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14. ABSTRACT
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**RPPR Final Report**  
as of 25-Jan-2023

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**Final Report** for Period Beginning 15-Apr-2017 and Ending 14-Aug-2022

**Title:** Control of Universal Scaling, Noise Strength, and Pattern Formation in Critical Dynamics

**Begin Performance Period:** 15-Apr-2017

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**Report Term:** 0-Other

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**Distribution Statement:** 1-Approved for public release; distribution is unlimited.

**STEM Degrees:** 15

**STEM Participants:** 22

**Major Goals:** Control of Universal Scaling, Noise Strength, and Pattern Formation in Critical Dynamics

The objective of our research program has been to build on a powerful and highly successful theory for non-linear stochastic dynamics of cooperative multi-component systems, namely critical dynamics, and upon drawing on considerable available experience in control theory, develop novel efficient protocols for:

- (1) steering multi-critical complex interacting dynamical systems toward certain desired universal scaling behavior;
- (2) externally controlling the strength of stochastic fluctuations and intrinsic noise in systems that are driven far from thermal equilibrium and display generic scale invariance;
- (3) selectively targeting and stabilizing specific self-generated spatio-temporal patterns in strongly fluctuating reaction-diffusion systems and epidemic models.

Over the past years, these ambitious research projects involved two postdoctoral researchers and a total of 14 Ph. D. and 8 undergraduate research students. This interdisciplinary research program could unfortunately not be completed within the allocated time scale. From further developments to follow in the future, the emergence of new concepts and innovative mathematical tools is anticipated. Our research team explored a wide range of paradigmatic systems that comprise more abstract investigations of fundamental models for control, driven oscillators, absorbing-state phase transitions, and driven lattice gases, but also potential and established

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applications that span from materials science such as magnetism and surface growth, to biological topics including biochemical kinetics, molecular motors, neuroscience, epidemiology, ecology, as well as evolutionary and social system dynamics. In the first two years of our ARO-funded research, the team mostly performed detailed numerical investigations to fully characterize the collective non-linear stochastic dynamics of these important test models. Over the past two years, we initiated and partially concluded studies to aim at the control of noisy complex interacting systems with many degrees of freedom towards desired features. Specifically, we have pursued the following five central questions:

- (i) Can we design efficient control mechanisms that would allow us to influence and drive scale-invariant critical dynamics towards certain targeted universality classes?
- (ii) Is it possible to externally control the strength of system-imminent fluctuations and even intrinsic reaction noise amplitudes to achieve desired observable output?
- (iii) May one exploit large-scale collective behavior of near-critical multiple-agent dynamical systems to exert global control through correlation-facilitated spreading of carefully posited local perturbations?
- (iv) Can we construct control schemes to specifically select for certain fluctuation-induced and noise-stabilized spatio-temporal patterns to generate desired morphologies in interacting many-particle and reaction-diffusion systems?
- (v) Is it feasible to extend powerful renormalization group ideas and techniques to systematically describe and classify control schemes in near-critical dynamical systems?

In our investigations of local control of universal dynamical critical scaling behavior, we utilized our broad expertise with various dynamic universality classes in and far away from thermal equilibrium, our versatility with extensive computer simulations and advanced mathematical tools that include path-integral representations of non-linear stochastic differential equations and ensuing analysis through dynamic renormalization group techniques, as well as our intimate familiarity with the universal short-time properties in the non-equilibrium aging relaxation regime as an effective diagnostic to fast detect and redirect emerging scaling behavior.

In the following, we summarize the most pertinent findings and conclusions of our ARO-funded research projects, with emphasis on unexpected emergent connections. More details are available in our annual progress reports, and of course in the 22 original peer-reviewed publications and one conference proceeding that resulted from our ARO-funded research, with two additional preprints currently under review. We further disseminated our results at 15 invited conference and 15 invited seminar talks, as well as through 39 contributed conference presentations.

**Accomplishments:** We had anticipated that strong, long-range correlations near critical points should facilitate the control of global properties through mere local perturbations, provided that the severe dynamical limitations induced by critical slowing-down can be overcome. For example, either suddenly switching on certain crucial control parameters or applying a periodic perturbation within a limited spatial region, and subsequently tracking the ensuing "damage" spreading through the entire system, we expected that the size of the thus modified region must exceed the correlation length of the targeted universality class, and concomitantly the frequency of the oscillatory drive should be small compared to the characteristic relaxation rate. Consequently, any effective control requires that the system not be initially set too close to the critical regime; yet on the other hand, it must display sufficient cooperativity for the effects of the local perturbation or feedback loop to eventually encompass its full spatial extent.

We had however underestimated the crucial influence of the inevitable interfaces separating the "bulk" system from the local region to which the control is applied. In fact, we realized that spatially heterogeneous non-equilibrium critical systems have hardly been studied at all in the pertinent literature. In inhomogeneous two-temperature driven lattice gases wherein a critical subspace is dynamically coupled to a generically scale-invariant region that is governed by distinct scaling exponents, we found that the presence of the interface tends to eliminate generic scale invariance in the "hotter" region, while the critical properties of the other domain persisted, and even in a subtle manner influenced novel scaling features in the complementary subspace. Moreover, unexpected spatial structures are induced in the non-critical region. In presently ongoing attempts in adjusting the dynamical scaling properties of anisotropic antiferromagnets in external magnetic fields near their bicritical point between the distinct model-C and model-F critical lines through locally quenching the relevant control parameters in a confined domain to different values, we too observe that criticality becomes erased in one region, where we instead find robust spin waves emanating from the other spatial regime. Intriguingly, this resembles the stabilization of spiral structures and hence

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preservation of biodiversity in a vulnerable May-Leonard ecology with cyclically competing species subject to asymmetric predation rates through immigration fronts that continuously intrude from a stable spatial patch with symmetric rates. Thus, our investigations of the central themes (1) and (3) above turned out to be intimately connected. The truly surprising emergence of quite similar fluctuation-induced pattern formation in near-critical and hence strongly excitable systems of quite diverse microscopic physical origins appears to point at a generic, universal phenomenon that could potentially be developed into a novel tool to control and (de-)stabilize macroscopic features in complex spatially extended non-linear stochastic many-body systems.

A large variety of systems that are driven far away from thermal equilibrium display generic scale invariance, with non-trivial dynamic scaling features, yet without the necessity to tune certain parameters to a critical point; these include paradigmatic models for driven diffusive systems and growing interfaces. In this context we achieved major progress in the exploration of control schemes that can be used in order to control the fluctuating interface width during non-equilibrium surface growth. In our work, we pursued different approaches to control the saturation of the mean surface roughness to a prescribed value for growth processes described by the Kardar-Parisi-Zhang (KPZ) equation in one dimension. When using non-linear feedback control, coupling effects of controlled (linear) and uncontrolled (non-linear) KPZ dynamics are observed during the control process which yields a temporal crossover behavior, accompanied with intriguing scaling properties, between intermediate-time kinetics governed by KPZ scaling and late-time linear relaxation. In the linear control process, on the other hand, the control of a finite number of Fourier modes maintains the intrinsic non-linearity of the system. A detailed numerical analysis to investigate the controlled dynamics subject to weak as well as strong non-linearity has been performed. In a continuing collaboration with our (former) postdoc Dr. Priyanka, we are exploring extensions to higher spatial dimensions, which pose quite non-trivial conceptual as well as technical numerical challenges. With (former) postdoc Dr. Yunlong Huang, we considered the one-dimensional KPZ equation driven by space-time white noise from the perspective of space discretization and control. After applying the logarithmic Hopf-Cole transformation to obtain a bilinear stochastic partial differential equation, we subjected it to uniform space discretization, resulting in a finite-dimensional Itô type stochastic differential equation with variable coefficients for the noise term (effectively locally varying temperature). We considered principled ways to control these coefficients to produce minimum variance of the interface roughness over a finite time horizon, utilizing the Hamilton-Jacobi-Bellman equation. In order to reduce the impact of the "curse of dimensionality", we developed an approximation method and resorted to the modern technology of deep neural networks to approximate the value function gradient.

Epidemiological, related population dynamics, as well as chemical kinetics models offer exciting research avenues to selectively target self-generated spatio-temporal structures in these systems. Especially interesting are noise-induced and -stabilized patterns in stochastic, spatially extended systems. In traditional attempts to control spatio-temporal transient chaos in spatial settings, these systems are often subjected to protocols that perturb them as a whole and stabilize globally a new dynamic regime, as for example a uniform steady state. We demonstrated that selectively perturbing only part of a system can generate novel space-time patterns that are not observed when the control scheme is applied to the entire system. Depending on the protocol used, these new patterns can emerge either in the perturbed or unperturbed region. Again, this invokes in an uncanny manner our intriguing findings for diffusively coupled inhomogeneous near-critical antiferromagnetic systems as well as driven lattice gases. Specifically, we studied two paradigmatic sets of models: We used a spatially localized time-delayed feedback scheme on the one-dimensional Gray-Scott reaction-diffusion system as well as the complex Ginzburg-Landau equation, and demonstrated, through direct numerical integration, the stabilization of novel spatially localized periodic and quasi-periodic space-time patterns. The mechanism underlying the observed pattern generation is related to diffusion across the interfaces separating the different regions. We combined different variants of three-species Lotka-Volterra or May-Leonard population dynamics models subject to cyclic predation akin to rock-paper-scissors games to study under which circumstances spontaneously emerging spatio-temporal spiral structures emerge and become stabilized even in a weak ecology close to an extinction threshold. We found that a sufficiently large symmetric, hence stable May-Leonard system induces planar population fronts that invade an even much bigger asymmetric, thus vulnerable region situated close to absorbing configurations, provided diffusive propagation through the induced spiral arms is slower than the effective periodic driving. We also explored control of the collective dynamics of molecular motors, neural networks, voter and replicator models, and flocks.

