is space time?
a spatiotemporal tiling of turbulence

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Session D37: Transitional Flows & Chaotic Dynamics: in honor of Bruno Eckhardt

APS March Meeting

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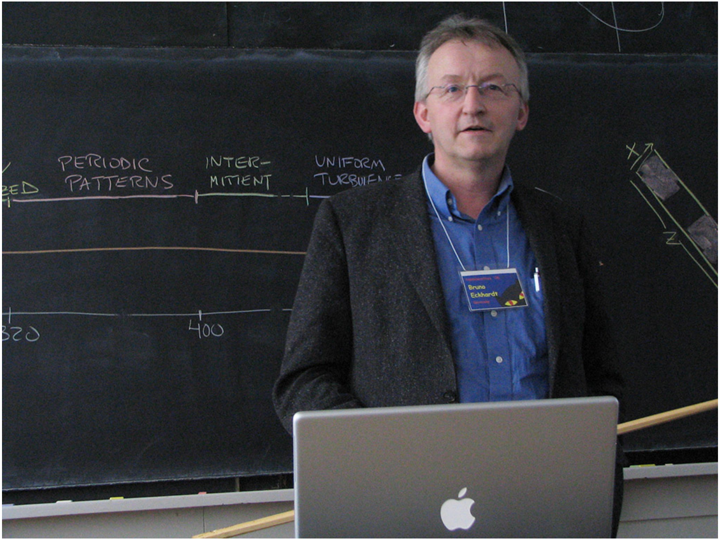
Bruno at Niels Bohr Institute, May 2006



Bruno's secret

keep it simple!

B Eckhardt[1] *Fractal properties of scattering singularities* (1987)

"··· model studied is the motion of a particle in a plane, elastically reflected by three circular discs centred on the corners of an equilateral triangle"

[1] B. Eckhardt, J. Phys. A **20**, 5971 (1987).

what is this? some background

this talk is an introduction to the

spatiotemporal cat[2]

the simplest example of the larger picture

spatiotemporal turbulence[3]

that motivates our study of discrete spatiotemporal lattices

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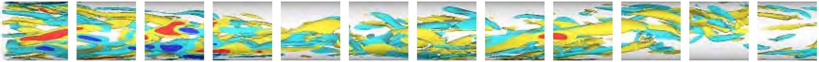
[2] P. Cvitanović and H. Liang, *Spatiotemporal cat: An exact classical chaotic field theory*, in preparation, 2020.

[3] M. Gudorf and P. Cvitanović, *Spatiotemporal tiling of the Kuramoto-Sivashinsky flow*, in preparation, 2020.

motivation : need a theory of large fluid domains

pipe flow close to onset of turbulence [4]



we have a detailed theory of small turbulent fluid cells

can we construct the infinite pipe by coupling small turbulent cells ?

what would that theory look like ?

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[4] M. Avila and B. Hof, Phys. Rev. **E 87** (2013)

the goal

build
a chaotic field theory

from
the simplest chaotic blocks

using

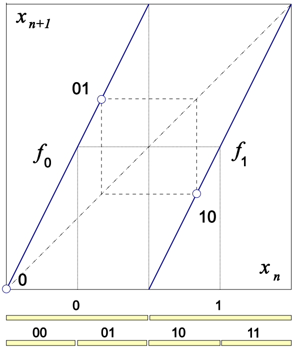
- time invariance
- space invariance

of the defining partial differential equations

1. a coin toss
2. temporal cat
3. spatiotemporal cat
4. bye bye, dynamics

fair coin toss (AKA Bernoulli map)

the essence of deterministic chaos



$$x_{t+1} = \begin{cases} f_0(x_t) = 2x_t \\ f_1(x_t) = 2x_t \pmod 1 \end{cases}$$

$\Rightarrow$ fixed point $\overline{0}$, 2-cycle $\overline{01}$, $\cdots$

a coin toss

the simplest example of deterministic chaos

what is (mod 1) ?

map with integer-valued 'stretching' parameter $s \geq 2$:

$$x_{t+1} = s\, x_t$$

(mod 1) : subtract the integer part $m_{t+1} = \lfloor s x_t \rfloor$
to keep fractional part ϕ_{t+1} in the unit interval $[0, 1)$

