# Quantifier Elimination by Cylindrical Algebraic Decomposition Based on Regular Chains

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## ABSTRACT

A quantifier elimination algorithm by cylindrical algebraic decomposition based on regular chains is presented. The main idea is to refine a complex cylindrical tree until the signs of polynomials appearing in the tree are sufficient to distinguish the true and false cells. We report on an implementation of our algorithm in the `RegularChains` library in MAPLE and illustrate its effectiveness by examples.

## Categories and Subject Descriptors

I.1.2 [**Symbolic and Algebraic Manipulation**]: Algorithms—*Algebraic algorithms, Analysis of algorithms*

## General Terms

Algorithms, Experimentation, Theory

## Keywords

quantifier elimination, cylindrical algebraic decomposition; regular chains; triangular decomposition

## 1. INTRODUCTION

Quantifier elimination over real closed fields (QE) has been applied successfully to many areas in mathematical sciences and engineering. The following textbooks and journal special issues [18, 12, 6, 3] demonstrate that QE is one of the major applications of symbolic computation.

It is well known that the worst-case running time for real quantifier elimination is doubly exponential in the number of variables of the input formula, even if there is only one free variable and all polynomials in the quantified input are linear, see the paper [5]. It is also well-known that QE based on Cylindrical Algebraic Decomposition (CAD) has a worst-case doubly exponential running time, even when the number of quantifier alternations is constant, meanwhile other QE algorithms are only doubly exponential in the number of quantifier alternations [20, 2]. Despite of these theoretical results, the practical efficiency and the range of the applications of CAD-based QE have kept improving regularly since Collins' landmark paper [10]. Today, CAD-based QE is available to scientists and engineers thanks to different software namely QEPCAD[1], Mathematica[2], REDLOG[3], SyNRAC[4], `RegularChains`[5].

In [9], together with B. Xia and L. Yang, we presented a different way of computing CADs, based on triangular decomposition of polynomial systems. Our scheme relies on the concept of *cylindrical decomposition of the complex space* (CCD), from which a CAD can be easily derived. Since regular chains theory is at the center of this new scheme, we call it RC-CAD. Meanwhile, we shall denote by PL-CAD Collins' projection-lifting scheme for CAD construction.

In [8], we substantially improved the practical efficiency of the RC-CAD scheme by means of an incremental algorithm for computing CADs; an implementation of this new algorithm, realized within the `RegularChains` library, outperforms PL-CAD-based solvers on many examples taken from the literature.

The purpose of the present paper is to show that RC-CAD, supported by this incremental algorithm, can serve the purpose of real QE. In addition, our implementation of RC-CAD-based QE is competitive with software implementing PL-CAD-based QE.

We turn our attention to the theoretical implication of performing QE by RC-CAD. If extended Tarski formulae are allowed, then deriving QE from a RC-CAD is a straightforward procedure, hence, we shall not discuss it here. In the rest of this paper, for both input and output of QE problems, only polynomial constraints (with rational number coefficients) will be allowed, thus excluding the use of algebraic expressions containing radicals.

In Collins' original work, the augmented projection operator was introduced in order to find a sufficiently large set of polynomials such that their signs alone could distinguish *true* and *false* cells. In [17], Hong produced simple solution formula constructions, assuming that the available polynomials in a CAD are sufficient to generate output formulae.

In his PhD thesis [4], Brown then introduced ways to add


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http://dx.doi.org/10.1145/2608628.2608666.

[1] QEPCAD: `http://www.usna.edu/CS/~qepcad/B/QEPCAD.html`
[2] Mathematica: `http://www.wolfram.com/mathematica/`
[3] REDLOG: `http://www.redlog.eu/`
[4] SyNRAC: `http://jp.fujitsu.com/group/labs/techinfo/freeware/synrac/`
[5] `RegularChains`: `http://www.regularchains.org/`