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**Training Opportunities:** Our PI team combined scientific expertise in the areas of critical dynamics and control theory, and broad experience with the modern analytical as well as numerical tools that are indispensable to address this set of intriguing and challenging scientific problems. Our postdoctoral research associates, graduate students, and undergraduate researchers benefited tremendously from their participation in these trans-disciplinary projects at the forefront of science. They were trained extensively in the mathematical modelling of complex stochastic dynamical systems, state-of-the-art data analysis, advanced computational algorithms, and sophisticated analytical methods. We organized a PI meeting at Blacksburg, VA in early June 2017; and prior to the Covid-19 pandemic met for collaborative discussions at College Park, MD in April and July, 2019.

Postdoctoral research associates (2):

- Dr. Yunlong Huang, Institute for Systems Research, University of Maryland, College Park, MD, full support October 2017 - August 2018. He assumed a full-time position as Research Engineer at Ford Center for Innovation and Research in Dearborn, MI, working on control and planning techniques in autonomous vehicles. In 2021, he moved to China to join Contemporary Amperex Technology Co. Ltd (CATL) in Fujian Province, a world-leading battery maker for electric vehicles.

- Dr. Priyanka, Center for Soft Matter and Biological Physics, Virginia Tech, Blacksburg, VA, full support January 2018 through January 2021. Priyanka had joined us from the International Centre for Theoretical Sciences (ICTS) at Bangalore, India. She is now a postdoctoral researcher at the University of Illinois at Urbana-Champaign.

Graduate STEM students (14):

- Ahmadreza Azizi, Physics, Virginia Tech, full summer graduate research assistantship 2017, 2018, and 2019; 1/2 graduate research assistantship fall 2017, spring 2018, fall 2018, spring 2019, and fall 2019.

Dr. Azizi defended his Ph.D. dissertation "Study of critical phenomena with Monte Carlo and machine learning techniques" on 7 May 2020. He is a Machine Learning Researcher at Zebra / Antuit.ai.

- Jacob A. Carroll, Physics, Virginia Tech, partial summer graduate research assistantship summer 2017 and 2018; 1/2 graduate research assistantship fall 2017, spring 2018, and fall 2018. Dr. Carroll defended his Ph.D. dissertation "Examining the dynamics of biologically inspired systems far from equilibrium" on 20 February 2019. Since 1 June 2019, Dr. Carroll has been a Senior Software Engineer at Lockheed Martin, Littleton, CO.

- Sheng Chen, Physics, Virginia Tech, full summer graduate research assistantship 2017; 1/2 graduate research assistantship fall 2017. Dr. Chen defended his Ph.D. dissertation "Population dynamics of stochastic lattice Lotka-Volterra models" on 5 December 2017. He is a Software Engineer with Facebook, New York, NY.

- Jason E. Czak, Physics, Virginia Tech, full summer graduate research assistantship 2019, 2020, and 2021; 1/2 graduate research assistantship spring 2020, fall 2020, spring 2021, fall 2021, and spring 2022. Dr. Czak defended his Ph.D. dissertation "A study of the effects of spatially localized time-delayed feedback on spatio-temporal patterns" on 2 May 2022. He holds a postdoctoral research position in Medical Physics at the University of Virginia, Charlottesville.

- Shengfeng Deng, Physics, Virginia Tech and Central China Normal University, Wuhan, China; no support through this award. Dr. Deng defended his Ph.D. dissertation "Phase transitions in unitary and binary stochastic contact processes" on 15 November 2020. He is currently a postdoctoral researcher at the Centre for Energy Research, Eötvös University, Budapest, Hungary.

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- Udit Halder, Engineering, University of Maryland;  
no support through this award.

Dr. Halder defended his dissertation "Optimality, synthesis and a continuum model for collective motion" in May 2019. Since 1 August 2019, he has held a postdoctoral position in Engineering (soft robotics) at the University of Illinois, Urbana-Champaign.

- Chinmay Katke, Physics, Virginia Tech,  
full summer graduate research assistantship 2020.

- Ruslan I. Mukhamadiarov, Physics, Virginia Tech;  
full summer graduate research assistantship 2017 and 2018;  
1/2 graduate research assistantship fall 2017, fall 2018, and spring 2019.  
Dr. Mukhamadiarov defended his Ph.D. dissertation "Controlling non-equilibrium dynamics in lattice gas models" on 24 February 2021. He is a postdoctoral guest scientist at the Max Planck Institute for the Physics of Complex Systems, Dresden, Germany.

- Riya Nandi, Physics, Virginia Tech,  
full summer graduate research assistantship 2017, 2018, 2019, and 2020;  
1/2 graduate research assistantship fall term 2017 and spring semester 2018;  
1/2 graduate research assistantship fall 2018, fall 2019, spring 2020, fall 2020, and spring 2021.  
Dr. Nandi defended her Ph.D. dissertation "Critical dynamics in Heisenberg antiferromagnets and molecular motor-inspired exclusion processes" on 4 March 2021. She is a postdoctoral research associate at the University of Geneva, Switzerland.

- Christy Pius, Physics, Virginia Tech,  
full summer I graduate research assistantship 2020.

- Vidya Raju, Engineering, University of Maryland;  
no support through this award.  
Dr. Raju defended her dissertation "Cognitive control, evolutionary games, and Lie algebras" in May 2019. She subsequently held a postdoctoral position in applied mathematics at the Harvard John A. Paulson School of Engineering and Applied Sciences 2019 - 2022, Cambridge, MA, and presently at New York University, New York.

- Shannon R. Serrao, Physics, Virginia Tech,  
full summer graduate research assistantship 2017, 2018, 2019, and 2020;  
1/2 graduate research assistantship fall 2017, spring 2018, spring 2019, fall 2019, and fall 2020; support through hourly wages during summer 2021.  
Dr. Serrao defended his Ph.D. dissertation "Stochastic effects on extinction and pattern formation in the three-species cyclic May-Leonard model" on 9 December 2020.

- James E. Stidham III, Physics, Virginia Tech,  
summer support per hourly wages 2017;  
full summer graduate research assistantship 2018;  
1/2 graduate research assistantship fall term 2018.  
Dr. Stidham defended his Ph.D. dissertation "Ordering processes and pattern formation in systems far from equilibrium" on 2 May 2022.

- Hong Yao, Physics, Virginia Tech,  
full summer graduate research assistantship 2019.  
Hong will defend his Ph.D. dissertation in the spring 2023.

Undergraduate STEM students (9):

- Harrison F. Andrew, Physics, University of Central Florida, Orlando, FL;

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support per hourly wages through ARO URAP supplemental award, summer 2018.

- M. Lazarus Arnau, Physics, Virginia Tech, Blacksburg, VA;  
support per hourly wages through ARO URAP supplemental URAP award,  
summer 2018; partial support per hourly wages fall 2018 through summer 2019;  
B.S. May 2020.

- Mira Eisenhauer, Data Science, Maggie L. Walker Governor's School,  
Richmond, VA; support per hourly wages through ARO URAP supplemental award, summer 2021.

- Nash Gatenby-Latham, Physics and Music, Virginia Tech, Blacksburg, VA;  
support per hourly wages through ARO URAP supplemental award, summer 2021.

- Jacob Hannah, Physics and Mathematics, Austin Peay State University,  
Clarksville, TN; support per hourly wages through ARO URAP supplemental  
award, summer 2021.

- Connor J. Mackert, General Engineering, Virginia Tech, Blacksburg, VA;  
support per hourly wages through ARO URAP supplemental award, summer 2019.

- Hana Mir, Physics, Virginia Tech, support per hourly wages through ARO  
URAP supplemental award, summer 2021; fall 2021; and spring 2022; B.S. May 2022.

- James E. Stidham III, Physics, Virginia Tech, Blacksburg, VA; B.S. May 2017.

- Austin "Ada" B. Warren, Physics, Virginia Tech, Blacksburg, VA;  
support per hourly wages, summer 2017; fall 2017; spring 2018; and summer 2018; B.S. May 2018.

