From atoms to structures – how spiders turn weakness into strength

Markus J. Buehler*

Laboratory for Atomistic and Molecular Mechanics, Department of Civil and Environmental Engineering, Massachusetts Institute of Technology, Cambridge, MA

* E-mail: mbuehler@MIT.EDU

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Massachusetts Institute of Technology

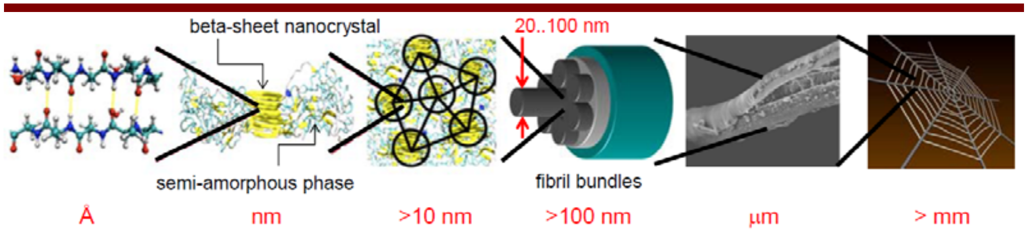
Steel: strength ~1 GPa
strong bonds

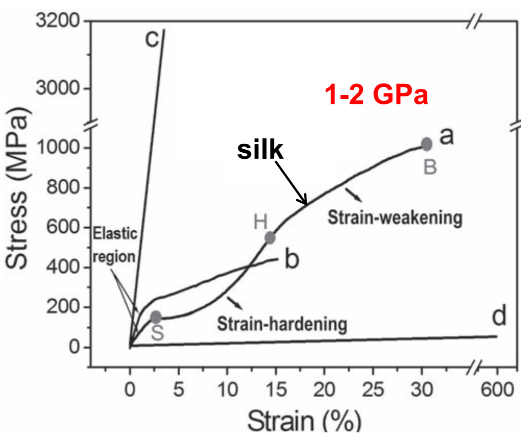
Spider silk: strength ~1-2 GPa & 60% strain @ failure
weak bonds

Made @ room temperature via self-assembly

Natural construction material

Structure & mechanical response of spider silk

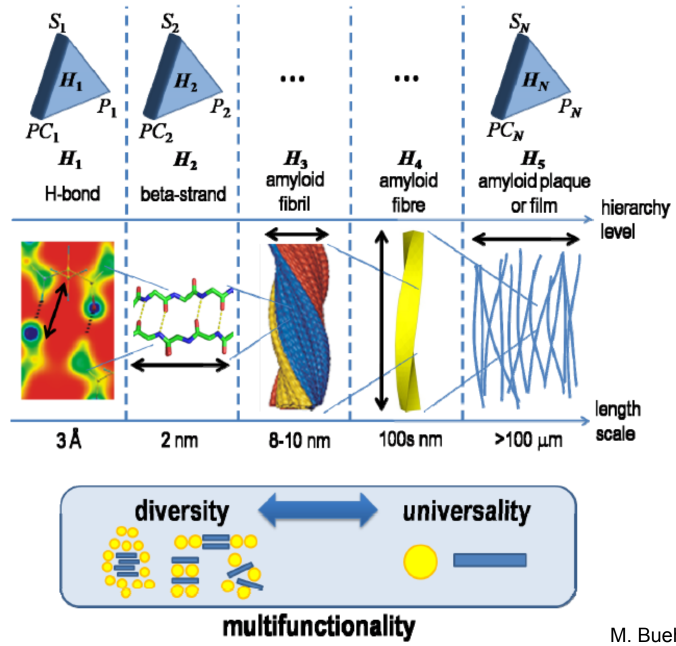




- ➢ Features structure from **nano** (H-bond, protein, nanostructure, etc.) to **macro** (spider web)
- ➢ Important chemical bond: **H-bond**

Z. Shao and F. Vollrath, *Nature*, 2002; N. Du *et al.*, 2010

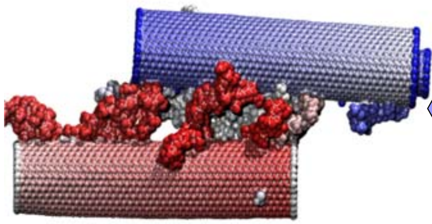
Universality-diversity paradigm



Create multifunctionality (diversity) by changing structural arrangements of few (universal) constituents rather than inventing new building blocks

M. Buehler, *Nature Nanotechnology*, 2010

Overarching goal: bioinspired design



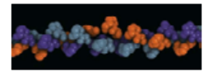
Synthetic fibers
(CNTs, polymer, etc.)

Natural fibers
(silk, wood, etc.)

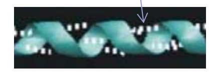
Protein structure, from gene to molecule

Sequence controls structure (AH vs. BS)

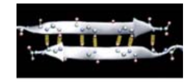
H-bonds



collagen (tropocollagen)



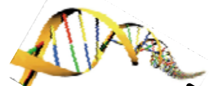
alpha-helix



beta-sheet

random coil (unstructured)

ACGT



Four letter code "DNA"
Genetic information

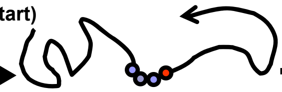
Combination of 3 DNA letters equals one amino acid (AA)

E.g.: Proline –
CCT, CCC, CCA, CCG …

Transcription/ translation

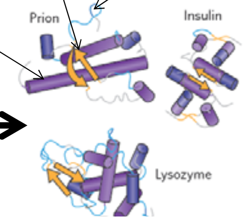
N-terminal (start)

C-terminal end



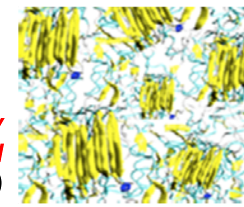
.. - Proline - Serine - Proline - Alanine - ..

Sequence of amino acids (polypeptide): 1D structur



Folded protein molecule (3D structure)

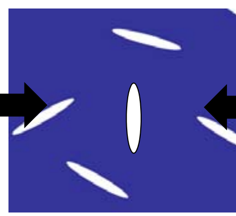
3 examples shown

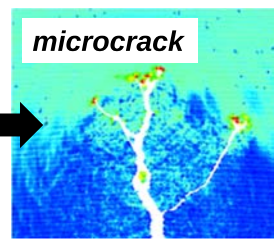


Hierarchical assembly forms protein material (silk, bone, tendon,…)

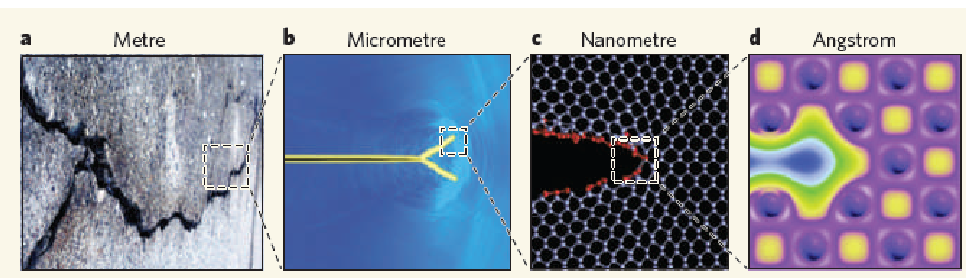
M. Buehler *et al.*, *Nature Materials*, 2009; *Nature Nanotechnology*, 2010, 2011

Material failure – across all scales





Airplane crash: failure of engineering structure



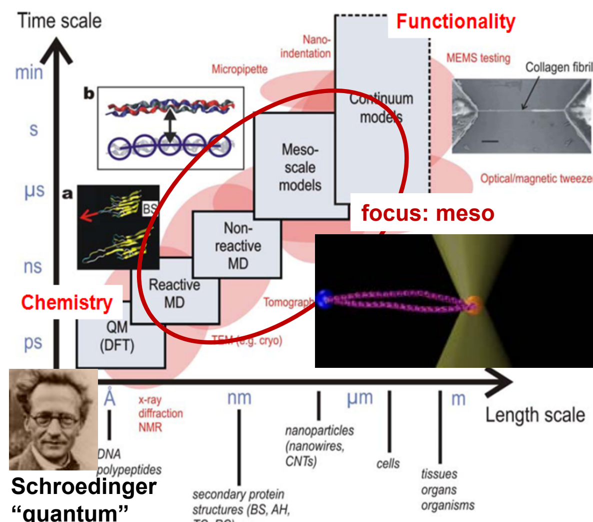
Earthquake: failure of the earth's crust

Buehler and Xu, *Nature*, 2010; M. Buehler and S. Keten, *Rev. Mod. Phys.* 2010

Approach & general impact

Buehler *et al.*, *Nature Materials*, 2009

***Combine theory & experiment** at multiple scales*



Schroedinger "quantum"

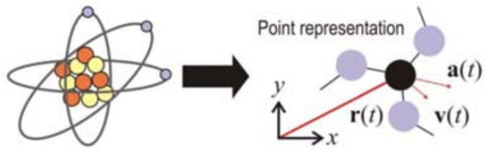
New paradigm to describe materials: Powerful bottom-up description of material mechanical properties by explicitly considering **hierarchical structure from chemical level upwards**

Basis: **chemistry force field models** derived from quantum mechanics (*i.e.*, QM, first principles)

Three-pronged research approach: "materiomics"
1. Simulation of different systems
2. Generalize insight through comparative study
3. Develop analytical models

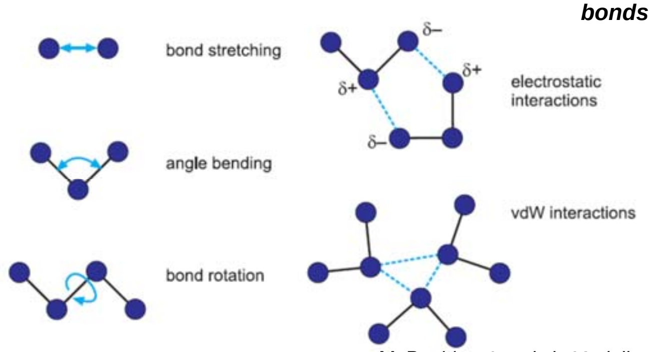
Linking chemistry, structure and mechanics

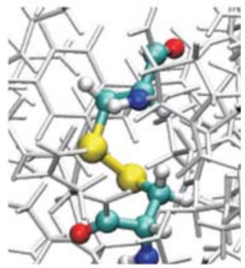
Molecular dynamics:
Fundamental model of materials "bottom-up"



$$U_{\text{system}} = U_{\text{bond}} + U_{\text{angle}} + U_{\text{torsion}} + U_{\text{Coulomb}} + U_{\text{vdW}} + \ldots$$

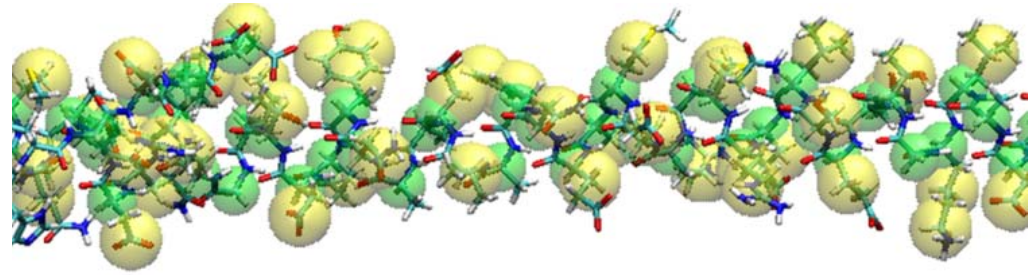
covalent bonds ***electrostatic bonds*** ***weak bonds***

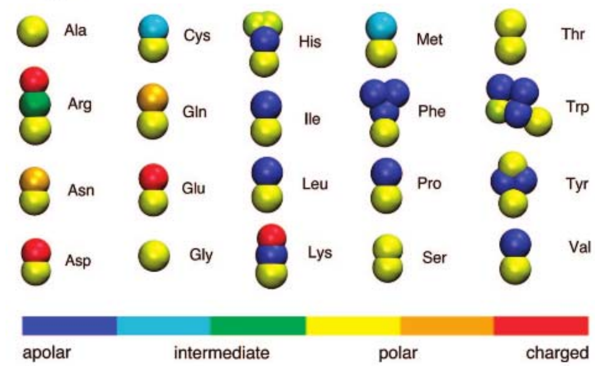




M. Buehler, *Atomistic Modeling of Materials Failure*, Springer, 2008

Coarse-graining approach – MARTINI



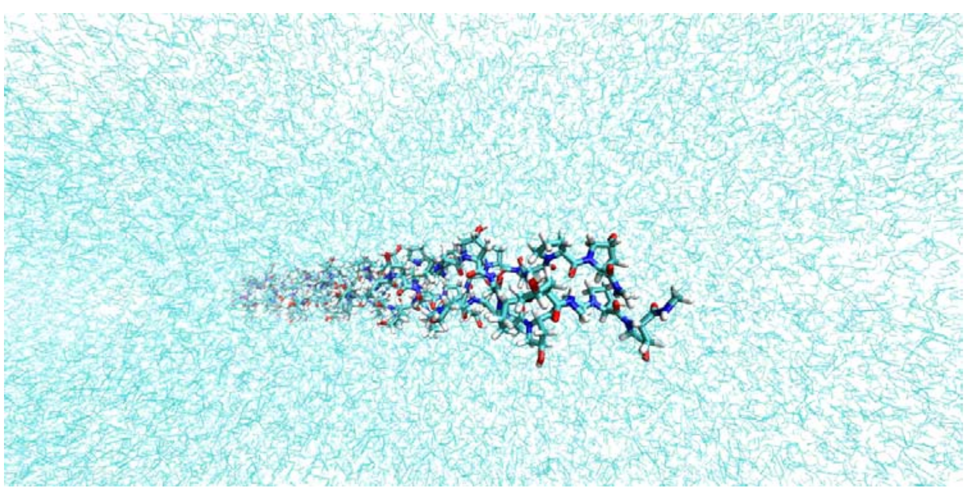


Time step ~20…40 fs (vs. 1-2 fs in MD)

