C. PROPOSAL DESCRIPTION

Integrable models and applications: from strings to condensed matter

EUCLID — **Eu**ropean **C**ollaboration **L**inking **I**ntegrability with other **D**isciplines

Coordinating node

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1a. RESEARCH TOPIC

Quantum field theory has grown from its beginnings in the 1940s into one of the most significant areas in modern theoretical physics. In particle physics, it underpins the standard model of the electromagnetic, weak and strong interactions, and is a major ingredient of string theory, currently the most promising candidate for an extension of the standard model to incorporate gravity. In statistical mechanics, the vital rôle of quantum-field-theoretic techniques has been recognised since the work of Wilson in the late 1960s. The ever-increasing use of the methods of quantum field theory in condensed matter physics demonstrates the growing practical importance of the subject, and at the same time provides a vital source of fresh ideas and inspirations for those working in more abstract directions. And last but by no means least, the last decade has seen a remarkable resurgence of interactions between the fields of pure mathematics and theoretical physics, much of it centered on quantum field theory and statistical mechanics.

For all of these successes, most of our knowledge about quantum field theory has traditionally come from methods which are 'perturbative', relying on approximation schemes which depend for their validity on the smallness of some parameter. One of the major challenges facing the subject has always been the need to develop reliable and effective 'non-perturbative' methods for circumventing these limitations. A unifying concept which is coming increasingly to the fore is *integrability.* The implications and scope of this idea have grown dramatically since its inception in the late sixties, when it was almost exclusively concerned with the construction of exact solutions to the classical equations of motion of physical non-linear systems in one space and one time dimensions. The concept has now been widened and covers any system, classical or quantum, which has sufficiently-many conservation laws that all physically-relevant quantities can be calculated exactly. These conservation laws will generally be associated with symmetries, but the symmetries may be hidden and their elucidation is often a challenging mathematical problem. And while it may be true in principle that exact results are available, turning this into practice can be extremely nontrivial. The payoff, however, is significant – quantum field theory breaks free from the limitations of perturbation theory, and previously unsuspected properties such as strong-weak coupling dualities are revealed. For these reasons the subject has been a source of fascination for mathematicians and physicists for many years. Most recently, it has also moved significantly closer to centre-stage for those more interested in concrete applications. In condensed-matter physics the predictions of integrability are now being confronted with experiments and are starting to face issues in subjects, such as superconductivity, of real technological importance. In the fundamental area of string theory, a subject of great cultural significance as our best hope for a unified theory of all the interactions in nature, results from workers in integrability are also coming to greater prominence, and the demand for their skills is growing.

Our proposal continues the scientific theme of two previous European networks, within the HCM and TMR programmes (ERBCHRXCT 920069 and ERBFMRXCT 960012), and aims to pin down the fundamental features of integrability, while simultaneously developing and widening its applications. We will make important contributions directly, support significant numbers of young European scientists at the beginnings of their careers, and provide a training programme which will equip them with the tools that they will need to work in this exciting and fast-developing field. A key feature of our network is the broad nature of its expertise. This breadth is essential in order to exploit fully the growing interactions between the different constituents. Traditionally this domain of mathematical physics has been one of Europe's strengths, and it is important to maintain and build on this position. The wide range of the subject, its ubiquity in physics and mathematics and its fundamental and challenging nature make it extremely attractive to many of Europe's finest young scientists. It is crucial that these assets remain in Europe in the long term, and it is only through continuing active support for training programmes on a pan-European scale that this goal can be achieved.

1b. PROJECT OBJECTIVES

The central research objective is to deepen the understanding of the physics of integrability, identifying the fundamental mechanisms and developing applications in a variety of contexts, from string theory to condensed matter physics.

Our specific objectives are aimed at the achievement of three broad goals, and advances on these will be made in parallel during the course of the project. The principal flow of ideas and results will be as follows:

Underlying mechanisms $\longleftrightarrow$ **Calculational aspects** $\longleftrightarrow$ **Applications**

In greater detail:

1) We shall identify new mechanisms underlying integrability.

The development of the appropriate mathematical tools is vital for furthering the applications of integrability; as a source of new abstract structures it is also leading to very fruitful interactions between mathematicians and physicists. New challenges are continually emerging, and the EUCLID partnership expects to make advances on the following topics:

a. The development and application of the theory of quantum algebras (in particular those of elliptic type) and their associated q-vertex operator algebras.

b. The algebraic geometry of integrability. At the classical level this is well-established; we will work to extend these results to quantum integrable systems.

c. The particular algebraic structures which arise in connection with boundary problems. For models possessing conformal symmetry, these are associated with the so-called weak Hopf algebras; once conformal symmetry is lost, solutions of the boundary Yang-Baxter equation are crucial. Developing these two strands is the initial goal; in the longer term, links will be built between them.

d. Analytic and functional-relations approaches. These ideas have been employed with increasing success in both lattice and continuum studies of integrability. We will develop their use, ultimately connecting with results obtained under objective 1b. In addition, links with other areas of mathematics and physics, such as matrix models, the theory of differential equations, and discrete integrability, will be pursued.

2) We shall develop the calculational aspects of integrability.

The acid test of integrability is its ability to produce concrete answers to well-posed questions – in other words, to get numbers out. This theme is therefore pivotal to our proposal, on the one hand substantiating the practicality of the more mathematical ideas, and on the other feeding solid results and calculational techniques on to those interested in specific applications. Work will focus on the following key areas:

a. Boundary conditions. This subject came to the fore during the period of our last TMR grant, and significant further progress is expected. A number of issues are particularly pressing, and progress on them will have significant repercussions:

- The classification of conformal boundary conditions. This has particular implications for the study of algebraic structures under objective 1c, and for the applications to D-brane physics under objective 3c.
- The classification of integrable boundary conditions in non-conformal continuum models, both classical and quantum, and their relationship with lattice model results.
- Dynamical aspects of boundary problems, including the calculation of correlation functions in conformal models, the calculation of scattering amplitudes in massive models, the study of renormalisation group flows, and the investigation of duality properties.

b. Finite-size effects. Putting a system into a finite box probes many interesting physical properties, and often reveals a wealth of hidden mathematical structure. The following techniques will be refined and exploited:

- Exact methods for continuum models (Thermodynamic Bethe Ansatz, Non-Linear Integral Equations, and the functional-relations ideas mentioned under objective 1d).

- – The parallel treatment of lattice models.
- – The verification of exact results through numerical approximation schemes (Monte-Carlo, 'truncated conformal space').
- – The use of finite-size effects to study bulk and boundary renormalisation group flows.

c. Correlation functions and form factors. These quantities are usually of most immediate relevance to applications, and recent progress indicates that major breakthroughs will be made in the near future. We will concentrate on the following problems:

- – Correlation functions in solvable lattice models, at finite temperatures, with time dependence and in the presence of boundaries.
- – Long distance asymptotics of correlation functions, and relations with the field theory limit.
- – Development of the form-factor approach, both on the lattice and in the continuum, and its link with the formal algebraic structures of objectives 1a and 1b.

3) We shall apply these results to specific physical problems.

The scope of integrability both as a theoretical laboratory for ideas in quantum field theory and as a source of answers to questions of independent physical interest has seen an unprecedented growth in the last few years. This is one of the reasons why our proposal is particularly timely. The expertise that we have assembled allows us to be confident of progress in the following specific areas, which range from traditional questions of quantum field theory through topics in gauge and string theory to applications in condensed matter physics:

a. General aspects of quantum field theory. We will further analyse integrable quantum field theories which exhibit unstable particles and particle production, and use exact and approximate methods developed in the study of integrability to obtain non-perturbative results for non-integrable models.

b. Quantum structure of gauge theories. The works of Seiberg and Witten and of Maldacena, among others, have opened up a route to exact results in higher-dimensional theories. The rôle of classical integrability (eg Calogero-Moser models) in the phase structure of these models will be exploited.

c. D-brane physics and string theory. We will apply the boundary conformal field theory results obtained under objectives 1c and 2a to concrete problems in D-brane physics, and in the longer term apply perturbed (non-conformal) boundary field theories studied under objectives 2c and 2d to issues in tachyon condensation and moduli spaces of D-branes. Results will be compared with those from other non-perturbative approaches, such as the construction of supergravity solutions. The coupling of two-dimensional gravity to matter will be analysed, as part of a general study of non-compact conformal field theories and their applications in string theory.

d. Disordered systems and non-equilibrium statistical mechanics. The methods of conformal field theory and integrability will be applied to these problems, which offer particular challenges to traditional field theory and are frequently of experimental relevance.

e. Mesoscopic systems, quantum transport. The quantum Hall Effect, the Kondo problem, and the transport properties of quantum dots and wires provide the most immediate testing-grounds for the ideas of integrability, and are also of direct interest to experimentalists. All will be studied during the course of the project, and contacts with experimental groups will be established.

Predecessors of this network have functioned extremely well, and have provided a framework for a large fraction of the European activity in the area. With the benefit of the inclusion of a number of further institutions, we have now assembled a comprehensive pan-European expertise. Detailed milestones are given in section 4 below, but throughout, calculational aspects will occupy centre-stage as a conduit for ideas.

It is always difficult to anticipate the impact of theoretical work of this type – connections often emerge only once research is underway, and these can greatly add to the significance of a given domain. One instance of this is the heightened interest in boundary conditions in conformal field theories which has been provoked by the discovery of D-branes. However, we highlight objectives **1b**, **2a,c** and **3d,e** as especially challenging, and advances in them will certainly constitute major breakthroughs. Section 3 below contains more details of how we expect them to be attained, for the example cases of objectives **1b**, **2c** and **3e**.

2. SCIENTIFIC ORIGINALITY

State of the art

The idea of integrability for a finite system of particles in interaction in classical mechanics starts in the 19th century and is associated with Liouville's theorem, which states that the system is integrable provided there are as many conserved quantities in involution as there are degrees of freedom. For nonlinear wave equations (field theories) parallel ideas have been developed from the 1960s, starting with the pioneering work on the sine-Gordon and KdV systems by Skyrme and others, both in the classical and quantum domains. During the 1970s and 1980s a start was made on classifying integrable quantum field theories and elucidating their properties, for example S-matrices (Zamolodchikov and Zamolodchikov and others), and form factors (Karowski and others). The study of their formal mathematical structure was also initiated, principally by Faddeev and co-workers. More recently the separation of variables method, related to the Hamilton-Jacobi theorem in classical mechanics, was extended by Sklyanin to the realm of quantum integrable models, under the name of the functional Bethe ansatz.

Particularly tractable and valuable examples of integrable quantum field theories are the conformal field theories, which were studied intensively following the seminal work of Belavin, Polyakov and Zamolodchikov in 1983. Special examples of these underpin string theory while others are relevant to the description of certain statistical mechanical systems at criticality. In 1989, Zamolodchikov noted that many non conformally-invariant quantum integrable models could be regarded as perturbations of conformal field theories, thus opening the door to conformal perturbation theory as well as providing new insights into the nature of integrability itself. During the 1990s, building on work of Cardy, Sklyanin, Ghoshal and Zamolodchikov, and others, much attention has focussed on the issue of incorporating boundary conditions in conformal field theory and integrable field theory. This has revealed unexpected insights into the nature of the bulk theories themselves, and led to the possibility of new applications. Very recently the relevance of algebraic structures known as weak Hopf algebras to boundary conformal field theory has been realised, a development pioneered by members of the Saclay and Sofia teams of our proposal.

