Memory Formation in Driven Disordered Systems – Dead or Alive

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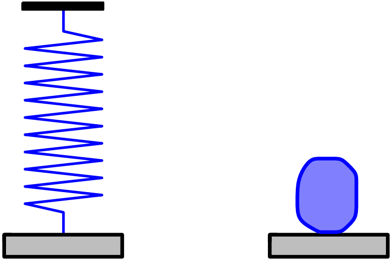
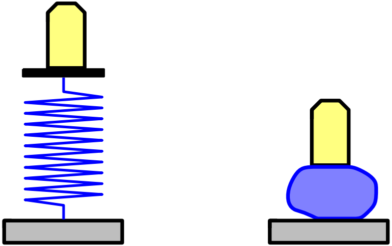
Reversible *vs.* irreversibe deformations and memory

- Suppose we load a spring and a sand bag with varying loads ...



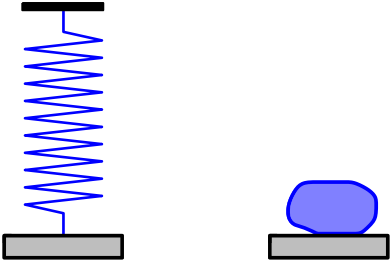
Reversible *vs.* irreversibe deformations and memory

- Place two identical **medium** loads on each ...



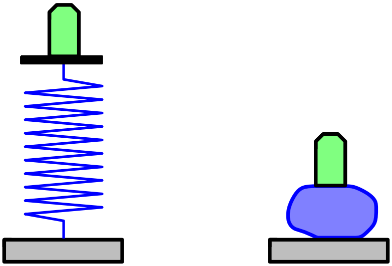
Reversible *vs.* irreversibe deformations and memory

- Remove loads.
- Spring **restores** initial position, sand bag **remains** deformed.



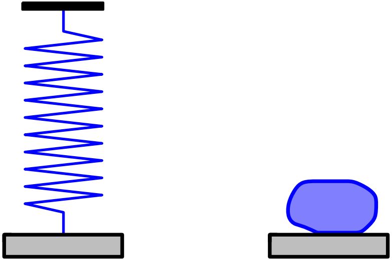
Reversible *vs.* irreversibe deformations and memory

- Next place identical **lighter** loads on spring and bag.
- Spring compresses less, while sand bag **retains** deformed state.



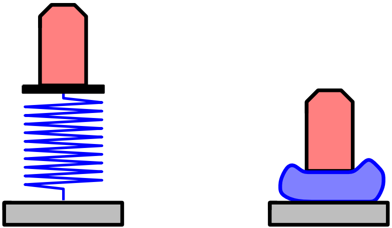
Reversible *vs.* irreversibe deformations and memory

- Removing the lighter load, spring returns to initial position.
- Sand bag **retains** initial deformation:
- Sand bag keeps a **memory** of initial loading.



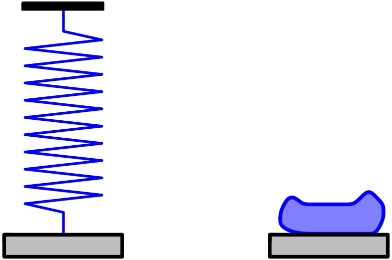
Reversible *vs.* irreversibe deformations and memory

- Place next identical **heavier** loads.
- Spring compresses more than before.
- Sand bag also **deforms** further.



Reversible *vs.* irreversibe deformations and memory

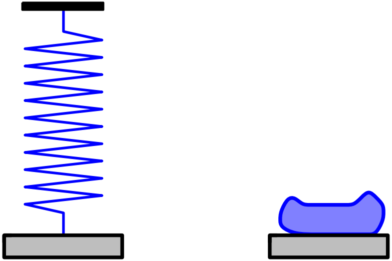
- Remove heavy loads.
- Spring **restores** its uncompressed state.
- Sand bag remains in **further deformed** state.



Reversible *vs.* irreversibe deformations and memory

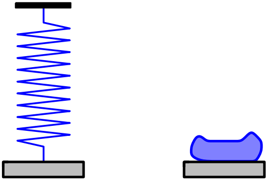
Sand bag:

- Retains **memory** of past deformations.
- Placing **heavier** load on sand bag, $\Rightarrow$ **memory** of previous load is **lost**.
- Memory is **overwritten** by **heavier** load.



Reversible *vs.* irreversibe deformations and memory

Two "devices", two different responses:



- Spring: **perfectly elastic**: returns to **same** position when unloaded. **No memory of its loading history.**
- Sand bag: **plastic**: **retains memory of loading history:** memory of **largest load**.
- **Spring:** "records" instantaneous state of loading, *e.g.* like a kitchen scale.
- **Sand bag:** "records" extreme loading event in its history $\Rightarrow$ future response is **history-dependent**.

Recap – Memory Formation

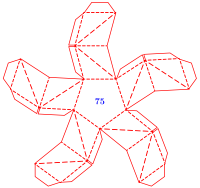
- Example of system that can record the largest applied load.
- Simple prototype of a system interacting with a changing environment:
  - **System:** sand bag,
  - **Changing Environment:** various loads placed on sand bag,
  - **Effect on system:** altering shape of sand bag.
- Main ingredients:
  - **Disorder**
  - **Large number of degrees of freedom**

Q: How do we characterize systems that retain a memory of their past environments?

Outline of this talk

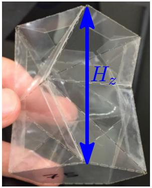
- **Memory formation** in **driven soft-matter systems.**
- Focus on **athermal, quasi-static (AQS)** response to driving.
- Response to AQS driving can be captured via **state transition graphs**: $\Rightarrow$ **Dynamical features are encoded in graph topology**
- Demonstrate how these ideas can be used to **understand and utilize** memory formation.
- **Applications:** Show that these ideas can be used to analyze
  - **dynamics of a sheared amorphous solid**,
  - **biological evolution in changing environments**.

