A life with Algebra

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Conference for my 70^{th} birthday, Roma 9 June 2011

Laurea Roma, 1963, Ph. D. Chicago 1966

I was a student of HERSTEIN, Chicago 1987

My work

I count 80 published research papers, plus 5 preprints of present research, 3 books, 5 lecture notes, 14 communications or seminars for a total of 107

Non commutative Algebra

I started with *Non commutative Algebra*.
In this field I have written 25 papers and one book, plus 5 papers and a lecture note on *quantum groups*

Non commutative Algebra

In 1964–65 there was a special year on Algebra in Chicago, with Amitsur, Paul Cohn, Jacobson and many others, there I started to learn *Rings with polynomial identities*

3 theorems impressed me most

1. the Amitsur–Levitzki identitity $\sum_{\sigma\in S_{2n}} sign(\sigma)x_{\sigma(1)}\cdots x_{\sigma(2n)} = 0$ for $n\times n$ matrices.
2. The Theorem of Amitsur that the free algebra modulo the identities of $n\times n$ matrices is a domain order in a division algebra of order n^2 over its center.
3. The Theorem of Kaplansky that primitive PI algebras are finite matrices.

My Ph. D. program

These Theorems suggested the possibility of doing some kind of *non–commutative affine algebraic geometry* where points have coordinates *matrices* and equations are non–commutative.

A first encounter with *invariants*

In developing this program I met naturally *invariants of matrices* as follows. If X is a 2×2 matrix the Cayley–Hamilton theorem gives

$$X^2 - tr(X)X + \det(X) = 0$$

If Y is another matrix you get thus

$$[X^2, Y] = tr(X)[X, Y] \implies Tr(X) = [X^2, Y][X, Y]^{-1}$$

the trace is a non–commutative rational function! So is the determinant!

$$\det(X) = [X^2 Y, XY][Y, XY]^{-1}$$

A first encounter with *invariants*

So, Amitsur had introduced the division algebra $D(m; n)$ of *rational functions* in m–matrix variables ($m \geq 2$) and I discovered that its center is the field of invariants under conjugation of the space of m–tuples of matrices. In order to do this I introduced the *ring of generic matrices*.

Hilbert's 17^{th} problem, a non commutative version

I took serioulsy working with rational functions of matrices so I asked if a symmetric positive rational function is always a sum of functions $F(X)F(X)^t$. With Murray Schacher we proved a weaker result, and only recently it was shown that the stronger conjecture

is false. 

Il calcolo letterale

I took serioulsy working with rational functions of matrices but we really do not have a satisfactory theory of normal forms as for commutative variables, the only complete case is for 2×2 matrices, which I proved using invariants and standard monomials.

My paper Computing with 2×2 matrices was rejected by Inventiones.

A first encounter with *invariants*

At that time *Invariant Theory* was knowing a big revival and people were reading again the fundamental papers of Hilbert.

Mike Artin

Mike Artin read my thesis and developed a beautiful characterization of Azumaya algebras by PI theory, at the same time he used Hilbert's invariant theory to study semisimple representations of algebras, since they correspond to *closed orbits*.

Mike Artin

also asked if invariants om m–tuples of matrices were generated by *traces of monomials* i.e. elements $tr(X_{i_1}X_{i_2}\dots X_{i_m})$,

we did not realize that

there was a paper by Sibirskii (1968) and a large literature by authors working on continuum mechanics on this topic (Rivlin, Spencer, Smith).

I never understood if one could consider this statement known to, say, Gordan!!

Invariants of matrices

nevertheless I wrote a big paper on Invariants of matrices and discovered that all relations could be derived from the Cayley–Hamilton identity. This was proved independently by Razmyslov who also proved the best estimates for bounding the degrees of the generators of invariants.

Invariants of matrices

It took me several years to fully understand that,

when computing with matrices, the operation of trace should be included!

in 1987 I presented to Herstein (the last time I saw him before his death in 1988) one of my best results in non commutative algebra:

"A formal inverse to the Cayley–Hamilton Theorem"

Positive characteristic

I started to see if, by pure arguments of non commutative algebra one could develop the Theory in all characteristics, where a priori it was unclear if Hilbert's theory could apply. In particular I showed that the algebra of invariants of matrices is finitely generated (now a consequence of general theory).
Finite generation of invariants is *Hilbert's* 14^{th} *problem*

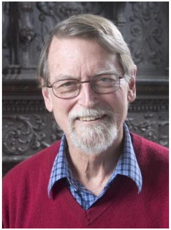
Hilbert's 14^{th} problem

Is the ring of invariants of an algebraic group acting on a polynomial ring always finitely generated?
No, a counterexample was constructed by Masayoshi Nagata in 1959. 

