TOWARD A MATHEMATICAL THEORY OF MEMORY

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IN COOPERATION WITH THE 9TH NASA GODDARD CONFERENCE

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MEMORY, COMMUNICATION, PROCESSING:

THREE FACETS OF AN UNDERLYING REALITY

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MEMORY.COMMUNICATION.COMPUTATION.:
Three Facets of an Underlying Reality

abstract

This talk explores the why, whence and whither of memory in the context of its communication and computation companions. The three facets of memory (bits), communication (bits per second) and computation (operations per second) form a constantly changing tri-stranded braid which presents new opportunities and challenges with every major advance in any one of the three. In "The Mathematical Theory of Communication", Claude Shannon taught us that information is the property of an event in context. The context of memory involves communication and computation. What is needed is "The Mathematical Theory of Memory".

FORWARD
THE MATHEMATICAL THEORY OF MEMORY
NEED FOR A QUANTITATIVE THEORY NOW

Although

- there have been 50 years of rapid progress in digital stored systems without a mathematical theory of memory
- there is a relatively clear path for another factor of 100 in storage density and a concomitant decrease in cost per unit capacity in sight over the next ten years

The *limitation* in use of storage technology is no longer technological but sociological. While the cost per bit has decreased and continues to decrease dramatically in time, the cost in management functions per bit has increased and continues to increase significantly as a function of time. A mathematical theory of memory which takes into account the end-to-end considerations which go into practical use of memory in a total information system would enable global rather than local optimization by system designers.

At the system level all data may be viewed as a combination of user data and metadata, or data about the data. This simple dichotomy, and the fact that the data storage hierarchy has been appreciated for five decades from both a technological and a business view, have made the optimization of the design of memory systems which involve balanced optimizations of size, cost, and latency a commonly accepted and relatively easily understood process. However, the extreme scaling which is presently occurring and shows no signs of abatement for the next decade and the convergence of previously disparate architectural concepts, make the need for a mathematical theory of memory of fundamental importance at this point in the evolution of information technology.

INTRODUCTION
ON TRINITIES

We humans are emersed in a world of threes:

- religion: Father, Son, Spirit
- sociology: parent, child, progeny
- government: executive, judicial, legislative
- psychological: charity, esteem, love.
- perspective: Gödel, Escher, Bach

In business, we concentrate on the three most significant points; in the United States our area codes and exchanges are triplets. Three seems to provide a stability that two or four or more do not. Three points determine a plane and so our tables and chairs inevitably made up of unequal supports come to rest on one set of three or another often in a multistable rocking pattern. Perhaps our human fascination of threes is a reflection of a fundamental property around which our universe has been constructed. Or perhaps it is a first order approximation of what we experience.

In 1928, R. V. Hartley published a paper entitled "Matter: A Mode of Motion" in which he described a theory which envisions elementary particles to be the result of energy emanating from a point and reflecting back from a sphere whose radius is characteristic of the particle. Matter itself is a manifestation of energy in motion. The theory was not substantiated by empirical evidence and fell by the wayside.

In the early part of the twentieth century, Schroedinger and others promulgated a theory which has stood the test of time and empirical evidence. In this theory, matter has both a particle and a wave nature. The theory stops short of attempting to explain how this intuitively contradictory state of affairs can coexist except to say that there is a transition from dominant particle-like behavior at large scales to dominant wave-like behavior at small scales.

The reason for presenting these two views is that the notion that one fundamental thing may be viewed as a mode of another fundamental thing is deeply entrenched in science and has played a basic role in enhancing our ability to understand our world.

The trinity that we will discuss today…

Memory, computation, and communication may be viewed as modes of each other. For example, a communication channel which can simultaneously transmit all information of relevance in a particular domain can substitute for storing information about that domain. Among the first implementations of stored bits was the use of the delay in a radio propagation channel in upstate New York to deliver the "stored" information in a known time after it was sent into the radio channel for a round trip delivery. Domain specific processing may be viewed as

resulting in determination of one of a number of choices which can be achieved by a table lookup function in a suitable memory. A very large memory in a handheld device may take the place of communications for a number of domain specific applications. Although no facet completely represents any other facet under all conditions that there is a triplet of properties which are important and the capability provided by any facet can be enhanced by for the capability of the other facets.

PRELUDE
Memory in Context

My father was born in 1913, the year the income tax was instituted in these United States and just three years after a dramatic appearance of Halley's comet in 1910. So dramatic was the memory of Halley's comet to my grandfather that my father lived all his life in anticipation of the return of Halley's comet turn in 1986. Although the comet failed to live up to its dramatic showing of three-quarters of a century earlier, my father experienced a deep satisfaction in fulfilling a memory conveyed to him seven decades ago.

My father is now 87 and is experiencing severe senile dementia. I had just visited him over a weekend when I went to an airport on Monday for a business trip. There I saw the CNN poster "you are what you know". My father knows very little of what he once knew or at least it appears to the world that this is so. Can the CNN poster be read as "for each memory my father loses he becomes less because he knows less"? Although my

father can independently recall very little information, he does recognize information which I tell him which is based on what he once told me. In other words, although he is able to independently access very little information, once I build a bridge he remembers the information and the surrounding events, often supplying more details than I currently know or perhaps ever knew. This has led me to modify in my own thoughts the CNN poster to include: "you are what you know...and can access...and process". Without assistance my father "knows" very little. With my help he can access much of the repertoire of memories that he could once independently retrieve. He can add facts to these memories, embellish them, relive them in his mind, and once again enjoy the experience.

Our mass storage systems are much like this. Information locked away in them certainly must be accessed, that is, communicated from one point to another, and processed for some purpose. Just as information is a property of an event in context, memory is the property of an event in the context of communication and processing in order for the stored memory to be able to realize its full potential.

So should there be a triplet of sayings that CNN espouses:

- you are what you know
- you are what you can access
- you are what you can compute?

To "know" is fleeting but to "remember", in the full triune sense, is everything. What we need is "The Mathematical Theory of Memory", a work on the same fundamental scale as Claude Shannon's 1948 "The Mathematical Theory of Communication".

"You are what you know", states a current CNN advertisement, which tacitly assumes what is stored is accessible and processible.

PRELUDE
Memory vs Time

One of the consequences of Einstein's remarkable theories of relativity is the fact that time is not the fundamental basis of our universe that it intuitively appears to be. Nevertheless, we humans persist in believing and living as though *time* were the fundamental independent parameter that drives, and ultimately ends, our lives. And we constantly wage war against time in our thoughts and in our actions.

Shakespeare has told us "the child is father to the man" and more poignantly:

> "Tomorrow, tomorrow and tomorrow
> Creeps in this petty pace from day to day
> To the last syllable of recorded time;
> And all our yesterdays have lighted fools the way to dusty death
> Out, Out, brief candle!

Life is but a walking shadow, a poor player
That struts and frets his hour upon the stage
And then is heard no more.
It is a tale told by an idiot, full of sound and fury, signifying nothing.

Macbeth, Act5, Scene 5

Memory is a property of nature which preserves what was **and it is a property of living things** which wages war against time. When memory succeeds, what was yesterday will be tomorrow. A rock solidified out of the primordial melt three and one-half billion years ago *persists* and we have learned much about its origin by reading the record it has preserved. A two thousand year old tree clinging to the cliffs on the Oregon coast *persists* - and records its persistence in its substance. In a series of rings the tree quietly records the triumph of life over time. By nuances in the size and shape of its rings, the tree also preserves characteristics of its environment which time has sought to eradicate.

In the caves at France, twenty thousand years ago, early humans recorded aspects of their lives and environment using archival storage media that pass the archival test of the National Archives and Records Service [NARS]. We perceive this stored information today and infer characteristics and qualities of the environment and life of the people who, so long ago, successfully defeated time.

At this conference today we are engaged on a great battlefield of this war with time. Although we are creating storage at an ever-accelerating pace, we are creating memories even faster. Today we will discuss how we are drawing on the allied forces of computation and communication to tilt the battlefield in our favor.
One way is by not ignoring the lessons of history.

INTRODUCTION

“WHO OF US WOULD NOT BE GLAD TO LIFT THE VEIL BEHIND WHICH THE FUTURE LIES HIDDEN; TO CAST A GLANCE AT THE NEXT ADVANCES OF OUR SCIENCE AND AT THE SECRETS OF ITS DEVELOPMENT DURING FUTURE CENTURIES?”

Source: David Hilbert, “Mathematical Problems”, International Congress of Mathematicians, Paris, 1900, Göttinger Nachrichten, pp 253-297, 1900

A VIEW FROM 50,000 FEET

- **~ 10^{18} B DIGITALLY STORED ON EARTH (~ 1 EXA BYTE)**
- **~ 15% IS OPTICAL**
- **OPTICAL HEADS FLY 50,000 TIMES FURTHER AWAY THAN MAGNETIC HEADS (~20NM)**
- **THE DATA STORAGE PYRAMID IS <u>ACCEPTED</u> AS TECHNOLOGICAL AND BUSINESS REALITY**

10^{21}B

UPPERBOUND STORAGE FOR ALL THE WORDS SPOKEN BY ALL HUMANS FOR THE PAST 10,000 YEARS

EVIDENCE FOR A TRIUNE STRUCTURE OF NATURE

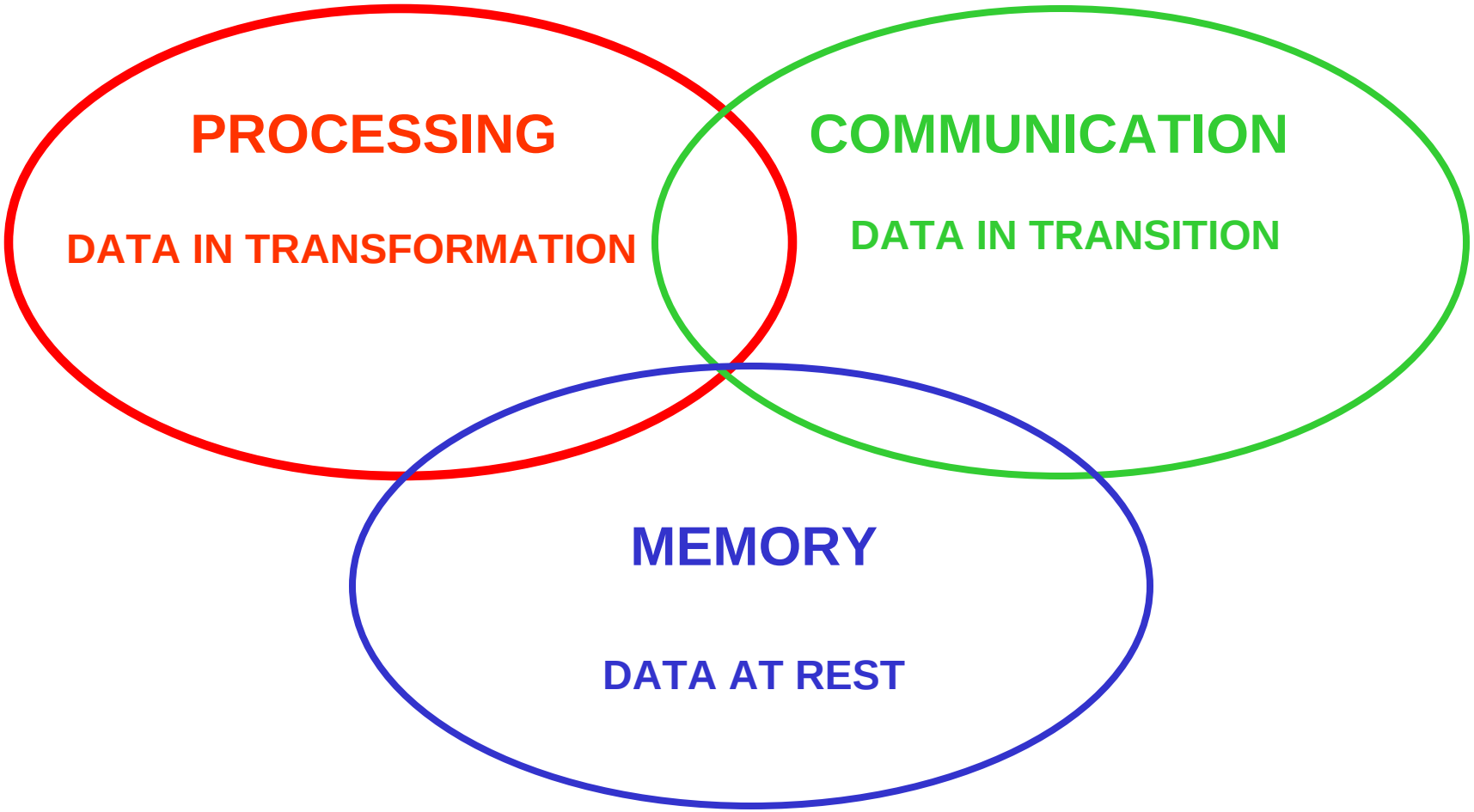
KNOWLEDGE	**MEMORY**	**GÖDEL**	**THEORY**	**FATHER**
INFORMATION	**PROCESSING**	**ESHER**	**EXPERIMENT**	**SON**
DATA	**COMMUNICATION**	**BACH**	**SIMULATION**	**HOLY SPIRIT**
TRANSMITTER	**PETER**	**CHARITY**		
CHANNEL	**JAMES**	**ESTEEM**		
RECEIVER	**JOHN**	**LOVE**		

EVIDENCE FOR A TRIUNE STRUCTURE TO PARTS OF HUMAN NATURE

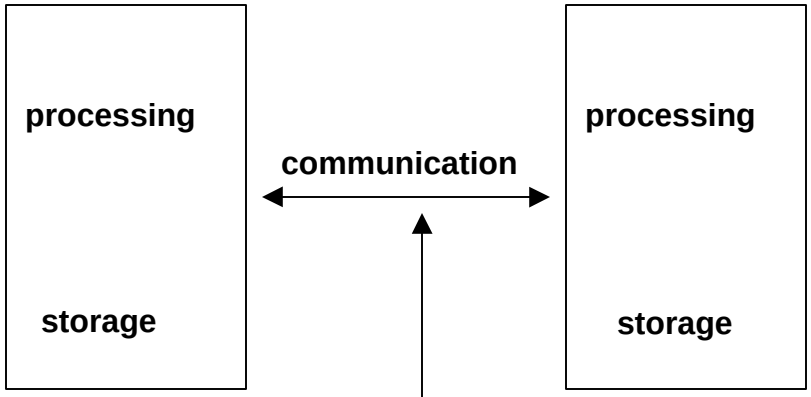
JAMES	MARTIN	JOHN	RICHARD	LYNDON
EARL	LUTHER	FITZGERALD	MILHOUS	BAINES
RAY	KING	KENNEDY	NIXON	JOHNSON

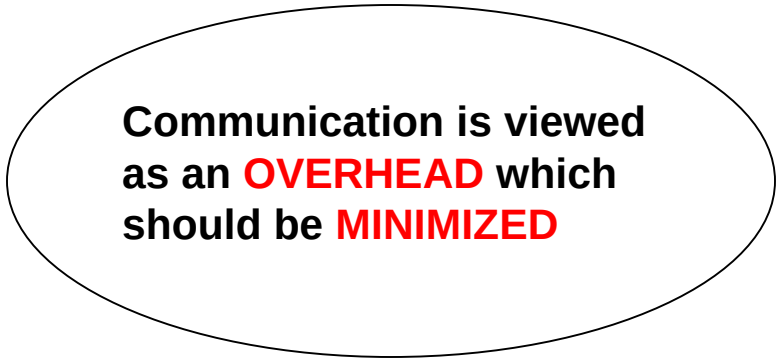
JOHN	SIRHAN	JAMES	FRANKLIN	DWIGHT
WILKES	BISHARA	KNOX	DELANO	DAVID
BOOTH	SIRHAN	POLK	ROOSEVELT	EISENHOWER

INFORMATION/KNOWLEDGE SYSTEMS

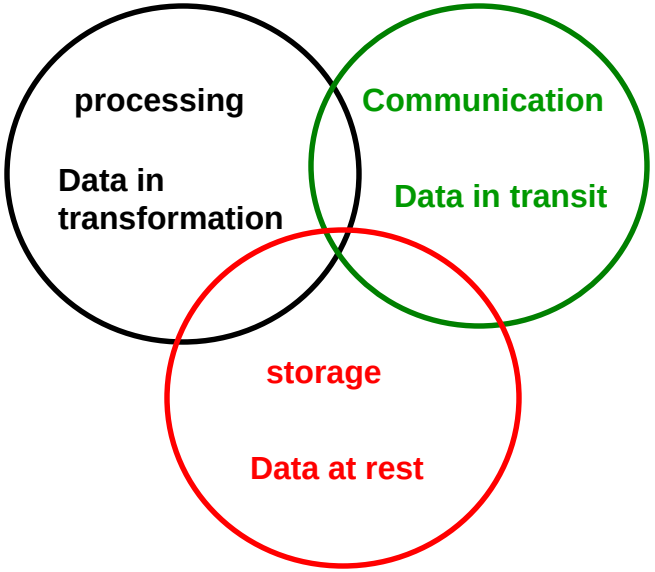


What is





What could be



Communication can be viewed as RESOURCE to be UTILIZED

For example: to achieve covert communication without high computational demands

SOME DEFINITIONS

- **STORE** — from Latin "in-staur-ave"
  - to steer
  - to guide the course of something in motion
- **RE-COLLECT** — to collect, gather or assemble again (something scattered)
- **RECOLLECT** — to recall to mind, recover knowledge of by memory; from Latin recolligere: to remember
- **MEMORY** — the capacity of retaining and reviving facts, events, impressions, information; recalling and recognizing experiences
- **RECOLLECTION** — to draw from memory

PRELUDE

PRELUDE

- **1910 … 1913 … 1986**
- **CNN: “YOU ARE WHAT YOU KNOW”**
- **ON SENILE DEMENTIA**
  - **YOU ARE WHAT YOU KNOW**
  - **YOU ARE WHAT YOU CAN ACCESS**
  - **YOU ARE WHAT YOU CAN COMPUTE**

MEMORY VS TIME

- **TIME IS NOT THE FUNDAMENTAL BASIS OF OUR UNIVERSE**
- **SHAKESPEARE**
  - **"…the child is father to the man…"**
  - **"Tomorrow, tomorrow and tomorrow**
    Creeps in this petty pace from day to day
    To the last syllable of recorded time;
    And all our yesterdays have lighted fools the way to dusty death
    Out, Out, brief candle!
    Life is but a walking shadow, a poor player
    That struts and frets his hour upon the stage
    and then is heard no more.
    It is a tale told by an idiot, full of sound and fury,
    signifying nothing.