1/10th of particles

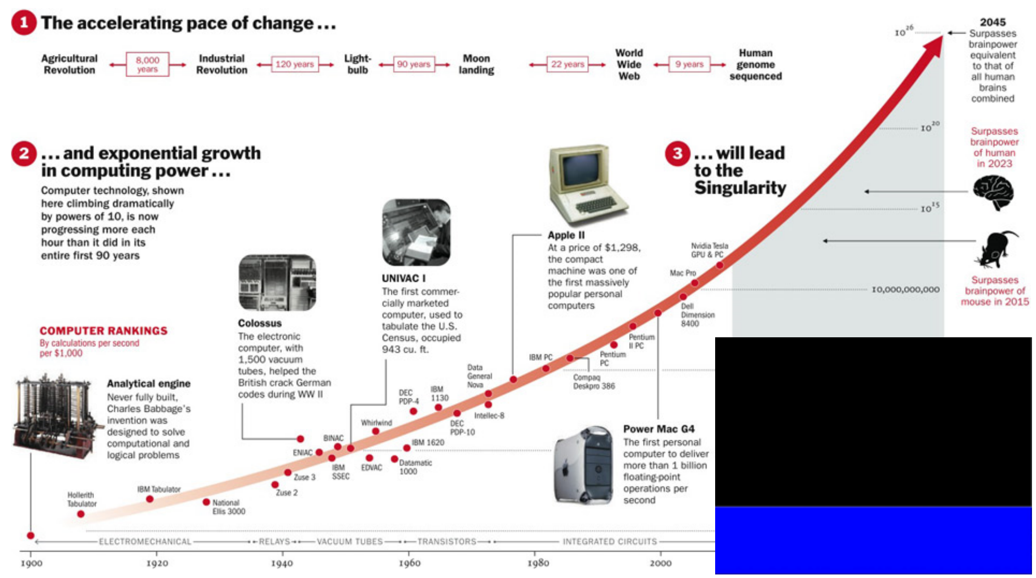
L. Monticelli, S.K. Kandasamy, X. Periole, R.G. Larson, D.P. Tieleman, S.J. Marrink. The MARTINI coarse grained forcefield: extension to proteins. *JCTC*, 4:819-834, 2008

Molecular simulation – movie



Large-scale simulation of complex biomolecules now possible

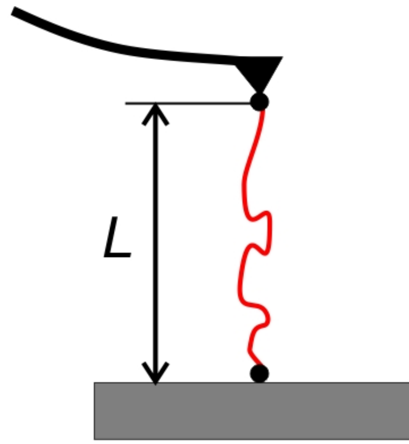
Emergence of opportunity

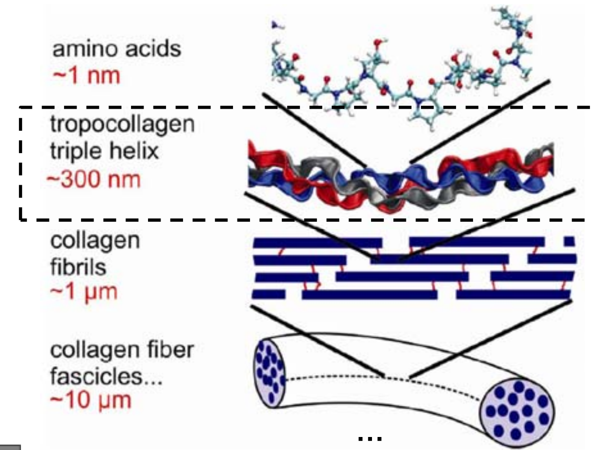


Source: TIME magazine

Supercomputing is a key tool

Pulling on a single collagen molecule

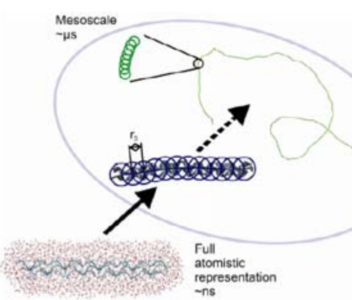




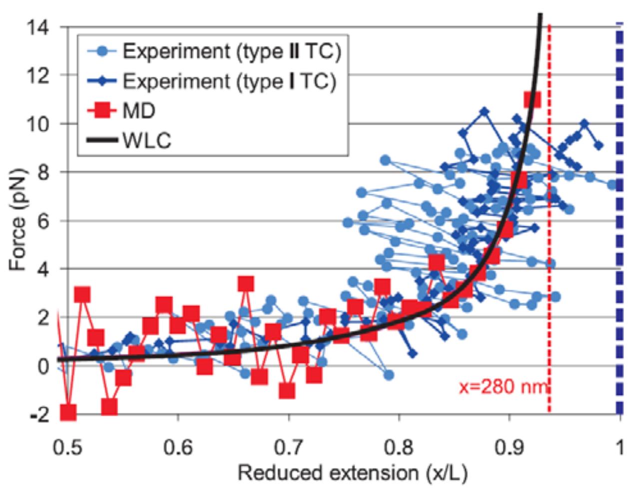
M.J. Buehler, *Proc . Nat'l Academy of Sciences USA*, 2006

Pulling on a single collagen molecule

Coarse-graining



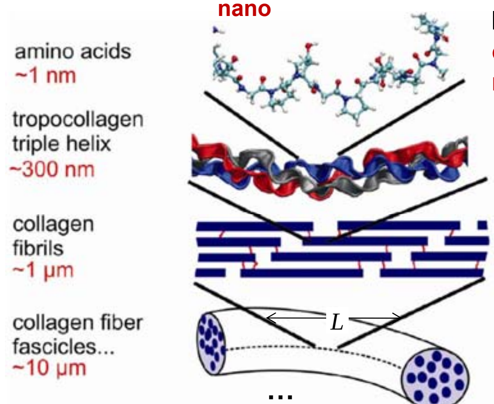
Mechanism:
Entropic elasticity
(change in configurational entropy)



Advancement in experimental equipment:
Have quantitatively confirmed predictions from our simulations

Sun *et al*., *J. Biomechanics*, 2004; Buehler and Wong, *Biophys. J., 2007*

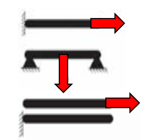
Use approach to understanding healthy collagen: bottom-up material description

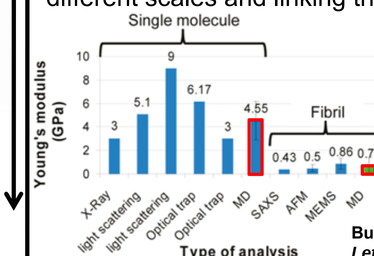


Collagen forms tissues such as: tendon, bone, cornea

Intellectual challenge: Push chemical concepts to larger scales (H-bonds, reactivity…)

Achievement: Predicted large-scale mechanical properties by systematically studying properties and mechanisms (s.a.: stretching, bending, slip, molecular breaking…) at different scales and linking them





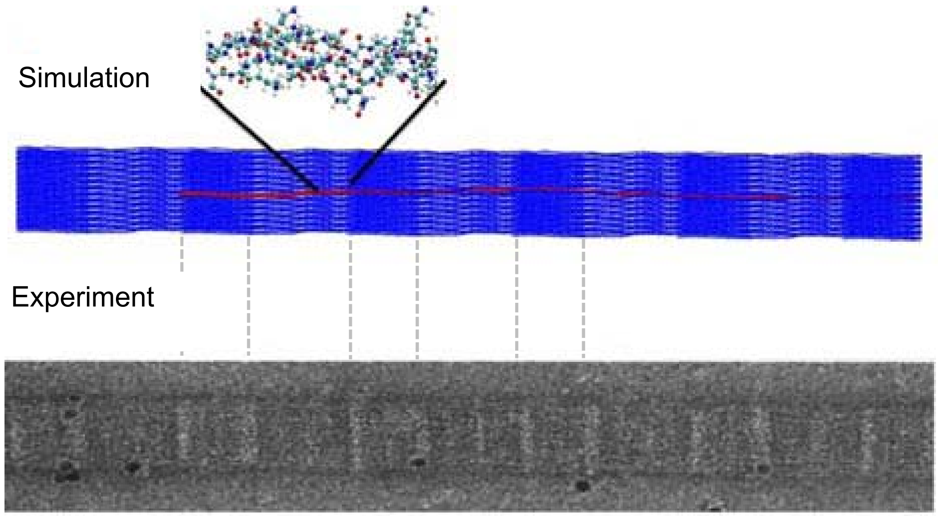
Validate by direct comparison with experiment

Buehler *et al*., *Nano Letters*, 2011

Push mechanics concepts to smaller scales (modulus, strength…)

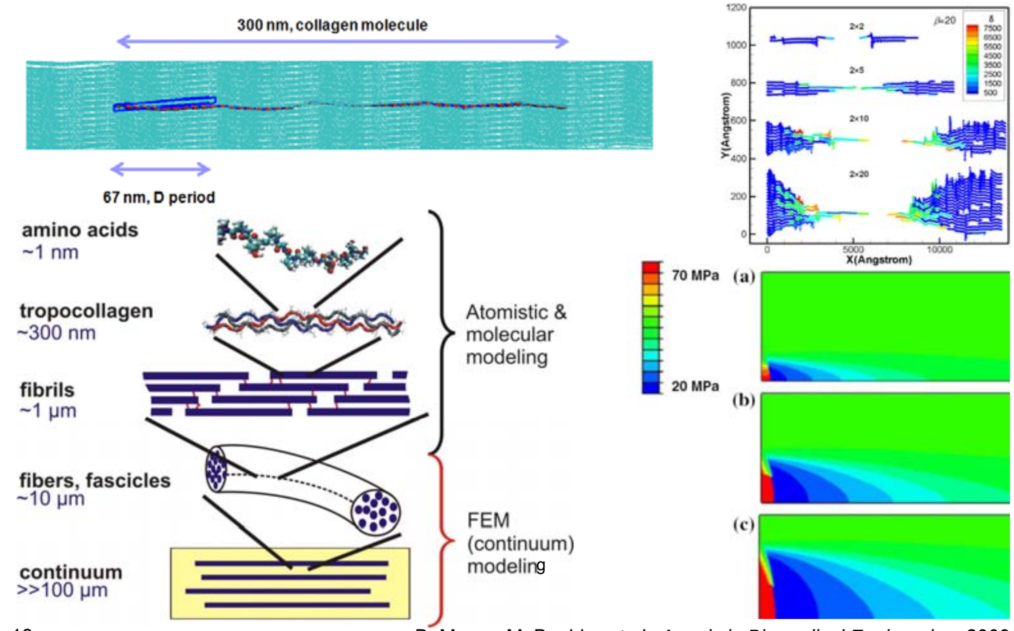
Buehler, *PNAS*, 2006; *Nano Letters*, 2011

Atomistic model of collagen fibril vs. experiment



Gautieri, Redaelli, Buehler *et al.*, *Nano Letters*, 2011

Hierarchical features of soft collagenous tissue



B. Moran, M. Buehler *et al.*, *Annals in Biomedical Engineering*, 2009

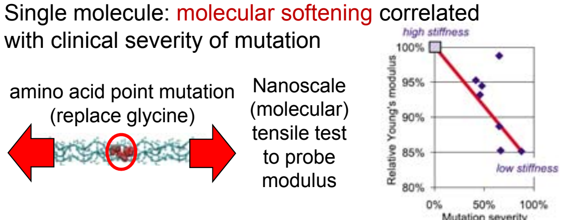
Impact: Understanding collagen mechanics in disease conditions

Bottom-up model enables changing chemical properties of molecules (e.g. mutation that causes *osteogenesis imperfecta* (OI) or brittle bone disease)

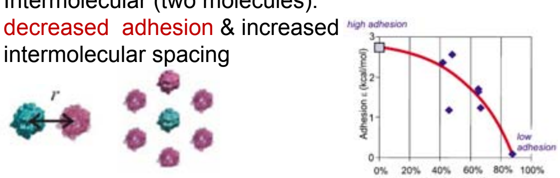
Based on a systematic analysis predict properties at fibril scale: change of deformation mechanism (stretching, slip, breaking)

Impact: Through these efforts understand physiological and disease mechanisms—correlate chemical with mechanical signatures with clinical disease severity
Results in potential new concepts for disease diagnosis and treatment

