Seeking simplicity in complexity: A physicist's view of vulcanized media

Paul M. Goldbart
School of Physics
Georgia Institute of Technology

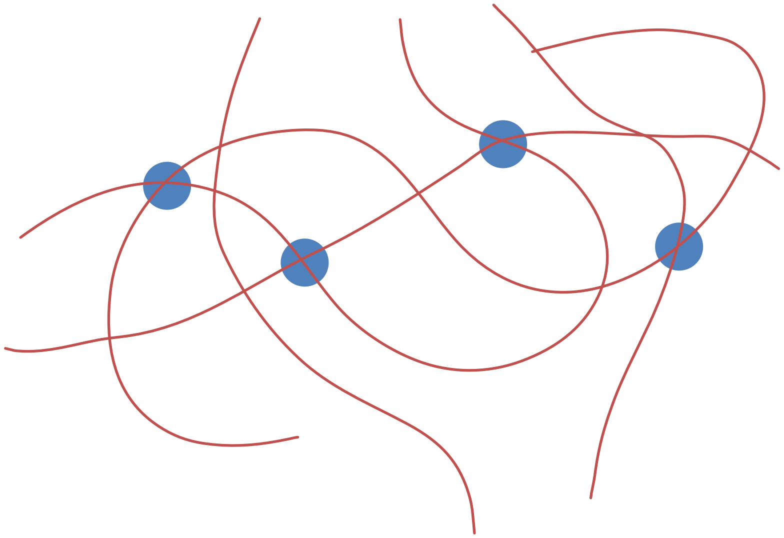
Aspen | July 2017

Leo Kadanoff
(1937-2015)

Ken Wilson
(1936-2013)

Sam Edwards
(1928-2015)

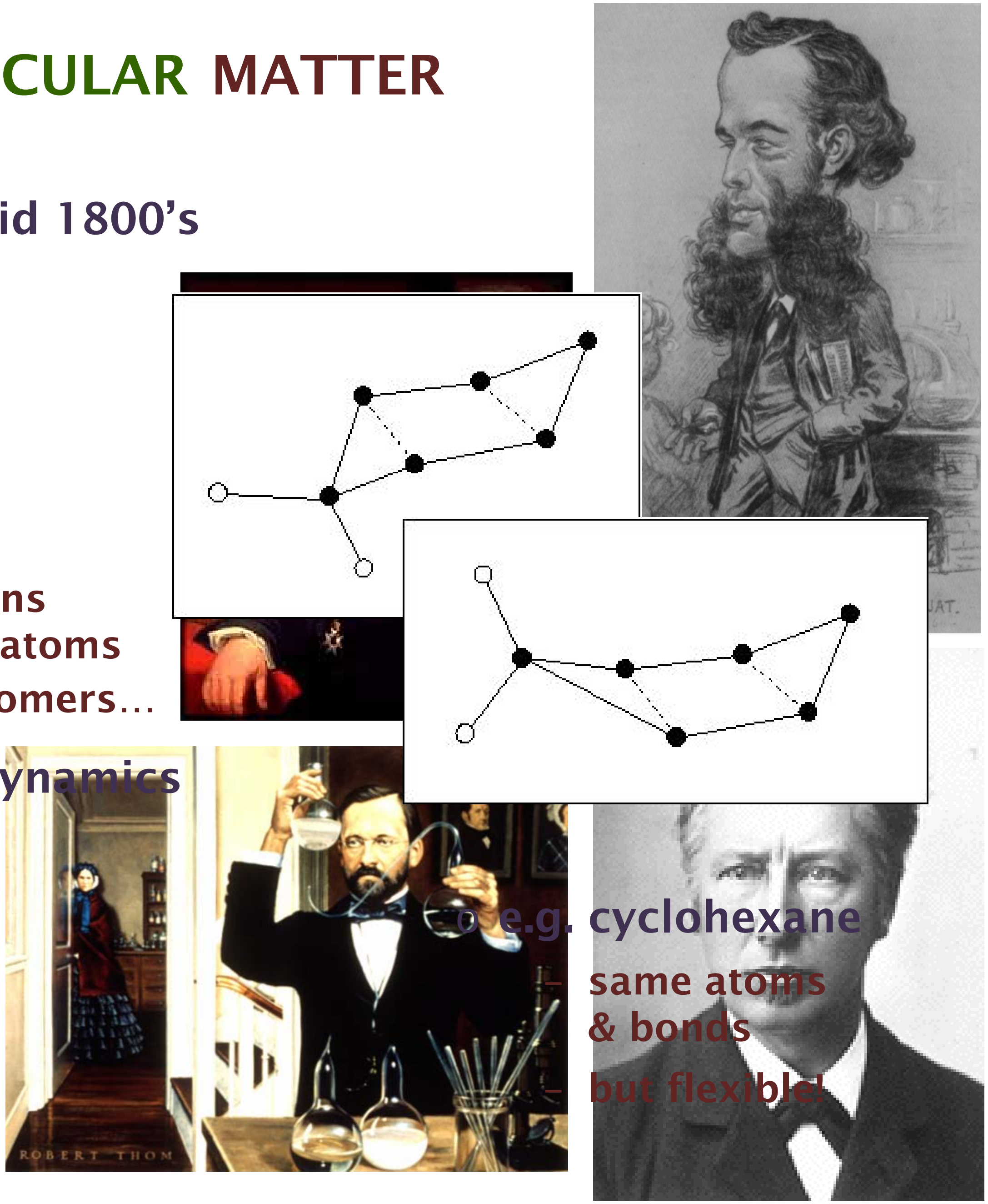
VULCANIZED MATTER



- what is it ?
- what’s unusual about it ?
- why is it *complex* ?

LET'S BEGIN WITH MOLECULAR MATTER

- structure of matter ~ mid 1800's
  - Berzelius, Kekulé, Pasteur, van 't Hoff,…
  - chemical reactions, optical activity
- emerging picture
  - molecules = 3D patterns of chemically bonded atoms
  - structural- & stereo-isomers…
- classification, but not dynamics
  - until quantum theory



- e.g. cyclohexane
  - same atoms & bonds
  - but flexible!

JUST ONE OF VAN ’T HOFF’S CRITICS…

“…there is an overgrowth of the weed of the seemingly learned and ingenious but in reality trivial and stupefying…

[which is] being dragged out by pseudoscientists from the junk-room which harbors such failings of the human mind, and…

[is being] dressed up in modern fashion and rouged freshly like a whore whom one tries to smuggle into good society where she does not belong.”

“Whoever considers this apprehension to be exaggerated should read, if he can manage it, the recently published pamphlet, “The arrangement of atoms in space”… which teems with fantastic trifles.”

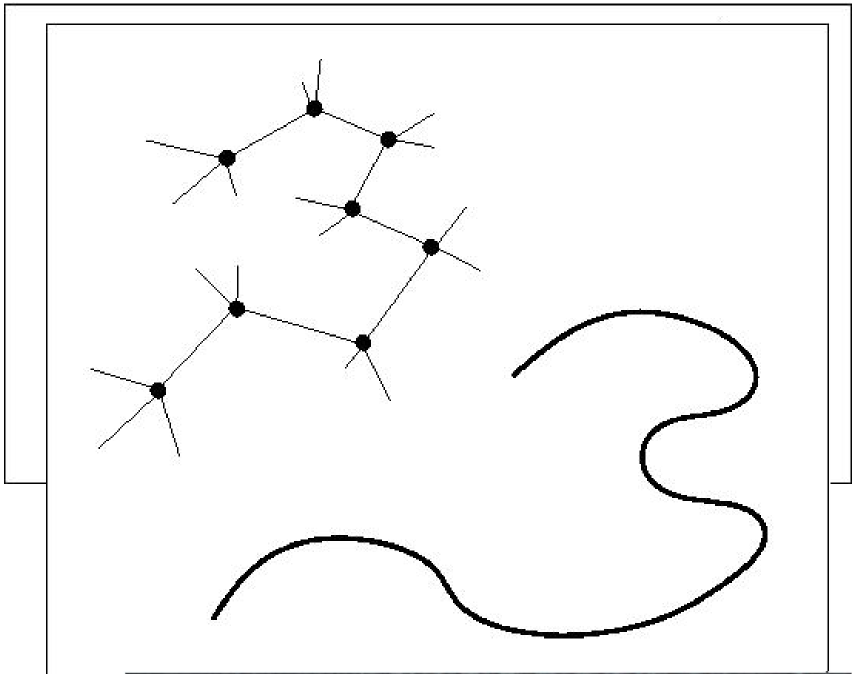
Hermann Kolbe (1818-1884)

“The modern chemical theory has two weak points. It says nothing either about the relative position or the motion of the atoms within the molecule.”

Jacobus Henricus van't Hoff (1852-1911), Chemistry Nobel Laureate (1901), in “The arrangement of atoms in space”

NOW FOR MACROMOLECULAR MATTER

- much longer molecules (eg PE)
- amplified flexibility, random coils
- but do they exist ?

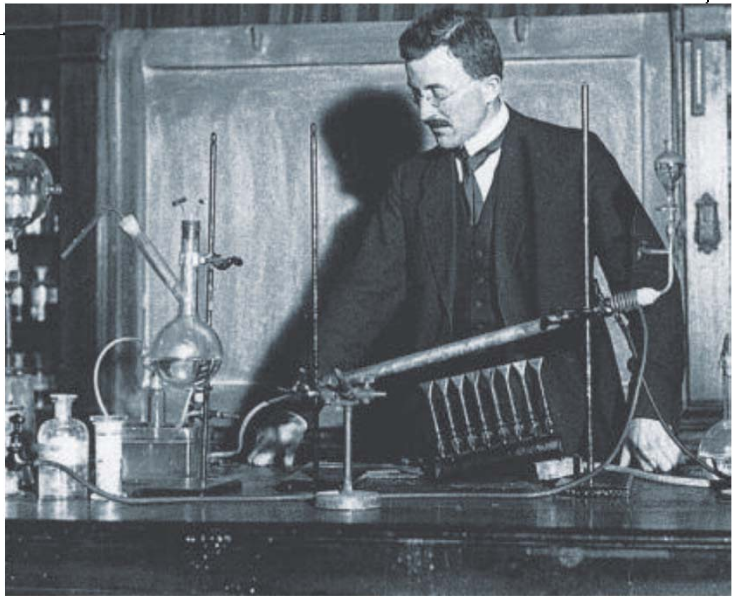


"Dear colleague, drop the idea… large molecules… with a molecular weight higher than 5000 do not exist. Purify your products… they will crystallize & prove to be low molecular compounds!"

Heinrich Wieland
Chemistry Nobel Laureate (1927)

"colleagues were very skeptical [asking] why I was neglecting [low molecular chemistry for] *Schmierenchemie* or grease chemistry."

