Nick Trefethen
Oxford Mathematical Institute

Who invented the great numerical algorithms?

Slides available at my web site:
www.maths.ox.ac.uk/~trefethen

A discussion over coffee.

Ivory tower or coal face?

SOME MAJOR DEVELOPMENTS IN SCIENTIFIC COMPUTING

(29 of them)

Before 1940

Newton's method
least-squares fitting
Gaussian elimination
Gauss quadrature
Adams formulae
Runge-Kutta formulae
finite differences

1940-1970

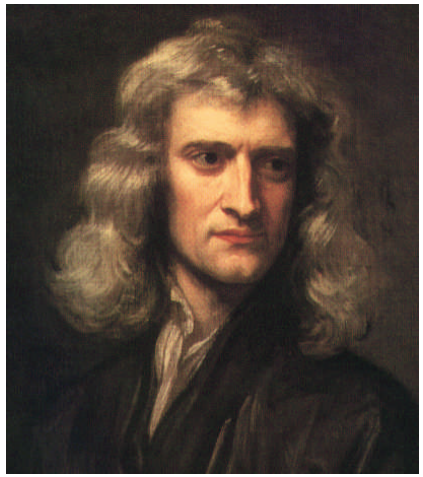
floating-point arithmetic
splines
Monte Carlo methods
simplex algorithm
conjugate gradients & Lanczos
Fortran
stiff ODE solvers
finite elements
orthogonal linear algebra
QR algorithm
Fast Fourier Transform
quasi-Newton iterations

1970-2000

preconditioning
spectral methods
MATLAB
multigrid methods
IEEE arithmetic
nonsymmetric Krylov iterations
interior point methods
fast multipole methods
wavelets
automatic differentiation

Before 1940

Newton's Method for nonlinear eqs.



Heron, al-Tusi 12c, Al Kashi 15c, Viète 1600, Briggs 1633…

Isaac Newton 1642-1727
Mathematician and physicist
Trinity College, Cambridge, 1661-1696
(BA 1665, Fellow 1667,
Lucasian Professor of Mathematics 1669)
De analysi per aequationes numero terminorum infinitas **1669** (published 1711)
After 1696, Master of the Mint

Joseph Raphson 1648-1715
Mathematician at Jesus College, Cambridge
Analysis Aequationum universalis **1690**
Raphson's formulation was better than Newton's ("plus simple" - Lagrange 1798)
FRS 1691, M.A. 1692
Supporter of Newton in the calculus wars—*History of Fluxions,* 1715

Thomas Simpson 1710-1761
1740: *Essays on Several Curious and Useful Subjects…*
1743-1761: Royal Military Academy, Woolwich
Important!—first to treat non-polynomial equations, first to treat systems of eqs.

Least-squares fitting

Carl Friedrich Gauss 1777-1855

Mathematics, astronomy, geodesy, magnetism

1792-1795: Braunschweig Collegium Carolinum

1795, but not published until 1809
(→ big fight with Legendre)

(During this time as a teenager in Braunschweig he also discovered the binomial theorem, quadratic reciprocity, arithmetic-geometric mean…)

1807-1855: University of Göttingen

Adrien-Marie Legendre 1752-1833

1791-1833: Académie des Sciences, Paris

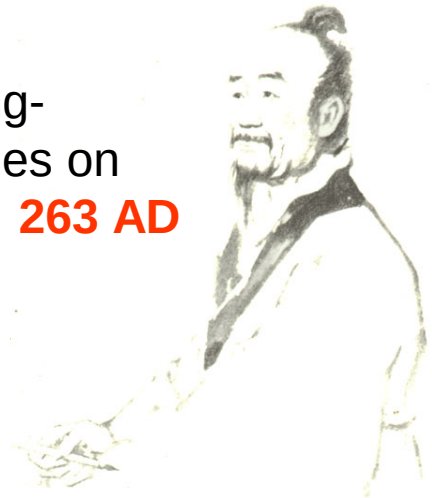
1805 "Sur la méthode des moindres carrés"

applications to orbits of comets

Gaussian elimination for linear systems of eqs.

Liu Hui c. 220 – c. 280

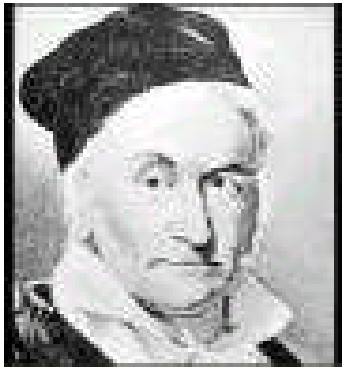
Chinese mathematician discusses already long-established elimination method in commentaries on *The Nine Chapters on the Mathematical Art* **263 AD**



Cardano (154), Peletier (1554), Buteo (1560), Gosselin (1577), ... **Newton** 1720...