A further convergence has been the merging, since the late seventies, of integrable quantum field theory with the statistical mechanics of integrable lattice models (Heisenberg, Ising, and generalizations), where similar underlying structures of integrability have been discovered (Bethe ansatz method, Yang-Baxter relations, Baxter's Q-operator). These models had been studied for many years, not only as models for specific physical systems, but also (in their continuum limits) as microscopic realisations of integrable field theories, including conformal field theories. The subject dates back to Bethe's solution of the Heisenberg spin chain (a model of magnetism) in 1931 and Onsager's solution of the Ising model in 1944. Onsager's work had a profound impact on physics, since it settled, in the affirmative, the longstanding question of whether phase transitions could be described within Gibbs' approach to statistical mechanics. The full richness of lattice integrability began to emerge with Baxter's solution of the eight-vertex model in 1972. Modern treatments are closely allied to the theory of quantum groups and the algebraic Bethe ansatz techniques of Faddeev and co-workers. Two recent developments of considerable promise are the emerging picture of 'elliptic quantum groups', associated with a dynamical version of the Yang-Baxter equation, and the explicit solution of the quantum version of the inverse scattering problem for a large class of integrable quantum lattice models, including the Heisenberg spin chains (Maillet and co-workers).

In other areas of physics the impact of integrability is also being felt. The impact of Onsager's solution on the theory of phase transitions has already been mentioned; and many fundamental discoveries in quantum field theory, such as the Montonen-Olive duality which can be found in four dimensions, were anticipated by properties of two-dimensional, integrable, models. In addition, integrable models are coming increasingly to have a *direct* relevance in higher numbers of dimensions. In string theory the fact that the world-sheet of a string is described by a conformal field theory has been recognised since the early days, and the classifications of conformal field theories have been of relevance to the construction of string backgrounds. Polchinski's discovery that D-branes can be understood using boundary conformal field theory has re-invigorated the subject, and perturbations of these theories are now under investigation as a means of studying various dynamical processes in string theory, such as tachyon condensation. Results from these studies are now being compared with alternative approaches such as supergravity solutions, and are providing important checks of the consistency of string theory. And finally, the theory of *classical* integrable systems is returning to prominence as the appropriate mathematical setting within which to discuss the phase structure of quantum gauge theories, again making contact with results from string theory.

Contribution to advancing the state of the art

We are at a point when the most profound mathematical implications of integrability are starting to be revealed. At the same time, the applications of the subject are emerging in previously unsuspected areas of physics. Progress will be most rapid if the new insights can be communicated between the different areas as efficiently as possible, and for this a coordinated research effort across the full range of the subject is essential. At the moment Europe is playing a leading rôle in these developments. Our work will lead to significant advances in the state of the art in the following respects:

1) Underlying mechanisms

a. the rôle of quantum algebras will be elucidated, the resolution of the quantum inverse problem for their infinite dimensional representations (relevant for integrable field theories) obtained, and connections with the q-Virasoro algebra understood;

b. progress will be made towards the quantisation of the ideas of algebraic geometry to give the appropriate framework to understand the quantum separation of variables;

c. the appropriate algebraic framework within which to treat boundary problems will be found;

d. the use of functional relations in integrable models will be extended, and connections with other branches of mathematics exploited.

2) Calculational aspects

a. an understanding of the space of conformal boundary conditions for significant classes of conformal field theories will be achieved; the set of known boundary scattering amplitudes will be extended to many further models, and the topology of the flows between conformal boundary conditions will be clarified;

b. the exact treatment of finite-size effects in integrable systems, with and without boundaries, will be developed, and the relationship between continuum and lattice results will be understood; the treatment of these effects in related non-integrable models will be developed;

c. tractable expressions for correlation functions and their long distance asymptotics will be obtained for a large variety of models, both on the lattice and in the continuum.

3) Applications

a. the properties of integrable models with unstable particles and particle production, and the loss of integrability induced by non-integrable perturbations, will be better understood;

b. our understanding of the phase structure of gauge theories will be deepened by the use of techniques of classical integrable systems;

c. a rigorous understanding of the space of conformal boundary conditions and the flows between them will lead to new understandings of the possible behaviours of D-branes; Liouville theory will be developed into an effective tool in the investigation of string theory;

d. the rôle of conformal field theories in the study of low-dimensional disordered systems will be better understood, leading to new insights into the nature of disorder in general; steps will be taken towards an understanding of the universal aspects of non-equilibrium statistical mechanics;

e. applications of integrability to systems of real experimental and technological interest will start to emerge. In particular, results on quantum transport in multichannel and spin systems, and on finite size and decoherence effects in strongly-correlated mesoscopic systems, will be obtained.

These are some of the specific advances that it is possible to anticipate ahead of time. However we stress that much of our interest in this project lies in the interdisciplinary links that it will generate. These will inevitably result in unexpected directions for future work. By continually monitoring our progress, in particular via the annual network conferences, we will be in a position to adjust our efforts and channel our activities into the most beneficial directions.

3. RESEARCH METHOD

Mathematical/theoretical physics is an interdisciplinary field. Many of the outstanding achievements in the area in the last 20 years have arisen as a result of the migration of ideas across the mathematics–physics divide. Our network boasts a great richness of expertise in a wide range of techniques on both sides of this interface, and an important part of our research methodology is the fostering of links between workers in the different specialities.

These specialities split naturally into eight overlapping disciplines:

IQFT	—	Integrable Quantum Field Theory
AAI	—	Algebraic Aspects of Integrability
SLM	—	Solvable Lattice Models
CSM	—	Condensed Matter/Statistical Mechanics
2DCFT	—	2-Dimensional Conformal Field Theory
DBP	—	D-Brane Physics
AdS/CFT	—	AdS/CFT correspondence and Super-symmetric Gauge Theories
CI	—	Classical Integrability

The immediate linkages between the disciplines are summarized in the following diagram.

General research methodology

As described in the previous sections, the main goal when dealing with an integrable model is to actually *solve* it. This includes the identification of the underlying mechanisms responsible for its integrability (of algebraic or geometrical nature), and their effective use through the design of methods to compute all physically relevant quantities (spectrum, S-matrix, correlation functions). In turn, these results are needed to apply the model to situations of physical interest, which might range from string theory to condensed matter systems.

In fact, a generic quantum integrable model can be viewed in many different ways. Suppose the initial description is in terms of an integrable quantum field theory; then it can usually be obtained as a suitable continuum limit of a solvable lattice model of statistical mechanics. Both have underlying dynamical symmetry algebras - sometimes a quantum group. The field theory can usually also be described as a perturbation of a conformal field theory.

To obtain a full understanding of a given problem (in particular in a form suitable for its applications to physically interesting situations) it is usually necessary to develop each of these descriptions (hence using several complementary techniques, all of them present in the different partners of the EUCLID proposal), and then to marry them in a coherent way.

We now give more details of the methods we shall be applying to the project. To be as specific as possible, we will take three challenging and representative examples chosen among the three main categories of our objectives, and for which major breakthroughs are expected.

Methodology in specific examples

Quantized algebraic geometry: In the classical case, the group theoretical methods and the algebro-geometrical methods are well understood. At the quantum level, the development of the group theoretical aspects is a well known success and has provided the new concept of quantum groups; the quantum algebro-geometrical aspects however remain to be obtained. Building on the known classical picture for classical integrable models, our plan is to investigate the nature of the quantum deformations of Riemann surfaces and Jacobi varieties which appear in the form factor formulae of Smirnov (obtained first for the zero genus case); we will then use the quantum separation of variables method (Sklyanin's functional Bethe ansatz) and ideas related to Baxter's Q-operators, as well as the theory of quantum algebras and their representation theory, to extend this picture to higher genus. In particular, the recent algebraic resolution of the quantum inverse scattering problem for solvable lattice models by Maillet and collaborators will be used as a guideline. None of these approaches separately could lead to a description of a quantized version of the concepts of algebraic geometry in a form suitable for quantum integrable models and their algebraic structures. But we expect that by using them together we will be able to get a fully coherent mathematical understanding of this problem.

Correlation functions: To tackle these problems, we will merge the various lattice approaches (q-vertex operator, algebraic Bethe ansatz and the solution of quantum inverse scattering problem) with continuum field theory techniques (in particular perturbed CFT and form factors approach) together with the quantized algebraic geometry concepts developed above to obtain general methods for computing tractable expressions for correlation functions both at short and long distances. The necessary specialities are present in members of the EUCLID proposal (see the table in section 4). This will also involve particular asymptotic analysis techniques that are typical of classical integrable models.

For *applications* to condensed matter physics, integrable models and conformal symmetry methods will be combined with renormalization group calculations, out-of-equilibrium field theory techniques and boundary integrable field theories together with numerical methods (see below), to give a global understanding of these systems. Important for these applications will be the results obtained above for correlation functions and form factors (or more generally, matrix elements of quantum observables between eigenstates). This is true even in non-integrable situations, since they can be approached as perturbations of integrable models. These techniques, inherited from field theory, have already proven to be very useful in calculating physical properties of condensed matter systems.

Calculational techniques and tools

While much of our work will be performed analytically, there will also be a large rôle for computers – these are of use both in analytical work (for example in the use of computer algebra packages such as Maple and Mathematica) and in numerical studies, such as Monte Carlo simulations, the truncated conformal space approach, and numerical solution of the thermodynamic Bethe Ansatz equations.

All institutions in the proposal are able to provide workers with the standard computing facilities, and are each well-equipped with workstations capable of performing small to medium sized numerical and algebraic calculations. For larger-scale computing needs, we have in particular access to the INFN distributed computer environment. Through collaboration this national resource will become available to network members on a Europe-wide basis.

Through our schools, workshops and the transfer of post-docs (particularly in the secondment scheme) we will be able to educate each other in these necessary complementary skills to maximize the efficiency of our research.

4. WORK PLAN

The size of our network means that we can draw on expertise in all aspects of integrability in order to achieve our research goals, and also means that we can provide a comprehensive training programme to enable our postdocs to contribute in significant ways towards these goals. The training will be enhanced through the schools and the secondment scheme, explained in section 10 below. One of the main organisational challenges on the scientific side of the project will be to ensure efficient communications, so as to utilise these complementary resources to the greatest possible extent. The postdocs will be an important part of the communication mechanism: by spending part of their time at another institution through the secondment scheme (see section 10), both their training, and the transmission of skills and information between partners, will be enhanced.

Our knowledge base splits naturally into the eight overlapping research disciplines listed in section 3 above. The principal concentrations of expertise in these areas amongst our nodes, and their direct relevance to our research goals, are summarised in the following table:

	IQFT	AAI	SLM	CSM	2D CFT	DBP	AdS/ CFT	CI
1. U.York	*	*	*					*
2. INRNE.Sofia	*	*		*	*	*	*	
3. CNRS.Site Alpes	*	*	*	*	*		*	
4. ENS.Lyon	*		*	*	*		*	*
5. LPM.Montpellier	*	*		*	*			
6. FU.Berlin	*	*	*	*	*			
7. PI.Bonn	*			*	*	*	*	
8. ELTE.Budapest	*					*	*	*
9. INFN.Bologna	*			*			*	
10. SISSA.Trieste	*	*		*				*
11. U.Santiago	*			*		*	*	*
12. U.Durham	*		*		*	*	*	
13. KC.London	*	*			*	*	*	
Relevance to research objectives	All	1a,b,c	1a,b 2a,b,c 3d,e	3a,d,e	1c,d 2a,b 3d,e	2a 3c	1b 3b,c	1b,d 3b

During the course of the project we shall make advances in the three main subject-areas, that is on the underlying mechanisms of integrability, on calculational aspects and on applications. Each area will influence the others, so that as the project evolves it will be necessary to reconsider the work plan and make revisions in the light of the progress made by the network members and also by the worldwide research community at large.

Our work plan is divided into two phases: the first leading up to the mid-term review at the end of year two, and the second covering the remainder of the contract and culminating in the final network conference. Intermediate network conferences will allow us to monitor progress towards our milestones and allow adjustments to be made as necessary.

