Remembering Georges Lochak[1]

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I was not very knowledgeable about the physics of Georges Lochak but I liked him very much as a cultured and most agreeable person, who organised memorable meetings in magnificent settings. The first part of this talk will be mainly reminiscences of my several long-ago encounters with him. The second part will be physics, as nontechnical as I can make it.

April 1982. I first met Georges and enjoyed the hospitality of the Fondation Louis de Broglie. The location was a villa outside Perugia; the title of the meeting was *The Wave-Particle Dualism: A Tribute to Louis de Broglie on his 90th Birthday.* A highlight for me was meeting Alain Aspect and hearing him present his then recent experiment demonstrating that quantum physics violates the John Bell inequality, thereby showing, contra Einstein, that ‘spooky action at a distance’ definitely exists. (I say “definitely”; that’s my opinion: there is a vast literature, mostly pro but some is con.) That conference was also where I had the pleasure of meeting Pierre Lochak.

For me, the Perugia meeting was also an opportunity to publish a paper I had submitted to a different meeting, where the cowardly editor refused to accept, at the end of the paper, my acknowledgment: “This work was not supported by any military agency”. The Fondation had no such compunction, and publication was straightforward. That paper, *Structures in semiclassical spectra: a question of scale*, showed that understanding the full richness of the connections between quantum and classical physics requires analysis of different scales in relation to Planck’s constant: on each scale, different borderland phenomena

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[1] Text of speech at the Sorbonne, 12 February 2022

appear, revealing different features of the classical limit.

Georges gave a speech in a grand hall underneath the city walls, to thank the mayor for supporting the meeting. He was perfectly capable of speaking English but was hesitant to do so. He asked my partner Monica (now my wife) to translate, and she agreed. She had learned perfect French growing up in Romania; but had only just moved to Bristol, and her English, although good, was not yet perfect. It was quite a challenge for her to provide instant translation of Georges's mesmerising oration, in rolling high formal French (reminding me of Charles de Gaulle).

The meeting combined philosophy as well as physics. I wasn't pretending when I angered Isabelle Stengers by telling her that I didn't know what structuralism is. She was more angry when I teased her (when I was pretending) with my psychoanalytical definition of Semiotics: between ego-otics and id-iotics.

September 1982. Monica and I attended a 'Colloque de Cerisy' in the Château de Cerisy-la-Salle in Normandy: *Logos et théorie des Catastrophes*, celebrating the work of René Thom. The venue was managed by two intimidating sisters, who wrote in advance to all participants, warning us that dinner on the first night would be at 20:00 precisely, and anyone who arrived late would miss it. We decided to travel by bike: taking the ferry from England to Cherbourg and then cycling to the chateau. It was a long hard ride, and despite our best efforts we arrived, disappointed and hungry, at 20:15 – to discover that we had made a mistake and were a day early! It was splendid to sleep with our faces brushed by bats, and to have the castle to ourselves for a day, in that season of calvados.

Usually, the events at the Centre culturel de Cerisy-la-Salle were about philosophy or literature or music, often slanted towards postmodernism - decidedly not Anglo-Saxon. But on this occasion the intellectual tone was lowered to include mathematics, with physics scraping in at the bottom. Also participating was a philosopher's dog: Alcibiade, who sat quietly through all the lectures, except for barking when a speaker made a particularly pretentious remark – or so it seemed to us.

On this second occasion, Georges was accompanied by Michou. It was a delight to get to know them as a couple. One magical evening, they drove us to the seaside to see the luminescence in the waves breaking on the beach. And in those days, when personal electronic devices were largely unfamiliar, we were impressed when Georges proudly showed a gadget that would reveal the location of the key to their new Renault car.

There were many talks, straddling the borders between physics, mathematics and philosophy, not only from Georges and from René Thom but other leaders of the developing theory of singularities, including Christopher Zeeman and David Ruelle. My talk was titled *Breaking the paradigms of classical physics from within.* The paradigms, that had recently been demolished by the works on chaos and fractals, were: the determinist fallacy, the smoothness prejudice, and the reductionist dogma, linked by the concept of singularities.

