Hard Disk Drives:
The Giants of the Storage Industry

Cloud Storage

IOT Storage

Internal Media

Archival Storage

Internal PC Storage

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Flash Memory Summit

Reynold B. Johnson (1902-1998). American inventor and computer pioneer. Long time employee of IBM. Considered the "Father" of the disk drive.

Native of Minnesota to family of Swedish immigrants. BS in Educational Administration 1929 from Univ. of Minnesota..
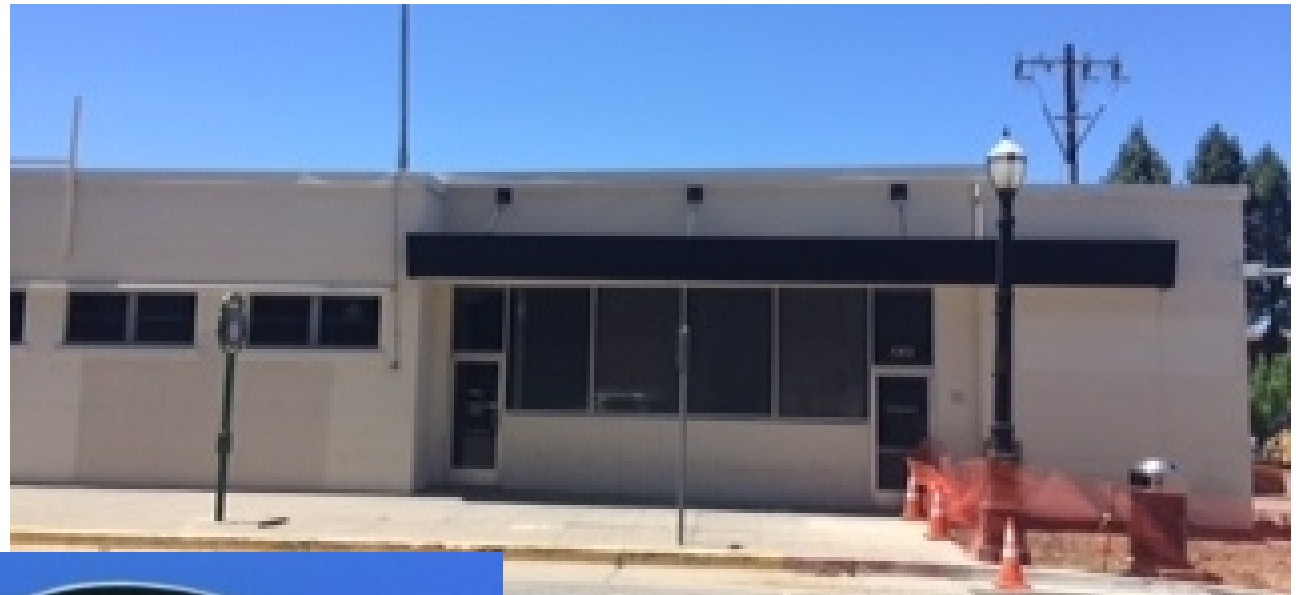
As a high school teacher in Michigan, he invented an electronic test scoring machine, the rights were purchased by IBM in 1930 and he was hired by IBM to work at the Endicott, NY lab.

In 1952 IBM sent him to San Jose, California to create and manage a West Coast Lab where he led a research team which developed the disk drive technology. In 1956 IBM released the RAMAC system which launched a multi-billion dollar industry.

Awarded 90 patents, Computer Pioneer Award (1987), National Medal of Technology and Innovation award from President Reagan in 1986, Franklin Institute Certificate of Merit in 1996.

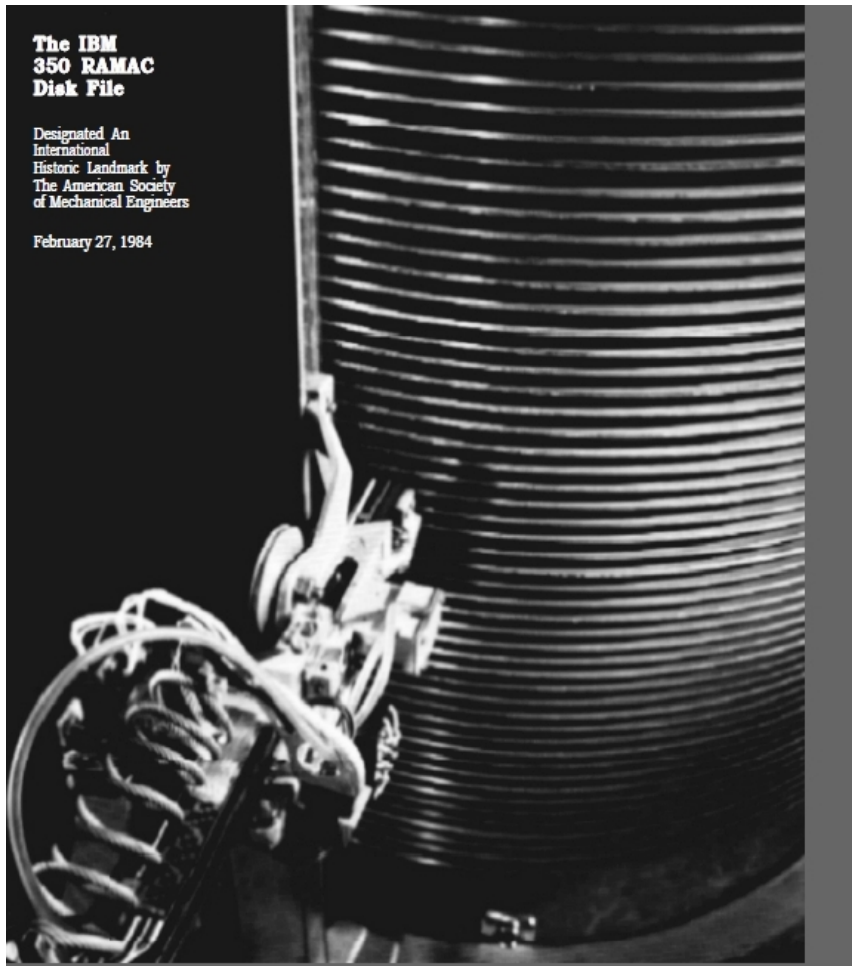IEEE Reynold B. Johnson Information Storage Award was established in 1991.

It All Started here, 99 Notre Dame Avenue, San Jose, California

They Started It All

The IBM
350 RAMAC
Disk File

Designated An
International
Historic Landmark by
The American Society
of Mechanical Engineers

February 27, 1984

RAMAC Pioneers:
Al Hoagland, Jack Grogan,
Lou Stevens

The Storage "Journey"

1956 IBM RAMAC 5 MB
$10,000,000/GB

2017 WD Ultrastar 12 TB
$0.04/GB

60+ Years of Technical Progress

Ed Grochowski

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Albert S. Hoagland earned a PhD. in electrical engineering from UC Berkeley.

Responsible for the magnetic head for RAMAC.

