POCKET COMPUTING

An Exhibit at The Computer Museum
Boston, Massachusetts USA

The Exhibit

Today pocket calculators are so pervasive that we almost take them for granted. Portable and convenient, people use them to do everything from their math homework, and balancing their checkbooks, to calculating the expected return on investments, and designing airplanes and automobiles. The pocket electronic calculators widely used today are only about fifteen years old. However, the need for pocket calculators is ancient. For centuries people from virtually every culture have built small computing devices to carry in their pockets or attach to their clothing.

To present this story The Computer Museum is developing an exhibit titled "Pocket Computing." By combining historic artifacts with the latest technologies, the exhibit will present man's continual efforts to supplement his personal abilities to remember and calculate with devices that he can carry with him. The exhibit will also illustrate the diverse purposes for which pocket calculators have been constructed, and the mechanical and mathematical concepts behind these miniaturized devices. It will be an exciting experience for visitors of all ages and backgrounds.

Since the interesting and unique aspect of pocket calculators is the way in which they are used, the backbone of the exhibit will be a display of people who have used pocket calculators: from ancient shepherds using pebbles to count their flocks; to a 16th-century Japanese silk merchant with his soroban; to an engineer with his slide rule; to school children completing their homework with electronic calculators. This series of small settings will combine historic artifacts with the outfits and tools appropriate to the users of the calculators. Visitors will immediately appreciate the contexts of these settings and identify important themes in the story of pocket calculating. In addition, a small display of calculating artifacts will accompany each setting to show other related devices of the period.

The historical account of the pocket calculator will be only part of the exhibit. Associated with each seminal calculator will be an area where visitors can try their own hand at solving problems using the device. Visitors will discover what it was like to use sorobans, Napier's Bones, or slide rules. Accompanying these interactive displays will be presentations using video tapes that tell the historical and cultural importance of each device. For example, the working sorobans will be complemented by a display of their importance in Japanese education and society, including a video of school children competing on sorobans. These interactive areas will involve visitors in the exhibit, allowing them to explore how calculating was performed in times and cultures different from their own.

The final area of the exhibit will focus on the technology of the present and future. A section where visitors can use state-of-the-art electronic calculators will allow them to put older devices in perspective. A wide collection of electronic pocket devices will illustrate the incredible increase in power and reduction in size and price that has occurred in pocket calculators over the past fifteen years. With this increasing power calculators have started to perform new and different tasks, such as doubling as personal portable data bases. The pioneering role of the Japanese in the manufacture and application of the electronic calculator will be an important theme in this section of the exhibit. At the end of this section visitors will be invited to offer their speculations on how they will be using pocket calculators in the future.

Background

The Computer Museum is a public non-profit institution supported extensively by companies in information processing industries. For example, Hewlett-Packard has provided support for the Pocket Computing exhibit. The Museum is dedicated to impartially preserving the history of the computer revolution. All donations to the Museum are tax-deductible.

"Pocket Computing" is being developed by Gregory W. Welch, a Harvard University graduate in the History of Science who has developed exhibits at The Computer Museum for the past three years. The exhibit is scheduled to open at The Computer Museum, Boston, Massachusetts, USA on October 9, 1986. It will occupy approximately 1000 square feet of space in a gallery reserved for special exhibitions and will be in place for one year. Over 100,000 visitors are expected to view the exhibit.

The Collection

Among the historic pocket calculators contained in The Computer Museum's collection are:

- a set of Napier's Bones from the 17th century
- an 18th century example of Leadbettor's slide rule
- a French brass sector and divider from the 18th century
- the Webb adder from the late 19th century
- various examples of Fowler's circular slide rules
- the Golden Gem calculator
- the Curta calculator
- the Bowmar Brain electronic calculator, c. 1971
- the TI Datamath calculator
- the National Semiconductor Novus 650
- early Sinclair electronic calculators
- the HP-35

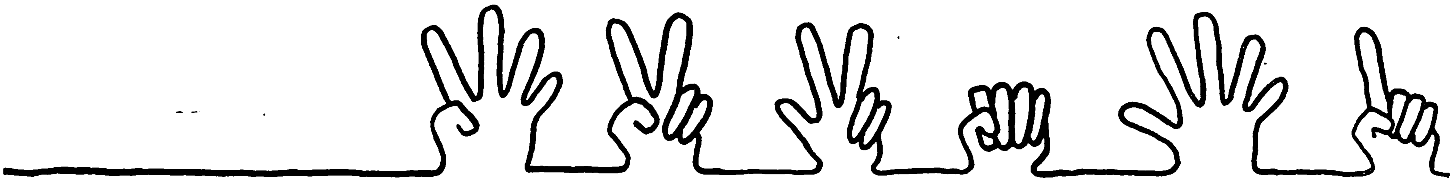
Museums take the opportunity to expand their collection while developing exhibits. While The Computer Museum has a substantial number of pocket computing devices, there are gaps in its collection. Most notable is a paucity of Japanese products. As innovators in the miniaturization of calculators, Japanese firms such as Sharp have brought pocket electronic calculators into every day use around the globe. It is, therefore, important for Japanese products to be represented in the Museum's collection.

Ideally The Museum would like an example of every calculator manufactured by Sharp for its permanent collection. For the purpose of the Pocket Computing exhibit we seek essentially four artifacts from Sharp:

1) an example of their first pocket calculator,
2) an example of their most sophisticated or powerful calculator,
3) an example of their smallest calculator,
4) an example of their most unique or curious pocket calculating or memory device.

Documentation regarding operation, price, and history of each device would be much appreciated. Additional Japanese artifacts we are are seeking for the exhibit are: ancient miniaturized sorobans, a video tape of school children using sorobans, and an ancient silk merchant's jacket. All these pieces will help us develop an exhibit which shows not just the most advanced calculators, but also the history of their development, and some of the myriad purposes for which they have been designed.

Each donation will be duly acknowledged as part of The Computer Museum's permanent collection which includes a label on exhibited items identifying the donor, and mention in the Museum's Collection Report distributed annually to all Museum members. The donation of these artifacts to The Computer Museum will ensure that the position of Japanese firms in the development and production of pocket calculating devices is appropriately acknowledged and preserved.



ON ONE HAND...

Pocket calculators then and now

A new exhibit for **The Computer Museum** by The Office of Michael Sand

7·7·80
REVIEW & SUGGESTIONS FOR IMPROVING CALCULATOR SLIDE SHOW

FOR THE MOST PART THE PRESENTATION IS COHESIVE, THE STRUCTURE (12 GENERATIONS) IS STRONG AND WORKABLE, THE INFORMATION IS CLEAR AND UNDERSTANDABLE.

THE FOLLOWING IS A SLIDE BY SLIDE CRITICISM:

"HELLO, MY NAME IS GWEN BELL..."

THE INTRO SECTION IS A BIT TOO MUCH INFORMATION. ANOTHER PHOTO OF GWEN, A TITLE, A MORE GRADUAL ENTRANCE INTO THE HISTORY OF CALCULATORS, AND SOME RE-WRITING WOULD HELP THE AUDIO SEGMENT. THE VOICE TONE IS MUCH DRIER AS THE PROGRAM OPENS THAN WHEN IT PROCEEDS LATER.

#3 #4 OPENING GRAPHICS - THE FOUR GENERATIONS (POSTER) AND THE B+W TREE ARE VERY WEAK - NOT CLEARLY UNDERSTOOD - RESHOOT EACH OF FOUR GENERATIONS NEEDS SEPARATE SLIDE?

#5 WE CAN PHOTOGRAPH ~~ABAK~~ ABACUS PROPERLY

6 DON'T UNDERSTAND THIS SLIDE - (MODERN ABACUS WITH TRADE NAME VISIBLE)

7 MISSING

8 THE LINE CUT CAN BE RE PHOTOGRAPHED AS A REVERSE FILM NEG W/COLOR

9-10 RESHOOT QUIPU (10) BETTER CHART GRAPHIC NEEDED

11 IMPROVED PORTRAIT OF NAPIER

13+14 CHANGE VERTICAL SLIDES TO HORIZONTAL - RE SHOOT NAPIER'S BONES

15 LINE CUT OF HAND-SET TYPE SETTER - DOESN'T SYNC W/ NARRATOR NOT CLEAR

16 PHOTO OF HAND-SCRIBED TABLES SHOULD BE MUCH CLOSER
NO VERTICAL SLIDES

17 WHY THAT BOOK - CHEMISTRY + PHYSICS - RESHOOT

18 MISSING

19+20 SHOULD BE RE PHOTOGRAPHED

22 RUG IS ODD BKGRD FOR SLIDE RULE

25 RESHOOT V. BUSH

26 BETTER GRAPHIC NEEDED

27 VERTICAL - NARRATOR TALKS ABOUT A LETTER, SLIDE SHOWS
A DRAWING - SAME AS #29 ?

29 RE SHOOT

31 BETTER PHOTO OF PASCAL NEEDED - VERTICAL

32 PASCAL'S BOX - LOUSY COLOR + EXPOSURE

33 RESHOOT PASCAL'S DWG

35

37 NEED BETTER GRAPHIC

38 VERTICAL - NEED BETTER PORTRAIT LEIBNIZ

39 IMPROVE COLOR - REVERSE NEG

40 LOUSY COLOR PHOTOG

42 COLOR NEG

43 NARRATOR TALKS ABOUT LETTER FROM SCIENTIFIC AMERICAN - SLIDE SHOWS
PORTRAIT - SHOW ARTICLE OR QUOTE & BETTER PORTRAIT

45 BETTER COLOR

46 COLOR NEG

47 BETTER COLOR

48 VERTICAL

49 BETTER GRAPHIC NEEDED

50 NEED BETTER PORTRAIT

51 BETTER COLOR

52 & 53 REVERSE COLOR NEG

54 VERTICAL

55 NEED BETTER GEOGRAPHIC PHOTO

56 LOUSY COLOR

57 VERTICAL

58 BETTER PORTRAIT

59 NEED BETTER PHOTO

60 " "

62 VERTICAL

63 RESHOOT

64 IMPROVE BURROUGHS PORTRAIT

65 LOUSY COLOR

68 VERTICAL

69 + 70 RESHOOT
BETTER FRAMING

71 POOR GRAPHIC
(GENEAOLOGY POSTER)

LAST LINE:

"...displaced by
digital computers."

DOES THAT NEED
CLARIFICATION ?

digital ?

5/21/80 Wed 0:00:50 4/28/80 Wed 0:01:18 4/3/80 1/30/80 Wed

9:30:29 GKB

CALCULATOR SLIDE TALK FOR DIGITAL COMPUTER MUSEUM

SLIDE	TEXT
GB & exhibit	Hello, I'm Gwen Bell the Assistant Keeper of the Digital Computer Museum.
NSF roots	This talk describes the evolution of calculators -- one ancestral root of the computer tree. The National Science Foundation identifies four -- punched card equipment, telephone switching techniques, radio and tv, and desk calculators.
Cal poster	All pre-computing calculators are grouped into families and generations each characterized by different technologies. 1600 marks the emergence of manual calculating devices starting the 4th pre-computer generation; the 3rd generation begins in 1800 when mechnical control devices emerged; 1890 starts the

electro-mechanical generation; and 1930 marks the first generation before computers. Each generation is approximately half the length of time of the generation that precedes it, illustrating the increasing rate of change.

An Abacus	Long before mechanical calculators, abacus-like devices were developed and widely used. Europeans often claim the Egyptians invented the abacus and the Romans improved it by eliminating beads.
Soroban	The Chinese also claim its invention with the Japanese soroban improvement with the elimination of two beads.
Soroban/calc	The Japanese are still working the problem . In 1979 they combined a soroban with an electronic calculator making a dual processor system.
Counting table	Historically, the use of balls -- as in this early reckoning table -- or knots --
Quipu	as in this Inca quipu -- have been common devices for making calculations.
poster	About 1600 the three families of calculators started: look up tables, rules for analog computation, and simple mechanical

calculators.

John Napier	John Napier a Scottish mathematician, developed the key ideas at the base of two of these lines.
Napier's bones	He inscribed the first look-up tables on all sides of tiny sticks of ivory. Each rod bears a multiplication table for a particular digit. Multiplication and division are handled by addition and subtraction, providing a quick readout of products.
Napier's bones 2	Napier's bones probably spawned the first pocket calculator -
French calc.	this early 18th century combination of an abacus and Napier's bones, enclosed in a small wooden box with a slate on the back.
Typesetter	With the perfection of printing devices and refinement in the production of paper, the carry-about sticks were replaced by books of tables.
Page of errors	Books often had so many mistakes that whole volumes of corrections had to be printed. Other times errors were introduced as a copyright strategem.
Chem Rubber Hbk	With electronic memory storage becoming smaller and smaller, books of tables such as

the Chemical Rubber Handbook containing mathmatical formula, physical properties, and conversions, will probably disappear to be replaced by pocket calculators that remember the information and produce answers on demand.

Bones & calc

We will, in fact, be back to a device about the size of Napier's bones but that contains millions of times more information.

Slide rule

Napier's 1614 concept of logarthms provide the basis for the slide rule--an analog calculating device.

Gunter Scale

The first slide rule did not look like these modern ones. It had no moving parts but used a compass to make computations. This is part of an original straight logarithmic scale invented by Edmund Gunter in 1620. A year later, in 1621, William Oughtred claimed to have used two of Gunter's lines to make a straight logarithmic slide rule and in 1630, a circular slide rule.

Thatcher rule

In the mid nineteenth century, slide rules were refined -- the Thatcher rule contains many number series;

Table & rule

Another inscribed tablular material;

Bouchon

And the gentleman could have one in the form of a pocket watch.

Planimeter	Engineers using slide rules began to integrate these with gears to make measurements. The planimeter calculates the area as its diameter is drawn. The answer is read on an inscribed rule.
Bush analyzer	In 1930, at M.I.T., Vannevar Bush at completed the epitome of the analog calculator, a differential analyzer on which variables are rpresented by the number of revolutions of mechanical shafts --
calculator tree.	The third set of ideas starting in the early sixteen hundreds relate to the evolution of the desk calculator.
Schickard device	In a letter dated September, 1623, Wilhelm Schickard of Tubingen, Germany, wrote to Dr. Hammer of Stuttgart, "The same thing which you have done by hand calculation, I have just recently tried to do in a mechanical way."
Sch machine	"I have constructed a machine which atuomatically reckons together the given numbers in a moment, adding subtracting, multiplying and dividing."
Sch drawing	The next letter contained sketches of the machine, and a third told the sad story of the machine's being destroyed in fire.

Sch drawing	It's hard to tell how successful his machine would have been because of the lack of precision work at that time.
Pascal photo	The famous French mathematician and philosopher, Blaise Pascal -- at age 19 in 1642 -- built several mechnical calculators, causing ripples of concern about unemployment among the tax administrators -- of which his father was one.
Pascal calc.	Numbers are represented on the calculator by the position of a ten-tooth gear. Two features merit special note. One, the carry mechanism, a weighted ratchet gradually storing energy as it approaches 9. When it passes from 9 to 0, the ratchet is released and in falling transfers a unit to the wheel of the next higher order.
Pascal draw	Two, complement arithmetic was used for subtraction because the wheels could only go clockwise.
Modern pascal	These wheels are significant -- before Pascal and Schichard no one used a wheel in a digital calculator.
Pascal calc.	None of the Pascal adders worked very well. The mechanisms were forever out of order and only Pascal and one of his workment could fix

	gears above the cylinders and these in turn engaged the adding section.
Leibniz machine	Much to Leibniz's disappointment, his machines did not meet his intended excellence. Only one such machine was built, but it provided the basis of the first really successful and practical mechnical calculator,
Thomas Arith	the Thomas Arithmometer. First introduced in 1820, thirty years later it was a commercial success.
drum drawing	Thomas used the stepped drum principle of Leibniz in conjunction with a simple system of counting gears and an automatic carry.
Thomas	For all this, it met with resistance. Scientific American wrote in 1849, that the Thomas machine is "said to be one of the most astonishing pieces of mechanism that has ever been invented, but to our view, its complexity shows its defectability." Which goes to show how wrong predictions can be --
Arithmometer	the Thomas Arithmometer was still selling in the 20th century.
Millionaires	The Millionaire, invented in 1893 by Otto Steiger, was the first major direct multiplying calculator that was a commercial success.