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### Results Dissemination: Published Peer-Reviewed Papers (22):

- Ruslan I. Mukhamadiarov and Uwe C. Täuber, "Effects of lattice dilution on the non-equilibrium phase transition in the susceptible-infectious-recovered model", *Physical Review E* 106, 034132 - 1-8 (23 September 2022) [arXiv: 2206.03906].
- Hana Mir, James Stidham, and Michel Pleimling, "Emerging spatiotemporal patterns in cyclic predator-prey systems with habitats", *Physical Review E* 105, 054401 – 1-10 (2 May 2022).
- Ruslan I. Mukhamadiarov, Shengfeng Deng, Shannon R. Serrao, Priyanka, Lauren M. Childs, and Uwe C. Täuber, "Requirements for the containment of COVID-19 disease outbreaks through periodic testing, isolation, and quarantine", *Journal of Physics A: Mathematical and Theoretical* (23 December 2021) [medRxiv: 2020.10.21.20217331].
- Jason Czak and Michel Pleimling, "Spatiotemporal patterns emerging from a spatially localized time-delayed feedback scheme", *Physical Review E* 104, 064213 – 1-9 (20 December 2021).
- Riya Nandi, Uwe C. Täuber, and Priyanka, "Dynein-inspired multilane exclusion process with open boundary conditions", *Entropy* 2021, 1343 - 1-13 (14 October 2021) [arXiv:2108.13608].
- Shannon R. Serrao and Uwe C. Täuber, "Stabilizing spiral structures and population diversity in the asymmetric May-Leonard model through immigration", *European Physical Journal B* 94, 175 - 1-15 (24 August 2021) [arXiv:2105.08126].
- Shannon R. Serrao, Tim Ritmeester, and Hildegard Meyer-Ortmanns, "Rare extinction events in cyclic predator-prey games", *Journal of Physics A: Mathematical and Theoretical* 54, 235001 - 1-17 (7 May 2021) [arXiv: 2105.11929].
- Priyanka, Uwe C. Täuber, and Michel Pleimling, "The role of the non-linearity in controlling the surface roughness in the one-dimensional Kardar-Parisi-Zhang growth process", *Journal of Physics A: Mathematical and Theoretical* 54, 154002 - 1-18 (23 March 2021) [arXiv:2101.01868].
- Riya Nandi and Priyanka, "One dimensional exclusion process with dynein inspired hops: Simulation and mean-field analysis", *Journal of Statistical Physics* 182, 29 - 1-19 (1 February 2021) [arXiv:2002.09978].
- Ruslan I. Mukhamadiarov, Shengfeng Deng, Shannon R. Serrao, Priyanka, Riya Nandi, Louie Hong Yao, and Uwe C. Täuber, "Social distancing and epidemic resurgence in agent-based susceptible-infectious-recovered models", *Scientific Reports* 11, 130 - 1-8 (8 January 2021) [arXiv:2006.02552].
- Ruslan I. Mukhamadiarov, Priyanka, and Uwe C. Täuber, "Parallel temperature interfaces in the Katz-Lebowitz-Spohn driven lattice gas", *Journal of Statistical Mechanics* 2020, 113207 - 1-20 (27 November 2020) [arXiv: 2009.05650].
- Riya Nandi and Uwe C. Täuber, "Critical dynamics of anisotropic antiferromagnets in an external field", *Physical Review E* 102, 052114 - 1-8 (11 November 2020) [arXiv:2008.11541].
- Shengfeng Deng, Wei Li, and Uwe C. Täuber, "Coupled two-species model for the pair contact process with diffusion", *Physical Review E* 102, 042126 - 1-18 (22 October 2020) [arXiv:2007.09496].
- Navid Ghaffarzadegan, Lauren M. Childs, and Uwe C. Täuber, "Diverse computer simulation models provide unified lessons on university operation during a pandemic", *BioScience* 71, 113-114 (15 October 2020). [Including an acknowledgement to ARO funding was not possible for this brief opinion piece.]
- Ahmadreza Azizi and Michel Pleimling, "Critical phenomena in the presence of symmetric absorbing states: A microscopic model with tunable parameters", *Physical Review E* 102, 022112 - 1-8 (10 August 2020) [arXiv: 2007.10933].

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- Yunlong Huang and P. S. Krishnaprasad, "Sub-Riemannian geometry and finite time thermodynamics Part 1: The stochastic oscillator", *Discrete and Continuous Dynamical Systems S* 13, 1243-1268 (April 2020).
- Priyanka, Uwe C. Täuber, and Michel Pleimling, "Feedback control of surface roughness in a one-dimensional KPZ growth process", *Physical Review E* 101, 022101 - 1-8 (3 February 2020) [arXiv:1912.04789].
- Ruslan I. Mukhamadiarov, Priyanka, and Uwe C. Täuber, "Transverse temperature interfaces in the Katz-Lebowitz-Spohn driven lattice gas", *Physical Review E* 100, 062122 - 1-13 (16 December 2019) arXiv:1907.08576].
- Jacob Carroll, Ada Warren, and Uwe C. Täuber, "Effects of inhibitory and excitatory neurons on the dynamics and control of avalanching neural networks", *Physical Review E* 99, 052407 - 1-13 (17 May 2019) [arXiv:1809.01646].
- Riya Nandi and Uwe C. Täuber, "Nonuniversal critical aging scaling in three-dimensional Heisenberg antiferromagnets", *Physical Review B* 99, 064417 - 1-6 (19 February 2019) [arXiv:1809.07799].
- Ahmadreza Azizi, James Stidham, and Michel Pleimling, "Dynamic critical properties of non-equilibrium Potts models with absorbing states", *Journal of Statistical Mechanics* 2018, 103208 - 1-19 (24 October 2018) [arXiv:1809.08366].
- Shannon R. Serrao and Uwe C. Täuber, "A stochastic analysis of the spatially extended May-Leonard model", *Journal of Physics A: Mathematical and Theoretical* 50, 404005 - 1-16 (7 September 2017) [arXiv:1706.00309].

### Conference Proceedings (1):

- Vidya Raju and P.S. Krishnaprasad, "A variational problem on the probability simplex", *Proc. 57th IEEE Conference on Decision and Control*, 3522-3528, IEEE, New York (2018).

### Book Chapter (1):

- Uwe C. Täuber, "Fluctuations and correlations in chemical reaction kinetics and population dynamics", in: "Chemical kinetics beyond the textbook", eds. K. Lindenberg, R. Metzler, and G. Oshanin, Chapter 1, 28 pages, World Scientific Publ. (2019) [arXiv:1807.01248].

### Manuscripts under review (2):

- Vidya Raju and P. S. Krishnaprasad, "Lie algebra structure of fitness and replicator control", submitted to *Journal of Geometric Mechanics* [arXiv:2005.09792].
- Udit Halder, Vidya Raju, Matteo Mischiati, Biswadip Dey, and P. S. Krishnaprasad, "Flocks, games, and cognition: a geometric approach", submitted to *Systems and Control Letters* [arXiv:2208.03786].

We presented our findings at these conferences, workshops, and schools:

- SIAM Conference on the Life Sciences, Pittsburgh, PA, July 2022.
- APS March Meeting, Chicago, IL, March 2022.
- TRIPODS virtual Winter School at Johns Hopkins University – MINDS, January 2022.
- Northrop Grumman virtual Research Symposium, October 2021.
- Virtual APS March Meeting, March 2021.
- 11. Theoretikerworkshop der jDPG (11th Young German Physical Society Theory Workshop) "Stochastische Modelle in der Physik", January 2021.
- Northrop Grumman virtual Research Symposium, October 2020.

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- 86th Annual SESAPS Meeting, Wrightsville Beach, NC, November 2019.
- Northrop Grumman Research Symposium, Anaheim, CA, 23 October 2019.
- 7th Annual Virginia Soft Matter Workshop, Charlottesville, VA, September 2019.
- Workshop "The Many Facets of Non-equilibrium Physics: From Many-Body Theory to Quantum Thermodynamics", Mazara del Vallo, Italy, July 2019.
- 15th International Workshop "Magnetism and Superconductivity at the Nanoscale", Coma-ruga, Spain, July 2019.
- 11th Annual Summer School "Soft Solids and Complex Fluids", Amherst, MA, June 2019.
- SIAM Conference on Applications of Dynamical Systems, Snowbird, UT, May 2019.
- APS March Meeting, Boston, MA, March 2019.
- IEEE Conference "Decision and Control", Miami, FL, December 2018.
- 85th Annual SESAPS Meeting, Knoxville, TN, November 2018.
- 6th Virginia Soft Matter Workshop, Blacksburg, VA, September 2018.
- Workshop "Information Engines at the Frontiers of Nanoscale Thermodynamics", Telluride Science Research Center, CO, July 2018.
- Northrop Grumman Research Symposium, Baltimore, MD, April 2018.
- Workshop "Information Engines at the Frontiers of Nanoscale Thermodynamics", Telluride Science Research Center, CO, August 2017.
- Bangalore School on Statistical Physics VIII, International Centre for Theoretical Sciences Bangalore, India, July 2017.
- New Trends in Applied Geometric Mechanics, ICMAT, Madrid, Spain, July 2017.
- Dynamical Systems and Geometric Mechanics, Munich, Germany, June 2017.

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**Honors and Awards:** PI Uwe C. Täuber was appointed Lead Editor of Physical Review E, January 1, 2021.

Postdoc Dr. Priyanka was invited by the editors of Journal of Physics A: Mathematical and Theoretical to contribute to the "Emerging Talents 2021" article collection with our paper "The role of the non-linearity in controlling the surface roughness in the one-dimensional Kardar-Parisi-Zhang growth process."

Graduate student awards:

Jacob A. Carroll:

- Finalist, American Physical Society Topical Group of Statistical and Nonlinear Physics Outstanding Graduate Student Speaker Award, March 2019.

- Ray F. Tipsword Graduate Scholarship, Department of Physics, Virginia Tech, April 2018.

- Lubna R. Ijaz Scholarship, Department of Physics, Virginia Tech, April 2017.

Sheng Chen: Ray F. Tipsword Graduate Scholarship, Department of Physics, Virginia Tech, April 2017.

Jason E. Czak: Hassinger Graduate Fellowship, Department of Physics, Virginia Tech, April 2021.

Ruslan I. Mukhamadiarov:

- Ray F. Tipsword Graduate Scholarship, Department of Physics, Virginia Tech, April 2020.

- Clayton D. Williams Graduate Fellowship, Department of Physics, Virginia Tech, April 2019.