    Macbeth, Act 5, Scene 5

MEMORY VS TIME

- **MEMORY WAGES WAR WITH TIME**
- **20,000 YEARS AGO IN FRANCE …**
- **ALLIES OF MEMORY: COMPUTATION & COMMUNICATION**

HISTORICAL PERSPECTIVE

GREEK ANTECEDENTS

SOCRATES - b 469 BC Athens d 399 BC

- wrote nothing; key disciples: Xenophon; Plato

PLATO - b 428 BC Athens d 348 BC

- established School of Philosophy 388 BC
- key disciple: Aristotle (whose writings take the form of dialogues with Socrates as the chief speaker)
- wrote: - Republic
  - Symposium
  - Phaedrus (in which a person, Phaedo speaks with Socrates)

ON THE QUINTESSENCE OF MEMORY

- **WRITING IS VISIBLE SPEECH FROM WHICH A READER MAY RECONSTRUCT THE VOCAL MESSAGE**
- **FIRST WRITINGS: ~ 3000BC**
  - **SUMERIANS IN LOWER MESOPOTAMIA**
  - **EGYPTIANS**

ON THE QUINTESSENCE OF MEMORY (CON'T)

- **In Plato's *Phaedrus,* Socrates tells a story about the Egyptian God, Thoth, inventor of arithmetic, geometry, astronomy, dice, and writing:**
  - **Thoth to Egyptian King Thamus: "As for writing, here is an accomplishment which will improve both the wisdom and the memory of Egyptians."**

THAMUS REPLIED:

“Those who acquire writing will cease to exercise their memory and become forgetful; they will rely on writing to bring things to their remembrance by external signs instead of their own resources. What you have invented is a recipe for recollection not for memory. People will receive a quantity of information from script; they will look knowledgeable, when in fact they will be quite ignorant.”

SOCRATES:

"Writing will not help in the search for truth…a painting looks like a living being but if you ask it a question it is mute… if you ask written words a question you get the same answer over and over. Writing cannot distinguish between suitable and unsuitable readers: it can be ill-treated or unfairly abused, but it cannot defend itself. In contrast, truths found in the art of dialectic CAN defend themselves. Thus, the spoken word is superior to the written word!"

After Michael Coe

Breaking the Maya Code

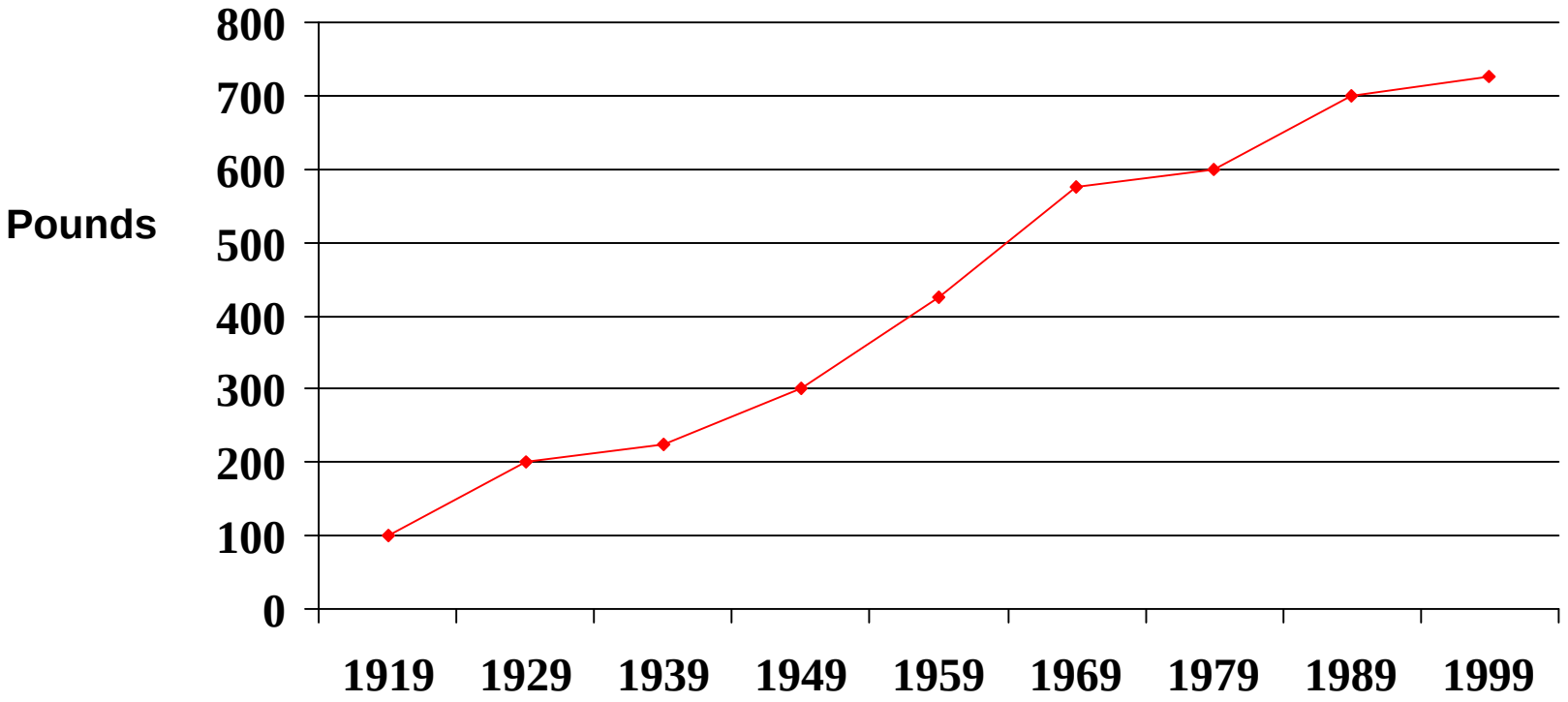
IMAGINE HOW OUR WORLD WOULD DIFFER IF ODYSSEUS HAD HAD A CELL PHONE

STORAGE TECHNOLOGIES

NINE STORAGE TECHNOLOGIES

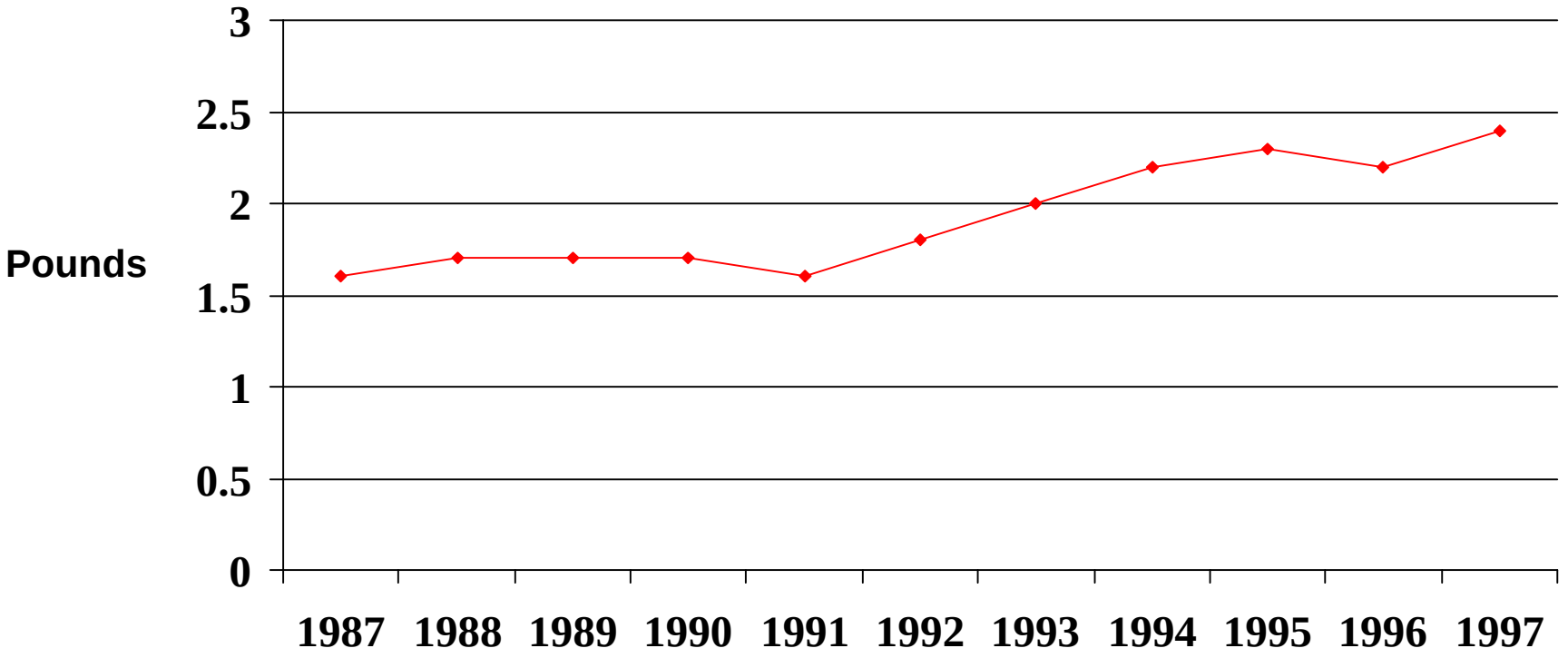
- **ROCK (STRUCTURE, PETROGLYPHS, PICTOGRAPHS)**
  E.G., EASTER ISLAND, E.G. SW, FRANCE STONEHENGE
- **PAPER (INKS)**
- **FILM (SILVER OR DYE)**
- **MAGNETIC**
- **MAGNETO OPTICAL**
- **OPTICAL (PHASE CHANGE)**
- **OPTICAL (HOLOGRAPHIC)**
- **MEMS SENSORS ON A MEDIA SLED**
- **COMMUNICATION LOOPS**
  - - - - -
  - - - - -
  - - - - -

U.S. CONSUMPTION OF PAPER AND PAPERBOARD PER CAPITA, 1919-1999



Source: S. Adams. The Corporate Memory Concept, 1995

U.S. CONSUMPTION OF PAPER FOR FILE FOLDER PER CAPITA, 1987-1997



Source: S. Adams, The Corporate Memory Concept, 1995

MANAGING PAPER STORAGE

THE BAD

- **3 % incorrectly filed**
- **7 % never found**
- **~ 3 hours/week/person seeking mislabeled, misfiled or lost documents**

THE GOOD

- **easy personalization by markup**
- **easy parallel view**
- **low cost**

CHANGING MORES

Yesterday

PRINT → COPY → DISTRIBUTE

Today

DISTRIBUTE → VIEW → PRINT

Source: S. Adams, The Corporate memory Concept, 1995

DIGITAL PAPER

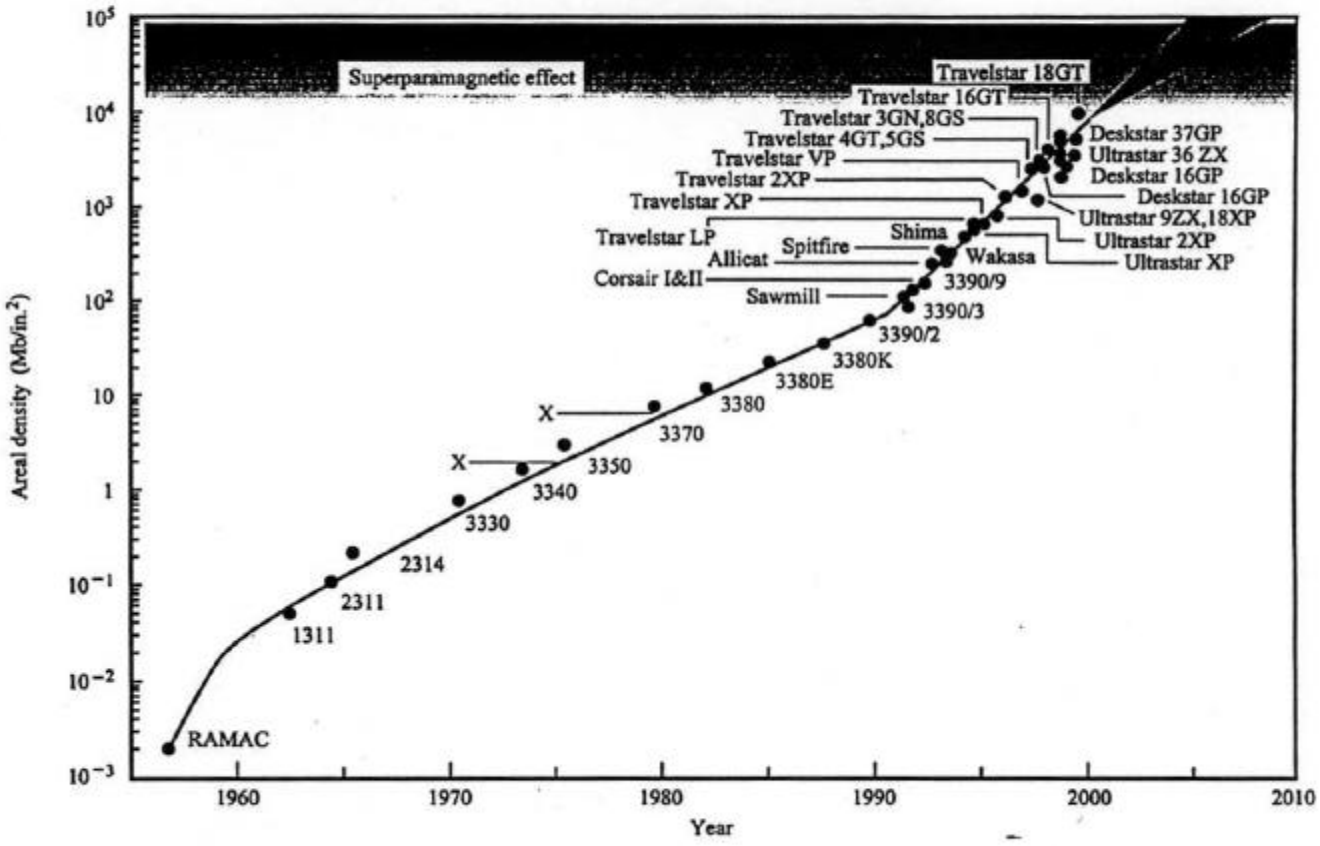
- **ANOTO (SWEDEN)**
  - **6 X 6 .1MM 4 POSITION MODULATED DOTS IN 2MM X 2MM SQUARES**
  - **$2^{72} \sim 4.710^{21}$ PATTERNS**
  - **ABOUT TWICE THE SURFACE AREA OF THE EARTH**
- **ERICSSON CHATPEN WITH A CLOCK, ~400 PAGES OF DOT PATTERNS PER MB, AND ABILITY TO TIME STAMP SEQUENCE OF DOT PATTERNS**
- **BUSINESS MODEL: SELL PAPER (OR OTHER) "DOT-PATTERN REAL ESTATE" AS DIGITAL PAPER**

MAGNETIC MEMORY

KEY FACTORS IN MAGNETIC STORAGE PROGRESS

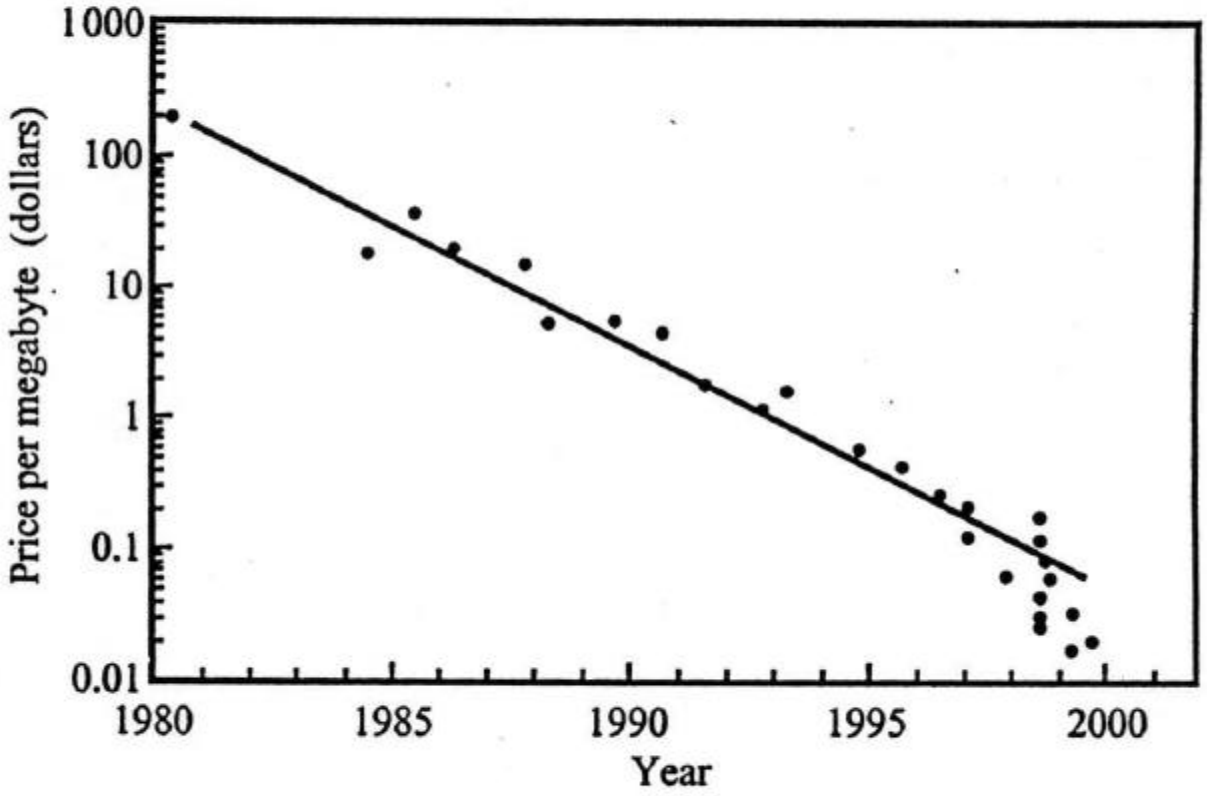
- **Mass Production**
- **Lowering Costs**
- **Higher Yields**
- **Innovation in mechanics, materials manufacturing, integration, heads, signal processing, aerodynamics**
- **Head Size Decreases → Head Flies Closer**
  (few mm across) (£20 nm)
- **Spin Raster → Faster Data Rater**
  (£10,000 RPM)
- **Data Storage Pyramid**

