Materials through the lens of memory

Memory formation in matter;   KITP Santa Barbara; February 15, 2018

https://www.pinterest.com/pin/292734044509882622/

What is memory? Stored information about past history.

Can information left behind (by design or manipulation of materials) provide insight about process or material?

Is study of residual information content useful?

There are as many forms of memory as there are ways of perceiving, and every one of them is worth mining for inspiration.

Twyla Tharp -- *The Creative Habit*

Many examples of memories in matter

Stone and chisel / Paper and pencil
Photograph / Phonograph
Computer: e.g., magnetic domains
Associative memory in neural nets (Hopfield model)

Kaiser effect: remembers largest strain
Kovacs effect: remembers waiting time
Return-point memory in magnets: Nested hysteresis curves
Pulse duration memory
Multiple transient memories (charge density waves; non-Brownian suspensions)
Multiple memories in jammed solids

Echoes: spin; (anharmonic) phonon
Aging, rejuvenation and memory in glasses
Dynamical systems - remembering initial conditions

Shape-memory alloys
Designing in function: memory

General questions

Basic operations of memory: imprinting, reading and erasure of information

What constitutes a memory?
Are there different categories of memory?
How many memories can be stored (capacity)?
What is entropy of a memory?
What is plasticity?

Principles used to store memories

What does system need to store memories?
(many degrees of freedom, out of equilibrium, not chaotic, no instability …)

Memory stored in path
- Marginal states

Memory stored in static positions
- Minima in a landscape

Memories in complex energy landscapes
Oscillatory sheared jammed solids

After few oscillations, system finds periodic orbit
traversing many energy barriers, visiting many energy minima.

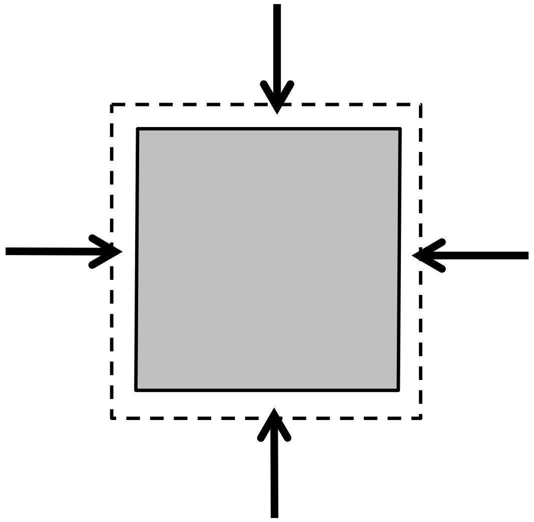
Memories very easy to encode
break few bonds, adjust few neighbors.

This is not only way in which this complex energy landscape can be manipulated to form a memory: *tuning by pruning*.

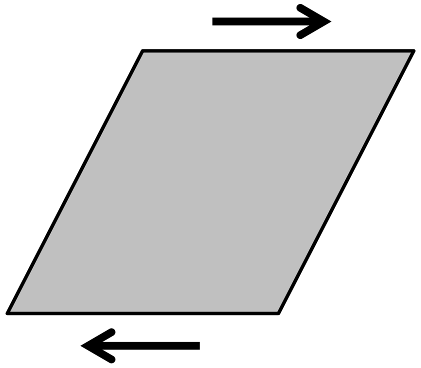
Designing auxetic response in disordered materials

Moduli: Response to compression or shear

B
(bulk modulus)



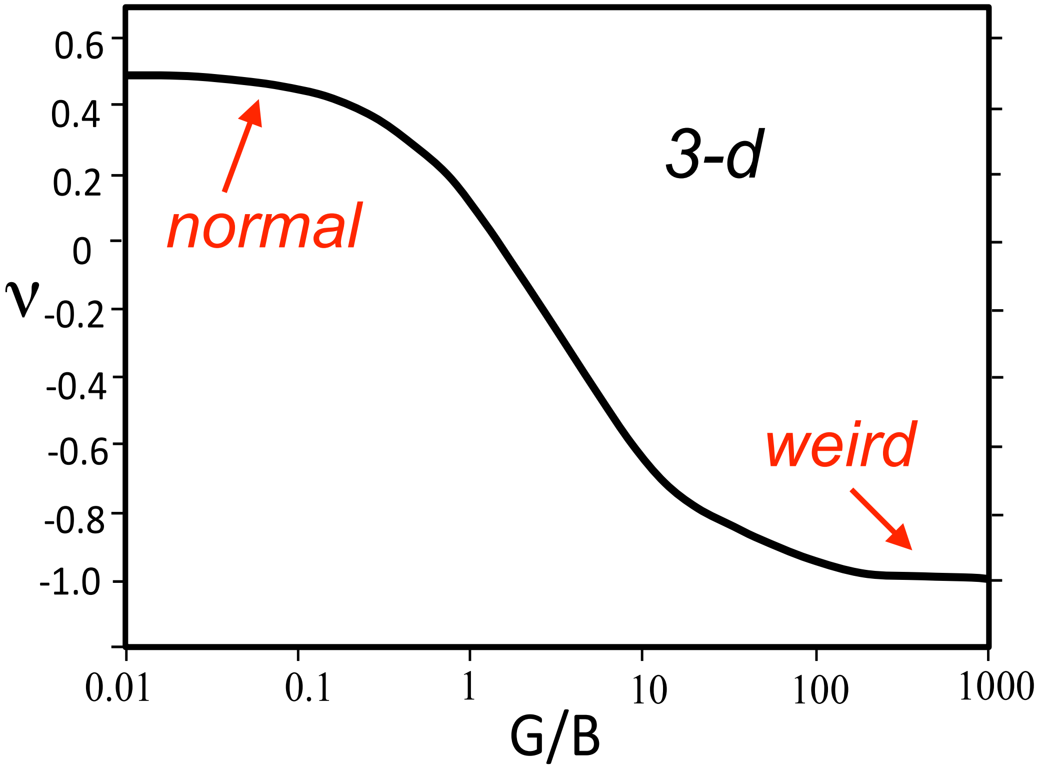
G
(shear modulus)



In crystals, G comparable to B

G/B ⇒ ν (Poisson ratio)

Does disorder matter?

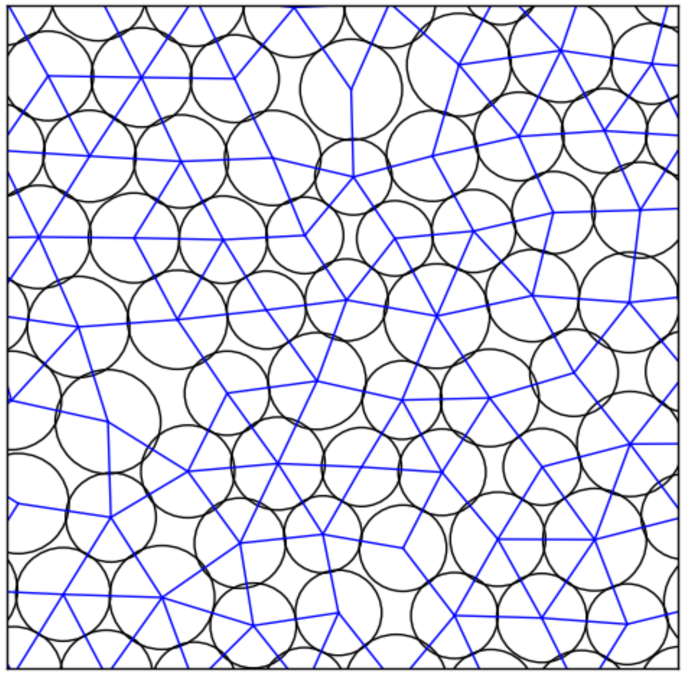


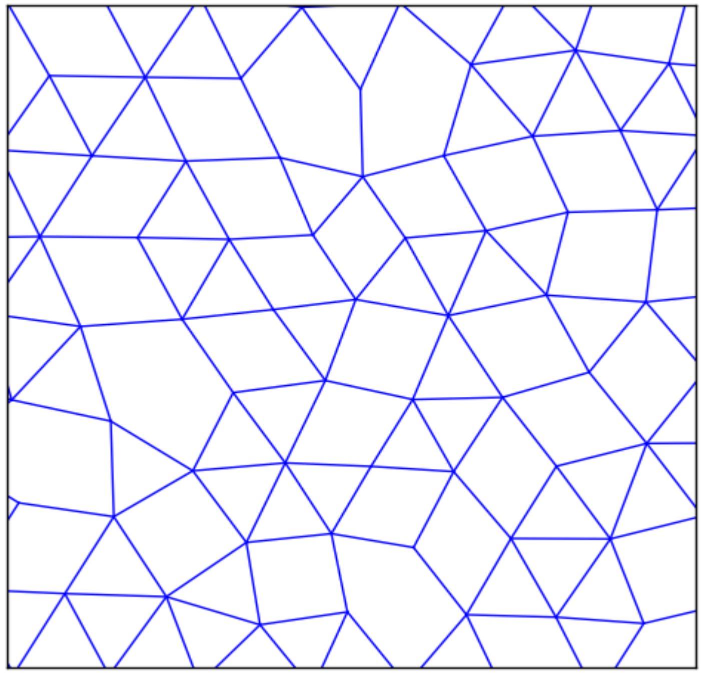
Make network from jammed sphere packing

Replace sphere centers by nodes
Replace overlap interactions with unstretched springs

Jammed
sphere packing

Spring
network





How are jammed solids different from crystals?
Bond-level response

Crystal:

(i) Identical cells repeated symmetrically & interminably:
all bonds contribute equally to any global quantity

