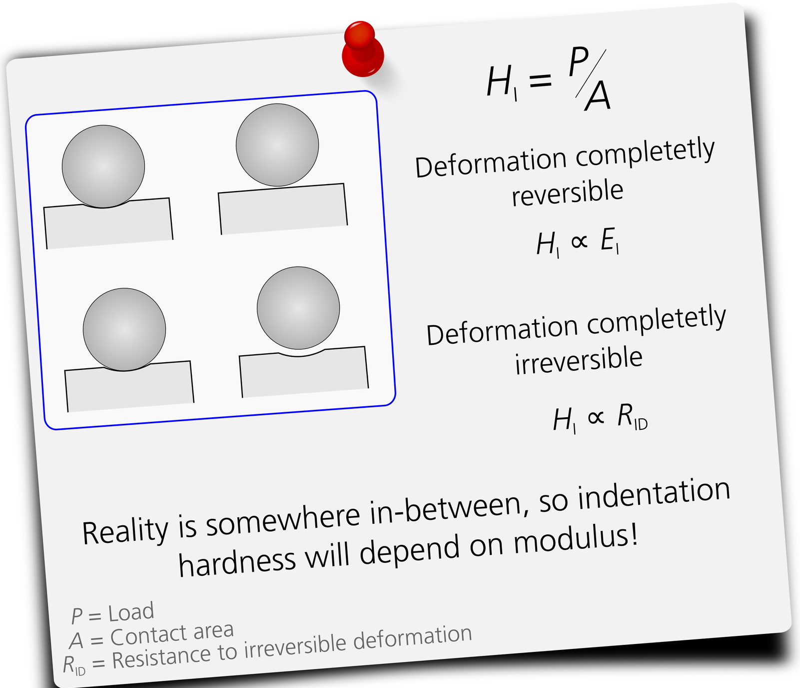
$$H_I = P/A$$

Load (P), Contact area (A)

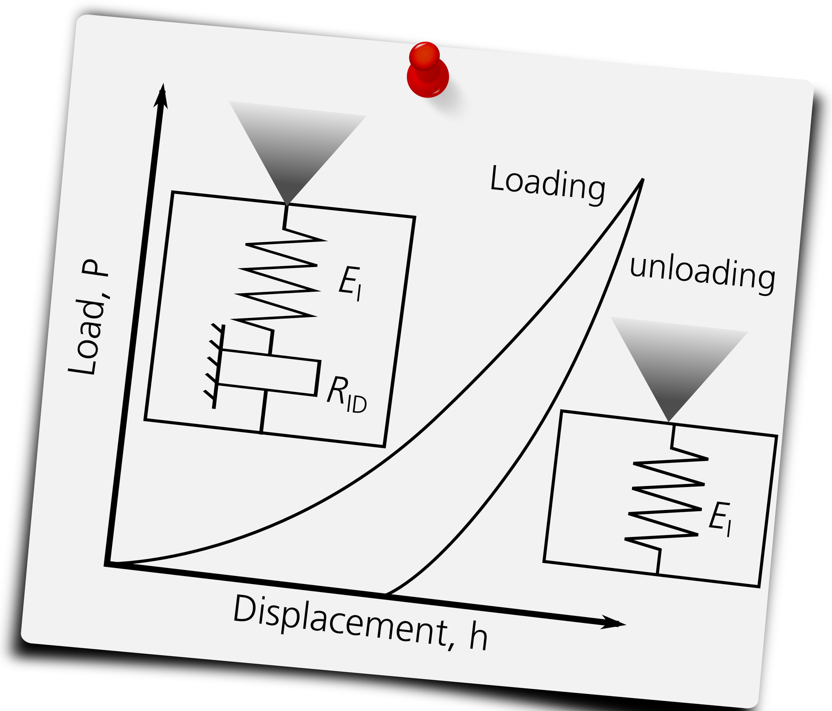
Indentation hardness is directly proportional to indentation modulus



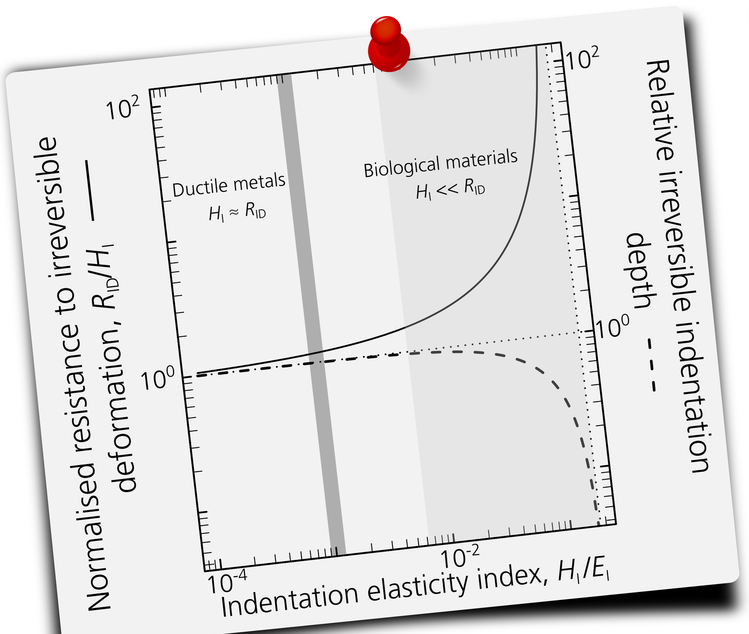
What is the origin of this correlation?