Joseph Lagrange 1736-1813

Symmetric quadratic forms **1759**



Carl Friedrich Gauss 1777-1855

Symmetric systems, normal eqs. **1809**

Carl Gustaf Jacob Jacobi 1804-1851

1826-1844: U. of Königsberg
General systems **1857** (posthumous)

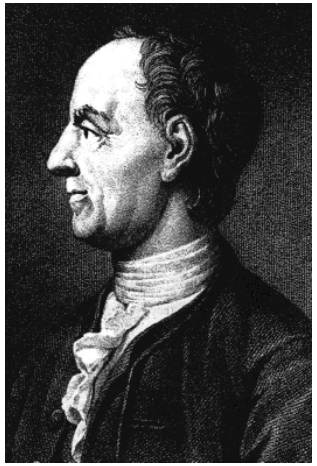
Gauss quadrature for numerical integration

Carl Friedrich Gauss 1777-1855

"Methodus nova integralium valores per approximationem inveniendi", *Comment. Soc. Reg. Sient. Götting. Recent.* **1814**

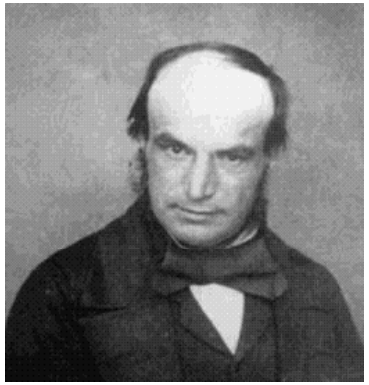
Gauss did it by continued fractions and hypergeometric functions. Today's. more familiar interpretation via orthogonal polynomials was developed by **Jacobi** (1804-1851) in **1826**.

Adams formulae for ODEs



Leonhard Euler 1707-1783

1727-1741: St. Petersburg Academy
1768: *Institutiones Calculi Integralis*
1741-1766: Berlin Academy
1766-1783: St. Petersburg Academy



John Couch Adams 1819-1892

astronomer and mathematician; predicted existence of Neptune
1839-1892: Cambridge U.—Senior Wrangler 1843
1855?: work on multistep methods
1858-1892: Lowndean Professor of Astronomy and Geometry
Declined both knighthood and Astronomer Royal post

Francis Bashforth 1819-1912

influential ballistics expert
1840-1843: Cambridge U.—Second Wrangler 1843
1864-1872: Prof of Applied Maths, Royal Military Acad, Woolwich
1883: paper on Adams methods (fcalculating shapes of drops).

Runge-Kutta formulae for ODEs

Like Adams formulas, these are a generalization of Euler.
Coriolis 1830s had some 2nd-order formulas. Then —

Carl David Tolme Runge 1856-1927

1895 *Math. Anal.*, "Über die numerische Auflösung…"

Karl Heun 1859-1929

PhD. 1881 Göttingen, Prof. Theoretical Mechanics Karlsruhe
1900 *Zeit. Math. Phys.*, "Neue Methode zur approximativen Integration…"

Martin Wilhelm Kutta 1867-1944

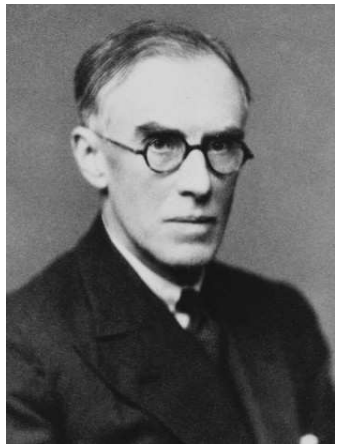
1901 general R-K theory, *Zeit. Math. Phys.*, "Beitrag zur näherungsweisen Integration…"

Also Nyström 1925, Moulton 1926, von Mises 1930, and in the computer era, John Butcher.

Finite differences for PDEs

Lewis Fry Richardson 1881-1953
Richard Southwell 1888-1970

Richard Courant 1888-1972
Kurt Friedrichs 1901-1982
Hans Lewy 1904-1988



John von Neumann 1903-1957
Peter Lax ≈1926-

1940 – 1970

Floating point arithmetic

Konrad Zuse 1910-1995

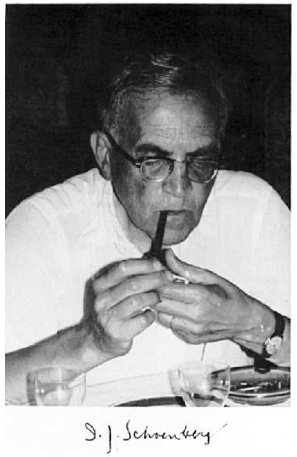
Civil engineer by training
Worked on computers beginning in 1934
“Zuse Apparatebau” company founded in Berlin 1940
Z1 computer, completed in Berlin **1936**
much further developed: Z3 computer, 1941
22-bit floating point binary arithmetic
(14 bits for fraction, 8 for exponent)
1Hz, programmable, stored data but not program
Machine was destroyed in 1945 air raids

Zuse was also an artist.

Splines

Paul de Faget de Casteljau 1930-
French mathematician/physicist
1958-1992: Citroën; unpublished work in **1958**

Pierre Bezier 1910-1999
1933-1975: engineer at Renault
1960: beginning of CADCAM work, Bezier curves



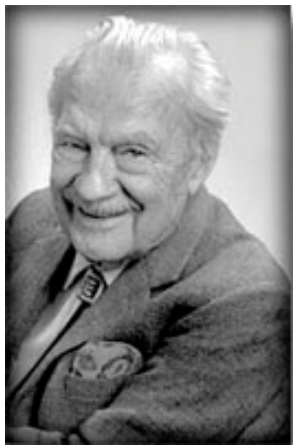
Isaac Jacob ("Iso") Schoenberg 1903-1990
Born in Romania (Landau's son-in-law). To USA in 1930.
Chicago, Harvard, Princeton, Swarthmore, Colby…
1941-1966: University of Pennsylvania
1943-1945: Army Ballistic Research Laboratory
1946: two papers on splines
1966-1973: U. of Wisconsin

