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Statistical Mechanics and Two-Dimensional Turbulence

Fluid Mechanics Journal Club
\( z \)

\[
\# \text{ the of white balls at time } t, \quad \# \text{ the of black balls at time } t, \quad (t) \mathcal{M} = \mathcal{Y}, \quad (t) \mathcal{B} = \mathcal{Y}
\]

\[
(I - \mathcal{N}, \cdots, I', 0, 0 = \mathcal{Y}) \quad \\Rightarrow \quad \mathcal{N}^{/(2\mathcal{Y} + \mathcal{a})}_{\mathcal{Y}} = \mathcal{Y}
\]

\[
\begin{pmatrix}
0 & 0 & \cdots & 0 & 1 \\
\vdots & \ddots & \ddots & \ddots & \vdots \\
0 & \cdots & -I & \cdots & 0 \\
\vdots & \ddots & \ddots & \ddots & \vdots \\
0 & 0 & \cdots & 0 & 1 & 0 & 0 \\
0 & 0 & \cdots & 0 & 0 & 1 & 0
\end{pmatrix}
\]

Unitary transformation and its eigenvalues

Recurrent with periodicity \( N \)

Total number of states: \( 2^N \)

Prelude – Kac’s Ring Dynamics
Each step, \( q \) balls change from white to black, \( \gamma - \lambda \) balls change from black to white.

\[
\begin{align*}
\dot{(q)} \gamma (\gamma \gamma - 1) (0) \gamma &= (q) \gamma \\
(q) \gamma (\gamma \gamma - 1) &= [(q)m - (q)q] \gamma - (q) \gamma = (1 + q) \gamma
\end{align*}
\]

Existential Kinetics

\[
q = \frac{N}{\alpha} = \frac{(q) \Lambda}{(q)m} = \frac{(q)B}{(q)q}
\]

Stochastic:

\[
\begin{align*}
:\&(q) \Lambda - (q)B \equiv (q) \gamma \\
\# \text{ the of white balls in front of a marker at time } t,
\# \text{ the of black balls in front of a marker at time } t
\end{align*}
\]
Coarse-graining and Chaos (Noves Resolution)

Average over time (Boltzmann Ergodicity)

Average over random initial conditions (Gibbs Mixing)

(Thermodynamic Limit) \( N \to \infty \)

Inverisible behavior and monotonic

\( \mathcal{N} \mathcal{V} = \left\langle \mathcal{Z} \mathcal{V} \right\rangle \quad 0 = \left\langle \mathcal{V} \right\rangle \)

Mean and Variance of

\( (\mathcal{Z} - \mathcal{V}) \mathcal{Z} = \mathcal{V} \mathcal{P} \)

Probability \( \mathcal{P} \)
Epilogue – Dissipation, Irreversibility, and Vanishing Viscosity

Theorems and Techniques in Statistical Mechanics

Hamiltonian Formulation of 2-D Euler Equation

(0 = \lambda = \mu)

Vorticity Conservation and Entropy Conservation

Euler’s Equation, and Vorticity

Two-Dimensional Turbulence – Navier–Stokes Equation, Euler

Gibbsian Statistical Mechanics at Constant Temperature

\textit{r}-Space, \textit{r}-Space, Liouville Equation, and Entropy

Prelude – M. Kac’s Ring and Its Dynamics

Outline
\[
\left[ (n^3 d) \frac{\mathcal{H} \varepsilon}{\varepsilon} + (n^3 b) \frac{\mathcal{H} \varepsilon}{\varepsilon} \right] \mathcal{N} = \mathcal{H} \varepsilon \\
0 = \mathcal{H} \varepsilon / (\mathcal{H} \mathcal{P})
\]

\[
((\mathcal{H} d, (\mathcal{H} b)) \mathcal{H} = (\mathcal{H} \mathcal{P})
\]

\[
\begin{align*}
\mathcal{H} d \varepsilon / \mathcal{H} \varepsilon &= \mathcal{H} b \\
\mathcal{H} b \varepsilon / \mathcal{H} \varepsilon &= \mathcal{H} d
\end{align*}
\]

Hamiltonian Equation (a system of ODEs)

Hamiltonian Dynamics: \( (d, b) \mathcal{H} = (N d, N b, \ldots, d, b) \mathcal{H} \)
Boltzmann's Statistical Mechanics for Ideal Gas

