Algorithms Help Control **Social Dynamics**

Prof. Massimo Fornasier does not need a crystal ball to see into the future. He uses the power of mathematics instead. At his Chair of Applied Numerical Analysis at TUM, he develops processes and models that have been proven to deliver reliable forecasting results.

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Algorithmen zur sozialen Kontrolle

An seinem Lehrstuhl für angewandte numerische Analyse in Garching arbeitet Prof. Massimo Fornasier mit seinem Team an der mathematischen Modellierung hochdimensionaler Probleme – also einem Wissensgebiet, das sich mit der mathematischen Beschreibung von Problemen befasst, bei deren Darstellung man mit der Berechnung von Länge, Breite, Höhe und vielleicht noch der Zeit nicht sehr weit kommt. Wie er unlängst beweisen konnte, sind soziale Dynamiken auch „bloß" ein hochdimensionales Problem. So hat er Algorithmen entwickelt, mit denen er das Verhalten von Menschen in einer Gruppe sehr präzise berechnen, prognostizieren und sogar beeinflussen kann.

Die Lösung liegt dabei in der Kunst der Reduktion und in der Betrachtung von Menschen als physikalische Teilchen. „Als Masse verhalten sich Menschen durchaus ähnlich wie Teilchen von Flüssigkeiten oder Gasen", erklärt er seinen Ansatz. Um die Bewegungsrichtung großer Mengen von Gasmolekülen mit hoher Wahrscheinlichkeit berechnen zu können, müsse man nicht die genauen Eigenschaften jedes einzelnen Teilchens kennen. „Es genügt, ihre durchschnittlichen Eigenschaften zu kennen", sagt Fornasier.

Mithilfe von Computersimulationen konnte er damit bereits mögliche kollektive Verhaltensmuster einer großen Anzahl sich wechselseitig beeinflussender Individuen in einer aktuellen Situation darstellen. Dass diese virtuellen Multiagentensysteme durchaus mit realem Gruppenverhalten übereinstimmen, bestätigte ein Experiment, das die Mathematiker der TUM im Mai 2015 in Zusammenarbeit mit dem Consiglio Nazionale delle Ricerche (CNR) und der Universität „La Sapienza" in Rom durchführten. Dabei hatten die Forscher zwei Gruppen von etwa 40 Studierenden damit beauftragt, ein bestimmtes Ziel in einem Gebäude zu suchen. In die eine Gruppe hatten sie allerdings zwei „Undercoveragenten" eingeschleust, die zielstrebig in eine vorgegebene Richtung gingen. Damit allein brachten sie die Gruppe dazu, ihnen wie Schafe dem Leithammel zu folgen. Wie sie auch beweisen konnten, gelten diese Ergebnisse ebenfalls für sehr große Gruppen. „Tatsächlich reichen zwei bis drei solcher Agenten pro hundert Menschen aus", sagt Fornasier.

Mit seinen Algorithmen für soziale Dynamiken lassen sich effiziente Möglichkeiten finden, die für mehr Planbarkeit und Sicherheit sorgen. Zum Beispiel, wenn es darum geht, große Besuchermengen durch Gebäude zu dirigieren, Verkehrsflüsse zu optimieren oder Evakuierungen optimal durchzuführen. Bei allen denkbar positiven Anwendungsmöglichkeiten stellt sich in diesem Zusammenhang natürlich auch die Frage nach den Risiken. Da seine mathematischen Modelle in einer völlig abstrakten Umgebung formuliert sind, können sie leicht an verschiedene Situationen angepasst werden, in denen Interaktionen von Menschen eine Rolle spielen. Ganz gleich, ob es sich nun um Finanzmärkte oder Meinungsbildungsprozesse handelt. So ist die Möglichkeit der Einflussnahme auf das Verhalten sozialer Systeme ein zweischneidiges Schwert. „Die gute Nachricht in diesem Zusammenhang ist, dass wir auch bewiesen haben, dass das Verhalten nicht für alle Typen von Dynamik und nicht in allen Situationen so leicht vorauszusagen ist", kann Fornasier beruhigen. □