Developed the 1301 as a follow-on to RAMAC, containing vertically aligned read/write aerodynamically flying heads, one per disk surface, hydraulic actuator and a type of perpendicular magnetic recording
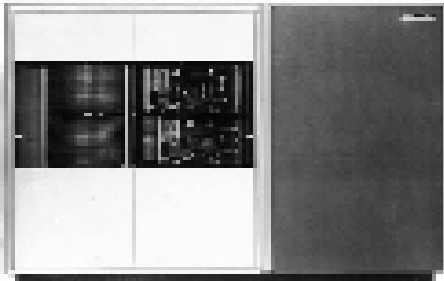
IBM 1301 Disk Storage Unit

Aso involved were **Jack Harker** and **Al Shugart.**
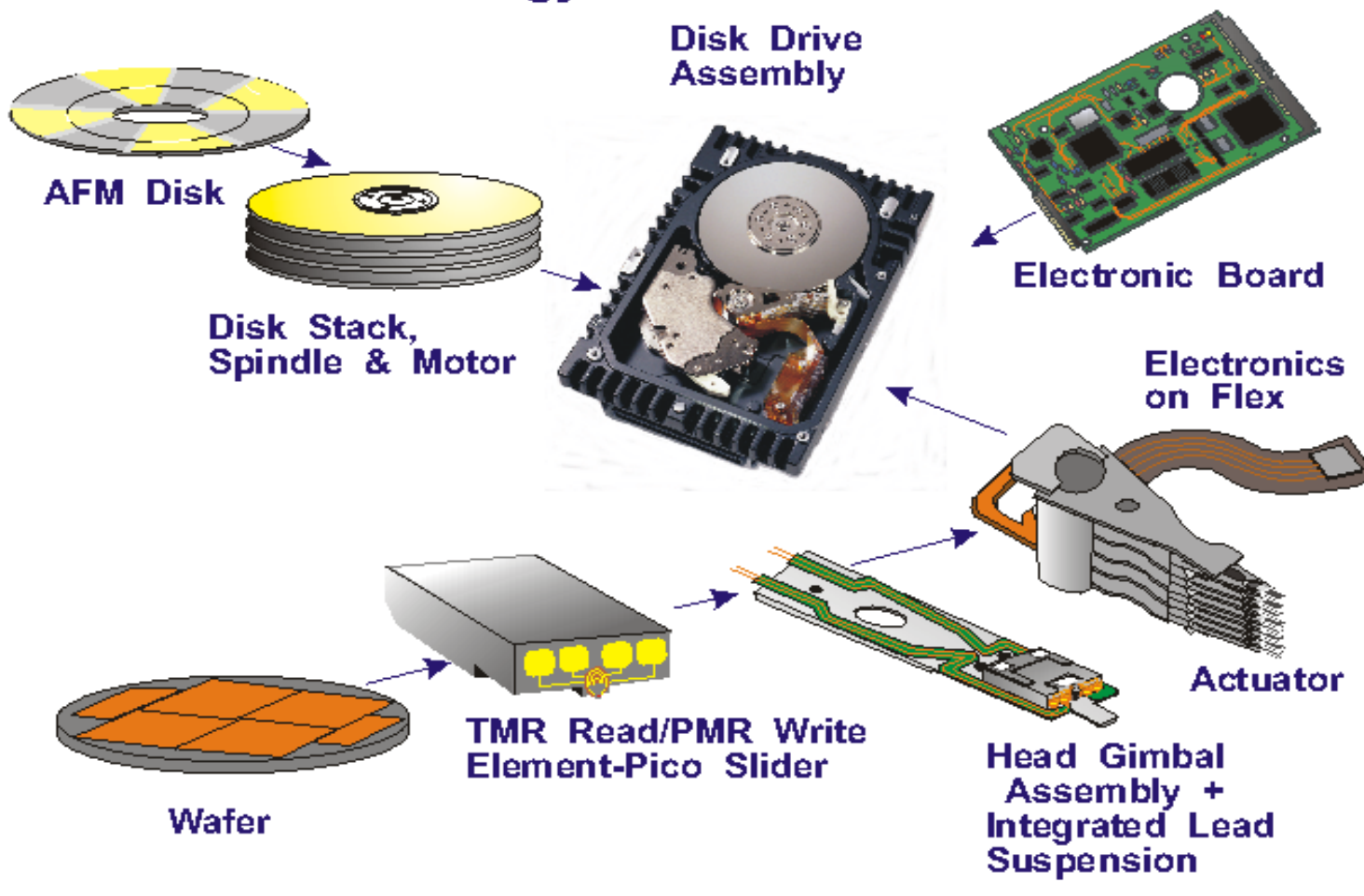
1301 shipped in 1961 and replaced RAMAC.

Hoagland established data centers in UC San Diego, Carnegie Mellon Univ. and Santa Clara University. In 1984 he became its director.

The industry recognizes Al as the designer of the first magnetic recording head, and a principal educator for students.
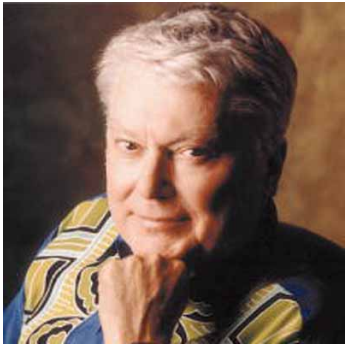
Hard Disk Technology

Disk Drive Assembly

AFM Disk

Disk Stack, Spindle & Motor

Electronic Board

Electronics on Flex

Wafer

TMR Read/PMR Write Element-Pico Slider

Head Gimbal Assembly + Integrated Lead Suspension

Actuator

HDD Components

Ed Grochowski

Alan F. Shugart (1931-2006) graduated from the Univ. of Redlands in engineering physics. He joined IBM in 1951 and transferred to the San Jose Lab where he worked on RAMAC. He was promoted to Product Mgr. responsible for all IBM storage Products. He joined Memorex in 1969 as VP in the development a series of IBM compatible disk drives, including a floppy drive .

He recognized that a hard disk drive could replace a floppy drive as a valuable, high capacity product for the emerging desktop computers. A colleague, **Finis Conner,** was also convinced that personal computers required a small form factor hard disk drive and Shugart in 1979 founded Seagate Technology with Conner. Seagate became a major supplier of disk drives, producing 5.25-inch, 3.5-inch and 2.5 inch disk drives.

He received the 1997 Reynold Johnson award for information storage systems and was a fellow of the Computer History Museum for lifelong contributions to the modern disk drive industry. Al is known as a leading member of the Silicon Valley engineering industry, taking pride in his informal business style.

Finis F. Conner (1943-) A San Jose State graduate, was convinced that hard disk storage was crucial to the growth of the computer business. With **Alan Shugart**, he founded Seagate Technology in 1979 to manufacture 5.25 inch hard drives, just as the desktop revolution was beginning.

Finis formed Conner Peripherals in 1986 with **John Squires**, an engineer from Miniscribe, Inc. to produce 3.5-inch disk drives. The product was faster, more reliable, consumed less power and could withstand greater shocks.