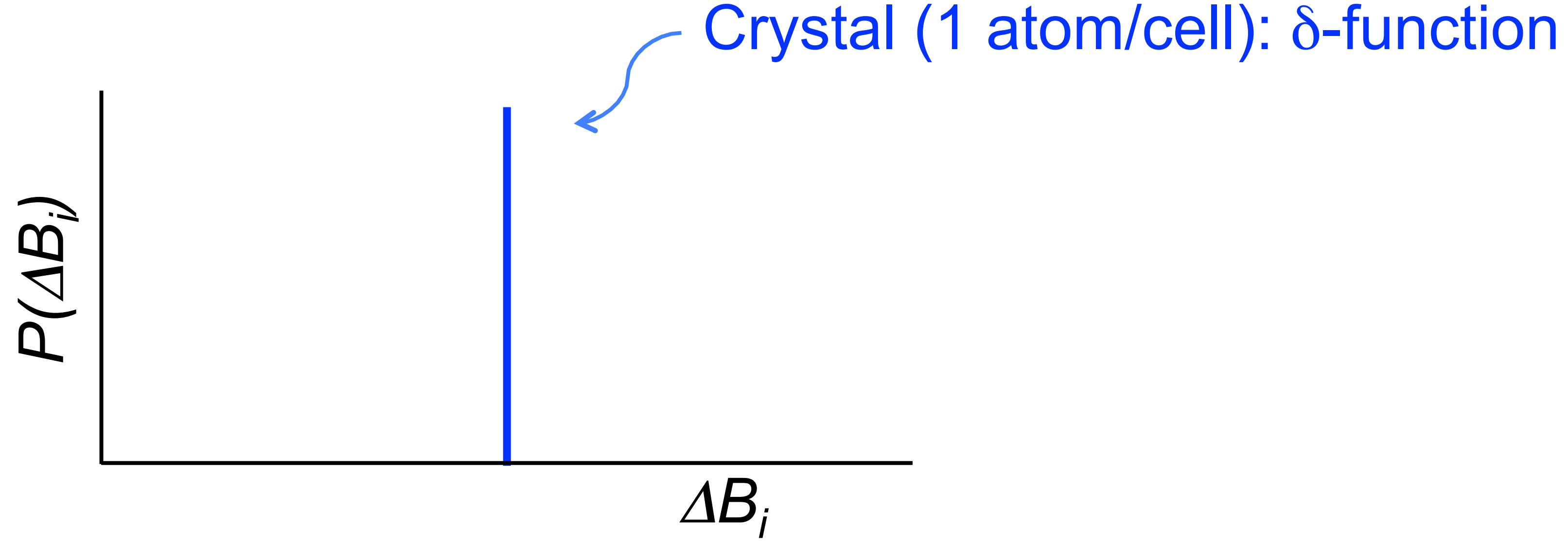
(ii) Remove any bond →
resistance to shear and resistance to compression drop in tandem

Result of removing bond

Remove an arbitrary bond, *i*: measure ΔB_i and ΔG_i
(decrease in bulk & shear moduli)

Replace bond and remove another: measure ΔB_j and ΔG_j

Measure distributions $P(\Delta B_i)$, $P(\Delta G_i)$



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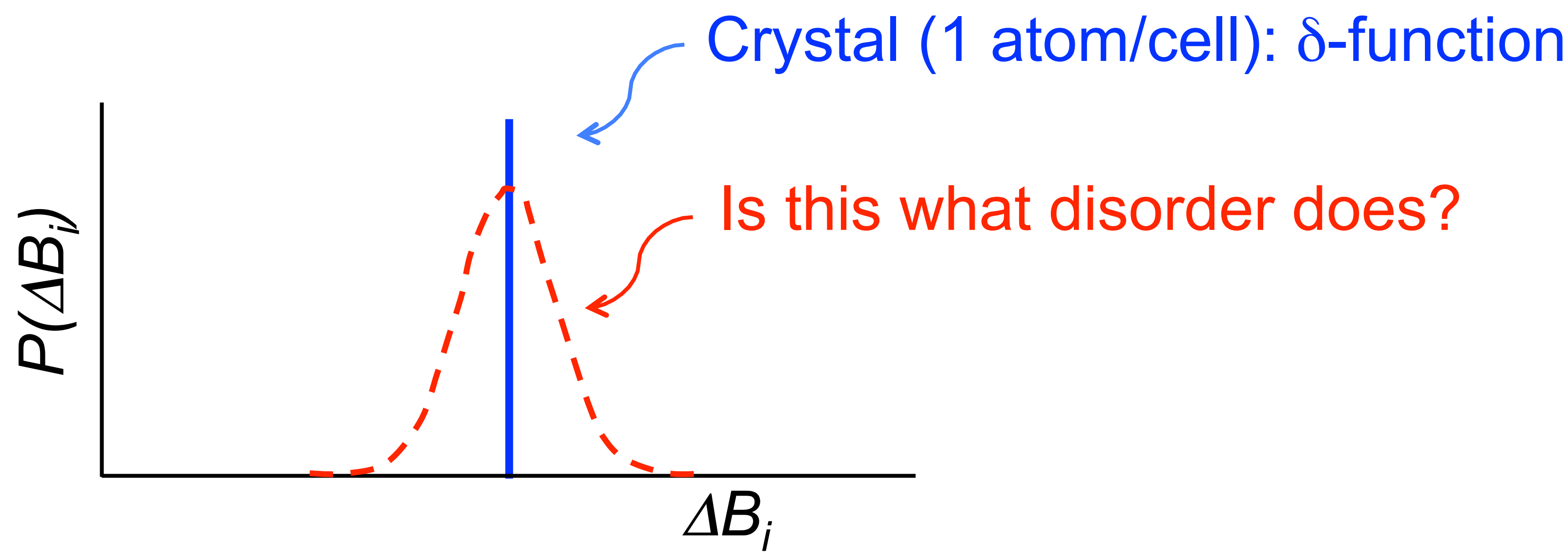
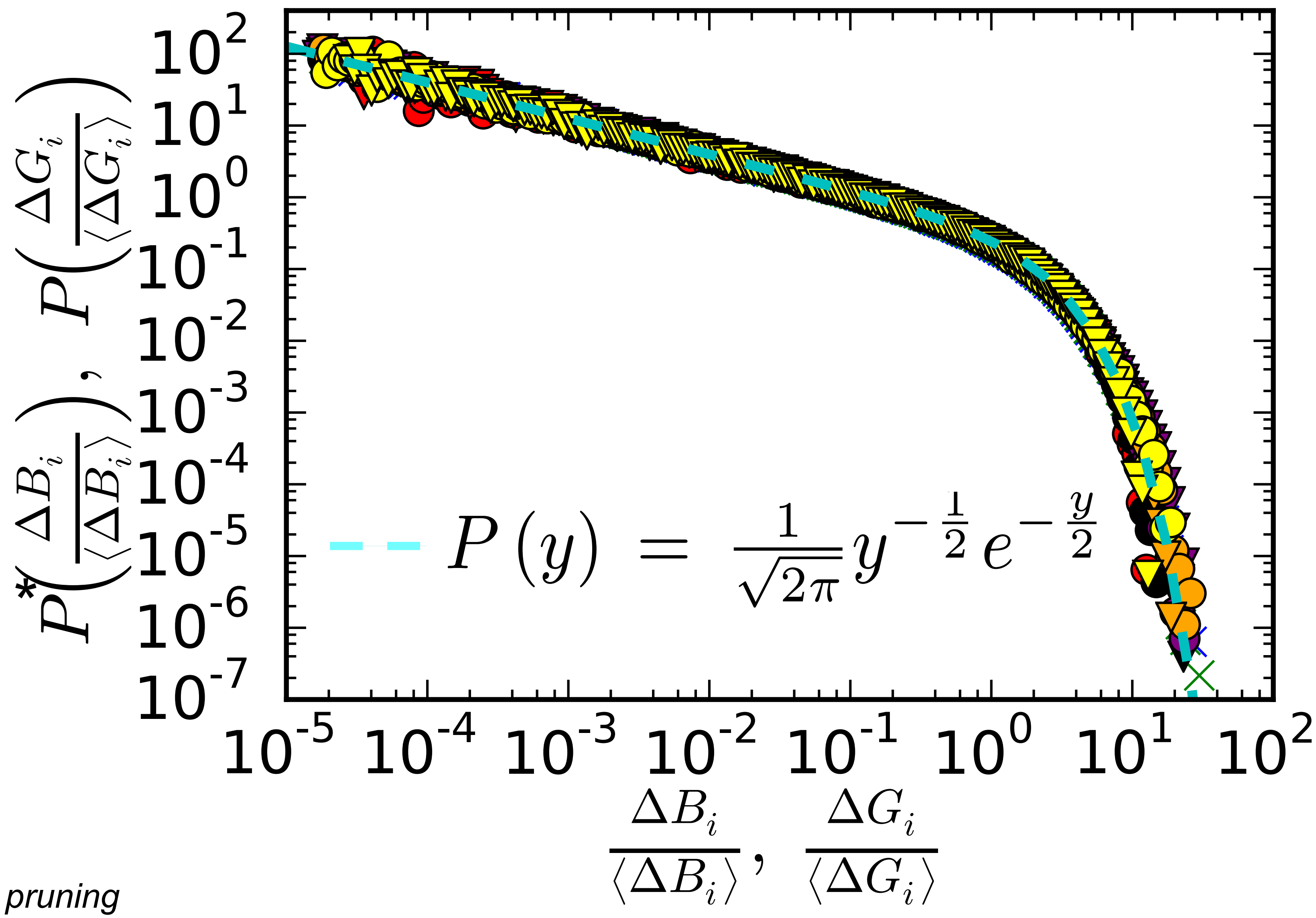


New principle for disordered matter:

(1) Distribution of bond-level response



* *after pruning*

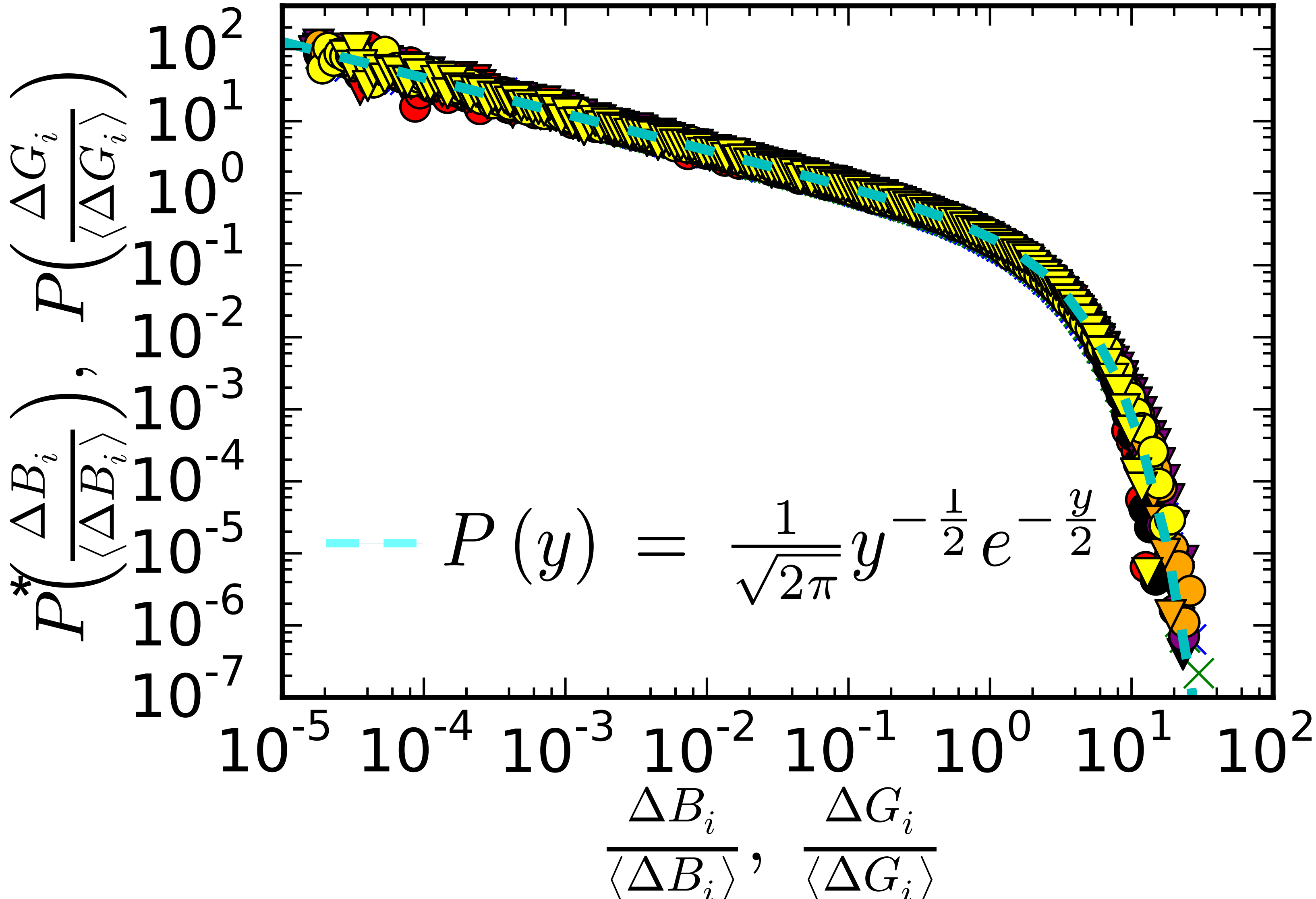
Distributions are broad, continuous, “universal”

Goodrich, Hexner, Liu

New principle for disordered matter:

(1) Distribution of bond-level response

(2) Independence of bond's contribution to responses



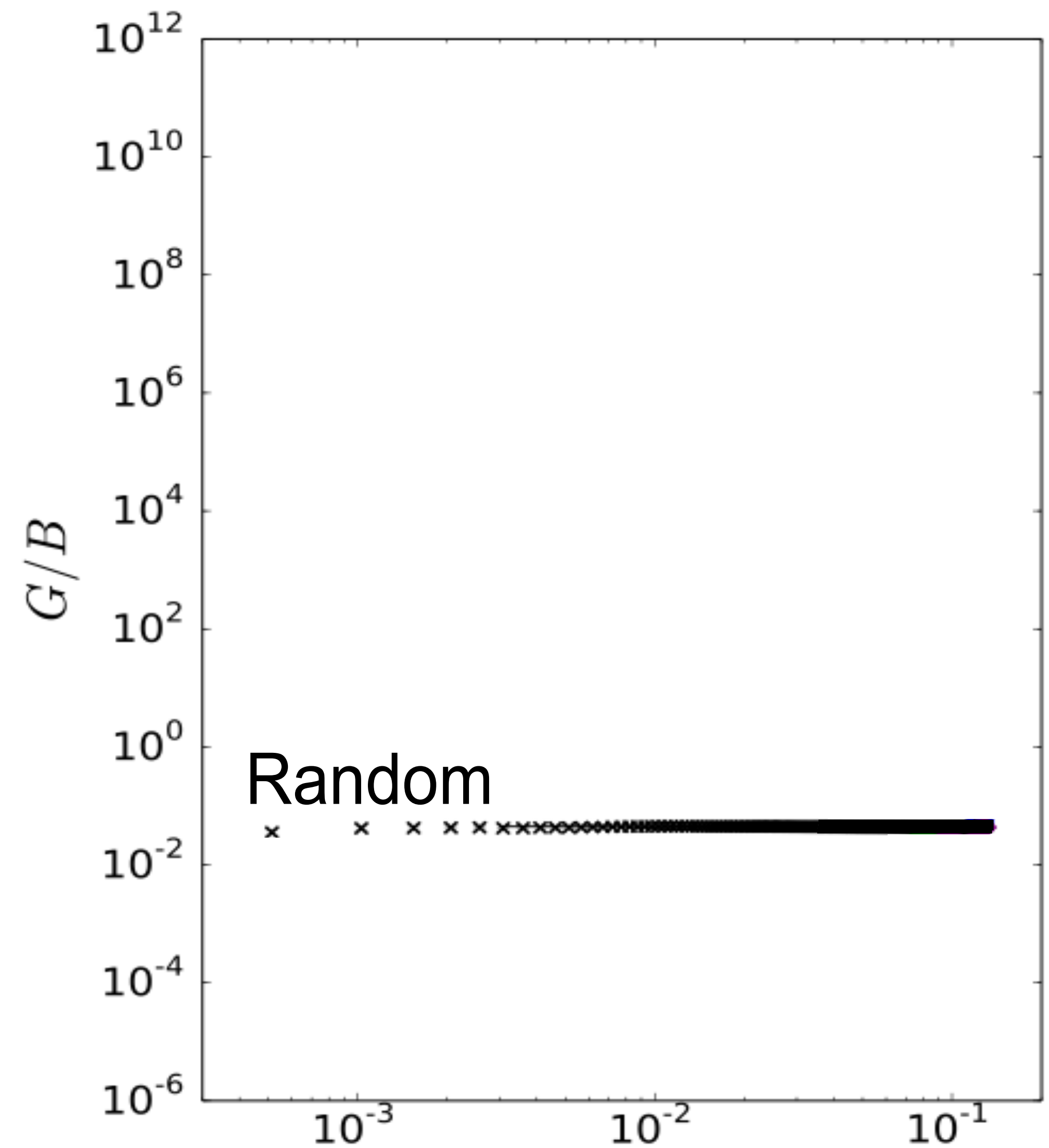
* *after*

Distributions are broad, continuous, "universal"

Contribution to B <u>uncorrelated</u> with contribution to G

Goodrich, Hexner, Liu

Prune bonds to create novel, desired property



ΔZ (# above rigidity threshold)

Prune bonds at random
(rigidity percolation)
$\Rightarrow G/B \sim \mathcal{O}(1)$

Ellenbroek, Zeravcic, van Saarloos, van Hecke: *Europhys. Lett.* (2009).