Origami-bellows as a mechanical memory device

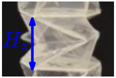


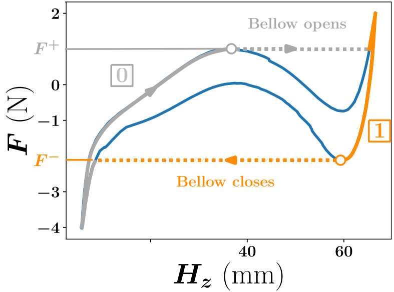
Folding

Bellow open 1

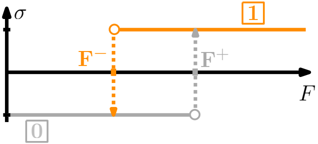


Bellow closed 0

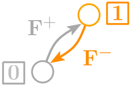




Preisach Element (Hysteron)



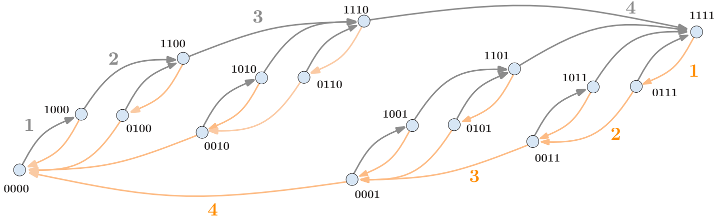
Graph representation

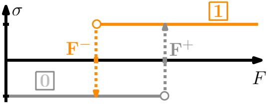


Hysteresis:
$F^- < F^+$

(Jules, Reed, Daniels, **MM**, & Lechenault Phys. Rev. Res. (2022))

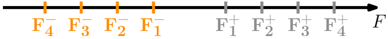
A stack of four bellows – The Preisach Model





Switching Sequence:

Down: 1 → 2 → 3 → 4 Up: 1 → 2 → 3 → 4



Preisach Model:

Each hysteron changes state:

- **based on F,**
- **its current state (history)**

INDEPENDENTLY

By INDEPENDENCE label hysterons s.t.

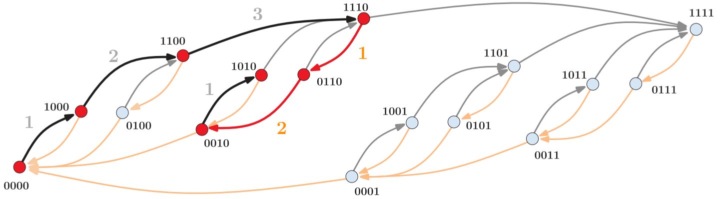
Up: 1 → 2 → 3 → 4

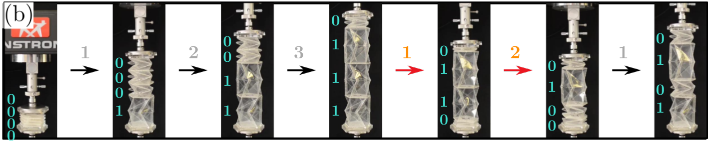
Using different bellows we can alter down sequence (call it ρ)

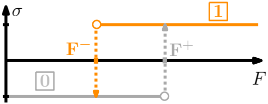
$$\rho = 1\,2\,3\,4$$

(Jules, Reed, Daniels, **MM**, & Lechenault Phys. Rev. Res. (2022))

A stack of four bellows – The Preisach Model







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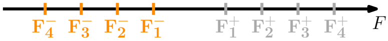
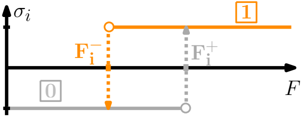


(Jules, Reed, Daniels, **MM**, & Lechenault Phys. Rev. Res. (2022))

The (discrete) Preisach Model in a nutshell

Suppose we have a system with N hysterons: $\boldsymbol{\sigma} = (\sigma_1, \sigma_2, \ldots, \sigma_N)$ **is a state,** $\sigma_i = 0, 1$



Switching fields: $F_1^{\pm}, F_2^{\pm}, \ldots, F_N^{\pm}$

$F_i^- < F_i^+$

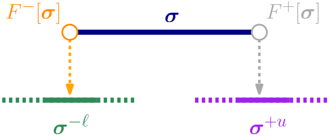
$\sigma_i = 1$ **requires** $F > F_i^-$
$\sigma_j = 0$ **requires** $F < F_j^+$

POSSIBLE ONLY IF $\boldsymbol{\sigma}$ such that:

$$F^-[\boldsymbol{\sigma}] \equiv \max_{\{i:\sigma_i=1\}} F_i^- < \min_{\{j:\sigma_j=0\}} F_j^+ \equiv F^+[\boldsymbol{\sigma}]$$

(Stability condition, determines the set of states)

Let ℓ and u be the sites were the max **and** min **are attained**



$\Rightarrow$ **Single site flips suffice to regain stability**
NO AVALANCHES!

(M.M. Terzi & **MM** PRE **102** (2021) 012122)

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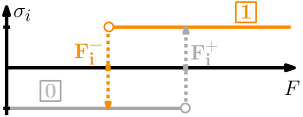

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By INDEPENDENCE label hysterons s.t.

Up: $1 \to 2 \to \ldots \to N$

Down: $\rho_1 \to \rho_2 \to \ldots \to \rho_N$

(M.M. Terzi & **MM** PRE **102** (2021) 012122)

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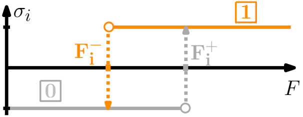

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Switching Sequence $\boldsymbol{\rho}$ determines transition graph between $(00\dots0)$ and $(11\dots1)$!

(M.M. Terzi & **MM** PRE **102** (2021) 012122)

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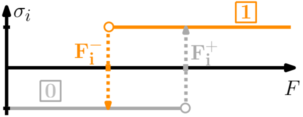

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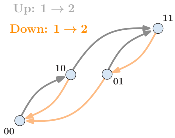

$\boldsymbol{\rho} = \mathbf{1\,2}$

(M.M. Terzi & **MM** PRE **102** (2021) 012122)

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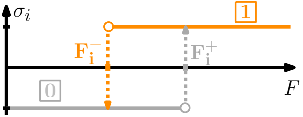

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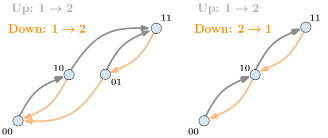
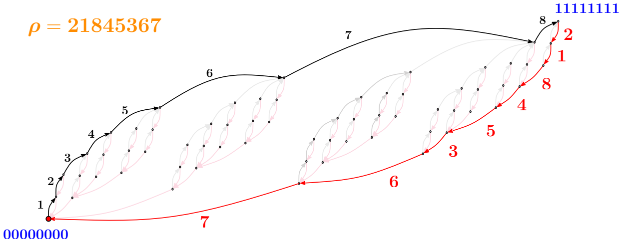


$\boldsymbol{\rho} = 1\,2$ $\qquad$ $\boldsymbol{\rho} = 2\,1$

(M.M. Terzi & **MM** PRE **102** (2021) 012122)

The Preisach Model and Return Point Memory (RPM)



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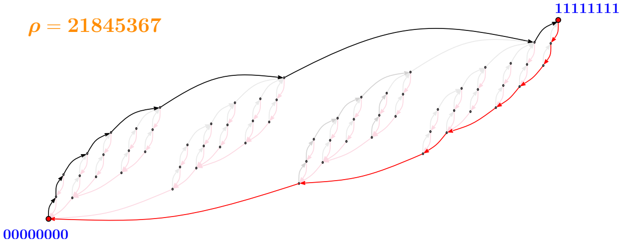
Switching Sequence ρ COMPLETELY determines the transition graph between $(00\ldots0)$ and $(11\ldots1)$!

