Ecological collapse and the phase transition to turbulence

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SCALING LAWS FOR ISING MODELS NEAR $T_c$*

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Abstract

A model for describing the behavior of Ising models very near $T_c$ is introduced. The description is based upon dividing the Ising model into cells which are microscopically large but much smaller than the coherence length and then using the total magnetization within each cell as a collective variable. The resulting calculation serves as a partial justification for Widom's conjecture about the homogeneity of the free energy and at the same time gives his result $sv' = \gamma' + 2\beta$. 
How was critical phenomena solved?

- Common features
  - Strong fluctuations
  - Power law correlations

- Can we solve turbulence by following critical phenomena?
- Does turbulence exhibit critical phenomena at its onset?

- Ben Widom discovered “data collapse” (1963)
- Leo Kadanoff explained data collapse, with scaling concepts (1966)
- Ken Wilson developed the RG based on Kadanoff’s scaling ideas (1970)
“EXPLORING IS BORING”

-NO FURRY THREE-YEAR OLD EVER
Transitional turbulence: puffs

- Reynolds’ originally pipe turbulence (1883) reports on the transition

“Flashes” of turbulence:
Deterministic classical mechanics of many particles in a box ➔ statistical mechanics
Deterministic classical mechanics of infinite number of particles in a box

= Navier-Stokes equations for a fluid

⇒ statistical mechanics
Deterministic classical mechanics of infinite number of particles in a box

= Navier-Stokes equations for a fluid

⇒ statistical mechanics
Turbulence is stochastic and wildly fluctuating

Soap film experiment

Turbulence generates structure at many scales

Soap film experiment

Scale invariance in turbulence

- Eddies spin off other eddies in a Hamiltonian process.
  - Does not involve friction!
  - Hypothesis due to Richardson, Kolmogorov, ...
- Implication: viscosity will not enter into the equations
Scale invariance in turbulence

- Compute $E(k)$, turbulent kinetic energy in wave number range $k$ to $k+dk$
  - $E(k)$ depends on $k$
  - $E(k)$ will depend on the rate at which energy is transferred between scales: $\varepsilon$

- Dimensional analysis:
  - $E(k) \sim \varepsilon^{2/3} k^{-5/3}$

A.N. Kolmogorov
The energy spectrum

\[ E(k) = \frac{1}{2} \frac{d(u_k^2)}{dk} \]

Integral scale

Inertial range

Dissipation
Pipe flow

\[ \text{Re} \equiv \frac{VR}{\nu} \quad \text{Roughness} \equiv \frac{r}{R} \quad \text{Friction Factor}, f \equiv \frac{\tau}{\rho V^2} \]

\( \text{Re} = \text{Reynolds number} \quad \nu = \text{viscosity/density} = \text{kinematic} \)
Pipe flow

\[ Re \equiv \frac{VR}{\nu} \]

Roughness \( \equiv \frac{r}{R} \)

Friction Factor, \( f \equiv \frac{\tau}{\rho V^2} \)

\( Re = \) Reynolds number \( \nu = \) viscosity/density = kinematic
Q. What is the universality class of the transition to turbulence?
Transitional turbulence: puffs

- Reynolds’ originally pipe turbulence (1883) reports on the transition

“Flashes” of turbulence:
Precision measurement of turbulent transition

Q: will a puff survive to the end of the pipe?

Many repetitions $\Rightarrow$ survival probability $P(Re, t)$
Phase diagram of pipe flow

Single puff spontaneously decays

Laminar

Metastable puffs

Spatiotemporal intermittency

Expanding slugs

\( \text{Survival probability } P(\text{Re}, t) = e^{-\frac{t-t_0}{\tau(\text{Re})}} \)

Avila et al., Science 333, 192 (2011)

Hof et al., PRL 101, 214501 (2008)

Decaying Turbulence:
- Injection (L = 3380)
- Hof et al. (2008)
- Kuik et al. (2010)
- Avila et al. (2010)

Spreading Turbulence:
- Injection
- Obstacle
- DNS 1
- DNS 2

\( \tau \sim \exp(\exp \text{Re}) \)

Avila et al., (2009)
Phase diagram of pipe flow

Single puff spontaneously decays

<table>
<thead>
<tr>
<th>laminar</th>
<th>metastable puffs</th>
<th>spatiotemporal intermittency</th>
<th>expanding slugs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Re = 1775</td>
<td>2100</td>
<td>2500</td>
<td></td>
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</tbody>
</table>

