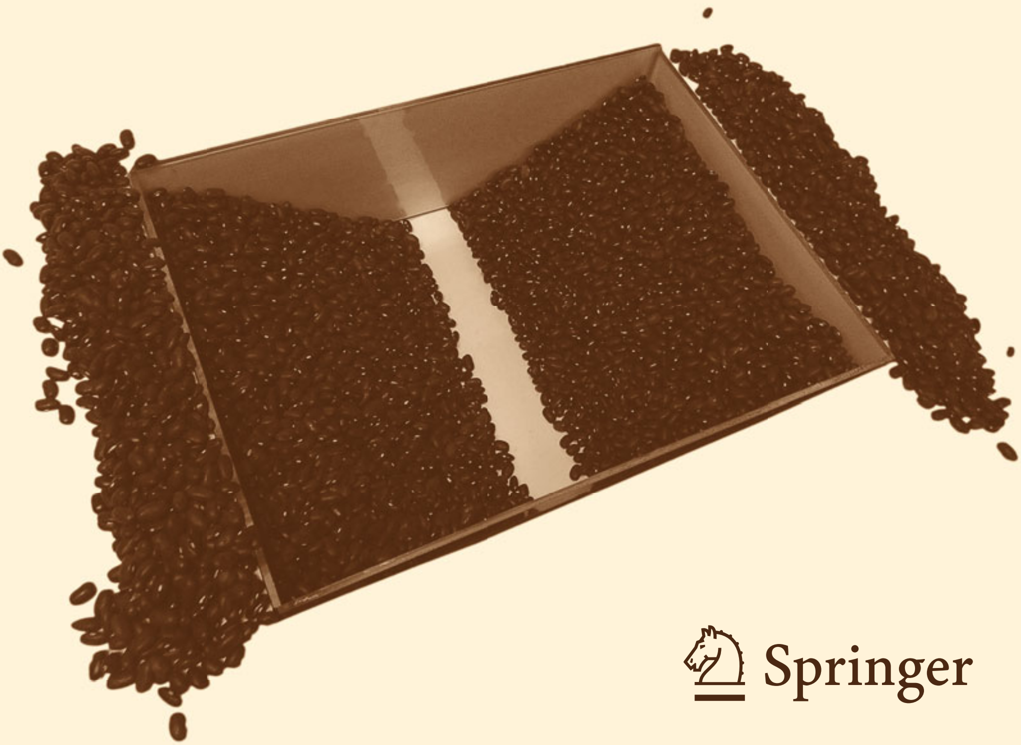
Ernesto Altshuler

# Guerrilla Science

## Survival Strategies of a Cuban Physicist



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## Survival Strategies of a Cuban Physicist

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*To Mercedes, José, Aramis and Patricia*

# Acknowledgements

I would have never dared to write this book without the initial momentum provided by Prof. Richard Packard (University of California at Berkeley). “You should write a book on your inexpensive experiments”—he more or less told me few years ago. I just couldn’t turn deaf ears to one of the finest experimental physicists I’ve ever met. The result is a book that concentrates more on the ways to do science than on the final results of the scientific endeavor. Those ways have been hard—sometimes *really* hard—during the last decades.

“Climbing up mountains makes men into brothers”[1] wrote José Martí—whom I regard as the greatest of Cubans—in his campaign diary. Running the risk of sounding a bit pompous, I might say that this book is my diary of climbing the mountain of science in “high tropicality conditions”—no less than 90% of my scientific work has been done in Cuba. Along the way, colleagues and students have become brothers and sisters. I am more than grateful to them. A surge of names immediately floods my mind: Sergio García, Oscar Arés, Armando Aguilar, Andrés R.R. Papa, Victoria Venegas, Celia Hart, Carlos Abascal, Pedro Muné, Alfo José Batista-Leyva, Jorge Luis González, Luis Flores, Carlos Martínez, Jorge Musa, Juan López, Jorge Barroso, Oscar Sotolongo, Roberto Mulet, Milenis Acosta, Alexander Hernández, Raiden Cobas, Claro Noda, Gustavo Sánchez, Osvanny Ramos, Ernesto Estévez, Reinaldo García, Etién Martínez, César Sánchez, Lenin del Río, Yuriel Núñez, Javier Fernández, Rogelio Díaz, Carlos Pérez-Penichet, Alejandro Borroto, Alexey Cruz, José Ramón Fernández, Nuris Figueroa, Alejan-

[1] Subir montañas hermana hombres (Campaign diary, May 14, 1895).

dro Lage, Sebastián Bianchini, Alberto Batista, Anier García, Eduardo Testé, Frank Tejera, Harol Torres, Alberto González-Pita, Laciel Alonso, Andy Scott García, Alfredo Reyes, Gabriela Rodríguez, Leonardo Domínguez, Vicente Díaz, Alfredo González, Gustavo Viera, Antonio Serrano, and Joaquín Amigó—several of them mentioned later in this book. I acknowledge my professors at the Physics Faculty, University of Havana, from whom I enjoyed an undergraduate education of the highest quality; unfortunately, the entire list would take several pages. Finally, I thank the Institute of Science and Technology of Materials at the University of Havana (IMRE) for hosting my lab and for continued help for decades.

In a different way, I must thank an extended family of numerous people outside Cuba from whom I have learned a lot, and who have helped decrease the level of tropicality of my research—and, eventually, of my life: Francesco Cino Matacotta, Suso Gygax, Georg Soerensen, Paco de la Cruz, Pablo Levy, Ariel Dobry, Félix Requejo, Hernán Pastoriza, Daniel López, Petr Nozar, Mladen Prester, Ricardo Decca, Carlos Durán, David Wald, Lucica Miu, John R. Clem, Joseph Ashkenazi, Jonathan Wu, José Edelstein, Ching-Wu Chu, Kevin Bassler, George Reiter, Carlos Lugo, Maya Paczuski, Yu-Yi Xue, Heinrich Jaeger, Jin Peng, Bern Lorenz, Eli Zeldov, Jossi Paltiel, Gemunu Guanaratne, Gustavo Tavizón, Sylvio Quezado, Wilfredo, Harald Weber, Victor Buntar, Carlos Ordóñez, Marcos Tadeu d'Azeredo Orlando, Renato Jardim, Tom Henning Johansen, Knut Jorgen Måløy, Eirik Flekkøy, Pavlo Mikheenko, José Eduardo Wesfreid, Hans Herrmann, Eric Clément, Stéphane Douady, Kamran Behnia, Mauricio Hoyos, Laurette Tuckerman, Dwight Barkley, David Quèrè, Frédérique Auger, Philippe Petitjeans, Renaud Toussaint, Jean Schmittbuhl, Jean-Christophe Geminard, Anke Lindner, Irene Ippolito, Gastón Miño, Rodrigo Soto, Jon Otto Fossum, Paul Dommersnes, Arne Skjeltorp, Geir Helgesen, Elisabeth Bouchaud, Leander Michels, Zbigniew Rozynek, Steinar Raaen, Giovani Vasconcelos, Mario Font, Andrei Martínez-Finkelshtein, Patrick Tabeling, Stéphane Santucci, Kevin Robbie, Bob Behringer, Doug Durian, Carlos Ruiz, Felipe Pacheco, Troy Shinbrot, Raúl Cruz, Martín Pastor, Diego Maza, Ángel Garcimartín, Iker Zuriguel, Thorsten Pöschel, Jonathan Kollmer, Leo Kadanoff, Scott Waitukaitis, Francoise Brochard, David Hu, Devaraj Van der Meer, Daniel Bonn, Marcelo Magnasco, and Albert Libchaber.

My mother, Mercedes Álvarez, and my father, José Altshuler, set me off on the path of curiosity at an early age, so they are ultimately responsible for this book. Finally, I thank my wife Aramis Rivera and my daughter Patricia, who have equally suffered and enjoyed it, though more in the flesh than on paper.

# Contents

# 1
# Guerrilla Science

*Each evening at dusk, a man in a wheelchair is pushed down to the water's edge by a friend. There, as the sun sinks into the ocean, and the night fills the sky, the invalid sings spine-tingling arias into the nocturnal void […] Much like the sea that extends to the world beyond while hemming the island in, its atmosphere is both lyrical and melancholic, liberating and imprisoning at the same time.*

Jon Lee Anderson
in "The Plague Years" (The New Yorker, Jan 26, 1998, p. 62)

In the afternoon of March 13, 1993, I was at home, immersed in Michael Tinkham's book "Introduction to Superconductivity" to prepare for one of my Ph.D. examinations. The storm of the century was gusting past outside. Suddenly, somebody knocked at the door to announce the unexpected: sea water was invading the garage of our building, and our family car was in danger. Adrenaline immediately flooded my body, Michael Tinkham's book hit the floor, and I flew eight stories downstairs in a matter of seconds to reach the garage. Indeed, a powerful stream of water was flowing down the access ramp, from street level into the garage, some five feet below. It was impossible to drive the car up the stream, so I tried to raise it onto four construction bricks, in the hope that the water level would not exceed a couple of feet in depth—the record up until then. I vividly remember that I was able to put the hydraulic jack under the car's first tire with little trouble, but I had to splash my head into water—glasses included—to position the jack


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under the fourth tire, just a couple of minutes later. Completely powerless, I watched the car tilting and sinking into the water, like a miniature version of the Titanic. In a last attempt to save something valuable, I tried to remove the battery, but electric shocks through my hands made me give that up, too… very timely, considering that I was already in the process of drowning. I ran back upstairs to my apartment, went out to the balcony, and started to swear in anger against the furious wind for several minutes, until I ran out of voice. Then, I picked up my camera, put it on film, and silently took pictures of Havana's flooded streets.

I defended my Ph.D. on June 13, 1994—exactly fifteen months later.
The film containing the flood photos was lost due to a developing mistake.
The car was rebuilt after three years of hard work.

Since the movie "Buena Vista Social Club", it has become cliché in international media to show the contrast between Havana's crumbling buildings and the talented people that come to live in those buildings. Even though it is a somewhat skewed view of reality, I would still accept that the cliché captures the essence: Havana is—and has been for decades—an eroded city, inhabited by many well educated, resilient people. You may find an economist raising pigs at home to get some extra food; a neurosurgeon driving through the night in a refurbished LADA turned into a TAXI; or a physicist plunging into the sea on Havana's skyline to supplement his family's diet with the occasional octopus. The same picture can be extended to the whole country—a country in pain.

In contrast to disciplines like medicine or biology—where individuals such as Carlos J. Finlay and Felipe Poey became world-recognized figures of Cuban science more than a century ago—physics has only a modest tradition in the country. The most prominent Cuban physicist in the first half of the XX century was Manuel F. Gran—an inspiring teacher and an enormously cultured man who published detailed and rigorous physics textbooks, but almost no original research. The situation was more or less the same until the late 1950s, when a social transformation catalyzed a number of radical measures: from nationalizations of foreign companies, to the Reform of Higher education in 1962. One of its enthusiasts would say: "It was a time of little control, so one could swiftly do a lot of good things!" One of those "good things" was to immediately force scientific research into Cuban universities.

In October 1960, the US imposed an "embargo"[1] that has been evolving right up to the present day. It makes it extremely difficult to purchase

[1] Called "El Bloqueo" in Cuba.

US-made scientific equipment in Cuba. However, collaboration with the former socialist block—especially the Soviet Union—as well as individual scientists from Europe, Latin America, and even the US, has helped the development of Cuban physics since the early 1960s.


Soviet electronic equipment was heavier and probably noisier than its US counterparts, but it worked. Thanks to it, Cuban physicists were able to achieve many things in a couple of decades, including fabricating solar cells, and designing original experiments to be performed in microgravity conditions during a joint Cuban-Soviet space flight in 1980, to cite two examples.

Being a country obstinately focused on social and political rather than economic goals, the Cuban economy became critically dependent on its connections with the former Soviet Union, which used to send oil to Cuba in exchange for Cuban sugar, regardless of the ups and downs in their prices on the international market.

So, with the disappearance of the socialist block by 1990, the island was inevitably to pay the consequences: Cuba found itself alone, and the economy sank like never before, reaching an absolute low in the period 1993–1994. People lost many pounds of body weight, blackouts were common, transportation collapsed, balseros stampeded to the North… it was hard to survive, and even harder to do science. One exception was biomedical research, were resources were more or less systematically injected by the government.

By the end of the 1990s the economy started to improve—basically thanks to the promotion of tourism, neglected for decades prior to that—but the infrastructure for physics had frozen in the early 1990s: as time went by, the Soviet electronics got even noisier… or just stopped working altogether.

For many Cuban researchers, the choice was to emigrate—a tendency that continues today. For my part, I felt I could not leave a country in pain.

My strategy to survive as an experimental physicist in "high tropicality conditions" was to violate the boundaries of "safe science", invading zones where I was not a specialist, looking further afield for new phenomena, seeing scientific instruments in everyday objects, attacking and retreating from serendipitous findings like a guerrilla. Facing challenges became a natural part of my way of doing science, and I started to feel an immense sensation of freedom. Now I'm addicted to it.

In the following pages I shall exorcise my addiction—a very personal matter with some scientific consequences.

# 2
# The Chinese Connection

*Prediction is very difficult,*
*especially about the future.*

(attributed to) Niels Bohr

When I handed this fellow 10 bucks for a sack of Chinese ball bearings smuggled out of the bicycle workshop on September 12, 1997, nobody but me suspected that he was contributing to the first Cuban tabletop experiment in the field of natural catastrophes.

I had talked to the guy a few days before when I spotted him coming out of the workshop where bikes were assembled, near the Iron Bridge—a place you don't visit just for the fun of it. In those days, Cuba was slowly emerging from the economic debacle of the early 1990. The crisis had tossed myriads of Cubans onto heavy bicycles with curious brand names such as *Flying Pigeon* and *Forever Bicycle,* massively imported from China. The good part of it—at least from the particular point of view of a stubborn scientist like me—was that there where zillions of ball bearings rolling around all over the country. So I had just got a couple of thousand of them thanks to my "contact" at the bike assembling workshop… and to my humble savings during a recent trip to the Superconductivity Lab at the "Abdus Salam" International Centre for Theoretical Physics (ICTP) in Trieste, Italy.



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## 2.1 From Vortices to Grains

**Flash anecdote**

The guerrilla style extended far beyond the lab itself—it had invaded all aspects of our science-making process. Perhaps the most picturesque part of it was its influence on the mail exchanges relating to the publication of scientific papers in international journals. At a time when electronic mail and web pages were not the standard, conventional mail was an essential step to getting your results published. But due to the chronic lack of gas, letters came very late from the regional post office to the university post office. Knowing that referee's reports to our papers were probably sleeping in a pile waiting to be picked up became a genuine torture. So I made an unofficial agreement with the fellows in charge of the post office: with a handful of brave colleagues, I would collect all the mail for the University of Havana (typically a 10-foot tall pile sitting in a corner of the regional post office), transport it on several Chinese bikes to the University campus, sort it out, and remove our own mail—including any of the eagerly awaited referees' reports!

But to understand the meaning of my tangentially delictual affair, I must go back a little in time. As mentioned earlier, I had defended my Ph.D. thesis in the field of High $T_c$ superconductivity in 1994—almost at the very bottom of the economic crisis. Superconductors—discovered by Heike Kamerlingh-Onnes in Leyden back in 1911—are materials able to support a transport current with practically zero dissipation, and to shield any applied magnetic field if they are cooled below a *critical temperature*, $T_c$.[1] For several decades after 1911, the highest known $T_c$ for any superconductor was as low as a few degrees kelvin. In 1986, Bednorz and Müller (IBM—Zürich) broke theoretical predictions by discovering a new type of superconductor, very different from the existing ones: they were copper oxides, rather than metals or metal alloys. Furthermore, their critical temperature could be as high as 40 degrees kelvin. Following these first steps, a group in the US led by C.W. Chu discovered a compound based on yttrium, copper, barium, and oxygen (YBCO for short) which established a new record critical temperature at 93 K. That produced a true commotion in the scientific community: the new material could be in the superconducting state at temperatures above the boiling point of liquid nitrogen, so experiments suddenly became accessible to many labs all over the world. Moreover, applications seemed to be just around the corner. Many research teams with previous experience in

[1] Strictly speaking, the survival of the superconducting state also requires that the applied magnetic fields and currents not be excessively big.

**Fig. 2.1** A family portrait of Cuban experimental superconductivity. A few members of the Superconductivity Laboratory, University of Havana, posing in front of the lab's entrance, circa 1995. From *left* to *right*, *top row* Oscar Arés (head of the lab.), Celia Hart, Pedro Muné (visiting from the University of Oriente), and Claro Noda. *Bottom row* Luis Flores, Roberto Mulet, and Ernesto Altshuler

superconductivity just connected their "turbo mode", and international competition went out of control. In fact, shortly after the publication of the YBCO discovery, a three-day, nonstop meeting was held in New York to discuss the subject—it was nicknamed "The Woodstock of Physics".[2]

Professor Sergio García and the technician Armando Aguilar synthesized the first YBCO ceramic pellet at the University of Havana as early as April, 1987, just two months after publication of the discovery by the US team. That kicked off the creation of the Superconductivity Laboratory at the University of Havana, headed by Prof. Oscar Arés: state-of-the-art ovens, some electronic equipment, and even a vibrating sample magnetometer were purchased with a grant given by the State.[3] Some time afterwards, I managed to join the lab, partly due to the fact that Sergio had supervised my research in the field of magnetism during my undergrad years at the University of Havana (1981–1986). Coincidentally, my research as an undergrad had focused on the study of a magnetic phase with a perovskite structure… the same basic structure as the YBCO compound (Fig. 2.1).

[2] That was a reference to the rock festival celebrated in Woodstock (USA) in 1969, under the maxim "Three days of love, peace, and music". Probably several scientists involved in the high $T_c$ revolution had participated—or at least, been influenced—by the 1969 Woodstock festival.

[3] Unfortunately, the lab was hurried up to spend the grant, so the resulting equipment was quite useful, but not the ideal choice for characterizing superconductors.


**Fig. 2.2** Dirty versus clean Physics. *Left* The "dirty" experimental physicist performed measurements on inexpensive, superconducting ceramic samples. Due to the very inhomogeneous nature of the ceramics, it turns out to be quite difficult to understand in depth the experimental results. The "clean" physicist, illustrated by a theoretician on the *right*, can allow himself (or herself) to model superconductivity from first principles, which is not an easy task, especially in the field of high temperature and "exotic" superconductors (Cartoon taken from the author's Ph.D. thesis)

As early as 1989, I had started doing measurements on ceramic superconductors with the tools at hand: a current source, a microvoltmeter, liquid nitrogen … and hand-made cryogenic inserts. Ceramic superconductors could be made using simple resources (some chemicals, mortars, an oven, and a bottle of oxygen), so they were the obvious choice. However, ceramics are non-homogeneous samples composed of relatively homogeneous superconducting grains interconnected by "weak links".[4] In contrast to more sophisticated samples like superconducting single crystals and epitaxial thin films, it was very hard to study the properties of the high $T_c$ superconducting material the grains were made of: we jokingly called it "dirty physics". We spent years figuring out how to get the "intrinsic" properties of the grains by measuring "extrinsic" ceramic properties in a scenario where only small magnetic fields and temperatures above 77 K were available to us. But I might say that we succeeded (Fig. 2.2).

[4] These can be modeled as *Josephson junctions*: typically superconductor-insulator-superconductor sandwiches through which the superconducting charge carriers (pairs of electrons called *Cooper pairs*) can tunnel thanks to quantum effects.

Thanks to two projects supported by the Third World Academy of Sciences (TWAS), with grants totalling 15,000 USD or so, we were able to further improve the quality of our measurements, especially due to the introduction of British made lock-in amplifiers, and a state-of-the-art temperature controller.[5] After a few years of frantic experiments with such a setup, I defended my Ph.D. in 1994. It is worth mentioning that in the early nineties I had been invited to wonderful workshops organized at Cino Matacotta's Lab in the *International Centre for Theoretical Physics*[6] (Trieste, Italy). I had also spent three months at Suso Gygax's Lab in *Simon Fraser University* (Vancouver, Canada) and short periods at the Low Temperature Lab headed by the legendary Paco de La Cruz in the *Centro Atómico Bariloche* (Argentina). But, at the same time, I had a very strong psychological necessity to face the challenge of doing most of my work at home. So, almost 100% of the material included in my Ph.D. thesis was measured in our own lab.

**Flash anecdote**

We had always transferred liquid nitrogen to perform superconductivity experiments a primitive way: holding in the air the heavy dewar, pouring its content into smaller containers, and then pouring them into the measuring system. It was a hard an inefficient way to do the job. During a visit to the Centro Atómico Bariloche (Argentina), they kindly constructed for me a simple system to extract liquid nitrogen from our storage dewar in a more civilized way. It basically consisted in a siphon with a heating element fed by a 220 V connection that would increase the pressure inside the dewar. On October 30, 1995, I rushed in the lab to install the transfer system. I introduced it into the dewar, and connected the heating element to the 220 V outlet. Nothing happened, though: it seemed that the rubber and metal part supposed to seal tightly the opening of the dewar was too loose. Without disconnecting the 220 V, I pushed down the sealing part very hard with both hands. The water condensed onto it made such a good job conducting electricity through my arms and chest, that I was almost electrocuted. Nowadays, we continue transferring liquid nitrogen in the old fashioned way.

But precisely due to the fact that I had seen the world, I understood how difficult it would be to compete in the league of fully equipped labs with

[5] Our system worked really well, partially thanks to the careful design of the measuring probe—especially the wiring between the sample at low temperatures and the external measuring apparatus. It has produced data for dozens of papers and academic degrees. We still use it for investigating superconducting tapes.

[6] Today called the "Abdus Salam" International Centre for Theoretical Physics.

**Fig. 2.3** Superconductivity in high tropicality conditions (HTC). *Left panel* Home-made inserts to perform transport measurements in superconducting samples at liquid nitrogen temperature and above. The mummy-like stick at the bottom includes a long cooper coil (wrapped in masking tape) to apply a magnetic field to the sample, while it is positioned at different heights inside a liquid nitrogen reservoir—a simple way to control the sample's temperature without loss of homogeneity in the applied magnetic field. *Right panel* A magnetic shield to do measurements using a superconductor-based sensitive detector of magnetic fields (SQUID). The handwritten "brand name" reads "Tropical SQUIDs, Inc." All these devices were made back in the early 1990s

a decade's experience in the field of superconductivity and low temperature physics (Fig. 2.3). I guess that, at the time of my Ph.D. defense, I was subconsciously conceiving an expansion of my research endeavors out of a survival instinct… but the leap would come naturally, as we will see below.

I have mentioned before that the mysterious magnetic field dependence of the transport properties of ceramic superconductors could be understood by assuming that those materials were made of "strongly superconducting" grains, linked by "weakly superconducting" unions whose transport abilities would rapidly decay when they feel a relatively small magnetic field. The grains, on the other hand, behave as so-called type II superconductors. As a chain breaks by its weakest step, a ceramic superconductor will start dissipating energy as soon as one of the weak inter-grain links breaks. But it breaks more or less easily depending on the performance of the strongly superconducting grains surrounding it. So, the behavior of the weak links—directly measurable through the transport properties of the whole ceramic sample—would serve as a "local probe" to investigate the properties of the grains. Then, the "intrinsic properties" of the superconducting material can be reached by measuring the "extrinsic properties" of the ceramic (see Annex A).

In order to understand what happens inside the superconducting grains as the applied magnetic field changes, we need to know that they create shielding currents as soon as an external magnetic field is applied, in such a way that the magnetic field induction inside the sample is practically zero (Meissner state). However, as the external field is further increased, there is a moment when the superconducting shielding currents are no longer able to prevent the flux lines from penetrating the superconductor. In a type II superconductor—which is the case of our grains—it does not mean that the external field will "rush" inside the sample. Instead, the field enters from the boundaries, quantized as *vortices*, i.e., discrete lines of magnetic field surrounded by circular currents, each one containing one flux quantum.[7] As the external magnetic field increases further, more and more vortices enter from the edges due to the "magnetic pressure". But their penetration is prevented by defects in the material (called *pinning centers*) where vortices find it energetically favorable to be trapped. Since vortices repel each other, new ones entering from the edges "push" the vortices that penetrated before further inside. The overall result is that the density of vortices is bigger near the edges, and decreases towards the center: when the averaged vortex density profile decreases linearly, we say that the superconductor obeys *Bean's critical state model.*[8] Importantly, when the magnetic field is decreased and eventually taken to zero, some vortices are still trapped inside the superconductor at some pinning centers, so there is a remnant magnetization—this is hysteresis.

**Flash anecdote**

I was unable to use my small TWAS grants to purchase US-made equipment. My golden dream of having a brand new *Stanford Research Systems* lock-in amplifier in the lab was just that: a dream. So, we purchased more or less equivalent equipment from lesser known brands. In fact, we were joking all the time about an imaginary situation. There are these two British engineers drowning their boredom in beer at the pub, and the cell phone of one of them rings. The guy answers the call; his face lights up. He hangs up, and tells his partner: "John, I suggest we abandon our pints on the spot, rush to the garage, and assemble another lock-in amplifier: those freakish Cubans have just called again, mate!" (Seriously speaking, I must say that our British-made lock-in amplifiers are still working nicely after two decades!).

[7] The circular currents in a vortex typically have a diameter of one tenth of a micrometer. Each vortex contains one flux quantum, corresponding to approximately $2 \times 10^{-15}$ Tm$^2$.

[8] If the external magnetic field is increased a lot, the density of vortices can be so high inside the sample that the internal average field is similar to the field outside: the sample is no longer able to shield the external field; superconductivity has been completely destroyed.

I have always said that a type II superconductor is like a bus in Havana: at the first stop, the bus is empty, while the "magnetic field" (i.e., a crowd of people) is waiting outside. As the doors open, the magnetic field enters the bus as individual vortices (i.e., individual people) that repel each other, while feeling the "magnetic pressure" of the external crowd. As they enter, the human vortices are not distributed evenly inside the bus: people tend to be "pinned" close to the doors, because they want to be near them to be sure to get off after a few stops. The result is Bean's model for urban transportation: the density of "human vortices" is higher near the doors and decreases toward the center of the bus.[9] In that case, we also have a "remnant magnetization": there is always a fistful of passengers that fall asleep and don't get off when the bus reaches its final destination—they remain "pinned" at their sites.

**Flash anecdote**

It was in the mid nineties, and one of my grad student had spent months fighting bureaucracy to collect the paperwork for joining a Brazilian Ph.D. program. He had reached the point of being nuts about the whole process (a state of mind that psychologists and physicists working on granular matter may coin *The Brazil Nuts Effect*). That morning, when he turned on the lab's light to pick up the bunch of papers for a crucial interview at the Brazilian embassy, he found that all his precious documents were bonded together as chains hanging from the lab's ceiling, while "La Chica de Ipanema" started to play in the background. When I arrived later on, I found a gallows rope hanging just above my seat. Fair enough: my practical joke had gone a little bit too far (I perfectly remember that the toughest part had been to find a version of "La Chica de Ipanema" recorded on a cassette. Compared to that, connecting the power wire of the tape recorder in series with the light switch was a piece of cake).

The first time I seriously considered doing science beyond superconductivity was the night of April 29, 1994. I was having a glance at an issue of "Mundo Científico" (a Spanish version of the French journal *La Recherche*), just to relax from the stress of the preparation for my Ph.D. defense, and I found this paper on granular matter. I immediately identified a lot of analogies between vortex physics and sandpile physics, and became extremely excited. From that very moment—as usually happens—I wished I could simply forget the Ph.D. defense (which finally took place on June 13), and dive into sandpile and "vortex pile" physics. In particular, I realized how

[9] Of course, this profile eventually relaxes—a phenomenon called "flux creep" in superconductors—after a number of bus shakings when passing by potholes in the street… but that is a different story.

similar the Bean model is to the formation of a granular pile—or a granular heap against a wall, as illustrated in Fig. 2.4b. I vividly remember my excitement when they discussed "sandpile" avalanches, and I realized that the same could be the very mechanism behind the Bean model in superconductors! However, I soon discovered that the idea had been proposed long before by people as illustrious as Pierre Gilles de Gennes. In his classic 1966 book *Superconductivity of Metals and Alloys*, he wrote: "We can get some physical feeling for this critical state by thinking of a sand hill. If the slope of the sand hill exceeds some critical value, the sand starts flowing downwards (avalanche). The analogy is, in fact, rather good since it has been shown (by careful experiments with pickup coils) that, when the system becomes overcritical, the lines do not move as single units, but rather in the form of avalanches including typically 50 lines or more".

I immediately suggested to my student Roberto Mulet to start running simulations on vortex avalanches—which he did brilliantly, as usual—but my own experiments on the subject would be performed only years afterwards during a postdoc at the Texas Center for Superconductivity (Univer-

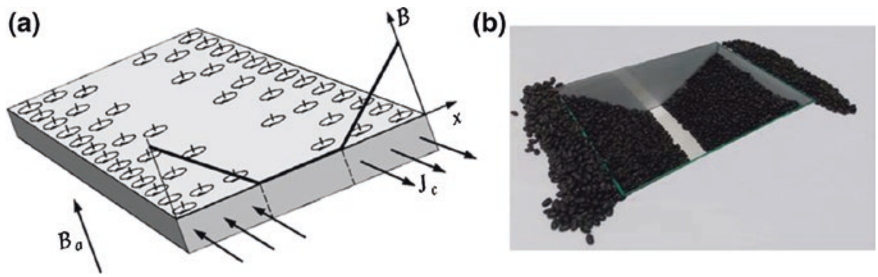


**Fig. 2.4** Bean on beans. **a** The critical state for a type II superconductor. In response to an applied field ($B_a$) bigger than the so-called *first critical field* ($B_{c1}$), vortices enter the superconductor from the edges. The competition between the external field "pushing" them in and the pinning centers trying to prevent their penetration results in a higher density of vortices near the edges that decreases towards the center of the sample. A "mesoscopic" picture of it—created by Charlie Bean in the early 1960s—says that the material responds to the applied field by establishing a circulating critical current ($J_c$) which produces a magnetization that partially compensates the external field, whence the resultant magnetic induction inside the sample decreases linearly from the edges to the center. This is a non-equilibrium situation, where the slope of $B(x)$ equals the critical current $J_c$. **b** Critical state in a box of beans. As black beans are pushed inside a plastic box through its edges, the competition between gravity pushing in and the effective friction results in a linear critical slope quite analogous to the one in Bean's model. In both systems, avalanches may occur as the external force slowly increases

sity of Houston) in the period 1999–2000, not exactly a typical scenario for guerrilla science![10] However, vortex avalanches kicked off my "phase transition" into the wonderful world of "simple" experiments: if I did not have at home the resources for doing experiments in vortex avalanches in 1994…. why shouldn't I try sand?

## 2.2 Debugging Granular Piles

So I started to play with the idea of studying avalanches in granular matter right, after reading the popular account in *Mundo Científico* in 1994. It is fair to say that the breakthrough that had renewed the international interest of physicists in sandpiles was the concept of *self-organized criticality* (SOC), proposed by Per Bak and co-workers in 1987. They said that systems with many degrees of freedom (lots of grains, in the case of a sandpile), when slowly excited (grains added one by one in the case of a sandpile), would evolve into a very robust structure (a conical shape with a well-defined angle of repose in the case of a sandpile) through an avalanche mechanism—just as in a typical sandpile! Bak and co-workers would add a more stringent element, though: the size distribution of those avalanches would follow a power law, a typical behavior seen in critical phenomena. So, if one patiently measured the size of the avalanches occurring in a "slowly excited" sandpile and plotted the avalanche size distribution, a power law should emerge. In addition to this, Bak and co-workers claimed that the slope of that distribution (presumably a *critical exponent* of the system) should be robust against variations in the experimental parameters. Those avalanches—following SOC ideas—would explain 1/f noise, ubiquitous in nature. Inspired by such ambitious claims, several researchers at prestigious institutions temporarily cleared their workbenches of expensive equipment, and replaced it by sandpiles. The first results, viewed through the prism of critical size-scaling ansatzes, seemed to corroborate SOC ideas.[11]

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[10] There, a number of fortunate facts allowed me to actually quantify vortex avalanches: the enormous support and patience of Director C.W. (Paul) Chu, my close relation with Norwegian top-expert in magneto-optical imaging Tom. H. Johansen—who was visiting the Texas Center for Superconductivity at the time—and the long-distance, but crucial collaboration with the Israeli researcher Eli Zeldov and his student Yossi Paltiel.

[11] In fact, I felt a strong connection with an enthusiastic fistful of scientists like Heinrich Jaeger (University of Chicago) and Franco Nori (University of Illinois) who were actually moving back and forth between superconductivity and granular matter in those years.

**Flash anecdote**

During the period 1994–1996 I became a bit obsessed with the subject of *circular vortices*: in a superconducting torus, it is possible to induce donut-like vortices if an axial current circulates along a wire that traverses the torus along its symmetry axis. That should produce a voltage drop in the superconductor, as the vortex radii shrink or expand—a beautiful scenario described by Michael Tinkham in his well known textbook *Introduction to superconductivity*. My undergrad student Roberto Mulet had made nice calculations relating to this phenomenon, but I wanted to measure it. Unfortunately, all my attempts failed miserably. I probably overestimated the size of the voltage… or my equipment was just not good enough! The worst part is that I had discussed the idea in January 1995 with John R. Clem (one of the most prominent figures of vortex physics who has recently passed way)… and he suggested that I stop working on that subject.

If people at IBM were playing with sand, why shouldn't we? In Cuba, we don't have much fancy equipment, but we have tons of beautiful sand all over the place! So I started putting together an experiment to look at avalanches in three-dimensional (i.e., conical) piles. The idea was to add sand to a flat, circular base and observe avalanches, then look at the effect of vibrations on them (in order to model thermal activation in superconductors—a subject where my student Roberto Mulet had been working theoretically at great speed and with remarkable success).

However, instead of avalanches, a completely unexpected phenomenon showed up. We called it later on "revolving rivers", but it will be explained in detail in the next chapter. To get rid of the "politically incorrect" phenomenon, Mulet suggested using peas (called *chícharos* in Cuba) instead of sand, so I immediately called the device "El Chicharotrón". I should have never followed the suggestion of a theoretically-minded guy: the revolving rivers disappeared indeed, but were substituted by an army of hungry bugs (called *gorgojos* in Cuba) that readily attacked the peas. And I certainly did not want my avalanches to be triggered by such SOC-less causes!

So, taking advantage of the fact that my wife does research in the field of porous materials, I replaced peas by zeolite pellets. However, the whole setup still did not want to work properly. In the end, I bet on a trade-off: I would sacrifice the dimensionality of the pile and the mystery of vibrations, in favor of being able to control the addition of grains, and to get more detail on the structure of the pile (To be honest, I have to accept that the sheer didactic strength of the two-dimensional system to be used in class was the key element that changed my mind).

So I started to fabricate two-dimensional piles "trapped" between two vertical sheets of glass separated by one bead diameter—a Hele-Shaw cell, in technical language. The cell would rest on a digital weighing scale to measure variations in the weight of the pile, allowing us to measure off-the-edge avalanches, i.e., bursts of grains escaping from the sides of the cell. In a later development, we could take pictures of the pile and analyze its structure. We used for that a very simple webcam handled by a friend from the US. A big problem remained, though: we wanted to add particles from the top one by one in a completely controlled way, just as required by the "canonical" ideas of self-organized criticality (SOC). With the help of undergrad student Claro Noda and engineer Carlos Martínez, we constructed a device able to deliver beads one by one, directly inspired by a TIC-TOC candy deliverer—some elements of the structure were made out of Chinese "Meccano" parts that used to be my favorite toy when I was a kid in the late 1960s.[12] But, after trying very hard to make it work with zeolite pellets, I had to accept that a less interesting material would be better: ball bearings. We searched for months to find these, until the decisive encounter at the Iron Bridge described at the beginning of this chapter (Fig. 2.5).

A typical sequence of events during one experiment was like this: a ball bearing was dropped on the pile built into a Hele–Shaw cell resting on a scale. There may or may not occur an off-the-edge cascade of balls—i.e., an *off-the-edge avalanche*. In any case, the scale, which was connected to a computer, detected any mass difference before and after bead addition, and also detected when the system was ready to receive a new addition (i.e., when all ball re-accommodations were over). In a more advanced version of the *Chicharotrón*—implemented by a former pharmacy and later physics undergrad student, Osvanny Ramos—a picture of the resulting pile was taken after each new bead was added. In fact, as the picture was taken, a real time *Voronoi* triangulation of its structure was constructed: we were forced to do this, since we did not have enough hard disk space to store the whole photo each time! The cycle was repeated hundreds of thousands of times, in order to improve statistics. The hypnotic sound of each bead dropping on the pile every few seconds would eventually be interrupted by a "prrrshhhsss" sound, triggered by a big avalanche. That particular sound, easily identified from every corner of the lab, invaded us with spikes of happiness during the whole day. I was actually very proud, not only about the functioning of the

[12] In those years, toys were basically provided by the Cuban state once a year, during Christmas, in special stores. The distribution of toys used to take a few days, and long lines of kids and parents crowded the stores, following an order established randomly with some anticipation—a way to guarantee equality for all. Three toys were assigned per kid: a "basic" one (ideally a bike!), and two "supplementary" ones. The whole situation was quite stressful to me, especially when I was not very lucky to get low numbers in the line: I never got a soviet bike, but certainly a few Chinese Meccanos.

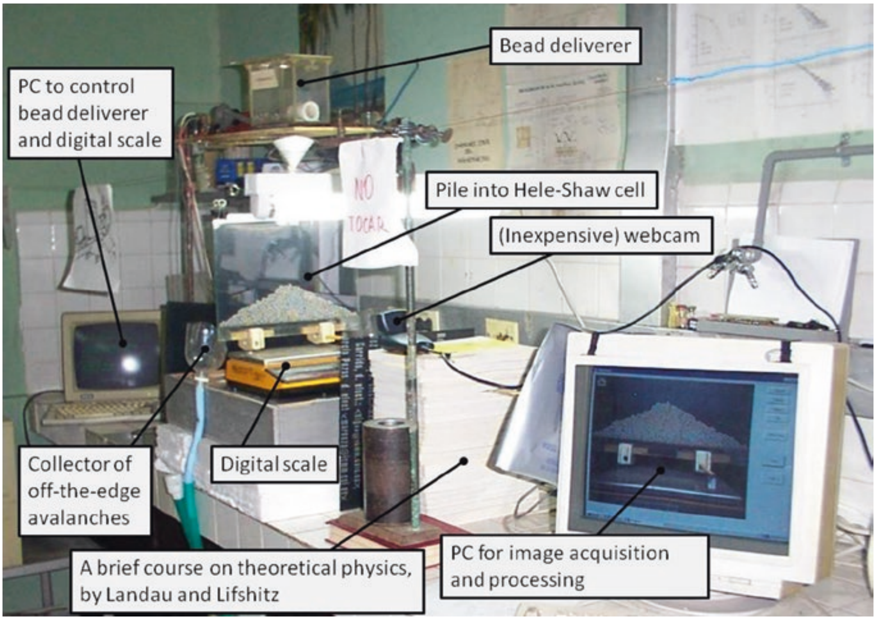


**Fig. 2.5** El chicharotrón. A system to quantify avalanches occurring when steel beads are added from the *top*, one by one, to a two-dimensional pile. A digital scale measured the beads that eventually abandoned the pile by the edges (off-the-edge avalanches), while a digital camera took pictures of the pile between bead additions, in order to study the structure of the pile, and also to measure "internal" avalanches. In a later version of the experiment, the scale was eliminated. Photo taken circa 2000

*Chicharotrón*, but also for its robustness against all odds: the program would stop or fix the problem if, for example, the bead to be added was not actually added, or if the mechanism got jammed, or if the electricity went off, etc. We rarely lost a big set of data (Fig. 2.6).