(**MM** & M.M. Terzi AHP **20** (2019) 2819 – 2872)



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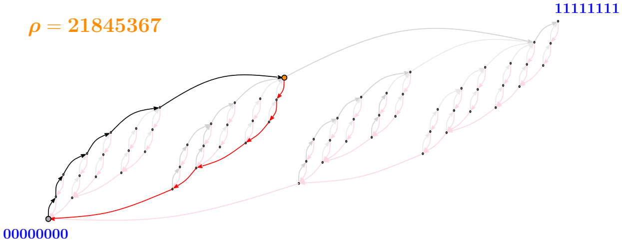

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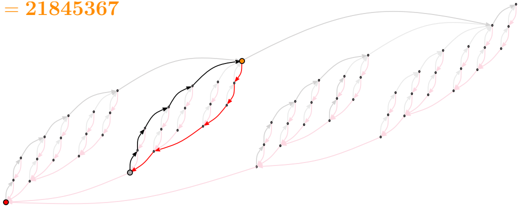

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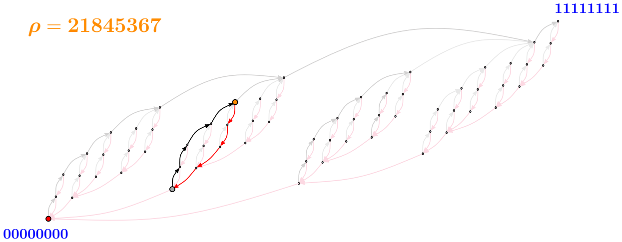

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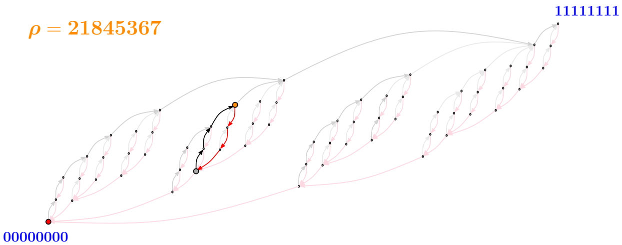

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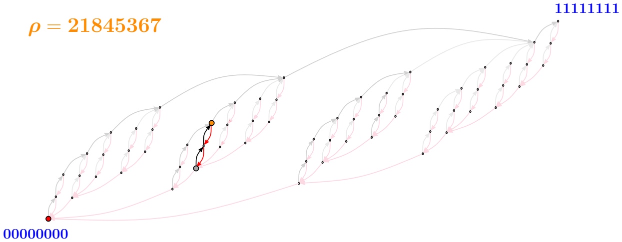

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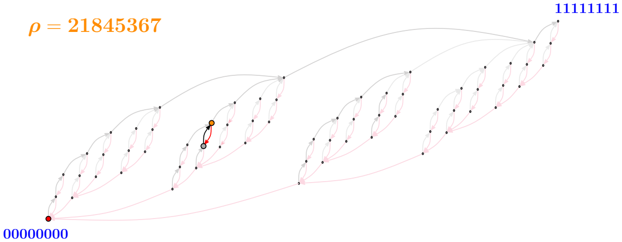

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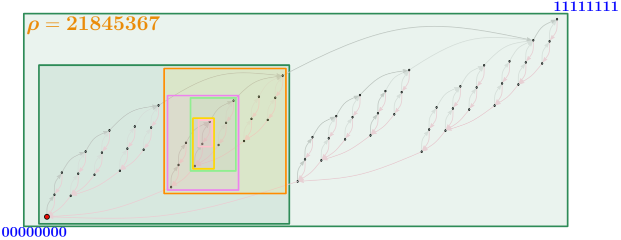

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loop Return Point Memory (ℓRPM) as topological feature of transition graph

$\Rightarrow$ Hierarchical Structure of loops nested within loops

"Every loop is existed from its end points!"

(**MM** & M.M. Terzi AHP **20** (2019) 2819 – 2872)

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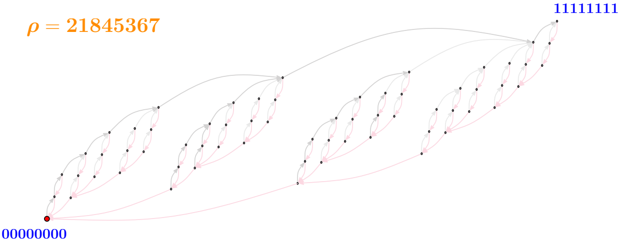

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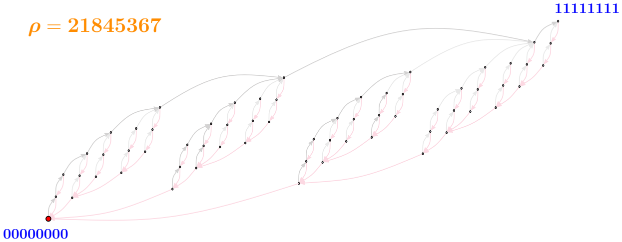
Given ρ what is the number of vertices in the main loop?

M.M. Terzi & **MM** PRE **102** (2021) 012122,
P. L. Ferrari, **MM** & M.M. Terzi AIHPD 2022

The Preisach Model and Return Point Memory (RPM)

$\rho = 21845367$



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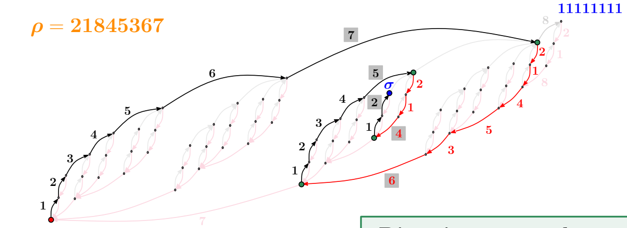
Given ρ what is the number of vertices in the main loop?
ANSWER: It is equal to the # of increasing subsequences contained in ρ

M.M. Terzi & **MM** PRE **102** (2021) 012122,
P. L. Ferrari, **MM** & M.M. Terzi AIHPD 2022

The Preisach Model and Return Point Memory (RPM)

$\rho = 21845367$



Directions to reach σ:
00000000 → 7 → 6 → 5 → 4 → 2 :σ

2 4 5 6 7 is an increasing subsequence of $\rho = 21845367$

Switching Sequence:

Up: $1 \to 2 \to 3 \to 4 \to 5 \to 6 \to 7 \to 8$

Down: $2 \to 1 \to 8 \to 4 \to 5 \to 3 \to 6 \to 7$

Given ρ what is the number of vertices in the main loop?