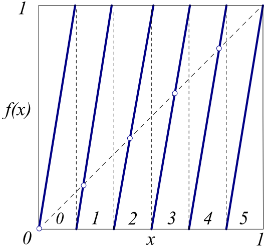
$$\phi_{t+1} = s\phi_t - m_{t+1}\,, \qquad \phi_t \in \mathcal{M}_{m_t}$$

m_t takes values in the s-letter alphabet

$$m_t \in \mathcal{A} = \{0, 1, 2, \cdots, s-1\}$$

a fair dice throw

slope 6 Bernoulli map



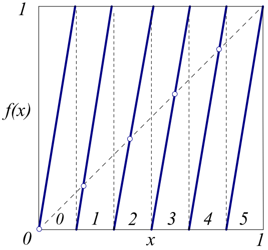
$$\phi_{t+1} = 6\phi_t - m_{t+1}\,,\ \phi_t \in \mathcal{M}_{m_t}$$

6-letter alphabet
$m_t \in \mathcal{A} = \{0, 1, 2, \cdots, 5\}$

6 subintervals $\{\mathcal{M}_{m_1}\}$

what is chaos ?

a fair dice throw



each subinterval contains a periodic point, labeled by $\mathrm{M} = m_1 m_2 \cdots m_n$

$N_n = 6^n$ unstable orbits

6 subintervals $\{\mathcal{M}_{m_1}\}$, 6^2 subintervals $\{\mathcal{M}_{m_1 m_2}\}, \cdots$

definition : chaos is

positive Lyapunov ($\ln s$) + positive entropy ($\frac{1}{n} \ln N_n$)

the precise sense in which

dice throw is an example of deterministic chaos

lattice Bernoulli

now recast the time-evolution Bernoulli map

$$\phi_{t+1} = s\phi_t - m_{t+1}$$

as a 1-step difference equation on the temporal lattice

$$\phi_t - s\phi_{t-1} = -m_t \,, \qquad \phi_t \in [0,1)$$

with a field ϕ_t, source m_t
on each site t of a 1-dimensional lattice $t \in \mathbb{Z}$

write an n-sites lattice segment as
the lattice state and the symbol block

$$\Phi = (\phi_{t+1}, \cdots, \phi_{t+n}) \,, \quad \mathsf{M} = (m_{t+1}, \cdots, m_{t+n})$$

think globally, act locally

Bernoulli equation at every instant t, local in time

$$\phi_t - s\phi_{t-1} = -m_t$$

is enforced by the global equation

$$\left(1 - s\sigma^{-1}\right) \Phi = -\mathsf{M}\,,$$

where the $[n\times n]$ matrix

$$\sigma_{jk} = \delta_{j+1,k}\,, \qquad \sigma = \begin{pmatrix} 0 & 1 & & & \\ & 0 & 1 & & \\ & & & \ddots & \\ & & & 0 & 1 \\ 1 & & & & 0 \end{pmatrix}$$

implements the 1-time step operation

think globally, act locally

solving the lattice Bernoulli equation

$$\mathcal{J}\Phi = -\mathsf{M}\,,$$

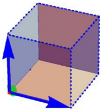
with the $[n \times n]$ matrix $\qquad \mathcal{J} = 1 - s\sigma^{-1}\,,$

can be viewed as a search for zeros of the function

$$F[\Phi] = \mathcal{J}\Phi + \mathsf{M} = 0$$

the entire global lattice state Φ_M is now

a single fixed point $(\phi_1, \phi_2, \cdots, \phi_n)$



in the n-dimensional unit hyper-cube $\qquad \Phi \in [0,1)^n$

orbit Jacobian matrix

solving a nonlinear $F[\Phi] = 0$ fixed point condition with Newton method requires evaluation of the $[n \times n]$ orbit Jacobian matrix

$$\mathcal{J}_{ij} = \frac{\delta F[\Phi]_i}{\delta \phi_j}$$

what does this global orbit Jacobian matrix do?