Survival probability \( 1 - P(\text{Re}, t) = e^{-\frac{t-t_0}{\tau(\text{Re})}} \)

Avila et al., Science 333, 192 (2011)
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Decaying Turbulence:
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- DNS 2

Puff lifetime

Mean time between split events

\[ \begin{align*}
\text{Survival probability:} & \quad 1 - P(\text{Re}, t) = e^{-\frac{t-t_0}{\tau(\text{Re})}} \\
\text{Decaying Turbulence:} & \quad \text{Injection (L = 3380)} \quad \text{Hof et al. (2008)} \quad \text{Kuik et al. (2010)} \quad \text{Avila et al. (2010)} \\
\text{Spreading Turbulence:} & \quad \text{Injection} \quad \text{Obstacle} \quad \text{DNS 1} \quad \text{DNS 2}
\end{align*} \]
Phase diagram of pipe flow

Single puff spontaneously decays

laminar

metastable puffs

spatiotemporal intermittency

expanding slugs

Re

1775

2100

2500

Survival probability $1 - P(\text{Re}, t) = e^{-\frac{t-t_0}{\tau(\text{Re})}}$


Song et al., *J. Stat. Mech.* 2014(2), P020010

Puff lifetime

Mean time between split events

Puff lifetime vs. Re

Survival probability vs. t

1 - P vs. t(D/U)

Puff lifetime vs. ln(\ln(\tau))
Phase diagram of pipe flow

Single puff spontaneously decays

laminar metastable spatiotemporal expanding

Super-exponential scaling:

$$\frac{\tau}{\tau_0} \sim \exp(\exp \text{Re})$$


Puff lifetime

Mean time between split events
MODEL FOR METASTABLE TURBULENT PUFFS

Re

laminar

metastable puffs

spatiotemporal intermittency

expanding slugs

Re

1775

2100

2500
DP & the laminar-turbulent transition

- Turbulent regions can spontaneously relaminarize (go into an absorbing state).
- They can also contaminate their neighbourhood with turbulence. (Pomeau 1986)
Directed Percolation Transition

- A continuous phase transition occurs at $p_c$.

Hinrichsen (Adv. in Physics 2000)

- Phase transition characterized by universal exponents:

$$\rho \sim (p - p_c)^\beta \quad \xi_\perp \sim (p - p_c)^{-\nu_\perp} \quad \xi_\parallel \sim (p - p_c)^{-\nu_\parallel}$$

\[\text{to DP models}\]
DP in 3 + 1 dimensions in pipe

Puff decay

Slug spreading

Sipos and Goldenfeld, *PRE* 84, 035304(R) (2011)
Turbulent transients: Puffs

- We can measure the survival probability of active DP regions, like Hof et al. did in pipe experiments:

\[
P(\text{Re}, t) = e^{-\frac{t-t_0}{\tau(\text{Re})}}
\]

Hof et al. (PRL 2008)

Sipos and Goldenfeld, *PRE* 84, 035304(R) (2011)
Turbulent transients: Puffs

- The lifetime $\tau$ fits a super-exponential scaling

$$\frac{\tau}{\tau_0} \sim \exp(\exp \text{Re})$$

---

Hof et al. (PRL 2008)

M. Sipos and NG, *PRE* 84, 035304(R) (2011)
Super-exponential scaling and extreme statistics

• Active state persists until the most long-lived percolating “strands” decay.
  – extreme value statistics

• Why do we not observe the power law divergence of lifetime of DP near transition?

• Close to transition, transverse correlation length diverges, so initial seeds are not independent
  – Crossover to single seed behaviour
  – Asymptotically will see the power law behavior in principle

\[ \xi_\perp \sim (p - p_c)^{-\nu_\perp} \]
MODEL FOR SPATIOTEMPORAL INTERMITTENCY

Very complex behavior and we need to understand precisely what happens at the transition, and where the DP universality class comes from.
Logic of modeling phase transitions

Magnets

Electronic structure

Ising model

Landau theory

RG universality class
Logic of modeling phase transitions

Magnets
- Electronic structure
  - Ising model
  - Landau theory
  - RG universality class

Turbulence
- Kinetic theory
  - Navier-Stokes eqn
  - ?
  - ?
Logic of modeling phase transitions

**Magnets**
- Electronic structure
  - Ising model
  - Landau theory
  - RG universality class

**Turbulence**
- Kinetic theory
  - Navier-Stokes eqn

Red arrows indicate possible connections or correspondences between concepts.
Identification of collective modes at the laminar-turbulent transition

To avoid technical approximations, we use DNS of Navier-Stokes
Observation of predator-prey oscillations in numerical simulation of pipe flow

Simulation based on the open source code by Ashley Willis: openpipeflow.org
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Disney
Winnie The Pooh
Winnie The Pooh AND THE BLUSTERY DAY
Based on A.A. Milne’s Classic Tales
What drives the zonal flow?