First phase (years one and two) – work distribution and milestones

First we show the overall distribution of activity on the objectives during the first two years of the proposal. The joint activity will be founded on the many strong collaborations that already exist between our partners. More details of these are given on the individual pages in section 5 below.

Participant	Objective 1				Objective 2			Objective 3				
	a	b	c	d	a	b	c	a	b	c	d	e
1. U.York		•	•	•	•		•		•			
2. INRNE.Sofia			•		•				•	•		
3. CNRS.Site Alpes [1]	•	•	•		•						•	•
4. ENS.Lyon [2]		•	•				•		•		•	•
5. LPM.Montpellier				•	•	•						•
6. FU.Berlin [1]				•		•	•	•			•	•
7. PI.Bonn [2]									•		•	•
8. ELTE.Budapest						•	•	•				
9. INFN.Bologna				•		•			•			•
10. SISSA.Trieste [2]					•		•	•	•		•	•
11. U.Santiago [1]						•		•	•	•		•
12. U.Durham [2]	•		•	•	•	•			•	•		
13. KC.London [1]	•				•	•				•		

Our research objectives were detailed in sections 1b and 2 of this document. Below, we give a set of milestones that will enable us to judge our progress towards these goals at the half-way stage of the project, that is, at the mid-term review at the end of year two. We also indicate some of the main collaborative axes around which efforts towards these milestones will be based.

In the list of milestones, [1] indicates that a postdoc starting in year 1 is expected to assist the completion of the particular task, and likewise for [2]. (The same convention is used to convey the postdoc destinations in the table.)

1) Underlying mechanisms

a. Connections between q-Virasoro and elliptic algebras established (Annecy[1] – Heriot-Watt)

b. Preliminary work only (York – Saclay – Jussieu)

c. Separate understandings of the algebraic structures of boundary theories, conformal (Sofia – Saclay – Lyon) and non-conformal (York – Durham)

d. Functional relations related to theory of differential equations (York – Bologna – Durham[2])

2) Calculational aspects

a. Classifications of boundary conditions in classes of conformal field theories (Sofia – Saclay)

b. Development of TBA techniques (Montpellier – Tours – Bologna – Durham[2]); full implementation of the truncated conformal space method for boundary field theories (Budapest – Kings[1])

c. Computation of the long-distance asymptotics of correlation functions for a variety of spin chains (York – Lyon[2] – Berlin[1])

3) Applications

a. Completion of research objective (Berlin – Budapest – Trieste[2] – Santiago[1])

b. Role of Calogero-Moser models in SUSY gauge theory established (Santiago – Swansea)

c. Spaces of conformal boundary conditions relevant to string backgrounds understood and related to supergravity solutions (Sofia – Bilbao – Durham – Kings)

d. Further exactly-solvable examples of non-equilibrium statistical mechanics discovered and analysed (Berlin – Bonn[2] – Trieste)

e. Transport properties of multichannel and spin systems analysed and compared with experiment (Lyon – Berlin[1] – Bonn – Trieste[2] – Madrid)

Second phase (years three and four) – work distribution and milestones

By the second phase, we expect new collaborations to have formed as a result of contacts established at our meetings and schools, resulting in a spreading of the work effort on each objective to further partners. In addition, new directions of research will have emerged during the first two years of the project. For these reasons our plans for the final two years are much more tentative than those for the first phase, and will be re-examined with particular care by the Scientific Steering Committee of the Management Committee during the mid-term review. With these caveats in mind, we give the following pattern of work and set of milestones for the second phase:

Participant	Objective 1				Objective 2			Objective 3				
	a	b	c	d	a	b	c	a	b	c	d	e
1. U.York [3]	•	•	•	•	•		•		•			
2. INRNE.Sofia			•		•				•	•		
3. CNRS.Site Alpes	•	•	•	•	•						•	•
4. ENS.Lyon [2]	•	•	•	•			•		•	•	•	•
5. LPM.Montpellier [3]				•	•	•				•		•
6. FU.Berlin				•	•	•	•			•	•	•
7. PI.Bonn [2]									•	•	•	•
8. ELTE.Budapest [3]						•	•					
9. INFN.Bologna [3]				•		•			•			•
10. SISSA.Trieste [2]		•			•	•	•		•		•	•
11. U.Santiago						•			•	•		•
12. U.Durham [2]	•	•	•	•	•	•			•	•		
13. KC.London	•				•	•			•	•		

Key: [2] indicates a postdoc continuing from year 2; [3] indicates a postdoc starting in year 3.

1) Underlying mechanisms

a. Resolution of the quantum inverse problem for infinite-dimensional representations (York – Lyon – Jussieu)

b. The beginings of quantum algebraic geometry established (York – Saclay – Jussieu – Trieste)

c. Algebraic structures of conformal and non-conformal boundary models put on a unified footing (York – Sofia – Saclay – Lyon – Durham)

d. Functional-relations approach linked with results from objective 1b (York – Saclay – Jussieu – Durham[2])

2) Calculational aspects

a. Understanding of boundary conditions and scattering amplitudes in non-conformal (massive) models (York[3] – Montpellier[3] – Berlin – Durham)

b. Classifications of boundary flows using finite-size effects (Budapest[3] – Bologna[3] – Kings)

c. Tractable expressions for lattice correlation functions found and compared with continuum results (York – Lyon[2] – Berlin – Trieste)

3) Applications

a. Objective already achieved in first phase

b. Explorations of phase structure of gauge theories bringing in further classical integrable systems (Trieste – Santiago – Durham – Swansea)

c. Perturbations of boundary conformal field theories including Liouville theory applied to string theory processes such as tachyon condensation (Montpellier – Berlin – Durham – Kings)

d. Disordered systems treated using conformal field theories, and results compared with numerical simulations (Saclay – Lyon – Hannover – Trieste)

e. Decoherence effects in strongly-correlated mesoscopic systems treated and compared with experiment (Saclay – Lyon – Bonn[2] – Firenze – Trieste[2])

Timetable of network conferences, schools and workshops

	Year 1		Year 2			Year 3		Year 4	
	Apr	Sep	Apr	Sep	Nov	Apr	Sep	Apr	Sep
1. U.York	-	-	-	-	mtr	-	-	-	-
2. INRNE.Sofia	-	-	-	c	-	-	-	-	-
3. CNRS.Site Alpes	-	-	-	-	-	-	-	-	-
4. ENS.Lyon	-	-	-	-	-	-	-	-	c
5. LPM.Montpellier	-	-	s	-	-	-	-	-	-
6. FU.Berlin	-	-	-	-	-	-	-	w	-
7. PI.Bonn	-	-	-	-	-	-	-	-	-
8. ELTE.Budapest	s	-	-	-	-	-	-	-	-
9. INFN.Bologna	-	c	-	-	-	-	-	-	-
10. SISSA.Trieste	-	-	-	-	-	s	-	-	-
11. U.Santiago	-	-	-	-	-	-	c	-	-
12. U.Durham	-	-	-	-	-	-	-	-	-
13. KC.London	-	-	-	-	-	-	-	-	-

s: Network School

w: Network Workshop

c: Network Conference

mtr: Mid-Term Review

(The network will also support the 2003 and 2005 Bologna workshops, as explained in section 10.)

Finally we give the distribution of effort between the partners over the full duration of the contract:

Participant	Young researchers to be financed by the contract (person-months) (a)	Researchers to be financed from other sources (person-months) (b)	Researchers likely to contribute to the project (number of individuals) (c)
1. U.York	24	312	11
2. INRNE.Sofia		192	8
3. CNRS.Site Alpes	24	456	16
4. ENS.Lyon	24	372	12
5. LPM.Montpellier	24	288	10
6. FU.Berlin	24	216	7
7. PI.Bonn	24	204	7
8. ELTE.Budapest	24	192	7
9. INFN.Bologna	24	324	11
10. SISSA.Trieste	24	204	7
11. U.Santiago	24	360	13
12. U.Durham	24	408	15
13. KC.London	24	372	13
Totals	288	3900	137

5. COLLECTIVE EXPERTISE

Over the past nine years, as a consequence of two European Networks (in HCM and TMR) we have constructed a European school in this area. The current proposal gathers together almost all the available expertise in order to concentrate on training an important part of the next generation of young scientists. In the UK, the large group at Durham is joined by King's College London and Swansea, and the newly established but already substantial group at York. In France, the groups in Saclay and Paris VI are joined with the large groups in Lyon, Annecy and Montpellier. In Italy, the groups in Trieste, Bologna and Firenze are well-established in the area of the proposal, especially applications. The same is true for the smaller partners in Germany, Hungary, Bulgaria and Spain: all are established in one or more areas of the proposal, and will be able to contribute in a significant way to the combined effort. A summary of the distributions of research specialities between our partners is contained in the first table of section 4.

In addition, we have been able to involve some of the finest world experts on integrability from outside Europe, as external expertise. All have agreed to support our network, and we hope to associate them with the training of young researchers by organising lecture series or mini-courses in their specialities, and by on occasion inviting them to lecture at our network schools. Grants will be sought for elsewhere to finance their visits. This external expertise is distributed in five different institutions, in Japan, Russia and the USA.

We first summarise the content of our network; see also the map in the appendix to this document.

European partners:

- **Member 1 - U.York - York-Mons** [U.K.]
- **Member 2 - INRNE.Sofia - Sofia** [Bulgaria]
- **Member 3 - LAPTH.Annecy - Annecy–Saclay** [France]
- **Member 4 - ENS.Lyon - Lyon–Jussieu** [France]
- **Member 5 - LPM.Montpellier - Montpellier–Tours** [France]
- **Member 6 - FU.Berlin - Berlin** [Germany]
- **Member 7 - PI.Bonn - Bonn–Hannover** [Germany]
- **Member 8 - ELTE.Budapest - Budapest–Szeged** [Hungary]
- **Member 9 - INFN.Bologna - Bologna–Firenze–Torino** [Italy]
- **Member 10 - SISSA.Trieste - Trieste** [Italy]
- **Member 11 - U.Santiago - Santiago de Compostela–Madrid–Bilbao** [Spain]
- **Member 12 - U.Durham - Durham–Heriot-Watt** [U.K.]
- **Member 13 - KCL.London - KCL–Swansea–Cambridge** [U.K]

External expertise:

- **Yukawa Institute - Kyoto** [Japan]
- **Landau Institute - Moscow Region** [Russia]
- **Steklov Mathematical Institute - St Petersburg** [Russia]
- **University of Virginia - Charlottesville** [U.S.A.]
- **Rutgers University - Piscataway** [U.S.A.]

On the following pages, an indication of the already-existing links between our partners has been given by marking with a '**C**' papers written in collaboration with workers currently at other nodes of the network.

To estimate the proportion of an individual participant's time spent on the project it is assumed a senior academic/researcher will allow 50% of his/her time, while more junior colleagues will allocate 75% of their time.

Member 1 – Department of Mathematics, University of York, UK

Pascal Baseilhac	(M-CF, Y)	Nicolai Kitanine	(RA, Y)
Yves Brihaye	(Professor, M)	Niall MacKay	(Lecturer, Y)
Ed Corrigan *	(Professor, Y)	Jean Nuyts	(Professor, M)
Gustav Delius	(AF, Y)	Evgueni Sklyanin	(Reader, Y)
Anastasia Doikou	(RF, Y)	Tony Sudbery	(Professor, Y)
Clare Dunning	(RF, Y)		

* Proposal co-ordinator

(AF= Advanced Fellow; M-CF = Marie-Curie Fellow; RA= Postdoc; RF= Research Fellow; Y=York; M=Université de Mons-Hainaut)

There are 3 PhD students in York, and 3 in Mons, currently working in the research area of the proposal.