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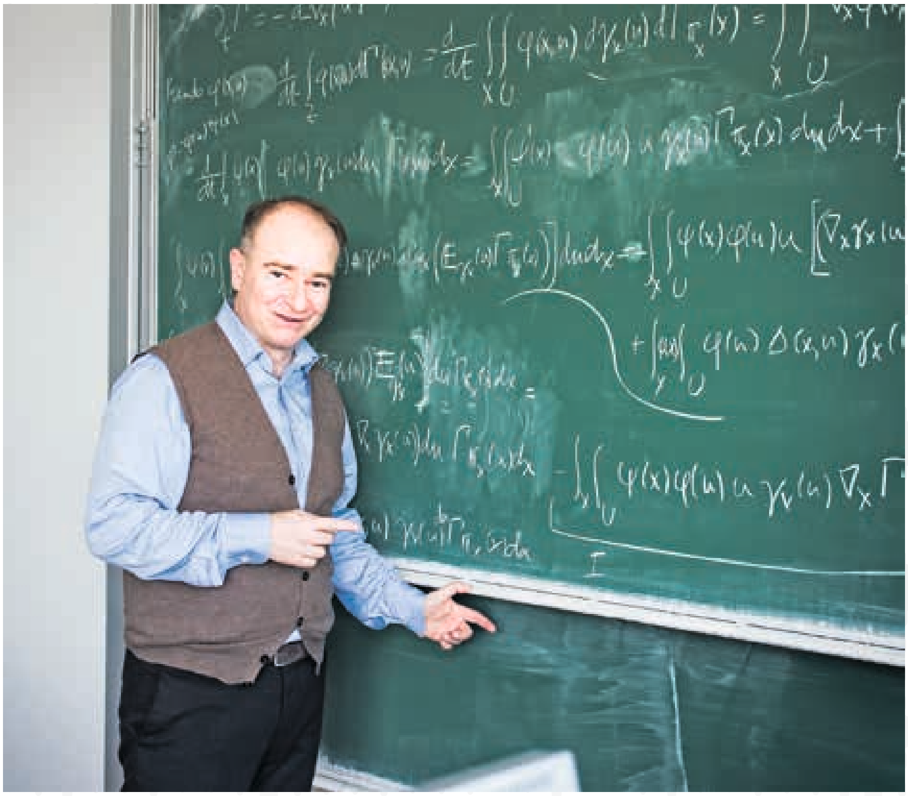
“Performing numerical simulations based on the complex data from social behavior is one of the key challenges of the 21st century.”

Massimo Fornasier

The world of big data is opening up new opportunities in the realm of forecasting. In theory, at least. Even though rapid advances in technology have led to an explosion in the availability of data in recent years, this has not led to a corresponding gain in knowledge. This is particularly true in the case of models for forecasting social dynamics. The reason lies in the fact that human behavior is influenced by a complex interplay between physical, emotional, cognitive and social factors. The rise of Twitter and other social networks means that data is no longer just two-dimensional – it cannot be described as easily as something like an ultrasound, for example. The evaluation of complex data often results in very large systems of equations and the computing power required to find a solution is rising exponentially in tandem. As such, even state-of-the-art supercomputers can in many cases struggle to meaningfully process the raw data. “We call this phenomenon the curse of dimensionality,” explains mathematician Massimo Fornasier. Along with his team in Garching, he uses highly efficient algorithms to solve such high-dimensional problems. “Performing numerical simulations based on this data is one of the key challenges of the 21st century,” he maintains.

His models are based on the idea that the dynamics of a multi-layered overall system are governed by just a few classification parameters. “Simply put, we want to be able to understand and organize complexity,” says Fornasier as he describes his research. His algorithms are essentially nothing more than programmed sieves that sort through a huge volume of data to find the information that corresponds to a certain



Using mathematics to describe how a person – a so-called agent – behaves within a crowd: Agent's movements are highly probabilistic because they depend, for instance, on obstacles or on how neighboring agents may behave. Mathematically, this is represented by a probability distribution of possible moves for each agent.
The blackboard shows a system of two time dependent equations, which Fornasier uses to describe the behavior of several agents within a crowd and the evolution of the respective probability distributions of their moves.

