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My Life in Computer Algebra

Franz Winkler

Abstract

After having spent more than 40 years in Mathematics, and in particular in Computer Algebra, I recollect stages in my scientific career and I explain the connections between my different areas of interest.

My scientific career

Looking back after about 40 years of scientific activities, from 1979 to 2021, I have been wondering whether there is a guiding principle, a kind of “Ariadne’s thread”, in my scientific career. I have worked on elimination theory, decision problems in equational logic, on geometric theorem proving, algebraic curves, and algebraic differential equations. Is this a collection of topics dictated by chance, or can I discern a stringent path leading from my scientific beginnings to my current interests?

Well, the leading theme throughout all my scientific career from 1979 until now is definitely “Computer Algebra”, the scientific field of combining algebraic reasoning with questions of computability. Without even knowing the word I started out writing my diploma thesis at the university of Linz on Buchberger’s algorithm for computing Gröbner bases. Mine was the second implementation – the first had been undertaken by my advisor Bruno Buchberger in an assembler language – of an algorithm for computing Gröbner bases. The program was written in FORTRAN, based on the SAC-II system of George Collins. But from SAC-II I could only use the implementation of long integers. The whole arithmetic of polynomials I had to write myself, because the representation of SAC-II was recursive and therefore not very suitable for Gröbner bases. My thesis also gave a formal correctness proof of the algorithm.

In 1979 I received a Fulbright Scholarship to study in the USA. During a year at the Rensselaer Polytechnic Institute (RPI) in Troy, New York, I learned from Bob Caviness and David Saunders that there is this new scientific field of “Computer Algebra”. One of my first activities in the algebra seminar was to present a talk on the theory of Gröbner bases, which was initially received very skeptically. Was a decision of the ideal membership problem really possible? Yes, it was. Later I also presented a similar talk at the IBM research center in Yorktown Heights. With Kamal Abdali I worked in a project on automatically generating verification conditions via lambda calculus. Apart from all these scientific stimuli, Eva and I enjoyed a year of carefree student life in the USA.

Back at the university of Linz after this fascinating year, I began doctoral studies under the advisorship of Bruno Buchberger. I derived some first results on the complexity of Gröbner bases, and I investigated relations between the theory of Gröbner bases and equational logical theories. In particular I studied the algorithm of Knuth and Bendix for the completion of systems of rewrite rules. I started giving lectures on computer algebra, and I wrote my first paper with Collins and Mignotte as co-authors on exact arithmetic in various domains. In the summer of 1984 I finished my doctoral degree (PhD in Mathematics). For receiving the promotion document I had to wait until January 1985, the reason being that I was awarded the distinction “sub auspiciis praesidentis rei publicae” for excellence in my studies from high school up to the PhD. This distinction is awarded by the President of the Austrian republic; and the president’s appointment schedule was booked out from summer of 1984 to the end of January 1985.

But starting in September 1984 I again took a position in the USA, this time as a Visiting Assistant Professor at the University of Delaware. Bob Caviness was now chairman of the Computer Science department there, and he had invited me. Moreover, David Saunders, Greg Butler and George Collins had also moved there, making the University of Delaware the center of computer algebra. Besides my teaching duties I continued my studies of completion algorithms and Gröbner bases. At UoD I learned what it means to be a professor and an active researcher. Two years I spent in this dense computer algebra environment. I spoke at the conference EUROCAL’85, I presented my work at SMU in Dallas, Texas, and at RPI, and I gave an invited talk at the conference “Computers & Mathematics” at Stanford University.

Now I had reached a point which forced me to make up my mind. Bob Caviness offered me a tenure track position at UoD and at the same time a position at my Alma Mater Kepleriana in Linz, now Johannes Kepler University (JKU), became available. Bruno Buchberger offered me a position in his research group, which would finally evolve into the Research Institute for Symbolic Computation (RISC). I decided to rejoin Bruno’s group as an assistant professor, with the prospect of getting Habilitation. Throughout these years I have been wondering how my career might have evolved had I decided otherwise. For two years my position was financed by “Österreichische Forschungsgemeinschaft”, an Austrian society for supporting scientific activities. They granted such a position to recipients of a doctorate ”sub auspiciis”. In this project I continued my investigation of completion algorithms for bases of polynomial ideals and axiom systems for equational theories.

