

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 were 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.

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).

²That 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.

³Unfortunately, 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).

⁴These 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 and 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

⁵Our 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.

⁶Today 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!).

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

⁸If 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

⁹Of 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 over-critical, 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-

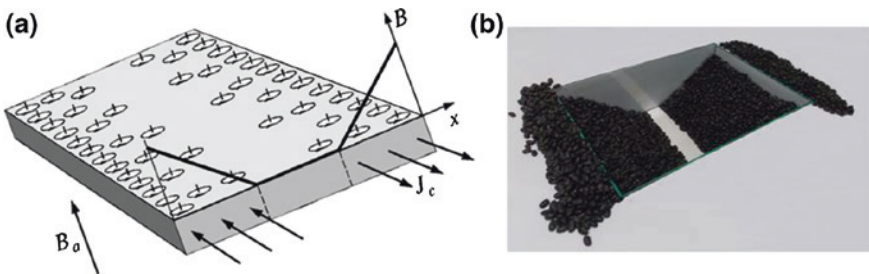


Fig. 2.4 Bean on beans. **a** The critical state for a type II superconductor. In response to an applied field (B_a) bigger than the so-called *first critical field* (B_{c1}), vortices enter the superconductor from the edges. The competition between the external field “pushing” them in and the pinning 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

¹⁰There, 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.

¹¹In 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 *chicharos* in Cuba) instead of sand, so I immediately called the device “El Chicharrotrón”. 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 *Chicharrotrón*—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 “prrrshhhss” 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

¹²In 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.

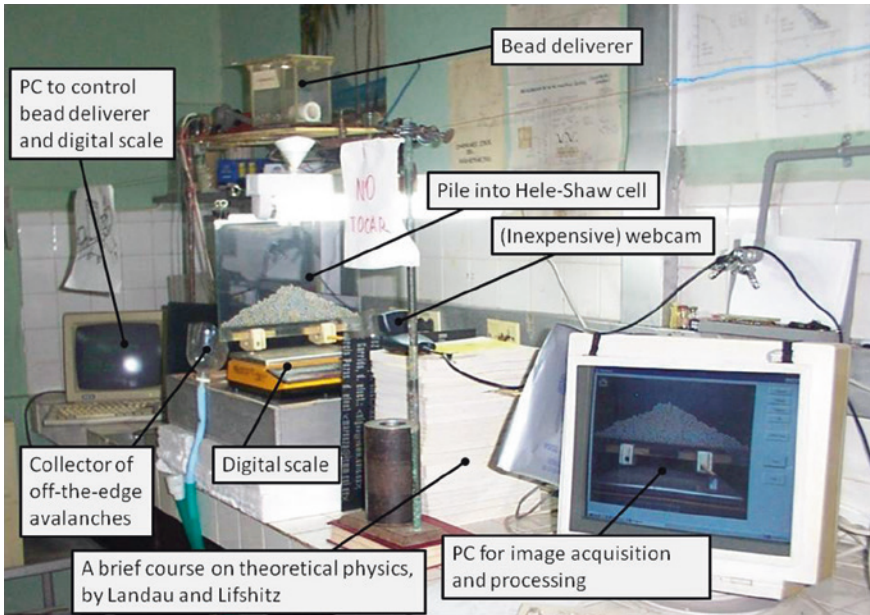


Fig. 2.5 El chicharrotrón. A system to quantify avalanches occurring when steel beads are added from the top, one by one, to a two-dimensional pile. A digital scale measured the beads that eventually abandoned the pile by the edges (off-the-edge avalanches), while a digital camera took pictures of the 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

Chicharrotrón, 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 *Chicharrotrón* 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,