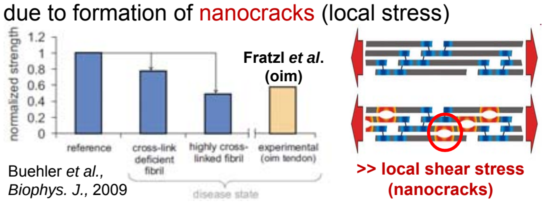
Single molecule: molecular softening correlated with clinical severity of mutation



Intermolecular (two molecules): decreased adhesion & increased intermolecular spacing



Result: At physiologic fibril level: reduced strength due to formation of nanocracks (local stress)

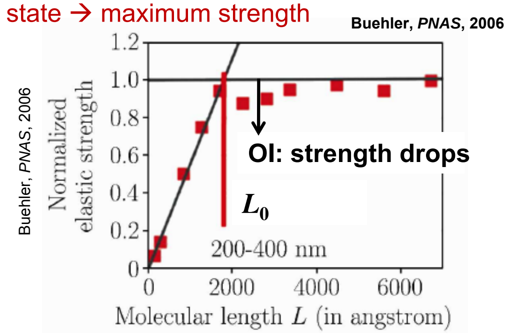


Buehler *et al.*, *Biophys. J.*, 2009

Analytical scaling law of physiological and disease collagen

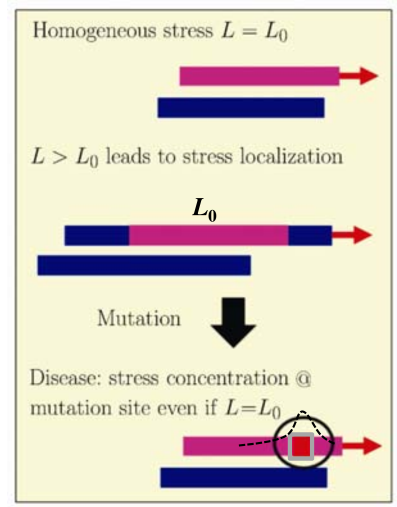
Through simulation: identified how molecule length controls strength of fibrils
At $L=L_0$ ~ 200-400 nm: homogeneous stress state → maximum strength

Buehler, *PNAS*, 2006



Physiological collagen molecule length: L~300 nm
Model critical molecular length & scaling for transition from homogeneous to localized slip using mechanics theory (fracture mechanics & shear lag model): $L_0 \sim \sqrt{2\gamma E}/\tau_{\text{shear}}$ $\quad L/L_0$

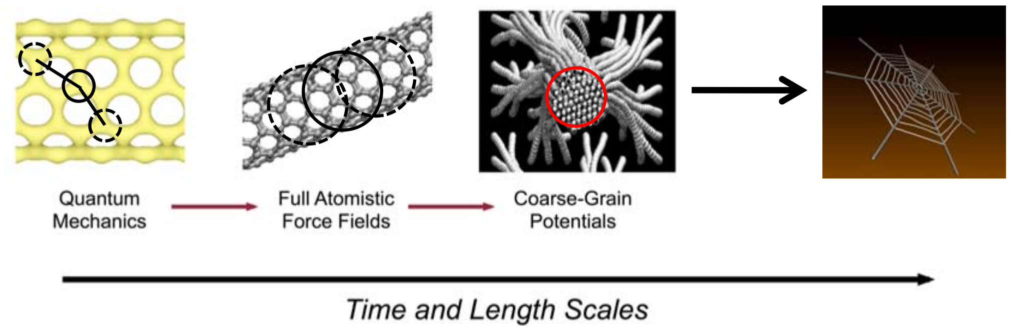
Analytical model explains mechanism in disease state



Gautieri, Uzel, Buehler *et al.*, *Biophys. J.*, 2009

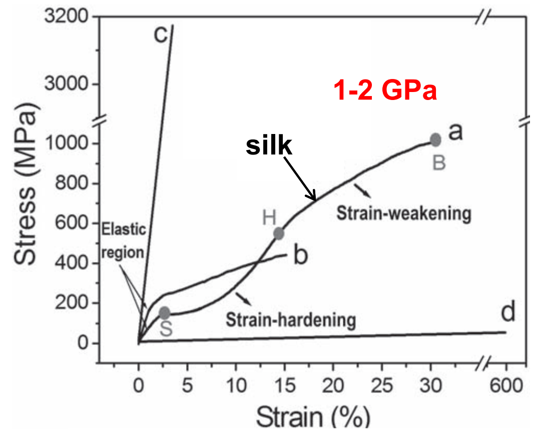
Enables a multi-scale approach

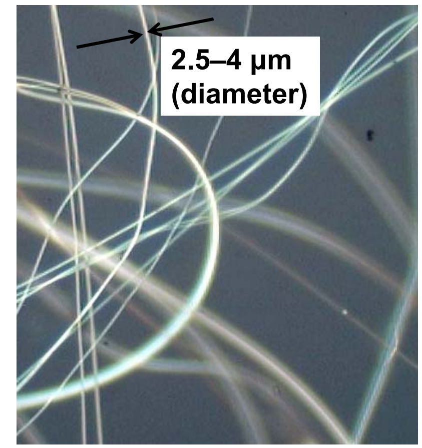
- The basis of multi-scale methodology is the parameterization of “coarse-grain” models through analysis of more complex and sophisticated “fine-grain” models.
- Already a common practice to “train” atomistic force-fields for molecular dynamics simulations via results from quantum mechanics (e.g. DFT), extended across all scales



Mechanical response of spider silk

How can we explain the mechanical properties of spider silk from a fundamental & mechanistic perspective?

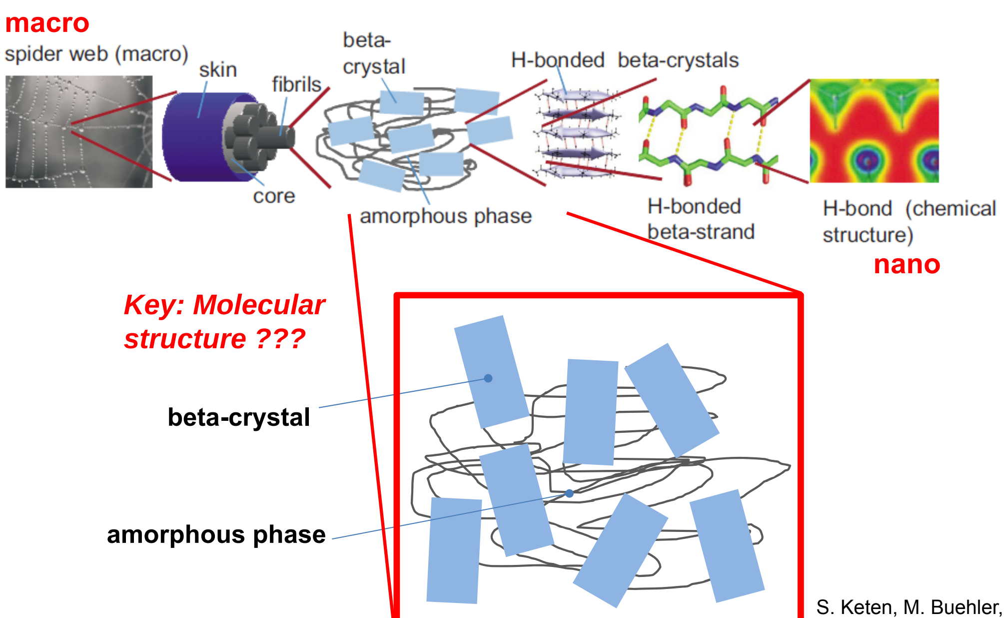




Under polarized light
http://www.microlabnw.com/

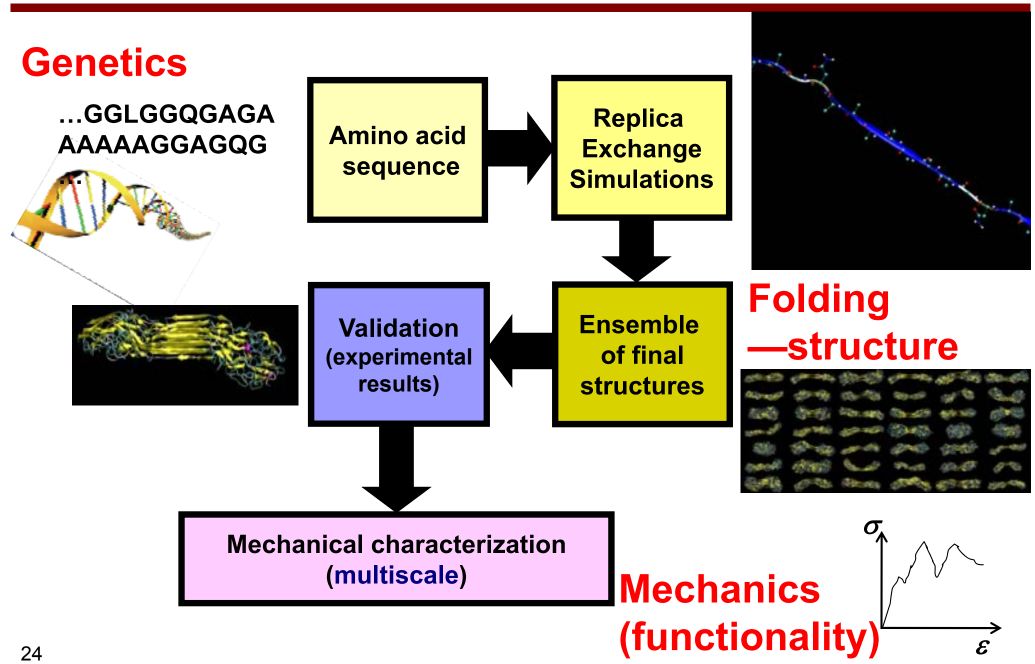
Z. Shao and F. Vollrath, *Nature*, 2002

Spider silk’s hierarchical structure

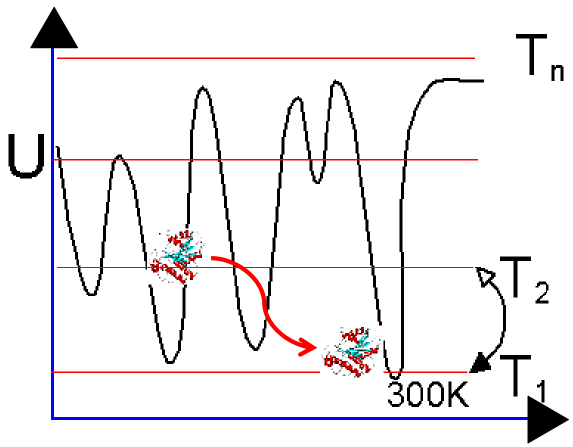


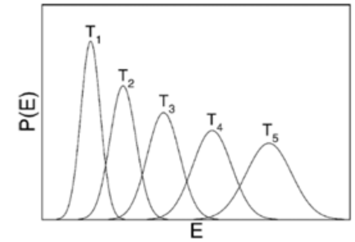
S. Keten, M. Buehler, *APL*, 2010

Structure prediction and functional properties



Replica Exchange approach (parallelized)

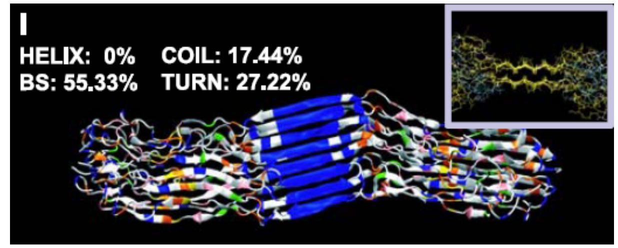


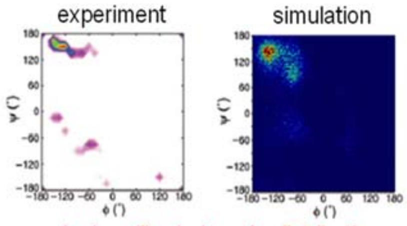


Simulate copies of same system with different temperatures
Exchange configurations between them
Evaluate most stable configurations obtained at low temperature = **solution "ensemble" of structures**

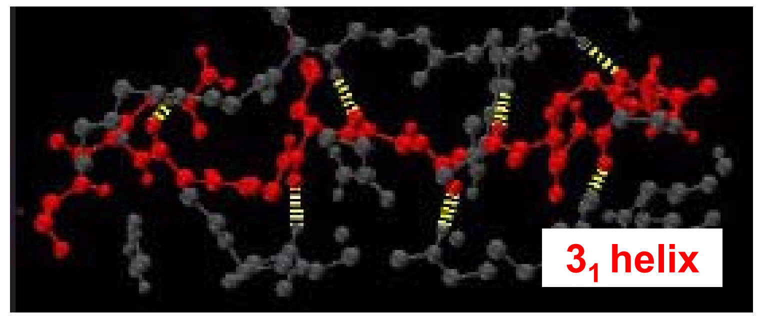
S. Keten, M. Buehler, *APL,* 2010

Detailed view of structure & mechanics



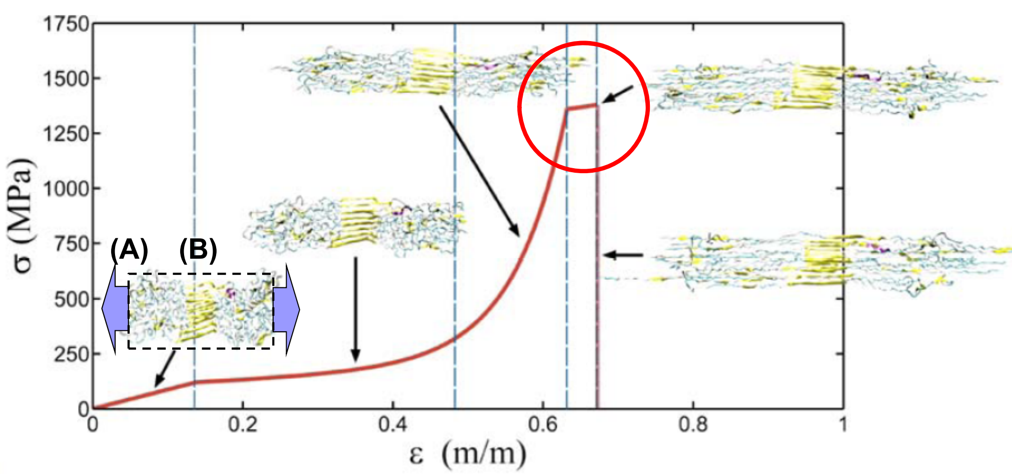


Composite of ordered-semi-amorphous structure (sequence controlled)