The joint distribution of initial and final states is called the phase space:

\[ N(d', b) = (d', b) \]

is called the phase space:

\[ 0 = \ell \rho / (\ell) S \rho \]

\[ dp b \rho (\ell', d', b) n \log (\ell', d', b) n \int = (\ell) S \]

Gibbs Entropy Conservation

\[ 0 = \ell \rho / (\ell) d \rho \]

\[ (\ell', (\ell) d', (\ell) b) n = (\ell) d \]

Phase Space Volume Conservation

\[
\left[ \frac{\gamma d \rho}{n \rho} \frac{\gamma b \rho}{H \rho} - \frac{\gamma b \rho}{n \rho} \frac{\gamma d \rho}{H \rho} \right] \nabla^2 = 0
\]
With the Stosszahlansatz, Boltzmann entropy increases without the collision term \( f = 0 \).

Without the collision term, \( 0 < \frac{\mathcal{H}}{\mathcal{H}} \).

\[
\int \int \mathcal{H} = (\mathcal{H}) \mathcal{H}
\]

Boltzmann's function \( \mathcal{H} \) is

\[
((\mathcal{H} \mathcal{H})(\mathcal{H} \mathcal{H})) = (\mathcal{H} \mathcal{H}) = (\mathcal{H})(\mathcal{H}) = (\mathcal{H})
\]

\[
\int \int \mathcal{H} = (\mathcal{H}) \mathcal{H}
\]

Boltzmann's Equation
\[
\cdot (\mathcal{H}^L \Delta L^B y + \mathcal{H} \Delta \omega) \cdot \Delta \frac{\omega}{u} + (\tau, \Lambda, x) \mathcal{H}^x \Delta \cdot \Lambda - \approx \frac{\mathcal{C}}{(\tau, \Lambda, x) \mathcal{H}} \mathcal{C}
\]

Maxwell distribution

\[
\Rightarrow
\]

each

BBCKY (Born, Bogoliubov, Green, Kirkwood, Yvon) hier-
\[ \mathcal{H} \frac{\Delta^m}{\mathcal{L}^m} + [\mathcal{H}(\mathbf{X} - \Lambda \mu)] \cdot \Delta^m \mathcal{I} + \mathcal{H}^x \Delta \cdot \Lambda - = \frac{\mathcal{I}}{\tau, \Lambda} \mathcal{H} \mathcal{O} \]

In terms of distribution

\[ (\tau) f + \Lambda \mu - \mathbf{X} = \Lambda \mu \]

\[ \Lambda = \mathbf{x} \]

equation (SDE)

A system at constant temperature with stochastic differential

universal

system of physical interest is really isolated from the rest of the
system caused by its environment or some other source (no
interchange and not necessarily an isolated system is
the foundations for statistical mechanics of an isolated system is

(M. Kac) It may be that the ergodic approach to develop

Gibbsian Statistical Mechanics
\[ \text{Equilibrium distribution} \]
\[ 0 = \text{viscous forces} \int \int \frac{\nabla \cdot \mathbf{v}}{\rho} \]

0 = \text{u (or mean)} vorticity when \text{vorticity}

\[ \mathbf{u} + (\mathbf{\zeta} \cdot \mathbf{\omega}) - \mathbf{\zeta} \cdot \mathbf{\omega} = \mathbf{u} + \mathbf{\zeta} \cdot \mathbf{\omega} - \mathbf{\zeta} \cdot \mathbf{\omega} = \mathbf{\zeta} \cdot \mathbf{\omega} \]

\text{Equation for Vorticity}

\[ \mathbf{\phi} \cdot \mathbf{\zeta} = \mathbf{\zeta} \cdot \mathbf{\omega} = \mathbf{\zeta} \cdot \mathbf{\omega} \]

\text{Hodge-Decomposition of Vorticity and Vorticity}

\[ \mathbf{\phi} \cdot \mathbf{\zeta} \cdot \mathbf{\omega} + \mathbf{d} \cdot \mathbf{\omega} = \mathbf{\zeta} \cdot \mathbf{\omega} + \mathbf{\zeta} \cdot \mathbf{\omega} \]

