GEOMETRY AND ANALYSIS
Seminars 1995 – 96

Björn E. J. Dahlberg

Abstract

The following list gives a brief summary of the activities for the academic year 1995 – 96. For the convenience of the readers we have included a short bibliography for each seminar.

Contents

Chapter 1

Differential Equations

1.1 Shadowing of orbits of ODE's

Abstract The existence of a true orbit near a numerically computed approximate orbit - shadowing - is discussed. Some recent results will be presented.

Speaker B. E. J. Dahlberg

Date 1995–10–23

References

1. B. A. Coomes, H. Koçak, K. J. Palmer, "Rigorous computational shadowing of orbits of ordinary differential equations", *Numer. Math.* **69** (1995), 401–421.

1.2 Global integrals of plane vector fields

Abstract Consider a smooth, non-vanishing vector field $V = (p, q)$ in R^2 and the associated linear PDE

$$p\frac{\partial u}{\partial x} + q\frac{\partial u}{\partial y} = 0.$$

C^1–solutions of this PDE with non–vanishing gradients are called integrals of V. The existence of integrals is important, for instance when one tries to write a linear hyperbolic PDE in the normal form. This topic is not well treated in the standard texts in the field; the lecture will begin by giving some examples of the ignorance and confusion surrounding this area.

We will give a survey of the existence and non–existence results for integrals of vector fields.

Speaker B. E. J. Dahlberg

Date 1995–11–24

References

1. H. H. Alden, "solution of $f(x,y)\frac{\partial z}{\partial x} + g(x,y)\frac{\partial z}{\partial y} = 0$ in a neighborhood of a singular point", *American J. of Math.* **56** (1934), 453–458.
2. W. Kaplan, "Regular curve–families filling the plane I", *Duke Math. J.* **7** (1940) 154–185.
3. R. Finn, "On the uniformizaiton of plane direction fields, and of second order partial differential equations", *Proc. Camb. Phil. Soc.* **73** (1973) 87–109.
4. E. Kamke, "Über die partielle Differentialgleichung $f\frac{\partial z}{\partial x} + g\frac{\partial z}{\partial y} = h$", *Math. Z* **41** 1938 56–66.
5. E. Kamke, "Über die partielle Differentialgleichung $f\frac{\partial z}{\partial x} + g\frac{\partial z}{\partial y} = h$ II", *Math.* Z **42** 287–300.
6. N. Levinson, "The first boundary value problem for $\varepsilon\Delta u + Au_x + Bu_y + Cu = D$ for small ε", *Ann. Math.* **51** (1950) 428–445.
7. J. L. Weiner, "First Integrals for a Direction Field on a Simply connected Plane Domain", *Pacific Journal of Mathematics* **132** (1988) 195–208.

1.3 Non–existence of smooth integrals of vector fields

Abstract We will discuss examaples of smooth vector fields in the plane with-

out smooth integrals. The examples are due to Wazewski (1934) and Weiner (1988).

Speaker B. E. J. Dahlberg

Date 1995–12–01

References

1. T. Wazewski, "Sur un problème de caracatère intégral relatif à l'equation $\frac{\partial z}{\partial x} + Q(x,y)\frac{\partial z}{\partial y} = 0$", *Mathematica Cluj* **8** 1934 103–116.
2. J. L. Weiner, "First Integrals for a Direction Field on a Simply connected Plane Domain", *Pacific Journal of Mathematics* **132** (1988) 195–208.

1.4 The Riccati operator $\frac{du}{dx} + u^2$ is a folding

Abstract We will discuss some results by McKean and Scovel on the geometric properties of the Riccati operator with periodic boundary conditions.

Speaker B. E. J. Dahlberg

Date 1995–12–08

References

1. H. P. McKean, "Singularities of a simple elliptic operator", *J. Diff. Geom.* **25** (1987) 157–165.
2. H. P. McKean and J. C. Scovel, "Geometry of some simple Nonlinear Differential Operators", *Ann. Scuola Norm Sap. Pisa Cl Sci.* **4** (1986), 299–346.