The Squires' prototype used software to position the recording head rather than hardware. In 1987, desktop sales were booming and small form factor drives were in demand. Notebook computers were emerging.

In 1989 Conner launched a 2.5-inch disk drive, which became in high demand. Conner, Shugart and Squires developed the small form factor drive aimed at the small computer market, but it soon became apparent that these form factors offered mechanical stability, high performance at lower power. These factors ushered in their use in enterprise computer systems.
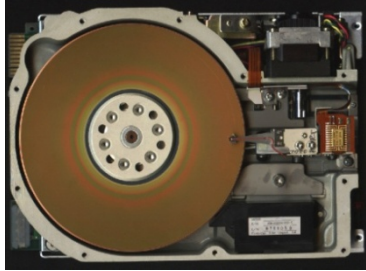
The **ST-506** was the first 5.25-inch hard drive introduced in 1980 by Seagate Technology. It stored 5 megabytes and cost $1500. This product started a family of products (ST-412, ST-225) which progressively increased drive capacity by 2X. All three used MFM coding. The ST-506 connected to a computer system through a disk controller and the interface between this controller and drive. It was derived from the SA1000 interface, based on the floppy drive interface, but was limited to a 5 Megabit/s transfer rate. It was adopted by numerous drive manufacturers and became an industry standard. Seek time averaged 170 ms, similar to a floppy drive or today's optical drive. Many other drive companies introduced products using the same connectors and signals based on ST-506, and IBM chose to use it, acquiring adapter cards from WD for the PC/AT. From IBM's endorsement, most drives in the 1980's were based on ST-506.

Due to the complexity of ST-506 controller and cabling, these led to newer solutions as SCSI and ATA (IDE).

HDD Form Factor Evolution

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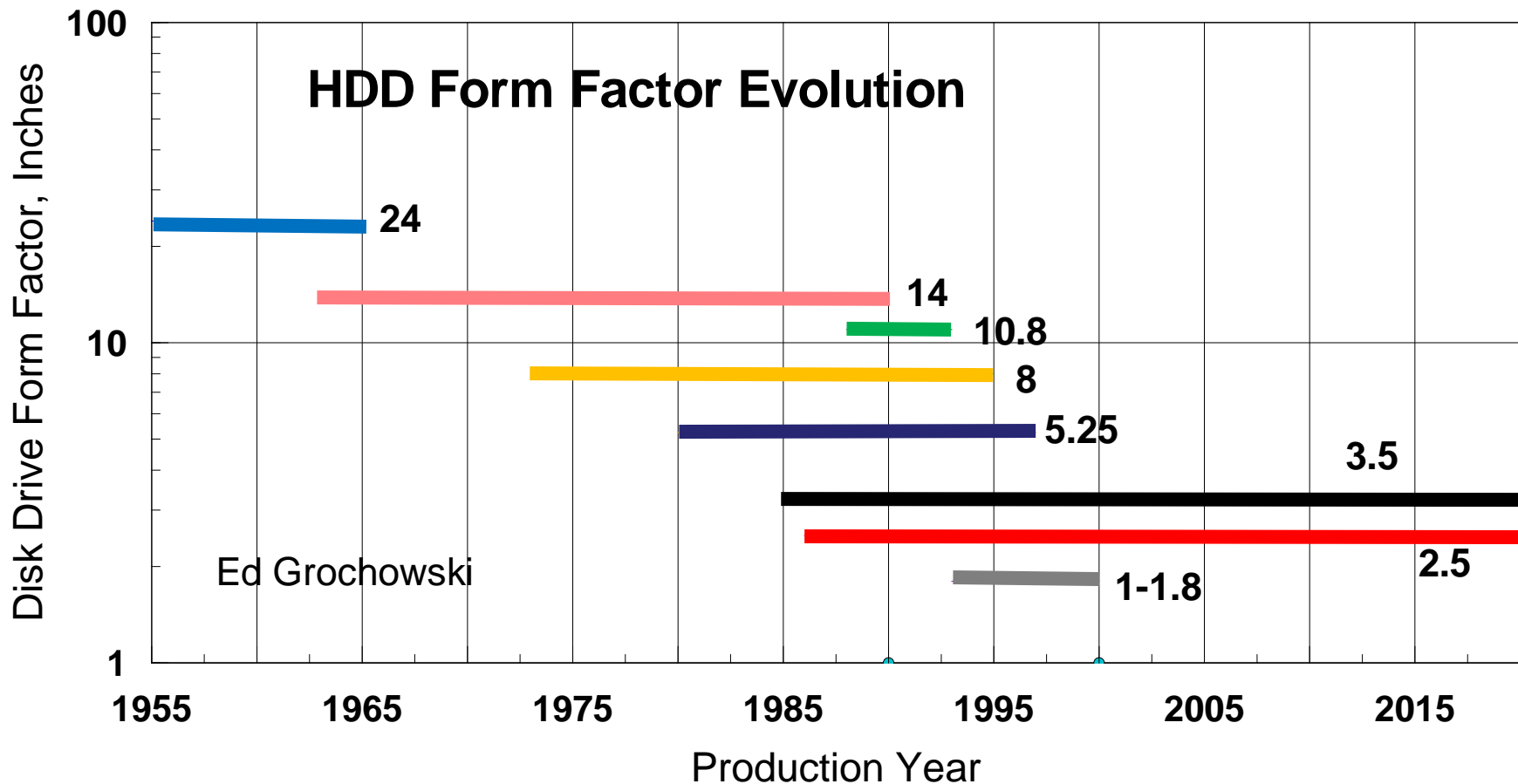
John Squires worked with **Terry Johnson** at Miniscribe and joined Conner Peripherals in 1986 to create the CP340. This 3.5 inch product had a closed loop dedicated servo, low power and mechanical robustness. This newer drive was microprocessor controlled using an embedded servo on the disk itself, allowing track density to be increased beyond conventional stepper motors. The CP340 was the first in this form factor. (Ref. USP 4979056, "Disk drive system controller architecture", John Squires, 1990)

Inside view of CP340 disk drive

Finis found a willing customer, Compaq Computer, who purchased 90% of the production in 1987. Conner offered a IDE/ATA version to this customer along with a SCSI version for the enterprise market. The design demonstrated in the CP340 is considered the basis of many newer designs, including a 2.5 inch technology which was applied for the mobile market.

James N. Porter (1931-2012) was often known as "the Dean of Storage analysts". He received a bachelors degree in Advertising from San Jose State. He joined paper manufacturer Crown Zellerbach, a company that received a RAMAC in 1956. It was this experience that developed his lifelong interest in storage technologies.

He joined Memorex in 1968 and in 1974 he started his own consulting firm, publishing Disk/Trend, an annual market study for the disk drive and data storage Industry. This series of reports was considered the industry standard for market storage studies.

Jim continued to be in high demand, speaking on panels and presenting his findings at storage conferences worldwide. He was a founder and major participant in several industry associations, addressing storage and technology trends. He was founder of the Computer History Museum's Special Interest Group which advises the curators on historical events and significant contributors.