Hermann Staudinger, autobiography (1961)
Chemistry Nobel Laureate (1953)



SOME SCALES FOR A TYPICAL MACROMOLECULE

- monomers repeated <u>extraordinarily many</u> times

~ 25,000 carbon atoms

~ 75,000 atoms in all

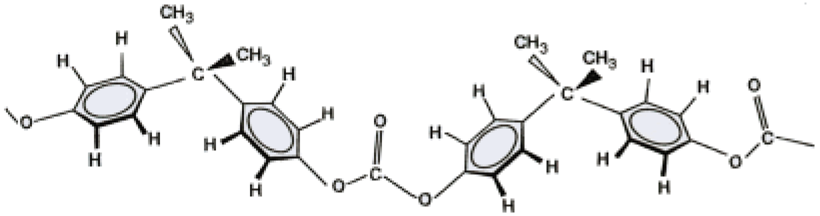
~ 5 μm along backbone

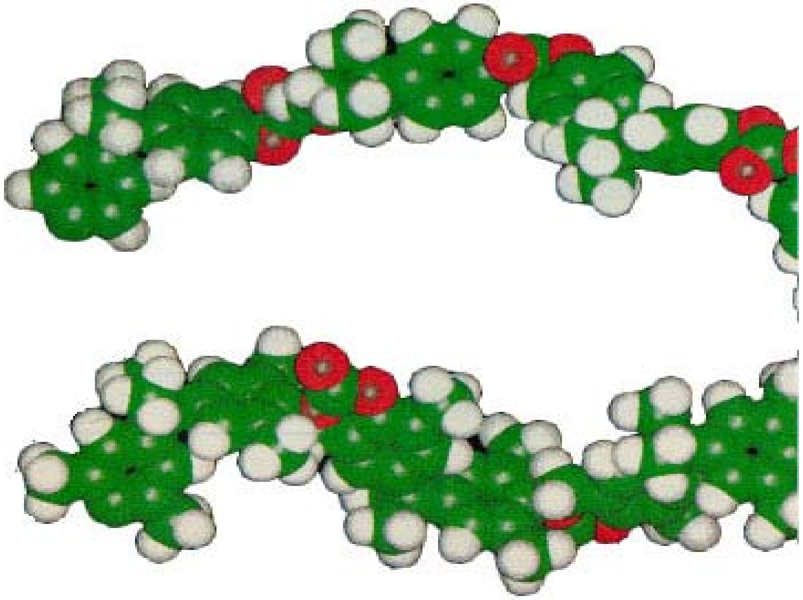
~ 0.1 μm across coil

bending length ~1 nm

length/dia. ~ 6,000

25 m mouse cable





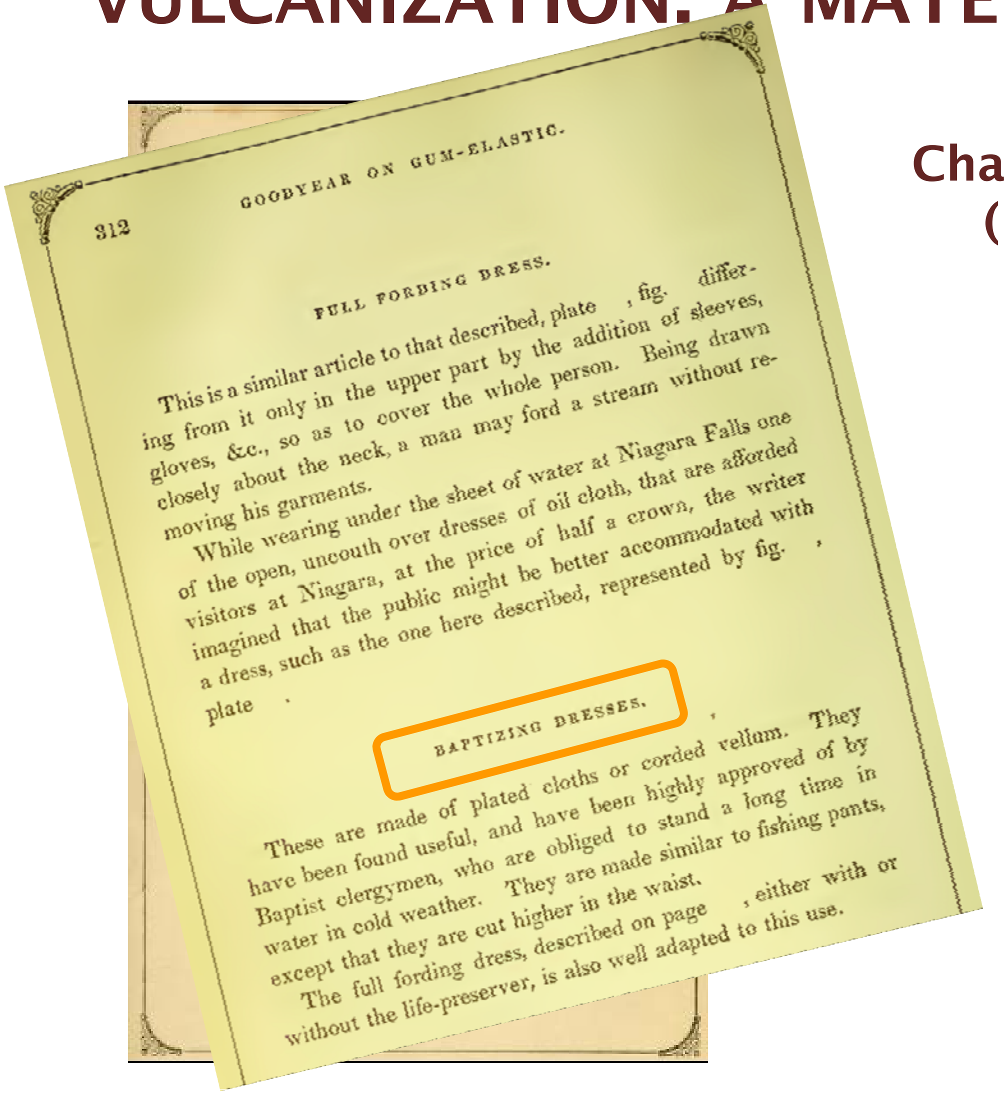
as van ’t Hoff & Staudinger surely understood…

> “All truth passes through three stages:
> First, it is ridiculed;
> Second, it is violently opposed; and
> Third, it is accepted as self-evident.”
>
> A. Schopenhauer (1788-1860)

MACROMOLECULAR MATTER

- e.g. natural rubber (polymerized isoprene), spider silk, polyethylene, chewing gum, plastics, resins…
- many biological & synthetic forms

VULCANIZATION: A MATERIALS REVOLUTION



312 GOODYEAR ON GUM-ELASTIC.

FULL FORDING DRESS.

This is a similar article to that described, plate , fig. differing from it only in the upper part by the addition of sleeves, gloves, &c., so as to cover the whole person. Being drawn closely about the neck, a man may ford a stream without removing his garments.

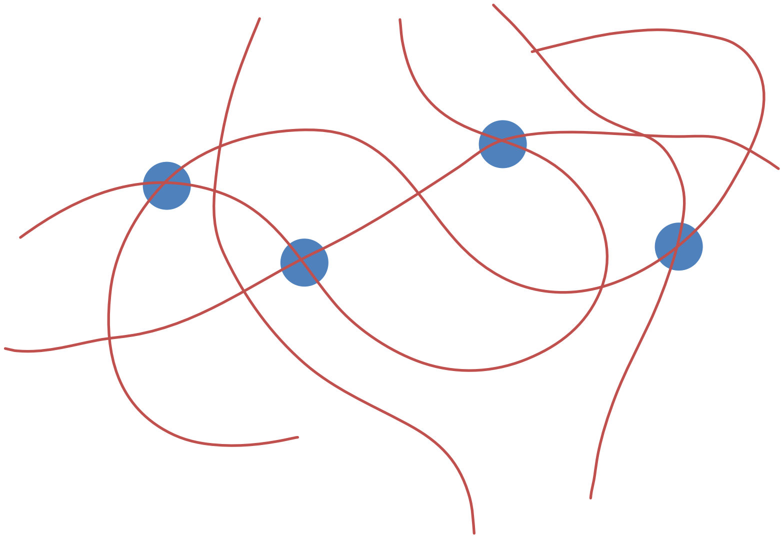
While wearing under the sheet of water at Niagara Falls one of the open, uncouth over dresses of oil cloth, that are afforded visitors at Niagara, at the price of half a crown, the writer imagined that the public might be better accommodated with a dress, such as the one here described, represented by fig. , plate .

BAPTIZING DRESSES.

These are made of plated cloths or corded vellum. They have been found useful, and have been highly approved of by Baptist clergymen, who are obliged to stand a long time in water in cold weather. They are made similar to fishing pants, except that they are cut higher in the waist.

The full fording dress, described on page , either with or without the life-preserver, is also well adapted to this use.

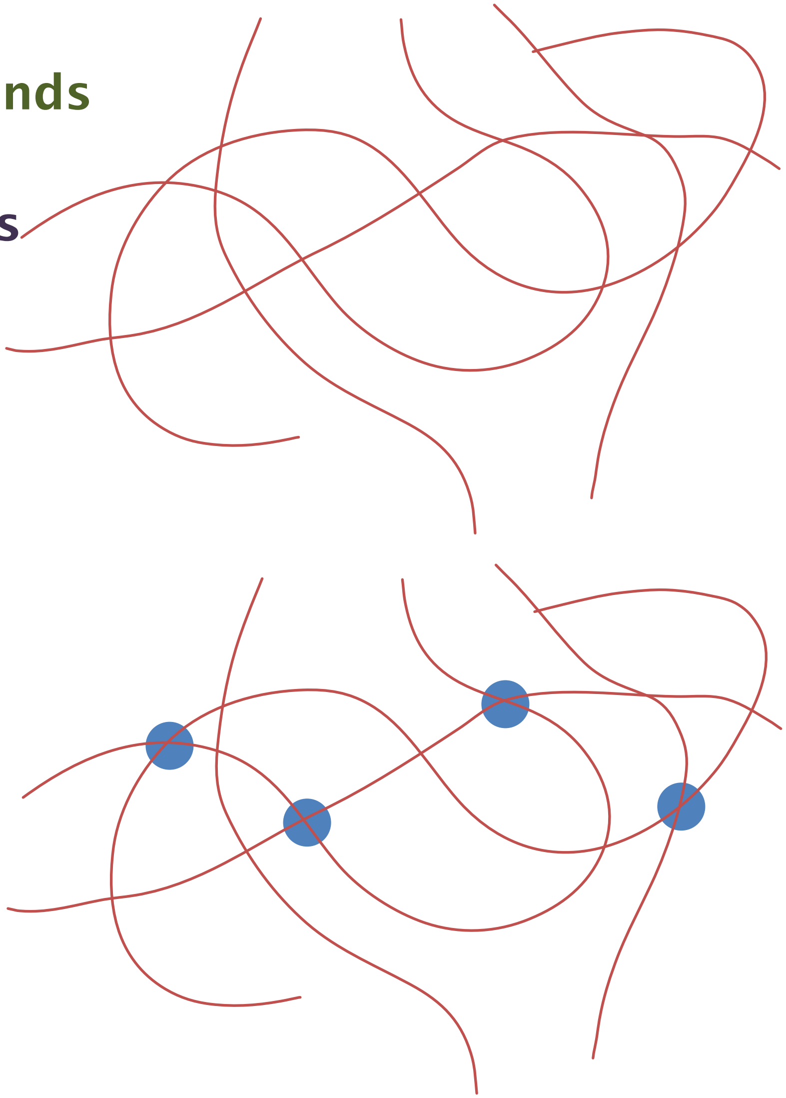
Charles Goodyear
(1800-1860)



345 pages of commercial applications within 14 years of the discovery

WHAT'S UNUSUAL ABOUT VULCANIZED MACROMOLECULAR

- randomly add permanent chemical bonds
  - into melts or solutions of macromolecules or small molecules
- what emerges ?
  - random space-filling network, thermally fluctuating
  - random (but equilibrium!) solid
  - similar to glass ?
- architectural complexity
  - annealed but also quenched freedoms



➢ vulcanization (vulcan, volcano,…) Hayward (1838), Goodyear (1839)

SCALES FOR VULCANIZED MACROMOLECULAR MATTER

- elastic moduli
  - o crystalline solids
    - bulk or shear $\sim \mathrm{Ry}/a_{\mathrm{Bohr}}^3 \sim m^4 e^{10}/h^8$
    - experimental values $\sim 10^{12}\mathrm{erg}/\mathrm{cm}^3$
  - o rubber
    - bulk: comparable
    - shear: ~100,000 times smaller

- reversible extensibility
  - o crystal: ~1%
  - o rubber: ~700%

o e.g. 1% extension of 1mm wire
- steel ~ 350 lbs
- rubber ~ fractions of an ounce

GOAL: TO UNDERSTAND…

- **emergent collective properties characteristic of this random solid**

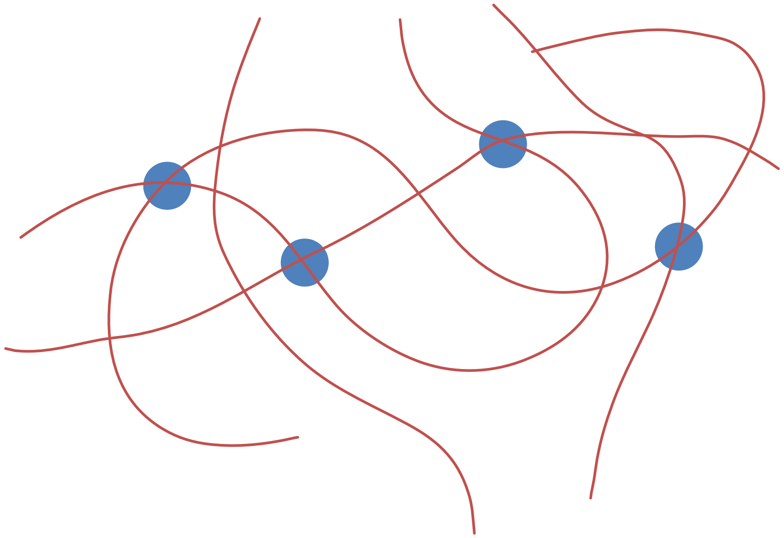
- **what properties ?**
  - **structure**
  - **elasticity**
  - **heterogeneity**

    emergent: ***not meaningful for an isolated polymer***

  - **applications:** ***blends, liquid crystalline elastomers (not today)***
- **how can we capture these theoretically ?**
- **is there any universality to them ?**