ANSWER: It is equal to the # of increasing subsequences contained in ρ

MOREOVER: each increasing subsequence encodes a deformation history!

M.M. Terzi & **MM** PRE **102** (2021) 012122,
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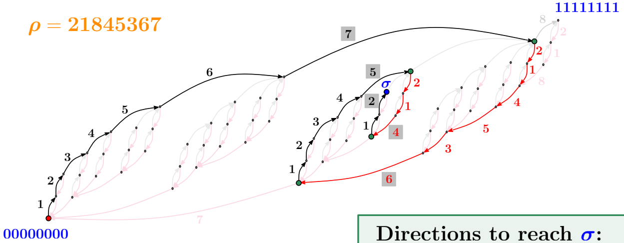

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Histories are mapped into states

M.M. Terzi & **MM** PRE **102** (2021) 012122,
P. L. Ferrari, **MM** & M.M. Terzi AIHPD 2022

Recap: Memory formation in driven disordered systems

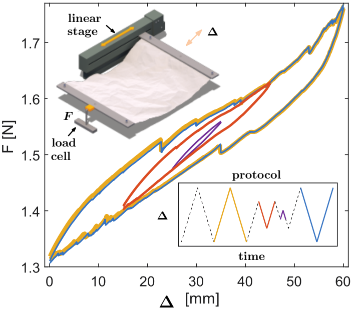
- **Return point memory (RPM)** is one way of **encoding memory of deformation history**.
- **Memory and history-dependence** become **topological features** of transition graph (***t*-graph**) $\Rightarrow$ **loop return point memory (ℓRPM)**, **MM** & Terzi, AHP (2019).
- Preisach model: **simplest model with ℓRPM**.
- More **complicated ℓRPM systems**: Random field Ising model with ferromagnetic interactions, models of depinning, i.e. elastic manifolds in random media. **Consequence of no-passing** (Middleton 1992): **partial order on configurations that is preserved by dynamics**.
- Systems that exhibit **ℓRPM approximately**: the sheared amorphous solids (**MM**, S. Sastry, K. Dahmen & I. Regev, PRL (2019)).

Where to go from here

- The **Preisach Model:**
  - Hystorically, introduced to describe hysteresis in magnetic materials (Preisach 1935).
  - "Ideal gas" of **memory formation**:
    - Hysterons do not interact, switching thresholds do not depend on states of the other hysterons. $\Rightarrow$ **switching order ρ fixed.**
- **Hysteron interactions $\Rightarrow$ rich & versatile dynamics**: hysterons can be **created, destroyed and altered**.
- **Possible directions:**
  - **Device Design**: mechanical sensors, automata & A/D converters of environmental signals, control systems (Lechenault & van Hecke groups),
  - **Adaptive evolution in a changing environment:** (Das, Krug & MM, 2022)
  - Understanding the dynamics of **non-quenched**, i.e. **co-evolving (annealed) disorder** in driven disordered systems: **yielding and irreversibility transition** in sheared amorphous solids.

Where to go from here? Understanding annealed disorder

Periodically compressing/uncompressing a crumpled sheat:
(Shohat et al. PNAS 2022)



Cyclic Response achieved after a number of driving cycles

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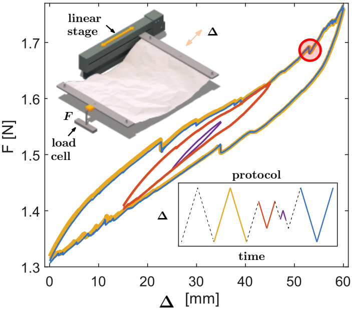

Cyclic Response achieved after a number of driving cycles

Cyclic Response has discontinuities

Can be traced back to creases and wrinkles:

localized, bi-stable elements

⇒ hysterons

Mechanical annealing:

⇒ interacting hysteron system

⇒ hierarchy of nested cycles

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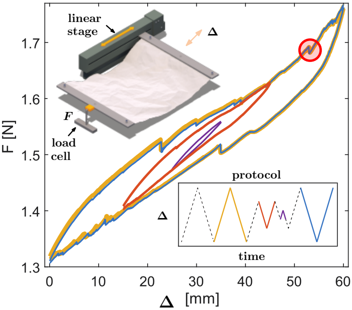

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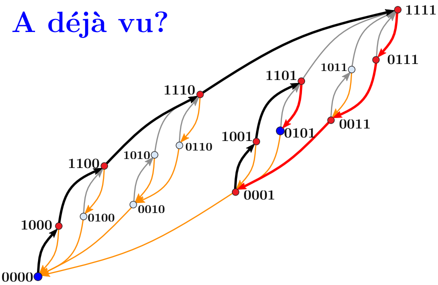
A déjà vu?



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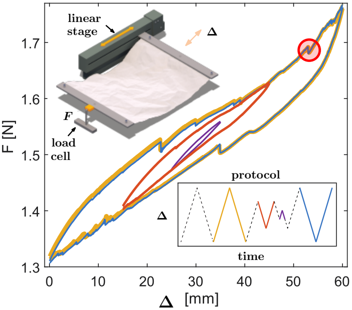

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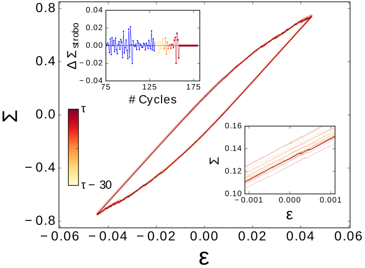
Simulations: (Kumar et al. JCP 2022)

Periodically shearing an amorphous solid



Probing molecular glasses via t-graphs

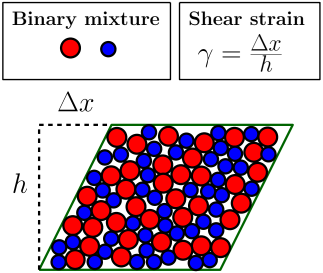
- Under cylic loading ⇒ evolution into periodic response.
- Periodic response ⇒ sequence of **mechanical instabilities**.
- **Periodicity:** these instabilities are repeatedly retriggered, ⇒ **reversible instabilities**.
- **Transient towards periodicity: Trial & Error** or **Evolution**?

What characterizes the attainment of periodic response?