MAGNETIC DISK STORAGE AREAL DENSITY VS. YEAR OF IBM PRODUCT INTRODUCTION

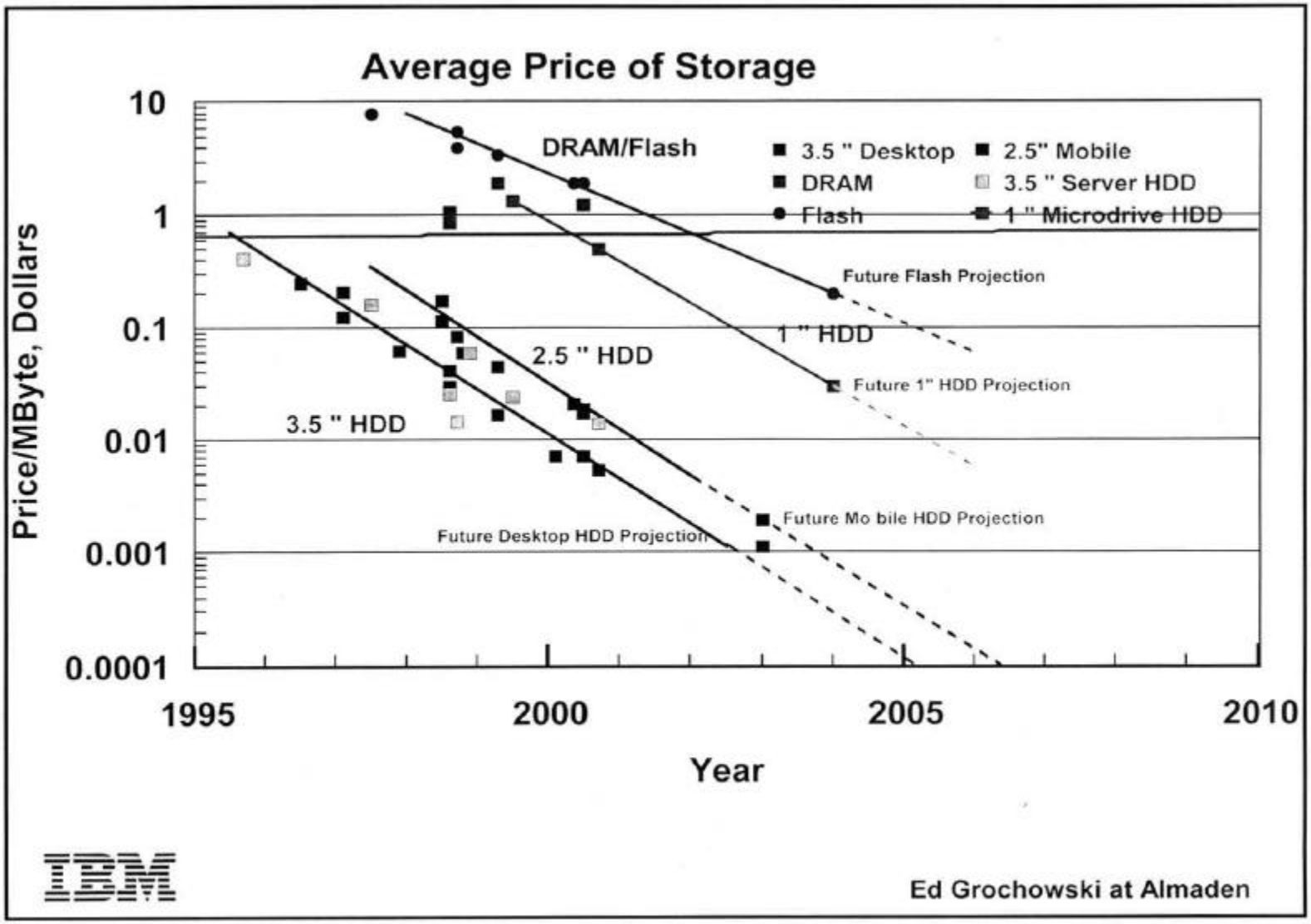


Source: D. Thompson, J. Best, The Future of Magnetic Data and Storage Technology, IBM J. Res Dev, May 2000

PRICE HISTORY OF HARD DISK PRODUCTS VS. YEAR OF PRODUCT INTRODUCTION

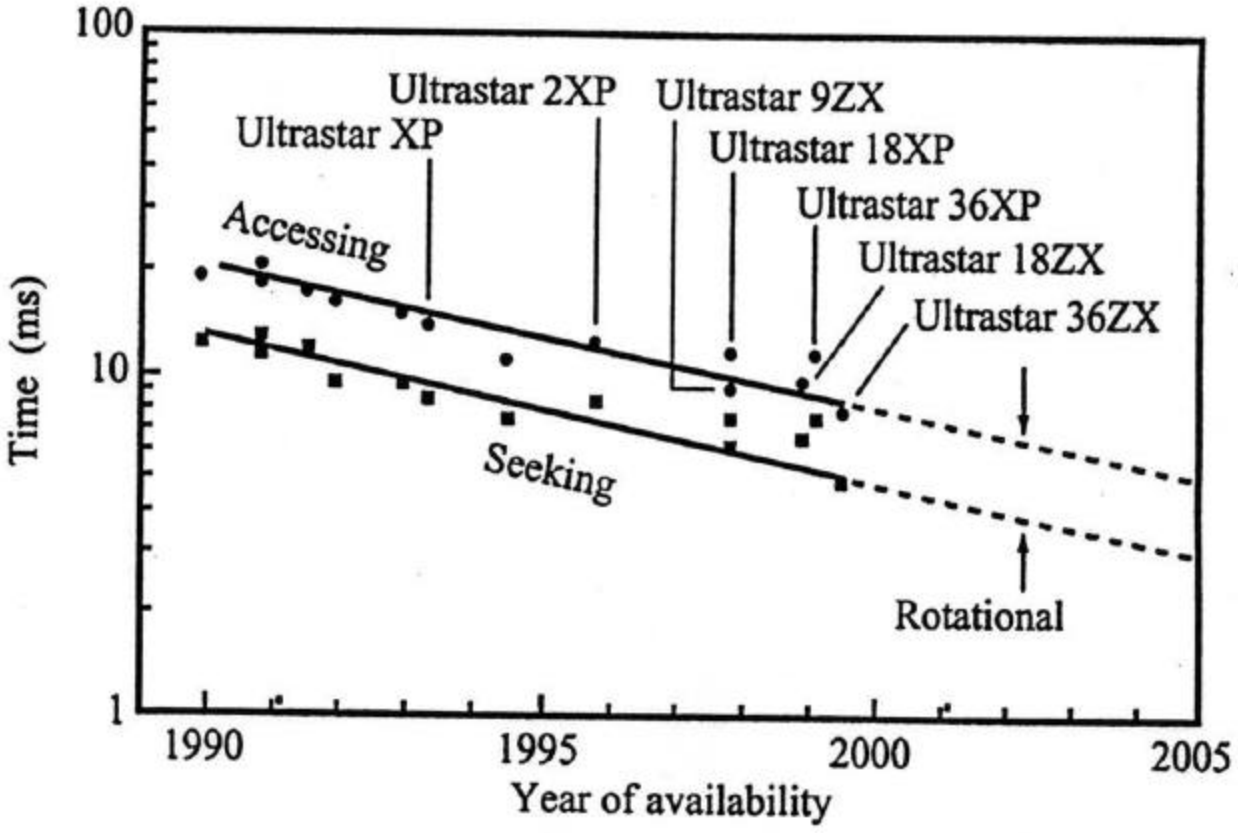


Source: D. Thompson, J. Best, The Future of Magnetic Data and Storage Technology, IBM J. Res Dev, May 2000



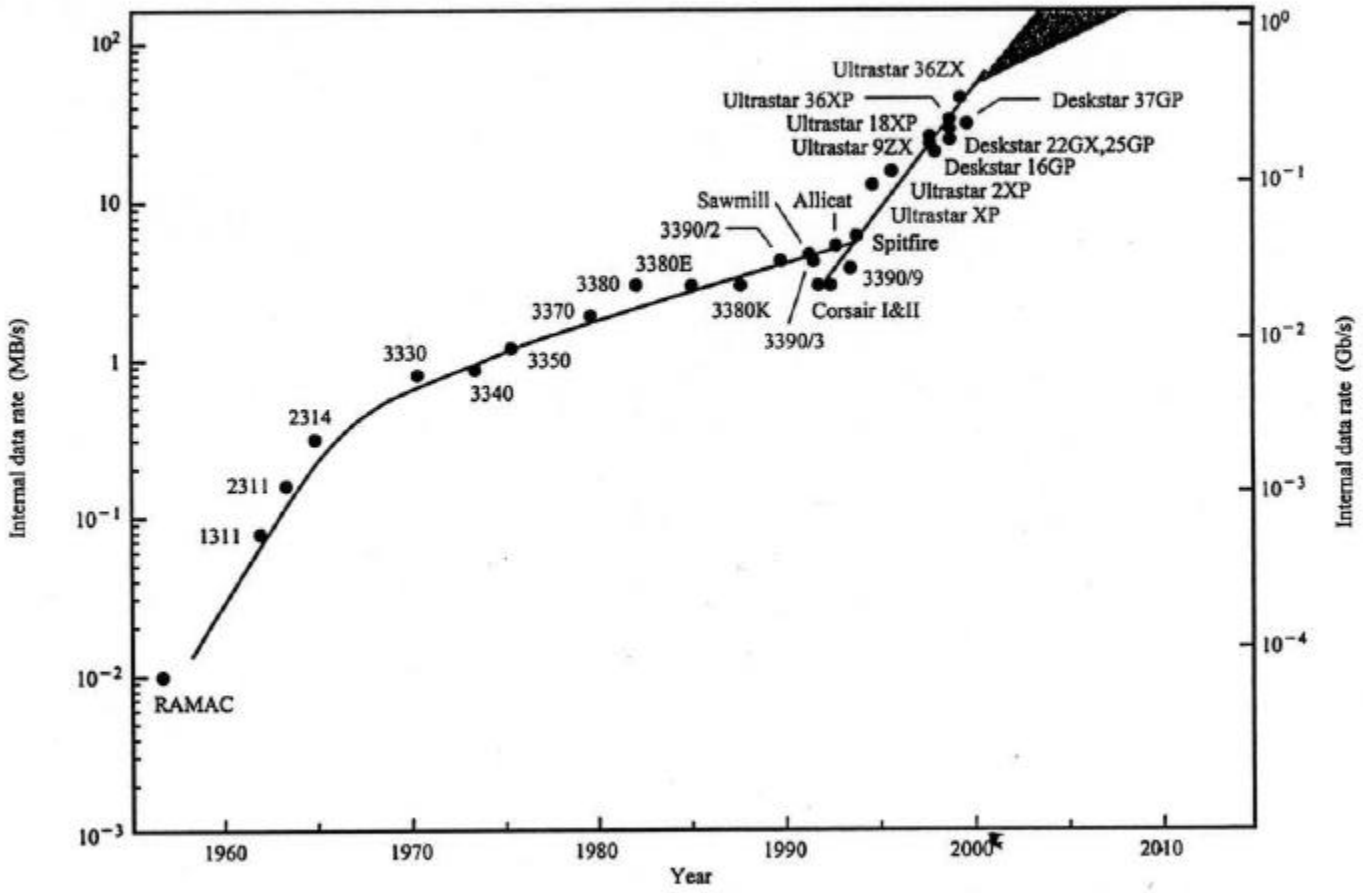
oemprc2000ag.prz

PERFORMANCE HISTORY OF IBM DISK PRODUCTS WITH RESPECT TO ACCESS TIME



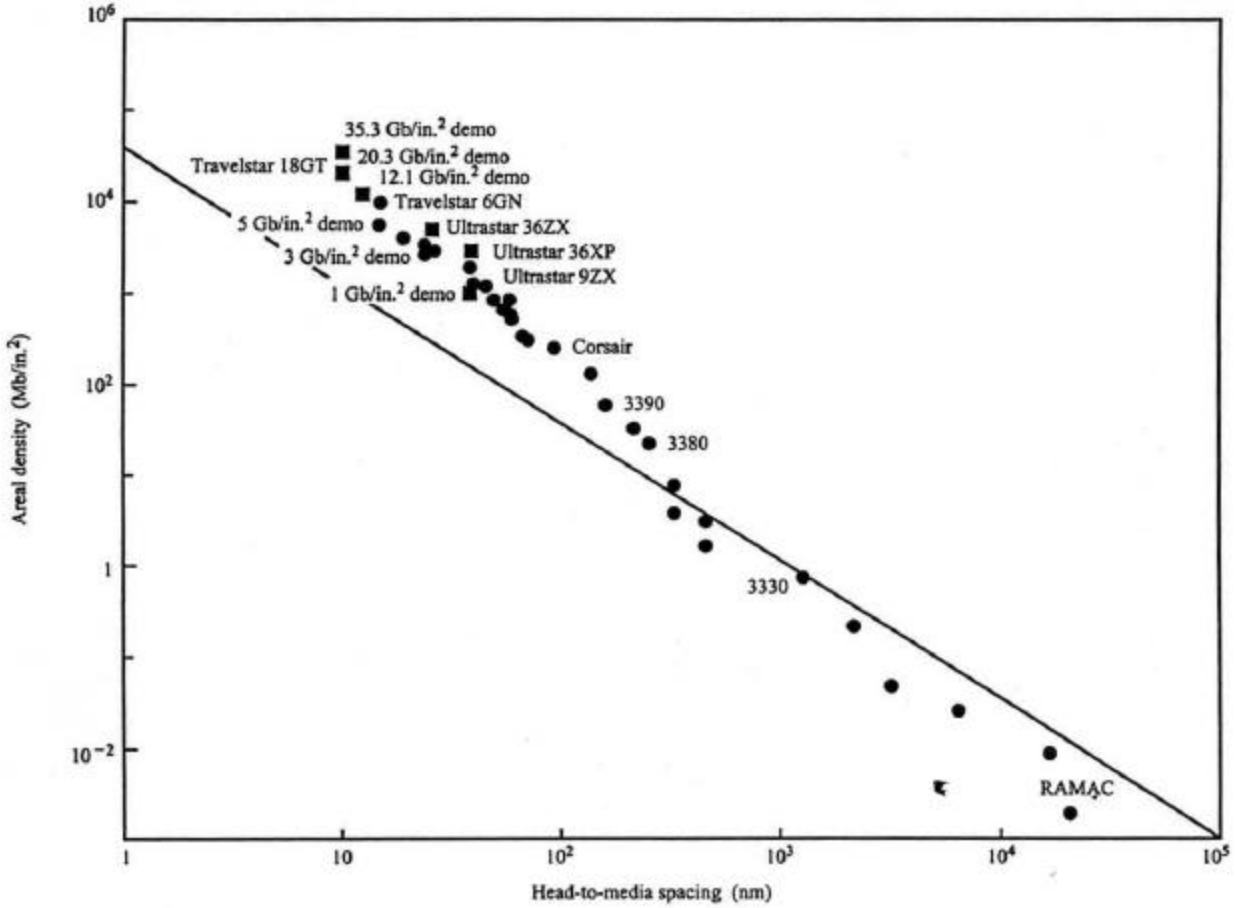
Source: D. Thompson, J. Best, The Future of Magnetic Data and Storage Technology, IBM J. Res Dev, May 2000

PERFORMANCE HISTORY OF IBM DISK PRODUCTS WITH RESPECT TO DATA RATE



Source: D. Thompson, J. Best, The Future of Magnetic Data and Storage Technology, IBM J. Res Dev, May 2000

HEAD-TO-MEDIA SPACING IN IBM MAGNETIC HARD DISK DRIVES VS. PRODUCT AREAL DENSITY



Source: D. Thompson, J. Best, The Future of Magnetic Data and Storage Technology, IBM J. Res Dev, May 2000

MAGNETIC MEMORY TODAY

- **$32B/YEAR WORLDWIDE (CF $23B DRAM)**
- **TRACKS: 1 NM ® .5 NM ® .3 NM**
- **SUBSTRATE: AL ® GLASS (RIGIDITY)**
- **IBM'S MICRODRIVE: 1 GB/27MM DIAM ® 2.4 Gb/CM^2**
- **100'S GRAINS/BIT**
- **DENSITY DOUBLING EACH YEAR 1997 - 2005**
- **1¢ / MB**

MAGNETIC MEMORY
TODAY'S PROMISES

- **APRIL 2000 (FUJITSU) 8.7Gb/CM^2 ® 50 WITH**
  2 LAYERS PERPENDICULAR
  Co RUTHENIUM Co RECORDING

- **OCT 1999 (IBM) 5.4 Gb/CM^2**

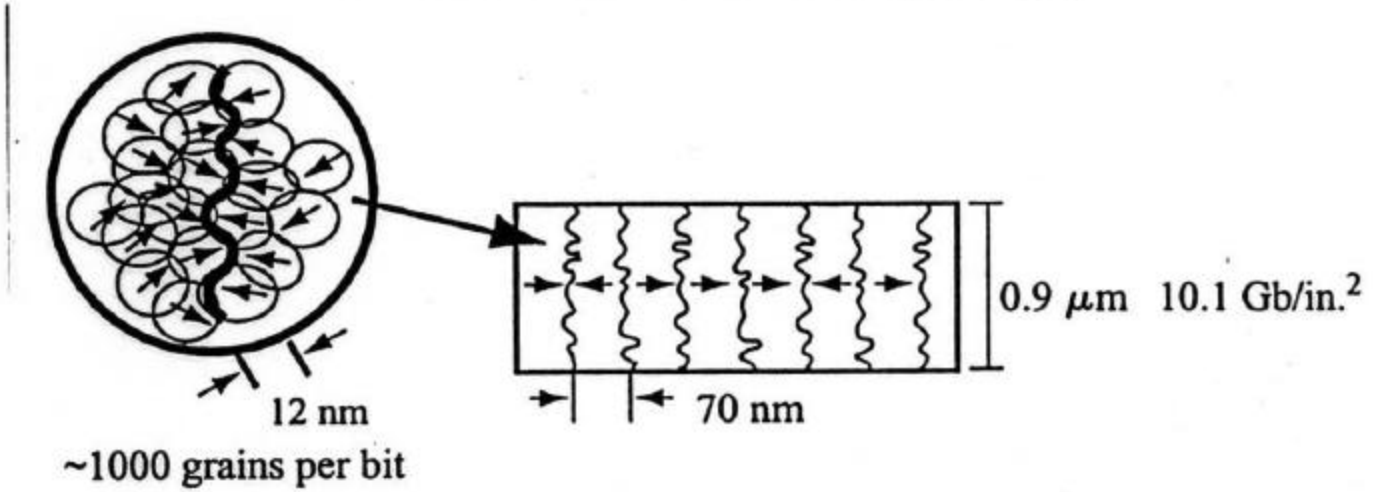
- **MAY 1999 (IBM) 3.1 Gb/CM^2**

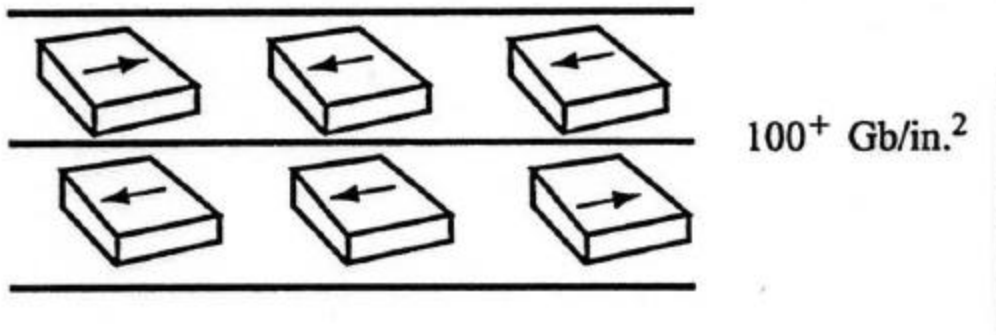
MAGNETIC MEMORY
TODAY'S PROMISES

- **SUPER PARAMAGNETIC EFFECT: ^{3} 10 NM GRAIN**
  IMPLIES < 1000 Gb/CM^2

- **ORGANICALLY GROWN MAGNETIC THIN FILM ON PATTERNED MEDIA ® 700 Gb/CM^2**
  (SINGLE GRAIN/BIT)

