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INSTITUTO DE CIENCIAS MATEMÁTICAS

EDITORIAL

A new year has begun, and another has come to an end, which makes us especially aware of the ICMAT as a "home for mathematics" that is open to the international community. This Newsletter contains information about some of the most interesting results that have recently been obtained at the Institute. However, it is also worth pointing out that the influence of a centre like the ICMAT is not confined to a mere list of its publications and its members, but will always extend to cover all the results, projects and collaborations that originate in our facilities and go on to bear fruit later, very often far from where they started. The prime objective of the ICMAT is mathematical research, arising from the stimulus of that original thought which produces decisive advances in science, enriching our knowledge of nature and leading to applications that were frequently once unimaginable.

Appointments for the next four years of new faculty members belonging to the three universities of the Institute were completed in January, with the ratification of the Steering Committee for the proposal drawn up by the Joint Committee (consisting of the three universities and the CSIC), and which had already received approval from the Governing Board of the ICMAT. We welcome these new members and congratulate those renewing their membership of the Institute. There is no doubt that their abilities, good work and dedication will help the ICMAT continue to advance, with an exciting project which this year includes the application for the third Severo Ochoa Centre of Excellence award. We are fully justified in feeling optimistic for its renewal, especially because of the enthusiastic and favourable report we have received from the external Scientific Committee appointed by the Ministry of Science, Innovation and Universities. However, we take this application very seriously, since the Severo Ochoa funding is vital for maintaining the activities of the Institute.

The appointment process as set out in the statutes has revealed an ostensible lack of symmetry between the CSIC and the three universities (UAM, UCM and UC3M). This is an important matter that should be addressed again when the statutes and the partnership agreement come up for revision. This asymmetry is also clear in the amount of red tape from the CSIC that the Institute has to deal with, which far exceeds the administrative formalities required of the other three institutions. The recent restructuring of the divisions in the CSIC is also a cause for concern, since there is no mathematician on the Commission that affects us directly and is charged with decisions concerning new posts and resources. This has revived some ghosts from the past, when we lacked any mathematical interlocutor on the commission. Negotiations with the CSIC Board have failed to yield a solution, a situation we made clear during the visit to the Institute by the coordinators of the area and the associate vice-president of research on February 5th.

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Image: ICMAT.

Antonio Córdoba.

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Since its creation, the ICMAT has belonged by right to the SOMMA (Severo Ochoa and Maria de Maeztu) network of institutions that have received funding through these two projects of excellence. The network is an interesting club whose aim, among others, is to act as a lobby for science and as an interlocutor for the Ministry. It is a mouthpiece for the expression of informed opinion and for putting forward measures to improve the management of these institutes, a task that is indispensable for enabling us to compete in better conditions in the world league of science. In the hypothetical pyramid of mathematics in a country, research occupies the upper vertex; the main base is education and the body the transfer of knowledge. The interrelation and communication between these three strata are fundamental for the health of the system. The ICMAT finds its natural niche on this vertex, and I believe we can say with pride that we have performed very well. We have shown ourselves to be adept at resolving conjectures that have been the object of mathematical desire, at producing good theorems that have been published in the best journals, and at successfully obtaining competitive projects from the Ministry, the ERC and the European Commission.

There is no doubt that the base of education is vital: together with the study of one's own language, mathematics plays a crucial role in general education. It is precisely through elementary arithmetic and geometry that deductive reasoning can best be taught, and thus install an operational system in the human brain. This is a difficult task that requires a great deal of support, both in the production of appropriate texts and in raising society's awareness of the important role played by mathematics. The ICMAT is itself committed to this valuable task. By means of our Communication Bureau, we collaborate with initiatives such as "*Café y Teoremas*" in the El País daily, or with the "*Mi científica favorita*" project, funded in part by the FECYT. We have also participated in the production of books as back-up material for Secondary Education, in collaboration with Spanish Federation of Societies of Teachers of Mathematics. It is important not to lose sight of the fact that the status we enjoy imposes its own restrictions. The ICMAT seal requires that whoever is involved in outreach must speak with due authority, and have a thorough knowledge of a subject when writing about it, while taking care to make it accessible to the public at large and putting it across with a modicum of originality.

Finally, the body: the transfer of knowledge. According to a fairly generalized opinion, we are on the threshold of a fourth industrial revolution in which the word "algorithm" is the key, and in which the centaur consisting of a mathematician with his or her computer is perhaps the most highly evolved specimen of contemporary technology. This explains the demand for mathematicians and computer scientists by industry, medical facilities, financial entities, security firms, telephone companies and large shopping centres. The change in the quality of students who reach degree level in mathematics has been both spectacular and highly positive. The same may be said of a numerous collective of mathematicians with a sound background in the discipline, capable of undertaking such tasks, contributing with their knowledge to improve the running and competitiveness of business and companies, and forming part of their necessary advisory bodies in matters of research and development.

The prosperity of the country depends on these things. So, what part should a centre like the ICMAT play in these affairs? This is an important question about which it seems to me that our faculty should pause to take stock and test its strengths. Mathematical problems stemming from the business sector pose real intellectual challenges; they constitute an incentive for the quality mathematical research that is our *raison d'être* and are undoubtedly always welcome. The work of the ICMAT in all these areas promises to be of great importance in the coming years.

Antonio Córdoba, ICMAT director and Professor in Analysis at Universidad Autónoma de Madrid.

Image: ICMAT.

REPORT: The Theory of Moduli Spaces: The Treasure Map

A thematic trimester devoted to the so-called *theory of moduli spaces*, organized by the ICMAT Donaldson-Hitchin Laboratory, was held at the Institute at the end of 2018. This field, the origins of which date from the middle of the 19th century with the work of the German mathematician, Bernard Riemann, is of great interest for solving problems in algebraic geometry, differential geometry and topology. It also has profound connections with quantum field theory and other areas of theoretical physics. "Moduli spaces are at the heart of classification problems in algebraic geometry. They are also related to the idea of quantization, which is a universal concept, and for that reason they are extremely useful", says ICMAT researcher, Mario García-Fernández, who is our guide to this incursion into the world of moduli spaces.

Ágata Timón García-Longoria. Classification is one of the great obsessions of mathematicians. It enables order to be established in abstract spaces, and provides a deep understanding of the type of elements of which they are composed as well as the relations among them. There are outstanding results obtained in this regard during the last century, such as the Poincaré-Perelman theorem, which classifies closed and simply connected 3-dimensional and states that only one such type exists: the 3-dimensional sphere. In general, the problem of classification in mathematics starts from a collection of objects one wishes to classify and an equivalence relation between them. This relation indicates which objects are the same and which are different. On the one hand, solving this problem involves making a list of all the categories of objects (a list modulo equivalence), and on the other establishing invariant quantities that help to differentiate between any two given objects. However, when it comes to the *theory of moduli spaces*, things are not quite so simple; for each choice of discrete invariants a continuum of parameters is obtained.

A simple example is the problem of differentiating circles in the Euclidian plane. A circle is defined by its centre (a point on the plane; that is, two coordinates), and its radius (a positive real number). If we consider all the circles with the same equivalent radius (that is, if we can take one to the other by means of a translation), then the radius alone suffices to parametrize the set. While it is not possible to make a list of the circles in the Euclidian plane, since it has an innumerable infinity of parameters, a certain structure exists in the continuum; for example, one may decide when one circle is larger than another. If, furthermore, one takes the "degenerate circles", given by cases of zero or infinite radius, and distinguish between them, the resulting moduli space is once again a circle.

This example illustrates three basic characteristics of the theory of moduli spaces. "On the one hand, when the space of equivalence classes is endowed with a natural structure, the moduli space resembles to a certain extent that which it classifies. On the other hand, the lack of finitude in the classification may be offset by adding degenerate objects, which could give rise to a compact moduli space (that is, a list can no longer be made, but at least we can try to construct something that can be held in the palm of the hand). Furthermore, in order for the moduli to possess the first property, it is on many occasions necessary to distinguish between some of the degenerate objects (in the previous example, if the zero is not identified with the infinite, one obtains a closed interval rather than a circle)", explains Mario García-Fernández, a doctoral assistant professor at the Autonomous University of Madrid and a member of the ICMAT at the Donaldson-Hitchin Laboratory, involved in the field of algebraic geometry.

An artisanal job of great technical difficulty

The first reference to the *moduli* appeared in 1857 in a paper entitled *Theorie der Abel'schen Functionen* by the German mathematician, Bernard Riemann, in the *Journal für die reine und angewandte Mathematik*. In this work, the researcher used the concept as a synonym for parameter to prove that on a compact, connected, orientable surface with g holes (genus), the conformal structures depend on $3g - 3$ complex numbers. However, it was not until the 1960s that David Mumford gave a formal definition based on the modern theory of schemes by the mathematician Alexander Grothendieck.

At the outset, algebraic geometers were interested in classifying algebraic varieties (defined as points that evaluate to zero on a collection of polynomials, known for obvious reasons as *zeros*) considered within a complex space. In this case, two varieties are considered to be equivalent if it is possible to transform one into the other in a linear manner. Nevertheless, it was soon realized that it was also possible to construct moduli spaces for more sophisticated objects (such as varieties, schemes, bundles, sheafs, etc.) by employing the so-called *geometric invariant theory*. This theory, introduced by Mumford, studies the points of an algebraic variety modulo the equivalence given by the symmetries of action of a group. For the space that parametrizes the orbits to have a new structure of algebraic variety, certain pathological objects (unstable or semi-stable) that "stick" to others in the orbit space are identified (and, in some cases, discarded). As García-Fernández explains: "In each particular problem, the choice and identification of pathological objects, as well as those that appear represented in the moduli, constitutes an artisanal job of great technical difficulty". Certain topological objects being fixed, the moduli is an algebraic variety that usually has singularities.

Moduli spaces are also employed in the field of differential geometry to classify geometric structures (tensors, connections, etc.) module symmetries in a fixed ambient variety. Both the initial parameter space and the group (diffeomorphisms, bundle automorphisms) have an infinite dimension, so the use of the theory of Banach spaces is necessary to construct the moduli spaces.

Once the moduli space has been obtained, its topology is sometimes studied in order to obtain information of the variety in which the classified objects *reside*. "This idea is similar to the Feynman path integral: one considers the moduli space of all the objects of a certain type within a space M (for instance, the connections that satisfy a partial differential equation), and the quantities in this space are measured: that is, one tries to *integrate*, in the manner of Feynman, on all the paths in order to find the partition function in his theory", says García-Fernández. In practice, *to integrate* means to measure *cohomological quantities*. To this end, the moduli space must be compact, so it is important to compactify by adding pathological objects. Simon Donaldson applied these ideas to the 4-manifold connection space in the 1980s, which led him to his polynomial invariants (and a Fields Medal in 1986).

