

Extreme Events in Biological Function

Workshop Report — NSF-Simons National Institute for Theory and Mathematics in Biology (NITMB), Chicago, June 1–5, 2026

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Overview

The workshop ‘Extreme Events in Biological Function’ convened roughly 50 mathematicians, physicists and quantitative biologists at the NITMB for five days of research talks, lightning talks and unstructured collaboration time. Its premise was to reevaluate how noise is regarded in living systems. Robustness in biological decision-making has traditionally been framed as a problem of tolerating stochastic variation; the threshold-based bistable switch is a canonical example. A growing body of work over the past five years points instead to the complementary paradigm that extreme and rare events possess effectively deterministic, and therefore predictable, qualities which biological systems can harness.

The scientific program comprised roughly two dozen invited talks spanning extreme value theory, large deviations, first-passage and search processes, stochastic reaction networks and rare-event sampling, with applications ranging from intracellular signaling and neuronal calcium dynamics to bacterial growth, ecological foraging and collective animal behavior. Participants came from institutions in the United States, Canada, the United Kingdom, France, Italy, Mexico, Korea and Australia, and included a deliberate mix of senior researchers, early-career faculty, postdoctoral fellows and graduate students.

Scientific themes

Extreme first-passage times. A central thread was the theory of the fastest of many searchers: when N independent random walkers seek a target, the time of the first arrival scales with the shortest geodesic path and becomes essentially deterministic as N grows, in stark contrast to the mean first-passage time of a single searcher. Talks by Sean Lawley (universality and its breakdown in extremes of diffusion), Jay Newby (extreme first-passage times for populations of identical rare events), Hwai-Ray Tung (extreme first-passage with fast immigration) and Bhargav Karamched (entropic collapse in combinatorial geometries) mapped out the regimes in which this universality holds, where it fails, and how geometry, immigration and heterogeneity among searchers alter the leading-order asymptotics. Denis Grebenkov surveyed scenarios that remain under-studied, including extremes in confined and heterogeneous media.

Large deviations and rare-event dynamics. James MacLaurin presented a large-deviations framework for piecewise-deterministic Markov processes with application to stochastic calcium waves, and Lea Popovic examined the sensitivity of autocatalytic reaction networks to rare fluctuations. Tom Chou considered ordered events in birth–death processes, and James Holehouse and Andrew Mugler addressed how noise shapes the evolution and transience of distributions of subpopulation growth rates, illustrating how population-level phenotypes can be dictated by a small fraction of atypical cells or bacteria.

Search, foraging and anomalous transport. Sidney Redner opened the second day with foraging and starvation dynamics; Denis Boyer and Aanjaneya Kumar discussed diffusion with stochastic synthesis and degradation; and Daniel Gomez and Justin Tzou presented complementary analyses of Lévy-flight search in one- and two-dimensional geometries.

Altogether these talks connected the microscopic statistics of individual movement to the efficiency of search at the population scale.

Cellular and physiological mechanisms. Jun Allard used stochastic calculus to analyze tethered molecular reactions, Gregory Handy presented a reduced Markov-chain model of IP3-receptor calcium release, Anna Nelson modeled microtubule polarity in neurons, Jayson Cortez described plasmid clustering, and Nadia Loy gave a statistical-mechanics account of cell re-orientation under stretch. Hyunjoong Kim examined rare inference failures and the cost of certainty in cellular decision-making, and Jae Kyoung Kim closed the meeting with a talk on structural buffering as a route from noise to precision.

Populations, evolution and collectives. Trevor GrandPre showed how trait-space patterning depends on the tempo and mode of mutation, Erin Beckman presented the chase-escape-with-conversion model of competing spatial populations, and Zachary Kilpatrick demonstrated how social discounting enables fast and reliable collective escape in groups.

Outcomes and emerging directions

Several themes emerged from the discussion sessions. First, the universality of extreme first-passage asymptotics is now well understood for homogeneous diffusive searchers, and the frontier has moved to heterogeneity: searchers with distinct diffusivities or dynamics, targets that are themselves dynamic, and populations that are replenished or depleted during the search. Second, the community identified a need for numerical methods and benchmark problems for rare-event sampling in spatially extended biological models, where naive Monte Carlo is prohibitively expensive and existing importance-sampling schemes are not yet standard. Third, there was strong interest in connecting extreme-event theory to experimental data in immune recognition and neuronal signaling, where single-molecule and single-cell measurements now resolve the tails of the relevant distributions.

To facilitate progress in these frontier problems and sustain connections made at this workshop, we plan to hold follow-up minisymposia at related meetings (e.g. SMB 2027 and SIAM Dynamical Systems 2027) with a view towards submitting a proposal for a follow-up workshop provisionally to be held in three years time (2029) .

Participant feedback

An anonymous survey administered by the Northwestern University Program Evaluation Core on the fourth day of the workshop drew 44 responses. The response was strongly positive: 93% of respondents said the workshop was worth their time, 100% would recommend future NITMB events to colleagues, 98% would consider attending another NITMB workshop, and 91% reported being more likely to invest time at the NITMB as a result of attending. On the scientific side, 91% said the workshop exposed them to mathematics that was new to them, 95% encountered new technical language, 89% felt better equipped to apply mathematical tools to biological questions, and 80% reported increased confidence in interdisciplinary communication. Participants reported an average of 4.5 new professional connections each, and 89% agreed that the meeting provided opportunities for network-building that will continue beyond the event.

Written comments singled out the coherence of the program and the caliber of the talks. One participant wrote that "from the perspective of a coherent research program, this was one of the best workshops I've attended," and another described the talks as "a higher bar than the average workshop or conference," with a "perfect mix of applied modeling and mathematical talks." Several respondents remarked on the sense of an emerging research direction around search processes with a fluctuating number of searchers (immigration, mortality and dynamic

redundancy), and on the value of having the people developing that direction in one room. The plenary talks by Sidney Redner, Jun Allard, Denis Grebenkov and Andrew Mugler were repeatedly mentioned for their accessibility and pedagogical clarity. Multiple participants reported that new collaborations were initiated during the week.

The most consistent constructive suggestion, raised by roughly a fifth of respondents, was increase representation of experimental biologists in any future meetings, both to present unsolved problems in which extreme-value reasoning might apply and to discuss how extreme statistics can be measured in real data; several noted that the program was weighted toward first-passage and foraging problems and would benefit from a broader range of biological applications and intellectual lineages. Individual respondents also suggested coverage of the Luria–Delbrück experiment as a historical anchor for extreme events in biology, stochastic resetting and non-Markovian processes, and more computational methods. Some felt the lightning talks were valuable for encouraging young researchers but less effective at communicating results. This valuable feedback is clear guidance for a follow-up meeting: pairing each mathematical session with an experimental counterpart, and widening the invitation list beyond the core first-passage community.

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