Carl de Boor 1937-
Born in what became East Germany. To USA in 1959.
1960-1964: General Motors (grad student intern)
1962: first of many publications on splines
Purdue, Michigan…
1972- U. of Wisconsin

Monte Carlo simulation methods

Stanislaw Ulam 1909-1984
Born in Poland, to USA in 1935, pure mathematician by training
Princeton, Harvard, Wisconsin, USC
1943-1965: Los Alamos (key figure in hydrogen bomb)
1965-1984: Dept. of Mathematics, U. of Colorado

John von Neumann 1903-1957
Born in Hungary, to USA in 1930, pure mathematician by training
Manhattan Project, Los Alamos, Atomic Energy Comm.
1930-1957: Princeton U. & Inst. Advanced Study



Nicholas Metropolis 1915-1999
Greek-American, physicist by training
Oscillated between U. of Chicago and Los Alamos
1932, 1941, 1945, 1948, 1957, 1965

1947: Invention by Ulam & von N. for applications in neutron diffusion

1949: publication of “The Monte-Carlo Method” by Ulam & Metropolis

Also Fermi, Richtmyer, …

Simplex algorithm for linear programming

Leonid Kantorovich 1912-1986

1934-1960 Professor of Mathematics, Leningrad State U.
1939: *Mathematical Methods in the Organization and Planning of Production*
1975: Nobel Prize in Economics

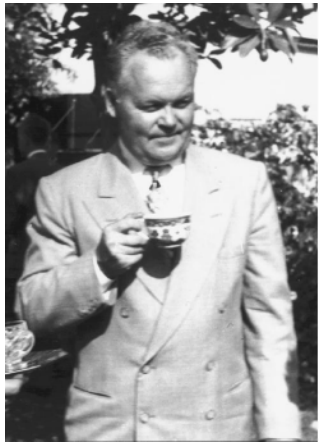
George Dantzig 1914-2005

1941-1946: Head of Combat Analysis Branch, US Air Force Statistical Control
1944: War Department Exceptional Civilian Service Medal
1946: receives PhD at UC Berkeley
1947: Simplex algorithm
1948: Koopmans coins expression “linear programming”
1947-1952: Mathematical Advisor, US Defense Department
1952-1960: RAND Corporation
1960-1966: UC Berkeley
1966-2005 : Stanford U.

Conjugate gradient and Lanczos iterations

Cornelius Lanczos 1893-1974

Born in Hungary: Fejér, Einstein, …
1931-1949: Purdue and Boeing
1949-1952: Inst. Numer. Anal., NBS, UCLA
1952-1972: Dublin Inst. Adv. Study, Ireland



Magnus Hestenes 1906-1991

late 1920s-1947: University of Chicago
1947-1973: UCLA
1949-1952: Inst. Numer. Anal., NBS, UCLA

Eduard Stiefel 1909-1978

eminent in geometry and physics as well as computation
Swiss Federal Institute of Technology

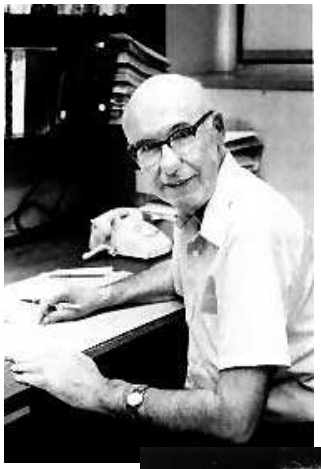
1952: landmark papers by Lanczos and Hestenes & Stiefel

Fortran

John Backus 1924-2007

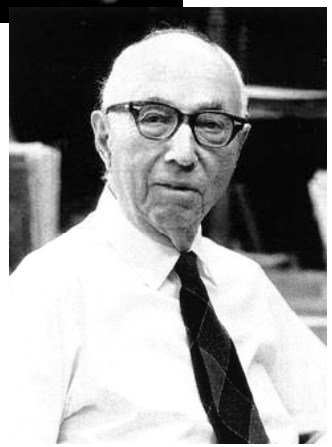
grew up in Delaware, USA
a poor student; disorganized early career
with some years in US Army
1949: AB in Mathematics, Columbia U.
1950-1991 IBM
1954: first paper about Fortran; programming team is built
1957: Fortran released by IBM
1975: National Medal of Science
1977: Turing Award

Stiff ODE solvers



Charles Francis Curtiss 1921-2007

1938-2007: Dept. Chemistry, U. Wisconsin (student, professor, emeritus) interrupted by govt. work in WWII



Joseph Oakland Hirschfelder 1911-1990

1937-1981: Dept. Chemistry, U. Wisconsin

1943-1946: group leader, Los Alamos

1946: Chief Phenomenologist, Bikini Bomb Test

1952: “Integration of stiff equations” with Curtiss, *PNAS*

Nat. Academy of Science; Nat. Medal of Science 1976

Germund Dahlquist 1925-2005

Royal Institute of Technology, Sweden

1963: “A special stability problem for linear multistep methods…”, *BIT*

C. Willliam Gear 1935-

1956-1990: U. of Illinois

1965, 1966 and others: visits to Argonne National Lab

1967: first paper on stiff solvers

1971: *Numerical Initial-Value Problems in ODEs*

1990-2000: NEC

Finite elements for PDE

Richard Courant 1888-1972
1943 ”Variational methods…”
(landmark paper, but attracted no notice till later)

Finite elements grew out of the aeronautical engineering of the 1950s.
Additional names include Martin, Turner, Irons, Kelsey, Topp.