David A. Thompson received a PhD. in electrical engineering from Carnegie Institute of Technology in Pittsburgh in 1966. He joined IBM Research transferring to the Almaden Research Center.
He was elected a fellow of the IEEE, a member of the National Academy of Engineering in 1988, and awarded Inventor of the Year by New York State Patent Law Assoc.

Inducted into the Silicon Valley Engineering Hall of Fame in 1996, he shared the honor with IBM co-inventor **Lubomyr Romankiw** for their invention of thin film read/write head. (USPatent # 4,295,173). This head design increased the density

of data stored on magnetic disks by utilization of lithography masking, thin film deposition and electroplating processing, replacing the ferrite head which required mechanical trimming and wire wrapped coils. The new film head could be manufactured using processing techniques known in the silicon semiconductor industry.

The fundamental inductive element of this thin film head continues to be the basis of today's write magnetic sensor.

Read/Write Sensor Evolution

Thin Film Inductive
Read/Write Head
Coil, Pole Geometries
   Controlled By Semi-
   conductor Type Process
NiFe Poles
Two Contact Structure

Ferrite Inductive MnFe
Read/Write Head
Wire wound coil
Machined Pole Pieces
Gap Width Controlled
   By Films And Assembly
   Tolerances
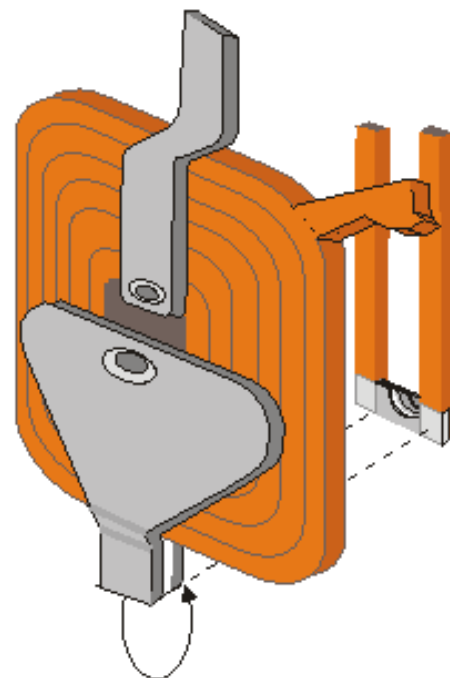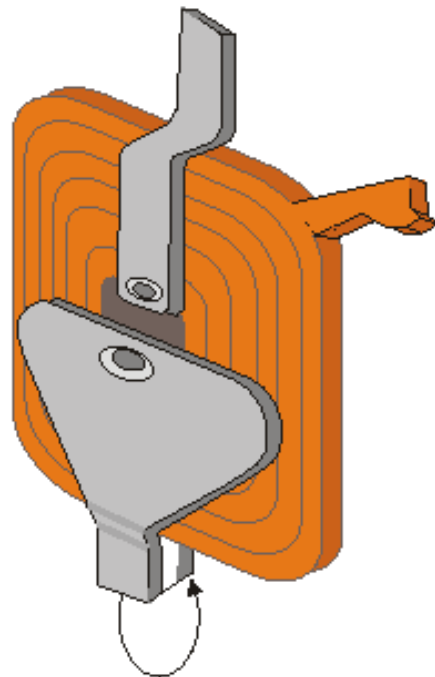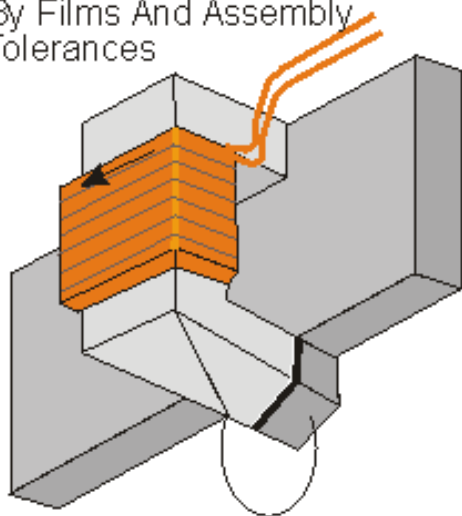
Thin Film Inductive Write
GMR/TMR Read Head
Write Wide-Read Narrow
Four Contact Structure
Pinned, Free Films
Antiferromagnetic Exchange Film

Edward Grochowski

Albert Fert graduated from the University of Paris, in 1963 with a PhD. and ScD. In 1988 he discovered the Giant Magnetoresistive effect (GMR) by observing the behavior of Cr/Fe multiLayers at high magnetic fields. With Peter Gruenberg, he was awarded the **Nobel Prize** in Physics in 2007 for this discovery as well as for the development of spin electronics.

He is currently an Emeritus Professor at University-Sud and a member of the French Academy of Science.

Peter A. Gruenberg was awarded a PhD. In physics in 1969 from Darmstadt University of Technology and later joined the Institute for Solid State Physics in Julich. In 1968 he discovered the antiparallel exchange coupling between ferromagnetic layers separated by a thin non-ferromagnetic layer which led to discovery of the GMR effect. This was accomplished independently and simultaneously with Fert, with whom he shared the 2007 **Nobel Prize** in Physics. Both innovators contributed to understanding the GMR effect which is the basis of today's read head used in magnetic hard disk drives.

Stuart S.P. Parkin was awarded his PhD. at Cambridge in 1980. He joined IBM Research in San Jose in 1982, working on magnetic thin film structures and nanostructures exhibiting the giant magnetoresistance (GMR) effect. In 1991 he discovered transition metal multilayer GMR systems. He shared the American Physical Society's International Materials Prize (1994) and the European Physical Society's Physics Prize (1997) for this work. He is a Fellow of the American Physical Society, and appointed a member of the Academy of Technology. In 2014 he was awarded the **Millennium** technology prize (1M Euros). He made contributions leading to the understanding of GMR devices, suitable for hard disk drive read heads.
Working with storage researchers and engineers, practical new generation GMR devices were developed functioning at the magnetic fields in hard disk drives.

