

# SYMPLECTIC AND LIE ALGEBRAIC TECHNIQUES IN GEOMETRIC OPTICS

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## Abstract

We will show the usefulness of the tools of Symplectic and Presymplectic Geometry and the corresponding Lie algebraic methods in different problems in Geometric Optics.

## 1 Introduction: Symplectic and Presymplectic geometry

Geometric techniques have been applied to physics for more than 50 years in many different ways and they have provided powerful methods of dealing with classical problems from a new geometric perspective. Linear representations of groups, vector fields, forms, exterior differential calculus, Lie groups, fibre bundles, connections and Riemannian Geometry, symmetry and reduction of differential equations, etc..., are now well established tools in modern physics. Now, after more than twenty years of using Lie algebraic methods in Optics by Dragt, Forest, Sternberg, Wolf and their coworkers, we aim here to establish the appropriate geometric setting for Geometric Optics. Applications in computation of aberrations for different orders will also be pointed out.

The basic geometric structure for the description of classical (and even quantum) systems is that of symplectic manifold. A *symplectic manifold* is a pair  $(M, \omega)$  where  $\omega$  is a nondegenerated closed 2-form in  $M$ . If  $\omega$  is exact we will say that  $(M, \omega)$  is an *exact symplectic manifold*. Let  $\tilde{\omega} : \mathfrak{X}(M) \rightarrow \Lambda^1(M)$  be given by  $\tilde{\omega}(X) = i(X)\omega, \tilde{\omega}(X)Y = \omega(X, Y)$ . The two-form  $\omega$  is said to be nondegenerate when  $\tilde{\omega}$  is a bijective map. Then  $M$  is even-dimensional and it may be used to identify vector fields on  $M$  with 1-forms on  $M$ . Vector fields  $X_H$  corresponding to exact 1-forms  $dH$  are called Hamiltonian vector fields. The 2-form  $\omega$  is said to be closed if  $d\omega = 0$ .

The simplest example is  $\mathbb{R}^{2n}$  with coordinates  $(q^1, \dots, q^n, p_1, \dots, p_n)$  endowed with the constant 2-form  $\omega = \sum_{i=1}^n dq^i \wedge dp_i$ . Closedness of  $\omega$  is very important because Darboux theorem establishes that for any point  $x \in M$  there exists a local chart  $(U, \phi)$  such that if  $\phi = (q^1, \dots, q^n; p_1, \dots, p_n)$ , then  $\omega|_U = \sum_{i=1}^n dq^i \wedge dp_i$ . Consequently, the example above is the local prototype of a symplectic manifold. It is also well known that if  $Q$  is the configuration space of a system, its cotangent bundle,  $T^*Q = \bigcup_{q \in Q} T_q^*Q$ , called phase space, is endowed with a canonical 1-form  $\theta$  on  $T^*Q$  such that  $(T^*Q, -d\theta)$  is an exact symplectic manifold. More especcially, if  $(q^1, \dots, q^n)$  are coordinates in  $Q$  then  $(q^1, \dots, q^n, p_1, \dots, p_n)$  are coordinates in  $T^*Q$  and  $\theta = \sum_{i=1}^n p_i dq^i$ ,  $\omega = \sum_{i=1}^n dq^i \wedge dp_i$ .

A Hamiltonian dynamical systems is a triplet  $(M, \omega, H)$  where  $M$  is a differentiable manifold,  $\omega \in Z^2(M)$  is a symplectic form in  $M$  and  $H \in C^\infty(M)$  is a function called Hamiltonian. The

# Symplectic Techniques In Physics

**Tao Wei**

## Symplectic Techniques In Physics:

**Symplectic Techniques in Physics** Victor Guillemin, Shlomo Sternberg, 1990-05-25 Symplectic geometry is very useful for clearly and concisely formulating problems in classical physics and also for understanding the link between classical problems and their quantum counterparts. It is thus a subject of interest to both mathematicians and physicists though they have approached the subject from different view points. This is the first book that attempts to reconcile these approaches. The authors use the uncluttered coordinate free approach to symplectic geometry and classical mechanics that has been developed by mathematicians over the course of the last thirty years but at the same time apply the apparatus to a great number of concrete problems. In the first chapter the authors provide an elementary introduction to symplectic geometry and explain the key concepts and results in a way accessible to physicists and mathematicians. The remainder of the book is devoted to the detailed analysis and study of the ideas discussed in Chapter 1. Some of the themes emphasized in the book include the pivotal role of completely integrable systems, the importance of symmetries, analogies between classical dynamics and optics, the importance of symplectic tools in classical variational theory, symplectic features of classical field theories and the principle of general covariance. This work can be used as a textbook for graduate courses but the depth of coverage and the wealth of information and application means that it will be of continuing interest to and of lasting significance for mathematicians and mathematically minded physicists.