John H. Argyris 1913-2004

Born in Greece; much of career at U. of Stuttgart, Germany
1960 *Energy Theorems and Structural Analysis*

Ray W. Clough 1920-
1950s: Boeing?
1960 “The finite element in plane stress analysis”
1970- : Professor of Structural Engineering, UC Berkeley
eminent authority in earthquake engineering
1994: National Medal of Science

Other key early figures include Babushka & Zienkewicz

Orthogonal linear algebra

Wallace Givens 1911-1993

1950s and1960s: Argonne National Laboratory
Later, professor at U. of Tennessee
1958: introduction of Givens rotations

Alston Householder 1904-1993

1946-1969: Oak Ridge National Laboratory
1958: 4-page paper introducing Householder reflections
1964: *The Theory of Matrices in Numerical Analysis*

Gene Golub 1932-2007

Professor at Stanford from mid-1960s.
Key early contributions to many topics including SVD and least-squares
1965: "Numerical methods for solving linear least-squares problems"

QR algorithm for matrix eigenvalues

Heinz Rutishauser 1918-1970
ETH Zurich
1958 LR algorithm

V. N. Kublanovskaya 1920-

Steklov Institute of Mathematics, St. Petersburg
1961 “On some algorithms for the solution of the… eigenvalue problem”

J. G. F. Francis 1934-

Late 1950s: National Research Development Corporation, London
Assistant of Christopher Strachey
1961 ”The QR transformation…” I & II, *Computer J.*

James H. Wilkinson 1919-1986

Undergraduate in Mathematics at Cambridge
1940-1946: war work related to numerics and ballistics
1946: Turing’s assistant on Pilot Ace Computer
1946-1986: National Physical Laboratory
1965: *The Algebraic Eigenvalue Problem*
1969: FRS
1970: Turing Award

Fast Fourier Transform

Gauss 1805 (unpublished) age 28, 2 years before Fourier!
Runge 1903 Yates 1937 Stumpff 1939
Thomas 1948 Danielson & Lanczos 1942 Good 1958
Wheeler… Gentleman…

Modern birth due to Tukey & Garwin & Sande in 1963, leading to **1965** Cooley-Tukey paper in *Mathematics of Computation*

John Tukey 1915-2000

Princeton University, founder of Statistics Dept.
(also Bell Labs and consultant to U.S., govt. & industry)

Richard Garwin 1928-

Watson Scientific Lab, Columbia U. (later at TJ Watson)
Well known physicist with major involvement in H-bomb
FFT motivation related to detection of Soviet nuclear tests.

James W. Cooley 1926-

IBM TJ Watson Research Center. U. Rhode Island.

Quasi-Newton iterations for optimization

The field was launched between 1959 and 1970.

William Davidon 1927-

1954 PhD in Physics, U. Chicago

1959: “variable metric” report at Argonne National Lab.

(It was finally published in 1991, first issue of *SIOPT*)

1961-1991: Prof. of Physics and Maths, Haverford Coll

Michael Powell 1936-

1959-1976 Harwell A.E.R.E.

1976- DAMTP, U. of Cambridge

1983 FRS

Charles Broyden 1933-2011

1955-1965: English Electric

1965: “good” and “bad” Broyden methods

1967-1986 U. of Essex

1990-2003 U. of Bologna

Roger Fletcher 1939-

1969-1973 Harwell A.E.R.E…. U. of Leeds

1963: Davidon-Fletcher-Powell paper

1971-2005 U. of Dundee

2003 FRS

1970 – 2000

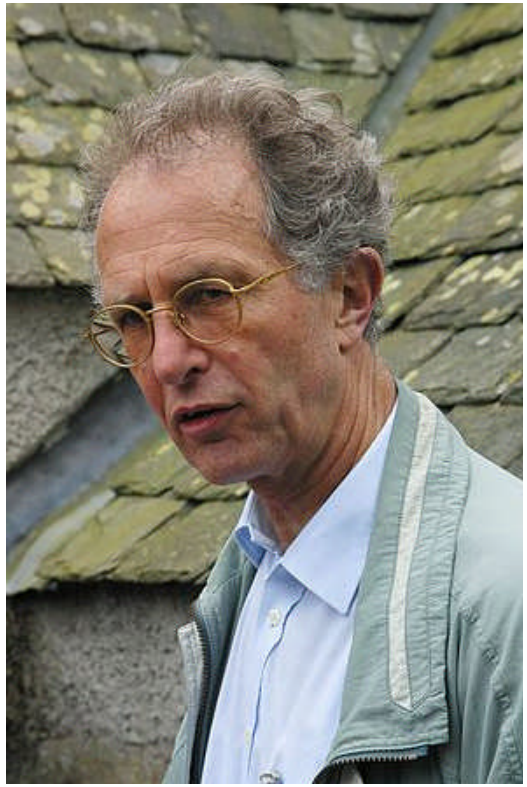
Preconditioning for iterative solution of linear systems

Many people contributed to the discovery of preconditioning, including Evans, Varga, Wachspress, Golub, Concus and O'Leary. Yet there was a particular preconditioner that made the idea famous and is still one of the most effective today: incomplete factorization.