Mill drawing	It incorporated a mechanical multiplication table instead of using repeated additions.
Millionaire broch.	The basic millionaire model was repeatedly tried to be improved upon -- 6 digit, then 8 digit, and finally ten digit machines were made.
8 digit	A keyboard and eventually a motor were added to meet competition. In 1935, production was stopped after 4,655 Millionaires had been sold.
Time line	The ideas of Frank Baldwin and Wilsodt Odhner formed the basis of electrico-mechanical calculators.
Baldwin	In 1873, Baldwin applied for a patent for a machine that replaced the Leibniz and Thomas cylinders with a single cylinder
Baldwin machine	from whose periphery a variable number of teeth (1 through 9) protrude according to the motion of the setting lever. The levers project through slots at the front of the machine.
Baldwin drawing	When the lever is set, corresponding numbers of teeth project from the wheel.
Bald draw ii	With a crank of the handle the projecting teeth mesh with a cogwheel activating a digit

	wheel, and the numbers corresponding to the projecting teeth appear in the register.
Odner machine	A year later in Russia -- another one of those historical accidents happened -- a Swede, Wilgodt Odhner, patented a machine that was almost identical to Baldwin's.
Odner factory	In 1886, Odhner began to manufacture in Russia, selling all over Europe except in Germany,
Brunvisa	where the patent rights were bought by another firm that placed a similar, and more successful machine on the market -- the Brunsvisa.
Walter	And then the Walther. These machines can still be seen in operation today.
Curta calc.	The Curta represents the end of this evolutionary line -- a hand held rotary calculator.
Felt	The development of key punch equipment for telegraphy and typewriting, led to the possibility of a key punch calculator. Dorr E. Felt, a 24 year old machinist,
Macaroni box	went shopping on Thanksgiving Day 1884. He bought a macaroni box, some meat skewers, staples, elastic bands and string.

Mac box ii	By New Year's Day, he had put together the prototype comptometer -- the first successful keydriven calculator.
Comp key	He knew his machines must calculate faster than accountants, many of whome could mentally add four columns of figures at one time.
Comptometer	It was a struggle to get the machines on the market because he had to train the operators. One of the things to learn was complement arithmetic, first introduced in the Pascal adder.
Comptometer ad	The Comptometer advertised as "the machine gun of the office," and the Burroughs keydriven adding machines became the extremely popular.
Burroughs	William Burroughs got his idea of building a calculator while working with Baldwin.
Burroughs mach	In 1888, he obtained his first patent and had made 50 machines by the next year...but they proved impossible for anyone but Burroughs to operate.
Side view	After they were recalled, he invented a corrective automatic device.
Burroughs use	At the turn of the century the manually operated Burroughs and Comptometers were the workhorses of office forces,
Burroughs	but these were soon to be replaced by

electrified machines.

Monroe electric — In 1912, Frank Baldwin joined forces with Monroe to form the Monroe calculator Company,

Monroe electric — pioneering electric keypunch adding machines, that predominated the office in the electronic generation.

Poster — The families of pre-computing devices described developed no new significant members after 1930. Their use proliferated through the fifties, began to diminish in the sixties and are being totally displaced by digital computers.

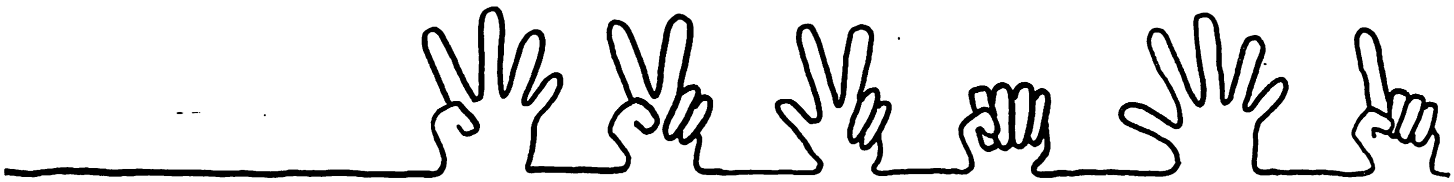
them.

Moreland adder Sir Samuel Moreland, Master of Mechanics to King Charles II of England developed three Pascal-like machines. Although they were quite pretty they didn't advance any new principles and were no more successful than Pascal's.

Mech cal line A more widely used set of calculating devices may be traced back to the stepped reckoner, developed by Gottfried Wilhelm Leibniz of Germany in 1671.

Leibniz Familiar with the machines of Pascal, Leibniz envisioned a calculator that could perform the four arithmetic functions with speed and accuracy.

stepped wheel His machines, which he called his living bank clerks, had two basic elements; a collection of pin wheels for adding and a movable carriage that could follow decimal places when multiplying. The two sections were lined by stepped cylinders containing ridge-like teeth of different lengths corresponding to the digits 1 through 9. Turning the crank that connected the cylinders engaged the smaller



ON ONE HAND...

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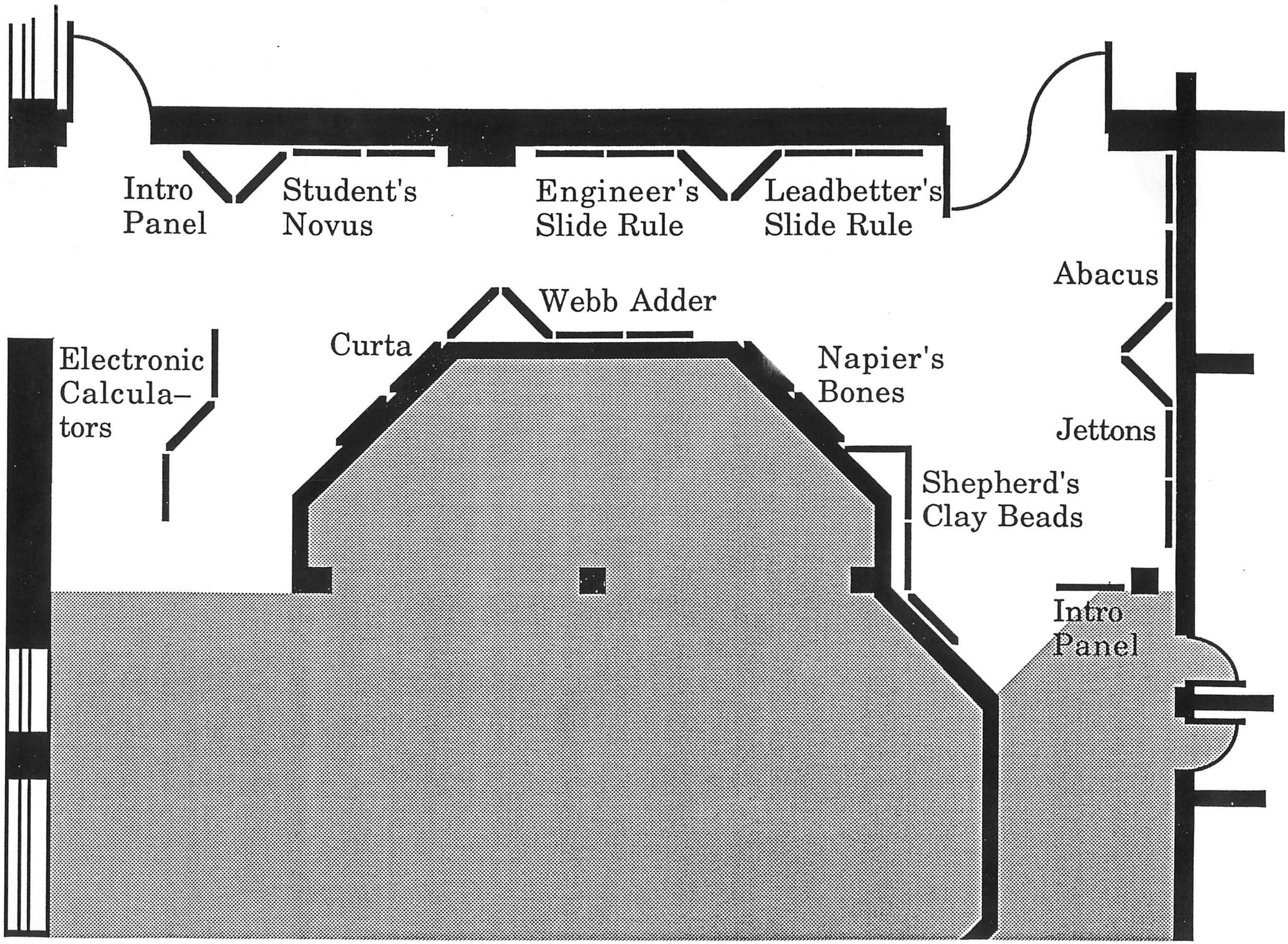
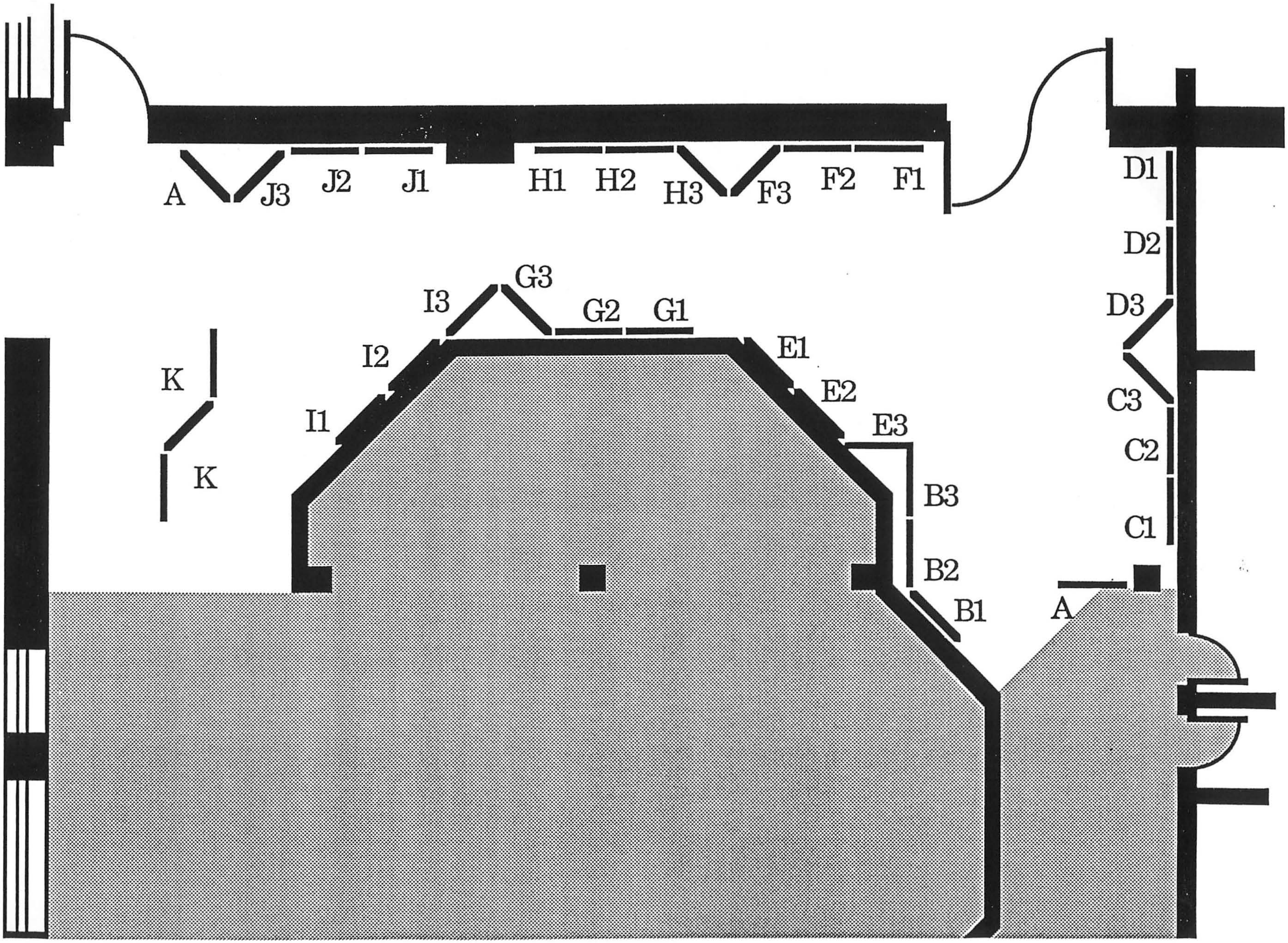
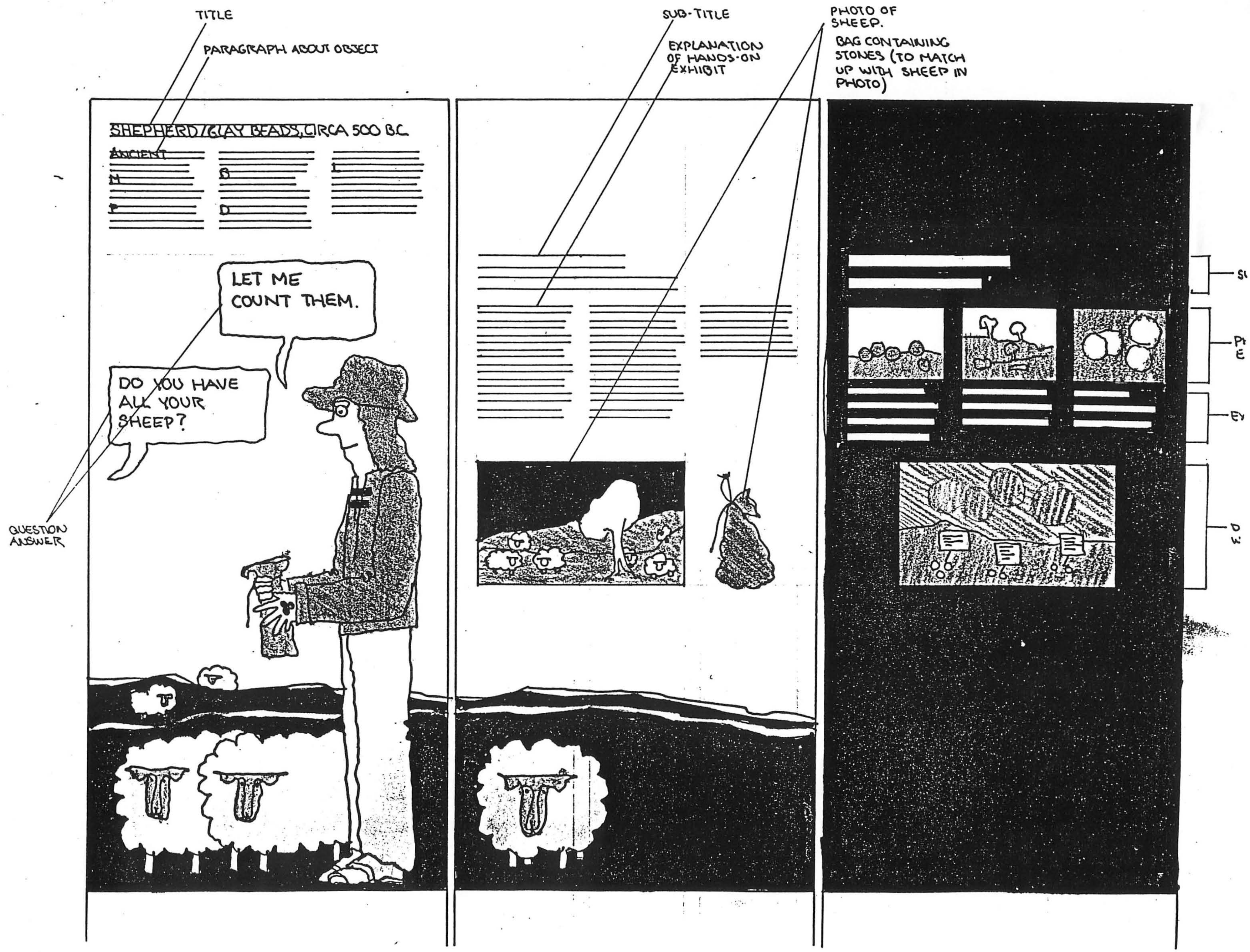

Intro
Panel
Student's
Novus
Engineer's
Slide Rule
Leadbetter's
Slide Rule
Abacus
Webb Adder
Curta
Electronic
Calcula-
tors
Napier's
Bones
Jettons
Shepherd's
Clay Beads
Intro
Panel



A
J3
J2
J1
H1
H2
H3
F3
F2
F1
D1
D2
D3
C3
C2
C1
G3
I3
G2
G1
I2
E1
E2
E3
I1
K
K
B3
B2
B1
A


TITLE
PARAGRAPH ABOUT OBJECT
SUB-TITLE
EXPLANATION OF HANDS-ON EXHIBIT
PHOTO OF SHEEP.
BAG CONTAINING STONES (TO MATCH UP WITH SHEEP IN PHOTO)
SHEPHERD/CLAY BEADS, CIRCA 500 B.C.
ANCIENT
LET ME COUNT THEM.
DO YOU HAVE ALL YOUR SHEEP?
QUESTION
ANSWER

8

B1 Shepherd

Heading: Shepherd's Clay Beads / Circa 500 B.C.