What characterizes the yielding transition?

Probing molecular glasses via t-graphs

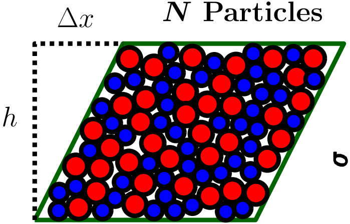
- **Focus on amorphous solids** under externally applied **shear strain**:
  - Amorphous = non-crystalline structure, **disordered.**
  - Numerically achieved by considering binary mixtures of particles of **different sizes**, prevents crystallization.
  - Particles interact with each other.
- **AQS dynamics:** (Maloney & Lemaître PRE **74** (2006) 016118):
  - Athermal: ignore thermal activation processes ⇒ mechanical equilibria
  - Slowly varying shear strain γ_t: **fast relaxation** to new mechanically stable configuration ⇒ rate-independent response ⇒ quasi-static process.



The Yielding transition

System

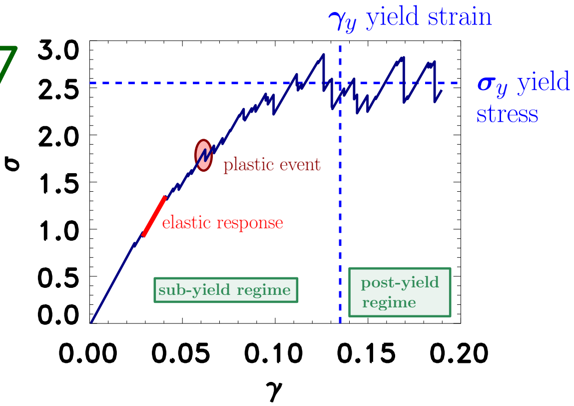
***N* Particles**



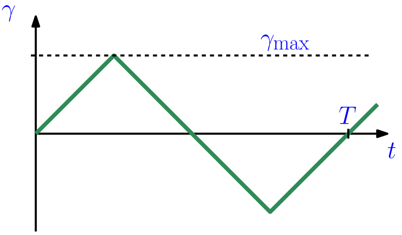
Shear strain:

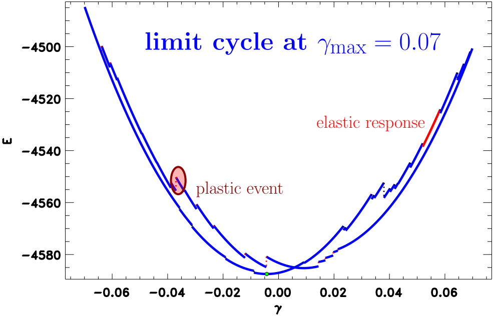
$$\gamma = \frac{\Delta x}{h}$$

AQS Stress σ vs. Strain γ Response: monotonously increasing shear strain



Cyclic Response under Oscillatory Shear Strain:





Irreversibility Transition:

Transient to limit-cycle diverges as $\gamma_{\max} \nearrow \gamma_c$.

Pine, Gollub, Brady & Leshansky Nature **438** 997 2005; Corte, Chaikin, Gollub & Pine Nat. Phys. **4** 420, 2008 ...

How can we understand the evolution?

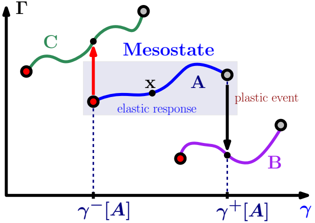
t-graphs and mesostates

Configuration Space for N-particles: $\boldsymbol{\Gamma}$
N-particle configuration: $\boldsymbol{x}$
Deformation parameter: γ
AQS dynamics:

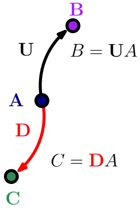
$$\boxed{E = U(\boldsymbol{x}, \gamma),} \qquad \text{(potential energy)}$$

Stable Configurations $\boldsymbol{x}$ evolve with γ until they become unstable:

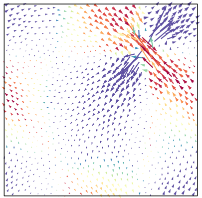
$$\Rightarrow \boldsymbol{x}(\gamma) \quad \text{for} \quad \gamma^- < \gamma < \gamma^+$$



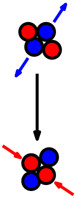
Mesostate transitions are plastic events!



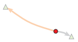
plastic events are localized rearrangments:
$\boldsymbol{A} \rightarrow \boldsymbol{B}$



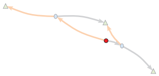
e.g.



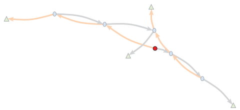
t-graph acquisition from simulations – Generation 1



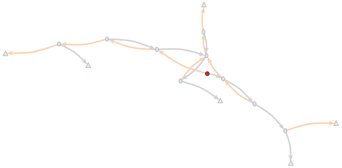
t-graph acquisition from simulations – Generation 2



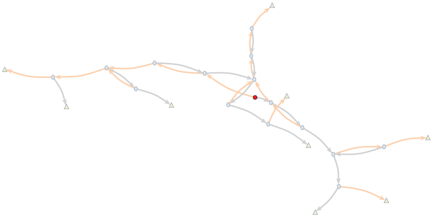
t-graph acquisition from simulations – Generation 3



t-graph acquisition from simulations – Generation 4



t-graph acquisition from simulations – Generation 5



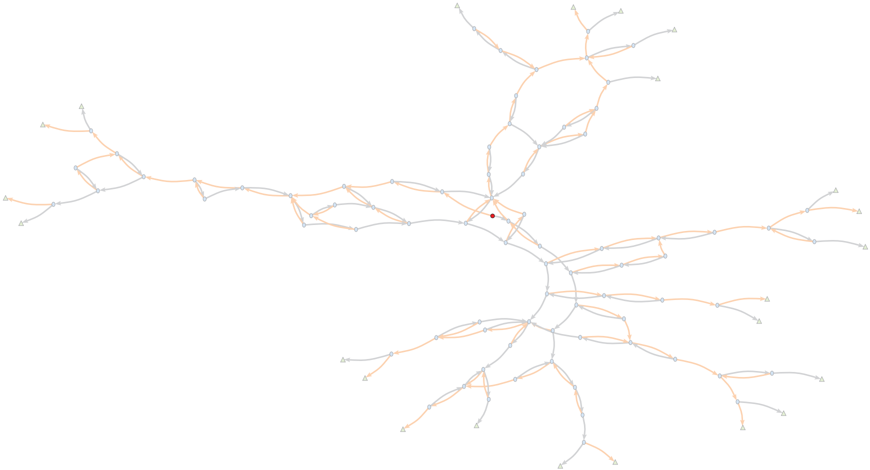
t-graph acquisition from simulations – Generation 6