\text{Navier-Stokes Equation:}

\text{Two-Dimensional Turbulence}
Conservation of total (or mean) enstrophy when \( \eta = \nu = 0 \)

\[
\frac{d}{dt} \int \int 2 \zeta^2 \, dx \, dy = 0
\]

Rewrite the Equation for Vorticity with \( \eta = \nu = 0 \)

\[
\partial_t \zeta = -\left( \partial_y \psi \right) \left( \partial_x \zeta \right) + \left( \partial_x \psi \right) \left( \partial_y \zeta \right)
\]

Consider \( N \) point vorticities

\[
\zeta(x, y, t) = \sum_{k=1}^{N} c_k \delta(r - r_k(t))
\]

Since \( \nabla^2 \psi = -\zeta \), by Green's function

\[
\psi(r) = -\int \frac{1}{2\pi} \int \frac{1}{\log |r - r'|} \zeta(r') \, dr' = \sum_{k=1}^{N} c_k \log |r - r_k|.
\]
Logarithmic interaction potential.

The $N$ point vortices follow a Hamiltonian dynamics with

$$\left| c_i \lambda - \lambda \right| \log c_i \lambda \mathcal{Z} \sum_{i=1}^{N} \frac{\nu}{1} = (N \lambda \cdots \lambda, \lambda) \mathcal{H}$$

with

$$\frac{\forall x \in \forall y \in \theta e}{\forall y \in \forall x \in \theta e} - \frac{\forall y \in \forall x \in \theta e}{\forall y \in \forall x \in \theta e} \sum_{N=1}^{\gamma} = \frac{\forall \theta}{\forall e}$$

then

$$(\forall \lambda \cdots \lambda, \lambda) \Theta (\forall \lambda - \lambda) \mathcal{Z} \sum_{N}^{\gamma} N \lambda p \cdots \lambda p \int \cdots \int = (\forall \lambda, \lambda)$$

Let
The Fundamental Question (U. Frisch)
\[ \begin{aligned}
\mu \gamma b + \frac{\gamma x \theta}{H \theta} &= \frac{\gamma p}{\gamma \theta} \\
\mu \gamma f + \frac{\gamma h \theta}{H \theta} &= \frac{\gamma p}{\gamma \theta}
\end{aligned} \]

which is equivalent to SDE:

\[ \left\{ \left( \frac{\gamma x \theta}{H \theta} \right) \frac{\gamma h \theta}{\theta} + \left( \frac{\gamma h \theta}{H \theta} \right) \frac{\gamma x \theta}{\theta} \right\}^{\frac{1}{\gamma}} = \frac{\gamma \theta}{(\mu, \mu', \mu''; 1, I, t', \cdots, I, I, \cdots)^{\Phi}} \]

is consistent with the following PDE:

\[ (\gamma \theta)(\gamma x \theta) + (\gamma x \theta)(\gamma h \theta) - (\gamma h \theta + \gamma x \theta) \mu = \gamma \frac{\theta}{\phi} \]

Vorticity form of Navier-Stokes Equation:

![A Bold Conjecture (H. Qian, November 2000)](image_url)
\[ \phi + \frac{\gamma}{2} \left( \frac{A_1}{\sin A_1 + C} + \frac{C_1}{\sin A_1 - C} \right) = \phi \]

\[ \cdot \left( 1 + \frac{A_1}{\sin A_1 + C} \right) = \phi \left( 1, x/2 \right) \]

\[ \cdot \left( 1 + \frac{C_1}{\sin A_1 - C} \right) = \phi \left( 1, x/2 \right) \]

\[ \cdot \left( 1 + \frac{A_1}{\sin A_1 + C} \right) = \phi \left( x/2 \right) \]

\[ \cdot \left( 1 + \frac{C_1}{\sin A_1 - C} \right) = \phi \left( x/2 \right) \]

\[ \cdot \left( 1 + \frac{A_1}{\sin A_1 + C} \right) = \phi \left( C_1 x \right) \]

\[ \cdot \left( 1 + \frac{C_1}{\sin A_1 - C} \right) = \phi \left( C_1 x \right) \]

Two Vortices

Hamiltonian Dynamics of Point Vortices
\[
\begin{align*}
\log \frac{2^\gamma}{2\gamma} & = \langle \langle \gamma, \gamma \rangle \rangle \\
\frac{2^\gamma}{2\gamma} & = (\langle \gamma, \gamma \rangle) H
\end{align*}
\]


\(\gamma \neq 2\).