1. fundamental fact !
2. global stability of lattice state Φ, perturbed everywhere

(1) fundamental fact

to satisfy the fixed point condition

$$\mathcal{J}\Phi + \mathsf{M} = 0$$

the orbit Jacobian matrix $\mathcal{J}$

1. stretches the unit hyper-cube $\Phi \in [0, 1)^n$ into the n-dimensional fundamental parallelepiped
2. maps each periodic point Φ_{M} into an integer lattice $\mathbb{Z}^n$ point
3. then translate by integers M into the origin

hence N_n, the total number of solutions = the number of lattice points within the fundamental parallelepiped

the fundamental fact[5] :

$$N_n = |\mathrm{Det}\,\mathcal{J}|$$

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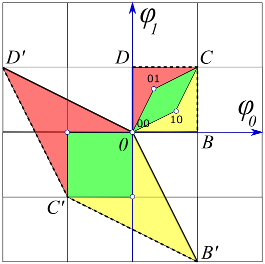
[5] M. Baake et al., J. Phys. A **30**, 3029–3056 (1997).

example : fundamental parallelepiped for $n = 2$

orbit Jacobian matrix, unit square basis vectors, their images :

$$\mathcal{J} = \begin{pmatrix} 1 & -2 \\ -2 & 1 \end{pmatrix} ; \quad \Phi_B = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \to \Phi_{B'} = \mathcal{J}\,\Phi_B = \begin{pmatrix} 1 \\ -2 \end{pmatrix} \cdots ,$$

Bernoulli periodic points of period 2



$N_2 = 3$

fixed point Φ_{00}

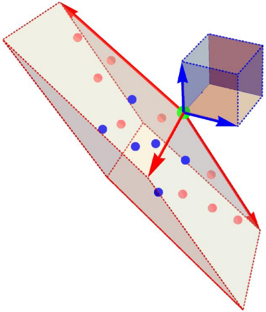
2-cycle Φ_{01}, Φ_{10}

square $[0BCD] \Rightarrow \mathcal{J} \Rightarrow$ fundamental parallelepiped $[0B'C'D']$

fundamental fact is a fact for any n

$n = 3$ example

$\mathcal{J}$ [unit hyper-cube] = [fundamental parallelepiped]



unit hyper-cube $\Phi \in [0, 1)^n$

$n > 3$ cannot visualize

a periodic point $\rightarrow$ integer lattice point, • on a face, • in the interior

(2) orbit stability vs. temporal stability

orbit Jacobian matrix

$\mathcal{J}_{ij} = \frac{\delta F[\Phi]_i}{\delta \phi_j}$ stability under global perturbation of the whole orbit

for n large, huge $[dn \times dn]$ matrix

Jacobian matrix

J^n propagates initial perturbation n time steps

small $[d \times d]$ matrix

J and $\mathcal{J}$ are related by[6]

Hill's (1886) remarkable formula

$$|\mathrm{Det}\,\mathcal{J}| = |\det(\mathbf{1} - J^n)|$$

[6] G. W. Hill, Acta Math. **8**, 1–36 (1886).

by 1989 we forgot Bruno’s secret

Cvitanović & Eckhardt[7] *Periodic orbit quantization of chaotic systems* (1989)

“$\cdots$ computing from a few periodic orbits highly accurate estimates of a large number of quantum resonances for the classically chaotic 3-disk scattering problem”

this time I’ll keep it simple!

[7] P. Cvitanović and B. Eckhardt, Phys. Rev. Lett. **63**, 823–826 (1989).

how come $\mathrm{Det}\,\mathcal{J}$ counts periodic points ?

in 1984 Ozorio de Almeida and Hannay[8] related the number of periodic points to a Jacobian matrix by their

principle of uniformity

“periodic points of an ergodic system, counted with their natural weighting, are uniformly dense in phase space”

where

natural weight of periodic orbit M

$$\frac{1}{|\det(1 - J_M)|}$$

[8] A. M. Ozorio de Almeida and J. H. Hannay, J. Phys. A **17**, 3429 (1984).

"principle of uniformity" is in[9]

periodic orbit theory

known as the flow conservation sum rule :

$$\sum_{\mathsf{M}} \frac{1}{|\det(1 - J_{\mathsf{M}})|} = \sum_{\mathsf{M}} \frac{1}{|\mathrm{Det}\,\mathcal{J}_{\mathsf{M}}|} = 1$$

sum over periodic points Φ_{M} of period n

state space is divided into

neighborhoods of periodic points of period n

[9] P. Cvitanović, "Why cycle?", in *Chaos: Classical and Quantum*, edited by P. Cvitanović et al. (Niels Bohr Inst., Copenhagen, 2020).

how come a $\mathrm{Det}\,\mathcal{J}$ counts periodic points ?

flow conservation sum rule :

$$\sum_{\phi_i \in \mathrm{Fix} f^n} \frac{1}{|\mathrm{Det}\,\mathcal{J}_i|} = 1$$

the number of Bernoulli periodic lattice states

$N_n = |\mathrm{Det}\,\mathcal{J}| = s^n - 1$ for any n

topological zeta function

the generating function that sums up number of periodic points N_n to all orders is called 'topological zeta function'

$$1/\zeta_{\mathrm{top}}(z) = \exp\left(-\sum_{n=1}^{\infty} \frac{z^n}{n} N_n\right)$$

for Bernoulli :

$$1/\zeta_{\mathrm{top}}(z) = \frac{1 - sz}{1 - z}$$

solved!