Riya Nandi:

- Ladies of Robeson graduate award, Department of Physics, Virginia Tech, April 2021.

- Clayton D. Williams Graduate Fellowship, Department of Physics, Virginia Tech, April 2020.

- James R. Dunn Award, Department of Physics, Virginia Tech, April 2019.

- Ray F. Tipsword Graduate Scholarship, Department of Physics, Virginia Tech, April 2018.

Shannon R. Serrao: Graduate Wan-Zia Scholarship, Department of Physics, Virginia Tech, April 2017.

James E. Stidham III: William E. Hassinger Graduate Fellowship, Department of Physics, Virginia Tech, April 2019.

Undergraduate student awards:

Hana Mir:

- College of Science Outstanding Senior Researcher Award, Virginia Tech, April 2022.

- Robert Lee Bowden, Jr. Essay Prize, Department of Physics, Virginia Tech, April 2021.

- Robert C. Richardson Scholarship, Department of Physics, Virginia Tech, April 2021.

James E. Stidham III: H.Y. Loh Award, Department of Physics, Virginia Tech, April 2017.

Austin "Ada" Warren: Hugh D. Ussery Scholarship, Department of Physics, Virginia Tech, April 2017.

Invited Conference Presentations (15):

- Shannon R. Serrao and Uwe C. Täuber,  
"Spatially inhomogeneous stochastic cyclic competition models: Stabilizing vulnerable ecologies through

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immigration waves",  
SIAM Conference on the Life Sciences, Pittsburgh, PA, 14 July 2022.

- P. S. Krishnaprasad,  
"Games, flocks and cognition",  
TRIPODS virtual Winter School at Johns Hopkins University - MINDS, 20 January 2022.

- P. S. Krishnaprasad,  
"Autonomy and Geometry",  
Northrop Grumman virtual University Research Symposium, 19 October 2021.

- Priyanka, Uwe C. Täuber, and Michel Pleimling,  
"Control of the surface roughness during a growth process described by the Kardar-Parisi-Zhang equation",  
2021 virtual March Meeting of the American Physical Society, 15 March 2021.

- Uwe C. Täuber,  
"Raumzeitliche Korrelationen in stochastischer Populationsdynamik (Spatio-temporal correlations in stochastic population dynamics)",  
virtual lecture, 11. Theoretikerworkshop der jDPG (11th Young German Physical Society Theory Workshop)  
"Stochastische Modelle in der Physik", 9 January 2021.

- P. S. Krishnaprasad,  
"Flocks, games and cognitive control",  
Northrop Grumman virtual University Research Symposium, October 2020.

- P. S. Krishnaprasad,  
"Cognitive control, evolutionary games and Lie algebras",  
Northrop Grumman Research Symposium, Anaheim, CA, 23 October 2019.

- Ruslan I. Mukhamadiarov, Priyanka, and Uwe C. Täuber,  
"Temperature interfaces in the Katz-Lebowitz-Spohn driven lattice gas",  
International Workshop "The Many Facets of Non-equilibrium Physics: From Many-Body Theory to Quantum Thermodynamics", Mazara del Vallo, Italy, 12 July 2019.

- Shannon R. Serrao, M. Lazarus Arnau, and Uwe C. Täuber,  
"Spatially extended stochastic rock-paper-scissors and May-Leonard models",  
SIAM Conference on "Applications of Dynamical Systems", Snowbird, UT, 19 May 2019.

- Yunlong Huang,  
"Optimal control of KPZ Equation using deep reinforcement learning",  
Workshop on Information Engines at the Frontiers of Nanoscale Thermodynamics, Telluride Science Research Center, Telluride, CO, July 2018.

- P. S. Krishnaprasad,  
"Cognitive control, evolutionary games and Lie algebras",  
Northrop Grumman Research Symposium, Baltimore, MD, 17 April 2018.

- P. S. Krishnaprasad,  
"Subriemannian geometry and finite time thermodynamics (optimality and cycles)",  
Workshop on Information Engines at the Frontiers of Nanoscale Thermodynamics, Telluride Science Research Center, Telluride, CO, August 2017.

- P. S. Krishnaprasad,  
"Flocks and form",  
New Trends in Applied Geometric Mechanics - An International Conference in Honor of Darryll Holm, ICMAT, Madrid, Spain, July 2017.

- P. S. Krishnaprasad,  
"Optimality, geometry and cycles,"

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Dynamical Systems and Geometric Mechanics – An International Conference in Honor of Jürgen Scheurle, Munich, Germany, June 2017.

- Uwe C. Täuber,  
"Critical Dynamics", five invited lectures,  
Bangalore School on Statistical Physics VIII, International Centre for Theoretical Sciences Bangalore, India, 3-7 July 2017.

Invited Seminar Presentations (15):

- Uwe C. Täuber,  
"Stochastic spatial predator-prey models",  
virtual International Webinar on Physics, Pabna University of Science and Technology, 4 June 2021.

- Uwe C. Täuber,  
"Stochastic spatial predator-prey models",  
virtual Theory Club Seminar, Laboratoire Matière et Systèmes Complexes, Université de Paris, 22 March 2021.

- P. S. Krishnaprasad,  
"Games, Lie algebras and control",  
virtual College of Engineering Seminar, Michigan State University, 2 October 2020.

- Ruslan I. Mukhamadiarov, Priyanka, and Uwe C. Täuber,  
"Temperature interfaces in the Katz-Lebowitz-Spohn driven lattice gas",  
Joint SISSA / ICTP Seminar, Scuola Internazionale Superiore di Studi Avanzati, Trieste, Italy, 21 November 2019.

- Uwe C. Täuber,  
"Stochastic spatial predator-prey models",  
Soft Matter / Biophysics Seminar, Ludwig-Maximilians-Universität Munich, Germany, 22 October 2019.

- Uwe C. Täuber,  
"Stochastic spatial predator-prey models",  
Theorie Seminar, Friedrich-Alexander-Universität Erlangen-Nürnberg, Germany, 14 October 2019.

- Ruslan I. Mukhamadiarov, Priyanka, and Uwe C. Täuber,  
"Temperature interfaces in the Katz-Lebowitz-Spohn driven lattice gas",  
Theorie-Kolloquium, Universität zu Köln, Germany, 11 October 2019.

- Ruslan I. Mukhamadiarov, Priyanka, and Uwe C. Täuber,  
"Temperature interfaces in the Katz-Lebowitz-Spohn driven lattice gas",  
DAMTP Statistical Physics and Soft Matter Seminar, University of Cambridge, U.K., 8 October 2019.

- Uwe C. Täuber,  
"Stochastic spatial predator-prey models",  
Applied Mathematics and Math-Bio Seminar, University of Leeds, U.K., 2 October 2019.

- Ruslan I. Mukhamadiarov, Priyanka, and Uwe C. Täuber,  
"Temperature interfaces in the Katz-Lebowitz-Spohn driven lattice gas",  
Applied Nonlinear Dynamics Seminar, University of Leeds, U.K., 1 October 2019.

- Ruslan I. Mukhamadiarov, Priyanka, and Uwe C. Täuber,  
"Temperature interfaces in the Katz-Lebowitz-Spohn driven lattice gas",  
Statistical Physics and Complexity Seminar, University of Edinburgh, U.K., 25 September 2019.

- Uwe C. Täuber,  
"Stochastic spatial predator-prey models",  
Seminar, Swiss Federal Institute of Aquatic Science and Technology Eawag, Dübendorf, Switzerland, 2 September 2019.

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- Uwe C. Täuber,  
"Stochastic spatial predator-prey models",  
Colloquium, Universidade do Minho, Braga, Portugal, 5 June 2019.

- Uwe C. Täuber,  
"Stochastic spatial predator-prey models",  
Colloquium, Universidade de Lisboa, Lisbon, Portugal, 29 May 2019.

- Ruslan I. Mukhamadiarov, Priyanka, and Uwe C. Täuber,  
"Temperature interfaces in the Katz-Lebowitz-Spohn driven lattice gas",  
Statistical Physics Seminar, University of Maryland, College Park, MD, 23 April 2019.

### Protocol Activity Status:

**Technology Transfer:** During 2017-2021 there has been a sustained collaboration with Northrop Grumman, with support for unrestricted basic research by P. S. Krishnaprasad. The collaboration consisted of sharing ideas and results in game theory, nonlinear control, and cognitive architectures for control through one-to-one interactions and presentations at the annual symposia organized by Northrop Grumman. The uses of the shared ideas at Northrop Grumman are unknown and possibly related to proprietary projects.

