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Heterogeneity for Flocking and Computation: From Biology to Mathematics

By Arthur N. Montanari, Ana Elisa D. Barioni, and Adilson E. Motter

In a murmuration of starlings, abrupt evasive maneuvers from a few birds in response to a passing falcon can trigger a collective response across the whole group. Within a fraction of a second, local turns are amplified through thousands of neighboring interactions between birds, and the entire flock twists and folds as if it were a single organism. During the annual northbound migration of sardines along the coast of South Africa, dense schools rapidly reorganize into spinning bait balls when dolphins approach, using collective geometry to confuse predators and dilute individual risk. On land, herds of millions of wildebeest coordinate traveling direction and timing across open plains and narrow passages during their yearly migration throughout the Serengeti. Desert locusts also march across long distances in the Sahel and Arabian Peninsula, producing vast swarms that move as a unit when tactile stimulation and high population density trigger a phase transition from individualistic to coordinated behavior in the form of rolling waves.

These coordinated group dynamics are often used as a defense mechanism to avoid predation, but they can also support sensing and navigation. Across these and many other examples, animal groups exhibit *collective computation*: a distributed information-processing system in which local interactions give rise to rapid global decision-making. These interactions are mediated by an underlying interaction network, defined by sensory and communication constraints on vision, touch, hydrodynamic, and acoustic cues. No single agent can influence more than a small number of others, yet information propagates at astonishing speed; for example, a small change in speed and direction by a few Pacific blue-eyed fish in response to a threat is sufficient to trigger an escape wave that propagates through the entire school within seconds [3]. Understanding how this computation works—i.e., what information is processed, how it is propagated, and when the dynamics are robust to noise—has become a central question in the study of collective animal behavior. This problem has also sparked strong interest in engineering, where these principles can be applied to the design of swarms of mobile robots, interacting self-driving vehicles, and flocks of drones [5, 6] (see Figure 1).

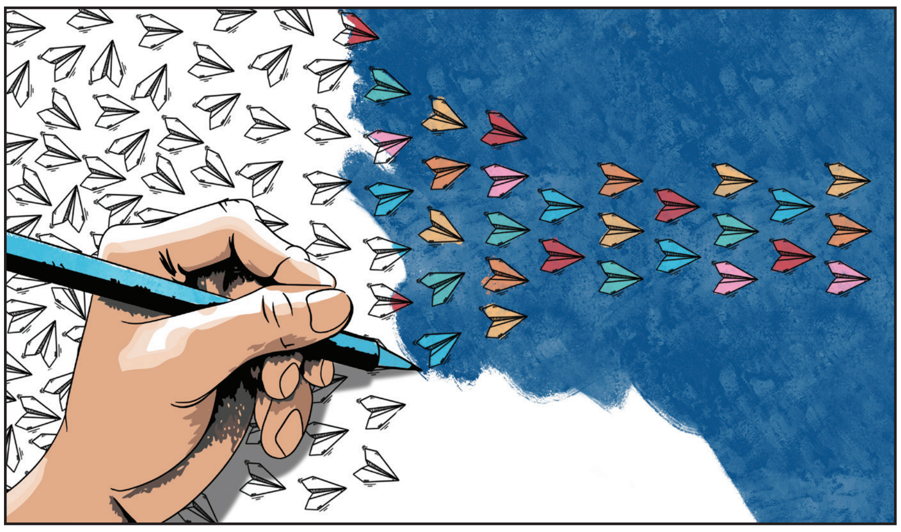

Figure 1. *Artistic conception of heterogeneity as a design mechanism for flocking. Figure courtesy of Camila F. Montanari.*

Given these biological and physical motivations, one might expect the foundational model of flocking to emerge from applied mathematics, physics, engineering, or biology; however, the most influential early model came instead from computer science. In 1987, Craig Reynolds introduced the *boids* model—short for bird-like droids—while working on realistic animation for computer graphics, with the end goal of creating believable collective motion on screen [7]. In this model, each agent follows just three rules:

1. Alignment (match velocity with nearby agents)
2. Separation (avoid crowding neighbors)
3. Cohesion (move toward the center of mass of neighbors).

See **Flocking and Computation** *on page 3*

Why Does Wildfire Smoke Circulate in One Direction?

By Matthew R. Francis

The increased frequency and intensity of wildfires are disastrous consequences of climate change, with effects reaching far beyond the immediate geographical area where they occur. Scientists uncovered an unexpected side-effect of wildfires from the satellite observation of smoke vortices in the stratosphere 35 kilometers above Earth's surface from 2019-2020 Australian wildfires (see Figure 1). Swirls of particles can be a thousand kilometers across—much wider than the wildfires that produced them—and persist for weeks, altering the chemistry of the stratosphere by trapping ozone, carbon monoxide, and water vapor.

The circulation of the smoke particles was not a surprise, but their swirling pattern was: the entire collection of particles rotated in one direction. This defied what typically occurs with other atmospheric vortices, where the top of the vortex rotates in one direction while the bottom rotates the opposite way. To understand this phenomenon, researchers modeled the way smoke rises and circulates.

"The new idea is the participation of the smoke in its own dynamics," Kasturi Shah, an applied mathematician at the University of Cambridge, said. In other words, the vortices observed by satellites are a nonlinear process whereby the smoke particles themselves are partial drivers behind swirling patterns rather than simply passive participants. "The smoke is absorbing sunlight, so it's actually contributing to heating. That heating is setting up the winds and the circulation."

In a paper with Peter Haynes of the Massachusetts Institute of Technology [2], Shah developed simplified dynamical models that reproduce the observed consequences of wildfires: the rising of the smoke and the formation of vortices that rotate in a single direction. She noted that both better data and more detailed simulations are needed, but their theoretical model agrees with work performed independently by other researchers [1].

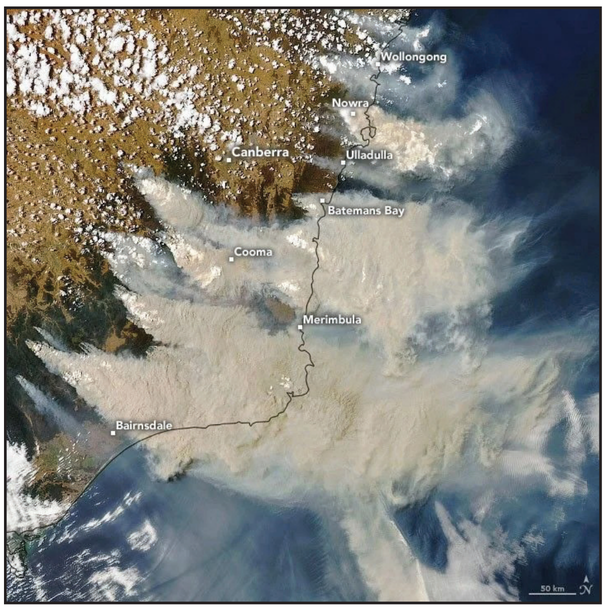

Figure 1. *Satellite image of the Australian wildfires in January 2020. While each fire was geographically small, the smoke they produced spread out into a much wider region, which created unexpected one-directional smoke-swirling behavior. Image courtesy of Joshua Stevens/National Aeronautics and Space Administration Earth Observatory.*

You Spin Me Round

Scientists have studied vortices in a variety of contexts for a long time, as they are of interest in everything from meteorology to plasma physics. The rotation of Earth, for instance, produces large-scale swirls in the atmosphere and water known as the Coriolis effect. Meteorological vortices are further classified as cyclonic or anticyclonic, based on their direction of rotation: in the Northern Hemisphere, cyclones rotate counterclockwise in accordance with the Coriolis effect, while in the Southern Hemisphere they spin clockwise. Anticyclones spin in opposite directions in each hemisphere, due to different atmospheric conditions; Jupiter's Great Red Spot is an anticyclone wider than Earth that has been observed for centuries.

Earth-observation satellites identified large anticyclones in the stratosphere containing carbon-rich particles from the 2017 Canadian wildfires, the 2019-2020 Australian fires, and the 2019 eruption of the island volcano Raikoke in the Pacific Ocean between Japan and the Kamchatka Peninsula. These anticyclones were flat ellipsoids in shape, extending 500 to 1000 kilometers horizontally—much larger in extent than the wildfires or volcano that produced them—but only about five kilometers thick. Each of these vortices persisted for several weeks.

Researchers that attempted to model this anticyclonic phenomenon encountered a major difficulty. If smoke particles were governed by ordinary atmospheric dynamics, the vortices should be anticyclonic at higher elevations and cyclonic at lower heights—otherwise known as a dipole vortex—rather than the monopole single-direction rotation that they observed. However, as Shah, Haynes, and others realized, the simplest models assumed that smoke particles were just along for the ride, at the mercy of atmospheric dynamics. Instead, they found that because the smoke particles are larger and heavier than typical atmospheric molecules, and dark in color, they absorb a disproportionate amount of sunlight and heat up.

"What goes into [our] model [is] the heating provided by the smoke itself and the dynamics of a rotating atmosphere," Shah said. Those warm particles rising

See **Wildfire Smoke** *on page 4*

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Decision-making With Vector-valued Objectives Under Model Uncertainty

Reflections on the SIAM Postdoctoral Support Program

By Gabriela Kováčová
and Igor Cialenco

We had the honor and privilege to be among the first participants to benefit from the SIAM Postdoctoral Support Program[1] — an initiative backed by the SIAM Postdoctoral Support Fund,[2] which was established through a generous gift from Drs. Martin Golubitsky and Barbara Keyfitz. The program provides targeted funding for mentor-mentee pairs from distinct institutions with the goal of fostering research collaboration and supporting professional development. Thanks to this support, we—Gabriela Kováčová as the mentee and Igor Cialenco as the mentor—were able to expand our research pursuits in decision-making with a more fundamental approach, exploring deeper theoretical questions while building a strong collaborative foundation. Although we had worked with each other prior, the research visits made possible by this program allowed us to tackle a broad and substantive research problem together, rather than a more narrowly-scoped project. During these visits, we engaged in productive brainstorming sessions to generate new ideas and gain a deeper understanding of the structure of the underlying problems. These interactions also provided an opportunity to discuss various aspects of careers in the mathematical sciences at length.