In the following decades, this approach has facilitated the response to questions such as: How many rational curves pass through a certain number of points? As García-Fernández explains: "A classical problem that was partially solved thanks to the moduli theory was the Clemens' conjecture about the number of rational curves (2-spheres) on 3-dimensional Calabi-Yau manifolds". Philip Candelas, Xenia De la Ossa, Paul S. Green and Linda Parkes predicted the numbers of the Clemens' conjecture by means of the moduli space of the Calabi-Yau manifold, relating it with that of its mirror. Subsequently, Maksim Kontsevich proved these predictions by using the moduli space of Mumford stable curves. "This led to the modern version of *counting curves*," says young researcher García-Fernández, "which is enumerative geometry. A mainstay of this theory is the definition of an "integration theory" (*virtual cycles*) in moduli spaces".

From algebraic origins to string theory

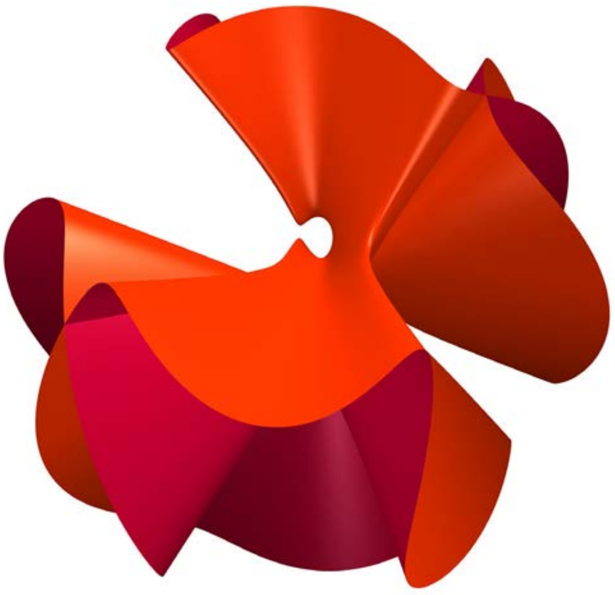
"The moduli problem, that is to say the study of spaces that parametrize different types of geometric structures in algebraic and differential geometry, is in itself a universal and central problem in mathematics", says Óscar García-Prada, and adds: "Of course, the fact that moduli problems are closely linked to quantization makes it even more interesting".

It was as a result of this relation that at the end of the 1970s some unexpected applications to physics emerged. "With the birth of quantum field theory, in particular the Feynman path integral method and the later development in the 1950s by Yang and Mills of gauge theories, moduli spaces became a subject of interest for physicists", explains García-Fernández. In this context, the moduli space is used to classify classical solutions of field theory (solutions to a system of partial differential equations) module physical equivalence. "This is a key idea in the quantization of the theory".

"I understand mathematics as a study of how we perceive the world. From this point of view, quantization is a process by which we infer a structure in the traces of experience of the microscopic world, based on our abstract methods for ordering the experiences of the macroscopic world (on our scale)", muses García-Fernández, and goes on to say that: "In this process, moduli theory arises mysteriously from the Feynman path integral. Seen in that light, it seems to me that quantization, which leads us from macroscopic ordering to microscopic ordering, is something more fundamental than moduli theory".

Whatever the case, from the early 1980s the applications of this theory became increasingly numerous; in topology, differential geometry, algebraic geometry, representation theory and so on. As García-Fernández states: "Moduli spaces are inherent to classification problems in algebraic geometry. They are associated with the idea of quantization, which is a universal concept, and that's why they are so useful".

At present, the construction of "quantum invariants" of knots using moduli spaces is a very active area in topology, and so is the so-called Bridgeland theory of stability conditions, in relation to moduli spaces of bundles. "On the one hand, a stability condition is the tool required for detecting pathological objects in the construction of a moduli. On the other, all these conditions together give rise to a complex manifold with a very complicated topology. This manifold is a mathematical version of what physicists refer to as the "Kähler moduli" in a Calabi-Yau manifold. Physicists observed that certain surgeries in a Calabi-Yau manifold gave rise to a continuous process in their theory. Mathematically speaking, the aim is to understand whether a universal object exists that survives these surgeries. This object is the "derived category", says García-Fernández, "and also its space of stability conditions". This without doubt is a research field in a state of expansion, with relations ever more numerous in physics and with extraordinary depth, which will enable us to discover unimaginable mathematical treasures.



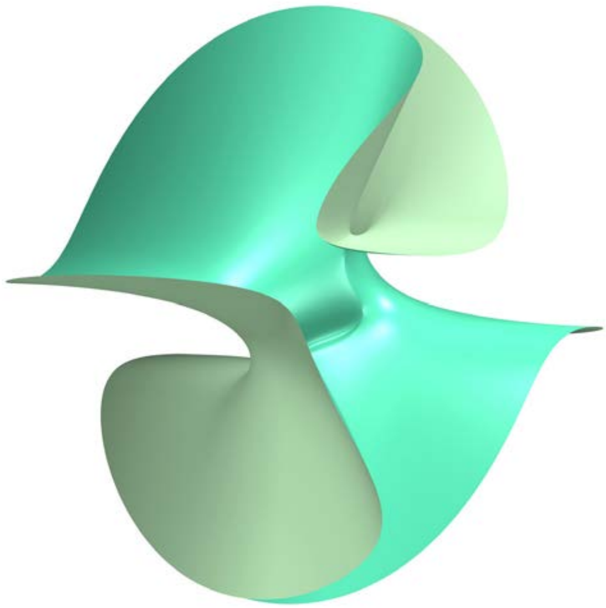


Image: Dr Tom Coates (Imperial College London).

Fano manifolds are algebraic geometry objects studied with moduli spaces theory also.

Hot topics in moduli space theory

During the months September, October, November and December, 2018, a thematic trimester devoted to moduli space theory and organized by the Donaldson-Hitchin Laboratory was held at the ICMAT. The schedule included two schools and a conference, a visitors' programme and a regular seminar. The opening event was a conference, "Group actions in algebraic and symplectic geometry", which took place on October 2nd and 3rd, and in which a roundtable discussion aimed at mathematicians in general was held, chaired by Dame Frances Kirwan, Savilian Professor of Geometry at Oxford University and member of the ICMAT external advisory committee. Over these months, more than 70 researchers from 15 countries visited the centre to share their results from basic areas of moduli spaces: Higgs bundles, mirror symmetry and Langlands duality, Gauge theory, special holonomy and special metrics.

Gauge theories

In the 1980s, Michael Atiyah and Raoul Bott studied the Yang-Mills equations, which are fundamental equations of theoretical physics describing elementary particles, on Riemann surfaces, when they introduced the mathematical version of gauge theories. As described by Mario García-Fernández, "this theory consists in the study of *connections*, certain objects that generalize the notion of magnetic field in physics and the notion of parallel transport in geometry. These connections must satisfy a partial differential equation analogous to Maxwell's equations or to the most complicated Yang-Mills equations in the standard model". The main goal of this study on gauge theory is the moduli space of solutions to the said equation, modulo symmetries.

One example of Gauge Theory is Donaldson's theory. Simon Donaldson constructed highly subtle invariants of 4-dimensional differentiable manifolds. His works became popular in the area and led to the Seiberg-Witten theory of invariants, which provides more efficient ways of calculating invariants. As researcher Mario García-Fernández says: "The basic idea is to study the geometric and topological properties of moduli spaces for connections on a fixed manifold M, thereby obtaining topological invariants of this manifold. This idea is reminiscent of the Feynman path integral in quantum field theory".

In the 1990s, Donaldson and Richard Thomas proposed a generalization of gauge theories for manifolds of higher dimensions, which gave rise to the modern Donaldson-Thomas theory of invariants. More recently, studies have begun on gauge theory in 7 and 8 dimensions for metrics with holonomy G2 and Spin (7). The study of gauge theory in higher dimensions is a hot topic and a source of increasing activity. The Simons Foundation has recently devoted one of its prestigious projects of collaboration to this subject.

Higgs bundles

Higgs bundles constitute a particular case of gauge theory and also arose from the Yang-Mills equations. The solutions to these partial differential equations in dimension four (the usual space-time dimension) lead to the so-called *instantons*. Nigel Hitchin studied instantons in R4, which are symmetrical in translation in two directions. These equations extend from the plane to more sophisticated objects such as Riemann surfaces, and are those called Hitchin equations, which lead to the *Higgs bundles*.

Image: ICMAT.

Image: ICMAT.

The Research Programme on Moduli Spaces held several scientific activities. Left picture: Participants in the school and workshop on Special Metrics and Gauge Theory, celebrated from 10 to 14 December 2018 at the ICMAT. Right picture: Participants in the School and Workshop on New Trends in Higgs Bundle Theory, celebrated from 12 to 16 November 2018.

"The space of solutions to these equations is extremely rich. They have a fundamental connection with the study of topological objects, such as the representation of the fundamental group of a surface", explained Oscar García Prada in an article published in the journal *Notices* of the *American Mathematical Society*. This *representation* is a way of expressing the fundamental group, which we wish to understand, by means of matrices. "In general, it's not easy to understand the representations of a fundamental group. To do so, Higgs bundles are used, a concept of algebraic geometry that dates back to the polynomial equations that define space", says Carlos Simpson, a researcher at the CNRS Laboratoire J.-A. Dieudonné and the University of Nice. Simpson was one of the plenary speakers at the congress New Trends in Higgs Bundle Theory, held at the ICMAT.

Image: ICMAT.

Carlos Simpson (Laboratoire J.-A. Dieudonné, CNRS, and Niza University) was one of the plenary speakers of the New Trends in Higgs Bundle Theory Workshop, taken place at the ICMAT.

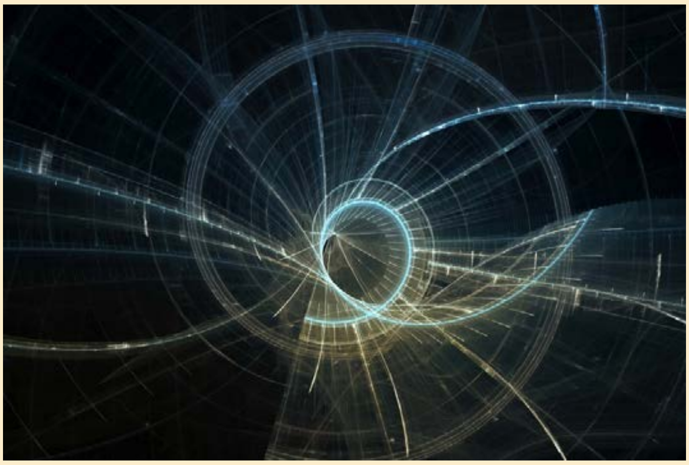
Higgs bundles are manifested in different forms; as solutions to certain differential equations; as algebraic objects that correspond to representations and homomorphisms of the fundamental group; as objects in algebraic geometry, and to algebraic moduli spaces that are useful for defining invariants of dimension 3. "Nigel Hitchin's fundamental contribution was proving that you can do without one of these objects by resolving a certain nonlinear partial differential equation (known as the *Hitchin equation*)", states Simpson.