OUTLINE

- matter: molecular, macromolecular, vulcanized
- the random solid state & its emergent collective properties
- statistical *mechanics*, done statistically
- detecting localization
- order parameters & field theories
- encoded emergent structure
- encoded emergent elasticity
- fluctuations & criticality
- some remarks



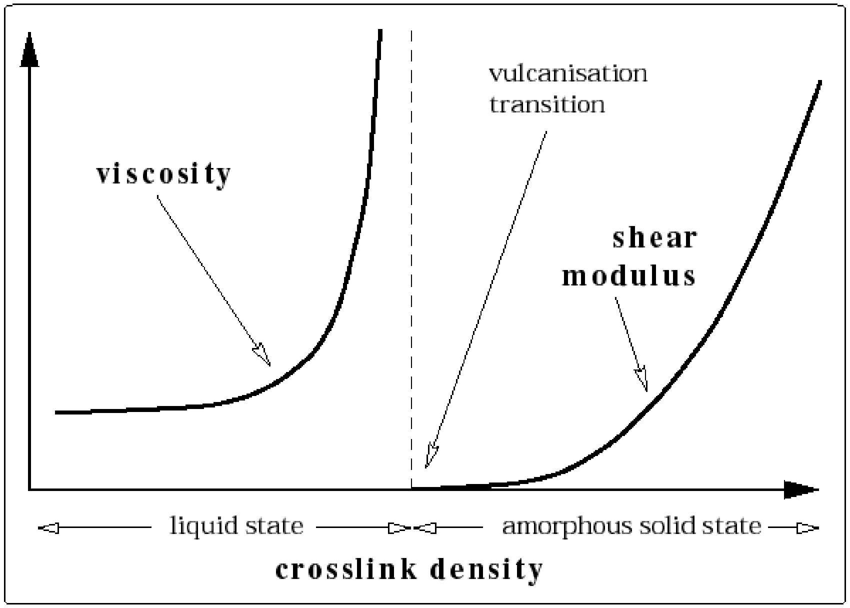
SUFFICIENT VULCANIZATION TRIGGERS A RANDOM EQ'M SOLID

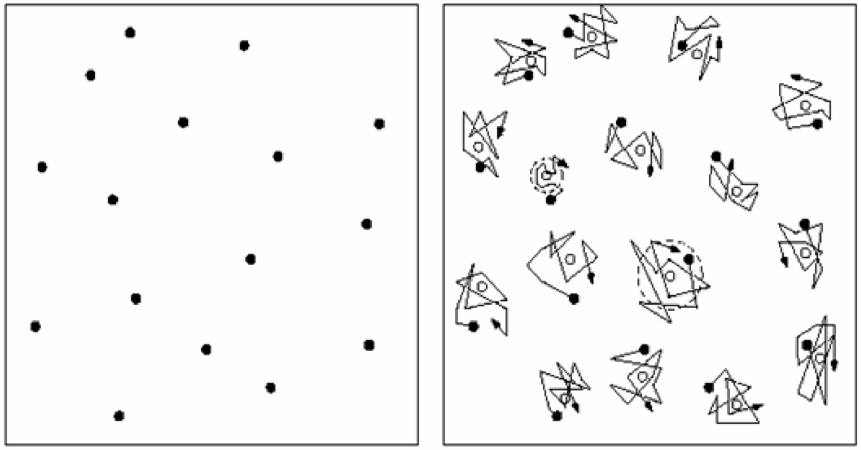
- first, add bonds…

- macro
  - liquid to solid
  - retains macro homogeneity

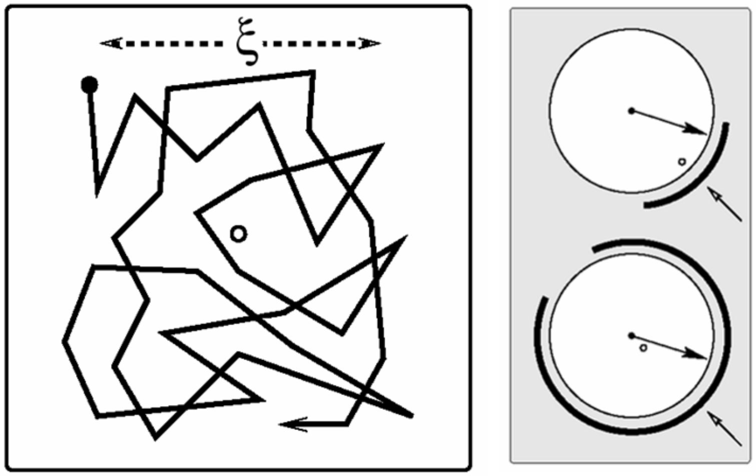
- micro
  - localization
  - transl invariance spont broken
  - but inhomogeneously

- can we understand…
  - transition ?
  - implications ?





DETECTING LOCALIZATION OF A PARTICLE

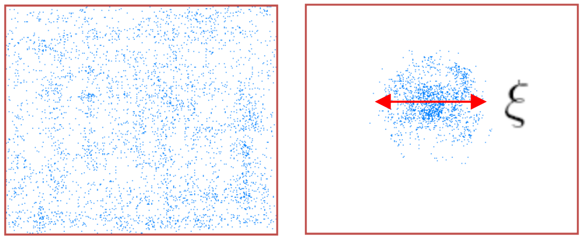


- begin with one particle
  - position $\mathbf{R}$
  - choose wave vector $\mathbf{k}$
  - equilibrium / thermal average $\langle \cdots \rangle$
    - if delocalized $\langle \exp i\mathbf{k}\cdot\mathbf{R}\rangle = 0$
    - if localized $\langle \exp i\mathbf{k}\cdot\mathbf{R}\rangle \approx \exp i\mathbf{k}\cdot\langle\mathbf{R}\rangle \exp(-k^2\xi^2/2)$

random mean position

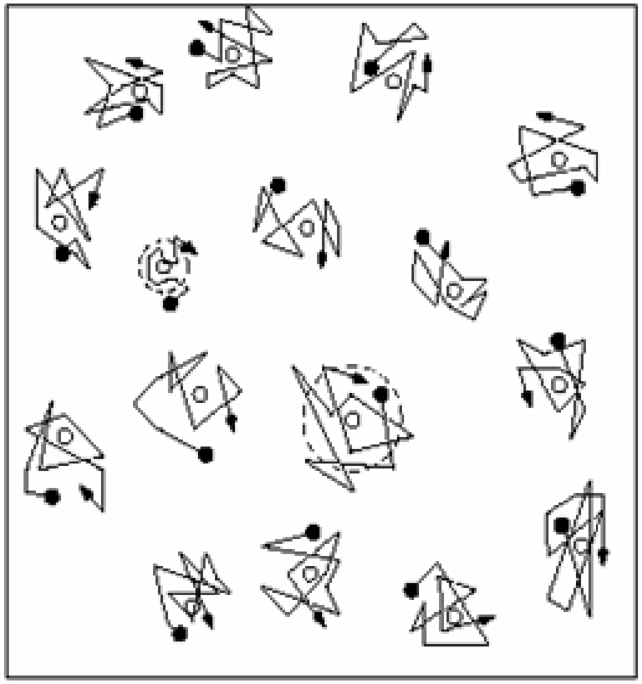
random r.m.s. displacement

(localization length) ξ



prob distrib of p'cle position

DETECTING THE RANDOM SOLID



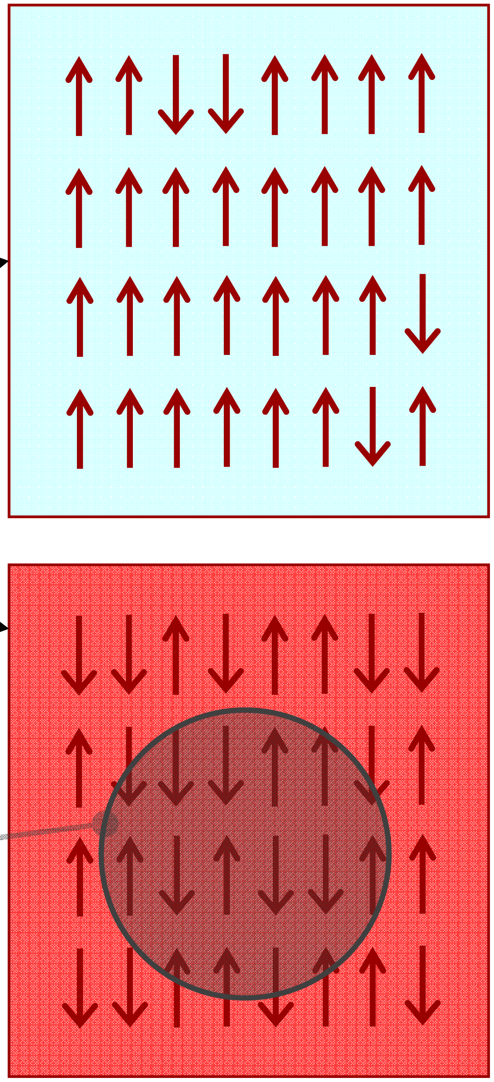
- **collection of particles**
  - labels $j = 1,\ldots, J,$ positions $\mathbf{R}_j$
  - averages: equilibrium $<\Lambda>$, QRV $[\Lambda]$
- **a randomly localized particle**

$$\langle \exp i\mathbf{k}\cdot\mathbf{R}\rangle \approx \exp i\mathbf{k}\cdot\langle\mathbf{R}\rangle \exp(-k^2\xi^2/2)$$

- **try** $\Omega(\mathbf{k}) = \left[\frac{1}{J}\sum_{j=1}^{J}\langle \mathrm{e}^{i\mathbf{k}\cdot\mathbf{R}_j}\rangle\right]$
  - doesn't discriminate between liquid & random solid states
- **try** $\Omega(\mathbf{k}^0,\mathbf{k}^1,\ldots,\mathbf{k}^n) = \left[\frac{1}{J}\sum_{j=1}^{J}\langle \mathrm{e}^{i\mathbf{k}^0\cdot\mathbf{R}_j}\rangle\langle \mathrm{e}^{i\mathbf{k}^1\cdot\mathbf{R}_j}\rangle\cdots\langle \mathrm{e}^{i\mathbf{k}^n\cdot\mathbf{R}_j}\rangle\right]$
  - does discriminate, via analog of Edwards-Anderson order parameter
  - replicas yield such entities naturally

WARM-UP: CONVENTIONAL PHASE TRANSITIONS

- e.g. ferromagnetism
  - spins on a lattice
  - energy favors alignment
    - broken symmetry
  - entropy favors randomness
    - symmetry
  - temperature
    - controls trade-off
  - microscopic model vs.
    coarse-grained field theory
    - introduce magnetization density $m(x)$
    - can derive FT or argue for it
    - identifies essential aspects
    - universality



FIELD THEORY APPROACH: FERROMAGNETISM

$$\mathcal{F} \sim \int d^D x \left\{ t\, m(x)^2 + |\nabla m|^2 + g\, m(x)^4 \right\}$$

space dimension

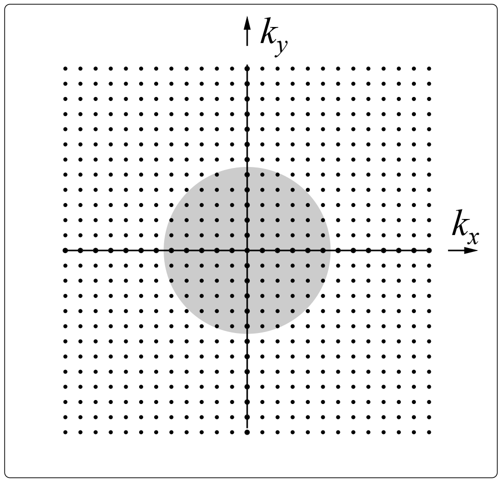
temperature control parameter

$t = (T - T_\mathrm{c})/T_\mathrm{c}$

order parameter:
local magnetization density

nonlinear
coupling

- **LW effective Hamiltonian allows for spatially varying mag den configs**
- **detect FM via eq'm magn density**
- **T controlled breaking of spin-rotation symmetry**
- **low T: eq'm m nonzero**
- **high T: eq'm m zero**