Our motivation for this line of research is rooted in two central themes in decision-making: *time inconsistency* and *model uncertainty*. Both of these topics have been studied extensively, particularly over the past two decades. In the context of stochastic control, time inconsistency refers to a class of finite-horizon problems for which the dynamic programming principle (DPP), or Bellman principle of optimality, does not hold. As a result, such problems cannot be solved by a backward recursive procedure. A prominent example is the multi-period portfolio optimization problem under mean-risk criteria. This approach to asset management was originally proposed in the 1950s by the Nobel laureate Harry Markowitz, who argued that investors should evaluate portfolios not only based on their expected returns, but also on their risk, which could be measured, for example, by the variance or standard deviation of returns. Since maximizing the mean return and minimizing the risk are competing objectives, the mean-risk problem is naturally a bi-objective problem. Within the last decade, multi-objective dynamic problems were successfully tackled by deriving a counterpart of DPP that was appropriate for multi-objective problems [8], thus making the problem time consistent. This development is our main reason for considering problems with vector-valued objectives. Other approaches to time-inconsistent stochastic control problems include the so-called *sub-game perfect* approach [3] or dynamic adjustment of the optimization criteria [6].

Model uncertainty refers to the inability to accurately model the dynamics of the underlying stochastic system due to incomplete information, ambiguity about the model, or presence of unobservable factors. It is also referred to as Knightian uncertainty after Knight [7]. For stochastic controlled systems, this means that the controller does not know the true law of the underlying stochastic process *a priori*, but only knows that it belongs to a given family of probability laws. Here, the controller faces not only the randomness of the controlled system, but also the Knightian uncertainty. A significant body of literature is devoted to this problem, particularly for problems in finance and economics wherein flawed models can lead to erroneous investment decisions, ineffective risk management strategies, and inaccurate pricing of financial instruments. One approach to tackle this challenge is through *robust optimization* or a minimax approach, which seeks controls that perform well across various possible models [5]. Other approaches include adaptive control, Bayesian control, adaptive-robust control, and strong robust control [1]. All such methods fundamentally rely on time consistency of the original problem without model uncertainty, however the literature on time-inconsistent control problems that are subject to model uncertainty is sparse. In [2] the authors use the sub-game perfect approach to time-inconsistency and adaptive robust control for model uncertainty. To the best of our knowledge, studying time-inconsistent problems under model uncertainty through the lens of multi-objective stochastic control—while a natural and conceptually appealing approach—remains largely unexplored, with our work being the first to systematically develop this perspective. This enabled us to utilize our combined experiences in model uncertainty and multi-objective control, fostering the development of a novel research direction.

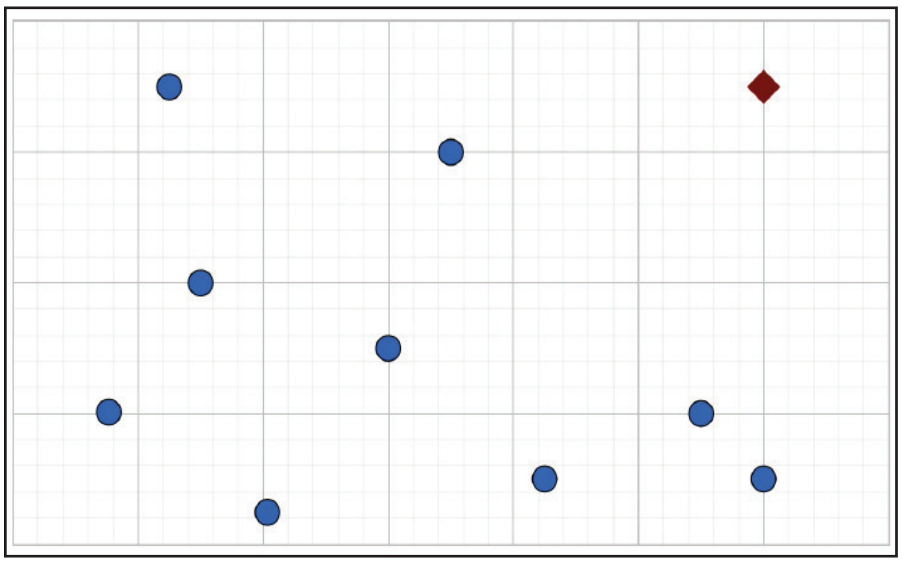

Figure 1. *The blue circles represent a set of vectors $A \subseteq \mathbb{R}^2$ over which we take supremum with respect to coordinate-wise order. Red square is the smallest upper bound for A. Figure courtesy of the authors.*

Formulation of the Problem

We assume that the model uncertainty is modeled as a family of distributions $\mathbb{Q}(\Theta) = \{\mathbb{Q}^\theta : \theta \in \Theta\}$ of the stochastic factor $(Z_t, t = 0,1,\ldots,T)$, parametrized by θ, which belongs to the model uncertainty set $\Theta \subset \mathbb{R}^k$. Consider the controlled dynamics of the state process $(X_t)_{t\in\mathcal{T}}$ and control $(\varphi_t)_{t\in\mathcal{T}}$ given by

$$X_{t+1} = F(t, X_t, \varphi_t, Z_{t+1}), \varphi_t \in A_t(X_t),$$
$$t = 0,1,\ldots,T,$$

where $A_t(x)$ is the feasible set. For simplicity, consider a risk-neutral decision maker interested in the expected terminal multi-loss $\mathbb{E}[\ell(X_T)]$, where $\ell : \mathbb{X} \to \mathbb{R}^d$. If the true model $\theta^* \in \Theta$ for the stochastic factor was known, we would be studying a multi-objective control, without model uncertainty, of the form

$$\underset{(\varphi_t,\ldots,\varphi_{T-1})\in\mathcal{A}^t(X_t)}{\text{minimize}} \quad \mathbb{E}_t^{\theta^*}[\ell(X_T)]$$
$$\text{with respect to } \preceq,$$

where $\preceq$ is a pre-order on the space of $\mathscr{F}_t$-measurable random vectors with corresponding ordering cone $\mathscr{L}_t(C)$. The most commonly used pre-order is the component-wise partial order $\leq$ generated by $\mathscr{L}_t(\mathbb{R}^d_+)$ (see Figures 1 and 2, the latter on page 5). The value function of a multi-objective control problem should be a set-valued functional that attains the so-called upper image of the multi-objective problem [8, 9],

$$\mathcal{V}_t^{\theta^*}(X_t) = \mathrm{cl}\Big(\Big\{\mathbb{E}_t^{\theta^*}[\ell(X_T)] \,|$$
$$(\varphi_t,\ldots,\varphi_{T-1}) \in \mathcal{A}^t(X_t)\Big\} + \mathscr{L}_t(\mathbb{R}^d_+)\Big).$$
$$(1)$$

See **Vector-valued Objectives** *on page 5*

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[1] https://www.siam.org/programs-initiatives/programs/siam-postdoctoral-support-program/

[2] https://www.siam.org/publications/siam-news/articles/siam-establishes-postdoctoral-support-fund/

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Flocking and Computation

Continued from page 1

Despite their simplicity, these rules generate collective motion with remarkably lifelike behavior akin to schools, herds, and flocks. The model was quickly adopted by the film industry—most famously to simulate bat swarms in *Batman Forever*—and later used in video games such as $ABZ\hat{U}$, where advances in processors and graphics cards allowed thousands of agents to be simulated and rendered in real time.

Physicists and applied mathematicians subsequently recognized flocking as a paradigmatic example of self-organization. This led to the influential *Vicsek model,* introduced in 1995 as a minimal description inspired by statistical physics [9]. The model can be viewed as a nonequilibrium analogue of the two-dimensional XY model: instead of spin particles interacting on a fixed lattice, self-propelled particles (agents) move at constant speed v_0 while reorienting their headings θ_i to ensure local alignment. Denoting the position of agent i as $\boldsymbol{q}_i$, the discrete-time dynamics can be formulated as

$$\begin{cases} \boldsymbol{q}_i(t+1) = \boldsymbol{q}_i(t) \\ +v_0 \Delta t \begin{bmatrix} \cos\theta_i(t) \\ \sin\theta_i(t) \end{bmatrix}, \text{(motion)} \\ \theta_i(t+1) = \theta_i(t) \\ +\dfrac{1}{d_i(t)} \sum_j A_{ij}(t)\Big(\theta_j(t) - \theta_i(t)\Big) \\ + \text{noise, (alignment)} \end{cases} \tag{1}$$

where $A(t)$ is the adjacency matrix associated with a network structure and $d_i(t) = \sum_j A_{ij}$ represents the node in-degree. The adjacency matrix encodes the time-varying interactions, often defined through distance-weighted couplings of the form $A_{ij}(t) \propto \|\, \boldsymbol{q}_i(t) - \boldsymbol{q}_j(t)\, \|^{-\beta}$, for $\beta \geq 0$ [2]. Despite accounting only for velocity alignment (the first of Reynolds' rules) while neglecting inertia and explicit attraction-repulsion forces, this simple model exhibits a transition from disordered to coherent motion as the density of agents increases or noise decreases (see Figure 2). The Vicsek model thus provided a theoretical framework for addressing foundational questions, such as the critical density required for self-organization.

A central issue that emerged from this line of work concerns the nature of the interaction network, i.e., who influences whom in the group and if interactions are determined by the distance between agents or some other criteria. Empirical field studies of starling flocks indicate that self-organization is mediated mainly by *topological* interactions, in which each bird responds to a fixed and relatively small number of neighbors. This challenged earlier distance-based assumptions [1]. In controlled lab environments, ray tracing (another technique borrowed from computer graphics) allowed researchers to extract interaction networks directly from video recordings [8]. These studies revealed that animal groups are governed by interaction networks that are weighted, directed, and complex.

However, network structure is only part of the story. Over the past decade, ethologists increasingly recognize another crucial dimension in animal behavior: *agent heterogeneity*. Early models treated agents as identical, but real biological systems are not. Individuals vary in size, sensory acuity, reaction time, and cognitive ability; they also exhibit consistent behavioral differences, with varying levels of boldness, sociability, or exploratory tendency. Empirical studies of fish schooling show that certain inter-individual behavioral differences improve group-level organization and cohesion, demonstrating that collective behavior depends not only on interaction rules but also on the agents' individual behavior [4]. These studies also make the point that heterogeneity is not noise to be averaged out, but a resource exploited to facilitate coordinated responses, damp fluctuations, and prevent group fragmentation — contrary to the old saying that birds of a feather flock together.