We first used the *Chicharotrón* to investigate how robust the avalanche distributions were against changes in the nature of the base of the pile. Being a two-dimensional system, the one-dimensional base turned out to be quite important, not only from the point of view of the pile structures, but from the point of view of the avalanche distributions. I made four different bases: from the one labeled "Gap0", where a row of beads were glued to the bottom boundary touching each other, to "Gapran", with air gaps of 0, 1, 2, and 3 mm randomly located between the (4 mm-diameter) beads glued to the base. I remember perfectly that I picked the air gap sequence by tossing dice on the couch in my living room. Experiments showed that Gap0 data gave relatively good power laws in the avalanche size distributions, but the critical size scaling for different pile sizes was poor. On the other hand,


**Fig. 2.6** The dangers of avalanches

the best critical size scaling was found for Gapran piles, although the size distribution for each pile size was not such a nice power law. Other types of basis showed a jungle of intermediate and confusing distributions. It was also observed that critical size scaling was better for piles with more disordered free surfaces (a "surface disorder coefficient" was defined to quantify it). We spent months debating how to interpret the tons of data, until one day, while discussing at the blackboard to prepare a last-minute seminar that Osvanny had to present before an examining board, it occurred to me that random bases were "more SOC" than ordered bases—exactly the opposite of our preconceived ideas. Osvanny just said "Me gusta!" (I like it!). Perhaps everything was just an untold agreement to beat the seminar's deadline, but the fact is that the interpretation has remained as "the chosen one". In fact, we concentrated only on Gapran bases for experiments over the next few years, since they offered the "best SOC scenario", so to speak.

In any case, the result was surprising: the "most random" piles—generated by the Gapran base—showed the best collapse of off-the-edge avalanche size distributions for piles of different sizes, corresponding, in principle, to a true power-law distribution for an ideal, infinitely large pile. That suggested

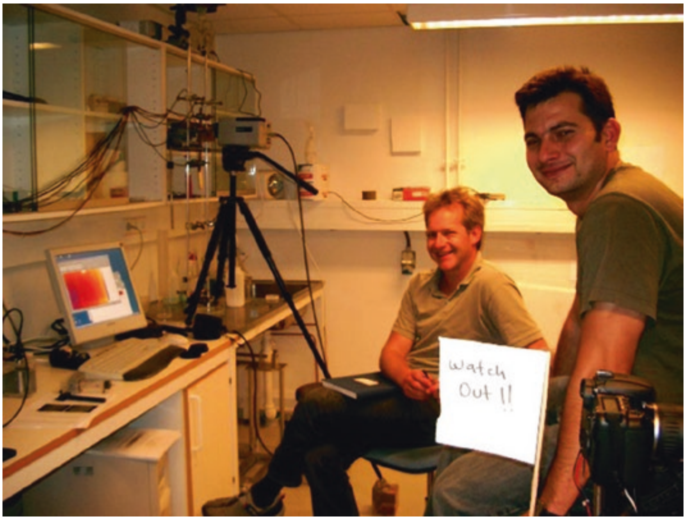


**Fig. 2.7** Knut Jorgen Måløy (*left*) and Osvanny Ramos (*right*) at Knut Jorgen's Lab (Physics Department, University of Oslo), in August, 2006

that SOC behavior in two-dimensional, real sandpiles, actually depends on experimental details. So, the real world needed a "soft version" of SOC.

However, we were not entirely happy with our definition of avalanche—or with any experimental definition of avalanche reported in the literature so far. To be fair with the original SOC idea, we needed somehow to count not only the off-the-edge avalanches, but those associated with all the bead shifts occurring between one addition and the next. This difficult task was tackled by Osvanny, carefully programming image differences between one picture and the next—he basically taught himself how to do it from scratch.[13]

## 2.3 Are Avalanches Predictable?

In fact, the experiments reached their greatest accuracy when redone years afterwards at the Physics Department, University of Oslo, with the collaboration of Knut Jorgen Måløy (Fig. 2.7). There, a number of improvements were introduced: the size of the piles was increased to reach a bigger span of avalanche sizes (that allowed us to skip the use of critical size scaling to

[13]When a new student approached him asking about the possibility of joining my research group, he would say: "If you don't know how to program, you are dead. To work with Altshuler you have to be a programmer… 'cause he doesn't know how to program!" (That "filtering" was of great help, I'd say).

analyze the data); and the resolution of the digital camera was improved, increasing the accuracy in the measurement of avalanches. The avalanches were defined as the number of beads that moved, in the whole pile, between two addition events.

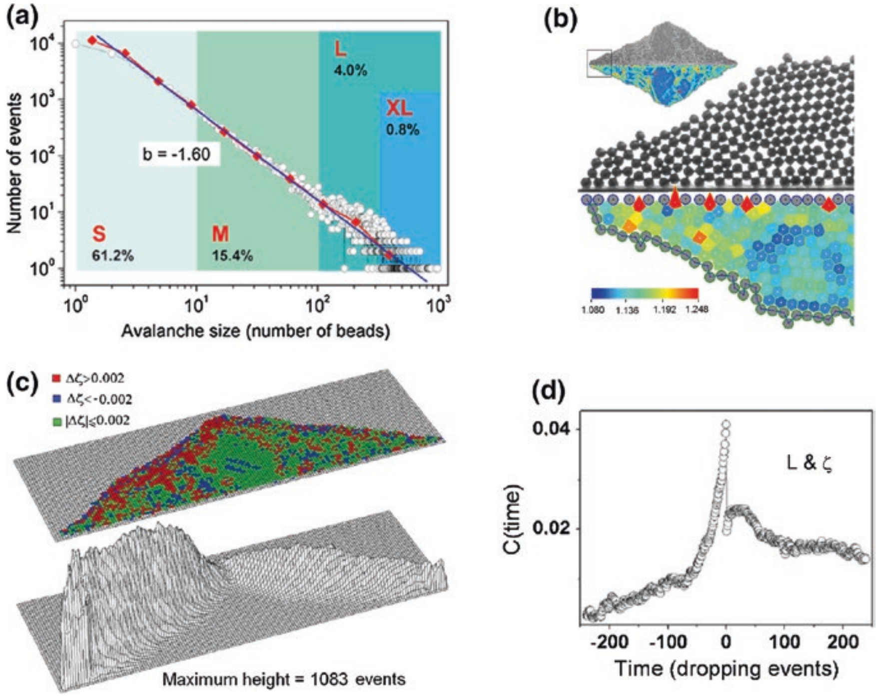


**Fig. 2.8** Learning to predict from a tabletop granular pile. **a** Distribution of avalanche sizes for a two-dimensional pile of beads, which follows a power law with a slope of $-1.60$. Avalanches—defined as the total number of beads changing position between two addition events—are grouped as small (S), medium (M), large (L), and extra-large (XL), as their size grows. **b** Internal structure of a pile with a reflection (*colors*) in the space of the so-called *shape factor* $\zeta$. After finding the center of the beads and making a Voronoi triangulation, we define $\zeta = C^2/(4\pi S)$, where $C$ is the perimeter and $S$ the area of each Voronoi cell. *Dark blue cells* correspond to high order, almost hexagonal, regions (high $\zeta$ values), while *red cells* correspond to highly disordered regions (low $\zeta$ values). **c** *Top* Difference between the local averages of the $\zeta$ values at one step before a large avalanche and at 50 steps before a large avalanche. *Red* indicates that the disorder increases, *blue* that order increases, and green that there is no variation in $\zeta$. Notice that red predominates over blue. *Bottom* The cumulative number of sites involved in large avalanches during a large experiment. The match between the *red color* at the *top* and the landscape at the *bottom* corroborates the idea that, on average, *disorder increases before a large avalanche takes place*. **d** The last statement is globally corroborated by the time correlation between the average shape factor in the whole pile and the occurrence or large avalanches

New experiments under these conditions resulted in the first "direct" observation of power law distributed avalanche sizes in real piles (Fig. 2.8a). Furthermore, the structural disorder of the whole pile was quantified, and its time correlation with the avalanche time series turned out to "hint" at the proximity of "the next big avalanche" (Fig. 2.8b–d). Osvanny gave arguments demonstrating that it could only occur if the slope of the power-law distribution was bigger than unit—a bold statement that made me challenge his ideas rather insistently to begin with. Once I was convinced, Osvanny had to fight much tougher unknown referees, until he won the publication battle. His sense of focus over the years was (and still is!) truly admirable.

All in all, Osvanny's work suggested that real systems showing power-law distributions of events allow the prediction of big events, if the time evolution of the appropriate structural data is available and a smart enough prediction algorithm is implemented. We speculate that this may be true not only in the case of laboratory sandpiles, but perhaps also for earthquakes[14] and other natural or human-related disasters, like the Cuban economic earthquake in the early 1990s that had made it so hard to get 2000 ball bearings to run a simple tabletop experiment.

## Bibliography

Altshuler, E., García, S. and Barroso, J. *Flux trapping in transport measurements of* $YBa_2Cu_3O_{7-x}$*: a fingerprint of transport measurements*, *Physica C* 177: 61 (1991)

Altshuler, E., Ramos, O., Martínez, C., Flores, L.E. and Noda, C. *Avalanches in one-dimensional piles with different types of bases, Physical Review Letters* 86: 5490 (2001)

Altshuler, E. *Vortex avalanches in type II superconductors: the sandpile perspective* in Vlaev, Gaggero and Dvoeglazov (eds.) "Some Contemporary Problems of Condensed Matter Physics in Contemporary Fundamental Physics", Nova Science Publishers, 2001 (ISBN 156 072 8892)

Altshuler, E. and T. H. Johansen, *Experiments in vortex avalanches, Reviews of Modern Physics,* 76: 471 (2004)

Altshuler, E., T. H. Johansen, Y. Paltiel, Peng Jin, K. E. Bassler, O. Ramos, Q. Chen, G. F. Reiter, E. Zeldov and C. W. Chu *Vortex avalanches with robust statistics observed in superconducting niobium, Physical Review B* 70: 140505 (R) (2004)

[14] In fact, the intensity distribution of earthquakes follows the so-called Gutenberg-Richter law, which is a power law with a slope between 1 and 2.

Ananthaswamy, A., *Beads get ball rolling on avalanche prediction, New Scientist,* 4 March 2009

Baracca, A., Renn, J. and Wendt, H. (eds) "The History of Physics in Cuba", Springer, 2014

Borroto, A., Del Río, L., Arronte, M., Johansen, T. H. and Altshuler, E.*, Modeling transport properties of inhomogeneous superconductor-metal composites, Applied Physics Letters* 105: 202604 (2014)

Bak, P., C. Tang, and K. Wiesenfeld, *Self Organized Criticality: an explanation of 1/f noise*, *Phys. Rev. Lett.* **77**,111 (1987)

Bak, P., 1996, *How Nature Works—The Science of Self-Organized Criticality* (Copernicus, New York)

Bean, C. P. Physical Review Letters **8**, 250 (1962)

de Gennes, P. G., 1966, *Superconductivity of Metals and Alloys* (Benjamin, New York)

Ramos, O., E. Altshuler, E. and K. J. Måløy, *Avalanche prediction in a self-organized pile of beads, Physical Review Letters* 102: 078701 (2009)

Ramos, O. Scale invariant avalanches: a critical confusion (*Book chapter*, *reviewed by H. J. Jensen*) in B. Veress and J. Szigethy (eds.) Horizons in Earth Science Research. Vol. 3 (Nova Science Publishers, Inc. 2011) pp 157–188

R. Reid and B. Hayes *¡Viva la Ciencia!, American Scientist* (Sept-Oct 2004) (http://www.americanscientist.org/template/AssetDetail/assetid/35553)

M. Tinkham, 1975 *Introduction to Superconductivity* (Mc Graw-Hill, New York)

# 3
# Strange Phenomena in Cuban Sands

*The greatest joy is the unexpected.*

(Attributed to) Sophocles

## 3.1 Echoes of a Failed Class Demonstration: The Revolving Rivers

Excited by the elegant analogies one could establish between the critical state in type II superconductors and sandpiles, I rapidly decided to introduce them in class during a course on superconductivity I taught in 1994 at the Physics Faculty, University of Havana. Being an advocate of tabletop experimental demonstrations in class, I decided to show the students that a sandpile grows by avalanche dynamics—the paradigm of self-organized criticality (SOC) proposed by Per Bak and coworkers a few years before. Nothing could be simpler: by pouring sand on a table through a funnel, I expected to see the "classical" avalanche behavior, i.e., as the pile grew, sudden slides of sand unevenly distributed in space and time, should keep the angle of the pile around a pretty well defined value.

**Flash anecdote**

Most Cuban scientists belong to the *National Union of Workers of Education, Science and Sports*. The Union selects every year a number of *National Vanguards* among the most hard-working teachers, scientists, sports trainers, etc. Thanks to my scientific "merits", I was elected National Vanguard in the year 2001–there



E. Altshuler, *Guerrilla Science*, DOI 10.1007/978-3-319-51624-0_3

were a few dozen of them, I believe. In that occasion, the Union gave us our diplomas in a scenario that would have made *Stakhanov* very proud: we were invited to go to pick potatoes in the countryside. That was not unusual to a Cuban of my generation. But in this case, a truly unexpected scenario was waiting for us when we reached the working place: a battery of loudspeakers had been setup in the open, in such a way that, while picking potatoes in the furrows under the drilling tropical sunshine, we were systematically congratulated and cheered up by people from the Union. Moreover, the chiefs of our respective working brigades (democratically voted in situ) went to the improvised microphones—one after the other—to challenge the other brigades in a frantic competition to finish first picking up all the potatoes in their assigned areas. We were working hard—all of us were indeed hard workers by definition—but also laughing hard at the completely surrealistic situation we were trapped in.

So I decided to get a bunch of this incredibly fine and white sand I had seen by chance in a store room at the back of the Institute of Science and Technology of Materials (University of Havana), to be used for some unknown project. "Taking out a bit won't hurt anybody"—I justified to myself. Only months later I learned that the sand in question had been brought from a place called "Santa Teresa" in Pinar del Río province (some 200 km west from Havana) and was meant to feed a plant to produce silicon-based semiconductors. So, I took a couple of kilos of sand, and returned to my lab to polish up details for my class demonstration.[1]

So I clamped a funnel on a lab holder, and started pouring sand on a table. With a mix of fascination and preoccupation I realized that, instead of finding sudden, intermittent avalanches, a pile formed which had a thin river of sand on one side flowing from the apex of the pile to the edge of its base. The river rotated about the pile, depositing a new layer of sand with each revolution, thereby causing the pile to grow. For small piles the river was steady and the resulting pile was smooth. For larger piles, the river became intermittent and the surface of the pile became undulating. Years later, I would coin the serendipitous phenomenon "revolving rivers". But when I first saw it, I did not use elegant words to describe what was effectively a disaster for the demonstration I had planned for the next class.

[1] Over the years, I would return to the place to take further samples of "Santa Teresa" sand, and I noticed that the initial big pile was decreasing in size too fast. Then one gloomy afternoon I found myself standing with an empty bucket in the middle of a completely sandless room. It hadn't happened due to erosion or other natural causes, or to the fabrication of semiconductors, and definitely not to my periodic withdrawals: I suspect that my beloved sand had been used as a vulgar construction material, and lies somewhere in the walls of Havana, a crime that reminds me of Poe's "The Cask of Amontillado".

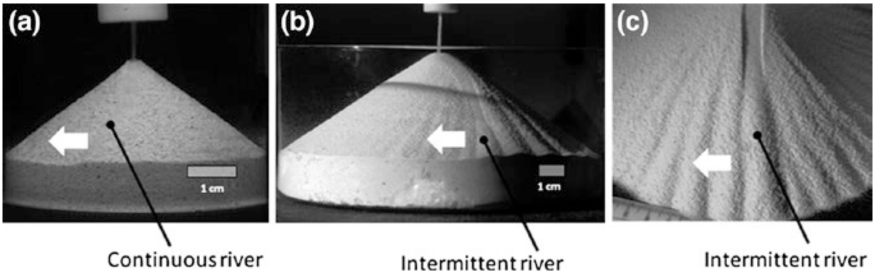


**Fig. 3.1** Revolving rivers. When Santa Teresa sand is poured into a relatively small glass cylinder, a continuous revolving river appears, as shown in (**a**). If a wider cylinder is used, intermittent rivers appear, as shown in (**b**). In **c**, we show a top view of the intermittent rivers for a pile formed on a flat, open surface. The white arrows indicate the direction of rotation of the rivers, which can be clockwise or counterclockwise, depending on random fluctuations at the beginning of the experiment. In the continuous regime, sand just flows down the hill along the river, forming a stream that slowly moves laterally as a whole. In the intermittent regime, a sudden burst of sand first flows down, and then an uphill front travels from the lower edge of the pile up to a certain height, after which a further sudden burst of sand flows downhill, by the side of the previous event, which is seen as the river moving laterally around the pile

Anger was actually mixed with deep preoccupation, since I had before my very eyes what seemed a direct violation of the self-organized criticality paradigm that I was preparing to explain in class. So I momentarily skipped the demonstration, which was re-designed in later courses using a two-dimensional pile of beads… a much more "didactic" approach that I described in detail in the previous chapter. I had come across the revolving rivers phenomenon as soon as I picked up the first sand available, so I naturally assumed it was a very well known physical effect. So, the mysterious "Santa Teresa" sand was put to sleep in the darkness of a cupboard under a laboratory table—the same table upon which El Chicharotrón would soon be built. For six years the bag of Santa Teresa sand would feel the hypnotic vibrations of the avalanches produced by El Chicharotrón a few inches above it.[2] But the sleeping beauty would only be awoken years afterwards… thanks to a casual conversation with physicist Kevin Bassler (Fig. 3.1).

I met Kevin at the University of Houston, where I was doing a postdoc in the group of C.W. Chu—founder of the Texas Center for Superconductivity (TcSUH). My fascination with vortex avalanches made me follow my own

[2] She would also feel the scorpions (known in Cuba as *alacranes*) constantly chasing roaches in the darkness—a somewhat strange but rather typical feature of our lab's ecosystem.

way in Chu's lab, trying to detect them in superconducting niobium by using micro Hall probe arrangements. Although it was not one of Chu's lines of research, he was very patient with me—perhaps due to the many hours I dedicated to my passion for research, which seemed to resonate with his Spartan work ethic.[3] In parallel with the work in Chu's group, I was collaborating with Kevin, Maya Paczuski, and George Reiter at the Physics Department, University of Houston, which probably constituted one of the world's hardest core SOC groups. In fact, Per Bak himself (Maya Paczuski's husband) was seriously considering joining the department at the time. I had the opportunity to meet him personally. He even insisted on going to the lab to see my experiments on vortex avalanches first hand.

**Flash anecdote**

One of the young researchers of our group had a girlfriend that had been a little bit over-protected by her parents during her whole life. It happened in the mid 1990s, where food was scarce, and everybody moved around in heavy Chinese bikes. Our colleague was painfully pedaling up the hill of G-street, near the University of Havana, in the middle of a burning sunshine, with his fiancé sitting in the back of the bike. At some point, it seems that she felt too hot, and came up with a peculiar solution to the matter. She just told her soaking-wet boyfriend: "Honey, would you please speed up, so I get some breeze on my face? It's so hot, you know!"

Kevin and I were always engaging in scientific arguments on many physics topics, all of which he used to win. At some point, I told him that SOC in real sand should not be taken for granted, since sands showed this "revolving river" effect. He suddenly got very excited. "Ernesto, that is a very important thing; I just can't believe it". When I said to him that the effect would be found in any sand, he challenged me to make a practical demonstration for him. Absolutely certain of my success, I went to one of the parking lots outside, collected some sand into an envelope, got a funnel from the lab, and went back to Kevin's office. I cleared the papers on one table, and started to form a pile of sand using the funnel. I felt really embarrassed when no trace of revolving rivers showed up: just random avalanches, as expected by any sensible person using any sensible sand. I started to doubt my own recollections of the phenomenon, so I sent an email message to my then undergrad

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[3] Shortly after my arrival at the Texas Center for Superconductivity, I had my first scientific meeting with C.W. Chu. He decided the time and place: Sunday August 8, 1999, at 11 AM, at a MacDonald's near TcSUH.

student Osvanny Ramos, who was in Cuba at the time. I described to him exactly where the Santa Teresa sand could be found, and the exact funnel I had used to see the revolving rivers—it would be easy for him, since the stuff was just under the table he was using to do the Chichartotrón experiments. In the afternoon I received the answer by email: "That sand you told me is so white, so fine… and, by the way, it does produce piles with these river-like flows of sand…" Upon my return from the States, the first thing I did was to take a video of the revolving rivers with my second hand *Magnavox* camera bought on e-bay while in Houston, and send Kevin the VHS cassette with somebody travelling back to the States. He was finally convinced! In the following months, I worked frantically doing experiments on the revolving rivers phenomenon, with the help of Osvanny Ramos, Etién Martínez—a first-year undergrad student at the time—and even my wife, Aramis. A couple of years later the resulting article would be published in collaboration with Kevin.

One of the many things we had to figure out was whether the sand from Santa Teresa was truly unique regarding the appearance of revolving rivers…. and serendipity helped us again. One day, Etién was watching the TV news, and they presented a report about a person whose hobby was to collect different kinds of sand from all over the world. He lived in a place called Santiago de las Vegas, some 20 km south-west of the university. After a couple of days, Etién showed up at his place equipped with a funnel, a metal holder, and a steely determination to check all the sands he could get his hands on. The sand collection enthusiast—whom I later identified as Eros Salinas, a geographer also teaching at the University of Havana—was indeed very kind: Etién was not only able to try more than 100 types of sand from all over the world, but he was invited to have lunch. The result was that 11 sands showed revolving rivers, around 10% of the statistical sample. However, nobody knew why: the revolving sands didn't look especially similar to each other… or especially different from the non-revolving ones!

However, it was possible to establish a quite good phenomenological characterization of the revolving rivers. For example, the "phase diagram" shown in Fig. 3.2 indicates for which flows and radial sizes the piles show continuous or intermittent rivers, and where the transitions between one and the other take place.

In addition, it was not difficult to reproduce some of the features in the behavior of the revolving rivers by simply using mass conservation—or, more

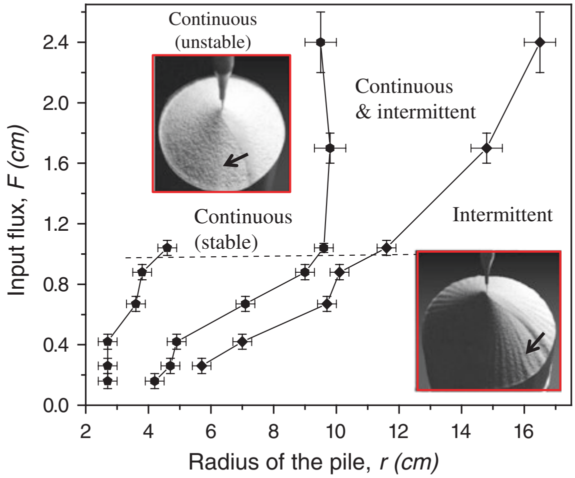


**Fig. 3.2** "Phase diagram" of the revolving rivers for "Santa Teresa" sand. Along the horizontal and vertical axes we have the radius of the pile and the sand flow feeding the pile. Let us suppose that we move from left to right in the diagram along the dotted horizontal line. When the pile's radius is smaller than approximately 4 cm, continuous rivers appear and disappear: in fact, that happens in many granular materials. Continuous rivers stabilize—describing full revolutions around the pile with no interruptions—within the interval from 4 to 8 cm, approximately. Between 8 and 10 cm, the rivers are sometimes continuous, and sometimes intermittent. Intermittency stabilizes for piles of radius bigger than 10 cm, approximately. That behavior is true regardless of whether the piles are formed in cylinders of different radii, or just on a flat surface (in the first case, the radius is fixed for each glass size and, in the second case, it increases continually as more sand is added to the pile)

exactly, volume conservation.[4] The idea is to assume that the volume of sand deposited on each cycle due to a flow $F$ is distributed as a uniform layer of material on the conical surface of the pile—the layer grows laterally on the surface, and its "growing front" is precisely the river. Figure 3.3a shows our simplified model for a conical pile growing on a horizontal open surface, which assumes that the thickness of the deposited layer is constant (implying a constant $\delta r$ length at the base of the pile). The resulting formulas for the frequency of rotation of the river along the pile as a function of time and the pile radius are:

$$\omega = \frac{2}{(\tan\theta)^{1/3}} \left(\frac{\pi}{3}\right)^{2/3} F^{1/3} \frac{1}{\delta r} \frac{1}{t^{2/3}} \tag{3.1}$$

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[4]Granular matter can either contract or expand under different circumstances, so the effective density of the medium is not necessarily constant during a given experiment. Then, establishing a simple proportionality between mass and volume in our case is just an approximation.

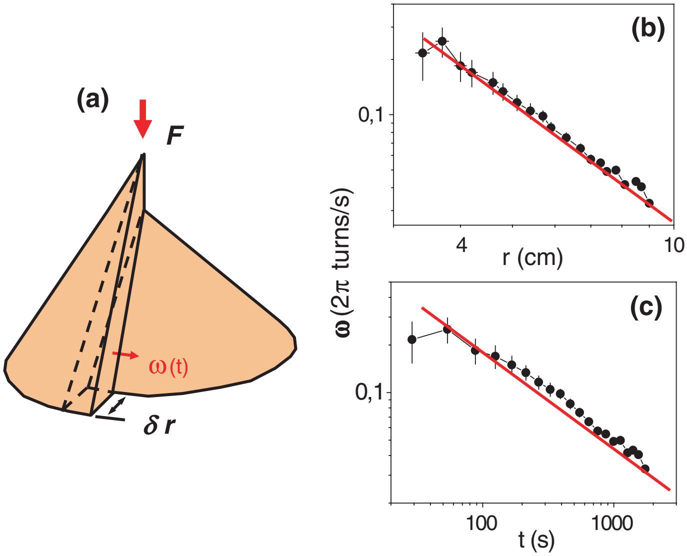


**Fig. 3.3** Modeling Santa Teresa piles on a table. **a** A simple geometrical model for a growing sandpile on a horizontal open surface: the sand is added from top at a certain flow rate F (volume/time), and is deposited as a layer that exceeds the previous base radius by $\delta$r. The "river" revolves around the pile with an angular frequency $\omega$. The points in graphs (**b**) and (**c**) show the experimental evolution of the revolving frequency versus radius and time, respectively, in log-log plots. The continuous lines correspond to formulas (3.1) and (3.2), where the following experimental parameters have been used: $F = 0.4$ cm$^3$, $\theta = 33°$, and $\delta$r $= 0.4$ cm$^3$

$$\omega = \frac{2F}{\tan\theta}\frac{1}{\delta r}\frac{1}{r^2} \tag{3.2}$$

where $\theta$ is the angle of the pile's slope relative to the horizontal. As can be seen in Fig. 3.3b and 3.3c, the expressions (3.1) and (3.2) quite closely reproduce the experimental evolution of the revolving frequency. Intuitively, it is clear why it decreases in time: the same amount of injected sand needs more and more time to cover the ever-growing surface of the conical pile. It is worth saying that the previous description is valid only for piles growing on a horizontal surface: if the pile is grown into a straight cylindrical container, its radius is constant, and so is the revolving frequency.

Our model is able to predict the behavior of the revolving frequency, but does not explain why the rivers appear in the first place, or why they rotate. We have just taken it for granted that they occur for some reason probably associated with the characteristics of the grains and their statistical size distribution.

## 3.2 An Open Problem in Three Steps

Beyond the simple prediction of the revolving frequencies, we can "dissect" the revolving rivers problem into three questions: (a) Why does a river form and stabilize on the pile surface? (b) Why does the river revolve around the pile either to the left or to the right? (c) Why is there a transition from the continuous to the intermittent regime in the rivers as the pile radius increases?

Let us discuss first questions (b) and (c), and then move on to (a).

Question (b) can be answered qualitatively with the help of Fig. 3.4, corresponding to a pile that grows on a horizontal open surface. The situation is easier to explain for the intermittent regime, but the idea can be extended to the continuous one: an avalanche occurs along a random radial direction, and, as it reaches the lower edge of the pile, the sand stops flowing downhill. As new sand enters the system, a front grows up from the base of the pile to the apex, following the "groove" carved by the downhill avalanche. This process results in an increase of the local slope of the pile. As the uphill front gets near the top of the pile, the river becomes unstable, and the next downhill avalanche occurs, say, to the left of the original one: that produces a slight deformation of the "surface topography" that "pushes" all future avalanches to the left of the previous ones. It is a memory effect. An analogous mechanism takes place in piles grown on cylindrical containers, like a whisky glass. However, if the pile grows on top of an upside-down whisky glass, as soon as the edge of the pile meets the edge of the cylinder, the river no longer revolves: all the sand entering from the top flows out of the system and no instability is produced to "push" the river sideways.[5]

Question (c) can be "isolated" experimentally in the following way. One can consider that once a river is established, the three-dimensional flow typical of "normal" sandpiles is restricted to a two-dimensional flow along the groove associated with the river. So, the revolving rivers can be taken as two-dimensional rivers revolving around the pile at an appropriate frequency. But we can "construct" an "independent" two-dimensional river by making sand flow between two vertical plates with a separation similar to the width of the rivers we see on the piles—a Hele–Shaw cell (see Fig. 3.5a). We did this and found that, as the two-dimensional pile grew, we did indeed first get continuous rivers, and then intermittent rivers, just like in the original piles.

[5]This particular experiment was inspired by physicist Hans Herrmann during a meeting in Brazil: he commented, as though it were the most natural thing in the world, that when *any* granular pile reaches the edge of a table, a stable river of flowing sand establishes, pouring sand off the table.

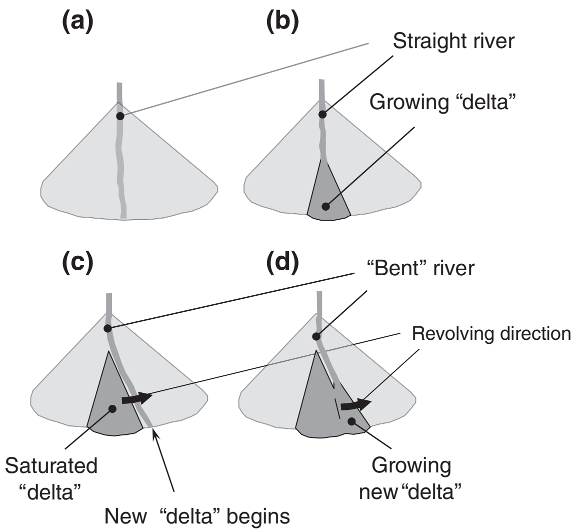


**Fig. 3.4** Why rivers revolve around the pile. **a** At the beginning, a straight river is formed. **b** Once the initial avalanche associated with the river meets the base of the pile, an "up front" grows, producing a delta-like sub-pile that rests on the pile's surface. **c** As the up front is high enough to become unstable, the river deviates to one of the sides of the delta. **d** A new up front starts to grow, forming a new asymmetric delta that will "push" new deltas to the same side

This experiment had been made before, but curiously enough, researchers had concentrated on the description of the intermittent flow: the continuous regime and the transition between the two had received little attention.

Figure 3.5b shows clear experimental evidence of the transition for our experiments, using a spatial-temporal diagram whose construction is explained in the figure caption. The smooth part of the diagram shown there corresponds to the continuous regime, while the "step-like" section corresponds to the intermittent regime. In the latter, the almost horizontal sections correspond to sudden downhill avalanches that make the edge of the pile advance from left to right. The vertical parts, on the other side, are the intervals where the pile does not advance from left to right: the uphill front is just moving up, adding a new layer of sand to the pile, parallel to the previous free surface. The diagram clearly indicates that the transition from the continuous to the intermittent regime is quite sharp. Putting together a series of such diagrams based on videos taken for different input flows and separations between the glass sheets of the Hele–Shaw cell, one can construct the "phase diagram" shown in Fig. 3.5c, which can be compared to the "phase diagram" of the revolving rivers in 3D piles.

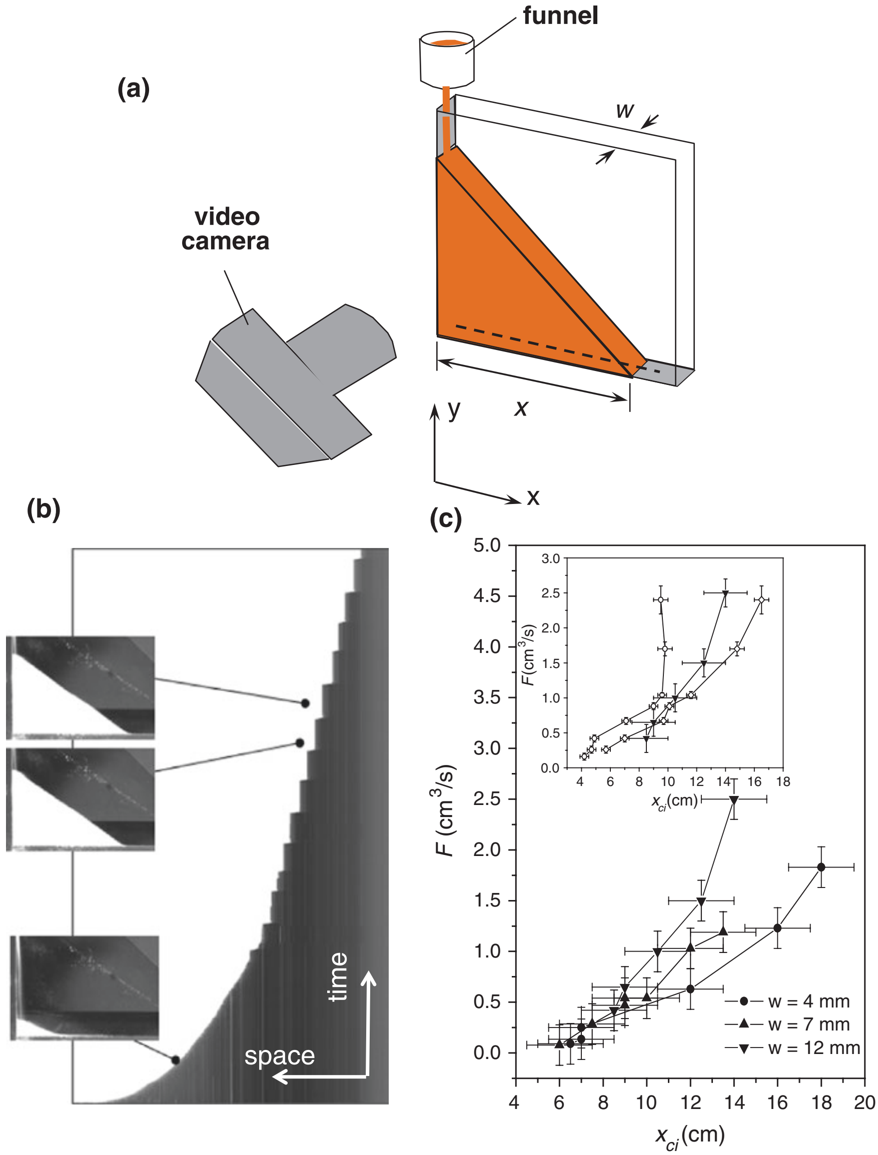
(a)
funnel
w
video
camera
y
x
x
(b)
time
space
(c)
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
F (cm3/s)
4
6
8
10
12
14
16
18
20
$x_{ci}$ (cm)
w = 4 mm
w = 7 mm
w = 12 mm
3.0
2.5
2.0
1.5
1.0
0.5
0.0
F(cm3/s)
4
6
8
10
12
14
16
18
$x_{ci}$(cm)

**Fig. 3.5** Continuous to intermittent transitions. **a** Sandpile formation on a Hele-Shaw cell: the size of the sandpile base, $x$, grows as sand is added from the upper left corner. At the beginning, the pile grows continually. After a certain "critical size", $x_{ci}$, the flow becomes intermittent (i.e., after a sudden avalanche down the hill, an up front grows to the top until a new avalanche takes place… and so on). **b** A spatial-temporal diagram based on a sequence of pictures of the evolution of the pile. The diagram has been constructed in the following way: one video of the pile formation is separated into a sequence of pictures. We then extract from each image the line of pixels indicated in (**a**) by the *dotted line*, and then organize one line of pixels on top of the other from bottom to top, as time goes by. In the resulting diagram shown in (**b**), *white* and *black* areas correspond to sand and background, respectively. Then, the horizontal growing velocity of the pile near its bottom is given by the inverse of the slope of the boundary between the white and black areas at any given moment. So, if the lower edge of the pile is not growing, the graph will show it as a vertical line. **c** Graph of the critical size where the transition occurs at different flows, measured for three different widths of the Hele-Shaw cell. It has been constructed from a series of spatial-temporal graphs like the one illustrated in (**b**). The inset shows a version of the graph in Fig. 3.2 for the revolving rivers. Notice the overall similarity between the curves (it is difficult to establish the width of the river in the pile, since it is not constant, but its average width is definitely between 4 and 12 mm for the case illustrated in the inset)

The existence of continuous and intermittent phases can be explained, at least for the case of a Hele–Shaw cell, by solving the so-called BCRE equations with the appropriate boundary conditions. The BCRE model was proposed by Bouchaud, Cates, Ravi-Prakash, and Edwards in 1994–1995 to explain the behavior of thick granular flows. They assumed that a granular flow on a pile is composed of two phases: a static one, and a rolling (or flowing) one on top of the first. The BCRE equations describe the evolution of the thicknesses of each of these layers, taking into account the fact that grains from the static layer can be eroded and become part of the flowing layer, while grains in the flowing layer can be advected and become part of the static phase. The BCRE equations were solved by Dorogotsev and Mendes in 1999 for the case of a pile in a Hele–Shaw cell. They found a continuous regime if the pile started to form in an empty cell, and an intermittent regime if it started to flow from a pile whose slope had reached an "angle of repose". However, the *transition* from the continuous to the intermittent behavior as the size of the pile increases was not predicted from the BCRE model.