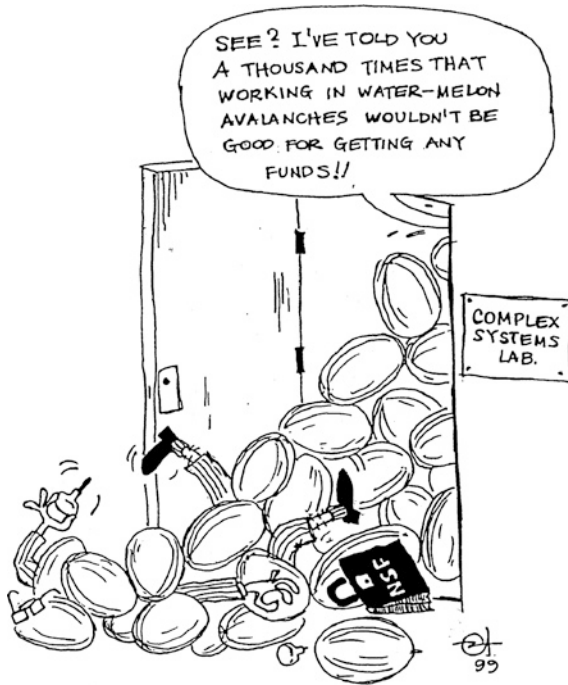


Fig. 2.6 The dangers of avalanches

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

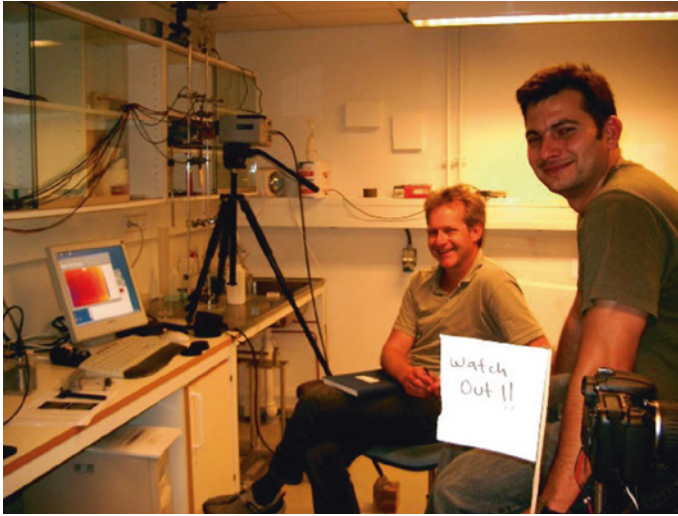


Fig. 2.7 Knut Jorgen Måløy (*left*) and Osvanny Ramos (*right*) at Knut Jorgen’s Lab (Physics Department, University of Oslo), in August, 2006

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

¹³When 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.

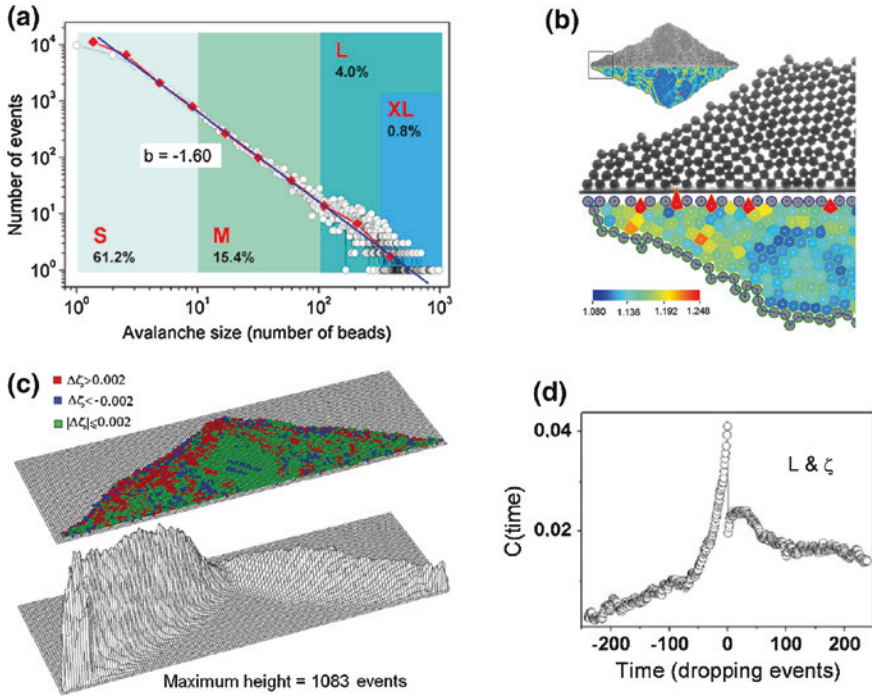


Fig. 2.8 Learning to predict from a tabletop granular pile. **a** Distribution of avalanche sizes for a two-dimensional pile of beads, which follows a power law with a slope of -1.60 . Avalanches—defined as the total number of beads changing position between two addition events—are grouped as small (S), 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* ζ . 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 ζ values), while *red cells* correspond to highly disordered regions (low ζ values). **c** *Top* Difference between the local averages of the ζ 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 ζ . 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 of 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 earthquakes¹⁴ 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.

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¹⁴In 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.

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