A crucial question is whether these insights can be translated into engineered systems. Like animal groups, a swarm of autonomous drones must move cohesively, avoid collisions, track targets, and make real-time decisions under uncertainty. One influential framework to model these systems was introduced by Reza Olfati-Saber, who formulated flocking as a control-theoretic problem [6]. We can illustrate the model considering the problem of a flock tracking a moving target with position $\boldsymbol{q}^*(t)$. The position $\boldsymbol{q}_i(t)$ of agent i is governed by the (continuous-time) second-order differential equation

$$\ddot{\boldsymbol{q}}_i = \underbrace{\sum_j A_{ij}(\boldsymbol{q})(\dot{\boldsymbol{q}}_j - \dot{\boldsymbol{q}}_i)}_{\text{alignment}} - \underbrace{\nabla V(\boldsymbol{q})}_{\text{separation}} + \underbrace{b_i(\boldsymbol{q}^* - \boldsymbol{q}_i) + c_i(\dot{\boldsymbol{q}}^* - \dot{\boldsymbol{q}}_i)}_{\text{cohesion}}, \tag{2}$$

where each term has a clear behavioral interpretation. The first term enforces velocity alignment through network interactions, much like the Vicsek model. The second term introduces separation through a carefully designed energy function $V(\boldsymbol{q})$ whose minima correspond to lattice-like formations; dynamically, the swarm performs a gradient descent on this landscape toward preferred spatial configurations. The final term enforces cohesion, with the feedback gains b_i and c_i controlling how strongly each agent is attracted to the target. Taken together, the model implements all three Reynolds' rules (see Figure 3).

This formulation can explicitly incorporate agent heterogeneity: the feedback gains b_i and c_i encode how strongly each agent responds to positional and velocity deviations from the target motion. Allowing these parameters to vary across agents captures heterogeneity in actuation and responsiveness. Our recent work shows that such heterogeneity substantially improves stability, convergence, and decision-making [5]. In particular, flocks with tunable heterogeneous parameters converge to a desired formation significantly faster than their homogeneous counterparts, accelerating convergence time by approximately 40 percent (see Figure 4a). Agent heterogeneity enhances collective decision-making even in unmapped environments with obstacles, reducing both collision risk and flock fragmentation (see Figure 4b).

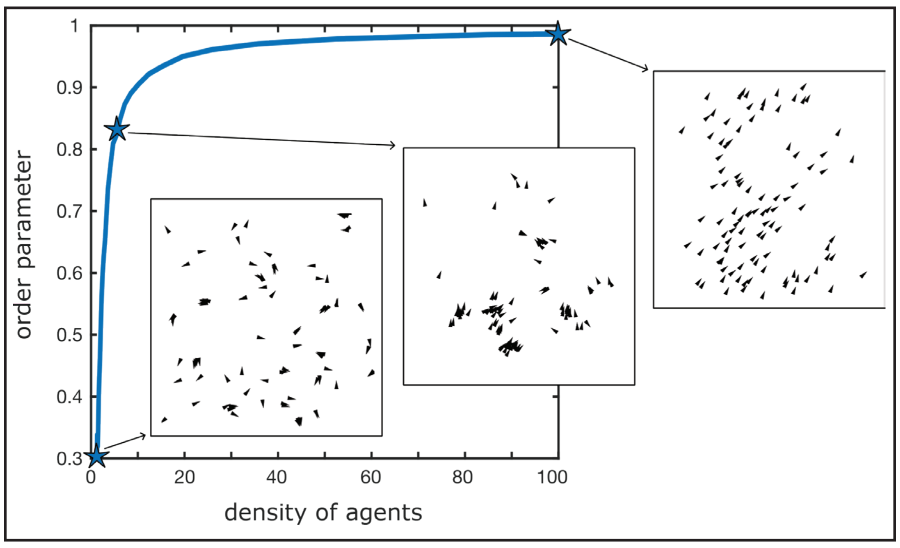

Figure 2. *Phase transition in a Vicsek-type model from a misaligned to aligned flocking state as a function of the density of agents. The results are shown for a time-varying interaction network whose interaction weights are inversely proportional to the inter-agent distances (using periodic boundary conditions). Figure courtesy of Arthur N. Montanari.*

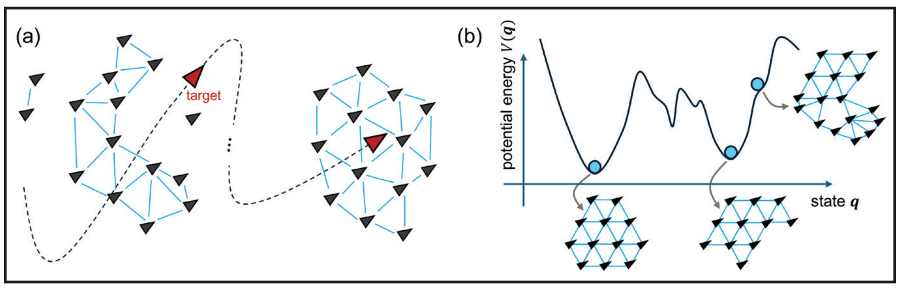

Figure 3. *Collective dynamics and computation in the Olfati-Saber model.* **3a.** *Flock converging toward its control objective: a lattice-like formation centered at the target position.* **3b.** *Diagram of the energy landscape V as a function of the agents' position state $\boldsymbol{q}$, quantifying the state deviation from a desired lattice configuration. The state evolution toward low-energy configurations can be interpreted as a form of collective computation, in which agents seek to minimize a global objective through local interactions, as in many neurocomputational models. Figure courtesy of Arthur N. Montanari.*

From a biological perspective, heterogeneity serves multiple functional roles: a small number of bold individuals can emerge as leaders and guide the group; variability in response times can stabilize collective motion and suppress noise; and sensory diversity can enhance global awareness. Translating these principles into mathematical language leads naturally to models with heterogeneous gains, delays, and interaction rules. These models are directly relevant to engineering applications involving multi-agent systems. As both natural and artificial flocks can be inherently heterogeneous, understanding when diversity enhances flocking, and when it suppresses it, is an exciting frontier in the mathematics of collective behavior.

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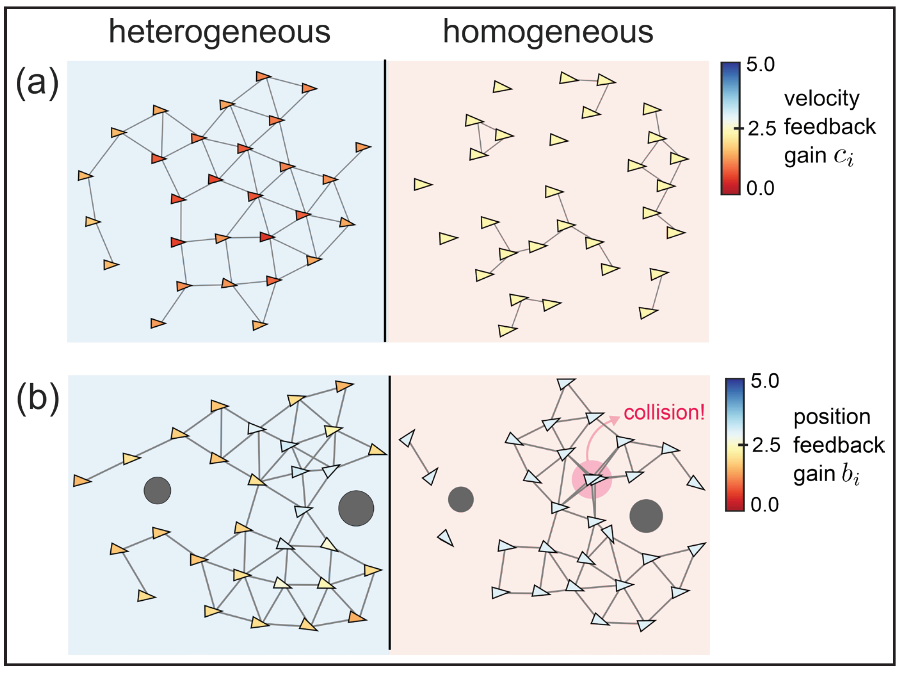

Figure 4. *Flocking promoted by heterogeneity.* **4a.** *For identical initial conditions, the snapshots show that the heterogeneous flock converges to a connected, lattice-like formation, while the homogeneous flock remains disconnected.* **4b.** *When navigating an environment with obstacles, the heterogeneous flock maintains a connected formation, while, in the homogeneous case, the flock fragments and agents collide. In the heterogeneous flocks, agents at the front tend to exhibit distinct gains than those at the center, distinguishing their roles in leadership and group cohesion. See web version of this article for a corresponding animation. Figure courtesy of Arthur N. Montanari.*

Wildfire Smoke

Continued from page 1

into the stratosphere change the dynamics that govern them, leading to a kind of feedback effect. “You end up with a slightly asymmetric pattern where the contours of the smoke, and therefore the heating, are bunched at the top [of the vortex].”

The higher density of warm smoke particles suppresses the counter-rotation, leaving a monopole vortex like those seen in satellite observations.

Turn Turn Turn

To simplify the physics, Shah and Haynes ignored the ellipsoidal character of the smoke vortices, instead assuming a cylindrical axisymmetric geometry. That reduced the model to two dimensions: radial and vertical (r,z), with rotational symmetry around the center of the vortex. Since the smoke vortices are geographically large, the Coriolis effect dominates over small-scale inertial forces, which allowed them to apply further simplifications to the physical model.

With these approximations, the governing equations for the system become:

$$\frac{\partial v}{\partial t} + fu = 0$$

$$f\frac{\partial v}{\partial z} = \frac{R}{H_0}\frac{\partial T}{\partial r}$$

$$\frac{1}{r}\frac{\partial}{\partial r}(ru) + \frac{1}{\rho_0}\frac{\partial}{\partial z}(\rho_0 w) = 0$$

$$\frac{\partial T}{\partial t} + w\left(\frac{\partial T_B}{\partial z} + \frac{\partial T_B}{7H_0}\right) = Q_S - \alpha T$$

where (u,v,w) are the radial, azimuthal, and vertical components of the air velocity. The temperature is divided into a background component $T_B(z)$ and a horizontally varying component $T(r,z)$, R is the ideal gas constant, and f is the Coriolis frequency. The air density $\rho_0(z)$ decreases exponentially with height, while the parameters H_0 and α describe atmospheric stratification and the rate of cooling, respectively. Finally, $Q_S(r,z,t)$ is a heating function directly proportional to the concentration of smoke particles.