This is 'periodic orbit theory'
And if you don't know, now you know

coin toss ? that's not physics

a field theory should be Hamiltonian, because

- that is physics
- Quantum Mechanics demands it

need a system as simple as the Bernoulli, but mechanical

so, we move on from running in circles,

to a mechanical rotor to kick.

1. a coin toss
2. **a kicked rotor**
3. spatiotemporal cat
4. bye bye, dynamics

field theory in 1 spacetime dimension

we now define

the cat map in 1 spacetime dimension

then we generalize to

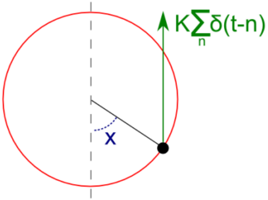
d-dimensional spatiotemporal cat

1. cat map in Hamiltonian formulation
2. cat map in Lagrangian formulation (so much more elegant !)

Hamiltonian formulation

example of a “small domain” dynamics : a single kicked rotor

an electron circling an atom, subject to
a discrete time sequence of angle-dependent kicks $F(x_t)$



Taylor, Chirikov and Greene standard map

$$
\begin{aligned}
x_{t+1} &= x_t + p_{t+1} \qquad \mod 1, \\
p_{t+1} &= p_t + F(x_t)
\end{aligned}
$$

→ chaos in Hamiltonian systems

the simplest example : a cat map evolving in time

force $F(x) = Kx$ linear in the displacement x , $K \in \mathbb{Z}$

$$\begin{aligned} x_{t+1} &= x_t + p_{t+1} \qquad \mod 1 \\ p_{t+1} &= p_t + Kx_t \qquad \mod 1 \end{aligned}$$

Continuous Automorphism of the Torus, or

Hamiltonian cat map

a linear, area preserving map of a 2-torus onto itself

$$\begin{pmatrix} \phi_t \\ \phi_{t+1} \end{pmatrix} = J \begin{pmatrix} \phi_{t-1} \\ \phi_t \end{pmatrix} - \begin{pmatrix} 0 \\ m_t \end{pmatrix}, \qquad J = \begin{pmatrix} 0 & 1 \\ -1 & s \end{pmatrix}$$

for integer “stretching” $s = \mathrm{tr}\, J > 2$ the map is
hyperbolic $\to$ a fully chaotic Hamiltonian dynamical system

Lagrangian formulation

cat map in Lagrangian form

replace momentum by velocity

$$p_{t+1} = (\phi_{t+1} - \phi_t)/\Delta t$$

formulation on temporal lattice is pretty[10] :

2-step difference equation

$$\phi_{t+1} - s\,\phi_t + \phi_{t-1} = -m_t$$

integer m_t ensures that

ϕ_t lands in the unit interval

$$m_t \in \mathcal{A}\,, \quad \mathcal{A} = \{\text{finite alphabet}\}$$

[10] I. Percival and F. Vivaldi, Physica D **27**, 373–386 (1987).

think globally, act locally

temporal cat at every instant t, local in time

$$\phi_{t+1} - s\,\phi_t + \phi_{t-1} = -m_t$$

is enforced by the global equation

$$(\sigma - s\mathsf{1} + \sigma^{-1})\,\Phi = -\mathsf{M}\,,$$

where

orbit Jacobian matrix

$$\Phi = (\phi_{t+1}, \cdots, \phi_{t+n}), \quad \mathsf{M} = (m_{t+1}, \cdots, m_{t+n})$$

are a lattice state, and a symbol block

and $[n \times n]$ orbit Jacobian matrix $\mathcal{J}$ is

$$\sigma - s\mathbb{1} + \sigma^{-1} = \begin{pmatrix} -s & 1 & & & 1 \\ 1 & -s & 1 & & \\ & 1 & & \ddots & \\ & & & -s & 1 \\ 1 & & & & -s \end{pmatrix}$$