Geometric invariant theory

(or GIT) is a method for constructing quotients by group actions in algebraic geometry, used to construct moduli spaces. It was developed by David Mumford in 1965, using ideas from the paper

(Hilbert 1893) in classical invariant theory.



Mumford's conjecture

In order to apply the theory of Hilbert in positive characteristic Nagata and Mumford understood that the basic property is *geometric reductivity* so Mumford conjectured that *reductive groups (as for instance the general linear group) are geometrically reductive*

Weyl–Schur duality

I discovered Weyl's book, *the classical groups* and the many facets of the interplay between invariants and representations, as the Theory of Schur, so I thought that one could try to prove Mumford's conjecture for the linear group $GL(V)$ by showing that the group algebra of the symmetric group S_∞ in the limit of the actions of S_m on $V^{\otimes m}$ is in some weak sense *semisimple* (no nil ideals).

Formanek (1976) was visiting Pisa

and told be that he had proved that $F[S_\infty]$ has no nil ideals (not what I wanted), so we adapted his theorem and obtained Mumford's conjecture for classical groups. The general Theorem was obtained at the same time by structure Theory by Haboush.

Characteristic free invariant theory

The time was ripe to try to understand how much of Weyl's book would carry over to finite characteristic. Several inputs came in this direction and also my collaboration with Corrado De Concini started on this problem. On one hand I listened to a talk by Giancarlo Rota who had just developed the *Theory of double standard tableaux*, then we discovered a paper of Igusa on projective normality of the Grassmann variety via ideas on tableaux

due to Hodge. 

Characteristic free invariant theory

With Corrado we developed a fair amount of this theory using a mix of geometry and combinatorics. Then this theory led us to a deep exchange with Seshadri and his school. Seshadri was generalizing the Theory of Hodge from a completely different (more geometric) viewpoint.

Characteristic free invariant theory

In a different direction this led us to study a general theory of invariant ideals (generalizing determinantal ideals) with Eisenbud, this was a germ for a very long different trip into *enumerative geometry*

Inequalities

My last paper, properly on invariant theory, was with Gerald Schwarz,

this put us in an interesting (but puzzling) contact with the physicists who were trying to understand *grand unification* of forces.

Matrices and singularities

before plunging into *enumerative geometry* I should recall the very fruitful collaboration with Hanspeter Kraft and the deep theory of singularities for closures of conjugacy classes that we developed, by a mix of geometry, invariant theory and representation theory.

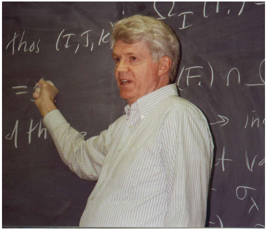
Those were exciting years.

Hilbert's 15^{th} problem and Enumerative geometry

asks for a Rigorous foundation of Schubert's enumerative calculus, we were puzzled when we learned that *There are 3264 conics tangent to 5 generic conics* Chasles 1864. I remember listening to a lecture by Israel Vaisencher who explained the beautiful theory of *complete conics* which lies behind this computation.

Hilbert's 15^{th} problem

More or less at the same time Bill Fulton gave some lectures in Cortona on the topic and I recalled a weird conversation with George Kempf on complete linear systems.



Hilbert's 15^{th} problem

Maybe Corrado remembers different inputs, anyway we started to try to understand if there was a general Theory behind.

Hilbert's 15^{th} problem

We discovered papers by Semple and Tyrell who did very explicit matrix computations.

Equivariant embeddings

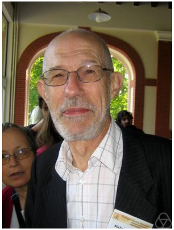
At the same time it was available the Theory of *torus embeddings* on one hand, on the other Luna and Vust had started a very general Theory.

Equivariant embeddings

Finally Demazure had developed a theory of degenerations of symmetric spaces for the case of classical groups.

Wonderful embeddings

With Corrado we were able to generalize the methods of Semple and Tyrell and develop a general construction of a *wonderful model* for symmetric varieties which included also Demazure's models. We then were able to transform Kleiman's theory into a general theory of *Halphen rings*.