Dialogue: "Let me see if I have all of my sheep."

Story: Ancient shepherds placed a clay bead or pebble in their sachel for each sheep thet let out to graze in the morning. By comparing the number of beads to the number of sheep at the end of the day they could tell if they had lost any sheep. Using pebbles to represent numbers was the basis of calculating for many early civilizations

B2 Interactive

Task: Compare the beads in the satchel with the sheep that the shepherd leaves with in the morning, and again with the sheep that she heads home with to see if they are all there.

Tools: A burlap satchel mounted to the wall contains clay beads which can be felt through the cloth, but not removed.

Two (2) illustrations, one showing the shepherd and her flock starting out in the morning, and the other when she is about to return home in the evening.

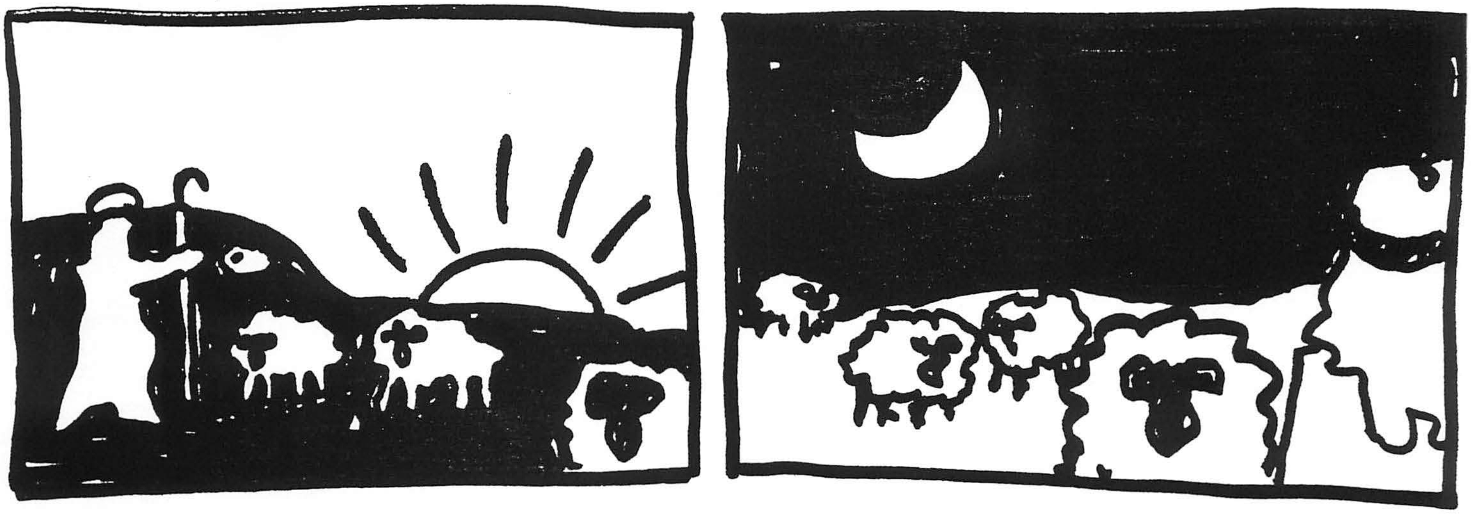
If you have the right # of tokens and the right # of sheep, then she can go home.

B3 Visuals

None

B4 Display Case

Artifacts: Tally Stick
Korean Computing Rods
Roman Bones Styluses



C1 Pasta Maker

Heading: Jetons / Circa 1400 A.D.

Dialogue: How much for 3 lbs of Linguini?

Mama Mia! Let me check!

Story: Instead of pebbles, an Italian Pasta Maker from the middle ages used copper coins called "Jetons" (from the French verb "jeter" meaning "to throw") to calculate the price of her wares. The coins were moved about a set of lines representing the different values of ten (ones, tens, hundreds, etc.). Since Roman numerals then used were difficult to caculate with by hand, jetons allowed her to find the price of many pounds of pasta and calculate change must faster.

C2 Interactive

Task: Simple addition problem.

ie. 1lb of pasta is ___ therefore 6lbs is ___

Include roman numerals in the explaination.

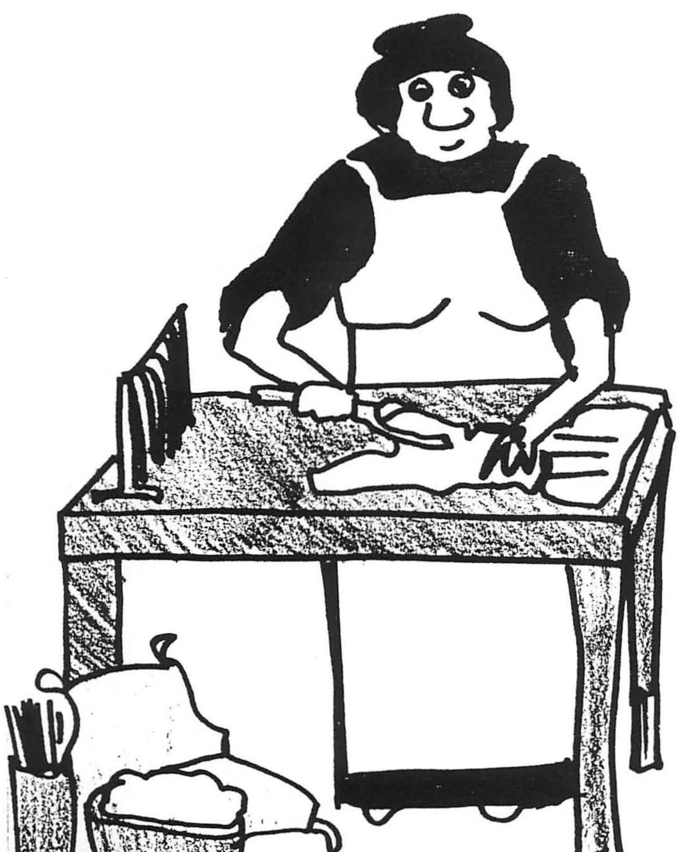
Tools: Velcro jettons and matching strips on the graphic panel.

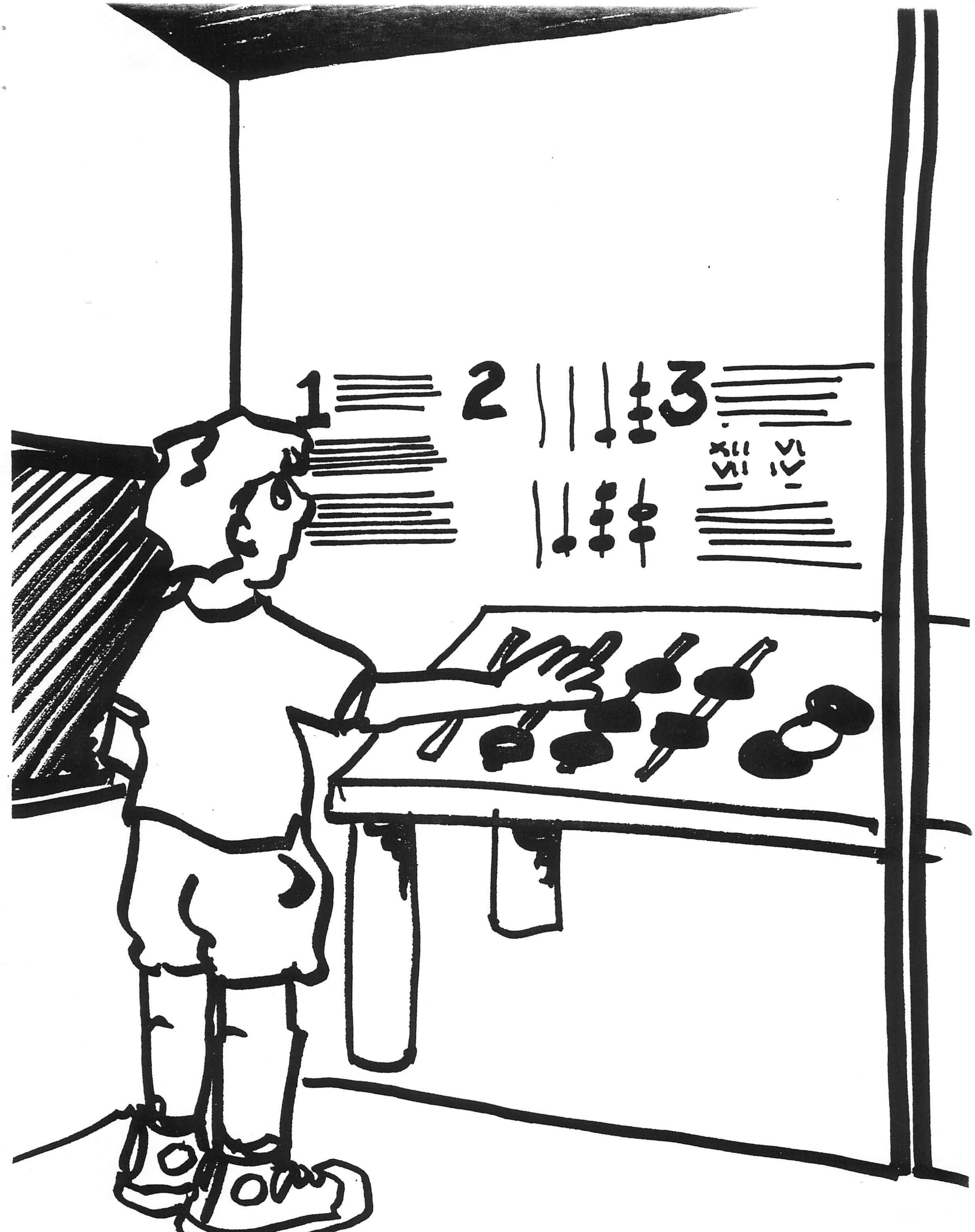
C3 Visuals

- Contest between Jettons & Arabic figuring
- Image from Darius vase
- Dutch Jetton Cylinders
- Schwarzenberg's Der Tevtsch Cicero
- Livre Des Getz: late 15th century

C4 Display Case

Artifacts: Jetons
Pasta




1
2
3

D1 Silk Merchant

Heading: Abacus / Circa 1450 A.D.

Dialogue: "Hmmm... 35 yen for 10,000 bolts of silk. Is that a fair price?"

Story: A miniturized abacus was useful to the 15th century Chinese silk merchant on his travels to help quickly calculate the price of quantities of silk. An improvement on the loose pebble and coin counters used since ancient times, the wire–strung bead abacus originated dureing the Middle Ages in the Middle East and from there spread east. In many parts of the world abaci continue to be widely used.

D2 Interactive

Task: Simple written steps and diagrams which teach the fundamentals of using the abacus.

1st–the units,
then 5's and 10's,
and finally the carry into the next row

Tools: Simple store bought abacus mounted on a rail infront of panel.

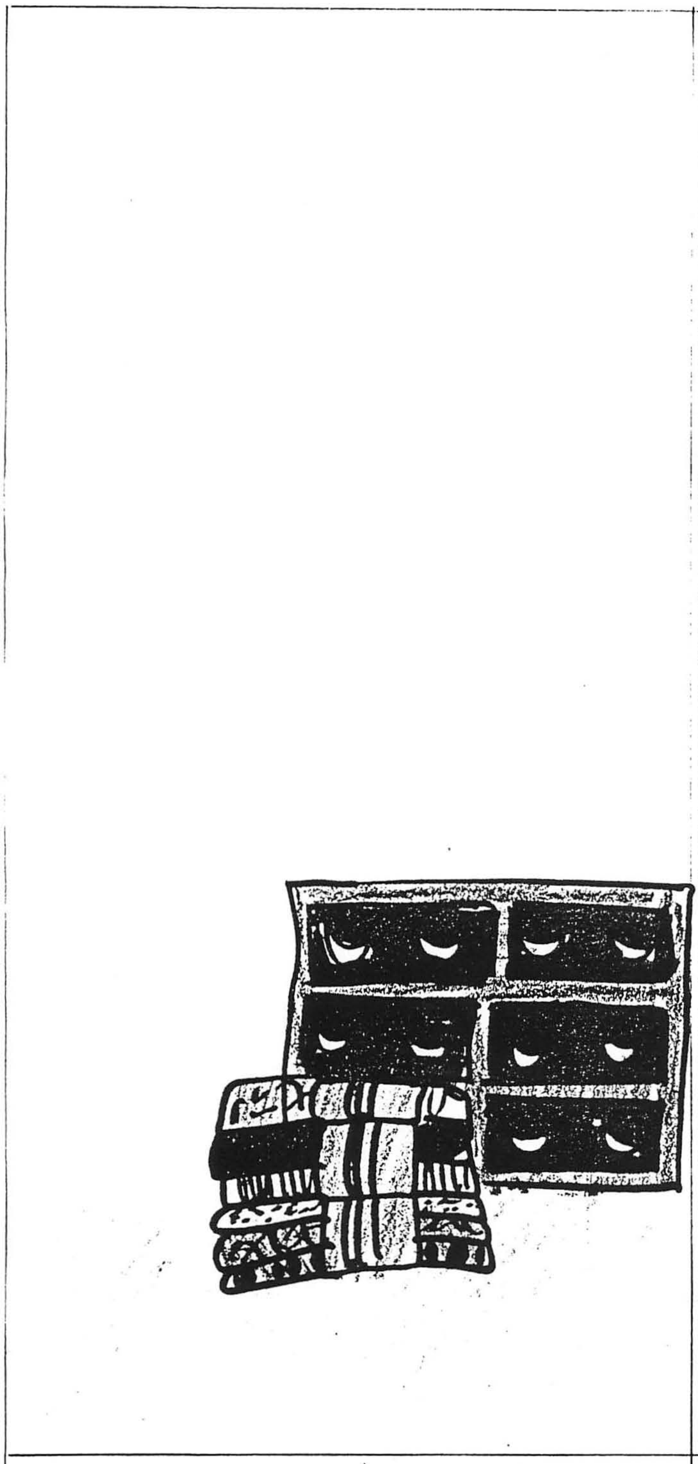
Possibly a group of school desks in the center of the room with mounted abacus on them, and more advanced problems to work through.