And then I started to design my first real reseach project “Algorithmen und Software für die Algebraische Geometrie (ASAG)” (in English: Algorithms and software for algebraic geometry). I sent the application to the Austrian National Science Foundation (Fonds zur Förderung der wissenschaftlichen Forschung, FWF); and it got granted! This was the first of 12 research projects funded by FWF. Throughout most of my career, from 1988 to 2021, my research group was supported by FWF; and for this I will always be thankful.

At the conference dinner of SYMSAC 1986 at the University of Waterloo, Canada, I was sitting at a table with Tomás Recio from the Universidad de Cantabria, Santander, and Juan Llovet from the Universidad de Alcalá, Madrid. This was one of the luckiest coincidences in my life. It was the start of a life long relation with colleagues in Spain, in particular in Madrid and Santander. Tomás visited me at JKU, and in October 1988 a young PhD student from the Universidad de Alcalá, Rafael Sendra, came to spend a year of studies with me. In the summer semester of 1989 I employed him in my research project ASAG, and we started to work on rational parametrization of algebraic curves, making the theory of Hilbert and Hurwitz algorithmic. Little did I know at the time that this would be the beginning of a life long cooperation and friendship. Together with Rafael I have published 14 papers and a book on Rational Algebraic Curves, in 2008 we organized the conference "International Symposium on Symbolic and Algebraic Computing (ISSAC)" together, and from 1988 on there was barely a year in which we did not visit each other, either in Alcalá/Madrid or in Hagenberg/Linz. Only the recent COVID pandemic forced us to shift our cooperation to cyberspace.

In February 1989 RISC moved to the newly renovated Castle of Hagenberg, 20km from the campus of JKU. Bruno, with his extraordinary talent for motivating people, had convinced the local government to dedicate the castle to RISC. Bruno and RISC later were the driving forces in building up the extremely successful Software Park of Hagenberg. For me personally the next crucial step was that I got Habilitation at the university in 1990. As an associate professor I had a much more stable position. I began to cooperate with and visit colleagues at other universities, in Europe, China, USA. And now that I had habilitation, I could advise my own PhD students; they started to come from Austria, Europe, and the whole world; 25 up to now. Many of them are now professors at universities in Europe, USA, China, Japan, and South America, or they work successfully in other professions.

Twice, in 1990 and in 1992, I organized a Summer School in Computer Algebra, in which invited professors, among them Hans Zassenhaus from Ohio State and Bob Caviness, lectured to an audience of PhD students and postdocs from Europe and beyond. In the summer of 1992, together with my colleagues at RISC Hoon Hong and Dongming Wang, we gathered a group of researchers, amoung them Bruno Buchberger, Rüdiger Loos, Volker Weispfenning, Albrecht Beutelspacher, George Collins, Chandrajit Bajaj, Marie-Francoise Roy, Wen-Tsün Wu, Dana Scott, Jürgen Richter-Gebert, Teo Mora, for a workshop on "Algebraic Approaches to Geometric Reasoning" in the Castle of Weinberg, in the vicinity of Hagenberg.

These activities marked the beginning of my involvement in a multitude of conferences and workshops as general chair, program chair, local organizer, session organizer etc. For instance in 2008 I organized the computer algebra conference ISSAC at RISC, and together with Kosaku Nagasaka I served as general chair for ISSAC in 2014. I found out that serving the scientific community in this way is not only a distraction from the central goal of advancing the frontier of science, but in fact it gave me the opportunity of getting to know and starting collaborations with many fellow computer algebraists. In this way I made many friends in the field, and perhaps also a few enemies (I hope not too many).

To hold a secure position as associate professor at RISC freed me from the constant need to produce several research publications every year. It gave me the freedom to devote my time also to other activities which required a longer gestation period before bearing fruit. In the 1990s I started a book project on computer algebra. For about 2 years I devoted at least an hour per working day to the compilation of material for this book, until finally in 1996 I could publish it with Springer-Verlag under the title of "Polynomial Algorithms in Computer Algebra". Work on this book yielded great benefits for my teaching and it helped me to understand a wider area of computer algebra, going well beyond my necessarily narrow field of expertise and research. After 2000 I turned my attention to problems in differential algebra: first to differential elimination theory and then to factorization and invariants of linear differential operators.