This correspondence between topology and classical algebraic geometry is, according to Simpson, the great virtue of Higgs bundles. "In this way, things can be defined by using polynomial equations and by studying the moduli spaces; or all the possible Higgs bundles can be parametrized in order to obtain an algebraic variety, given by polynomial equations, and thereby apply the techniques of basic algebraic geometry. It enables you to use techniques in one direction to prove things in the other direction, and vice-versa", explains this North American mathematician, a doctor from Harvard University who has occupied chairs at the Université Toulouse III and at the University of Nice.

Mirror symmetry

In four dimensions, elementary particles have associated with them a certain *spin* (rotation in one direction or another); if we imagine a world where they rotated in the other direction, this would therefore be symmetrical with the first. "It turns out that this direction of rotation depends on the space chosen in the theory. The mirror symmetry theory states that both options for the spaces would be in some way paired. At first this seemed rather improbable, but later classes of sufficiently large examples were generated, and at present it seems that this "paired" reality is in fact true", explains Philip Candelas, professor at Oxford University, and the person who gave the talk "The zeta-function for one-parameter families of Calabi-Yau manifolds"at the "Special Metrics and Gauge Theory" conference-school.

"Some properties of these spaces are difficult to calculate for one of the twins, but easy to do for the other. By using mirror symmetry, one may assume that it is more or less the same in both and study it in the easy case", continues Candelas. The truth is that it is a speculative theory, and mathematicians are still trying to prove it. As Xenia de la Ossa, likewise a professor at Oxford University, goes on to say: "Many of the available proofs are based on physical experiments, which lack mathematical rigour".



Moduli spaces theory has strong connections with the string theory, quantum field theory, and other fields of the theoretical physics.

In any event, some interesting mathematics has been developed along the way. As De la Ossa states: "the idea of mirror symmetry has been extended to other structures in string theory, such as branes". Simpson gives an example: "Right now we are wondering if the Hitchin fibration for a group and the Hitchin fibration for the Langlands dual group are mirror to each other." The geometric Langlands program states that an identification must exist between the local systems on the curves of the representations of the fundamental group of the curve in a Langlands dual group. "Works have recently been published that seek to understand this duality by means of mirror symmetry".

"Mirror symmetry was discovered in string theory when it was observed that two Calabi-Yau spaces with different topologies could give rise to the same superconformal field theory", explains Mario García-Fernández. In mathematics, this identification between physical theories is manifested geometrically by moduli spaces. He goes on to say that "if two Calabi-Yau spaces, X and Y, mirror each other, then the moduli space that parametrizes the complex deformations of X is identified with a quantum correction of the moduli space that parametrizes the metric deformations of Y".

Once again, this enables certain problems to be studied in an easier way. As García-Fernández states: "Whereas the complex moduli space can be described in terms of classical algebraic geometry, the *quantum corrections* of the moduli space require the use of the powerful techniques of enumerative geometry". This fact has led to, for example, the Gromov-Witten modern theory of invariants, which count 2-spheres compatible with the complex structure of a Calabi-Yau.

INTERVIEW: Xenia de la Ossa and Philip Candelas, University of Oxford researchers, collaborators and married couple

Xenia de la Ossa: "My autonomy as a researcher is often called into question"

Image: ICMAT.

Xenia de la Ossa, and Philip Candelas (University of Oxford) were speakers in the School and Workshop on Special Metrics and Gauge Theory.

Laura Moreno Iraola and Ágata Timón. **Xenia de la Ossa (Oxford University) and Philip Candelas (Oxford University), scientific collaborators and married couple, have moved back and forth between physics and mathematics from the beginning of their careers. They are both currently engaged in research work in the field of algebraic geometry and its interactions with physics, especially in string theory. We spoke to them during their latest vist to the ICMAT, where they delivered talks as part of the School and Workshop on Special Metrics and Gauge Theory, which took place in December of last year as the closing event of the Thematic Trimester on Moduli Spaces, held at the Institute between September and December.**

How did you first get involved in mathematics?

X: As a child I never had any problems with mathematics. I always liked the subject, but I never imagined devoting my career to it. Even when I entered university, I didn't think I would end up studying Physics and Mathematics because I enrolled in Biology in Guatemala. During my first year there I enjoyed the Physics and Mathematics courses, and thanks to some very good teachers I saw what these disciplines were all about and switched courses to Physics. Some years later I did my doctorate in that subject. Mathematics came in little by little, through my research work.

P: It was at school, I guess, but not right away. I developed a particular liking for mathematics when I was about fifteen and ended up studying that subject at Cambridge. As part of that course there was the chance of opting for theoretical physics and that's what I chose. Later I went to Oxford to do my doctorate and that's when I started to do research. I've always been on the mathematical side of physics, especially when I specialized in string theory, whose sophistication pushed me further towards mathematics.

What was your first contact with mathematical research?

X: It was when I did a Master in Costa Rica. I had a very good supervisor and I started researching with him. In fact, we published a paper together. Then I started my doctorate and I carried on working with him.

Your first contributions were to do with theoretical physics, in string theory and with algebraic geometry. How did you get into that? Why were you interested in that field?

X: Not only algebraic geometry, but also geometry in general, which appears in string theory. I learned about mathematics little by little, from the questions that arise in string theory. For example, according to that theory, space has 10 dimensions, put you have to obtain theories in four dimensions. So there must exist an inner space, which has to be small and whose properties have an enormous impact on the properties of 4-dimensional physics. There's a very nice dictionary between the mathematical properties of this inner space and physics. For example, the form of this inner space has to do with how many particles there are in the theory. These spaces can become deformed and one of them describes the physical quantities in four dimensions. Certain mathematical structures are significant in physical theory. Other parameters also exist that are more hidden.

"For example, according to that theory, space has 10 dimensions, put you have to obtain theories in four dimensions. So there must exist an inner space, which has to be small and whose properties have an enormous impact on the properties of 4-dimensional physics"

What part does algebraic geometry play in all this?

X: Algebraic geometry is a way of studying spaces explicitly. For instance, a circle can be described as a quadrastic equation in a plane. In other dimensions, it's possible to describe very complicated spaces by giving polynomials in ambient spaces. The topology of space can be highly complicated; there may be hollows, contortions, etc., that tell you something about the physics.

How do a married couple come to devote themselves to mathematical research and collaborate together at the same time?

X: It can get very noisy; there's a lot of argument. When your partner is also a colleague you talk about the same thing all the time. Our daughters make fun of us because of this.

P: Because when we sit down to dinner we carry on talking about the problem we're working on.

X: But apart from that, it's like working with any other professional colleague. Each one of us has their own collaborators, but we're always writing something together.

Have you ever noticed that more importance is given to Candelas' work than to De la Ossa's because she's a woman?

X: Yes, that often happens, right up to the present time, especially the continuous calling into question of my autonomy. Furthermore, when people give talks and speak about our work, they just refer to Philip, even when I'm sitting in front of them. That's still happening now, and Philip is aware of it too. It's difficult and hard to remedy.

Do you belong to any association or collaborate in meetings or conferences devoted to promoting equality in mathematics?

X: In my daily work, I'm always trying to ensure that women don't get overlooked. Although there aren't very many of us, the fact that only men get scheduled to speak in scientific conferences cannot be justified. Sometimes it happens openly, but at other times it's an unconscious bias. For my own part, I try to counteract this situation as far as I can in my daily work. I've also organized conferences for women at the intersection between physics and mathematics. The idea is to create a network of contacts with other women to discuss this issue and see what can be done to solve it.

What's the current situation of women in mathematics? Have you noticed any change since you were a student?

X: i think there's a greater awareness of the issue now, but I haven't noticed any improvement. There hasn't been any increase in the presence of women. I don't feel that the situation is any different.

What initiatives do you think can be taken to achieve a real equality?

X: It's a difficult subject. I don't really know what to say, except to carry on working to get rid of discrimination in your day-to-day work. Not only gender discrimination, but also racial discrimination.

P: With the outreach we have at the moment, and with many initiatives, attempts are being made to encourage young women to take up a career in research.

X: Yes, and not only girls, but disadvantaged boys as well. There's been some improvement in that respect, but I still don't think the situation has changed much in spite of that. I don't have the statistics, but I speak to other women about this problem, and many of them, whether young or mature, still feel the effects of discrimination. It's still happening with our own daughters.

De la Ossa: "In my daily work, I'm always trying to ensure that women don't get overlooked. Although there aren't very many of us, the fact that only men get scheduled to speak in scientific conferences cannot be justified"

ICMAT QUESTIONNAIRE: Frances Kirwan (University of Oxford)

"The ICMAT has an excellent environment for doing mathematical research"

Image: ICMAT.

Frances Kirwan (Universidty of Oxford) is a member of the ICMAT External Scientific Committee.

Frances Kirwan (University of Oxford), ICMAT External Scientific Committee member, is an expert in algebraic and symplectic geometry, specially, in moduli spaces and geometric invariant theory (GIT), and its connection with Symplectic geometry. Kirwan is a Professor at University of Oxford and the first woman in becoming a *Savilian Professor* at the same institution. She studied Mathematics at the *Clare College* of Cambridge and did her PhD under the supervision of the Fields Medal Michael Atiyah at University of Oxford. Her work has earned her numerous awards, among which may be mentioned her fellowship in the Royal Society and that she became the second female president of the London Mathematical Society (2003 - 2005).

She visited the ICMAT as a speaker in the Group actions in algebraic and symplectic geometry activity of the research thematic on moduli spaces (celebrated from September to December 2018).

Laura Moreno Iraola

Why did you choose mathematics ahead of any other subject?

I was interested in other subjects such as history at school, but I knew that I could continue my interest in those subjects by reading while I wouldn't be able to continue my interest in maths without studying it at university.

Besides mathematics, which activities do you like most?

Reading, going on long walks in the countryside.

How was your first encounter with mathematical research? How did you become interested in algebraic and Symplectic geometry?

I chose an essay topic (on uniform locales) which involved a little research when I was in my final year as an undergraduate at Cambridge doing Part III Maths. Martin Hyland, who supervised that essay, suggested I might consider a PhD in algebraic geometry.

You studied your PhD under the supervision of Sir Michael Atiyah, how did you become his student? What did you learn most from him? What was your experience of working with him like? Have you been collaborating with him since then?

I was brought up in Oxford, and when I was staying at home with my parents during my last year at Cambridge I had the chance to meet Michael and get his advice on what to do next ... in particular whether to apply for PhDs in the US. He told me to put his name on my application form if I decided to apply to Oxford, which I did.

If you could have a one hour blackboard discussion with an ancient scientist, who would you choose to meet and what would you discuss?

Maybe Erastosthenes (ancient Greek mathematician, calculated the circumference of the Earth with astonishing accuracy in the third century BC) about his calculations (including the tilt of the Earth's axis and possibly the distance of the Earth from the sun) and creation of maps of the world with parallels and meridians, etc.

Are you working on a new paper right now? What is it about?

Several. One is about Morse theory.

You gave the "Moduli spaces of unstable curves" colloquium at the ICMAT last October; could you give us an idea about this subject?