S. Keten, M. Buehler, *APL,* 2010; *Roy. Soc. Interface*, 2010; Highlight in *Science*, 2010

Nanoscale mechanism of deformation

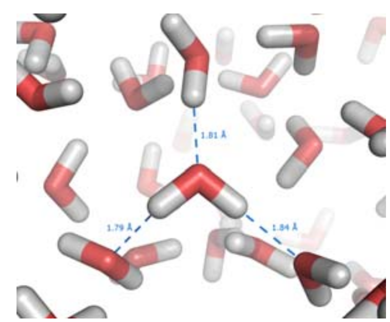


Semi-amorphous region (A) provides **ductility** (molecular unfolding of 3_1-helices)
Beta-sheet crystal (B) provides **strength** (controls maximum force; breaking of crystal) – **features weak H-bonding**

Weakness of H-bonds (inferior building block)

controls unique properties of water
Water: liquid @ 300K
Protein: solid @ 300K

WHY?

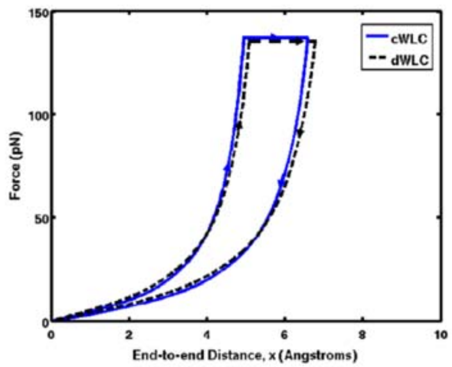


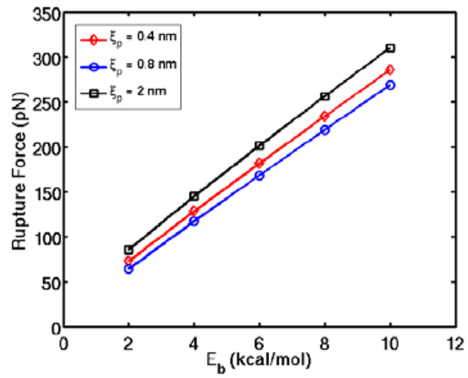
individual H-bonds in water

H-Bond energy: 2-10 kcal/mol

Thermal energy scale
$k_B T \approx 0.6$ kcal/mol (room temp)

Strength prediction of beta-strands



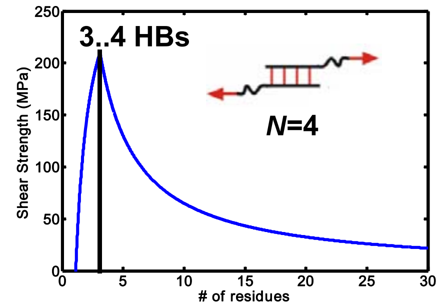


Energy dissipation model (cWLC and dWLC)

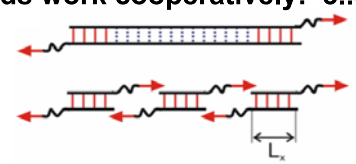
Strength prediction variations in persistence length variations in H-bond energy

S. Keten and M.J. Buehler, *Nano Letter, PRL,* 2008*;* M. Buehler and S. Keten, *Rev. Mod. Phys.*, 2010

Scaling of strength of H-bond assemblies

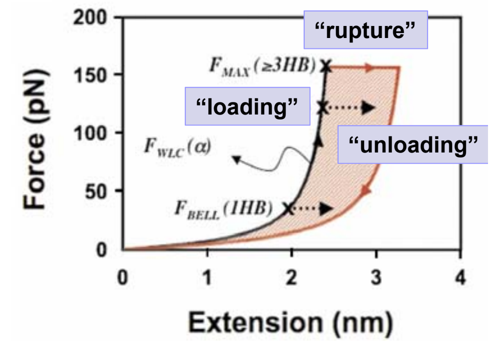


Characteristic maximum number of H-bonds work cooperatively: 3..4 H-bonds



Many small segments with 3-4 HBs each enhance the strength multiple times

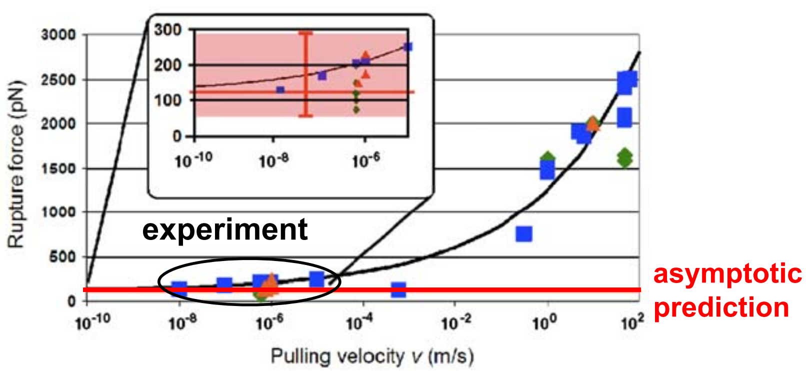
Intrinsic energetics, nanomechanics, and structural confinement control strength properties: **Reach strength at characteristic dimension of H-bond clusters**



Keten and Buehler, *Nano Letters,* 2008,
Buehler *et al., Prog. Mat. Science,* 2008

Validation against experiment

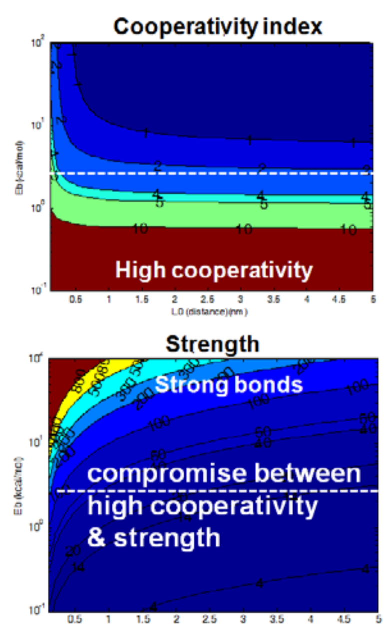
Simple model explains **many** experiments,
has implications for a wide range of polymeric materials



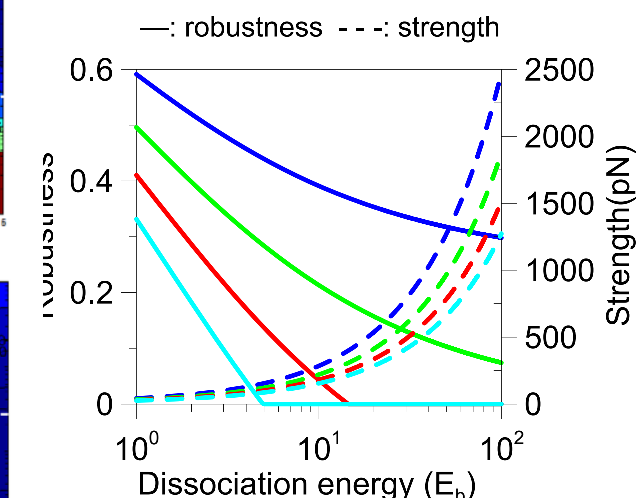
Theory predicts near-equilibrium strength of beta-proteins accurately to be around 50-300 pN.

Keten and Buehler, *PRL*, 2008, Ackbarow, Keten *et al., J. of Phys. Cond. Matt.*, 2009

Scaling laws define constraints on architecture (laws); operate at each scale

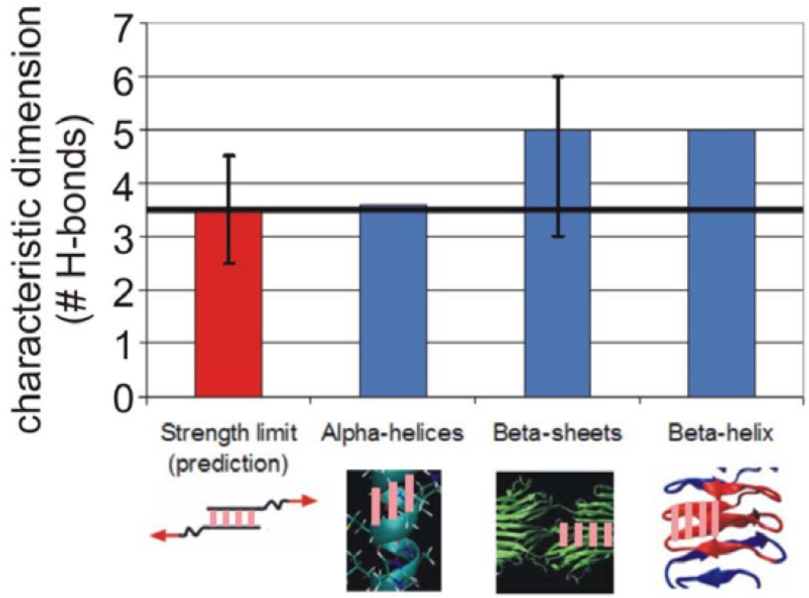


High cooperativity requires: weak bonds AND soft polymer



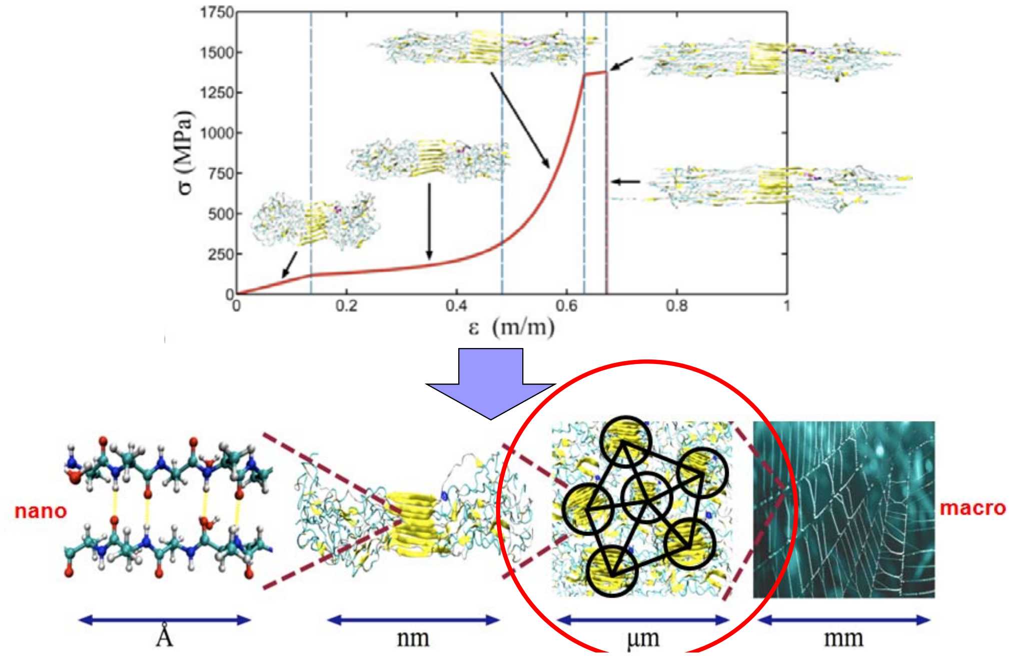
C.C. Chou *et al.*, Interface Focus, 2011; Keten and Buehler, *PRL*, 2008; Buehler and Keten, *Rev. Mod. Phys.*, 2010

Scaling empirically confirmed: H-bond cluster size in natural proteins



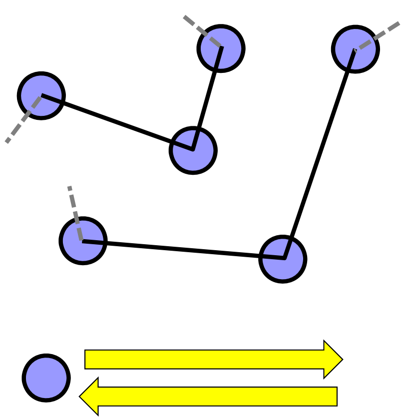
S. Keten and M.J. Buehler, *Nano Letters, PRL*, 2008*;* M. Buehler and S. Keten, *Rev. Mod. Phys.* 2010