The numerical solutions to these coupled nonlinear equations showed that the strength of the heating makes a profound difference to the vortices, particularly in the presence of wind shear in the stratosphere.

“When the heating is weak, this vortex structure is quite weak,” Shah explained, which means wind shear simply destroys it. “If smoke gets injected into the stratosphere, there needs to be enough black and brown carbon to absorb enough sunlight such that it’s strong enough to resist the shear.”

Where There’s Smoke

The next steps, which are already underway, are to create three-dimensional simulations to understand how ellipsoidal vortices form and persist. These models do more than simply explain why vortices are monopole in character, they could provide help for modeling changes in stratospheric chemistry.

“Understanding where these solid particles end up is quite important,” Shah said. “Wildfire smoke particles provide surfaces on which chemical reactions take place that affect stratospheric ozone.”

In other words, fires that cover a relatively small area on Earth’s surface could have detrimental effects high above ground. Shah argued that this means we need to collect higher quality satellite data more frequently to better understand these effects and guide modeling techniques. Since there are only a relatively small number of events studied so far, it is quite probable that with the increase in wildfire occurrence and severity due to climate change, more smoke anticyclones have happened but went unidentified.

Shah also noted that the wildfires that produced these vortices happened in the summer in the hemisphere where they occurred, which is important for several reasons. First, wildfires are simply more likely in summertime, when conditions tend to be drier — though that’s changing with global warming. Second, the stratosphere is more turbulent in wintertime, which might make smoke vortices more unstable. However, with large-scale alterations in the atmosphere as the result of climate change,[1] combined with increased risk of fire throughout the year, all those conditions might not hold forever.

“One extremely challenging thing is to identify where the wildfire smoke has been injected into the stratosphere,” Shah said. “That can be on sometimes quite small scales. Once the smoke has coalesced on a scale that is resolved by the satellites, that’s when you detect it, [which is] an observational challenge.”

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[1] https://climate.mit.edu/explainers/polar-jet-stream-and-polar-vortex

Vector-valued Objectives

Continued from page 2

Moreover, it is also known that the appropriate counterpart of DPP for a multi-objective problem is a recursion of the set-valued value function known as the *set-valued Bellman's principle*:

$$\mathcal{V}_t^{\theta^*}(X_t) = \mathrm{cl}\Big\{\mathbb{E}_t^{\theta^*}[Y] \,|\, \varphi_t \in A_t(X_t),$$
$$Y \in \mathcal{V}_{t+1}^{\theta^*}(F(t, X_t, \varphi_t, Z_{t+1}))\Big\}. \tag{2}$$

These results are significant because, when viewed through the lens of set optimization, they uncover a structure that directly parallels the single-objective case, thereby extending familiar principles to the multi-objective setting. (1) represents the (set-optimization) infimum of the multi-objective problem, and the set-valued Bellman principle (2) can be interpreted analogously as a recursive (set-optimization) infimum that reduces the problem to a sequence of one-step problems. Additionally, the time consistency properties of the problem can be also established within the framework.

A Robust Perspective on Vector-valued Control

As a first attempt at handling multi-objective control under model uncertainty, in [4] we opted to explore the robust approach and establish the corresponding set-valued Bellman's principle of optimality.

The first question that needed to be tackled was the interpretation of the supremum in the arising min-max multi-objective problem. The existing literature on static robust vector optimization consists of two main approaches in interpreting the supremum of vectors: as a vector (ideal point) or as a set. To gain initial insight into the problem, we began by studying the structurally simpler, even if more conservative, option of interpreting the supremum of collection of vectors as a single vector (called *ideal point supremum*) with the property of being the smallest among the upper bounds (see Figure 1, on page 2). Some of the nontrivial challenges that we had to address were the existence, uniqueness, and the attainability of the supremum when taking across the models $\theta \in \Theta$; all being obvious in the scalar case. We note that when saying an *ideal point supremum*, represented through the operators *v-sup*, we refer to a point corresponding to an idealized scenario or model.

With these issues sorted out, we formulate the robust multi-objective control problem as follows:

$$\underset{(\varphi_t,\ldots,\varphi_{T-1}) \in \mathcal{A}^t(X_t)}{\text{minimize}} \quad \underset{\theta\in\Theta}{\text{v-sup}}\ \mathbb{E}^{\theta}[\ell(X_T)]$$
$$\text{with respect to } \leq .$$

The corresponding set-valued value function is defined as

$$\mathcal{V}_t^{\Theta}(X_t) = \mathrm{cl}\Bigg(\Bigg\{ \underset{\theta\in\Theta}{\text{v-sup}}\ \mathbb{E}^{\theta}[\ell(X_T)] \,|$$
$$(\varphi_t,\ldots,\varphi_{T-1}) \in \mathcal{A}^t(X_t) \Bigg\} + \mathscr{L}_t(\mathbb{R}_+^d)\Bigg).$$

The next key question was whether the set-valued Bellman's principle (2), or a version of it, is still valid for the robust framework. Without any further assumptions, the short answer is yes, but only in its weaker form. Namely, the DPP is a set relation, corresponding to an inclusion, between the true value function and its recursive version. Moreover, by means of counter examples, we showed that this result is sharp (see Figure 2).

Even in the scalar case, the DPP for robust stochastic control problems holds only if the set of probability measures $\mathbb{Q}(\Theta)$ satisfies an additional structural condition, known as *rectangularity property* (or *m*-stability). This property essentially requires the family of models to be sufficiently rich to ensure dynamic consistency, thus we had to establish an analogous property for vector-valued problems that ensured a stronger and fully appropriate version of the Bellman principle. The main technical difficulties arose from the non-uniqueness and, in general, the non-attainability of the v-sup. As a result, we prove that under this new notion of rectangularity for $\mathbb{Q}(\theta)$, the following strong set-valued Bellman's principle holds

$$\mathcal{V}_t^{\Theta}(X_t) = \mathrm{cl}\ \Bigg\{ \underset{\theta\in\Theta}{\text{v-sup}}\ \mathbb{E}_t^{\theta}[Y] \,|\, \varphi_t \in A_t(X_t),$$
$$Y \in \mathcal{V}_{t+1}^{\Theta}(F(t, X_t, \varphi_t, Z_{t+1}))\Bigg\},$$

as well as a time consistency property of the dynamic robust problem.

Current Developments and Future Directions

The results obtained for robust multi-objective control are encouraging and highlight the potential of this new research direction on multi-objective control under model uncertainty. Our work represents a first glimpse into the potential research endeavors on the subject, with numerous interesting and challenging open problems. For instance, it is well known that the robust approach described tends to be overly conservative, and exploring alternative methods for handling model uncertainty in the multi-objective setting is not merely a theoretical exercise, but also of significant practical importance.

In an ongoing follow-up project, we are currently investigating the Bayesian approach within the context of multi-objective control. This involves formulating the control problem as a Markov decision process, performing Bayesian updating of posterior beliefs about the underlying distribution $\mathbb{Q}(\theta)$, and understanding how to extend the state space to include these beliefs as part of the value function's arguments.

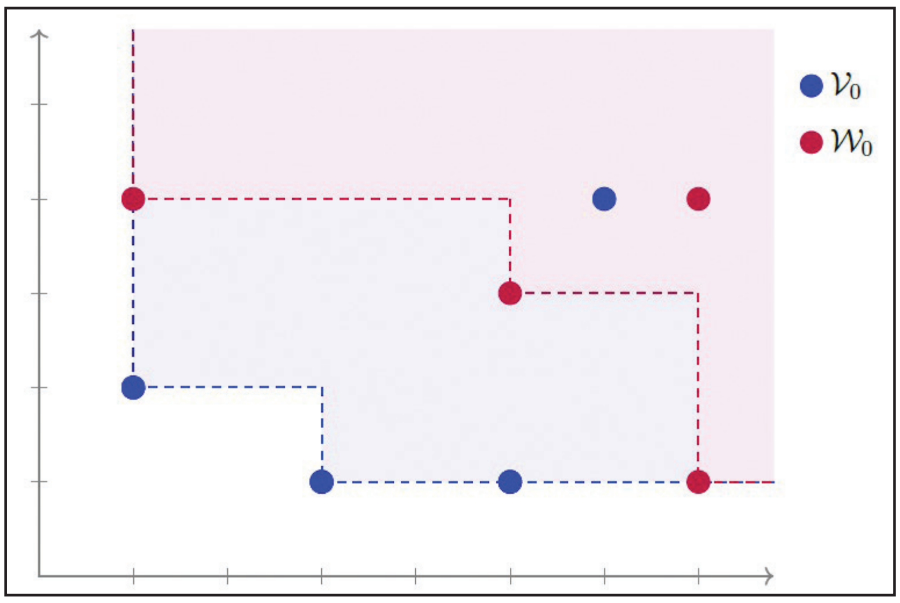

Figure 2. *Weaker form of the set-valued Bellman's principle. Blue set is the value function of the (true) robust multi-objective problem, red set is the value function of recursive counterpart. Figure courtesy of the authors.*

Another important research direction where substantial progress is still needed is the development of efficient algorithms for solving multi-objective control problems. Addressing these computational challenges is also part of our planned work.

Concluding Remarks

The SIAM Postdoctoral Support Program was an enriching experience that elevated the process of postdoctoral training and encouraged academic career growth. We are especially grateful for the program's travel support for research meetings and conferences. This facilitation is particularly important in the current landscape, where many postdoctoral positions come without a dedicated budget for travel or research. We wish to express our sincere gratitude to Drs. Martin Golubitsky and Barbara Keyfitz for their generous gift that made this experience possible, as well as to the SIAM staff for their guidance throughout this program.