Research Expertise

Integrable classical and quantum field theory, statistical mechanics and quantum groups Sklyanin is one of the pioneers in this area and has been responsible for discovering and developing much of the algebraic structure which underpins integrability. Corrigan, Delius and MacKay have worked in the area for many years contributing to a number of discoveries, particularly in the contexts of affine Toda field theories and principal chiral models, and developing non-perturbative methods. Recent work has included investigating boundary effects. Dunning is expert on the theory and applications of the Thermodynamic Bethe Ansatz. Doikou and Kitanine are experts in the areas of spin chains and other exactly solvable models. Delius, MacKay, Sklyanin and Sudbery have developed and extended the theory of quantum groups and their representations; Sklyanin was responsible for their discovery in the context of quantum integrable systems. Brihaye and Nuyts have contributed to the development of group and Lie algebra theory, including supersymmetry, and their applications to physics.

Training Expertise

The York group was established in October 1999 when Corrigan, Delius and MacKay moved to York and were soon joined by Baseilhac, Doikou, Kitanine, Dunning and two graduate students; Sklyanin joined the group in 2001. All the senior members have supervised graduate students and postdocs, and have lectured at advanced schools and/or run conferences or workshops. The small group at Mons has long-running collaborations with Bonn, Durham and York, has trained a number of students, and is willing to host workshops and meetings. There is a lively programme of postgraduate lectures and seminars.

Existing research links with other teams

With **Sofia** on algebraic methods and quantum groups (Dobrev – Sudbery): with **Lyon** on spin chains (Maillet – Kitanine); with **Montpellier** on non-perturbative calculations in affine Toda field theory (Fateev – Baseilhac); with **Bonn** on supersymmetric algebras (Devchand – Nuyts); with **Durham** on quantum field theory with boundaries, the TBA, and algebraic and non-perturbative methods (P. Dorey, Fairlie, Taormina, Tateo – Brihaye, Corrigan, Dunning, Nuyts); with **Cambridge** on integrable field theory (Evans – MacKay).

Two recent publications (see also members 4 and 13)

1. E. Corrigan and A. Taormina, *Reflection factors and a two-dimensional family of boundary bound states in the sinh-Gordon model*, J. Phys. **A33** (2000) 8739. (**C**)

2. P.E. Dorey, C. Dunning and R. Tateo, *Differential equations for general $SU(N)$ Bethe Ansatz systems*, J. Phys **A33** (2000) 8427. (**C**)

Member 2 – Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria

Vladimir Dobrev	(SR)	Valentina Petkova	(SR)
Alexander Ganchev	(SR)	Yassen Stanev	(SR)
Ludmil Hadjiivanov	(SR)	Marian Stanishkov	(SR)
Emil Nissimov	(SR)	Ivan Todorov *	(Professor, A)

* Scientific officer in charge of the work

(A= Academician; SR= Senior Researcher; below the researchers are referred by initials)

There are 4 PhD students in Sofia currently working in the research area of the proposal.

Research Expertise

The group in Sofia has a long standing experience in various aspects of quantum field theory and of conformal and superconformal symmetry. Earlier techniques developed for models in arbitrary dimensions find now applications to string theory. The group has been also active in the development of 2-dimensional Conformal Field Theory (2D CFT).

2D CFT: *Wess-Zumino-Witten (WZW) and related models, representation theory, quantum symmetries:* (VD, AG, LH, VP, YS, MS, IT) Braid group statistics; fusion rules; (indecomposable) representations of affine algebras, quantum groups and exotic bialgebras; reflections equation algebras; rational CFT extensions of $W_{1+\infty}$; equivalence of categories of Moore-Seiberg and truncated reps of quantum groups; fractional level WZW models. *Canonical quantization:* (LH, IT) quadratic Poisson brackets; dynamical R-matrices; logarithmic CFT; generalized BRS operators. *Fractional quantum Hall effect:* (IT) parafermionic and orbifold Hall states with nonabelian excitations.

Boundary CFT: (VP, YS, IT) 2D CFT on open and unoriented surfaces; classification of boundary conditions and crosscap states; weak Hopf algebras; open strings; canonical approach to boundary WZW models.

Integrable Models (EN, MS) additional (hidden) symmetries in integrable models; supersymmetric and non-commutative integrable models; integrable perturbations of CFT models.

D>2 CFT (VD, YS, IT) AdS/CFT correspondence; global conformal invariance, correlation functions; anomalous dimensions in super Yang-Mills theory.

Training Expertise

The Sofia group has a long tradition of organising meetings and schools. It also has a strong PhD programme with main emphasis in the last decade being 2D CFT.

Existing research links with other teams

With **York** on quantum algebras (Sudbery – Dobrev); with **Annecy** on algebraic structures (Arnaudon – Dobrev); with **Saclay** on boundary CFT (Zuber – Petkova); with **Lyon** on canonical WZW (Gawedzki – Todorov); with **Bonn** on quadratic algebras (Rittenberg – Ganchev); with **Bologna** on IQFT (Ravanini – Stanishkov); with **Florence** on Quantum Hall effect (Cappelli – Todorov); with **Trieste** on IQFT (Fioravanti – Stanishkov); with **King's** on W-algebras (Watts – Ganchev, Petkova).

The Sofia group has also a long standing collaboration with both **Budapest** and **Trieste**.

Two recent publications (see also member 9)

1. K. Gawedzki, I.T. Todorov, P. Tran-Ngoc-Bich, *Canonical quantization of the boundary Wess-Zumino-Witten model*, hep-th/0101170. (**C**)

2. V.B. Petkova and J.-B. Zuber, *Generalised twisted partition functions*, hep-th/0011021, Phys. Lett. B to appear. (**C**)

Member 3 – LAPTH-Annecy and SPhT-Saclay, France

Daniel Arnaudon	(Dr., A)	Jean-Claude Le Guillou	(Prof., A)
Michel Bauer	(Dr., S)	Vincent Pasquier	(Dr., S)
Michel Bergère	(Dr., S)	Eric Ragoucy	(Dr., A)
Denis Bernard	(Dr., S)	Ara Sedrakian	(Dr., A)
Philippe DiFrancesco	(Dr., S)	Didina Serban	(Dr., S)
Burkhard Eden	(Postdoc, A)	Emery Sokatchev	(Prof., A)
Luc Frappat	(Prof., A)	Paul Sorba *	(Prof., S)
Riccardo Guida	(Dr., S)	Jean-Bernard Zuber	(Dr., S)
Ivan Kostov	(Dr., S)		

* Scientific officer in charge of the work

(A=LAPTH-Annecy, S=SPhT-Saclay)

There are 2 PhD students in Saclay and 1 in Annecy working in the research area of the proposal.

Research Expertise

In Annecy, the team constituted by D. Arnaudon, L. Frappat, E. Ragoucy, P. Sorba has a long expertise in infinite dimensional (super)algebras and deformed algebras with applications to integrable systems (I.S.). More precisely: quantum groups and spin chain systems, W-(super)algebras and Toda field theories; Yangians, elliptic algebras, deformed Virasoro and W-algebras and their connections; staggered I.S.; strongly correlated fermionic systems (with J.-Cl. Le Guillou). E. Sokatchev and B. Eden are developing results on the Maldacena conjecture relating string theory to conformal field theory on the boundary; E. Sokatchev is also working on superconformal theories in different dimensions.

The Saclay group involved in the earlier development of conformal field theories (C.F.T.), has also a long working tradition in the I.S. and matrix theories (i.e. classification of C.F.T. with central charge < 1; identification of Yangian and quantum group symmetries in C.F.T. and I.S.; developments of modern techniques of random matrix models, etc). Its orientations are today: Developments of the techniques of C.F.T. and I.S., with or without boundaries (D. Bernard, R. Guida, J.-B. Zuber); Applications of C.F.T. to condensed matter such as the quantum Hall effect (M. Bergere, V. Pasquier, D. Serban) and to disordered systems and localisation problems in condensed matter (M. Bauer, D. Bernard, D. Serban); Applications of matrix theory to topology, fluctuating geometries and string theories (Ph. DiFrancesco, I. Kostov, J.-B. Zuber).

Training Expertise

LAPTH has a long experience in the organisation of international conferences and workshops. Some of the permanent members of other teams did their postdoctoral studies at the SPhT-Saclay where series of lectures on modern theoretical physics are regularly organized and collected.

Existing research links with other teams

With **Sofia** on quantum algebras (Dobrev – Arnaudon) and on boundary CFT (Petkova – Zuber); with **Jussieu** on elliptic algebras (Avan – Arnaudon, Frappat, Ragoucy) and on integrable systems (Smirnov – Bernard); with **Montpellier** on quantum groups (Buffenoir, Roche – Arnaudon, Ragoucy); with **Firenze** on higher dimensional conformal field theories (Cappelli – Guida).

There are strong connections between LAPTH and the Lyon group, both having been part of the same laboratory ENSLAPP (from 1990 to 1997). Also links have been established with Durham (P. Dorey) and York (Corrigan) on integrable systems with boundaries.

Two recent publications (see also member 2)

1. D. Arnaudon, J. Avan, L. Frappat, E. Ragoucy and M. Rossi, *On the quasi-Hopf structure of deformed double Yangians*, math.QA/0001034, Lett. Math. Phys. **51** (2000) 193. (**C**)

2. V.B. Petkova and J.-B. Zuber, *The many faces of Ocneanu cells*, hep-th/0101151, Nucl. Phys. **B** to be published. (**C**)

Member 4 – Laboratoire de Physique, ENS Lyon, France

Jean Avan	(CR-CNRS, L)	Krzysztof Gawedzki	(DR-CNRS, E)
Olivier Babelon	(DR-CNRS,L)	Jean-Michel Maillet *	(DR-CNRS, E)
David Carpentier	(CR-CNRS, E)	Marc Magro	(MC-ENSL, E)
Pascal Degiovanni	(CR-CNRS, E)	Pierre Pujol	(MC-ENSL, E)
Francois Delduc	(DR-CNRS, E)	Fedor Smirnov	(DR-CNRS, L)
Laurent Freidel	(CR-CNRS, E)	Michel Talon	(CR-CNRS, L)

* Scientific officer in charge of the work

(CNRS = Centre National de la Recherche Scientifique; CR = Charge de recherche, DR = Directeur de recherche, MC = Maitre de conference, E = ENS.Lyon, L = LPTHE, Paris 6 University)

There are 3 PhD students in ENSL-LPTHE working in the research area of the proposal.

Research Expertise

The teams in ENS.Lyon and LPTHE.Paris have a long-standing expertise in integrable systems, conformal field theory, and their applications. Relevant contributions deal with quantum algebras, form factors and correlation functions, topological field theories, conformal field theories (and boundary effects), and their applications to condensed matter theories and turbulence. Recent works and projects involved—quantization of the algebro-geometric methods in integrable systems and form factors (Babelon, Smirnov, and Talon in collaboration with Bernard in Saclay); quantum algebras (elliptic algebras, twisted Yangians and their doubles) (Avan in collaboration with Arnaudon, Frappat, Ragoucy, Sorba in Annecy and Rossi in Durham); exact determination of correlation functions of quantum integrable models in the algebraic Bethe Ansatz framework (Maillet in collaboration with Kitanine in York, Terras in Rutgers and Slavnov in Moscow); classical integrable hierarchies and their supersymmetric extensions (Delduc); description of boundary degrees of freedom in CFT, relations between CFT and topological field theories, applications to the non-commutative geometry of stringy branes and to the quantum Hall effect (Gawedzki partly in collaboration with Todorov in Sofia); non-perturbative methods in supersymmetric quantum gauge theories and quantum gravity (Magro, Freidel); application of conformal field theory and integrable models to condensed matter involving disordered systems, strongly correlated systems, and decoherence phenomena (Carpentier, Degiovanni, Pujol).