Two limiting cases



A lumped parameter model for indentation



Resistance to irreversible deformation (Indentation hardness, Indentation modulus, Geometrical constant)

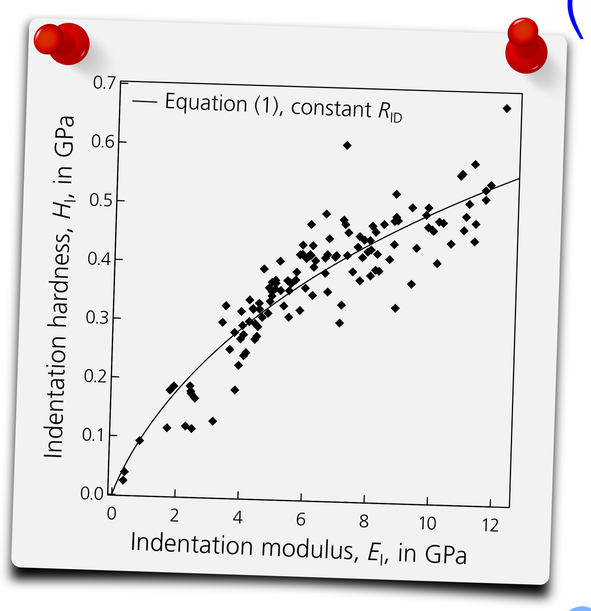
$$R_{ID} = \frac{H_I}{\left(1-\sqrt{H_I/E_I}\sqrt{2/\tan(\beta)}\right)^2} \quad (1)$$

Indentation hardness is not an accurate measure for resistance to irreversible deformation in biological materials

Three examples where this matters

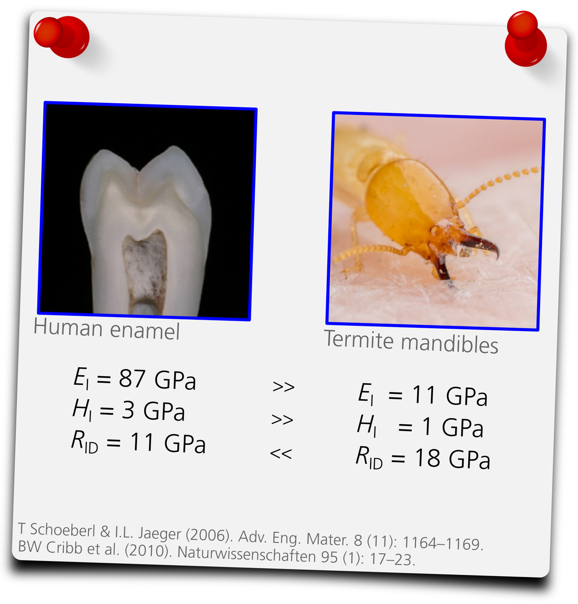
(I)

Anisotropic materials (example: adhesive hairs of tarantulas, indented at different angles relative to their longitudinal axis)



~ Changes in elastic properties affect indentation hardness

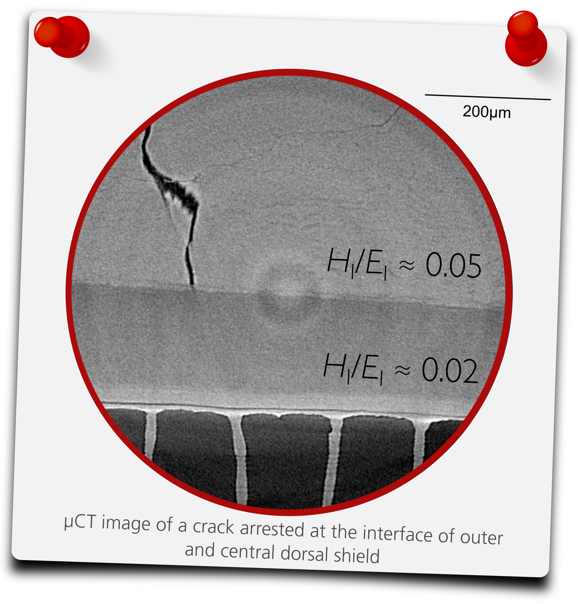
(II)



Tools which need to be wear resistant (example: cutting/grinding tools)

~ High indentation hardness does not imply high resistance to irreversible deformation *per se*