It was about moduli spaces of unstable curves. Moduli spaces are used in classification problems in geometry; one of the main hopes is to understand better how to classify different sorts of geometric objects.

You are member of the external scientific committee of the ICMAT, what would you highlight most of the Institute?

It has an excellent environment for doing mathematical research.

You were convenor of the EWM (European Women in Maths) in 2008, how did you become part of this? What was your work about?

I think I first got involved through Caroline Series, who was one of the founder members of EWM. I became convenor at a time when EWM was having some difficulties but it seems to be flourishing now. I went to a very enjoyable EWM meeting in Graz a couple of weeks before my visit to ICMAT this autumn.

From your point of view, what is the current situation of women in mathematics? Was it different when you were a student and postdoc? Do you think it is changing for the best?

I think many things are getting better, though I didn't have any difficulties as a graduate student at Oxford where, for historical reasons related to the former women's colleges and the joint appointment system, there were already 8 or 10 women with permanent academic positions in the maths department when I started as a graduate student. But one thing which (perversely) makes things more difficult for women (and also men) these days is the much greater availability of postdoctoral positions. When I started out you had to be very lucky to get any sort of postdoctoral position, but if you got one you were much more likely than is the case now to get a permanent position. These days mathematicians are expected to move from one postdoctoral position to another several times before getting a permanent position, probably in many different institutions and different countries. Although that can be very rewarding, it creates many difficulties for people with partners and families.

"Moduli spaces are used in classification problems in geometry; one of the main hopes is to understand better how to classify different sorts of geometric objects"

From your experience, which activities do you think are better for addressing this issue?

I wish I knew.

Do you usually get involved in meetings, talks or committees about gender equality in mathematics? In which way? Could you describe any of them?

I have been involved with EWM and some activities organised by the London Mathematical Society in the UK, for example trying to encourage more schoolgirls to study maths in the final years of school and at university.

Image: ICMAT.

Frances Kirwan gave a colloquium at the ICMAT in October.

SCIENTIFIC REVIEW: A resolution of Guth's conjecture regarding the Kakeya problem on algebraic varieties

Original Title: "On the polynomial Wolff axioms"
Authors: Nets H. Katz (California Institute of Technology) and Keith M. Rogers (ICMAT)
Source: *Geometric and Functional Analysis*, 28 (6), pp 1706-1716
Date of online publication: September 14th, 2018
Link: https://link.springer.com/article/10.1007/s00039-018-0466-7

Fourier analysis describes the process of decomposing a signal into its frequencies and then recomposing the signal from the frequencies. It has proved to be an extremely useful tool in mathematics, physics and technology. For example, for storing and sending sound files in a more efficient way. The human ear cannot hear very high or very low frequencies, so these can be discarded before storing the Fourier transform of a signal, thus saving memory. In order to reproduce the new sound, the signal is recomposed by adding up the terms of the series.

Unfortunately, however, the process is not infallible, and it is not always true that when the frequencies are summed up again, the resultant signal sounds like the original one. Whether Fourier series, in space with n→1, converge to the original signal or not is connected to whether tubes with arbitrary positions, but dfferent directions, overlap *a lot* or not. This is because the signal can be further decomposed into *wave-packets* which essentially live on the tubes. Although there may be cancelation when summing up the wave-packets, the main issue, ignoring the oscillation, is how much the tubes can intersect. This is quantified precisely in the *Kakeya conjecture*.

The first connection between Fourier series and the Kakeya conjecture was made in a seminal work by Charles Fefferman [6] in 1971. This connection was later fleshed out in works by Jean Bourgain [1] in 1991 and Terence Tao [13] in 1999. However, the Kakeya conjecture had been studied much earlier, for other reasons. The problem, as initially considered, was to determine how large a set must be for a needle to be continuously turned around within it, pointing in every possible direction as it turns, before eventually returning to its original position. Surprisingly, sets exist that satisfy this property and which have arbitrarily small Lebesgue measure (the technical term for area or volume). Indeed, there are *Kakeya sets* (sets containing a unit line segment in every direction) with zero measure.

However, there are zero measure sets which are smaller than others. For example, a line in is clearly smaller than a plane because it is one-dimensional, whereas the plane is two-dimensional. The Kakeya conjecture states that *Kakeya sets* must have dimension *n*. That is to say, although they can have zero measure, they cannot be any smaller than that.

The Kakeya conjecture in was solved by Antonio Córdoba [3] and Roy Davies [4] in the 1970s (the oscillatory versions of the problem were solved by Charles Fefferman [5], Lennart Carleson and Per Sjölin [2]). However, for higher dimensions, the conjecture has resisted the best efforts of the harmonic analysis community ever since.

Now, in [11], Nets Katz and Keith Rogers have proved a weak form of the Kakeya conjecture in higher dimensions, under the assumption that the line segments have some additional algebraic structure. The problem is first discretized, so that the angle between any two-line segments is greater than 1/*x*, where *x* is a large number. If we assume that the line segments are all found on the surface of a two-dimensional cone in , it is easy to deduce that there can be no more than a constant multiple of *x* line segments. In [11], the correct bound was proved for any real algebraic variety in any dimension, confirming a conjecture of Larry Guth [7]. Furthermore, a generalized version was proved that considers semi-algebraic sets rather than algebraic varieties, thereby solving a problem posed by Guth and Joshua Zahl [8].

Furthermore, in [9], Jonathan Hickman and Rogers proved that if a Kakeya set has no algebraic structure at all, then in that case the Kakeya conjecture is also true. Balancing between this and the result of [11], they showed that Kakeya sets cannot be too small in any case, even when the sets have an intermediate amount of algebraic structure. For certain ambient dimensions *n*, this argument improves the best previously known lower bounds (obtained by Katz and Tao [12], on the one hand, and by Wolff [14] on the other) for the fractal dimension of any Kakeya set. Progress on one of the oscillatory versions of the problem was also obtained in [10].

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SCIENTIFIC REVIEW: Global solutions for the surface quasi-geostrophic equation

Original Title: "Global smooth solutions for the inviscid SQG equation"
Authors: Ángel Castro, Diego Córdoba y Javier Gómez-Serrano
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The Surface Quasi-Geostrophic equation was originally derived for modelling the movement of large masses of air in the atmosphere and, in particular, for frontogenesis, the formation of sharp fronts between masses of hot and cold air. This is an equation that reduces the dynamics of fluids from three to two dimensions, by eliminating altitude and working on a plane – in this case, the surface of the Earth, taken over a small region so that its curvature can be disregarded. The equation is given in terms of temperature and is an evolution equation. Given some initial conditions of temperature for an initial time, the solution of the equation yields as a result the temperature over subsequent time. Once the temperature is known, the movement of the fluid can be determined. In this paper, [1], the study is conducted on all the plane , although studies exist in which bounded regions are also considered.

Despite the use that the SQG equation may have in other sciences, this is not the characteristic that has prompted the interest of the authors of this present study. In [2], Peter Constantin, Andrew Majda Esteban Tabak pointed out that the structure of the equation is similar to that of the Euler equation for an incompressible fluid. Indeed, in both the Euler 3D equation for the formulation of vorticity and the equation for the gradient of the temperature on the SQG equation, a transport term appears, with a velocity given by an operator of degree -1 in derivatives and a quadratic term that involves singular integrals. However, the Euler equation considers the evolution of a vector of three components in 3 dimensions and an SQG with a scalar in two dimensions, the latter therefore being easier to manage. In turn, the Euler equation is a limit case of the Navier-Stokes equation, in which the viscosity of the fluid is taken to be zero. The burning issue in fluid mechanics is to determine whether the Navier-Stokes solutions are globally regular or if on the other hand they develop singularities in finite time. This question remains unresolved in both the Navier-Stokes equations and the Euler equation. Constantin, Majda and Tabak studied the SQG equation with the aim of gaining a greater understanding of the Euler equation, and the authors of this paper have followed in their footsteps. The search for singularities in the SQG equation could provide a better understanding of the mechanisms governing the behaviour of the Euler equation.

Until the publication of the paper, it was known that the SQG equation remained smooth for a short time interval, regardless of the initial conditions, but the only known examples in which the solutions remained smooth over all time were the trivial stationary solutions, when the temperature is given by any radial function.

In this paper, [1], the authors show that families of initial conditions exist such that the solution is smooth over all time, without the development of any singularity. Such solutions consist of a global rotation with constant angular velocity of the temperature. To achieve the proof, the problem is reduced analytically to check an open condition that is then rigorously demonstrated by means of computer-assisted proofs using interval arithmetic.

The analytical part is based on the application of the Crandall-Rabinowitz theorem, which involves the study of the spectrum of the operator given by the linearization of the SQG equation. It is this study that requires the obtention of certain bounds of the eigenvalues of the linear operator, which, module small errors that can be estimated with pen and paper, are given by enormous but explicit expressions, and it is the obtention of these bounds for which the computer is employed. The philosophy of interval arithmetic is as follows: a computer is unable to yield rigorously the result of any operation because only an infinite amount of numbers is available in its register. Nevertheless, this register of numbers can be used to work with a finite number of intervals covering a large part of the real number line, and it is with these intervals that rigorous estimates of complex operations can be obtained. For example, if we wish to add A plus B, it may be said that A is in interval I and B is in interval J; the sum of I plus J produces the interval K, and then it may be rigorously stated that the result of A plus B is within K. If the interval K is sufficiently small, whatever this may mean in your problem, you have won.

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SHE DOES MATHS: Makrina Agaoglou

Mathematics for protecting the oceans

Image: Makrina Agaoglou.

Makrina Agaoglou is a postdoctoral researcher at the ICMAT. Image: Makrina Agaoglou.

Makrina Agaoglou (Thessaloniki, 1986) gained her PhD in Applied Mathematics at the Aristotle University of Thessaloniki in 2015 with a thesis entitled *Bifurcation and Stability of Periodic Solutions in Nonlinear Lattices with Analytical Methods*, which she completed under the supervision of Vassilis Rothos. Since January, 2016, she has been a postdoctoral fellow at the University of Massachusetts Amherst, the Aristotle University of Thessaloniki and the Mathematical Institute of the Slovak Academy of Sciences in Bratislava. Since 2018, she has been a postdoctoral researcher at the ICMAT under the supervision of Ana María Mancho.

Research Areas:

Dynamical Systems, Ordinary and Partial Differential Equations, Nonlinear Waves, Solitons, Chaos, Fluid Dynamics, Patterns Formation, Bifurcation Theory.

Javier Fuertes. When the fishing vessel "Oleg Naydenov" caught fire in 2015 off the coast of Gran Canaria carrying 1,400 tons of fuel, the rescue mission cost the Spanish state 43 million euros. This type of incident could be handled better if we had a greater understanding of geophysical flows; specifically, the processes of transport and mingling of different media in the ocean. Mathematics, and in particular dynamical systems and computational techniques, are vital tools in this task. Makrina Agaoglou at the ICMAT is conducting research in these types of phenomena, which could also be applied to the study of the dispersion of plastic and other waste, the proliferation of algae, nutrients and heat. These are just some of the pressing problems in coastal areas, with great economic repercussions for public administrations, environmental protection organizations, port authorities and industry.