pattern. "We reduce the parameters to an absolute minimum to then draw conclusions applicable to a larger quantity." The process can be described as a mathematical balancing act consisting of many small arithmetical adjustment steps. The mathematical model that eventually emerges from these iterations has to be as simple as possible in order to be manageable, but should at the same time be as complex as necessary. The next step is a question of simulating the system as such. "This means that we have to develop algorithms that allow us to simulate the process with sufficient accuracy."
Together with his working group in Garching, he has already developed algorithms for a series of highly complex and thus higher-dimensional problems from real life, which produce such reduced or – as the researchers call them – "sparsely populated" results. Applications for his mathematics include marketing strategies, financial portfolio management, image compression and painting restoration. One example is the restoration of an Andrea Mantegna fresco in a church in Padua, which was almost totally destroyed by bombing in 1944. All that remained of the almost 1,000 m^2 artwork dating from the 15th century were tens of thousands of painted puzzle pieces rescued from the piles of rubble after the attack. These fragments, which made up less than one tenth of the original fresco, were cleaned, sorted and photographed in the early 1990s. Using the digital photos, Fornasier was able to develop an algorithm to automatically assign each fragment to its original position in the fresco.
Impressive as this is, Fornasier knows that his mathematical models are capable of so much more. He recently proved in a European Research Council project with EUR 1.123 million in funding that his process can also very accurately analyze, forecast – and even under certain conditions influence – social dynamics.

Cloud-like patterns of movement

We already know that highly efficient algorithms are used in direct marketing so that companies can identify customers' preferences based on their Internet usage and use these insights to recommend further products. "The programs running in the background of the websites of market leaders like Amazon and Netflix are getting better all the time at customizing the content presented to users," says Fornasier. Their forecasting abilities are limited, however, by the myriad factors that influence individual behavior. "But things look quite different if people are considered as part of a crowd," Fornasier points out. He and his team have recently proven mathematical laws that demonstrate how surprisingly easy it is to automatically generate precise mathematical models for specific, relatively simple group interactions based on observed dynamics data.
He has observed striking structural similarities with phenomena from the world of physics. This is especially true in situations where there is limited room for maneuver because of environmental constraints and rules – for example in road traffic or in social networks. "In those cases, masses of people behave like gas clouds," he explains. These consist of many atoms, which have their own mass, have a position and a speed at all times, and exert forces on each other through ▷

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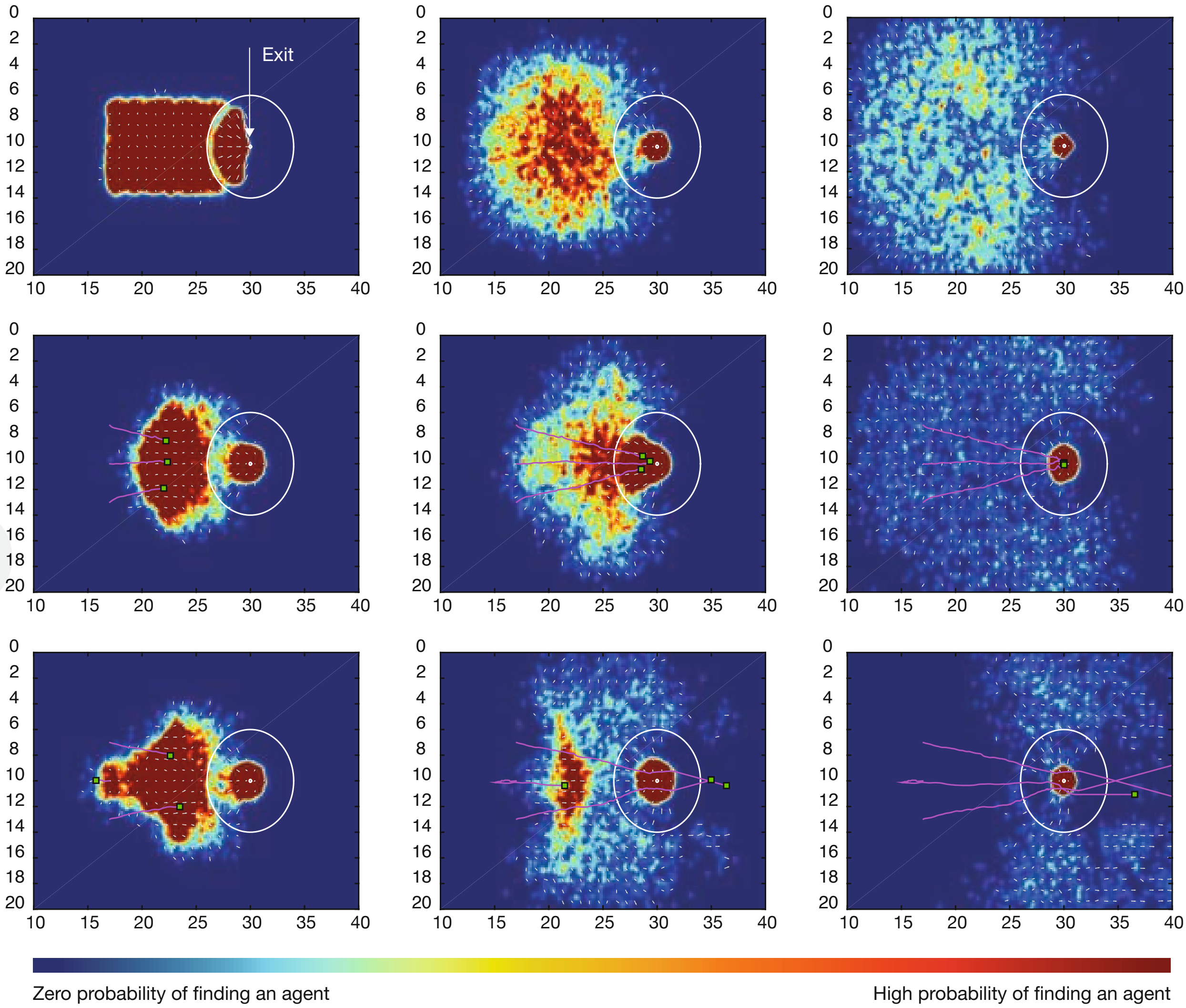
“Once we can calculate the behavior of a group of interacting agents in advance, we are only one small step away from being able to steer them.”