Training Expertise

Members of ENSL have organized and contributed to workshops, conferences and summer schools in the area of the proposal (eg Les Houches 1995 on "Quantum Symmetries"), and LPTHE was one of the organizers of a semester (September 1996– February 1997) on Integrable Systems at the Centre Emile Borel in Paris. All senior members have supervised graduate students and post-docs.

Existing research links with other teams

With **York** on spin chains (Kitanine – Maillet); with **Sofia** on turbulence and boundary conformal theories (Todorov – Gawedzki); with **Annecy** on elliptic algebras (Arnaudon, Frappat, Ragoucy – Avan); with **Saclay** on turbulence (Bernard – Gawedzki).

There are also links with the external expertise: with St. Petersburg on the quantum inverse problem (Maillet), with Kyoto on form factors (Miwa – Smirnov), and with Rutgers on correlation functions (Terras, Lukyanov – Maillet).

Two recent publications (see also member 2)

1. F. Smirnov, *Dual Baxter equations and quantization of the affine Jacobian*, J. Phys. A: Math. Gen **33** (2000) 3385.
2. N. Kitanine, J.M. Maillet, V. Terras, *Correlation functions of the XXZ Heisenberg spin- 1/2 chain in a magnetic field*, Nucl. Phys. **B567** (2000) 554. (**C**)

Member 5 – CNRS13-LPM et UMR6083 (Laboratoire de Physique Mathématique) Montpellier, France

Eric Buffenoir	(Researcher, CR)	Noureddine Mohammedi	(MC, T)
Vladimir Fateev *	(Researcher, DR)	Andre Neveu	(Researcher, DR)
Peter Forgács	(Professor, T)	Michel Rausch de Traubenberg	(MC, M)
Frederic Geniet	(MC, M)	Philippe Roche	(Researcher, CR)
Pierre Grangé	(Researcher, DR)	Alexei Zamolodchikov	(Researcher, DR)

* Scientific officer in charge of the work

(DR = Directeur de Recherches CNRS, CR = Chargé de Recherches CNRS, MC=Maître de Conférences, M = Université Montpellier II, T= Université de Tours)

Average of 4 students working on the project.

Research Expertise

Quantum Groups. E. Buffenoir and P.Roche have developed *harmonic analysis on non-compact quantum groups*. These algebraic structures appear in different physical models among which quantum gravity and the strong-coupling Liouville problem.

Conformal field theory and integrable models. V. Fateev and Al. Zamolodchikov are leaders in the present developments on *boundary conformal field theory*, on *dualities* between strong and weak couplings, on *finite size effects* and on the calculation of *correlation functions* in integrable quantum field theories. P. Forgács has good expertise on classical and quantum aspects of integrable field theories (monopoles, instantons and other classical solutions, applications of the Thermodymical Bethe Ansatz in bosonic and fermionic models).

Classical and Quantum Dualities in σ models. Members of the Tours group have been very active in this area, and N. Mohammedi has a longstanding experience in renormalization and higher loop calculations in σ models.

Application to Condensed matter. With solid-state experimentalists, F. Geniet has analysed the breakdown of the quantum Hall effect, indicating that the crucial parameter of this breakdown is the electric field rather than the current.

Training Expertise

The Montpellier group has organised a summer school on conformal field theory in 2000 in the TMR network. A. Neveu is the director of a CNRS "Groupement de Recherche" on integrable systems the rôle of which is in particular to organise yearly (at least) meetings where young French researchers can get acquainted with the latest developments.

Existing research links with other teams

With **York** on non-perturbative calculations in affine Toda theory (Baseilhac – Fateev); with **Annecy** on quantum groups (Arnaudon, Ragoucy –Buffenoir, Roche); with **Budapest** on duality in integrable systems (Balog, Palla – Forgács) (there is a PhD student (cotutelle) with Forgács and Palla as supervisors). Strong contacts exist with **Bologna** , Rutgers and the Landau Institute on finite size effects. A meeting in Kyoto which was organized in June 1999. On applications to condensed matter, an experiment has been approved in Grenoble to study the results of the investigations of the **ENS Lyon** group on the fractional quantum Hall fluid.

Two recent publications

1. E. Buffenoir, P. Roche, *Tensor Products of Principal Unitary Representations of Quantum Lorentz Group and Askey-Wilson Polynomials*, J. Math. Phys. **41** (2000) 7715.

2. J. Balog, L. Palla, P. Forgács, *A two dimensional integrable axionic σ-model*, Phys. Lett. **B484** (2000) 367. (**C**)

Member 6 – Freie Universität Berlin (Inst. für Theor. Physik), Germany

Hrachik Babujian	(Researcher)	Ingo Peschel	(Professor)
Andrei Bytsko	(Humboldt fellow)	Michael Karowski	(Researcher)
Olalla Castro-Alvaredo	(Postdoc)	Joerg Teschner	(Researcher)
Andreas Fring *	(Researcher)		

* Scientific officer in charge of the work

There will be 3 PhD students in Berlin working in the research area of the proposal.

Research Expertise

Form factors and correlation functions M. Karowski, A. Fring, O. Castro-Alvaredo and H. Babujian have expertise in the computation of form factors and the computation of correlation functions. Models studied are the Sine-Gordon, affine Toda and the homogeneous Sine-Gordon theories.

Renormalization group scaling functions O. Castro-Alvaredo and A. Fring have constructed various RG scaling functions by means of form factors, the Thermodynamic Bethe Ansatz and q-deformed Virasoro characters.

Statistics in lower dimensions A. Bytsko and A. Fring have studied various aspects of the ambiguity of statistics (Haldane and Gentile) in lower dimensions in the context of the Thermodynamic Bethe Ansatz and Virasoro characters.

Spin chains M. Karowski, I. Peschel and H. Babujian are experts on quantum spin chains. They employed the (off-shell) Bethe Ansatz and vertex operators. Models studied are Heisenberg models, finite-size Ising models and stochastic models.

Stochastic Models I. Peschel has investigated one-dimensional transport and reaction-diffusion models, their relation to spin-chains and their exact solution, e.g. via matrix product states.

Non-rational CFT J. Teschner is an expert in various aspects of non-rational CFT which include their correlation functions, harmonic analysis and the formulation with boundaries.

Numerical Methods O. Castro-Alvaredo, A. Fring and I. Peschel have expertise in various numerical methods. These include for instance Monte Carlo methods to compute the correlation functions from form factors, iterative methods to solve the non-linear TBA integral equation and the density-matrix renormalization method which allows to treat very long quantum chains.

Training Expertise

The FUB group is associated since 1994 to the Sonderforschungsbereich (SfB288) and is participating in the organization of the annual conference near Berlin. Part of the group is participating in the regular workshop on “Foundation on Quantum Field Theory”. The 5-th workshop was hold in December 1999 at the FUB.

Existing research links with other teams

With **Bonn** on lattice models (Rittenberg – Peschel); with **Santiago** on homogeneous Sine-Gordon models (Miramontes – Castro-Alvaredo, Fring); with **Swansea** on Toda theory (Olive – Fring).

Two recent publications (see also members 7 and 11)

1. B. Davies and I. Peschel, *A unified treatment of Ising model magnetizations*, Ann. Physik. (Leipzig) **6** (1997) 187.

2. O.A. Castro-Alvaredo and A. Fring, *Indentifying the operator content, the homogeneous Sine-Gordon models*, hep-th/0008044, Nucl. Phys. **B** to be published.

Member 7 – Physikalisches Institut, Bonn University, and Institute for Theoretical Physics, Hannover University, Germany

Jan von Delft	(Professor, BN)	Werner Nahm	(Professor, BN)
Chand Devchand	(Researcher, MD)	Rubik Poghossian	(Researcher, BN)
Michael Flohr	(Researcher, HA)	Vladimir Rittenberg *	(Professor, BN)
Rainald Flume	(Professor, BN)		

* Scientific officer in charge of the work

(BN = Bonn; MD= Math. Dept. Bonn; HA= Hannover)

There are 6 PhD students in Bonn currently working in the research area of the proposal, and 1 in Hannover.

Research Expertise

Integrable models and applications, supersymmetric Yang-Mills theories.

Logarithmic conformal field theory and applications to disordered systems. Moduli spaces of conformal field theory.

Drinfeld twists in q-affine and elliptic algebras.

Quantum dots with Kondo correlations, superconductivity in ultrasmall metallic grains, applications of the Gaudin-Richardson exact results to experiments.

Applications of algebraic methods to the study of phase transitions in non-equilibrium statistical physics.

Applications of special geometric structures to super Yang-Mills theories in higher dimensions.

Training Expertise

European Research Conference, "Advanced Quantum Field Theory", La Londe les Maures, 1996; "School and Workshop on Logarithmic Conformal Field Theory and its Applications" Tehran, 2001

Existing research links with other teams

With **Mons** on supersymmetric algebras (Nuyts –Devchand); with **Sofia** on quadratic algebras (Ganchev – Rittenberg); with **Annecy** on quadratic algebras (Arnaudon – Rittenberg); with **Lyon** on Seiberg-Witten potentials (Magro); with **Lyon, Trieste, Durham** on integrable systems (Pujol, Mussardo, P. Dorey – Rittenberg); with **Montpellier** (Mohammedi); with **Berlin** (Babujian, Peschel – Flume, Rittenberg); with **Durham** on string theory and on instanton calculus (Khoze, Taormina – Nahm); with **King's** on CFT (Gaberdiel, Recknagel, Watts – Flohr, Nahm); with **Swansea** on CFT (Olive – Nahm).

Two recent publications

1. H.M. Babujian and R. Flume, *Off-shell Bethe Ansatz equation for Gaudin magnets and solutions of Knizhnik-Zamolodchikov equations*, Mod. Phys. Lett. **A9** (1994) 2029, hep-th/9310110. (**C**)
2. W. Nahm and K. Wendland, *A Hiker's Guide to K3*, Comm. Math. Phys. **216** (2001) 85, hep-th/9912067.

Member 8 – Institute for Theoretical Physics, Eötvös University, Budapest, Hungary

Zoltán Bajnok	(Postdoc, E)	László Palla *	(Professor, E)
János Balog	(Research Prof., R)	Gábor Takács	(Postdoc, E)
László Fehér	(Professor, SZ)	Péter Vecsernyés	(Research Prof., R)
Zalán Horváth	(Professor, E)		

* Scientific officer in charge of the work

(E= Eötvös University; R= Research Inst. for Particle and Nuclear Physics, Hungarian Academy of Sciences (Budapest) ; SZ= Szeged University)

There are 4 PhD students in Budapest/Szeged currently working in the research area of the proposal.

Research Expertise

DdV (NLIE) and TBA approaches to 2d integrable models – Some members of the Budapest group have been active in this area, and played a major rôle in clarifying the finite volume spectra of the Sine Gordon model and checking the correctness of S matrices for some sigma models.

Application of TCSA to integrable and non integrable 2d models – The k-folded and two frequency Sine Gordon models have been analyzed by this method leading to a discovery of an IR phase transition in the latter model.

Hamiltonian phase-space methods in the description of low dimensional integrable system – Members of the group have been very active in studying the classical phase-space aspects of conformal field theories, such as WZNW and Toda theories, and in exploring their non-linear, extended conformal and Poisson-Lie, symmetry algebras as well as the related hierarchies of soliton equations.

Form factor bootstrap in 2d integrable models – A member of the Budapest group is among the first to use this method to compute four point correlation functions in $O(n)$ σ-models to compare with the results of Monte Carlo simulations.

Training Expertise

ELTE has a strong tradition of organising meetings and schools, most recently a five-day long Summer School followed by a three day long Johns Hopkins Workshop on Nonpertubative QFT Methods and their Applications in August 2000. Eótvös University also runs a full MSc and PhD programme.