Henk van der Vorst 1944-

1970s-2005: Universities of Delft and Utrecht, Netherlands
1977: original paper on incomplete LU factorization
2006: knighted (Ridder in de Orde van de Nederlandse Leeuw)

one of van der Vorst's watercolors



Spectral methods for PDE

Important work in 1950s and 1960s by Lanczos, Clenshaw, Elliott, Fox and Mason et al.
Contributions also from Kreiss and Oliger and others.
These methods were made famous by:

Steve Orszag 1943-

1966?-1984: Applied Mathematics, MIT
1971: series of major papers on spectral methods in fluid mechanics
(Orszag coined the phrase “spectral methods”)
1984-1998: Prof. of Applied Mathematics, Princeton U.
1998- Prof. of Mathematics, Yale U.
Orszag's son Peter is currently Director of U.S. Office of Management & Budget

David Gottlieb 1944-2008

From Israel; came to USA in 1972
1972-1976: MIT and ICASE (NASA Langley)
1977: spectral methods book by D.G. and S.A.O.
1976-1985: Dept. of Applied Mathematics, Tel-Aviv U.
1985-2008: Prof. of Applied Mathematics, Brown U.

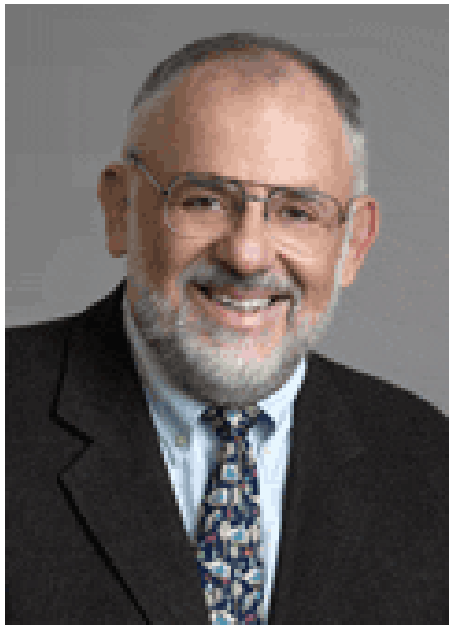
MATLAB

Cleve Moler 1939-

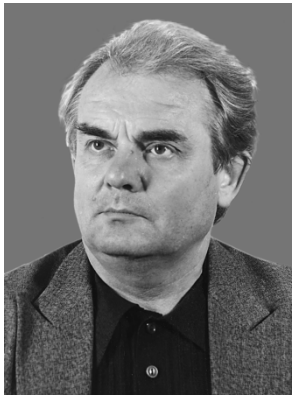
Author of EISPACK, LINPACK, four textbooks

high school Utah, BA Caltech, PhD Stanford
1965-1973: U. of Michigan
1973-1984: U. of New Mexico
strong links with Argonne National Laboratory
1977: creation of first version of Matlab
1984: Jack Little founds MathWorks
1985: first Matlab sale (Feb. 10)
1984-1989: Moler employed at Intel and Ardent
1989: joins MathWorks as Chief Scientist

N.B.: Matlab is 60% as old as Fortran!

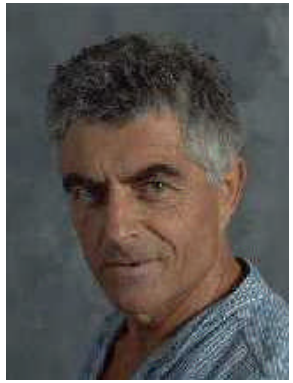


Multigrid Methods for PDE



R. P. Fedorenko 1930-2009

1961: invention of 2-grid and later multigrid method.
This work extended also by N. S. Bakhvalov, 1966.



Achi Brandt 1938-

1963- : Applied Mathematics, Weizmann Institute, Israel
1973: first paper on multigrid methods
1977: 57-page paper in *Mathematics of Computation*

Wolfgang Hackbusch 1948-

1976: Independent rediscovery of multigrid
1982- : Professor of Applied Maths., U. Kiel
199?-: director of Max-Planck Inst. In Leipzig

IEEE arithmetic

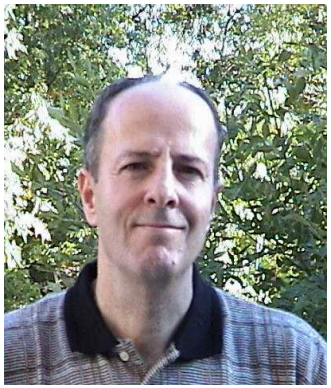
William ("Velvel") Kahan 1933-

late 1960s- : Dept. of Mathematics, UC Berkeley
1977: the draft IEEE floating-point standard released
1985: adoption of the standard after much wrangling
1989: Turing Award

Nonsymmetric Krylov iterations for large matrix problems

Many contributors including Arnoldi, Elman, Schultz, Freund, Gutknecht.

P. K. W. Vinsome 19??-
Shell Petroleum Co.
1976 paper on Orthomin



Youcef **Saad** 1950-
Yale University, U. of Minnesota
1986: GMRES paper with Schultz

Henk van der Vorst 1944-
Professor of Mathematics at U. of Utrecht
1986: BiCGSTAB paper—most cited maths paper in 1990s
1996: Jacobi-Davidson paper with Sleijpen

Dan Sorensen 1947-
Argonne National Laboratory
Rice U.
1992: implicitly restarted Arnoldi
1996: *ARPACK User's Guide* with Lehoucq and Yang

Interior Point Methods for optimization

Earlier work by Carroll (1961) and Khachiyan (1979) and also by Fiacco & McCormick (1968), Margaret Wright (1976) and others on barrier methods.