Springer's Theory

The 80's were years in which deep connections between representation theory and geometry were discovered and it was natural to look at some of these aspects, in particular with Corrado we solved a beautiful conjecture of Kraft and then George Lusztig visited Roma for a year (1987?), we wrote a very difficult paper together with Corrado, at times we despaired to be able to finish it and I think it was only a very odd combination of rather different ways of thinking Mathematics which allowed us to be successful.

Quantum groups

I was not eager to work on Quantum groups but was dragged by Corrado who had written an important paper with Victor Kac. We wrote some very complicated and technically extremely heavy papers, and I am not sure if anybody read them! Then we tried to understand the point of view of Drinfeld and discovered the beautiful theory of Kohno–Drinfeld and the connection,

via the work of Vassiliev and Kontsevich, with knot theory.

Knots and braids

With the experience on wonderful models we developed a very combinatorial and geometric theory aimed at replacing configurations of hyperplanes with normal crossing singularities. We then applied the Theory to the ideas of Drinfeld and Kontsevich on the Kniznik–Zomolodchikov equation and the universal Vassiliev invariant.

Knots and braids

Later on Corrado started a fruitful collaboration with Salvetti and again dragged me into the game. We wrote a mysterious paper on the equation of degree 6, a *tour de force* in homotopy theory and obstruction theory (something I missed to learn as a student in Chicago).

$n!$

Here I acted mostly as a catalyzer

hyperplane arrangements, polytopes and box–splines

we arrived to this naturally from our theory of wonderful models trying to understand a discussion with Michele Vergne. It was very curious to enter in the world of splines and numerical analysis

Index and splines, The *REAL SURPRISE*

was to discover the applications to index of transversally elliptic operators and equivariant K–theory, the theory of Dahmen–Micchelli from numerical analysis was the *perfect fit* for index theory

Murphy's law or a *Variation of Peter Principle*

"In Research Every (ambitious) Scientist Tends to Rise to His Level of Incompetence."

Non linear PDE's

My last adventure has been in PDE, and the responsible is my daugther Michela who started to ask me a seemingly innocuous problem on Euclidean Geometry and then dragged me into the mysteries of KAM theory.

The culprit

My papers

1 Sopra un teorema di Goldie riguardante la struttura degli anelli primi con condizioni di massimo.
Atti Accad. Naz. Lincei (8) 34 (1963)

2 Sugli anelli principali ed un teorema di Goldie.
Atti Accad.Naz. Lincei (8) 36 (1964)

3 (with L. Small) On a theorem of Goldie.
Journal of Algebra v. 2 3, pp.80-84 (1965)

My papers

4 Su un teorema di Faith-Utumi.
Rend. Mat. Pura e Appl. (5) 24 (1965)

5 (with S. A. Amitsur) Jacobson rings and Hilbert algebras with polynomial identities.
Ann. Mat. Pura e Appl. (4) 71 (1966)

6 The Burnside problem.
Journal of Algebra 4 3, pp. 421-425 (1966)

My papers

7 Non commutative Jacobson rings. Ann. Scuola Norm. Sup. Pisa (3) 21 (1967)

8 Non commutative affine rings. Atti Accad. Naz. Lincei Memorie (8) 8 (1967)

9 (with L. Small) Endomorphism rings of modules over PI-algebras. Mathematics Zeit. 106 (1968)

My papers

10 Sugli anelli non commutativi zero dimensionale con identitĹ polinomiale.
Rend. Circ. Mat. Palermo (2) 17, pp. 5-12 (1968)

11 Sulle identitĹ delle algebre semplici.
Rend. Circ. Mat. Palermo (2) 17 (1968)

12 A non commutative Hilbert Nullstellensatz.
Rend. Mat. e appl. (5) 25 (1966)

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Ring theory. Acad.Press,pp. 287-295 (1972)

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Symposia Mathematica v. VIII Acad. Press, pp. 295-308 (1972).