Massimo Fornasier



To simulate the behavior of very large human crowds comprising millions, Fornasier calculates the probability density rather than individual trajectories for each person. The image shows the simulation of the behavior of a human crowd in a room with no obstacles and one exit, expressed as probability of a person being in a certain location. Dark red equals high probability, dark blue equals zero probability. The white arrows indicate the locally averaged direction and speed of the agents.

First row: Under normal circumstances, the persons who can see the exit move towards it (left). Some group mates close to them follow (middle). The persons farthest away split into several groups moving into random directions and never reach the exit (right).

Second row: Three informed leaders (green, with pink trajectories) move straight towards the exit (left). All others follow, causing heavy congestion around the exit, which delays the evacuation (middle). Eventually the probability of finding a person still in the room is very low (right).

Third row: Three informed leaders move along trajectories which have been calculated with the aim of optimizing the flow (left). Congestion is avoided and flow through the exit is increased (middle). The probability of a person not reaching the exit is nearly zero (right).

Graphics with the kind agreement of the authors: Picture credit: G. Albi, M. Bongini, E. Cristiani and D. Kalise. Invisible Control of Self-Organizing Agents Leaving Unknown Environments, SIAM J. Appl. Math., 76(4):1683-1710, 2016. G. Albi and M. Bongini have been collaborators within Fornasier’s ERC Starting Grant project “HDSPCONTR”.

their electric charges. The important calculation criterion is not the position or speed of the individual particles – or individuals – at any one time, but rather how they behave as a mass on average.

In this context, Fornasier likes to refer to the science fiction writer Isaac Asimov. The Russian had invented the science of "psychohistory" in his celebrated Foundation Series. In the novels, the scientist Hari Seldon – who was also a mathematician – used this analogy of gas kinetics and collective behavior to predict the future of mankind for millennia. Fornasier's models bring this science fiction surprisingly close to scientific reality. Incidentally, the mathematician and his team have also elaborated on a new application for the Boltzmann equation, which physicists commonly use to calculate the statistical distribution of particles in gases. In particular, the scientists' capabilities are not just limited to describing collective behavioral patterns and visualizing them in computer simulations. They have also developed tools to help them see into the future. "Once we can calculate the behavior of a group of interacting agents in advance, we are only one small step away from being able to steer them," says Fornasier.

He found empirical evidence for this in an experiment undertaken with colleagues in May 2015 in cooperation with the Consiglio Nazionale delle Ricerche (CNR) and the University of Rome "La Sapienza" in Italy. As part of this project, the researchers divided 80 students into two groups and gave them the task of finding a specific location in a building. The scientists had planted two "undercover agents" into one of the groups and instructed them to walk very determinedly in a pre-defined direction. It turned out that their determined behavior very quickly induced the entire group to start following them. The mathematicians were also able to prove in this experiment that the movement of large groups of people can be steered with surprisingly little effort. "In fact, two to three agents per 100 individuals are sufficient," says Fornasier.