think globally, act locally

solving the temporal cat equation

$$\mathcal{J}\Phi = -\mathsf{M}\,,$$

with the $[n\times n]$ matrix $\qquad \mathcal{J} = \sigma - s\mathbb{1} + \sigma^{-1}$

can be viewed as a search for zeros of the function

$$F[\Phi] = \mathcal{J}\Phi + \mathsf{M} = 0$$

where the entire global lattice state Φ_{M} is

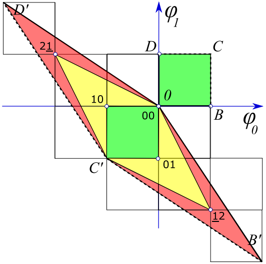
a single fixed point $(\phi_1, \phi_2, \cdots, \phi_n)$

in the n-dimensional unit hyper-cube $\Phi \in [0,1)^n$

fundamental fact in action

temporal cat fundamental parallelepiped for period 2

square $[0BCD] \Rightarrow \mathcal{J} \Rightarrow$ fundamental parallelepiped $[0B'C'D']$



$N_2 = |\mathrm{Det}\,\mathcal{J}| = 5$

fundamental parallelepiped
$=$ 5 unit area quadrilaterals

again, one periodic point per each unit volume

temporal cat topological zeta function

again, can evaluate

$$N_n = |\mathrm{Det}\,\mathcal{J}|$$

substitute the number of periodic points N_n into the topological zeta function

$$\begin{aligned} 1/\zeta_{\mathrm{top}}(z) &= \exp\left(-\sum_{n=1} \frac{z^n}{n} N_n\right) \\ &= \frac{1 - sz + z^2}{(1-z)^2} \end{aligned}$$

solved!

what continuum theory is temporal cat discretization of?

have

2-step difference equation

$$\phi_{t+1} - s\,\phi_t + \phi_{t-1} = -m_t$$

use discrete lattice derivatives

Laplacian in 1 dimension

$$\phi_{t+1} - 2\phi_t + \phi_{t-1} = \Box\,\phi_t$$

to rewrite cat map as an (anti)oscillator chain

$d = 1$ damped Poisson equation (!)

$$(\Box - s + 2)\,\phi_t = -m_t$$

did you know that a cat map can be so cool?

a reminder slide, to skip : Helmholtz equation in continuum

inhomogeneous Helmoltz equation

is an elliptical equation of form

$$(\Box + k^2)\,\phi(x) = -m(x)\,, \qquad x \in \mathbb{R}^d$$

where $\phi(x)$ is a C^2 function, and $m(x)$ is a function with compact support

for the $\lambda^2 = -k^2 > 0$ (imaginary k), the equation is known as the screened Poisson equation[11], or the Yukawa equation

[11] A. L. Fetter and J. D. Walecka, *Theoretical Mechanics of Particles and Continua*, (Dover, New York, 2003).

that's it! for spacetime of 1 dimension

lattice damped Poisson equation

$$(\Box - s + 2)\phi_z = -m_z$$

solved completely and analytically!

think globally, act locally - summary

the problem of enumerating and determining all global solutions stripped to its essentials :

1. each solution is a zero of the global fixed point condition

$$F[\Phi] = 0$$

2. global stability : the orbit Jacobian matrix

$$\mathcal{J}_{ij} = \frac{\delta F[\Phi]_i}{\delta \phi_j}$$

3. fundamental fact : the number of period-n orbits

$$N_n = |\mathrm{Det}\,\mathcal{J}|$$

4. zeta function $1/\zeta_{\text{top}}(z)$: all predictions of the theory

1. a coin toss
2. a kicked rotor
3. spatiotemporal cat
4. bye bye, dynamics

herding cats in d spacetime dimensions

start with

a cat map at each lattice site

talk to neighbors

spacetime d-dimensional spatiotemporal cat

- Hamiltonian formulation (awkward, forget about it)
- Lagrangian formulation (elegant)

spatiotemporal cat

consider a 1 spatial dimension lattice, with field ϕ_{nt}
(the angle of a kicked rotor "particle" at instant t, at site n)

require

- each site couples to its nearest neighbors $\phi_{n\pm1,t}$
- invariance under spatial translations
- invariance under spatial reflections
- invariance under the space-time exchange

obtain[12]