The motion is a rigid rotation \((C_1 - C_2)\).

\(\langle \gamma, \gamma \rangle \) the

The motion has a constant center \((C, B)\), and the distance

\[V = \frac{1}{\gamma} \langle \gamma, \gamma \rangle + \frac{1}{\gamma} \langle \gamma, \gamma \rangle\]

\[C, B = \gamma (\gamma, \gamma) + \gamma (\gamma, \gamma)\]

Constants of Motion
where \( \phi \) is the orientation of the triangle spanned by the edge \( \mathbf{A} \) and \( \mathbf{B} \), and \( v = m/\mu \). When \( \mathbf{A} \neq 0 \), the three-vortices problem has trajectories.

The center of the three vortices is a constant of motion. The center of the three vortices, which is a function of the area of the triangle, is defined as for counterclockwise and \(+1\) for clockwise.

\[
\begin{align*}
\frac{c_3 + c_2}{c_1 + c_2} + \frac{c_3 + c_1}{c_1 + c_2} + \frac{c_3 + c_2}{c_1 + c_2}
\end{align*}
\]

Introducing
Theorem (M. Qian & Y.-F. Jiang, 1983)

The equilateral solution when the three vortices are collinear. Then if $c_1 + c_2 \neq 0$, then $c_3$ has a unique, stable periodic orbit.

If $c_1 > 0$, $c_1 + c_2 > 0$, then $c_3$ is nonsingular.

Restricted Three Vortices

\[ \forall \{0, 1, 2, \ldots, n\} = \mathcal{D} \] is a compact domain which is bounded by $\partial \mathcal{D}$

\[ (n - m)\overline{1} = \frac{\mathcal{L} \partial}{\mathcal{L} \partial} \] (similar to)

\[ (n - m)\overline{2} = \frac{\mathcal{L} \partial}{\mathcal{L} \partial} \] (similar to)

\[ (m - n)\overline{3} = \frac{\mathcal{L} \partial}{\mathcal{L} \partial} \] (similar to)
triangle is a unstable configuration. If $c_1c_2 > 0$, then it has infinite number of periodic and quasi-periodic solutions.
\[ \Lambda p x p^{b e} d \in b e d \int p y_1 = S \Lambda p x p (\Lambda x)^{b e} d (\Lambda x) e \int = e \]

where \( S L - e = A \)

\[ \Lambda p x p_{L y} / e \int p y_1 = \Lambda Z \int p y_1 = \Lambda A \]

where: \( p y_1 / e \int \Lambda Z = \Lambda e \)

\( (\Lambda x)^{b e} d = (\Lambda x)^{b e} d \)

to its energy: \( \Lambda e \in \int p y_1 / e \int \Lambda Z = \Lambda e \)

Boltzmann's law: the probability of a configuration is related to its free energy of a macroscopic state, \( \Lambda \), is related to its free energy and its probabilistic interpretation. From Eq. (1)

Free Energy, Probabilistic, and Thermodynamic Equilibrium
Coarse-Graining Invariance of Free Energy
\[
\begin{align*}
\forall \theta \in \mathcal{A}, \quad \forall \mathcal{G} - \mathcal{E} = n, \\
\forall \mathcal{G} - \mathcal{E} = m
\end{align*}
\]

\text{where}

\[
\begin{array}{c|c}
\mathcal{G} & \mathcal{E} \\
\hline
\mathcal{G} & \mathcal{E} \\
\hline
\mathcal{G} & \mathcal{E} \\
\hline
\mathcal{G} & \mathcal{E}
\end{array}
\]

\text{Transfer Matrix Method (E. Montroll, 1941)}

\{s\} all possible

\[
(\{s\}) \mathcal{B} \mathcal{G} - \mathcal{E} \quad \bigotimes \quad = (\mathcal{G}) \mathcal{N} \mathcal{G}
\]

\text{Partition function}

\[
(1 + \{s\}) \bigotimes_{N} \frac{2}{\mathcal{G}} + \{s\} \bigotimes_{I-N} I = (\{s\}) \mathcal{B}
\]