But still, having embarked on an academic career, I was not really satisfied until I would reach the top. So I started to apply for the position of Full Professor at universities in Austria and Germany. As my list of publications grew longer, I got closer and closer to my goal. In Tübingen, Karlsruhe, and Bonn (GMD) I was in the final group of contenders and I was invited to give talks in the process of selecting professors there. And then Dana Scott retired from his professorship at RISC and a call for application was sent out. How could I not grasp the "kairos", this unexpected opportunity? I simply had to apply. And out of the approximately 30 applicants my colleague Hoon Hong was given first place and I came in second. But Hoon accepted a position at NCSU, and so I became Full Professor at RISC by October 1, 1998. But barely had I settled into my new responsibilities, that Bruno Buchberger expressed his desire to be relieved from his duties as chairman of RISC. And so just one year after my promotion to Full Professor I had to step in as chairman. This meant to be responsible for the functioning of a big institute, with approximately 12 faculty members, 25 PhD students, postdocs, visitors, and other personnel. And on top of that RISC owned a small company, the RISC Software Company, which clearly needed some kind of restructuring and focusing. So the first years after becoming professor and chairman of RISC were dominated by getting to grips with the functioning of the RISC institute and giving a new starting kick to the RISC company. In the first task I was overwhelmingly supported by my colleagues in the RISC faculty, and in the second I was successful in convincing a young colleague to take up the position of CEO of the company. The university laws were modified and in 2004 ownership of the RISC Software Company changed from RISC to JKU. I could put a thriving company into the hands of the university. Presently RISC Software has approximately 50 employees and is a very successful spin-off of JKU, actually of RISC.

What I also inherited as chairman was a very successful program in PhD studies in Symbolic Computation. I considered it my duty to continue this beacon project. The university never did and still does not provide any financial support for this program. It was no mean job to come up with a constant flow of money for the group of approximately 25 PhD student from all over the world. But all my fellow faculty members supported me in employing students in their research projects, and the local government of Upper Austria generously paid for several scholarships. I myself have advised 25 PhD students between 1990 and now. Many of my former PhD students have embarked on successful academic careers or are applying their knowledge in companies. I am proud of all of them!

But life as a professor does not only mean to do research. Another central aspect is teaching. We have to pass on our enthusiasm for critical thinking and enlargement of the horizon of knowledge to the next generation. This might sometimes feel like a burden, but it is definitely a noble duty. Already in 1982, during my studies for the PhD, I started to teach Computer Algebra; and I have kept doing so until now. Other lectures were devoted to Linear Algebra, Logic, Commutative Algebra and Algebraic Geometry, Differential Algebra, Coding Theory, Cryptography, Introduction to Computer Science, Theory of Computation. And I will be teaching The Method of Mathematics and the Sciences at the Catholic University of Linz after the retirement from my professorship at JKU. I have run a weekly seminar on Computer Algebra since 1988, in which I have had quite a number of mathematical colleagues as speakers. Now, in this last semester, the COVID crisis presents an unwelcome challenge to this program of invitations. But on the other hand, we are having a virtual seminar in which I can gather speakers from all over the world, including some of my former students. I have heard it said that in order to really understand a branch of science you have to offer a course on it; and several times I have had exactly this experience.

During many years I also involved myself in political aspects of my university. For several periods I was elected into the Senate of JKU, I was speaker of the professors in the School of Science and Technology (Technisch-Naturwissenschaftliche Fakultät, TNF), and I served on a number of committees. Having retired from the chairmanship of RISC in 2009, I envisaged a return to full-time devotion to research and teaching. But I had reached a professional age in which it becomes harder and harder to stear clear of administrational duties. In 2013 my colleagues in the TNF convinced me that I should take on the job of the Dean of TNF for 2 years. And afterwards I served for nearly 4 years as Speaker of the Department of Mathematics. In these positions I spent many an hour in meetings and committees. But I could also promote some personal goals, like fostering the careers of young colleagues.