Existing research links with other teams

With **Tours** on dual σ-models and on monopoles (Forgács – Horváth, Palla) (Forgács and Palla jointly supervise a PhD student ('cotutelle')). With **Bologna** on applications of the NLIE approach to finite-size scaling (Ravanini – Takács); with **King's** on integrable 2d models (Watts –Takács).

A joint application to the Royal Society for a project grant, "Investigation of two dimensional quantum field theories in finite volume", has been made by Bajnok, Palla and Takács in collaboration with Watts (King's) and P. Dorey (Durham). This is also supported by a grant from the Hungarian Ministry of Education (FKFP-0043/2001).

Two recent publications (see also members 5 and 9)

1. J. Balog, L. Feher and L. Palla, *Chiral extensions of the WZNW phase space, Poisson-Lie symmetries and groupoids*, Nucl. Phys. **B568** (2000) 501-540.

2. Z. Bajnok, L. Palla, G. Takacs and F. Wagner, *The k-folded sine Gordon model in finite volume*, Nucl. Phys. **B587** (2000) 585.

Member 9 – Istituto Nazionale di Fisica Nucleare (INFN), Italy

Francesco Bastianelli	(UR, BO)	Domenico Seminara	(UR, FI)
Andrea Cappelli	(DR, FI)	Emanuele Sorace	(PR, FI)
Michele Caselle	(PA, TO)	Paolo Valtancoli	(R, FI)
Filippo Colomo	(R, FI)	Maxim Zabzine	(PF, FI)
Elisa Ercolessi	(UR, BO)	Roberto Zucchini	(UR, BO)
Francesco Ravanini *	(R, BO)		

* Scientific officer in charge of the work

(R = INFN Researcher; PR = INFN Senior Researcher; DR = INFN Dirigent of Research; UR = University Researcher; PA = Associate Univ. Professor; PF = Postdoctoral Fellow; BO = Bologna; FI = Firenze; TO = Torino)

There are 4 PhD students in INFN BO–FI–TO currently working in the research area of the proposal.

Research Expertise

Finite Size Effects in Integrable QFT – Major contributions have been given (BO group) to the study of Bethe Ansatz nonlinear integral equations governing scaling functions and Renormalization Group Flows.

Quantum Hall Effect – FI group has given the most important contributions to the discovery and exploit of W_∞-symmetry to describe edge states in QHE.

Irrelevant fields in 2d statistical mechanical models and their CFT interpretation. The TO group is investigating thermal and magnetic perturbations of the Ising model in this respect.

Integrable Systems and Quantum Groups – Part of the FI group has found new types of quantum groups and has applied q-oscillators to statistical models with frustration.

CFT and SCFT in higher dimensions have been studied in the approach of AdS/CFT correspondence by members of the BO group.

Training Expertise

BO has a strong tradition of organising every two years a Workshop on CFT and Integrable Models that has become a reference point for European researchers of the area. FI is preparing a new facility to host Summer Schools and Concentration Periods Programmes. Training postdocs experience is well established through the INFN Postdoctoral Fellows and the Universities “Assegni di Ricerca” Programmes. Each of the 3 universities involved (among the biggest and most famous of Italy) has a full Laurea and PhD training in Physics that includes a Math.Phys. curriculum.

Existing research links with other teams

With **Sofia** and **Saclay** on Quantum Hall Effect (Todorov, Guida –Cappelli); with **Sofia**, **Budapest** and **Durham** on IQFT, and NLIE’s in Finite Size Effects (Stanishkov, Takács, P. Dorey, Tateo – Ravanini); with **Swansea** on AdS/CFT and supersymmetric gauge theories (Dunbar – Seminara).

Colomo has a longstanding collaboration with people at the Steklov Institute.

Two recent publications

1. G. Feverati, F. Ravanini and G. Takacs, *Nonlinear Integral Equation and Finite Volume Spectrum of Sine-Gordon Theory*, Nucl. Phys. **B540** (1999) 543. (**C**)
2. A. Cappelli, L.S. Georgiev and I.T. Todorov, *A Unified Conformal Field Theory Description of Paired Quantum Hall States*, Comm. Math. Phys. **205** (1999) 657. (**C**)

Member 10 – Scuola Internazionale Superiore di Studi Avanzati, Trieste, Italy

Davide Controzzi	(Lecturer)	Gesualdo Delfino	(Lecturer)
Boris Dubrovin	(Full Professor)	Michele Fabrizio	(Associate Professor)
Gregorio Falqui	(Associate Professor)	Davide Fioravanti	(Visiting Postdoc)
Giuseppe Mussardo *	(Full Professor)		

* Scientific officer in charge of the work

There are 4 PhD students in SISSA currently working in the research area of the proposal.

Research Expertise

Statistical Field Theories

Members of the SISSA group have been very active in Quantum Field Theories and in their applications to statistical mechanics and condensed matter problems. Significant contributions have been recently obtained in the calculation of universal amplitudes of systems near their critical point – a set of quantities of experimental relevance –, and in the characterisation of random systems.

Boundary Field Theories

Members of the SISSA group have been actively involved in the study of boundary effects in Quantum Field Theories, such as the behaviour of correlation functions and the free energy, and in the explicit calculation of reflection amplitudes for several theories of statistical interest.

Integrable Models

Quantum and classical integrable models are the subject of an intense research activity within the SISSA group. Exact scattering theories for different quantum field theories (with kink excitations or with infinite number of resonance states or in a presence of vacuum instability) have been studied and their physical relevance fully analysed. Members of the group are also expert on Bethe Ansatz techniques in lattice integrable models.

Training Expertise

As one of Italy's leading centres for higher learning and research, the activity in SISSA is extremely concerned with the education and training of young researchers. Post-doctoral researchers and students can highly benefit from the presence of strong scientific groups such as Mathematical Physics, Condensed Matter Theory and Elementary Particle Theory. SISSA has only PhD programs and a strong activity in the organization of meetings and advanced workshops, the most recently one on *Quantum Field Theory, Non-Commutative Geometry and Quantum Probability* (March 2001). The vicinity of the International Centre of Theoretical Physics and other activities in SISSA such as the Interdisciplinary Laboratory of Interdisciplinary Studies or the School in Science Communication help create a stimulating atmosphere for young scientists.

Existing research links with other teams

With **Sofia** (Stanishkov – Fioravanti) and with **Durham** (Rossi – Fioravanti) on integrable systems.

Two recent publications

1. D. Fioravanti, G. Mussardo, P. Simon, *Universal Amplitude Ratios of the Renormalization Group: Two-Dimensional Tricritical Ising Model*, Phys.Rev.E63:016103,2001. (**C**)
2. G. Delfino, *Correlators in Integrable Quantum Field Theory: the Scaling RSOS Models*, Nucl.Phys.B583:597-613,2000

Member 11 – Universidad de Santiago de Compostela, Spain

Ana Achúcarro	(Reader, B)	J. Luis Miramontes *	(Professor, S)
Enrique Alvarez	(Professor, M)	Tomas Ortín	(CR, M)
Jose L.F. Barbón	(Reader, S)	Alfonso V. Ramallo	(Professor, S)
Roberto Emparán	(Reader, B)	Joaquin Sánchez-Guillén	(Professor, S)
Jose M.F. Labastida	(Professor, S)	Jose M. Sánchez de Santos	(Lecturer, S)
Pablo M. Llatas	(Lecturer, S)	German Sierra	(CR, M)
Javier Mas	(Reader, S)		

* Scientific officer in charge of the work

(B= Univ. de Bilbao; S= Univ. de Santiago de Compostela; CR= CSIC Researcher; M= Inst. de Física Teórica, Madrid)

Average of 5 PhD students in Santiago, 2 in Bilbao and 1 in Madrid currently working in the research area of the proposal.

Research Expertise

Integrable quantum field theories and soliton equations. (Miramontes, Sánchez-Guillén) Integrability of two-dimensional relativistic soliton theories. Exact S-matrices in non-abelian affine Toda theories. Thermodynamic Bethe Ansatz techniques and finite size effects in integrable models. Lie algebraic formulation of integrable soliton equations. Geometric construction of integrable theories in higher dimensions and their soliton solutions.

Branes, String theory and Duality. (Barbón, Emparán, Alvarez, Labastida, Llatas, Mas, Ortín, Ramallo, Sánchez de Santos) Dualities and non-perturbative effects in String theories, Supersymmetric gauge theories and Supergravity. AdS/CFT correspondence. Applications to the calculation of topological invariants. Born-Infeld description of D-branes. Supersymmetric effective actions and soft supersymmetry breaking. Branes and non-commutative geometry.

String theory and gravitation. (Achúcarro, Emparán, Ortín) Description of p-branes and black holes in string and M-theory. Black holes and the AdS/CFT correspondence. Brane-world scenarios.

Renormalisation group and condensed matter physics. (Sierra) Applications of integrability in statistical mechanics and condensed matter physics.

Training Expertise

USC has experience in organising schools, workshops and conferences. During the last 7 years, an annual Autumn School in theoretical physics for graduate students and young researchers has been hosted. An international school on Supersymmetry in the theories of fields, strings and branes, addressed to advanced graduate students, was held in 1999. USC also runs a full PhD programme.

Existing research links with other teams

With **Berlin** on homogeneous Sine-Gordon models (Castro-Alvaredo, Fring – Miramontes); with **Durham** on string theory and gravitation (Charmousis, Gregory, Johnson – Emparán, Achúcarro); with **Swansea** on integrable quantum field theories and soliton equations (Hollowood – Miramontes, Sánchez Guillén); there are also strong links with **Durham** (P. Dorey – Miramontes) on this subject.

Two recent publications

1. O.A. Castro-Alvaredo, A. Fring, C. Korff and J.L. Miramontes, *Thermodynamic Bethe Ansatz of the Homogeneous Sine-Gordon models*, Nucl. Phys. **B575** (2000) 535–560. (**C**)

2. A. Chamblin, R. Emparan, C.V. Johnson, R.C. Myers, *Holography, thermodynamics and fluctuations of charged ads black holes*, Phys. Rev. **D60**:104026,1999. (**C**)

Member 12 – Dept. of Mathematical Sciences, Durham University, U.K.

Peter Bowcock	(Lecturer, D)	Paul Mansfield	(Professor, D)
Christos Charmousis	(Postdoc, D)	Marco Rossi	(Postdoc, HW)
Patrick Dorey *	(Reader/AF, D)	Bernd Schroers	(Lecturer/AF, HW)
David Fairlie	(Professor, D)	Richard Szabo	(Lecturer/AF, HW)
Davide Fioravanti	(Postdoc, D)	Roberto Tateo	(AF, D)
Ruth Gregory	(RSF, D)	Anne Taormina	(Lecturer, D)
Clifford Johnson	(Senior Lecturer, D)	Robert Weston	(Lecturer/AF, HW)
Valentin Khoze	(Reader, D)		

* Scientific officer in charge of the work

(AF = Advanced Fellow; RSF = Royal Society Fellow; D = Durham; HW = Heriot-Watt)

There are 7 PhD students in Durham, and 1 in Heriot-Watt, currently working in the research area of the proposal.

Research Expertise

Integrable Quantum Field Theory. (Bowcock, Dorey, Fioravanti, Mansfield, Tateo, Taormina, Rossi, Weston) Renormalisation group flows, boundary effects and integrability of two-dimensional models both in the continuum and on the lattice; Thermodynamic Bethe Ansatz techniques and finite-size effects in integrable models; connections between the Bethe Ansatz and the theory of ordinary differential equations.

Conformal Field Theory and representation theory. (Bowcock, Fioravanti, Rossi, Taormina, Weston) Conformal, superconformal and elliptic algebras; the representation theory of affine super Lie algebras and fractional level CFT.