Nanoscale mechanism of deformation

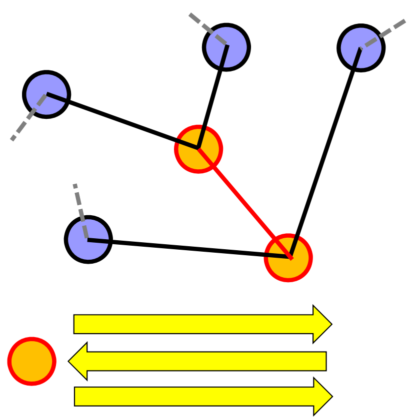


How to build a well-connected network

Each node has maximum of two connections

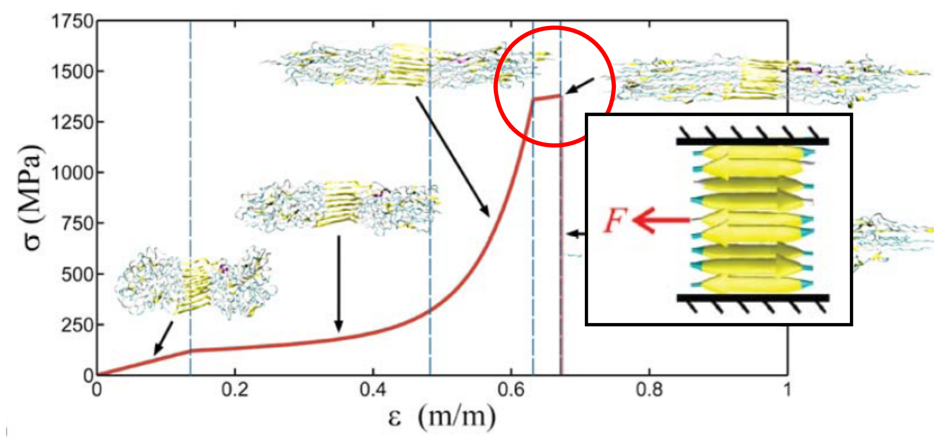


Each node has maximum of three connections (here: full percolation since fully connected)



Thus: Larger stacks of beta-sheets leads to better percolation and thus better material properties

Nanoscale mechanism of deformation

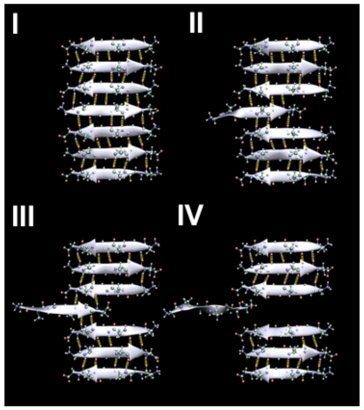


How does the stack height (crystal size) influence mechanical properties?

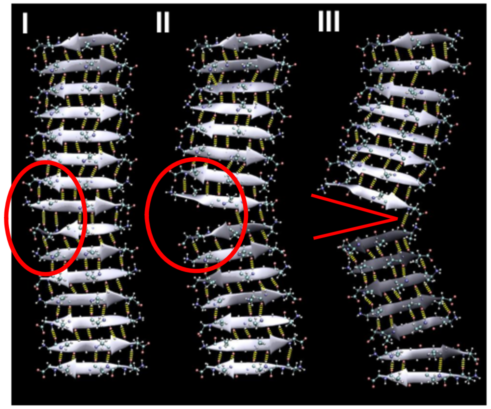
test with lateral loading model

Size effects in silk nanocrystals

pull-out setup (small system)



pull-out setup (large system)



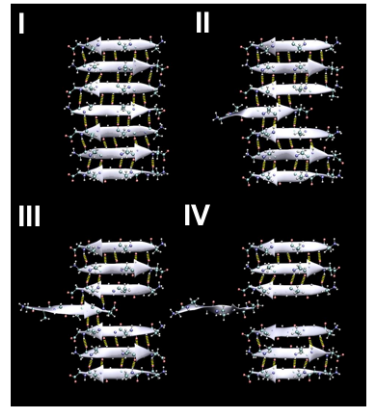
stick-slip mechanism

crack formation & propagation

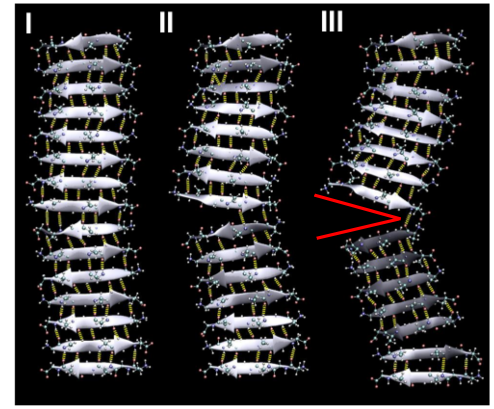
Keten, Xu, Ihle, Buehler, *Nature Materials,* 2010

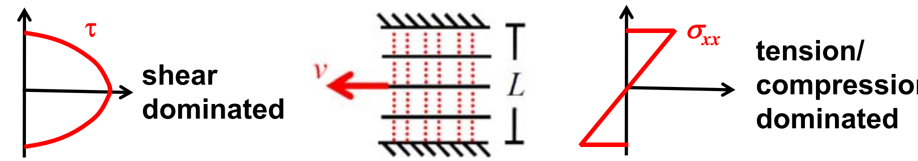
Size effects in silk nanocrystals

pull-out setup (small system)



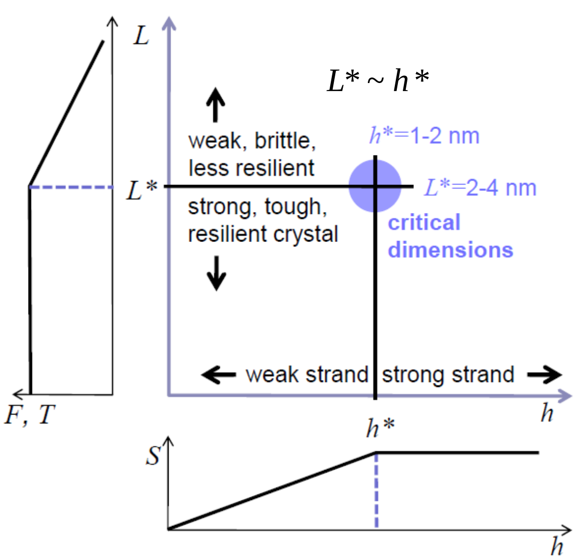
pull-out setup (large system)

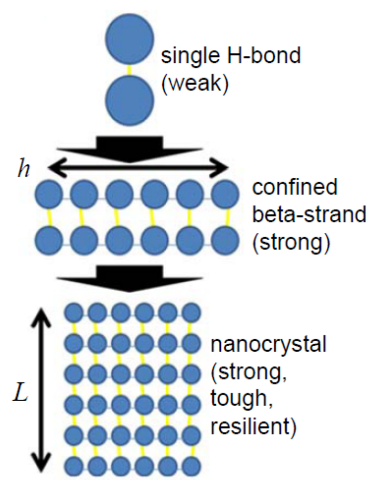




Keten, Xu, Ihle, Buehler, *Nature Materials,* 2010

How weakness is turned to strength



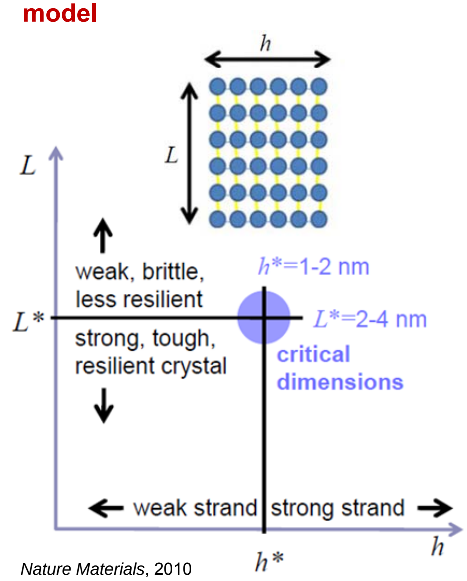


Natural silk: *L=2-7 nm and *h** =2-3 nm**

Keten, Xu, Ihle, Buehler, *Nature Materials,* 2010

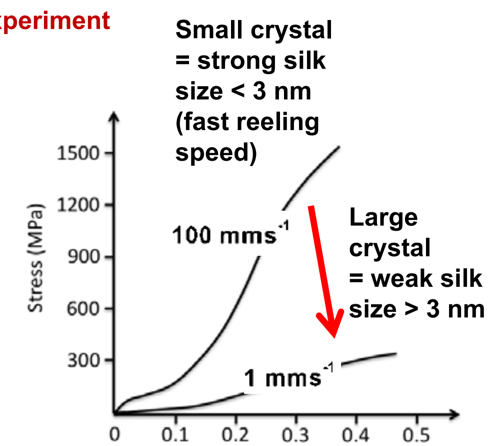
Model explains experimental results: increase in beta-sheet crystal size results in loss of strength

Derived critical length scales from atomistic and analytical model



Nature Materials, 2010

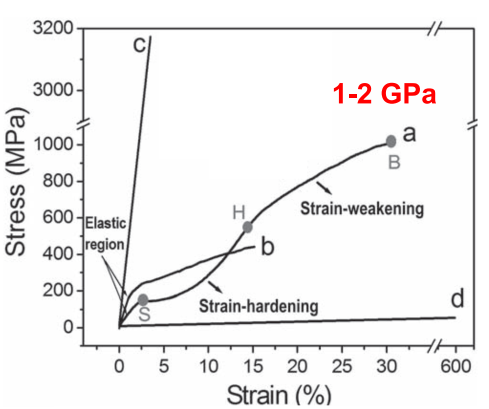
Critical length scales measured in experiment

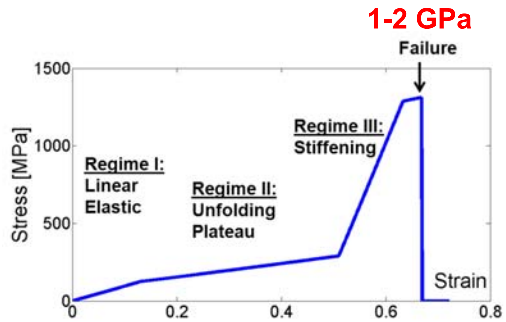


Experiment: N. Du *et al.*

Confirms hypothesis (predicted using mechanics theory)

Fundamental challenge: Scaling up…





Molecular-level properties are very similar to macroscale experimental results (surprising when compared to other materials)

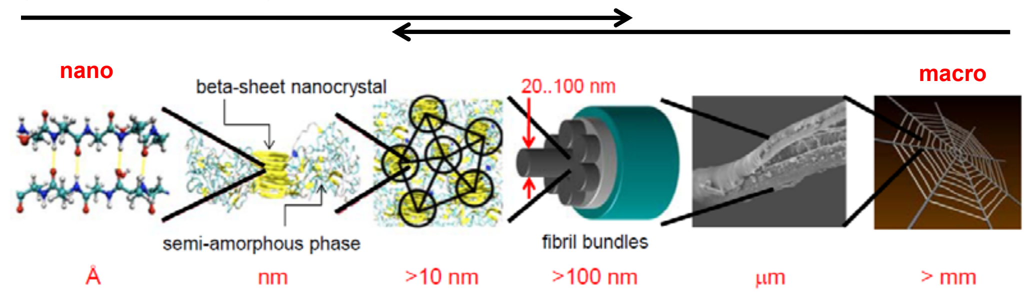
WHY?