About 15 years ago I reoriented myself for the last time; I shifted my scientific interest from parametrization of algebraic varieties to symbolic solution of algebraic differential equations. Feng and Gao from the Chinese academy of sciences in Beijing had published papers in which they applied our work on parametrization of curves to the question of whether an autonomous algebraic ordinary differential equation of order 1 has a rational (general) solution, and in the positive case to the determination of such a rational solution. I became extremely interested in this new application of algebraic geometry, and together with PhD students and my colleague Rafael Sendra in Madrid we extended the reach of this new idea to non-autonomous equations, to high order equations, to algebraic solutions, to power series solutions and we even took first steps in algebraic partial differential equations. And this is most probably my last area of interest in computer algebra, after Gröbner bases and elimination theory, equational theorem proving, geometric theorem proving, parametrization of varieties, differential elimination and factorization of linear differential operators.

After retiring from my active position as professor of mathematics at JKU in the fall of 2021 I will still be an avid observer of progress in computer algebra and mathematics in general. But my interest will be shifting to problems of epistemology. In 2018 I gave a talk at the Ludwig-Wittgenstein-Symposium on "Das Unendliche im mathematischen Alltag" (the infinite in every day mathematics). And I have very concrete teaching plans for explaining the methods of mathematics and the natural sciences to students in humanities. So I guess I will not be in danger of getting bored.

Looking back over my career in mathematics and computer algebra in particular, I have to admit that I was extremely fortunate. After having finished my high school (Gymnasium) years in Salzburg in 1974, I had a hard time deciding which field of studies to choose. I liked languages, I liked philosophy, and I also liked mathematics in particular in connection to this new aspect of informatics. Ultimately I decided to go for this modern aspect of computing in mathematics. And my choice proved perfect for me. Little had I known that high school mathematics, which was more like strictly following a cooking recipe, enjoyed only a slight similarity to the mathematics I would do at university. But the rigor and the emphasis on strict formal correctness was something that proved to be natural for my way of thinking.

So instead of taking a job in industry after my graduation, I went for a PhD and a career as a research mathematician. And I found out that mathematics opens doors all over the world. Mathematics is definitely the most international of all scientific fields. Literature, humanities, even economics and law are clearly strongly biased by cultural influences. Whereas certainly there is German or English literature, market oriented or state dominated economy, European or Chinese law, open physics and physics protected by state secrets, there is no such thing as Western, Asian, or clandestine mathematics. In fact, mathematics was a kind of protected and well guarded secret art in the distant past, in times of Tartaglia and Cardano. But not any more! My experience was that I could go to research centers and universities all over the world, in Europe, America, Asia, Australia, and I could find colleagues who spoke my mathematical language. And often exchange in this mathematical lingua franca led to personal exchange, visits with family, and relationship and even friendship for many years to follow. I have hosted a great number of mathematicians and computer scientists as guests in my computer algebra research group at RISC. On the other hand I have given approximately 150 talks at universities worldwide, and I have been invited as a visiting professor at institutions all over the world, in Japan, Spain, China, Australia, Hungary, USA, the Czech Republic, Greece, Romania, Russia, England, and Lithuania.

Mathematics and Computer Algebra provided me with an interesting and satisfying intellectual life, and offered me the key to visiting people all around the world and enjoying their friendship. For this I am deeply grateful.

My research topics

General Computer Algebra

When I moved to RPI (Rensselaer Polytechnic Institute) in Troy, New York, in 1979, I learned that what I had been investigating in my Master Thesis at JKU was actually Computer Algebra. In a course on Higher Algebra by David Saunders and in a Reading Course by Bob F. Caviness I got a first inkling of what might be computable symbolically in algebra. First I leared about new investigations of Euclid's algorithm for polynomial GCD computation, and modular versions of it, which compute the GCD over the integers by several homomorphic images and finally combining them via the Chinese remainder algorithm. I was also interested in factorization of polynomials together with the ideas of Berlekamp for factorization modulo a prime and subsequent Hensel lifting. Collins' algorithm for cylindrical algebraic decomposition and theorem proving over real closed fields was a source of great inspiration.

In 1982 I wrote my first publication together with Collins and Mignotte on exact arithmetic in various algebraic domains [1]. Over the years I published several overview articles on computer algebra, cf. [9, 19, 20, 32, 43, 52, 62, 70, 72]. My teaching and research in this area culminated in my book on Polynomial Algorithms in Computer Algebra [B4]. I was also involved in several tutorial and editorial book projects, see [B1, B2, B8, B11, B12, B13].