**Flash anecdote**

During 2014, on several occasions I used my car to move the whole experimental setup for sand flows back and forth from the lab to an apartment Etién Martínez had borrowed. He convinced me using the argument that he could do experiments round the clock there. On one occasion, however, he made a curious request: "Ernesto, before going to my apartment to pick up the stuff,

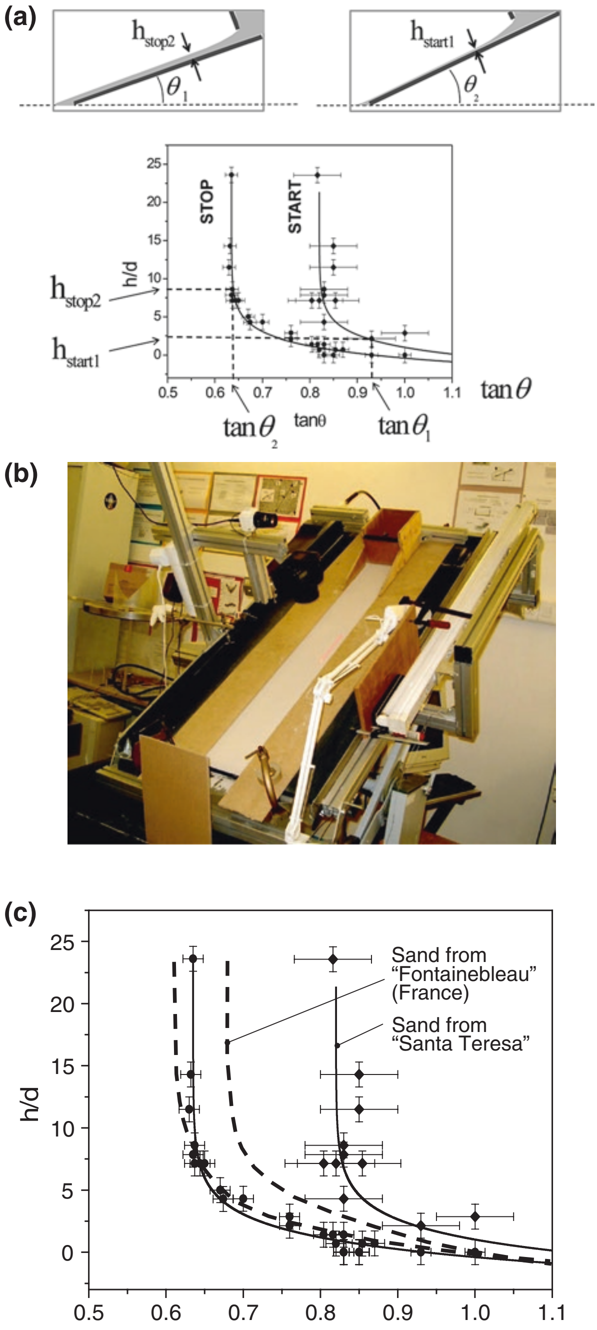
(a)
$h_{stop2}$
$\theta_1$
$h_{start1}$
$\theta_2$
STOP
START
h/d
$h_{stop2}$
$h_{start1}$
25
20
15
10
5
0
0.5
0.6
0.7
0.8
0.9
1.0
1.1
$\tan\theta$
$\tan\theta_2$
tanθ
$\tan\theta_1$
(b)
(c)
Sand from
"Fontainebleau"
(France)
Sand from
"Santa Teresa"
h/d
25
20
15
10
5
0
0.5
0.6
0.7
0.8
0.9
1.0
1.1

**Fig. 3.6** Avalanche instabilities on an incline. **a** A plane is first inclined at an angle $\theta_1$, and sand is released from a horizontal slit at the top. As a result, a layer of sand of thickness $h_{stop}$ is deposited on the surface. Then, the inclination is slowly increased until the sand becomes unstable at $\theta_2$, which produces an avalanche. The final thickness of the layer is labeled $h_{start}(<h_{stop})$. The two pairs of values are plotted on the graph at the bottom (thicknesses are normalized to $d$, the average grain diameter). The rest of the graph is constructed on the basis of analogue experiments starting at different values of the inclination angle. The process results in a pair of curves START and STOP between which there is a region of metastability. Each curve can be described by the expression $\frac{h_{START,STOP}}{d} \sim \ln\left(\frac{\tan\theta - \mu_{START,STOP}}{\delta\mu}\right)$ where $\mu_{START}, \mu_{STOP}, \delta\mu$ are fitting constants. If the vertical sections of the START and STOP curves are widely separated horizontally (as in the case of the Santa Teresa sand), the values of $\mu_{START}$ and $\mu_{STOP}$ are quite different between them. **b** Real setup used to measure the avalanche diagram for Santa Teresa and other sands at the ESPCI (the sand is the very clear band along the center of the incline, bounded by two sheets of plywood). The thickness of the layer of sand is measured by shining a laser beam on the sand at a very small angle relative to its surface: the position of the laser spot on the sand surface is very sensitive to the thickness of the layer of sand. **c** Resulting avalanche diagrams for Santa Teresa sand (*continuous lines*) and for Fontainebleau sand (*dotted lines*). Notice that the first is much wider horizontally than the second

I need you to take me first to a glass workshop to cut this large piece of glass into 50 cm by 20 cm strips"—pointing to a big plate of glass I had meticulously stored in the lab for a long time. I did it, but not very enthusiastically, after being told about the cause of the detour: during a night of scientific desperation, my MSc student had cut up a glass cupboard of the borrowed apartment to construct new Hele–Shaw cells, and now he was rushing to replace it, since the owners were coming back from vacation!

Based on image analysis of sand flows in Hele–Shaw cells, Etién has recently found evidence indicating that sand tends to compact more in the intermittent than in the continuous regime. This observation may be relevant for the storage of granular matter in industry, or even for the interpretation of geological phenomena.

One curious thing about the continuous to intermittent transition *in Hele–Shaw cells* is the fact that *it happens for almost all sands*. It suggests that the real "personality" of the Santa Teresa sand is not to show the continuous to intermittent transition in a 2D scenario like a Hele Shaw cell, but its ability to produce stable rivers on the surface of a conical pile, transforming the 3D scenario into a "rotating" 2D scenario. That leads us back to question (a).

So, what can we say about question (a)? In 1999 Adrian Daerr and Stéphane Douady published a now classic experiment to study granular instabilities, producing different types of avalanches as explained in Fig. 3.6a. In 2006 Eric Clément, from the ESPCI (Paris, France) suggested

**Fig. 3.7** Bike violence in Strasbourg. Renaud Toussaint trying to set his bike free from a lock whose key was lost. People in the car at the back do not seem to approve the scene. Photo taken in 2007

to me to carry out such experiment with the Santa Teresa sand, to identify any differences with other sands, and this I did.[6] Figure 3.6c indicates that sand from Santa Teresa produces wider stability diagrams than other "typical" sands… something that might be related to the fact that the grooves carved by the rivers on the pile's surface are more stable in Santa Teresa than in "common" sands. It might explain the robustness of the rivers. In fact, when one forms a conical pile using "common" sand, rivers do appear, but they only last for a very short time: the sand walls forming the groove are not stable enough, and are immediately destroyed.

In 2007 I carried Santa Teresa and a few more sands to the *Institut de Physique du Globe de Strasbourg* (France), where Renaud Toussaint (Fig. 3.7) helped to characterize the sands. After several tests, such as scanning electron microscopy, grain size distribution analysis using a laser technique, and the determination of the composition of the individual grains, we were unable to determine the distinctive "microstructural" features of the Santa Teresa sand that make it so special (Fig. 3.8).

[6]Besides being a scientific visionary, Eric is an irrepressible enthusiast. On that occasion his energy was so great and the lab so crowded that, as he showed me how to work with the experimental apparatus, his head bumped on several occasions against the sharp corners of the incline (see Fig. 3.6b). Each time he automatically shouted "merde"… with no effect at all on his enthusiasm.

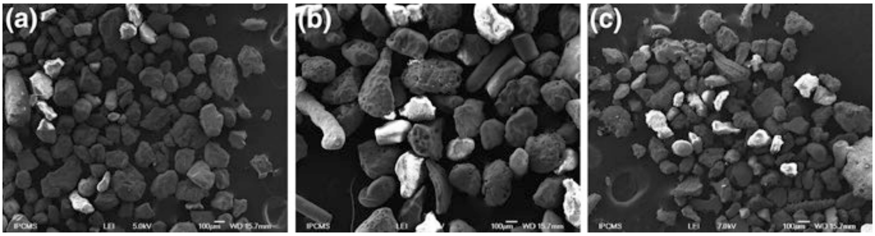

**Fig. 3.8** Which sand produces rivers? Scanning electron microscope images of three different sands **a** Silicon-rich Santa Teresa sand. **b** Calcium carbonate-rich sand from famous "Varadero" beach in Matanzas province (200 km to the east of Havana). **c** Another silicon-rich sand of unknown origin. Only sand **a** shows revolving rivers. The width of each image in real life is approximately 3 mm

To make things even more puzzling, the Santa Teresa sand stopped showing revolving rivers after many experiments: some kind of aging process seemed to take place (which is quite stressful, since our local reserve of the "good sand" is finished). Stéphane Douady has seen the same in "singing sands" from the Ghord Lahmar region in Morocco. As those sands flow, the moving grains vibrate synchronously as they pass over each other, producing incredible organ-like sounds. As Stéphane puts it poetically, sands brought from Morocco to his laboratory in France stopped singing after some time, "because they felt homesick". What seems to happen is that, after many experiments, a smooth layer of silica gel on the grains' surface—apparently a key factor in the production of sound—goes away. Perhaps the same is true for Santa Teresa sand, but it remains an open question for the time being.

## 3.3 Uphill Bumps: Moving Against the Flow

Let us suppose that the Hele–Shaw cell described earlier is set on a table, in such a way that, when the pile grows enough to reach the end of the cell, the sand just falls across the edge of the table and hits the floor (Fig. 3.9a). In such a scenario, the flow inside the cell can only be continuous, since there is no horizontal surface at the end of the pile to "support" a new uphill front.

While performing the experiments to study the continuous to intermittent transition under the conditions just described, Etién Martínez eventually forgot to stop feeding the cell, and the sand actually reached its end, turning the lab floor into a perfect place for tap dancing. But in the process, Etién and Ovanny observed a curious phenomenon that had nothing to do with the original idea of the experiment: the random appearance of small

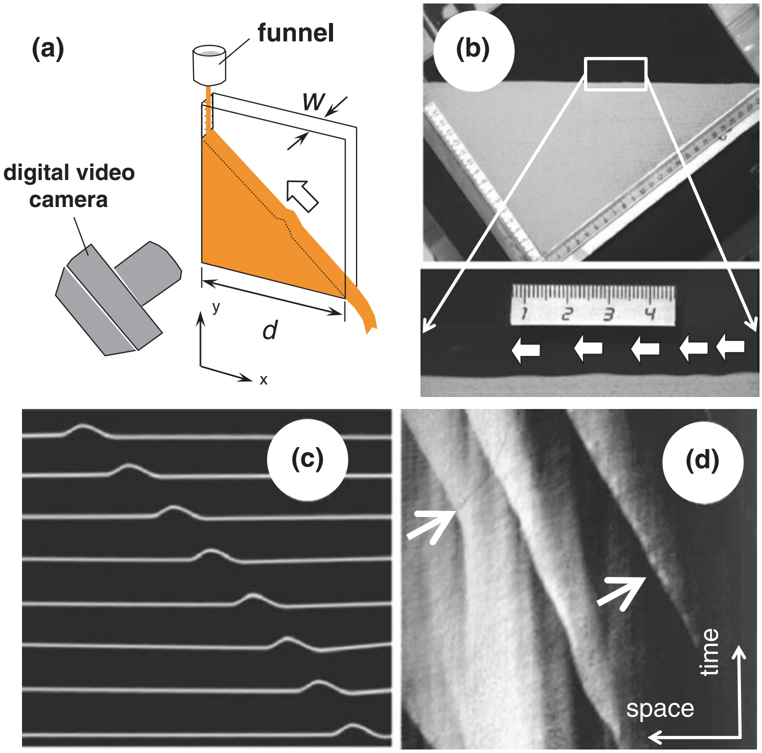


**Fig. 3.9** Uphill bumps phenomenology based on a very simple setup. **a** Sketch of the experimental setup. **b** One picture taken by the camera in (**a**), with a zoom of one section of the surface where uphill bumps can be seen (the minimum division of the scale shown is 1 mm). *Thick arrows* in (**a**) and (**b**) indicate the direction of motion of the bumps. **c** A sequence of pictures of the surface of the pile (after digital treatment), where one bump moves from right to left as time increases from bottom to top. **d** A spatial-temporal diagram of the movement of a few bumps. The diagram has been constructed in the following way: one video of the uphill bumps is separated into a sequence of pictures. A horizontal line of pixels located slightly above the average surface of the pile is extracted from each picture, and then organized one on top of the other from bottom to top, as time goes by. Then, any moving feature in the video—like the front of one bump moving at approximately constant speed—is seen in the spatial-temporal diagram like a line (or band) whose slope is inversely proportional to the velocity of the bump. A feature moving at zero speed will show up as a vertical line

deformations on the free surface of the flowing sand, first near the lower end of the cell (like little hills of 1 cm length and around 1 mm height), then suddenly starting to move uphill against the flow for several centimeters, until they disappeared. Osvanny suggested to Etién to make further tests of the new observation, so they also set off in that direction. We later learned that the phenomenon had already been observed in other sands by Taberlet and co-workers in 2004, but the bumps had been described as forming "trains". In our case, we found some individual uphill bumps, standing alone, so we called them "solitary waves". In 2006, I had the opportunity to take nice fast-camera videos of the phenomenon while at Knut Jorgen Måløy's Lab (Physics Department, University of Oslo).

Figure 3.9d shows a spatial-temporal diagram where the uphill movement of a few bumps can be identified (the figure caption explains how the diagram was obtained). The inclined, straight feature indicated by the right arrow corresponds to a bump that passed across the field of vision at constant speed from right to left (a movement from left to right would have produced a line with a positive slope). Notice that any other bumps around are moving with the same speed and in the same direction. However, perhaps the cutest information from the diagram lies in the feature indicated by the left arrow: a bump was "born" at some moment, stayed in place for a short time (as revealed by the vertical segment), and then "awakened", i.e., it started to move in the same direction and with the same speed as its colleagues!

The uphill bump mechanism can be described "phenomenologically" using an idea proposed by Oscar Sotolongo, then head of the "Henri Poincaré" Cathedra for Complex Systems at the University of Havana (Fig. 3.10). A granular flow can be described by Saint-Venant equations (equivalent to mass and momentum conservation applied to a fluid flow), conveniently adapted to granular flows by the introduction of an effective friction force acting on the flowing layer of grains that depends on the depth of the layer.[7] Sotolongo found a specific depth dependence of the friction term that allows one to transform the modified Saint-Venant equations into the so-called Kortweg–de Vries equation (KdV), whose best known solutions are the *solitons*. A soliton is a single perturbation that travels long distances preserving its shape. However, we cannot say that ours are true solitons for two reasons: (a) after several centimeters of travel, the uphill bumps eventually disappear and (b) we have never seen two bumps collide and emerge from the collision without losing their individual identities—a second property of any feature deserving the name "soliton". So we cautiously called our bumps "solitary waves". Finally, it is worth mentioning that the depth dependence of the friction coefficient that converts the Saint-Venant equations into the KdV equation was chosen

[7] The BCRE model can be derived from the so-called Saint-Venant equations, after introducing a number of approximations.

**Fig. 3.10** Oscar Sotolongo (*right*) and Etién Martínez (*left*) discussing at the whiteboard circa 2004

ad hoc, and has never been corroborated experimentally—a task extremely difficult to achieve.

But what is the detailed mechanism of bump formation and movement? They may be produced by a "stop-and-go" mechanism, suggested to me by Stéphane Douady when I met him briefly at the École Normale Supérieure de Paris in 2006. The stop-and-go mechanism is easily illustrated in the case of urban traffic. Assume you are driving on a congested street, and a policewoman (or policeman) standing at the curb captures your attention: you slow down for a while, but then she (or he) stares coldly at you, making you accelerate back to your original speed—"stop-and-go" dynamics. Interestingly, this maneuver forces the car right behind you to do the same, actually coming closer to you than normal, so a zone of "higher car density" has been created. Under certain circumstances, this "perturbation" moves backwards, while the cars actually move forwards.

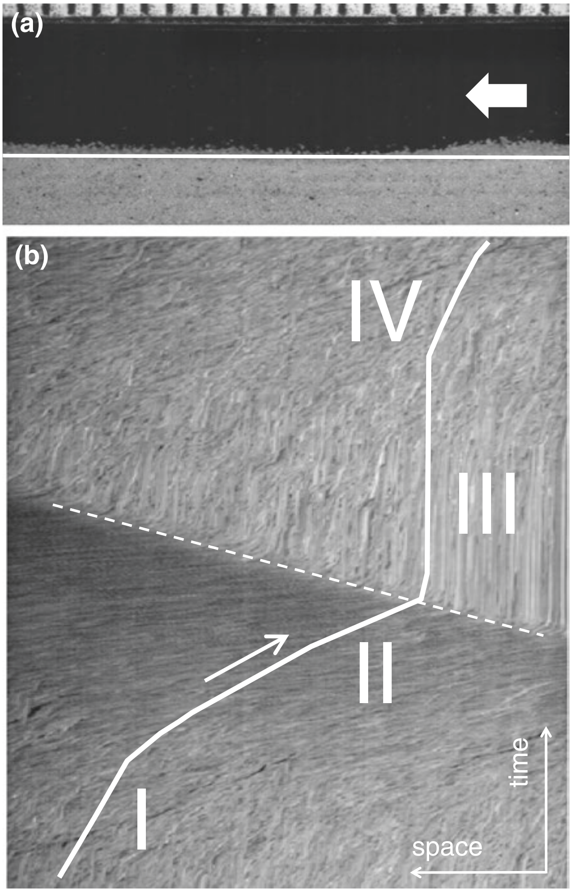


**Fig. 3.11** Picturing the uphill bumps mechanism: a challenge that could not be met with cheap equipment. **a** A fotogram from a single bump extracted from a sequence of pictures taken at 6000 frames per second (the smallest division of the scale on top is 1 mm). **b** Spatial-temporal diagram taken along the horizontal line seen in (**a**), where "averaged" trajectories of particles can be identified (the line in (**a**) has been taken at a depth where many advection and erosion events take place). In *region* I, the particles move at a certain velocity from left to right. As the bump approaches from the right, particles suddenly increase their speeds, as seen in region II. In region III, particles have been stopped, and are at rest in the static layer, "waiting" for the bump to pass above them from right to left. When the bump has almost finished its passage, particles are eroded back to the flowing layer (*region* IV) and regain a left to right velocity that approaches the one they had in *region I*. Notice that the dotted line indicates the velocity of the bump front: as expected, it is smaller in magnitude than the particle speeds in regions I, II, and IV, and its direction is opposite to that of the particle velocities in those zones

The same dynamics seems to explain the counter-stream movement of bumps in granular flows: a local perturbation occurs in such a way that an abnormally large amount of grains originally belonging to the flowing layer get advected into the static layer, thus producing a hill-shaped "bump". As more and more grains are advected and stuck to the left part of the hill, the grains on the right-hand side are eroded, and re-incorporate back into the flowing layer. The result is a bump that moves from right to left, while the average flow of grains is actually from left to right. (In the explanation, "left" and "right" have the meaning illustrated, for example, in Fig. 3.9b and c.)

It would be nice to be able to track individual grains in a video and say "Aha! This specific grain was advected and then eroded as the bump passed by". But that is very difficult to do even in the case of high quality, high speed videos of fine sands like that from Santa Teresa. However, appropriate spatial-temporal diagrams from such videos strongly suggest that stop-and-go is the right mechanism, as illustrated in Fig. 3.11. Of course, I recognize that getting this piece of evidence was beyond the abilities of a cheap second-hand e-bay camera: it was obtained with a state-of-the-art high speed camera, at 6000 frames per second, using a nice microscope lens, and lots of watts of artificial illumination at Knut Jorgen's lab in Oslo.[8] Unfortunately, science sometimes requires more than a guerrilla-style approach.

## Bibliography

Altshuler, E., Ramos, O., Martínez, E., Batista-Leyva, A. J., Rivera, A., & Bassler, K. E. (2003). Sandpile formation by revolving rivers. *Physical Review Letters, 91,* 014501.

Altshuler, E., R. Toussaint, E. Martínez, O. Sotolongo-Costa, J. Schmittbuhl and K.J. Måløy *Revolving rivers in sandpiles: from continuous to intermittent flows, Physical Review E* 77: 031305 (2008)

Aranson, I. S., & Tsimring, L. S. (2006). *An introduction to the dynamics of granular material: theoretical concepts*. *Reviews of Modern Physics, 78,* 641–692.

Bouchaud, J.-P., Cates, M. E., Prakash, J. R., & Edwards, S. F. (1995). *Physical Review Letters, 74,* 1982.

Dorogotsev. S.N. and J.F.F. Mendes, *How sandpiles spill: sandpile problem in a thick flow regime, Phys. Rev. Lett.* **83**: 2946–2949 (1999)

[8] Although he had authored classic works in the field of dry granular media, Knut Jorgen used his high speed camera mainly for the study of fast phenomena in fluid-injected granular media—a tabletop model of oil extraction processes.

Daerr, A., & Douady, S. (1999). *Two types of avalanche behavior in granular media*. *Nature, 399,* 241.

Douady, S., Manning, A., Hersen, P., Elbelrhiti, H., Protière, S., Daerr, A., et al. (2006). *Song of the dunes as a self-synchronized instrument*. *Physical Review Letters, 97,* 018002.

Kong, X.-Z., Hu, M.-B., Wu, Q.-S., & Wu, Y.-H. (2006). *Kinetic energy sandpile model for conical sandpile development*. *Physics Letters, 348,* 77–81.

Mallogi, F., Lanuza, J., Andreotti, B., & Clément, E. (2006). *Erosion waves: Transverse instabilities and fingering*. *Europhysics Letters, 75,* 825–831.

Martínez, E., Pérez-Penichet, C., Sotolongo-Costa, O., Ramos, O., Måløy, K. J., Douady, S., et al. (2007). *Uphill solitary waves in granular flows*. *Physical Review E, 75,* 031303.

## Wikipedia Links

https://en.wikipedia.org/wiki/Revolving_rivers

## YouTube Links

Videos on revolving rivers using Santa Teresa sand http://www.youtube.com/watch?v=dATX3Vt0268

S. Douady showing singing sands in the Moroccan desert http://www.youtube.com/watch?v=t6Zt4XCHj3U

# 4
# Lab-in-a-Bucket: Low Budget Experiments in the Solar System

*I thought I would be an astronomer when I grew up. I vividly remember, however, a fear that by the time I was an adult, astronomers would have to do their work in space. I was not sure that would be safe enough.*

Edward Witten

*in One hundred reasons to be a scientist* (ICTP, 2004)

For a number of apparently disconnected reasons, I remember very well the year 1969—when I was a 6 year old kid. Perhaps one of the main reasons is that I still keep a pencil drawing where two space explorers are taking samples from the Moon's soil with mysterious instruments looking like elongated spoons. The drawing was inspired by the TV images of Neil Amstrong and Edwin Aldrin on the Moon's surface, which I had the unique opportunity to watch in real time on our old *Admiral* TV set in Havana.[1] I perfectly remember my father saying to me: "Watch this, Ernesto; this is History". Later on, I remember having watched on that same TV set a dramatic departure from Moon to Earth, where only one engine of the lunar spacecraft was still working. I do not know if, subconsciously, that shaped my later lack of interest in astronomy—perhaps in resonance with Ed Witten's feeling as a kid. However, many years after that, I flirted with space exploration from a relatively safe place: a steel spiral staircase on Earth. In this chapter I shall explain how that happened.

[1] At certain times of the year, meteorological factors work out in such a way that TV transmissions from the south of Florida can easily reach the north shore of Cuba after travelling 90 miles across the Florida straits. And it happened at the right time during that prominent year of my life.



E. Altshuler, *Guerrilla Science,* DOI 10.1007/978-3-319-51624-0_4

## 4.1 Infinite Penetration into Granular Matter

For quite a few years, my young colleague Claro Noda had been pushing us to find uses for wireless sensors—he had been a radio amateur from an early age, and had never forgotten his first love. So I took it as a personal challenge. Indeed, I spent a some time figuring out experiments that could *only* be performed using wireless sensors. Due to the global explosion of wireless computer games, cell phones, and the like, the prices of such devices were falling fast in the early 2000s, eventually reaching the level of our hyper-low budget possibilities. So I couldn't miss the opportunity to do something off-mainstream with them.

People had studied the penetration of an intruder into granular matter, sometimes using accelerometers embedded inside the intruder—say, a sphere of the size of a ping-pong ball launched into a sand container—resembling to some extent the impact of an asteroid on a planetary surface. But a wired accelerometer would be good enough for that study. By July 2010, I had the first opportunity to conceive one such experiment critically involving wireless accelerometry. Carlos Ruiz, a Mexican researcher I had met years before in Eric Clément's group at the PMMH-ESPCI (Paris), invited me to his lab in Monterrey for a couple of weeks. Carlos showed me a number of ongoing projects, and I immediately got excited by one of them: they were studying the penetration of metal spheres into a 6-m-long, 50-cm-diameter silo full of expanded-polystyrene beads (those beads are used to make the extremely light white material used in the packaging of delicate merchandise). The idea was to show that the ultra-light granular material had a then unknown behavior: if the mass of the intruder was big enough, it would never stop sinking into the silo. In spite of that, however, it would reach a terminal velocity—just like an intruder falling into a conventional fluid—and would keep it, in principle, forever. Carlos' Ph.D. student Felipe Pacheco—an extremely energetic and clever fellow—was in charge of the experiment: using an air blower, he would first inject air from the bottom of the silo—which was set up in the empty space surrounded by the main stairs inside the building—and then would go upstairs to drop the spherical intruder. The latter was attached to a thin, black and white striped thread, so while the ball was falling inside the silo, a fast camera would record the passage of the stripes, making it possible to measure the penetration velocity: it was a low-budget project, but the fast camera made it too expensive for my tropical mindset. So I immediately suggested to Carlos that he should complement his experiments with similar ones using wireless accelerometers fixed inside the intruder: in such a way, we would not only have a direct measure of its *acceleration* (providing a direct estimate of the force), but we would also eliminate any influence of the thread attached to the intruder in the original version of the experiment. Carlos bought the idea, as well as some accelerometers, both for his lab… and for ours! (Fig. 4.1).

With the collaboration of my Cuban colleague Alfo José Batista-Leyva (who was spending a few months at Carlos' lab), we frantically performed several experiments using wireless accelerometers during my visit from July 24 to August 7, 2010. As in any new project, we faced all kinds of unexpected challenges. For example, since the intruder penetration was no longer "guided" by a thread, I had to design a manually-operated magnetic device to release it from the top of the silo in order to avoid any tiny initial rotation or lateral velocity, which would dramatically complicate the experiment. On the other hand, without a thread to "fish back" the intruder after it stopped at some point inside the 6-m-long silo, we had to recover it by hand after each penetration experiment, using an opening we made at the bottom of

**Fig. 4.1** The Infinite Penetration experimental team in Monterrey, Mexico. From *right* to *left* Carlos Ruiz, the author, Felipe Pacheco, Alfo José Batista-Leyva, and the upper part of the 6-m-long granular silo (Photo taken in July 2010)

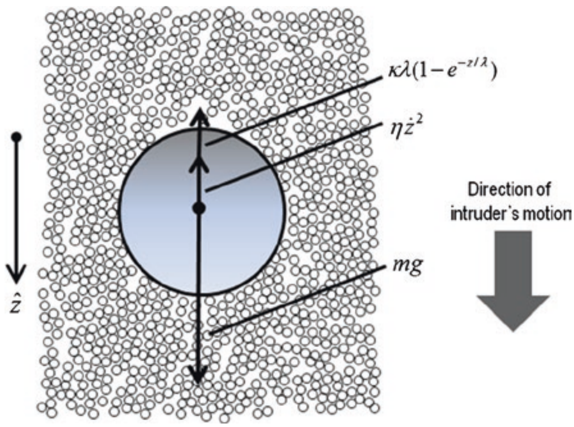


**Fig. 4.2** Force diagram for a spherical intruder penetrating a granular medium

the silo. This posed an even less trivial problem: after being scolded a number of times by the cleaning ladies for flooding the pristine institute's hall with sticky, electrically charged expanded polystyrene beads, we had to design a special "trap" that would allow us to introduce our arm and recover the intruder without losing too many grains. I guess I went up and down those stairs many hundreds of times during these experiments.

In the end, it was truly comforting to see that the results from the acceleration approach using wireless sensors was consistent with the "velocimetric" version using the striped thread—although the latter turned out to be more precise in the end. All in all, we were able to demonstrate experimentally the truth of the equation of motion for the penetration of an intruder as hypothesized by Carlos:

$$m\ddot{z} = mg - \eta\dot{z}^2 - \kappa\lambda\left(1 - \mathrm{e}^{-z/\lambda}\right) \tag{4.1}$$

This is just second Newton's law applied to our case: the left-hand side is the mass of the intruder ($m$) times its acceleration, and the right-hand side contains the three main forces acting on the intruder, as illustrated in Fig. 4.2. The first term corresponds to the gravitational force pointing downwards (here $g \approx 9.11$ m/$s^2$ is the Earth's gravitational acceleration). The second represents a "granular viscosity" due to collisions with grains as the intruder penetrates into the material, and points upwards, opposing the penetration process.[2]

[2] Actually, the fact that the velocity is squared can be debated—for small penetration speeds it may go linearly with the velocity, as for penetration in conventional fluids. In addition, the physical origin of the viscosity term can also be debated.

The third term is associated with the so-called *Janssen effect*, typical of granular matter, which I will explain in more detail. As early as 1895, the German engineer H.A. Janssen concluded that, in contrast with the case for a liquid, the pressure in a silo full of granular matter does not increase linearly with depth, but saturates. Following his observation in corn silos, the pressure increases with depth as $p \sim (1 - e^{-z/\lambda})$, where $\lambda$ is a characteristic length of the order of the lateral size of the silo. That formula tells us that, at small depths below the surface, the granular pressure goes as $p \sim z$, as in a liquid, but when we go deep enough into the silo (i.e., for large values of $z$), the pressure will be a constant. This is because friction between the granular medium and the lateral walls of the silo at a certain depth can propagate through the medium by "force chains", which resemble the way Romans constructed wide arches of stones without using cement. Hence, an ensemble of force chains "standing" on the walls of the cylinder can actually compensate the weight of the granular column above, i.e., the granular column is like a "solid plug" that shields the space underneath the plug from feeling the pressure. The last term on the right-hand side of Eq. (4.1) captures that behavior: at small penetrations, the intruder feels a "hydrostatic-like" force proportional to depth, but, when penetrating deeper, it feels a nearly constant upward force originating from friction with the walls. And *that* suggests that, if a granular silo is long enough, our intruder may reach a saturation of the force associated with the extreme right-hand term in (4.1), and end up falling with a *terminal velocity*—an effect that saves your life when you jump from a plane using a parachute. In the case of granular matter, we demonstrated that it can only occur if the mass of the intruder is big enough (or its density big enough compared to the density of the granular matter around it). Below such a "critical mass" the intruder would simply stop in the middle of the silo, as usually happens in everyday experience: you drop a rock on a sandy beach, and it doesn't penetrate very far into the sand.

The possibility of getting a terminal velocity in a granular material—equivalent to reaching an "infinite penetration"—as suggested by (4.1), had never been demonstrated experimentally, and we actually did it using Carlos' long silo. But we had a winning experimental *duo*: an extremely light granular material, and a long enough silo.

Figure 4.3a shows a sketch of the penetration depth from the surface versus time taken from our experiments: if the mass was small enough, a final finite depth was reached, as illustrated by the two blue curves. However, if the mass of the intruder was big enough, the penetration looked boundless, at least within our 6-meter-long silo, as represented by the yellow, green, and red curves. The velocity of the intruder can be calculated as the time derivative

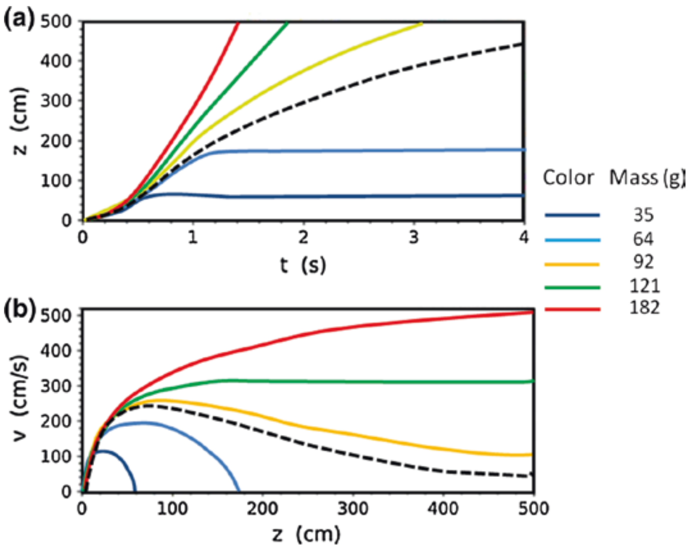


**Fig. 4.3** Sketch of the penetration of a spherical intruder into a granular silo. **a** Penetration depth (measured from the free surface of the granular material) versus time for various masses of the intruder. **b** Penetration velocity of the intruder versus depth, for various masses. The dotted line, corresponding to a mass $m_c = 85.94$ g, is an estimation of the boundary that separates the regions were the intruder penetrates a finite distance (*curves below the line*) and infinitely (*curves above the line*)

of the curves presented in Fig. 4.3a, and the relation between the penetration and the time in the experiment can also be established. Combining those elements, we can construct Fig. 4.3b, where the penetration velocity is plotted against the penetration depth—the "natural variable" of (4.1), so to speak. As expected, from small enough masses (blue curves), the intruder reaches a zero velocity at final depths, i.e., it stops at some point inside the silo. However, for higher masses, a "terminal velocity" seems to be reached (yellow and green curves), and the intruder only stops when it hits the bottom of our silo. For even bigger masses (red curve), the velocity seems still to be growing when the intruder hits the ground. All In all, the behavior represented by the yellow, green, and red curves had never been seen in granular matter.

In order to find the "critical mass" that separates the finite from the infinite penetration regions of the intruder, we notice that the terminal velocity must be reached when the acceleration goes to zero, ideally at an infinite depth inside the silo. So, letting $\ddot{z} = 0$ and $z \to \infty$ in (4.1) and solving for the velocity, we get the following formula for the terminal velocity:

$$V_T^2 = \frac{1}{\eta}(mg - \kappa\lambda) \tag{4.2}$$

Now, if we plot the experimental values for $V_T^2$ vs. $m$, the intercept with the horizontal axis (corresponding to the mass value for which $V_T = 0$) will correspond to the critical mass $m_C$ separating the finite and infinite penetration regions. For our experimental conditions, we found $m_C = 85.95$ g, corresponding to the black dotted lines in Fig. 4.3.

Equation (4.1), however, turns out to be more complex than one might expect. The parameter $\kappa$ involved in the Janssen-like term might naively be assumed to be an "intrinsic" parameter which only depends on the nature of the granular matter involved. But that is not the case. Doug Durian's group at UPenn (US) has shown, for example, that it depends on the nature of the intruder. For example, a spherical intruder has a different $\kappa$ than, say, a conical one. Moreover, as a result of a comment made by Doug Durian himself after a presentation I made at the 2012 Gordon Research Conference on Granular and Granular-Fluid Flow, (Davidson, North Carolina, July 2012), I decided to check back home the effect of the diameter of the cylindrical container, the height of the granular column, and the roughness of the inner walls of the container on $\kappa$. I asked undergrad students Harol Torres and later on, Vicente Díaz, to perform the experiments. We used the same granular matter as in our previous experiments in Carlos' lab (the granular matter was taken to Cuba inside a couple of pillowcases from Mexico, by the way). Our intruders were ping-pong balls equipped with wireless accelerometers inside, with a mass smaller than the critical mass measured in our Mexican experiments. Cylinders of different diameters and lengths were tried, and their inner walls where covered with sandpapers of different roughness[3]. Harol and Vicente found that $\kappa$ decreases when the diameter of the cylinder of the granular column increases, until it reaches saturation at a column radius of approximately 6–7 intruder diameters (smaller, by the way, than the diameter of the silo used in the Mexican experiments). The same occurs when the height of the granular column is increased. So, *confinement* seems to change essential features of how force chains interact with an intruder inside a container—the reality seems more complex than just Janssen's law. It is worth adding that a smaller, but still measurable effect was also found in connection with the nature of the walls: the rougher the walls, the bigger the value of $\kappa$. A curious phenomenon occurs for narrow containers with diame-

[3]Curiously enough, a collection of different sandpapers were bought in a hardware store named Clas Olsen, in Trondheim, Norway, and brought to Cuba by one of my wife's Ph.D. students. Even more curiously, one of the cylinders used in the experiments was the cardboard case of a bottle of 15-year-old whisky kindly provided by colleague Dave Sumpter—probably not exactly for scientific purposes.

ters somewhat bigger than that of the intruder: it basically does not penetrate into the granular bed. I feel like calling it "the inverse Beverloo law"… but that discussion is beyond the scope of this book. Let us look instead at the dependence of $\kappa$ on … gravity.

## 4.2 Going Wireless Finds Its Match

Although I found the work performed in Carlos' team quite beautiful and certainly very entertaining, I kept looking for a tougher challenge that would involve my wireless accelerometers. Then, I became aware of news that motivated me to consider granular matter at low gravities.

*Spirit* was the same of one of the two unmanned vehicles (or rovers) that NASA sent to Mars in 2004 to explore the planet's surface. Each one was a six-wheeled vehicle crowned by a wide solar panel—it curiously resembled its much less celebrated grandparent, the Soviet Lunokhod 1 which explored the Moon in 1970.[4] The Mars rovers were extremely successful: they analyzed the surface of Mars for a period far longer than originally foreseen by NASA, covering a distance of more than 8 km instead of the originally scheduled 600 m.[5] But the mission came to an end due to a quite unexpected fact: on May 1, 2009, the rover got trapped in a shallow, apparently harmless dune of Martian sand located in a site called *Troy.* NASA scientists on Earth conducted simulations and experiments to figure out a way to free Spirit from its granular trap. In particular, at the Jet Propulsion Lab, the motion of a clone of *Spirit* was studied in a sand box of granular matter with a similar composition to the soil at Troy. However, the rover's mass was decreased in such a way that it was equivalent to the weight expected on Mars, i.e., roughly 40% of its equivalent on the Earth.[6] Unfortunately, by January 26, 2010, NASA officials had to announce that the rover was likely irrecoverably obstructed by its location in the soft soil.

In view of that, I found it exciting to apply the philosophy of the "spherical cow" to the Mars rover: why not study the penetration of a spherical intruder into granular matter at gravities smaller than Earth's?

[4] https://en.wikipedia.org/wiki/Lunokhod_programme.
[5] https://en.wikipedia.org/wiki/Spirit_%28rover%29.
[6] http://www.nasa.gov/mission_pages/mer/freespirit.html.


Of course, trips to Mars or even zero-G planes were not exactly within my reach, so I decided to use a more down-to-earth setup, so to speak: an Atwood machine. Invented by George Atwood in the XVIII century, it ideally consists of two objects of masses $m_1$ and $m_2$ connected by an inextensible massless string over an ideal massless pulley. If $m_1 = m_2$, the machine is in neutral equilibrium for any position of the weights. When $m_1 \neq m_2$, the masses experience a constant acceleration. Let us suppose that one of the masses is actually a box with a laboratory inside: if it is falling at acceleration $a_{bucket}$ relative to the ground, scientists inside the lab will feel an effective acceleration $g_{eff} = g - a_{bucket}$ smaller than that on Earth (this is reminiscent of the famous Einstein thought experiment of the falling elevator). If instead of falling, the bucket is moving up, one will feel a bigger acceleration inside it: $g_{eff} = g + a_{bucket}$. So, by tuning the relation between $m_1$ and $m_2$ appropriately, it is possible to do an experiment inside the falling lab that matches the gravity on the surface of Mars, for example. In summary, the idea was to study the penetration of a spherical intruder into a bed of granular matter inside the falling laboratory—under conditions that would simulate an experiment on Mars… or on other planets (real or fictitious), depending on the choice of masses $m_1$ and $m_2$.

But, how could we construct a practical falling lab? The answer was to combine a falling bucket with wireless technology. Imagine that the falling mass is actually a bucket almost completely filled with a light granular material, such as expanded polystyrene beads. A wireless accelerometer A would be attached to the wall of the bucket. On top of the bucket, an electromechanical arm would hold a spherical intruder, ready to be dropped into the granular bead at the appropriate moment. The intruder would contain a wireless accelerometer B inside. So, the sequence of a typical experiment would be like this: (a) adjust masses $m_1$ and $m_2$ in such a way that the bucket falls (or rises) with the desired acceleration relative to the ground; (b) when the external computer reading the data from accelerometer A sees that the falling acceleration is stabilized, it wirelessly orders the electromechanical arm to release the intruder into the granular material; (c) the wireless accelerometer (which has been on since the beginning of the experiment) measures the acceleration of the intruder's center of mass as it penetrates the granular bed, while it "feels" an acceleration smaller (or larger) than Earth's gravitational acceleration; (d) shortly after the penetration process has ended, the bucket is stopped mechanically–either by a manually-controlled break… or by the ground, when we lose control of the break! So, we needed to fabricate an Atwood machine able to move with a constant acceleration in the range from 0.4 to 1.2 $g$ for a few seconds. A simple calculation indicated that our device had to be several times bigger than those typically used in physics laboratories: we ended up constructing a 15-m-tall Atwood machine!