2-dimensional coupled cat map lattice

$$\phi_{n,t+1} + \phi_{n,t-1} - 2s\,\phi_{nt} + \phi_{n+1,t} + \phi_{n-1,t} = -m_{nt}$$

[12] B. Gutkin and V. Osipov, Nonlinearity **29**, 325–356 (2016).

write the spatial-temporal differences as discrete derivatives

Laplacian : in $d = 1$ and $d = 2$ dimensions

$$\Box\,\phi_t = \phi_{t+1} - 2\phi_t + \phi_{t-1}$$
$$\Box\,\phi_{nt} = \phi_{n,t+1} + \phi_{n,t-1} - 4\,\phi_{nt} + \phi_{n+1,t} + \phi_{n-1,t}$$

$$-m_{nt} = \phi_{n,t+1} + \phi_{n,t-1} - 2s\,\phi_{nt} + \phi_{n+1,t} + \phi_{n-1,t}$$

the cat map is thus generalized to

***d*-dimensional spatiotemporal cat**

$$(\Box - d(s-2))\phi_z = -m_z$$

where $\phi_z \in \mathbb{T}^1$, $m_z \in \mathcal{A}$ and $z \in \mathbb{Z}^d$ = lattice sites

spatiotemporally infinite ‘spatiotemporal cat’

discretized linear PDE

d-dimensional spatiotemporal cat

$$(\Box - d(s-2))\,\phi_z = -m_z$$

is linear and known as

- Helmholtz equation if stretching is weak, $s < 2$
  (oscillatory sine, cosine solutions)
- damped Poisson equation if stretching is strong, $s > 2$
  (hyperbolic sinches, coshes)

the nonlinearity is hidden in the "source"

$$m_z \in \mathcal{A} \text{ at lattice site } z \in \mathbb{Z}^d$$

the simplest of all ‘turbulent’ field theories !

spatiotemporal cat

$$(\Box - d(s-2))\phi_z = -m_z$$

can be solved completely (?) and analytically (!)

assign to each site z a letter m_z from the alphabet $\mathcal{A}$.

a particular fixed set of letters m_z (a lattice state)

$$\mathsf{M} = \{m_z\} = \{m_{n_1 n_2 \cdots n_d}\}\,,$$

is a complete specification of the corresponding lattice state Φ

(from now on work in $d = 2$ dimensions, ‘stretching parameter’ $s = 5/2$)

think globally, act locally

solving the spatiotemporal cat equation

$$\mathcal{J}\Phi = -\mathsf{M}\,,$$

with the $[n\times n]$ matrix $\quad \mathcal{J} = \sum_{j=1}^{2}\left(\sigma_j - s\mathbb{1} + \sigma_j^{-1}\right)$

can be viewed as a search for zeros of the function

$$F[\Phi] = \mathcal{J}\Phi + \mathsf{M} = 0$$

where the entire global lattice state Φ_{M} is

a single fixed point $\Phi_{\mathsf{M}} = \{\phi_z\}$
in the LT-dimensional unit hyper-cube $\Phi \in [0,1)^{LT}$

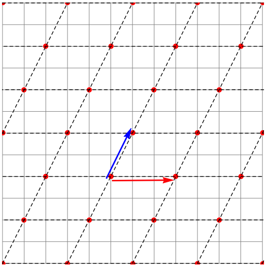
L is the 'spatial', T the 'temporal' lattice period

Bravais lattices

2-dimensional *Bravais lattice* is an infinite array of points

$$\Lambda = \{n_1 \mathbf{a}_1 + n_2 \mathbf{a}_2 \,|\, n_i \in \mathbb{Z}\}$$

example : $[3\times 2]_1$ Bravais tile



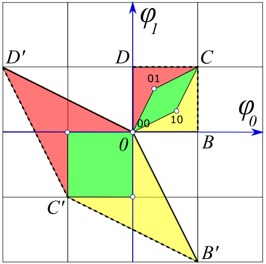
basis vectors
$\mathbf{a}_1 = (3,0)$, $\mathbf{a}_2 = (1,2)$

6 field values, on 6 lattice sites $z = (n,t)$, $[3\times 2]$ rectangle:

$$\begin{bmatrix} \phi_{01} & \phi_{11} & \phi_{21} \\ \phi_{00} & \phi_{10} & \phi_{20} \end{bmatrix}$$

fundamental fact works in spacetime (!)

recall Bernoulli example ?