\text{Energy for N spins}

\text{Statistical Mechanics of 1-D Ising Model}
\[ \max \chi = \{ \chi, \chi \} \text{max} = N \mathcal{O} \log \frac{N}{1} \lim_{N \to \infty} \]

\[ \left( \begin{array}{c} \chi \\mathcal{O} + \chi \\mathcal{O} \\ \chi \\mathcal{O} + \chi \\mathcal{O} \end{array} \right) \left( \begin{array}{cc} m & m/n \\ m/n & m/n \end{array} \right) = N \mathcal{O} \]

The partition function can be computed

\[ \frac{\chi}{n} + \varepsilon(n - 1) \chi \leq (n + 1) \frac{\chi}{n} = \varepsilon \chi \]

and eigenvalues
\[
\left( \begin{array}{c}
\frac{\mathcal{Z}^m + \alpha}{I + \mathcal{Z}^m \alpha} \\
\frac{\mathcal{Z}^m}{I} 
\end{array} \right) = \left( \begin{array}{c}
( - | - ) \mathcal{d} \\
( + | - ) \mathcal{d} 
\end{array} \right)
\]

Markov Representation and Correlation Function

\[
\left\{ \begin{array}{l}
0 > \alpha A' \infty \leftarrow m \\
0 < \alpha A' \infty \leftarrow m \\
\alpha A' I = m \\
\mathcal{M} A' I = \alpha \\
\end{array} \right\} = + \mathcal{d}
\]

\[
\frac{\alpha / \mathcal{V} + \mathcal{V} m_{\mathcal{Z}}(\alpha / I - I) \land \mathcal{Z} m(\alpha / I + I) + \alpha / \mathcal{V} + \mathcal{V} m_{\mathcal{Z}}(\alpha / I - I)}{\alpha / \mathcal{V} + \mathcal{V} m_{\mathcal{Z}}(\alpha / I - I) \land \alpha / \mathcal{Z} m + \alpha / \mathcal{Z} + \mathcal{V} m(\alpha / I - \mathcal{Z} \alpha / I)} = + \mathcal{d} - I
\]

\[
\frac{\alpha \mathcal{V} + \mathcal{V} m_{\mathcal{Z}}(\alpha - I) \land \mathcal{Z} m(\alpha + I) + \alpha \mathcal{V} + \mathcal{V} m_{\mathcal{Z}}(\alpha - I)}{\alpha \mathcal{V} + \mathcal{V} m_{\mathcal{Z}}(\alpha - I) \land \mathcal{Z} m + \alpha \mathcal{Z} + \mathcal{V} m(\alpha - \mathcal{Z} \alpha)}
\]
\[
\left( \begin{array}{cc} 1 & -1 \\ 1 & 1 \end{array} \right) \mathcal{L} \left( \begin{array}{cc} (-|-)d & (-|+)d \\ (+|-)d & (+|+)d \end{array} \right) \left( \begin{array}{cc} -d & 0 \\ 0 & +d \end{array} \right) (I - 'I) = \langle \mathcal{f} + \mathcal{s} + \mathcal{s} \rangle
\]
Theorem I

\[ \left( \eta', \Lambda \right) \hat{\mathcal{O}} \]

The analyticity of partition function

\[ \frac{\eta \log \Lambda}{(\eta', \Lambda) \hat{\mathcal{O}}} \hat{\mathcal{O}} \bigg| \log \left( \frac{\Lambda}{\eta} \right) \Lambda \bigg| \lim_{\eta \to \infty} = \frac{\mathcal{J} \mathcal{B} \mathcal{G}}{d} \]

The thermodynamic density

\[ \left( \eta', \Lambda \right) \hat{\mathcal{O}} \bigg| \log \left( \frac{\Lambda}{\eta} \right) \Lambda \bigg| \lim_{\eta \to \infty} = \frac{\mathcal{J} \mathcal{B} \mathcal{G}}{d} \]

The thermodynamic pressure

\[ \mathcal{J} \mathcal{B} \mathcal{G}/\eta N \sum_{N}^{i=1} \mathcal{J} \mathcal{B} \mathcal{G} = \left( \eta', \Lambda \right) \hat{\mathcal{O}} \]

The Grand Partition Function for an Open System

\[ \left( \text{C.N. Yang} \& \text{T.D. Lee}, 1952 \right) \]