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Journal of Algebra v.22 2, pp. 309-315 (1972)

My papers

16 Rings with polynomial identities.
Pure and Applied Mathematics v. 17, M.Dekker (1973)

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Symposia Mathematics v.XI Acad. Press, pp. 143-159 (1973)

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Israel Journal of Mathematics 19 (1974)

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Journal of Algebra 36 1, pp. 128-150 (1975)

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Advances in Mathematics 19 3, pp. 292-305 (1976)

21 Central polynomials and finite dimensional representations of rings.
Atas Esc. Algebra I.M.P.A. pp. 2-31 (1973)

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22 (with M. Schacher) A non commutative real Nullstellensatz and Hilbert's 17th problem.
Ann. of Mathematics (2) 104 (1976)

23 The invariants of $n?n$ matrices.
Bull. Am. Mathematics Soc. 82 6, pp. 891-892 (1976)

24 The invariant theory of $n?n$ matrices.
Advances in Mathematics 19 (1976)

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25 (with C. De Concini) A characteristic free approach to invariant theory.
Advances in Mathematics 21 (1976)

26 Les base de Hodge dans la theorie des invariants.
Séminaire d'algébre P. Dubreil. Lecture Notesin Mathematics 641, Springer (1978)

27 Positive symmetric functions.
Advances in Mathematics 29 2, pp.219-225(1978)

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28 (with H. Kraft) Classi coniugate in GL(n,C).
Rend. Sem. Mat. Padova 59. pp.209-222 (1978)

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Inv.Math. 53, pp.227-247 (1979)

30 Trace identities and standard diagrams.
Ring theory. Lecture notes in Pure and Appl. Mathematics 51 M. Dekker, pp. 191-218 (1979)

My papers

31 Sulla formula di Gordan Capelli. Univ. Ferrara (1979)

32 Invariante. Voce Enciclopedia, VII. Einaudi pp.891-949 (1979)

33 Young diagrams, standard monomials and invariant theory. Proc. I.C.M. Helsinki. Acad. Sci. Finnica, pp.537-542(1980)

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34 (with C. De Concini and D.Eisenbud) Young diagrams and determinantal varieties.
Inv. Mathematicae 56, pp.129-165 (1980)

35 Algebre cicliche e problema di Luroth.
B.U.M.I. (5) 18-A, pp. 1-10 (1981).

36 (with H. Kraft) Minimal singularities in GL_n.
Inv. Mathematicae 62, pp.503-515 (1981)

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Inv. Mathematicae 64, 203-219 (1981)

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Astérisque 91 (1982)

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Commentarii Mathematici Helvetici 57, pp. 539-602 (1982)

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Brandeis Lecture Notes 1, (1982)

41 (with C. De Concini) Complete Symmetric Varieties.
C.I.M.E. 1982, Springer Lecture Notes 997, pp. 1-44 (1983)

42 Computing with 2?2 matrices.
Journal of Algebra, v.87,n. 2, 342-359 (1984)

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Advanced Studies in Pure Mathematics 6, Algebraic groups and related topics pp.481-513 (1985)

44 (with G. Schwarz) Inequalities defining orbit spaces.
Inv. Math.v. 81, 3,pp. 539-554 (1985)

45 (with G. Schwarz) The geometry of orbit spaces and gauge symmetry breaking in supersymmetric gauge theories.
Physics Letters B (1985)

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Duke Mathematical Journal 58, pp. 585-594, (1986)

47 A formal inverse to the Cayley Hamilton theorem.
Journal of Algebra 107 1, pp.63-74 (1987).

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Algebraic groups Utrecht 1986, Springer Lecture Notes 1271,pp.143-175 (1987)

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Ann. Inst. Fourier T. XXXVII 4, pp. 161-166 (1987).

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Banach Center Publications, v. 20, pp. 365-372 (1988)

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Comm.Mathematics Helvetici 63, pp. 337-413 (1988)

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Advances in Mathematics, v. 69 1,pp. 93-108 (1988)

53 (with C. De Concini, G. Lusztig) Homology of the zero set of a nilpotent vector field on a flag manifold.
Journal of A.M.S.,v. 1, pp. 15-34 (1988)

54 Imagination and the building of Mathematics,
Lexicon Philosophicum 3,pp.1-4 (1988)

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55 L'immaginario matematico, problemi classici e congetture.
Fondamenti 10, pp. 77-93 (1988)

56 (with E. Arbarello, C. De Concini, V. Kac) Moduli Spaces of Curves and Representation Theory.
Comm. Math.Phys. 117, pp. 1-36 (1988)

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Algebraic K-Theory: Connections with Geometry and Topology.
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Astérisque 173-74, pp. 271-279 (1989)

59 (with L. Le Bruyn) Semisimple representations of quivers.
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61 The toric variety associated to Weyl chambers Mots, Hermes (1990)

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Advances in Mathematics, v. 82, n. 1,pp.1-34 (1990)

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Operator algebras, Unitary Representations, Enveloping Algebras, and Invariant Theory. Progress in Mathematics Vol. 92, BirkhŁuser, pp. 219-262 (1990)

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