Recently he has exploited GMR in a new type of random access memory cell (MRAM) that Is a true non volatile RAM which exhibits high speed and high density.
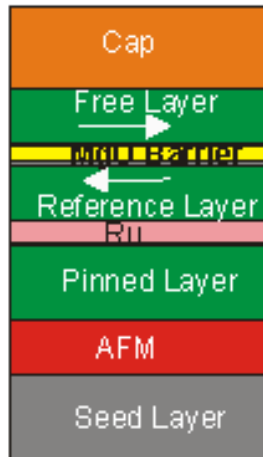
Bruce A. Gurney joined the IBM Almaden Research Center in 1987 after receiving a PhD in Physics from Cornell Univ. He is a Fellow of the American Physical Society and an IEEE Fellow, has authored over three dozen papers on magnetic recording, and holds over 25 patents. He also managed the recording head and nanostructure group for Hitachi Global Storage Technologies.
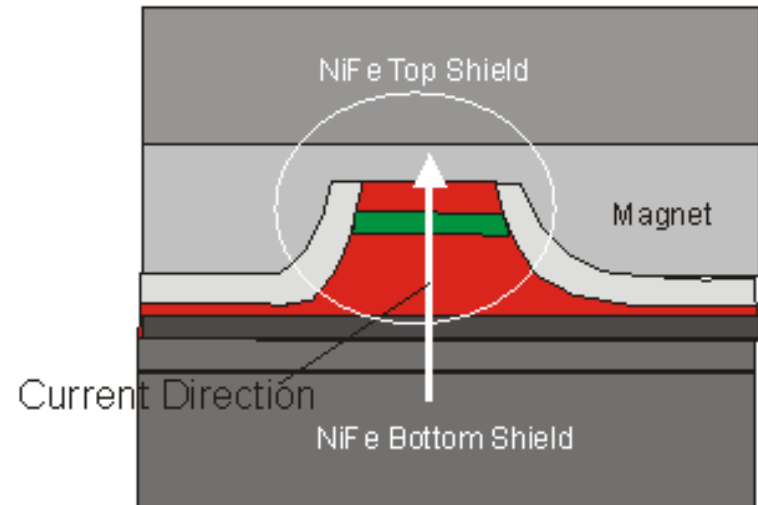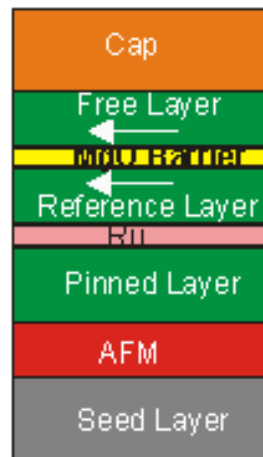
With **Virgil S. Speriosu** he developed a practical GMR sensor (spin valve) which has become the prototype for all GMR heads. This head technology has extended the capacity and performance of disk drives. He demonstrated the GMR effect at Low magnetic fields in disk drives. With Speriosu, he received the 2004 Reynold B. Johnson award for the GMR work.

CPP TMR Read Head Technology

Non-Conducting

Cap
Free Layer →
MgO Barrier
Reference Layer ←
Ru
Pinned Layer
AFM
Seed Layer

Conducting

Cap
Free Layer ←
MgO Barrier
Reference Layer ←
Ru
Pinned Layer
AFM
Seed Layer

NiFe Top Shield

Magnet

Current Direction

NiFe Bottom Shield

CPP GMR TMR2011
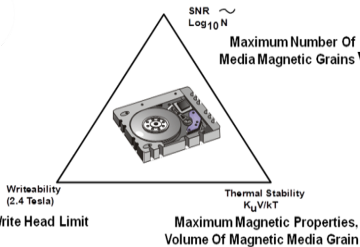
Edward Grochowski

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Mark Kryder received a PhD. from the California Institute of Technology. In 1978 founded the Magnetic Technology and Data Storage Systems Center at CMU. In1998 he was senior VP and chief technical officer at Seagate Technology. He learned increasing areal density would be limited based on thermal decay, and that introducing perpendicular magnetic recording (PMR) would enable much higher and stable bit densities. PMR had been previously proposed by **Shunichi Iwasaki**, of Tohoku University. Kryder led a storage investigation in San Jose, CA, under the National Storage Industry Consortium to study the implementation of PMR and by 2005 all hard disk drives used this bit orientation. He was the recipient of the 2014 Benjamin Franklin Medal in Electrical Engineering, with Iwasaki.

MAGNETIC TECHNOLOGY TRILEMMA

$SNR \sim Log_{10} N$

Maximum Number Of Media Magnetic Grains

Writeability (2.4 Tesla)
Inductive Write Head Limit

Thermal Stability $K_U V/kT$
Maximum Magnetic Properties, Volume Of Magnetic Media Grain

Ed Grochowski

He is an elected fellow of the NAE, a fellow of the American Physical Society and the IEEE, and was awarded the IEEE Reynold B. Johnson Information Storage Systems Award.

Stanley H. Charap received a PhD. from Rutgers University in Physics and joined Carnegie Mellon University in Pittsburgh, PA. He became professor emeritus at this university. He is an IEEE fellow.
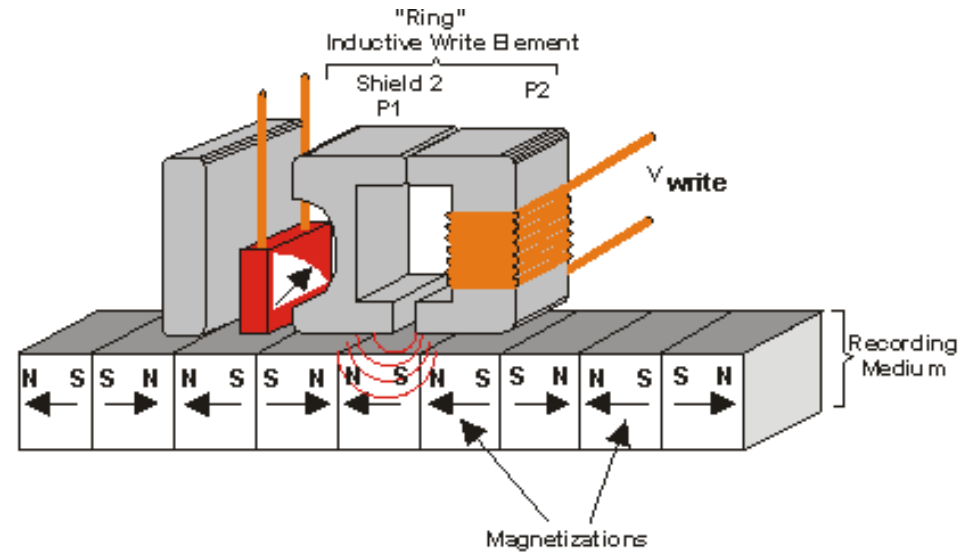His awards include 2008 Reynold B. Johnson Data Storage Device Technology Award, IEEE Achievement Award, IEEE Millennium Medal and the Technical Achievement from the National Storage Industry Consortium.
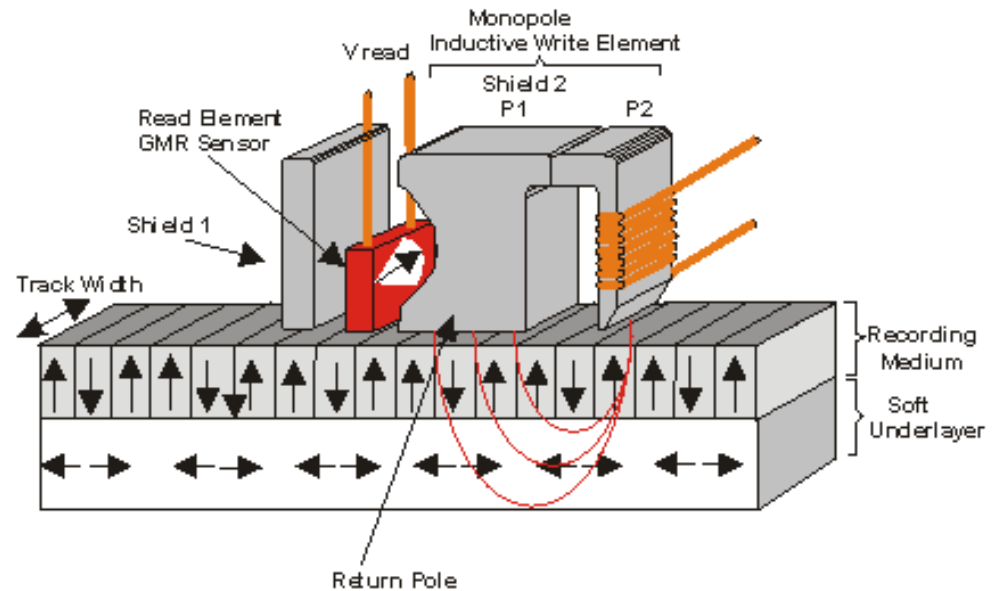
He identified a phenomenon, **superparamagnetism**, that limits the increase in areal density of hard disk drives, occurring at smaller disk bits. Thermal instability would limit data retention. This research was considered critical to future disk drive capacity. As a result, new disk media materials and structures were implemented, including a migration from the in-use longitudinal recording to (PMR).
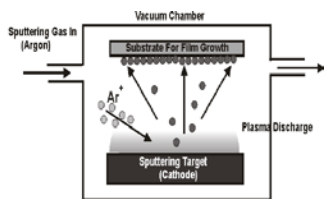
Longitudinal Recording
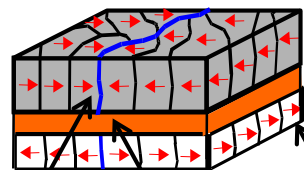
Perpendicular Recording