Gröbner bases and elimination theory

During my master studies under the advisorship of Bruno Buchberger at the Department of Mathematics at JKU I implemented the program system SAC-1 (Symbolic and Algebraic Computing) of George Collins on an IBM 360/44. SAC-1 was running under FORTRAN IV, and on top of it I built my program "GB" for transforming a basis for a multivariate polynomial ideal F into a Gröbner basis. This was actually the second implementation of Buchberger's algorithm, after his own in assembler language in the 1960s. My thesis [T1] contained a description of the algorithm, a formal correctness proof, a set of examples, and a listing of the program.

In the work on my PhD thesis [T2], again under Buchberger's advisorship, I continued the investigation of Gröbner bases, and I extended my interest to other completion algorithms, such as the one for equational theorem proving by Donald E. Knuth and Peter B. Bendix. I could demonstrate that Buchberger's algorithm and the Knuth-Bendix algorithm can be seen as variants of a more general completion algorithm.

After having published my results on Gröbner bases [2, 4, 5, 7, 8, 10, 14] and equational theorem proving (see below) in several conference and journal papers, I finally collected them in my Habilitation thesis [T3].

But I came back to Gröbner bases over time and my interest in this topic did not wane, cf. [38, 42, 50, 54, 55, 56, 59, 61, 64]. As an editor I tried to disseminate knowledge of this important theory in the mathematical community [B6, B7].

Equational theorem proving

Equational theorem proving tries to solve the following problem: given a finite system of axioms E in first order logic, all universally quantified, and a universally quantified formula F; can F be proven from E, i.e., $\vdash_E F$? For instance, can we prove

$$\forall x, y : (x^{-1} \cdot (x \cdot y))^{-1} = (x^{-1} \cdot y)^{-1} \cdot x^{-1}$$

from the axioms of a group? Knuth and Bendix proposed to orient the axioms in E, thereby transforming E into a system of rewrite rules R, and subsequently trying to complete R, i.e., adding rules so that the resulting system R' can reduce the two sides of an equation to the same normal form whenever the equation is provable from E. In this process we have to order terms, which is not always possible.

I have contributed to this theory in my PhD dissertation [T2] and also in my Habilitation thesis [T3], as well as in several papers [3, 6, 12, 13, 63].

Geometric theorem proving and symbolic geometric computation

Here we typically consider a geometric configuration describable by polynomial equations, inequations, and sometimes also inequalities. And we want to show that a given formula in this theory is provable from the configuration. As an example one might take the Theorem of Pascal, which states the following: consider 6 points $P_1, \ldots, P_6$ on an irreducible conic, and let them be the vertices of an irregular hexagon; then the 3 pairs of opposite sides of the hexagon meet at three collinear points.

A great breakthrough has been achieved by Wu Wen-tsün who employed algebraic characteristic sets to this problem. But one can also fruitfully apply Gröbner bases towards this goal.

I have contributed to this investigation in [11, 14, 18, 30, 44, 52], and I have co-organized workshops on this topic and co-edited the proceedings [B3, B9].

Rational parametrization of algebraic curves

This has been one of my most productive areas of interest. An algebraic curve $\mathcal{C}$ is the zero locus of a bivariate polynomial $f(x, y)$; this might be called the implicit representation of the curve. For a curve given implicitly it is easy to check whether a point is on the curve, whereas it is time consuming to provide points with coefficients in a desired domain. A rational parametrization of the curve is in some sense a solution of the equation $f(x, y) = 0$ in terms of x and y. It is a birational mapping from the line onto the curve, $t \mapsto (x(t), y(t))$. It is not so obvious how to check whether a given point is on $\mathcal{C}$, but it is trivial to output any number of points with coordinates in a desired domain. So actually we want both representations.