1.5 Discrete one–dimensional quasi–periodic Schrödinger operators and other quasi–periodic skew–products

Abstract Quasi–periodic Schrödinger operators have been a very active field of research during the last twenty years. An important tool in this study has been perturbation theory of KAM–type. Such perturbation theory is the basic ingredient both in the theorem of Dinaburg–Sinai from the mid–70s on Floquet solutions and absolutely continuous spectrum and in the theorem of Fröhlich–Spencer–Wittver and Sinai from the late–80s on localized solutions and pure point spectrum.

We shall describe these results and later improvements. We shall also discuss generalizations to more general skew products.

Speaker L. H. Eliasson, KTH, Stockholm

Date 1996–04–26

References

1. L. H. Eliasson, "Floquet Solutions for the 1–Dimensional Quasi–Periodic Schrödinger Equation", *Commun. Math. Phys.* **146** (1992), 447–482.
2. L. H. Eliasson, "On the discrete one–dimensional quasi–periodic Schrödinger equation and other smooth quasi–periodic skew products", Preprint.
3. L. H. Eliasson, "Discrete one–dimensional quasi–periodic Schrödinger operators with pure point spectrum", Preprint.

1.6 Eigenfunctions, Nodal Sets and the Multiplicity of Eigenvalues of Laplace Operators

Abstract We shall describe a result of S–Y Cheng. The result is that the multiplicity of the first non–trivial eigenvalue is at most 3 for the Laplace–Beltrami operator of a surface homemorphic to the 2–sphere.

Speaker B. E. J. Dahlberg

Date 1996–05–03

References

1. L. Bers, "Local Behavior of Solutions of General Linear Elliptic Equations", *Commun. Pure Appl. Math.* **VIII** (1955) 473–496.

2. S–Y Cheng, "Eigenfunctions and Nodal Sets", *Comment Math. Helv.* **51** (1976) 43–55.

Chapter 2

Differential Geometry

2.1 A converse of the four vertex theorem

Abstract Let C be a smooth Jordan curve in the plane. Assume that C is not a circle. The classical four vertex theorem now says that the curvature has at least four local extreme values. In this lecture we shall characterize those smooth and periodic functions that represent the curvature of smooth Jordan curves. We'll achieve this by first establishing a sharpended version of the four vertex theorem. Using this sharper form of the four vertex theorem, we'll describe an algorithm for constructing closed curves with a prescribed curvature.

Speaker B. E. Dahlberg

Date 1995–11–06

References

1. B. E. J. Dahlberg, "The Converse of the Four Vertex Theorem", Preprint.
2. D. Fog, "Über den Vierscheitelsatz und seine Verallgemeinerungen", *Sitzungsbereiche der Berlin Akademie der Wissenschaft*, 251–254, 1933.
3. H. Gluck, "The converse of the four vertex theorem", *L'Enseignement Mathématique, II^e Serie*, Tome **XVII**, 295–309, (1971).
4. S. B. Jackson, "Vertices for plane curves", *Bull Amer. Math. Soc.* **50** 564–578, 1944.

5. A. Kneser, “Bemerkungen über die Anzahl der Extrema der Krümmung auf gesclossenen Kurven und über verwandte Fragen in einer nicheuklidische Geometrie”, Festscrift Heinrich Weber. Teubner 1912, 170–180.

6. S. Mukhopadhyaya, “New Methods in the geometry of a plane arc”, *Bull. Calcutta Math. Soc.*, **1**, 31–37, 1909.

7. R. Osserman, “The four–or–more vertex Theorem”, *Amer. Math. Monthly* **92** (1985), 332–337.

8. L. Vietoris, “Ein einfacher Beweis des Vierscheitelsatzes der ebenen Kurven”, *Archiv der Mathemaik* **3**, 97–102, 1952.

2.2 The Differential Geometry of Linear Programming: The vector fields of Karmarkar's Algorithm for Linear Programming

Abstract The Karmarkar Algorithm finds the optimum of an LP–problem by an iteration procedure in the interior of the feasible polytope. The steps are determined by a certain vector field, the so–called projective scaling vector field. The algorithm can therefore be viewed as a discretization of an integral curve of this vector field.

Speaker B. E. J. Dahlberg

Date 1996–04–19

References

1. D. A. Bayer and J. C. Lagarias, “The Nonlinear Geometry of Linear Programming I. Affine and Projective Scaling Trajectoreis”, *Trans. Amer. Math. Doc.* **314**, 499–525, 1989.