D3 Visuals

- Silk Merchant's Shop Interior #1
- Silk Merchant's Shop Interior #2
- Video

D4 Display Case

Artifacts: Abacus
Soroban
Ancient Arab Astrolabe
Small Soroban
(books)
"How to Use the Chinese Abacus"



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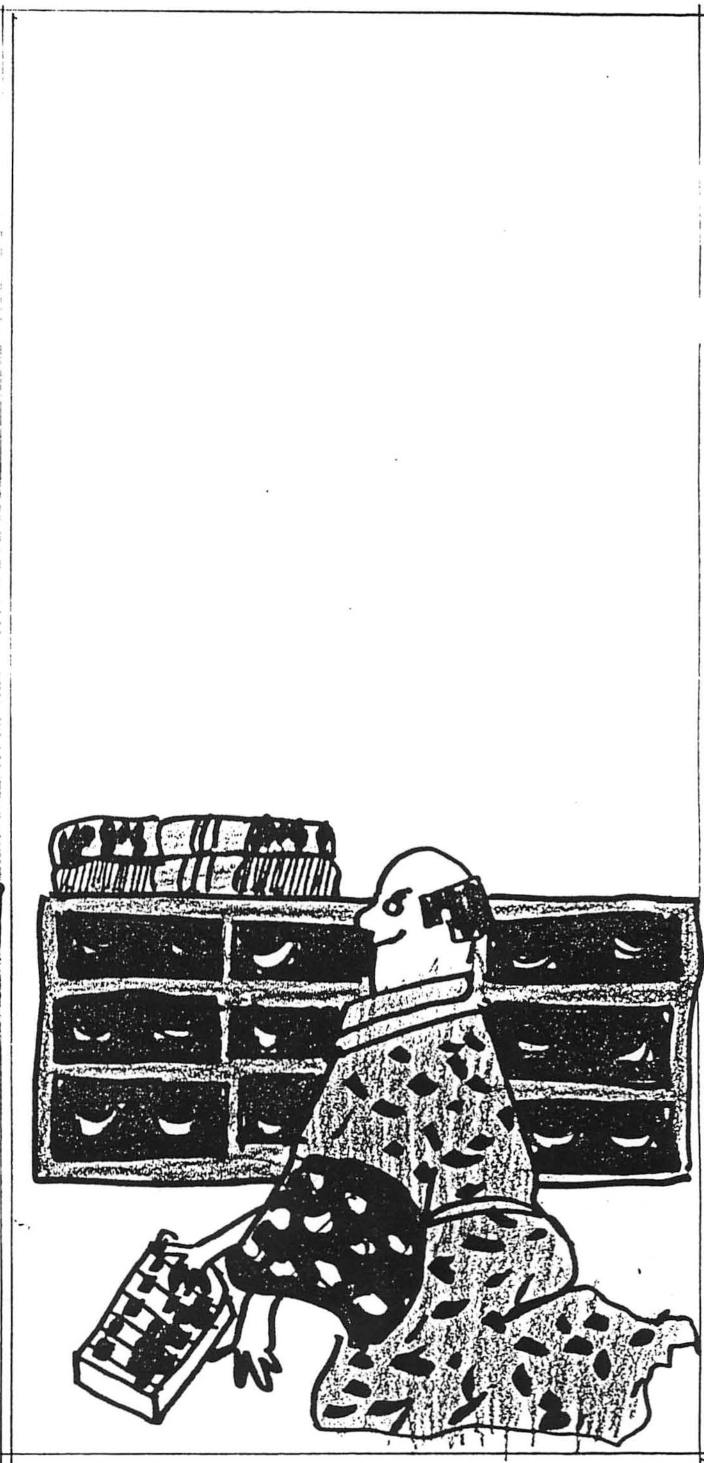


A


1.
2

E1 Astronomer

Heading: Napier's Bones / Circa 1630 A.D.

Dialogue: "What will be the possition of Venus 3 months from now?"

Story: Invented in the early 1600's by the Scottish mathematician, John Napier, "Napier's Bones" made the lengthy calculations of 17th–century mathematicians and astronomeres less mentally taxing and prone to errors. Pocket–sized books of mathematical tables were also useful. Tables of logarithms allowed complicated multiplication to be reduced to addition problems.

E2 Interactive

Task: Simple multiplication problem

Figure out how many days old you are, based on how many years.

Tools: A large simplified model of Napier's Bones with three moving pieces, graphic representation for the rest of the set.

E3 Visuals

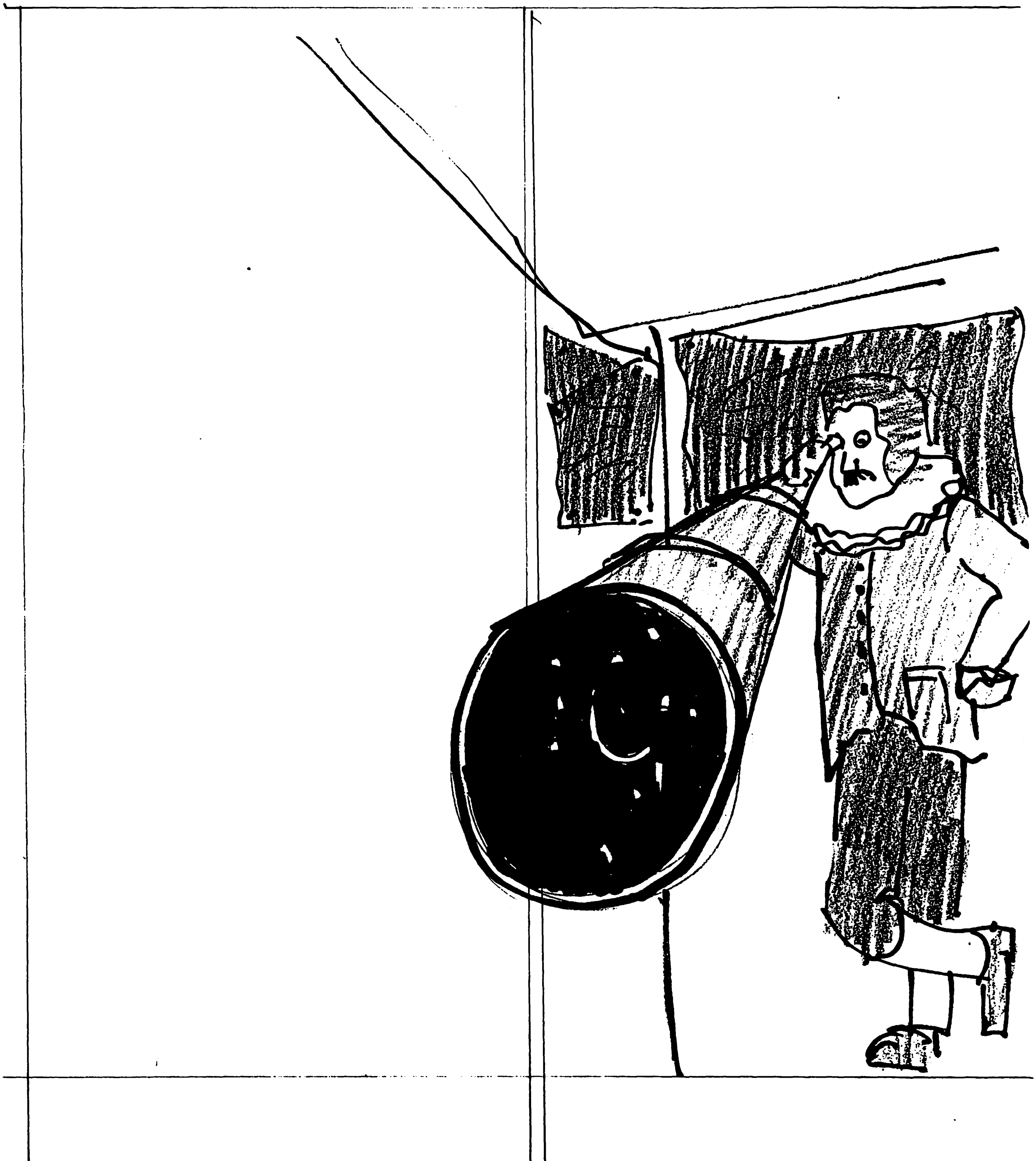
- •The Octagon Room
- •15th Century Star Chart
- •Kepler's Rudolphie Tables
- •Kepler's Calculations

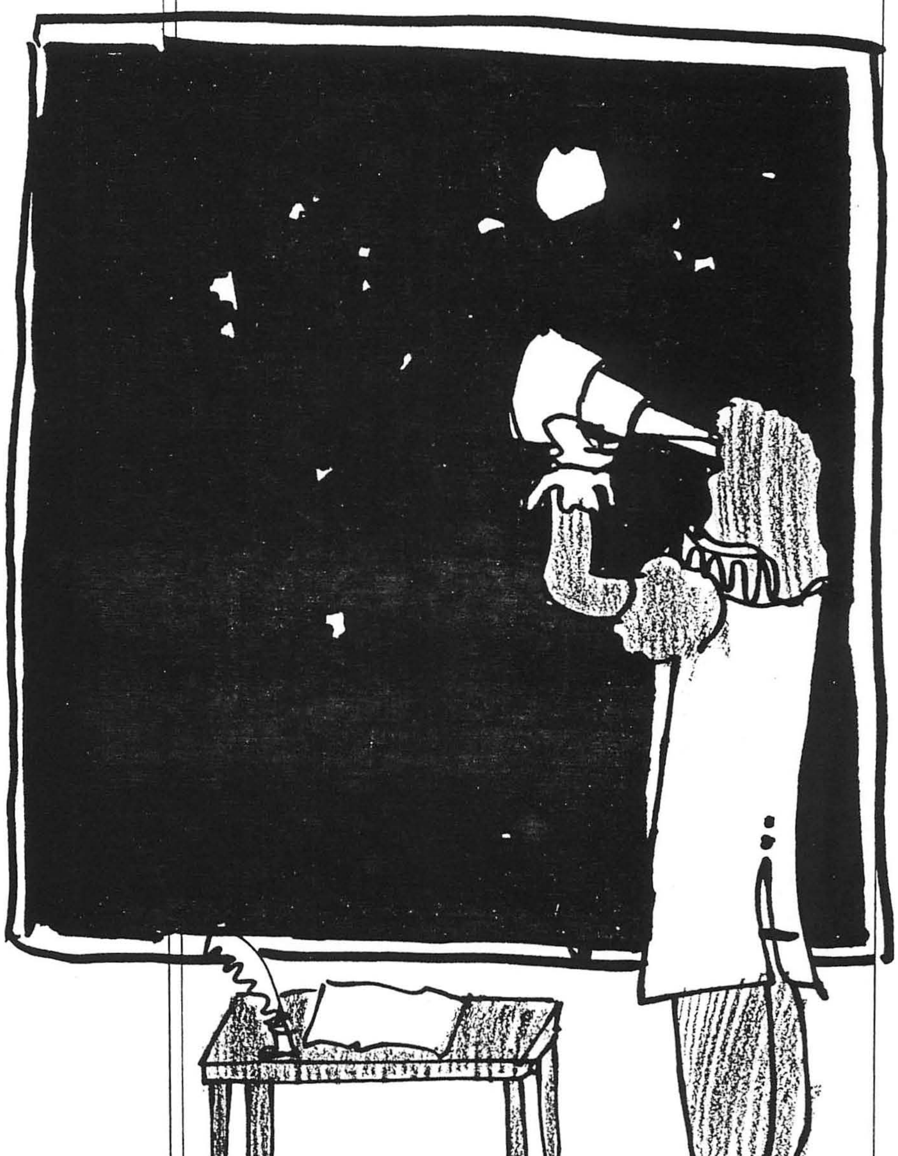
E4 Display Case

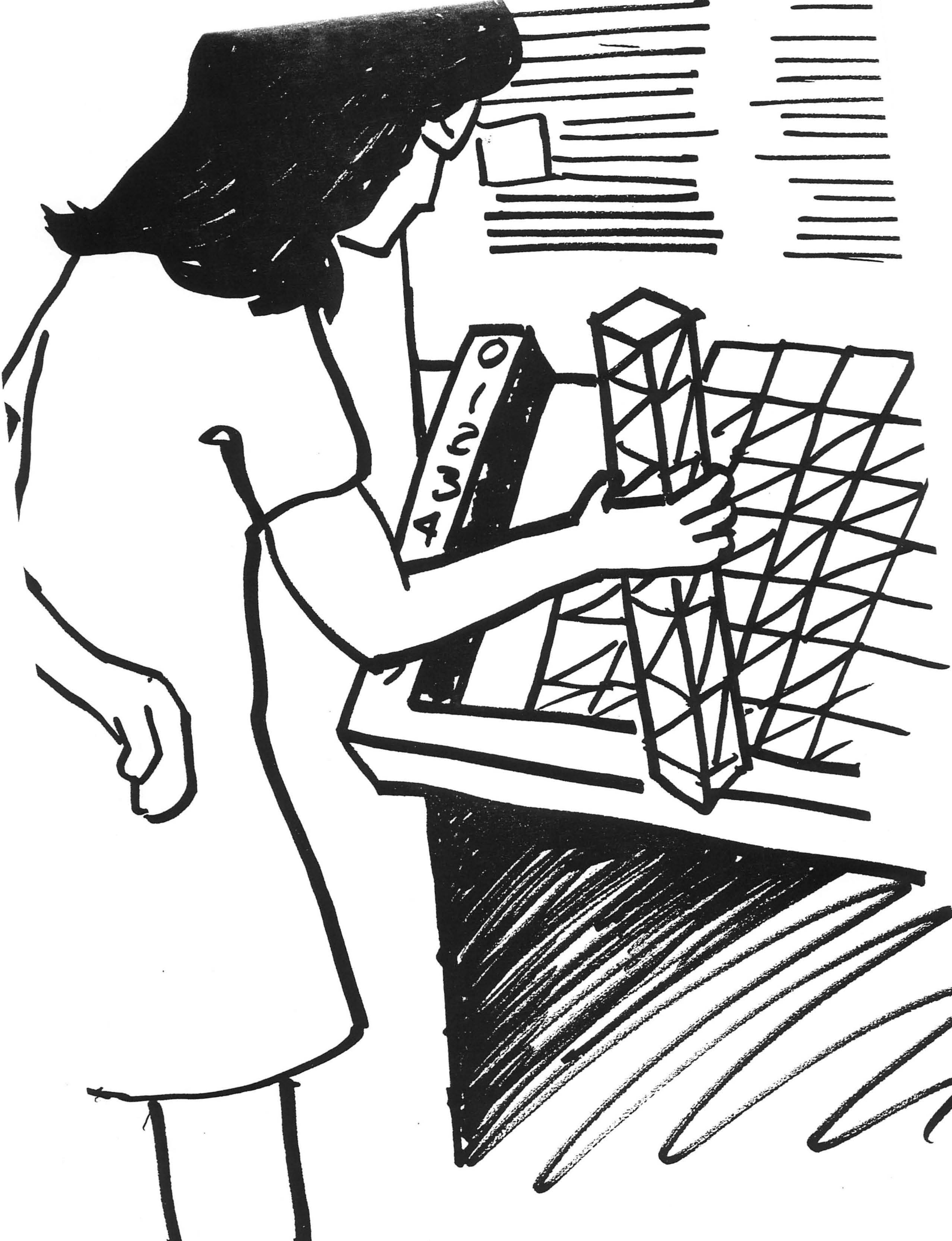
Artifacts: Napier's Bones
Universal equinoctail dail w/ compass
QuadrantFrench Pocket Calculator

"Tables of Logarithms 1/6"
Tables De Sinus Tangentes et Secantes
Electrical Tables and Memoranda
Molesworth's Pocket Book of Engineering Formula
Day's Ready Reckoner and People's Calculator

Set of Pocket Drawing Instruments
Rabdologiae






0 1 2 3 4

F1 Tax Assesor

Heading: Leadbetter's Slide Rule and Measuring Devices / Circa 1750

Dialogue: "Hey, how much tax do I owe?"

"Hold still my good man. I'll tell you in a moment!"

Story: In the 17th century the English government set up an efficient system for collecting excise taxes on ale and wine. The scientific tax assesors developed slide rules to calculate the duty owed on a stock of liquor. These slide rules gave the amount of ale or wine contained in a keg based upon its construction, external dimensions, and the depth of the liquor in the keg. The tax levied on alcohol was not very popular, and led to many political clashes.