T. Giesa, M. Arslan, M. Buehler, *Nano Letters,* 2011

Approach to understanding silk: bottom-up material description

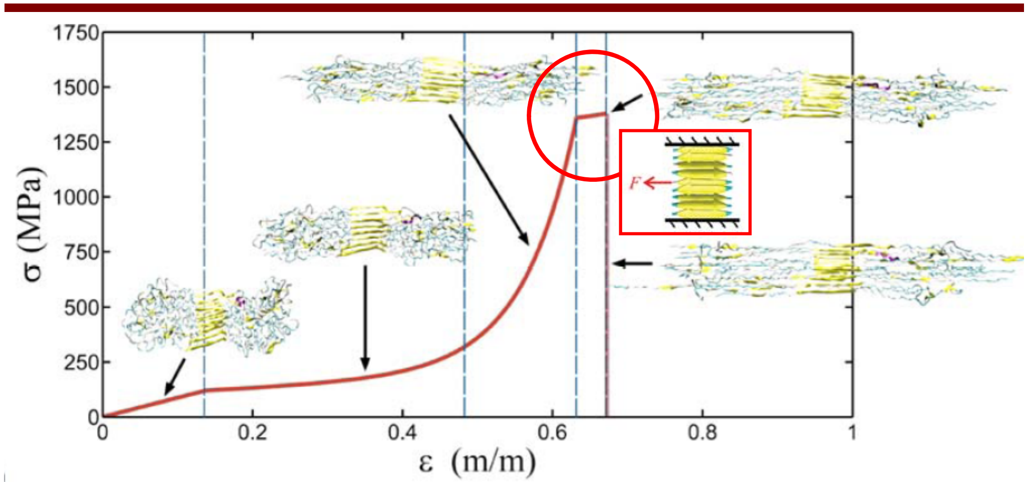
Intellectual challenge: Push chemical concepts to larger scales (H-bonds, reactivity…)

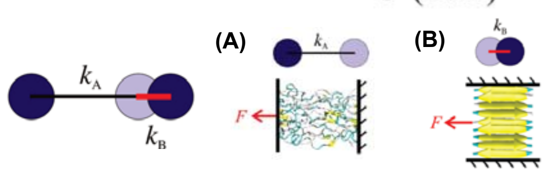
Push mechanics concepts to smaller scales (modulus, strength…)



Nova, Buehler *et al. Nano Letters*, 2010; M. Arslan *et al., Nano Letters,* 2011

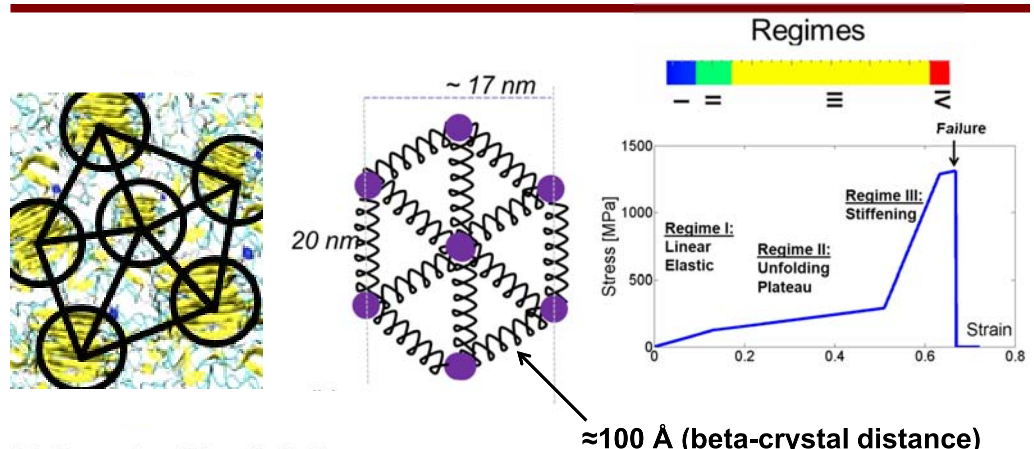
Nanoscale mechanism of deformation





Semi-amorphous region (A) provides ductility (molecular unfolding of 3_1-helices)
Beta-sheet crystal (B) provides strength (controls maximum force; breaking of crystal)

Particle-based mesoscale model of silk



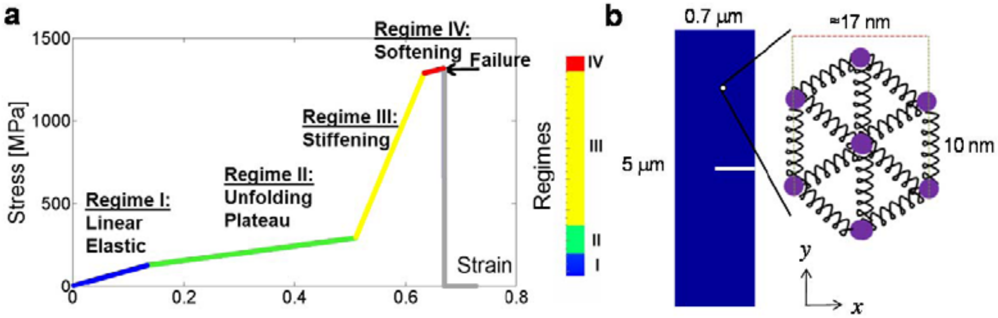
(a) Geometry of the silk fibril

(b) Triangular mesh mesoscale particle-spring model setup,

(c) Stress–strain curves obtained from fitting the atomistic simulations of the silk fibril.

T. Giesa, M. Arslan, M. Buehler, *Nano Letters,* 2011

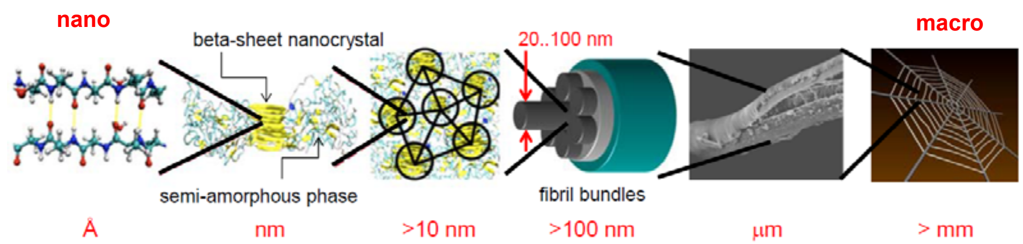
Particle-based mesoscale model of silk

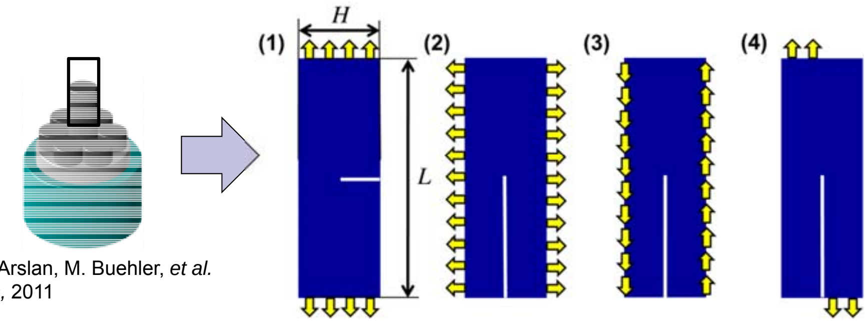


$$F_b(\lambda_b) = \begin{cases} k_1 r_0(\lambda_b - 1), & 1 < \lambda_b < \lambda_{b1} \\ k_1 r_0(\lambda_{b1} - 1) + k_{1-2} r_0(\lambda_b - \lambda_{b1}), & \lambda_{b1} < \lambda_b < \lambda_{b2} \\ k_1 r_0(\lambda_{b1} - 1) + k_{1-2} r_0(\lambda_{b2} - \lambda_{b1}) + k_{2-3} r_0(\lambda_b - \lambda_{b2}), & \lambda_{b2} < \lambda_b < \lambda_{b3} \\ k_1 r_0(\lambda_{b1} - 1) + k_{1-2} r_0(\lambda_{b2} - \lambda_{b1}) + k_{2-3} r_0(\lambda_{b3} - \lambda_{b2}) + k_{3-4} r_0(\lambda_b - \lambda_{b3}), & \lambda_{b3} < \lambda_b < \lambda_{b4} \\ 0, & \lambda_b > \lambda_{b4} \end{cases}$$

T. Giesa, M. Arslan, M. Buehler, *Nano Letters,* 2011

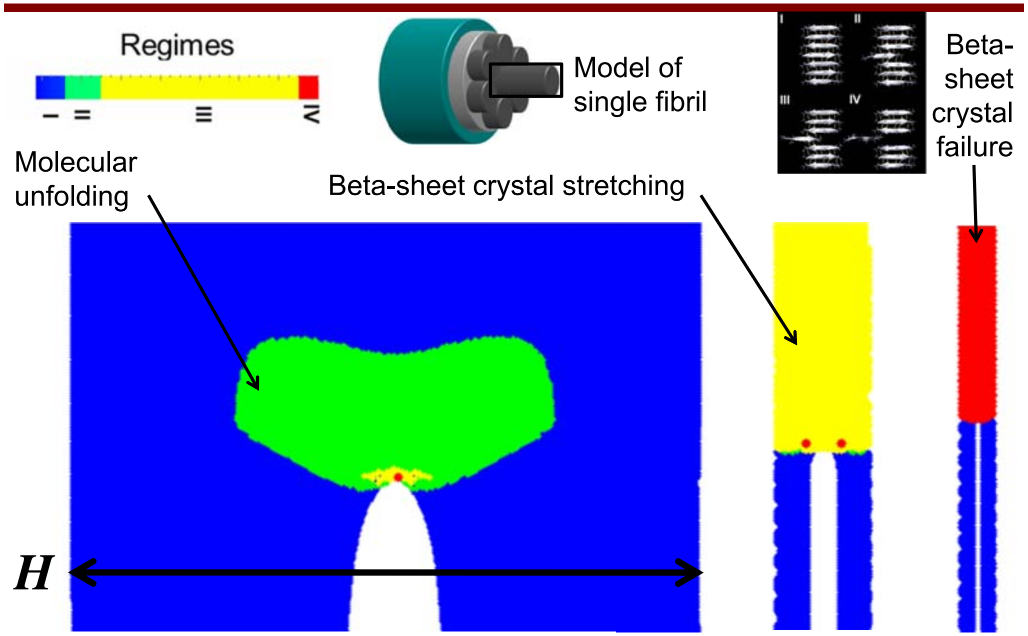
Multiscale approach of fibrils





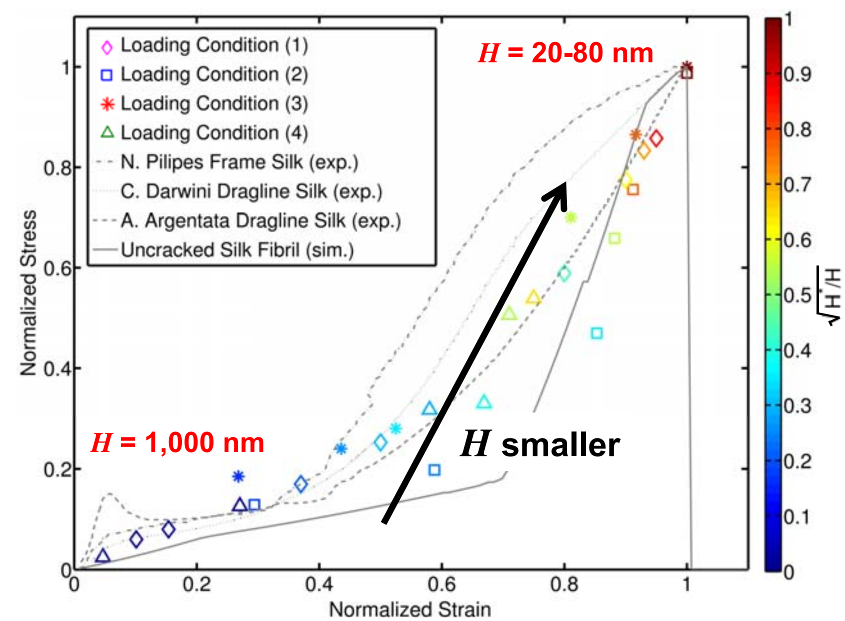
T. Giesa, M. Arslan, M. Buehler, *et al. Nano Letters,* 2011

Particle-based mesoscale model of silk



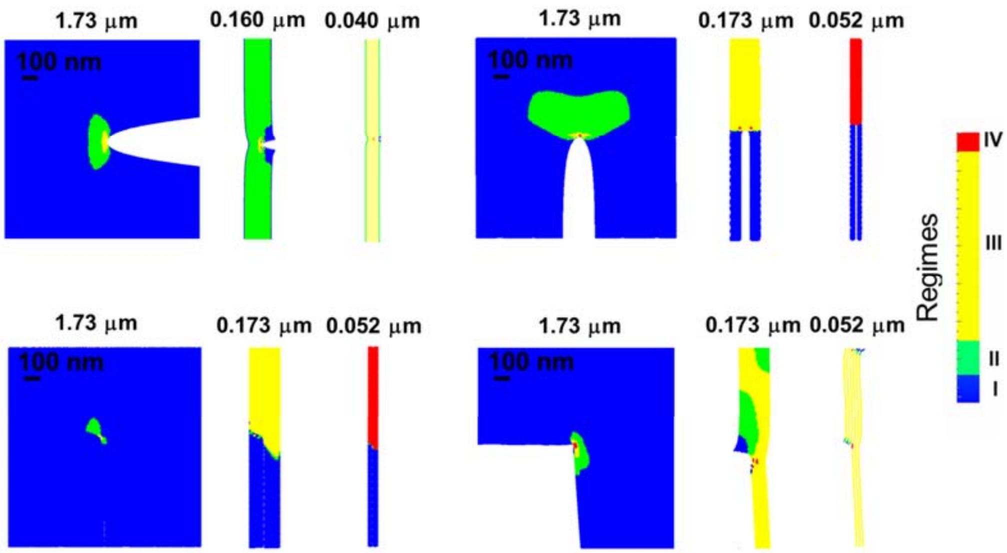
T. Giesa, M. Arslan, M. Buehler, *Nano Letters,* 2011

Confinement critical for macroscale strength



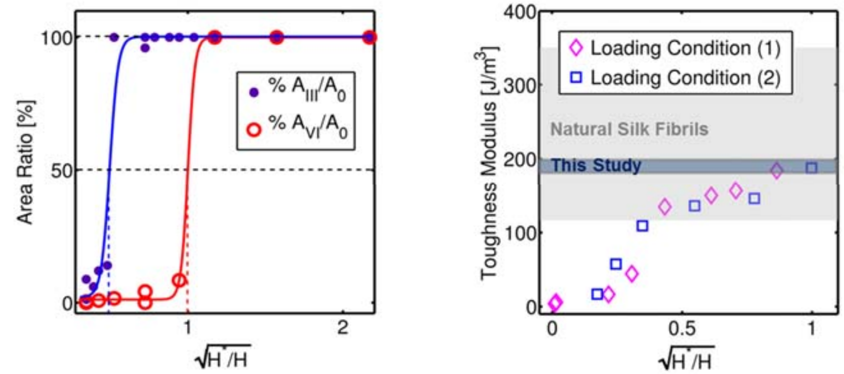
T. Giesa, M. Arslan, M. Buehler, *Nano Letters,* 2011