In particular, Agaoglou is developing mathematical methods capable of determining new data of interest in physical systems, such as the velocity of particle propagation between cells or a better understanding of the different types of laser. She has specialized in theoretical and computational dynamical systems as well as analysis applied to the study of nonlinear waves in ordinary and partial differential equations. She has also worked on reaction-diffusion systems, which are used to model the formation of patterns in nature; for example, the pigmentation of different animals and other biological processes such as angiogenesis in tumour growth, the dynamics of nephrons in the kidneys, the study of the Klein-Gordon equation and the nonlinear Schrödinger equations, applied to the modelling of nonlinear optical systems and condensed matter physics.

In addition to her mathematical research, Agaoglou is also interested in the social aspects of science. Together with ICMAT researcher Patricia Contreras, she has been one of the organizers of WOMAT, an association of women researchers in Madrid, the aim of which is the creation of a more inclusive mathematical community to highlight women's role in research. The first meeting of this association was held at the ICMAT on December 10th, 2018, when in a relaxed and informal atmosphere over coffee the participants came together to share ideas and discuss projects. The fourth such meeting will take place in March this year.

PORTRAIT: Diego Alonso Orán, predoctoral student at the ICMAT

"Research is a merry-go-round, with ups and downs and continuous learning"

Image: Diego Alonso Orán.

Diego Alonso Orán studies the behaviour of solutions of partial differential equations arising from fluid mechanics at the ICMAT.

Diego Alonso Orán (Santa Cruz de Tenerife, 1991) has been a ICMAT researcher for four years, after studying a Master's in Mathematics and applications at the UAM. In April, he defends his PhD about the behaviour of solutions to the surface quasi-geostrophic equation, studied under the supervision of Antonio Córdoba (ICMAT-UAM).

Laura Moreno Iraola. Diego Alonso Orán (Santa Cruz de Tenerife, 1991) is on the last lap of his doctoral thesis. He has spent the last five years at the ICMAT researching the behaviour of solutions to the surface quasi-geostrophic equation under the supervision of Antonio Córdoba (director of the Institute and professor at the Autonomous University of Madrid). Specifically, this equation is used for modelling certain atmospheric phenomena, such as the formation of singular fronts (frontogenesis), in the highly active research field of incompressible fluid mechanics. He is proud of his relation with Córdoba, with whom he shares a passion for music as well as mathematics, and to whom he feels very close. As he says: "It's a privilege to be able to talk to him and discuss not only mathematics but life in general".

Alonso's passion for mathematics comes from his family background. His father is a teacher of mathematics, and from his early childhood instilled in him a love of the discipline. Although at first he felt an attraction for engineering, he eventually realized that he particularly liked the mathematical side of that subject. He studied Mathematics at the University of La Laguna, of which he cherishes good memories and where he made friends with classmates with whom he studied Algebra and Number Theory as well as playing chess and card games in the canteen.

After finishing his degree, he moved to Madrid to do a Master in Mathematics and Applications at the Autonomous University, which was when he decided to specialize in fluid mechanics. His end-of-master assignment was supervised by Diego Córdoba, a researcher and the scientific director of the Severo Ochoa Project at the ICMAT. He says that this last stage was decisive for his choice of research as a professional career; it enabled him to read scientific articles for the first time, and to be in contact with the Institute and its members as well as attending seminars and conferences. It was in this way that he realized how much he enjoyed it, and says that starting a doctoral thesis was the next natural step in his career.

Alonso has spent most of last year, and all of this, moving from one university to another. After completing a stay at the Courant Institute of Mathematical Sciences in New York, where he worked with Vlad Vicol, he went to the University of Bonn (Germany). He spent three months there working in collaboration with Juan José Velázquez, a former member of the ICMAT, until returning to Madrid to finish and defend his thesis in April of this year, should all go according to plan.

This mathematician describes the world of research as a "merry-go-round" on which you experience both good and difficult moments, but which provides you with access to new places and enables you to learn constantly. And so it remains now, since he is currently combining work on his thesis with studies in a new field for him; stochastic partial differential equations, a subject he is pursuing together with two doctoral students from Imperial College London.

So how does he see the future? "In the short term, I'd like to continue doing research, either in or outside of Spain, but in the mid- and long-term I'm not sure, because I know that attaining a stable job in this area is a bit complicated", concludes Alonso.

INTERVIEW: Interview to Ali Nesin, Leelavati Prize 2018 for public outreach in mathematics

"A combination of learning and daily life in the Nesin Math Village"

Image: Burak Barutçu.

Ali Nesin received the Leelavati Prize for the creation and development of the Nesin Mathematics Village.

The life of Ali Nesin, university professor and recent recipient of the International Mathematical Union prize for increasing public awareness of mathematics, took a decisive turn in 1995. After the death of his father, the celebrated author Aziz Nesin, he was obliged to leave the USA, where he was an assistant professor at the University of California, Irvine, and return to Turkey to take up the reins of the Nesin Foundation. At that time, this organization was devoted to providing children from economically deprived families with access to education. At the same time, the Istanbul Bilgi University offered him the post of head of its Department of Mathematics. To Nesin, these two jobs seemed to dovetail together: the foundation's vision of education as an investment in the future, and the chance to train a new generation of mathematicians at the university who could "change the future of Turkey".

These two ideas crystallized in the Nesin Mathematics Village, a place designed for people of all ages to come together, share experiences and study mathematics. Located among olive groves just a few kilometres away from the ruins of Ephesos (Turkey), the stone buildings occupy a space that started out as an alternative to the expensive summer schools by which Nesin sought to furnish his university students with an education in mathematics that would launch them on an international career. Some years later, the Village has become a point of encounter and communion for lovers of mathematics of all ages. We spoke to him about this project on his return from the Congress of the International Mathematical Union in Rio de Janeiro, where he was awarded the Leelavati Prize.

Ágata Timón García-Longoria

Where did the idea for the Nesin Mathematics Village come from?

It was more of a need than an idea. I'd been organizing summer schools for ten years. They were held over two months. In the first year they were only for my students, but in the second year we decided to open them up to all university students, both graduates and undergraduates. They were a big success, but they became more expensive because of tourism. What's more, we weren't very happy with the location, and I came up with the idea of having our very own place. In the beginning I was planning on a modest location, but unfortunately my friend Sevan Nisanyan, our "architect", wasn't able to build a cheap place and ended up doing it in style.

You had to overcome some big problems at the start, didn't you?

Yes, it was a terrible time. The police came along and state inspectors; we had to pay exorbitant taxes and were taken to court... Sevan Nisanyan spent some time in jail, but he managed to escape and now lives in Greece as a political refugee.

What were your aims at the outset?

The initial intention was to make the Village a place for university students only, but there was a great demand for summer schools for secondary school pupils. So that's what we did; we set up two summer schools, each one lasting a fortnight.

Where did the funding come from?

At the start, we thought that the Turkish Council for Education and Scientific Research would support the project, and so it did for the first year. After that they turned off the tap, for political reasons, of course, and we found ourselves without any money. So we set up more summer schools for secondary school students, because unlike university students, these pupils, or rather their parents, were prepared to pay for the costs. We also had to extend the facilities. We built more classrooms, more dormitories, more accommodation for teachers, a bigger dining hall, a bigger kitchen and laundry… We had to ask people for donations for this, and happily they responded generously.

I understand that the Village is self-managed thanks to co-operation by everyone involved. What's day-to-day life like there?

In the summer, the Village is only for secondary school, university and post-graduate students. They get up at 7.00 am and have breakfast until 8.00, which is when classes begin. They are divided into two sessions, each lasting approximately two hours. We have lunch at 12.00 and then do the daily chores. All the students are assigned different tasks around the Village; peeling potatoes, cleaning, doing the washing, watering the garden and so on. At 4 o'clock we go back to class until 8 o'clock. Then we have dinner, and after that take care of any more jobs that need doing. Sometimes we organize talks or sometimes musical evenings. Secondary school students get two-hour study sessions every two days.

What happens in the Village before and after summer?

We get visits from small research groups throughout the year. Two teachers with three students, for example, plus their families. We provide them with everything they need and they don't have to pay for anything. All we ask of them is to prove new theorems. Then in the spring and autumn we receive primary school pupils. Sometimes I teach them through play. I present them with a game and at first I win every time. Eventually they learn my strategy and then of course they start winning. You should see how delighted they are when they manage to beat me. Sometimes we hold workshops, talks and scientific meetings.

So what happens in the Nesin Village that doesn't happen in other places?

For Turkish students it's a place they can't find anywhere else. First of all, they have as much freedom as they wish – they can enjoy the architecture, the plants, the hidden shrines, the open sky… It's a really beautiful place. We respect nature as much as we can; we plant thousands of trees. Furthermore, relations between teachers and students are very relaxed and friendly. We don't treat the students like babies but like grown-ups. Everything is explained; nothing is given without reason. What's more, we give them the time to understand and discover most of the concepts themselves. They feel as if they are being treated with respect and they like that. They respond very well, because they want to show that they deserve this respect.

After the recognition given to the Nesin Mathematical Village by the international mathematical community, what are your plans for the future?

I want to open a secondary school. Well, not a school actually, but another village like the Math Village, where students and teachers can live side by side, where learning, teaching and daily life are all combined. It'll be something out of the ordinary; a place where, I hope, our educational system will be open to question. At the moment, given my reputation, the authorities refuse to give me the necessary permits. Next week I'm meeting the Minister for Education, and I hope I can convince him to get the project off the ground.

Image: Ali Nesin.

The Nesin Mathematics Village.

TELL ME ABOUT YOUR THESIS: Víctor Arnaiz Solórzano

Image: ICMAT.

In his thesis, Víctor Arnaiz Solórzano studied the Schrödinger equation in the semiclassical regime.

Title of the thesis: "Semiclassical measures and asymptotic distribution of eigenvalues for quantum KAM systems"

Author: Víctor Arnaiz Solórzano (ICMAT-UAM).

Supervisors: Fabricio Macià Lang (UPM) and Keith Rogers (ICMAT).

Date of submission: 18th of December, 2018.

Víctor Arnaiz Solórzano (ICMAT-UAM). The correspondence principle between quantum and classical mechanics, stated for the first time by Niels Bohr in 1923, postulates that the laws of classical mechanics should emerge from the theoretical principles of quantum mechanics when the systems under consideration lie in a "macroscopic" regime. Bohr roughly describes this regime as that in which the quantum numbers of the system are *large*, either because the system is excited up to high energy values or because it is described by many quantum numbers.