t-graph acquisition from simulations – Generation 7

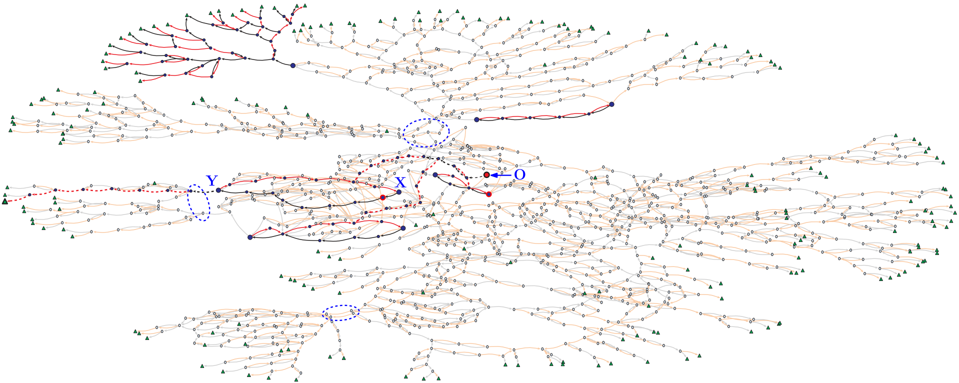
t-graph acquisition from simulations – Generation 8

t-graph acquisition from simulations – Generation 9

t-graph acquisition from simulations – Generation 10

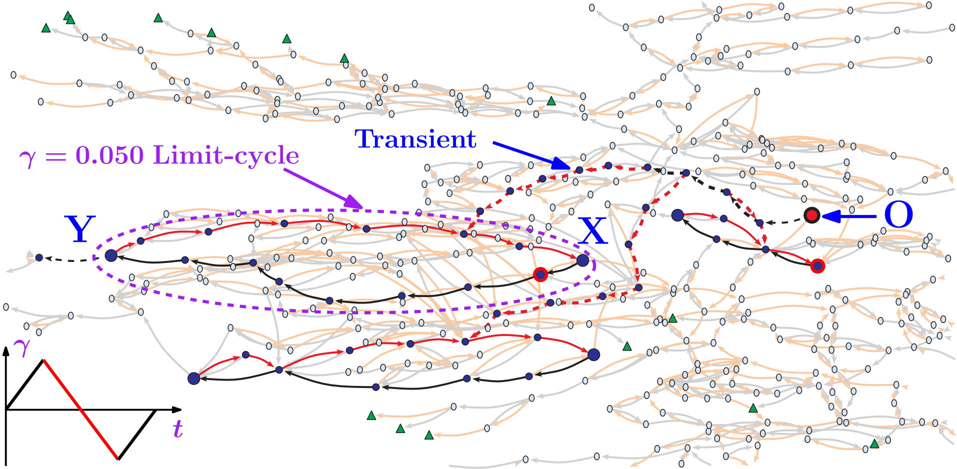


The lay of the land — $g = 25$, $\mathcal{N} = 1416$ mesostates



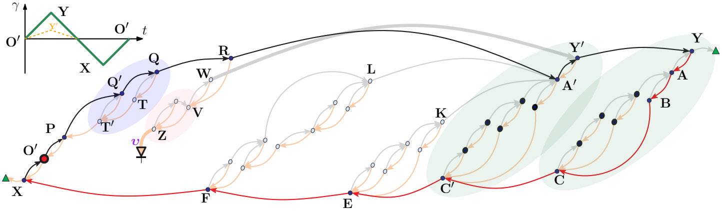
- Degeneracy: many deformation paths lead to the same state
  $\mathcal{N} = 1416 \ll 2^{26} \approx 6 \times 10^7$
- Bottlenecks, tree-like regions & loops

Transients and limit-cycles



Interacting Soft-spot systems

Mungan *et al.* PRL 2019



Oscillatory Shear does not just lead to cyclic response! We get more than we asked for: a hierarchy of nested cycles

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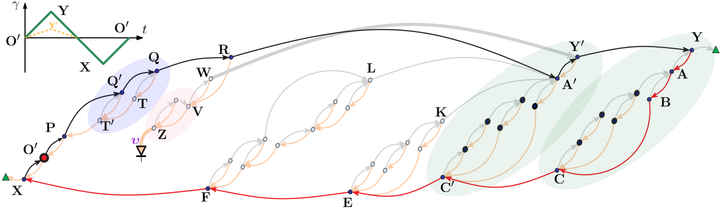

Oscillatory Shear does not just lead to cyclic response! We get more than we asked for: a hierarchy of nested cycles

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Cyclic Response achieved after a number of driving cycles
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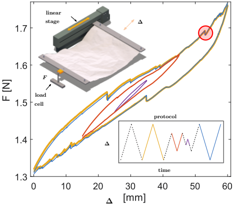

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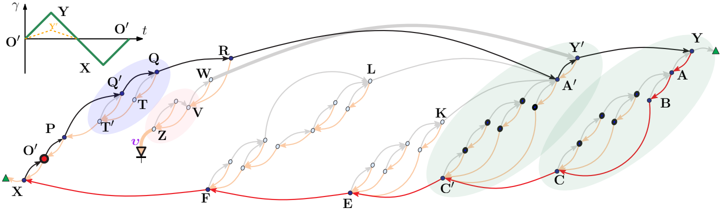

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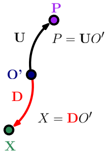
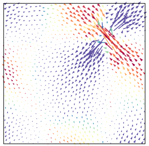
Mesostate transitions are plastic events!

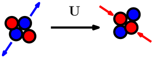


plastic events are localized rearrangments: $O' \to P$



soft-spots

e.g.