Goodrich, Hexner, Liu

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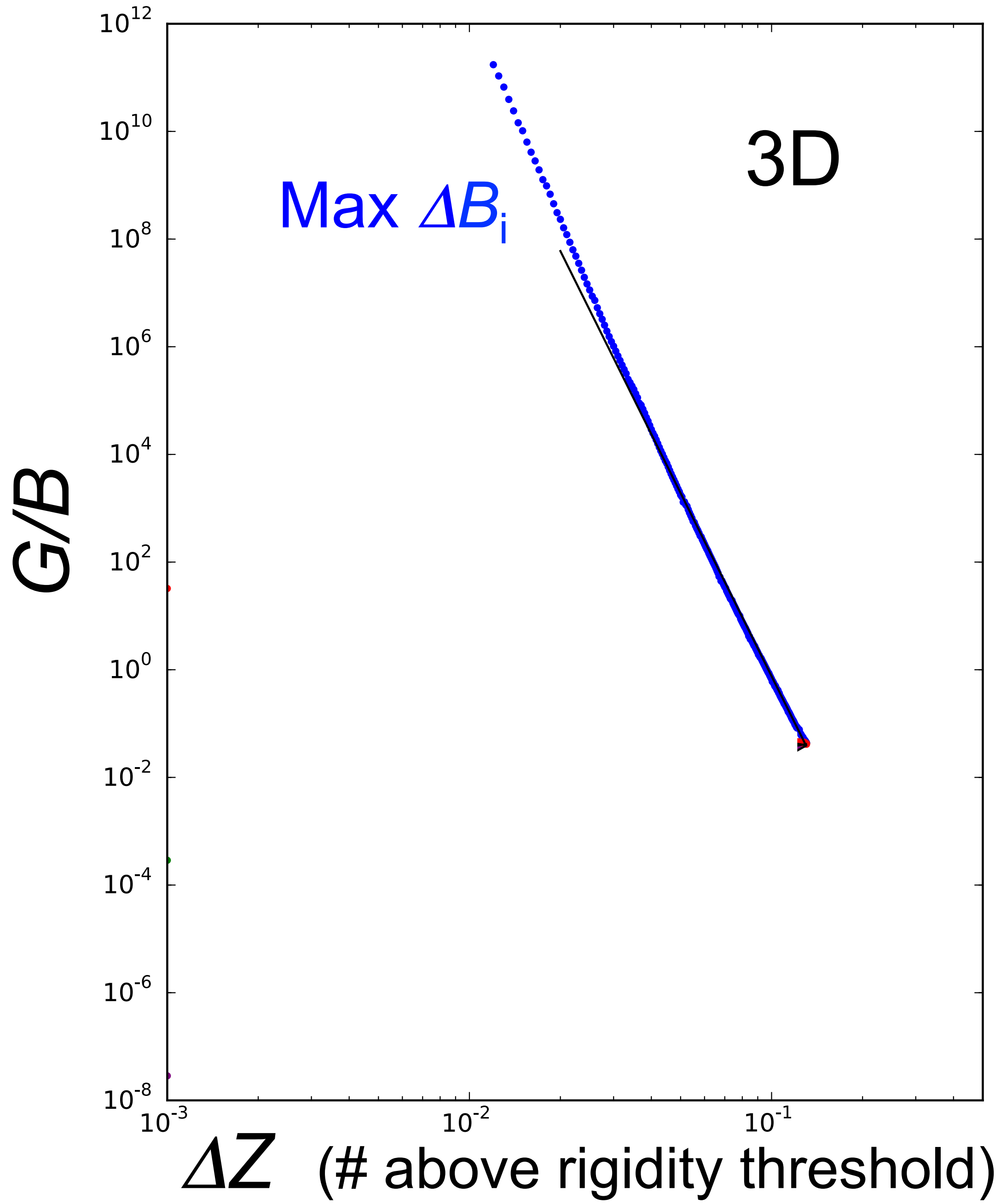


Prune bonds with maximum ΔB_i:

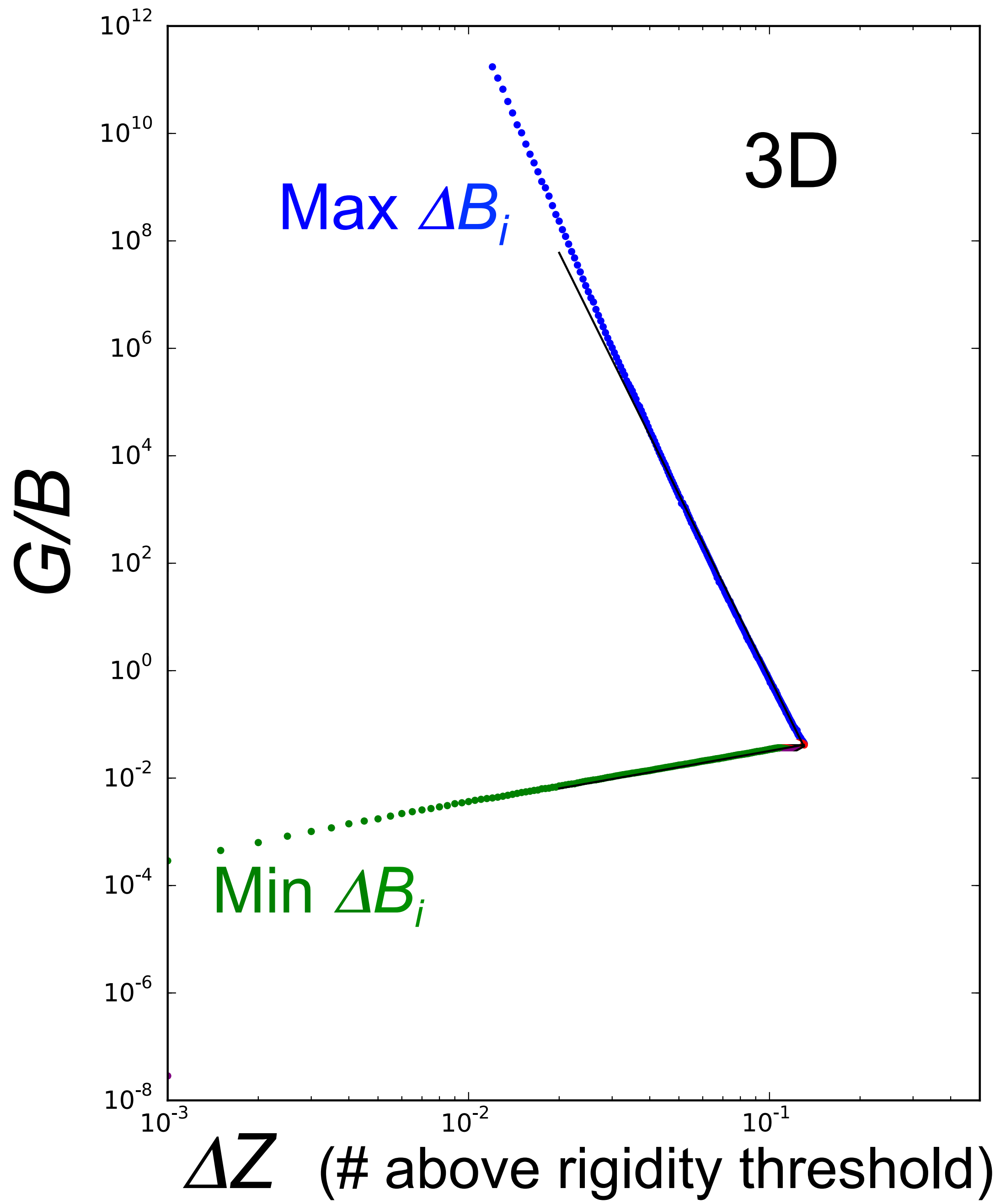
B 0; $G \sim \Delta Z$

$\Rightarrow G/B \rightarrow \infty$

Auxetic limit: $\nu = -1$

Goodrich, Hexner, Liu

Prune bonds to create novel, desired property



Prune bonds with maximum ΔB_i:

$B \ 0$; $G \sim \Delta Z$

$\Rightarrow G/B \rightarrow \infty$

Auxetic limit: $\nu = -1$

Prune bonds with minimum ΔB_i:

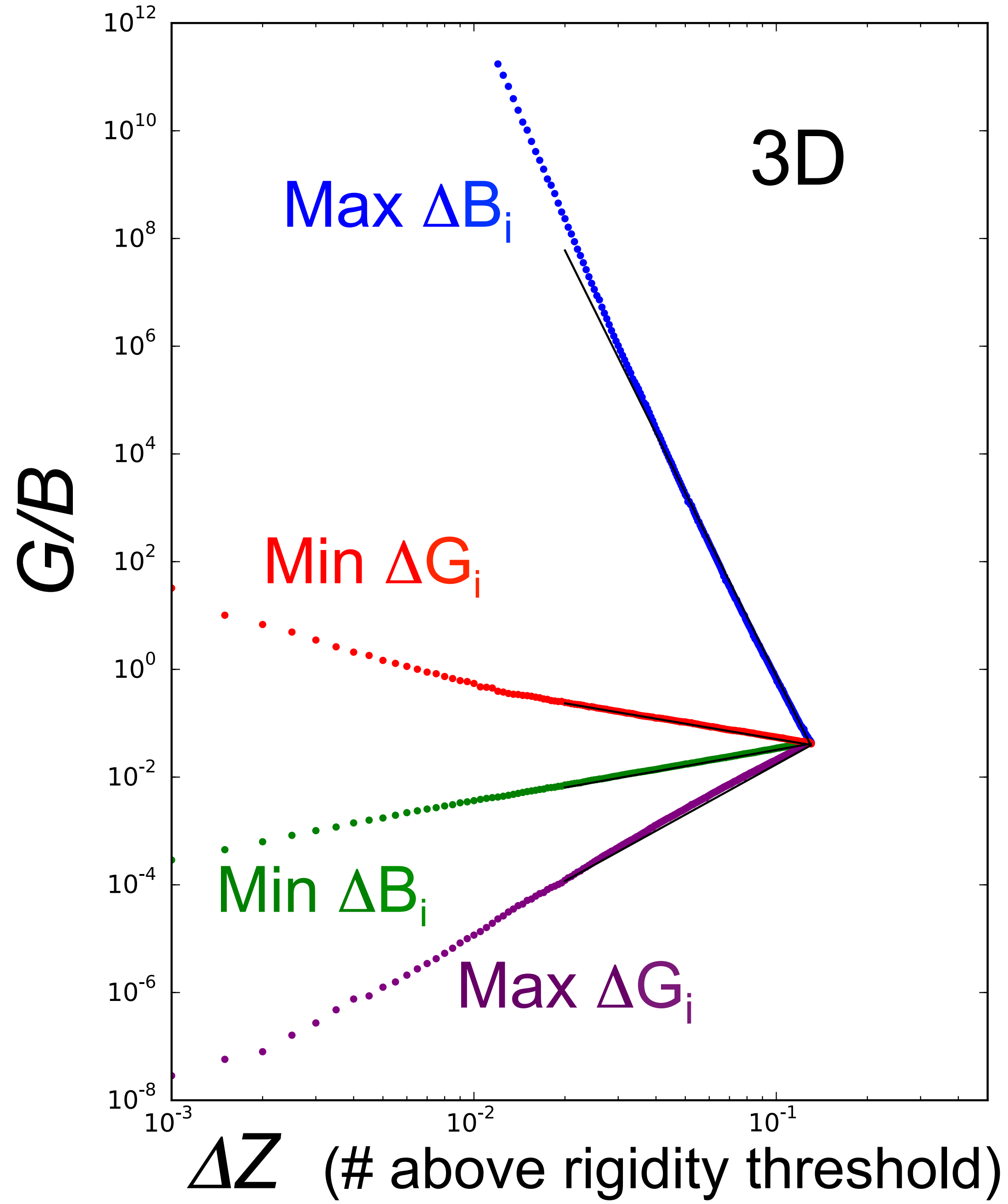
$B \sim$ constant; $G \sim \Delta Z$

$\Rightarrow G/B \rightarrow 0$

Incompressible limit: $\nu = +½$

Goodrich, Hexner, Liu

Prune bonds to create novel, desired property



Prune bonds with max ΔB_i
$\Rightarrow G/B \rightarrow \infty$

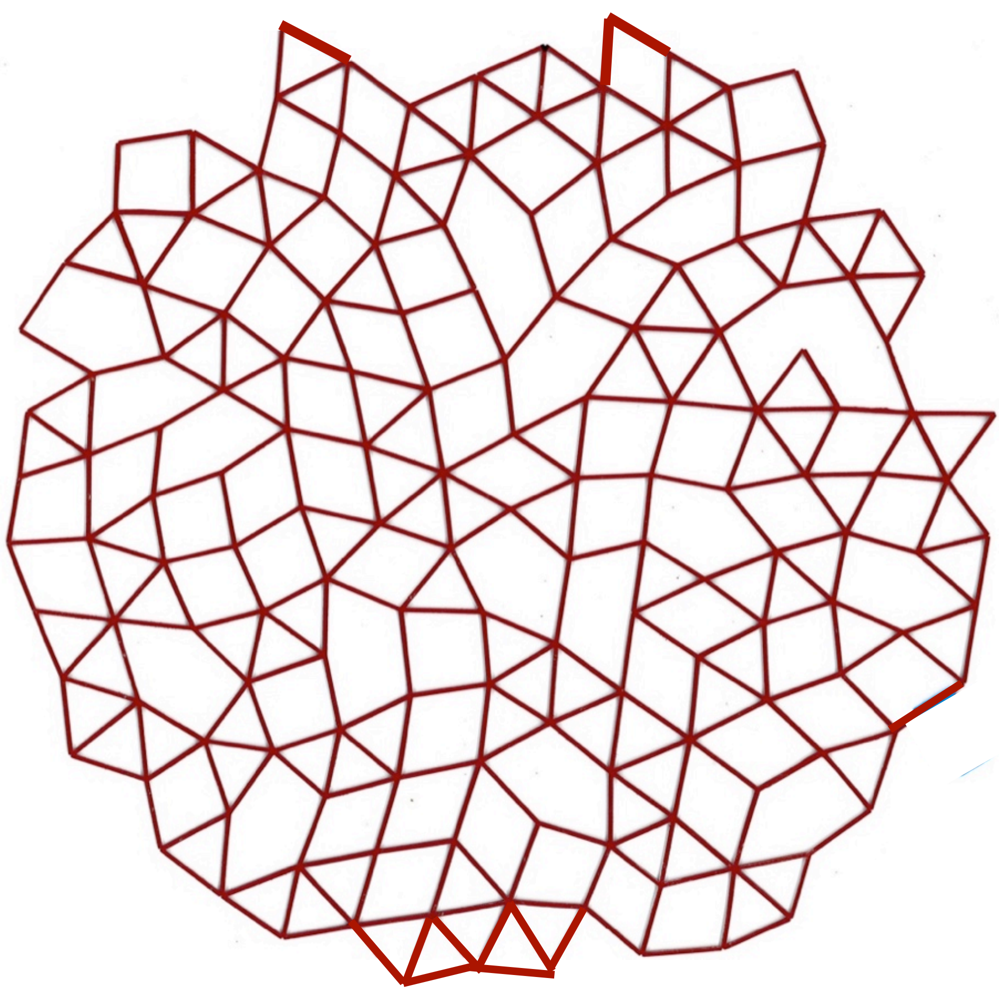
Prune bonds with min ΔG_i
$\Rightarrow G/B \rightarrow \infty$

Prune bonds with min ΔB_i
$\Rightarrow G/B \rightarrow 0$

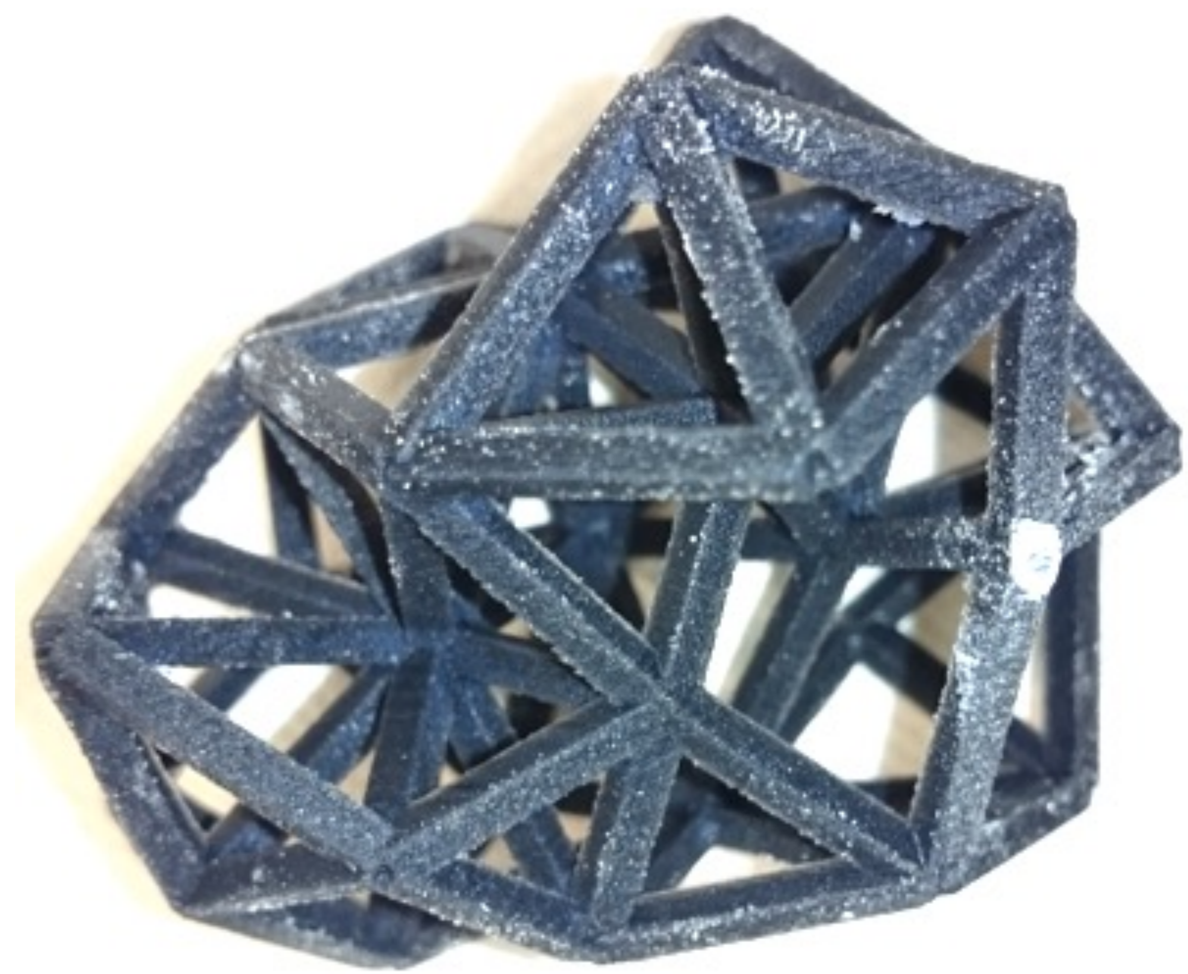
Prune bonds with max ΔG_i
$\Rightarrow G/B \rightarrow 0$

Goodrich, Hexner, Liu

Make them in the lab



2D
(laser-cut sheets)



3D
(3D printer)