However, the rigorous formulation of this principle is not a simple problem, since such fundamental notions in quantum mechanics as Heisenberg's uncertainty principle or the probabilistic interpretation of the Schrödinger wave function do not appear to be easily reducible to the deterministic laws of classical mechanics. Furthermore, the classical and quantum models belong to very different mathematical worlds. While quantum formalism considers the observables (or "measurable" quantities) of a system as self-adjoint operators acting on a certain Hilbert space – the possible results are precisely the spectral values of the associated operator – in classical mechanics, in its Hamiltonian formulation, the observables are functions of a differentiable manifold known as phase space (space of positions and moments) whose values determine the (classical) state of the system, which is described in the language of symplectic geometry. In this sense, quantum mechanics takes place in the world of functional analysis, spectral theory and probability, while classical Hamiltonian mechanics is founded on symplectic differential geometry.

Surprisingly, these two apparently widely separated models can be connected to formalize the correspondence principle and other physical-mathematical phenomena of a similar nature. From the mathematical point of view, the basic ideas behind this date from the study of geometrical optics and the WKB (Wentzel-Kramers-Brillouin) approximation method for obtaining highly oscillating solutions of certain PDEs of undulatory type (such as the wave equation or Schrödinger's equation). These types of solutions, known as Gaussian beams, can be described asymptotically on the basis of certain differential equations related with the underlying classical mechanics. For example, the Eikonal equation describes the evolution in the phase of the Gaussian beams associated with the wave equation, while the Hamilton-Jacobi equation does so with the Schrödinger equation.

These ideas have been dusted off in recent decades, together with the study of *pseudodifferential and microlocal analysis*, which enables the localization of some properties of wave propagation, such as wave-front-sets, in small regions of the phase space, which has led to the development of a research area called *semiclassical analysis*, which covers many partial differential equation problems concerning this particle-wave, classical-quantum duality.

In my thesis ("Semiclassical measures and asymptotic distribution of eigenvalues for quantum KAM systems"), we address the study of the Schrödinger equation in the semiclassical regime, that is, when the wave length of the solutions is comparable with a small parameter $h > 0$ with respect to the metric size. This parameter is sometimes identified with the normalized Planck constant. Asymptotically as $h \to 0$, classical mechanics emerge and influences the behaviour of the solutions to the Schrödinger equation. More precisely, we study the case in which the Schrödinger operator (the observable associated with the total energy of the system) is a small perturbation of the quantum harmonic oscillator (the system of d-oscillators with independent frequencies); or, more generally, is the quantization of a KAM (Kolmogorov-Arnold-Moser) Hamiltonian; in other words, a small perturbation of a completely integrable system characterized by the presence of a large number of invariant tori by the dynamics.

The main goal of our study is understanding the Wigner distribution associated with the solution Ψ to the Schrödinger equation. This object was first introduced by Eugene Wigner in 1932 when studying the quantum corrections for classical statistical mechanics. It concerns an extension to phase space of the probability density function $|\Psi|^2$ associated with the position (which measures the probability of finding the quantum particle with wave function Ψ in each region of the position space). This object is not a probability density because it does not take positive values, and thus it is sometimes known as the Wigner *quasiprobability distribution*. Nevertheless, taking the limit $h \to 0$, one obtains that the weak limits of sequences of Wigner distributions are positive Radon measures in the phase space, and under a certain control of the scale of the oscillations developed throughout the sequence, they are in fact probability measures. These measures are known as *semiclassical measures* and were introduced by Patrick Gérard, Luc Tartar, Pierre-Louis Lions and Thierry Paul in the early 1990s.

These semiclassical measures constitute a very powerful object in the asymptotic study of solutions to the Schrödinger equation and other wave equations, because they exhibit properties of propagation and invariance that can be described in terms of Hamiltonian mechanics on the phase space. Furthermore, in the case of the Schrödinger equation, by projecting the semiclassical measures onto the position variable, one obtains the so-called *quantum limits*, which are extremely important in the study of the dispersive properties of Schrödinger's dynamics on Riemannian manifolds.

In the first part of this thesis, which constitutes a joint work with Fabricio Macià, we obtain results on the properties of propagation and invariance of the semiclassical measures associated with solutions to the Schrödinger propagation equation given by a small perturbation of the quantum harmonic oscillator. Likewise, we show applications of these results for the solutions to the stationary Schrödinger equation. In particular, we prove that a small perturbation of the harmonic oscillator may destroy the minimal sets (invariant tori) on which the successive Wigner distributions of the eigenfunctions of the Hamiltonian may become concentrated at the limit $h \to 0$ if resonances exist between the oscillator frequencies. However, if the frequency vector of the harmonic oscillator is Diophantine; that is, the quotients between its components approximate "badly" by rational numbers, we prove that the maximal invariant tori (KAM tori) are more stable and can be accumulation sets of successive Wigner distributions associated with the time-dependent Schrödinger equation for long polynomial time ranges.

In the second part of the work, undertaken in collaboration with Gabriel Rivière, we use the ideas outlined above to study the non-self-adjoint case. Here we study the asymptotic distribution, when $h \to 0$, of the spectral values of a semiclassical non-self-adjoint operator (depending on the parameter h), given by a small perturbation of the quantum harmonic oscillator. This problem is related to the study of the energy decay for solutions to the damped wave equation. The results obtained show the influence of the perturbation on the strip of the complex plane, where the characteristic values of the operator may concentrate, and the scale at which such concentration occurs. With hypothesis of analyticity on the operator symbol, we prove that the eigenvalues cannot accumulate close to the real line; that is, a spectral gap exists. In the differentiable case, the estimate we obtain is weaker, although it allows us to obtain an uper bound on the norm of the resolvent of the operator, which is useful for obtaining precise energy decay rates for solutions to the damped wave equation.

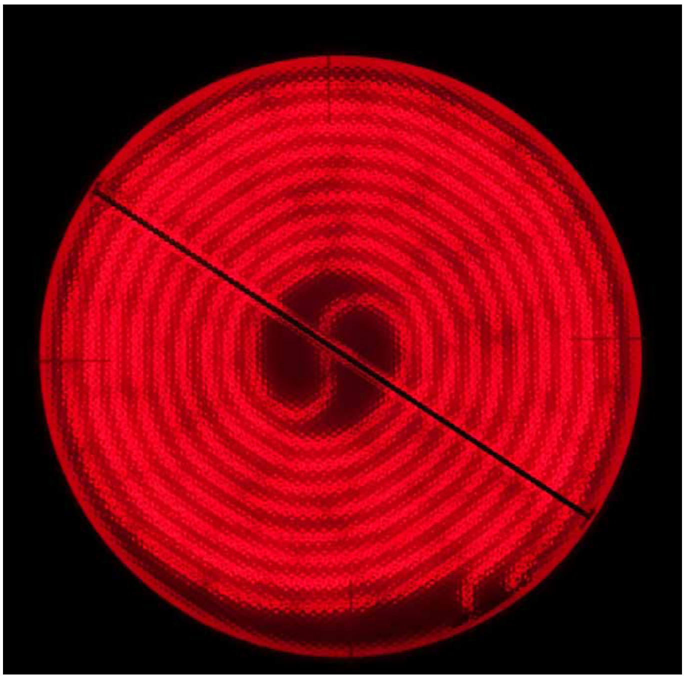
Finally, the last part of this thesis addresses the study of semiclassical measures associated with small perturbations of an order-one Hamiltonian, at the moment variable, with constant coefficients (frequencies) on the torus. If the perturbation is also of order-one (not necessarily of constant coefficients), we prove that for a Cantor set of Diophantine frequencies, the point spectrum of the operator is stable (the eigenvalues move slightly, but remain being eigenvalues). Moreover, for these frequencies we characterize the accumulation points of the sequences of Wigner distributions associated with the stationary Schrödinger equation. Precisely, the semiclassical measures are given by those probability measures supported on each of the invariant tori by the non-perturbed Hamiltonian flow, which have been slightly deformed by the perturbation. This result may be regarded as a semiclassical version of the classical KAM theorem on perturbations of vector fields on the torus.

If the perturbation is bounded and sufficiently small (in terms of the semiclassical parameter), we obtain a renormalization result; that is, we prove the existence of an integrable operator such that, added to the perturbed operator, renormalizes it by giving rise to a new integrable operator, unitarily equivalent to the operator without perturbation. Consequently, we obtain that the sets of quantum limits and the semiclassical measures of successive eigenfunctions for the renormalized operator coincide with those of the non-perturbed operator.

More information.

MATHEMATICS TODAY ICMAT News

Mathematics for predicting the movement of points of maximum heat



The paper "Approximation theorems for parabolic equations and movement of local hot spots" has been accepted for publication in the *Duke Mathematical Journal*.

The vitro-ceramic hobs in our kitchens reach their highest temperature at the centre. However, it would be possible to heat them so that the points of maximum heat changed according to any selected point. This is what ICMAT researchers Alberto Enciso and Daniel Peralta, together with María Ángeles García-Ferrero, a researcher at the Max Planck Institute in Leipzig have managed to demonstrate in an article entitled "Approximation theorems for parabolic equations and movement of local hot spots", published in the *Duke Mathematical Journal.*

"Heat modelling is one of the classical problems in physics, and also one of the great milestones in mathematics, since it is the source of a branch of mathematics called harmonic analysis", says Enciso. Heat diffusion is described by an equation obtained on the basis of Fourier's law – which establishes how energy is conducted through a material – and on the principle of conservation of energy. The result is a partial differential equation of a parabolic type.

The equation shows how the temperature in a region varies over time. While it is not easy to obtain the solutions, it is possible to study their properties. Specifically, one of the interesting aspects to be studied is the maximum values and their evolution over a certain period of time. Now, Enciso, Peralta and García-Ferrero have proved that the movement of these points of maximum temperature can be described if the appropriate initial conditions of the equation are chosen; that is, the heat distribution at the starting point.

These researchers have managed to develop new approximation theorems for parabolic equations. In particular, they have extended to the parabolic case the theory that Enciso and Peralta created for studying the geometric properties of elliptic equations, and which among other things they employed to demonstrate a conjecture proposed by Lord Kelvin almost 150 years ago. Enciso and Peralta were awarded the "Barcelona Dynamical Systems" Prize from the *Societat Catalana de Matemàtiques* in 2015 for this achievement. They have also received recognition with the award of two projects from the European Research Council (ERC), and hope to use these techniques in new contexts.

Alberto Enciso, Mª Ángeles García-Ferrero, and Daniel Peralta-Salas. "Approximation theorems for parabolic equations and movement of local hot spots". Duke Math. J. Volume 168, Number 5 (2019), 897-939.

Women mathematicians, Unite!

Image: ICMAT.

Last WOMAT meeting at the ICMAT.

On December 10th, 2018, the first meeting of WOMAT, the association of women researchers in mathematics, was held in its home city of Madrid. The association was recently started by ICMAT members Makrina Agaoglou and Patricia Contreras Tejada. These meetings, to which all the women involved in mathematical research in Madrid are invited, have the aim of "stimulating interaction and providing a space where women researchers can get together to talk about the circumstances that affect them as female mathematicians" in a relaxed and informal way over a cup of coffee.

"Women are a minority in the mathematical community. The causes of this situation are many, and include implicit and explicit bias, cultural traditions and stereotypes, which often mean that women are faced with greater adversity than men in their academic careers. We believe that things do not have to be, nor should be, this way. The mathematical community should ensure that women are supported in their work, encourage them to pursue their academic careers fully, and attract more women to take up positions in research fields."