On to September 1984. Another Fondation de Broglie meeting, in the spectacular setting of Peyresq, an abandoned village on a mountaintop, restored as a centre for conferences. We drove there with our six month old son Tom. During the lectures, Christopher Zeeman and Martin Kruskal alternately dandled Tom on their knees; this could have been a distraction for the speakers but fortunately wasn't. The accommodation was comfortable though somewhat rustic. Michou reported with amusement that Georges ran screaming out of the shower after encountering a huge spider; as a fellow arachnophobe, this destroyed the enjoyment of my showers for the rest of the conference.

The meeting was *Dynamical systems: a renewal of mechanism.* This posed a problem for me. I could speak with some confidence about quantum theory, as in Perugia, and at least pretend to discuss philosophy, as in Cerisy-la-Salle. But how could I dare to talk about classical mechanics in the presence of world-leading dynamicists and mathematicians, includings James Callahan, Joseph Ford, Uriel Frisch, Luigi Galgani , Martin Kruskal, René Thom and Christopher Zeeman? But none of them were experimentalists, so I resolved the dilemma by demonstrating chaos with a magnetic pendulum toy: illustrating the theory by modelling the mechanism at successively more sophisticated levels. The title of my talk was *The unpredictable bouncing rotator: a chaology tutorial machine.*

Some years later (I don't remember how many) I was invited by Georges to speak at the Institut Louis de Broglie Seminar in Paris, in the Conservatoire des arts et métiers. It was a slightly surreal occasion. Around that time, I read Umberto Eco's novel *Foucault's Pendulum*, whose dramatic opening pages are set in the mysterious atmosphere of the basement of the Conservatoire, with the pendulum swinging among the earliest motor vehicles and aircraft.

I chose to speak about the Aharonov-Bohm phenomenon, a fundamental and subtle quantum effect. My audience consisted of members of the Institut, mostly elderly. During the discussion afterwards, I felt I had entered a time-warp. Those men (no women, as I recall) seemed trapped in the 1920s and 1930s, with conversations like this: "Bohr said. . . ", "but Einstein's reply was. . . ", "no, no, what about Schrödinger's response?..."

Afterwards, I met Georges several times. He visited us in Bristol, accompanied by Pierre. And we, en famille, visited Georges and Michou in their apartment in the Rue de Picpus. My memory is of them as the most gracious hosts - and the food! I particularly recall crème de Roquefort (recently, I tried to recreate it), and, while accompanying them to a family picnic in the Mer de Sable, the joyful cry "Et voila: le camembert!"

Now we come to physics. Georges was fascinated by monopoles, especially Dirac's, and wrote about them. My involvement with this area is indirect - a kind of abstract overlap. Before describing my monopole. I need to talk a little about abstractions. Usually I illustrate physics with pictures, but here I address the challenge of describing ideas using only words (this seems appropriate for abstractions).

Nonscientists find physics difficult. A common view is that this is because the ideas in our subject are abstract. This is not the reason. Built in to the very essence of our humanity is that we invent abstractions and come to regard them as real. An example is money. I can convince you that money is abstract, simply by asking: "The money in your bank account. Where is it, exactly?" Maybe physics is difficult because the abstractions are difficult? Certainly one must master difficult techniques and procedures to succeed in physics. But so it is with other abstractions: with music, you must practice long and hard. And money: to me, the financial concepts I would need to master if I wanted to be rich are impenetrably complex. The real reason why physics is hard to understand is not that it involves difficult abstractions; it is simply that the abstractions in our subject are unfamiliar. I will try to explain.

Objects that are electrically charged, positively or negatively (for example electrons, which are negative), exert forces on other charged objects, changing how they move, even when the two objects are not in contact. Faraday had the idea, which was both visual and abstract, to imagine each electrical object as the source of an influence – a 'field' – throughout the space surrounding it – by means of which it would act on other electrical objects. For a small object – an abstractly idealised point charged particle – its electric field can be represented as arrows, pointing outwards if it is positively charged and inwards if it is negative. This ‘particle plus field’ is called an electric monopole.