• Interaction in two fluid model
  – Turbulence, small-scale \((k>0)\)
  – Zonal flow, large-scale \((k=0,m=0)\): induced by turbulence and creates shear to suppress turbulence

1) Anisotropy of turbulence creates Reynolds stress which generates the mean velocity in azimuthal direction

\[ \frac{\partial}{\partial t} \langle u_\theta \rangle = -\frac{\partial}{\partial r} \langle (\tilde{u}_\theta \cdot \tilde{v}_r) \rangle - \mu \langle v_\theta \rangle \]

2) Mean strain shear decreases the anisotropy of turbulence and thus suppress turbulence
What drives the zonal flow?

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2) Mean strain shear decreases the anisotropy of turbulence and thus suppress turbulence
Normal population cycles in a predator-prey system

\[ \theta \approx \pi/2 \]

\( \pi/2 \) phase shift between prey and predator population

Persistent oscillations + Fluctuations

https://interstices.info/jcms/n_49876/des-especies-en-nombre
Q. What is the universality class of the transition to turbulence?

Tentative answer: directed percolation ... but why?
Strategy: transitional turbulence to directed percolation

Directed Percolation

Reggeon field theory (Janssen, 1981)

Field Theory

Two-fluid model

(Classical) Turbulence

Predator-Prey

Extinction transition (Mobilia et al., 2007)

(Wikimedia Commons)

(Pearson Education, Inc., 2009)

(Boffetta and Ecke, 2012)
Introduction to stochastic predator-prey systems
Prey consumes resource and grows
Cartoon picture for normal cycles ($\pi/2$ phase shift)

- **Prey** consumes resource and grows
- **Predator** eats prey and grows

Diagram showing the flow of resource to prey to predator, with population over time.
Prey decreases due to predation by predator

Cartoon picture for normal cycles ($\pi/2$ phase shift)
Cartoon picture for normal cycles ($\pi/2$ phase shift)

Resource → Prey → Predator

(3) Predator decreases due to lack of prey
Cartoon picture for normal cycles ($\pi/2$ phase shift)

Prey increases because of lower predation pressure
Cartoon picture for normal cycles ($\pi/2$ phase shift)

Resource → Prey → Predator

Predator increases again due to increasing prey

(5)
Cartoon picture for normal cycles ($\pi/2$ phase shift)

![Diagram showing interactions between resource, prey, and predator with population and time axes](image)

- Resource → Prey → Predator

Population vs. Time graph showing oscillations.
Cartoon picture for normal cycles ($\pi/2$ phase shift)

- Resource → Prey → Predator

**Predator** can only start to grow after **prey** grows and before **prey** declines

Phase shift is a quarter period

$\theta = \pi/2$
Models for predator-prey ecosystem

- Deterministic models

Lotka-Volterra equations

Satiation model (Holling type II function)

θ ≈ π/2

No persistent oscillations

No fluctuations
Models for predator-prey ecosystem

- Deterministic models
  - Lotka-Volterra equations
    - No persistent oscillations
  - Satiation model (Holling type II function)
    - \( \theta \approx \pi/2 \)
    - No fluctuations

- Stochastic individual level model
  - Fluctuations in number → demographic stochasticity that induces quasi-cycles

Models for predator-prey ecosystem

- Deterministic models
  - Lotka-Volterra equations
  - Satiation model (Holling type II function)

- Stochastic models
  - Fluctuations in number → demographic stochasticity that induces quasi-cycles
    - Quasicycles emerge from intrinsic demographic stochasticity

Individual-level stochastic model of predator-prey dynamics

\[ A \xrightarrow{d_1} E \]  \hspace{1cm} \text{Predators}

\[ B \xrightarrow{d_2} E \]  \hspace{1cm} \text{Prey}

\[ BE \xrightarrow{b} BB \]

\[ AB \xrightarrow{p_1} AA \]

\[ AB \xrightarrow{p_2} AE \]