2. D. A. Bayer and J. C. Lagarias, “The Nonlinear Geometry of Linear Programming II. Legendre Transform Coordinates and Central Trajectories”, *Trans. Amer. Math. Soc.* **314**, 526–581, 1989.

3. N. Karmarkar, “A new polynomial–time algorithm for linear programming”, *Combinatorica* **4**, 373–395, 1984.

4. N. Karmarkar, “Riemmanian Geometry Underlying Interior–Point Methods for Linear Programming”, *Contemporary Mathematics* **114**, pp. 51–76, “Mathematical Developments Arising from Linear Programming”, J. C. Lagrias and M. J. Todd, Editors, American Mathematical Society, Providence, Rhode Island, 1990.

5. J. C. Lagarias, “The Nonlinear Geometry of Linear Programming III. Projective Legendre Transform Coordinates and Hilbert Geometry”, *Trans. Amer. Math. Soc.* **320**, 193–225, 1990.

Chapter 3

Discrete Geometry

3.1 Thurston's proof of Koebe–Andreev's theorem

Abstract The main result is that a plane triangulation is combinatorically equivalent to the nerve of a circle packing. this result was first established by Koebe.

Speaker B. E. J. Dahlberg

Date 1995–10–09

References

1. I. Carter and B. Rodin, "An inverse problem for circle packings and conformal mapping", *Trans. Amer. Math. Soc.* **334** (1992) 861–875.

2. P. Koebe, "Kontaktprobleme der konformen Abbildung", *Sächs. Akademie der Wissenschaften Leipzig*, Math. Phys. Klass **88** (1936) 141–164.

3. A. Marden and B. Rodin, "On Thurston's formulation and proof of Andreev's theorem", *Computational Methods and Function Theory*, St Ruscheweyh, E. B. Seff, L. C. Salinas, R. S. Varga (eds), Lecture Notes in Mathematics **1435**, pp 103–115.

3.2 Thurston's construction of the Riemann mapping

Abstract The main result is that the Riemann mapping can be constructed from triangulations and circle packings.

Speaker B. E. J. Dahlberg

Date 1995–10–16

References

1. I. Barany, Z. Furedi and J. Pach, "Discrete convex functions and proof of the six circle conjecture of Fejes Toth", *Can. J. Math.* **XXXVI** (1984), 560–576.
2. B. Rodin, "Schwarz's lemma for circle packings", *Inv. Math.* **89** (1987) 271–289.
3. B. Doin, "Schwarz's lemma for circle packings II", *J. Differential Geom.* **30** (1989) 539–554.
4. B. Rodin and D. Sullivan, "The Convergence of Circle Packings to the Riemann Mapping", *J. Differential Geom.* **26** (1987) 349–360.

3.3 Dirichlet integrals and the Delaunay triangulation

Abstract Consider the class of planar triangulations with a fixed set $\mathcal{P}$ of vertices. Fixing the values at the vertices, then each triangulation $\mathcal{T}$ gives rise to a piece–wise linear function with the associated Dirichlet integral $\mathcal{D}(\mathcal{T})$.

Rippa has proved the remarkable result that $\mathcal{D}(\mathcal{T})$ is minimized when $\mathcal{T}$ is the Delaunay triangulations, which is independent of the values at the nodes. We shall give a new and geometric proof of this result.

Speaker B. E. J. Dahlberg

Date 1995–11–14

References

1. A. Okabe, B. Boots and K. Sugihara, "Spatial Tessellations Concepts and Applications of Voronoi Diagrams", John Wiley & Sons, 1992.
2. S. Rippa, "Minimal roughness property of the Delannay triangulation", *Computer Aided Geometric Design* **7** (1990) 489–497.

3.4 Cauchy's Rigidity Theorem

Abstract There is a vague statement by Euclid claiming that two convex plyhedra with congruent faces are in fact congruent. This was established by Cauchy as a young mathematician. Many geometers consider his proof as the most beautiful result in geometry. The general problem of rigidity of surfaces and manifolds is not fully understood, even today.