For more information and to apply, visit the SIAM Postdoctoral Support Program webpage.[3] The next priority deadline will be ***November 1, 2026.***

The SIAM Postdoctoral Support Program is made possible by gifts to the SIAM Postdoctoral Support Fund, which was established by Drs. Martin Golubitsky and Barbara Keyfitz. If you would like to make a contribution to the SIAM Postdoctoral Support Fund, please visit the SIAM website.[4]

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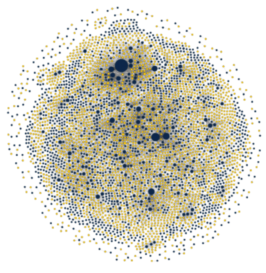
[4] https://www.siam.org/get-involved/ways-to-support/support-our-mission/



The Meanings of Foucault's Pendulum

BOOK REVIEW

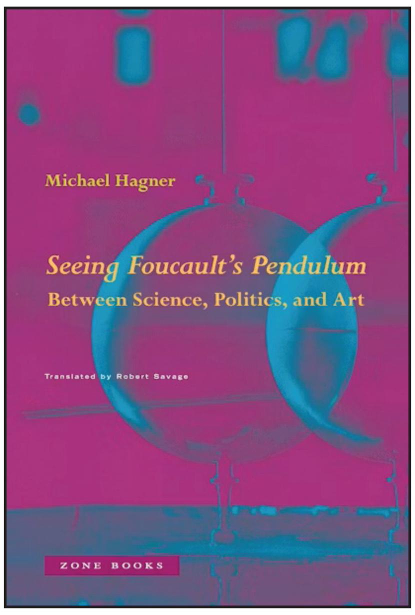
By Ernest Davis

Seeing Foucault's Pendulum: Between Science, Politics, and Art. *By Michael Hagner. Translated by Robert Savage. Zone Books, New York, NY, September 2025. 320 pages, $38.00.*

In 2018, the eminent German artist Gerhard Richter designed a permanent installation for the Dominican Church in Münster titled "Two Grey Double Mirrors for a Pendulum" ("Zwei Graue Doppelspiegel für ein Pendel"). Quoting from *Seeing Foucault's Pendulum,*

> The work consists of a Foucault pendulum with a 28.75-meter-long steel cable and a 48-kilogram metal ball swinging over a circular disk made of graywacke, an ancient sedimentary rock. An electromagnetic drive ensures a constant amplitude of oscillation. The stone plate has a circumference of 5.6 m and is engraved on its outer rim with a 360-degree scale in 12-degree increments. The gray of the sandstone is picked up in four 6-meter-high, 1.34-meter-wide glass panels. These are mounted in pairs on the transept walls ... The backs of the panels are covered in gray enamel.

Michael Hagner, a distinguished historian of science at ETH Zürich, was invited to write a brief historical essay contextualizing this artwork. His essay turned into *Seeing Foucault's Pendulum: Between Science, Politics, and Art,* a 300-page book originally published in German in 2021 but later translated by Robert Savage and published in English in 2025. Despite the book's subtitle, however, there is not much about politics in the narrow sense, and even less about science. In particular, there is no explanation of the fact that the rotational period of the pendulum is 24 hours divided by the sine of its latitude. Likewise, descriptions and explanations of devices similar to Foucault's pendulum are often left frustratingly unclear. Overall, however, the book is remarkable and mind-expanding, combining the histories of science, culture, and iconography.



Seeing Foucault's Pendulum: Between Science, Politics, and Art. By Michael Hagner, translated by Robert Savage. Courtesy of Zone Books. Jacket design by Julie Fry.

The early chapters of *Seeing Foucault's Pendulum* are primarily a historical recounting of the effort to find purely terrestrial evidence of the rotation of the Earth. It turns out that the rotation of the pendulum path was observed as early as about 1661. The posthumous papers of Vincenzo Viviani (1622-1703), a student and assistant of Galileo, contain the following observation, "We have observed that all pendulums suspended by a single thread deviate from their vertical plane ... from right to left in the front part." However, Viviani and his associates failed to connect this to the rotation of the Earth, in part because Galileo had asserted that no terrestrial experiment could ever demonstrate the Earth's rotation. Ironically, Galileo's successors prioritized his dogma over their own experimental results.

Many people, from Robert Hooke in 1680 to Johann Friedrich Benzenberg in the early 19th century, attempted to experimentally demonstrate the impact that the Earth's rotation imposes onto a falling object. Though there was some evidence of the predicted drift eastward and southward, it proved to be difficult to shield the falling objects from perturbations sufficiently and thus obtain a reliable and convincing result.

The book next provided a biographical sketch of Léon Foucault. By 1851, Foucault had achieved a considerable reputation as an inventor and experimental physicist. Working with bacteriologist Alfred Donné, he had made important innovations in photomicrography. Working with his longtime mentor, astronomer François Arago, he produced the first daguerreotype of the sun. In 1849 he created a stage effect for Giacomo Meyerbeer's opera *La Prophéte*, producing the effect of a sunrise by shining a huge spotlight powered by an arc lamp directly at the audience — a wonderous feat at the time. In 1850, he demonstrated that the speed of light in water is slower than in air, establishing (so it was thought at the time) the truth of the wave theory of light.

Also in 1850, Foucault conceived the design of his pendulum by extrapolating from a well-known phenomenon:

> The pendulum experiment ... emerged not from a cosmological research tradition, but from a locally rooted technoscientific practice ... For example, attach a flexible steel rod to a lathe and set it in motion. If you then rotate the entire lathe in any given direction, the swinging rod does not follow its rotational movement but maintains its plane of oscillation.

Foucault realized that the same thing could happen with the rotation of the Earth; the pendulum would continue swinging in the same plane (more precisely, in as close to the same plane as possible) while the Earth rotates beneath it. From the perspective of the Earth-bound observer, the path of the pendulum slowly rotates clockwise (in the Northern Hemisphere). In January 1851, he successfully performed the experiment using a five-kilogram pendulum on a two-meter steel cable. In March, with the permission of Louis-Napoleon Bonaparte, then president of the French Republic, he installed a pendulum consisting of a 28-kilogram bob attached to a 67-meter wire in the Panthéon in Paris. It swung with an oscillation period of 16 seconds over an octagonal

See **Foucault's Pendulum** *on page 7*

The Dynamics of Debt

A Computational Framework for Chip-firing and Network Stability

By Dhyey Mavani

SOFTWARE AND PROGRAMMING

Consider a chain of companies linked by trade credit. In this case, a supplier extends credit to a manufacturer, the manufacturer to a distributor, and the distributor to a retailer, with additional cross-credit occurring between some of them. Some firms hold cash, while others carry net debt. The system is dynamic: a company in distress might receive payment from a neighbor or extend credit to stabilize the chain. The central question is one of global stability. Given this topology of who trades with whom, and an initial distribution of cash and debt, is there a sequence of payments (or debt restructurings) that restores solvency to every company (i.e., node) in the network?

Until now, simulating these complex, cascading network dynamics required researchers to rely on manual calculations or bespoke, computationally expensive scripts. The open-source `chipfiring` Python package [5] changes this paradigm by providing a standardized and highly-optimized software ecosystem that makes the simulation and analysis of these discrete network flows accessible, visual, and computationally tractable at scale.

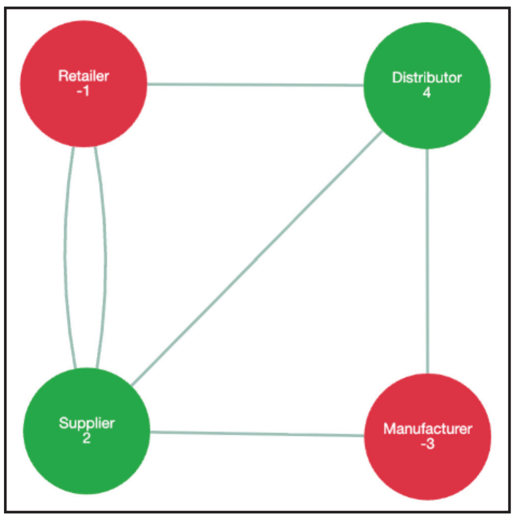


Figure 1. *A sample configuration of the chip-firing game. Vertices with negative integers represent debt. The software calculates if lending "moves" can resolve this debt globally. Figure courtesy of the author, produced using the `chipfiring` Python package.*

Chip-firing sits at the intersection of combinatorics, physics (specifically self-organized criticality), and algebraic geometry. Despite the successes that came with the generalized Riemann-Roch theorem for graphs, which identified structural relationships between discrete topologies [1], the bridge between theoretical abstraction and experimental verification has historically been precarious. By standardizing the algorithms used in previous systems, the `chipfiring` package enables researchers to cast their hypotheses onto complex graph structures, bringing mathematical capabilities from ad-hoc analysis to robust experimentation.

The Abstraction: From Supply Chains to Matrices

In the language of the software, a network is modeled as a multigraph, and the distribution of resources across that network is called a divisor — a term borrowed from algebraic geometry that hints at the deep connections between discrete games and the study of algebraic curves [2].

The rules of this economy are purely local. A move occurs when a vertex either simultaneously lends to or borrows from all of its neighbors. Mathematically, the system's transitions are represented using discrete Laplacian matrices. This formulation reveals the system's Abelian property, as the order in which nodes lend or borrow does not alter the final state. This critical property transforms what could be a chaotic, path-dependent sequence of transactions into a structured algebraic problem, allowing the software to definitively answer if a configuration is "winnable," i.e, it can reach a state where no node is in debt.

Automating the Firefighters: Dhar's Algorithm

Determining if a game is winnable by brute force is highly inefficient due to the combinatorial explosion of possible moves. To solve this, the `chipfiring` package implements Dhar's Algorithm, a method originally motivated by the study of sandpile models in physics [3].

The algorithm employs a vivid "burning" metaphor that is modeled directly in the software's architecture. To test the stability of a network configuration, the system designates a specific node as the "sink" and imagines setting it on fire. The edges of the graph act as combustible material, attempting to carry the fire to neighboring nodes. However, each node is defended by "firefighters," which represent the amount of cash currently held at that vertex.