Partition Function and Phase Transition
If in the complex plane a region $\mathcal{R}$ containing a segment of the positive real axis is always free of roots, then in this region

\[ \left( \frac{\dot{\gamma}}{\gamma} - 1 \right) \prod_{x_{\text{max}}=1}^{N} \mathcal{C} = \mathcal{O} \]

Theorem 2

nonreal are positive.

can be real and positive since all the coefficients in the polynomials are only

where $\gamma$ are the roots of the polynomial. None of the roots

\[ \mathcal{C} = \prod_{x_{\text{max}}=1}^{N} (\dot{\gamma}/\gamma) \]

Let $\gamma = \frac{\dot{\gamma}}{\gamma}$, called regularity (activity), then $\mathcal{O}$ is a poly-

omial in $\gamma$ of finite degree, hence the following is possible:

\[ \lim_{n \to \infty} \mathcal{O} - \Lambda \]

Furthermore, this limit is a continuous, monotonic, increasing function of the shape of $\Lambda$. Furthermore, for all real value of $\frac{\dot{\gamma}}{\gamma}$ as $\Lambda$ approaches $\mathcal{O}$, $\log_{1-\Lambda} \dot{\gamma}$
Phase Transition

The quantity \( \frac{1}{V} \frac{\partial}{\partial \mu} (\theta \log Q) \) does not, however, always approach a limit \( \rho \) for all values of \( y \). For some systems, when \( V \to \infty \), the roots of the polynomial approach to the real axis, say, \( y_1^*, y_2^* \). In this case, there are three phases. At \( y = y_1^*, y_2^* \), the pressure is continuous (by theorem 1), but its derivative \( \rho \) has in general a discontinuity. It can be shown that \( \rho \) increases across the discontinuity. The order of a phase transition is defined by the order of the discontinuity.

Furthermore, the limits which are analytic with respect to \( y \):
where \( C \) is a normalization constant depending on \( n, u, \) and \( \beta \) is \( z = 2 \). (1) 

\[
\left( \frac{2\beta}{\sqrt{z}} \right)^i \sum \frac{f_x}{f} + \sum |f_x - \hat{f}_x| \in \sum \frac{f}{f} = (u_1, \ldots, u_n) M
\]

where

\[
u u_1 \cdots u_n M \mathcal{G} - \mathcal{E} \mathcal{C} = u_1 \cdots u_n (u_1, \ldots, u_n) M
\]

each of the small intervals are [\( [x, x] \)] is \( 1 + 2 \), then probability for finding an eigenvalue within \( \mathcal{G} \) is \( 1 + \mathcal{G} \), \( \mathcal{G} = \frac{2\sqrt{z}}{\beta} \), \( \mathcal{G} = \frac{2\sqrt{z}}{\beta} \).

If \( M \) is a Hermitian matrix whose elements were chosen at ran-

\[ \text{Theorem 1} \]

P.J. Dyson, 1962

Random Matrices and Their Eigenvalues
Starting from any initial condition whatever, its eigenvalues

\[
\left( f^L W \right)^{\mathcal{L}} \frac{\mathcal{L} W \mathcal{L}^T}{\mathcal{E}} \frac{\partial u}{\partial t} + \frac{\mathcal{L} W \mathcal{L}^T}{\mathcal{E}} \frac{\partial u}{\partial t} = \mathcal{L} \mathbf{u} = \mathbf{0}
\]

is the simple harmonic law
to the simple independent Brownian motion according

\[
N > N > I \quad \mathcal{W}
\]

When a matrix \( \mathcal{W} \) with all its elements \( \mathcal{W} \) is invertible, \( \mathcal{W} \)

Theorem 2

on \( \mathbb{R}^n \) with no flux boundary condition.

(2)

\[
\left( \frac{\partial^2}{\partial x^2} \mathcal{L} \right)^{\mathcal{L}} \frac{\mathcal{L} \mathcal{L}^T}{\mathcal{E}} u + \frac{\mathcal{L} \mathcal{L}^T}{\mathcal{E}} \frac{\partial u}{\partial t} = \mathcal{L} \mathbf{u} = \mathbf{0}
\]

Using the theorem on random matrix to solve the diffusion

equation
of motion (2) of the time-dependent Coulomb gas. Execute a Brownian motion obeying the equation $I^x \cdots I^x u^x \cdots$
The Kac ring model.
0.045\cdot \exp(-x^2/2/800)”