F2 Interactive

Task: Figure how much tax to charge the Tavern Owner based on the amount of rum he has sold.

Use the tools to measure the volume of rum in the barrel, vs. the total volume of the barrel, and plug those numbers in on the slide rule to figure the tax.

Tools: Rum Barrel (free standing or half round mounted to the panel)

Semi-fixed dip stick with pre–painted wet mark

Tape measure (fixed to the barrel)

Simplified slide rule (mounted to panel)

F3 Visuals

Various Etchings (Holgarth)

F4 Display Case

Artifacts: Leadbetter's Slide Rule
Gauging Rod


XXX
XXX
XXX
XXX

G1 Dry Goods Clerk

Heading: Webb Adder / Circa 1890

Dialogue: "Hey son, check around to see how many beans we have left!"

Story: The Webb Adder was useful for counting stock. Though it could only add, it was faster and more accurate than hand tabulation. The idea of using a stylus to advance gears to perform addition dates to 1642 when the French mathematician Blaise Pascal invented a calculator called the Pascaline. Many miniturized mechanical calculators built for the pocket operated on similar principles.

G2 Interactive

Task: Take inventory of the ages of people in your family, classroom, or group you are with today.

Enter each of the ages seperatly without counting.

Tools: "SEE" adder

Diagrams and visuals of how the "adder" works

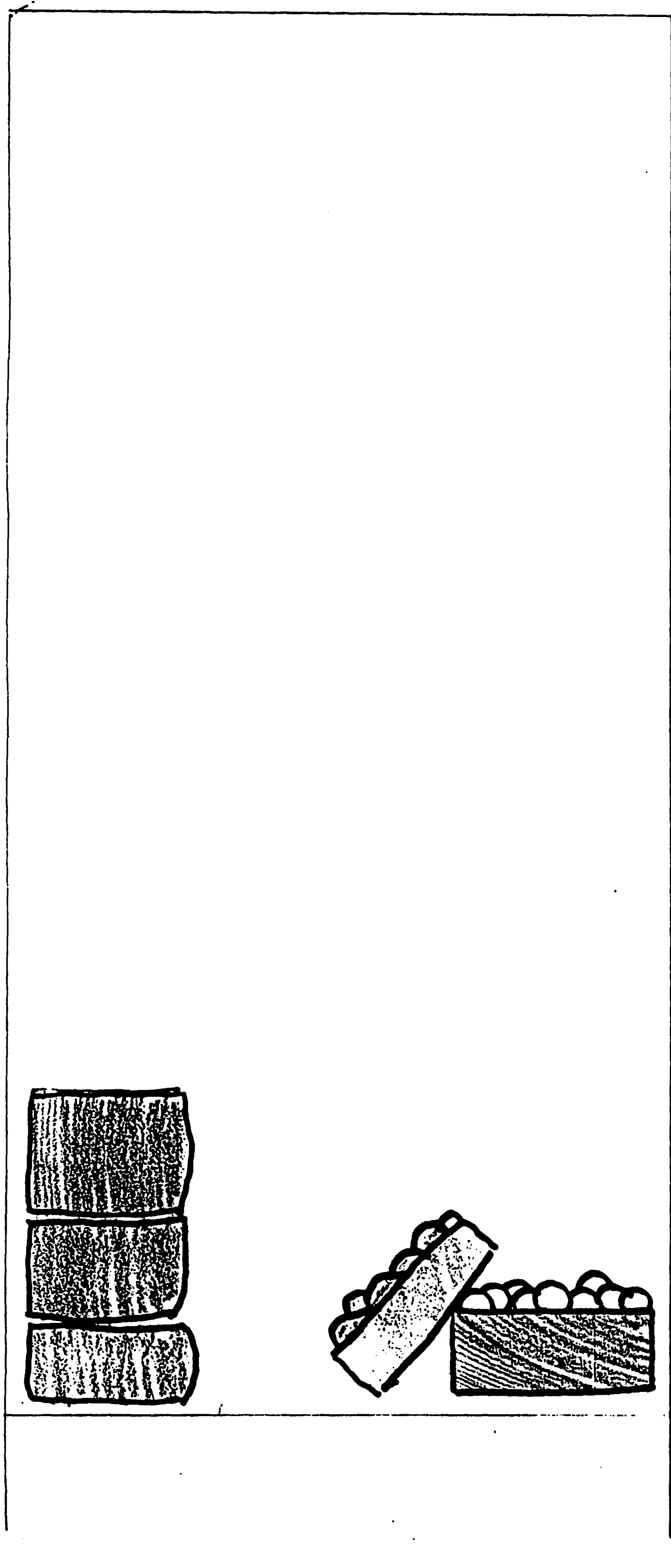
Illustrations of various groups of people and there ages

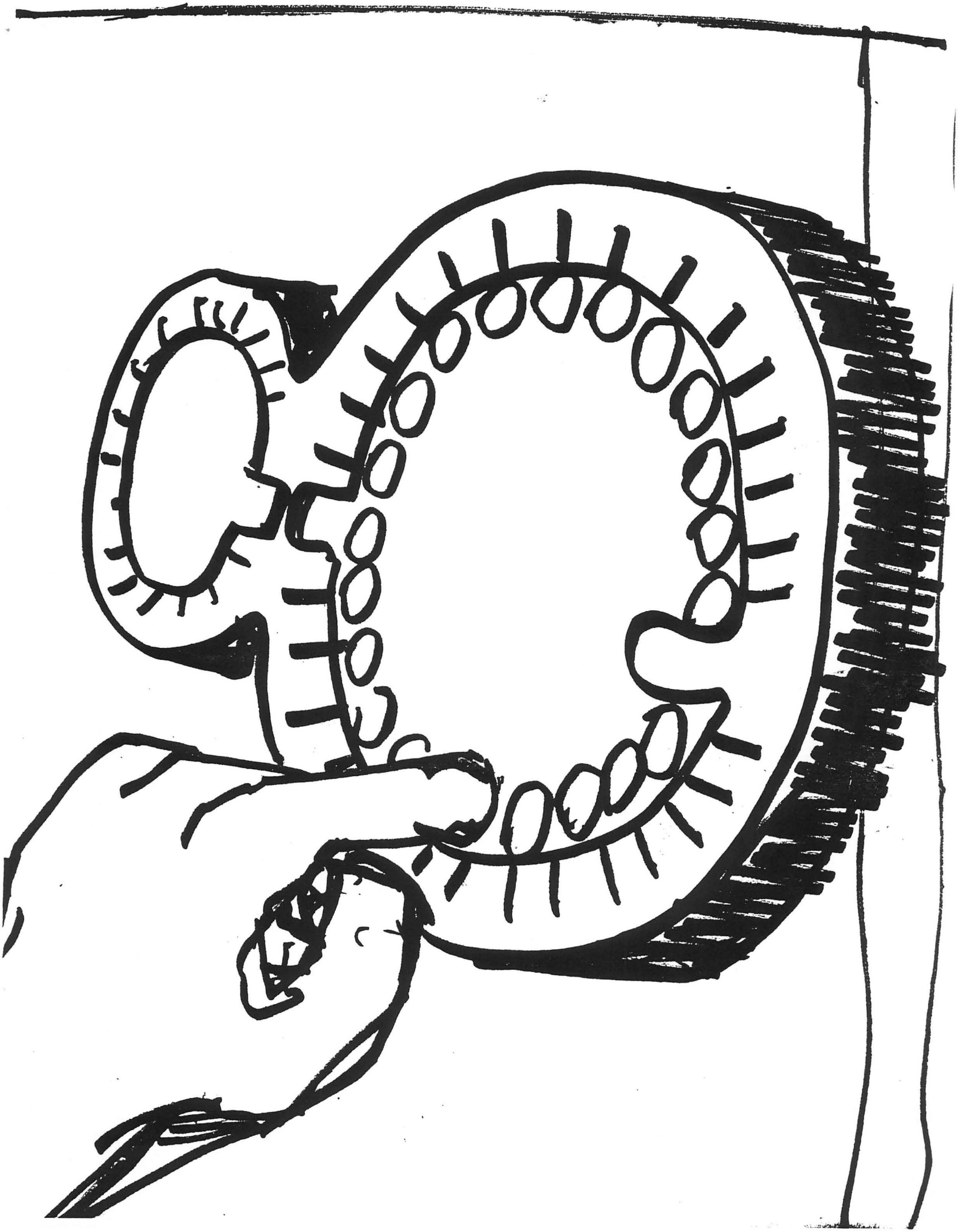
G3 Visuals

Photo–details of mechanical calculators

G4 Display Case

Artifacts: Webb Adder
Brical Pocket Adding Machine
IBM Hexadecimal Adder
SEE Calculator
The Addist
Golden Gem Adding Machine
Golden Gem Calculator
Addiator
Totalisateur
Calcumeter
Adding Machine





H1 Engineer

Heading: Engineer's Slide Rule / Circa 1940

Dialogue: "How many people will this elevator hold before the cable snaps?"

Story: The slide rule (or "slip stick" as it was nick–named) was the constant companion of engineers and scientists through the 1960's. It was designed to make the complicated calculations often required in engineering much simpler. However, it took to use well, and its accuracy was limited by its size and the fineness of its graduations. Slung from the belt, or stuck in the pocket, the slide rule was the mark of a serious scientist.

H2 Interactive

Task: Simple multiplication problem

Tools: Slide Rules and diagrams to show how to use them

H3 Visuals

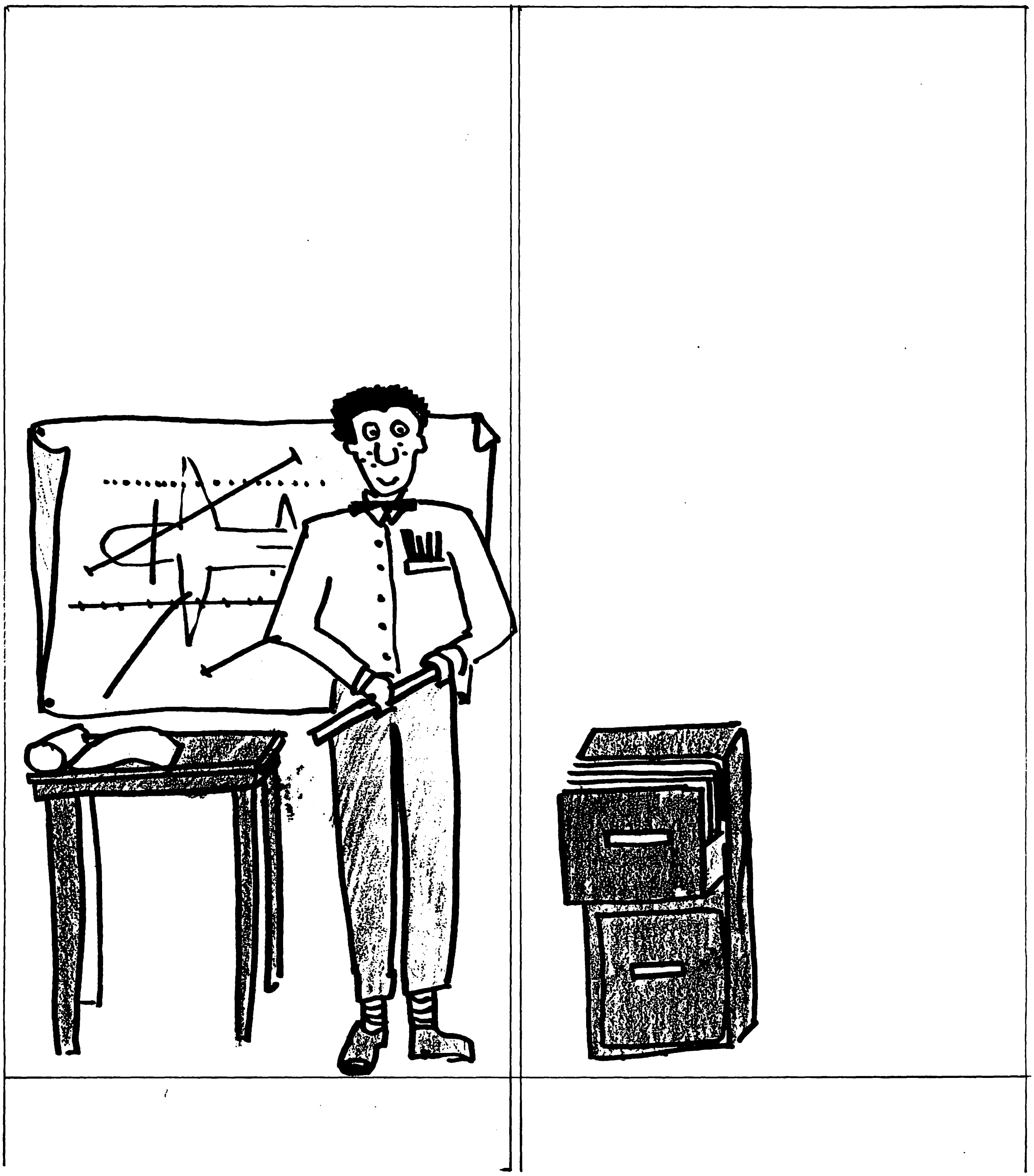
- Eugene Dietzgen Co. Catalogue
- Keuffel & Esser Co. Catalogue
- Phot–details of

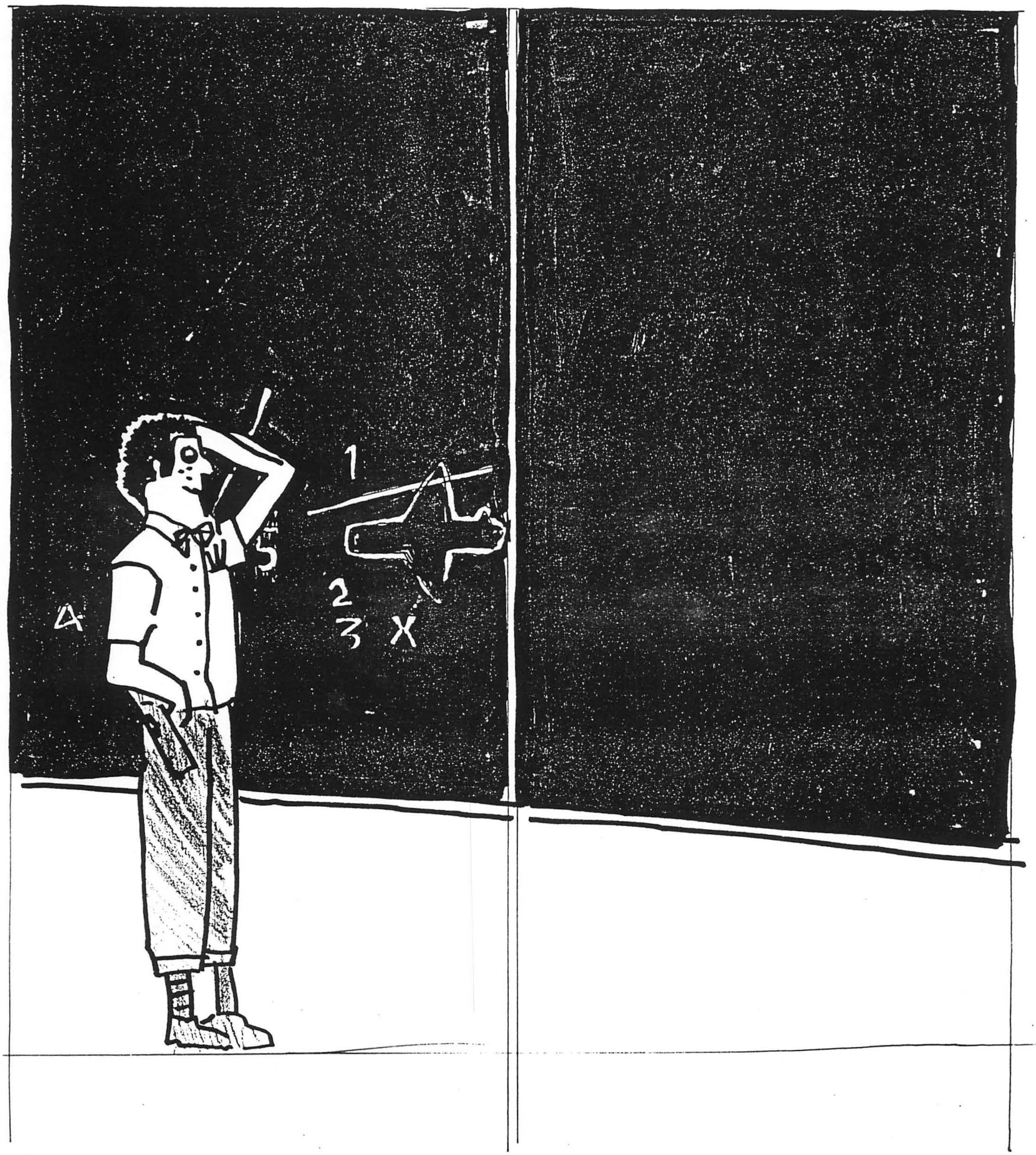
H4 Display Case

Artifacts:
Flight Plan Calculator
Circular Price Calculator
Otis King's Pocket Calculator
Calculex Patent Circular Slide Rule
Dietzgen Redirule Slide Rule
Radio Communication Slide Rule
Fowler Universal Slide Rule
Hockey's Secret Code Maker & Decoder
Trigonometric Slide Rule
Calculigraphe
Hydrocalculator
Ohm's Law Calculator
Harvard Project Physics
Decibel Slide Rule
Reactance Slide Rule
Circular Concise Slide Rule
Date Slid Rule
Circular Slide Rule
Gunter Rule
Calculex
The "Unique" Log–Log Slide Rule
Biomate
Boucher's Calculator
The Mechanical Engineer
Brass Sector
Brass Dividers
Map Measure
Map Measurer
Horse Meter
Musketry Rule Model of 1918
Pocket Planimeter
Probability of Destruction Calculator
Le Prompt Calculateur Des Arts Industriels et du Commerce
Vector Type Log–Log Dual Base Speed Rule, Model N4T
IBM Machine Load "Computer" Slide Rule
Pocket Set of Drawing Instuments
Hurter & Driffield's Actiniograph