This was the main motivation behind the creation of WOMAT, the association of women researchers in mathematics with its base in Madrid. According to Makrina Agaoglou and Patricia Contreras Tejada, the two ICMAT researchers who have set up the association, the goal is to "open up the way to a more inclusive mathematical community in Madrid".

This was the main motivation behind the creation of WOMAT. According to Makrina Agaoglou and Patricia Contreras Tejada, the two ICMAT researchers who started the association, the goal is to "open up the way to a more inclusive mathematical community in Madrid". How do they propose to do this? The first activity is this monthly meeting of women mathematicians, three of which have already been held. In addition, a web page has been set up on the website of the ICMAT, which has pledged its support for the initiative. Posters illustrating the gender gap in mathematics have also been circulated to the faculties and departments of mathematics in Madrid, and on March 1st a talk will be given by Havi Carel, professor of philosophy at Bristol University and expert in unconscious prejudices, which determine how we judge and are judged by others in society and, in this case, in the world of science.

Jared Aurentz (ICMAT) awarded a "la Caixa" Junior Leader postdoctoral fellowship

Image: Jared Aurentz

Jared Aurentz (ICMAT) will research the areas of decision theory, risk analysis, machine learning, and applied statistics.

ICMAT researcher Jared Aurentz is one of the 30 people chosen in the "la Caixa" Postdoctoral Junior Leader programme 2018, a fellowship lasting three years for conducting research in the areas of decision theory, risk analysis, machine learning and applied statistics. His main goal is to develop mathematical models and a corresponding software package to facilitate the decision-making process. A large part of the theoretical section of the project, which is endowed with 300,000 euros, is based on adversarial risk analysis, a research line developed by David Ríos, director of the AXA Chair at the ICMAT.

Ana María Mancho (ICMAT), guest speaker at one of the most important congresses on fluid dynamics in the world

Image: Ana María Mancho.

Ana María Mancho gave one of the eight invited talks, entitled "Revealing Lagrangian pathways for transport in a turbulent ocean.

More than three thousand researchers from departments of physics, mathematics, engineering, and atmospheric and ocean sciences met in Atlanta on November 18th, 19th and 20th, 2018. They were there to attend the 71st annual meeting of the American Physical Society's (APS) Division of Fluid Dynamics, one of the most important scientific events in this field. On this occasion, Ana María Mancho, senior scientist at the CSIC and the ICMAT, gave one of the eight invited talks, entitled "Revealing Lagrangian pathways for transport in a turbulent ocean". Few Spanish scientists have been distinguished before with this honour. On one previous occasion, Javier Jiménez Sendín (Technical University of Madrid) was a guest speaker in 2012.

Experts in group theory meet at the ICMAT

Some 40 researchers in the field of group theory met for the third consecutive year at the conference "Groups in Madrid", which was held at the ICMAT on November 22nd and 23rd, 2018. The event concerns group theory, a research field whose roots are found in Galois theory, number theory, representation theory and geometry. Over a period of two days, those who attended shared the latest advances in this field, one which currently enjoys great activity and with a notable presence in other field of mathematics.

The meeting included seven talks given by researchers of both sexes belonging to universities and institutions such as the CNRS (France), the University of the Basque Country, the *Università degli Studi di Firenze* and the ETH Zürich-Zentrum. One of these speakers was Gunter Malle (TU Kaiserslautern), a speaker at the 1998 International Congress of Mathematicians (ICM) in Berlin and a researcher recognized with an Advanced Grant project from the European Research Council (ERC). The organizers of the event were Yago Antolin (ICMAT-UAM), Javier Aramayona (ICMAT-UAM), Andrei Jaikin-Zapirain (ICMAT-UAM) and Carolina Vallejo (ICMAT).

Politicians pledge to roll out urgent measures to promote science in Spain at the 100xciencia forum

The '100xciencia.3: Bridging Science and Society' conference was held on November 15th, 2018, an event co-organized by the Severo Ochoa and María de Maeztu SOMMa Alliance, which forms part of the ICMAT, and the CNIO. The conference provided a platform for different debates on the relation between science and society, including a round-table discussion with representatives from the political parties PSOE, PP, Podemos, Ciudadanos and PdCat. They all agreed to carry out short-term measures for reducing bureaucracy and improving the system of science and innovation.

Representatives from research centres belonging to the SOMMa Alliance, consisting of 41 Severo Ochoa and María de Maeztu Centres and Units of Excellence, including the ICMAT, came together at the Spanish National Research Centre for the third edition of the 100xciencia conference, the first to be held after the constitution of this alliance in October, 2017. Attention was focused on the importance of the participation of society in science. The round-table discussion, called "The media as channelling agents for science", included the participation of leading journalists in Spain, such as Patricia Fernández de Lis (director of Materia, El País), Pampa García Molina (coordinator and editor-in-chief of the SINC Agency), Noemí Gómez (scientific journalist at EFE), Antonio Martínez Ron (journalist and populariser of science with Naukas) and Mónica Salomone (scientific journalist). A round table called 'The scientific empowerment of society', chaired by Rosina Malagrida, head of the *Living Lab de Salud de IrsiCaixa*, was devoted to a debate on the importance of empowering different social actors in matters of science.

The research centres and units belonging to the SOMMa Alliance were able to present some of their most noteworthy initiatives for scientific education and citizen participation in science, which provide inspiring examples for other units and centres as well as facilitating the exchange of best practice, which is one of the objectives of the Alliance.

Strategic Network in Mathematics, a union for stimulating national research

Funded by the Spanish Ministry of Economy and Business, the aim of the *Red Estratégica en Matemáticas* (REM – Strategic Network for Mathematics) is to promote mathematical research and its applications. "This science plays a crucial role in technological progress and in improving living conditions", says Tomás Chacón, director of the REM and of the *Instituto de Matemáticas de la Universidad de Sevilla* (IMUS), one of the institutes belonging to the network. In addition to the IMUS, the REM is also composed of the Barcelona Graduate School of Mathematics (BSGMath), the *Centre de Recerca Matemàtica* (CRM), the Basque Center for Applied Mathematics (BCAM), the *Instituto de Ciencias Matemáticas* (ICMAT), the *Red de Institutos Universitarios de Matemáticas* (RedIUM), the Spanish Network for Mathematics and Industry (Math-in) and the Spanish Public Centres of Higher Education.

Founded in July, 2017, the REM is making its main results available during this 2018-2019 course, among which is the publication in April this year of two macro-studies on the scope of mathematical research in Spain. The first report will quantify the scientific impact of mathematical research in the country over the last decade. The second, drawn up by the AFI company (*Analistas Financieros Internacionales*), will address the impact on the economy and employment of the transfer of mathematical knowledge.

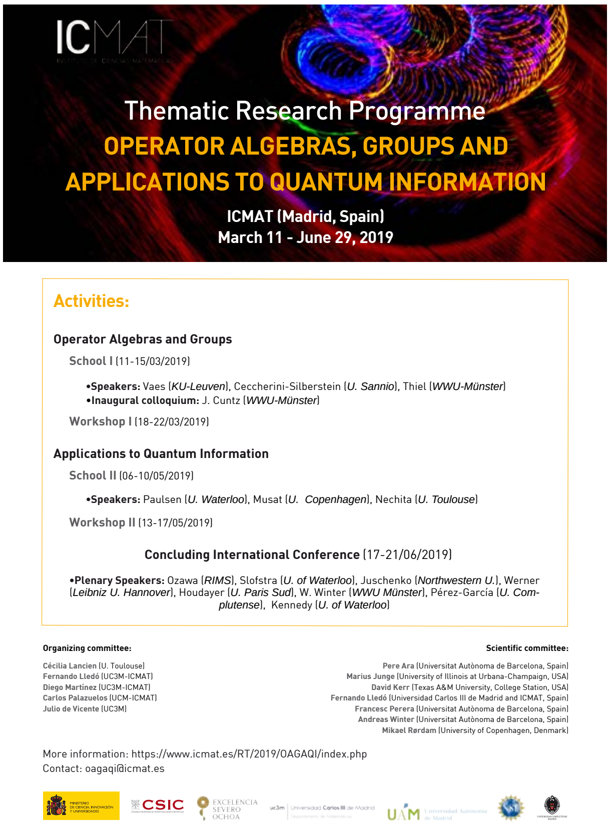
In several European countries, such as France, the United Kingdom and the Basque Country, studies of this type have been conducted that indicate the significant effect of mathematics on employment and added value, with its contributions to the GDP of between 10% and 15%. In a few months' time, the REM will provide the data on the Spanish GDP. "It's very plausible that the implantation of mathematical technology in the Spanish productive sector will result in an increase in the GDP, reaching values similar to those recorded in these other countries", says Peregrina Quintela, president of the Math-in network and member of the REM Management Committee. She goes on to state that: "Mathematics is of great help to companies in decision-making as well as improving productive processes and the optimization of their resources".

One of the aims of the REM is to improve the strategic positioning of mathematics in Spain. To that end, it will stimulate collaboration between the centres making up the Network by optimizing the results and resources already available; by outreach, as the best way to improve social perception of science, and by the internationalization of Spanish mathematics. To carry out these tasks, it has a budget of 120,000 euros until July, 2019.

Conferences, schools and thematic trimesters

Registration for the 'Operator Algebras, Groups and Applications to Quantum Information' thematic trimester starts

Image: ICMAT.



Between March 11th and June 29th of this year, the ICMAT is organizing the 'Operator Algebras, Groups and Applications to Quantum Information' thematic trimester, which will be attended by specialists in the fields of mathematical physics, noncommutative algebra, dynamical systems, group theory, harmonic analysis, topology and quantum theory. The main aim is to promote interaction between all these fields, with particular emphasis on their application to quantum information.

The trimester includes two research schools, three conferences and an inaugural discussion. It is already possible to register for the different activities through the ICMAT website. The scientific programme is divided into two main areas: operator Algebra and groups and Applications to the theory of quantum information.

The organizing committee of this conference consists of Cécilia Lancien (Université de Toulouse), Fernando Lledó (UC3M-ICMAT), Diego Martínez (UC3M-ICMAT), Carlos Palazuelos (UCM-ICMAT) and Julio de Vicente (UC3M). The researchers who make up the scientific committee are Pere Ara (Department of Mathematics, Universitat Autònoma de Barcelona, Spain), Marius Junge (Department of Mathematics, University of Illinois at Urbana-Champaign, USA), David Kerr (Department of Mathematics, Texas A&M University, College Station, USA), Fernando Lledó, Francesc Perera. (Department of Mathematics, Universitat Autònoma de Barcelona, Spain), Andreas Winter (Department of Physics, Universitat Autònoma de Barcelona, Spain) andy Mikael Rørdam (Department of Mathematics, University of Copenhagen, Denmark).