Confinement critical for macroscale strength



T. Giesa, M. Arslan, M. Buehler, *et al.*, *Nano Letters,* 2011

Confinement critical for macroscale strength



Critical fibril length-scale H^*=20-80 nm

Reach theoretical strength of material

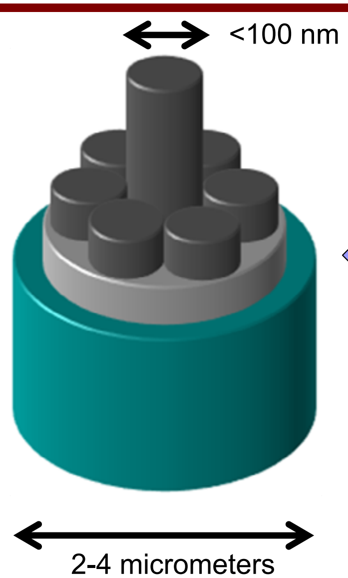
All material participates in unfolding and failure, specifically all beta-sheet nanocrystals

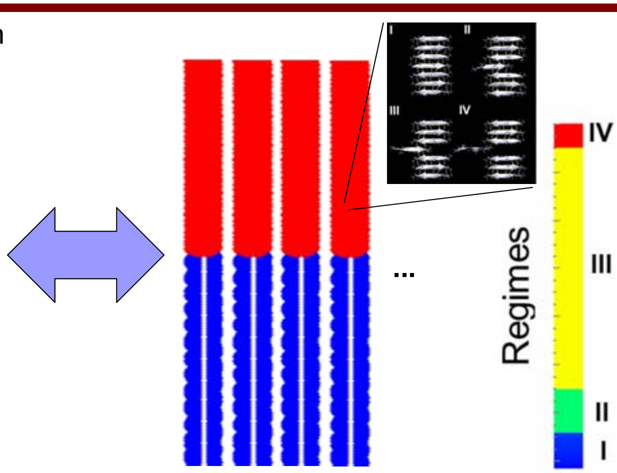
Toughness modulus ≈200-500 MJ/m³ (experiment)

≈200 MJ/m³ (prediction here)

T. Giesa, M. Arslan, M. Buehler*, Nano Letters,* 2011

Fibers are bundles of fibrils





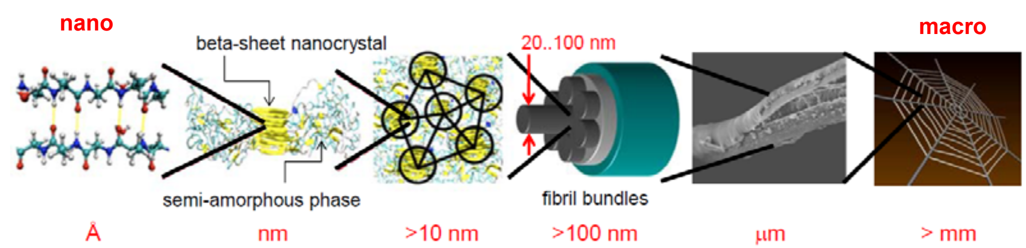
Fibril bundle

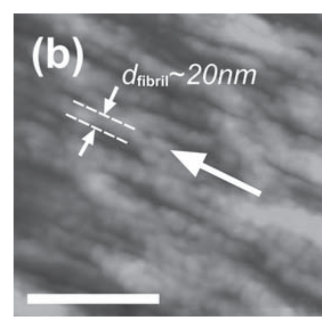
Each fibril in homogeneous stress state

Unfolding & stretching of beta-sheet nancrystals

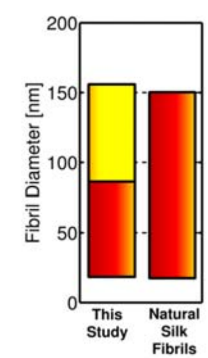
T. Giesa, M. Arslan, M. Buehler, *et al.*, *Nano Letters,* 2011

Confinement found in natural silk fibrils

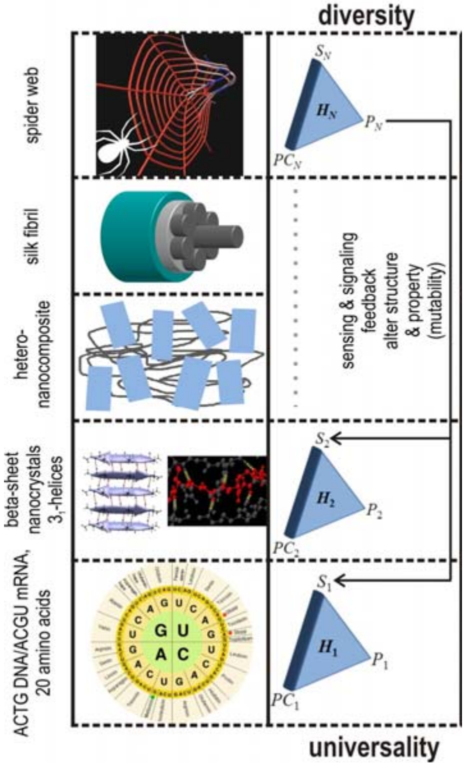




Experimental reference:
Fibril size ranges from 20-100 nm



T. Giesa, M. Arslan, M. Buehler, *et al.*, *Nano Letters,* 2011



•**Functional properties** emerge due to interactions of building blocks at different scales

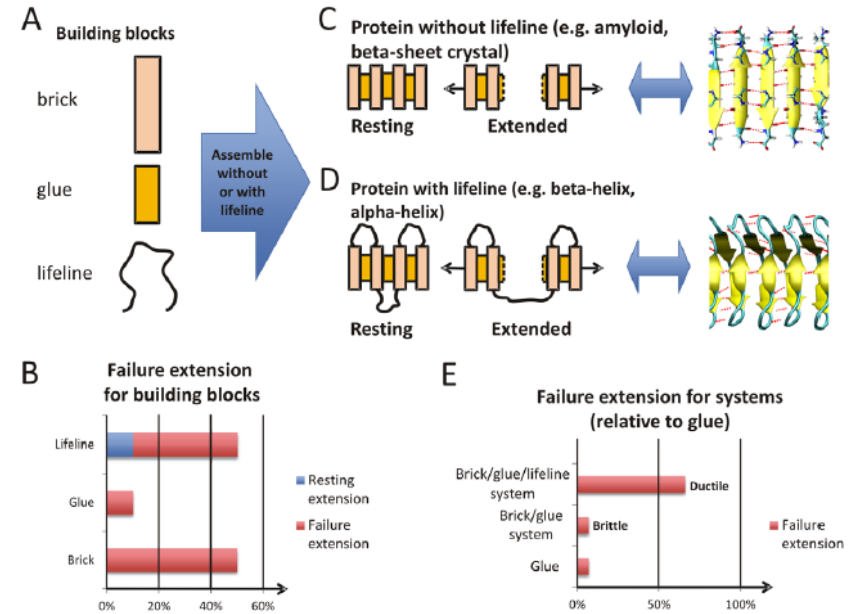
•**Scaling laws** govern how structures at specific scales must form in order to be used as “new” building blocks as next hierarchy levels

•Scaling laws may involve parameters from **different hierarchical levels**

Can we formulate this in a self-consistent way, *i.e.* to describe it in a generic mathematical model that can be solved for different situations (similar to BCs)?

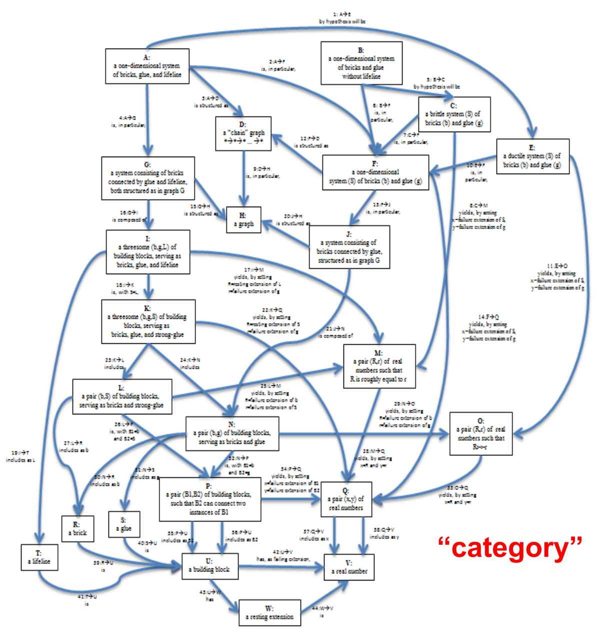
M. Buehler, *Nano Today*, 2010

Category theory—describe system by relationships between elements: ologs



D. Spivak, T. Giesa, L. Wood, M. Buehler, *PLoS ONE*, 2011

Category theory—describe system by relationships between elements: ologs



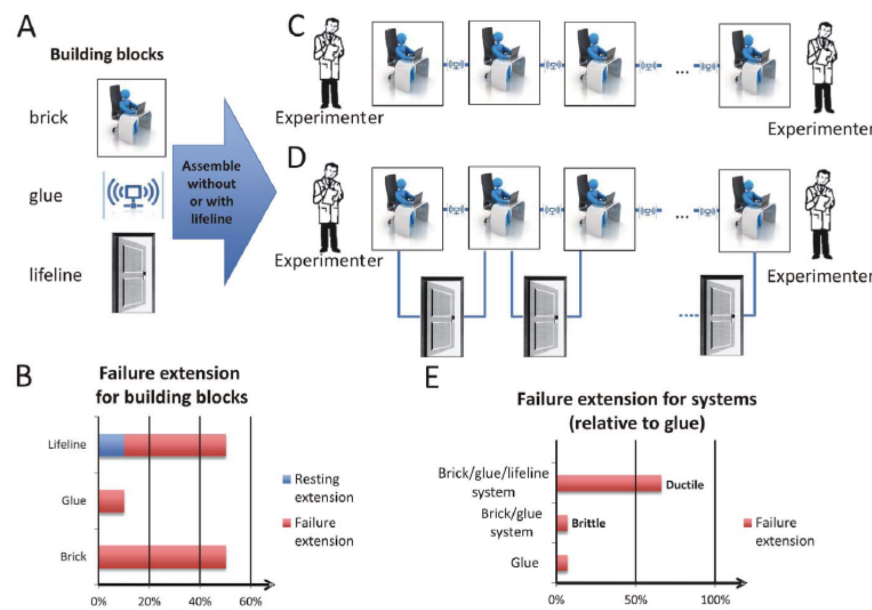
Category theory: S. Eilenberg S. MacLane (1942–45)

➢ Functionality emerges from **interplay between building blocks**
➢ Defined by **interactions** between them, use physics from theory/simulation/ experiment to build olog

“category”

D. Spivak, T. Giesa, L. Wood, M. Buehler, *PLoS ONE*, 2011

Category theory—describe system by relationships between elements: ologs



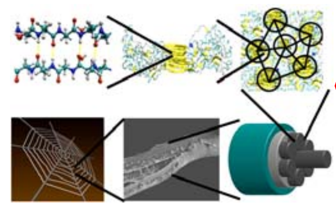
D. Spivak, T. Giesa, L. Wood, M. Buehler, *PLoS ONE*, 2011 “functors”

Type	Type Labels	Protein Specific	Social-network Specific
A	a one-dimensional system of bricks, glue, and lifeline	beta-helix	social network with wireless & physical passageways
B	a one-dimensional system of bricks and glue without lifeline	beta-sheet nanocrystal	social network with wireless, without physical passageways
C	a brittle system (S) of bricks (b) and glue (g)	brittle protein filament	brittle social network
D	a “chain” graph *→*→* … →*	chain shape for protein	chain shape for network
E	a ductile system (S) of bricks (b) and glue (g)	ductile protein filament	ductile social network
F	a one-dimensional system (S) of bricks (b) and glue (g)	beta-helix / beta-sheet nanocrystal	social network
G	a system consisting of bricks connected by glue and lifeline, both structured as in graph G	lifeline protein of specified shape	lifeline social network of specified shape
H	a graph	shape of protein	shape of network
I	a threesome (b,g,L) of building blocks, serving as bricks, glue, and lifeline	amino cluster, H-bond, backbone	transceiver, wifi system, physical passageway
J	a system consisting of bricks connected by glue, structured as in graph G	protein of specified shape	social network of specified shape
K	a threesome (b,g,S) of building blocks, serving as bricks, glue, and strong-glue	amino acid cluster, H-bond, backbone	transceiver, wifi system, physical passageway
L	a pair (b,S) of building blocks, serving as bricks and strong-glue	amino acid cluster, backbone	transceiver, physical passageway
M	a pair (R,r) of real numbers such that R is roughly equal to r	e.g. R = 20.5 r = 23.45	e.g. R = 20.5 r = 23.45
N	a pair (b,g) of building blocks, serving as bricks and glue	amino acid cluster, H-bond	transceiver, wifi system
O	a pair (R,r) of real numbers such that R>>r	e.g. R = 100 r = 20.6	e.g. R = 100 r = 20.6
P	a pair (B1,B2) of building blocks, such that B2 can connect two instances of B1	e.g. amino acid and backbone	e.g transceiver and wifi
Q	a pair (x,y) of real numbers	e.g. x = 20.55, y = 50.6	e.g. x = 20.55, y = 50.6
R	a brick	amino acid cluster	transceiver
S	a glue	H-bond cluster	wifi connection
T	a lifeline	backbone	physical passageway
U	a building block	basic unit of material	basic unit of social interaction
V	a real number	e.g. 181.2	e.g. 181.2
W	a resting extension	e.g. 61 Angstrom	e.g. 1/100 error/bit