- **instability/resolution**
  - **modes in Fourier space**
  - **condensation at zero $\mathbf{k}$**

VULCANIZED MATTER: STAT MECH DONE STATISTICALLY

Sir Sam Edwards

Complicating factors, new & old

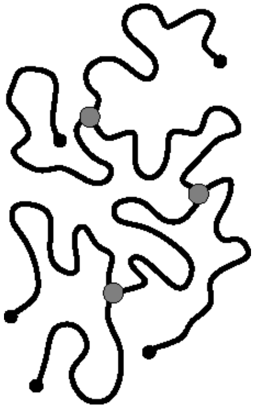
- fluctuations, repulsion
- crosslink constraints
- hidden spontaneous symmetry breaking

Edwards' strategy

- specify constraints
- average over phase space (p.s.) of accessible polymer conformations

$$\langle\mathcal{O}\rangle = \frac{\int d(\text{p.s.})\, \mathrm{e}^{-\mathcal{H}(\text{p.s.})/T}\, \mathcal{O}(\text{p.s.})\, \Delta(\text{constraints})}{\int d(\text{p.s.})\, \mathrm{e}^{-\mathcal{H}(\text{p.s.})/T}\, \Delta(\text{constraints})}$$

- then average <u>observables</u> over constraints
  - replicas – a smart encoding



INTERMEZZO: THE REPLICA TRICK

- Difficulty
  - shouldn’t average partition function over QRVs
  - should average intensive or extensive observables
  - hard! logs or quotients
- Trick for free energy, […] indicates quenched info average

$$[F] = -T[\ln \mathcal{Z}] = -T \lim_{n\to 0} \left([\mathcal{Z}^n] - 1\right)/n \quad \text{uses} \quad z^n = \mathrm{e}^{n \ln z} = 1 + n \ln z + \mathcal{O}(n^2)$$

- Example: spin glasses $\mathcal{Z}(J) = \mathrm{Tr}_S\, \mathrm{e}^{\sum_{j<k}(J_{jk}/T)S_j S_k}$

$$\begin{aligned} \left[\mathcal{Z}(J)^n\right]_J &= \left[\mathrm{Tr}_{S^1} \cdots \mathrm{Tr}_{S^n}\, \mathrm{e}^{\sum_{\alpha=1}^{n} \sum_{j<k}(J_{jk}/T)S_j^\alpha S_k^\alpha}\right] \\ &= \mathrm{Tr}_{S^1} \cdots \mathrm{Tr}_{S^n}\, \mathrm{e}^{\sum_{\alpha\beta} \sum_{j<k,l<m}[(J_{jk}/T)(J_{lm}/T)]S_j^\alpha S_k^\alpha S_l^\beta S_m^\beta} \end{aligned}$$

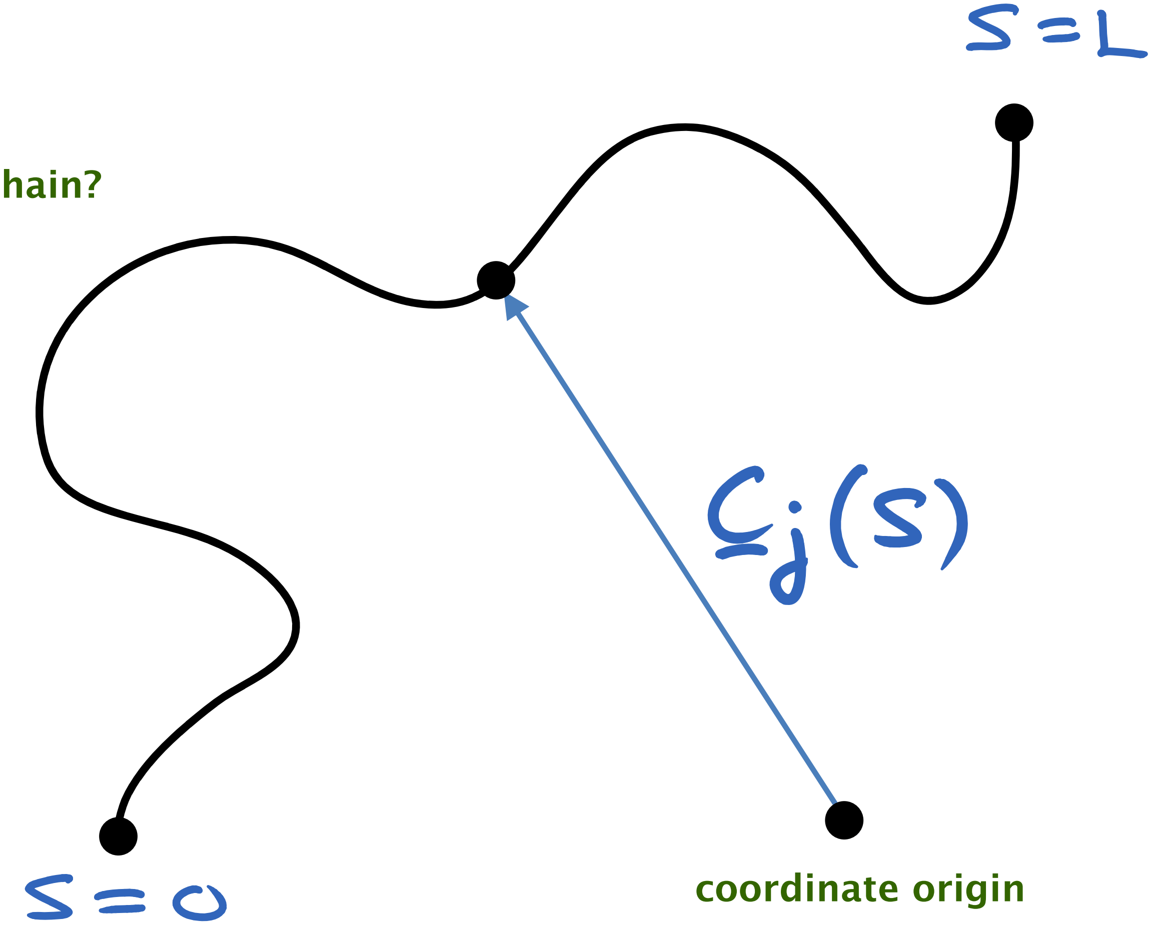
- Consequences
  - upside: effective pure system; downside: coupled replicas
- Physical interpretation
  - n systems, same quenched disorder, independent thermal fluctuations
  - n measurements on same system, long time-separations

STRATEGY

- we have an order parameter
- how can we compute it ?
  - microscopic model
    - flexible polymers confs
    - random constraints
  - statistical mechanics + replicas
  - derive (or argue for) a field theory
    - a Landau-Wilson effective Hamiltonian
    - a little strange !

VULCANIZED MATTER: STAT MECH DONE STATISTICALLY

- **which chain? index *j***
- **which segment on a chain?**
  arclength *s*



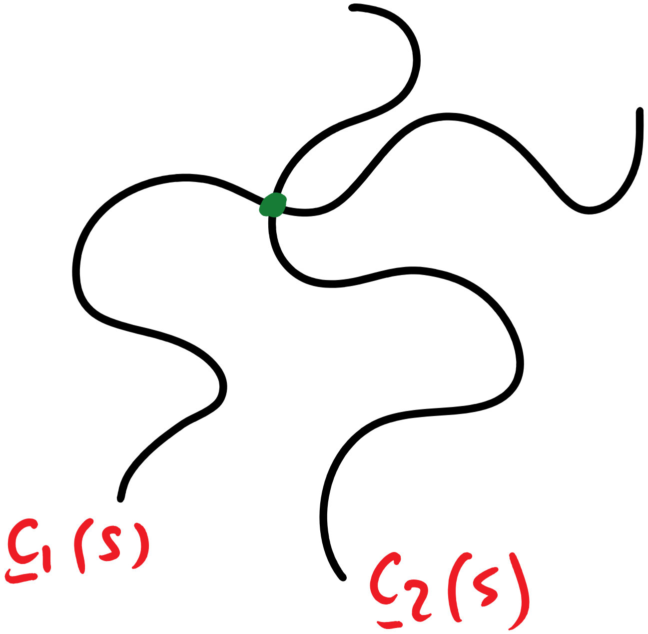
coordinate origin

VULCANIZED MATTER: STAT MECH DONE STATISTICALLY

$$Z \sim \int \prod_j \mathcal{D}\underline{c}_j \; \exp(-H/T) \prod_m \delta\left(\underline{c}_{j_m}(s_m) - \underline{c}_{j'_m}(s'_m)\right)$$

partition function

constraints – quenched random



random constraint probability

$$P \sim \int \prod_j \mathcal{D}\underline{c}_j \; \exp(-H/T) \prod_m \delta\left(\underline{c}_{j_m}(s_m) - \underline{c}_{j'_m}(s'_m)\right)$$

VULCANIZED MATTER: STAT MECH DONE STATISTICALLY

$$\int d(\mathrm{DIS})\, P(\mathrm{DIS})\, Z(\mathrm{DIS})^n$$

Competition/
frustration

$$\sim \int \mathcal{D}\underline{c}^0\, \mathcal{D}\underline{c}^1 \cdots \mathcal{D}\underline{c}^n$$

$$\mathrm{Exp} - \sum_\alpha \sum_j \int ds\, |d\underline{c}_j^\alpha/ds|^2$$

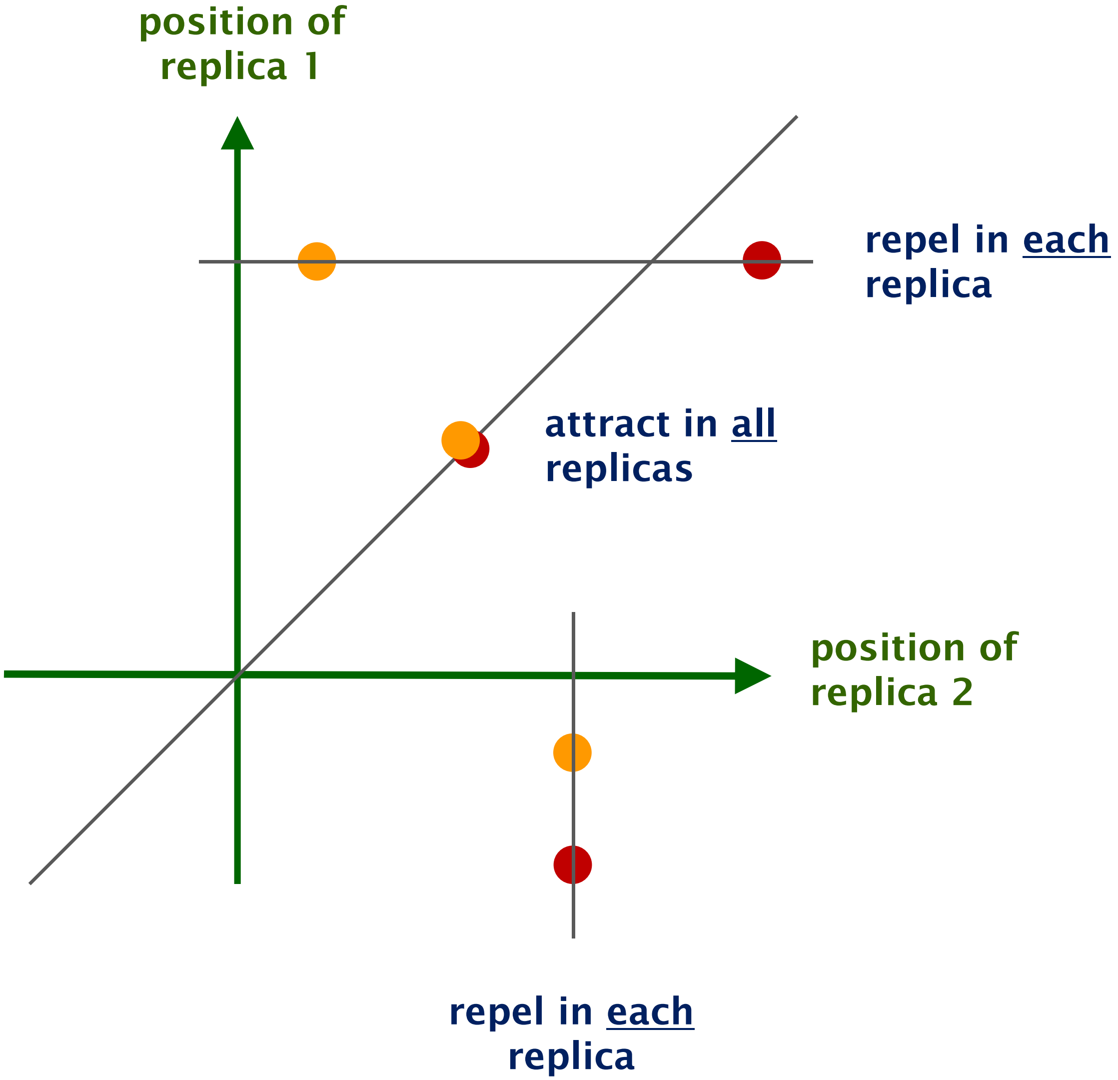
particle
repulsion

$$\times\ \mathrm{Exp} - \lambda \sum_\alpha \sum_{jk} \int ds\, dt\, \delta(\underline{c}_j^\alpha(s) - \underline{c}_k^\alpha(t))$$