MAGNETIC TRANSITIONS FOR SCHEMES INVOLVING MANY GRAINS PER BIT AND ONE GRAIN PER BIT





Source: D. Thompson, J. Best, The Future of Magnetic Data and Storage Technology, IBM J. Res Dev, May 2000

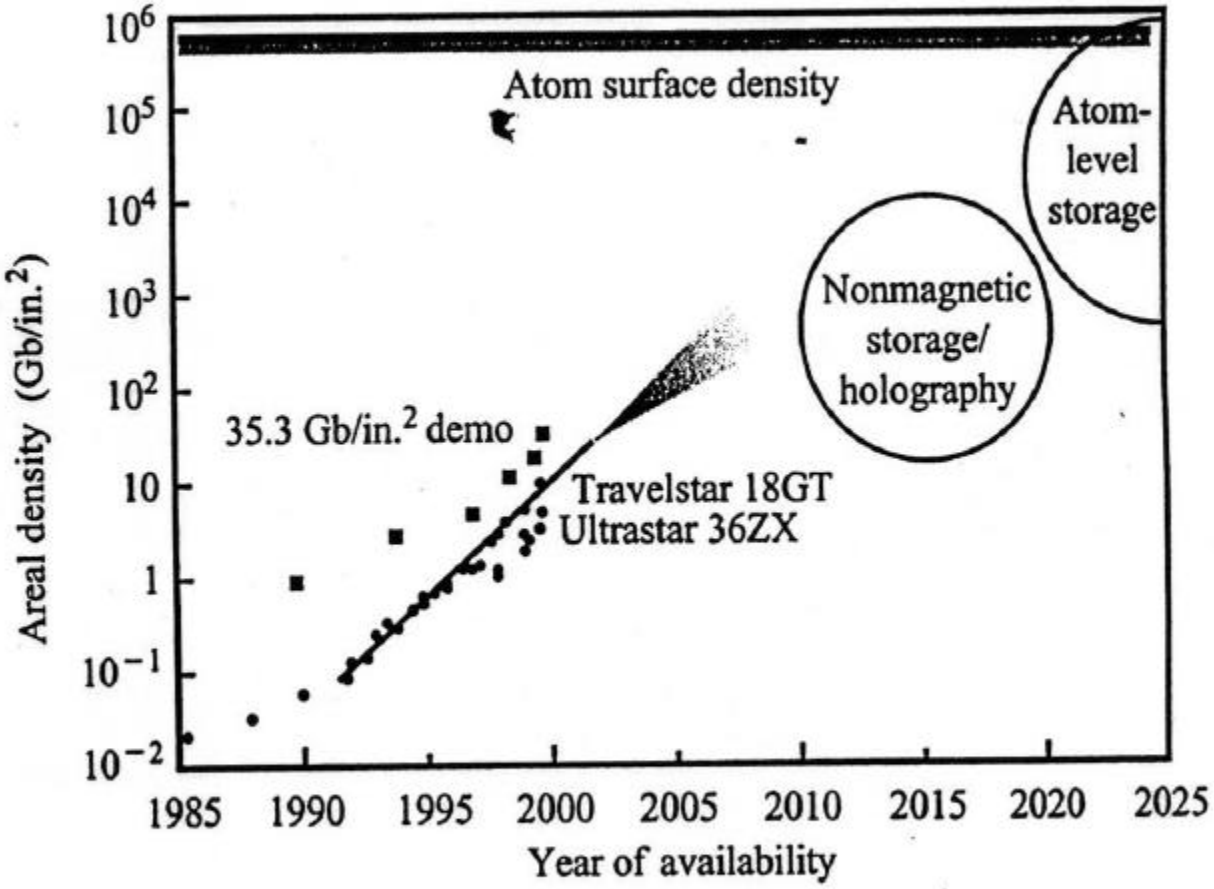
MAGNETIC MEMORY
A PROMISE FROM THE PAST

- **SUPER PARAMAGNETIC EFFECT ® SPONTANEOUS DEMAGNITIZATION (THERMAL SELF ERASURE) FOR GRAINS BELOW 10NM**

- **TERA STORE'S SOLUTION: COMBINED MAGNETIC AND OPTICAL STORAGE**
  - **1995 GOAL 30 GB 130 MM**
  - **1997 GOAL 20 GB 130 MM**
  - **1998 GOAL 10 GB 130 MM**
  - **TODAY — GONE**


ome things in life are never certain

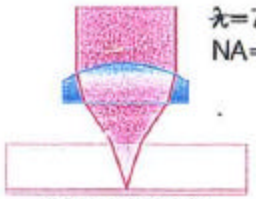
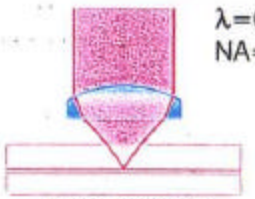
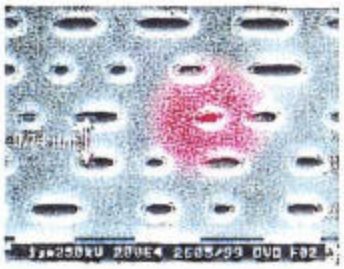
LONG-TERM DATA STORAGE ROADMAP



Source: D. Thompson, J. Best, The Future of Magnetic Data and Storage Technology, IBM J. Res Dev, May 2000

OPTICAL MEMORY

THREE GENERATIONS OF OPTICAL DISC SYSTEMS

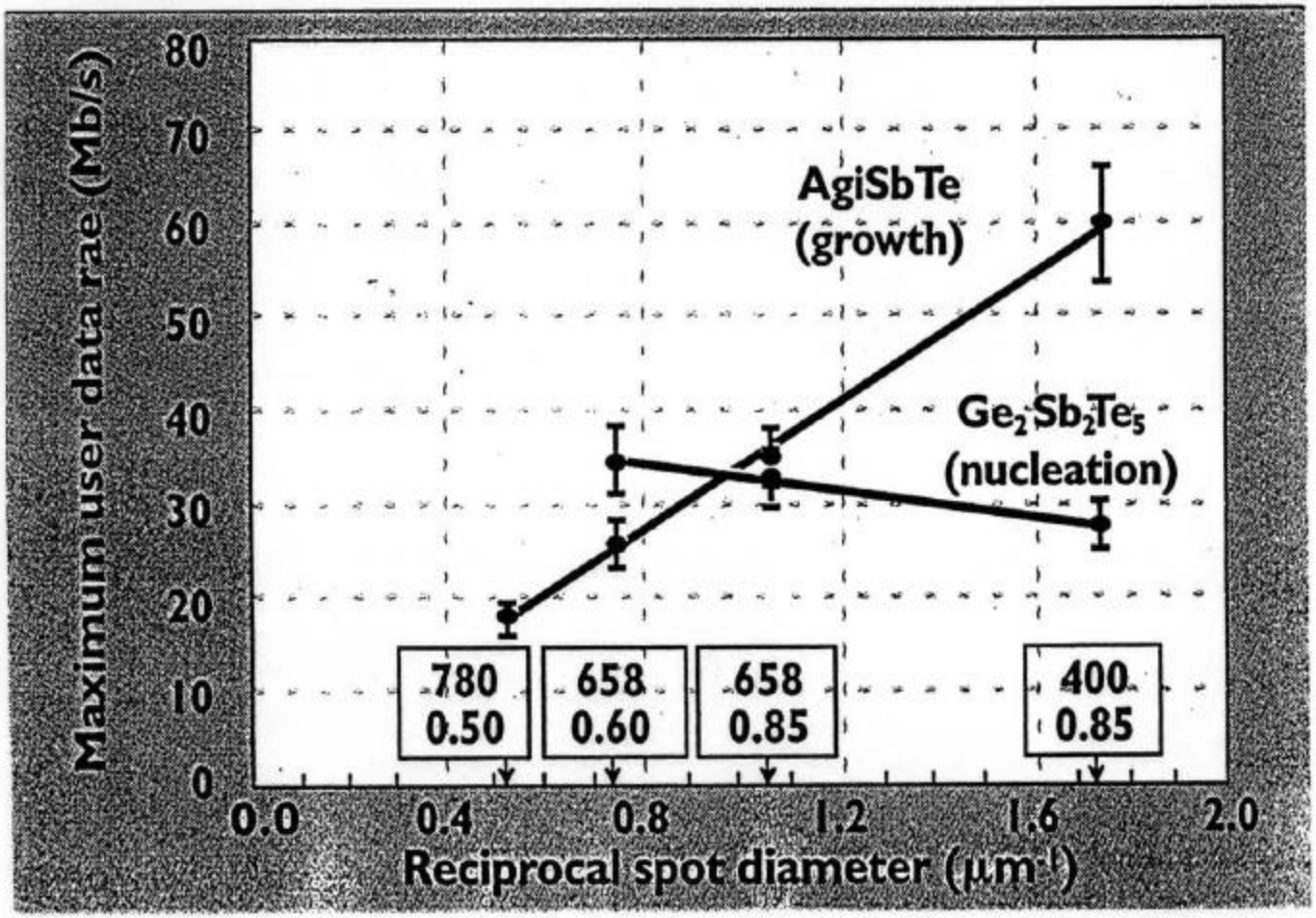
CD	DVD	DVR
 λ=780 nm NA=0.45 1.2 mm substrate	 λ=650 nm NA=0.6 0.6 mm substrate	 λ=400 nm NA=0.85 0.1 mm cover layer
		

Source: H. van Houten, W. Leibrandt, Phase Change Recording. *Communications of the ACM.* [Nov 2000/Vol. 43, No.1] p.70

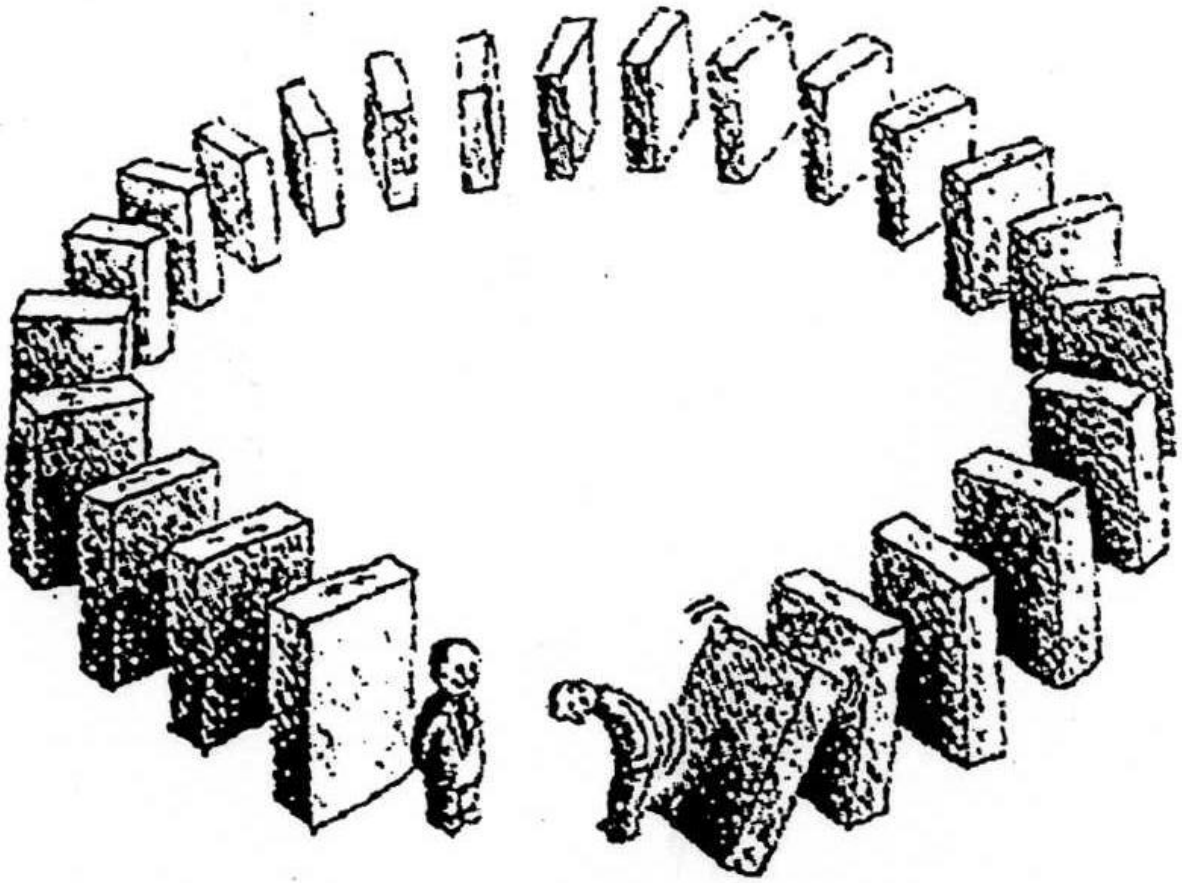
Optical Phase Change

CD	DVD	DVR
650 MB	4.7GB	22GB
CD-ROM	DVD-ROM	
CD-RW	DVD-RW	
	DVD-RAM	

THE AGINSBTE PHASE-CHANGE MATERIAL IS A "FAST GROWTH MATERIAL" RESULTING IN HIGHER DATA RATES FOR SMALLER SPOT SIZES



Source: H. van Houten, W. Leibrandt, Phase Change Recording. *Communications of the ACM.* [Nov 2000/Vol. 43, No.1] p.71



Chen/Satire & Humor/Beijing

NETWORKED MEMORY

NETWORKED MEMORY

- **CONNECTED MEMORY YIELDS INTELLIGENT BEHAVIOR**
  - **PROVERBS 6:6: "GO TO THE ANT THOU SLUGGARD; CONSIDER HER WAYS AND BE WISE"**
  - **KING HENRY V: "FOR SO WORK THE HONEYBEES, CREATURES THAT BY A RULE OF NATURE TEACH THE ACT OF ORDER TO A PEOPLED KINGDOM"**
  - **GROUP LIVING ENHANCES SURVIVAL**

NETWORKED STORAGE

PROS

- REDUCES WASTE
- REDUCES UPGRADE TIME
- REDUCES BACKUP INCONVENIENCE
- SIMPLIFIES MANAGEMENT
- INCREASES DATA AVAILABILITY
- ENABLES SHARING

CONS

- INCREASED SYSTEM COMPLEXITY
- INCREASED TECHNOLOGY COSTS
- INCREASED PRIVACY/SECURITY RISKS

NETWORKED ATTACHED STORAGE : STORAGE AREA NETWORK

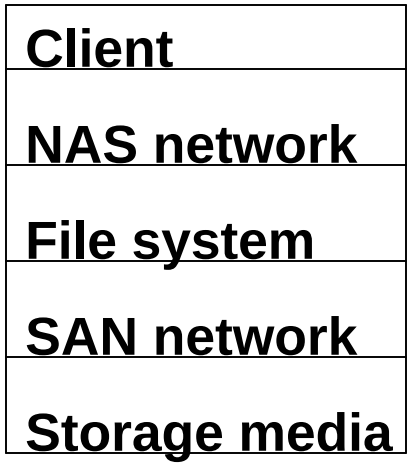
…the yin and yang of networked memory...

NAS

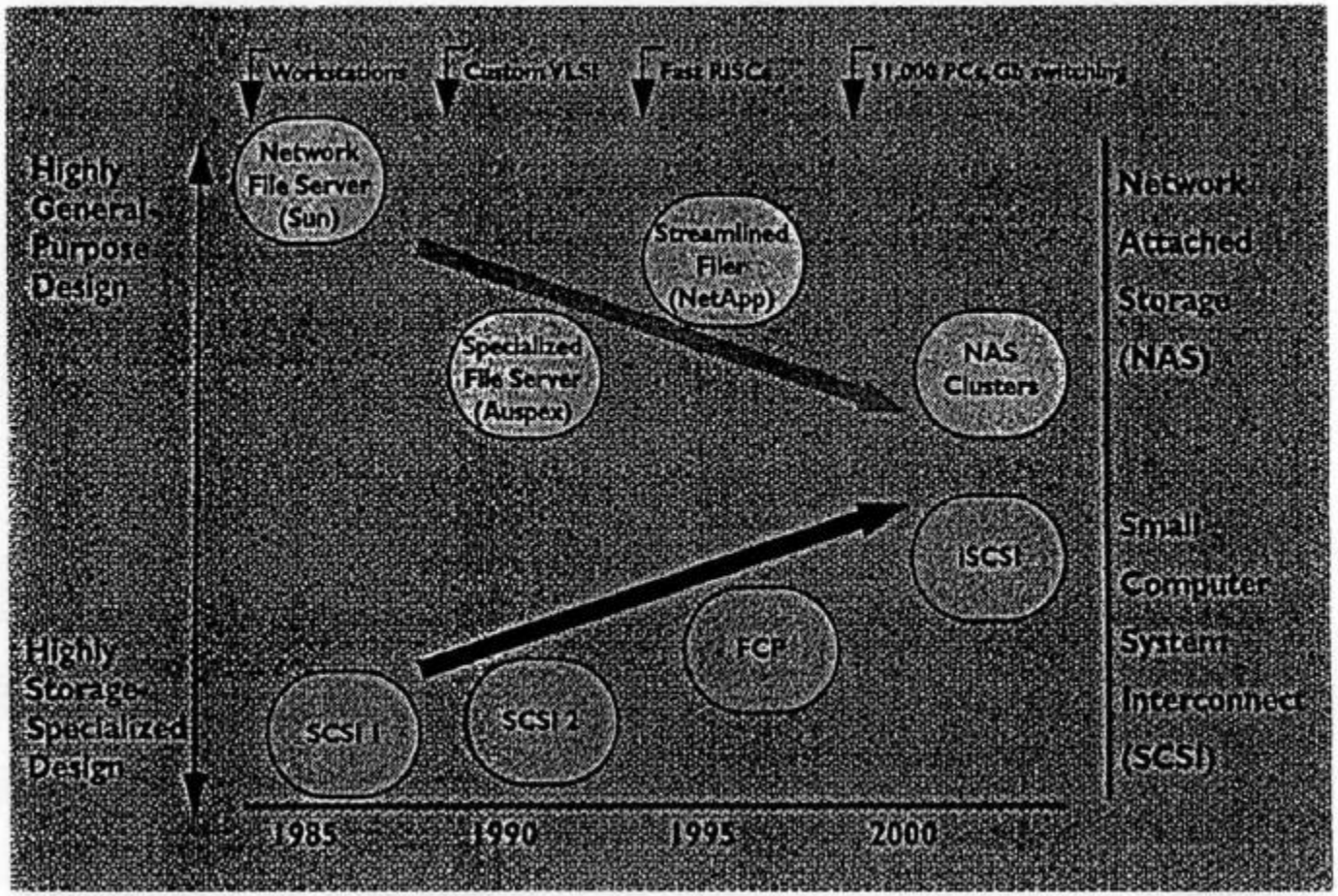
- File system functionality & data abstractions
- Installed and configured without interrupting client machines
- Typically Gigabit Ethernet based