Extinction/decay statistics for stochastic predator-prey systems
Derivation of predator-prey equations

Zonal flow-turbulence

Predictor/Zonal flow

Prey/Turbulence

Predator-prey

\[ B + E \xrightarrow{b} B + B \]
\[ B + B \xrightarrow{c} B + E \]
\[ A + B \xrightarrow{p} A + A \]
\[ A + B \xrightarrow{p'} A + E \]
\[ B \xrightarrow{m} A \]
\[ A \xrightarrow{d_A} E \]
\[ B \xrightarrow{d_B} E \]
Survival probability near extinction

• Decay of population is a memoryless process
  – Extract lifetime in both decay and splitting modes

• Log-linear plot of lifetime shows curvature
  – superexponential dependence on prey birth rate
Ecology = turbulence = DP

Shih, Hsieh, NG (2015)

Hof et al., PRL 101, 214501 (2008)

Sipos and Goldenfeld, PRE 84, 035304(R) (2011)
Universality class of the transition
Strategy: transitional turbulence to directed percolation

Field Theory

Directed Percolation

Reggeon field theory (Janssen, 1981)

(Classical) Turbulence

Two-fluid model

Predator-Prey

Extinction transition (Mobilia et al., 2007)

(Boffetta and Ecke, 2012)

(Wikimedia Commons)

(Pearson Education, Inc., 2009)
Universality class of predator-prey system near extinction

Basic individual processes in predator (A) and prey (B) system:

Death
\[ B_i \xrightarrow{d_B} E_i \quad A_i \xrightarrow{d_A} E_i \quad B_i \xrightarrow{m} A_i \]

Birth
\[ B_i + E_j \xrightarrow{b} B_i + B_j \quad A_i + B_j \xrightarrow{p} A_i + A_j \]

Diffusion
\[ B_i + E_j \xrightarrow{D} E_i + B_j \quad A_i + E_j \xrightarrow{D} E_i + A_j \]

Carrying capacity
\[ B_i + B_j \xrightarrow{c} B_i + E_j \]
Universality class of predator-prey system near extinction

Near the transition to prey extinction, the prey (B) population is very small and no predator (A) can survive; A ~ 0.

Death

\[ B_i \xrightarrow{d_B} E_i \]

\[ A_i \xrightarrow{d} E_i \]

\[ B_i \xrightarrow{m} A_i \]

Birth

\[ B_i + E_j \xrightarrow{b_{ij}} B_i + B_j \]

\[ A_i + B_j \xrightarrow{p_{ij}} A_i + A_j \]

\[ A_i + E_j \xrightarrow{p_{ij}} E_i + A_j \]

Diffusion

\[ B_i + E_j \xrightarrow{D_{ij}} E_i + B_j \]

\[ A_i + E_j \xrightarrow{D_{ij}} E_i + A_j \]

Carrying capacity

\[ B_i + B_j \xrightarrow{c_{ij}} B_i + E_j \]
Universality class of predator-prey system near extinction

Near the transition to prey extinction, the prey (B) population is very small and no predator (A) can survive; \( A \sim 0 \).

\[
\begin{align*}
\text{Death} & : \quad B_i \xrightarrow{d_B} E_i \\
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\text{Carrying capacity} & : \quad B_i + B_j \xrightarrow{c_{ij}} B_i + E_j
\end{align*}
\]
Universality class of predator-prey system near extinction

Near the transition to prey extinction, the prey (B) population is very small and no predator (A) can survive; $A \sim 0$.

- **Death**
  \[ B_i \xrightarrow{d_B} E_i \]
  
- **Birth**
  \[ B_i + E_j \xrightarrow{b} \langle ij \rangle B_i + B_j \]
  
- **Diffusion**
  \[ B_i + E_j \xrightarrow{D} \langle ij \rangle E_i + B_j \]
  
- **Carrying capacity**
  \[ B_i + B_j \xrightarrow{c} \langle ij \rangle B_i + E_j \]
Universality class of predator-prey system near extinction

Near the transition to prey extinction, the prey (B) population is very small and no predator (A) can survive; A ~ 0.