I mentioned the idea to my MSc student Carlos Pérez-Penichet—a young guru in experimental physics, from electronics to informatics.[7] In spite of the potential craziness of the project, he was immediately hooked. I also recruited Eng. Gustavo Sánchez and first-year undergrad students Harol Torres and Alberto González. But the project would take some time to crystallize.

With the Atwood idea in mind, by February, 2011, I had previously bought the "minimal gear" in a CLAS OLSEN hardware store in Trondheim, Norway[8]: I simply showed up at the boats section and got a few meters of heavy duty rope and pulleys for boat sails. If tough sailors like present-day Vikings are happy with this gear, the stuff must work for our little experiment back in Havana—or so I assumed.

So, using the precious items brought from Trondheim, we put together the 15-m long device in the central space of a square iron staircase, and started to do trials with just one accelerometer inside the bucket.[9] The performance was terrible: the fluctuations in the acceleration were of the order of magnitude of $g$: the whole thing did not want to work. After a few days of failed attempts to get a steady acceleration, we concluded that the inex-

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[7] He was actually another step in the decade-long chain of such gurus in our lab, starting with electrical engineer Carlos Abascal in the late 1980s, and followed by physicists Luis Flores, Claro Noda, Carlos Pérez-Penichet, and Leonardo Domínguez.

[8] I was spending one month at the Norwegian University of Science and Technology (NTNU) to give a course on Granular Matter, hosted by Prof. J.O. Fossum, with significant support from the *Erasmus Mundus* European program.

[9] I must thank the cooperation of the Institute of Materials Science and Technology of the University of Havana (IMRE) for allowing us to use their stairs, in spite of certain inconveniences associated with our experiment. For example, as big screws and other metal pieces accidentally fell from time to time, loudly bumping against the steel staircase, researchers in the building preferred to stay inside their labs during the bucket experiments.

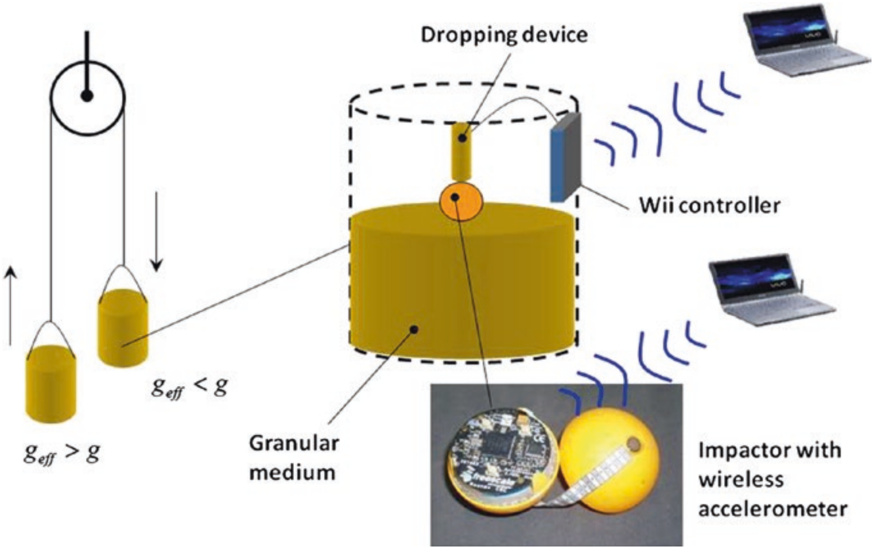



**Fig. 4.4** Lab-in-a-bucket setup. *On the left*, a representation of the 15-m-tall Atwood machine used in the experiments. If the laboratory is a bucket attached to the *right* or *left* arm, experiments inside the bucket take place at accelerations smaller or bigger than Earth's, respectively. In the *center*, a simplified scheme of the bucket including its main components

pensive rope I had bought was acting as a spring, which oscillated madly, with the main frequency depending on the length of rope between the pulley and the bucket—a textbook behavior indeed. I realized sadly that my experiment couldn't be almost for free… I needed "serious investment", so to speak. The problem was solved by April, 2011, when my ex-student Osvanny Ramos (who had just got a permanent position at the University of Lyon, France) got me a piece of multi-wire stainless steel cable several meters long, for approximately 200 euros. It became the most expensive piece of experimental equipment used in the lab-in-a-bucket project (Fig. 4.4).[10]

Back home, we decided to celebrate the arrival of the new steel cable by also replacing the sailing boat pulley by a more appropriate one. We needed a wheel with a bigger mass, to decrease mechanical vibrations even further. I luckily detected a heat-exchanger from an old air conditioning console in a junkyard near the laboratory, and—after lots of heavy hammering and grease—I took from it a nice pulley of 50-cm diameter. It was just perfect. We finally put together the whole Atwood machine, and it rapidly became

[10]The two laptops used to control accelerometers A and B had been previously donated by Norwegian colleagues K.J. Måløy and J.O. Fossum.

clear that the vibrations had been greatly reduced. As a matter of fact, Osvanny's stainless steel cable was several meters longer than needed, but in high tropicality conditions, it would just have been a crime cutting off the remainder. Instead, I decided to use the extra meters as a "tail" attached to the counterweight: that tail would serve to stop the machine manually when the bucket got dangerously close to the ground. We could do it by clutching the rapidly sliding tail as hard as possible—of course, using a pair of heavy-duty gloves. The students would take care of preparing the experiment in the bucket and setting up the ground-based computer, i.e., the intellectually elevated stuff. For my part, I preferred rather to take care of those features of the experiment where an error could jeopardize the entire project: so, I was the one with the heavy duty-gloves on (Fig. 4.5).

Now, we had to put into practice the experimental concept described above, i.e., the wireless control of the system.

Firstly, we deployed the wireless accelerometer B inside the ping-pong ball in such a way that it would measure its vertical acceleration during the penetration process (and also for a few seconds before and after, by the way). We used our "powerhouse" instrument: a commercial three-axis accelerometer embedded in the ZigBee platform, able to transmit a maximum of 120 data points per second, and a resolution in acceleration better than 0.1 m/s$^2$, which cost roughly 100 USD.[11] A ground computer would pick up the vertical acceleration measured by the ZigBee wirelessly as the intruder penetrated the granular bed.

Then, we had to attach accelerometer A to the bucket… but we also needed to release the intruder at exactly the right time. We solved both problems by modifying two gadgets: a wii controller for computer games, and a CD player. Carlos Pérez and Gustavo Sánchez would modify each of them, respectively. Before launching the bucket, our ping-pong ball was hanging from a horizontal cover fixed to the bucket, thanks to a magnet glued on top of the ball (the distances where chosen in such a way that the lower part of the intruder was gently touching the free surface of the granular bed before being released). The intruder was in place, because the magnet was attracted to a piece of iron attached to the mobile part of a CD-player mechanism mounted on the outer side of the bucket's cover: if the CD-player was activated, the mechanism pulled up the piece of iron, and the intruder was dropped inside the granular material. The activation signal came from a modified wii controller attached to the bucket. Given that

[11] I must say that other labs around the world have "discovered" and purchased this nice and inexpensive instrument thanks to our "advertisement".

**Fig. 4.5** Lab-in-a-bucket hardcore team (2012). From *right* to *left* undergrad students Harold Torres and Alberto González (holding the probe sphere), engineer Gustavo Sánchez, and the author. The potential beauty of the bucket suffered for reasons of weight: one rim from the author's car was used as a "shock absorber" at the bottom, and fluorescent lamp transformers were attached to its sides to adjust the acceleration of the system. One can see the steel cable used in the Atwood machine on the author's shoulder, and the author is wearing a critical part of the setup: a pair of heavy duty gloves. In the background one can see the steel spiral staircase where the experiments were performed

these have tiny accelerometers inside, we picked up the signal of the vertical acceleration of the bucket through the wii using a ground computer. When the computer measured an approximately constant acceleration, it sent a signal back to the wii, which in turn ordered the CD-player to release the ping-pong ball. And the actual penetration experiment started.[12]

Figure 4.6 shows a typical record of the normalized acceleration $a/g$ of the intruder relative to the bucket, (where $a$ is calculated as the difference between the acceleration of the bucket relative to the ground, and that of the intruder relative to the ground, which is given by the accelerometer deployed inside it). The particular record shown in Fig. 4.6 took place when the bucket was falling at an acceleration of $0.55\ g$ relative to the ground, so the effective acceleration felt by the granular matter inside it is $g_{eff} = 0.45\ g$, which corresponds approximately to the gravity at the surface of Mars. Figure 4.7

[12] A video of one typical experiment can be watched at https://www.youtube.com/watch?v=e7Q-RrVzVL4&feature=youtu.be.

shows in detail the "region of interest" taken from graphs equivalent to those in Fig. 4.6, for different effective gravities.

In Fig. 4.7a, the normalized acceleration of the intruder relative to the bucket is shown for different effective gravities (the positive reference points downwards). The curves have all the same features: as the intruder is released at $t = 0$, its acceleration increases, pointing in the downward direction—i.e., it gains speed in the initial phase of the penetration—but, due to the effects

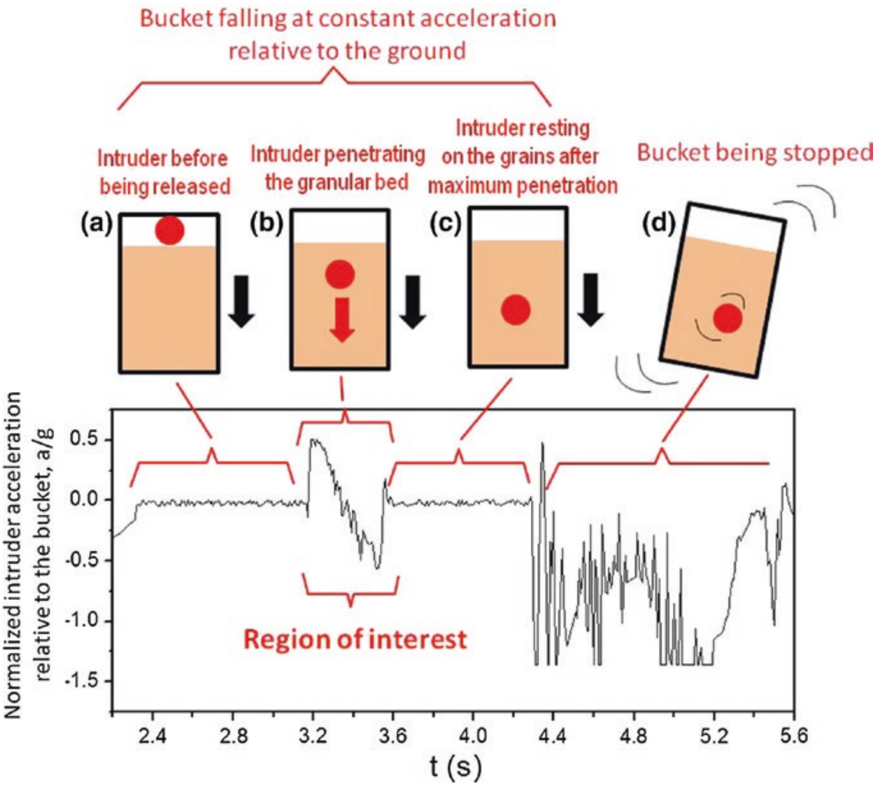



**Fig. 4.6** The intruder's acceleration recorded in a typical experiment, as derived from the data of the accelerometer planted inside the intruder. In the experiment illustrated here, the bucket is falling at an acceleration of $0.55\,g$ relative to the ground (represented by the *black arrows*), so any object resting inside the bucket "feels" an effective acceleration equivalent to that on Mars: $g_{eff} = 0.45\,g$. The graph below plots the acceleration of the intruder relative to the bucket as time goes by (the positive direction points downwards). **a** The intruder is hanging just above the granular free surface, before being released: it is at rest relative to the bucket. **b** The intruder has been released, and is penetrating the granular bed. **c** The intruder has reached its maximum penetration depth $z_{\text{sink}}$ and is again at rest relative to the falling bucket. **d** The bucket is stopped suddenly just before touching the ground

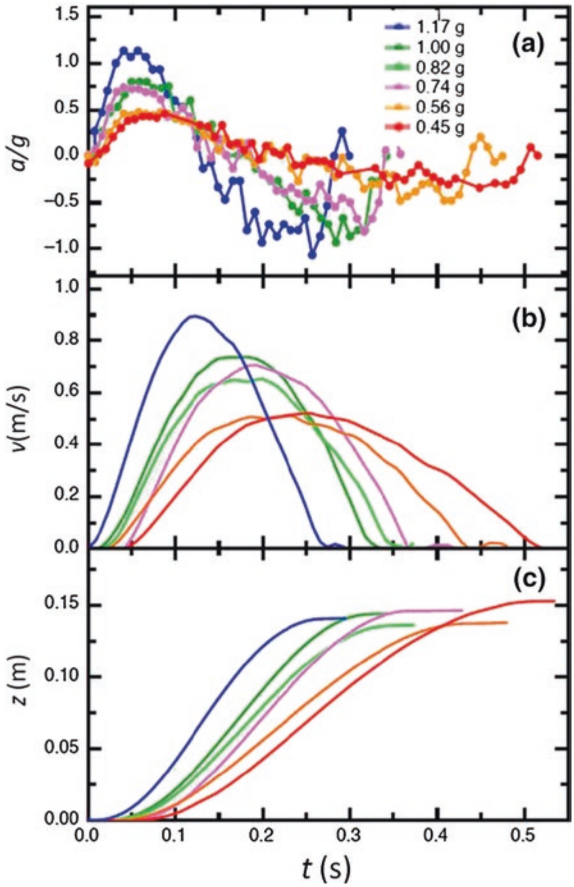



**Fig. 4.7** Dynamics of the intruder relative to the bucket at different effective gravities: experimental results. **a** Acceleration versus time. **b** Velocity versus time. **c** Sinking depth versus time. The different colors correspond to different effective accelerations $g_{eff}$

of the granular medium, the acceleration starts to decrease after reaching a maximum.[13] It eventually crosses the zero line and then its absolute value increases, pointing in the upward direction—i.e., the granular friction starts to "win" over gravity. After reaching a minimum, the acceleration goes to zero, meaning that the intruder is resting at its final penetration depth relative to the granular surface, which we will call $z_{\mathrm{sink}}$. One of the clearest

[13]The value of the maximum coincides approximately with the value of $g_{eff}$ corresponding to the specific experiment, which means that at that moment the sphere is almost free falling: this is logical, considering that during the first section of the motion there is negligible resistance by the granular material.

differences between the graphs at different gravities is the fact that, as the gravity decreases, the total sink time (i.e., the time needed to reach $z_{\mathrm{sink}}$) increases. On the other hand, the absolute values of the maxima and minima of the acceleration decrease. Then, we may conclude that the same intruder penetrating the same kind of granular soil on Mars will take a longer time, and will be submitted to less stress than it would be, say, on Uranus.

**Flash anecdote**

During a visit to the University of Navarra, I left my students in charge of the lab-in-a-bucket project. The bottom panel shows an electronic message I received from them during those days. Its Joyce-like style goes textually like this: "I tell you that we have just arrived from doing some "launchings", and everything was going very well, we were launching 0.6 g, until suddenly in one launch the counterweight started to oscillate, hitting the bucket in such a way that the latter swung too hard, so the rope went off the pulley, the bucket fell practically in free fall and, as it reached the ground became *talc* [a Cuban expression for something that completely fell apart]; the release system once again [also became talc], but, at the same time, the counterweight also went down at full speed […] and hit the staircase right where the laptops where sitting, hitting and damaging the screen of Luis A.'s mini [a Mexican student that temporarily joined the crew]. Then, it fell very near where Gustavo was stopping the experiment downstairs…" There are a few more lines explaining the disaster in further detail, but the author does not feel in the mood to translate any more.


If we integrate the graphs shown in Fig. 4.7a over time, we get those corresponding to the velocity versus time shown in Fig. 4.7b, which show maxima that decrease in intensity with the effective gravity. Finally, the graph in

Fig. 4.7c is the result of integrating the velocity records over time, resulting in the penetration depth versus time. These graphs show a quite unexpected result: the total penetration depth $z_{\text{sink}}$ is about the same for all effective gravities. This result was hard for me to believe: I guessed that such a complicated experiment and the indirect measurement of the penetration were fooling us somehow. So, I asked our ex-student Raúl Cruz—at the time holding a permanent position at the University of Navarra (Spain)—to do full-3D realistic finite element simulations of our system. The results of the simulation completely coincided with our experiments. Moreover, I asked him to extend them for gravities bigger and smaller than the ones we were able to reach in the lab, and the trends were the same. I have to accept that, for the first time in my life, I relied on a computer simulation to convince me that an experiment was right.

*Intuitively speaking, the situation was like this:* as the gravity decreases, the effective weight of the intruder also decreases… but it is compensated by a "softening" of the network of force chains inside the granular material, associated with an "opening-up" of the grain packing at lower gravities. The Archimedean force acting upwards on the intruder also changes with gravity, but it is way too small to be responsible for the penetration dynamics by itself.

In Fig. 4.8 we can see a quantification of some of the results I have described above (in all cases the black dots correspond to experimental results, and the open dots to simulations). The upper figure shows the maximum sink depth for gravities ranging from that corresponding to asteroids, to some higher than that of Jupiter. In all cases, $z_{\text{sink}}$ is of the order of 14–15 cm (i.e., approximately constant). The middle figure indicates that the time taken by the intruder to reach $z_{\text{sink}}$ increases with the effective gravity as[14] $t_{\text{sink}} \sim g_{\mathit{eff}}^{-1/2}$. If we fit (4.1) to our experimental data for different gravities, we get the graph at the bottom, which says that the mysterious parameter $\kappa$ is proportional to the effective gravity.[15] If we re-insert this in the equations, we get both the constancy of the maximum penetration depth, and the $t_{\text{sink}} \sim g_{\mathit{eff}}^{-1/2}$ dependence.[16] So, a consistent picture emerged

[14] An analogous result had been previously reported by Daniel Goldman and Paul Umbanhowar (Georgia Tech) in 2008.

[15] A similar result had been previously reported by T.A. Brzinski, III, P. Mayor, and D.J. Durian (UPenn) in 2013, based on experiments which imitate different gravities by using various levels of air-fluidization of the granular bed.

[16] Scott Waitukaitis, at the time a Ph.D. student of Heinrich Jaeger's at the University of Chicago, collaborated with us in the interpretation of the data—he had been aware of our work since his participation in the workshop "Complex Matter Physics: Materials, Dynamics and Patterns" (March*COM*eeting'12), held in Havana in March, 2012.

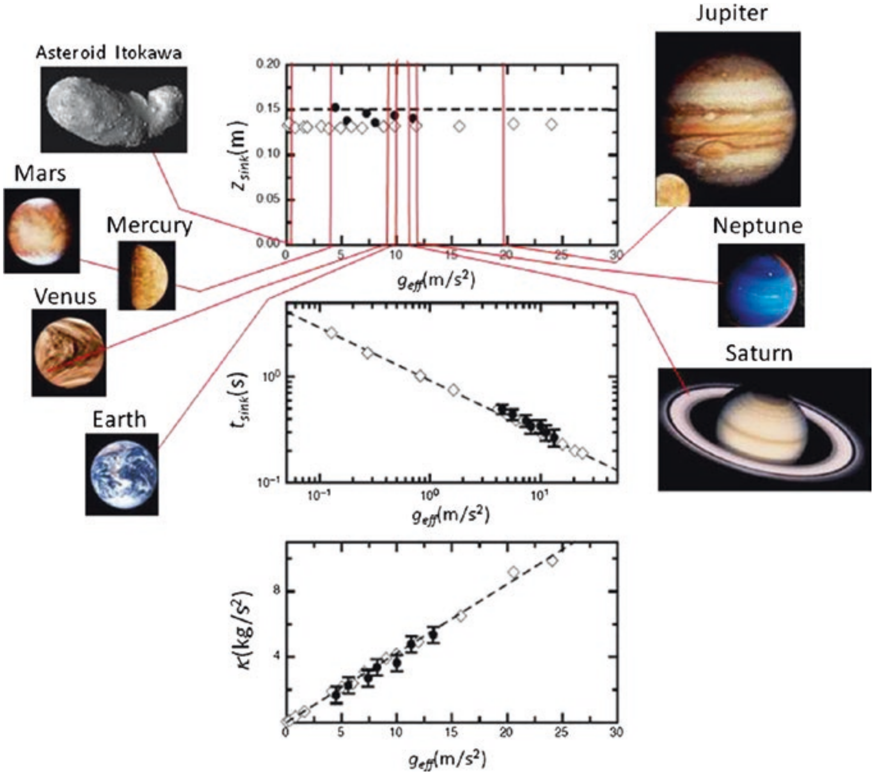



**Fig. 4.8** How the penetration of an intruder into granular matter depends on gravity—combined experimental and simulational data. **a** Maximum penetration depth as a function of effective gravities ranging from that of asteroid Itokawa, to values higher than the gravity on the surface of Neptune. **b** Total sink time versus effective gravity and **c** parameter $\kappa$ appearing in (4.1) as a function of the effective gravity. *Black* and *open symbols* correspond to experimental and simulation data, respectively

regarding the effect of gravity in the penetration of an intruder into granular matter.

It is worth mentioning that, in Fig. 4.7a, quite large fluctuations are seen in the acceleration of the intruder (the fluctuations are smoothed out in the lower graphs of the same figure, due to the integration process). Those fluctuations talk about the detailed dynamics of the penetration process: force chains that oppose the penetration of the intruder are constantly breaking, while new chains are dynamically building up. From the graph it is also seen that the fluctuations in the intruder's acceleration are more pronounced in the second half of the penetration process, i.e., when the "stopping forces" are "winning" over gravity. Then, a natural question arises: How does the intensity of these fluctuations depend on gravity? We have observed, for example, that the intensity of fluctuations increases as gravity increases and, particularly, that the increase in the intensity of the fluctuations in the second part of the penetration process becomes more evident as the gravity increases. That might imply that, if we drop a probe on the surface of Neptune, its landing should be much more "bumpy" than a probe landing on Mars (provided that there is the same kind of granular soil in both places!).

Now, let us go back to the case of the Mars rover trapped in a dune of sand. Let us assume, for a moment, that our spherical intruder actually works as a model for a rover wheel, and that our granular matter made of polystyrene beads has the same general behavior as the granular soil of Mars. Let us also assume that the maximum penetration of a wheel into a sandy dune is an important parameter that controls the ability of the rover to move forward and free itself from a dune. Our experiments suggest that the total penetration of the wheel does not depend on the gravity. So, if we want to do experiments on Earth with a clone of a Mars rover, should we decrease the mass of the device in such a way that its weight is equivalent to that under the gravity of Mars? The answer is not trivial, but I would say "No! Just do the tests on the clone with its original mass".

Of course, there are too many "ifs" before reaching that conclusion. A better approach would be to study how a rover—or a single wheel—would behave on a sandy soil under different gravities.

### 4.2.1 Lab-in-a-Bucket, Reloaded

The *Proyecto Delta*—the Delta Project—is an idea organized by Professors Fernando Rodríguez, David Darias, and an enthusiastic fistful of colleagues from the Mathematics Faculty, University of Havana. They rent a theater in the neighborhood of "El Vedado" (Havana) every week—or as many weeks as they can—and offer an interactive show where a "presenter" on stage and a "virtual presenter" on a screen give humoristic talks and remarks about a number of topics related to science and technology: from computer games, to the definition of beauty. The audience—typically a few hundred—hook to a WiFi network in the theater using their cell phones, and send comments, jokes, and questions, which are displayed on screen, and commented by the presenters. The best joke or comment sent by the audience gets a prize typically consisting of an "articulate chocolate bar" (i.e., a broken chocolate bar), and a pack of condoms. In each show, there is an invitee that generally gives a talk about a scientific topic with a humoristic twist

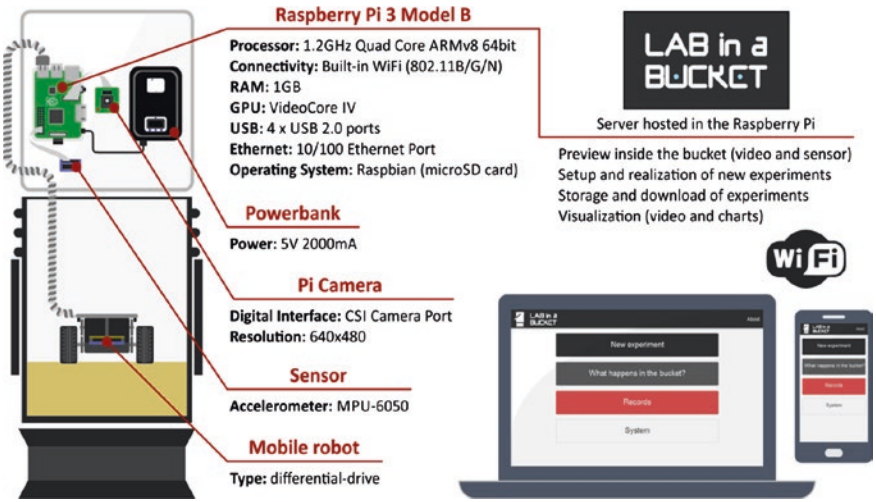



**Fig. 4.9** Lab-in-a-bucket, reloaded. *On the left,* can be seen a sketch of the bucket equipped with a Raspberry platform that controls the motion of the model rover inside, as well as a camera and accelerometers. *On the right*, devices where the software of the device can be downloaded and run

(or the other way around), and then is eventually "cross-examined" by the audience. I myself have been invited a couple of times. Around 2014, I gave a talk related to the lab-in-a-bucket experiment.

In February 2016, a young engineer from the CUJAE[17] called Gustavo Viera came to see me in my lab: he had attended the lab-in-a-bucket presentation at the Delta project, and wanted to join the bucket experiments, along with his colleague Antonio Serrano. They were trained in the construction and control of robots using the Raspberry Pi platform… he even brought one of his little "rovers" with him… Needless so say, I immediately suggested reviving the lab-in-a-bucket experiments (which had been abandoned for a couple of years) to study how a rover moves off on a sandy soil, under different gravities—I would never have been closer to an actual Mars rover! Gustavo asked me to let him bring the bucket to his place. A few days afterwards, the device was hard to recognize: the rusty ballast made of fluorescent light transformers had disappeared, and the bucket had been painted black—to some extent, you could forget that it was actually an ordinary bucket. But more importantly, the electronics for data acquisition had been changed conceptually, as illustrated in Fig. 4.9. The Raspberry platform would now take control of the experiment in real time, taking over the role

[17] "José Antonio Echeverría" Technological University.

of the two ground-based laptops in our original lab-in-a-bucket setup during the experiment. It could connect, though, with a ground-based device through WiFi, allowing laptops, tablets, or cell phones to access the software via a web browser. The ground level device would order the system to start the measurement, check what was happening inside the bucket thanks to a miniature camera, and download through WiFi any data recorded inside the bucket during the experiments, a posteriori. In a word, the lab-in-a-bucket had become a much more open and elastic measuring tool for many types of experiments under variable gravity (Fig. 4.10).

Our initial project is indeed to order a model rover to start moving as the bucket is falling at the appropriate acceleration—then we will evaluate the "start-off efficiency" by comparing the horizontal length covered by the rover's center of mass, and compare it with the length of perimeter rolled by the wheels. However, after doing some preliminary experiments, we have concluded that, if one wants to understand the precise mechanisms, one should study the motion of a single, independent wheel. So inside the bucket we are now installing a wheel that will move along a circular path, revolving around the vertical symmetry axis of the bucket.

**Fig. 4.10** Lab-in-a-bucket hardcore team, reloaded (2016). *From right to left* young engineers Antonio Serrano and Gustavo Viera (holding the model rover), undergrad engineering student Joaquín Amigó, and the author. As compared to the 2012 version, the bucket has a much more professional look (and a new concept regarding hard and software), thanks to the new correlation of forces: three engineers… and only one physicist

Only the future will tell if a project like the lab-in-a-bucket costing just a few hundred dollars can throw a bit of light on some of the ups and downs of billion-dollar space exploration projects.

## Bibliography


Altshuler, E., Torres, H., González-Pita, A., Sánchez-Colina, G., Pérez-Penichet, Waitukaitis, S. and Hidalgo, R. C. *Settling into dry granular media at different gravities, Geophysical Research Letters* **41**, 3031 (2014)

T.A. Brzinski III, P. Mayor, and D. J. Durian, *Depth-dependent resistance of granular media to vertical penetration*, *Physical Review Letters* **111**, 168002 (2013)

Complexperiments (video of a lab-in-a-bucket experiment) https://www.youtube.com/watch?v=e7Q-RrVzVL4&feature=youtu.be

D. I. Goldman and P. Umbanhowar, *Scaling and dynamics of sphere and disk impact into granular media, Physical Review E* 77, 021308 (2008)

Katsuragi, H. and Durian, D. J., *Unified force law for granular impact cratering, Nature Physics* **3**, 420 (2007)

Pacheco-Vázquez, F., Caballero-Robledo, G. A., Solano-Altamirano J. M., Altshuler, E., Batista-Leyva, A. J. and Ruiz-Suárez, J. C. *Infinite penetration of a projectile into a granular medium Physical Review Letters* **106**, 218001 (2011)

Powell, D. *Free-falling against the grain, Science News,* 5 June 2011 (http://www.sciencenews.org/view/generic/id/330783)

Ruiz-Suárez, J. C., *Penetration of projectiles into granular targets, Reports on Progress in Physics* **76**, 066601 (2013)

Sperl, M., Experiments on corn pressure in silo cells—translation and comment of Janssen's paper from 1895, *Granular Matter* **8**, 59 (2006)

Stone, R., *In from the cold*, *Science* **348**, 746 (2015) (http://news.sciencemag.org/latin-america/2015/05/feature-cold)

# 5 Garbage Experiments

*One man's trash is another man's treasure.*

American idiom

When people look up at the clouds, they imagine faces, dogs, landscapes… When I look down at a pile of junk garbage, I see scientific setups. If the reader suspects that some of the experiments described in previous chapters are just garbage, in the present chapter he (or she) is absolutely certain to be exposed to garbage science.

As in other countries, the pejorative name of dumpster divers (*buzos*) is used in Cuba for people that systematically check garbage containers in the streets, looking for empty bottles and cans to give away to recycle—or any other useful stuff. I myself like sea diving but, to be honest, I am also pretty fond of certain kinds of garbage diving. In fact, I practice it nationally and internationally, as we will see below. I am a *scientific dumpster diver* (SDD).

But let me talk first about a leading figure in the field of SDD: our colleague (and PhD in geophysics) Gustavo Sánchez-Colina. Thanks to him, our lab is packed, for example, with piles of old Soviet printed circuits (I must recycle some of these resistors!—he says), an *Underwood* typewriter (that I call "Gustavos' Enigma machine"), and enormous piles of original *Scientific American* magazines from the early 1950s.

One afternoon near the end of 2012, there was a little quarrel between Gustavo and another SDD aficionado, shortly after the people from the Electronics department (IMRE, University of Havana) dumped a lot of old



E. Altshuler, *Guerrilla Science*, DOI 10.1007/978-3-319-51624-0_5


**Fig. 5.1** *At the heart of a scientific dumpster diving conflict*: the Soviet-era noise diode 2D7S

electronic equipment and spares in the garbage containers a few meters from our lab. Gustavo basically got everything: in particular, he seized a box with about 20 strange-looking, Soviet-era diodes (Fig. 5.1).[1] The other guy was really upset: That's not fair: you could spot it right from your lab, man!—he raged. Gustavo partially smoothed out the conflict by displaying his best smile… and handing his critic 5 diodes (the other 15, by the way, are still sitting somewhere in a corner of the lab).

But the biggest prize on this occasion was not involved in the conflict: an old electromagnetic horizontal shaker for stirring chemical solutions, produced in the German Democratic Republic by the firm MLM. The device was refurbished by Gustavo and converted into our official shaker to study the sinking of intruders into granular media in Hele-Shaw cells, as we will see later on.

[1] *Noise diode 2D7S*, according to the original datasheet, or a cryptic "Tubo eléctrico y semiconductor especial" (Special electric and semiconducting tube), according to the handwritten inventory description on the box.

## 5.1 A Transverse Point of View

The truth is that I had never been interested in shaking granular matter: I knew perfectly well that my options of vibrating and shaking devices would hardly compete with the sophisticated ones used in laboratories abroad.[2] But my colleague Renaud Toussaint (Institut de Physique du Globe, Strasbourg, France) and I had recently obtained a French project that supported the PhD work of Gustavo, co-advised by Renaud and myself.[3] It was a nice opportunity to do quite a bit of scientific exchange… and Renaud was greatly interested in the fluidization of granular beds by shaking, since it has a clear geophysical interest in scenarios like earthquakes, for example. In fact, fluidization (or liquefaction) due to shaking (or a combination of shaking and the presence of water in the soil) is indeed a quite relevant subject. The effects of soil liquefaction due to earthquakes have caused numerous human and material disasters throughout history: some of the latest and best documented are those associated with the destruction of San Francisco's Marina district in 1989, during the Loma Prieta earthquake (USA), and the extensive damage of many residential areas in Turkey due to the 1999 earthquake (Fig. 5.2).

Our first laboratory experiments were performed at Renaud's group in Strasbourg during a one-month visit in August–September 2013, where I coincided with Gustavo and Alfo José Batista—the other two Cubans directly involved in the project. Renaud suggested constructing a bigger version of a three-dimensional setup to horizontally shake a box of sand he had already been using in the lab, and look at the penetration process of an intruder into the fluidized granular matter. In order to do that, we first went to a pet shop and bought a glass aquarium. Then we mounted it on drawer slides and used a motor-and-lever system to make it oscillate horizontally. Renaud—originally trained as a theoretician—had recently turned into an experimentalist with a certain dose of playfulness, so his lab was full of wonders. One of them was a Go-Pro camera that I immediately attached to the

[2] A notable exception was my attempt to use a curious device called a "buttkicker" vibrator, kindly donated by my Canadian colleague Kevin Robbie. My failure to turn his philanthropy into science has tormented me for many years.

[3] *The Physics of natural catastrophes: learning to predict and mitigate* (Funds for Priority Solidarity, France, 2013). It seems that the critical point at which Renaud won a "poker hand" for us was when he showed up at the French Embassy in Havana in March, 2012, wearing a *guayabera* (Cuban national shirt, so to speak), combined with colorful shorts and sandals. I should remark that the lower end of the *guayabera* was stuffed inside the shorts, so it can be described as an extremely unconventional outfit.

**Fig. 5.2** *Tilting due to liquefaction. Picture taken after the the Izmit earthquake, Turkey, August 17, 1999. (Image courtesy of Mustapha Meghraoui)*

lateral side of the aquarium in such a way that the sink process could be followed from the box's oscillating reference frame… until the intruder disappeared completely into the sand. I also extended my passion for miniature accelerometry by attaching an accelerometer inside the intruder… and a second one on the oscillating box, in order to compare the two signals—I will explain this idea in more detail below. Although we started with the wireless accelerometers I had used in previous experiments (see the last chapter), Renaud introduced us to the wonders of the free and inexpensive platform *Arduino* to construct devices that could pick up the signal of a tiny accelerometer (and also a gyroscope), and store the information in situ, in such a way that it could be USB-downloaded to a computer after the experiment was finished. Unfortunately, our system for shaking the heavy sandbox using a motor and a lever system was not robust enough to obtain a nice sinusoidal oscillation. Next year, however, Renaud would buy a professional electromagnetic shaker, and the scenario would change radically.

Upon my return to Cuba I decided to built a two-dimensional version of the setup made in Strasbourg. On the one hand, it would be good to be able to take videos of the *whole* penetration process of the intruder while the accelerometers where also at work—after all, it was the only way to test the capacity of the accelerometric technique to follow the sink dynamics.

On the other hand, Gustavo had to spend most of his time in Cuba, and I could not imagine stopping the experimental work just because we were in Havana.

Fortunately, our scientific dumpster diving abilities saved the day. As in the Strasbourg setup, the idea was to horizontally oscillate a container full of granular matter (say, a Hele-Shaw cell consisting of a parallelepiped with two transparent vertical plates), and observe how an intruder (say, a little box fitting between the transparent plates) would sink into the granular bed. My proposal, however, was to replace the "truly three-dimensional" aquarium by a "quasi-two-dimensional" one with two parallel transparent plates, separated by a small distance, just a little bit bigger that the intruder's thickness—also called a Hele-Shaw cell (see Fig. 5.3). Since the MLM garbage shaker was not actually very powerful, we needed to make a very light

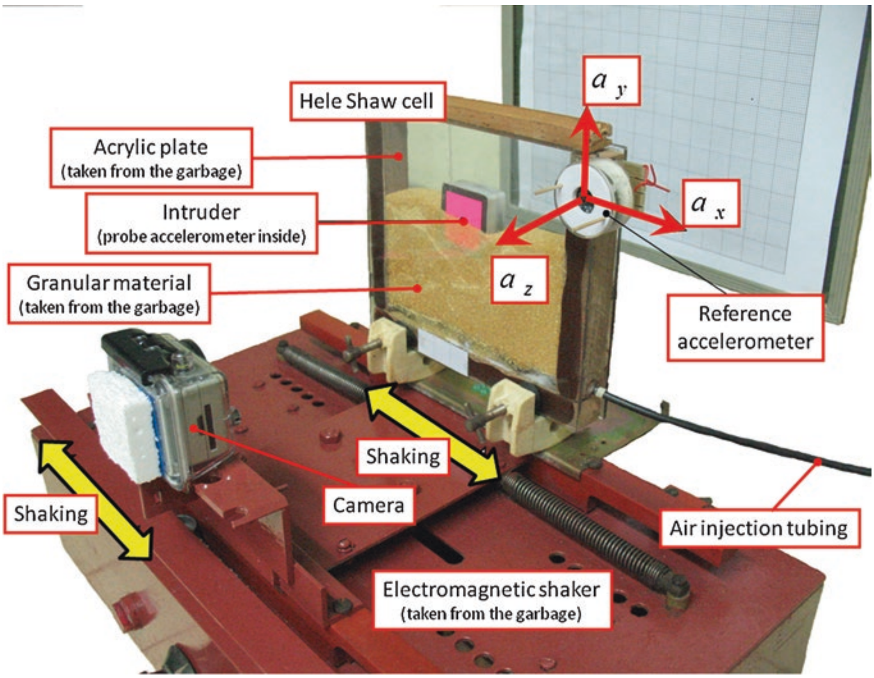



**Fig. 5.3** *A garbage-based set up*. A Hele-Shaw cell is mounted on an electromagnetic shaker taken from the garbage. The cell is made of garbage acrylic plates, and contains granular matter made of ion-exchange beads also found in the garbage. The basic non-garbage materials are a Go-Pro camera, and two wireless accelerometers. When I told the students to clean up the lab in order to decrease the overall amount of garbage in the photo, they found a way around that by just erasing the background digitally. They respect garbage-based-science too much, I guess

Hele-Shaw cell to fix on top of it. The natural material of choice for the front and rear walls was glass, but it was too heavy, given our experimental limitations. The solution to that problem was again found in the garbage… although this time not in Havana, but on the other side of the Atlantic. One day during one of my trips to Paris to work in Eric Clément's group at the École Supérieure de Physique et de Chimie Industrielles de la Ville de Paris (ESPCI), I was walking along *rue Monge*, and… voilà!: I spotted this one-square-meter, one-millimeter thick, transparent acrylic plate resting against a garbage can. I just didn't hesitate: I immediately seized of it.

**Flash anecdote**

In March 2012, we took part in the "Complex Matter Physics: Materials, Dynamics and Patterns" (March*COM*eeting'12): a wonderful scientific rendezvous organized in Old Havana thanks to the energy and momentum of our Norwegian colleagues Jon Otto Fossum and Tom Henning Johansen—although I have to say that the organizational work almost kills me. Several scientists from Europe, Latin America, and the States attended the meeting. In the night before the inauguration, there was a major power failure in Old Havana: a big explosion of a transformer followed by a massive blackout. On the opening day, two young Norwegian students came to me, very concerned by an earthquake they had experienced the night before. They had felt the ground tilting in their hotel room, but that had just been the natural continuation of a similar experience an hour before in a bar. Two key elements might help interpret the situation: (a) there are no official reports of "feelable" earthquakes in the history of Havana and (b) alcohol is nearly one order of magnitude less expensive in Cuba than in Norway. But a year afterwards, I learned that there were indeed very slight ground tremors in Havana during those days. Now I believe that the young Norwegians actually had been accurate human seismometers.