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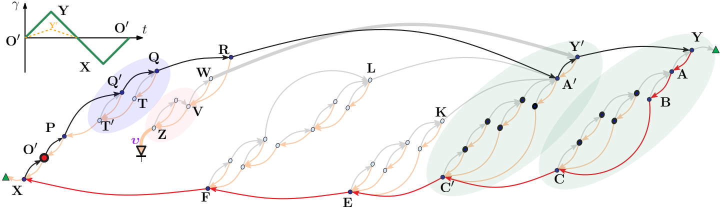

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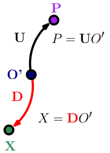

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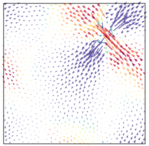

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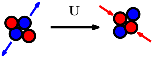
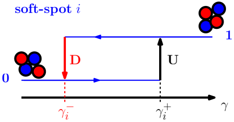
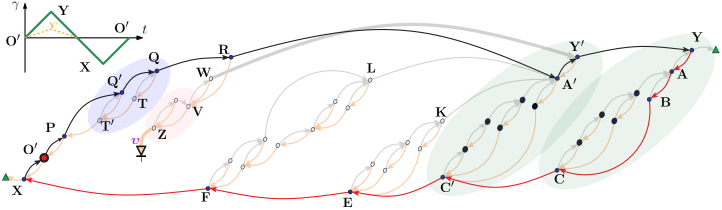


soft-spots as two-state systems:

soft-spot i



Interacting Soft-spot systems



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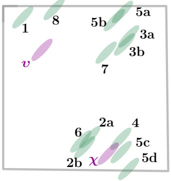

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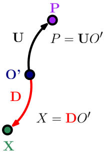

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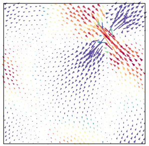

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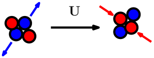

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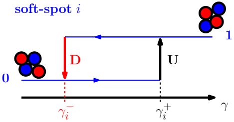

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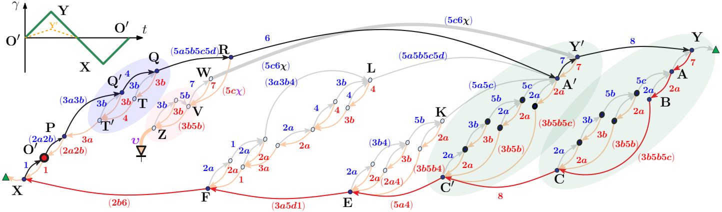
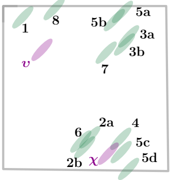


Mungan *et al.* PRL 2019



Oscillatory Shear does not just lead to cyclic response! We get more than we asked for: a **hierarchy** of nested cycles

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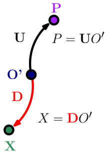

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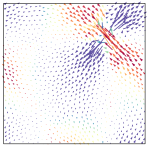

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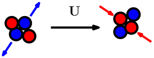

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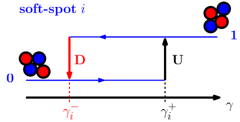

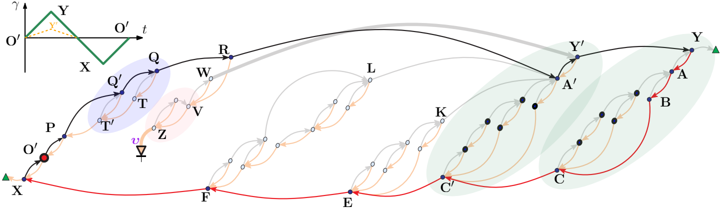

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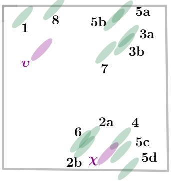

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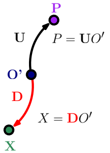
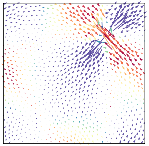
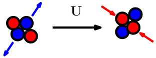


plastic events are localized rearrangments: $O' \to P$



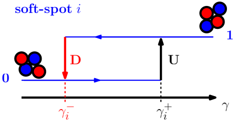
soft-spots

e.g.



soft-spots as two-state systems:

soft-spot i



Soft-spots interact:

can alter $\gamma_j^{\pm}$

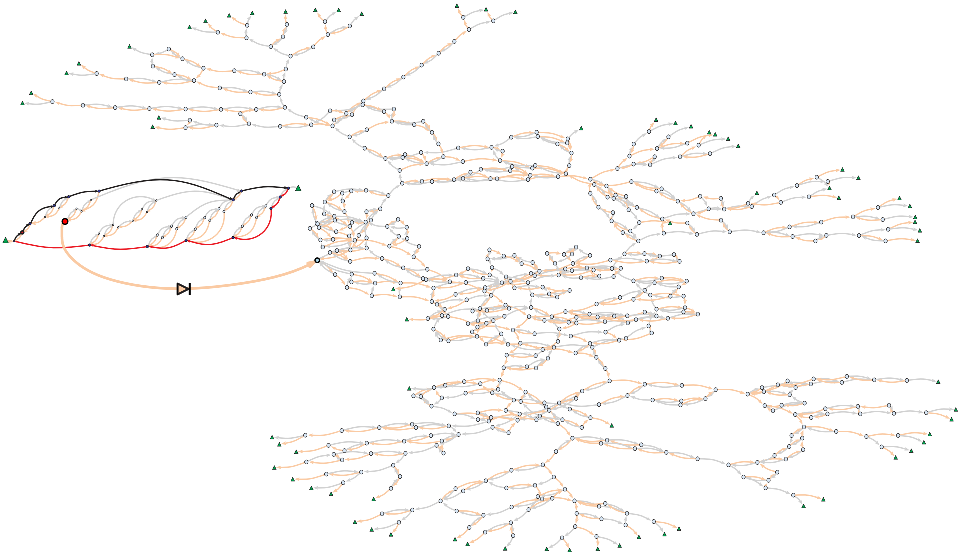
enable/disable switching behavior

of other soft-spots

Transient towards cyclic response

- **Mechanical Aging:** Emergence of interacting soft-spot system
- **Persistence & Robustness:** Soft-spots play nice (most of the time) $\Rightarrow$ hierarchy of nested cyles
- **Selection & Memory:** Emergent soft-spot system determined by form of periodic loading, e.g. amplitude of oscillation ...

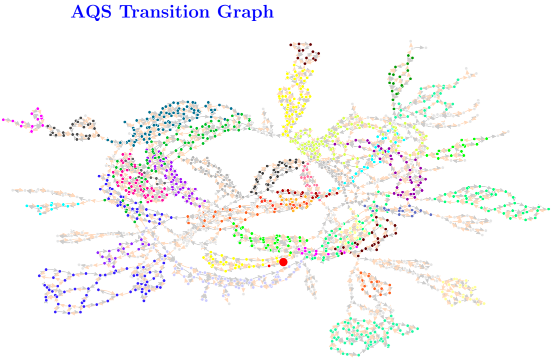
Down the rabbit hole – total irreversibility