# Quantifier Elimination And Cylindrical Algebraic Decomposition

Hoon Hong

**Quantifier Elimination And Cylindrical Algebraic Decomposition:**

*Quantifier Elimination and Cylindrical Algebraic Decomposition* Bob F. Caviness,Jeremy R. Johnson,2012-12-06 George Collins discovery of Cylindrical Algebraic Decomposition CAD as a method for Quantifier Elimination QE for the elementary theory of real closed fields brought a major breakthrough in automating mathematics with recent important applications in high tech areas e g robot motion also stimulating fundamental research in computer algebra over the past three decades This volume is a state of the art collection of important papers on CAD and QE and on the related area of algorithmic aspects of real geometry It contains papers from a symposium held in Linz in 1993 reprints of seminal papers from the area including Tarski s landmark paper as well as a survey outlining the developments in CAD based QE that have taken place in the last twenty years *Computer Algebra in Scientific Computing* François Boulier,Matthew England,Timur M. Sadykov,Evgenii V. Vorozhtsov,2020-10-17 This book constitutes the refereed proceedings of the 22nd International Workshop on Computer Algebra in Scientific Computing CASC 2020 held in Linz Austria in September 2020 The conference was held virtually due to the COVID 19 pandemic The 34 full papers presented together with 2 invited talks were carefully reviewed and selected from 41 submissions They deal with cutting edge research in all major disciplines of computer algebra The papers cover topics such as polynomial algebra symbolic and symbolic numerical computation applications of symbolic computation for investigating and solving ordinary differential equations applications of CAS in the investigation and solution of celestial mechanics problems and in mechanics physics and robotics *Simple Solution Formula Construction in Cylindrical Algebraic Decomposition Based Quantifier Elimination* Hoon Hong,1992 **Automated Deduction in Geometry** Francisco Botana,Pedro Quaresma,2015-07-17 This book constitutes the thoroughly refereed post workshop proceedings of the 10th International Workshop on Automated Deduction in Geometry ADG 2014 held in Coimbra Portugal in July 2014 The 11 revised full papers presented in this volume were carefully selected from 20 submissions The papers show the trend set of current research in automated reasoning in geometry Computer Algebra in Scientific Computing Vladimir P. Gerdt,Wolfram Koepf,Werner M. Seiler,Evgenii V. Vorozhtsov,2016-09-08 This book constitutes the proceedings of the 18th International Workshop on Computer Algebra in Scientific Computing CASC 2016 held in Bucharest Romania in September 2016 The 32 papers presented in this volume were carefully reviewed and selected from 39 submissions They deal with cutting edge research in all major disciplines of Computer Algebra *Artificial Intelligence and Symbolic Computation* Jaques Calmet,2006-09-13 This book constitutes the refereed proceedings of the 8th International Conference on Artificial Intelligence and Symbolic Computation AISC 2006 held in Beijing China in September 2006 The 18 revised full papers presented together with 4 invited papers were carefully reviewed and selected from 39 submissions Based on heuristics and mathematical algorithmics artificial intelligence and symbolic computation are two views and approaches for automating mathematical problem solving The papers address all current aspects in the area of symbolic computing and AI mathematical

foundations implementations and applications in industry and academia The papers are organized in topical sections on artificial intelligence and theorem proving symbolic computation constraint satisfaction solving and mathematical knowledge management **Real Algebraic Geometry and Ordered Structures** Charles N. Delzell,James J. Madden,2000 This volume contains 16 carefully refereed articles by participants in the Special Semester and the AMS Special Session on Real Algebraic Geometry and Ordered Structures held at Louisiana State University and Southern University Baton Rouge The 23 contributors to this volume were among the 75 mathematicians from 15 countries who participated in the special semester Topics include the topology of real algebraic curves Hilbert s 16th problem moduli of real algebraic curves effective sums of squares of real forms Hilbert s 17th problem efficient real quantifier elimination subanalytic sets and stratifications semialgebraic singularity theory radial vector fields exponential functions and valuations on nonarchimedean ordered fields valued field extensions partially ordered and lattice ordered rings rings of continuous functions spectra of rings and abstract spaces of higher level orderings and real places This volume provides a good overview of the state of the art in this area in the 1990s It includes both expository and original research papers by top workers in this thriving field The authors and editors strived to make the volume useful to a wide audience including students and researchers interested in real algebraic geometry and ordered structures two subjects that are obviously related but seldom brought together *Computer Aided Verification* Constantin Enea,Akash Lal,2023-07-17 The open access proceedings set LNCS 13964 13965 13966 constitutes the refereed proceedings of the 35th International Conference on Computer Aided Verification CAV 2023 which was held in Paris France in July 2023 The 67 full papers presented in these proceedings were carefully reviewed and selected from 261 submissions The have been organized in topical sections as follows Part I Automata and logic concurrency cyber physical and hybrid systems synthesis Part II Decision procedures model checking neural networks and machine learning Part II Probabilistic systems security and quantum systems software verification **Mathematical Software – ICMS 2018** James H. Davenport,Manuel Kauers,George Labahn,Josef Urban,2018-07-17 This book constitutes the proceedings of the 6th International Conference on Mathematical Software ICMS 2018 held in South Bend IN USA in July 2018 The 59 papers included in this volume were carefully reviewed and selected from numerous submissions The program of the 2018 meeting consisted of 20 topical sessions each of which providing an overview of the challenges achievements and progress in a subeld of mathematical software research development and use *Computational Algebra and Number Theory* Wieb Bosma,Alf van der Poorten,2013-03-09 Computers have stretched the limits of what is possible in mathematics More they have given rise to new fields of mathematical study the analysis of new and traditional algorithms the creation of new paradigms for implementing computational methods the viewing of old techniques from a concrete algorithmic vantage point to name but a few Computational Algebra and Number Theory lies at the lively intersection of computer science and mathematics It highlights the surprising width and depth of the field through examples drawn from current activity ranging from category