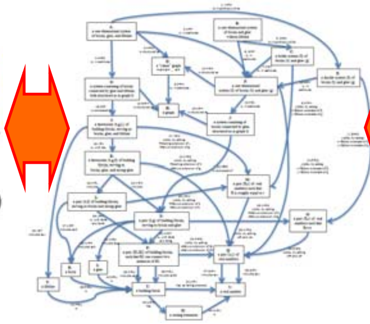
D. Spivak, T. Giesa, L. Wood, M. Buehler, *PLoS ONE*, 2011

Category theory representation

Hierarchical biological material (e.g. silk) or synthetic material



Category theory representation (olog)
Description of how “function” emerges is identical/similar in silk or language, albeit building blocks are different



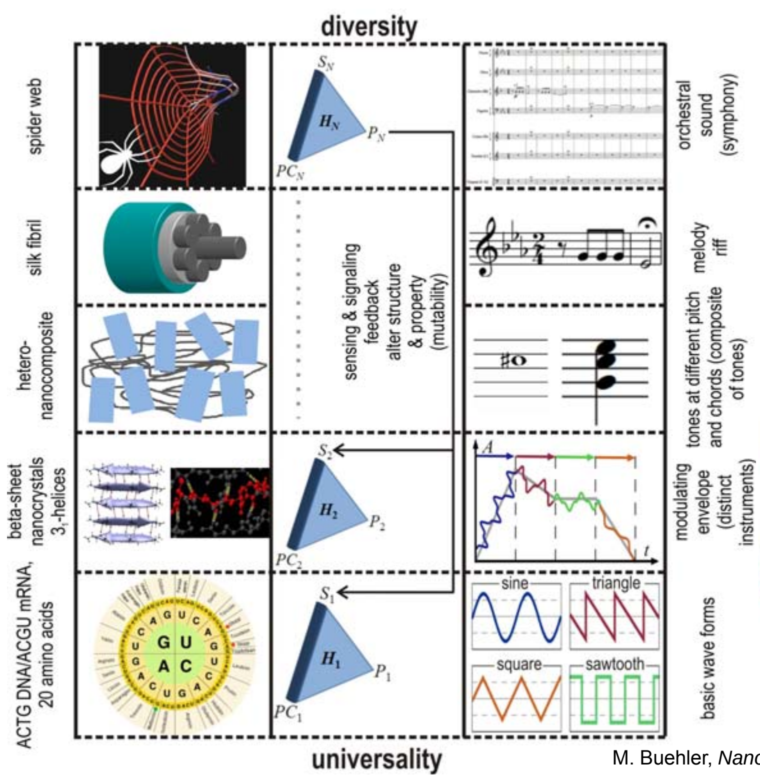
Language, music, social networks

⋮

Solve olog for different “BCs”: change building blocks

D. Spivak, T. Giesa, L. Wood, M. Buehler, *PLoS ONE*, 2011

protein

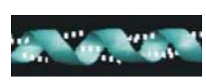


music

M. Buehler, *Nano Today*, 2010

Challenges and opportunities

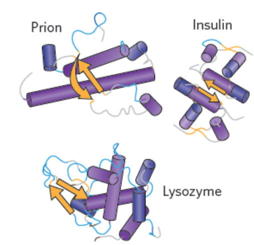
Biology (building blocks)



alpha-helix

beta-sheet

random coil (unstructured)

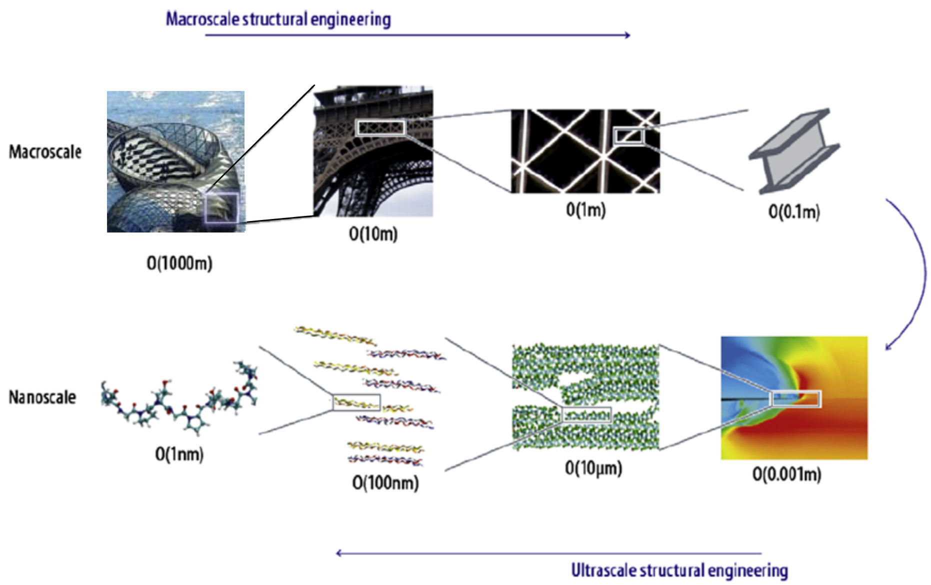


Can NOT predict function

Architecture & civil engineering

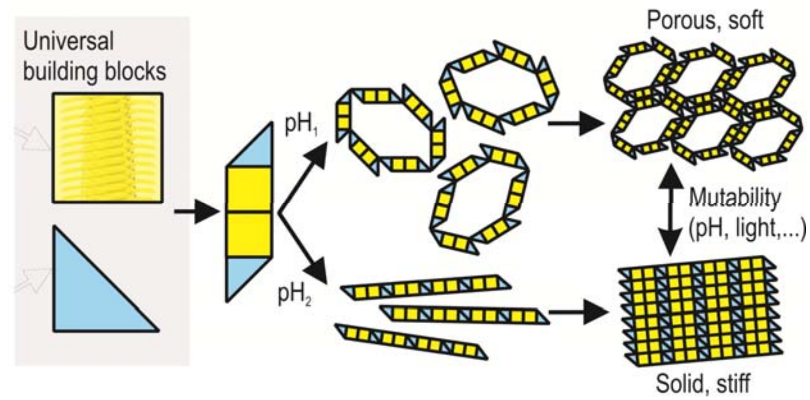
Can PREDICT function

Merger of structure and material: structural engineering at all scales



Ackbarow, Buehler *et al., Materials Today*, 2007

*We can use **simple building blocks, assembled in different geometries**, to create **enhanced material properties** (do not need complex or functional building blocks)*

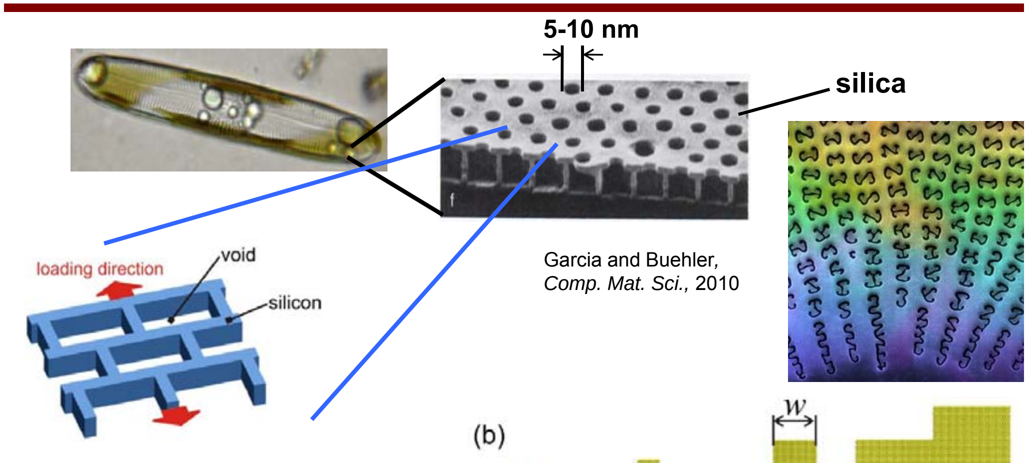


Silicon and silica are brittle materials

Example: fracture of silicon crystal

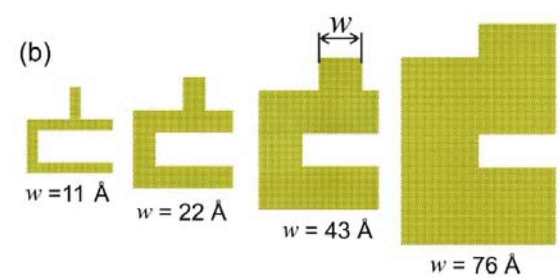
D. Sen, C. Thaulow, M.J. Buehler *et al., Phys. Rev. Lett.*, 2010

Diatoms – Nature's flexible armor



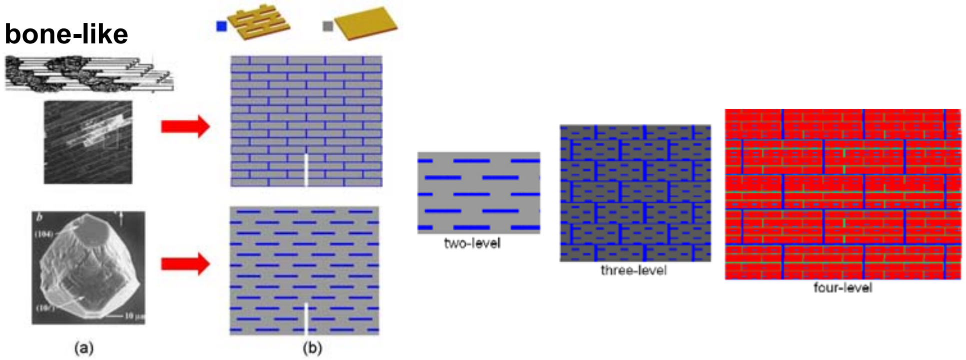
Garcia and Buehler, *Comp. Mat. Sci.*, 2010

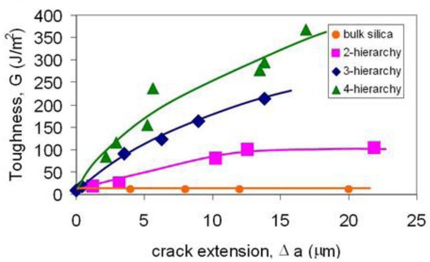
Nanopores create strong & tough material (no longer brittle)

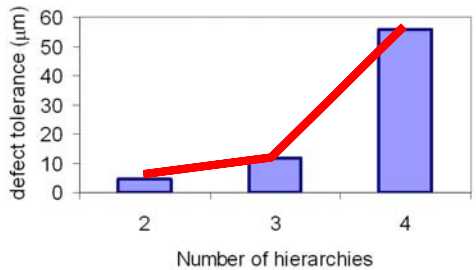


Hierarchies result in defect tolerant behavior

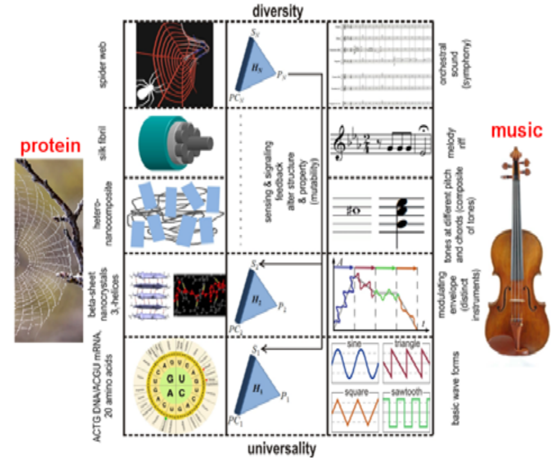
Sen, Buehler, *Scientific Reports*, 2011







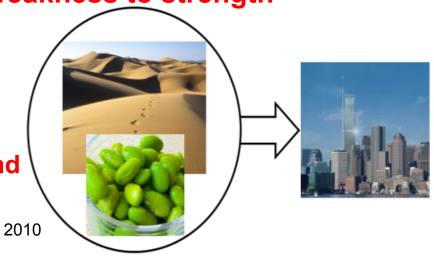
Summary: **Universality-diversity paradigm**



Paradigm uncovered:

- **Create multifunctionality (diversity) by changing structural arrangements of few (universal) constituents: geometry controlled by confinement/scaling laws**
- **No reliance on invention of new building blocks**
- **Departure from widely used engineering approach: Turn weakness to strength**

Engineering impact: Bioinspired materials; *i.e.* define properties, geometry etc. of materials other than protein, e.g. metal-polymers by applying scaling laws: Use silica (sand), clay, and soy beans transformed to create high tech materials



M. Buehler, *Nature Nanotechnology*, 2010; *Nano Today*, 2010