However, as I walked triumphantly back to the ESPCI, I realized that it would be a bit odd to see me entering through the main gate in the middle of the morning with a big, and potentially dirty plastic plate. So, as many dumpster divers probably do, I concealed the thing behind an electrical (or telephonic?) control box right at the corner of *rue Monge* and *rue de Mirbel*.[4] I'd come back late at night to complete my SDD activity.[5] Once home—I was living at the time in an ESPCI apartment inside the institute—I washed and cut the plate into pieces that would fit into my luggage. The acrylic plates would land safely in my lab a few days later, before the excited faces of my students. Finally, we needed a nicely-shaped and relatively light granular material to fill up the Hele-Shaw cell. The problem was solved by a quick SDD operation in the garbage dump of the Chemistry department (University of Havana) where a few kilos of discarded ion-exchange resin, consisting of spherical grains, were collected.

The setup was completed (almost) with a Go-Pro video camera provided by Renaud—not taken from the garbage, as far as I know. Given its lightness, we fixed it to the shaker in such a way that it would oscillate synchronously with the Hele-Shaw cell: this guaranteed that we could take videos of the sinking process in a reference frame at rest relative to the granular medium. As suggested above, including accelerometers inside and outside the intruder would actually be very useful to study the sink process in a three-dimensional system, where the intruder would eventually escape any possibility of getting video-taped as it sank completely into the granular material. Finally, to help the fluidization process, a device to inject air in the upward direction was also installed at the bottom of the cell. Gustavo put together the setup with the (now) diligent help of undergraduate student Laciel Alonso.[6]

One might believe that a single accelerometer would be enough to follow the sink dynamics of the intruder—just as presented in the previous chapter. However, the vertical penetration of the intruder into the laterally shaken cell was relatively slow as compared to our previous experiments with ultra-light granular matter (see Chap. 4). So, a single accelerometer inside the intruder just measuring the vertical acceleration would yield a very noisy signal. I therefore proposed a "way around" the problem: comparing the

[4] I wonder what the customers sipping their café at the restaurant *Le Village Monge*, just across the street would think of my strange activity.

[5] Honestly, there was no reason to be ashamed. I have seen enthusiastic Parisians parking their *voitures* near world famous *rue Mouffetard* to dive into a massive dump of furniture, books, old shoes, porcelain figures… whatever you care to imagine.

[6] After a "turbulent" beginning in our group when he started to work in the field of bacterial dynamics a couple of years earlier, Laciel was "recycled" by the then MSc student Etién Martínez into the Hele-Shaw work. It was a lucky move: Laciel showed to be very sharp in the mechanical design of the cell, and later on he would provide useful insights into interpretation of the data.

outputs of two accelerometers measuring the *horizontal (and not the vertical)* acceleration of both the oscillating cell and the intruder: since the shaking acceleration was quite large, the horizontal signals would be easier to measure. But, how could they help us to figure out the sinking process of the intruder *along the vertical*? The idea was to compare the output of the two accelerometers—more exactly, to measure their temporal correlation.

Figure 5.4 illustrates qualitatively how the correlation helps us to know when the intruder has reached the "jammed phase" at the bottom of the granular medium. As time goes by, the intruder (equipped with a red accelerometer) sinks through the fluid granular phase (from $t_0$ to $t_1$), and starts to reach the "jammed" granular phase by $t_2$, where it stays from $t_3$ to $t_4$. From $t_0$ to $t_2$ the motion is quite "free" along the vertical axis, and the intruder does not very closely follow the horizontal motion of the granular medium: there, one would expect a relatively poor—but increasing—correlation between the signals measured by the black (*Ref*) and red (*Probe*) accelerometers. From $t_3$ to $t_4$ the intruder has "anchored" itself onto the "jammed" granular phase, so it is able to follow the horizontal motion of the cell quite closely: the correlation is expected to become strong and stabilize. As the horizontal acceleration is oriented in the *x* direction for both accelerometers (*Ref* and *Probe*), we will compare both data sets $a_{x,R}$, $a_{x,P}$ using a modification of the so-called Pearson correlation coefficient aimed at decreasing the noise in the output. The modification consists in calculating the evolution

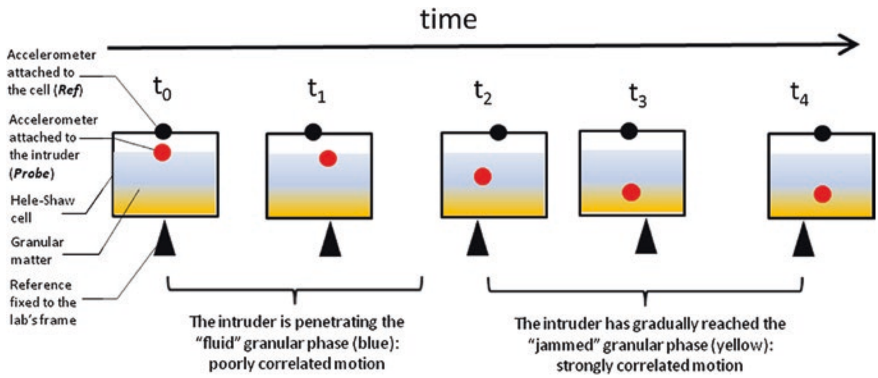



**Fig. 5.4** *Illustrating the working principle of lock-in accelerometry*. From $t_0$ to $t_1$, the intruder penetrates more or less freely through the fluid layer of material (*blue*), so it hardly follows the shaker's horizontal oscillations: accelerations at the black and red spots are poorly correlated. From $t_3$ to $t_4$, the intruder is partially stuck in the "jammed" phase (*yellow*), so it quite closely follows the horizontal motions of the cell: the accelerations measured at the black and red spots are now quite strongly correlated

of the Pearson coefficient within time intervals of size $D$, each one starting at time $k$, as follows:

$$C(k) = \frac{\sum_{i=k}^{k+D} a_{x,R}(i) a_{x,P}(i)}{\left[\sum_{i=k}^{k+D} \left(a_{x,R}(i)\right)^2 \sum_{i=k}^{k+D} \left(a_{x,P}(i)\right)^2\right]^{\frac{1}{2}}} \tag{5.1}$$

**Flash anecdote**

Whenever I asked MSc student Etién Martínez to clean up the lab after his messy experiments on granular matter, he was always able to do it in the blink of an eye. I had been happy for a long time, until I discovered his secret: all the lab's junk (including non-garbage junk!) was just "bulldozed" into the Faraday cage sitting dark and unused in the lab—see picture. Etién called it "the ultimate experiment in granular packings". I called it otherwise.

In the formula above, $i$ represents the sampled time index and $N$ is the total number of experimental data points (so $k$ runs from 1 to $N$–$D$). A typical output from a real experiment is illustrated in Fig. 5.5. In Fig. 5.5a, we see the depth to which the intruder has penetrated the granular material, as monitored by the Go-pro camera fixed to the oscillating hele-Shaw cell: after a fast sink period of less than 1 s, the intruder reaches the boundary between the fluid and jammed phases, finally reaching the jammed phase in approximately 3 s, where it stops sinking—at least during the total duration of the experiment. Figure 5.5b shows the correlation between the accelerations measured by the *Ref* and *Probe* accelerometers, using formula (5.1). There, we see, at least, a distinctive plateau after approximately 3 s, indicating the moment where the intruder has "anchored" onto the "jammed

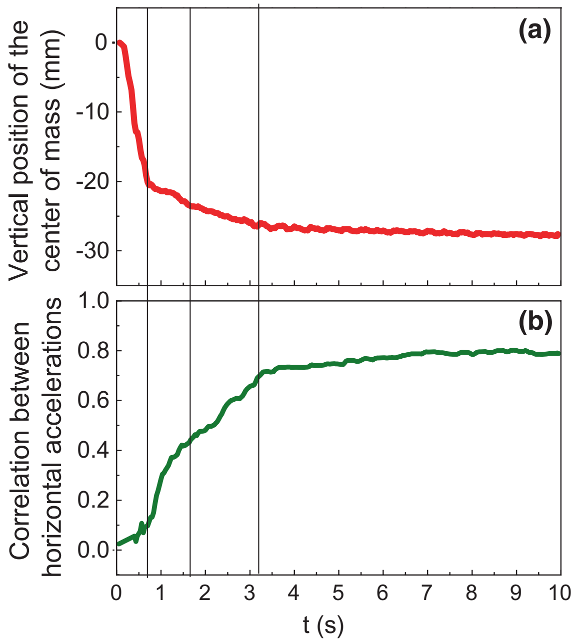



**Fig. 5.5** *Following the sinking of an intruder through lock-in accelerometry*. Time evolution of **a** the penetration depth of the intruder's center of mass, **b** correlation coefficient for a square intruder penetrating into a horizontally shaken Hele-Shaw cell

phase" near the bottom of the Hele-Shaw cell. So, if we were not able to see the sink process—as in a realistic 3D scenario—we could figure out when the intruder had "touched bottom".

So, we just needed to name our technique. I found it fun to borrow from a different experimental field where I had worked for many years: superconductivity. In order to measure the tiny voltage signals typical of superconducting samples, we use a special device called a *lock-in amplifier*. The idea is to "excite" your sample using a sinusoidal signal. The sample deforms the signal in a way that depends on its chemical and physical characteristics—the ones we want to look at. But those signals are "bombarded" by all kinds of unwanted noise: for example, parasitic voltages induced in the cables attaching the sample to the "outside world" by the unavoidable electromagnetic radiation of the environment. Since the lock-in amplifier "knows" the frequency and phase of the excitation (or reference) signal, it is able to discern what part of the sample output signal is due to spurious noise, and what part is due to interesting physical phenomena produced inside the sample. Since our system also compares an oscillatory signal used to “excite” our intruder (the output of the *Ref* accelerometer) with the acceleration of the sample (the output of the *Probe* accelerometer), we called the idea *lock-in accelerometry*. However, for the time being it is just a developing concept. I am sure that more details of the sink process can be obtained by looking more closely at the correlation between the accelerometers. Renaud Toussaint, for example, has suggested that incorporating another miniature device in the system—a gyroscope, for example—might provide the critical amount of data needed to follow the sink process in detail.

## 5.2 Sink Versus Tilt: The Role of Foundations

By October, 2016 Gustavo, Alfo and I coincided again at Renaud’s lab. The old wheel-and-lever shaker had been replaced by a serious electromagnetic one, so the sink experiments in a three-dimensional sandbox could be performed properly (see Fig. 5.6).

Taking into account the power of the new shaker, we used a new—and bigger—plastic box moving on two drawer sliders bought in a hardware shop. Then, we started once again to study the penetration of 3D-printed cylinders adjusted to have the same density as the granular bed—for the sake of simplicity. Since the cylinders would not sink completely under the sur-

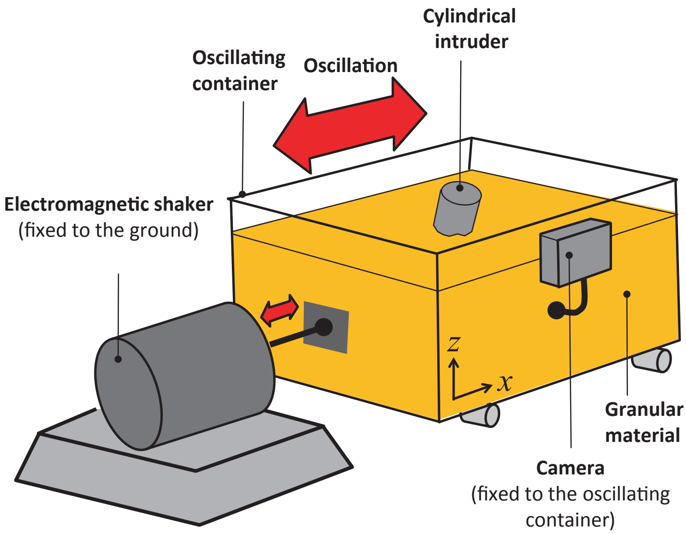



**Fig. 5.6** *A laboratory-scale earthquake*. Experimental system to study the penetration of a cylindrical intruder into a laterally shaken granular bed

face of the granular material, we did not use accelerometric measurements, and concentrated on video analysis. Following the same idea applied to the Hele-Shaw cell experiments, we attached a Go-Pro camera to one side of the box, so the videos of the penetrating objects could be recorded relative to the accelerating sand bed.

This time, besides working with conventional cylinders with a flat bottom, I suggested changing the "foundation" of some of them by attaching a ring to their underside, I was expecting that the ring would slow down the vertical sink process—in my mind, it would make the flow of sand around the lower end of the cylinder more difficult, thus retarding the vertical sinking. But the first experiment proved me wrong: for the shaking frequencies and amplitudes available in the lab, *cylinders with rings had a tendency to tilt laterally instead of sinking vertically*! As in the case of the revolving rivers experiment, it took some time to convince ourselves that the tilting we observed for the ring cylinders was not a mere fluctuation in the experiments: it was indeed perfectly repeatable.

So, we had two types of behavior. Let us start by discussing the case of the cylinders with flat bottoms. Such cylinders sink vertically as soon as the lateral shaking starts, until they reach a final depth $\Delta h$ under the sand. The final depth depends on the shaking strength, expressed as the maximum horizontal acceleration of the box of sand divided by the acceleration due to gravity, denoted by $\Gamma$, as shown on the horizontal axes in Fig. 5.7c, d. In Fig. 5.7c, we can see that the cylinder doesn't sink for values of $\Gamma$ smaller than a certain threshold. After that, $\Delta h$ increases more or less linearly with $\Gamma$, until it saturates when the entire cylinder has disappeared under the sand, and its "head" is just at the level of the surface.[7] One can explain that behavior using previous knowledge on the fluidization of shaken granular matter: above a certain acceleration threshold, the thickness of the fluidized layer in a shaken container (blue-shaded in Fig. 5.4) is known to increase its depth more or less linearly with $\Gamma$. If we assume that our cylinders just sink through the fluidized layer of the shaken granular bed until they are stopped by reaching the jammed phase (yellow-shaded in Fig. 5.4), it is easy to understand the behavior observed in Fig. 5.7c. The last piece of the puzzle is this: why does the cylinder not go on sinking for large enough shaking strengths when the fluidized layer is thicker than its length? The answer is that our cylinder was designed in such a way that its density matches that of the granular bed, so it sinks until the whole cylinder is entirely immersed in the sand… and then it

[7] Up to this point, the system can be monitored using a video camera. But if the cylinder goes further inside the granular bed, videos are of no use, and lock-in accelerometry could then play a central role.

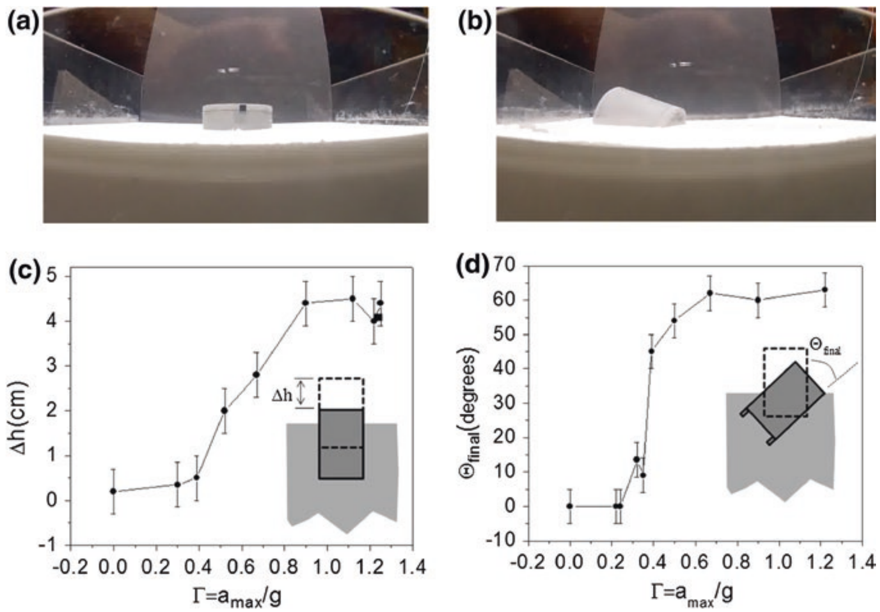



**Fig. 5.7** *The dramatic effect of foundations on granular matter fluidized by shaking*. **a** Photograph of the final position of a no-ring cylinder on a granular bed shaken at a dimensionless acceleration of 0.8. **b** Same for a ring-cylinder. **c** Final sink depth for a no-ring cylinder, as a function of the dimensionless acceleration. **d** Final tilt angle for a ring-cylinder, as a function of the dimensionless acceleration (the ring-cylinder also sinks, of course, but we have not included the corresponding graph here)

just floats at that depth (in analogy to a conventional liquid). By analyzing the digital videos of the sinking process, one can also follow the details of the sinking process at a given value of Γ, as time goes by. The process can be understood using the equation of motion (4.1), after introducing a few approximations—but we are not interested in such details here.

Now, we discuss the case of cylinders with a ring glued to the bottom. The explanation of why those tilt rather than sink vertically into shaken sand is actually very easy to understand at a qualitative level. *Dangerously easy to understand*, I'd say. The basic idea can be illustrated by a classic maneuver known to "magicians". If a standard glass is sitting on a tablecloth, and we pull it off fast enough, the glass basically remains standing directly on the table at the same spot as before. But, if the bottom of the glass is dirty and sticky (in such a way that the friction between it and the tablecloth increases considerably), there is plenty of opportunity for the glass to tilt and tumble when the tablecloth is pulled away. This failure occurs because, while its lowest point will feel a pulling force due to friction, its center of mass will feel

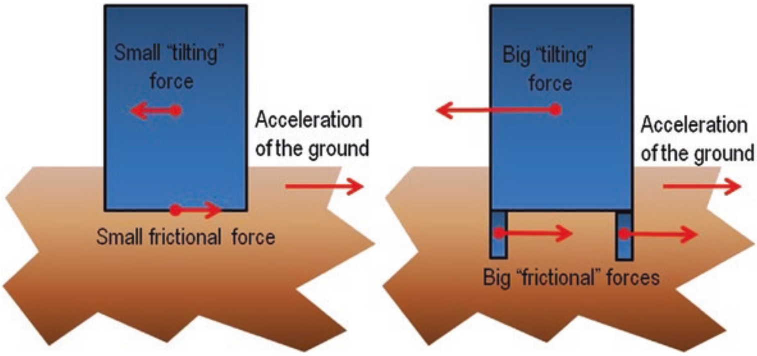



**Fig. 5.8** *A simplified explanation of sink versus tilt behaviors. On the left*, a non-ring cylinder is sketch when the ground is accelerating to the right: small frictional forces near the base cause a small torque. *On the right*, a ringed cylinder experiences much stronger forces on its "feet", causing a sizable torque that eventually ends up tilting the cylinder

an inertial force in the direction opposite to the pulling action: the combined effect of the two forces will make the glass tilt, and eventually tumble. The cylinder with a ring attached behaves like the glass with a sticky bottom: when it sinks a bit, the ring "anchors" into a deeper, less fluidized layer of sand, while the rest of the cylinder is still in the fluidized phase. The ring bottom is then pulled laterally more than its body by the oscillating sand, just as the sticky tablecloth pulls the bottom of the glass, and makes it tumble[8]—see Fig. 5.8. As pointed put before, this simple explanation is dangerous in many ways. For example, if $\Gamma$ is big enough, the cylinder always tends to tilt, and the same occurs for a wider range of $\Gamma$ if the cylinder is modified in such a way that its center of mass is closer to the top. On a more psychological side, it may be that other scientists will under-appreciate the originality of our experiments, since… *they were so predictable*!

Although our experimental system is still quite far removed from real scenarios of man-made constructions under the effects of soil fluidization due to earthquakes, it is hard to avoid pointing out some curious facts. For example, the Kocalei earthquake occurring on August 17, 1999, had various different effects on many constructions in the city of Adapazari, Turkey. According to observers, some buildings sank vertically into the soil, others tilted, and some even suffered lateral translation over the ground. To what

[8] The actual situation is much more complicated: the tilt occurs at the same time as the cylinder is sinking, so the horizontal friction—and associated torques—are correlated with the vertical motion.

extent were the sinking, tilts, and shifts of the buildings a consequence of the type of foundations in each case?

If we were able to accurately predict what kind of foundations would make a tall building sink or tilt under an earthquake, we could jokingly imagine the construction company doing a survey among future apartment owners: In the case of an earthquake, would you prefer the building to sink, or to tilt? I guess the answer would depend very strongly on the storey you are supposed to live in!

Of course, earthquakes are not the only kind of natural phenomena that can produce damage associated with soil fluidization. A serious problem with the sandy beaches to the east of Havana is erosion: extreme meteorological events such as hurricanes have decreased the extent and quality of the sand on those beaches. Fluidization of the sand in shallow waters is one of main ingredients of that process. The importance of soil fluidization is easily illustrated by a simple experiment: if a 1-kg rock is deposited on the sandy soil under a few centimeters of water, the simple action of low-intensity waves, combined with the fluidization of the soil under the rock will make it roll and move relatively large distances within minutes. One of our ideas in the framework of the project on natural catastrophes is to try to quantify that motion by planting accelerometers in rocks of different sizes and shapes and following their dynamics under shallow waters on Havana's eastern beaches. Figure 5.9 shows a "model rock" where a compact Arduino

**Fig. 5.9** *Arduino on the rocks*. *Left panel* a marine rock removed from the sandy bottom of "Santa María" beach in Havana, with a hole made in it. On the rock are visible an Arduino equipped with the gyroscope-accelerometer sensor, and a Bluetooth module (the picture includes the battery holder and the battery, separately). *Right panel* the electronics is shown almost completely inserted into the rock. In order to protect it from the water, it must be sealed inside a plastic bag. The rock is about 20 cm across

**Fig. 5.10** *A biblical image: aiming at the miracle of stones and sensors*. On February 2015, some of the participants in the French-Cuban project "The Physics of Natural Catastrophes—learning to predict and mitigate"—planted small accelerometers and data-loggers into rocks at "Santa María" beach, some 20 km east of the city of Havana. In the picture, taken by the author on February 25, 2015, we can see Alfo, Renaud, and Gustavo, from *left* to *right*. The bluish balloons on the ground are jellyfish that explain why Cubans do not like to swim at some beaches in "winter time". Renaud did anyway

platform—including a tiny accelerometer and gyroscope—can be deployed in order to store data associated with the motion of the rock.

The picture in Fig. 5.10 was taken during a session, where we did some preliminary experiments on the matter at "Santa María del Mar" beach, in Havana. By September 23, 2016, Gustavo defended his PhD at the Institute de Physics du Globe (IPGS), associated with the University of Strasbourg, co-advised by Renaud and the author. The co-advising agreement between the University of Havana and the IPGS—plus the extra-support provided by the French embassy in Havana—gave critical momentum to the research project, which was developed both in Strasbourg and in Havana, as mentioned earlier.

## Bibliography

Ackermann, S. J., "Cuban and American Physics", *American Scientist*, **104**, 142 (2016). http://www.americanscientist.org/issues/pub/cuban-and-american-physics

Sánchez-Colina, G., Alonso-Llanes, L., Martinez, E., Batista-Leyva, A. J., Clement, C., Fliedner, C., Toussaint, R. and Altshuler, E. *"Lock-in" accelerometry to follow sink dynamics in shaken granular matter, Reviews of Scientific Instruments* **85**, 126101 (2014)

Tennakoon, S. G. K., Kondic, L. and Behringer, R. P. *Onset of flow in a horizontally vibrated granular bed: Convection by horizontal shearing*, *Europhysics Letters* **45**, 470 (1999)

Bray, J. D and Stewart, J. P. Damage *patterns and foundation performance in Adapazari, in Kocalei, Turkey earthquake of August 17, 1999*. Reconnaisance Report, Earthquake Spectra **16** (Suppl. A), 163–189 (2000)

Sánchez-Colina, G., Clément, C., Batista-Leyva, A. J., Altshuler, E. and Toussaint, R. *Sink vs. tilt penetration into shaken granular matter: the role of foundation.* In preparation (2016)

# 6
# A Reason to Drink Coca Cola

*By working on a somewhat wrong idea*
*you can often get a good idea.*
*But this takes time and you need*
*sympathetic and helpful colleagues.*

Martin Perl.
in "One hundred reasons to be a scientist"
(ICTP, 2004)

No. I'm afraid that this chapter is not connected with the recent developements in the relations between Cuba and the States.

In later chapters, I will discuss our experiments on the escape of panicked ants. The corresponding paper, published in 2005, produced an enthusiastic reaction from Iker Zuriguel—a young and energetic professor at the University of Navarra (Spain) specializing in granular matter. Driven, perhaps, by his early enthusiasm, the granular materials group at the University of Navarra invited me to their lab for two months in the period October–November 2012.

On the first day of my stay, there was a meeting with the members of the group in the office of Diego Maza. Diego, Iker, and Ángel Garcimartín were seated at a small round table with me. The grave manners and impressive physical stature of Diego, combined with the seriousness of the rest of the participants, reminded me of a scene in The Godfather—I just couldn't help it. The spirit of the discussion, however, could not be farther away from the



E. Altshuler, *Guerrilla Science,* DOI 10.1007/978-3-319-51624-0_6

typical cliches associated to the picture: they had told me beforehand that what they wanted from me was to introduce new ideas in the lab.

Given the great experience of the group in the field of granular matter, the invitation looked challenging. I proposed a number of ideas, which were thoroughly discussed and enriched by my Spanish colleagues.

I was then conducted to the lab—a very well equipped, neatly organized place—where they offered me free access to two of their nicest pieces of equipment: a professional vibrating platform and a professional high-speed camera. Taking into account the fact that my home analogues would be a 5-inch loudspeaker and an e-bay VHS camera, I now felt fully equipped for a conventional war. Time would soon demonstrate, however, that I would tilt the scenario significantly towards my usual guerrilla style, though not on purpose.

To start with, I had never attempted to do research work in the field of vibrated granular matter, since the only vibrators at home where, as I have said, fairly small loudspeakers.[1] These have a crucial disadvantage. First, even if they are fed by a sinusoidal signal, there is no guarantee that the vibration will be perfectly sinusoidal. Second, if large masses were deposited on the loudspeakers, the amplitude of vibration would decrease—probably in addition to some extra awful deformation of the vibration waveform.

## 6.1 The "Granular Vesicle Effect": A Frustrating Experiment

But now I was faced with the unusual exigency of creating some meaningful experiments for a *real* vibrator. A casual conversation I had had in Oslo with the Norwegian physicist Eirik Flekkøy a few months earlier came to my mind: "When I do my laundry", he said, "I have repeatedly observed that big pieces—like blankets—tend to 'engulf' small pieces of clothing". I told him that I had observed the same at home, so it might be a "universal" phenomenon. I suspected that it could be related with the *clustering* in granular materials when they are in a state of strong agitation and relatively small concentration (then called *granular gases*): a small number of particles collide, so they lose a part of their kinetic energy as heat. As a consequence, their average speed is decreased and they stay together. Then, other

[1] Notice that the work described in the previous chapter on laterally shaken granular matter was performed years after my visit to Navarra.

particles collide with them, also losing kinetic energy and joining the initial seed… After many cycles like that, the granular gas shows *clusters* of low-energy grains in a sea of very high-energy grains—eventually a single cluster may emerge, comprising all particles. My guess was that the socks and other small pieces of clothing would behave as granular particles agitated by the washing machine. Eventually, they would form a granular cluster… that could be "stabilized" inside a big piece of clothing, like a blanket. Actually, the blanket would be like a "nucleating spot" for clustering since the particles trapped inside would rapidly lose kinetic energy hitting the massive blanket. That effect—I fantasized—could be interesting perhaps in biotechnology: I jokingly called it "the granular vesicle". Now, I had the opportunity to check the hypothesis through a controlled experiment where the washing machine was replaced by a vibrator, small plastic disks would play the role of socks and other small pieces of clothing, and the role of the blanket would be played by… a plastic washer with an opened section (Fig. 6.1).

Later I learned that the idea could be taken as a two-dimensional version of the "Granular Maxwell Demon" published by H.J. Schlichting and V. Nordmeier in a paper written in German in 1996, and then modeled theoretically by

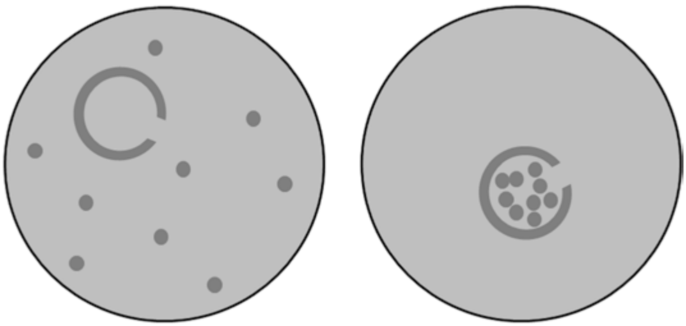


**Fig. 6.1** The *granular vesicle*: a failed experiment. A circular platform is vibrated vertically (i.e., perpendicularly to the plane of the paper). A number of disk-like grains rest on the vibrating plate, as well as a washer with an "open door". Both the grains and the washer have an intentionally uneven bottom surface, so the vertical vibration of the platform produces (hopefully) random motion on its surface (i.e., in the plane of the paper). *Left* Initial configuration of the grains and washer. *Right* After some time, the grains are supposed to be "engulfed" by the washer. It never worked: we were unable to tune the experimental parameters in such a way that the flux of grains getting into the vesicle was greater than the flux getting out

J. Eggers in 1999.[2] In their experiment, a box of "diluted" granular matter with a vibrating bottom was separated into two equal compartments by a vertical wall with a thin horizontal slit that allowed grains to pass from either compartment to the other. If the shaking energy was very high, the two compartments would exhibit the same granular density. But *if the vibrational excitation was properly tuned*, a symmetry breaking would occur: one of the compartments would "trap" a larger amount of grains, as a result of their preferential passage from the other compartment through the slit.

However, my two-dimensional version of the granular Maxwell demon did not work: for the short times and within the range of shaking energies I used for the experiment—there was a stringent deadline!—I never observed a hint of engulfing behavior: grains entered the washer with approximately the same probability as they escaped, so no trapping would occur. Perhaps due to the low dimensionality of my experiment, the energy input from the bottom was too great if compared with the energy loss due to inter-particle collisions and the collisions between them and the walls of the washer.

## 6.2 While Biding My Time: The Birth of the Vibrot

From time to time my Spanish colleagues would visit me down in the lab to see what was going on, give suggestions and explaining the details of equipment I was not used to—among them, postdoc Martín Pastor, the embodiment of kindness. After a few days of unsuccessful attempts, one afternoon Diego was trying to modify the grains (or the washer?) in the granular vesicle experiments, and I was waiting for my turn to get to the experimental setup. While biding my time, I decided to apply the knowledge rapidly acquired after many attempts to make the grains move laterally with the help of vertical vibration. There was a Coca Cola bottle and a rubber broom to sweep the lab floor. I just removed three rubber hairs from the broom, cut one end of each of them at approximately 45° relative to their main axis, removed the cap from the Coca Cola bottle, and glued the three legs onto it, as shown in Fig. 6.2. After a few minutes for the glue to dry, I interrupted Diego in pure Cuban: "¿Me das un chance para hacer una pruebita ahí, por

[2] An extension of the three-dimensional granular Maxwell demon would be studied by D. van del Meer and others at the University of Twente (Netherlands) within the next few years.

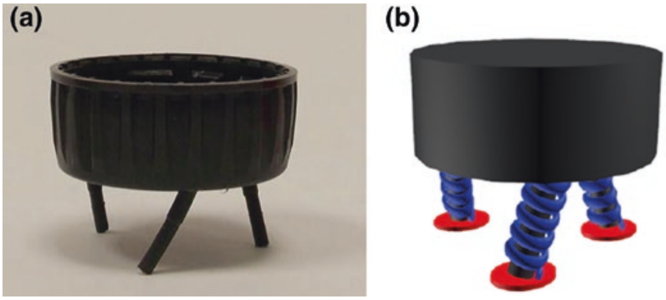



**Fig. 6.2** *The first vibrot: reality* versus *model*. **a** A Coca Cola cap with three rubber legs is able to rotate around a vertical axis when submitted to vertical vibrations. **b** A simple model of a vibrot where the legs are replaced by springs

favor?"[3] Then, I just dropped the device onto the surface of the vibrator: magically, smoothly, it started to rotate around an axis perpendicular to the vibrating surface.

We looked at each other in silence, and understood that something new had come to life—perhaps not relevant to the fields of science and technology… but quite possibly to the toy industry. Since it rotated due to the input of vibrational energy, I called it *vibrot*.

I thought it would have been fun to put together a "granular gas" of vibrots and compare it with two-dimensional, "conventional" granular gases, but we were too short of time. So, the following week would be devoted to characterizing the motion of the device, and, hopefully, the last couple of weeks would serve to write a paper on it—which we did.

The first thing we observed was that there were three prerequisites for the device to convert vibrational energy into rotational: (a) the legs should break the axial symmetry of the *vibrot*, (b) there should be a non-negligible friction between the legs and the ground, and (c) there should be some elastic part in the *vibrot* (in our case, the rubber legs).

Using the fast camera, we were able to characterize the dependence of the rotation frequency and other parameters on the dimensionless (maximum) acceleration of the vibrating plate, defined as

$$\Gamma = a_{\mathrm{max}}/g = A(2\pi f_v)^2/g$$

where $A$ and $f_v$ are the amplitude and the frequency of vibration of the platform. Figure 6.3 shows how the rotation frequency of the vibrot depends on

[3] "Would you please give me a chance to make a little test over there, please?"

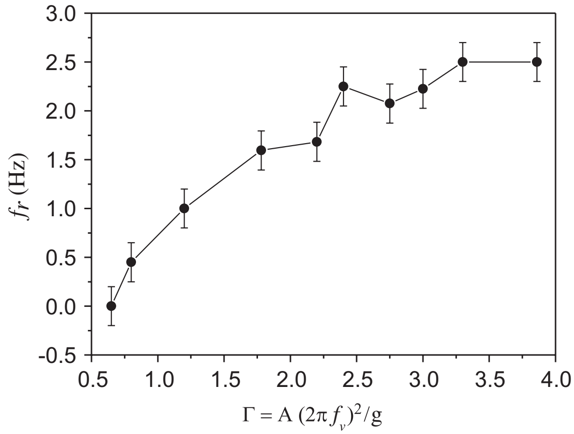



**Fig. 6.3** *Rotation frequency of the vibrot as a function of the vibration acceleration*. The frequency of rotation increases with the vibration until the device gets too unstable, and eventually tumbles over

$\Gamma$.[4] For small enough dimensionless accelerations, the device does not rotate: this is due to the fact that it needs a minimal "jump strength" to temporarily decrease the effective weight of the device[5] in such a way that the tangential friction is small enough for the legs to slide laterally across the horizontal surface… making the *vibrot* rotate. For the specific device corresponding to Fig. 6.3, the threshold dimensionless acceleration is approximately 0.6. As $\Gamma$ gets bigger, the rotation frequency increases, until it seems to saturate around 3.5 (the cause of the saturation is not trivial, since many phenomena are competing here, including the lack of stability of the device, which tumbles over all the time beyond $\Gamma \approx 4$). Interestingly enough, beyond $\Gamma = 1$ the device starts to detach from the surface during certain "flying periods", as represented in Fig. 6.4.

Of course, all those measurements could have been performed without using the fast camera. For example, the rotation frequency of the *vibrot* can be measured by counting the time $\Delta t$ needed to complete 10 full turns, and the angular frequency of rotation would be just $\omega_r = (10 \times 2\pi)/\Delta t$.

[4] Notice that $\Gamma = 1$ means that the maximum acceleration produced by the vibrating plate is equal to $g$. So, if a ball, for example, is put on the vibrator and subjected to $\Gamma > 1$, the object will detach from the surface during certain intervals within one cycle (we refer to this as "flying").

[5] This is analogous to the smaller weight we feel in an elevator that increases its speed (i.e., accelerates) as it goes down… something exploited in the lab-in-a-bucket project presented in Chap. 4.

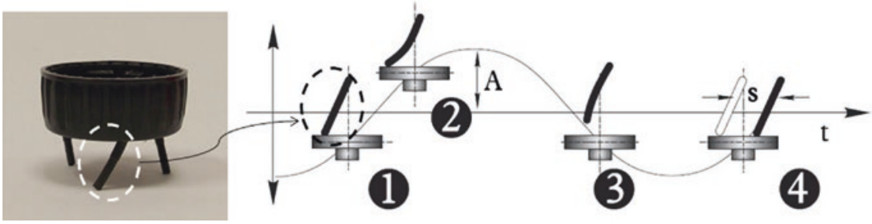



**Fig. 6.4** *How a single leg works*. In this cartoon we illustrate the motion of a vibrot leg within a cycle in which it moves laterally a length *s* (stride). *1* The platform starts to accelerate upward. *2* As the platform reaches the end of its upward movement, the leg has moved up and also bent, accumulating some elastic energy, part of which will be used to advance laterally to the right. *3* The platform has moved down, and the leg is "flying" after releasing part of its elastic energy. *4* As the platform returns to a position equivalent to (*1*), the leg has moved a total stride length *s*, to the right. The situation is the same for the other two legs, and this causes the rotation of the *vibrot*: the smaller the distance from the legs to the center of rotation, the bigger the resulting rotation frequency of the device. This mechanism may change for different experimental conditions: for example, if the *vibrot* is heavy enough, the "flying" stage illustrated in (*3*) is replaced by the leg sliding across the horizontal surface from left to right. Notice the similarity between the jumping mechanics of a single vibrot's leg and jumping mechanics of, say, a kangaroo… with the important difference that, in the latter, the body of the animal "vibrates" relative to the ground thanks to its biological energy

The functioning of a single vibrot can be fully understood in terms of classical mechanics, thanks to the talent of three undergrad students from the Higher Institute of Applied Science and Technology (Instec, Cuba) and the Physics Faculty, University of Havana. Danger Pérez-Adán, Victor Freixas, and Harol Torres arrived independently at the vibrot model illustrated in Fig. 6.2b: a massive body stands on three inclined legs formed by linear springs. The models were slightly different in the approach to the frictional interaction between the legs and the ground. When the three students teamed together, they successfully reproduced the vibrot's motion from two points of view: a purely Newtonian one, and the Lagrangian formulation of the model. The results were presented in a special session during the meeting *Complex Matter Physics: active matter, dynamics and patterns*, March*COM*eeting'15 (Havana, June 26–28, 2015).[6]

[6]Christian Scholz, a young German researcher who presented a very detailed computational simulation of the vibrot's motion using the finite-element method in the same meeting, right after the Cuban students, started his talk with "Well, you know, we Germans solve problems with a hammer". Of course, it was just a German joke about Germans: the "classic" Cuban approach and the "computational" German approach complemented each other perfectly.

**Flash anecdote**

Immediately after the design of the first *vibrot*, we needed to try new "models". So, I asked a few people in the department not to throw away the caps of Coca Cola bottles they got from the machine. News spread virally. As a result, within the next few days I found it hard to deal with the pile of Coca Cola caps left on my desk. I suspect that science catalyzed the consumption of the beverage quite a bit during those frantic days at the University of Navarra.