Gauge theories and the AdS/CFT correspondence. (Fairlie, Johnson, Khoze, Mansfield, Schroers) Monopoles and instantons in gauge theories; tests of the AdS/CFT correspondence from instanton calculus and anomaly calculations; application of D-brane probe techniques to the study of gauge theories.

String theory and gravitation. (Charmousis, Fairlie, Gregory, Johnson, Szabo, Taormina) D-branes, dualities and non-perturbative effects in string theory; their study via the construction of black hole and D-brane solutions in supergravity.

Training Expertise

Durham runs an annual set of MSc lectures in particle theory, and has also hosted many schools and conferences, most recently a Summer Institute in 1996, one-day meetings on conformal field theory and integrable models in 1998 and 1999, and a meeting on Quantum Groups in 1999. There is also much activity centred on the new 'Institute for Particle Physics Phenomenology'.

Existing research links with other teams

With **York** on IQFT (Corrigan, Dunning – P.Dorey, Tateo, Taormina); with **Mons** on algebraic and non-perturbative methods (Brihaye, Nuyts – Fairlie, Taormina); with **Annecy** on CFT (Frappat, Sorba – Rossi); with **Bologna** on IQFT (Caselle, Ravanini – P.Dorey, Tateo); with **Bilbao** on string theory and gravitation (Achúcarro, Emparan – Charmousis, Gregory, Johnson); with **King's** on CFT and IQFT (Watts – Bowcock, P.Dorey, Taormina, Tateo); with **Swansea** on gauge theories and AdS/CFT (N Dorey, Hollowood – Khoze).
Links also exist with **Bonn** on string theory and instanton calculations (Nahm –Khoze, Taormina), and with Kyoto (Miwa – Weston) on IQFT and Moscow (Feigin – Bowcock, Taormina) on CFT.

Two recent publications (see also members 1, 3, 10, 11, 13)

1. J. Hong, S-J. Kang, T. Miwa and R. Weston, *Mixing of Ground States in Vertex Models*, J. Phys. **A31** (1998) L515-L525, hep-th/9804063.

2. N. Dorey, T.J. Hollowood, V.V. Khoze, M.P. Mattis and S. Vandoren, *Multi-instanton calculus and the AdS/CFT correspondence in $N=4$ superconformal field theory*, Nucl. Phys. **B552** (1999) 88, hep-th/9901128. (**C**)

Member 13 – King's College, London, U.K.

Tomasz Brzezinski	(Lecturer, S)	Nick Dorey	(Reader/AF, S)
David Dunbar	(Senior Lecturer, S)	Jonathan Evans	(Researcher/AF, C)
Matthias Gaberdiel	(Researcher/RSF, K)	Peter Goddard	(Professor, C)
Tim Hollowood	(Reader/AF, S)	David Olive	(Professor, S)
Andrew Pressley	(Professor, K)	Andreas Recknagel	(Lecturer, K)
Frederik Roose	(Postdoc, K)	Anni Sinkovics	(Postdoc, S)
Gérard Watts *	(Lecturer, K)		

* Scientific officer in charge of the work

(AF= Advanced Fellow; RSF= Royal Society Fellow; S= Swansea; C= Cambridge; K= KCL)

There are 6 PhD students within the node currently working in the research area of the proposal.

Research Expertise and existing research links with other teams

Integrable Quantum Field Theory. (Evans, Hollowood, Olive, Recknagel, Watts) Toda theory – integrability and scattering matrices; Supersymmetric scattering theories; Renormalisation group flows in massless and massive theories; Numerical and analytic studies of finite-size scaling.

Algebraic Aspects of Integrability. (Brzezinski, Hollowood, Pressley, Recknagel, Watts) Representation theory of quantum groups, Yangians and W-algebras; Applications of representation theory to Quantum scattering in integrable models and to structure of CFT.

Two-dimensional conformal field theory. (Gaberdiel, Goddard, Olive, Recknagel, Watts) The axiomatic development of CFT and its applications; logarithmic conformal field theories;

D-brane physics. (Evans, Gaberdiel, Recknagel, Roose) The application of CFT in string theory; The study of Dirichlet branes in string theory using conformal field theory; non-BPS D-branes; D-branes in Gepner models.

AdS/CFT correspondence (N. Dorey, Dunbar, Evans, Hollowood, Olive, Sinkovics) Supersymmetric gauge theories and integrable structures and exact results in supersymmetric field theories; Structure of gravity and supergravity singularities; The use of instantons and monopoles in semi-classical analysis.

Training Expertise

The groups are very experienced in the training of postdocs, through previous HCM and TMR networks and grants from PPARC, EPSRC and other funding agencies. They also regularly organise meetings and schools, most recently: (KCL) one-day meetings on Boundary CFT (2000), String theory (2001) and Integrable and Conformal field theory (2001) and (Swansea) UK Summer Institute, 1999. Furthermore Cambridge will host Strings 2002. KCL and Cambridge both also run full postgraduate courses in Theoretical and Mathematical Physics.

Existing research links with other teams

With **York** on IQFT (MacKay – Evans); with **Sofia** on CFT (Ganchev, Petkova – Watts); with **Berlin** on IQFT (Fring – Olive); with **Bonn** on AdS/CFT, supersymmetric gauge theories and CFT (Flohr, Nahm – Gaberdiel, Olive, Recknagel, Watts); with **Budapest** and **Durham** on IQFT (Takács, P. Dorey, Tateo – Watts) with **Bologna** and **Santiago** on AdS/CFT and supersymmetric gauge theories (Seminara – Dunbar and Miramontes – Hollowood); with **Durham** on AdS/CFT and supersymmetric gauge theories (Khoze, Travaglini – N. Dorey, Hollowood).

Two recent publications (see also member 12)

1. P. Dorey, I. Runkel, R. Tateo and G. Watts, *g-function flow in perturbed boundary conformal field theories*, Nucl. Phys. B **571** (2000) 457 hep-th/9909216. (**C**)

2. J.M. Evans, M. Hassan, N.J. MacKay, A.J. Mountain, *Conserved charges and supersymmetry in principal chiral and WZW models*, Nucl. Phys. B **580** (2000) 605 , hep-th/0001222. (**C**)

External expertise

Yukawa Institute - Kyoto [Japan]: Tetsuji Miwa, Ryu Sasaki.
Landau Institute - Chernogolovka [Russia]: Alexander Belavin, Boris Feigin.
Steklov Mathematical Institute - St Petersburg [Russia]: Ludwig Faddeev, Piotr Kulish.
University of Virginia - Charlottesville [U.S.A.]: Paul Fendley.
Rutgers University - Piscataway [U.S.A.]: Sergei Lukyanov, Alexander Zamolodchikov.

Research Specialities

	IQFT	AAI	SLM	CSM	2D CFT	DBP	AdS/ CFT	CI
Yukawa - Japan	*	*	*					*
Landau - Russia	*	*		*	*			*
Steklov - Russia	*	*	*		*			*
Virginia - U.S.A.	*		*	*				
Rutgers - U.S.A.	*	*		*	*			

Existing research links with teams in the proposed network

Integrable field theory:

- **Yukawa/U.Durham** (Miwa, Sasaki – Weston, P. Dorey)
- **Yukawa/U.York** (Sasaki – Corrigan)
- **Yukawa/ENS.Lyon** (Miwa – Smirnov)
- **Rutgers/LPM.Montpellier** (Lukyanov, A. Zamolodchikov – Fateev, Al. Zamolodchikov)
- **Virginia/LPM.Montpellier** (Fendley – Al. Zamolodchikov)
- **Steklov/U.York** (Faddeev – Sklyanin)

Conformal field theory:

- **Landau/U.Durham** (Feigin – Bowcock, Taormina)
- **Landau/FU.Berlin** (Belavin – Fring)
- **Rutgers/LPM.Montpellier** (Lukyanov, A. Zamolodchikov – Fateev, Al. Zamolodchikov)

6. COLLABORATION

The teams will generate interactions in the same manner as they have done in the past: building on existing collaborations and encouraging new ones to develop by providing a stimulating atmosphere at the conferences and schools we organize, and by facilitating exchanges. As can be seen from the research links given in section 5, there is already a strong base of collaborations between our partners, in part as a result of the two previous European networks with which most of them have been associated.

Typically, collaboration in theoretical physics is carried out by email or other electronic means, which work very well. It is likely that face to face interaction is most important in the initial stages and at the 'writing up' stages of a project.

Each of the young researchers employed by partners within the Network has funds to enable extended visits to other partners, in particular under the secondment scheme (see section 10). These have a dual purpose: to facilitate collaboration and to enhance training by allowing the young scientists to work with the other partner(s).

There are a number of smaller groups which we have deliberately incorporated into the main partners (York includes Mons (2 workers); Montpellier includes Tours (2); Bonn includes Hannover (1); Budapest includes Szeged (1); Bologna includes Torino (1); Santiago includes Bilbao (2)) and we have done this in order to make use of the important extra expertise available, and to allow small amounts of funding to be allocated without enlarging the financial management structure. Also, some of the partners are constructed of two or more substantial parts where existing collaborations are sufficiently well-established at the scientific and managerial levels. (We made similar arrangements which worked successfully within a previous TMR Network.)

We have purposely arranged a school and a network conference in the Budapest and Sofia nodes during the first two years of the contract, so as to integrate these slightly more isolated partners fully into the network.

7. ORGANISATION AND MANAGEMENT

The overall responsibility for the management of the network rests with the network coordinator, Edward Corrigan, of the Department of Mathematics, University of York. He will chair a Management Committee which will include at least one member from each participating node, including the scientific coordinator for that node. The Management Committee will meet regularly (at least every six months from the beginning of the programme), to oversee and monitor the operations of the network, ensuring:

(1) that the annual meetings, schools and workshops are properly organized and advertised;

(2) that the postdoctoral appointments are made according to the proposed schedule, or to revise the schedule if circumstances change, and that postdocs do spend time appropriately with another partner;

(3) that the annual reports, financial and scientific, are produced and delivered in the required formats, and without delay;

(4) that a set of web-pages recording the activities of the network are maintained as a means of monitoring network activities and disseminating joint results.

The Scientific Steering Committee, chaired by Jean-Michel Maillet (ENS-Lyon), will be set up as a subcommittee of the Management Committee to monitor the network research programme, to draft the annual scientific reports, and to advise the Management Committee of actions which might need to be taken in the light of changing circumstances. The day-to-day organization of the work of the researchers employed under the contracts will be the responsibility of the coordinators of the partners at which they are employed.

It is intended that postdoctoral researchers will be recruited on the following pattern: four in each of years 1,2,3 of the contract to ensure that years 2 and 3 have eight young researchers in post. Appointments will be made at partner level in consultation with the management committee. The years in which nodes will advertise vacancies will be decided in advance by the Management Committee. Short visits/exchanges will be decided at the level of the partners involved.

A provisional programme of network-financed workshops/schools/conferences has already been made and meetings of the management committee will coincide with these. Additions of smaller-scale network meetings to the network programme and any changes to the major programme will be made after consultation with all partner coordinators. The organization of each meeting will be the responsibility of a special local organizing committee created for this purpose. All meetings will be advertised to all partner members via email and through the network web-site. László Palla (Budapest) will be the member of the Management Committee with overall responsibility for the Network's meetings.

Research will be monitored by the Scientific Steering Committee via email between the partner coordinators, via a collection of published articles by partner members which will be maintained on the network web-pages (for a possible format, see http://fourier.dur.ac.uk:8000/TMR/data.html), and via presentations at network meetings. The results of joint research will be disseminated more widely via electronic e-print archives, publication in refereed journals and presentations at other national and international conferences and workshops.