SAN

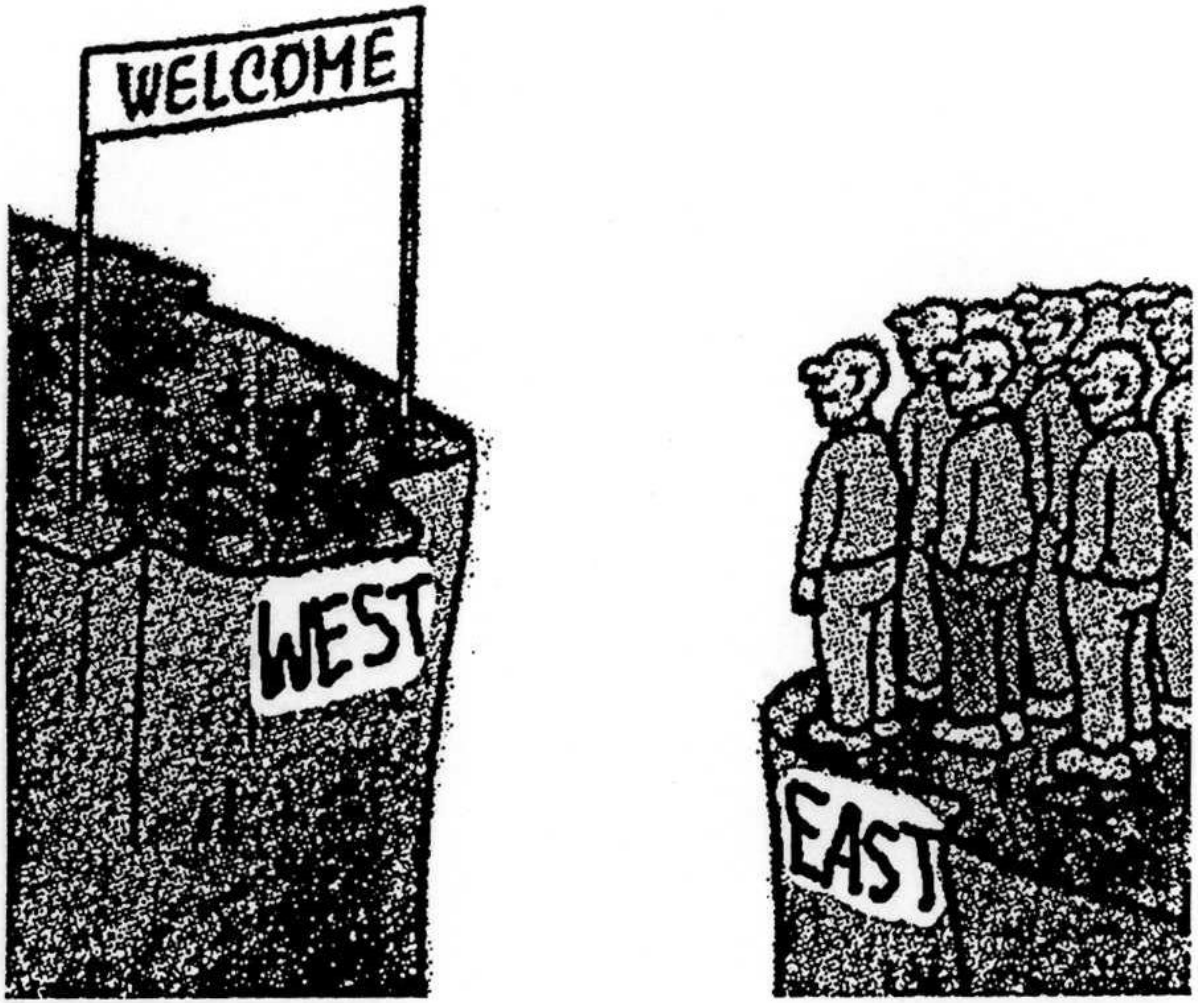
- Memory-like interfaces which represent multiple-disks as one
- Typically fiber channel based with SCSI signaling and congestion control



CONVERGENCE OF SCSI NETWORKING (SAN) AND NETWORK FILE SYSTEMS (NAS)



Source: G. Gibson, R. Van Meter, Network Attached Storage Architecture, *Communications of the ACM.* [Nov 2000/Vol. 43, No.1] , p.41



Jonita/Sturshel/Sofia

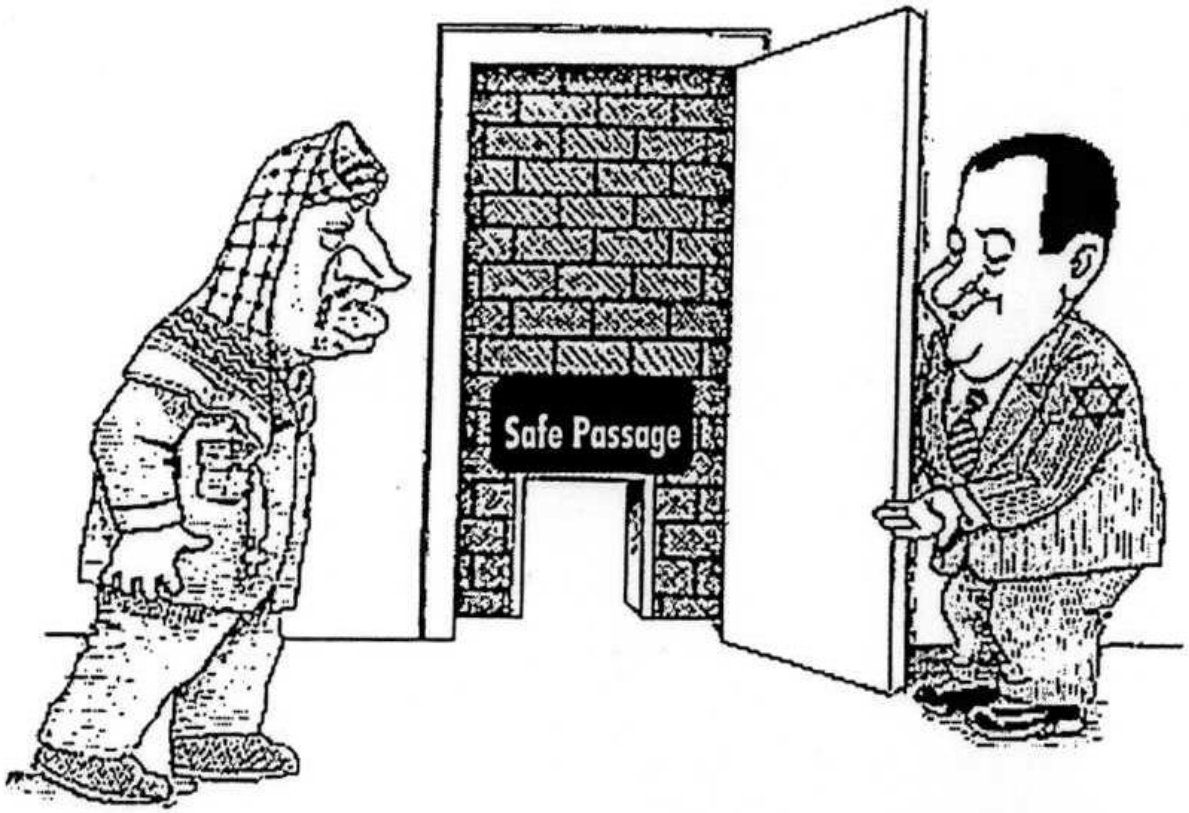
SCALING SIZE STRESSES IMPLEMENTATION MECHANISMS

WHAT IS BEING SCALED	WHAT MECHANISMS ARE STRESSED?
number of client and server nodes	resource, discovery; network bandwidth and congestion control; addressing
distance	network congestion and flow control; latency and round-trip dependencies; resource discovery; security; network routing
aggregate and individual bandwidth	interconnect technology; protocol processing in client and server OS
number and size of files	application addressing; file metadata management
directory size and tree depth	file metadata management; round-trip time for repeated name lookup

Source: G. Gibson, R. Van Meter, Network Attached Storage Architecture, *Communications of the ACM.* [Nov 2000/Vol. 43, No.1] , p.40

TOTAL OWNERSHIP MEMORY COSTS

- **$ FOR MEMORY > 50% $ FOR DATA CENTERS**
  - **® 75% OVER NEXT FEW YEARS**
- **MANAGEMENT $ > EQUIPMENT $ (~ $300/GB/YEAR)**



Gomaa/Al-Ahram Weekly/Cairo

SOME CHARACTERISTIC PARAMETERS OF NETWORKED STORAGE

- DEPLOYMENT
- MANAGEMENT
- BACKUP
- AVAILABILITY
- SHARING
- ACCESS CONTROL
- CAPACITY
- LATENCY
- DENSITY
- ENERGY
- STORAGE ABSTRACTION INTERFACE
- BOTTLENECKS
- CONTROL/DATA COMMUNICATION PATHS
- CLUSTERING
- GEOGRAPHIC DISPERSION
- METADATA
- AAA
- PARALLELIZATION

ON MYTHS

THE DANGER OF MYTHS ILLUSTRATED BY THE MYTH OF THE IDEOGRAPH

ATHANASIUS KIRCHER (1602-1680

- **TAUGHT THAT IDEOGRAPHS CONVEY MEANING INDEPENDENT OF LANGUAGE**

THE DANGER OF MYTHS ILLUSTRATED BY THE MYTH OF THE IDEOGRAPH

Jean-Francois Champollion (1790-1832

- used the Rosetta Stone [1798 Greek, demotic, Hieroglyphic] to overturn Kircher's 200 year old uncritically accepted misconception

- 1824 Summary of Hieroglyphic System of the Ancient Egyptians

  - largely phonetic
  - alternate spellings were used for same sound
  - calligraphic beauty & religious reverence played a role in the writing

Example: Chinese is not ideographic or alphabetic; it is logographic: combination of a semantic element and a phonetic element [logograph is a written sign that represents a morpheme "in"-"cred"-"ible"]

METCALFE'S LAW

METCALFE'S LAW

- **The cost of deploying a network of N nodes scales approximately linearly with N (for large N)**
- **The potential value scales approximately as N squared (for large N)**

POTENTIAL VALUE OF A NETWORK SCALES AS N SQUARED FOR LARGE N IF

- **ALL INTERACTIONS HAVE POTENTIAL VALUE WHICH IS**
  - **POSITIVE**
  - **APPROXIMATELY EQUAL**
- **THE SUM OF PAIRWISE INTERACTIONS REFLECTS THE OVERALL VALUE**
- **SIMULTANEOUS INTERACTIONS AMONG MULTIPLE ENTITIES CAN BE NEGLECTED**

CAVEATS ON N SQUARED SCALING OF NETWORK VALUE

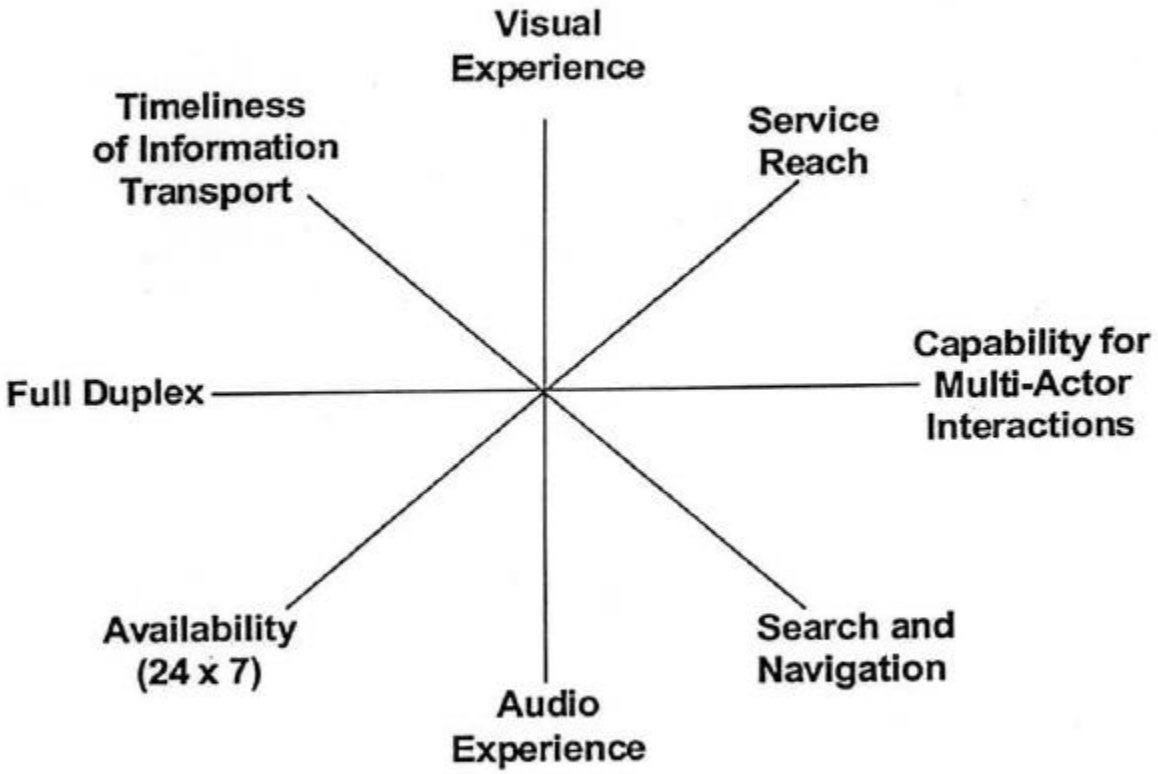
- **MANY POTENTIAL PAIRWISE INTERACTIONS DO NOT OCCUR**
- **DYNAMIC RANGE OF THE VALUE OF INDIVIDUAL PAIRWISE INTERACTIONS IS VERY LARGE**
- **THE "VALUE MATRIX" IS SPARSE AND CLUSTERED**
- **VALUE OF AN INTERACTION IS A DYNAMIC FUNCTION OF SUBSIDIARY PARAMETERS SUCH AS CONTENT, QUALITY, AND LATENCY**
- **M-WAY SIMULTANEOUS INTERACTIONS HAVE SIGNIFICANT VALUE**

INTUITIVE VIEW OF USER PERCEIVED VALUE OF A NETWORK OF N NODES THROUGH KEY ATTRIBUTES

EXAMPLE: ATTRIBUTES USED TO COMPARE

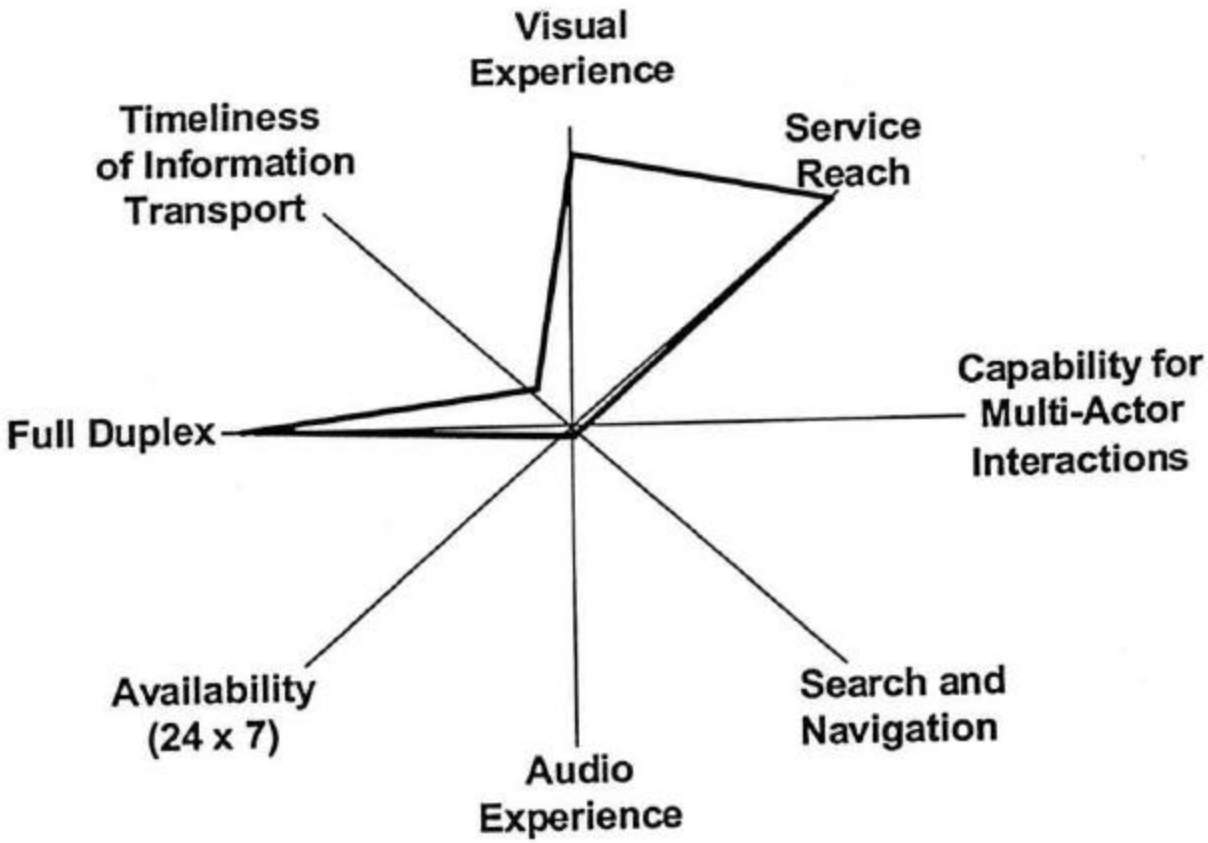
- SNAIL MAIL
- FAX
- E-MAIL
- INTERNET
- E-TAILING
- E-TRADING