While vibrots may seem like a useless intellectual *divertimento*, our paper published in *Plos One* had the most unexpected consequences. For example, the Italian physicist Matteo Crivela was inspired by our vibrots to conceive "active sculptures": they were basically elegant pieces of bent metallic foils able to rotate on a vibrating surface (Fig. 6.5). As in our case, the rotation speed can be controlled by tuning the vibration of the plate. Also as in our case, key ingredients are needed to make these works of art rotate: a structure with broken symmetry, made from elastic materials. Another connection with the world of art, but in a more *detectivesque* fashion, is the explanation Ángel Garcimartín has proposed to solve the mystery of a revolving statue at the Manchester Museum. The Egyptian statute—dedicated to the godess Osiris—was reported in 2013 to move slowly round by as much as 180° during daytime, in spite of the fact that it was inside a transparent cage. In competition with all kinds of mystical explanations, Ángel just proposed that the statue behaved like a vibrot in response to the vibrations produced by the hundreds of visitors as they walked into the museum during the day.

**Fig. 6.5** *One of Mateo Crivella's vibrot-inspired sculptures* (*Photo* Courtesy of Matteo Crivella)

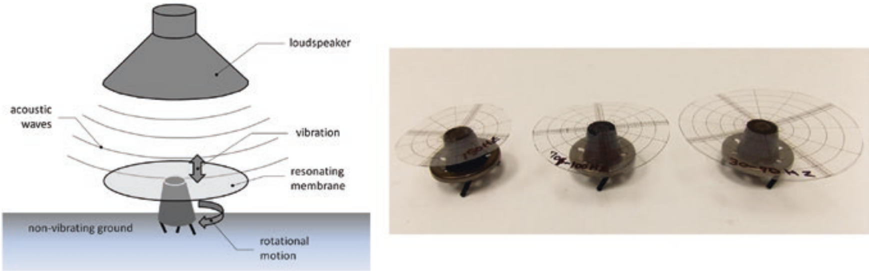



**Fig. 6.6** *Acoustically excited vibrots. Left panel* Working principle. *Right panel* Real vibrots able to rotate when "fed" by acoustic signals of approximately 150, 70–100, and 30–70 Hz from *left* to *right*, respectively

In any case, I felt that the "device-on-a-vibrating-plate" version of the vibrot was nice, but "too demanding" in terms of mechanical activation: there should be a way to inject vibrational energy without directly touching the device. It was logical to think that one could vibrate the "body" of the vibrot instead of the ground by sending acoustic energy from the outside, thus making it rotate on a non-vibrating surface. This was achieved by "disguising" the vibrots with "Mexican hats": a circular piece of overhead projector film was fixed horizontally onto the "head" of the vibrot, in such a way that it would resonate with acoustic waves sent by a loudspeaker. As a result, the entire vibrot would vibrate vertically relative to the fixed horizontal surface. Then, the rotation mechanism would be activated. The overall idea is shown in the left panel of Fig. 6.6. Moreover, by cutting "Mexican hats" of different diameters it would be possible to change their resonance frequency, whence vibrots wearing different-sized hats would be activated at different acoustic frequencies, or in different frequency intervals. The right panel of Fig. 6.6 shows the actual realization of those ideas. Notice, by the way, that this idea frees the vibrot from an expensive vibrating platform, shifting it closer to the "guerrilla-science" style.

## 6.3 And Now What?

Acoustically excited vibrots may, of course, open the way to applications beyond the toy scenario. For example, one may ask whether miniature, acoustically-driven vibrots can be designed to swim into fluids like bacteria. *E. coli*, for example, is a bacterium comprising a 2-µm "massive" head and 10-µm long, screw-like flagella able to rotate in such a way that it "pushes forward" the body of the swimmer. One can imagine that an *E. coli* inspired micro-vibrot could navigate inside the human body—and even drill into blood clogs or tumors—by guiding them and feeding energy to them using an external ultrasound source that makes them vibrate, then navigate, while rotating.[7] Ultrasound seems a natural way to drive such swimmers, especially at frequencies in the MHz range, where sound waves produce minimal deleterious effects on biological systems: in fact, ultrasonography is a well developed and widely used medical tool. After all, ultrasound is used nowadays to "explode" micro-droplets containing a "drug cargo" when they have reached an appropriate target inside the human body—for example, a tumor. Why not use the same energy source to manipulate a tiny vibrot?

On September 15, 2013, I gave a seminar at the Center for Multi-scale Simulations (University of Erlangen-Nuremberg, Germany), thanks to the kind invitation of its director, Thorsten Pöschel. I had the opportunity to have a tour of their facilities—including a number of nice experimental setups, which finished with a group meeting. Thorsten immediately went to the point: "Ernesto, we would like to hear about new ideas". I was caught completely off-guard, but I guess I had some training in the matter during my recent visit to the University of Navarra. In any case, it was challenging to discuss ideas about granular matter before one of the top specialists on the subject. I do not remember exactly what proposals I made, but Thorsten showed interest in the "granular vesicle" I had tried unsuccessfully at the University of Navarra. I also mentioned the idea for experimental study of a "rotational granular gas" (or more generally, "rotational granular ensemble" RGE) using vibrots as granular particles (i.e., the grains would dissipatively exchange angular rather than linear momentum, as in the case of a "conventional" granular gas). Two years later, Thorsten invited me back to Germany: this time I would speak at a quite peculiar meeting: "Granular matter in low gravity" (Erlangen, March 25–27, 2015). I was immediately surprised by a beautiful poster presented by Christian Scholz and Thorsten himself, describing some preliminary results on an ensemble of interacting vibrots! They had taken up my suggestion to work on rotational granular gases seriously. As illustrated in Fig. 6.7(*left*), Christian had designed a kind of vibrot that could be mass-produced by 3D printing: *guerrilla physics had turned into conventional war!*[8] Actually, to the design illustrated in Fig. 6.7(*left*) they had added four radial protuberances sticking out from the circular "head" of

[7] Metallic micro-rods a few microns long have been driven at speeds of approximately 200 microns/s along the axial direction, using ultrasound waves in the MHz range. The motion, caused by the asymmetry along the axis of the rod, does not involve rotation around its axis.

[8] Christian's mass production of vibrots may well have saved numerous scientists from overweight due to possible over-exposure to soft-drink overdoses in the name of science.

each vibrot ("ears"), in such a way that it could interact with another vibrot, if it was near enough. Then, the authors had dropped a few dozen such vibrots onto a vibrating plate, as illustrated in Fig. 6.7(*right*). In addition, they put together a homogeneous mixture of "dextrogirous" and "levogirous" vibrots to look at their interaction: preliminary results suggested clustering of the two kinds (this result looks counter-intuitive, since the same kind of vibrots should get jammed, while a "perfect solution" of the two kinds of vibrots should rotate easily).

**Flash anecdote**

During the meeting *Complex Matter Physics: active matter, dynamics and patterns* (Havana, June 26–28, 2015), Christian Scholz presented the nice work he had started in the field of interacting vibrots in Thorsten Pöschel's group (University of Erlangen-Nuremberg, Germany). At the end of the meeting, Christian made one of the least expected requests coming from a person visiting Cuba for the first time: *is there any heavy-metal concert I could go to before I leave*? As the local organizer of the meeting, it was a really tough challenge. I passed it to my undergrad student Alfredo Reyes, who did a splendid job: Christian was delighted to attend a concert of the local band "Zeus" just the night before leaving.

These days, vibrot-related experiments are getting more and more fun at the Center for Multi-scale simulations: under the supervision of Thorsten Pöschel, my ex-student Harol Torres is performing beautiful experiments in which an ensemble of 3D printed vibrots "try to escape" from one room to another through a constriction.

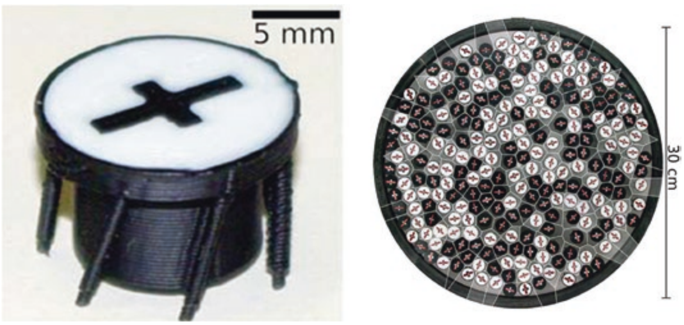



**Fig. 6.7** *A flock of vibrots.* Christian Scholz and Thorsten Pöschel 3D-printed vibrots like the one shown in the *left panel*: as in the case of the original (Cola-cola-cap) vibrots, they can be "levogirous" or "dextrogirous", depending on the direction of inclination of the legs. In the *right panel*, a mix of interacting dextrogirous and levogirous vibrots tend to segregate when vibrated on a circular plate

## Bibliography

E. Altshuler, J. Martín-Pastor, A. Garcimartín, I. Zuriguel and D. Maza. *Vibrot, a Simple Device for the Conversion of Vibration into Rotation Mediated by Friction: Preliminary Evaluation. PLOS ONE* **8**, e67838 (2013)

Alexander, R. M., 2006, *Principles of animal locomotion* (Princeton University Press).

I. Goldhirsch and G. Zanetti. *Clustering instability in dissipative gasses.* Physical Review Letters **70**, 1619 (1993)

J. Eggers, *Sand as Maxwell's daemon*, Physical Review Letters **83**, 5322 (1999)

K. van der Weele, D. van der Meer, M. Versluis and D. Lohse, *Hysteretic clustering in a granular gas,* Europhysics Letters, **53**, 328 (2001)

A.J. Liu and S. R. Nagel, *Nonlinear dynamics—Jamming is not just cool any more,* Nature **396**, 21 (1998).

D. van del Meer, K. van del Weele, abd D. Lohse, *Sudden collapse of a granular cluster*, Physical Review Letters **88**, 174302 (2002)

W. Wang, L. A. Castro, M. Hoyos and T. E. Mallouk, *Autonomous motion of metallic microrods propelled by ultrasound*, ACS nano **6**, 6122 (2012)

Ch. Scholz and T. Pöschel *Actively rotating granular particles manufactured by rapid prototyping,* Revista Cubana de Física **33**, 37 (2016)

Torres, H., Freixas, V. M. and Pérez-Adán, D., *The Newtonian mechanics of a vibrot*. Revista Cubana de Física, **33**, 39 (2016)

### All videos in

http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0067838#s5

### Matteao Civela

http://www.matteocrivella.com/-resonating-rotation-of-a-rigid-body/

### Blog at Investigación y Ciencia, by Garcimartín

http://www.investigacionyciencia.es/blogs/fisica-y-quimica/9/posts/vibrots-11171

# 7
# Should We Be a Little Afraid to Urinate?

*Whatever a scientist is doing—reading, cooking, talking, playing—*
*science thoughts are always there at the edge of the mind.*
*They are the way the world is taken in;*
*all that is seen is filtered through an ever present scientific musing.*

Vivian Gornick
in “Women in science—then and now” (The Feminist Press at the city of New York, 2009)

Some readers might have the impression that the title of the previous chapter is not completely appropriate for a book on “guerrilla science”. In this chapter, I’ll do my best to please the purists by presenting a scientific challenge not associated with Coca Cola caps, but rather to a typical South American drink: *mate*.

Mate, however, is an absolute alien in Cuba where coffee—and, of course, rum—tend to dominate the folkloric beverage scene. But once in a while mate also shows up in Cuba. In September 2005, Sebastián Bianchini—an Argentinian from Bariloche—began his studies at the Physics Faculty, University of Havana, thanks to an agreement between Argentina and Cuba. The first stuff he put in his luggage was, of course, his mate-sipping gear: a calabash gourd (sometimes called *el mate*) that contains the infusion, the metallic straw used to sip it (*la bombilla*), and, of course, the mate leaves—caffeine-rich dried leaves of the herb *Ilex paraguariensis*. The mate preparation



E. Altshuler, *Guerrilla Science,* DOI 10.1007/978-3-319-51624-0_7

procedure used by Sebastián was quite simple: you put a fistful of mate leaves inside the gourd, and pour hot water into it from a second container—a pitcher, for example. Then, you sip the resulting mixture using the metal straw.[1] At some point during 2008, Sebastián noticed a curious phenomenon: when pouring the hot water into the mate-filled gourd from a pitcher, as the level of the liquid of the lower container increased, there was a moment when a few mate leaves suddenly "climbed" up the falling stream of water, finding their way into the pitcher. He observed the phenomenon very closely, making sure that the upper container was not touching the surface of the lower one: there was actually an "anti-natural" motion of mate leaves up the stream of falling water. It was really amazing that the leaves could move up against gravity, and also against the drag associated with the falling water stream. Perhaps the matter had been profusely reported in the literature… but Sebastián did not know, and did not care: a good scientist always has an "inner child" on duty guard.

**Flash anecdote**

From February 28 to March 13, 2006, we celebrated the *First Latin American School on Statistical Physics and its Interdisciplinary Applications,* supported by the "Abdus Salam" ICTP—with Roberto Mulet as the main local organizer. Most activities took place at the main theatre of the Physics building (University of Havana), near the inner patio. Since the columns in the fourth floor were in bad shape, we were afraid that some fragments could fall in the patio, so we had to convince the participants to avoid passing by that area. I came up with a solution: I set up a "crime scene" on the floor of the patio: I scotch-taped the silhouette of a human body, and deployed a pair of broken eyeglasses nearby, conveniently sprinkled with tomato sauce. I assumed that the set up would transmit the "don't trespass" idea in a humoristic way. My surprise was great when many took it seriously on the first day of the workshop. It turned out to be a macabre, but very effective initiative. No one dared to step on the patio during the whole activity.

[1] Sometimes the beverage is so hot that it is really hard to hold the typically nickel-silver straw with your lips. I believe that Argentinians are genetically modified to develop Teflon-coated lips.


Soon afterwards, Sebastián told his curious observation to our young professor Alejandro Lage, who in turn, told Professor Roberto Mulet—my former student. As it was a very unusual phenomenon, Roberto asked me to get involved. At the time, I was very skeptical of the scientific novelty of Sebastián's observations: how could such a visible phenomenon, potentially important for contamination of water networks, not have been perfectly well known since ancient times? I also felt a bit wary of my ability to contribute, due to my limited experience in the field of fluid dynamics, one of the most "worked-out" areas of classical physics. In any case, Sebastián and Alejandro enthusiastically built their first experimental setup for the controlled measurement of this upstream contamination at the Biomaterials Lab, University of Havana, although it was soon moved to the Zeolite Engineering Lab (IMRE, University of Havana) after negotiating a spot on one of the tables with my wife, Aramis Rivera.[2] Their setup was very ingenious: water flowed continually from an upper container to a lower container through a slightly inclined channel, in such a way that the water would drop no more than 1 cm from the end of the channel to the surface of the water in the lower container. Figure 7.1 shows the "alchemy-like" configuration designed by Alejandro and Sebastián to guarantee that the water levels in both containers were constant throughout the experiment. Either mate leaves or chalk dust was added to the lower container while the water was flowing, and the upstream migration of mate or chalk particles from the lower container to the channel was filmed from above, using a camera facing downwards. They immediately discovered, among other things, that temperature differences between the upper and the lower containers played no essential role in the phenomenon. Figure 7.2(a) shows in more detail the disposition of the containers.

[2] The original idea had been to set it up in my lab, but we have always had a shortage of water in the afternoons (another aspect of what I sometimes call "science in high tropicality conditions")… and this experiment needed lots of water.

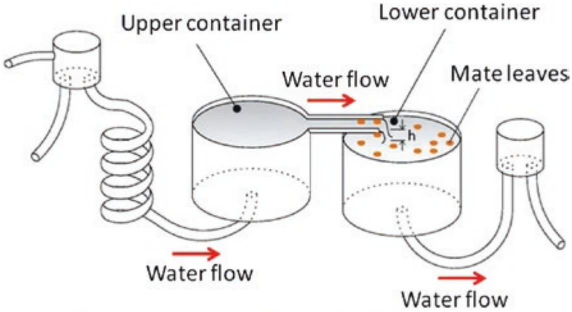



**Fig. 7.1** When Physics looks like Alchemy. *Upper panel* Sketch of the measuring system designed and constructed by Sebastián Bianchini and Alejandro Lage for the measurement of the upstream contamination effect. *Lower panel* Actual experimental setup at the Zeolites Engineering Lab, IMRE, University of Havana. The *lower* and *upper* containers would play the role of the calabash gourd and jar for pouring water during mater preparation, respectively. Tubing, jars, and other elements were purchased from street vendors in Havana

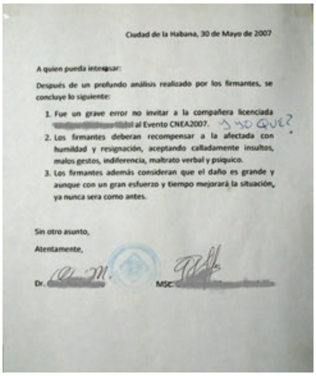
### Flash anecdote

In 2007, a student doing her M.Sc. degree in the lab felt bad about a decision taken by her thesis supervisors. To apologize, they posted on the lab wall the "official" letter photographed near this frame, which can be translated into English as follows:
*To whom it may concern*:
*After deep analysis by the undersigned, we have concluded the following*:

1. *It was a grave mistake not to have invited comrade Lic. Marissa Meleros Vitral to the event CNEA 2007.*
2. *The undersigned shall compensate the offended party with humility and resignation, quietly accepting insult, indifference, and verbal and psychological mistreatment.*
3. *In addition, the undersigned understand that the damage has been great. So, even if considerable effort and time may improve the situation, things will never be as they used to be.*

*With no further subjects to discuss,*
*attentively,*

*Signatures and official stamp*


Ciudad de la Habana, 30 de Mayo de 2007

A quien pueda interesar:

Después de un profundo análisis realizado por los firmantes, se concluye lo siguiente:

1. Fue un grave error no invitar a la compañera licenciada [redacted] al Evento CNEA2007. ¿Y YO QUE?
2. Los firmantes deberan recompensar a la afectada con humildad y resignación, aceptando calladamente insultos, malos gestos, indiferencia, maltrato verbal y psiquico.
3. Los firmantes además consideran que el daño es grande y aunque con un gran esfuerzo y tiempo mejorará la situación, ya nunca sera como antes.

Sin otro asunto,

Atentamente,

Dr. [redacted] MSc. [redacted]

Meanwhile, I was searching in the literature for a description of the phenomenon—it looked just impossible that such an evident effect could have gone unnoticed by natural philosophers for eons!—but the fact is that I found nothing. By the end of 2008, on one of my trips to Eric Clément's group at the ESPCI in Paris, I showed some of Sebastian and Alejandro's videos to a number of fluid dynamics experts, such as José Eduardo Wesfreid and David Quèrè. They had never seen the phenomenon before—but David suggested that I take a look at certain sections of his book "Capillarity and wetting phenomena: drops, bubbles, pearls, waves" (2004). I clearly remember when on 8 December I came across the so-called *Marangoni effect* in the book, and felt it could be a good candidate to explain the upstream contamination phenomenon! The Marangoni effect basically establishes that, if there is an interface between two fluids, and there is a difference in the surface tensions[3] across the interface, a force will develop perpendicular to the interface, pointing from the zone of lower surface tension to that of higher surface tension. If one assumed that somehow the addition of mate or chalk particles would decrease the surface tension at the surface of the lower container as compared to the non-contaminated water in the upper container, a Marangoni force would develop in the upstream direction that could "pull up" the contaminating particles. It was hard to believe that it could win over gravity and the drag of the downstream flow… but Marangoni looked like the best candidate for a plausible explanation. Although Alejandro and Sebastián had speculated that the surface tension could play some kind of role before, I was now sure that we needed to measure it.

[3]The surface tension is the result of the attractive force between the molecules at the interface of a fluid. Free falling liquid drops, for example, have a spherical shape due to the effect of the surface tension: the energy associated with it tends to minimize, which is equivalent to minimizing the total surface of the drop. And, for a given volume of liquid in the drop, the spherical shape guarantees the required minimal free surface.

Back in Cuba, I discovered that there was an apparatus for the measurement of surface tension in liquids boxed in one of the teaching labs, and I arranged for Sebastián to use it. His excitement after the first measurements is clear in the following e-mail dated March 26, 2009:

> Hi, Altshuler! I am writing to update you about the experiment. Yesterday—Thursday—I was in the biology building performing surface tension measurements on distilled water to which I added different amounts of mate leaves. The results I found, in spite of errors and difficulties, have surprised me very, very much. The MATE rapidly and brutally decreases the surface tension of water. So I decided to repeat the experiments this morning (from 7:00 AM in the biology lab). The results are surprising: although I have not yet estimated the errors, I am sure this will be of great use.[4]

Following his excitement, Sebastián decided to "officially" re-orient his diploma subject when he began his final year of undergrad studies in September, 2009. He quit his previous research in sensors and electronic instrumentation, and devoted himself fully to the upstream contamination phenomenon—Alejandro and myself would be his scientific advisors. In order to cross-check the Marangoni hypothesis, I suggested Sebastián to look at the effect of adding a surfactant[5] to the upper and the lower containers. My wife—who worked on the incorporation of medical drugs on porous materials and sometimes used surfactants—provided Sebastián with benzalkonium chloride. The results were quite convincing: if the upstream contamination had not started and the surfactant was added to the lower container, particles would rapidly climb up the stream. If the upstream contamination had started and the surfactant was added to the upper container, the contamination would immediately stop.

With the threat of a thesis deadline in mind, I started to write down a "Newtonian" model to explain the upstream contamination, where the Marangoni force acting on the contaminant particles would match the gravitational force and the Stokes-like drag of the flowing water from the upper to the lower container, resulting in particles moving upstream at constant speed. The model really improved in the hands of Alejandro—a gifted

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[4] Hola Altshuler! Te escribo para contarte como ha seguido el experimento. Ayer jueves estuve por la tarde en Biología haciendo mediciones de la tensión superficial de agua destilada añadiendo distintas cantidades de yerba mate. Los resultados que encontré a pesar de mis errores y las dificultades me han sorprendido muchísimo, EL MATE disminuye rápida y bestialmente la TS del agua. Por lo que decidí repetir el experimento hoy por la mañana (desde las 07:00 en Biología). Los resultados son sorprendentes: aunque aún no hice el cálculo de errores, estoy seguro que esto nos es de mucha utilidad.

[5] When added to a liquid, surfactants decrease their surface tension. Detergents are good examples of everyday surfactants.

mathematical mind—and was implemented computationally by Sebastián. It did indeed serve to explain some of the observed data reported in Sebastian's diploma thesis, like the advance of the contaminating front upstream inside the channel as time went by. Indeed, Sebastián's thesis was successfully defended on July 2, 2010 at the Physics Faculty, University of Havana.

Then, our work on the subject slowed down quite a bit: upon finishing his undergrad studies with us, Sebastián started a degree in biomedical physics, and later went back to Argentina. Alejandro, on the other hand, was extremely busy with his own PhD thesis—dealing with "hard core" statistical physics—which he brilliantly defended in 2012.

I still fought for some time with energy-based models to explain the phenomenon, but I did not trust my apparently wild estimates of the upstream forces experienced by the particles. After asking Sebastián and Alejandro for approval, I wrote a "minimalistic" paper on the matter and posted it in ArXiV on May 12, 2011—which, by the way, immediately got a nice review by MIT's Technology Review. Then, the subject got frozen.

The next chapter opened up in a quite unexpected way. Right after the end of the 2012 March Meeting of the American Physical Society, we organized in Havana a Workshop on Complex Matter Physics which we called, for short, March*COM*eeting (A meeting on Complexity celebrated in March!). Nearly a hundred scientists from Europe, Latin America, and the US attended—Leo P. Kadanoff gave the opening lecture. Both Prof. Jon Otto Fossum (Norway) and myself as main organizers agreed to give a lot of room to young speakers. The meeting embraced a wide range of topics in the physics of complex systems, typically connected with concrete physical, geophysical, and biological scenarios. I cannot say that the talk entitled "Characterizing and Improving Generalized Belief Propagation Algorithms on 2D Edwards-Anderson Model" by Alejandro Lage fitted particularly well in the context of the meeting. In fact, after a few days sensing the environment, Alejandro himself asked me if it would perhaps be better to give a talk on a little more easy-to-swallow subject like "Upstream contamination in water pouring", and this I enthusiastically accepted. The reaction of the audience was even more enthusiastic (I perfectly well remember looking round during Alejandro's talk and finding a smiling Heinrich Jaeger, University of Chicago, greeting us with his thumb up) (Fig. 7.3).

It was another participant, Troy Shinbrot (Rutgers University) who, in a completely unselfish gesture, offered to replicate our experiments. I really wanted to have a second—and in this case, definitively authorized—point of view, and suggested that we jointly publish a paper in the future. I felt that we could learn a great deal from his experimental, theoretical, and paper writing abilities. And that was indeed the case.

He recruited his Ph.D. student Theodore Siu, who would rapidly reproduce our main results at Troy's lab. It was such a relief! Better quality images and clever image processing was crucial to improve the characterization and understanding of our phenomenon—some of the results are displayed in Fig. 7.2. We conceived of a chalk particle at the interface between two seas: if a particle is

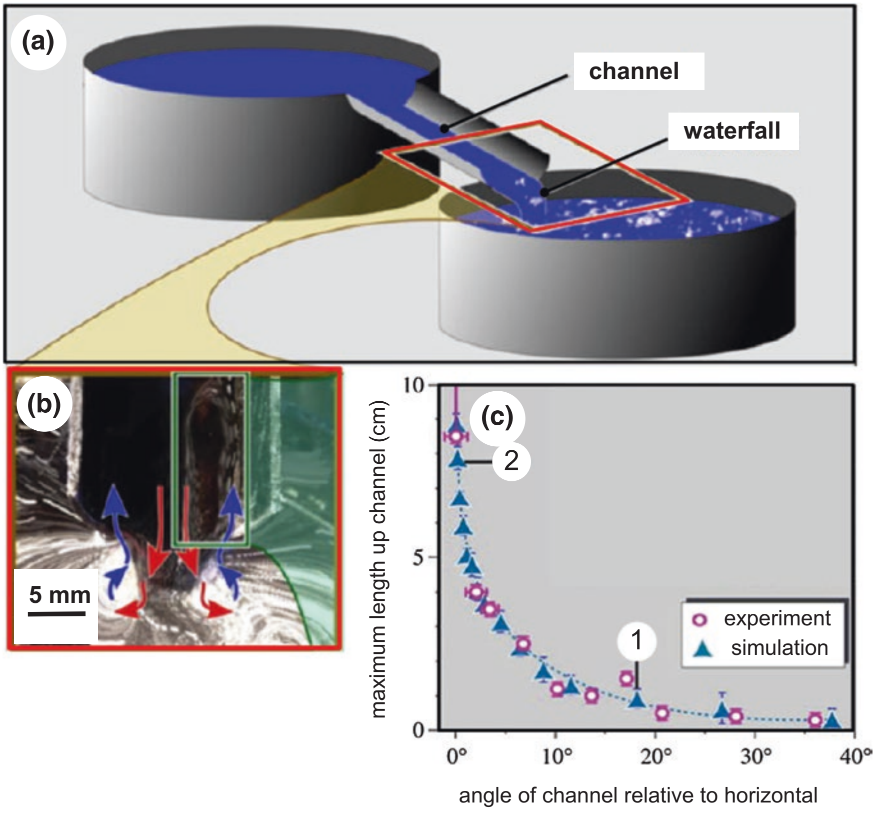



**Fig. 7.2** Upstream contamination by floating particles. **a** Sketch showing the basic idea of the experiment: a stream of clean water flows down a channel from an *upper* container to a *lower* one which is contaminated with mate (or chalk) particles. Eventually, particles climb upstream, invading the channel. **b** Superposition of images showing the traces of the particles moving upstream near the edges of the channel (*blue arrows*) and returning downstream near the center of the channel (*red arrows*). Notice that particles coming from the *lower* container describe vortices inside the channel—a trace of a vortex is located inside a *green box*. **c** Dependence of the maximum length contaminant particles penetrate into the channel as a function of its angle of inclination relative to the horizontal. Interestingly, particles can invade the channel as far as 10 cm for shallow inclinations. The data resulting in **b** and **c** was produced by Theodore Siu and Troy Shinbrot at Rutgers University (USA)

floating on the surface of the lower container, it is exposed to the pure water from the waterfall on one side, and to a more or less fixed concentration of solids on the opposite side, resulting in a difference in the surface tension across the particle—a version of the Marangoni effect. From our surface tension measurements, such a difference would be of the order of 0.01 N/m (newtons per meter of interface perpendicular to the force). If we multiply this by the typical diameter of a particle—say, 200 microns—we get an estimate of the total force on the particle propelling it upstream to be of the order of 2 μN. Following Newton's second law, this force divided by the mass of a typical particle gives its acceleration upstream. If we do the math with the mass of an actual chalk particle (of the order of 0.01 mg), we get an acceleration of 200 m/s$^2$ … around 20 times the acceleration of gravity! Even when this is an *upper estimate*, it illustrates that the upstream motion is indeed a quantitative possibility. With these ideas in mind, Troy himself made a computer model for the upstream contamination which was able to reproduce the experimental observations with great accuracy. For example, Fig. 7.2c illustrates how the model (triangles) is able to reproduce the experimental data describing the maximum length particles climb up inside the channel as a function of the inclination of the channel relative to the horizontal.


**Fig. 7.3** When disorder propels science. Instead of his original talk "Characterizing and Improving Generalized Belief Propagation Algorithms on 2D Edwards-Anderson Model "—as officially scheduled for MarchCOMeeting'12 (La Habana, March 2012)—Alejandro Lage (*left*) decided to change the subject slightly to "Upstream contamination in water pouring". The audience got quite interested

Moreover, Theo and Troy demonstrated experimentally that a pipette like the ones commonly used in chemistry labs can get contaminated if it is discharged onto the surface of a liquid contaminated with fluorescein particles, even without touching the surface: the particles actually travel upstream and find their way into the pipette!

Even today, a few years after the publication of our definitive paper on the subject, I feel a bit nervous when I get into a public toilet, and I'm forced to use tall urinals.


## Bibliography

Bianchini, S. Lage-Castellanos, A. and Altshuler, E., *Upstream contamination in water pouring* arXiv:1105.2585v1 [physics.flu-dyn] 12 May 2011

Bianchini, S. Lage, A., Siu, T., Shinbrot, T. and Altshuler, E., *Upstream contamination by floating particles,* Proceedings of the Royal Society A **469**, 20130067 (2013)

de Gennes, P.-G., Brochard-Wyart, F. and Quèrè, D., *Capillarity and wetting phenomena: drops, bubbles, pearls, waves,* Springer, 2004

Kavanau, J. Lee, *Countercurrent streaming in liquid surfaces and its relevance to protoplasmatic movements,* Science **136**, 652 (1962)

K.F.C., *Contaminants can flow up waterfalls, say physicists* (MIT Technology Review, 17 May 2011) (http://ad.doubleclick.net/click%3Bh%3Dv8/3b0a/3/0/%2a/c%3B240268131%3B0-0%3B1%3B12113661%3B3454-728/90%3B41834693/41852480/1%3B%3B~sscs%3D%3fhttps://market.android.com/details?id=edu.mit.technologyreview)

## Wikipedia Links

https://en.wikipedia.org/wiki/Upstream_contamination
https://en.wikipedia.org/wiki/Mate_(beverage)

# 8
# Smarter Than Bibijaguas

*What can we learn of moral value from the ants?*
*Nothing. Nothing at all can be learned from ants*
*that our species should even consider imitating.*

Edward O. Wilson
in "The Meaning of Human Existence" (Liveright Publishing, 2014)

Right in the middle of Cuba, the village of Trinidad hangs in time.

Being the 3rd town founded by the Spanish settlers in 1514 as Villa de la Santísima Trinidad, it became the *Mecca* of the Cuban "sacarocracy" between the XVII and XIX centuries: the fertile lands of the *Valle de los Ingenios* (Valley of the Sugar Cane Mills) brought a flourishing sugar economy to the area. However, with the decline of slavery and the emergency of the nearby city of Cienfuegos, the economic splendor of Trinidad had faded away by the second half of the XIX century. The construction of the Carretera Central (Central Highway) in the 1950s ignored the city and permanently locked Trinidad into the time capsule that now makes it such a charming and mysterious place.

It was in Cabagán, near Trinidad, that my mother's father earned a living by preparing breakfast for people working in the coffee plantations—he also owned some cows, presumably to guarantee the classic coffee-and-milk Cuban breakfast. He had arrived from Asturias (Spain) at the end of the XX century along with the tens of thousands of countrymen that travelled to Cuba in that period to establish themselves in the new land. He met my grandmother—also with an Asturian background—in Cuba, and went back



E. Altshuler, *Guerrilla Science,* DOI 10.1007/978-3-319-51624-0_8

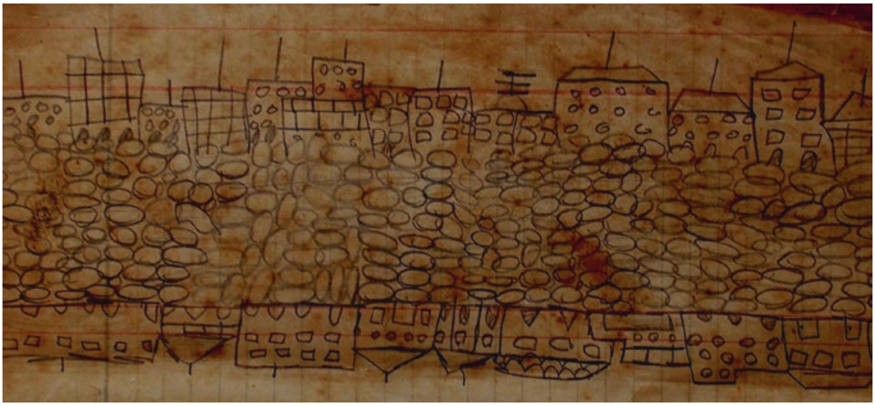


**Fig. 8.1** A naïve vision of a cobbled street. During my summer in Trinidad circa 1970 I filled a notebook with my typical drawings of the time: spaceships, complicated mechanisms that probably wouldn't work… However, the first page was decorated with an uncommon picture: a naïve version of Trinidad's *Callejón de Chinchiquirá*

to Spain just to get married in 1907. They raised a family in the Trinidad area during the following years.

Most of them, however, moved to Havana in the 1950s, with the exception of my mother's cousin, who lived in a small house in Trinidad until the 1970s. When I was a kid, I spent a couple of summers at her place, located on the *Callejón de Chinchiquirá.*[1] Some things I encountered during that period are now carved deep into my mind: the narrow cobbled streets; sleeping under a mosquito net; the charming smell of the food hawked by street vendors; a big dog that used to live in the house across the street, which I was able to stroke through the wooden *postigos*… and my observations of ants (Fig. 8.1).

Every morning I'd put some pieces of bread in the middle of the living room, and in a few hours a ten-foot-long file of tiny ants would carry the piece of bread—particle by particle—to a nest hidden someplace inside the wall. How did the first ant find the bread? How did she tell her partners to come and help her bring the food home? How was such a well organized foraging file established out of apparent chaos? It was truly marvellous, and I remember constructing a tall cardboard house around the piece of bread so that the foraging ants would have to go in and out all the time. The cardboard

[1] Or Alley of Chinchiquirá, but also called *Callejón del Coco* (Alley of the Coconut), and finally renamed as Francisco Pedersen street by the 1960s.

construction in the middle of the living room looked like the bell house sitting in the middle of the Valley of the Sugar Mills… Forty years later, during a short visit to Trinidad, I asked the new owners to let me see the house. The living room turned out to be disappointingly tiny in reality. But that, of course, was just a transient experience: the image of my childhood will last forever.

Of course, most kids—or more generally, human beings—have an "ant period" in their lives. The phenomenon seems to be quite universal, regardless of place and time. The Cuban national hero José Martí—a great writer, poet, journalist, and politician—wrote a letter to his daughter on April 9, 1895, shortly before being killed in his first battle against the Spanish colonial army in the Cuban fields. He asks his daughter María Mantilla to organize a school for girls during the winter time, and suggested many things they could do, including this:

*You could teach piano and reading, and perhaps Spanish […] and a geography class, with more physical geography than names […] and a science class […]. For that class, a book by Arabella Buckley called "The Fairy-Land of Science" would help very much, and the books by John Lubbock, above all "Fruits, Flowers and Leaves", and "Ants, Bees and Wasps".*[2]

**Flash anecdote**

One of my favorite subjects in optics is the human eye. One day in March, 2015, I was discussing it as part of the course on Optics and Modern Physics I was teaching to a class of biochemistry students at the University of Havana. It was a very motivated group, and I made good use of the opportunity to explain how the eye is used as a paradigm to fight evolutionism by defenders of the ideas of "Intelligent Design". I did not mention the words "religion" or "God". However, during the 5-min break, one of the students (an excellent one, by the way) approached me saying that "my class had been disrespectful"—we engaged in a short discussion where her main point was that the theory of evolution had not enough evidence to be taken as a sure thing. As a professor at the University of Havana, I have seen a growing proportion of anti-evolutionist thinking in life-science students since 2010 or so.

[2]Tú podrías enseñar piano y lectura, y español tal vez […] y una clase de geografía, que fuese más geografía física que de nombres […] y una clase de ciencias […]. Para esa clase ayudarían mucho un libro de Arabella Buckley, que se llama "*The Fairy-Land of Science*", y los libros de John Lubbock, sobre todo dos, "*Fruits, Flowers and Leaves*" y "*Ants, Bees and Wasps*". (Taken from José Martí, "Carta a María Mantilla, 9 de abril de 1895". Obras completas, tomo 5, pag 145, Editorial Ciencias Sociales, La Habana, 1975).

In a paper published in Nature in 1881, Lubbock himself shows his interest in exactly the same questions I had asked myself as a kid in Trinidad. His clever experiments to find out how ants recruit other nestmates after finding a source of food, and his vivid, humorous prose describing the results are so engaging that I allow myself to cite him here *in extenso*:

*It is unquestionable that if an ant or a bee discovers a store of food her comrades soon flock to the treasures […]. But it may be argued that this fact taken alone does not prove any power of communication at all. An ant observing a friend bringing food home might infer, without being told, that by accompanying the friend on the return journey she might also participate in the good things. […] It also occurred to me that some light would be thrown on the question by compelling the ant who found the treasure to return empty handed. If she took nothing home and yet others returned with her, this must be by some communication having passed.*

*I selected […] a specimen of Atta testaceo-pilosa […]. She was out hunting about six feet from home, and I placed before her a large dead bluebottle fly, which she at once began to drag to the nest, I then pinned the fly to a piece of cork, in a small box, so that no ant could see the fly until she had climbed up the side of the box. The ant struggled, of course in vain, to move the fly. She pulled first in one direction and then in another, but, finding her effort fruitless, she at length started off back to the nest empty-handed […]. My ant entered the nest but did not remain there; in less than a minute she emerged accompanied by seven friends. I never saw so many come out of that nest together before. In her excitement the first ant soon distanced from her companions, who took the matter with much sang froid, and had all the appearance of having come out reluctantly, or as if they had been asleep and were only half awake. The first ant ran on ahead, going straight to the fly. The others followed slowly and with many meanderings; so slowly, indeed, that for twenty minutes the first ant was alone at the fly, trying in every way to move it. Finding this still impossible, she again returned to the nest […]. Again she emerged in less than a minute with eight friends, and hurried on to the fly. They were even less energetic than the first party; and when they found they had lost sight of their guide, they one and all returned to the nest. In the meantime several of the first detachment had found the fly, and one of them succeeded in detaching a leg, with which she returned in triumph to the nest, coming out again directly with four or five companions.*

It is now known that there are several ways ants can recruit fellow ants inside the nest: emission of chemical substances known as *pheromones* able to engage different numbers of followers, physical contact between bodies, the emission of vibrations produced by rubbing two body parts together (an

**Fig. 8.2** Bibijaguas don't normally do this. The bibijagua (*Atta insularis*) is a leaf-cutting ant, endemic in Cuba. Ant workers basically use their jaws to cut and transport leaves and other plant parts, as well as moving dirt and larvae. The one in the photo was somehow persuaded by Claro Noda to use them in a more photogenic way

activity called *stridulation*), or even a lateral wagging of the body when the messenger ant confronts a nestmate, which has been interpreted as a "ritualization of food offering". However, only the pheromone-mediated communication is believed to be essential—the other ones are often supposed to "modulate" the main message associated with a pheromone or a combination of pheromones. Outside the nest, things look clearer for many types of ants: as an individual locates a source of food, it returns to the nest, leaving behind a foraging pheromone produced by its sting gland (typically a heavy organic compound such as 3-ethyl-2,5-dimethylpyrazine, $C_8H_{12}N_2$). This shows other ants the precise track to the food.[3] As more and more nestmates follow that track and deposit new pheromone trails when they return home from the foraging area, there is a positive feedback effect that reinforces the path, so that it becomes a *foraging trail*, where outbound ants move from the nest to the foraging area, and nestbound ones move in the opposite direction—hopefully carrying food. But there are even much subtler consequences. Let us suppose that two ants have independently found the same food source, but using paths of substantially different lengths. After the two successful explorers get back to the nest, leaving behind two pheromone tracks, other ants start to follow either one track or the other. However, more ants will pass by the shortest track because it takes less time to get to

[3] This mechanism was actually demonstrated by Sir John Lubbock himself.

the food and return home. Since those ants are also depositing pheromones, the result is that the shortest track is chemically reinforced to a greater extent than the longer one… until the latter is eventually abandoned by the foragers. This is a paradigmatic example of so-called *swarm intelligence*: each individual is actually unaware of the global picture (how could a 1-cm long ant have in mind the geometry of two different tracks each several meters long?), but the nonlinear interaction of the ants mediated by pheromones "optimizes" the global foraging behavior of the swarm. Of course, other forms of communication coexist along the foraging trail, some of them still mysterious. For example, outbound and nestbound ants constantly touch each other's antennas when they meet head-to-head (*mutual antennation*): that activity slows down the overall foraging speed, but little is known about its purpose, beyond the mere recognition of nestmates.