Edward Corrigan is currently Professor of Mathematics at the University of York, and Head of the Department of Mathematics. He moved to York from Durham (where he was also Head of Department from 1996-98). He has written over eighty articles in areas directly related to the principal topics of this network and was elected to the Royal Society in 1995. He has long experience of training graduate students (sixteen successfully completed PhDs), working with postdoctoral researchers, organising conferences and schools, and organising networks within the HCM (ERBCHRXCT 920069), TMR (ERBFMRXCT 960012), and INTAS programmes. He has also served on UK national committees in the Particle Physics and Astronomy and the Engineering and Physical Sciences Research Councils.

8. TRAINING NEED

Europe has an outstanding record and excellent current strengths in theoretical physics, and especially in this field. However, while there is excellent communication and collaboration within each country's theoretical physics community, and much collaborative work at senior levels, there is a need to focus on research at a European level, and to promote mobility among young researchers.

Over the last decade, EC programmes have done much to build a European feeling within the research community, leading to a tangible cooperative spirit. However, European universities and institutes are going to face large-scale retirements during the years 2005-2015, corresponding to the aging of the population of scientists contributing to the expansion which happened in many countries during the 1960s and 1970s. There is a need for young scientists to be trained in theoretical physics to maintain a pool from which the necessary replacements will be drawn.

Many senior researchers work in small groups which, although usually involved in international collaborations, often have limited opportunities for funding to exploit these in training young researchers. There is a tendency for young researchers to move to the United States to continue their training. We aim to prevent this by releasing the latent capacity for training that exists in the Union, building a unified European research community that can maintain its lead.

Our consortium already forms a large collaborative network, and many of us have demonstrated the effective use of HCM/TMR funding in training European—rather than nationally-minded young researchers. We are thus in an excellent position to offer European added value by training researchers in an environment of Europe-wide research of the highest calibre, maintaining a distinctively European culture of theoretical physics which builds on our national strengths and traditions. The multidisciplinary nature of this field, and the variety of different and complementary tools required from both mathematics and physics, attracts the brightest students.

Within our collection of partners there are a number of examples of young people who have been assisted at earlier stages of their careers by European Fellowships, or by participation in a training network. For example, László Fehér (Budapest) was an HCM postdoc and is now a Professor at Szeged; Patrick Dorey (Durham) was an EC Fellow and is now a Reader, and the Durham coordinator; Andreas Recknagel (King's) was an HCM postdoc and is now a lecturer; and Roberto Tateo (Durham), Michael Flohr (Bonn-Hannover), Anastasia Doikou (York) and Davide Fioravanti (SISSA/Durham) were TMR postdocs in our previous Network and now have long-term research positions.

There is a gradual increase in the number of women participating in theoretical physics (and there are eleven team members in the current proposal who are women). This is encouraging but it is a participation rate far lower than that which we should like to see. In recent years, we have seen an increase in the number of female graduate students and one of our tasks will be to seek ways to further the careers of these students. (For example, at York two of the current research fellows Anastasia Doikou (who was a postdoc directly from her PhD, funded by our previous TMR Network), and Clare Dunning (who completed her PhD in Durham in March 2001); Olalla Castro-Alvaredo (Santiago) is now in FU, Berlin; three others are Véronique Terras (PhD Lyon), now at Rutgers, Bénédicte Ponsot (PhD Montpellier), now at AEI-Potsdam and Reidun Twarock (PhD Clausthal) who came to York immediately after her PhD and has been appointed to a permanent lectureship at City University, London.)

There is a clear demand for theoretical physicists to fill permanent positions in Europe's universities, and the influx of these young researchers will contribute to our universities' ability, and that of our scientific culture generally, to cohere across the Union and compete with the rest of the world through the 21st century. Moreover, the field of research of the proposed network has traditionally been a driving force for progress in many areas of physics and mathematics. The tools, methods and concepts designed in this framework are expected to have an impact far beyond it. Hence, we expect young researchers trained in this area to be flexible and able to apply their expertise not only in this field but also in related areas of applied mathematics, and condensed matter and solid state physics. From experience, we are also aware that those theoretical physicists who do not remain in academia, are in demand from the financial, IT and other sectors, both for their skills and for the rigour of their intellectual training.

9. JUSTIFICATION OF THE APPOINTMENT OF YOUNG RESEARCHERS

Young researchers to be financed by the contract

Participant	Year 1	Year 2	Year 3	Year 4	Total
1. U.York			12	12	24
2. INRNE.Sofia					
3. CNRS.Site Alpes	12	12			24
4. ENS.Lyon		12	12		24
5. LPM.Montpellier			12	12	24
6. FU.Berlin	12	12			24
7. PI.Bonn		12	12		24
8. ELTE.Budapest			12	12	24
9. INFN.Bologna			12	12	24
10. SISSA.Trieste		12	12		24
11. U.Santiago	12	12			24
12. U.Durham		12	12		24
13. KC.London	12	12			24
Totals	48	96	96	48	288

There is a wealth of experience among senior researchers of the training of both post- and pre-doctoral young researchers.

All post-doctoral researchers will be joining groups containing experienced, full-time senior researchers and offering an active research environment. This will lead to an enhanced training function on a day-to-day basis, in addition to the specific activities such as schools and conferences described in the next section. To maintain attractiveness, each postdoctoral position is for two years, generally starting in October. The pattern of postdoc assignments to partners is intended to be flexible in the following sense. A single individual may wish to spend one year at each of two partners, or it may be appropriate for an individual to remain at one site for two years but making shorter visits to other partners. To some extent this depends on the circumstances of the individual which would be taken into account when making the appointment. Every postdoc will benefit from at least one extended stay at another partner node, under the secondment scheme.

In addition to salary commensurate with local scales, (and our experience with a TMR Training Network gives us confidence that these scales are sufficient to attract young postdocs), each young researcher is allocated 2000 Euro per year to be used by them to spend extended visits with other partners for the purpose of collaborative work.

No doctoral students have been allocated: this reflects the fact that adequate funding for PhD students is already available to our partners through other channels. We see the most pressing need in the training of young European scientists to be the provision of early postdoctoral opportunities, combined with incentives for these opportunities to be taken up in other countries of the Union, and it was with this in mind that we allocated our resources.

The internet is already the principal medium for advertising academic job vacancies. We will advertise on our own web-sites and on EU- and Europe-wide sites, but many nations' academic job markets still operate principally through national sites. We will ensure that our vacancies are advertised on all appropriate such sites.

We will ensure equality of opportunity by advertising on sites dedicated to the progress of women in science, and we will actively encourage applications from women and minorities.

Anne Taormina (Durham) will be the member of the management team with particular responsibility for promoting the participation of women within this network.

10. TRAINING PROGRAMME

The principal training received by the young researchers arises from the opportunity to work alongside leaders in the field and to receive regular critical and constructive response to their ideas. Each postdoc will be assigned a mentor with the duty to assist their rapid assimilation into the new environment and to monitor their progress throughout the appointment. One member of the Management Committee will be explicitly responsible for overseeing the programme of conferences and schools (László Palla, Budapest).

The main **collective** training of the junior researchers employed in the network will be through a programme of schools, workshops and conferences. In the course of the project we plan to hold:

- A minimum of three schools and a workshop. These will be devoted to specific themes (Applications, Mathematical Structure of Integrability, Non-perturbative Methods) and will offer training to postdocs and PhD students which is not available at a national level. The schools will be held in Budapest, Montpellier and Trieste during years 1, 2 and 3, and the workshop in Berlin during year 4;
- Four annual major network conferences in the Septembers of years 1,2,3,4 at which every partner will be represented, including postdocs and students, where the postdocs will have the opportunity to describe their work to their peer and senior members, and where the work done by each partner will be reviewed. These will be held in Firenze, Sofia, Santiago and Lyon;
- The mid-term review, to be held at York and accompanied by a short workshop at which the then current postdocs will be the principal speakers;
- The biennial conferences 'Conformal Field Theory and integrable models' held in Bologna are not specifically network meetings but they will be supported by the network because they allow a natural setting for experts outside the network to meet and inform network members, and for disseminating network results. These will occur in 2003 and 2005. It is intended that the annual network meeting in Firenze will occur in an adjacent week to the 2003 Bologna conference.

A more detailed schedule of these meetings is given in section 4. Specific funds have been allocated to support the four network conferences, the three schools, a workshop, the mid-term review workshop and the Bologna research conferences. The partners have extensive experience of attracting funds for conferences from external sources and in the course of the contract such conferences will be fully integrated into our network activities. As described at the end of section 5, partners of the Network have strong links with leading scientists in Japan (Kyoto), the USA (Rutgers and Virginia) and Russia (Saint Petersburg and Moscow). We plan to make use of this external expertise by inviting members of these groups to give series of lectures at our schools and conferences. Funds for this participation will be sought from elsewhere.

Our schools and meetings will be advertised to the wider community, encouraging attendance on a self-funding basis, so as to avoid an exclusive outlook which would miss opportunities both to foster our own growth and to promote our objective of a Europe-wide research culture.

As already remarked in section 8, there is a gradual increase in the number of women participating in theoretical physics. This is encouraging but the level of participation is much lower than it ought to be. We have also remarked that the number of female PhD students and postdocs is growing. It is our intention to involve our female members fully in the training activities of this network (Anne Taormina, Durham, will be the member of the Management Committee overseeing this aspect).

The **individual** training arrangements will include mobility funding to encourage all researchers in collaborative visits, and especially to enable young researchers to visit other partners of the network to collaborate and to learn new methods and techniques. In particular, we will implement a *secondment scheme* under which the network postdocs will be required to spend an extended period at one of the other nodes of the network. Specific funds have been set aside in our budget to cover the costs of these visits. Ph.D. students from our institutions will be funded to attend the network schools and workshops, and encouraged to play an active rôle. We shall also encourage the junior researchers to attend such personnel development courses that our institutions run — for example in presentation and computer skills – as appropriate.

11. MULTIDISCIPLINARITY IN THE TRAINING PROGRAMME

Much of our research is at the overlap of mathematics with physics. This overlap is treated differently in different countries, with some researchers employed at physics research institutes or in physics departments of universities, others in mathematics institutes or departments. Undergraduate training, too, is sometimes provided in physics degrees, sometimes in mathematics.

It is clear from the one-page summaries provided in section 5 that both traditions are represented within our proposal.

We have an opportunity to create synergies, drawing on the strengths of the two traditions and helping bind them together at all levels, from the undergraduate level (many of us have already participated in the Erasmus-Socrates programmes and are now entering bilateral agreements) through graduate training and on to subsequent careers. We shall take steps to achieve this within our programme of schools, conferences and workshops.

Moreover, in relation to the part of our proposal concerning applications of field theory and statistical mechanics to condensed matter physics, we will favour training at the interface between theoretical, condensed matter and solid state physics. The same applies at the level of research methodology, where our training will provide young workers with a blend of skills from the most theoretical through computer-aided analytical techniques to purely numerical work.

12. CONNECTIONS WITH INDUSTRY IN THE TRAINING PROGRAMME

There are no direct connections envisaged between our theoretical physics programme and industry. However, it is worth remarking that a number of our former PhD students and postdocs have gone on to successful careers in industry and commerce, and theoretical physicists seem to be particularly attractive within the financial sector. These contacts are being maintained, and we expect them to grow during the duration of the contract.

Moreover, at York, there is a research group (NNDG — Networks and Nonlinear Dynamics Group) interested in telecommunications and other traffic problems. It is clear that these problems from our point of view are examples of non-equilibrium statistical mechanics, which is being investigated theoretically in Bonn (Rittenberg). NNDG has close connections with several multinational industries and runs an MSc programme which includes modules on dynamical systems and their applications to the analysis of data. These are likely to be of value to other young scientists (PhD students and postdocs). While it is true we do not see immediate applications for most of our work, it is our intention to maintain an awareness of industrial scale problems of this kind which might be tackled in the future using some of our ideas or methods.

APPENDIX: MAP

Institutions associated with the proposal