Speaker B. E. J. Dahlberg

Date 1996–02–02

References

1. A. D. Alexandrov, "Konvexe Polyeder", Akad. – Verlag, Berlin, 1958.
2. A. L. Cauchy, Sur les polygones et les polyedres, Werke (2) 1 (Paris 1905) 26–38.
3. H. Gluck, "Almost all simply connected closed surfaces are rigid", in *Geometric Topology*, Lecture Notes in Math., No. **438**, Springer–Verlag, Berlin, 1975, 225–239.
4. J. Nash, "Real algebraic manifolds", *Ann. Math.* **56** (1952) 405–421.
5. I. J. Schoenberg and S. K. Zaremba, "On Cauchy's lemma concerning convex polygons", *Canada J. of Math.* **19** (1967) 1026–1071.
6. A. H. Wallace, "Algebraic approximation of curves", *Canada J. Math.* **10** (1958) 242–278.

3.5 Discrete Gauss curvature and convex representations of triangulations

Abstract We will discuss the problem of finding a triangulation with a prescribed boundary polygon. We will discuss a variational approach to this problem, where the main geometrical tool is the discrete Gauss curvature.

Speaker B. E. J. Dahlberg

Date 1996–02–09

References

1. N. Chiba, K. Onoguchi and T. Nishizeki, "Drawing Plane Graphs Nicely" *Acta Informatic* **22**, 187–201, 1985.
2. Y. Colin de Verdière, "Comment rendre géodésique une triangulation d'une surface?", *Enseignemant Math.* **37** (1991) 201–212.
3. W. T. Tutte, "Convex Representations of Graphs", *Proc. London Math. Soc.* **10**, 304–320, 1960.
4. W. T. Tutte, "How to Draw a Graph", *Proc London Math. Soc.* **13**, 743–767, 1963.

3.6 Discrete Riemann mappings and Computer aided design

Abstract We shall describe a method for obtaining a discrete version of the Riemann mapping of quadrilaterals onto rectangles.

Speaker B. E. J. Dahlberg

Date 1996–02–23

References

1. B. E. J. Dahlberg, "The Discrete Riemann Map", Preprint.

3.7 A variational approach to the Koebe circle packing

Abstract The circle packing theorem says that the 1–skeleton of a planar triangulation is the nerve of a circle packing of the sphere. We will survey some recent variational proofs of this theorem.

Speaker B. E. J. Dahlberg

Date 1996–03–23

References

1. W. Brägger, "Kreispackungen und Triangulierungen", *Enseignement Math.* **38** (1992) 201–217.

2. Y. Colin de Verdière, " omment rendre géodésique une triangulation d'une surface?", *Enseignemant Math.* **37** (1991) 201–212.

3. Y. Colin de Verdière, "Empilement de circles: Convergence d'une méthode de point fixe", *Forum Math.* **1** (1989) 395–402.

4. Y. Coln de Verdière, "Un principè variationnel pour les empilement de cercles", *Invent. Math.* **104** (1991) 655–669.

5. P. Koebe, "Kontaktprobleme der konformen Abbildung", *Sächs. Akademie der Wissenschaften Leipzig.* Math. Phys. Klass **88** (1936) 141–164.

Chapter 4

Functional Analysis

4.1 Generalized gradients and the inverse functions theorm for Lipschitz functions

Abstract I will in this seminar occasionally feature high–tech versions of various classical results. I will in this talk describe a concept of generalized gradient of a Lipschitz function. This will then be used to derive the inverse and implicit function theorems for Lipschitz mappings on $\mathbb{R}^d$. These results were found by various authors in the 1970's.

Speaker B. E. J. Dahlberg

Date 1996–03–08

References

1. F. H. Clarke, "On the inverse function theorem", *Pacific J. Math.* **64**, 1976, 97–101.

2. J. Warga, "An implicit function theorem without differentiability", *Proc. Amer. Math. Soc.* **69** (1978) 65–69.

4.2 The Hilbert metric and the Perron–Frobenius Theorem

Abstract We shall review the basic properties of the Hilbert metric for convex sets. Hilbert introduced this metric as a model for the hyperbolic geometry. Birkhoff (1957) observed that if a linear map L has a matrix with positive elements then L is a contraction on $\{x \in \mathbb{R}^n : x_k > 0\}$ under the Hilbert metric. This observation leads to a proof of the Perron–Frobenius theorem.

Speaker B. E. J. Dahlberg

Date 1996–04–12

References

1. F. L. Bauer, "An elementary proof of the Hopf inequality for positive operators", *Numerische Mathematik* **7**, 331–337, 1965.