*Atta insularis* is a leaf-cutter ant endemic to Cuba: they are quite big (their body can be 1-cm long), and black… which makes then very good candidates for observation with low-quality cameras! In Cuba, they are known as *bibijaguas* (Fig. 8.2). Like many other leaf-cutting ants, they have a well defined foraging cycle that repeats day after day. In most ocassions, the first bibijaguas start leaving the nest as the sun begins to go down. According to some authors, these are the so-called *patrollers*: they find the foraging area, and come back to the nest. Then, potential foragers inside the nest smell the scent of successfully returning patrollers (associated with the cuticular hydrocarbons covering their bodies). Some studies suggest that, if patrollers return frequently enough, ants start to abandon the nest, walking in the general direction of the foraging area. They may do it by following special pheromones left by the patrollers. But there are many other possibilities (or parallel mechanisms): are they guided by faint pheromones left by foragers from the previous day? Are they able to recognize reference points outside the nest? Do they orient themselves by the shape of the nest near the exit door?[4] I have observed that, during the first hour or so in the formation of the foraging lane, individuals advance in the direction of the foraging area, but many perform "U-turns" before reaching it and return to the nest, perhaps to reinforce the pheromone trail. The result is a "wide finger" of ants growing in the right direction. Inside the finger, the motion of the ants looks "turbulent", but that is just a transient situation. After a few hours, a well

[4] This cast some doubts on the "textbook" idea that ants start their foraging day by performing random walks in the search for food. Our observations of *A. insularis* suggest that this may be the scenario when the food area is identified *for the first time*: after that, ants will be collecting vegetal material in the same place for months on end.

defined trail, much narrower than the initial "advancing finger", is established between the door of the nest and the foraging area, typically located dozens of meters away from the nest. In the middle of the night, a densely populated file of outbound ants coexists with a nestbound file of ants returning from the foraging area, most of them loaded with almost perfect semicircular pieces of leaves cut by the ants themselves, or little flowers.[5] The whole process can be observed in terrains as featureless as the ground of a parking lot, where there is no chance of establishing a clear trail, something they would usually do in a field covered by grass. The vegetal material picked up in the foraging area is not itself food: it is used to grow a specific type of fungus inside the nest, and it is this that constitutes the actual food—the harvests are kept in ample chambers interconnected in an underground network of several cubic meters. They typically construct their nests under the ground in rural areas, but they can also admirably transform large networks of voids inside concrete floors into homes—for example, under a parking lot. *A. insularis* forages continually all night long, preying upon trees and harvests: they are considered a plague, and one that is very hard to eliminate. No wonder there is a Cuban saying to stress when someone can be considered very clever: "You are smarter than bibijaguas"![6]

A very puzzling part of the bibijaguas' daily foraging cycle is how they decide the time to start foraging and then to stop it: do they use external illumination as a clue? Or is it perhaps the temperature? Laboratory experiments in artificial nests at constant illumination and temperature suggest that ant swarms have an "internal" clock.[7] But how is this clock synchronized with the external world?

## 8.1 A Model for Ant Foraging

In an attempt to answer those questions, we started back in 2005 to design a detection setup able to collect data on the foraging activity of ants continually and automatically over several days under natural conditions. The idea

[5] In Córdoba, Argentina, I've seen ants that look exactly the same as *A. insularis*, and whose foraging activities (taking place along the grass separator between two lanes of a highway) look exactly the same—at least in my simplifying physicist's mind. Moreover, I have picked ants up from the ground that look exactly the same to me in the campus of the University of Sao Paulo, in Brazil.

[6] Tú sabes más que las bibijaguas, in Spanish.

[7] The experiments have been performed on other ant species, and the "internal period of activity" measured is of the order of 3 h (Boi et al. 1999).

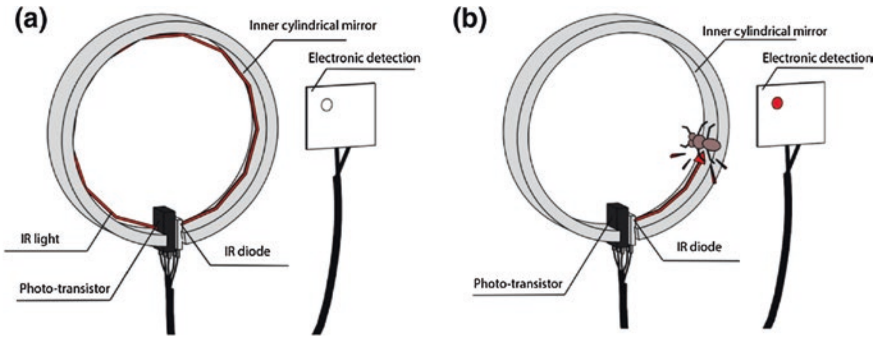



**Fig. 8.3** Principle of operation of the ant activity sensor. **a** When the infrared beam bounce all around the *inner* side of the ring and reached the detector (a phototransistor), activity is reported as zero. **b** If an ant interrupts the beam, a current spike is recorded. We defined *activity* as the number of such spikes every 30 s

was to create a system that would avoid data collection by direct observation, or the painstaking and difficult digital image-processing of very long videos. After a few years working with student Claro Noda on superconductivity instrumentation, he turned back to his teenage passion for wireless technology. He had discovered an inexpensive gadget able to collect data from one or more sensors using a single wire, with minimal energy consumption… and he tried to convince me to use it in some scientific problem. I immediately bought the idea, and suggested using it in the quantitative study of ants during foraging—at the time, I had just finished my work on ants escaping in panic (which will be described later on), so the ant topic was near the top of my list of scientific interests. The remaining problem was to identify an ant activity sensor compatible with the available electronics. As usual, Claro did a brilliant job in designing the system illustrated in Fig. 8.3, and linking it to inexpensive control and data storage electronics that was at the front line of (inexpensive) technology at the time.

As an ant crossed the ring at any point, it would cut the laser beam, and the resulting voltage spike would be stored. We then defined the "ant activity" as the number of such spikes occurring in a time interval of 30 s.[8]

Of course, there were some further experimental details to fix. The main one was to "convince" the ants to pass through the ring. We solved the problem by fixing it at the door of the nest, typically a circular hole of 1-in.

[8] So, our sensor was unable to distinguish between ants going in or out of the nest… but nothing is perfect in this life.

diameter (we actually fabricated tailored rings for different hole sizes). Under those conditions, ants would be forced to pass through our device. On some occasions, the ring was presumably treated as an alien object by the ants, and was readily buried in dirt. In such cases, we competed with ants in terms of perseverance: after repeating a few times the burying operation, ants just decided to let go and keep foraging as though nothing had happened.

In addition, there was an even more serious problem: if two ants entered at exactly the same time, the sensor would count only one spike. If such events were common, the measured activity would be smaller than the real activity. So the next step was to check that out on the ground, so to speak.

We would rapidly learn that the most difficult part of the story was to find an appropriate nest of bibijaguas: it had to be in the city,[9] because transportation is not easy, especially during the hours ants like to forage, and we also needed a location with some level of security, to avoid people stepping on the electronics, for example. We tried it at La Quinta de los Molinos—near our lab—where a few meters of our wiring disappeared one Sunday morning.[10] We finally settled on the patio of an early XX century house hosting a specialized library, located at the "Avenida de los Presidentes" near the Malecón (i.e., near the seashore) in La Habana.[11] In any case, Claro and undergrad physics student Javier Fernández were able to perform the first calibration of the system: they spent a few nights filming the activity at the nest door, while the sensor was working. After that, they would painstakingly analyze the videos, to count the number of ants passing through the door and compare it with the activity automatically acquired by the sensor. A calibration record like the one shown on the right of Fig. 8.4 demonstrated that the sensor was entirely reliable—i.e., linear—up to an activity of 40 ants per minute. That was the only time we worked like "standard biologists": after that, we would rely on the 24 h, 7-day automatic counting system, which was able to provide data no one else could get, as far as we knew.

[9] At some point, my students found a nice garden full of bibijaguas at the fancy beach of "Varadero" (more than 150 km east of Havana), but the measurements there never ended successfully: the competition with water sports and so on was too tough.

[10] Sometime after we saw a kid nearby flying a kite with a tail that looked suspiciously like it was made using our wire. But we didn't do anything about it.

[11] Moreover, thanks to the library's night guardian, nobody would get near the sensors—including, unfortunately, ourselves. But, if needed, our undergrad student Javier Fernández would stand on the curb outside the garden with his laptop, and download the precious data wirelessly.

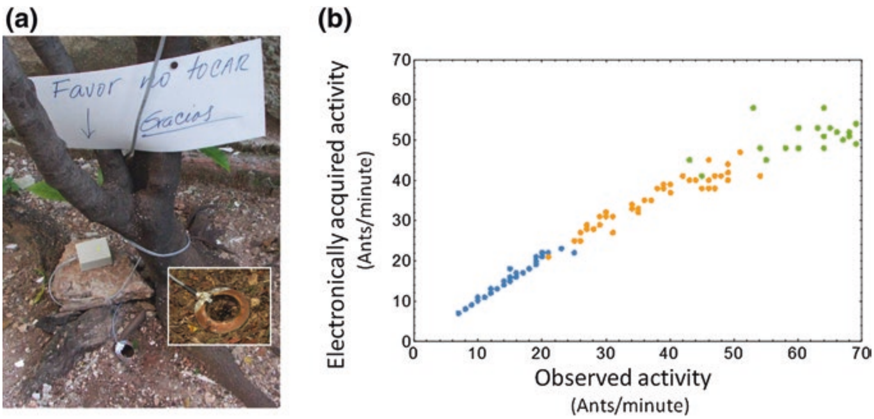



**Fig. 8.4** An ant activity sensor in the real world. **a** "Please do not touch. Thanks" is what is written on the sign above, hoping that people passing nearby would not remove the ant activity sensor from the door of the nest (see details in the inset). The sensor in the picture was deployed in 2005 in a garden at "Avenida de los Presidentes" street, near the Malecón (El Vedado, La Habana). **b** Calibration of a sensor like the one shown in **a**: in the graph, the *horizontal* and *vertical* axes correspond to the number of ants passing through the nest door, as ascertained by visual inspection and using our activity sensor, respectively. Notice that the sensor works linearly up to an activity of approximately 40 ants per minute. The *blue*, *orange*, and *green* dots correspond to observations made from 6 to 7 AM and 5 to 8 PM, from 4 to 5 AM and 9 to 11 PM, and from 12:30 to 3 AM, respectively (data collected and provided by student José Armando Godoy in 2015)

### Flash anecdote

On Sunday January 30, 2011, I introduced my (nearly) 7-year-old daughter to her first scientific endeavor, so to speak. I asked her to help me estimate the velocity of foraging bibijaguas near my in-laws' place, in the neighborhood of Arroyo Arenas. First, I asked her to track by eye individual nest-bound ants, and follow them for 10 m until they reached the door of the nest: meanwhile, I would measure the time using a chronometer, and calculate the average speed. We did that for several nest-bound ants. However, when I asked my daughter to track out-bound ants (starting from the nest door), she would suddenly stop for a couple of minutes, and complain: "I can't, dad; I can't!" After a few failed attempts, I started to get a bit mad. Then, she explained: "It is just that they go out, and after some time, they get back to the nest!" It was hard to believe, but I soon checked out myself that she was right. My daughter had just exposed me first hand to the "famous" U-turns performed by a fraction of out-bound ants, supposedly to reinforce the pheromone track in the direction of the foraging area!

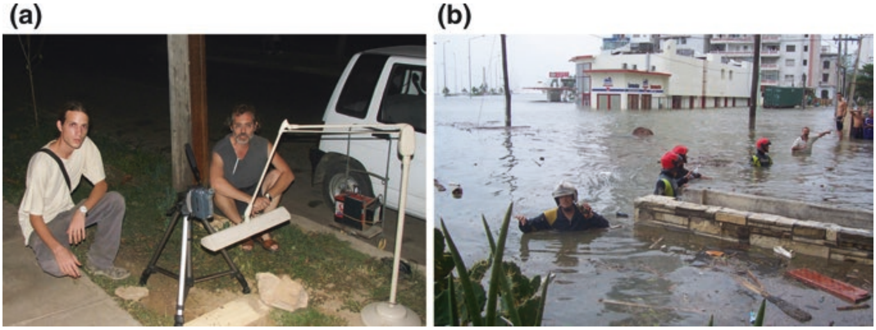



**Fig. 8.5** Wilma broke the boredom. **a** Undergrad student Carlos Pérez-Penichet (*left*) and the author filming foraging bibijaguas at "Avenida de los Presidentes" (Havana) during the night. The lamp and camera were fed from a DC to AC converter connected to the author's car battery, which can be seen to his *left*, in a trolley. **b** A few weeks later (October 24, 2005), the whole neighborhood was flooded due to the rise in sea level produced by hurricane "Wilma" passing near the Florida Straits. But just a few months later, bibijaguas started to forage again, in spite of the fact that their nests had been deep under sea water: single ants may be stupid, but a swarm of ants is a smart survival machine. One more reason why "You are smarter than bibijaguas" is a compliment in Cuba

The several occasions we spent setting up and calibrating the system in the middle of the night *and* in the middle of a major street like "Avenida de los Presidentes" was an integral social experiment beyond the limited scenario of ant societies. It was typical, for example, to have a share of curious people around. One night, one of the guys introduced himself as a dentist. After a very short preliminary chat, he opened fire: "You guys know, I do my job to make money. That's crystal clear to me. But, can you explain why on earth you take so much pain doing this stuff?" That happened in the presence of my students, who expected—I guess—a convincing response from my side. But, when I looked the guy in the eye and started my speech on the spiritual necessity of satisfying human curiosity, I experienced a certain feeling of ridicule. After all, the logical attitude is to spend nights observing ants in the jungle, with the Moon as your only witness… not in the middle of the city, with a greedy dentist and a couple of pimps supervising your activities!

Pimps apart, the output from our experiments was perhaps the first set of *quantitative* data concerning the activity of ants foraging in the wild, *measured continually second-by-second, for entire weeks*. It had been obtained without putting together a safari to Africa or the Amazon, just using electronics worth a couple of hundred dollars. However, while we were far enough from the natural dangers of a safari, we were not so far from the analogous ones expected in a subtropical island. On October 24, 2005, hurricane Wilma passed some 150 km north of Havana, producing an increase in the local sea level and furious waves along the Malecón. As a result, our beloved nests of *A. insularis* were flooded in sea water for days, eliminating any trace of foraging activity for months (Fig. 8.5).

Our experiments gave nice temporal series of activity that spanned several days of continuous data acquisition. I show a typical set of data in Fig. 8.6. A number of features can be noticed in the graphs. First, the temperature at the nest door has a 24 h cycle, with the maximum temperature located approximately after noon (each day, the temperature increases steeply, but decreases more slowly—the cooling down of the soil is indeed a slow process). The activity, on the other hand, shows a period of approximately 24 h, with a steep increase and slower decrease each day, in such a way that the activity maximum rarely coincides with the temperature maximum. One may believe that the temporal asymmetries in temperature and activity are trivially linked, but that doesn't seem to be the case. How do ants collectively decide to get out foraging every day? Are there ants going to the door every day to check illumination and/or temperature and see whether the environmental conditions are appropriate to go out? If they find those conditions appropriate, do they go back inside the nest to "wake up" their nestmates, as in the rather vivid account of ant recruiting described by Sir John Lubbock in 1881? On the other hand, given that ant nests completely isolated from external day-night cycles have been shown to have "spontaneous" cycles of collective activity, are these spontaneous cycles just replaced

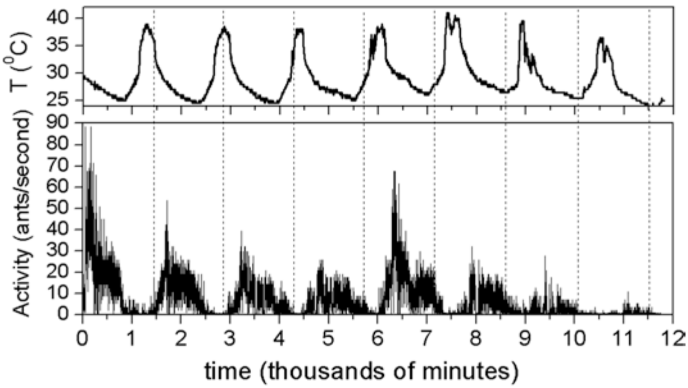



**Fig. 8.6** Quantifying the activity of ants in entirely natural conditions. The *top* graph shows the temperature at the door of an ant nest measured continually over a few days. The *bottom* graph displays the foraging activity over the same period of time. The *dotted lines* are located every 24 h

by the external "activity trigger" associated with day-night cycles, or is there perhaps some mysterious relation between the spontaneous and externally-driven cycles?

Trying to find some answers, we did several runs with the software MASON[12]—a program that reproduces the foraging of ants mediated by pheromones: an ant goes out from the nest, and after some random walk exploration of the field she finds food, then goes back to the nest, laying a trail of pheromone with a certain evaporation rate that one can adjust. Fresh ants coming out of the nest follow that track (eventually competing with different tracks laid by other ants), and finally the trail is established. With some help from Sean Luke—one of the creators of the program—we introduced the effect of temperature in several ways, inspired by behavioral data taken from the literature: we made the ant's velocity proportional to temperature (or its derivative), we made the pheromone evaporation rate proportional to temperature, etc., and then we "modulated" the code by introducing the time evolution of the temperature extracted from our experiments. We also tried to reproduce the activity asymmetry by programming a "distributed" foraging area, in contrast to the point-like model of the ant nest. In spite of the fact that MASON illustrates nicely several features of foraging ant trails, our modified versions were not good enough to explain the curious connection between the daily asymmetry of temperature and the daily asymmetry of foraging activity.

In 2006 we published the activity sensor details with some preliminary measurements, and decided to place the subject in cold storage until we could find a better explanation for the data. It was a tough decision, since it had been so time-consuming, and I suspected that nobody else had that kind of data.

Five years later, while spending three months in the very special environment of the Norwegian Academy of Sciences and Letters,[13] I received an unexpected e-mail message from David Sumpter, a very well known expert in the field of collective animal behavior. He had come across my published work on ant dynamics, and surprised me with an invitation to give a seminar in his group… at the University of Uppsala in Sweden. The convenience of being in Norway by chance was overwhelming—it just took a couple of milliseconds to say "Yes". The 72 h visit started the day after my birthday—

[12] MASON is a Java Multi-Agent Simulation library created, coincidentally, at the George Mason University, USA.

[13] I was taking part in a project on complex materials headed by my colleague Tom Henning Johansen (University of Oslo).

October 16th, 2011—and I gave the seminar "Some open (and not so open) questions in the dynamics of the Cuban ant *A. insularis*". I put a lot of emphasis on my frustrations in trying to explain the experimental activity series of the kind shown in Fig. 8.6. A month or so after that, David announced that my talk "had turned on the imagination" of Stamatios Nicolis—one of the postdocs in his group in Uppsala who had attended my seminar. During the following months Stam, David, and myself would try to understand and shape his differential equation model. Later on we would include in the team my undergrad student Frank Tejera, who had recently come from the city of Cienfuegos—near Trinidad—to continue his physics studies in Havana.

Let us consider first a situation where there is a flow of individuals ($\phi$), e.g., ants leaving the nest. Some of them are actively foraging ($A$) and some of them are "having a break", so we will call them inactive ($I$). Some inactive ones may eventually decide to abandon the foraging activity for good ($I^*$). In the model, ants become active with a probability $f(A, I)$, whose details we will not present here. Active ants, however, may become inactive with probability $k$, and inactive ants may retire completely from the process with probability $k^*$.[14] We can express all that with a system of coupled differential equations that reads

$$\begin{aligned} \frac{dA}{dt} &= \phi f(A, I) - kA \\ \frac{dI}{dt} &= kA - k'I \end{aligned} \tag{8.1}$$

The equations above work like this: when $I$ is small, almost all individuals become active, but as $I$ increases the retired ants serve to inhibit further recruitment. This type of model is generic and applicable to a wide range of situations beyond ant foraging, from social dynamics (e.g., gaze following in humans) to intracellular dynamics (e.g., calcium oscillations). If we solve the equations, within a certain range of the parameters $k$ and $k'$, we get oscillatory behavior, with a characteristic period that we will call $\tau_{\text{internal}}$. Oversimplifying quite a bit, this is a "collective version" of the period associated with a simple oscillating system, like a pendulum of fixed length.

[14] Notice that these parameters may describe, in a non-trivial way, the behavior and interactions among ants during foraging: pheromones, mutual antennation, body wiggling… all of it can be contained in $k$ and $k^*$!

The novelty of the model lies in incorporating exogenous forcing into the Eq. (8.1) in order to introduce the temporal variations of the environmental temperature—a much more complex version of a pendulum that one pushes periodically. Stam did it by adding a time dependent component $T(t)$ to the flow term. Equation (8.1) then became

$$\begin{aligned} \frac{dA}{dt} &= \phi\ [1 + T(t)]f(A, I) - kA \\ \frac{dI}{dt} &= kA - k'I \end{aligned} \tag{8.2}$$

To start with, we may assume the simplest model for the temperature variation: a sinusoid. So, we write

$$T(t) = \varepsilon \sin\left(\frac{2\pi}{\tau_{\text{external}}}\ t\right), \tag{8.3}$$

where $\tau_{\text{external}}$ can be taken as the length of a day, and $\varepsilon$ measures the intensity or amplitude of the external perturbation, i.e., it expresses how important the day-night cycle is for the activity of the nest. When we solve Eq. (8.2) taking (8.3) into account, we get the nontrivial behavior shown in Fig. 8.7.

We will look at the temporal evolution of the number $A$ of active ants as the main output parameter.[15] For small values of $\varepsilon$ (i.e., if the ants do not care much about the cycles of the external world), the activity is quasi-periodic (Fig. 8.6a): we can then define an average period, but its fluctuations increase with $\varepsilon$, as shown by the blue bars in Fig. 8.7e. As the forcing amplitude increases, the number of active ants changes its average period dramatically from the "internal" one (which is defined by the values of $k$ and $k'$), to the day-night one. During the transition, the fluctuations in the period are huge, as illustrated by the pink bars in Fig. 8.7e, and for this reason, we will call that region "chaotic".[16] Figure 8.7b also illustrates the "chaotic" nature of the activity. When ε keeps growing, i.e., the external temperature is more important to the ants, the activity enters a nice oscillatory region with a well-defined period coinciding with the day-night period (Fig. 8.7c). Here,

[15] Notice that it does not necessarily correspond to the activity of real ants… but we are boldly assuming so!

[16] However, to be chaotic in a rigorous way, one has to see whether the associated Lyapunov exponent grows fast enough.

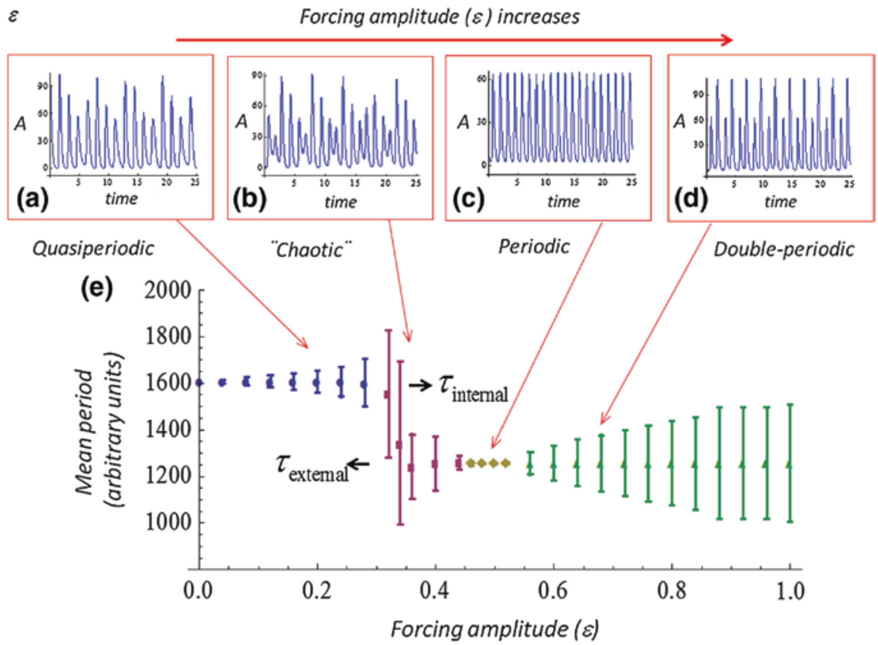



**Fig. 8.7** How day and night cycles force the collective activity of ants. The graphs show the main results of the model expressed in Eq. (8.2). From **a** to **d**, we can see the temporal evolution of the number of active ants when the influence of the external temperature cycles grows more and more important, as expressed in ε. In **e**, we can appreciate how the fluctuations in the mean period of the active ant cycles depends on ε. For small intensities of the external forcing, the number of ants first behaves quasi-periodically, with increasing fluctuations around an "internal" period typical of the "internal" dynamics of the swarm. As ε increases, the period falls into "chaotic" behavior with big fluctuations, finally switching to the forcing period, which becomes firmly established with small fluctuations for bigger values of ε. However, it begins to fluctuate significantly again at very high values of ε. We believe that foraging ants—and, perhaps not only ants—collectively adjust their interactions in such a way that they work in the quasi-periodic regime

we can say that the external forcing dominates the ant activity. The fluctuations are also very small, as seen in the olive bars of Fig. 8.7e. Finally, for very high values of $\varepsilon$, the day-night periodicity ceases: there are alternating peak intensities, as seen in Fig. 8.7d. Hence, we see that here the group under and over-responds to the external forcing. In addition, the period fluctuations increase dramatically (green bars in Fig. 8.7e).

We believe that social groups that have evolved to deal with changes in the external environment should exhibit dynamics consistent with the regions corresponding to Fig. 8.7a, b, where they respond flexibly. But how can this idea be applied to the case of bibijaguas? If we try to be as realistic as possible, we may forget about the idealized sinusoidal temperature variation given in formula (8.3), and introduce in Eq. (8.2) a value of $T(t)$ that closely follows the experimental temperature record displayed at the top of Fig. 8.6: this is shown at the top of Fig. 8.8. When we introduce it into (8.2) and solve for an appropriate choice of parameters $k$ and $k'$ as well as $\varepsilon$, we get the time evolution of the activity reproduced at the bottom of Fig. 8.8. As we can see, it displays all the relevant features seen in real life: (a) the activity rhythm is shifted from the temperature record in such a way that ants never work during the hottest hours, and (b) there is an asymmetry within each day—the activity increases sharply, and decreases more slowly. A subtler feature is also reproduced: the shift between temperature and activity as time goes by is not exactly the same every day. It suggests "elasticity" in the ants' response to the external conditions: some days they start foraging a bit earlier or a bit later. Following our model, this can be achieved by collectively tuning the internal period $\tau_{\text{internal}}$ (which is not so different from the 24 h day-night timing, as can be seen at the bottom of Fig. 8.7). In fact, to reproduce the experimental evolution of the activity shown at the bottom of Fig. 8.8, $\varepsilon$ *must be* located within the quasi-periodic regime represented by the blue vertical bars on that figure. In a word, the dynamics of foraging ants seems to

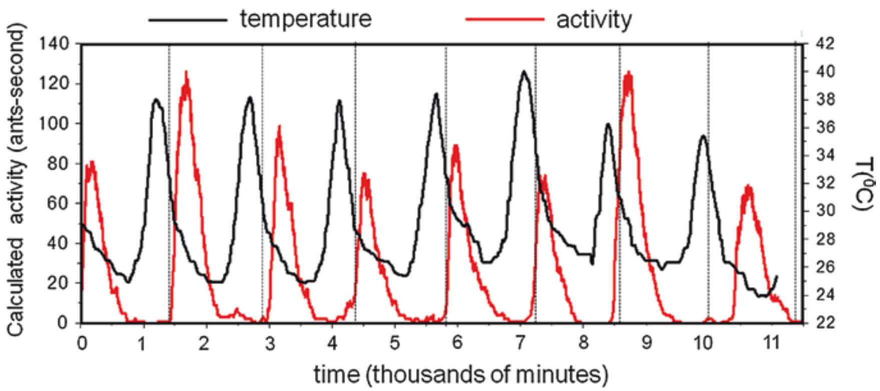
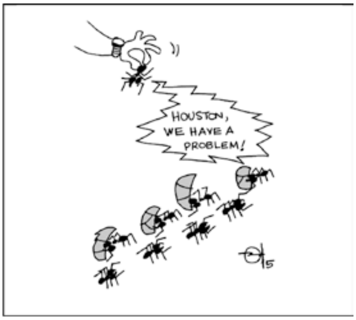



**Fig. 8.8** Simulating the activity of bibijaguas through equations. The *black lines* correspond to a function that reproduces the time evolution of temperature measured in the field (*top* graph of Fig. 8.6). The *red lines* correspond to the number of active ants versus time calculated using Eq. (8.2), where we have assumed that the temperature follows the *black line*. Notice the similarity between the *red curve* and the one at the *bottom* panel of Fig. 8.6. The parameters used to generate the curves correspond to the quasi-periodic regime illustrated in Fig. 8.7

"flirt" with chaos as a trade-off allowing them to have the elasticity they need to adapt to ever-changing external conditions. Maybe this idea makes our model valid for a wider universe of foraging activity in the biological world.

## 8.2 Foragers Under Attack

During our observations of foraging *bibijaguas* in the city of Havana, decimation of foraging ants was quite common. We have seen, for example, foraging trails crossing roads with moderate car traffic: every few minutes, several ants are crushed by a passing car. However, those events do not seem to much influence the activity cycles: only "space and/or time extended phenomena" like rain or sustained wind seem to be able to persuade ants to quit foraging one night. It is clear that there is a delicate compromise between the food needs of the colony, and the protection of the individuals. But how many ants can the colony afford to sacrifice for the sake of systematic foraging? Do foraging ants react individually or collectively to an external threat? These and related questions have rarely been addressed quantitatively in the literature: I decided to tackle them in 2011.




It is known that kidnapping *patrolling ants* during the first stages of the daily foraging cycle may suppress all foraging activity: Deborah Gordon and co-workers have shown through clever experiments that ants inside the nest need to smell a certain number of patrollers arriving back at the nest per unit time in order to "decide" upon going out to forage. So, if that frequency is held down by kidnapping patrollers, the whole foraging activity can be aborted. In fact, during our first experiments with ants in the early 2000s, we collected individuals by hand in the middle of the day, a few hours before the foraging activity reached its maximum. I was always puzzled by the fact that, after picking up a few ants, individuals inside the nest would stop going out. The method was so inefficient that I finally decided to pick the ants and do all experiments in the middle of the night, where foraging activity was near its maximum. Initially, when we collected ants during the daytime, we were probably picking up patrollers: as the rest of the ants inside the nest did not identify successful patrollers coming back to the nest frequently enough due to our “kidnapping activity”, they probably decided to stay safe at home. In any case, it had been a casual observation during ant collection for a different experiment.

What I really wanted now, was to check whether there was a “collective panic response” from the ants, associated with a spatially localized danger in the middle of the foraging activity—after all, it was a likely scenario in highly sociable animals like ants, where antennal contacts between outbound and nestbound ants occurred all the time, along the entire length of the foraging trail. For example, if some kind of attack took place a few meters away from the nest door, I expected an alarm signal to travel from the disturbance area to the nest door. In my compulsively simplifying physicist’s mind, I had guessed that a “solitary wave” of “hyperactivity”, or perhaps some kind of “density wave” moving away from the danger area, would be a reasonable consequence of a localized threat. I wanted to measure the velocity of such a wave—which, in my wildest dreams, would move even faster than the average moving speed of a single ant.

But, as we shall see, reality would prove itself to be disappointingly simpler than the already simplistic scenario I had conceived.

**Flash anecdote**

Since I basically work with undergrad students, the first half of July is essential to push forward scientific work: the students have finished their final exams, and have a couple of weeks free to do research. By the beginning of July 2016, students Alfredo Reyes and Gabriela Rodríguez had been expecting for some time to get a couple of dozen coleoptera from the species *Tenebrio molitor,* which is not a social insect like ants. We wanted to film them while exploring a flat area individually in order to compare their behavior with that observed in the case of *A. insularis*. Everything was prepared to carry out as many experiments as possible during the critical first half of July: we were just waiting for the phone call from our collaborators at the Biology Faculty, who were breeding the insects under controlled laboratory conditions. But we were not prepared for the kind of news we heard over the phone. My personal version of the matter goes like this: “As you know, they are fumigating everywhere against the mosquito… we happened not to be in the lab when the people in charge came in … and sadly, the whole generation of insects was killed…” There was a long silence at our end of the line…”But fortunately—they continued—a big strong male survived…will you take him?” We did indeed take him, but unfortunately he passed away within a day or two. Perhaps he had forgotten to take enough kryptonite!

In order to design a controllable experiment in natural conditions, I first had to select an appropriate foraging scenario. In order to be able to measure the maximum amount of information from the experiment—and considering the fact that our "sensor experts" had left the lab long ago—I preferred to use recording. So, finding a location where ants were foraging on a flat, featureless surface was essential to facilitate observations. After years of nest searching all over Havana, we discovered that the best foraging area was… just in our backyard, so to speak. Our lab has been for many years located in the main area of the Institute of Science and Technology of Materials (IMRE). I discovered that at the back of the small parking lot of our institute—just 50 m away from the lab—bibijaguas had a few nests inside the concrete. Every night, they would form a file travelling approximately 70 m to the foraging area, basically located in a garden nearby. To reach the place, the ants had to make several turns, following a number of meters of curb edges (ants love edges!), and, of course, crossing the parking area… so individuals were regularly crushed by cars as they started to forage in the late afternoon. The flat, clear concrete ground was perfect to film a trail of foraging ants in the middle of the night (Fig. 8.9).

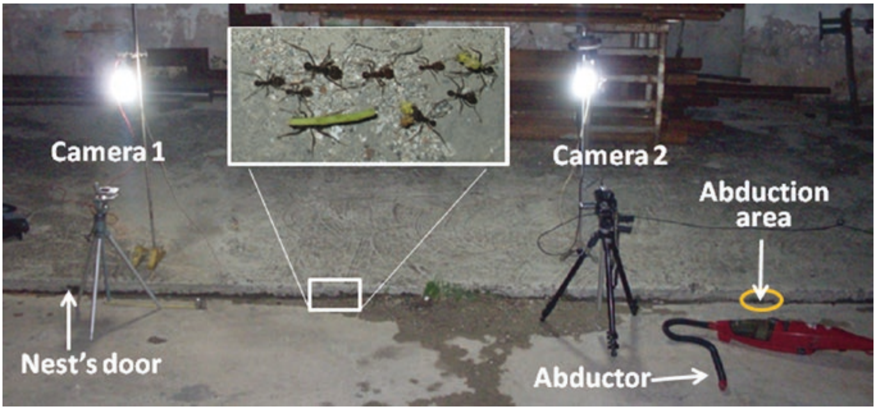



**Fig. 8.9** Abducting ant foragers. Camera 1 is very near the nest door, camera 2 is 3 m to the *right* of camera 1, and the abduction zone is 1 m to the *left* of camera 2. The abductor (a standard vacuum cleaner) rests on the ground to the *right* of camera 2. The inset shows a zoom on the foraging line, where outbound ants move from *left* to *right*, and nestbound ants (carrying vegetal material) move from *right* to *left*

Then, I had to decide how we would apply a spatially localized threat to the ants, a few meters away from their front door. The first candidate was a method I had inaugurated a decade earlier in a completely different experiment: the use of an insect repellent. However, it had several disadvantages in the present scenario: the main one was the fact that ants would carry the repellent odor on their bodies, so it would have been difficult to know if there was an "active" way to communicate danger information from individual to individual, apart from nestmates simply smelling the odor. Furthermore, the application of a chemical repellent on a certain region of the ground would produce a long-lasting effect, so experimental repetitions would have been quite difficult. The latter problem would be shared by other less polite methods for perturbing the foraging activity, such as crushing ants with a hammer. So, I decided to use a subtler kind of perturbation: abducting ants at a certain point of the trail. The abduction process would be performed using a domestic vacuum cleaner.[17]

The abduction was so gentle, that roughly 50% of the ants approaching the abduction area from the nest would detect that "something was going wrong", and would escape back to the nest after performing a "U-turn" (the other 50%, naturally, were sucked into the vacuum cleaner), as shown in Fig. 8.10. The situation was similar for the ants entering the abduction area from the foraging region. The result was that, during the abduction period, any trespassing of ants through the abduction area was suppressed, thereby facilitating the analysis. Most experiments were performed during the night by M.Sc. student Frank Tejera and undergrad Alfredo Reyes (who also did most of the video analysis a posteriori): it definitely provided tough competition for his hobby as a rock guitar player.

I hypothesized that ants escaping from the abduction area would transmit danger information to nestmates moving from the nest in the direction of the danger, which in turn would perform further "U-turns" to avoid the danger, as illustrated in Fig. 8.10b. That, of course, would ultimately cause a "cascade" of "U-turns", eventually bringing the whole foraging activity to a halt. The presence of "U-turn"-induced ants fleeing from the abduction zone can be detected by measuring the flow of ants (i.e., the number of ants passing per unit time) moving from right to left at camera 1, and comparing it with the same number measured at camera 2: if the former was

[17] We used a discount vacuum cleaner I had acquired during my postdoc in Houston in 2000. The device—bought at a K-Mart store during a "sale fever"—had been resting uselessly at home until it rose up from the ashes more than a decade later like a kind of phoenix, and turned into a scientific instrument.