Make negative Poisson ratio (auxetic) material: laser-cut sheet

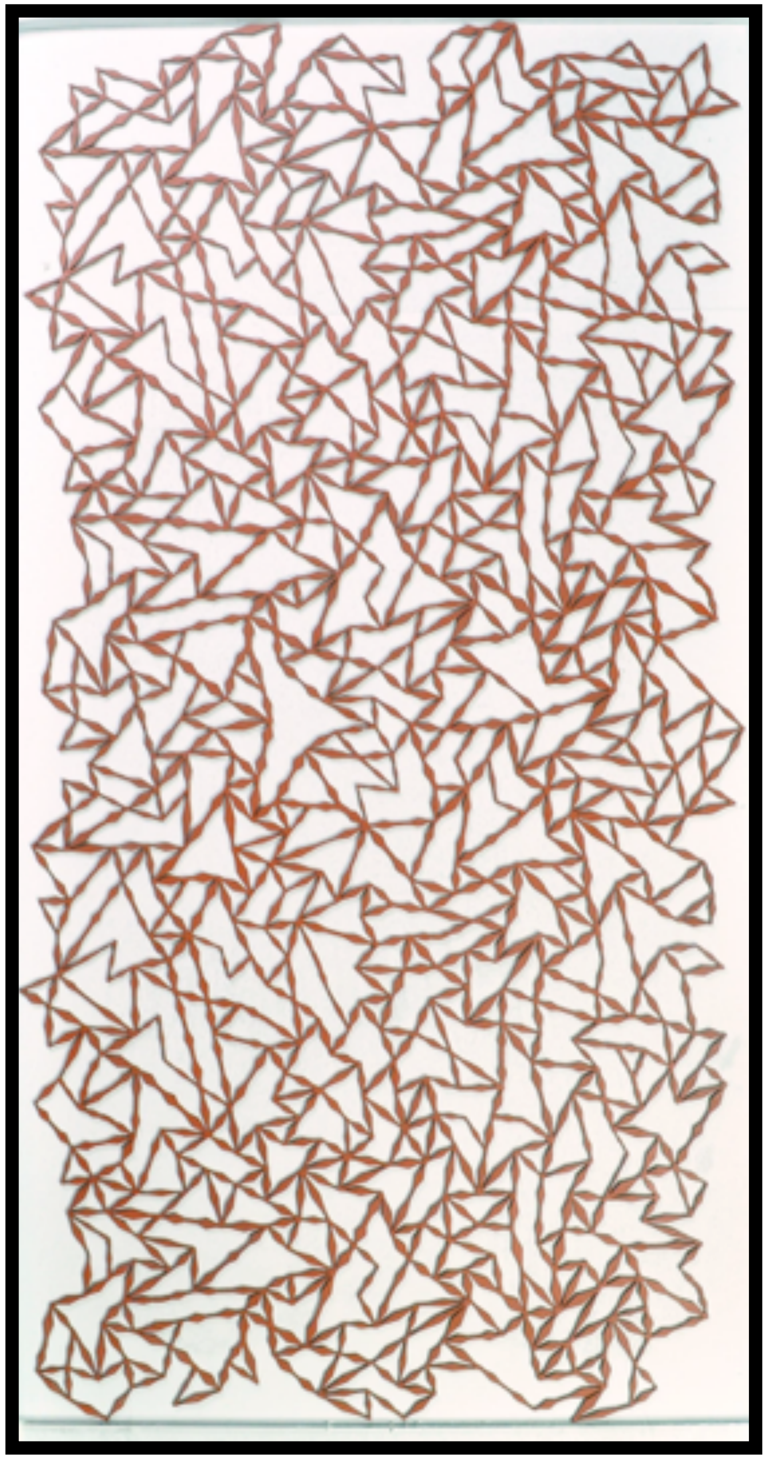
Need to include bond-bending forces:

Bond compression potential

$E(r) = k_{comp} (r - r_0)^2$

Bond bending potential

$E(\theta) = k_{bend} (\theta - \theta_0)^2$



Reid, Pashine, de Pablo

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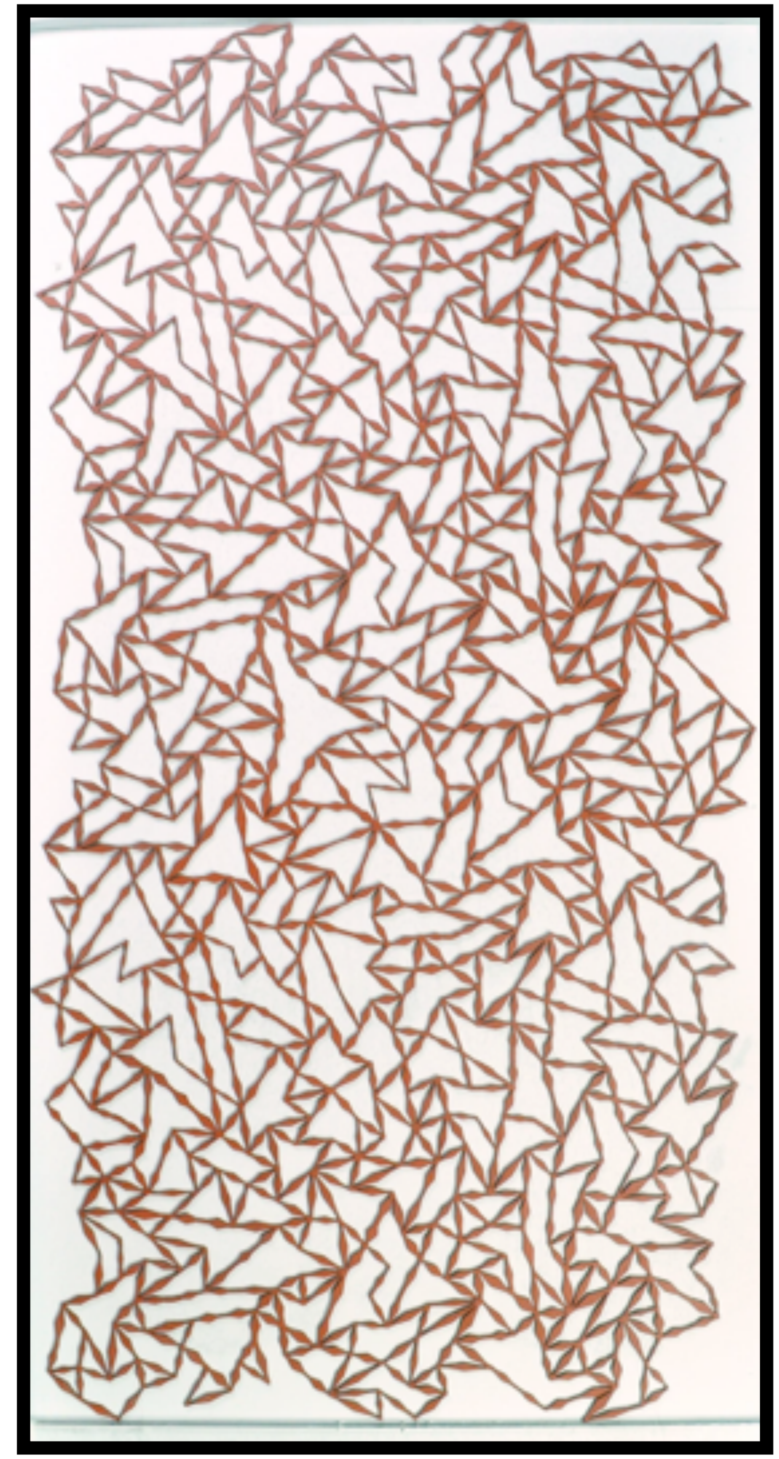
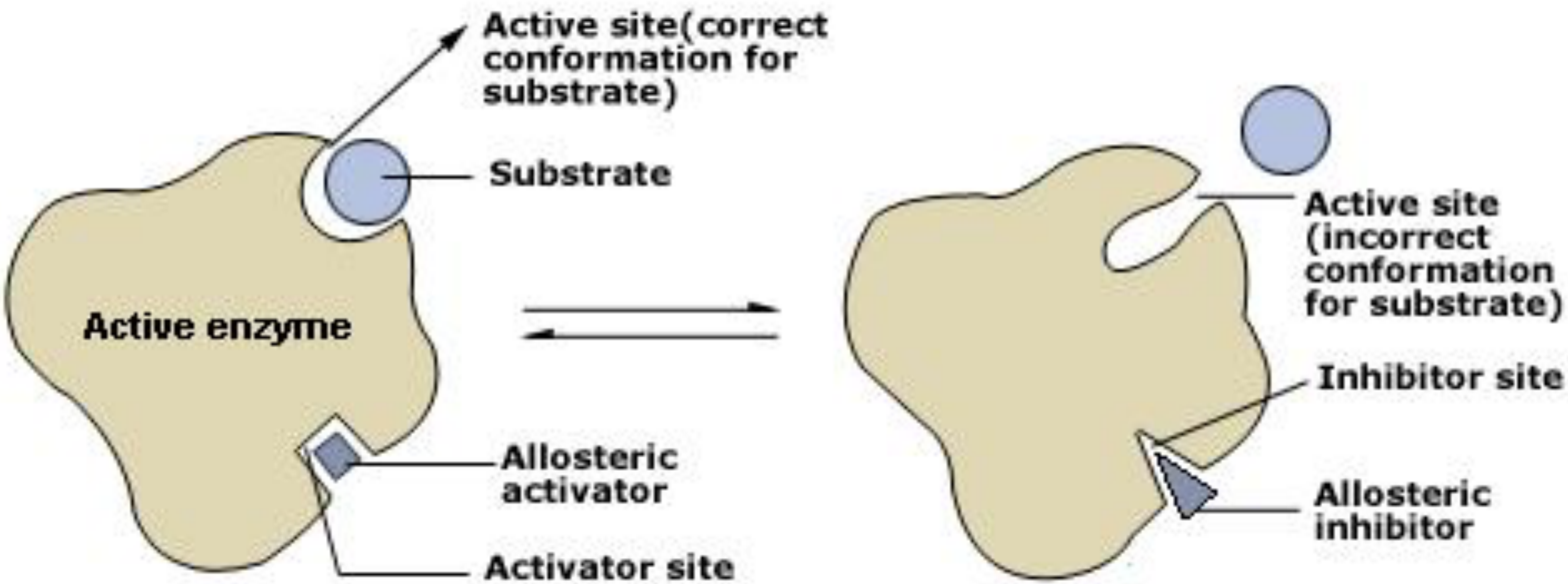


Reid, Pashine, de Pablo

How general is this behavior?
Control *local* (not just global) response

e.g., protein allostery:
Local deformation affects distant site



https://biology.stackexchange.com/questions/42725/difference-between-negative-allosteric-regulation-and-non-competitive-inhibition