As the fire attempts to spread, the defenses are tested. If a node possesses more cash than the number of incoming burning edges, the firefighters hold the line, and the node remains safe. If the cash is insufficient, the defense fails, the node burns, and the fire propagates further to its neighbors. If the fire consumes the entire graph, the financial configuration is deemed globally unstable. However, if the fire is contained, the unburnt nodes form a "legal firing set," a specific group of companies that can simultaneously extend credit to stabilize the network without driving themselves into insolvency. Crucially, the algorithm returns an acyclic orientation of the graph, leaving a topological footprint of how the fire traveled, which is essential for researchers who aim to study the geometric properties of the network.

Algorithmic Benevolence and Efficiency

Beyond standard stability checks, the package introduces efficient algorithms for "winnability determination." A key strategy implemented is the notion of *q-reduction* or "benevolence" [5]. In a financial network, this strategy asks if an one "benevolent" institution (vertex q) could volunteer to absorb all the debt in the system and dictate how it would impact the network. The algorithm concentrates all system debt onto q and iteratively checks if the remaining nodes can "bail out" q through a sequence of moves.

The package includes a specialized *efficient winnability determination* (EWD) module. Instead of random firing, EWD employs a reverse-distance prioritized approach [5]. It calculates a *breadth-first search* (BFS) from the source node and processes debt strictly from the furthest nodes inward. This ensures that once a peripheral node becomes solvent, it remains solvent, thus preventing the redundant cycles of debt that easily choke naive, brute-force scripts. This optimization allows the software to handle graphs of significant size and complexity.

From Simulation to Research: Rank and Gonality

While the underlying game makes for an excellent pedagogical puzzle, `chipfiring` is built to handle rigorous research demands, particularly regarding *graph gonality* [2].

Gonality is a measure of a graph's complexity, defined as the minimum degree of a divisor with a rank of at least one. In the supply chain analogy, "rank" measures the robustness of a network's solvency: a rank of k means the network can remain solvent even if k arbitrary units of cash are removed from the system.

Calculating rank is an non-deterministic polynomial-time hard problem for general graphs. For years, mathematicians relied on manual calculations for small graphs or wrote one-off, unoptimized scripts for specific research questions. The lack of tools created a barrier to entry; one could not

See **Dynamics of Debt** *on page 8*

Binoculars in Low Light

MATHEMATICAL CURIOSITIES

By Mark Levi

Some advertisers claim that binoculars with large objective lenses make objects appear brighter, thus making it easier to see in low light.

This sounds convincing: after all, a larger lens captures more light, and with more light entering the eye, objects appear brighter.

I used to believe this, but surprisingly perhaps, the claim is false. In a nutshell, the wider the objective is, the narrower is the angular range of the rays that make it to the eye. These two competing effects cancel each other exactly, as I show next.

Referring to Figure 1, each ray is characterized by the pair (x, y) where $x = \sin\theta$, with θ being the angle formed by the ray with the horizontal, and y is the coordinate of the intersection with the y-axis. The same ray, when crossing the X-axis (tangent to the pupil) in the figure, is similarly characterized by coordinates (X, Y), where $Y = \sin\Theta$. So, our binocular defines a mapping $\varphi : (x, y) \mapsto (X, Y)$. This map takes the left rectangle in Figure 1 to the right one. It is a fundamental fact that φ preserves area [1].

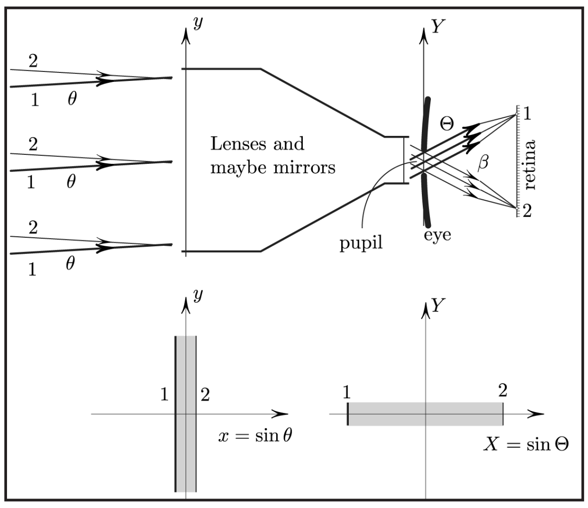


Figure 1. *Top: Parallel beams 1 and 2 are shown, entering and exiting. Bottom: Beams 1 and 2 correspond to the vertical boundaries of the rectangles. Area of the rectangle measures the flux of power carried across the vertical line by the rays corresponding to this rectangle. This is another interpretation of the Liouville measure.*

Now, here is a key point: *Area* (R) = *energy flux carried across the objective by the set of rays corresponding to* R.

It is important to note that $\varphi(R)$ is fixed by the size of the pupil and by the exit angle β between the two parallel beams in the figure, so that the area of φR and R are independent of the size of the objective. And so by the area = power remark, the power reaching the retina does not depend on the size of the objective, as claimed.

It remains to explain why area = power. I have to come clean and mention the unstated assumptions: (i) we are looking at a homogeneous object, such as a wall, and (ii) each point of the object emits photons equally in all directions.[1] By the assumption of isotropic emission of photons, the number of photons passing per unit of time through an infinitesimal segment dy in the directions between θ and $\theta + d\theta$ (where θ is the angle with the horizontal in Figure 1) is proportional to dy and to the component $\cos\theta$ of the velocity of the photons[2] normal to the segment i.e., to $dy \cos\theta \, d\theta = dy \, d(\sin\theta) = dy \, dx$. And so, $dy \, dx$ is not just the area, but also the energy flux.

A more rigorous explanation of why area = energy flux can be given by considering the phase space of photons, observing that the flow in this space is volume-preserving. The volume measures the number of photons, i.e., the energy. The flux thus measures the energy flux. Considering the tube of trajectories corresponding to the rays in Figure 1, one can conclude that fluxes through two different sections are equal; I omit the details.

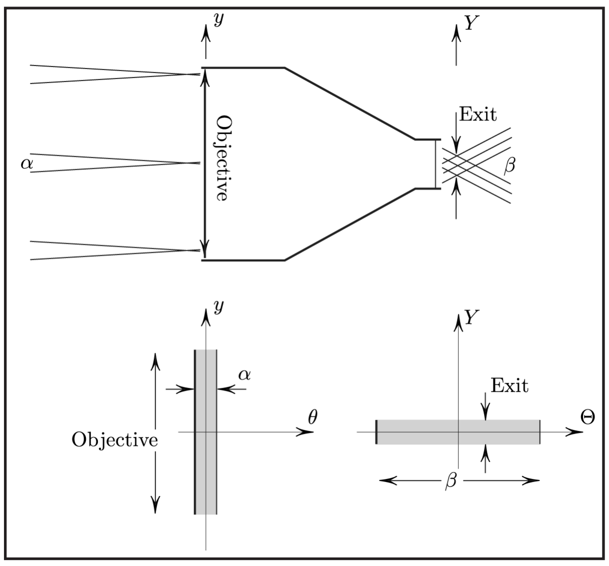


Figure 2. *The narrowest "neck" of the rays exiting the ocular is called the exit pupil. This is where the actual pupil is placed in Figure 1.*

Magnification as a Ratio

The binocular in Figure 2 magnifies by the factor β / α: indeed, β / α is the factor by which the images on the retina spread apart when viewed through the binocular versus the naked eye. Preferring to deal with angles θ and Θ, instead of their sines x and X, we note that the error in $\sin\alpha \approx \alpha$ with $|\alpha| < 20^\circ$ is about two percent, hardly noticeable in practice. With this approximation, area preservation gives

$$\text{Objective} \cdot \alpha = \text{Exit pupil} \cdot \beta,$$

and so β / α becomes

$$\boxed{\begin{array}{c}\text{Magnification}\\ \text{factor}\end{array} = \frac{\text{Objective diameter}}{\text{Exit pupil}}.}$$

This is an expression of the area-preservation of the map φ defined above. This area preservation can be viewed as a classical analog of the uncertainty principle: by narrowing the exit, we widen the angular range β.

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The figures in this article were provided by the author.

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[1] Without these assumptions, the size of the objective lens may actually matter. Indeed, imagine looking through the binocular at the moon at night. The energy reaching the retina will depend on the proportion of the dark background, and that proportion decreases as the magnification increases. But magnification increases with the size of the objective (according to the remark at the end of the article), and so the size of the objective matters in this (uninteresting) sense. However, once the moon occupies the full field of view, further increase in magnification/objective diameter will not make it brighter.

[2] Taking the speed of a photon to be 1.

Foucault's Pendulum

Continued from page 6

marked with a 360-degree scale. To make the effect of the rotation of the pendulum's path even more visually dramatic, Foucault placed a pile of sand in the pendulum's path which was gradually furrowed by a stylus attached to the bottom of the bob.

The demonstration was astonishingly successful. Crowds of people came to the Pantheon to gaze with awe at the pendulum's mysterious motion. Foucault himself described it as follows:

> The phenomenon unfolds calmly, inevitably, irresistibly, like the higher cause through which it is summoned. One feels, in seeing it born and growing, that it is not in the power of the experimenter either to accelerate or retard its manifestation. Everyone who witnesses this event, regardless of whether they have been converted to the conventional view [regarding the Earth's rotation], tarries for some moments in silent contemplation and generally draws away with a keener and livelier sense of our incessant mobility in space.

In the following years, further demonstrations of the Earth's rotations were developed. In 1852, Foucault himself designed a powerful gyroscope (a term he coined) that maintained its absolute orientation in space long enough for its rotation to be observed. Another remarkable demonstration, involving no moving parts, was described in 1855:

> In a secluded, shock-resistant location, a large glass bowl was filled almost to the brim with water. Once the surface had become completely still, a thin layer of water-repellent horsetail seeds was scattered evenly over the surface. Next, a thin line of coal powder was sprinkled centrally over the horsetail layer and a mark made on the edge of the bowl in the direction of the line. Over time, the black line appeared to move clockwise, like the pendulum, even though in reality the earth, along with the glass bowl, was moving from west to east around the motionless water.

Hagner's book next recounts the long history of installations of Foucault's pendulum and addresses the central questions of the book: Why did the pendulum have such an impact? What did it mean to the people who installed it and the audiences that viewed it? There are over 350 installations[1] of Foucault's pendulum, with one in every continent including Antarctica (at the South Pole), in 51 countries, and in 43 U.S. states in addition to Washington, D.C. What is the secret of its universal appeal?