Narendra Karmarkar 1957-

1978: BTech in Elect. Engr., IIT Bombay
1982?: PhD, U. C. Berkeley
1983-? AT&T Bell Labs
1984 :"A new polynomial time algorithm for linear programming," *Combinatorica*
Now lives in India

Fast Multipole Method for *N*-body simulation and more

Related earlier work by Barnes & Hut & others

Vladimir Rokhlin 1952–

Born in USSR; to USA in late 1970s
1976-1985: Exxon Production Research Co.
1983: PhD in Applied Mathematics, Rice U.
1985 "Rapid solution of integral equations…"
1985- Prof. of Computer Science, Yale U.

Leslie Greengard 1958–

From Boston, New York, New Haven
1987 M.D. and Ph.D. (Comp. Sci.) Yale U.
1987 "A fast algorithm for particle simulations", with Rokhlin
1989- Prof. of Mathematics, Courant Inst., NYU
Currently serving as Director.

Both VR and LG have eminent fathers.

Wavelets

Jean Morlet 1931-2007

Geophysicist at Elf Aquitaine / Oric

Work beginning 1975 leads to major publication **1982**

Also Alex Grossmann 1984, Stephane Mallat 1989,
Yves Meyer 1986

Ingrid Daubechies 1954-

Training in physics and mathematics
From Belgium; came to USA in 1987
1975-1987: Vrije Universiteit Brussel
1987-1994: AT&T Bell Labs; Rutgers U.
Big change in 1980s physics $\rightarrow$ mathematics
1988: “Orthonormal bases of compactly supported wavelets”
1993- : Princeton U.
MacArthur Prize and many others

Automatic differentiation

Many antecedents including Beda (1959), Wengert (1964), Speelpenning (1980), Kedem (1980), Rall (1981), Baur and Strassen (1984)… more recently Bischof & Carle (ADIFOR, 1991) and many others.

A central figure in the modern rebirth of these ideas (in particular the use of “reverse mode”) has been

Andreas Griewank 1950-

Argonne National Laboratory
Institute for Scientific Computing, TU Dresden
Humboldt-University Berlin

The Inventors

Adams	Argyris	Backus	Bashforth
Bezier	Brandt	Broyden	Clough
Cooley	Courant	Curtiss	Dahlquist
Dantzig	Daubechies	Davidon	de Boor
de Casteljau	Euler	Fedorenko	Fletcher
Francis	Friedrichs	Garwin	Gauss
Gear	Givens	Golub	Gottlieb
Greengard	Griewank	Hackbusch	Hestenes
Heun	Hirschfelder	Householder	Liu
Jacobi	Kahan	Kantorovich	Karmarkar
Kublanovskaya	Kutta	Lagrange	Lanczos
Lax	Legendre	Lewy	Metropolis
Moler	Morlet	von Neumann	Newton
Orszag	Powell	Raphson	Richardson
Rokhlin	Runge	Rutishauser	Saad
Schoenberg	Sorensen	Southwell	Stiefel
Tukey	Ulam	van der Vorst	Vinsome
Wilkinson	Zuse		

Who was an engineer?

Adams	**Argyris**	**Backus**	Bashforth
Bezier	Brandt	Broyden	**Clough**
Cooley	Courant	Curtiss	Dahlquist
Dantzig	Daubechies	Davidon	de Boor
de Casteljau	Euler	Fedorenko	Fletcher
Francis	Friedrichs	Garwin	Gauss
Gear	Givens	Golub	Gottlieb
Greengard	Griewank	Hackbusch	Hestenes
Heun	Hirschfelder	Householder	Liu
Jacobi	Kahan	Kantorovich	Karmarkar
Kublanovskaya	Kutta	Lagrange	Lanczos
Lax	Legendre	Lewy	Metropolis
Moler	Morlet	von Neumann	Newton
Orszag	Powell	Raphson	Richardson
Rokhlin	Runge	Rutishauser	Saad
Schoenberg	Sorensen	**Southwell**	Stiefel
Tukey	Ulam	van der Vorst	Vinsome
Wilkinson	**Zuse**		

Who was a physicist?

Adams	Argyris	Backus	Bashforth
Bezier	Brandt	Broyden	Clough
Cooley	Courant	Curtiss	Dahlquist
Dantzig	**Daubechies (½)**	**Davidon**	de Boor
de Casteljau	Euler	Fedorenko	Fletcher
Francis	Friedrichs	**Garwin**	**Gauss (½)**
Gear	Givens	Golub	Gottlieb
Greengard	Griewank	Hackbusch	Hestenes
Heun	Hirschfelder	Householder	Liu
Jacobi	Kahan	Kantorovich	Karmarkar
Kublanovskaya	Kutta	Lagrange	Lanczos
Lax	Legendre	Lewy	**Metropolis**
Moler	**Morlet**	von Neumann	**Newton (½)**
Orszag	Powell	Raphson	Richardson
Rokhlin	Runge	Rutishauser	Saad
Schoenberg	Sorensen	Southwell	Stiefel
Tukey	Ulam	van der Vorst	**Vinsome**
Wilkinson	Zuse		

Who was a chemist?