Death: $B_i \xrightarrow{dB} E_i$

Birth: $B_i + E_j \xrightarrow{b}\langle ij\rangle B_i + B_j$

Diffusion: $B_i + E_j \xrightarrow{L}\langle ij\rangle E_i + B_j$

Carrying capacity: $B_i + B_j \xrightarrow{c}\langle ij\rangle B_i + E_j$

Predator-prey = Directed percolation

Decoagulation
Annihilation
Diffusion
Coagulation
Master equation for predator-prey model

Basic individual processes in predator (A) and prey (B) system:

Death
\[ B_i \xrightarrow{dB} E_i \quad \quad A_i \xrightarrow{dA} E_i \]

Birth
\[ B_i + E_j \xrightarrow{b} \langle ij \rangle B_i + B_j \quad \quad A_i + B_j \xrightarrow{p} \langle ij \rangle A_i + A_j \]

\[ \partial_t P(m, n) = \text{stuff}(P(m, n), P(m \pm 1, n \pm 1), \text{etc...}) \]
Master equation as a quantum field theory

• Individuals in a population are quantized, so use annihilation and creation operators to count them and describe their interactions

  – When adding a new individual to the system, there is only one to chose

  – When removing an individual from the system there are many to chose

• Result: even classical identical particles obey commutation relations familiar from quantum field theory

Doi 1976; Grassberger & Scheunert 1980; Cardy & Sugar 1980; Mikhalov 1981; Goldenfeld 1982, 1984; Peliti 1985
Master equation as a quantum field theory

• Individuals in a population are quantized, so use annihilation and creation operators to count them and describe their interactions

• Time evolution given by Liouville equation

\[
|\psi\rangle = \sum P(m, n)|m, n\rangle
\]

\[
\partial_t |\psi\rangle = -\hat{H}(a, \hat{a}, b, \hat{b}) |\psi\rangle
\]

\[
\hat{H} = b_1(\hat{b}\hat{b} - \hat{b}^2b) + d_1(\hat{b}\hat{b} - b) + \frac{c}{V}(\hat{b}^2b^2 - \hat{b}\hat{b}^2)
+ \frac{p_1}{V}(\hat{a}\hat{a}\hat{b}\hat{b} - \hat{a}\hat{b}\hat{a}\hat{b}) + \frac{p_2}{V}(\hat{a}\hat{a}\hat{b}\hat{b} - \hat{a}\hat{b}\hat{a}\hat{b})
+ d_2(\hat{a}\hat{a} - a)
\]
Field theory for predator-prey model

- Near extinction model reduces to simpler system
  \[ A \rightarrow \emptyset \quad \text{with rate } \mu, \]
  \[ A + B \rightarrow A + A \quad \text{with rate } \lambda', \]
  \[ B \rightarrow B + B \quad \text{with rate } \sigma. \]
- Express as Hamiltonian
  \[
  H_{\text{react}} = - \sum [\mu (1 - a_i \dagger) a_i + \sigma (b_i \dagger - 1) b_i \dagger b_i + \lambda' (a_i \dagger - b_i \dagger) a_i \dagger a_i b_i]
  \]
- Map into a coherent state path integral
  \[
  S[\hat{a}, \hat{b}; a, b] = \int d^d x \int dt \left[ \hat{a} \left( \frac{\partial}{\partial t} - D_A \nabla^2 \right) a + \hat{b} \left( \frac{\partial}{\partial t} - D_B \nabla^2 \right) b \right.
  \]
  \[
  + \mu (\hat{a} - 1) a - \sigma (\hat{b} - 1) \hat{b} b e^{-a_0 \hat{b} b} + \nu (\hat{b} - 1) \hat{b} b^2 - \lambda (\hat{a} - \hat{b}) \hat{a} a b \bigg] \]
- Phase diagram

See Tauber (2012)
Extinction in predator-prey systems

• This field theory can be reduced to

\[ S_\infty[\tilde{\psi}, \psi] = \int d^d x \int d t \left[ \tilde{\psi} \left( \frac{\partial}{\partial t} + D_A (r_A - \nabla^2) \right) \psi - u \tilde{\psi} (\tilde{\psi} - \psi) \psi + \tau \tilde{\psi}^2 \psi^2 \right] \]

Action of Reggeon field theory and universality class of directed percolation (Mobilia et al. (2007))

• Summary: ecological model of transitional turbulence predicts the DP universality class
Puff splitting in ecology model

Driven by emerging traveling waves of populations
Stability of predator-prey mean field theory has a transition between stable node and spiral

- Near transition, no oscillations
- Away from the transitions, oscillations begin
Puff splitting in predator-prey systems