*Symplectic techniques in physics* Victor Guillemin, 1984

**Symplectic Techniques in Physics** Victor Guillemin, Shlomo Sternberg, 1983 Symplectic Fibrations and Multiplicity Diagrams Victor Guillemin, Eugene Lerman, Shlomo Sternberg, 1996-09-28 Applications of the techniques of symplectic geometry to describe symmetry breaking in quantum physics. *Symplectic Methods in Harmonic Analysis and in Mathematical Physics* Maurice A. de Gosson, 2011-07-30 The aim of this book is to give a rigorous and complete treatment of various topics from harmonic analysis with a strong emphasis on symplectic invariance properties which are often ignored or underestimated in the time frequency literature. The topics that are addressed include but are not limited to the theory of the Wigner transform, the uncertainty principle from the point of view of symplectic topology, Weyl calculus and its symplectic covariance, Shubin's global theory of pseudo differential operators and Feichtinger's theory of modulation spaces. Several applications to time frequency analysis and quantum mechanics are given, many of them concurrent with ongoing research. For instance a non standard pseudo differential calculus on phase space where the main role is played by Bopp operators, also called Landau operators in the literature, is introduced and studied. This calculus is closely related to both the Landau problem and to the deformation quantization theory of Flato and Sternheimer of which it gives a simple pseudo differential formulation where Feichtinger's modulation spaces are key actors. This book is primarily directed towards students or researchers in harmonic analysis in the broad sense and towards mathematical physicists working in quantum mechanics. It can also be read with profit by researchers in time frequency analysis providing a valuable complement to the existing

literature on the topic A certain familiarity with Fourier analysis in the broad sense and introductory functional analysis e g the elementary theory of distributions is assumed Otherwise the book is largely self contained and includes an extensive list of references

**An Introduction to Methods of Complex Analysis and Geometry for Classical Mechanics and Non-linear Waves** Daniel Benest,1994    **Numerical Methods in Applied Sciences** Wei Cai,1996    Understanding the Discrete Element Method Hans-Georg Matuttis,Jian Chen,2014-06-23 Gives readers a more thorough understanding of DEM and equips researchers for independent work and an ability to judge methods related to simulation of polygonal particles Introduces DEM from the fundamental concepts theoretical mechanics and solidstate physics with 2D and 3D simulation methods for polygonal particles Provides the fundamentals of coding discrete element method DEM requiring little advance knowledge of granular matter or numerical simulation Highlights the numerical tricks and pitfalls that are usually only realized after years of experience with relevant simple experiments as applications Presents a logical approach starting with the mechanical and physical bases followed by a description of the techniques and finally their applications Written by a key author presenting ideas on how to model the dynamics of angular particles using polygons and polyhedral Accompanying website includes MATLAB Programs providing the simulation code for two dimensional polygons Recommended for researchers and graduate students who deal with particle models in areas such as fluid dynamics multi body engineering finite element methods the geosciences and multi scale physics    Fortschritte der Physik ,1996    *Lectures on Symplectic and Poisson Geometry* Izu Vaisman,2000    **An Introduction to Symplectic Geometry** Rolf Berndt,2024-04-15 Symplectic geometry is a central topic of current research in mathematics Indeed symplectic methods are key ingredients in the study of dynamical systems differential equations algebraic geometry topology mathematical physics and representations of Lie groups This book is a true introduction to symplectic geometry assuming only a general background in analysis and familiarity with linear algebra It starts with the basics of the geometry of symplectic vector spaces Then symplectic manifolds are defined and explored In addition to the essential classic results such as Darboux's theorem more recent results and ideas are also included here such as symplectic capacity and pseudoholomorphic curves These ideas have revolutionized the subject The main examples of symplectic manifolds are given including the cotangent bundle Kähler manifolds and coadjoint orbits Further principal ideas are carefully examined such as Hamiltonian vector fields the Poisson bracket and connections with contact manifolds Berndt describes some of the close connections between symplectic geometry and mathematical physics in the last two chapters of the book In particular the moment map is defined and explored both mathematically and in its relation to physics He also introduces symplectic reduction which is an important tool for reducing the number of variables in a physical system and for constructing new symplectic manifolds from old The final chapter is on quantization which uses symplectic methods to take classical mechanics to quantum mechanics This section includes a discussion of the Heisenberg group and the Weil or metaplectic representation of the symplectic group Several appendices provide

background material on vector bundles on cohomology and on Lie groups and Lie algebras and their representations Berndt's presentation of symplectic geometry is a clear and concise introduction to the major methods and applications of the subject and requires only a minimum of prerequisites This book would be an excellent text for a graduate course or as a source for anyone who wishes to learn about symplectic geometry     **Acta Numerica 1992: Volume 1** Arieh Iserles, 1992-04-24

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**Geometric Numerical Integration** Ernst Hairer, Christian Lubich, Gerhard Wanner, 2002 Numerical methods that preserve properties of Hamiltonian systems reversible systems differential equations on manifolds and problems with highly oscillatory solutions are the subject of this book A complete self contained theory of symplectic and symmetric methods which include Runge Kutta composition splitting multistep and various specially designed integrators is presented and their construction and practical merits are discussed The long time behaviour of the numerical solutions is studied using a backward error analysis modified equations combined with KAM theory The book is illustrated by many figures it treats applications from physics and astronomy and contains many numerical experiments and comparisons of different approaches

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