Adams	Argyris	Backus	Bashforth
Bezier	Brandt	Broyden	Clough
Cooley	Courant	**Curtiss**	Dahlquist
Dantzig	Daubechies	Davidon	de Boor
de Casteljau	Euler	Fedorenko	Fletcher
Francis	Friedrichs	Garwin	Gauss
Gear	Givens	Golub	Gottlieb
Greengard	Griewank	Hackbusch	Hestenes
Heun	**Hirschfelder**	Householder	Liu
Jacobi	Kahan	Kantorovich	Karmarkar
Kublanovskaya	Kutta	Lagrange	Lanczos
Lax	Legendre	Lewy	Metropolis
Moler	Morlet	von Neumann	Newton
Orszag	Powell	Raphson	Richardson
Rokhlin	Runge	Rutishauser	Saad
Schoenberg	Sorensen	Southwell	Stiefel
Tukey	Ulam	van der Vorst	Vinsome
Wilkinson	Zuse		

Who was a mathematician?

Adams	Argyris	Backus	**Bashforth**
Bezier	**Brandt**	**Broyden**	Clough
Cooley	**Courant**	Curtiss	**Dahlquist**
Dantzig	**Daubechies (½)**	**Davidon**	**de Boor**
de Casteljau	**Euler**	**Fedorenko**	**Fletcher**
Francis	**Friedrichs**	Garwin	**Gauss (½)**
Gear	**Givens**	**Golub**	**Gottlieb**
Greengard	**Griewank**	**Hackbusch**	**Hestenes**
Heun	Hirschfelder	**Householder**	**Liu**
Jacobi	**Kahan**	**Kantorovich**	**Karmarkar**
Kublanovskaya	**Kutta**	**Lagrange**	**Lanczos**
Lax	**Legendre**	**Lewy**	Metropolis
Moler	Morlet	**von Neumann**	**Newton (½)**
Orszag	**Powell**	**Raphson**	**Richardson**
Rokhlin	**Runge**	**Rutishauser**	**Saad**
Schoenberg	**Sorensen**	Southwell	**Stiefel**
Tukey	**Ulam**	**van der Vorst**	Vinsome
Wilkinson	Zuse		

(Including computer scientists and statisticians, since very hard to distinguish)

Who was a professor?

Adams	**Argyris**	Backus	**Bashforth**
Bezier	**Brandt**	**Broyden**	**Clough**
Cooley	**Courant**	**Curtiss**	**Dahlquist**
Dantzig	**Daubechies**	**Davidon**	**de Boor**
de Casteljau	**Euler**	**Fedorenko**	**Fletcher**
Francis	**Friedrichs**	Garwin	**Gauss**
Gear	**Givens**	**Golub**	**Gottlieb**
Greengard	**Griewank**	**Hackbusch**	**Hestenes**
Heun	**Hirschfelder**	**Householder**	Liu
Jacobi	**Kahan**	**Kantorovich**	Karmarkar
Kublanovskaya	**Kutta**	**Lagrange**	**Lanczos**
Lax	**Legendre**	**Lewy**	**Metropolis**
Moler	Morlet	**von Neumann**	**Newton**
Orszag	**Powell**	**Raphson**	**Richardson**
Rokhlin	**Runge**	**Rutishauser**	**Saad**
Schoenberg	**Sorensen**	**Southwell**	**Stiefel**
Tukey	**Ulam**	**van der Vorst**	Vinsome
Wilkinson	Zuse		

(Including English academics like Raphson with titles other than professor)

Who had major involvement with government or industry?

Adams	**Argyris**	**Backus**	**Bashforth**
Bezier	Brandt	**Broyden**	**Clough**
Cooley	**Courant**	Curtiss	Dahlquist
Dantzig	**Daubechies**	**Davidon**	**de Boor**
de Casteljau	Euler	Fedorenko	**Fletcher**
Francis	Friedrichs	**Garwin**	**Gauss**
Gear	**Givens**	Golub	Gottlieb
Greengard	**Griewank**	Hackbusch	**Hestenes**
Heun	**Hirschfelder**	**Householder**	Liu
Jacobi	**Kahan**	**Kantorovich**	**Karmarkar**
Kublanovskaya	Kutta	Lagrange	**Lanczos**
Lax	Legendre	Lewy	**Metropolis**
Moler	**Morlet**	**von Neumann**	Newton
Orszag	**Powell**	Raphson	Richardson
Rokhlin	Runge	Rutishauser	Saad
Schoenberg	**Sorensen**	**Southwell**	Stiefel
Tukey	**Ulam**	van der Vorst	**Vinsome**
Wilkinson	**Zuse**		

59%

(i.e., near the time of their big contributions)

Who was German/Swiss/Austrian?

Adams
Bezier
Cooley
Dantzig
de Casteljau
Francis
Gear
Greengard
Heun
Jacobi
Kublanovskaya
Lax
Moler
Orszag
Rokhlin
Schoenberg
Tukey
Wilkinson

Argyris
Brandt
Courant
Daubechies
Euler
Friedrichs
Givens
Griewank
Hirschfelder
Kahan
Kutta
Legendre
Morlet
Powell
Runge
Sorensen
Ulam
Zuse

Backus
Broyden
Curtiss
Davidon
Fedorenko
Garwin
Golub
Hackbusch
Householder
Kantorovich
Lagrange
Lewy
von Neumann
Raphson
Rutishauser
Southwell
van der Vorst

Bashforth
Clough
Dahlquist
de Boor
Fletcher
Gauss
Gottlieb
Hestenes
Liu
Karmarkar
Lanczos
Metropolis
Newton
Richardson
Saad
Stiefel
Vinsome

Who was British?