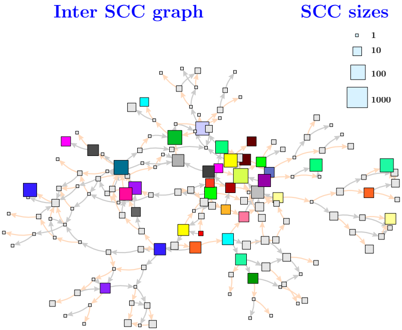


Mutual Reachability and Strongly Connected Components

- A pair of mesostates, A and B, is **mutually reachable**, if there exists some deformation path from A to B **AND** from B to A
- Mutual reachability (MR) is an equivalence relation $\Rightarrow$ partition of $\mathcal{S}$
- Equivalence classes under MR are called **strongly connected components (SCCs)**
- **Toplogy $\leftrightarrow$ Physics:**
  - Transitions **within** an SCC are reversible, **(reversible plasticity)**
  - Transitions **between** an SCC are irreversible, **(irreversible plasticity)**
  - **Any periodic response must be confined to a single SCC**

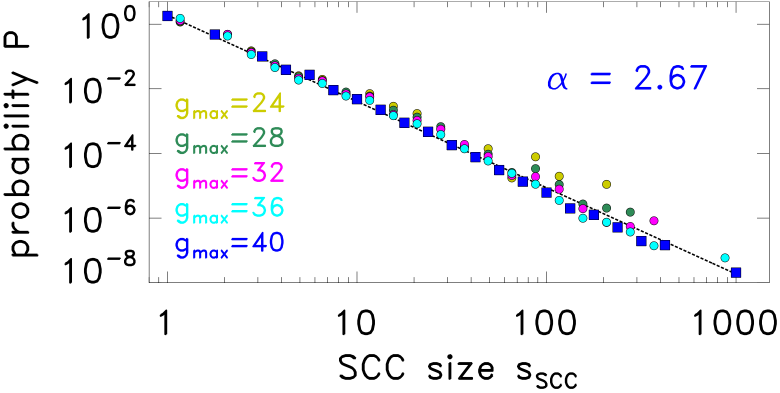
SCCs, reversible and irreversible transitions





- Irreversibility encoded in the transitions between SCCs
- $\Rightarrow$ inter-SCC transition graph (acylic)

SCC size distribution and length of transients



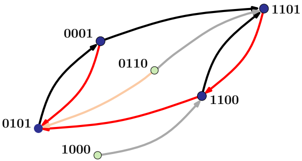
- cyclic response must be confined to a single SCC
- **large amplitude** cyclic response requires **large SCCs**
- **large SCCs are rare**, especially **close to yielding** (Regev et al. 2021)
- **transient length increase as amplitude increases**

A fitness landscape model describing the evolution of antibiotic drug resistance:

- The **trade-off induced fitness landscape model (TIL)** (S.G. Das, S.O.L. Direito, B. Waclaw, R. Allen & J. Krug, eLife **9** (2020) e55155):
  - Bacteria in environment of **varying antibiotic drug concentration** x.
  - L possible loci where mutations can occur.
  - Binary vector $\boldsymbol{\sigma} = (\sigma_1, \ldots, \sigma_L)$ encodes whether mutation at i is present ($\sigma_i = 1$) or absent ($\sigma_i = 0$).
- Environment characterized by **single parameter:** antibiotic concentration x.
- For each x: a mapping that assigns to each genotype $\boldsymbol{\sigma}$ a fitness $f_{\boldsymbol{\sigma}}$.

A fitness landscape model describing the evolution of antibiotic drug resistance

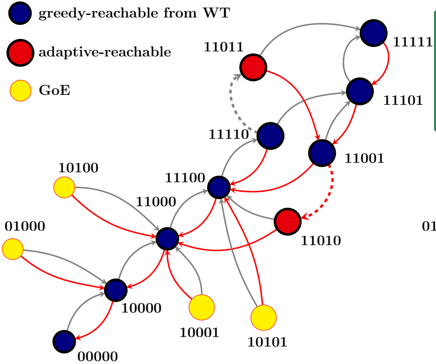
- **Goal:** Characterize the transition between genotypes as x is changed and fitness maxima change.
- **Motivation:**



- $L = 4$ mutation sites associated with an antibiotic resistance enzyme when subject to antibiotic at different concentrations.
- Black/Gray and Red/Orange arrows indicate transitions to new fitness peaks under incease and decease of concentration.
- Data compiled from M. Mira *et al.* Mol. Bio. Evol. **32** (2015) 2707.

The Das-Krug *et al.* trade-off induced fitness landscape model (TIL) as a system of interacting hysterons.

TIL Dynamics

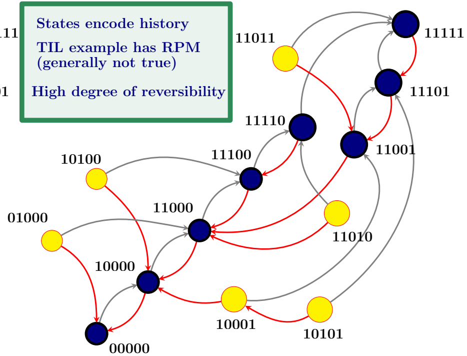


Preisach Dynamics

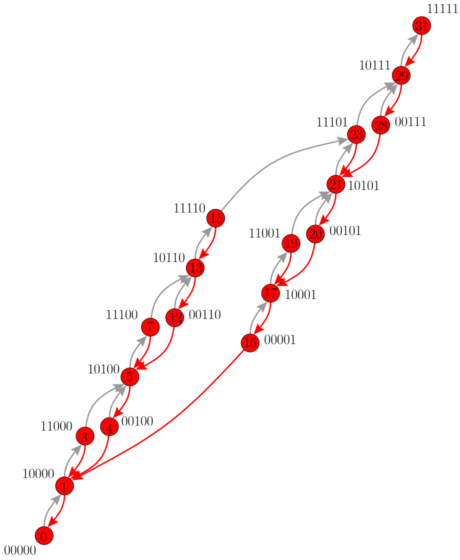
States encode history

TIL example has RPM (generally not true)

High degree of reversibility



TIL nested cycles



Outlook & Conclusions

- Overview of **memory formation** in **driven soft-matter systems.**
- Approach via state **transition graphs**.
- Glassy systems like the sheared amorphous solids:
    - Hysteron interactions ⇒ **rich & versatile dynamics**
    - The interacting hysteron system is often **emergent**: The exposure to external driving or interactions with environment shapes the formation of hysteron systems ⇒ **Aging**
    - Quenched vs. Annealed disorder.
- Parallels with **adaptive evolution** in biology.
- Connection with biology goes both ways, e.g. understanding evolution of antibiotic resistance:

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Featured in Physics

Driven Disordered Systems Approach to Biological Evolution in Changing Environments

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  - **Biological Systems:** Joachim Krug, Suman Das (U. Cologne)