Turning a parametric representation into an implicit one is a problem in elimination theory. The inverse problem, parametrization, is more challenging. In my first research project funded by FWF I started to work on this topic together with Rafael Sendra, who spent a year with me as an exchange student. We studied old papers by Hilbert, Hurwitz and Poincaré on this topic. In order to turn the ideas of Hilbert and Hurwitz into an algorithm, we had to investigate systems of adjoint curves, the computation of the genus of an algebraic curve, the process of blowing up a curve at a given point and many other details. Furthermore, our goal was to develop a symbolic algorithm. And this always means to be extremely careful about the coefficients in the intermediate data and in the final result. Hilbert and Hurwitz had already proven that if an algebraic curve can be rationally parametrized at all, then this can be achieved with coefficients in an algebraic extension of degree at most 2. In order to attain such an optimal result, we needed to delve into number theory and the question of finding rational points on curves.

For more than 20 years we advanced the theory of parametrization and we wrote a substantial number of papers on the topic [15, 17, 21, 22, 23, 24, 26, 28, 29, 31, 37, 39, 40, 41, 48]. We collected contributions towards this goal in a special issue of JSC [B5], and finally we published the monograph "Rational Algebraic Curves – A Computer Algebra Approach" [B10].

Differential algebra

About 20 years ago my scientific interest started to migrate towards computer algebra methods in differential algebra. Differential problems are ubiquitous in mathematical modeling of physical and scientific problems. Algebraic analysis of differential systems can help in determining qualitative and quantitative properties of solutions of such systems. In [45, 49] we have described several algebraic methods for investigating differential systems, in particular group analysis of differential equations and differential elimination.

Linear differential operators (LDOs) can describe an important class of differential equations. Together with my doctoral student Ekaterina Shemyakova we have worked on factorizing LDOs and on the problem of constructing full systems of invariants for LDOs; ref. [53, 57, 58, 60, 69]. In analogy to the purely algebraic situation, also in the differential case one can turn the question of common roots of LDOs into the question of vanishing of a certain determinant, the differential resultant. This we have investigated with Scott McCallum in [88].

Algebraic differential equations

Around 2008 I shifted my focus again. This move was motivated by colleagues from Beijing, Feng and Gao, who proposed to apply rational parametrization of algebraic curves to the problem of finding rational solutions of algebraic ordinary differential equations (AODEs). Based on our parametrization algorithm and in particular on degree bounds for the parametrization, they had described an algorithm for deciding whether an autonomous AODE of order 1 has a rational solution.

I was really surprised to see how our work on parametrization of curves had led to methods for finding symbolic solutions of differential equations. The general idea consists in first neglecting the differential aspect of the problem, and considering the equation as describing an algebraic curve or surface. A rational solution of the AODE yields a rational parametrization of the curve or surface, so we first decide the parametrization problem. In the positive case we need to decide whether a reparametrization might lead to a solution of the differential equation. I call this approach the algebro-geometric method.

With a series of PhD students, and together with my scientific friends in the group of Rafael Sendra, we extended the method of Feng and Gao to the non-autonomous case, to higher order, and to other types of solutions. We could even make first steps towards dealing with algebraic partial differential equations. In a great number of papers we have explained the algebro-geometric method [65, 66, 67, 68, 71, 74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84, 85, 86, 89, 90, 91].

Software

Throughout my career I have been involved in the creation of mathematical software. This started already with my diploma thesis [T1], in which I implemented Buchberger's algorithm for constructing Gröbner bases.

In the 1990s, together with my research group, we created the program system CASA, a special purpose system for computational algebra and constructive algebraic geometry, based on MAPLE; ref. [16, 25, 27, 46]. The motivating problem for CASA was the computation of rational parametrizations of algebraic curves. On the way to this goal we implemented faithful plotting of curves, genus computation, number theoretic methods for finding rational points on curves, systems of adjoint curves, etc.

I also cooperated with my colleague Wolfgang Schreiner on the topic of distributed computation for the analysis of algebraic curves; ref. [33, 34, 35, 36].

Various

During my research stay at NY University in 2003 I cooperated with Bhubaneswar Mishra and his group on the application of computer algebra to the creation of models for biological systems; ref. [47, 51]. I also cooperated in a project for applying computer algebra to problems in pattern recognition [73]. And 3 years ago, after having participated several times in the yearly "Austrian Ludwig-Wittgenstein-Symposium (ALWS)", I presented my understanding of the mathematical notion of infinity in a lecture at ALWS 2018; ref. [87].

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