M-theory

4 February to 19 July 2002

Report from the Organisers: RH Dijkgraaf (Amsterdam), M Douglas (Rutgers), JP Gauntlett (Queen Mary), C Hull (Queen Mary)

Scientific Background

Einstein's theory of gravity is not consistent with quantum mechanics - it cannot be quantised - and superstring theory is the only theory we have that provides a consistent quantum description of gravity. Moreover, it unifies gravity with the other forces, and so is a theory that could provide a unified description of all the forces and all the matter in the universe. To find a quantum theory of gravity and to find a unified theory of all the forces and particles of nature are the two main goals of current work in fundamental physics and it is remarkable that string theory has the possibility of solving both problems simultaneously.

There are five distinct superstring theories, all giving quantum theories of gravity. Discoveries in the mid-90's led to the conclusion that all five arise as different limits of a single theory, which has come to be known as M-theory. This conclusion came as a complete surprise, and had a dramatic impact on theoretical physics.

This "second superstring revolution" revealed remarkable connections between the various forms of the theory, leading to solutions of previously intractable problems. The most famous such solution, from 1994, was the Seiberg-Witten solution of N = 2 supersymmetric Yang-Mills theory, which produced the first analytic understanding of confinement in a four-dimensional gauge theory. This had important mathematical consequences as well, namely new four-manifold invariants which were comparable to but far simpler than those previously defined by Donaldson. This result was just the tip of an iceberg: it was soon found how to rederive it from string theory and M-theory in several ways, and it now forms part of a rich picture involving many inter-related supersymmetric theories arising from stringy geometry. The new picture goes far beyond strings in that it includes "branes", extended objects like the string but of higher dimension. These branes had been somewhat neglected in the early developments as, unlike the string, they can-not be used as the fundamental defining objects in the theory, but this is directly analogous to the status of instantons and monopoles in gauge theory, which turned out to be extremely important there. Indeed, the branes turn out to be key in all the recent developments. Moreover, it was learned that the non-perturbative structure of string theories is governed by new symmetries, called U-dualities.

Much has been learned about those special sectors of M-theory that can be described by string theories or supergravity theories, and of the remarkable duality symmetries that relate

such sectors, but much of M-theory remains a mystery. We have as yet no definition or formulation of the theory, and do not even know what the fundamental degrees of freedom should be. It seems likely that our notions of space and time will have to be modified, bringing in new mathematical structures such as non-commutative geometry, which has recently been shown to play an import-ant role. An important clue has been found in the recent discovery that M-theory, at least in certain backgrounds, has a "holographic" description in terms of a simple non-gravitational gauge theory or matrix theory.
The principal aim of the programme was to investigate the structure of M-theory, seeking clues as to its fundamental formulation and unravelling its physical consequences.

Organisation

The planning was shared between the four organisers, with C Hull the principal organiser. M Douglas, C Hull and JP Gauntlett were present for the entire workshop and shared the running of the programme. RH Dijkgraaf was unfortunately unable to attend as much as he had originally planned but played an active role, especially in the running of the Clay School.
For most of the programme, we had two seminars a week, on Tuesday and Thursday afternoons, which were well-attended. The rest of the time was left free to give participants time to continue their own research and to carry on more informal discussions. We also had two outstanding colloquia, given by RH Dijkgraaf and G Gibbons.
We had three major meetings. The programme started with a workshop on M-theory, Gravity and Geometry held from 11-15 February 2002 which helped ensure that there was full participation in the problematic early period of the programme. The Clay Mathematics Institute School on Geometry and String Theory, run jointly with the organisers of the Higher Dimensional Complex Geometry programme, was held from 25 March - 19 April 2002 and was a major focus of the programme, catalysing much fruitful interaction between the participants of the two concurrent programmes. The grand finale was Strings 2002, the annual international conference in string theory held at the Cavendish Laboratory, Cambridge, 15-20 July 2002, which attracted nearly 500 people from around the world and was the most important string theory conference of 2002.

Participation and Benefits

The programme was fortunate to have around 105 long-stay participants staying for periods of between three weeks and six months. In addition, there were about twenty short-stay participants. The programme ran at full capacity for almost its entire duration.
The programme proved very popular and there was a large number of people from around the world wanting to participate. Many people wanted to come in the period between the end of the US teaching year in mid-May and the strings conference in July. This made the job of the organisers in choosing whom to invite and for how long rather difficult, but we were pleased that most of the world's leading string theorists were able to attend. Many participants came for less than a month - one common concern was whether the facilities would allow them to work as effectively at the Newton Institute as at their home institution - but many were favourably impressed and said that if they had known how well things worked at the Institute, they would have wanted to come for longer.