2. F. L. Bauer, E. Deutsch and J. Stoer, "Abschätzungen für die Eigenwerte positiver linearer Operatoren", *Linear Algebra and its Applications* **2**, 275–301, 1969.

3. G. Birkhoff, "Extensions of Jentzsch's Theorem", *Trans. Amer. Math. Soc.* **85**, 219–227, 1957.

4. A. M. Bloch, "Steepest Descent, Linear Programming, and Hamiltonian Flows", *Contemporary Mathematics* **114**, pp. 77–90, "Mathematical Developments Arising from Linear Programming", J. C. Lagrias and M. J. todd, Editors, Amercan Mathematical Society, Providence, Rhode Island, 1990.

5. H. busemann, "The geometry of geodesics", Academic Press, New York, 1955.

6. H. Busemann, "Spaces with distinguished shortest joins", *Mathematical Developments Arising from Hilbert Problems*, Proc. Symp. Pure Math., vol **28**, Amer. Math. Soc., Providence R. I., 1976, pp 131–142.

7. H. Busemann and B. B. Phadke, "A general version of Beltrami's theorem in the large", *Pacific J. Math.* **115**, 299–315, 1984.

8. P. J. Bushell, "On the projective contraction ratio for positive linear mappings", *J. London math. Soc.* **6**, 256–258, 1973.

9. P. J. Bushell, "Hilbert's Metric and Positive Contraction Mappings in a Banach Space", *Arch. Rational Mech. Anal.* **52**, 330–338, 1973.

10. G. Frobeinius, "Über Matrizen aus positiven Elementen I", *Sitzungsberichte der Berlin Akad. Wiss.*, 471–476, 1908.

11. G. Frobenius, "Über Matrizen aus positiven Elementen II", *Sitzungsberichte der Berlin Akad. Wiss.*, 514–518, 1909.

12. F. R. Gantmacher, "*Applications of the theory of matrices*", Inter–science Publishers, New York, 1959.

13. D. Hilbert, "Über die gerade Linie als Kürzeste Verbindung zweier Punkte", *Math. Ann.* **46**, 91–96, 1895.

14. E. Hopf, "An inequality for positive lienar operators", *J. Math. Mech.* **12**, 683–692, 1963.

15. E. Kohlberg and J. W. Pratt, "The contraction mapping approach to the Perron–Frobenius theory: Why Hilbert's Metric?", *Math. Oper. Res.* **7**, 198–210, 1982.

16. M. G. Krein and M. A. Rutman, "Linear operators leaving invariant a cone in a Banach space", *Functional Analysis and Measure Theory*, Translation Series 1, Volume **10**, pp 199–325, American Mathematical Society, 1962.

17. A. M. Ostrowski, "Positive Matrices and Functional Analysis", *Recent Advances in Matrix Theory* (Editor H. Schneider), University of Wisconsin Press, Madison, Wisconsin, 1964.

18. O. Perron, "Zur Theorie der Matrices", *Math. Ann.* **64**, 248–263, 1908.

19. H. Samelson, "On the Perron–Frobenius Theorem" *Mich. Math. J.* **4**, 57–59, 1957.

Chapter 5

Applications

5.1 Stochastic and ergodic properties of certain Hénon maps

Abstract The theory of dynamical systems was during the 60:s and 70:s dominated by the theory of uniformly hyperbolic or Axiom–A dynamical systems. This was highly successful and lead to the development of a theory of attractors (Smale) and also a theory of stochastic behaviour: ergodic properties, exponential decay of correlation, central limit theorems (Sinai, Ruelle, Bowen).

In the present talk we discuss how this theory now have been essentially completely extended to certain non–uniformly hyperbolic dynamical systems, in particular the Hénon maps first considered by Carleson and myself [2]. (The setting in [2] was later extended to the case of homoclinic bifurcations [7]). In particular we indicate how to prove existence of so–called Sinai–Ruelle–Bowen (SRB) measures [4], exponential decay of correlation and Central Limit Theorems [5] and that the almost all points of the basin of attraction of these Hénon attractors are generic in the sense of Birkhoff for the SRB–measures [3].