ATTRIBUTES OF INFORMATION TECHNOLOGIES



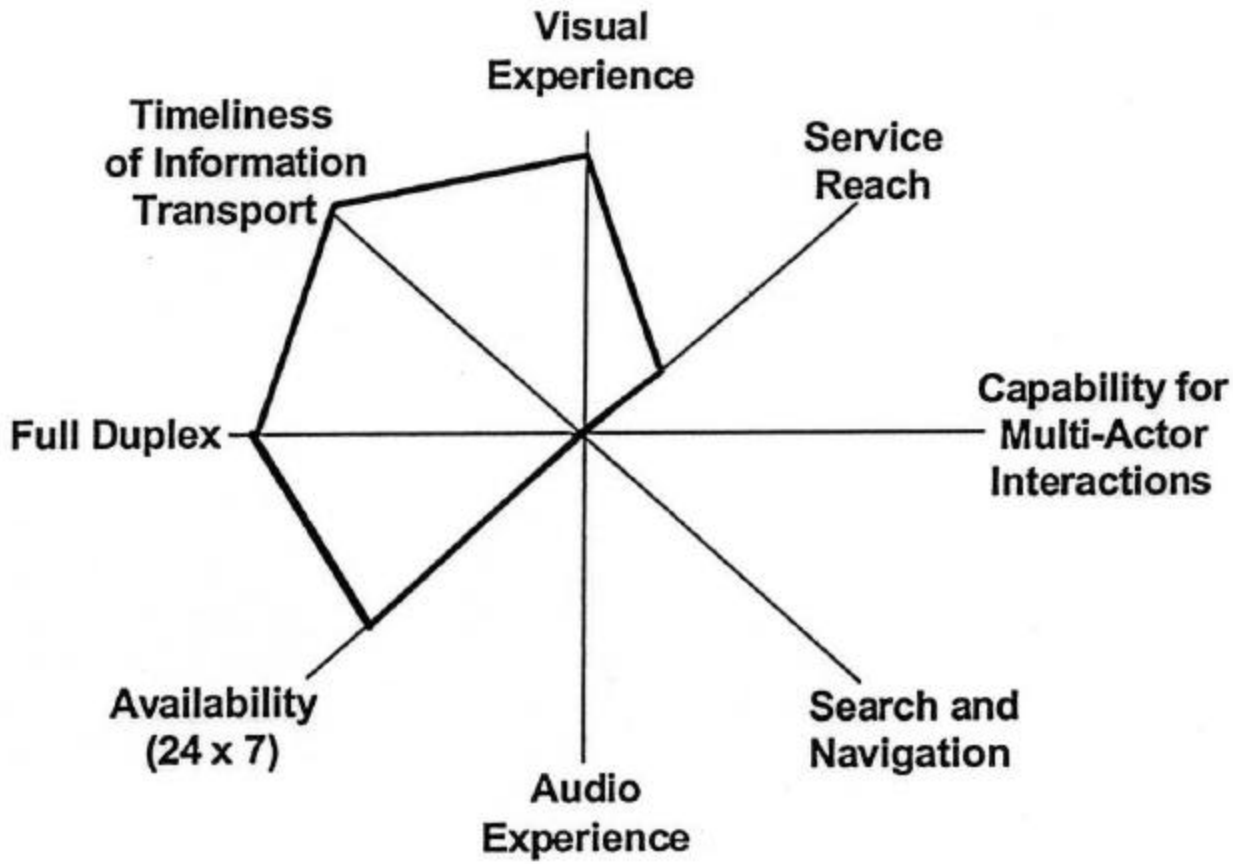
Source: D. Alberts, J. Garstka, F. Stein, NETWORK CENTRIC WARFARE, 2Ed. Rev., 1999

TRADITIONAL MAIL



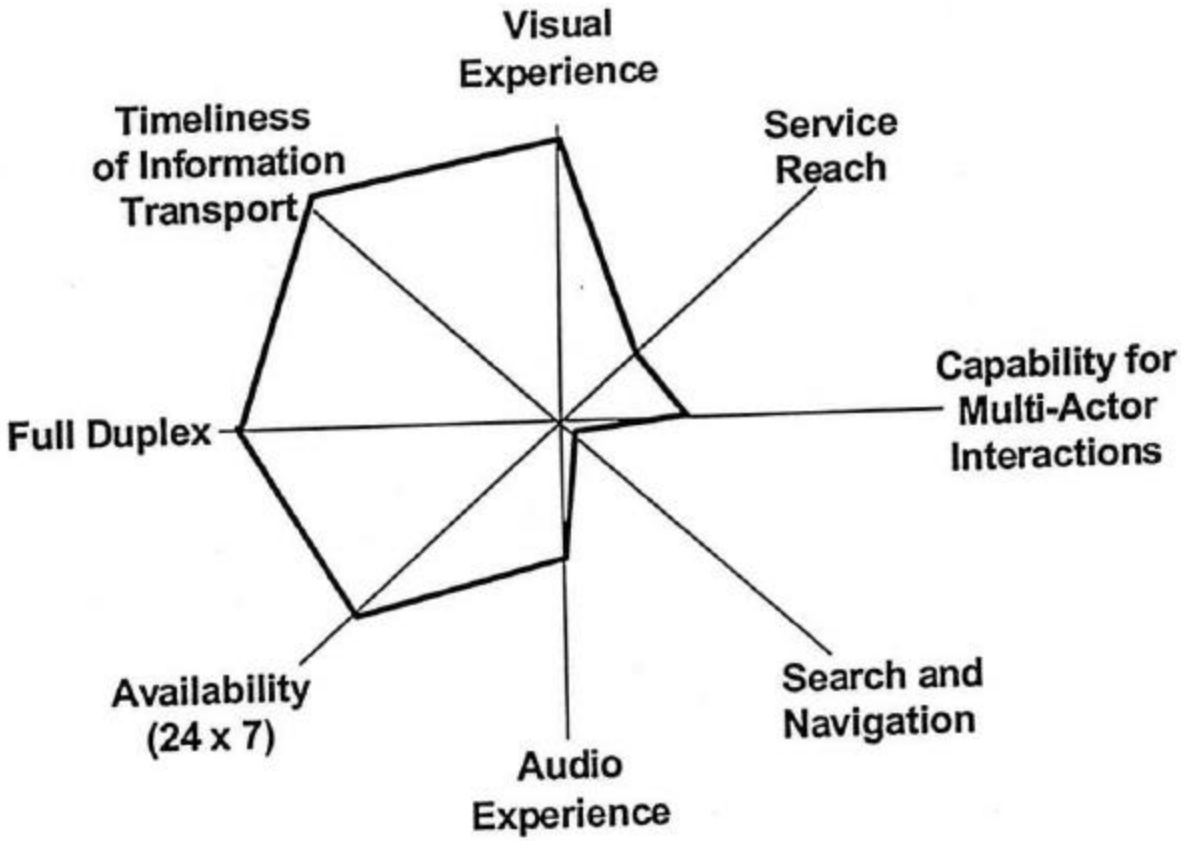
Source: D. Alberts, J. Garstka, F. Stein,
NETWORK CENTRIC WARFARE, 2Ed. Rev., 1999

FAX MACHINES



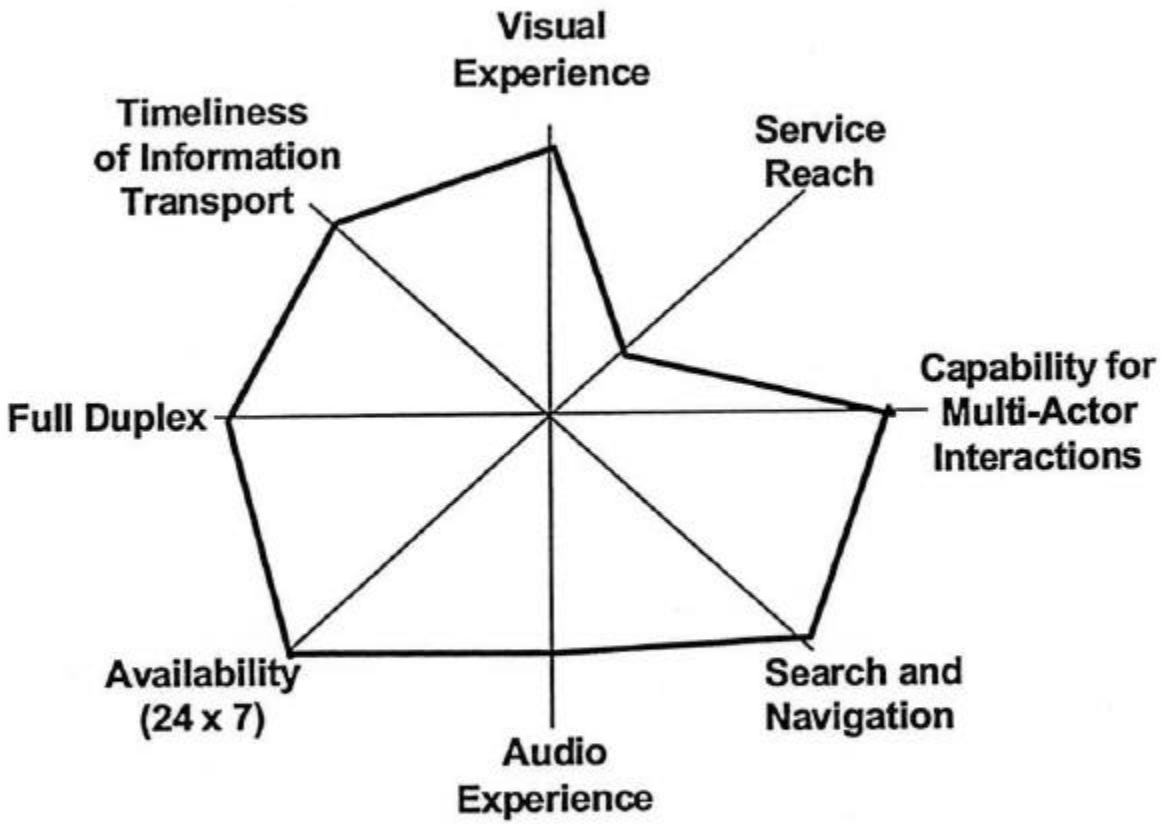
Source: D. Alberts, J. Garstka, F. Stein,
NETWORK CENTRIC WARFARE, 2Ed. Rev., 1999

E-MAIL



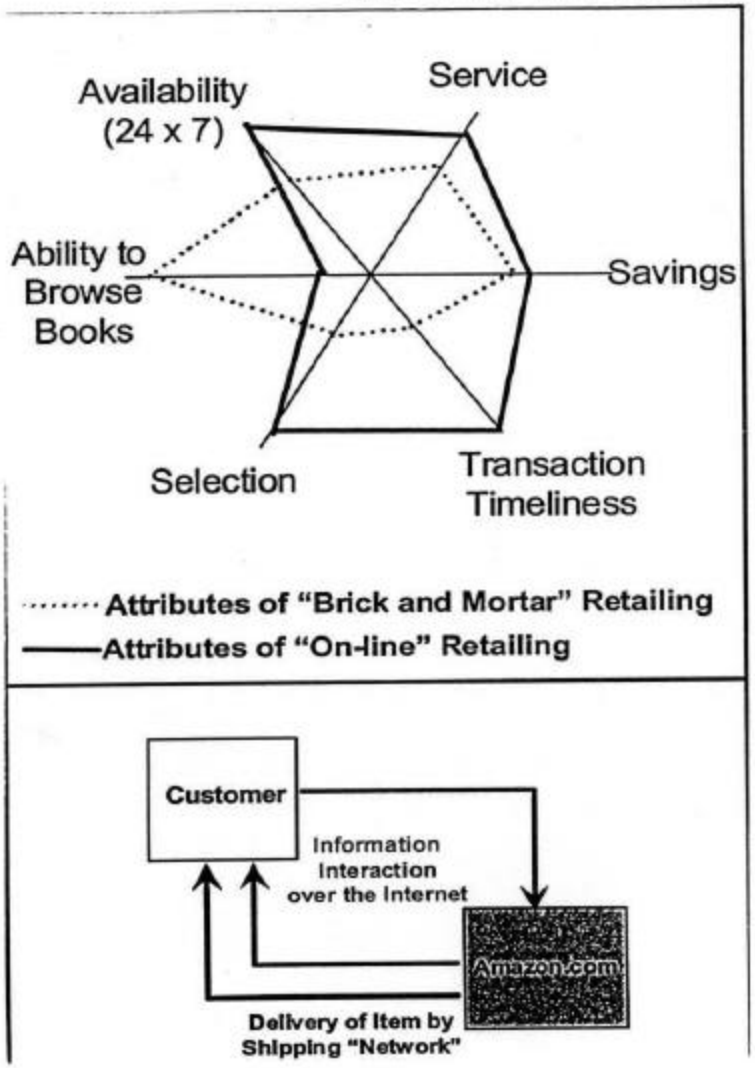
Source: D. Alberts, J. Garstka, F. Stein,
NETWORK CENTRIC WARFARE, 2Ed. Rev., 1999

WORLD WIDE WEB



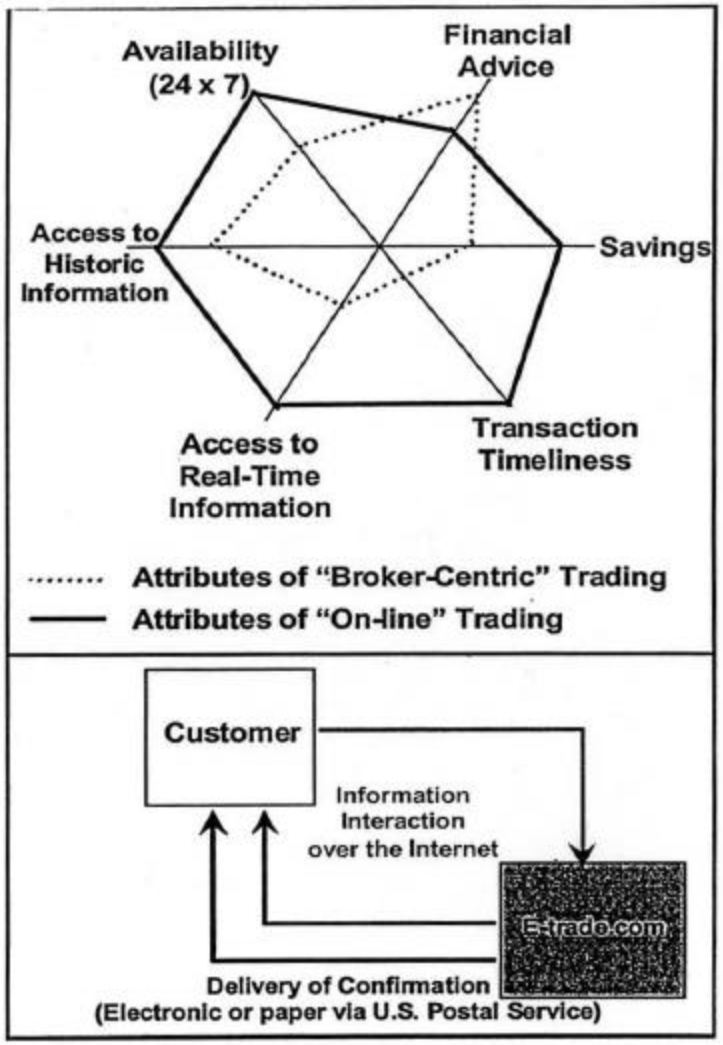
Source: D. Alberts, J. Garstka, F. Stein, NETWORK CENTRIC WARFARE, 2Ed. Rev., 1999

NET-CENTRIC VALUE CREATION-ON-LINE RETAILING



Source: D. Alberts, J. Garstka, F. Stein, NETWORK CENTRIC WARFARE, 2Ed. Rev., 1999

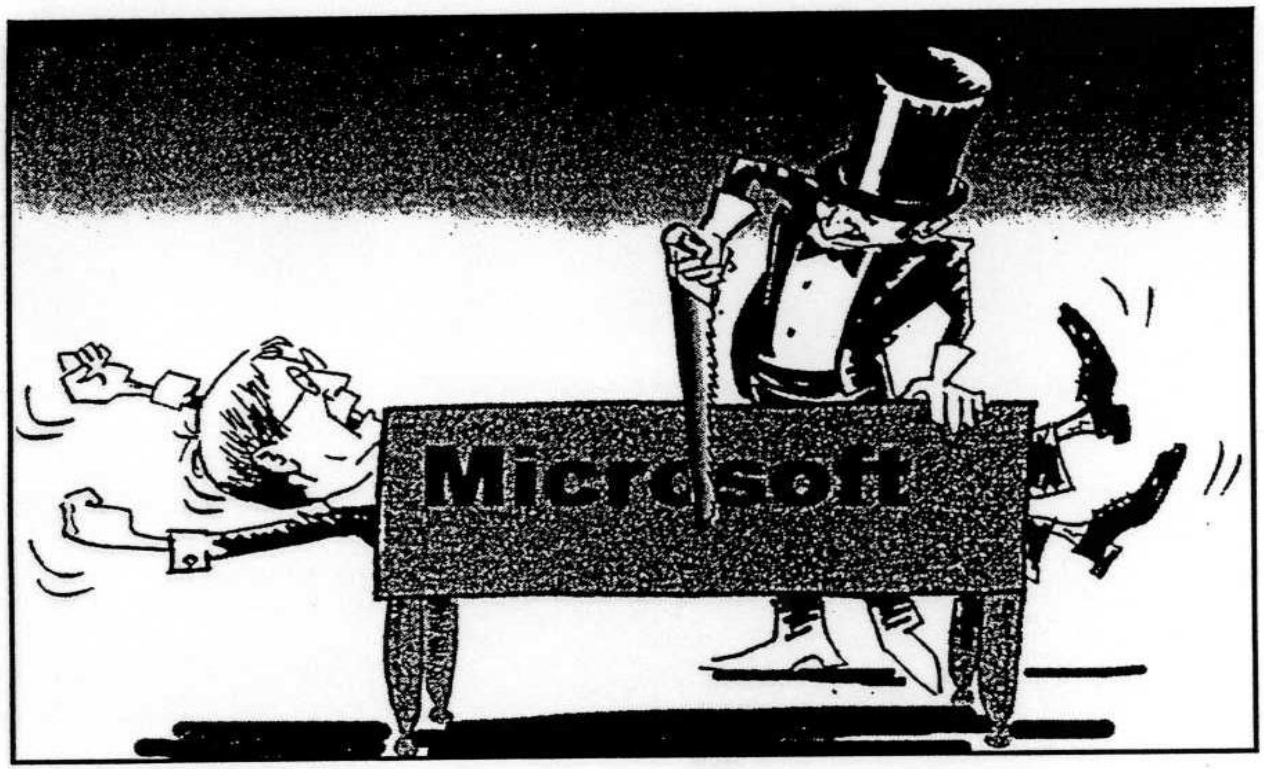
NET-CENTRIC VALUE CREATION-ON-LINE TRADING



Source: D. Alberts, J. Garstka, F. Stein, NETWORK CENTRIC WARFARE, 2Ed. Rev., 1999

Six Billion and Counting

Riber/Svenska Dagbladet/Stockholm



Zhang/*China Daily*/Beijing, China

CONTENT-BASED COMMUNICATION

CONTENT-BASED COMMUNICATION

"The semantic aspects of communication are irrelevant to the engineering problem."

The Mathematical Theory of Communication, Claude Shannon, 1948

- Shannon's view has served well for 5 decades but is being subsumed by emerging 21st century technology
- **Content based** network routing is in use for digital communications today and content addressable digital video systems have been demonstrated.

CONTENT-BASED COMMUNICATION (con't)

- **A Global InfoMorphing ExtraNet** has been conceived which uses information from all layers of the communication hierarchy to deliver dynamically user-tailored actionable information anywhere, anytime into any modality.
- The fact that the semantic content of the information is no longer irrelevant to the communication engineering problem presents opportunities for **new modes of interaction** with 21st century communication systems.

“THE DESCENT BECKONS AS THE ASCENT BECKONED

MEMORY IS A KIND OF ACHIEVEMENT.”