Recording Head Technologies

Ed Grochowski

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Sputter Deposition Chamber

CoPtCrB Magnetic Film
Ru Exchange Film
CoPtCrB Antiferromagnetic Film

Hal J. Rosen was awarded a PhD. from UC Berkeley and joined IBM Research at the Almaden Lab in 1985, investigating both optical and magnetic storage technologies. He later was associated with HGST. At IBM he managed a team of researchers including **Eric Fullerton, Thomas Albrecht** and **Kurt Rubin**, and performed fundamental work on disk structures for high density recording. They developed metal sputtering processing for these advanced disk media structures. Recognizing the work on supermagnetism limits, he developed the antiferromagnetic coupled media (AFC, USP 6773834) using a ruthenium film which allowed small media grains while exhibiting good thermal stability. His team then developed the fundamental media structure for perpendicular magnetic recording (PMR). This work produced the defacto standard for PMR in the industry and allowed very large increases in the data storage density for HDD.
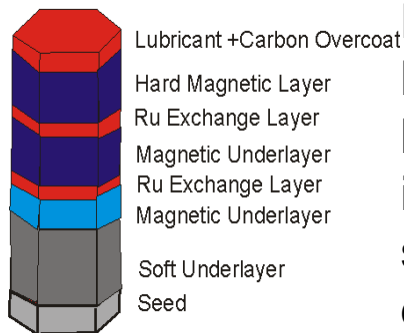
His team also developed the multiple film optical disk structure allowing storage of two overlying bits which may be addressed by a change in the laser beam focus. (USP 576118, 5745473).

Gerardo A. Bertero holds a PhD. in Materials Science from Stanford University, joined KOMAG in 1994 and was named Vice President of Sputter Research and Development in 2006. On the consolidation with Western Digital, he served as VP in R&D developing advanced magnetic recording media, and holds a Senior Director position in the Advanced Technology Office of WD. He has specialized in the synthesis, performance and characterization of magnetic materials and thin film structures.

Multilevel Magnetic Disk Media

Lubricant +Carbon Overcoat
Hard Magnetic Layer
Ru Exchange Layer
Magnetic Underlayer
Ru Exchange Layer
Magnetic Underlayer

Soft Underlayer
Seed

8-Layer ECC Media

Edward Grochowski

He is directly responsible for the learning and dissemination of key information and technology for disk drive products and has promoted the significant progress in the field. These include his work in magnetic read head antiferromagnetic layer, spin transfer for tunneling MR devices, PMR media, the development of media for high areal density disk media for disk drives and production tooling for the high volume output.

He has served the IEEE Magnetics Society as a Technical Advisor and also as chair person of the Santa Clara Valley chapter.
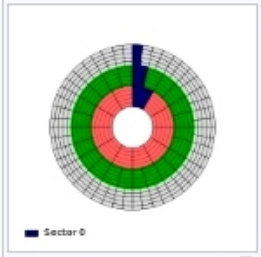
Storing data bits on the surface of a circular disk causes the inner tracks to be packed more densely than outer tracks. Zone bit recording, **ZBR**, divides the tracks in a number of zones. A result of ZBR is that data on the outermost zone will have the highest data transfer rate. More bits are stored outside the inner zones, increasing capacity by at least 15-20%. Most hard drives use ZBR. Data transfer rate zones are established for the tracks by preliminarily assigning each track to one of a plurality of data rate zones. ZBR was established by U.S.P. 4799112, "Method And Apparatus For Recording Data", **Robert A. Bremmer, Vladimir Kovner, Dennis Stone** assigned to Magnetic Peripherals, Inc.; U.S.P. 5087992, "Method For Assigning Tracks On A Magnetic Data Storage Disk To Different Frequency Zones", **Shafa Dehandeh, Stephen R. Genheimer, Steven L. Welty** assigned to Seagate Technology, Inc.; and U.S.P. 5258876, "Zone Bit Recording With Write Compensation", **Gina R. Danner, Evgeny J. Berzon** assigned to Seagate.

Gina Danner was awarded a PhD. In Electrical Engineering in 1987 from the University of Minnesota. She is presently Senior Director of Product Development at Seagate Technology.

Flash Memory
Summit 2017
Santa Clara, CA

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Francois Dolivo joined IBM Research in 1974 at the Zurich Lab in Reschlikon, Switzerland where he headed the magnetic recording group that developed the partial response signaling and maximum likelihood sequence (PRML) recording channel. He is an IEEE Fellow, member of the IBM Academy of Technology, IEEE Third Millennium Medal and PC Magazine Award for Technical Excellence.

The previous peak detection method to read stored bits became inaccurate as data densities increased. In 1990, Dolivo's work resulted in the industry's first hard disk drive using the new PRML channel. He joined **Evangelos Eleftheriou**, also a member of the Zurich Lab, and **Hisashi Kobayashi**, a professor at Princeton, in receiving the prestigious Eduard Rhein Foundation Technology Award in 2005.
It was Kobayashi who suggested data transmission could employed to detect bits and it was Eleftheriou who developed a new detection method, called Noise Predictive Maximum Likelihood sequence which increases the signal to noise ratio.

PRML rapidly became the de-facto industry standard, and its refinements are in use today.