(III)

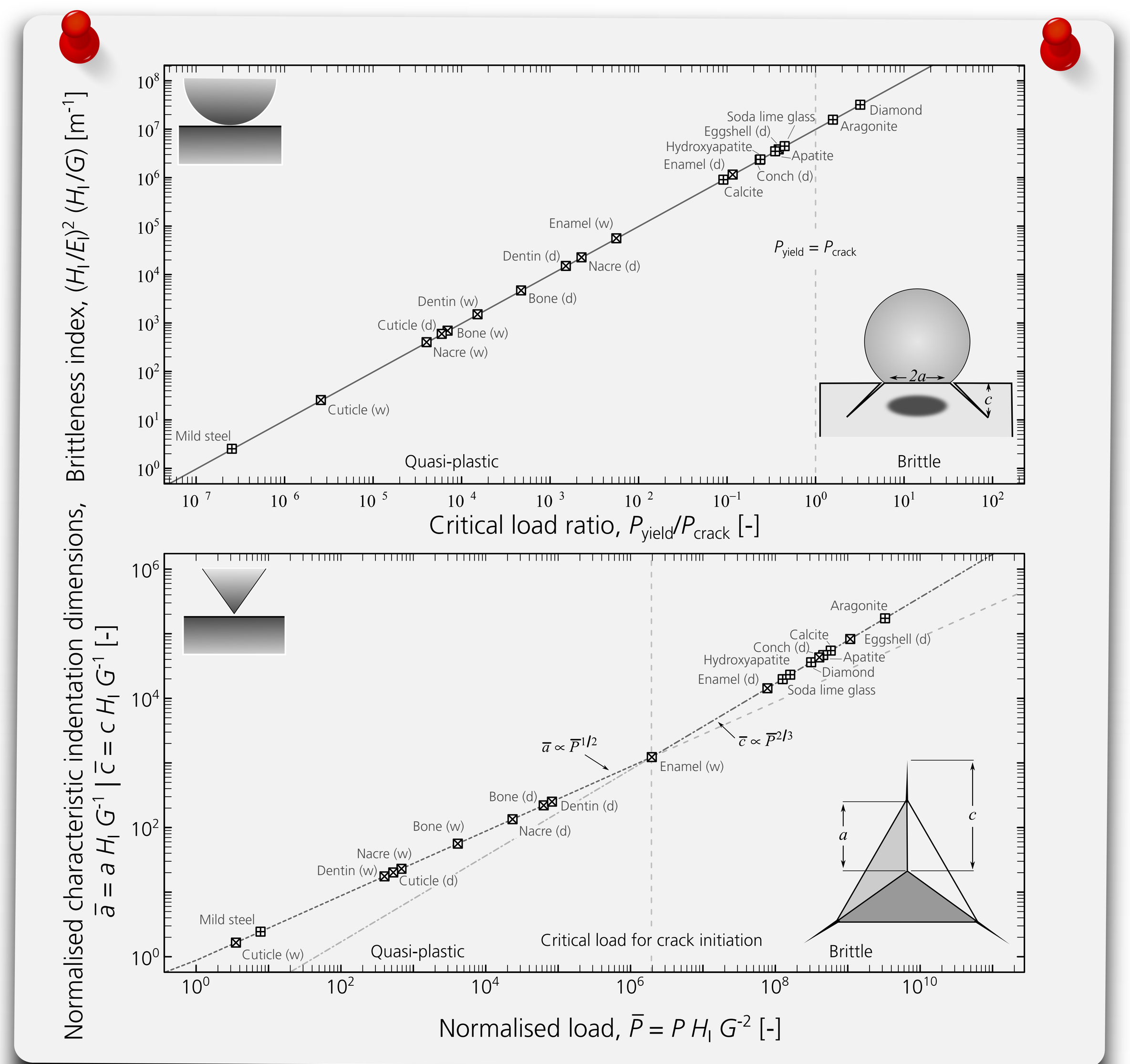


Structures which require high toughness (example: Dorsal shield of cuttlefish)

~Unusually low elasticity index may signify functional adaptation

Does indentation hardness tell us something about propensity to damage?

Inelastic deformation can occur *via* brittle fracture (cracking) or yielding (quasi-plastic deformation). Combined with the critical strain energy release rate, G, indentation hardness can serve as a brittleness index.



~Biological materials achieve high toughness *via* hydration and composite design, at the cost of being more susceptible to quasi-plastic deformation

Conclusions

~ Indentation hardness is an elastic-plastic hybrid property

~ Resitance to irreversible deformation depends on the ratio between indentation hardness and modulus

~ High toughness leads to dominance of quasi-plastic deformation

What are the structural features which allow quasi-plastic deformation in biological materials?

Labonte D, Lenz AK & Oyen ML (2017): On the relationship between indentation hardness and modulus, and the damage resistance of biological materials Acta Biomat, published online