WILLIAM CARLOS WILLIAMS

WHAT'S PAST IS PROLOGUE

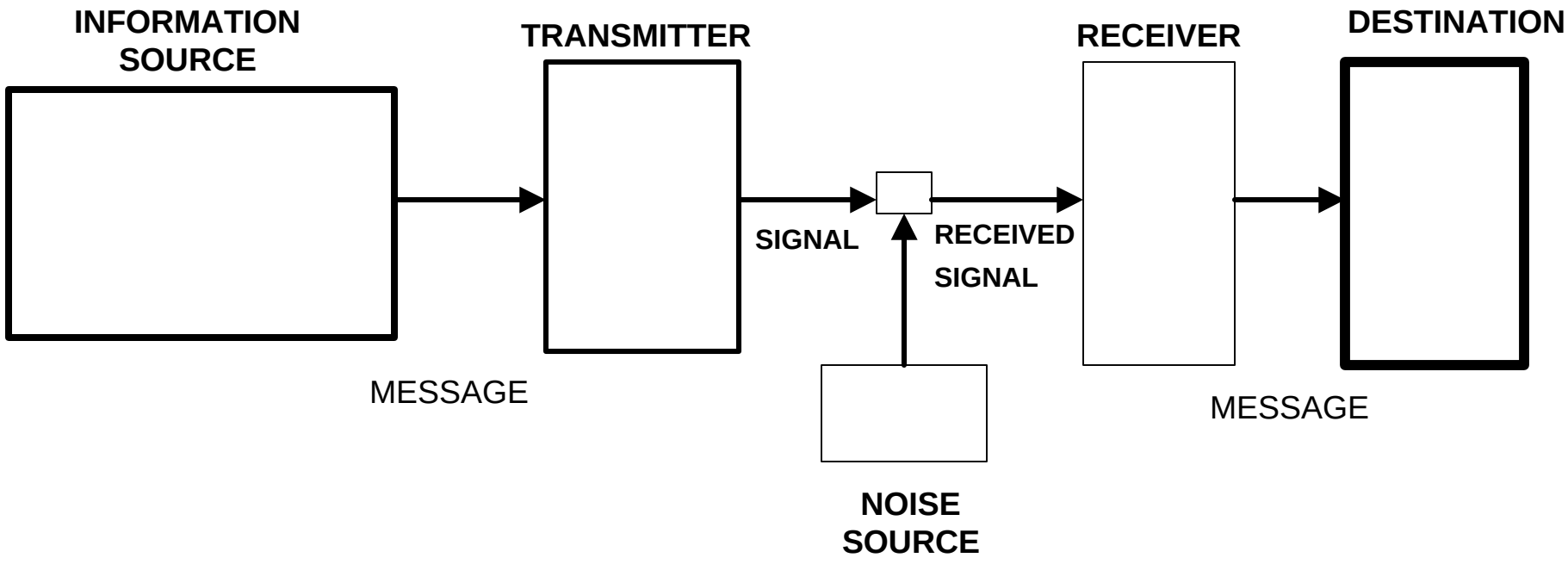
Plato: **"The written word is inferior to the spoken word."**

Shannon: **"The semantic aspects of communication are irrelevant to engineering problem."**

[PLATO] : [SHANNON] :: [INTERACTIVE TEXT] : [CONTENT-BASED ROUTING]

TOWARD A MATHEMATICAL THEORY OF MEMORY

SHANNON'S GENERAL COMMUNICATION SYSTEM



THE THEORIES OF

COMMUNICATION SYSTEMS

ANTECEDENTS

"…MODULATION METHODS…WHICH EXCHANGE BANDWIDTH FOR SIGNAL-TO-NOISE RATIO…"

ADDITIONAL CONTRIBUTIONS MADE BY THE THEORY

QUANTIFICATION OF

- "THE EFFECT OF NOISE IN THE CHANNEL"
- "SAVINGS POSSIBLE:
  - DUE TO THE STATISTICAL STRUCTURE OF THE ORIGINAL MESSAGE AND
  - DUE TO THE NATURE OF THE FINAL DESTINATION OF THE INFORMATION"

MEMORY SYSTEMS

ANTECEDENTS

NAS AND SAN SYSTEMS WHICH COMBINE NETWORKS, FILE SYSTEMS, AND MEMORY

ADDITIONAL CONTRIBUTIONS DESIRED FROM THE THEORY

QUANTIFICATION OF

- THE EFFECT OF PARTIAL OBSERVABILITY OF KNOWLEDGE, INFORMATION AND DATA
- SIMPLIFICATION AND OPTIMIZATION OF SYSTEM ARCHITECTURES
  - DUE TO DUAL STRUCTURE OF THE ORIGINAL KNOWLEDGE [KNOWLEDGE/METAKNOWLEDGE]
  - DUE TO GOAL OF STORING AND RECOLLECTING FOR ANY SPECIFIC APPLICATION ("DESTINATION")

ON VOCABULARY
(FOR TODAY'S PRESENTATION)

DATA	INFORMATION	KNOWLEDGE
ELEMENTS	*LINKED ELEMENTS IN A SET*	*DISTRIBUTED LINKED ELEMENTS IN A SET*
STORE	FILE	NETWORK
AND	AND	AND
RETRIEVE	RECALL	RECOLLECT

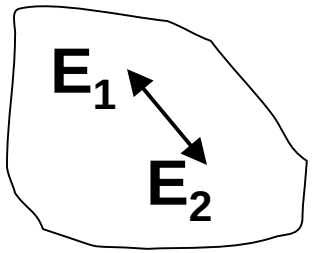
GOAL: A QUANTITATIVE THEORY OF { KNOWLEDGE / INFORMATION / MEMORY } SYSTEMS

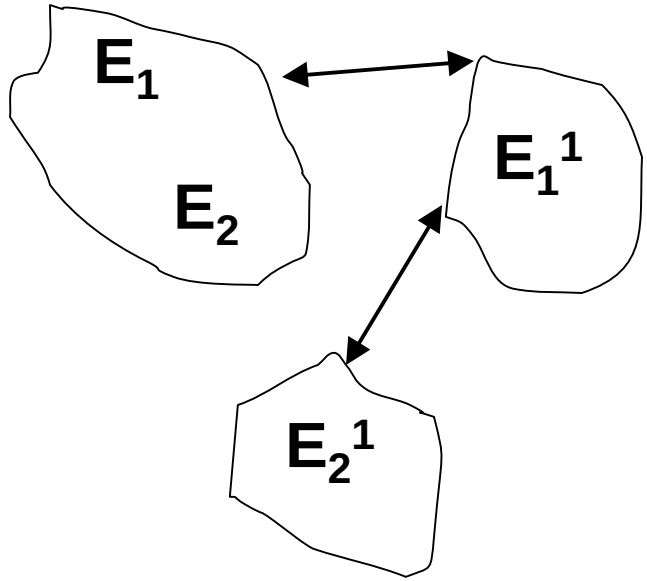
TERM CHOSEN FOR HISTORICAL AND SIMPLICITY REASONS

DATA INFORMATION KNOWLEDGE

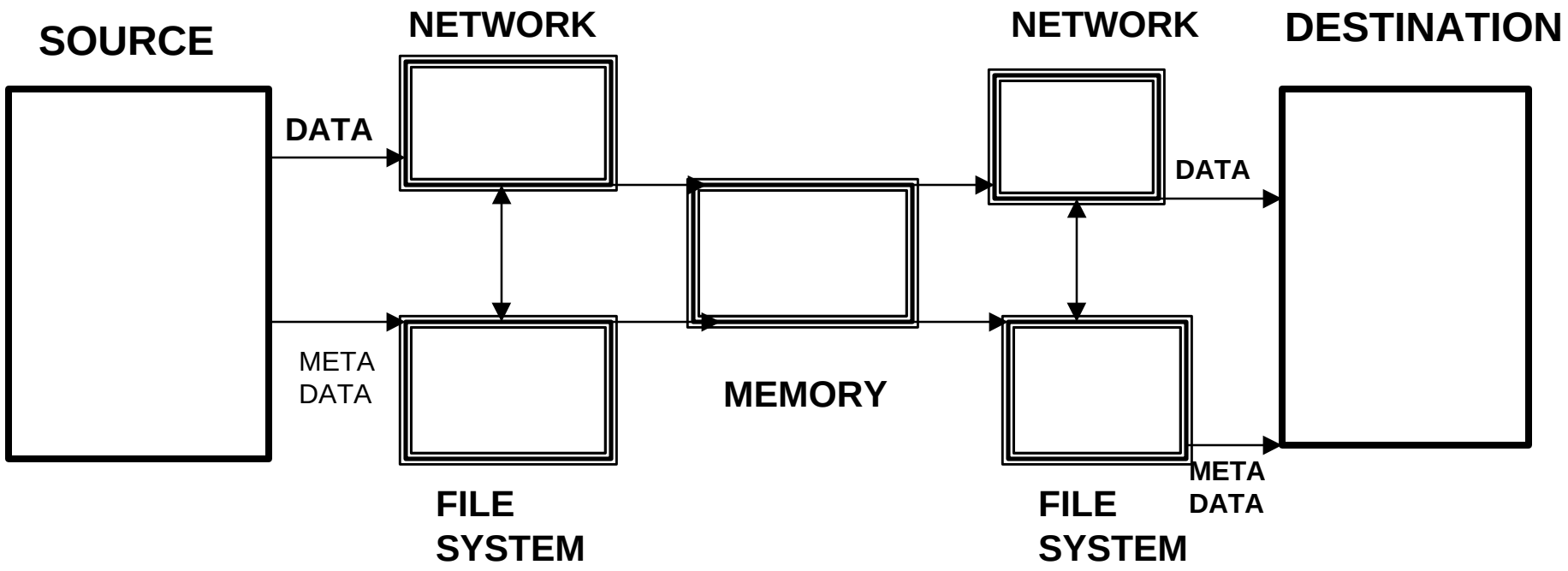
E_1

E_2





A GENERAL MEMORY SYSTEM

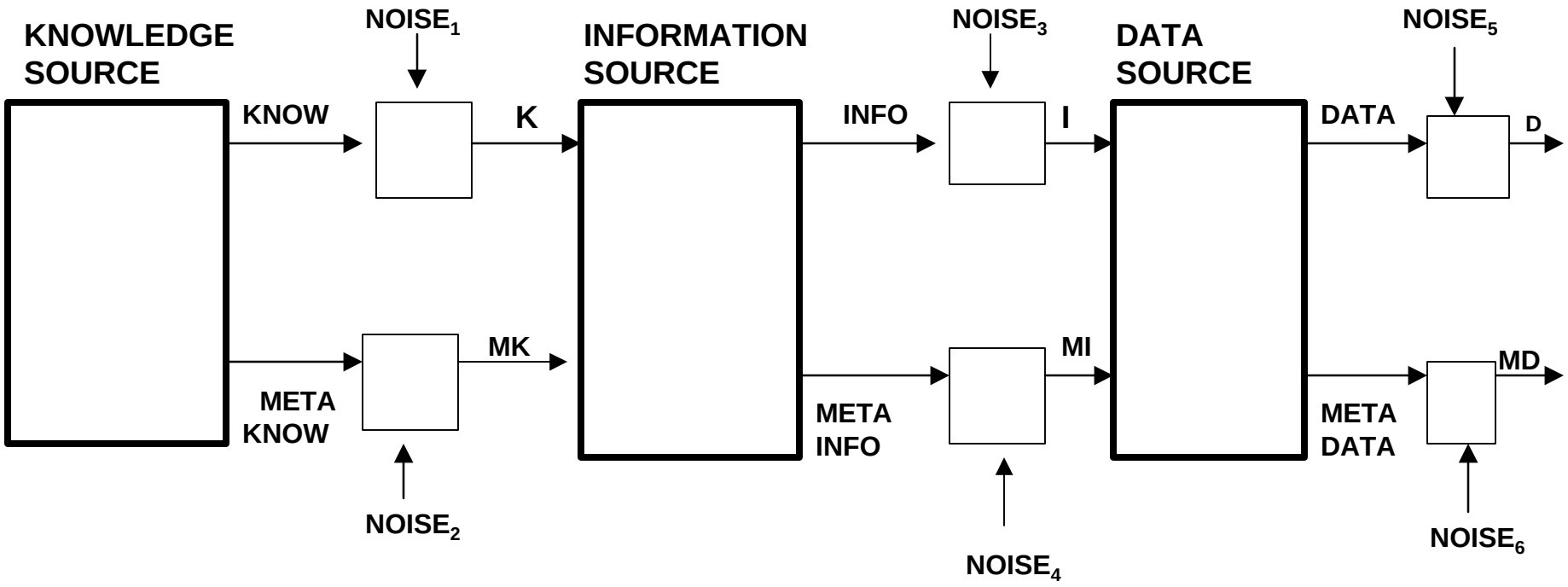


KNOWLEDGE

INFORMATION

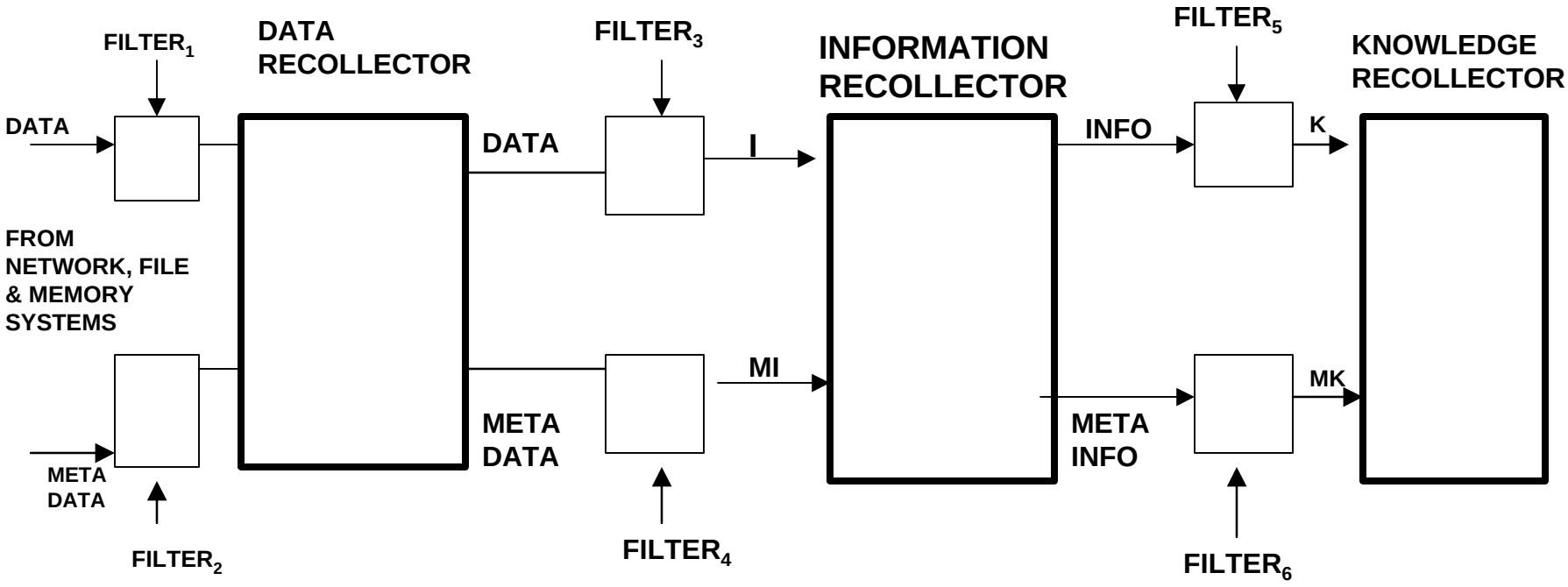
DATA

SOURCE



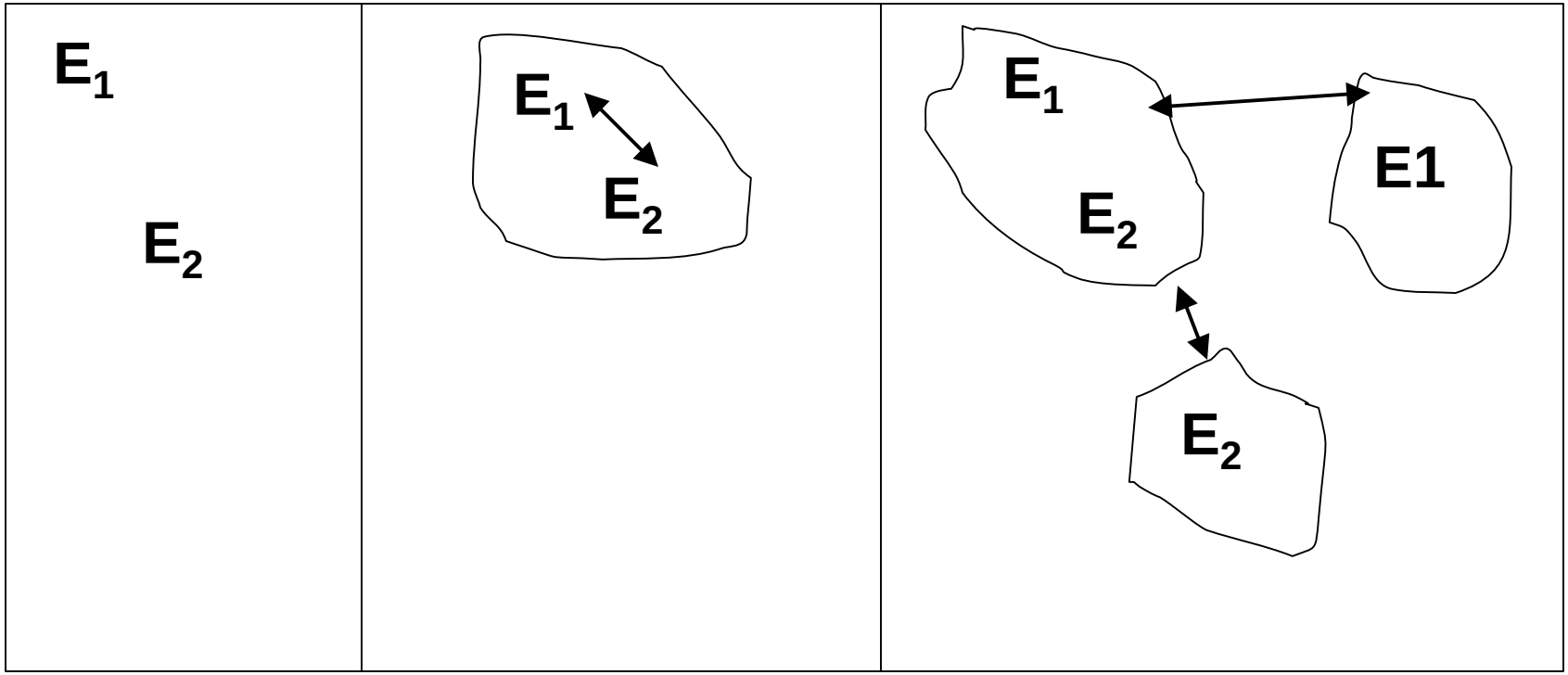
"NOISE IS USED IN AN "OVERLOADED" SENSE TO REPRESENT PARTIAL OBSERVABILITY WHICH IS CHARACTERIZED AS FULL OBSERVABILITY WITH A PROBABILITY STRUCTURE

DESTINATION/RECOLLECTION OF { KNOWLEDGE / INFORMATION / DATA }



"FILTER" IS USED IN AN "OVERLOADED" SENSE TO REPRESENT PARTIAL RECONSTRUCTION OF UNOBSERVABLE STATES BY USE OF STATISTICAL AND APPLICATION SPECIFICS