Adams	Argyris	Backus	**Bashforth**
Bezier	Brandt	**Broyden**	Clough
Cooley	Courant	Curtiss	Dahlquist
Dantzig	Daubechies	Davidon	de Boor
de Casteljau	Euler	Fedorenko	**Fletcher**
Francis	Friedrichs	Garwin	Gauss
Gear	Givens	Golub	Gottlieb
Greengard	Griewank	Hackbusch	Hestenes
Heun	Hirschfelder	Householder	Liu
Jacobi	Kahan	Kantorovich	Karmarkar
Kublanovskaya	Kutta	Lagrange	Lanczos
Lax	Legendre	Lewy	Metropolis
Moler	Morlet	von Neumann	**Newton**
Orszag	**Powell**	**Raphson**	**Richardson**
Rokhlin	Runge	Rutishauser	Saad
Schoenberg	Sorensen	**Southwell**	Stiefel
Tukey	Ulam	van der Vorst	Vinsome
Wilkinson	Zuse		

Who was born in the USA?

Adams	Argyris	**Backus**	Bashforth
Bezier	Brandt	Broyden	**Clough**
Cooley	Courant	**Curtiss**	Dahlquist
Dantzig	Daubechies	**Davidon**	de Boor
Bezier	Euler	Fedorenko	Fletcher
Francis	Friedrichs	**Garwin**	Gauss
Gear	**Givens**	**Golub**	Gottlieb
Greengard	Griewank	Hackbusch	**Hestenes**
Heun	**Hirschfelder**	**Householder**	Liu
Jacobi	Kahan	Kantorovich	Karmarkar
Kublanovskaya	Kutta	Lagrange	Lanczos
Lax	Legendre	Lewy	**Metropolis**
Moler	Morlet	von Neumann	Newton
Orszag	Powell	Raphson	Richardson
Rokhlin	Runge	Rutishauser	Saad
Schoenberg	**Sorensen**	Southwell	Stiefel
Tukey	Ulam	van der Vorst	Vinsome
Wilkinson	Zuse		

Who ended up in the USA?

Adams	Argyris	**Backus**	Bashforth
Bezier	Brandt	Broyden	**Clough**
Cooley	**Courant**	**Curtiss**	Dahlquist
Dantzig	**Daubechies**	**Davidon**	**de Boor**
de Casteljau	Euler	Fedorenko	Fletcher
Francis	**Friedrichs**	**Garwin**	Gauss
Gear	**Givens**	**Golub**	**Gottlieb**
Greengard	Griewank	Hackbusch	**Hestenes**
Heun	**Hirschfelder**	**Householder**	Liu
Jacobi	**Kahan**	Kantorovich	Karmarkar
Kublanovskaya	Kutta	Lagrange	Lanczos
Lax	Legendre	**Lewy**	**Metropolis**
Moler	Morlet	**von Neumann**	Newton
Orszag	Powell	Raphson	Richardson
Rokhlin	Runge	Rutishauser	**Saad**
Schoenberg	**Sorensen**	Southwell	Stiefel
Tukey	**Ulam**	van der Vorst	Vinsome
Wilkinson	Zuse		

How old were they?

eligible for the Fox Prize!

Adams 36
Bezier 50
Cooley 39
Dantzig 33
de Casteljau 28
Francis 27
Gear 32
Greengard 29
Heun 41
Jacobi 22,40
Kublanovskaya 32
Lax 35
Moler 38
Orszag 28
Rokhlin 33
Schoenberg 43
Tukey 50
Wilkinson 46

Argyris 47
Brandt 35
Courant 40,57
Daubechies 34
Euler 59
Friedrichs 27
Givens 47
Griewank 40
Hirschfelder 41
Kahan 44
Kutta 34
Legendre 53
Morlet ?
Powell 27
Runge 45
Sorensen 45
Ulam 38
Zuse 26

Backus 30
Broyden 32
Curtiss 31
Davidon 32
Fedorenko ?
Garwin 37
Golub 33
Hackbusch 28
Householder 54
Kantorovich 27
Lagrange 23
Lewy 24
von Neumann 44
Raphson 42
Rutishauser 28
Southwell 52
van der Vorst33,42

Bashforth 64
Clough 39
Dahlquist 38
de Boor 25
Fletcher 24
Gauss 18,32,37
Gottlieb 33
Hestenes 46
Liu 43
Karmarkar 27
Lanczos 59
Metropolis 33
Newton 27
Richardson 35
Saad 36
Stiefel 43
Vinsome ?

So, ivory tower or coal face?

The answer seems to be a blend:

Most of the big algorithms were invented by

academic mathematicians

who had

MAJOR involvement

with applications in industry or government.

What is the first great numerical algorithm of the 21st century?

CONCLUSIONS

- The inventors were/are almost all academic mathematicians
- Most were extremely eminent
- Their great discoveries came at all ages
- About half had major involvements with government or industry

  (That's *big* industry—AT&T, IBM, Boeing, etc.—
  and big government labs like Argonne, Harwell, NPL)
- Most were seriously involved with applications
- It's hard to disentangle the effects of WWII

What is the first great numerical algorithm of the 21st century?