$$\times\ \mathrm{Exp} + \mu \sum_{jk} \int ds\, dt \prod_\alpha \delta(\underline{c}_j^\alpha(s) - \underline{c}_k^\alpha(t))$$

controls crosslink density

VULCANIZED MATTER: STAT MECH DONE STATISTICALLY



WHAT'S THE FIELD IN THE LW FT FOR RANDOM SOLIDIFICATION ?

Standard technique (HS – see eg BGZ)

turns semi-micro model into a FT

Crosslink generated effective interaction ⇒

a real scalar field Ω

but on replicated space $\underline{x}^0, \underline{x}^1, \ldots, \underline{x}^n$

how many replicas? nearly one

WHAT'S THE FIELD IN THE LW FT FOR RANDOM SOLIDIFICATION ?

- it's precisely the "random localization detector"

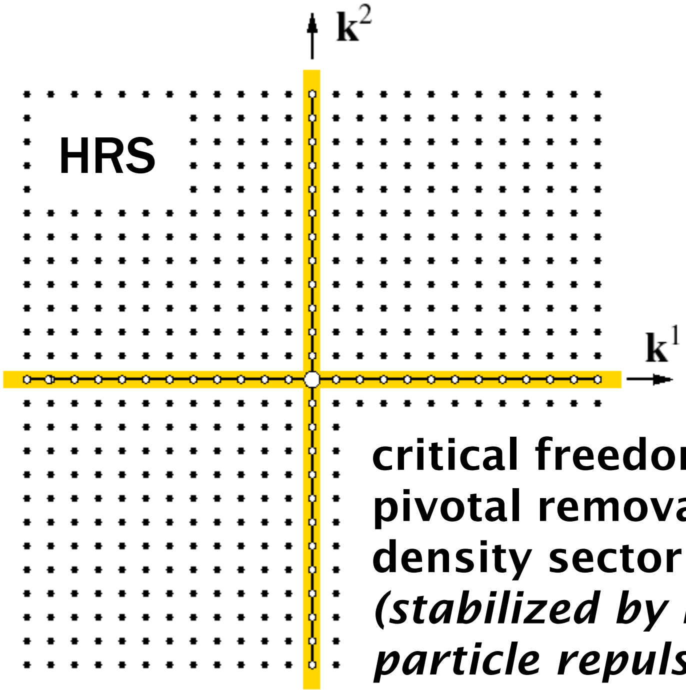
$$\Omega(\mathbf{k}^0, \mathbf{k}^1, \ldots) = \left[J^{-1} \sum\nolimits_{j=1}^{J} \langle \mathrm{e}^{i\mathbf{k}^0 \cdot \mathbf{R}_j} \rangle \langle \mathrm{e}^{i\mathbf{k}^1 \cdot \mathbf{R}_j} \rangle \cdots \right]$$

- or its <u>real-space</u> version $\Omega(\mathbf{x}^0, \mathbf{x}^1, \ldots)$
  - o <u>oddity</u>: lives on *1+n* copies of space
    (in the $n \to 0$ limit) from replicas
    - – *body* : center-of-mass of coords, macro space
    - – *soul* : dispersion, probes localization
  - o <u>virtue</u>: encodes rich statistical info
    about random solid state

FIELD THEORY APPROACH: RANDOM SOLIDIFICATION

$$\mathcal{F} \sim \int d^{(1+n)D}\widehat{x}\left\{-\frac{\tau}{2}\Omega(\widehat{x})^2 + \frac{\xi_0^2}{2}|\widehat{\nabla}\Omega(\widehat{x})|^2 - \frac{g}{3!}\Omega(\widehat{x})^3\right\}$$

- hats ? $\widehat{x} \equiv (\mathbf{x}^0, \mathbf{x}^1, \ldots, \mathbf{x}^n)$
- excess constraint density: τ
- object length-scale: ξ_0
- cubic nonlinear coupling: g
  - **derive semi-microscopically, or argue via symmetries, length-scales**
  - **looks simple**



critical freedoms: pivotal removal of density sector fluct's *(stabilized by inter-particle repulsion)*

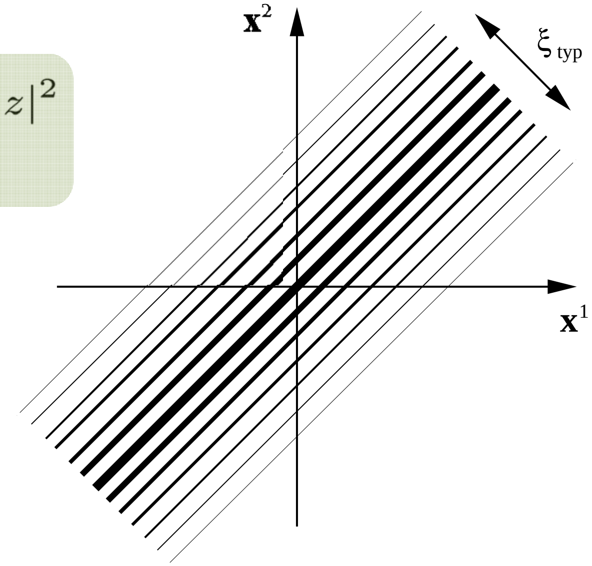
Castillo, Peng PhD theses

RANDOM SOLIDIFICATION: LANDAU / MFT / CLASSICAL

$$\mathcal{F} \sim \int d^{(1+n)D}\widehat{x}\left\{-\frac{\tau}{2}\Omega(\widehat{x})^2+\frac{\xi_0^2}{2}|\widehat{\nabla}\Omega(\widehat{x})|^2-\frac{g}{3!}\Omega(\widehat{x})^3\right\}$$

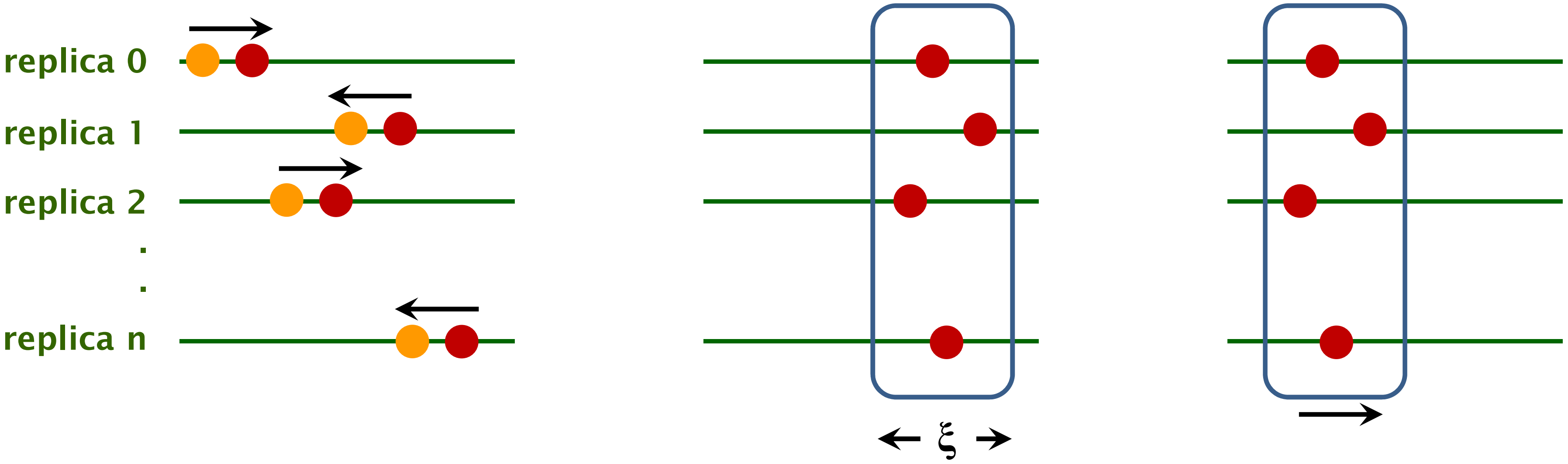
- **minimize…**
  - subcritical crosslink density $\Omega(\widehat{x})=0$
    - all delocalized
  - supercritical…

$$\Omega(\widehat{x}) \sim Q\int dz\int d\xi\,\wp(\xi)\,\mathrm{e}^{-\frac{1}{2\xi^2}\sum_{\alpha=0}^{n}|x^\alpha-z|^2}$$



- *ripple* in replicated space (glide?)
- 'molecular' bound state
- random localization:
  peak gives *fraction*, shape gives *distribution*
- so encodes statistical information about
  heterogeneity of random solid state *structure*

SYMMETRIES AND SYMMETRY BREAKING



replicas of two particle positions

effective Hamiltonian is invariant under independent translations of each replica

pattern of symmetry breaking

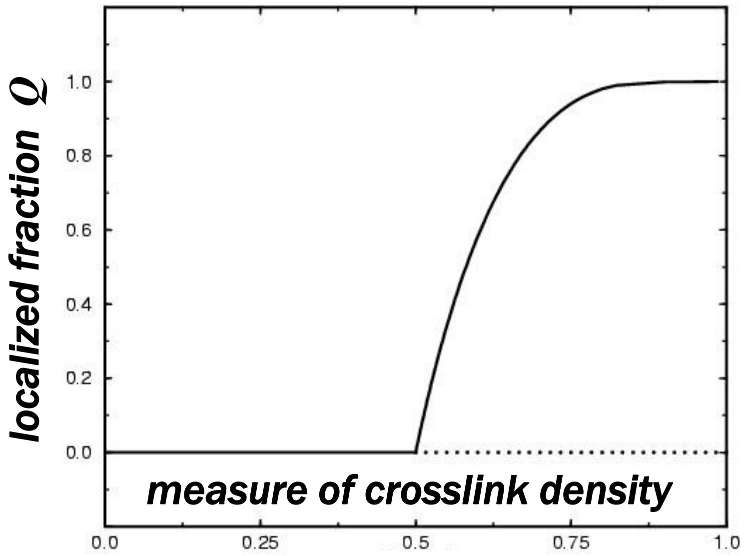
replicas lock to one another – this reflects localization

pattern of symmetry breaking

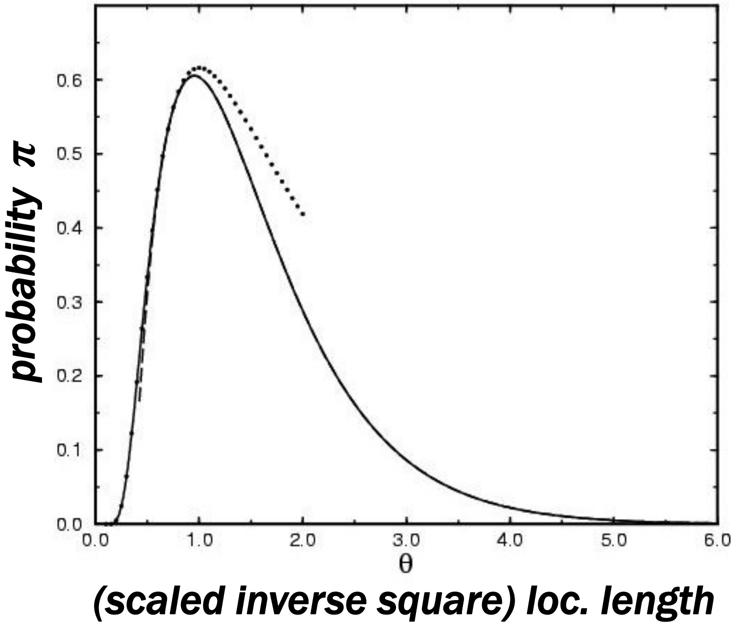
but common translation remains unbroken – this reflects macroscopic homogeneity