Puff-splitting in predator-prey ecosystem in a pipe geometry

Puff-splitting in pipe turbulence

Avila et al., Science (2011)
Pipe flow turbulence

Decaying single puff → metastable puffs → splitting puffs

laminar

Re

1775 2050 2500

metastable puffs → spatiotemporal intermittency → expanding slugs

Predator-prey model

nutrient only

metastable population → traveling fronts 

expanding population

prey birth rate

0.02 0.05 0.08
Pipe flow turbulence

Decaying single puff

Splitting puffs

lam

metastable

spatiotemporal expanding

decaying

nutrient only metastable population traveling fronts expanding population

prey birth rate

0.02 0.05 0.08

Measure the **extinction time** and the **time between split events** in predator-prey system.
Predator-prey vs. transitional turbulence

**Prey lifetime**

Mean time between population split events

**Turbulent puff lifetime**

Mean time between puff split events

*Avila et al., Science 333, 192 (2011)*

*Song et al., J. Stat. Mech. 2014(2), P020010*
Predator-prey vs. transitional turbulence

Prey lifetime

Turbulent puff lifetime

Extinction in Ecology = Death of Turbulence

Mean time between population split events

Mean time between puff split events

Avila et al., Science 333, 192 (2011)
Summary: universality class of transitional turbulence

Directed Percolation

Reggeon field theory (Janssen, 1981)

Field Theory

Extinction transition (Mobilia et al., 2007)

Predator-Prey

(Two-fluid model)

Direct Numerical Simulations of Navier-Stokes

(Classical) Turbulence

Boffetta and Ecke, 2012

Wikimedia Commons

Pearson Education, Inc., 2009
But Nigel, is this the transition to turbulence or a transition to turbulence?
Predator-prey oscillations in convection

The head pushes upward but the fluid above pushes back. So the head grows outward, until the outward pushing hot fluid is pushed back and under by the colder fluid.

A plume is an example of an emergent object.
Predator-prey oscillations in convection

Predator-prey oscillations in convection

Sustained shearing convection

Bursty shearing convection

Energy in zonal flow and vertical plumes shows predator-prey oscillations

D. Goluskin et al. JFM (2014)
Universal predator-prey behavior in transitional turbulence

- Experimental observations
  - L-H mode transition in fusion plasmas in tokamak
  - 2D magnetized electroconvection


Estrada et al. EPL (2012)
Transition to turbulence in Taylor-Couette flow

PHYSICAL REVIEW E 81, 025301(R) (2010)

Transient turbulence in Taylor-Couette flow

Daniel Borrero-Echeverry and Michael F. Schatz
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Randall Tagg
Department of Physics, University of Colorado, Denver, Colorado 80217-3364, USA
(Received 4 May 2009; revised manuscript received 2 December 2009; published 19 February 2010)

FIG. 1. Photographs of turbulent patches in TCF at Re=7500 with only the outer cylinder rotating. In this regime, turbulent patches coexist with the laminar flow and evolve in space and time. For all Re studied, these patches decay away in a probabilistic manner with a characteristic time scale $\tau$ dependent on Re. The photographs show a 25 cm high region of the flow.
Measurement of DP exponents

**Figure 1** | **Apparatus and snapshot of turbulent spots.**

**a**. Schematic of the apparatus. The aspect ratio of the channel is $2,352h \times 2h \times 360h$, where the depth $2h$ is 5 mm. **b**. Turbulent spots are visualized near the middle ($x = 3$ m) downstream location of the channel at $Re = 810$. The turbulent flows are injected by using a grid at the inlet ($x = 0$) of the channel. Visualization was assisted by means of micro-platelets and grazing angle illumination. Scale bar, 100 mm.
Conclusion

• Transition to pipe turbulence is in the universality class of directed percolation, evidenced by:
  – Puff lifetime as a function of Re
  – Extreme value statistics and finite-size scaling
  – Slug spreading rate as a function of Re

• How to derive universality class from hydrodynamics
  – Small-scale turbulence activates large-scale zonal flow which suppresses small-scale turbulence
  – Effective theory (“Landau theory”) is stochastic predator-prey ecosystem
  – Exact mapping: fluctuating predator-prey = Reggeon field theory = DP near extinction

• Observational signatures
  – Predator-prey near extinction shows superexponential lifetime scaling for decay and splitting of puffs
Turbulence is a life force. It is opportunity. Let's love turbulence and use it for change.

Lucky Numbers  34, 15, 28, 4, 19, 20