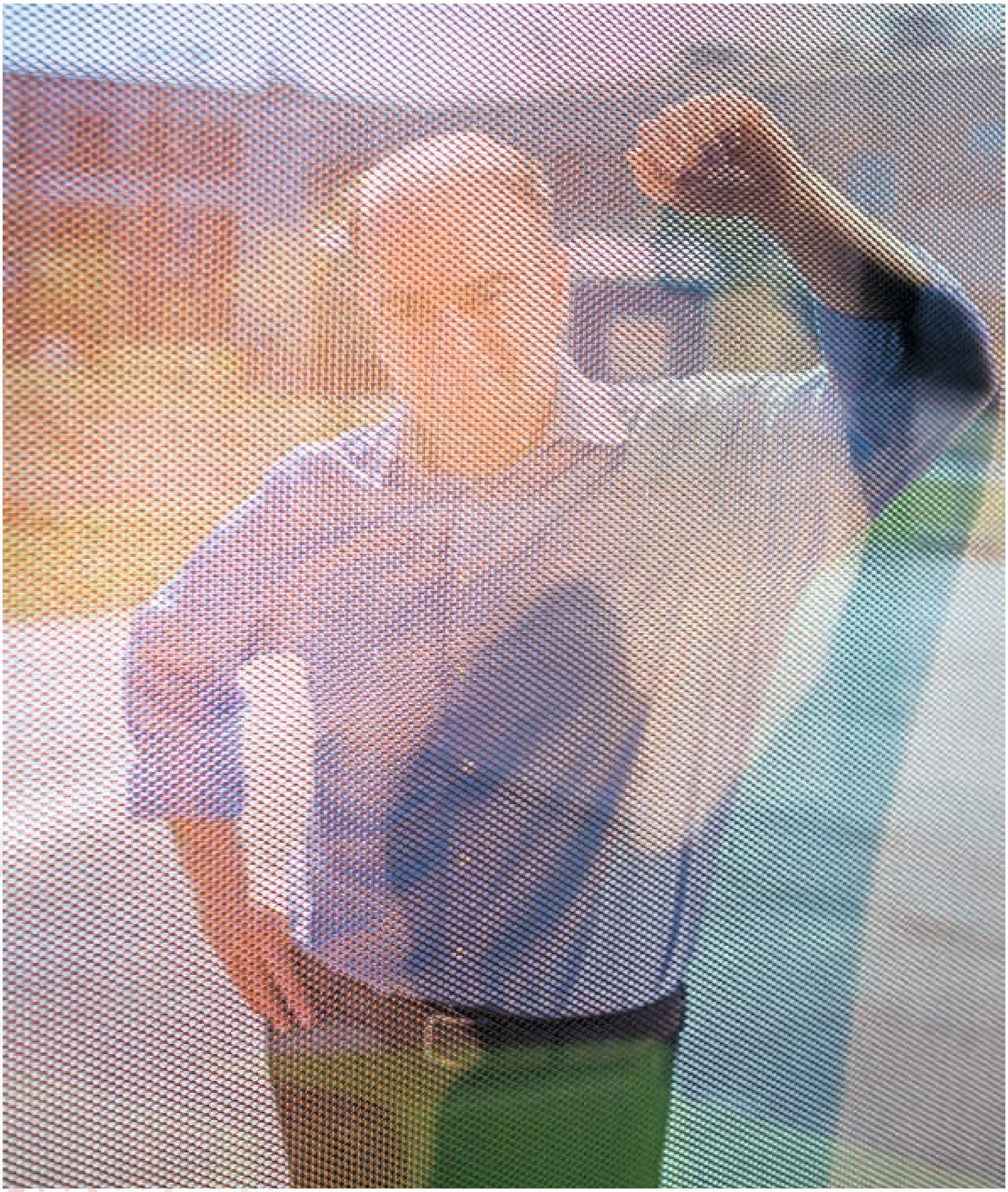
Herding dog strategy for opinion forming