### PARTICIPANTS:

**Participant Type:** Research Experience for Undergraduates (REU) Participant

**Participant:** Harrison F. Andrew

**Person Months Worked:** 3.00

**Funding Support:**

Project Contribution:

National Academy Member: N

**Participant Type:** Undergraduate Student

**Participant:** Michael Lazarus Arnau

**Person Months Worked:** 10.00

**Funding Support:**

Project Contribution:

National Academy Member: N

**Participant Type:** Research Experience for Undergraduates (REU) Participant

**Participant:** Mira Eisenhauer

**Person Months Worked:** 3.00

**Funding Support:**

Project Contribution:

National Academy Member: N

**Participant Type:** Research Experience for Undergraduates (REU) Participant

**Participant:** Nash Gatenby-Latham

**Person Months Worked:** 3.00

**Funding Support:**

Project Contribution:

National Academy Member: N

**Participant Type:** Research Experience for Undergraduates (REU) Participant

**Participant:** Jacob Hannah

**Person Months Worked:** 3.00

**Funding Support:**

Project Contribution:

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as of 25-Jan-2023

National Academy Member: N

**Participant Type:** Research Experience for Undergraduates (REU) Participant

**Participant:** Connor J. Mackert

**Person Months Worked:** 3.00

**Funding Support:**

Project Contribution:

National Academy Member: N

**Participant Type:** Undergraduate Student

**Participant:** Hana Mir

**Person Months Worked:** 5.00

**Funding Support:**

Project Contribution:

National Academy Member: N

**Participant Type:** Undergraduate Student

**Participant:** Austin "Ada" B. Warren

**Person Months Worked:** 11.00

**Funding Support:**

Project Contribution:

National Academy Member: N

**Participant Type:** Co PD/PI

**Participant:** Michel J. Pleimling

**Person Months Worked:** 10.00

**Funding Support:**

Project Contribution:

National Academy Member: N

**Participant Type:** Co PD/PI

**Participant:** P. S. Krishnaprasad

**Person Months Worked:** 13.00

**Funding Support:**

Project Contribution:

National Academy Member: N

**Participant Type:** Postdoctoral (scholar, fellow or other postdoctoral position)

**Participant:** Yunlong Huang

**Person Months Worked:** 11.00

**Funding Support:**

Project Contribution:

National Academy Member: N

**Participant Type:** PD/PI

**Participant:** Uwe C. Tauber

**Person Months Worked:** 10.00

**Funding Support:**

Project Contribution:

National Academy Member: N

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as of 25-Jan-2023

**Participant Type:** Graduate Student (research assistant)  
**Participant:** Udit Halder  
**Person Months Worked:** 1.00 **Funding Support:**  
Project Contribution:  
National Academy Member: N

**Participant Type:** Graduate Student (research assistant)  
**Participant:** Vidya Raju  
**Person Months Worked:** 2.00 **Funding Support:**  
Project Contribution:  
National Academy Member: N

**Participant Type:** Graduate Student (research assistant)  
**Participant:** Christy Pius  
**Person Months Worked:** 1.00 **Funding Support:**  
Project Contribution:  
National Academy Member: N

**Participant Type:** Graduate Student (research assistant)  
**Participant:** Hong Yao  
**Person Months Worked:** 3.00 **Funding Support:**  
Project Contribution:  
National Academy Member: N

**Participant Type:** Graduate Student (research assistant)  
**Participant:** Chinmay Katke  
**Person Months Worked:** 3.00 **Funding Support:**  
Project Contribution:  
National Academy Member: N

**Participant Type:** Graduate Student (research assistant)  
**Participant:** Sheng Chen  
**Person Months Worked:** 5.00 **Funding Support:**  
Project Contribution:  
National Academy Member: N

**Participant Type:** Graduate Student (research assistant)  
**Participant:** Shengfeng Deng  
**Person Months Worked:** 1.00 **Funding Support:**  
Project Contribution:  
National Academy Member: N

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**Participant Type:** Graduate Student (research assistant)  
**Participant:** Ahmadreza Azizi  
**Person Months Worked:** 15.00 **Funding Support:**  
Project Contribution:  
National Academy Member: N

**Participant Type:** Graduate Student (research assistant)  
**Participant:** Jacob A. Carroll  
**Person Months Worked:** 11.00 **Funding Support:**  
Project Contribution:  
National Academy Member: N

**Participant Type:** Graduate Student (research assistant)  
**Participant:** Jason E. Czak  
**Person Months Worked:** 15.00 **Funding Support:**  
Project Contribution:  
National Academy Member: N

**Participant Type:** Graduate Student (research assistant)  
**Participant:** Ruslan I. Mukhamadiarov  
**Person Months Worked:** 15.00 **Funding Support:**  
Project Contribution:  
National Academy Member: N

**Participant Type:** Graduate Student (research assistant)  
**Participant:** Shannon R. Serrao  
**Person Months Worked:** 15.00 **Funding Support:**  
Project Contribution:  
National Academy Member: N

**Participant Type:** Graduate Student (research assistant)  
**Participant:** James E. Stidham III  
**Person Months Worked:** 13.00 **Funding Support:**  
Project Contribution:  
National Academy Member: N

**Participant Type:** Postdoctoral (scholar, fellow or other postdoctoral position)  
**Participant:** Priyanka Priyanka  
**Person Months Worked:** 15.00 **Funding Support:**  
Project Contribution:  
National Academy Member: N

**Participant Type:** Graduate Student (research assistant)  
**Participant:** Riya Nandi

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**Person Months Worked:** 15.00  
Project Contribution:  
National Academy Member: N

**Funding Support:**

**International Travel:**

ITA 7 days

ESP 7 days

ITA 7 days

**International Collaboration:**

CHN

CHE

DEU

DEU

**ARTICLES:**

**Publication Type:** Journal Article      Peer Reviewed: Y      **Publication Status:** 1-Published

**Journal:** Journal of Physics A: Mathematical and Theoretical

Publication Identifier Type: DOI

Publication Identifier: 10.1088/1751-8121/aa87a8

Volume: 50

Issue: 40

First Page #: 404005

Date Submitted: 8/23/18 12:00AM

Date Published: 10/1/17 4:00AM

Publication Location:

**Article Title:** A stochastic analysis of the spatially extended May–Leonard model

**Authors:** Shannon R. Serrao, Uwe C. Täuber

**Keywords:** stochastic population dynamics, spatially extended May-Leonard model, spatio-temporal patterns, complex Ginzburg-Landau equation, intrinsic noise effects, field-theoretic analysis

**Abstract:** Numerical studies of the May-Leonard model for cyclically competing species exhibit spontaneous spatial structures in the form of spirals. It is desirable to obtain a coarse-grained evolution equation describing spatio-temporal pattern formation in such spatially extended stochastic population dynamics models. Extending earlier work on the corresponding deterministic system, we derive the complex Ginzburg-Landau equation as the effective representation of the fully stochastic dynamics of this paradigmatic model for cyclic dominance near its Hopf bifurcation, and for small fluctuations in the three-species coexistence regime. The internal stochastic reaction noise is accounted for through the Doi-Peliti coherent-state path integral formalism, and subsequent mapping to three coupled non-linear Langevin equations. This analysis provides constraints on the model parameters that allow time scale separation and hence a further reduction to just two coarse-grained slow degrees of freedom.

**Distribution Statement:** 3-Distribution authorized to U.S. Government Agencies and their contractors

Acknowledged Federal Support: Y

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## as of 25-Jan-2023

**Publication Type:** Journal Article      Peer Reviewed: Y      **Publication Status:** 1-Published

**Journal:** Journal of Statistical Mechanics: Theory and Experiment

Publication Identifier Type: DOI

Publication Identifier: 10.1088/1742-5468/aae2dd

Volume: 2018

Issue: 10

First Page #: 103208

Date Submitted: 7/25/19 12:00AM

Date Published: 10/1/18 4:00AM

Publication Location:

**Article Title:** Dynamic critical properties of non-equilibrium Potts models with absorbing states

**Authors:** Ahmadreza Azizi, James Stidham, Michel Pleimling

**Keywords:** absorbing states, classical phase transitions, dynamical processes, kinetic Ising models

**Abstract:** We present extensive numerical simulations of a family of nonequilibrium Potts models with absorbing states that allows for a variety of scenarios, depending on the number of spin states and the range of the spin-spin interactions. These scenarios encompass a voter critical point, a discontinuous transition as well as the presence of both a symmetry-breaking phase transition and an absorbing phase transition. While we also investigate standard steady-state quantities, our emphasis is on time-dependent quantities that provide insights into the transient properties of the models.

**Distribution Statement:** 3-Distribution authorized to U.S. Government Agencies and their contractors

Acknowledged Federal Support: Y

**Publication Type:** Journal Article      Peer Reviewed: Y      **Publication Status:** 1-Published

**Journal:** Physical Review B

Publication Identifier Type: DOI

Publication Identifier: 10.1103/PhysRevB.99.064417

Volume: 99

Issue: 6

First Page #:

Date Submitted: 7/25/19 12:00AM

Date Published: 2/1/19 5:00AM

Publication Location:

**Article Title:** Nonuniversal critical aging scaling in three-dimensional Heisenberg antiferromagnets

**Authors:** Riya Nandi, Uwe C. Täuber

**Keywords:** antiferromagnet, critical dynamics, aging scaling, autocorrelation function

**Abstract:** We numerically investigate the stationary and nonequilibrium critical dynamics in three-dimensional isotropic Heisenberg antiferromagnets. Since the nonconserved staggered magnetization couples dynamically to the conserved magnetization density, we employ a hybrid simulation algorithm that combines reversible spin precession with relaxational Kawasaki spin-exchange processes. We measure the dynamic critical exponent and identify a suitable intermediate time window to obtain the aging scaling exponents. Our results support an earlier renormalization-group prediction: While the critical aging collapse exponent assumes a universal value, the associated temporal decay exponent in the two-time spin autocorrelation function depends on the initial distribution of the conserved fields; here, specifically on the width of the initial spin orientation distribution.