Partial Response Maximum Likelihood)(PRML)Data Channel

Head Readback Voltage
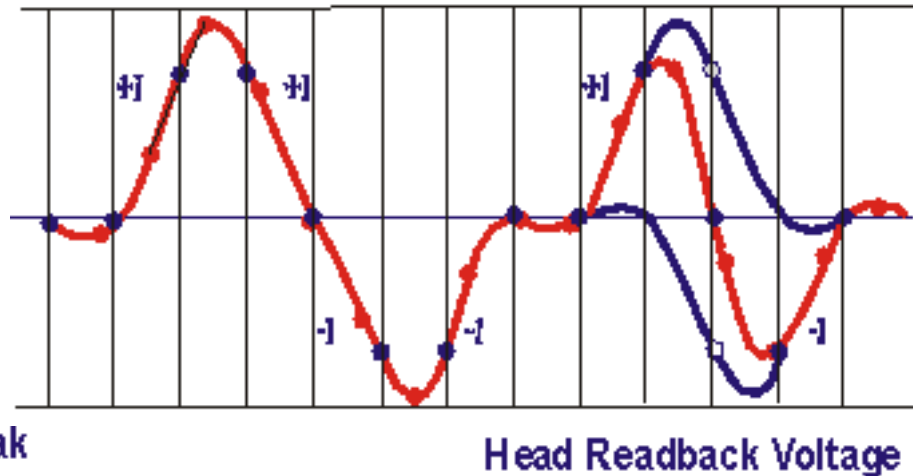
- Conventional channels detect peak of pulse
- PRML samples shape of pulse (PR)
- Two close transitions superimposed are detected with PRML
- Transition spacings can be closer
- Detector locates sequence most likely (ML) to explain all data
- Smoothes noise over sample set, improves SNR performance

Edward Grochowski

Martin A. Hassner received a PhD. from UCLA in 1980 in Electrical Engineering and joined IBM Research working on coding and signal processing.. He was convinced that the sector size of 512 bytes, a long time industry standard, was inefficient to utilize error correction codes. As data density increased, a larger percentage of the sector would be required for error correction codes. He proposed a new sector standard, 4096 bytes, for data stored on disks and with IBM colleague, **Edward Grochowski**, formed and industry-wide committee to establish this standard.

Preamble **S**ync Data ECC

~ 5% Overhead

>10 Bytes   >5   512   24-38
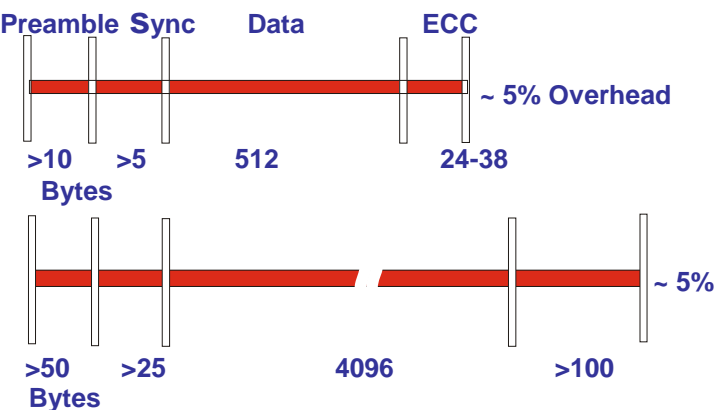
Today this new standard is used in the disk drive industry and is a principal characteristic of disk drives. A unique simulation technique allows systems to use 4096 byte sectored disk drives with a minimum of reprogramming.

~ 5%

>50 Bytes   >25   4096   >100

His work in modulation codes, specifically the 1,7 code, has been widely used through-out the industry. He holds 50 US patents and has received several IBM Innovation Awards.
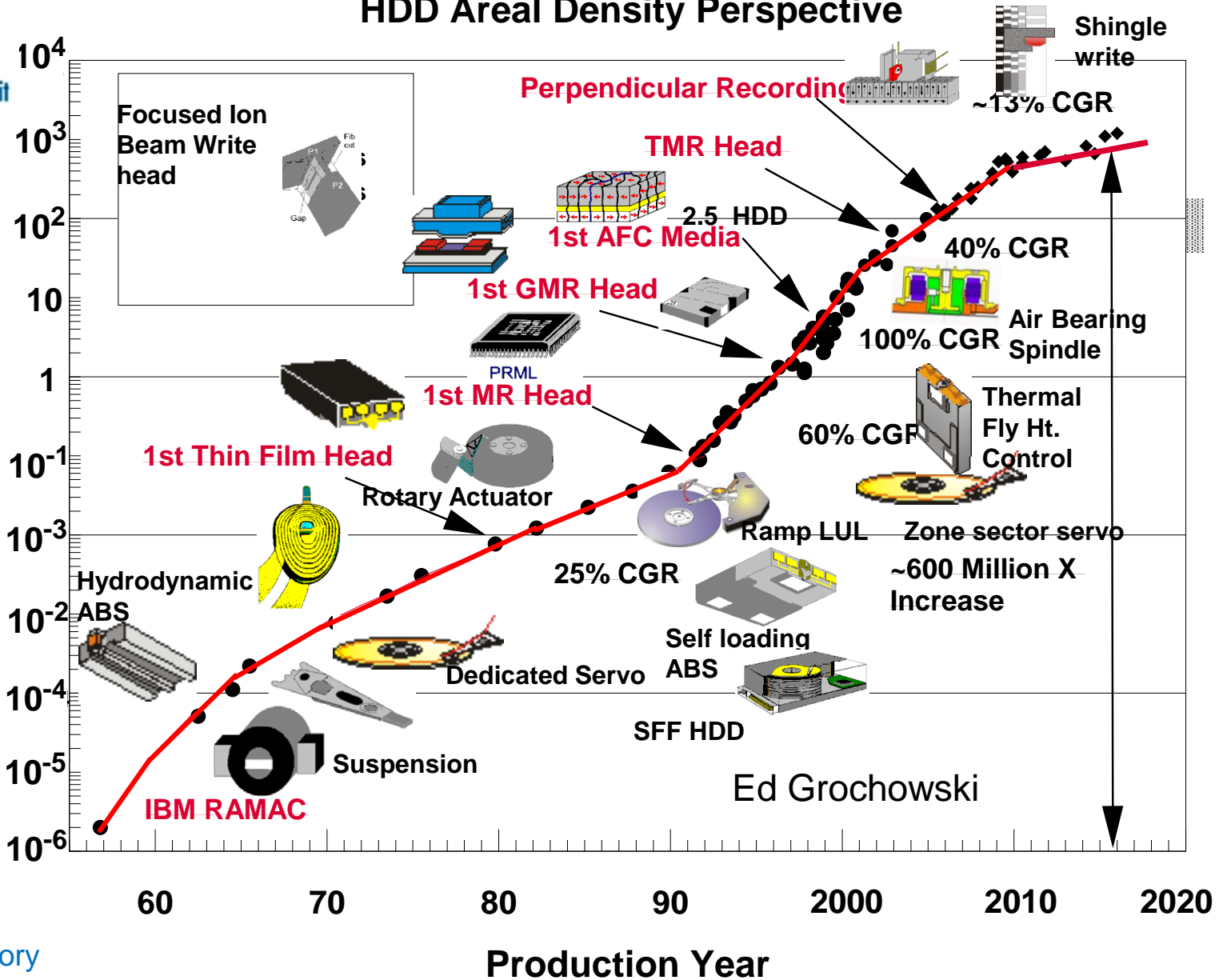
The RAID Team at UC Berkeley