Participants were in great demand to give seminars and lectures at other UK universities, and the availability of so many stars of the field was of considerable benefit for the UK community. Indeed, members of the UK community are now much encouraged to apply to hold future M-theory programmes at the Institute.

Meetings and Workshops

M-theory, Gravity and Geometry
European Superstring Theory Network Meeting,
11-15 February 2002
Organisers: C Hull, JP Gauntlett, M Perry, D Waldram

This was the third network meeting for the European Superstring Theory Network, and was sponsored by the European Union. This was a very successful meeting with around 80 participants and a full programme of research talks. The transparencies from the talks were eventually posted on the meeting's web-page.

Clay Mathematics Institute School on Geometry and String Theory
Workshop, 25 March - 19 April 2002
Organisers: M Douglas, A Corti, R Dijkgraaf,
J Gauntlett, M Gross, C Hull, A Jaffe, M Reid

This was run jointly with the organisers of the Higher Dimensional Complex Geometry programme, and the organising committee consisted of the organisers of the two programmes, working with A Jaffe of the Clay Institute. M Douglas, as the principal organiser of the school, put in considerable effort to make it so successful. The Clay Mathematics Institute provided generous funding for the school, enabling us to attract excellent students and lecturers.

Formal agreements for the school were finalised in February 2001, and the next few months were spent in planning and lining up speakers. Many top people were already planning to come to one of the workshops, and the prospect seemed sufficiently attractive to enough others to make attracting speakers fairly easy, even without offer-ing any compensation beyond expenses. Indeed, we were able to get many of the leaders in our fields. Almost all of the committed speakers were able to attend, though one was stopped by difficulties related to the US green card procedures.

Nearly sixty students participated, roughly half mathematicians and half physicists. Many local students and academics attended the lectures as well. Attendance was limited to 120 by the size of the lecture hall, a bound we attained a few times, but we did not need to turn people away. Most lectures had 70-80 in attendance.

String theory is a popular subject with two or three major schools devoted to it every year. Comparing this school with others on the interface between mathematics and physics, its main distinguishing feature was that it did not focus on a small area of common interest but rather discussed a broad variety of topics, loosely grouped in the following three categories: manifolds of special holonomy, derived categories and the McKay correspondence, and mirror symmetry. In addition, there were more general lectures introducing the key ideas and background material on both the physics and mathematics sides.

We had four lectures each day (except for March 29 before the Easter holiday), three of 90 minutes and a final late afternoon lecture of 60 minutes. Most of these were lecture series with about 15 seminars on more current research. We also had a poster session to allow students to present their own work.

There was an active social programme which centred around a series of four dinners. In addition we had a punting expedition, bus excursions to London and to East Anglia and football matches involving both students and lecturers. The participants, both students and speakers, were very enthusiastic about the social programme and it was an important contribution to the school's success.

It is planned to publish the contents of the lectures. This will probably be in two volumes, with the AMS publishing a monograph on derived categories, the McKay correspondence, mirror symmetry and related matters, and a separate volume covering the other lectures.

Strings 2002
Conference, 15-20 July 2002
Principal organiser: M Green

The climax of the programme was the annual international conference in string theory. This attracted nearly 500 people from around the world and was the most important string theory conference of 2002. The number of participants involved led to special problems, as it was hard to find suitable venues for a conference of that size. The conference sessions were in the end held at the Cavendish Laboratory, and the Newton Institute was not involved in the organisation of the meeting. However, all of the organisers of the programme were also members of the conference organising committees. Further information, together with transparencies of the talks, is available on the conference website http://www.damtp.cam.ac.uk/strings2002

Outcome and Achievements

The programme was an international event of high significance for the field, as were the Clay School and the Strings 2002 conference. For the duration of the programme, Cambridge was the inter-national focal point for string theory. UK scientists benefitted strongly through establishing new contacts and collaborations. Many students and researchers attended from across the UK.

Significant work was carried out during the programme on the following inter-related topics:

- Calabi-Yau manifolds and manifolds of special holonomy
- Derived categories of coherent sheaves and the McKay correspondence
- Geometry of M-theory solutions and their modifications due to branes
- D-geometry and conformal field theory
- Supersymmetric geometry and calibrations
- Holography and the correspondence between quantum gravity or string theory in anti-de Sitter space and conformal field theory on the boundary
- Duality symmetries and mirror symmetry
- String theory in plane wave geometries and the implications for gauge theory
- Time-dependent solutions, de Sitter space and cosmology in M-theory
- Topological field theory
- Black holes and the microscopic origin of entropy

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