theory graph theory and combinatorics to more classical computational areas such as group theory and number theory Many of the papers in the book provide a survey of their topic as well as a description of present research Throughout the variety of mathematical and computational fields represented the emphasis is placed on the common principles and the methods employed Audience Students experts and those performing current research in any of the topics mentioned above

Mathematical Software -- ICMS 2014 Hoon Hong,Chee Yap,2014-08-01 This book constitutes the proceedings of the 4th International Conference on Mathematical Software ICMS 2014 held in Seoul South Korea in August 2014 The 108 papers included in this volume were carefully reviewed and selected from 150 submissions The papers are organized in topical sections named invited exploration group coding topology algebraic geometry surfaces reasoning special Groebner triangular parametric interfaces and general **Some Tapas of Computer Algebra** Arjeh M. Cohen,Hans Cuypers,Hans Sterk,2013-03-09 In the years 1994 1995 two EIDMA mini courses on Computer Algebra were given at the Eindhoven University of Technology by apart from ourselves various invited lecturers EIDMA is the Research School Euler Institute for Discrete Mathematics and its Applications The idea of the courses was to acquaint young mathematicians with algorithms and software for mathemat ical research and to enable them to incorporate algorithms in their research A collection of lecture notes was used at these courses When discussing these courses in comparison with other kinds of courses one might give in a week s time Joachim Neub ser referred to our courses as tapas This denomination underlined that the courses consisted of appe tizers for various parts of algorithmic algebra indeed we covered such spicy topics as the link between Gr bner bases and integer programming and the detection of algebraic solutions to differential equations As a collection the not es turned out to have some appeal of their own which is the main reason why the idea came up of transforming them into book form We feIt however that the book should be distinguishable from a standard text book on computer algebra in that it retains its appetizing flavour by presenting a variety of topics at an accessible level with a view to recent developments

**Tapas in Experimental Mathematics** Tewodros Amdeberhan,Victor H. Moll,2008 Experimental Mathematics is a recently structured field of Mathematics that uses a computer and advanced computing technology as tools to perform experiments such as analysis of examples testing of new ideas and the search of patterns **Uncertainty-aware Integration of Control with Process Operations and Multi-parametric Programming Under Global Uncertainty** Vassilis M. Charitopoulos,2020-02-05 This book introduces models and methodologies that can be employed towards making the Industry 4 0 vision a reality within the process industries and at the same time investigates the impact of uncertainties in such highly integrated settings Advances in computing power along with the widespread availability of data have led process industries to consider a new paradigm for automated and more efficient operations The book presents a theoretically proven optimal solution to multi parametric linear and mixed integer linear programs and efficient solutions to problems such as process scheduling and design under global uncertainty It also proposes a systematic framework for the uncertainty aware

integration of planning scheduling and control based on the judicious coupling of reactive and proactive methods Using these developments the book demonstrates how the integration of different decision making layers and their simultaneous optimisation can enhance industrial process operations and their economic resilience in the face of uncertainty