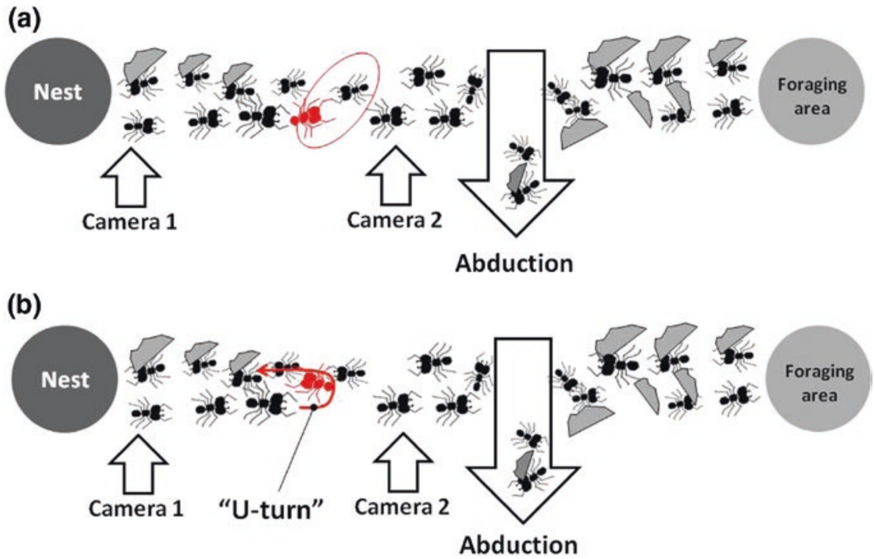



**Fig. 8.10** Sketch of the abduction experiment. **a** Some 50% of the ants are sucked up by the vacuum cleaner at the abduction area, while another 50% manage to escape, performing a "U-turn" back to the nest near the abduction area. Inside the *red ellipse*, such ants eventually touch ants going from the nest to the abduction area (one of them is represented in *red*). **b** We hypothesized that, due to the danger information received by the *red* ant, it would also perform a "U-turn", and escape back to the nest, instead of continuing to the abduction zone. That hypothesis would turn out to be wrong. The relative distance from the abduction zone to the foraging area has been reduced in the sketch so that it fits the available picture size

bigger than the latter, there were such "U-turns". Figure 8.11 shows the difference between the flows measured at camera 2 and camera 1 for a typical experiment: since it is approximately constant during the whole abduction time, we conclude that ants coming from the abduction area do not pass any danger information to their nestmates walking toward the danger area. Of course, we could also conclude that danger information is in fact transmitted, but that ants moving from left to right don't much like the idea of a "conspiracy theory"—deciding which one is the right conclusion would take us into the field of "ant psychology", so to speak! In any case, it seems that our spatially localized source of danger was unable to trigger a truly "global response" in the foraging activity of the ants.

Let me end by mentioning a refined version of the "collective panic response" hypothesis. In principle, transmission of information does not have to arise from a single ant-ant encounter: a worker going out from the

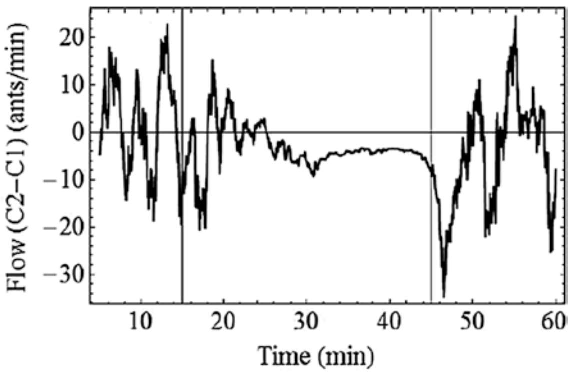



**Fig. 8.11** Difference between nestbound flows taken by the two cameras. The graph shows the difference bewteen the nestbound flow measured at camera 2 minus that measured at camera 1. Since there is no significant difference (as compared to the background before and after abduction), this means that no "U-turns" provoked by the abduction process occur between camera 1 and camera 2: outbound ants are not "convinced", by nestbound ants coming from the abduction area, to return to the nest. In addition, we were unable to detect such events by direct inspection of many ant-ant encounters

nest may "count" the number of contacts with panicked ants returning from the abduction zone. If the number or frequency of contacts is greater than a certain threshold, the ant may decide to perform a "U-turn" back to the nest. However, it is thought that foraging ants have a short memory for encounters: according to some authors, they do not remember for more than… 10 s. So, even in this scenario our experimental results suggesting no transmission of danger information are logical.

## 8.3 Symmetry Breaking in Escaping Ants

Until now, I have described our experiments on ants in the wild, but our affair with ants had started years before, with an experiment showing that swarm intelligence can eventually turn into swarm stupidity.

A paper in *Nature* in 2000, authored by Dirk Helbing and coworkers, modeled the behavior of humans in a panic situation. They basically solved numerically the equation of motion of a collection of particles that interacted like humans—at least in some approximation. Their equation had a few interesting ingredients. For example, granular-like forces representing the interaction of individuals with the walls of a room, forces representing the fact that humans in crowds don't like to touch each other (unless they are compelled to), and also "psychological" forces that make people follow the majority when submitted to panic. The concept of a "follow-the-crowd" kind of force had been conceived earlier by Vicsek and coworkers to model the dynamics of bacterial growth. I became subjugated by a particular computer experiment proposed in Helbing's paper: they put a crowd of individuals into a room with only two completely symmetric exits, and they were allowed to move according to a set of rules that reproduced quite well the behavior of "normal" human pedestrians. Under such conditions, people tended to go out using the two doors equally, and the time needed to evacuate everyone was short. However, to model human behavior in a "panic situation", Vicsek's rule was added: individuals felt a strong necessity to follow others. The result was that the escape symmetry was broken: more people tended to use one door than the other, and the resulting crowding dramatically increased the escape time. That scenario seems to be coherent with data obtained from surveillance cameras during fires and other panic-inducing situations in closed arenas. But systematic experiments in *true* panic would be clearly beyond the limits of scientific ethics.

In any case, Helbing's theory suggested that humans tend to behave irrationally when it comes to panic. And it is not difficult to see why. Picture yourself in a theatre with two rooms. Somebody shouts "FIRE!" and smoke starts to darken the place. For some reason, a lot of people are running frenetically in the same direction. Do you imagine yourself trying to remember where the widest or nearest door is located? I don't think so: in a fraction of a second's thought, you just assume that the people must be running that way because salvation can be found in that direction. And then you follow the crowd—you follow Vicsek's rule!

**Flash anecdote**

It was approximately the year 2006 when I "discovered" that illuminating the ants from below and filming from above was the best way to facilitate image processing. We did not have such a wide variety of light sources, so we used whatever we had at hand. I thought it was a great opportunity to use a powerful spotlight we had stored in the lab for a long time. So, we put our bunch of ants directly onto the flat glass of the spotlight, and turned it on, while filming with a CCD camera from above, plugged to a computer. A couple of students and myself enthusiastically stared at the computer screen… but there was no action at all: the ants became completely frozen on the screen as soon as the spotlight was turned on. Being an "old fashioned" guy, I left the students behind to discuss the subtleties of CCD saturation, and turned to the real scenario. The smell immediately revealed the problem: "We're frying'em up, guys; we're frying'em up!"—I shouted. We never attempted that experiment again.

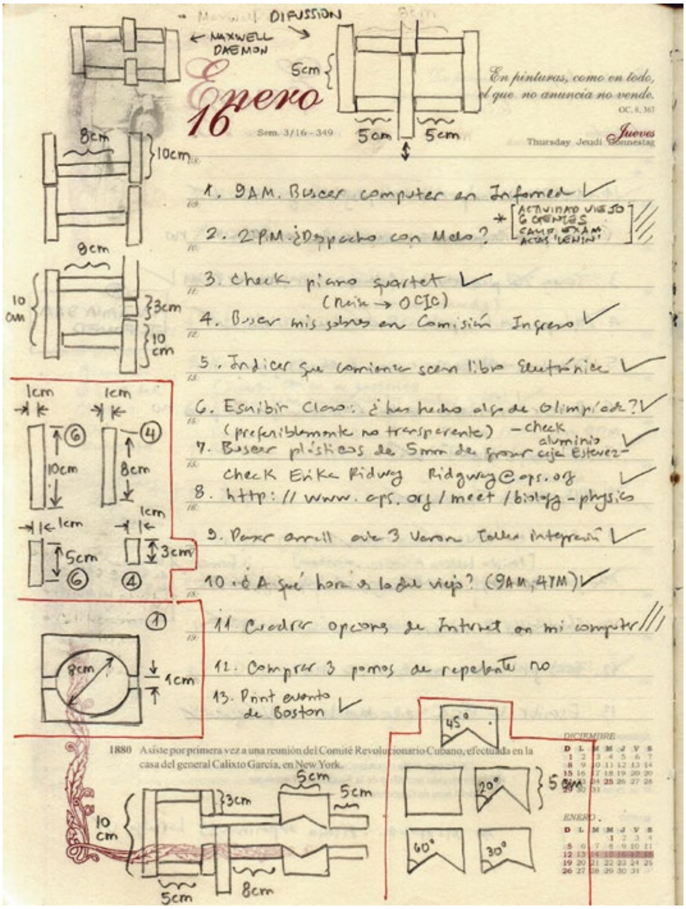



**Fig. 8.12** When bureaucracy meets science. Since the end of my undergrad studies in 1986, I religiously kept a diary to avoid forgetting daily tasks. As time went by and responsibilities increased, the diary became more and more eclectic. In the sample page shown on the *left* (January 16, 2003) one can find, for example, (2) An interview with the Physics Dean at the time, Osvaldo de Melo, (7) A reminder to search for 5 mm thick plastic sheets to construct cells for ant experiments, (9) A "methodological" meeting called "Integration Workshop", during which I tried to squeeze the time by sketching the different cell projects for ant experiments that can be seen around the text. Several sketches were actually constructed by the author, but only the circular cell with two exits shown near the *lower left* end of the page was systematically used in experiments with ants. The results were finally published approximately two years later

That was the point when I started to think about ants: if humans tend to be irrational when it comes to panic, perhaps we can learn from ants how humans behave in certain scenarios! At this point, I was very lucky to be a physicist: if I had been a biologist—especially a serious one—I would probably have discarded the idea of comparing the behaviors of two species so far removed from each other. But in the end, my professional inclination to do "academically incorrect" experiments won the day. On top of that, the experiment I had in mind was really inexpensive…

The first step was to select the right type of ants. I rapidly thought of bibijaguas for the two reasons explained at the beginning of the present chapter: (a) they were big and (b) they were black. Those two elements allowed us to use the second-hand camera I had bought during my 1999–2000 postdoc at the Texas Center for Superconductivity. After all, you couldn't ask miracles of my beloved Magnavox CVS325AV VHS-camera, which I still keep in its "original" Samsonite bag offered by the e-bay seller as a "hook" for naïve buyers like myself.

So, the idea was to construct a circular cell with two symmetrically positioned doors in its sides, put a bunch of ants inside, open the doors, and see how they escaped in low panic and in high panic conditions (Fig. 8.12). If the model by Helbing and coworkers was also valid for ants, I should observe a symmetric exit in the first case and an asymmetric exit in the second case.

Some technical details had to be fixed first, though. For example, a height of 5 mm was chosen for the cell in order to avoid ants running over the top of each other—I wanted a truly two-dimensional system.

But the worst part was, of course, to figure out a reasonable way to produce "panic". The first idea that occurred to me (as happens to many physicists when asked) is to increase the cell's temperature. But, besides being complicated from the instrumental point of view—at least in our laboratory conditions—that was a little bit inconvenient. Figure 8.13 shows how nonlinear the panic scenario can be if the temperature gets out of control. But the graph belongs more to the field of insect psychology—assuming that such a thing exists—than to the field of physics. In any case, I decided to use a small amount of insect repellent. I chose a mosquito repellent called *Citronella*, produced by *Labiofam* (La Habana, Cuba). The idea was noble: "induce panic, not death".

In order to avoid any "memory effects", we picked up a batch of 80 ants each time from a foraging trail in the field, brought them to the lab, did the experiment, and then released the ants back in the field. For the next experiment, we picked up a fresh batch of ants, and so on. It is worth noting that I tried several methods to pick up ants from the wild: one of them was to use a vacuum line with a trap, but, after swallowing a couple of bibijaguas (the vacuum was produced by sucking with the mouth), I decided to pick them up by hand, one by one. It was quite a job, especially in the summertime—but

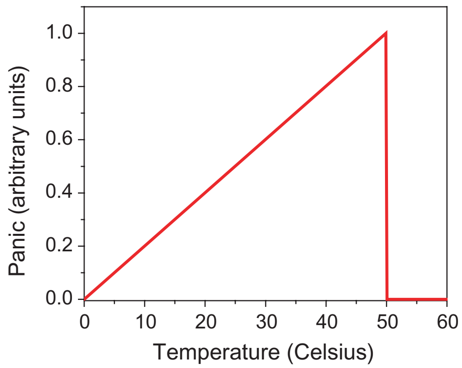



**Fig. 8.13** How should we induce panic in ants? If there was a well defined way to measure panic, the figure would represent a speculation of how it would depend on the temperature applied to the ants. As can be seen, an inconvenient nonlinearity arises at a certain temperature—which we could call "critical", paraphrasing the superconductivity jargon. But joking apart, we decided to produce "panic" in our ants by adding a small dose of insect repellent

more than a decade has passed, and we are still using the one-by-one handpicking method. Believe it or not, in this way the ants are not damaged at all.

So, typical experiments can be described as follows. Approximately 80 "fresh" ants were introduced into the cell, and rapidly covered by a glass sheet, with the two doors closed. In the case of a low panic experiment, the doors were just opened in a synchronized way after a few seconds, and the number of ants leaving from each door was counted. In the case of a high panic experiment, before opening the door, 50 μl of insect repellent was added through a 1 mm diameter hole in the middle of the covering glass,[18] and the two doors were opened after a few seconds (Fig. 8.14).

The simplest way to evaluate the use of the two doors for escape purposes was just to count the total number of ants escaping through each door as time went by. Figure 8.15 shows typical records for low-panic and high-panic experiments: while in the first the two doors are used in an approximately equivalent way, in the second, one of the doors is substantially preferred by the ants (depending on the repetition of the experiment, the chosen door could be on the right or the left, randomly). This breaking of the symmetry could not be put down to any lack of symmetry in the experimental setup.

[18] Thanks to the fact that the cell floor is "carpeted" with filter paper, a circular spot of repellent is established at the center of the cell, which guarantees a symmetric scenario.

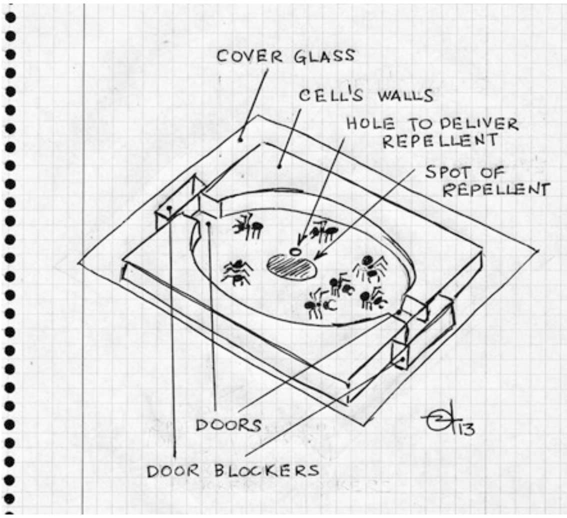



**Fig. 8.14** A minimalistic cell for panic experiments. The cell walls are made of two plastic *semicircles* of radius 4 cm and height 0.5 cm, with two symmetrically placed doors, each 1 cm wide. The doors can be blocked using two pieces of plastic of the same height as the walls. These parts rest on a horizontal sheet of filtering paper on a glass surface, and the system is covered by a glass sheet with a 1 mm diameter hole located at the center of the cell, which allows delivery of an insect repelling fluid inside

A simple way to quantify the symmetry breaking during escape is to define a symmetry-breaking parameter by

$$SB = \frac{|N_{left} - N_{right}|}{N} \times 100 \tag{8.4}$$

where $N$ is the total number of ants that escape during the whole experiment, and $N_{left}$ and $N_{right}$ are the numbers of ants that escape through the left and right doors, respectively. Notice that, if the same number of ants use both doors, $SB = 0\%$ (perfectly symmetric escape), while if all ants use either the right or the left doors, $SB = 100\%$ (completely asymmetric escape). For the specific experiments illustrated in Fig. 8.15, we get $SB \approx 10\%$ and $SB \approx 80\%$ by the end of the experiments illustrated in (b) and (d), respectively.[19]

[19] In order to estimate the symmetry-breaking parameters, we had to extrapolate the data for one of the two doors up to the end of the experiment.

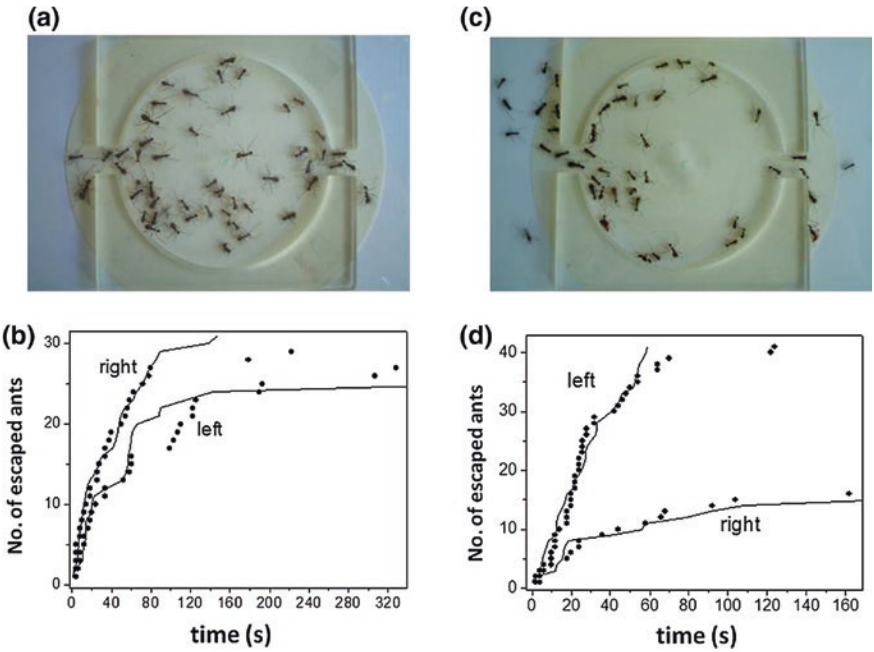



**Fig. 8.15** Typical experiments with ants escaping from a circular arena with two equivalent doors: **a, b** Low panic scenario. **c, d** High panic scenario. Null-hypothesis tests demonstrate that this difference is statistically significant: escape symmetry is indeed broken when the ants panic

After performing a few dozen experiments with and without adding repellent, we obtain the frequency of occurrence of different values of the symmetry-breaking parameter *SB*. As shown in Fig. 8.16, when no repellent is added—low panic experiments—the average value of *SB* is near 10%, while it rises to approximately 40% when repellent is added—high panic experiments. So, our experiment with ants demonstrates that panic induces over-use of one of the doors—just as in the case of humans, if we follow Helbing's model.

These results can be reproduced by a simple computational model programmed by undergrad student Yuriel Núñez. First of all, we proposed our own version of the "spherical cow": ants are just circles moving around in a circular cell with two equivalent exits along a diameter. The circles' sizes and velocities are distributed similarly to the size and velocity distribution of real ants. If an ant reaches a wall, it is reflected like a ping-pong ball.[20] If an ant

[20] Which is not very realistic from the biological point of view. But we should remember that our ants have already been approximated by circles!

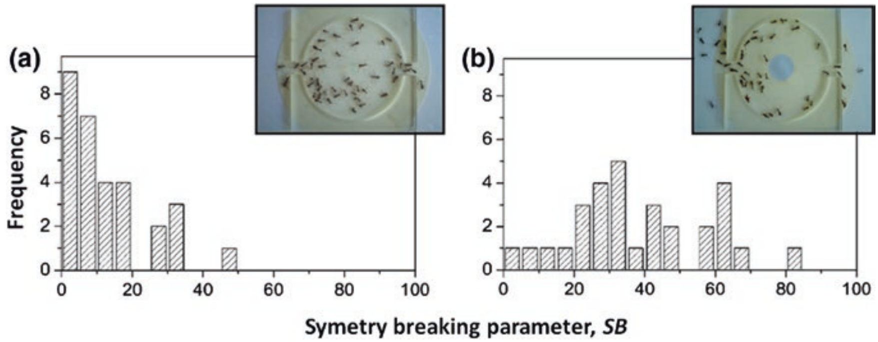



**Fig. 8.16** Statistics of symmetry breaking in escaping ants. **a** Frequency versus symmetry-breaking parameter for **a** non-repellent and **b** repellent experiments. The average values of SB are approximately 10 and 40%, respectively

approaches one of the exits within a distance equal to a certain "exit radius", the individual is taken out of the system. The exit radius is taken as 5 mm, which is the distance at which real ants realize that there is a door, following our observations. It was a bit trickier to reproduce the frontal encounters between ants computationally: in real life, ants briefly touch each other's antennas, and then basically continue moving in their original direction after stepping aside slightly. We implemented the following algorithm: when two ants bump into each other, they bounce back one step in a random direction, and in the next step, move forward in the direction they had before the encounter. If they bump into each other again, the algorithm repeats, until each one is finally able to continue its own path.

If one simulates the motion of 80 ants following the above described rules, and repeat it for a few hundred different initial conditions (i.e., different random distributions of the initial direction of motion), a statistical scenario consistent with Fig. 8.16a is obtained: we are able to reproduce the actual behavior of ants in "low-panic" conditions.

In order to simulate the behavior in "high panic conditions", we added two extra rules to our model. Firstly, we established a "forbidden spot" of 1 cm-radius at the center of the cell, imitating the area contaminated with the repellent fluid: any ant pointing towards the direction of the spot would re-orient randomly. Secondly, we introduced Vicsek's idea, by using formula (8.5) below to calculate the direction of motion of each ant in a certain time step, as a function of its direction and the direction of motion of the rest of the ants in the previous time step. Let us apply Vicsek's rule to the ant represented by a red dot in Fig. 8.17. The unit vector in the direction of motion of that ant in step $k$ is given by

$$\vec{e}_k = \frac{(1-p)\vec{e}_{k-1} + p\left\langle \vec{e}^{\,herd}_{k-1} \right\rangle}{\left|(1-p)\vec{e}_{k-1} + p\left\langle \vec{e}^{\,herd}_{k-1} \right\rangle\right|}. \tag{8.5}$$

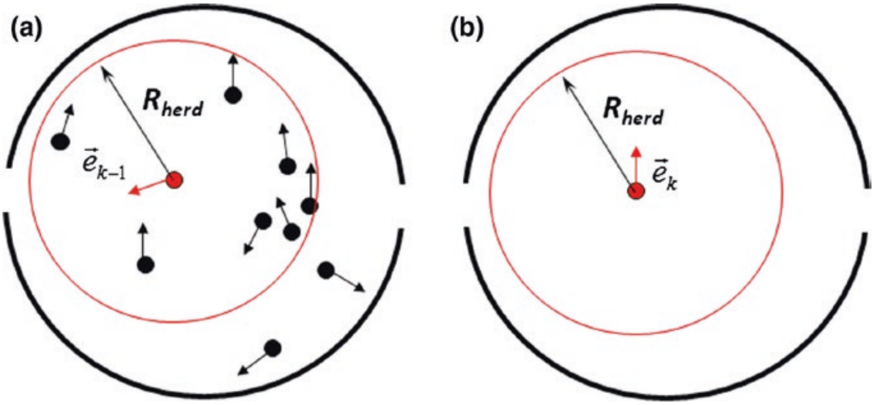



**Fig. 8.17** Deciding how to move next in panic conditions. **a** The ant represented by the *red dot* has a velocity represented by the *red arrow* at time $k - 1$. In order to decide where to move next, it examines the direction of motion of other ants (*black dots*) included in an imaginary *circle* of radius $R_{herd}$ which contains neighboring ants. (b) In the next time step $k$, the *red* ant decides to move in the direction represented by the *red arrow*, following formula (8.2) (other ants are not represented in that sketch for the sake of clarity). The radius of the cell is 5 cm

In the equation above, $\vec{e}_{k-1}$ is the unit vector in the direction of the velocity of our ant in the previous time step, and $\langle \vec{e}^{\,herd}_{k-1} \rangle$ is the unit vector along the average direction of motion in the previous time step of the "herd of ants" located inside a circle of radius $R_{herd}$ around our sample individual (see Fig. 8.17). Finally, $p$ is a number between 0 and 1 called the *panic factor*. Notice that, in (8.5), the denominator is just the module of the numerator, so $\vec{e}_k$ is actually a unit vector.

Let us illustrate the meaning of (8.5) using two extreme cases. The first one is when there is no panic, so $p = 0$. In this case, (8.5) reads $\vec{e}_k = \vec{e}_{k-1}/|\vec{e}_{k-1}|$, i.e., the ant does not care at all about what is going on around her: she just keeps moving in the same direction as before (notice that this is basically what ants do in the first version of our model, before introducing any "panic rules"). The second extreme takes place at maximum panic, when $p = 1$. Here, (8.5) reads $\vec{e}_k = \langle \vec{e}^{\,herd}_{k-1} \rangle / \left| \langle \vec{e}^{\,herd}_{k-1} \rangle \right|$, i.e., the ant reorients herself towards the average direction the herd was moving in the previous time step: being in a state of panic, she basically forgets her individuality, and "follows the crowd". When the panic factor takes some value between 0 and 1, the ant's decision about how to move in time step $k$ is a combination of "mixed feelings": following (8.5), she will move along a vector resulting from a combination between her own previous direction of motion and the previous direction of motion of other ants around her.[21] Figure 8.17 illustrates how the ant represented by a red dot reorients herself from time $k - 1$ to time $k$, taking into account her surroundings, with a panic factor between 0 and 1. In our simulations, we must calculate the direction of motion of each ant, at each moment, in this way.

If we run the simulation including Vicseks's rule a few hundred times, with a panic factor of 0.8 and a herd radius of 3.75 cm, we are able to reproduce the experimental results for ants in panic conditions, as reported in Fig. 8.16. All in all, our simple model is able to reproduce the behaviour of confined ants, in both low panic and high panic conditions.

The resulting paper, completely put together by physicists, was submitted to a "hard core" biological journal—*American Naturalist*. Naively, we assumed that our nice error bars would convince the referees about the correctness of the conclusions… but data processing in the biological world is not so simple: they asked for more repetitions, null-hypothesis statistical tests, and the like. In other words, we learned the hard way that a few experiments with a few dozen ants is much more statistically demanding than the typical "physicist's experiment", where many billions of Cooper pairs—for example—are involved. Besides performing far more experimental repetitions, I turned once more to my "secret weapon": Alfo José Batista, a physicist with enormous culture and myriad abilities that always makes me feel safe. He applied the Kolmogorov-Smirnov statistical test to the data, corroborating the significance of our results. So we finally published the paper, which is one of my top-cited! As a physicist, I'm still wondering how I should feel about that particular fact…

**Flash anecdote**

One night my wife Aramis and I worked until late in our respective labs, then walked home during the night. It was December 11, 1998, and the Havana Festival of New Latin American Cinema was drawing large crowds around the movie theaters. However, when we passed by the "Yara" theater, we found that it was easy to get in, so in we went. We had no idea what we would be watching. After sitting for 30 min, two guys walked on stage. It was hard to believe, but we identified one of them as Francis Ford Coppola himself! The other guy was the translator, who did not know what to do during the first 10 min, since Coppola started to address the audience in "broken Spanish", quite difficult to understand. Fortunately, a guy from the audience saved everyone (especially the translator) when he stood up and shouted: "Coppola, speak in English!" In

[21] That would demand a pretty high level of intelligence for an ant, but we have to remember once again that this is just a mathematical model.

brief, he introduced his film, and said that it had been presented for free to the Cuban audience. He withdrew, the lights went off, and the movie started. BUT the sound system was full of noise, and there were no captions. People started to complain in low voices. The movie stopped, the lights went on again, and another 20–30 min passed. Coppola and the translator came on stage once more, to loud applause. He was clearly very upset, and basically said that there had been sabotage (I remember that word well): he thought that the correct film had been swapped before leaving for Cuba. He offered all kinds of apologies, then withdrew once more to even louder applause. We quietly abandoned the theater, as did 2000 other people. Sometimes,

Havana is a surrealistic place.

But what justifies the tendency to "follow the crowd" from the adaptative point of view? Fish and many other social animals tend to respond to a threat by moving together as a school or herd: it looks like a reasonable strategy from more than one point of view. Not only do the "outer" swimmers or runners protect the inner ones from attack by a predator, but if the predator is fool (or myopic!) enough, the moving bunch may look like a big animal. In fact, you don't need to be seriously weak-minded or myopic: if you have snorkeled when a school of fish or shrimps suddenly comes towards you out of the blue, you have probably experienced a tense fraction of a second worrying about *what* exactly is coming in your direction. Once again, sudden panic momentarily blinds reason.

In the case of humans, following the majority is probably also a convenient survival strategy. However, I'm afraid that the tendency to form crowds is sometimes much less evolutionarily relevant than it is for lower animals: we crowd to watch a soccer game, to dance at a big party, or to attend a religious celebration in La Mecca. If any of these situations is met with a state of panic—due to a fire, or just to some immaterial feeling—humans may die crushed to the ground or walls by the multitude. And this has indeed happened in the three scenarios mentioned here.

In fact, Vicsek's rule pervades our everyday life when extrapolated to social psychology—where it can be connected to the concept of "social pressure": you do what you see people doing. For example, at least in Cuba, it is customary for a baby girl's ears to be pierced so that she can wear earrings as early as one month after birth. Normally, parents never ask their daughters whether they agree with such a modification of their bodies: they just transmit the social pressure exerted on them. My wife and I decided that my daughter would not have her ears pierced until she could make up her own mind about it. Over the years, we received a few veiled—and some unveiled—criticisms about the matter. Finally, she decided to have her ears pierced: the temptation to wear "real" earrings like the rest of the girls was too great. She bravely—and consciously—submitted herself to the wholly unnatural process when she turned just 9 years old. I could barely watch the process. In a nontrivial way, I am very proud of her.


Other invasive modifications of the body associated with social pressure are incredibly common—especially tattooing. If you are a young person these days, you need a really low panic factor in "our" Vicsek's model to resist the social pressure wanting you to tattoo your skin. Tattooing is, in principle, a non-erasable mark on your body that will be there until death: what message would you write or draw on your body which may be relevant enough to be consistent with your tastes, say, half a century later? Young people—and even not so young people—don't seem to care: the need to "follow the crowd" is too strong and people just don't give much thought to it. The following anecdote illustrates how far the "follow the crowd" instinct can be stretched as a "rationale" behind tattooing. A colleague of mine did not want her daughter—a 20 year old physics major—to have a tattoo. She used the obvious argument: "And how do you think the tattoo will look when you get old and your skin gets loose and wrinkled?" "No need to worry, mom"—the girl responded—"all my friends will have exactly the same problem!"

## Bibliography


Altshuler, E., O. Ramos, Y. Núñez, J. Fernández, A. J. Batista-Leyva and C. Noda *Symmetry breaking in escaping ants,* The American Naturalist 166: 643 (2005)

Boi, S., Couzin, I. D., Del Buono, N., Franks, N. R. and Britton, N. F. Coupled oscillators and activity waves in ant colonies. *Proceedings of the Royal Society of London B* **266**, 371 (1999)

Bonabeau, E., Dorigo M. and Theraulaz, G. (1999) *Swarm intelligence – From natural to artificial systems* (Oxford University Press)

Gordon, D. M., "Ant encounters. Interaction networks and colony behavior". Princeton University Press, 2010

Helbing, D., Farkas, I. and Vicsek, T. *Simulating dynamical features of escape panic,* Nature **407**, 487 (2000)

B. Hölldobler and E.O. Wilson (1990) *The ants*, first edition (Cambridge, Mass.: The Belknap Press of Harvard University)

Hu, D. L., Phonekeo, S., Altshuler, E. and Brochard-Wyart, F., *Entangled active matter: from cells to ants*. Accepted by European Physics Journal–Special topics **225**, 231 (2016)

Lubbock, J. *Observations on ants, bees and wasps – Power of Communication by something approaching to language*. Nature *23*, 255–258 (1881)

Nicolis S. C, J. Fernández, C. Pérez-Penichet, C. Noda, F. Tejera, O. Ramos, D. J. T. Sumpter and E. Altshuler. Foraging *at the Edge of Chaos: Internal Clock Versus External Forcing,* Physical Review Letters **110**, 268104 (2013)

Noda, C., J. Fernández, C. Pérez-Penichet, and E. Altshuler *Measuring activity in ant colonies,* Reviews of Scientific Instruments **77**, 126102 (2006)

Rusell, G. W. *Agression in the Sports World–a Social Physiological Perspective* (Oxford University Press, 2008)

Ruvinsky, J. *Small minds think alike Discover* vol. 26 No. 12 (Dec. 2005) http://discovermagazine.com/2005/dec/ants-stampede

Sumpter, D. J. T., *Collective animal behavior* (2010) (Princeton University Press)

Tejera, F., A. Reyes, and E. Altshuler, *Uninformed sacrifice: evidence against long-range alarm transmission in foraging ants exposed to localized abduction*, European Journal of Physics – Special Topics **225**, 665 (2016)

Vicsek, T. Czirók, A., Ben-Jacob, E., Cohen, I. and Schochet, O. *Novel type of phase transition in a system of self-driven particles*, Physical Review Letters **75**: 1226–1229 (1995)

## Wikipedia Links

https://en.wikipedia.org/wiki/Symmetry_breaking_of_escaping_ants

## YouTube Links

An experiment showing the symmetry breaking in escaping ants http://www.youtube.com/watch?v=6Rz8LNesxGs

# Annex A: How Grains Influence Weak Links in Ceramic Superconductors

As mentioned in the main text, the magnetic field dependence of the transport properties of superconducting ceramic samples—including hysteresis, relaxation, and other phenomena—can be understood by assuming that those materials are made of "strongly superconducting" grains, linked by "weakly superconducting" Josephson-like junctions, whose transport abilities decay rapidly when they feel a relatively small magnetic field. The grains behave as type II superconductors, so they are able to trap magnetic fields (due to the pinning of vortices) which would affect the currents circulating through the weak inter-grain junctions, even when the external magnetic field has been removed. Figure A.1 illustrates the mechanism responsible for the hysteresis (i.e., irreversible behavior) of the transport critical current density in a superconducting ceramic sample. The transport critical current density is the biggest current per unit area one can force to circulate through a superconducting sample without measurable dissipation (i.e., without detectable voltage measured in the direction of the applied current).

**Flash anecdote**

It happened in the early nineties, when food was scarce. As I entered the lab, I found this undergrad student—a sportive guy always hungry—enthusiastically chewing something. As the minutes went by and he kept chewing, I asked: I'm curious: is that chewing gum or something? Triumphant, the guy took the thing out of his mouth, and said: it is just this yummy stuff I found on the lab table….

It was the rubber separator I used to wear between my toes.



E. Altshuler, *Guerrilla Science,* DOI 10.1007/978-3-319-51624-0

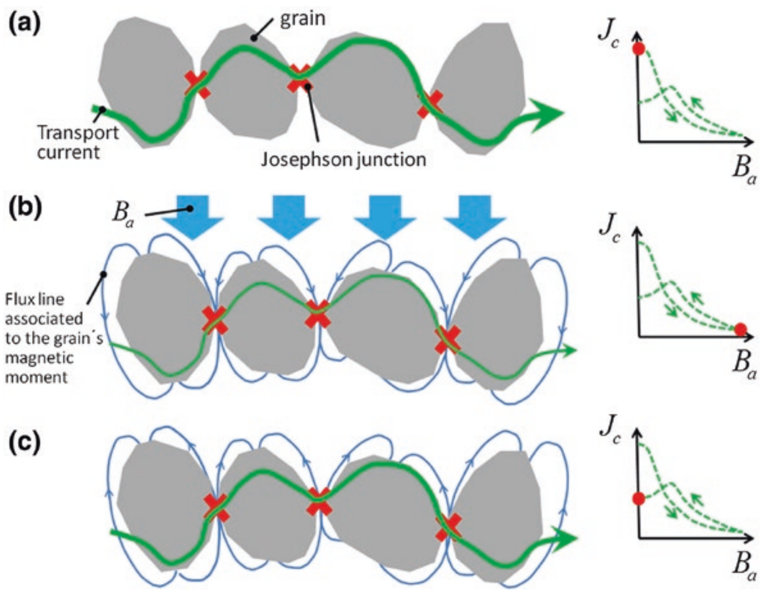



**Fig. A.1** High $T_c$ ceramics: mixing strong and weak superconductivity. Superconducting ceramics can be seen as a collection of strongly-superconducting grains (*grey particles*) linked by weakly-superconducting Josephson junctions (*red crosses*). When a transport current (*green arrow*) is forced through a ceramic sample, it must cross the weak links. **a** At zero applied field, the maximum transport current $J_c$ able to circulate without dissipation is big. **b** When an external magnetic field $B_a$ is applied (*thick blue arrows*), the grains develop magnetic moments in the opposite direction, resulting in extra magnetic field at the junctions (*thin blue arrows*). But they are very sensitive to the magnetic field. As a result, the transport critical current of the sample decreases more than expected from the direct effect of the external field. **c** The external field has been decreased to zero after having reached a maximum value. According to the so-called *critical state model*, the grains try to oppose the decrease in the external field inverting their magnetic moments, which anchor to a nonzero value even when the applied field is taken to zero. The junctions now feel a remnant field different from zero (*thin blue arrows*), so the value of the transport critical current density is smaller than the one before any field was applied: the transport properties are thus hysteretic relative to the history of the magnetic field, thanks to the irreversible behavior of the grains. Curves like the ones shown in *dotted lines* at the right of the figure can be measured with minimum equipment: a few liters of liquid nitrogen, a copper coil, a current source, and a simple microvoltmeter

During those days of joy (and hunger!) when we developed the "philosophy" of how to get intra-granular properties from "inter-granular" properties, I enjoyed the company of an enthusiastic crew of people. Besides my undergrad advisor Sergio García—like an older brother to me—there was the founder of the lab, Oscar Arés, and also Andrés R.R. Papa, Carlos Abascal, Carlos Martínez, Jorge Barroso, Pedro Muné, Alfo José Batista, and people younger than me, like Luis Flores, Claro Noda, Jorge Musa, Jorge Luis González, and Raiden Cobas… some of them scattered all over the world these days.

## Bibliography


Altshuler, E., García, S. and Barroso, J. (1991) Flux trapping in transport measurements of $YBa_2Cu_3O_{7-x}$ superconductors: A fingerprint of intragrain properties, *Physica C* **177**, 61 (1991)

Altshuler, E., Musa, J., Barroso, J., Papa, A.R.R. and Venegas, V. (1993) Generation of hysteresis $J_c(H_e)$ curves in veramic $YBa_2Cu_3O_{7-x}$ superconductors, *Cryogenics* **33**, 308

Altshuler, E., Cobas, R., Batista-Leyva, A.J., Noda, C., Flores, L. E., Martínez, C. and Orlando, M.T.D. (1999) Relaxation of the transport critical current high $T_c$ polycrystals, *Physical Review B* **60**, 3673

Batista-Leyva, A.J., Cobas, R., Estévez-Rams, E. Orlando, M.T.D., Noda, C. and Altshuler, E. (2000), E., Hysteresis of the critical current density in YBCO, HBCCO and BSCCO superconducting crystals: a comparative study, *Physica C* **331**, 57

Batista-Leyva, A. J., Cobas, R., Orlando, M. T. D. and Altshuler, E. (2003) Hysteresis and relaxation in $TlBa_2Ca_2Cu_3O_y$ superconducting polycrystals, *Superconductor Science and Technology* **16**, 857

Batista-Leyva, A. J., Orlando, M. T. D., Rivero, L., Cobas, R. and Altshuler, E. (2003) The resistive transition of $(Hg_{0.85}Re_{0.15})(Ba_{1-y}Sr_y)_2Ca_2Cu_3O_{8+\delta}$ superconducting polycrystals, *Physica C* **383/4**, 365