DATA INFORMATION KNOWLEDGE

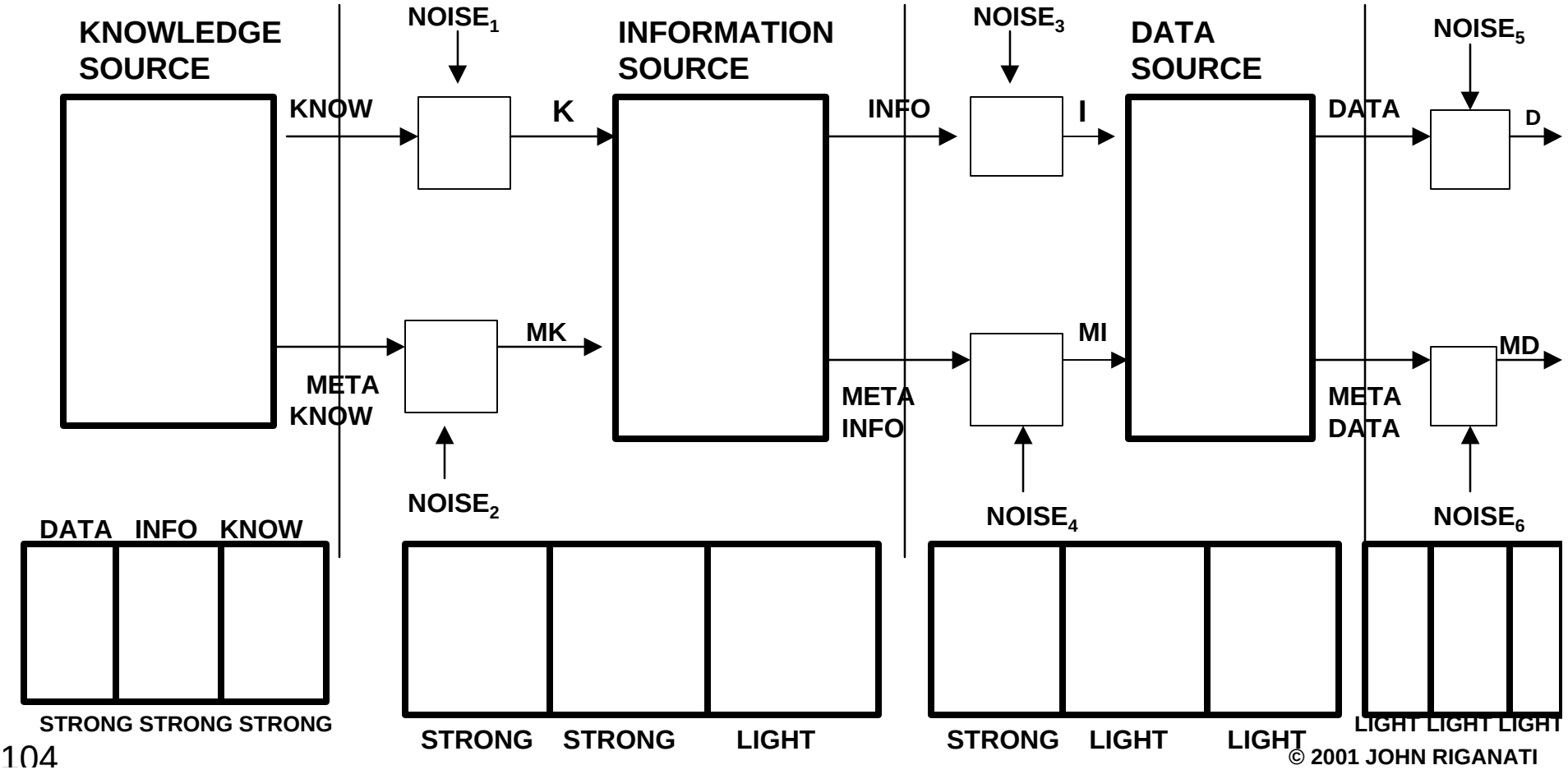


KNOWLEDGE

INFORMATION

DATA

SOURCE



CASE STUDY: A HUMAN RECOLLECTION OF FIFTH GRADE

- HOMEROOM TEACHERS NAME
- CLASSMATES
- FAVORITE ACTIVITIES
- THINGS NOT LIKED
- SOCIAL INTERACTIONS
- PLEASANT/NOT PLEASANT/ NEUTRAL ASSOCIATIONS
- …
- …
- ...

A RECOLLECTION IS A COMPOSITE OF MEMORIES GATHERED TO ATTAIN SOME GOAL, IN THIS CASE A "FIFTH GRADE GESTALT"

DEFINITIONS

LET [Mi] INDIVIDUAL MEMORIES FOR EXAMPLE, FIFTH GRADE WORLD

[Mj] RELATED INDIVIDUAL MEMORIES IN CURRENT PROFESSIONAL WORLD

[Mk] RELATED INDIVIDUAL MEMORIES IN CURRENT PERSONAL WORLD

SOME RELATIONAL OPERATORS:

- **CORRELATION, CROSS CORRELATION, LINKAGES, SIMILARITY/DISSIMILARITY MEASURES, ...**

SOME TYPES OF SIMILARITY MEASURES

TYPE	EXAMPLE
I. SUBJECT MATTER	NAMES OF PEOPLE WITH WHOM I INTERACT
II. TAXONOMETRIC	ALPHABETIC (GRETCHEN GOLDTHORPE, GOLDA MEIR)
III. EMOTIONAL RESPONSE • … • ...	RECESS, PARTIES, CONFERENCES

EXAMPLES

FAVORITE ACTIVITIES	PLEASANT ASSOCIATIONS	PEOPLE	ASSOCIATIONS
• RECESS	• BAND(DRUMS)	- GRETCHEN GOLDTHORPE - LORRAINE METZGER - JOHN RADELL	• 5G
• CONFERENCES	• CONCERTS	• COLLEAGUES	• 3G, 2.5G, 2G
• PARTIES	• CHOIR	• FRIENDS	• GOLDA MEIR

FIFTH GRADE

PROFESSIONAL WORLD NOW

PERSONAL WORLD NOW

EXAMPLE

ELEMENT BEING CONSIDERED	MEANING	APPLICATION	COMMENTS
5G	FIFTH GRADE "GOLDTHORPE"	USE OF SINGLE NUMERIC SINGLE ALPHABETIC COMBINATION TO REPRESENT COMPLEX OBJECTS	RELEVANT RELATIONSHIPS 2G, 3G,… TELECOMMUNICATION SYSTEMS
5G	FIFTH GENERATION COMPUTING SYSTEMS	STATUS OF PROGRESS RELATED TO MOORE'S LAW	- PHOTOLITHOGRAPHIC STATE-OF-THE-ART - .11 AND .07 MICRON FABRICATION - . . .

ON CAPACITY

COMMUNICATIONS SYSTEMS

ACHIEVEMENTS OF THE THEORY

MAXIMUM INFORMATION CAPACITY

QUANTITATIVELY RELATED TO CHARACTERISTICS OF THE CHANNEL AND THE PROBABILISTIC STRUCTURE OF THE SOURCE MESSAGES

MEMORY SYSTEMS

NEEDED FROM THE THEORY

MAXIMUM RECOLLECTION CAPACITY

QUANTITATIVELY RELATED TO

- **MEMORY STORAGE CAPACITY**
- **NETWORK CAPABILITY**
- **FILE SYSTEM'S ABILITY TO DELIVER STRUCTURED KNOWLEDGE AND META KNOWLEDGE**

IN RELATIONSHIP TO THE APPLICATION

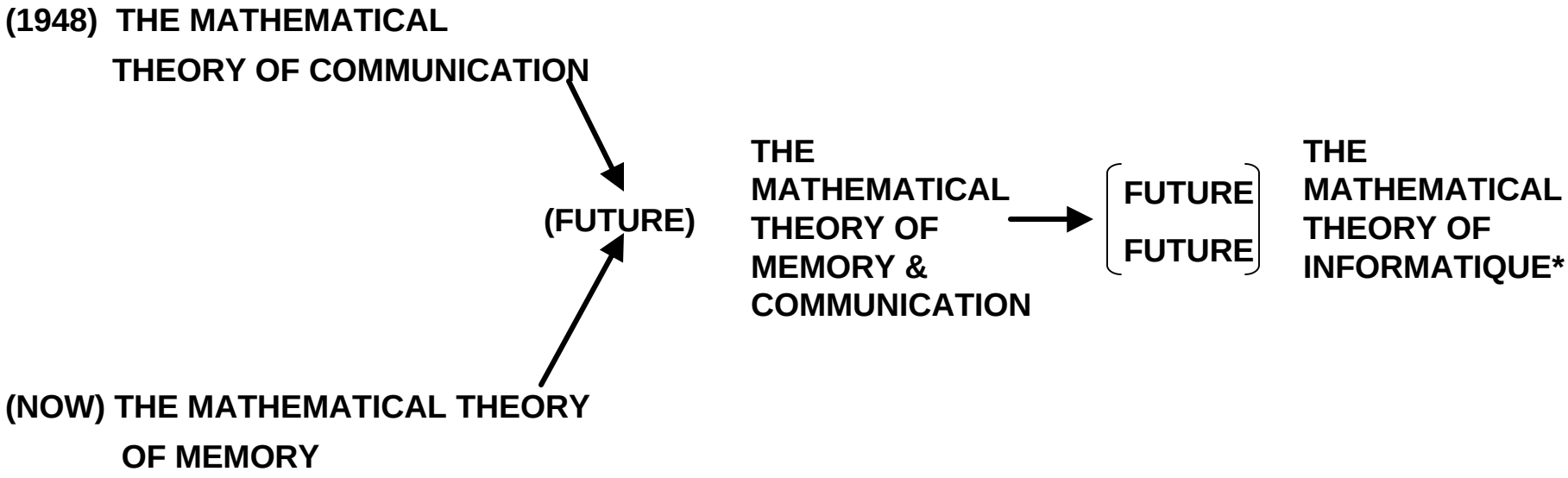
TWO KEY TOPICS
FOR CONSIDERATION RE:
THE MATHEMATICAL THEORY OF MEMORY

TOPIC	DISCUSSION
• ERGODICITY AND MARKOV CHAINS	SUNRISES, PINK AND PURPLE/DEGREE, CAPTURED ON FILM, . . .
• HIERARCHICAL VS FLAT ADDRESS SPACE MEMORY ARCHITECTURE	X REMINDS US OF Y; PDA'S USE HIERARCHIES TO REDUCE LATENCY; HUMAN FLAT ADDRESS MINDS (SINGULAR POINTS?); SEPARATING MEMORY ELEMENTS FROM THE CONDITIONAL PROBABILITY RELATIONSHIPS; DREAMS AS A WINDOW TO *YOUR* MEMORY ARCHITECTURE; BJS BUTCHER SHOP EXAMPLE

“IF WE DO NOT SUCCEED IN SOLVING A MATHEMATICAL PROBLEM, THE REASON FREQUENTLY CONSISTS IN OUR FAILURE TO RECOGNIZE THE MORE GENERAL STANDPOINT FROM WHICH THE PROBLEM BEFORE US APPEARS AS A SIMPLE LINK IN A CHAIN OF RELATED PROBLEMS.”

Source: David Hilbert, “Mathematical Problems”, International Congress of Mathematicians, Paris, 1900, Göttinger Nachrichten, pp 253-297, 1900

HYPOTHESIS



* INFORMATIQUE SUBSUMES: [KNOWLEDGE / INFORMATION / DATA] AND [COMMUNICATION] AND [PROCESSING]

“OCCASSIONALLY IT HAPPENS THAT WE SEEK THE SOLUTION UNDER INSUFFICIENT HYPOTHESES OR IN AN INCORRECT SENSE, AND FOR THIS REASON DO NOT SUCCEED.”

Source: David Hilbert, “Mathematical Problems”, International Congress of Mathematicians, Paris, 1900, Göttinger Nachrichten, pp 253-297, 1900

SOME QUESTIONS CONCERNING THE SUGGESTED APPROACH TO A MATHEMATICAL THEORY OF MEMORY

1. CAN A MATH THEORY OF MEMORY BE POSED AS A WELL FORMULATED PROBLEM?

2. IS THE USE OF A GENERALIZED NOISE AND STOCHASTIC PROCESSES TO REPRESENT PARTIAL OBSERVABILITY WELL FORMULATED? ARE THERE MORE EFFECTIVE WAYS TO REPRESENT THE INHERENT COMPLEXITY AND UNOBSERVABILITY ASSOCIATED WITH KNOWLEDGE IN THE NATURAL WORLD?

3. WHAT IS THE SIMPLIST ALL ENCOMPASSING MODEL OF A MEMORY SYSTEM? FOR EXAMPLE, HOW MANY NOISE SOURCES AND WHERE DO THEY ENTER, WHAT ARE THEIR CHARACTERISTICS? WHAT ARE THE CRITICAL ABSTRACTIONS NEEDED?

4. IS THE DUALITY KNOWLEDGE/METAKNOWLEDGE A FUNDAMENTAL PROPERTY FOR MEMORY SYSTEMS (ANALGOUS TO INFORMATION AS THE PROPERTY OF AN ELEMENT IN A SET (I.E. IN CONTEXT))?

5. ARE THERE OTHER HIERARCHIES WHICH MORE EFFECTIVELY REPRESENT DATA-INFORMATION-KNOWLEDGE?

6. SOME ASPECTS OF MEMORY ARE PRESENTED AS A "MODE OF COMMUNICATIONS"; SOME ARE PRESENTED AS A "MODE OF PROCESSING". HOW DO THESE DUALITIES ENTER QUANTITATIVELY INTO THE THEORY?

7. CAN A 100% TRUSTED SYSTEM BE CONSTRUCTED FROM ELEMENTS WHICH ARE (50+)% TRUSTED?

8. HOW TO QUANTIFY THE BOTTLENECKOLOGY [TERM COINED BY JACK WORLTON]: THEORETICAL AND PRAGMATIC?

“PERHAPS IN MOST CASES WHERE WE SEEK IN VAIN THE ANSWER TO A QUESTION, THE CAUSE OF THE FAILURE LIES IN THE FACT THAT PROBLEMS SIMPLER AND EASIER THAN THE ONE IN HAND HAVE BEEN EITHER NOT AT ALL OR INCOMPLETELY SOLVED.”

Source: David Hilbert, “Mathematical Problems”, International Congress of Mathematicians, Paris, 1900, Göttinger Nachrichten, pp 253-297, 1900

RANDOM THOUGHTS ON MEMORY

- **CNN: "YOU ARE WHAT YOU KNOW"**
- **INFORMATIQUE: YOU ARE THE SUM OF WHAT YOU HAVE EVER BEEN, INCLUDING YOUR INTERACTIONS WITH "OTHER" [ESPECIALLY LOVE-BASED INTERACTIONS]**
- **HUMANS ARE SOCIAL BEINGS: WE KNOW OURSELVES SUBSTANTIALLY BY HOW WE REFLECT OFF OTHERS…**
  - **WHAT IS PEER REVIEW?**
    "I THINK THIS IS GOOD AND MEMORABLE; WHAT DO MY PEERS THINK?"

RANDOM THOUGHTS ON MEMORY(CON'T)

- **IF YOU: LEARN, GATHER INFORMATION; PROCESS INFORMATION; CREATE AND COMMUNICATE A NEW THEORY; HAVE A STROKE, RECOVER FROM THE STROKE BUT WITH MEMORY LOSS, READ YOU OWN PAPERS AS A "REVELATION"**

- **IF THE ORIGINAL MEMORY IS GONE BUT THE PROCESSOR ARCHITECTURE REMAINS, AND APPRECIATES, IS THIS THEORY STILL "YOURS"? SUPPOSE THE PROCESSOR ARCHITECTURE IS DESTROYED, TOO, BUT OTHERS "REMEMBER"?**

The Telephone → The Web → The Borg

- **The Telephone was the solution to a deep human need: the need to communicate**
  - **within two years every major city in the United States had a telephone exchange**

- **The Web [not the Internet] was the solution to a deep human need: the need to be closely connected to communities of common interests**
  - **within two years of the introduction of the Web, the exponential growth which we are currently experiencing had begun**

- **The Borg is a jaundiced visionary's projection which is a solution to a deep human need: the need to know everything which is known by anyone, anywhere, at any time**
  - **a non-jaundiced "Borg," perhaps an InfoMorphing ExtraNet will grow with a double exponential**

The “Borg” Without the Horror

- **Horror and science fiction are grouped together by taxonomists who don’t know the difference**

- **Eliminate the following from the “Borg”:**
  - **ugly mechanical implant structures**
  - **the need to subsume everything [“resistance is futile”]**
  - **the thesis that self must be eliminated in order to have a community**

- **An “InfoMorphing ExtraNet” infrastructure can enable individuals to have all of the positive, glorious aspects of the Borg without the horror**

The Last Yard

- **TODAY**

  - User Tailored Actionable Information

- **TOMORROW**

  - The InfoMorphing ExtraNet

- **FUTURE YEAR**

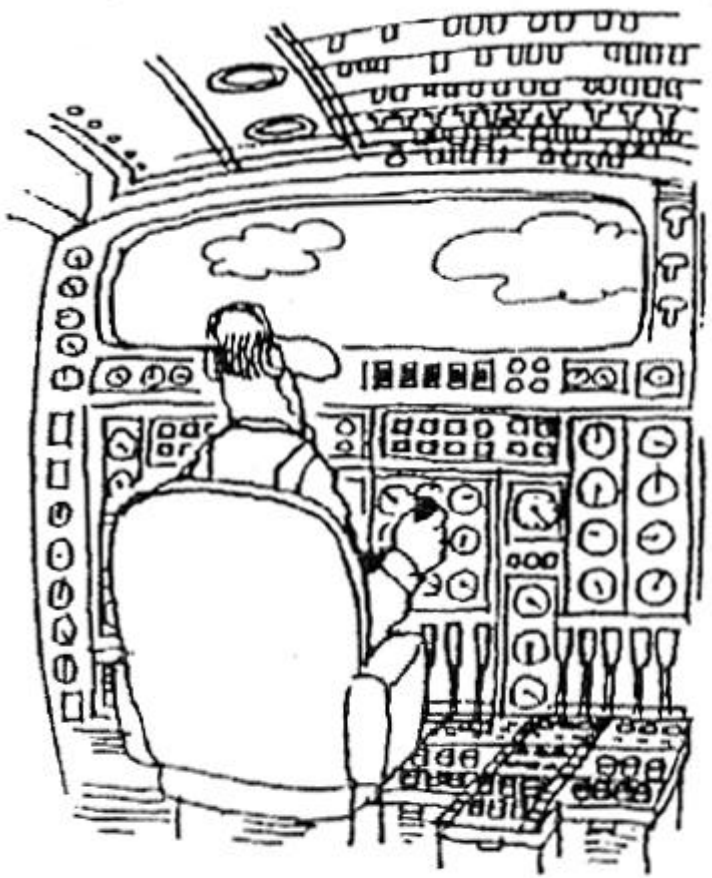
  - Braincasting

"Does he talk?"

Husband/Private Eye/London

"No, Isaac can't come out to play. His dad's gone to sacrifice him on the mountain."

Husband/The Oldie/London



TODAY

THE FUTURE

Fiddy/The Oldie/London


We Can Do It!
WAR PRODUCTION CO-ORDINATING COMMITTEE

ALL OF SCRIPTURE CAN BE SUMMARIZED IN ONE WORD:

REMEMBER

RABBI HESSHEL

WHAT IS MEMORY,

ANYWAY?