LANDAU: MINIMIZING GIVES…

- localized fraction Q
  - recovers Erdős-Rényi
  - classical percolation exponent

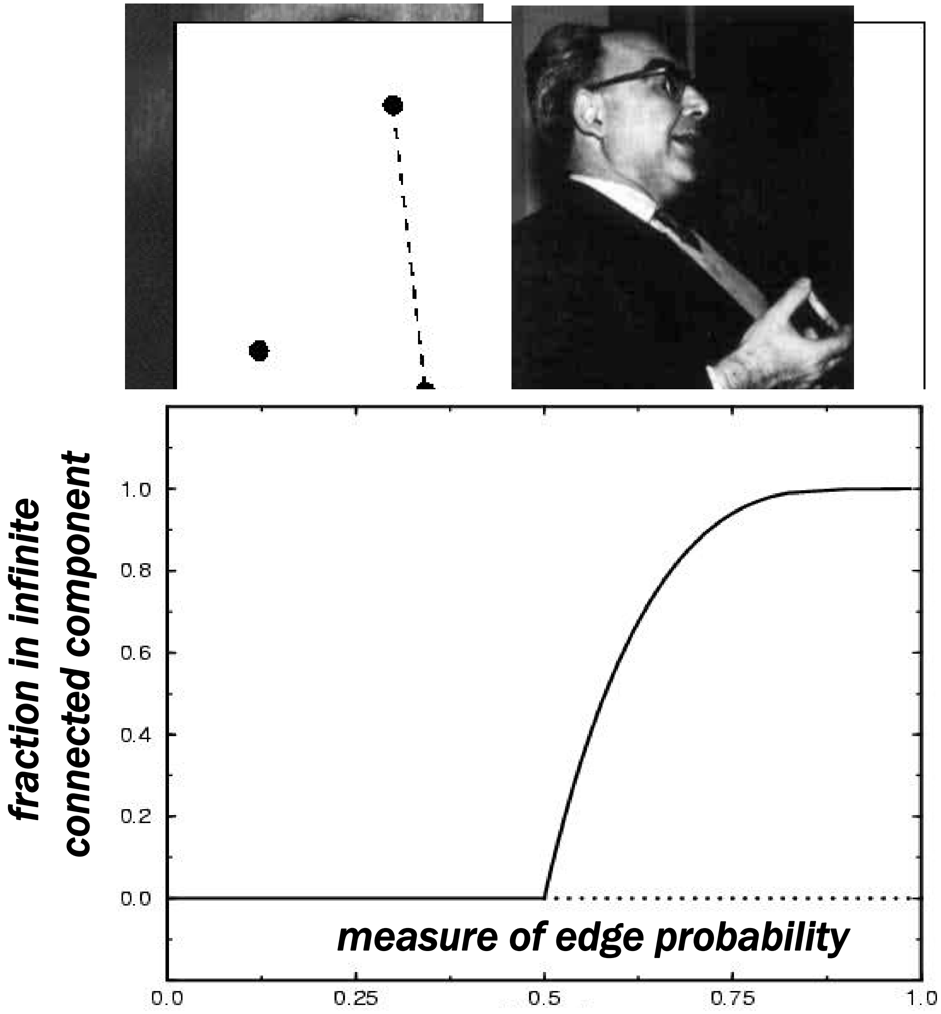


- distribution of localization lengths
  - predicts data collapse
  - universal scaling form
  - elementary derivation?



MATCHES RANDOM GRAPH THEORY

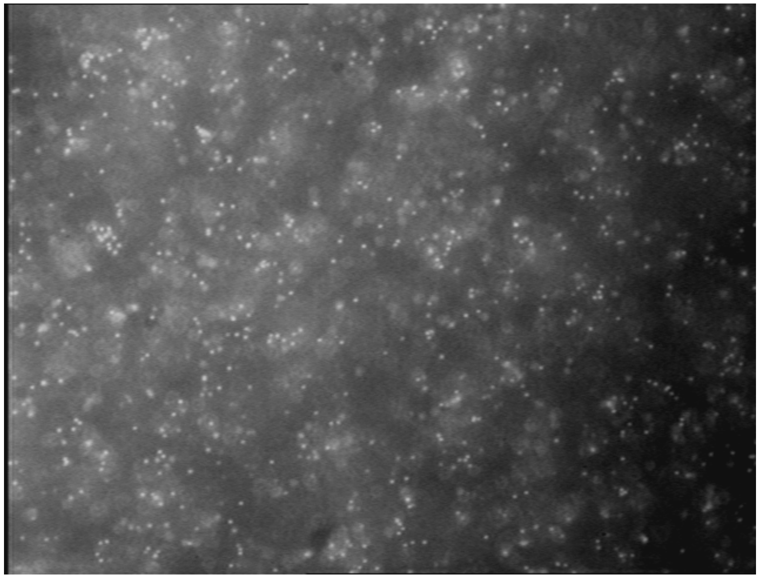
- a *statistical* phenomenon
- Erdős-Rényi (1960)



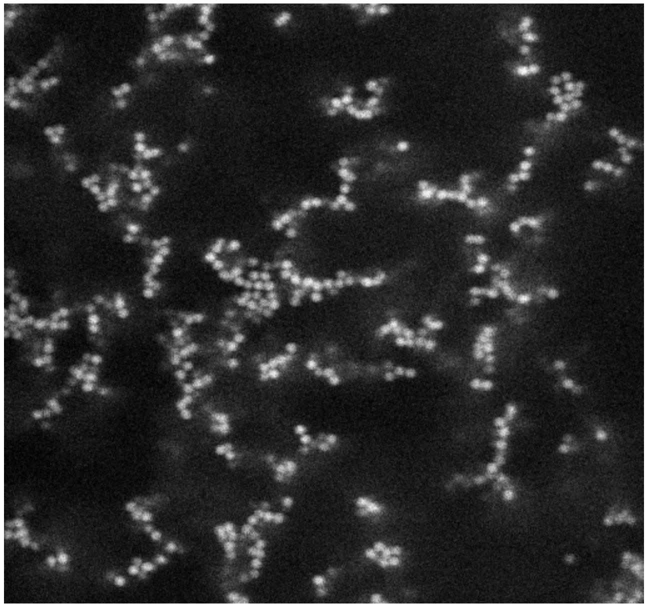
LANDAU THEORY VS EXPERIMENTS

- **Dinsmore/Weitz (U. Mass. Amherst/Harvard)**

Protein gels

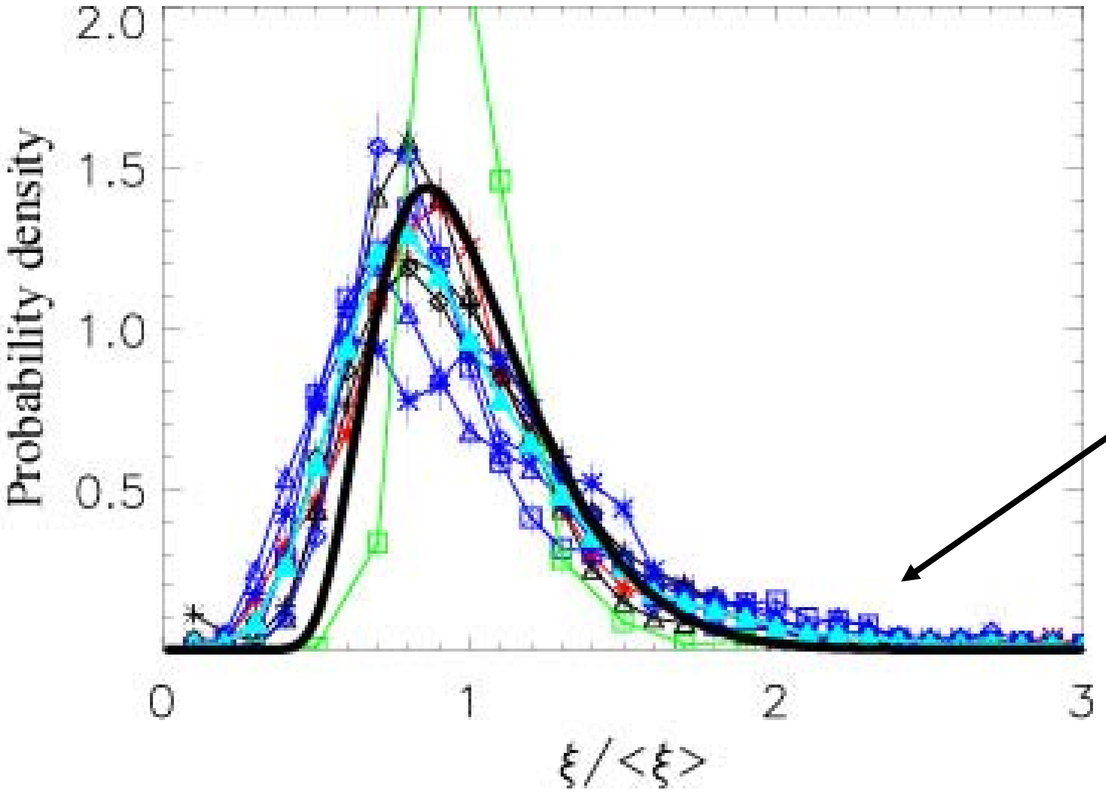


Colloidal gels



- roughly μm diameter particles
- confocal microscopy
- video imaging /particle tracking
- statistical analysis of motions
- μm-scale thermal fluctuations

LANDAU THEORY VS EXPERIMENTS



nearly log-normal

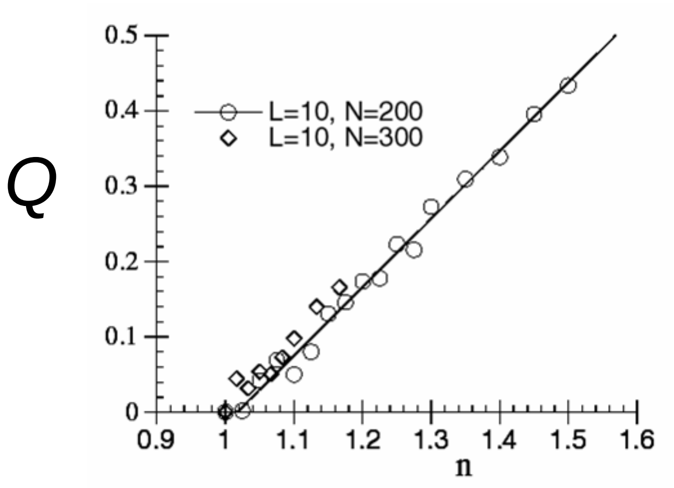
<u>Data on colloidal gels & protein gels</u>
(Dinsmore & Guertin, U Mass):

- **black**: **gelatin with fluorescent tracer beads**
- **blue**: **particle gels by depletion attraction**
- **red**: **particle gel by polycation adsorption**
- **green**: **colloidal crystal**