**Distribution Statement:** 3-Distribution authorized to U.S. Government Agencies and their contractors

Acknowledged Federal Support: Y

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## as of 25-Jan-2023

**Publication Type:** Journal Article      Peer Reviewed: Y      **Publication Status:** 1-Published  
**Journal:** Physical Review E  
**Publication Identifier Type:** DOI      **Publication Identifier:** 10.1103/PhysRevE.99.052407  
**Volume:** 99      **Issue:** 5      **First Page #:**  
**Date Submitted:** 7/25/19 12:00AM      **Date Published:** 5/1/19 12:00AM  
**Publication Location:**

**Article Title:** Effects of inhibitory and excitatory neurons on the dynamics and control of avalanching neural networks

**Authors:** Jacob Carroll, Ada Warren, Uwe C. Täuber

**Keywords:** neural network dynamics, avalanches, control

**Abstract:** The statistical analysis of the collective neural activity known as avalanches provides insight into the proper behavior of brains across many species. We consider a neural network model based on the work of Lombardi, Herrmann, De Arcangelis et al. that captures the relevant dynamics of neural avalanches, and we show how tuning the fraction of inhibitory neurons in this model alters the connectivity of the network over time, removes exponential cut-offs present in the distributions of avalanche size and duration, and transitions the power spectral density of the network into an “epileptic” regime. We propose that the brain operates away from this power-law regime of low inhibitory fraction to protect itself from the dominating avalanches present in these extended distributions. We present control strategies that curtail these power-law distributions through either random or, more effectively, targeted disabling of excitatory neurons.

**Distribution Statement:** 3-Distribution authorized to U.S. Government Agencies and their contractors  
**Acknowledged Federal Support:** Y

**Publication Type:** Journal Article      Peer Reviewed: Y      **Publication Status:** 1-Published  
**Journal:** Discrete & Continuous Dynamical Systems - S  
**Publication Identifier Type:** DOI      **Publication Identifier:** 10.3934/dcdss.2020072  
**Volume:** 0      **Issue:** 0      **First Page #:** 1  
**Date Submitted:** 7/30/19 12:00AM      **Date Published:**  
**Publication Location:**

**Article Title:** Sub-Riemannian geometry and finite time thermodynamics Part 1: The stochastic oscillator

**Authors:** Yunlong Huang, P. S. Krishnaprasad

**Keywords:** geometric control, maximum principle, heat engine

**Abstract:** The field of sub-Riemannian geometry has flourished through the strong interactions between problems arising in applied science (such as robotics) and questions of a pure mathematical character. Methods of control theory have been found to be basic tools for answering such questions. In this paper, we find a useful role for the vantage point of sub-Riemannian geometry in attacking a problem of interest in nonequilibrium statistical mechanics: how does one create rules for operation of micro- and nano-scale systems (heat engines) that are subject to fluctuations from the surroundings, so as to be able to do useful things such as converting heat into work over a cycle of operation? We exploit geometric optimal control theory to produce such rules selected for maximal efficiency. This is done by working concretely with a model problem, the stochastic oscillator. Essential to our work is a separation of time scales used with great efficacy by physicists and justified in the linear response regime.

**Distribution Statement:** 3-Distribution authorized to U.S. Government Agencies and their contractors  
**Acknowledged Federal Support:** Y

# RPPR Final Report

## as of 25-Jan-2023

**Publication Type:** Journal Article      Peer Reviewed: Y      **Publication Status:** 1-Published

**Journal:** Physical Review E

Publication Identifier Type: DOI

Publication Identifier: 10.1103/PhysRevE.100.062122

Volume: 100

Issue: 6

First Page #:

Date Submitted: 7/20/20 12:00AM

Date Published: 12/1/19 5:00AM

Publication Location:

**Article Title:** Transverse temperature interfaces in the Katz-Lebowitz-Spohn driven lattice gas

**Authors:** Ruslan I. Mukhamadiarov, , Uwe C. Täuber

**Keywords:** driven lattice gases, totally asymmetric exclusion process, Katz-Lebowitz-Spohn model, pattern formation, spatial inhomogeneities, blockage

**Abstract:** We explore the spatial patterns that emerge in a two-dimensional spatially inhomogeneous Katz-Lebowitz-Spohn (KLS) driven lattice gas with attractive nearest-neighbor interactions. The domain is split into two regions with hopping rates governed by different temperatures  $T > T_c$  and  $T_c$ , the critical temperature for phase ordering. The temperature boundaries are oriented perpendicular to the drive. In the hotter region, the system behaves like the (totally) asymmetric exclusion processes (TASEP), and experiences particle blockage in front of the interface to the critical region. Transport in the high-temperature subsystem is impeded by the lower current in the cooler region. The density profiles in both subsystems are similar to the open-boundary TASEP coexistence and maximal-current phases. If the lower temperature is set to  $T_c$ , we detect marked fluctuation corrections to the mean-field density profiles, e.g., the corresponding critical KLS power-law density decay near the interfaces.

**Distribution Statement:** 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info  
Acknowledged Federal Support: Y

**Publication Type:** Journal Article      Peer Reviewed: Y      **Publication Status:** 1-Published

**Journal:** Physical Review E

Publication Identifier Type: DOI

Publication Identifier: 10.1103/PhysRevE.101.022101

Volume: 101

Issue: 2

First Page #:

Date Submitted: 7/20/20 12:00AM

Date Published: 2/1/20 5:00AM

Publication Location:

**Article Title:** Feedback control of surface roughness in a one-dimensional Kardar-Parisi-Zhang growth process

**Authors:** , Uwe C. Täuber, Michel Pleimling

**Keywords:** Driven interfaces, Kardar-Parisi-Zhang equation, feedback control, surface roughness

**Abstract:** Control of generically scale-invariant systems, i.e., targeting specific cooperative features in nonlinear stochastic interacting systems with many degrees of freedom subject to strong fluctuations and correlations that are characterized by power laws, remains an important open problem. We study the control of surface roughness during a growth process described by the Kardar-Parisi-Zhang (KPZ) equation in 1+1 dimensions. We achieve the saturation of the mean surface roughness to a prescribed value using nonlinear feedback control. While the intermediate time kinetics is governed by KPZ scaling, at later times a linear regime prevails, namely the relaxation toward the desired surface roughness. The temporal crossover region between these two distinct regimes displays intriguing scaling behavior that is characterized by nontrivial exponents and involves the number of controlled Fourier modes. Due to the control, the height probability distribution becomes negatively skewed.

**Distribution Statement:** 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info  
Acknowledged Federal Support: Y

# RPPR Final Report

## as of 25-Jan-2023

**Publication Type:** Journal Article Peer Reviewed: Y **Publication Status:** 1-Published

**Journal:** Physical Review E

Publication Identifier Type: DOI

Publication Identifier: 10.1103/PhysRevE.102.022112

Volume: 102

Issue: 2

First Page #:

Date Submitted: 8/11/20 12:00AM

Date Published: 8/1/20 4:00AM

Publication Location:

**Article Title:** Critical phenomena in the presence of symmetric absorbing states; A microscopic spin model with tunable parameters

**Authors:** Ahmadreza Azizi, Michel Pleimling

**Keywords:** Absorbing states, critical phenomena, spin models, voter model

**Abstract:** The Langevin description of systems with two symmetric absorbing states yields a phase diagram with three different phases separated by critical lines belonging to three different universality classes: generalized voter, Ising, directed percolation. We present a microscopic spin model with two symmetric absorbing states that has the property that the model parameters can be varied in a continuous way. Extensive numerical simulations indicate that all features of the Langevin description are encountered for our two-dimensional microscopic spin model. The Ising and directed percolation lines merge into a generalized voter critical line at a point in parameter space that is not identical to the classical voter model. Different quantities are used to determine the universality classes of the order-disorder and absorbing phase transitions. Time time-dependent quantities at a critical point belonging to the generalized voter universality class reveal a more complicated picture.

**Distribution Statement:** 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info  
Acknowledged Federal Support: Y

**Publication Type:** Journal Article Peer Reviewed: Y **Publication Status:** 1-Published

**Journal:** Physical Review E

Publication Identifier Type: DOI

Publication Identifier: 10.1103/PhysRevE.102.042126

Volume: 102

Issue: 4

First Page #:

Date Submitted: 7/29/21 12:00AM

Date Published: 10/1/20 8:00AM

Publication Location:

**Article Title:** Coupled two-species model for the pair contact process with diffusion

**Authors:** Shengfeng Deng, Wei Li, Uwe C. Täuber

**Keywords:** Absorbing state phase transition, nonequilibrium critical dynamics,

**Abstract:** The contact process with diffusion defined by the binary reactions  $B + B \rightarrow B + B + B$ ,  $B + B \rightarrow ?$  and diffusive particle spreading exhibits an unusual active to absorbing phase transition whose universality class has long been disputed. Multiple studies have indicated that an explicit account of particle pair degrees of freedom may be required to properly capture this system's effective long-time, large-scale behavior. We introduce a two-species representation for the PCPD in which single particles B and particle pairs A are dynamically coupled according to the stochastic reaction processes  $B + B \rightarrow A$ ,  $A \rightarrow A + B$ ,  $A \rightarrow ?$ , and  $A \rightarrow B + B$ , with each particle type diffusing independently. Mean-field analysis reveals that the phase transition of this model is driven by competition and balance between the two species. We employ Monte Carlo simulations in one, two, and three dimensions to demonstrate that this model consistently captures the pertinent features of the PCPD. ...