The fact that his mathematical models are formulated in an entirely abstract framework makes them easily adaptable to a wide variety of situations in which interactions between multiple agents play a role. Fornasier takes the financial markets as an example of an arena where influence is exerted by a small number of agents. "There, precisely coordinated activities by big investors can result in sizable market movements," he explains. Maybe even more interesting is what Fornasier has learned about the dynamics of opinion forming within a group. His model shows that it is relatively easy to steer the thinking of individuals who are part of a group in a certain direction. "There is also a good model for this in nature," according to Fornasier. "To drive a herd of sheep in a desired direction, a good herding dog will always concentrate on the animal that is farthest from the group. They achieve their goal by reining in the most stubborn animal." When it comes to opinion forming in groups, it is also simply a matter of reining in the most ardent supporters of the views that go against the desired consensus. The rest of the group will then follow.

His findings are based on both theoretical results and numerical simulations, which are in turn based on opinion-forming models like those developed by the philosopher Rainer Hegselmann and the mathematician Ulrich Krause. What these say about opinion formation is that every group member adapts their opinion in line with those of the rest of the group in increments of time.

Fornasier and his colleagues are able to describe this alignment process using ordinary and partial differential equations. "Since all group members have their own opinion at the beginning, it is important that all agents share their information and points of view," he says of the principle. The consensus building happens in this process. This can only happen, however, if there is not too much separation. Agents who are ▷

Graphics: ediundsepp (Source: TUM)



Prof. Massimo Fornasier

A multi-dimensional researcher

With his mathematical models, Massimo Fornasier has a view on the world that is much more advanced than our three-dimensional observations. His special interest is the modeling of high-dimensional problems, where other dimensions in addition to length, height, width or time can be involved and which are therefore more difficult to conceive. The mathematician is able to present these problems using the formulas he has devised.
Fornasier was born in 1975 in the town of Feltre in the North-East of Italy. He has held the Chair of Applied Numerical Analysis at TUM since April 2011. His academic journey began at the University of Padua where he studied mathematics and completed his Doctorate in Computational Mathematics in February 2003. Between 2003 and 2009, he held the position of research associate at the Universities of Vienna, Rome, Marburg, Princeton and Linz. He has already received several awards for outstanding achievements in his field. These include the START Prize – the most prominent and highest endowed award for young scientists in Austria – and a Heisenberg professorship from the German Research Foundation. In 2009, he received the Prix de Boelpaepe for image processing from the Royal Academy of Science, Letters and Fine Arts of Belgium. In 2012, he became the first ever recipient of the newly created SIMAI award of the Italian Society for Applied and Industrial Mathematics. He also received a prestigious Starting Grant from the European Research Council in 2012. Prior to his appointment at TUM, Fornasier worked as a senior scientist at the Johann Radon Institute for Computational and Applied Mathematics (RICAM), which is part of the Austrian Academy of Sciences.

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When there is limited room for maneuver because of environmental constraints and rules, masses of people behave like gas clouds.

far apart from other individuals of the group do not exchange their views, which means that their position remains fixed. There is a way to bring these hardliners into the fold, however, according to the mathematician. “In the model, all we need to do is create one virtual agent and position them close to the extremists,” he explains. During the rapprochement process, the dissenter is gradually guided towards the opinion, which was literally brought nearer to him.

Fornasier’s social dynamics algorithms can help to find efficient solutions for planning and security issues in the real world. Examples of situations where this can come in useful include directing large numbers of visitors through buildings, optimizing traffic flows, and organizing evacuations in an emergency. For all the conceivably positive application scenarios that exist, there remains, of course, the question of potential risks. The possibility of exerting influence on social behavior is a double-edged sword. There is always the danger that the power of information will be abused through targeted manipulation and that democracy will thereby be undermined. Fornasier, however, excludes the possibility of his mathematical models being exploited to create totalitarian structures. “The good news in this context is that we have also proven that behavior is not so easy to predict or control for all kinds of dynamics and situations,” he says reassuringly. “We are lucky to have plurality of opinion and safeguards like the media or a multi-party system.” The scientists also found that the processes only work well in groups that show generalized patterns of behavior. However, as soon as the energy of individual agents crosses a certain threshold, the group of agents can no longer be moved in a concerted direction using simple, sporadic interventions. In other words, just as the best herding dog will fail to drive its herd of sheep home if the outliers dart away too quickly, algorithms too will become ineffectual in such scenarios. “The prospect of complete control will thus remain science fiction,” he says with conviction.

Birgit Fenzel