$[0BCD]$:
unit hyper-cube $\Phi \in [0,1)^n$

$[0B'C'D']$:
fundamental parallelepiped

$\mathcal{J}\,[0BCD] =$ fundamental parallelepiped $[0B'C'D']$

any spacetime, fundamental parallelepiped basis vectors $\Phi^{(j)}$
$=$ columns of the orbit Jacobian matrix

$$\mathcal{J} = (\Phi^{(1)}|\Phi^{(2)}|\cdots|\Phi^{(n)})$$

example : spacetime periodic $[3\times 2]$ Bravais block

$$F[\Phi] = \mathcal{J}\Phi + \mathsf{M} = 0$$

6 field values, on 6 lattice sites $z = (n, t)$, $[3\times 2]$ rectangle:

$$\begin{bmatrix} \phi_{01} & \phi_{11} & \phi_{21} \\ \phi_{00} & \phi_{10} & \phi_{20} \end{bmatrix}$$

$$z = (\ell t), z' = (\ell' t') \in T^2_{[3\times 2]}$$

vectors and matrices can be written in block form, vectors as 1-dimensional arrays,

$$\Phi_{[3\times 2]} = \begin{pmatrix} \phi_{01} \\ \phi_{00} \\ \hline \phi_{11} \\ \phi_{10} \\ \hline \phi_{21} \\ \phi_{20} \end{pmatrix}, \qquad \mathsf{M}_{[3\times 2]} = \begin{pmatrix} m_{01} \\ m_{00} \\ \hline m_{11} \\ m_{10} \\ \hline m_{21} \\ m_{20} \end{pmatrix}$$

with the $[6\times6]$ orbit Jacobian matrix in block-matrix form

$$\mathcal{J}_{[3\times2]} = \left(\begin{array}{cc|cc|cc} -2s & 2 & 1 & 0 & 1 & 0 \\ 2 & -2s & 0 & 1 & 0 & 1 \\ \hline 1 & 0 & -2s & 2 & 1 & 0 \\ 0 & 1 & 2 & -2s & 0 & 1 \\ \hline 1 & 0 & 1 & 0 & -2s & 2 \\ 0 & 1 & 0 & 1 & 2 & -2s \end{array}\right)$$

fundamental parallelepiped basis vectors $\Phi^{(j)}$ are the columns of the orbit Jacobian matrix

$$\mathcal{J}_{[3\times2]} = \left(\begin{array}{c|c|c|c|c|c} -2s & 2 & 1 & 0 & 1 & 0 \\ 2 & -2s & 0 & 1 & 0 & 1 \\ 1 & 0 & -2s & 2 & 1 & 0 \\ 0 & 1 & 2 & -2s & 0 & 1 \\ 1 & 0 & 1 & 0 & -2s & 2 \\ 0 & 1 & 0 & 1 & 2 & -2s \end{array}\right)$$

the 'fundamental fact' now yields the number of solutions for any s

$$N_{[3\times2]} = |\mathrm{Det}\,\mathcal{J}_{[3\times2]}| = 4(s-2)s(2s-1)^2(2s+3)^2$$

counting spatiotemporal cat solutions

1. can construct Bravais spacetime tilings, from small tiles to as large as you wish
2. for each Bravais spacetime tile $[L \times T]_S$, can evaluate

$$N_{[L \times T]_S}$$

the number of doubly-periodic lattice states for a Bravais tile

but, is this

chaos?

yes, short tiles are exponentially good ‘shadows’ of the larger ones, so can attain any desired accuracy

is spatiotemporal cat 'chaotic'?

in time-evolving deterministic chaos any chaotic trajectory is shadowed by shorter periodic orbits

in spatiotemporal chaos, any unstable lattice state is shadowed by smaller invariant 2-tori (Gutkin *et al.*[13,14])

next figure : code the M symbol block ϕ_{nt} at the lattice site *nt* with (color) alphabet

$$m_{t\ell} \in \mathcal{A} = \{\underline{1}, 0, 1, 2, \cdots\} = \{red, green, blue, yellow, \cdots\}$$