**Distribution Statement:** 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info  
Acknowledged Federal Support: Y

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## as of 25-Jan-2023

**Publication Type:** Journal Article      Peer Reviewed: Y      **Publication Status:** 1-Published

**Journal:** Physical Review E

Publication Identifier Type: DOI

Publication Identifier: 10.1103/PhysRevE.102.052114

Volume: 102

Issue: 5

First Page #:

Date Submitted: 7/29/21 12:00AM

Date Published: 11/1/20 4:00AM

Publication Location:

**Article Title:** Critical dynamics of anisotropic antiferromagnets in an external field

**Authors:** Riya Nandi, Uwe C. Täuber

**Keywords:** Critical dynamics, anisotropic antiferromagnets, dynamic scaling, aging

**Abstract:** We numerically investigate the nonequilibrium critical dynamics in three-dimensional anisotropic antiferromagnets in the presence of an external magnetic field. The phase diagram of this system exhibits two critical lines that meet at a bicritical point. The nonconserved components of the staggered magnetization order parameter couple dynamically to the conserved component of the magnetization density. Employing a hybrid computational algorithm that combines reversible spin precession with relaxational Monte Carlo updates, we study the aging scaling dynamics for the model C critical line, identifying the critical initial slip, autocorrelation, and aging exponents for both the order parameter and the conserved field. We further probe the model F critical line by investigating the system size dependence of the characteristic spin wave frequencies near criticality and measure the dynamic critical exponents for the order parameter including its aging scaling at the bicritical point.

**Distribution Statement:** 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info  
**Acknowledged Federal Support:** Y

**Publication Type:** Journal Article      Peer Reviewed: Y      **Publication Status:** 1-Published

**Journal:** Journal of Statistical Mechanics: Theory and Experiment

Publication Identifier Type: DOI

Publication Identifier: 10.1088/1742-5468/abc7b9

Volume: 2020

Issue: 11

First Page #: 113207

Date Submitted: 7/29/21 12:00AM

Date Published: 11/1/20 4:00AM

Publication Location:

**Article Title:** Parallel temperature interfaces in the Katz–Lebowitz–Spohn driven lattice gas

**Authors:** Ruslan I Mukhamadiarov, Uwe C Täuber

**Keywords:** driven diffusive systems, numerical simulations, fluctuation phenomena, stochastic particle dynamics

**Abstract:** We explore a variant of the Katz–Lebowitz–Spohn driven lattice gas in two dimensions, where the lattice is split into two regions that are coupled to heat baths with distinct temperatures. The geometry was arranged such that the temperature boundaries are oriented parallel to the external particle drive and resulting net current. We have explored the changes in the dynamical behavior that are induced by our choice of the hopping rates across the temperature boundaries. If these hopping rates at the interfaces satisfy particle-hole symmetry, the current difference across them generates a vector flow diagram akin to a vortex sheet. We have studied the finite-size scaling of the particle density fluctuations in both temperature regions, and observed that it is controlled by the respective temperature values... We have also considered another possible choice of the hopping rates across the temperature interfaces that explicitly breaks particle-hole symmetry...

**Distribution Statement:** 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info  
**Acknowledged Federal Support:** Y

## RPPR Final Report as of 25-Jan-2023

**Publication Type:** Journal Article      Peer Reviewed: Y      **Publication Status:** 1-Published

**Journal:** Scientific Reports

Publication Identifier Type: DOI

Publication Identifier: 10.1038/s41598-020-80162-y

Volume: 11

Issue: 1

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Date Submitted: 7/29/21 12:00AM

Date Published: 1/1/21 5:00AM

Publication Location:

**Article Title:** Social distancing and epidemic resurgence in agent-based susceptible-infectious-recovered models

**Authors:** Ruslan I. Mukhamadiarov, Shengfeng Deng, Shannon R. Serrao, , Riya Nandi, Louie Hong Yao, Uwe C

**Keywords:** Covid-19 pandemic; infectious disease spreading; epidemic resurgence; social distancing; stochastic spatial SIR model

**Abstract:** Once an epidemic outbreak has been effectively contained through non-pharmaceutical interventions, a safe protocol is required for the subsequent release of social distancing restrictions to prevent a disastrous resurgence of the infection. We report individual-based numerical simulations of stochastic susceptible-infectious-recovered model variants on four distinct spatially organized lattice and network architectures wherein contact and mobility constraints are implemented. We robustly find that the intensity and spatial spread of the epidemic recurrence wave can be limited to a manageable extent provided release of these restrictions is delayed sufficiently (for a duration of at least thrice the time until the peak of the unmitigated outbreak) and long-distance connections are maintained on a low level (limited to less than five percent of the overall connectivity).

**Distribution Statement:** 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info

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**Publication Type:** Journal Article      Peer Reviewed: Y      **Publication Status:** 1-Published

**Journal:** Journal of Statistical Physics

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Volume: 182

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Date Submitted: 7/29/21 12:00AM

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Publication Location:

**Article Title:** One dimensional exclusion process with dynein inspired hops: Simulation and mean field analysis

**Authors:** Riya Nandi, Priyanka

**Keywords:** Exclusion process · Molecular motors · Non-equilibrium stationary state · fluctuations

**Abstract:** We introduce a one-dimensional non-equilibrium lattice gas model representing the processive motion of dynein molecular motors over the microtubule. We study both dynamical and stationary state properties for the model consisting of hardcore particles hopping on the lattice with variable step sizes. We find that the stationary state gap-distribution exhibits striking peaks around gap sizes that are multiples of the maximum step size, for both open and periodic boundary conditions. We verified this feature using a mean-field calculation. For open boundary conditions, we observe damped oscillator-like distribution of particles over the lattice with a periodicity equal to the maximum step size. To characterize transient dynamics, we measure the mean square displacement that shows weak superdiffusive growth with exponent  $\approx 1.34$  for periodic boundary and ballistic growth for open boundary conditions at early times. We also study the effect of Langmuir dynamics on the density profile.

**Distribution Statement:** 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info

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**Publication Type:** Journal Article      Peer Reviewed: Y      **Publication Status:** 1-Published

**Journal:** Journal of Physics A: Mathematical and Theoretical

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Publication Identifier: 10.1088/1751-8121/abe753

Volume: 54

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Publication Location:

**Article Title:** The role of the non-linearity in controlling the surface roughness in the one-dimensional Kardar–Parisi–Zhang growth process

**Authors:** Priyanka, Uwe C. Täuber, Michel Pleimling

**Keywords:** surface roughness, control, Kardar–Parisi–Zhang equation

**Abstract:** We explore linear control of the one-dimensional non-linear Kardar-Parisi-Zhang equation with the goal to understand the effects the control process has on the dynamics and on the stationary state of the resulting stochastic growth kinetics. In linear control, the intrinsic non-linearity of the system is maintained at all times. In our protocol, the control is applied to only a small number  $n_c$  of Fourier modes. The stationary-state roughness is obtained analytically in the small- $n_c$  regime with weak non-linear coupling wherein the controlled growth process is found to result in Edwards-Wilkinson dynamics. Furthermore, when the non-linear KPZ coupling is strong, we discern a regime where the controlled dynamics shows scaling in accordance to the KPZ universality class. We perform a detailed numerical analysis to investigate the controlled dynamics subject to weak as well as strong non-linearity. ...

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**Publication Type:** Journal Article      Peer Reviewed: Y      **Publication Status:** 1-Published

**Journal:** Journal of Physics A: Mathematical and Theoretical

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Volume: 54

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Date Submitted: 7/29/21 12:00AM

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Publication Location:

**Article Title:** Rare extinction events in cyclic predator–prey games

**Authors:** Shannon R. Serrao, Tim Ritmeester, Hildegard Meyer-Ortmanns

**Keywords:** rare events, WKB-approach, evolutionary game theory, predator–prey dynamics, species extinction

**Abstract:** In the May-Leonard model of three cyclically competing species, we analyze the statistics of rare events in which all species go extinct due to strong but rare fluctuations. These fluctuations are from the tails of the probability distribution of species concentrations. They render a coexistence of three populations unstable even if the coexistence is stable in the deterministic limit. We determine the mean time to extinction by using a WKB-ansatz in the master equation that represents the stochastic description of this model. The calculation is reduced to a problem of classical mechanics and amounts to solving a Hamilton-Jacobi equation with zero-energy Hamiltonian. We solve the corresponding Hamilton's equations of motion in six-dimensional phase space numerically by using the Iterative Action Minimization Method. This allows to project on the optimal path to extinction, starting from a parameter choice where the three-species coexistence-fixed point undergoes a Hopf bifurcation...

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**Journal:** Journal of Physics A: Mathematical and Theoretical

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Volume: 55

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Date Submitted: 10/17/22 12:00AM

Date Published: 12/1/21 5:00AM

Publication Location:

**Article Title:** Requirements for the containment of COVID-19 disease outbreaks through periodic testing, isolation, and quarantine

**Authors:** Ruslan I Mukhamadiarov, Shengfeng Deng, Shannon R Serrao, , Lauren M Childs, Uwe C Täuber

**Keywords:** epidemic spreading, epidemic control, agent-based Monte Carlo simulations, 2D small-world networks

**Abstract:** We employ individual-based Monte Carlo computer simulations of a stochastic SEIR model variant on a two-dimensional Newman–Watts small-world network to investigate the control of epidemic outbreaks through periodic testing and isolation of infectious individuals, and subsequent quarantine of their immediate contacts. Using disease parameters informed by the COVID-19 pandemic, we investigate the effects of various crucial mitigation features on the epidemic spreading: fraction of the infectious population that is identifiable through the tests; testing frequency; time delay between testing and isolation of positively tested individuals; and the further time delay until quarantining their contacts as well as the quarantine duration. We thus determine the required ranges for these intervention parameters to yield effective control of the disease through both considerable delaying the epidemic peak and massively reducing the total number of sustained infections.