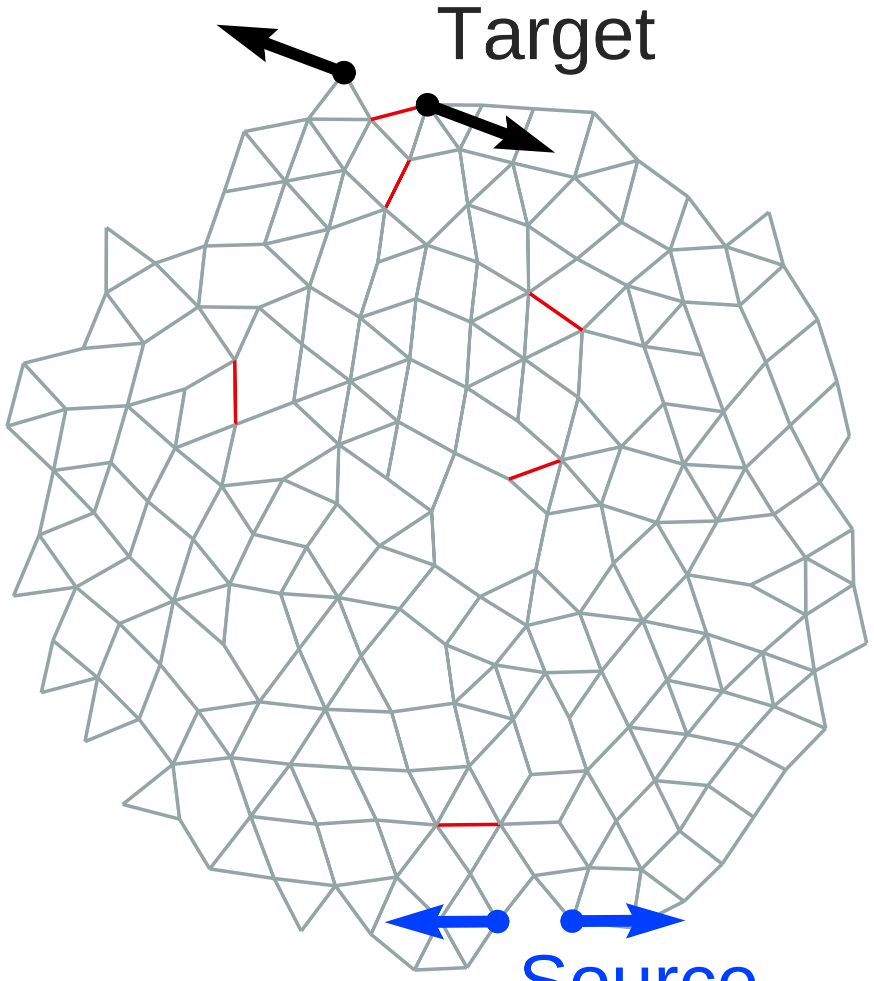
Remember Tsvi Tlusty's talk:

"Architecture and coevolution of allosteric materials," Yan, Ravasio, Brito, Wyart *PNAS* 2017
"Physical Model of Genotype-to-Phenotype Map of Proteins," Tlusty, Libchaber, Eckmann *PRX* 2017.

How general is this behavior?
Control *local* (not just global) response

Like protein allostery: Compress nodes locally

Distant site responds as desired



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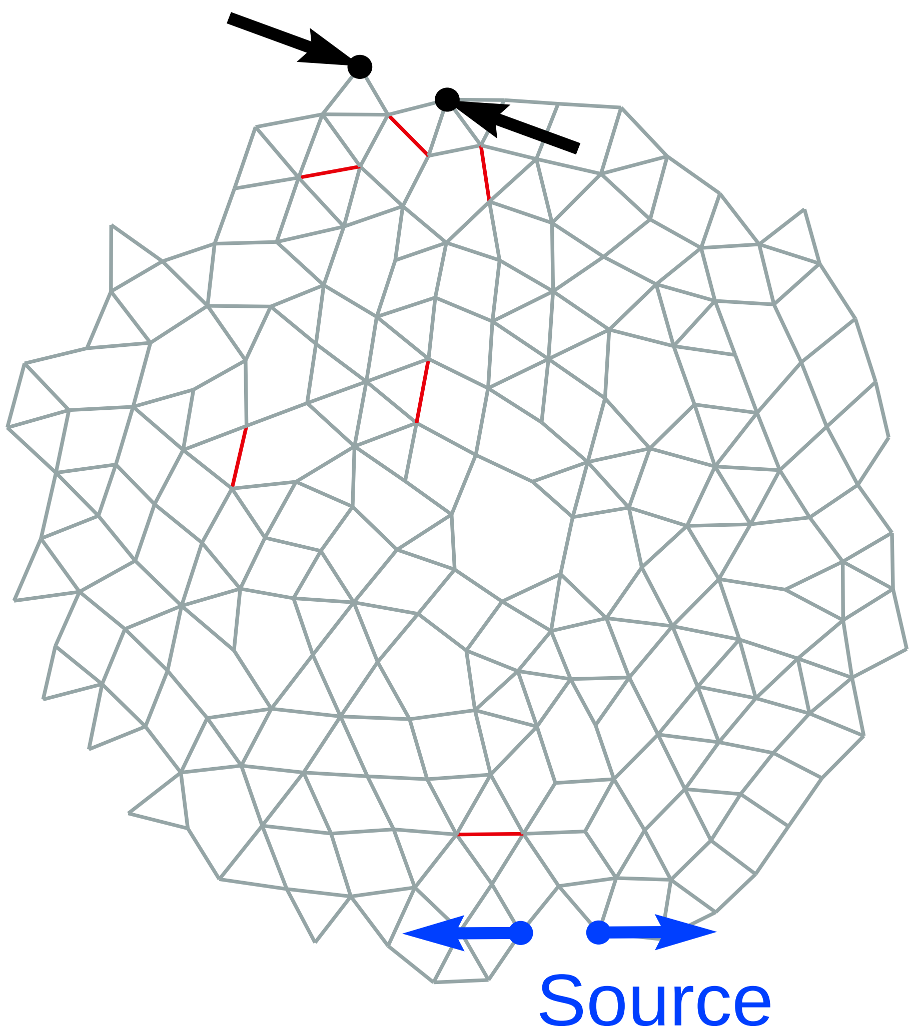
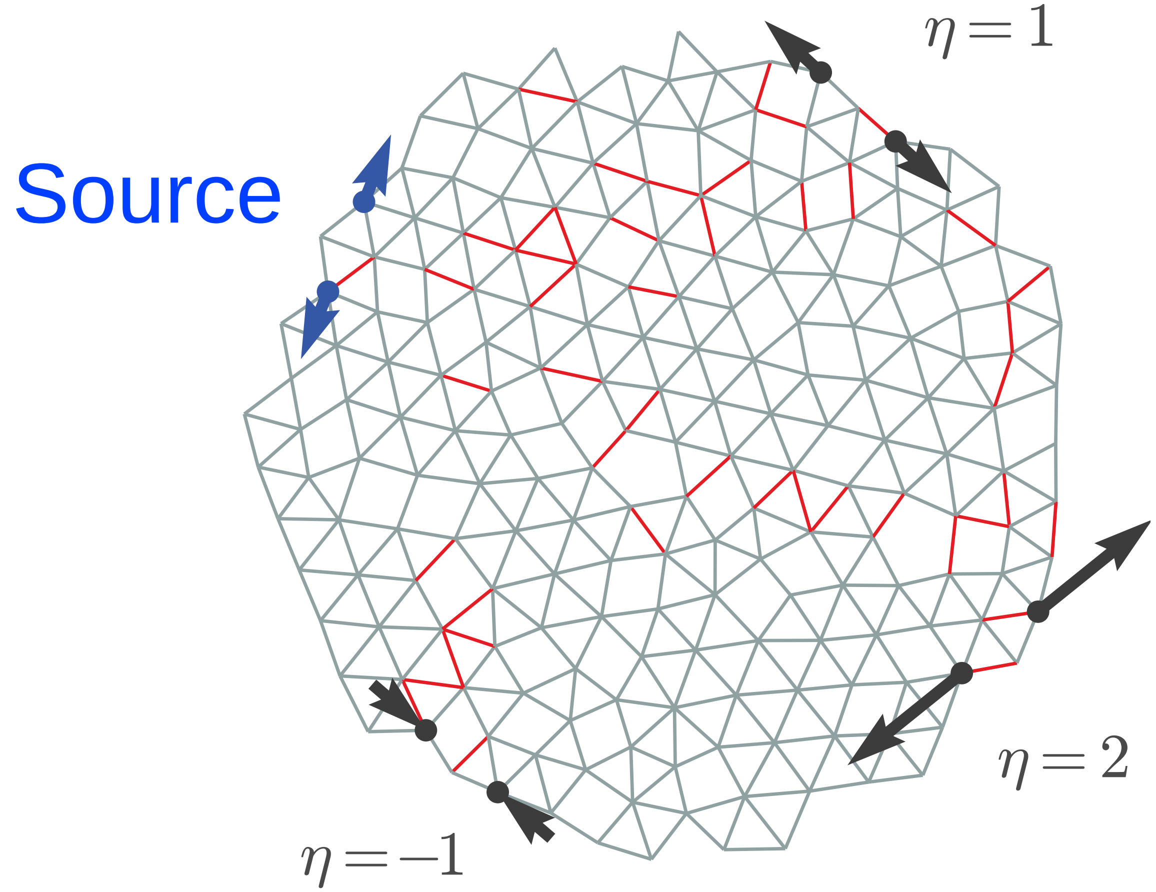
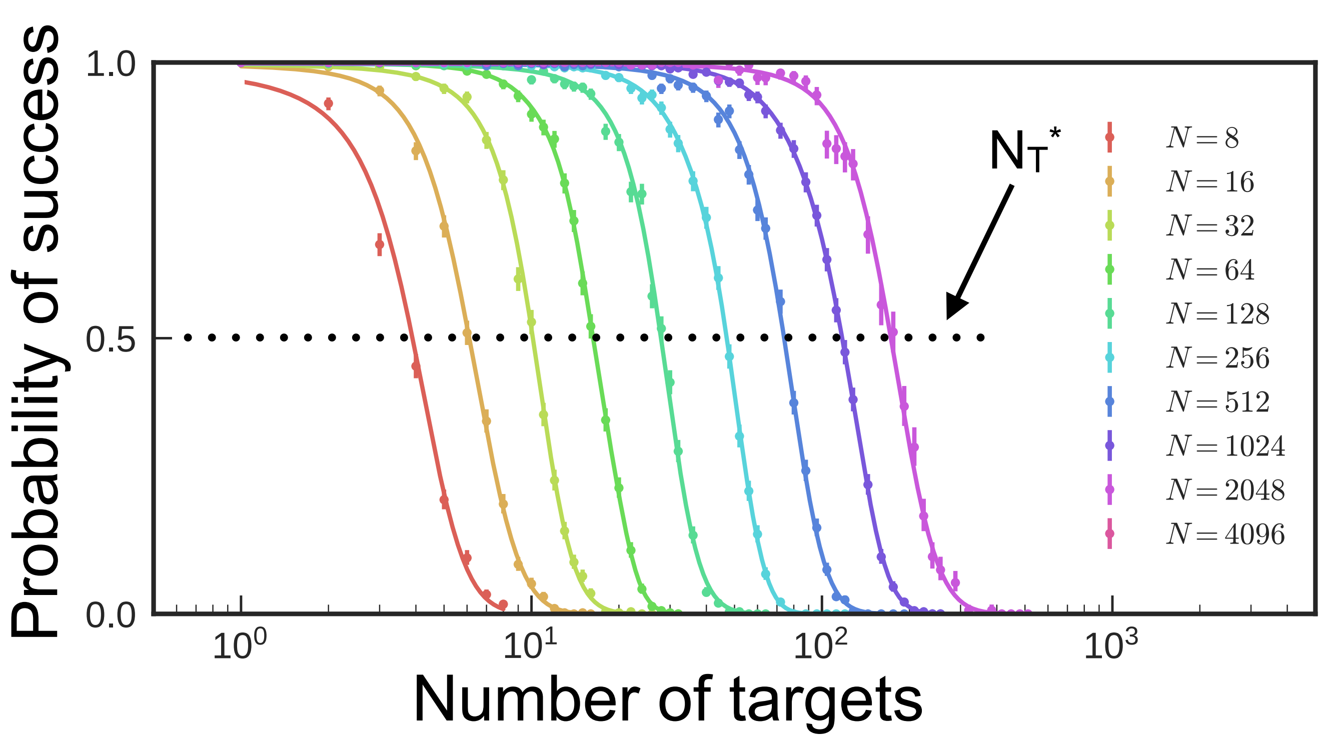
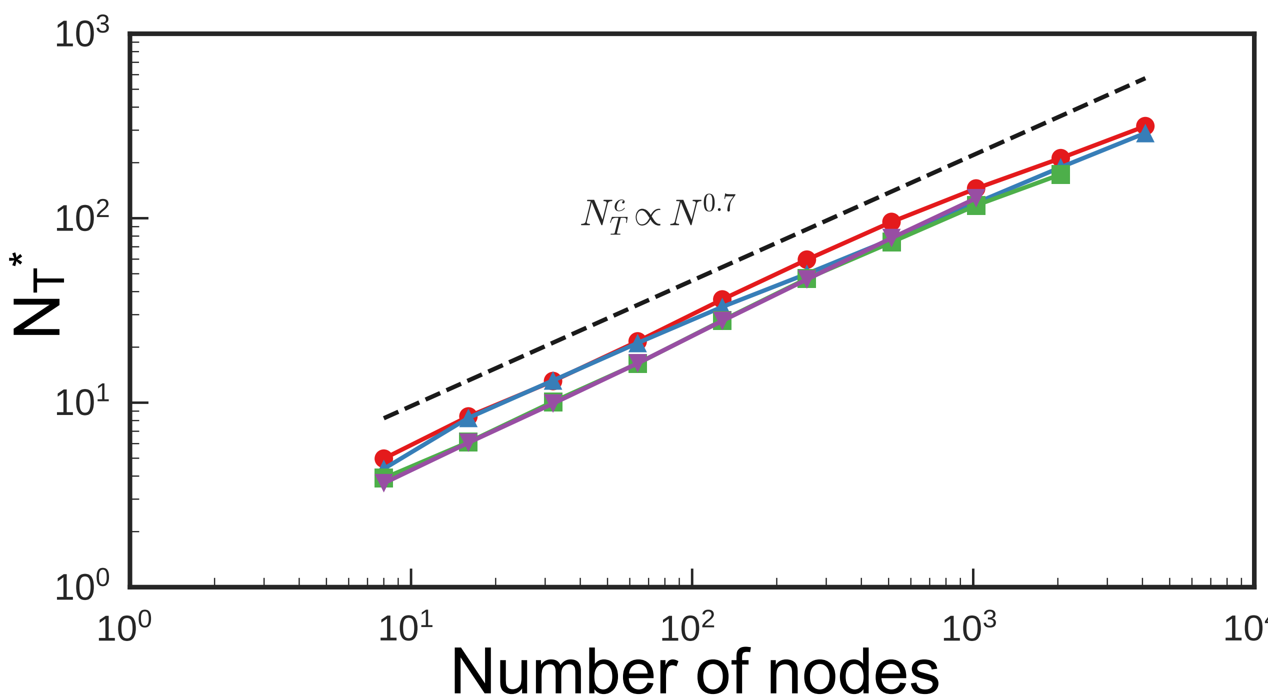