**Computer Algebra in Scientific Computing** Viktor G. Ganzha,Ernst W. Mayr,Evgenii V. Vorozhtsov,2012-12-06 Proceedings of the Third Workshop on Computer Algebra in Scientific Computing Samarkand Octobe5r 5 9 2000

**Polynomial Algorithms in Computer Algebra** Franz Winkler,2012-12-06 For several years now I have been teaching courses in computer algebra at the Universitat Linz the University of Delaware and the Universidad de Alcala de Henares In the summers of 1990 and 1992 I have organized and taught summer schools in computer algebra at the Universitat Linz Gradually a set of course notes has emerged from these activities People have asked me for copies of the course notes and different versions of them have been circulating for a few years Finally I decided that I should really take the time to write the material up in a coherent way and make a book out of it Here now is the result of this work Over the years many students have been helpful in improving the quality of the notes and also several colleagues at Linz and elsewhere have contributed to it I want to thank them all for their effort in particular I want to thank B Buchberger who taught me the theory of Grabner bases nearly two decades ago B F Caviness and B D Saunders who first stimulated my interest in various problems in computer algebra G E Collins who showed me how to compute in algebraic domains and J R Sendra with whom I started to apply computer algebra methods to problems in algebraic geometry Several colleagues have suggested improvements in earlier versions of this book However I want to make it clear that I am responsible for all remaining mistakes *Intelligent Computer Mathematics* Stephen M. Watt,Alan Sexton,James H. Davenport,Petr Sojka,Josef Urban,2014-06-30 This book constitutes the joint refereed proceedings of Calculemus 2014 Digital Mathematics Libraries DML 2014 Mathematical Knowledge Management MKM 2014 and Systems and Projects S P 2014 held in Coimbra Portugal during July 7 11 2014 as four tracks of CICM 2014 the Conferences on Intelligent Computer Mathematics The 26 full papers and 9 Systems and Projects descriptions presented together with 5 invited talks were carefully reviewed and selected from a total of 55 submissions The Calculemus track of CICM examines the integration of symbolic computation and mechanized reasoning The Digital Mathematics Libraries track evolved from the DML workshop series features math aware technologies standards algorithms and processes towards the fulfillment of the dream of a global DML The Mathematical Knowledge Management track of CICM is concerned with all aspects of managing mathematical knowledge in the informal semi formal and formal settings The Systems and Projects track presents short descriptions of existing systems or on going projects in the areas of all the other tracks of the conference **Artificial Intelligence and Symbolic Computation** Bruno Buchberger,John A. Campbell,2004-09-10 This book constitutes the refereed proceedings of the 7th International Conference on Artificial Intelligence and Symbolic Computation AISC 2004 held in Linz Austria in September 2004 The 17 revised full papers and 4

revised short papers presented together with 4 invited papers were carefully reviewed and selected for inclusion in the book The papers are devoted to all current aspects in the area of symbolic computing and AI mathematical foundations implementations and applications in industry and academia Artificial Intelligence, Automated Reasoning, and Symbolic Computation Jacques Calmet,2002-06-19 This book constitutes the refereed proceedings of the joint International Conferences on Artificial Intelligence and Symbolic Computation AISC 2002 and Calculemus 2002 held in Marseille France in July 2002 The 24 revised full papers presented together with 2 system descriptions were carefully reviewed and selected from 52 submissions Among the topics covered are automated theorem proving logical reasoning mathematical modeling algebraic computations computational mathematics and applications in engineering and industrial practice **Geometry and Robotics** Jean-Daniel Boissonnat,Jean-Paul Laumond,1989-10-11 The role played by hormones in the development and treatment of malignant tumors has been controversial for nearly 50 years The present volume concentrates on substantiated data obtained from the study of tumors developing from hormone related or hormone producing tissue for example the thyroid adrenal glands prostate and the female genital tract Combining expertise from the fields of molecular biology biochemistry and histopathology advances in the management of these tumors are elaborated The book also provides information on the endonuclear diagnosis of adrenal tumors Antihormones have proved to be important as they exhibit a destructive effect on prostate carcinomas and breast cancer In addition a special chapter discusses the diffuse endocrine cell system DECS Bridging the gap between molecular biology and endocrine therapy the editors present innovative data on many aspects of hormone related malignant tumors and offer both a survey of present knowledge and a basis for further research

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**Table of Contents Quantifier Elimination And Cylindrical Algebraic Decomposition**

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