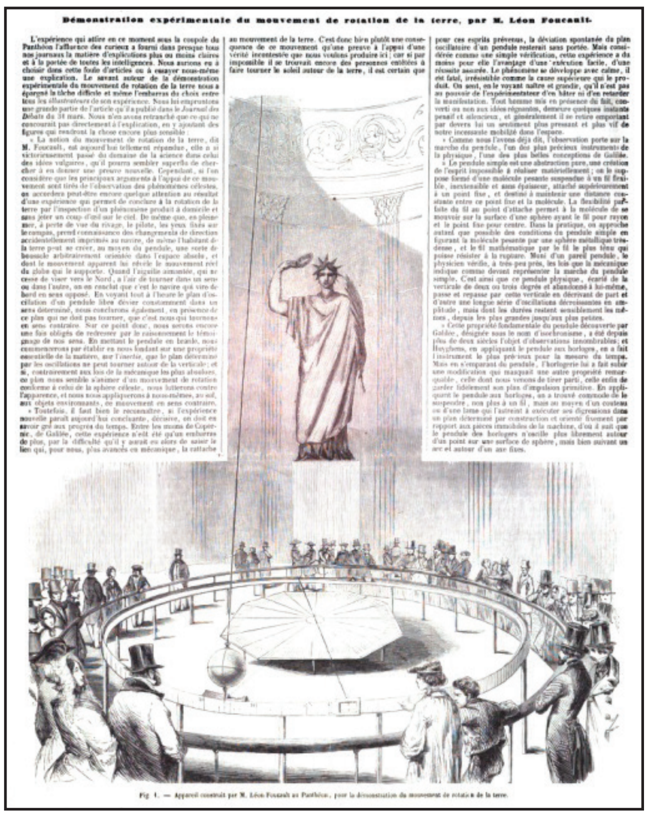
The book includes particularly detailed accounts of the installations of Foucault's pendulum in St. Isaac's Cathedral in Leningrad in 1931, in the main headquarters of United Nations (UN) in 1955, and in the Smithsonian National Museum of Science and Technology in 1964, as well as the original 1851 installation in the Paris Panthéon. Analyzing both the writings and the images that were published about each of these at the time, Hagner endeavors to discover how the meaning of the pendulum connects to the political, social, and educational purposes of their creators. He also ponders the question, for which there is much less documentation, of why each of these exhibits—apart from the one at the UN—was taken down only a few decades after being installed.

The last part of the book deals with the ways in which modern artists and writers—especially Richter and novelist/semiotician Umberto Eco, but also others—have used the Foucault pendulum. Here, Hagner's analysis turns to art criticism. For instance, he writes of Richter's installation:

> Entering the church through the portal, the visitor is as much struck by the interplay of the gray on the transept walls and the gray stone plate on the ground directly beneath the dome as by the oscillating pendulum itself. Only upon drawing closer are these visual impressions multiplied by the huge mirrors. One can focus on the pendulum, but in turning to face the walls, the church interior, pendulum, and observer are reflected to varying degrees as they combine with the different shades of gray. The burnished, flawless surfaces of the mirrors offer an apparently objective duplication of the scenery. Yet the ambiguity of the image they present, which reflects the surroundings while bleaching out the colors in the mirrored gray, generates an element of illusion that challenges the visitor to reexamine their own perceptions. Which brings us back to the fundamental questions: Who is doing the seeing here? And what do they see when they see?

As befits a book that deals in depth with the meaning of spectacles and images, *Seeing Foucault's Pendulum* is extensively illustrated with 19 color plates on glossy paper and 82 grayscale or line-drawing figures. It is a beautiful book.

The Foucault pendulum is and has always been a demonstration rather than a scientific experiment, discovery, or a means of measurement. It demonstrated that the Earth rotates around its axis despite the fact that most educated people in 1851 already believed that to be true. Traditionally, the history and philosophy of science measure the importance of an experiment or observation in terms of its impact on scientific theory; an important experiment is one that confutes an accepted theory or suggests a new one. The Foucault pendulum barely registers on that scale. Perhaps its ultimate importance is as a meta-level demonstration that that framework is inadequate. Perhaps the purview of those disciplines should be extended to include the kinds of questions raised in *Seeing Foucault's Pendulum*.



Démonstration expérimentale du mouvement de rotation de la terre, par M. Léon Foucault.

Fig. 1. — Appareil construit par M. Léon Foucault au Panthéon, pour la démonstration du mouvement de rotation de la terre.

Appareil construit par M. Leon Foucault au Panthéon. Figure from [1].

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Ernest Davis is a professor of computer science at New York University's Courant Institute of Mathematical Sciences.

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[1] https://en.wikipedia.org/wiki/List_of_Foucault_pendulums

Collaborative Workshop Fosters Community Among Institutions Across China

By Kivmars Bowling

This past April, the Institute of Computational Mathematics and Scientific/Engineering Computing[1] at the Chinese Academy of Sciences, Beijing[2] (ICMSEC-CAS) and SIAM jointly hosted the "ICMSEC-CAS/SIAM Publishing Workshop for Early Career Researchers." The workshop attracted over 85 registrants from more than 35 institutions in Beijing and across China and featured several sessions—delivered in Chinese—by SIAM journal editors and Fellows[3] offering guidance on how to become a journal author, be an effective peer reviewer, and responsible use of artificial intelligence (AI) in the context of research integrity.

This workshop was initiated to reflect the increasing number of Chinese researchers as both authors and readers across scholarly publishing; in 2023, China became the leading country[4] in terms of highly cited research, surpassing the U.S. This trend has only accelerated since, with the 2025 CWTS Leiden Ranking[5] showing Chinese universities dominate not only in number of publications, but in the number of highly-cited publications. Submissions to SIAM Journals from China continue to increase, and SIAM Journals receive more article downloads in China than any other country. Of course, some of these indicators are a function of the population size, but they also reflect the sustained and increased funding for science, technology, engineering, and mathematics (STEM) over recent decades.

Chinese research output will likely sustain this growth in quality and quantity in the coming years. With this broader trend in mind, ICMSEC professor and SIAM Fellow, Tao Zhou, and I co-organized the ICMSEC-CAS/SIAM workshop to foster community amongst Chinese researchers and students, as well as provide useful advice for achieving global impact via SIAM publications.

The workshop opened with an author-focused session from ICMSEC-CAS professors Zhiming Chen and Aihui Zhou, respectively recent and current editors for the *SIAM Journal on Numerical Analysis*[6] (SINUM). Chen and Zhou offered tips on how to become a journal author and shared what they look for when assessing new submissions to their respective journals.

Advice for new peer reviewers came from a session presented by Ya-xiang Yuan, ICMSEC-CAS professor and former editor of *SIAM Review*[7] and *SIAM Journal on Optimization*,[8] and Yongyong Cai, professor at Beijing Normal University and editor for SINUM. Their session discussed why reviewing matters, how to decide whether to accept an invitation to review, practical approaches to formulating a review, and professional best practices to follow.

A very lively session on AI and research integrity was then led by two editors of *SIAM Journal on Imaging Sciences*:[9] Bin Dong, professor at Peking University who also serves as an editor for *SIAM Journal on Scientific Computing*,[10] along with Chenglong Bao, professor at Tsinghua University. The pair discussed the SIAM Editorial Policy on Artificial Intelligence[11]—which is in the process of being updated—and asked broad fundamental questions about what AI will mean for authorship and reviewing in the future if AI capabilities eventually match or surpass human capabilities in a reliable way. AI tools are clearly speeding up some tasks tremendously—albeit with persistent risks and "hallucinations" [1]—but as they continue to improve, questions will arise about how a "good scientist" will be evaluated in the future. Even with the AI revolution happening, the session emphasized to early-career researchers that they must continue to build their core skills and independent thinking rather than relying on AI shortcuts, highlighting that human researchers must be able to assess *independently of AI* whether a result is correct and good.

Beijing University of Posts and Telecommunications visit with the Resource Development Department. From left to right: Desmond Tang, Rosa Perez, Kivmars Bowling, He Xuan, Angela Shi, Bella Zhao, and Gao Song. Figure courtesy of Zhang Li, Reader Services Department.

In addition, the workshop included detailed sessions with updates on the Peking University and CAS[12] student chapters. Professor Jun Hu of Peking University and Xinpeng Li, president of the CAS student chapter, provided respective updates on the chapters' annual meetings, which feature guest speakers, as well as career guidance events. Later, an update on the SIAM East Asia Section[13] was presented by Tao Zhou, who serves as the section's chair. These sessions exhibited the rich community building and activities that are engaging early career researchers both within and across institutions and the wider region. SIAM currently has four student chapters[14] in China: Beijing Computational Science Research Center, CAS, Peking University, and Wuhan University. We encourage faculty and librarians at other institutions to apply[15] to set up a SIAM student chapter at their university to cultivate community among students interested in applied mathematics and computational science.

Following the workshop, Rosa Perez, the Institutional Sales and Licensing Manager for SIAM, and I were honored to spend several days visiting partner librarians at Tsinghua University, Peking University, Beijing Institute of Technology, Renmin University of China, and Beijing University of Posts and Telecommunications. These visits allowed us to share updates about SIAM Publications[16]—including our new *SIAM Journal on Life Sciences*,[17] SIAM e-books,[18] and the SIAM Proceedings Collection[19]—as well as further information about SIAM's programs,[20] travel grants,[21] and student chapters, all topics that generated much interest. We also discussed the opportunities and challenges for librarians in China and made plans for further collaboration. Rosa and I are grateful to everyone for the warm welcome we received and the librarians' willingness to take time to show us around their beautiful libraries.

For those interested in viewing slides from the workshop, the following presentations are available on the SIAM website[22] as well as the event description and full agenda:

- "Becoming a Constructive, Efficient, and Reliable Reviewer" (English) by Ya-xiang Yuan of ICMSEC-CAS.
- "AI and Research Integrity" (slides in Chinese and notes in English) by Bin Dong of Peking University.
- "SIAM Student Chapter, Chinese Academy of Sciences - Update" (slides in Chinese and English) by Xinpeng Li of CAS.

For further updates about SIAM activities in China, follow the official SIAM WeChat account using the QR code in Figure 1. To provide feedback or ideas about how SIAM could hold future workshops in China, feel free to reach out to me at **bowling@siam.org.**

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Figure 1. *QR code for the official SIAM WeChat account.*

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[1] Kolda, T. (2026, May 1). A contract of trust: Artificial intelligence usage for SIAM journal submissions. *SIAM News, 59*(4), p. 10.