Speaker M. Benedicks, KTH, Stockholm

Date 1995–10–30

References

1. M. Benedicks, "New developments in the ergodic theory of nonlinear dynamical systems", *Phil. Trans. R. Soc. Lond.* A **346** (1994), 145–157.

2. M. Benedicks and L. Carleson, "The dynamics of the Hénon map", *Annals of Mathematics* **133** (1991), 73–109.

3. M. Benedicks and M. Viana, In preparation.

4. M. Benedicks and L–S Young, "Sinai–Bowen–Ruelle measures for certain Hénon maps", *Invent. Math.* **112** (1993) 541–576.

5. M. Benedicks and L–S Young, "Decay of correlation for certain Hénon maps", Preprint.

6. R. Bowen, "Equilibrium states and the ergodic theory of Anosov diffeomorphism", Springer Lecture Notes in Math., **470**, 1975.

7. L. Mora and M. Viana, "Abundance of strange attractors", *Acta Math.*, **171** (1993), 1–71.

8. S. Smale, "differentiable dynamical systems", *Bull. Amer. Math. Soc.* **73** (1967), 747–817.

5.2 The magical number seven plus/minus two

Abstract How much is too much? How many are too many? In a famous study these questions were studied by the psychologist Miller, in a paper with the above title. We will discuss this article and some related issues.

Speaker B. E. J. Dahlberg

Date 1995–12–15

References

1. G. A. Miller, "The magical number seven, plus or minus two: Some limits on our capacity for processing information", *The Psychological Review* **63** (1956), 81–97.

2. T. Nørretranders, "Märk Världen", Bonniers Alba, Stockholm 1993.

5.3 Introduction to Matrix Models of 2D Gravity and the mKDV Hierarchy

Abstract This is an introductory lecture for a general audience on the subject of matrix models and their applications to random surfaces, 2–dimensional gravity and string theory. No attempt will be made to review the various ramifications and more recent results in the field. Instead we will concentrate on the work which lead to nonperturbative solutions of 2d gravity.

2d gravity is studied as a model for quantum gravity with the hope that in two dimensions rather complex phenomena can be studied stripped of some complications while hopefully retaining many of the physical properties of the problem. Moreover, since strings are coordinate invariant 2d quantum field theories such systems can equally well be regarded as solvable models of string theory. In particular we will here focus on studying noperturbative effects because in string theory the perturbation series is evry badly behaved, being non–Borel summable.

The method reviewed here is to discretize the theory and then study the continuum limit of the random lattice model. There are many ways to do this, but the one we will discuss here is particularly simple. It involves sums over triangulations of Riemann surfaces, assigning all the links the same length. This is reparimetrization–invariant way of computing the sums over geometries were the degree of freedom is the number of triangles which meet at each vertex, a discrete analog of Gaussian curvature. The great advantage of this method is that the dual graph of triangulation is a Φ^3 theory Feynman diagram, a zero–dimensional field theory. Thus the discretized theory has been more successful than the corresponding continuum formulation. Here we will particularly emphasize the connection between 2d gravity and the Korteweg–de Vries equations, or as will be argued the modifed–KdV equations.

The lecture begins with a brief introduction to string theory then continues with a lengthier description of the discrete formulation. Here the partition function can be recast as an integral over matrices which can be calculated and the continuum limit studies. The results are discussed especially the connection with the KdV hierarchy of equations and the fact that the so–called string equations can be described as flatness conditions. These flatness conditions will be interpreted as consistency conditions for isomonodromic deformations of an equation with irregular singularity.

Speaker Anders Wätterstam, FOA, Stockholm

Date 1996–01–26

References

1. R. C. Penner, "The Decorated Teichmüller Space of Punctured Surfaces", *Commun. Math. Phys.*, **113** (1987), 299–399.

2. R. C. Penner, "Perturbative series and the moduli space of Riemann surfaces", *J. differential Geom.* **27** (1988), 35–53.

3. A. Wätterstam, "Gravity's rainbow: aspects of critical and non–critical string theory", Dissertation, Chalmers University of Technology, 1992.

Chapter 6

List of Speakers

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Chapter 7

Chronological Listing of the Seminars

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1996–04–12 The Hilbert metric and the Perron-Frobenius Theorem

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1996–05–03 Eigenfunctions, Nodal Sets and the Multiplicity of Eigenvalues of Laplace Operators