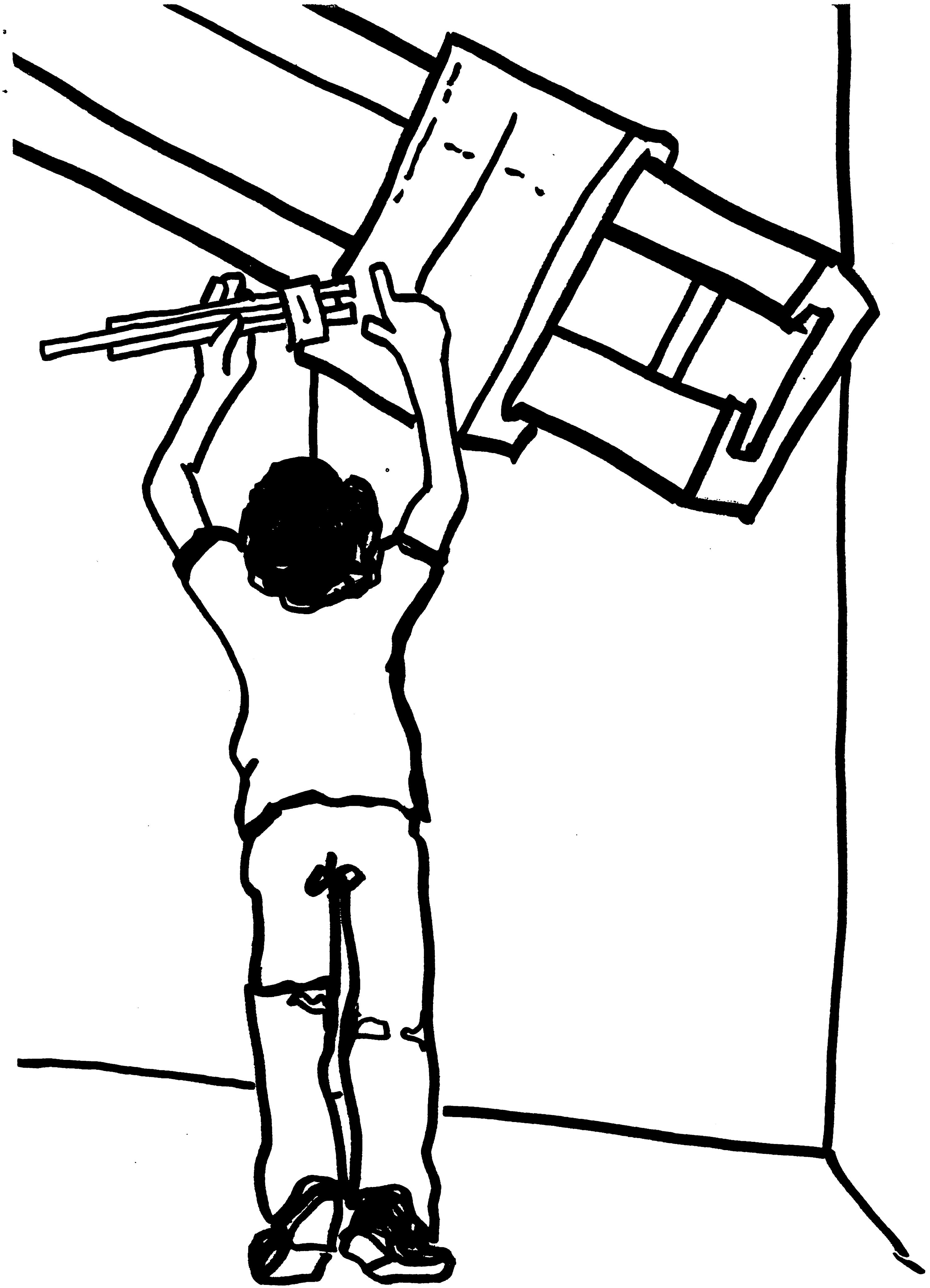
(Misc.)
Gunner's Sight

(Books)
The Slide Rule
Eugene Dietzgen Catalogue
Keuffel & Esser Co. Catalogue





1
5
2
3 X
4



I1 Rally Racers

Heading: Curta Calculator / Circa 1950

Dialogue: "We've gone 58 miles so far. How are we doing?"

"Too fast... I figure we should have only gone 42! Better ease up for a bit."

Story: The Curta Calculator's rugged design and accuracy made it a favorite of car rally racers who had to calculate the rate of their travel very percisely. Built with the percision of a fine watch, the Curta was the last word in mechanical pocket calculators. When electronic calculators became available in the 1970's the company soon went out of business.

I2 Interactive

Task: Simple currency exchange problems.

Calculate equivalents of a given amount in U.S. dollars of various denominations from around the world by plugging in the exchange rate, and cranking the curta the right number of times.

Tools: The curta (mounted in such a fasion that it may be used, but not harmed),

teaching diagrams (to show how to use it),

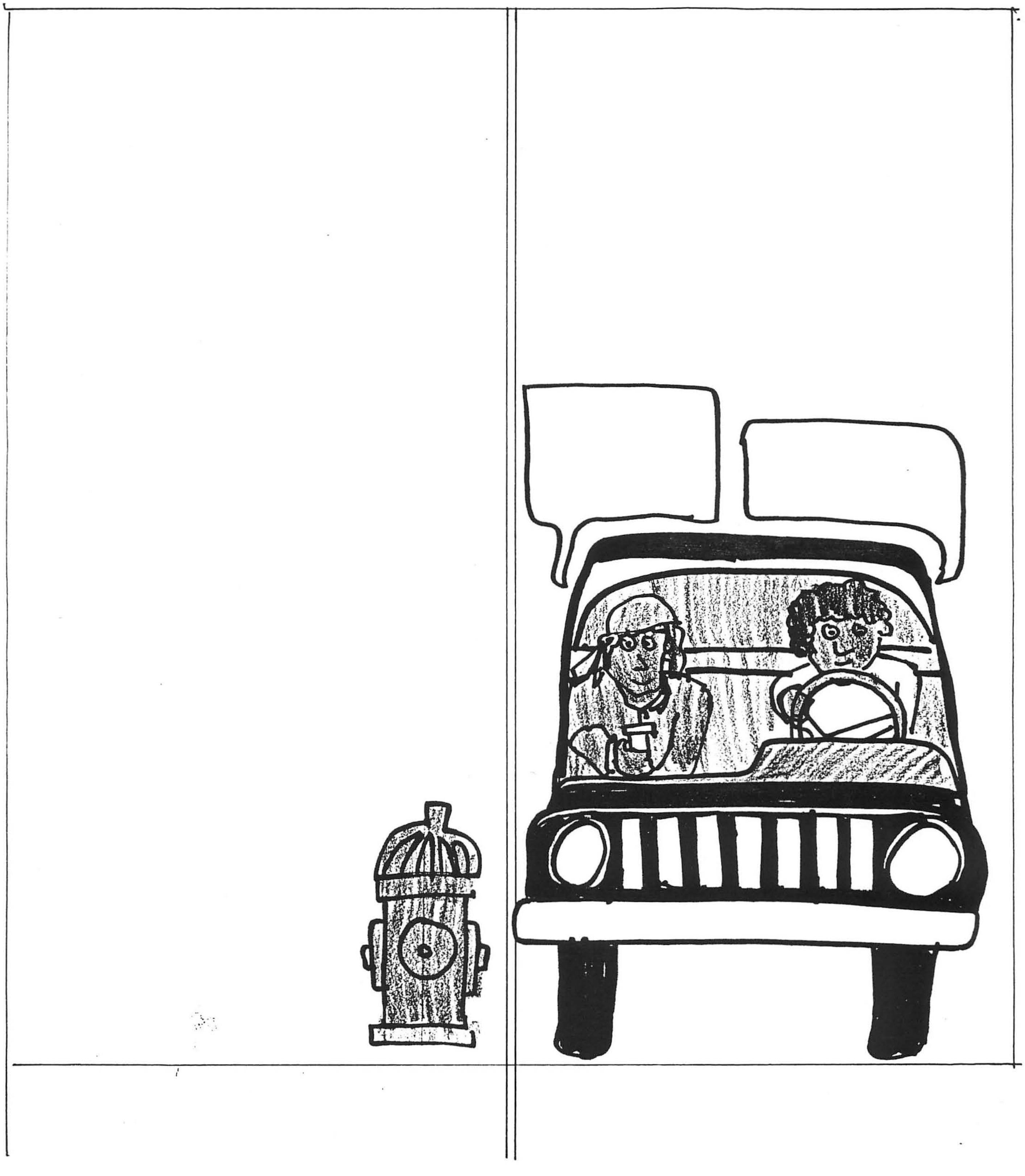
and several problems to solve.

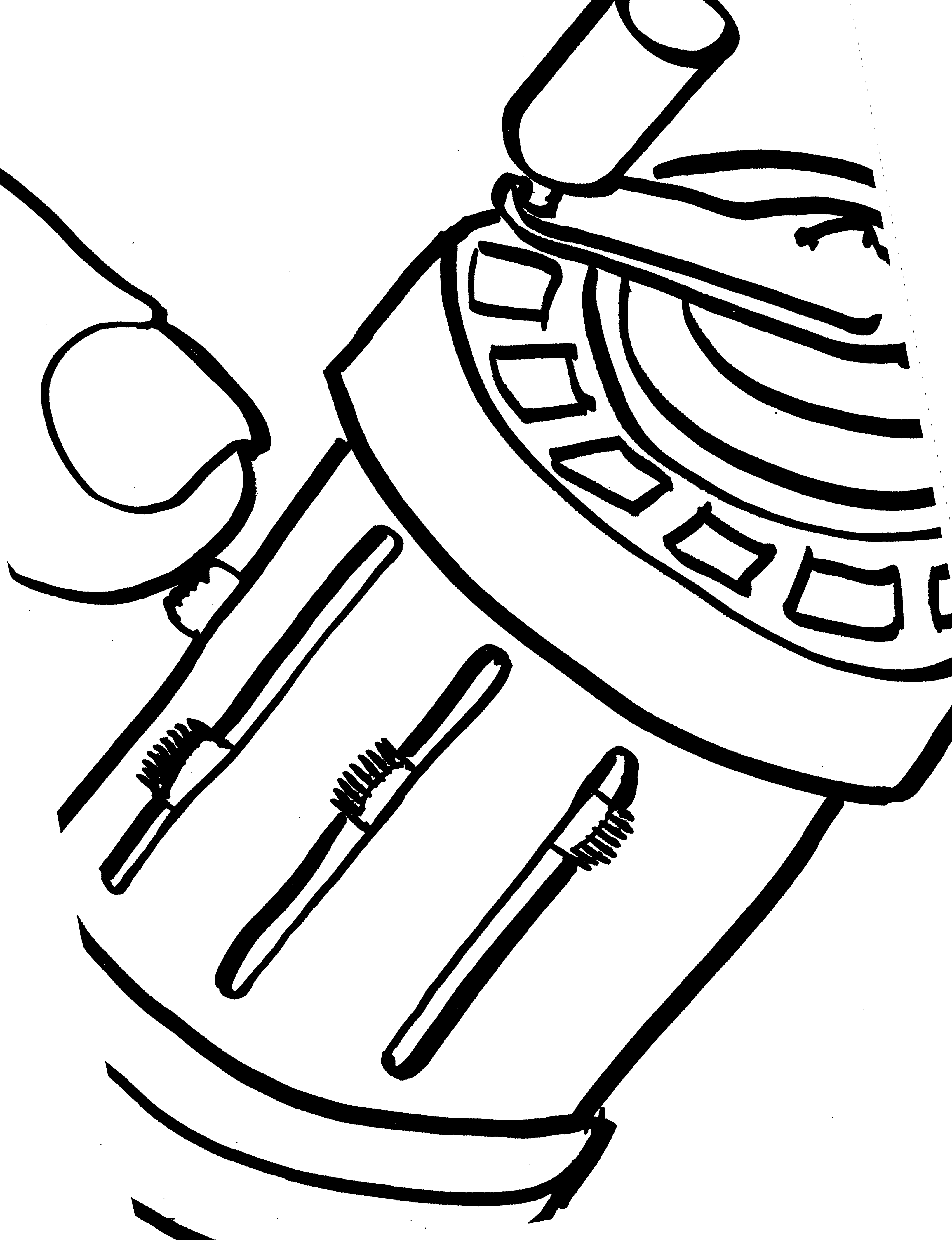
I3 Visuals

Photo–details of inside of Curta

I4 Display Case

Artifacts:
- Curta
- Baby Calculator
- Addometer
- VEOPAD
- Pocket Arithmograph
- EXACTUS
- The Adding Pencil
- B.U.G. Calculator





J1 Student

Heading: Student's Novus / Circa 1976

Dialogue: "Let's see... If I got 2 hits last night in three at bats, that brings my batting average to..."

Story: Dureing the mid–1970's inexpensive electronic pocket calculators became widely available. Students use such pocket calculators to help them with their homework, as well as many other every day calculations.

J2 Interactive

Task: Compute a series of batting averages base on available data.