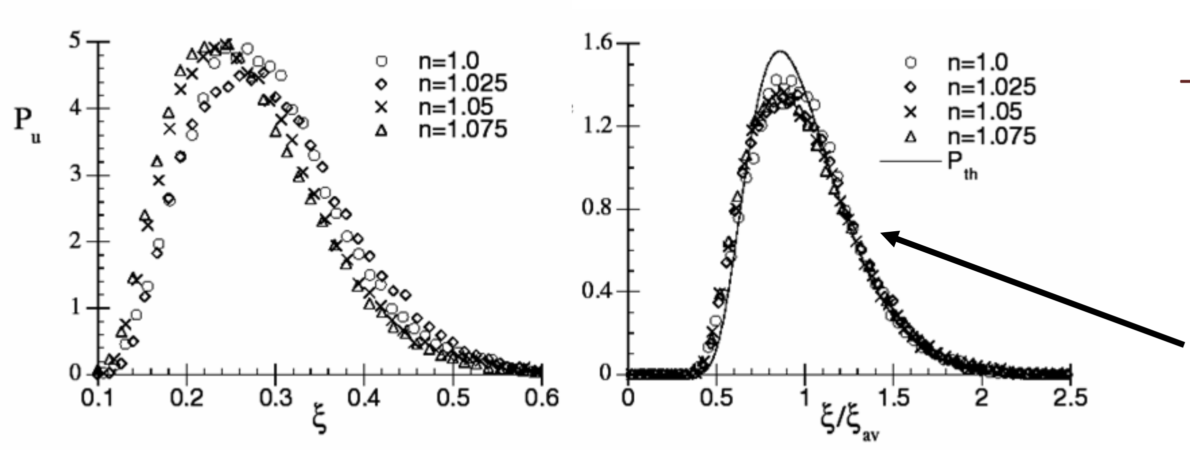
<u>Theory</u>: heavy black curve

LANDAU THEORY VS SIMULATIONS

- **Barsky-Plischke MD simulations**
  - o **continuous transition to amorphous solid state**



- N chains
- L segments
- n crosslinks per chain
- localized fraction Q grows linearly



- scaling & universality in distribution of localization lengths

nearly log-normal

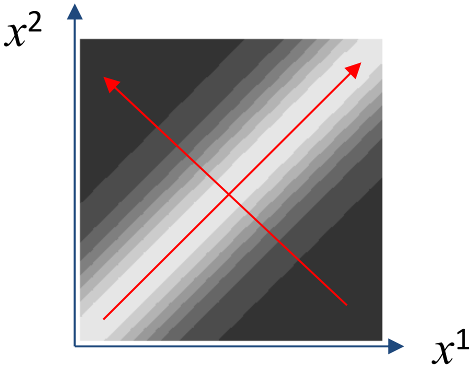
MEASURING THE DETECTOR ?

- in the detector…
  set most wave vectors to zero

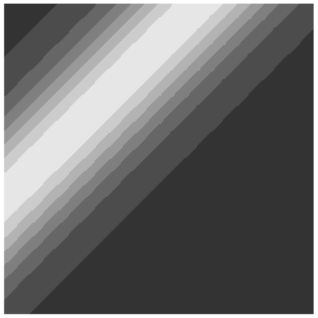
$$\Omega(\mathbf{0},\mathbf{k},-\mathbf{k},\mathbf{0},\ldots) = \left[J^{-1}\sum\nolimits_{j=1}^{J}\langle \mathrm{e}^{i\mathbf{k}\cdot\mathbf{R}_j}\rangle\langle \mathrm{e}^{-i\mathbf{k}\cdot\mathbf{R}_j}\rangle\right]$$

- o a part of the momentum-dependent scattering function
  - quasi-elastic ~ clustered correlator
  - incoherent ~ one particle at a time
- o encodes statistical info about random solid state
  - Laplace transform of distribution of localization lengths

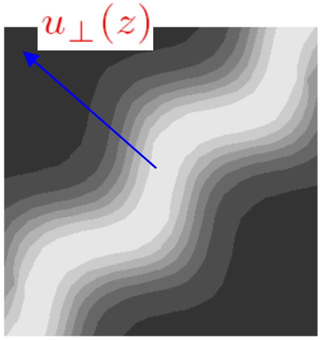
ELASTICITY OF THE RANDOM SOLID STATE



equilibrium state



symmetry related eq. state



Goldstone excitation

- **Goldstone modes, low-energy excitations**

$$\Omega(\widehat{x}) \sim Q \int dz \int d\xi\, \mathcal{P}(\xi)\, \mathrm{e}^{-\{|x^0 - z|^2 + \sum_{\alpha=1}^{n} |x^\alpha - z - \boxed{u^\alpha(z)}|^2\}/2\xi^2}$$

  - **parametrized by n fields u on real space z : *rippling the ripple***
  - **physically natural: replicas of elastic displacement fields**
  - **compute free energy cost**
    - **quadratic level gives average elastic properties**
    - **interactions give correlated fluctuations in elastic properties**
      - ***again* : statistical information about heterogeneity of random solid state *encoded* in replica structure**

**Mukhopadhyay,
Mao PhD theses**

ELASTICITY OF THE RANDOM SOLID STATE: MEAN

- **Average elastic properties obtained from quadratic-level free-energy cost of displacements**

$$\Delta\mathcal{F} = \sum_{\alpha=1}^{n} \frac{\rho}{2} \int dz \, \frac{\partial u_\nu^\alpha}{\partial z_\mu} \frac{\partial u_\nu^\alpha}{\partial z_\mu} + \cdots$$

mean # of links

$$\rho \approx \frac{k_{\mathrm{B}}\,T}{\xi_0^3} \left(\frac{\langle m \rangle}{m_{\mathrm{c}}} - 1 \right)^3$$

localization length-scale

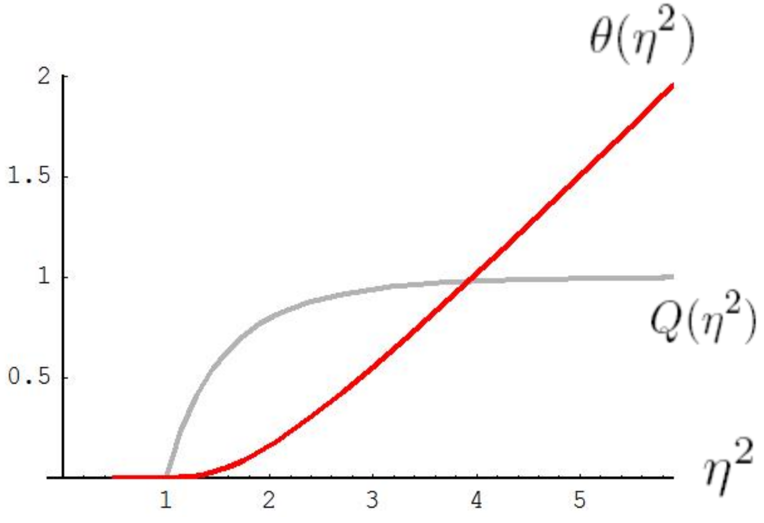
critical mean # of links

  - **implications of these phonon fluctuations in two dimensions & higher? (*not today*)**

ELASTICITY OF THE RANDOM SOLID STATE: MEAN

- average elastic properties obtained from quadratic-level free-energy cost of displacements
  - Lamé coefficients, stress
    more detailed view obtained via connection between randomly linked particle model (RLPM) & elastic phenomenology

$$\begin{array}{lrcl} \text{stress} & [\sigma_{\mu\nu}(z)] & = & 0 \\ \text{shear} & [\mu(z)] & = & (N/V)\,\theta\,k_{\mathrm{B}}\,T \\ \text{bulk} & [\lambda(z)] & = & (N/V)^2\,\nu^2 \end{array}$$



$$\theta \equiv -\tfrac{1}{2}\,\eta^2 Q^2 + e^{-\eta^2 Q} + \eta^2 Q - 1$$

N/V particle density

θ dim'less scaling function from RLPM

ν^2 excluded volume in RLPM

$\eta^2 = \langle m \rangle$ mean # of links to each particle

Mao PhD thesis

ELASTICITY OF THE RANDOM SOLID STATE: HETEROGENEITY

- statistics of elastic heterogeneity obtained from beyond-quadratic-level displacements
  - correlations in spatial fluctuations of Lamé coefficients, get via linked particle / elastic phenomenology connection
  - key results: all correlations with stress are long-ranged, e.g.

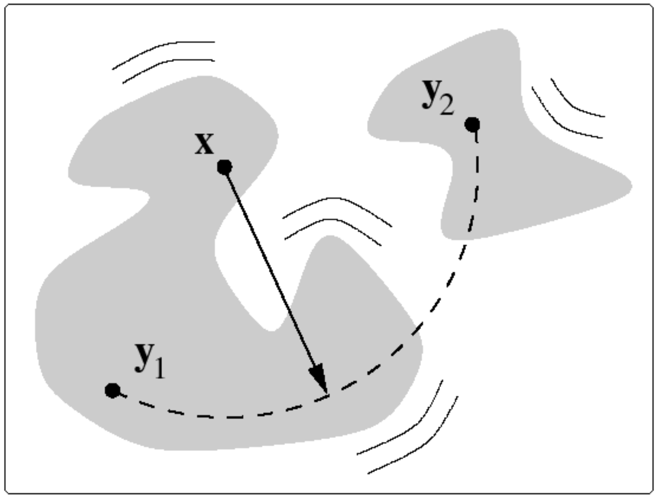
$$[\sigma(r)\,\sigma(0)] \sim \theta T^2(N/V)/r^3$$

  - all others are short-ranged $[\mu(z)\,\mu(0)]_{\mathrm{con}}$

N/V particle density; three dimensions

θ a dim'less scaling function from RLPM

BEYOND LANDAU



- fluctuations, criticality, universality
  - Ginzburg crosslink-density window

$$(\text{seg's per chain})^{-\frac{D-2}{6-D}}\,(\text{vol frac})^{-\frac{2}{6-D}}$$

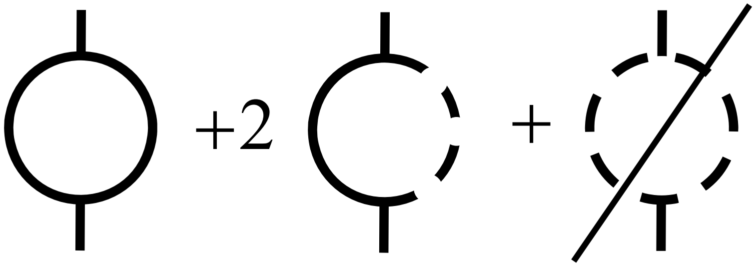
    - favors short chains, dilute systems, low dimensions (cf de Gennes, 1977)
    - critical dimensions: 2 & 6
  - critical state [cf Stenull-Janssen, 2001]
    - percolation questions get exactly percolation answers
    - so vulcanization field theory contains percolation
  - field correlations $\langle\Omega\Omega\rangle - \langle\Omega\rangle\langle\Omega\rangle$
    - liquid regime: mutual localization (aka clusters)
    - solid regime: not easy! correlations in motion (2D special) & structural heterogeneity, critical elasticity classes?