The BYMAT 2019 (Bringing Young Mathematicians Together) conference is back this year

The second edition of BYMAT – Bringing Young Mathematicians Together – is already under way. After last year's successful event, with an attendance of almost 200 people from 19 different countries and more than 75 institutions, this year the conference will be held again, from May 20th to May 24th, at the Institute of Mathematical Sciences (Madrid), for doctorate, master and final year students of mathematics and allied fields.

This will be the second conference of the BYMAT network, which supports young mathematicians in their professional careers both within and outside academia, and strengthens connections between mathematics and contemporary society. Registration is open until April 30th, 2019, and whoever wishes to participate in the conference with a short talk has until March 11th to send an abstract and/or poster proposal. Thanks to the collaboration of the BBVA Foundation, those from outside the Community of Madrid who wish to attend can apply to have their accommodation and travel expenses covered, also until March 11th.

The conference will include seven plenary talks given by Jan Maas (Institute of Science and Technology, Austria), Marina Logares (University of Plymouth, United Kingdom), Tong Tang (Hohai University, China), Rafael Ramírez Uclés (Universidad de Granada, Spain), Javier López Peña (University College London, United Kingdom), Anabel Forte (Universitat de València, Spain) and Isabel Fernández (Universidad de Sevilla, Spain). The programme will also include a series of short talks, poster sessions, chats and workshops on career opportunities as well as communication and outreach in mathematics.

Image: ICMAT.

Outreach

11F: recalling award-winning women scientists overlooked for the Nobel Prize, and women mathematicians

Image: ICMAT.

The ICMAT exhibited a poster of Maryam Mirzakhani, Fields Medal, in the 11 February 'escape road' frame.

The International Day of Women and Girls in Science took place this year on February 11th with more than one hundred activities in different locations in Spain. On Cantoblanco, the Autonomous University of Madrid campus, several centres belonging to the CSIC, including the ICMAT, together organized an "escape road", a route consisting of interactive panels and challenges representing the life and work of women Nobel Prize winners in the different branches of science, as well as women winners of Fields Medals (equivalent in mathematics to the Nobel Prize), together with those overlooked for these awards.

"We want to invite women university students to pursue a career in science. It's a wide-ranging, creative profession that poses fundamental questions; one in which you are never bored and allows you great independence", says Silvia Gallego Queipo, a researcher at the Institute of Materials Science in Madrid, one of the organizers of the event, together with the ICMAT, the Institute of Ceramics and Glass, the Institute of Catalysis and Petrochemistry, the Spanish National Centre for Biotechnology, the Severo Ochoa Centre for Molecular Biology, the Institute of Theoretical Physics and the Institute of Food Research Science.

One of the strategies for promoting these vocations is to raise awareness of the work of outstanding women scientists. To that end, the 'Escape-road" highlights women Nobel Prize winners in science as well as those unrecognized by that award, with the aim of providing role models and examples of inspiration for new generations of female university students. "We want to make visible the activity of women in science and dispel the stereotypes that stand in the way of girls pursuing scientific vocations", says Gallego. This initiative took the form of an exhibition of posters presenting a profile of women Nobel Prize laureates in scientific disciplines and women winners of Fields Medals. The posters were put on display in the different institutions participating in the event. Visitors were required to complete the route and respond to the questions via the QR codes on the posters.

It was possible to follow the route unguided between February 4th and 18th, while on February 11th a guided tour was available. Participants only needed a mobile phone with a QR code reader and the free Walla Me app. Those who completed the full route on the guided tour could enjoy a meal at the end, courtesy of the AMPHIBIAN European project.

A further purpose of the activity was to recognize the work of women scientists throughout history. In addition to the posters, a virtual exhibition shed light on women scientists who, in spite of their outstanding achievements, have not been distinguished with a Nobel Prize or a Fields Medal. Visitors had to search for these profiles using the Walla Me app in order to "rescue them from oblivion".

In addition to the escape road, on February 6th the ICMAT organized a workshop-talk to celebrate the 11 F. Ana Bravo, a professor at the UAM, member of the ICMAT and chair of the Institute's Gender Commission, presented the work of women mathematicians in the fields of arithmetic and geometry to 4th grade Secondary School pupils and 1st and 2nd year Baccalaureate students from the Montserrat de Madrid High School. On this occasion all those who attended were young women. "We wanted to make a selection from the most interested students in order to arouse a spirit among them as women scientists of the future," said Guillermo Rodríguez Biehn, the professor responsible for the activity at the centre.

For further information.

Mickaël Launay, author of *the great novel mathematics*, at Matemáticas en la Residencia

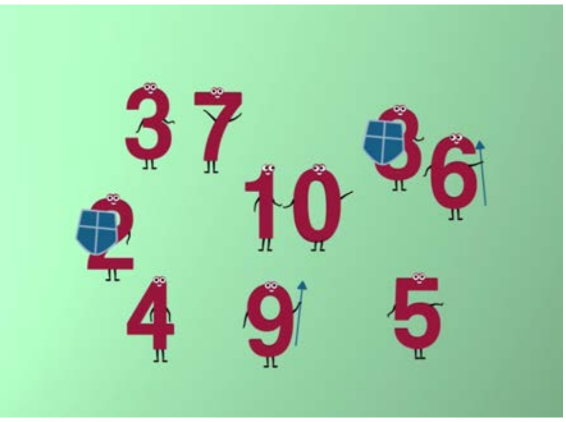
"However simple the level may be, mathematics constitutes an inexhaustible source of wonder and fascination", writes Mickaël Launay in his book "It All Adds Up: The Story of People and Mathematics", published in Spanish in 2017 by Paidós under the title "La gran novela de las matemáticas". "When we discover certain mathematical ideas for the first time, they buzz inside our heads", remarks this populariser of science. Launay, whose YouTube channel "Micmaths" enjoys more than 300,000 subscribers and 22 million hits, is one of the leading experts when it comes to transmitting this buzz to an audience encompassing all age groups.

This is exactly what he did on November 29th last year in a talk entitled "the importance of being inaccurate in mathematics", which he gave at the *Residencia de Estudiantes*, as part of the season of talks, "Matemáticas en la Residencia", organized by the ICMAT in collaboration with the CSIC Vice-Presidency of Organization and Scientific Culture and the *Residencia de Estudiantes*. In this talk, Launay spoke about research and creation in mathematics as a pathway to the unknown.

Mickaël Launay studied mathematics at the *École Normale Supérieure* and went on to complete his doctorate in Probability Theory. For more than 15 years he has been devoting himself to the popularization of mathematics in France, a task that has taken him to unexpected places, from the Louvre Museum to street fairs, passing on the way through research workshops with pupils in primary schools, where he says that although the teachers and children are surprised to see him, he is received with trust and doors are opened to curiosity and mathematical imagination.

The cartoon series Revoluciones matemáticas brings mathematics closer to young people

Image: ICMAT.



The second chapter of Revoluciones matemáticas shows the history of the numeration systems.

There are people in history who have changed the course of thought in mathematics, and thus in humanity as a whole. The ICMAT has launched *Revoluciones matemáticas* (Mathematical Revolutions), a cartoon outreach series depicting these turning points in history and their protagonists, some of whom may be known to the public in general. This project, in which the Divermates company and the animator Irene López have collaborated, consists of five episodes, each lasting approximately three minutes and expressly aimed at a young audience.

The first four videos of the series can be seen on the ICMAT YouTube channel. Each episode is devoted to an advance in mathematics that constituted a revolution both inside and beyond the scientific community, such as the numerical relations in nature as observed by Pythagoreans, the creation of the system of decimal numeration and the development of differential calculus. "Some of these discoveries have changed the lives of human beings as much as, if not more, than the use of fire or the invention of the wheel", says the director of Divermates, Nelo Mestre. This company has also devised complementary activities for each episode that can be followed up by teachers in the classroom.

The aim of the series is also to highlight the people behind these ideas. "The biographies of men and women mathematicians are largely unknown by the public at large, and especially by students. We think that these personal histories, in many cases very fascinating, can provide a good means of making mathematical knowledge much more real and relevant", said David Martín de Diego, director of the ICMAT Unit of Mathematical Culture.

The project was chosen in the CSIC General Foundation first call for applications for funding to promote scientific culture, *Cuenta la Ciencia* (Science Counts), which is also supported by funding from the ICMAT Severo Ochoa Project.

My favourite woman scientist II highlights the work of more than thirty women scientists

"How many women scientists do Primary School pupils of 5th and 6th grade know about?" This is the question with which the Institute of Mathematical Sciences (ICMAT) kicked off the initiative "My favourite woman scientist" in 2016, with the aim of making the role of women in science more widely known as well as encouraging scientific vocations in both girls and boys. Two years down the line, the second edition of the project was completed last October with the publication of "My Favourite Woman Scientist II", a new book dealing with the life and work of 33 female scientists for 5th and 6th grade pupils from 24 different Spanish Primary Schools. This project is co-funded by the Spanish Foundation for Science and Technology (FECYT), the Ministry of Science, Innovation and Universities and through the ICMAT Severo Ochoa programme. It has been conducted with the help of both teachers and pupils as well as ICMAT research and outreach personnel.

This new edition continues the work of the previous one, but with one difference: in the initial phase during the 2017/2018 course, students were required to choose women subjects who did not appear in the first edition, in order to draw up a more comprehensive catalogue of female scientists, and to show that the question posed at the outset of the project could have various responses. On completion of their research, the pupils expressed their results in original artworks. Each of the schools organized a competition to choose a maximum of six artworks (three from pupils in each year), which were then sent to the ICMAT for the final selection. Finally, the winning selections were published in the book.

These illustrations were backed up with written work in which, for outreach purposes, the scientific contributions of the women researchers were described, together with anecdotes about their lives and the major events in their respective careers. Thanks to this project, a total of 33 women scientists, most of them unknown to the general public, provide role models to help dismantle gender prejudice and encourage the scientific vocation of girls and boys.

My favourite woman scientist II is science outreach work intended to promote equality and scientific vocation. The hard-copy version is distributed to the schools taking part, and the digital version is available to download from the ICMAT website.

AGENDA

ICMAT scientific activities

Research program on 'Operator Algebras, Groups and Applications to Quantum Information'
Date: 11 March – 29 June 2019

BYMAT 2019 – Bringing Young Mathematicians Together
Date: 20 – 24 May 2019

JAE School 2019
Date: 10 – 22 June 2019

Summer School on Fluid Mechanics at the ICMAT
Date: 24 – 28 June 2019

XIII International ICMAT Summer School on Geometry, Mechanics and Control
Date: 8 – 10 July 2019

XXVIII International Fall Workshop on Geometry and Physics
Date: 2 – 6 September 2019

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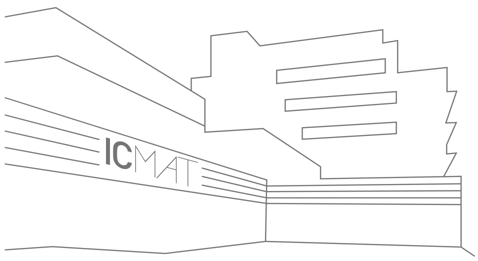

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