Tools: The Student's Novus

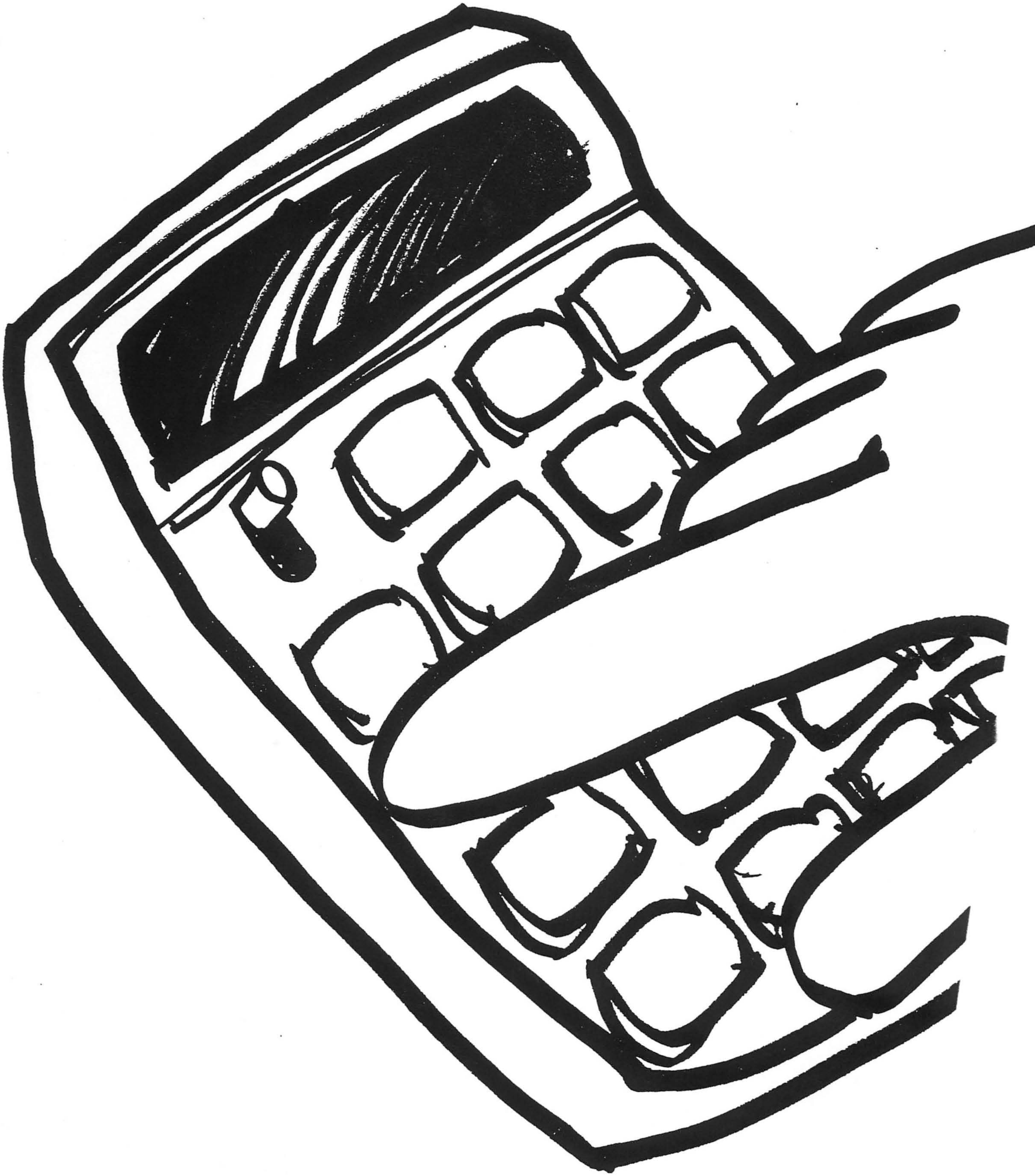
Step by step diagrams showing which keys to press etc.

J3 Visuals

Photo–details of PCB's &IC's

J4 Display Case

Artifacts:
Bowmar MX70 Memory Calculator
HP–55
HP–65
Novus 650 Fixed Point Calculator
Sinclair Cambridge Memory Calculator
Sinclair Sovereign Calculator
TI SR–50 Calculator
TI– 2500 Datamath Electronic Calculator
MX100 Scientific Brain
Time Watch Calculator
Casio Minicard fx–48 Scientific Calculator
LC–78 Electronic Card Calculator
Elsi–mate EL–835
Wizard of Wine
Stanley Calculator
HP–41CX
HP–71B
HP–12C
HP–01
HP–35
HP–41C
Casio FX–7000G
Casio DC–100
Casio DC–500
Casio TH–10
Casio SL–760
PD–100



K – Electronic Calculators

Heading: None circa 1970's – 1980's

Dialogue: None

Story: "Cheap" & "Available"

K – Interactives

Task: All will include a descriptive paragraph or two along with diagrams to help the visitor complete a series of complicated computations.

Tools: HP–35 Scientist / scientific computation (power and programability)

HP–12C Banker / interest computation

HP–41CV Astronaut / space shuttle navigation problem

HP–71B Serveyer / surveying computations

Misc. others / testing accuracy etc. etc. etc.

K –

POCKET COMPUTING EXHIBIT

Descriptive Outline

Ignore comments related to structural design of exhibit.

I. Overall Story
    A. Advantages and Needs
        1. convenience
            a. on-the-spot computing
        2. labor saving
            a. accuracy
            b. time-saving
    B. Diverse Users
        1. specialized
            a. inexpensive
    C. Diverse types
        1. different technologies
            a. different conceptual bases
                i. large concepts in small packages
    D. History and Trans-Cultural Themes
        1. used throughout history by virtually every culture
            a. fundamental to civilization
    E. Improvements
        1. increased power
        2. decreased cost

II. Overall Structure
    A. Two types of areas
        1. Users scenes
            a. backbone of exhibit
            b. series of nine scenarios
                i. w/ collection of similar technologies and periods
                    a) simple diplays of artifacts
                ii)historical stories
        2. Experience Cells
            a. large models of operation
            b. tie in with social stories

III. Users scenes

A. Nine scenarios of users of pocket calculators throughout the ages.

1. containing the artifacts, the pockets, and other paraphenalia enhancing the creation of the atmosphere in which device was used.

   a. Shepherd's clay beads, c. 500 B.C.
   b. French Baker, Jetons, c. 1400A.D.
   c. Chinese Silk merchant's abacus, c. 1500 A.D.
   d. Astonomer's Napier's Bones and Log Tables, c. 1630
   e. Tax Assessor, slide rule, c. 1700
   f. Clerk's mechanical adder, c. 1890
   g. Engineer's slide rule, c. 1940
   h. Car racer's Curta, c. 1950
   i. Student's Novus, c. 1976

B. Stories

1. People who use pocket computers
   a. why need, how helpful?
2. Diversity of uses
   a. specialized devices

C. Comments

1. Keep presentation simple
   a. little text
   b. let scenarios speak for themselves
      i. communication through design
2. accessible and entertaining to all visitors
   a. immediately communicative
   b. but detailed enough to interest "experts"

D. Scenarios accompanied by small collection of thematically rela ted artifacts.

1. Though primarily collection, give some brief text on overall aspects of technology, and specific artifacts, including historical/cultural importance
2. Between Clay Beads and Jetons
   a. anciet calculating and recording devices
      i. Roman styli
      ii. Korean Bones
      iii. Tally Sticks
      iv. Greek gears
         1) brief story
3. W/ Abacus
   a. Abaci
      i. from different cultures different designs different quality
4. W/ Astronomer
   a. Pocket books and Tables
      i. Tables De Sinus Tangentes et Secantes
      ii. Logarithm Tables
   b. astrolab

5. W/ Tax Assessor's Slide Rule
    a. analogue devices
        i. dividor
        ii. sector
        iii. quadrant
        iv. Gunter's rule
        v. Calculex
6. W/ Dry Googs Clerk
    a. mechanical, digital devices
        i. adding pencil
        ii. Golden Gem
        iii. Totalisateur
        iv. B.U.G Calculator
        v. Exactus
        vi. Webb Adder
    b. Story: digital calculation
        i. tie in with story at Giant Pascal gears
7. W/ Engineer
    a. other specialized analog devices
        i. slide rules
            a) nuclear destruction calculator
            b) musketry rule
            c) pilots dead reckoning rule
            d) one or two others
        ii. planimeter
        iii. map measurer
    b. slide rules of every shape and for every purpose
        i. analog computation
        ii. adaptability
8. W/ Novus
    a. early electronic pocket devices
        i. Bowmar
        ii. TI Datamath
        iii. Casio Elsimate
    b. calculators, watches, etc.
        i. ever smaller, ever more powerful
        ii. many specialized adaptations

IV. Experience cells

A. Large-scale model of operating principles behind essential technologies.

1. briefly discuss mathematical principles behind
    a. over-blown scale reflects large concpets in small packages.

B. In addition to technological aspect, talk about conceptual basis, and historio-cultural position

1. Giant Abacus
    a. moved beads representing units
    b. old, simple, digital (circa 1300 in China)
        i. but very efficient
        ii. historical origins
            1) counting beads/boards of Romans
            2) earlier in middle Asia
        iii. used by many cultures
    c. still widely used in Eastern Asia
        i. essential to arthmetic system
        ii. video of Japanese school children using
2. Giant Napier's Bones
    a. moved rods to set up problem, then head-hand figuring
    b. simple multiplication tool, manipulable table
    c. popular in Europe among scientists and mathematicians
        i. portrait of Napier
            1) "slippery errors" quote
3. Giant Slide Rule
    a. moving scales performed arithmetic
    b. used Napier's concept of logarithms to perform multiplication by the addition of lengths.
        i. analog computation
    c. very widely used and adapted in western culture through the 1970's
        i. Historical origins
            1) Galileo's rule?
            2) Gunther's rule
            3) sucessive developments
4. Giant Pascal gears
a. moved gears, teeth representing numbers
        i. performed arithmetic digitally
    b. allowed mechanical carry
c. principle used in many mechanical calculators thereafter
        i. historical origins
            1) Pascaline
5. Blow up of chip from HP-35
    a. no moving parts, electronic, moved electrons
        i. very fast
    b. microprocessor allowed hand-held electronic calculation
        i. Intel 4004
        ii. became progressively cheaper
        iii. virtually replaced all other devices except abacus
    c. need for handy powerful calculator
        i. video of Bill Hewlett
    d. many electronic devices operating
        i. showing varied uses and usefulness

C. Comments
1. very "visitor friendly" area geared toward novice
a. highly interactive
b. videos
2. historical themes to mesh with Users Scenes by giving backgound
3. discuss general properties of technology
a. above two points re-enforced in Collection Cases

VI. Specific Ideas
A. In cases of older technologies relate to those currently used.
1. e.g.: "Today pilots use electronic calculators that are specially modified for in-flight navigation.
B. At end of exhibit have visitor comment
1. "What would you like to have in your pocket in ten years?"
a. Or, contest to guess the pocket calculator will be in ten years.
C. Emphasize that human hand is first pocket calculator.

POCKET COMPUTING EXHIBIT

Descriptions of User Scenes with text

Objects	Text
[Shepherd/Clay Beads, Circa 500 B.C.]	
Sheepskin shepherd's garment, leather sachel, crook, shears, pasture w/ sheep backdrop	"Ancient shepherds placed a clay bead or pebble in their sachel for each sheep they let out to graze in the morning. By comparing the number of beads to the number of sheep at the end of the day they could tell if they had lost any sheep. Using pebbles to represent numbers was the basis of calculating for many early civilizations."
[French Baker/ Jetons, Circa 1400 A.D.]	
Baker's Apron and hat, Loaves of bread, board w/ flour and jetons	Instead of pebbles, a French baker from the middle ages used copper coins called "jetons" (from the French verb "jeter" meaning "to throw") to calculate the price of his wares. The coins were moved about a set of lines representing different values of ten (ones, tens, hundreds, etc.). Since Roman numerals then used were difficult to calculate with by hand, jetons allowed him to find the price of many loaves and calculate change much faster.
[Silk Merchant/ Abacus, Circa 1450 A.D.]	
Bolt of silk, Chinese jacket, scroll, bazaar backdrop	"A miniturized abacus was useful to a 15th-century Chinese silk merchant on his travels to help quickly calculate the price of quantities of silk. An improvement on loose pebble and coin counters used since ancient times, the wire-strung bead abacus originated during the Middle Ages in the Middle East and from there spread east. In many parts of the world abaci continue to be widely used."
[Astronomer/Napier's Bones, Circa 1630 A.D.]	

Antique telescope, sextant star charts, dividers, compasses, book of trig tables, appropriate jacket, observatory backdrop

"Invented in the early 1600's by the Scottish mathematician, John Napier, 'Napier's Bones' made the lengthy calculations of 17th-century mathematicians and astronomers less mentally taxing and prone to errors. Pocket-sized books of mathematical tables were also useful. Tables of logarithms allowed complicated mulitplications to be reduced to addition problems."

[Tax Assessor/ Leadbetter's slide rule, Circa 1750]

Long tweed overcoat, ledger, Quill pen, antique pen knife and ink well, ale cask, tape measure, dock backdrop

"In the 17th century the English government set up an efficient system for collecting excise taxes on ale and wine. The scientific tax assessors developed slide rules to calculate the duty owed on a stock of liquor. These side rules gave the amount of ale or wine contained in a keg based upon its construction, external dimensions, and the depth of the liquor in the keg. The tax levied on alcohol was not very popular, and led to many political clashes."

[Dry Goods Clerk/Webb Adder, Circa, 1890]

Sack of grain, etc. clipboard with stock ledger, clerk's vest, storage room backdrop

"The Webb Adder was useful for counting stock. Though it could only add, it was faster and more accurate than hand tabulation. The idea of using a stylus to advance gears to perform addition dates to 1642 when the French mathematician Blaise Pascal invented a calculator called the Pascaline. Many miniturized mechanical calculators built for the pocket operated on similar principles."

[Engineer/ Slide Rule, Circa 1940]

Windtunnel model airplane, short-sleeved white shirt with horn-rim geek glasses and plastic pocket protector.

"The slide rule (or "slip stick" as its was nick-named) was the constant companion of engineers and scientists through the 1960's. It was designed to make the complicated calculations often required in engineering much simpler. However, it took skill to use well, and its accuracy was limited by its size and the fineness of its gradations. Slung from the belt, or stuck in the pocket, the slide rule was mark of the serious scientist."

[Rally Racer/ Curta, Circa 1950]

Sport steering wheel, photo out front of car, dash board, driving gloves, rally jacket, log book.

"The Curta calculator's rugged design and accuracy made it a favorite of car rally racers who had to calculate the rate of their travel very precisely. Built with the precision of a fine watch, the Curta was the last word in mechanical pocket calculators. When electronic calculators became available in the 1970's the company soon went out of business."

[Pilot/ Navigation Rule, Circa 1960]

Leather flight jacket, instrument panel, clouds, charts

"Specialized slide rules help pilots chart their courses, estimate arrival times, and calculate other aspects of their flight according to changing conditions."

[Student/Novus, Circa 1976]

Math text book, homework, baseball mitt, etc. book bag, Calculator games book

"During the mid-1970's inexpensive electronic pocket calculators became widely available. Students use such pocket calculators to help them with their home work."

<title>
Pocket Computing

<primary text>
Today we almost take pocket calculators for granted. Portable and convenient, people reach for them them to do everything from their math homework, and balance their checkbooks, to calculate the expected return on investments, and design airplanes and automobiles. The pocket electronic calculator widely used today is only about fifteen years old. However, for centuries people from virtually every culture have built small devices to carry with them to perform calculations on the spot quickly and accurately.

<subtitle>
The First Pocket Calculator

<primary text>
The human hand is the first pocket calculator. Indeed, that most number systems around the world are based upon groupings of five or ten suggests that finger counting often led to the development of numbers. Many cultures through history have used hands to calculate and represent large numbers.

Venerable Bede's diagram of finger counting

This diagram from the 8th centruy illustrates a system of advanced finger counting used in Europe during the Middle Ages. Numbers up to 10,000 could be represented by various positions of the fingers. The ancient Greeks and Romans are also known to have had finger counting systems.

Can you represent your age on your fingers? Try the year of your birth.

<title>
THE ABACUS

<subtitle>
The History of the Abacus

<primary text>
The abacus is one of the oldest calculating devices known.

In its earliest forms the abacus was little more than a set of pebbles pushed about lines drawn in the dust or scratched on a flat surface. In fact, the English word "calculate" comes from the Roman word "calculus" meaning "pebble," and the word "abacus" derives from the Semtic word for dust, "abaq." Many ancient cultures from the Eygptians to the Romans calculated in this manner.