Peng, Mukhopadhyay PhD theses

PERCOLATION SECTOR

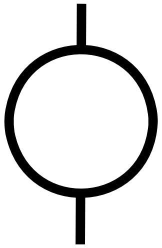
HRW percolation field theory

$$\int dx \left\{ \left(-\frac{\tau}{2}\phi(x)^2 + \frac{1}{2}|\nabla\phi(x)|^2 \right) - \left(-\frac{\tau}{2}\psi(x)^2 + \frac{1}{2}|\nabla\psi(x)|^2 \right) + \frac{g}{3!}\left(\phi+\psi\right)^3 \right\}$$



- ➢ **ghost field sign**
- ➢ **by-hand elimination**

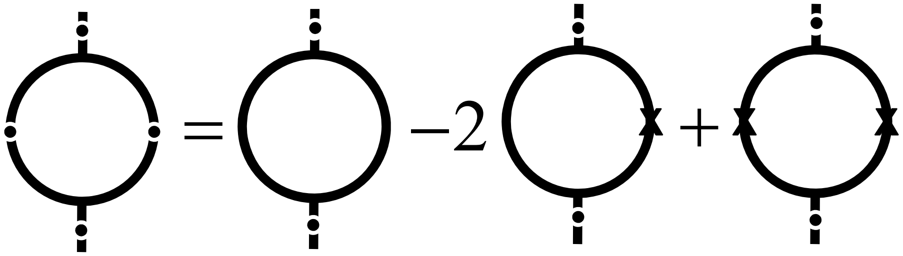
$\Rightarrow$ $-$



- **HRW: Houghton-Reeve-Wallace**
- **Peng-PMG: 1st order**
- **Janssen-Stenull, Peng et al: All orders**

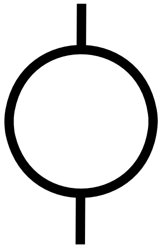
vulcanization field theory

$$\int d\hat{x} \left\{ -\frac{\tau}{2}\Omega(\hat{x})^2 + \frac{1}{2}|\hat{\nabla}\Omega(\hat{x})|^2 - \frac{g}{3!}\Omega(\hat{x})^3 \right\}$$



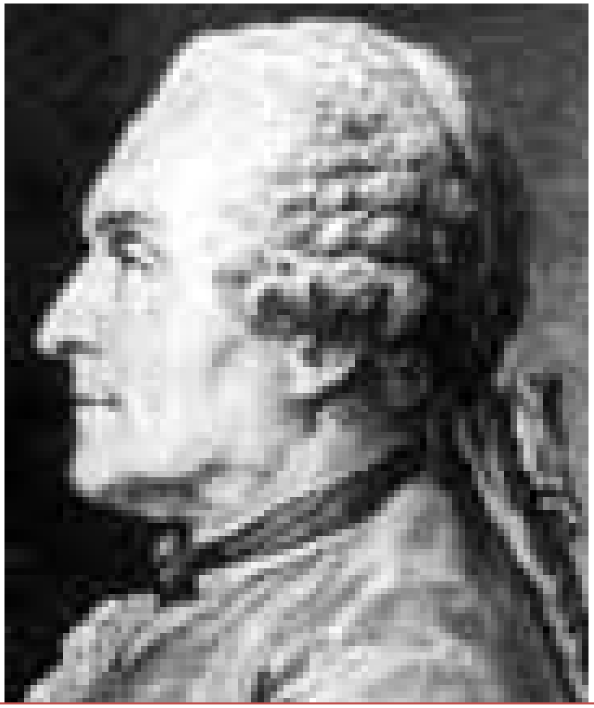
- ➢ **HRS constraint**
- ➢ **momentum conservation**
- ➢ **replica combinatorics**
- ➢ **replica limit**

$\Rightarrow$ $-$



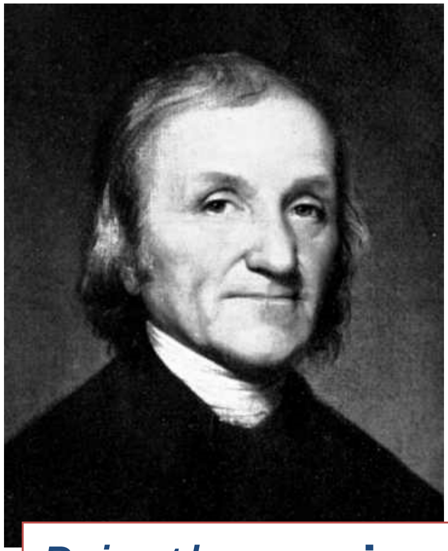
Historical intermezzo (after Morawetz, 1985)

Columbus (Haiti, 1492):
reports locals playing games with elastic resin from trees

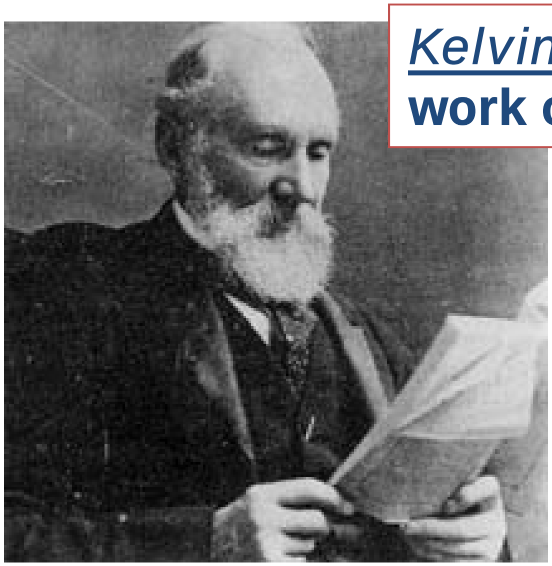


de la Condamine (Ecuador ~1740):
latex from incisions in Hevea tree, rebounding balls; suggests waterproof fabric, shoes, bottles, cement,…

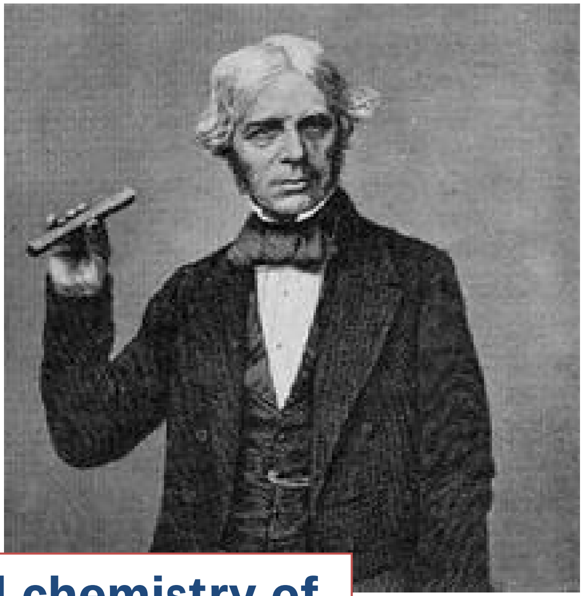
Historical intermezzo



Priestly: **erasing, coins name “rubber”** *(April 15, 1770)*



Kelvin (1857): **theoretical work on thermal effects**

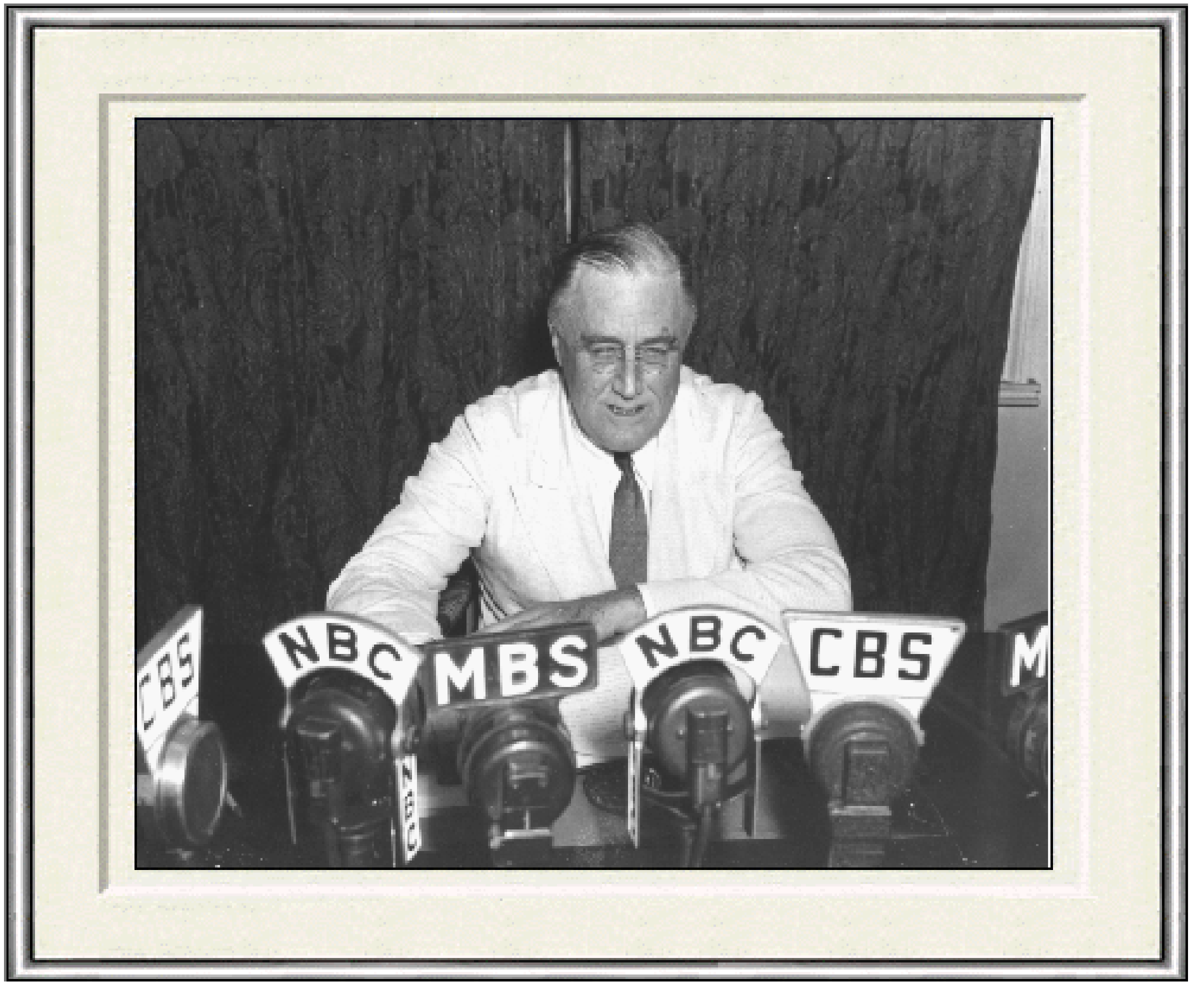


Faraday (1826): **analyzed chemistry of rubber -** *“…much interest attaches to this substance in consequence of its many peculiar and useful properties…”*

Joule (1859): **experimental work inspired by Kelvin**

Historical intermezzo

F. D. Roosevelt
(1942, Special Committee)



"…of all critical and strategic materials… rubber presents the greatest threat to… the success of the Allied cause"

US World War II operation in synthetic rubber second in scale only to the Manhattan project

Historical intermezzo

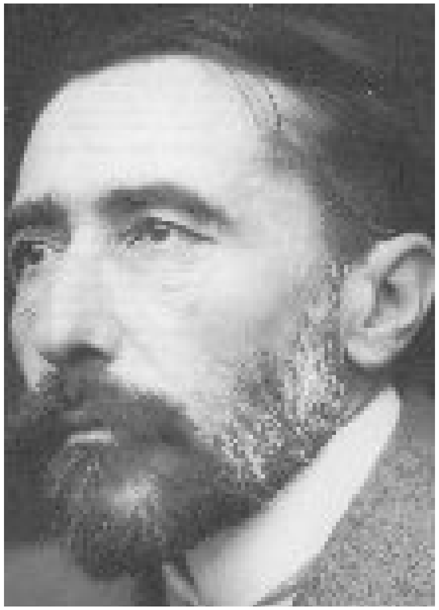
Goodyear **(in** *Gum-Elastic and its Varieties, with a Detailed Account of its Uses, and of the Discovery of Vulcanization; New Haven, 1855***):**
"… there is probably no other inert substance the properties of which excite in the human mind an equal amount of curiosity, surprise and admiration. Who can reflect upon the properties of gum-elastic without adoring the wisdom of the Creator?"

Historical intermezzo

Dunlop (1888): **invents the pneumatic tyre**

...which led to
"frantic efforts to increase the supply of natural rubber in the Belgian Congo…"
which led to
"some of the worst crimes of man against man"
(*Morawetz*, 1985)

Conrad (1901): *Heart of Darkness*



CONCLUDING REMARKS

- **what attracts physicists?**
- **not always in obvious settings**
- **random solid state**
  - **a *standard model*, its form strongly constrained**
  - **universality: classical & beyond**
  - **unified approach to…**

    structure, rigidity, heterogeneity,…

ACKNOWLEDGEMENTS

- **simulations: Barsky & Plischke**
- **experiments: Dinsmore & co-workers**
- **foundations: Edwards & co-workers**
- **related studies: Panyukov & co-workers,
Janssen-Stenull**
- **support: NSF & Georgia Tech**
- **and, of course,…**

WARM THANKS TO COLLABORATORS

colleagues:	Nigel Goldenfeld / Illinois Annette Zippelius / Göttingen
postdocs:	Xiangjun Xing → Shanghai Fang-Fu Ye → Beijing
graduate students:	Horacio Castillo → Ohio Kostya Shakhnovich → New York Weiqun Peng → Washington, DC Swagatam Mukhopadhyay → CSHL Xiaoming Mao → Michigan Bing Sui Lu → Lubljana
visitors:	Alan McKane / Manchester Christian Wald / Göttingen

REFERENCES AT: WWW.PHYSICS.GATECH.EDU/~PGOLDBART6/