**Distribution Statement:** 1-Approved for public release; distribution is unlimited.

Acknowledged Federal Support: **Y**

**Publication Type:** Journal Article      Peer Reviewed: Y      **Publication Status:** 1-Published

**Journal:** The European Physical Journal B

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Date Submitted: 10/17/22 12:00AM

Date Published: 8/1/21 4:00AM

Publication Location:

**Article Title:** Stabilizing spiral structures and population diversity in the asymmetric May–Leonard model through immigration

**Authors:** Shannon R. Serrao, Uwe C. Täuber

**Keywords:** Population dynamics, cyclic competition, Monte Carlo simulations, spontaneous structure formation, ecological stabilization

**Abstract:** We study the induction and stabilization of spiral structures for the cyclic three-species stochastic May–Leonard model with asymmetric predation rates on a spatially inhomogeneous two-dimensional toroidal lattice using Monte Carlo simulations. In an isolated setting, strongly asymmetric predation rates lead to rapid extinction from coexistence of all three species to a single surviving population. However, when the asymmetric competing system is coupled via diffusive proliferation to a fully symmetric May–Leonard patch, the stable spiral patterns from this region induce transient plane-wave fronts and ultimately quasi-stationary spiral patterns in the vulnerable asymmetric region. Thus, the endangered ecological subsystem may effectively become stabilized through immigration from even a much smaller stable region. We propose a (semi-)quantitative criterion for the spiral oscillations to be sustained in the asymmetric region.

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Volume: 23

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Publication Location:

**Article Title:** Dynein-Inspired Multilane Exclusion Process with Open Boundary Conditions

**Authors:** Riya Nandi, Uwe C. Täuber, Priyanka

**Keywords:** dynein motors; exclusion process; phase diagram; dwell time distribution

**Abstract:** Motivated by the sidewise motions of dynein motors shown in experiments, we use a variant of the exclusion process to model the multistep dynamics of dyneins on a cylinder with open ends. Due to the varied step sizes of the particles in a quasi-two-dimensional topology, we observe the emergence of a novel phase diagram depending on the various load conditions. Under high-load conditions, our numerical findings yield results similar to the TASEP model with the presence of all three standard TASEP phases, namely the low-density (LD), high-density (HD), and maximal-current (MC) phases. However, for medium- to low-load conditions, for all chosen influx and outflux rates, we only observe the LD and HD phases, and the maximal-current phase disappears. Further, we also measure the dynamics for a single dynein particle which is logarithmically slower than a TASEP particle with a shorter waiting time. Our results also confirm experimental observations of the dwell time distribution.

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Volume: 106

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Publication Location:

**Article Title:** Effects of lattice dilution on the nonequilibrium phase transition in the stochastic susceptible-infectious-recovered model

**Authors:** Ruslan I. Mukhamadiarov, Uwe C. Täuber

**Keywords:** SIR model, critical dynamics, dynamic isotropic percolation, quenched disorder

**Abstract:** We investigate how site dilution, as would be introduced by immunization, affects the properties of the nonequilibrium phase transition in the susceptible-infectious-recovered (SIR) model on regular cubic lattices. According to the Harris criterion, the critical behavior of the SIR model, which is governed by the universal scaling exponents of the dynamic isotropic percolation (DyIP) universality class, should remain unaltered after introducing impurities. However, when the SIR reactions are simulated for immobile agents on two- and three-dimensional lattices subject to quenched disorder, we observe a wide crossover region characterized by varying effective exponents. Only after a sufficient increase of the lattice sizes does it become clear that the SIR system must transition from that crossover regime before the effective critical exponents asymptotically assume the expected DyIP values. This transient region becomes drastically diminished when we enable diffusive agent mobility.

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Date Submitted: 10/17/22 12:00AM

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Publication Location:

**Article Title:** Emerging spatiotemporal patterns in cyclic predator-prey systems with habitats

**Authors:** Hana Mir, James Stidham, Michel Pleimling

**Keywords:** Population dynamics, cyclic competition, habitats, spatiotemporal patterns

**Abstract:** Three-species cyclic predator-prey systems establish spiral waves that allow species to coexist. We analyze a structured heterogeneous system which gives one species an advantage to escape predation in an "habitat" area and study the effect on species coexistence and emerging spatiotemporal patterns.

Counterintuitively, the predator of the advantaged species emerges as dominant species with the highest average density inside the habitat. The species given the advantage in the form of an escape rate has the lowest average density until some threshold value for the escape rate is exceeded, after which the density of the species with the advantage overtakes that of its prey. Numerical analysis of the spatial density of each species and of the spatial two-point correlation function for both inside and outside the habitats allow a detailed quantitative discussion. Our analysis is extended to a six-species game that exhibits spontaneous spiral waves, with similar results.

**Distribution Statement:** 1-Approved for public release; distribution is unlimited.

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**Journal:** Physical Review E

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Date Published: 12/1/21 5:00AM

Publication Location:

**Article Title:** Spatiotemporal patterns emerging from a spatially localized time-delayed feedback scheme

**Authors:** Jason Czak, Michel Pleimling

**Keywords:** Gray-Scott reaction-diffusion system, local control, spatiotemporal patterns, spatiotemporal transient chaos

**Abstract:** In attempts to manage spatiotemporal transient chaos in spatially extended systems, these systems are often subjected to protocols that perturb them as a whole and stabilize globally a new dynamic regime, as, for example, a uniform steady state. We show that selectively perturbing only part of a system can generate space-time patterns that are not observed when controlling the whole system. Depending on the protocol used, these new patterns can emerge either in the perturbed or the unperturbed region. Specifically, we use a spatially localized time-delayed feedback scheme on the one-dimensional Gray-Scott reaction-diffusion system in the transient chaotic regime and demonstrate, through numerical integration of the resulting kinetic equations, the stabilization of spatially localized space-time patterns that can be perfectly periodic. The mechanism underlying the observed pattern generation is related to diffusion across the interfaces separating the perturbed and unperturbed regions.

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### CONFERENCE PAPERS:

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**Conference Name:** 2018 IEEE Conference on Decision and Control (CDC)

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Conference Date: 17-Dec-2018

Date Published:

Conference Location: Miami Beach, FL

**Paper Title:** A variational problem on the probability simplex

**Authors:** Vidya Raju, P. S. Krishnaprasad

Acknowledged Federal Support: Y

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**DISSERTATIONS:**

**Publication Type:** Thesis or Dissertation

**Institution:** Virginia Polytechnic Institute and State University

Date Received: 30-Jul-2019

Completion Date: 2/20/19 6:35PM

**Title:** Examining the dynamics of biologically inspired systems far from equilibrium

**Authors:** Jacob A. Carroll

Acknowledged Federal Support: **Y**

**Publication Type:** Thesis or Dissertation

**Institution:** Virginia Polytechnic Institute and State University

Date Received: 30-Jul-2021

Completion Date: 12/9/20 3:42PM

**Title:** Stochastic effects on extinction and pattern formation in the three-species cyclic May–Leonard model

**Authors:** Shannon Reuben Serrao

Acknowledged Federal Support: **Y**

**Publication Type:** Thesis or Dissertation

**Institution:** Virginia Polytechnic Institute and State University

Date Received: 30-Jul-2021

Completion Date: 5/7/20 2:48PM

**Title:** Study of critical phenomena with Monte Carlo and machine learning techniques

**Authors:** Ahmadreza Azizi

Acknowledged Federal Support: **Y**

**Publication Type:** Thesis or Dissertation

**Institution:** Virginia Polytechnic Institute and State University

Date Received: 30-Jul-2021

Completion Date: 3/4/21 4:02PM

**Title:** Non-equilibrium dynamics in three-dimensional magnetic spin models and molecular motor-inspired one-dimensional exclusion processes

**Authors:** Riya Nandi

Acknowledged Federal Support: **Y**

**Publication Type:** Thesis or Dissertation

**Institution:** Virginia Polytechnic Institute and State University

Date Received: 30-Jul-2021

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**Title:** Controlling non-equilibrium dynamics in lattice gas models

**Authors:** Ruslan I. Mukhamadiarov

Acknowledged Federal Support: **Y**

**Publication Type:** Thesis or Dissertation

**Institution:** Central China Normal University

Date Received: 30-Jul-2021

Completion Date: 11/15/20 4:12PM

**Title:** Phase transitions in unitary and binary stochastic contact processes

**Authors:** Shengfeng Deng

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**Publication Type:** Thesis or Dissertation

**Institution:** Virginia Polytechnic Institute and State University

Date Received: 17-Oct-2022

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**Title:** Ordering processes and pattern formation in systems far from equilibrium

**Authors:** James E. Stidham III

Acknowledged Federal Support: **Y**

**Publication Type:** Thesis or Dissertation

**Institution:** Virginia Polytechnic Institute and State University

Date Received: 31-Oct-2022

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**Title:** A study of the effects of spatially localized time-delayed feedback schemes on spatio-temporal patterns

**Authors:** Jason E. Czak

Acknowledged Federal Support: **Y**

**Partners**

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I certify that the information in the report is complete and accurate:

Signature: Uwe Claus Tauber

Signature Date: 11/1/22 11:06AM

Contract Number: W911NF1710156

For this final report, I could not enter the following international travel information under Participants:

PI Uwe C. Tauber

International Travel (Duration of Stay):

PORTUGAL 51, SPAIN 14, FRANCE 20, SWITZERLAND 7, UNITED KINGDOM 35,  
GERMANY 14, ITALY 55