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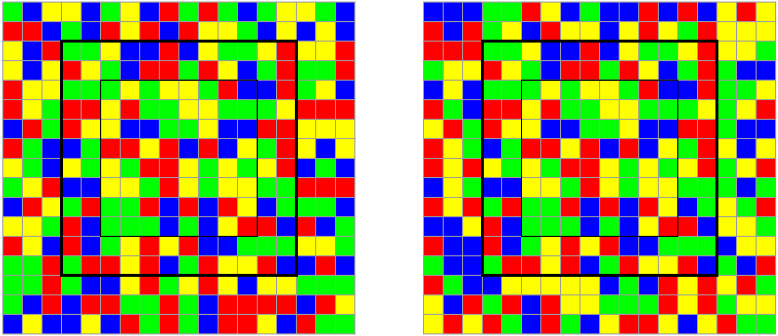
[13] B. Gutkin and V. Osipov, Nonlinearity **29**, 325–356 (2016).

[14] B. Gutkin et al., *Linear encoding of the spatiotemporal cat map*, 2019.

shadowing, symbolic dynamics space

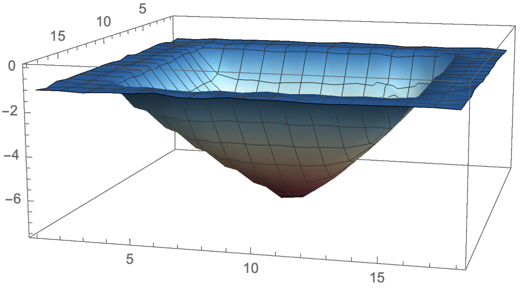


2d symbolic representation M_j of two invariant 2-tori Φ_j shadowing each other within the shared block $M_{\mathcal{R}}$

- border $\mathcal{R}$ (thick black)
- symbols outside $\mathcal{R}$ differ

$s = 7/2$ Adrien Saremi 2017

shadowing



the logarithm of the average of the absolute value of site-wise distance

$$\ln |\phi_{2,z} - \phi_{1,z}|$$

averaged over 250 solution pairs

note the exponential falloff of the distance away from the center of the shared block $\mathcal{R}$

$\Rightarrow$ within the interior of the shared block,

shadowing is exponentially close

zeta function for a field theory ???

‘periodic orbits’ are now invariant 2-tori (Bravais tiles)

each a spacetime lattice tile p of area $A_p = L_p T_p$
that cover the phase space with ‘natural weight’

$$\sum_p \frac{e^{-A_p s}}{|\mathrm{Det}\, \mathcal{J}_p|}$$

at this time :

- $d = 1$ cat map zeta function works like charm
- $d = 2$ spatiotemporal cat works
- $d \geq 2$ Navier-Stokes zeta is still but a dream

1. a coin toss
2. a kicked rotor
3. spatiotemporal cat
4. bye bye, dynamics

Bruno and Predrag in Kyoto, May 2006

insight 1 : how is turbulence described?

not by the evolution of an initial state

exponentially unstable system have finite (Lyapunov) time and space prediction horizons

but

by enumeration of admissible field configurations

and their natural weights

insight 2 : symbolic dynamics for turbulent flows

applies to all PDEs with translational symmetries

a d-dimensional spatiotemporal field configuration

$$\{\phi_z\} = \{\phi_z, z \in \mathbb{Z}^d\}$$

is labelled by a d-dimensional spatiotemporal block of symbols

$$\{m_z\} = \{m_z, z \in \mathbb{Z}^d\},$$

rather than a single temporal symbol sequence

(as is done when describing a small coupled few-“body” system, or a small computational domain).

insight 3 : description of turbulence by invariant 2-tori

1 time, 0 space dimensions

a phase space point is *periodic* if its orbit returns to itself after a finite time T; such orbit tiles the time axis by infinitely many repeats

1 time, d-1 space dimensions

a phase space point is *spatiotemporally periodic* if it belongs to an invariant d-torus $\mathcal{R}$,
i.e., a block $\mathsf{M}_{\mathcal{R}}$ that tiles the lattice state M,
with period ℓ_j in jth lattice direction

bye bye, dynamics

1. challenge : describe states of turbulence in infinite spatiatemporal domains
2. theory : classify, enuremate all spatiotemporal tilings
3. example : spatiotemporal cat, the simplest model of “turbulence”

there is no more time

there is only enumeration of admissible spacetime field configurations

goodbye

to long time and/or space integrators

they never worked and could never work

Mike, John, Predrag and Bruno, KITP - UCSB, February 2017