Kivmars Bowling is the Director of Publications at SIAM.

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[1] https://lsec.cc.ac.cn/

[2] https://english.cas.cn/

[3] https://www.siam.org/programs-initiatives/prizes-awards/fellows-program/

[4] https://www.nature.com/nature-index/news/nature-index-research-leaders-united-states-losing-ground-china-lead-expands-rapidly

[5] https://open.leidenranking.com/ranking/2025/list

[6] https://www.siam.org/publications/siam-journals/siam-journal-on-numerical-analysis/

[7] https://www.siam.org/publications/siam-journals/siam-review/

[8] https://www.siam.org/publications/siam-journals/siam-journal-on-optimization/

[9] https://www.siam.org/publications/siam-journals/siam-journal-on-imaging-sciences/

[10] https://www.siam.org/publications/siam-journals/siam-journal-on-scientific-computing/

[11] https://epubs.siam.org/artificial-intelligence

[12] https://lsec.cc.ac.cn/~siamstuc/

[13] https://www.siam.org/get-involved/connect-with-a-community/sections/east-asia-section-of-siam/

[14] https://www.siam.org/get-involved/connect-with-a-community/student-chapters/

[15] https://www.siam.org/get-involved/connect-with-a-community/student-chapters/start-a-chapter/

[16] https://epubs.siam.org/

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[18] https://epubs.siam.org/action/showPublications?pubType=book&notConceptID=115968

[19] https://epubs.siam.org/action/showPublications?pubType=proceedings&SeriesKey=pr

[20] https://www.siam.org/programs-initiatives/programs/

[21] https://www.siam.org/conferences-events/conference-support/travel-and-registration-support/

[22] https://www.siam.org/conferences-events/past-event-archive/2026-icmsec-cassiam-publishing-workshop-for-early-career-researchers/

Dynamics of Debt

Continued from page 6

easily test a hypothesis on a graph with hundreds of nodes or verify edge cases on complex topologies like "chains of loops" or fractal-like structures. By heavily optimizing the underlying firing algorithms, the `chipfiring` package makes these computations tractable for significant families of graphs.

Accessibility and Verification

A core design philosophy of `chipfiring` is accessibility. The tool leverages the Python ecosystem to easily integrate existing data science workflows with `pip install chipfiring`. For further intuition-building, the package includes an interactive, web-based visualizer that allows users to manually step through firing sequences, observe Dhar's algorithm spreading in real-time, and visually track the flow of resources across the network.

While the Python package focuses on simulation and experimentation, we have paralleled this work with the first-ever formal verification framework in Lean 4,[1] a functional programming language and theorem prover. ChipFiringWithLean[2] formally verifies the correctness of the chip-firing dynamics and the Riemann-Roch theorem itself. While the Python package allows for rapid hypothesis testing, the Lean formalization ensures that the underlying mathematical logic is unassailable [4].

Conclusion & Try It Out!

The bridge between abstract graph theory and computational implementation has often been precarious. With `chipfiring`, we aim to solidify this connection and provide a standardized, efficient, and visual set of tools for the applied mathematics community. Whether you are a student trying to win a chip-firing game with your friends, an applied mathematician modeling financial stability, or an algebraic geometer investigating the moduli space of tropical curves, `chipfiring` offers the algorithmic machinery to let you focus on the mathematics.

The package is open source and available on PyPI[3] and GitHub.[4] We invite the SIAM community to experiment with it, contribute to the codebase, and explore the fascinating dynamics of debt and benevolence on graphs.

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[5] Mavani, D.D., Ji, T., & Pflueger, N. (2025). chipfiring: A Python package for efficient mathematical analysis of chip-firing games on multigraphs. Preprint, *arXiv:2508.00269.*

Dhyey Mavani is an applied computational mathematician from Amherst College. He has created multiple open-source mathematical and statistical software packages.

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[1] https://live.lean-lang.org/

[2] https://github.com/DhyeyMavani2003/chip-firing-with-lean

[3] https://pypi.org/project/chipfiring

[4] https://github.com/DhyeyMavani2003/chipfiring

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Learn more: *siam.org/get-involved/connect-with-a-community/student-chapters*

Chapter Highlights

Pohang University of Science and Technology (POSTECH) hosted multiple sessions with distinguished researchers from various disciplines who showcased how they use mathematics in their work. Students gained valuable insight into real-world applications of mathematical concepts while connecting with experts for meaningful discussion and networking opportunities.

North Carolina State University student chapter organized a visit Sandia National Labs representative for an energizing session focused on internship pathways, career tracks, and job opportunities. Students gained valuable insight into industry careers and explored new possibilities for their futures.

POSTECH lecture attendees watch presentation

Seminar attendees pose for a picture at Università Di Pavia

Università Di Pavia student chapter hosted Professor Jochen Hinz for an engaging seminar on advanced Python techniques designed to elevate students' coding skills. Through hands on exercises and real world examples, Professor Hinz empowered attendees to practice new methods, strengthen their technical abilities, and prepare for success in their post-graduate careers.

Harvey Mudd College student chapter welcomed Dr. Sam Fleischer, Senior Quantitative Analyst for the LA Dodgers, for an engaging lecture on the power of data science in baseball operations. Students learned how analytics drives decision-making within the Dodgers organization and heard Dr. Fleischer's inspiring career journey from UC Davis to NASA and ultimately to Major League Baseball—highlighting the wide-ranging career paths available in mathematics.

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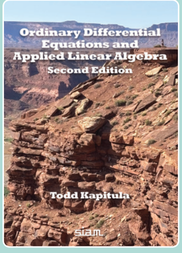

Todd Kapitula

This book helps students master linear algebra and ODEs in a one-semester course. The second edition of *Ordinary Differential Equations and Applied Linear Algebra* expands the learning experience by introducing case studies at the end of every chapter that examine SIR models, a model for lead poisoning, and the dynamics of strongly damped forced oscillators, among others. It adds end-of-chapter projects that allow students to explore the interplay between the creation of a mathematical model, the solution of the model, and the physical implications of the mathematical solution. Also new to the second edition is access to over 300 online homework problems embedded within the CMS *myOpenMath*.

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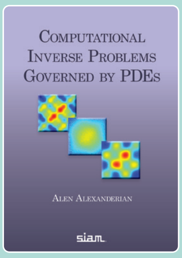

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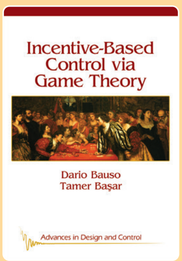

Dario Bauso and Tamer Başar

Engineering systems in today's economy are increasingly shaped by sharing—through shared logistics, joint investments, virtual power plants, and other cooperative structures—requiring models that account for decentralized decision-making and collective action. A central challenge is aligning self-interested behavior with system-wide objectives. *Incentive-Based Control via Game Theory* addresses this need with a design-oriented framework that uses game theory to engineer mechanisms and control strategies that drive agents toward stable, socially desirable outcomes under uncertainty. The book introduces engineering-focused topics rarely treated elsewhere, including dynamic coalitional games, reverse Stackelberg games, and rigorously analyzed best-response dynamics, while maintaining an application-driven perspective that connects mathematical theory to real-world implementation.

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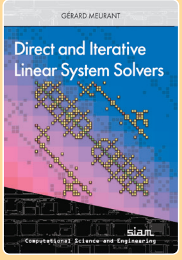

Gérard Meurant

Solving linear systems of equations is ubiquitous in scientific computing; therefore, numerical algorithms for solving them are paramount. This book describes the state of the art in direct and iterative methods for solving nonsingular linear systems of equations. Finite precision arithmetic and numerical experiments are emphasized. The author considers several variants of elimination methods, classical iterative methods, variants of the conjugate gradient method, and Krylov methods for nonsymmetric systems and describes many preconditioners. He describes and analyzes many numerical experiments with these methods, provides templates of codes for implementing these methods, and introduces more recent techniques like mixed precision and randomization.

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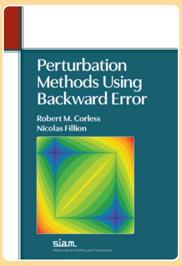

Robert M. Corless and Nicolas Fillion

Perturbation methods are old but powerful, and they remain in widespread use. Rather than producing numbers or pictures, they yield formulas whose value depends on the skill of the person (or machine!) interpreting them. This unique book presents several classical methods for solving perturbation problems. To ensure a uniform presentation and more reliable, interpretable results, it consistently uses backward error analysis. This provides a systematic way to assess the validity of approximate solutions while encouraging the modeler to examine how small changes in the data or model affect the result. To support this, the book uses the concept of a condition number, familiar from numerical analysis.

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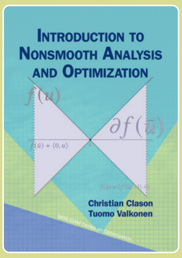

Christian Clason and Tuomo Valkonen

Functions that are not differentiable in the classical sense have become a central tool in modern mathematical models for imaging, inverse problems, machine learning, and optimal control of differential equations. These models are increasingly formulated in infinite-dimensional function spaces to be independent of problem size and discretization quality. This book presents a unified and rigorous introduction to the infinite-dimensional analysis and algorithmic solution of nonsmooth optimization problems arising from the above-mentioned models, from the necessary theoretical tools of nonsmooth analysis to state-of-the-art algorithms and their convergence and stability analysis.

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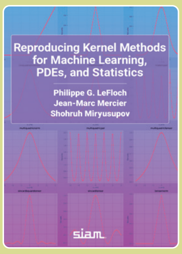

Philippe G. LeFloch, Jean-Marc Mercier, and Shohruh Miryusupov

This monograph develops a unified, application-driven framework for kernel methods grounded in reproducing kernel Hilbert spaces and optimal transport. The primary goal is to tackle industrial cases from computational physics and mathematical finance and discuss applications across various areas, such as statistics, or artificial intelligence (physics-informed systems, reinforcement learning, machine learning, generative methods, etc.).

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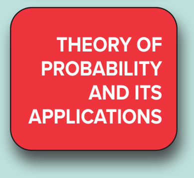

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