Rocks, Pashine, Bischofberger, Liu

How many target sites can be controlled by single source?







Jason Rocks, Henrik Ronellenfitsch, Andrea Liu, Eleni Katifori

Aging: memory of its history

Bonds under most stress deform plastically.

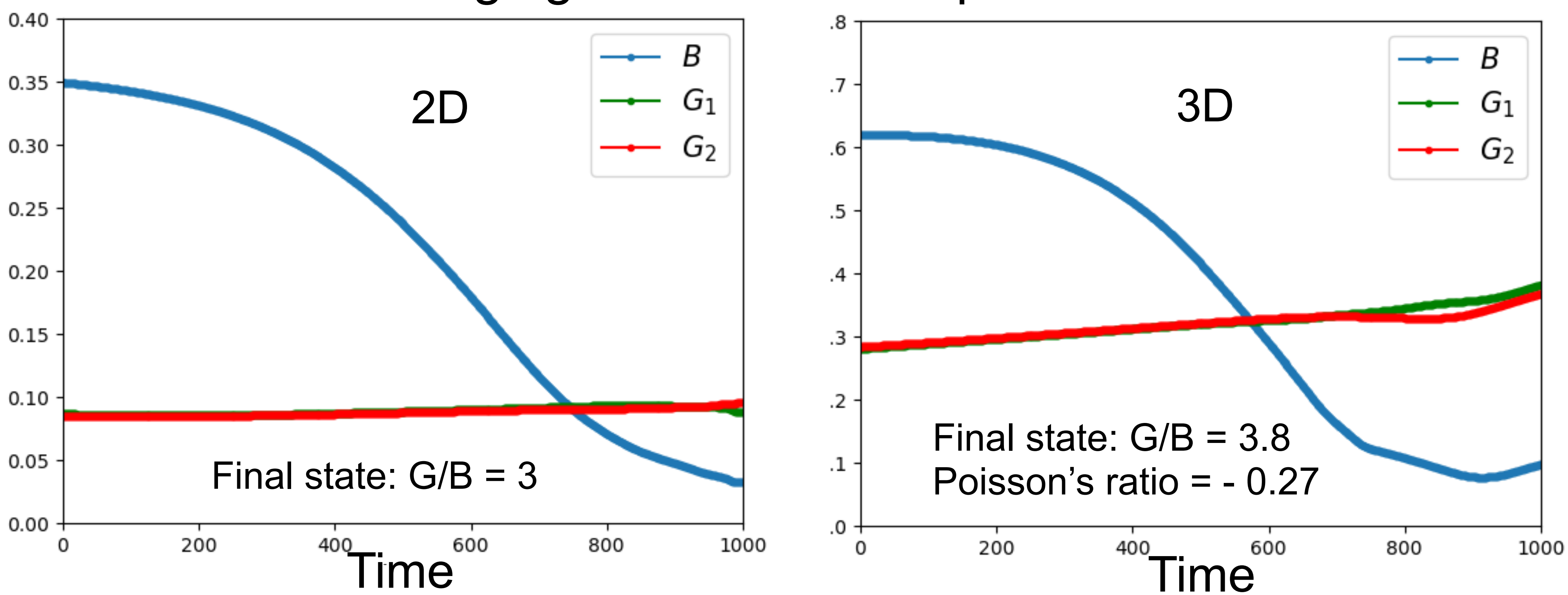
$$E = \frac{1}{2} K \sum_i (l_i - l_i^0)^2$$

Bonds with higher stress evolve faster than those with less stress.

$$\frac{dl_i^0}{dt} = -K(l_i - l_i^0)$$

Material not just weaker; changed character.

Aging under constant pressure



Directed aging

Daniel Hexner, Andrea Liu

Material memory

Encode a pathway for material behavior:

- Global (*e.g.*, selects Poisson's ratio)
- Local (*e.g.*, action-at-a-distance allosteric effects)

Material memory

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- Global (*e.g.*, selects Poisson’s ratio)
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Bullshit line

Greedy algorithms and aging

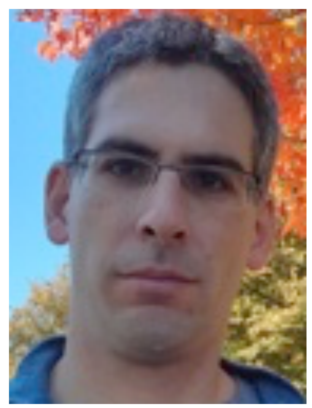
Locally finds optimum solution
goes downhill in landscape.

If material detects the landscape, directs aging
(not just weaker, but weaker with a purpose)

Creates a memory for design:
- Trains
- Reads out
- (Erases)

Andrea Liu

Carl Goodrich



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