There are also magnets, that exert forces on other magnets, and on moving electric objects nearby. Faraday also imagined that magnets would be a source of magnetic fields, as a convenient way to think about the interaction between magnets and charges. But there was a difference: there are no magnetic monopoles analogous to the electric ones: no isolated magnetic poles - at least, none have been discovered. Instead, the elementary magnetic unit is a dipole, whose field resembles that of two infinitesimally close positive and negative monopoles, with the arrows emerging from one side and returning into the other. Assemblies of electric monopole charges and magnetic dipoles, and their fields, enable all of the vast range of ‘electromagnetic’ phenomena to be understood and analysed. Much of the technology that dominates our civilisation has emerged from this understanding: electric motors and generators, radio, TV, radar, ...

The lack of symmetry – electric monopoles but not magnetic ones – was regarded as troubling, until Dirac, in work of extraordinary subtlety, beauty and imagination, found a way in which magnetic monopoles could exist in quantum physics, at least theoretically. None has been found, but his idea has given rise to extensive developments by theoretical physicists. These included Georges; much of his research was devoted to exploring quantum magnetic monopoles.

My monopoles are analogous, but at a higher level of abstraction, also in quantum physics. They require more explanation. As discovered by de Broglie and perfected by Schrödinger, microscopic objects (molecules, atoms, electrons, nuclei. . .), whose properties and behaviour quantum theory explains, can be described as waves: in one of its formulations, quantum theory is a wave theory. Small objects are described by waves, and the characteristic property of waves is phase. Phase describes the stage of a waves’s oscillations at any position and time. Therefore phase is fundamental in the quantum world. Associated with the quantum wave of a localised object is its energy, analogous to the frequency of a vibrating drum or guitar string, that causes them to radiate waves of sound. And, just as the frequencies of drums and strings can form a discrete set (only certain vibration frequencies can exist, others not), so small objects can exist only in certain ‘energy levels’.

This is already pretty abstract, but we are not quite done yet. To get to our monopoles, we go further. We influence quantum objects by interacting with them: by changing their environment, for example the electric or magnetic forces acting on them. In particular, this changes the phases of their associated waves. Particularly significant are cyclic changes, where the environment returns to its original state after some time. The resulting phase change depends on the way the environment has been changed, in particular its geometry; it is called the 'geometric phase'.

Why geometric? Because the mathematics underlying the phase change also describes familiar phenomena where the geometry is obvious. One example is the way a cat can land on its feet when dropped upside-down; it does this by changing its shape – its geometry. Analogous to the quantum geometric phase is the cat's 180 degree turn. And when you reverse-park a car into a narrow space, you often find yourself far from the edge of the road; you must perform a series of cyclic steer-and-drive manouevres – geometric manouevres – in order to get closer to the kerb. Here, the analogy to the quantum geometric phase is the sideways distance closer that you get after each manoeuvre.

For geometric phases, the environment is described by quantities that can be changed – they are called 'parameters'. You can think of them as coordinates along the axes of an abstract space. Don't be afraid of this abstraction; every time you see a graph, for example showing how the exchange rate between the euro and the UK pound changes over time, you are presenting behaviour – in that case financial – in geometrical form: in the two-dimensional abstract space, on paper or on a screen. So, the cyclic change of an environment is conveniently represented geometrically as a loop in parameter space. And each loop has its associated geometric phase.

A useful way to understand the phase is via an abstract field, consisting of arrows, existing in this parameter space. Each loop, describing how we cyclically change the environment of a quantum system, is threaded by these arrows, and the geometric phase can be quantitatively described by the threading; it is called the flux through the loop of the geometric phase field. It was a surprise to discover that this abstract geometric phase field has monopoles, analogous to the electric field monopoles associated with electric charges. The geometric phase monopoles are places where the energy of the object you are interacting with coincides with another one of its possible energies. These energy-level 'degeneracies' (as they are called) are particularly important places in the quantum space of parameters, because for loops close to the associated monopoles the geometric phase can be large.

Here we complete a nice intellectual circle. These abstractions piled on abstractions, involving loops in the parameter space describing environments, have direct experimental consequences. For example, in the physics of condensed matter, in which the quantum objects are electrons, in their lattices of atomic nuclei, the phase monopoles in the abstract geometric phase field, associated with energy-level degeneracies, play a central role in determining the electrical and magnetic properties of the matter, in ways leading to the discovery of new materials.

It is both a pleasure and an honour to have been invited to offer these few remarks inspired by the memory of Georges Lochak, and I thank you.