Randy H. Katz received a PhD. From UC Berkeley in 1980 in Computer Science. He is identified as a distinguished professor of Electrical Engineering and Computer Science at the University. He is a fellow of the Association for Computing Machinery, the IEEE, and a member of National Academy of Engineering as well as the National Academy of Arts and Sciences. He has publishe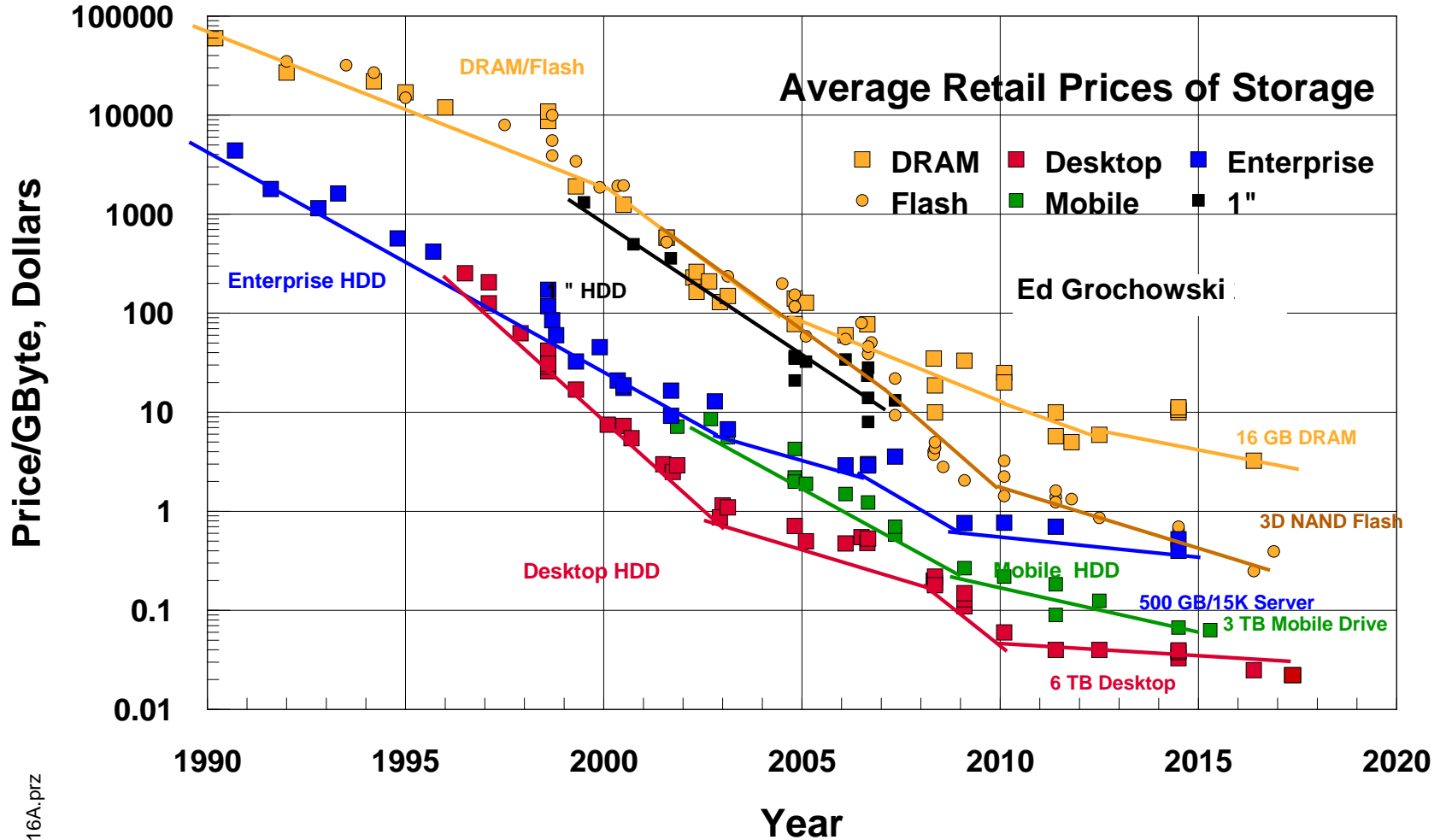d over 250 papers, and his text, Contemporary Logic Design has sold over 85K copies. He was awarded the IEEE James H. Milligan Award Education Medal in 2010. With UC Berkeley Researchers, **Dave Patterson, Garth Gibson** he developed Redundant Arrays of Independent Disks (RAID), an array of multiple disk drives which could outperform the standard and expensive mirroring arrays in use for high reliability storage. USP #4092732 filed by **Ken Ouchi** and **Brian Clark** from IBM in 1988 disclosed techniques employed in subsequent versions of RAID.

Based on the Berkeley work a number of standard schemes, called levels, each with associated data formats, standardized by the Storage Networking Industry Association (SNIA) in the Common RAID Disk Drive Format Standard. Today, most server network-based storage is based on RAID and many PC users employ hardware or software RAID systems.

HDD Areal Density Perspective

Ed Grochowski

arpers2016D.prz

Average Retail Prices of Storage

Flash Memory Summit 2017 Santa Clara, CA

oemprc2016A.prz

Summary and Conclusions

1. A 60+Year HDD History, Massive Technology Innovations

2. Many Storage "Giants" Have Participated

3. HDD/Storage Awards

4. HDDs Will Continue In Storage Market

5. HDD Is Presently The Low Cost Technology

6. HDD Products Will Continue To Migrate To Cloud Storage

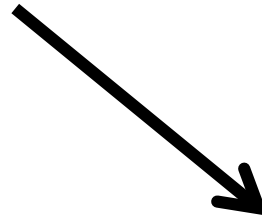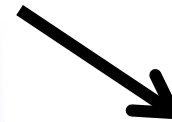7. By 2021 80% Storage Bytes Will Continue To Be HDD

Edward Grochowski

The Storage "Journey"

1956 IBM RAMAC 5 MB
$10,000,000/GB

2017 WD Ultrastar 12 TB
$0.04/GB

202X >20 TB
$0.02/GB

60+ Years of Technical Progress

John Slonczewski was awarded a PhD. in Physics in 1955 from Rutgers University and joined IBM Research. He is a Fellow of the Amercan Physical Society, IEEE Life Member, was awarded Neel Medal in Magnetism, IEEE Magnetics Society Achievement Award in 2012, O.E. Buckley Condensed Matter Physics Prize in 2013.

His work in magnetic anisotropy, magnetoresistance and spin transfer torque between magnetic films separated by tunnel barriers directly contributed to understanding the operation of spin transfer MRAM devices which have the potential for memory, storage

and logic applications. The fundamental predictions of spin momentum transfer to modify the magnetic orientation of free films describe the operation of STT RAM devices today. The full potential and application of STT RAM has yet to be realized for the future.