Darius Vase

<caption>
This figure from a 4th century B.C. Grecian vase depicts a king's treasurer using pebbles to calculate tribute.
<primary text>
In Europe during the Middle Ages abacus pebbles were replaced by metal coins. It was customary to give "nests" of new coins on New Years and dispose of the old coins in a river. At the same time as the Hindu-Arabic numeral system that we use today was introduced to Europe in the late Middle Ages the abacus faded from use in the West.

The abacus as we know it today, a rack of beads strung on wires, emerged in the Middle East sometime during the Middle Ages. From there it spread to southeastern Europe and Asia, where different cultures modified it. It is still widely used in the Far East.

The Chinese call their version of the abacus the "suapan," or "counting tray." It has round beads and is divided length-wise into two sections. The top section is called "heaven" and contains two beads, each worth five units. The bottom section is "earth" and contains five beads, each worth one unit. The suapan was in use in China by the 1300's, and became widely popular in 1593 when the mathematician Chen Ta-wei published a book on abacus computation.

The abacus was introduced to Japan from China. The Japanese made sharp edges on their beads, and used only one bead in "heaven" and four beads in "earth" to make operations faster. They called their abacus the "soroban." The soroban is still widely used in Japan everyday. School children are taught to use the soroban from a very young age, and it is essential to their notion of calculation.

The abacus is such as integral part of Oriental culture that in China May 10 is Abacus Day.

video of school competition

<caption>
Japanese school children engage in competitions to hone their skills on the soroban.

<subtitle>
Using the Abacus

<primary text>
Each collumn of beads on the abacus represents a different power of ten. The first collumn represents ones; the second tens; the third hundreds, and so forth. The abacus is set at zero when all the beads are pushed as far from the center horizontal bar as they will go. To enter a number hold the abacus level in one hand and push the appropriate number of beads toward the center bar. For example, to represent the number 48, in the first collumn to the right push three of the bottom beads up toward the bar, and one of the top beads down (the top beads represent five units),in the second collumn push four bottom beads up.

Can you represent your age on the abacus? How about the year of your birth?

Addition is performed by entering a new number [get good description Japanese st yle]

A problem like this was solved in ??? by ???. How fast can you solve it on this pocket calculator? On the abacus? Time your self with the stopwatch.

<title>
NAPIER'S BONES

<subtitle>
"slippery errors quote"

portrait of Napier

Rabdologiae

diagrams at each step

<primary text>
In 1617 John Napier, a Scottish baron, published a book describing a device to aid calculations. "Napier's Bones" were essentially a set of multiplication tables enscribed on rods so they could be repositioned in any order. They were an aid to pen and paper multiplication, division, and finding square and cube roots. Within a few years their use had spread among educated people throughout Europe and as far as China. Several improved versions were developed though the 19th century.

<caption>
John Napier, Baron of Merchiston, (1550-1617) inventor of Napier's calculating bones, and the discoverer of logarithms.

<caption>
The Rabdologiae contained instructions on the manufacture and use of Napier's calculating bones. Napier published the book shortly before his death at the insistance of his friend the Earl of Seton.

<subtitle>
Using Napier's Bones

<primary text>
Try this simple problem to understand how Napier's bones were used. Multiply 6 times 458.

- Position three rods along side the edge of the tray with the numbers 1-9 written on it so that the number 458 appears along the top of the three rods.
- Read off the the digits of the answer by adding the numbers between the diagonal lines in the sixth row.

    the units digit is 8
    the tens digit is 4+0=4
    the hundreds digit is 3+4=7
    the thousands digit is 2
    so the answer is 2,748

Notice that if the sum of the two numbers within the diagonals was greater than 9 that you would have to carry a 1 over to the next digit place. Also, to multiply by a number with more than one digit, you would repeat this process for each digit and than add together all the results by

hand, being sure to shift one decimal place to the left each time.
The value of Napier's Bones is more apparant when you consider that at the time it was introduced even the most educated people generally only knew their multiplication tables up to 5 times 5.

<title>
THE SLIDE RULE

<primary text>
The slide rule is a simple analogue calculating device, that takes advantage of the principle of logarithms. The primary scales on a slide rule (marked c and D) are drawn in such a way that one can multiply or divide numbers very simply.

To multiply two numbers you only need to know how to read the scales.

[diagram of scale]

Notice that you can at best only locate precisely a three digit number. Thus a quantity such as 10,547 would have to be estimated on the scale.

To multiply two numbers slide the C scale so that the 1 mark or index as its called is above the first factor on the D scale below it. The result of the multiplication is read on the D scale below the location of the sceond factor on the C scale.

OBJECT	TEXT
Early recording devices	To perform calculations it is necessary to express and record the figures you which to work with and the results you wish to find.
Roman Stylus	These styli were used by the ancient Romans to scratch numbers onto wax tablets. Though not as convenient or durable as our modern pen and paper, these tablets could be used to compute numbers on, and store important records.
English Tally Stick	These notched sticks were used to store financial records in Britain until the 19th century. The pattern of the notches represented a quantity of money. Large notches meant pounds, smaller ones shillings, and scratches pence. After a transaction was recorded the stick would be split in half down its length, and one half given to each party for their records.

Painting of Parliment burningLegend has it that in 1834 when the large store of government tally sticks were finally burned in the stoves of the House of Lords the heat was so great that the whole building caught fire and the entire British Parliment was burned to the ground.

OBJECT	TEXT
Korean Calculating Bones	Rods of bone, wood or ivory such as these were used in ancient China to aid calculation. The rods would be arranged in groups to represent numbers. A vertical rod meant 1, a horizontal rod meant 5. The rods above represent the number 627. In this way numbers were "written" down calculated in much the same way we write numbers on paper.
Chinese Charater.	The written Chinese characters for numbers took their form from the pattern formed by the rods when representing a number.
Logarithm Tables	Handy tables helped simplify calculations. In 1614 John Napier published his description of logarithms. The use of logarithms allowed lengthy multiplication and division problems to be reduced to more simple addition and

subtraction problems. Since the derivation of a logarithm is a lengthy calculation, it was useful to have large tables of pre-calculated logarithms for many numbers.

Perhaps an interactive terminal

What are Logarithms?

One way of writing 5x5 is 5^2. The two is called the "exponent", and means that five, the "base" is to be multiplied to itself 2 times. Similarly 3x3x3x3 equals 3^4. You will notice an interesting property of performing arithmetic with exponents if you look at what happens when you multiply two exponential quantities that have the same base. Consider:

$$
\begin{aligned}
4^5 \times 4^2 &= (4x4x4x4x4) \times (4x4) \\
&= 4x4x4x4x4x4x4 \\
&= 4^7 \\
&= 4^{5+2}
\end{aligned}
$$

Notice that if the bases are the same the new exponent is the sum of the two factor exponents. Therefore, if you can express factors etc. etc.

The logarithm of a number is the exponent to which a base number must be raised to equal the original number. For example, in base 10, the logarithm of 100 is 2, since 10 raised to the power 2 equals 100. Similarly, the log of 4 in base 2 is 2 since 2 raised to the power 2 equals 4. Things become a bit more complex when the number is not an even power of the base. For instance the log of 35 in base 10 is 1.544068044.

[I think perhaps an explananation of logarithms is beyond the scope and purpose of this exhibit.]

AstrolableAstrolabes, such as this Arabi c example, were used for many astronomical calculations. The upper dial has points indicating the positions of stars, while the lower plate has an etched map of the heavens on it. By manipulating the dial many values, ranging from the user's position, to the position of the sun and stars on any day of the year, could be found.

Divider

By adjusting the pivot point the proportional relationship between the width of the points at opposite ends could be adjusted.

HP-12C

When you entered the Museum you may have seen the Whirlwind computer calculate how much money an Indian might have today if he had invested the $24 he received for the sale of Manhatten Island in 1626. The Whirlwind computer took up a whole floor in a building and had to be programmed to solve the problem. Today you can solve this same problem with a few keystrokes on this HP-12C calculator. The HP-12C is a special financial calculator.

INSTRUCTIONS

1) Enter the number of years interest will accrue:

1986 - 1626 = 360 years

So, enter 360 followed by the key marked "n."

2) Enter the interest rate:
Enter 6 followed by the key marked "i".

3) Enter the ammount received for the sale of Manhatten:
Enter 24 followed by the key marked "CHS" and then the key marked "PV".

4) Press the button marked "FV". In a few seconds the amount of money the Indian will now have in the bank will appear.

The amount of money is so large it runs off the calculator's display. So the calculator expresses it in scientific notation. To find how much the number displayed is shift the decimal as many places to the right as the number appearing on the right of the display. The Indian would now have: $30,925,920,000.00. Over 30 **billion** dollars!

Using the 12C you can easily determine how long it will take you to save enough money to purchase soemthing you wish, or to find how much money you will have by a certain date.

Suppose you wisk to by a baseball glove that costs $12.00, and you deposit $2.00 of your allowance each month in an account that earns 10 percent interest each month. To find out how many months it will take you save up enough to buy the glove follow these instructions.

1) Enter the amount you wish to save:
Press 12 and then the key marked "FV".

2) Enter the ammount you will deposit each month:
Press 1, followed by the key "CHS" and then the key "PMT".

3) Enter the interest rate:
Press 10, and then the key marked "i".

4) Find the number of months you will have to save to buy the mitt.
Press the key marked "n". In a moment the answer will appear.
Because your account earns interest it will take you only 5 months to save $12!

Try a problem of your own.

Nixdorf MK-3000

Micro-electronics have made calculators useful for many new tasks. This device can translate simple phrases from one language to another. To find out how to say hello to a friend in another language Press the button marked "clr". First, set up the languages you wish to use. Press "f" then "stp" to change the first language. Continue pressing "stp" until you reach the language you wish to translate to, then press "bs" and press "stp" until the language you wish to translate from appears. Type in the word you wish to translate, and then press "def". You can examine the phrases in the calculator's memory by pressing "?" after a word, and then "stp" to see related expressions. Pressing "def" translates the phrase. Press "clr" after each translation. Notice that the phrases you can use are simple and limited.

The Nixdork MK-3000 was produced in the late 1970's by Nixdorf, the German Computer manufacturer. A wide range of cartidges were available for translating between many different languages, creating an electronic filing system, and performing numerical calculations.

HP-35

The HP-35 was the first scientific pocket calculator. It could very quickly and accurately perform many of the functions for which slide rules were used and that were too complicated for simple four-function calculators such as the earliest pocket electronic models. Since it was designed to perform the same functions as a slide rule, it was nick-named the "electronic slide rule."

One immediate advantage the HP-35 had over the slide rule was that it was much more accurate. You may recall how you had to approximate the location of a four digit number on the slide rule. You can enter an eight digit number on the HP-35.

Prior to the HP-35 to use a find the vaule of a function such as the sine of an angle required looking it up in a table, or being satisfied with the limited accuracy of a slide rule. The HP-35 could instantly calculate the sine of a number to eight decimal places. The same is true of other trignonmetric functions and logarithms.

Try the HP-35

Find the sine of an angle.
Enter the number then press "SIN".

Find the logarithm of a number in the same manner.

Try multiplying two numbers. Notice that if you try to enter the problem in the way you are used to writing it that you cannot find the = key or the answer. This is because Hewlett Packard calculators use a form of notation called "reverse Polish notoation." You must enter the two numbers and then the operation to be performed on them. for example: to mutliply 2 times 3, press 2 then the ENTER key then press 3 then the X key, the answer will then appear.

Now that you know how to use the HP-35 try a problem that will show you its power.

The fastest mental calculators in the world can compute the 13th root of a 100 digit number in less than two minutes. With the HP-35 you can perfrom this feat in a fraction of the time.

To indicate you want the 13th root taken enter 13, then press the 1/X button, and press ENTER. Now enter a 100 digit number: first enter 10 digits, then press the EEX key and enter 10. Now simply press the X^Y key. The 13th root of your number will appear almost instantly. With an electronic calculator you can beat the fast metnal calculator in the world!

Even thought the HP-35 is much more accurate than a slide rule, it too estimates answers beyond its capacity while calculating. For example, we know that (4/3)X3=4. But try this problem on the HP-35. In dividing 4 by 3 the calculator does not round off the tenth digit when the quotient runs over ten digits. Therefore, when you multiply by three again you come up short.
Try this test problem on some of the other calculators on display.

PD-100

We have seen that some of the earliest aids to calculation were little more than means of recording quantities. Today micro-electronic circuits allow us to store large amounts of information in our pocket.

This PD-100 is manufactured by Selectronics. In addition to being a four function calculator that can convert directly into metric quantities, it can store up to 2,040 characters of text in a filing system, enough for up to 100 addresses.

COMPUTERS IN YOUR POCKET: THE HISTORY OF HAND-HELD CALCULATORS

Checklist

1. Chinese Suapan
beads, wood, metal
c.1900
Peabody Museum of Salem
catalogue #: E6537
$250.

2. Jettons
metal
c.1600
Bell Collection
$200.

3. Japanese Soroban
beads, plastic, wood
c. 1980
Bell Collection
$50.

4. Rabdologiae, book
paper, skin
c.1617
Bell Collection
$1000.

5. Napier's Bones
wood
c.1700
Bell Collection
catalogue #: B27.79
$3000.

6. French Pocket Calculator
wood, paper, metal
c.1800
IBM Gallery of Science and Art
catalogue #: 61
$5000.

7. Logarithm Tables, book
paper, leather
c.1839
IBM Gallery of Science and Art
$5000.

8. Gunter's Rule $100.
wood
c.1800
The Computer Museum
catalogue #: XB41.79

9. Portable Sun Dial $5000.
metal
c.1800
Harvard University

10. Drawing Instruments $1000.
metal, ivory, skin
c.1850
Bell Collection
catalogue #: B224.82

11. Tax Assessor's Slide Rule $250.
wood
c.1850
The Computer Museum
catalogue #: XB108.80

12. Gauging Rod $250.
wood, metal
c.1850
Bell Collection
catalogue #: B208.82

13. Proportional Compass $500.
metal
c.1900
Bell Collection

14. Sector $500.
metal
Bell Collection
catalogue #: B304.84

15. Circular Slide Rule
metal, paper, lacquer
c.1850
The Computer Museum
catalogue #: X131.82
$300.

16. Boucher's Calculator
glass, metal
c.1890
The Computer Museum
catalogue #: X173.83
$150.

17. Artillery Officer's Slide Rule
metal
c.1915
Bell Collection
catalogue #: B83.86
$100.

18. Actinograph
wood, paper, metal
c.1910
Bell Collection
catalogue #: 306.84
$350.

19. Webb Adder
metal
c.1900
The Computer Museum
catalogue #: X522.84
$500.

20. Morland Calculator
metal, silk, animal shell
IBM Gallery of Science and Art
catalogue #: 66
$5,000.

21. Adding Pencil
metal
c.1950
Bell Collection
$25.

22. French Calculator $5000.
metal
c.1930
IBM Gallery of Science and Art
catalogue #: 65

23. Troncet Totalisteur $50.
metal, apper, bone, wood
c.1930
Bell Collection

24. Brical Adder $100.
metal
c.1930
The Computer Museum
catalogue #: X13.80

25. Le Prompt Calculateur $350.
metal, paper, plastic
c.1863
Bell Collection
catalogue #: B233.84

26. Golden Gem Adding Machine $50.
metal
c.1940
Bell Collection
catalogue #: B266.83

27. B.U.G. Calculator $500-
metal
c.1950
Bell Collection
catalogue #: B131.80

28. Addiator $25.
metal
c.1925
The Computer Museum
catalogue #: XD125.80

29. Baby Calculator $75.
metal
c.1929
The Computer Museum
catalogue #: X213.83

30. Model N4T Vector-Type Log Log Dual-Base Speed Rule $100.
plastic, metal
c.1950
The Computer Museum
catalogue #: X695.85

31. Otis King Slide Rule $200.
metal, plastic
c.1930
The Computer Museum
catalogue #: X214.83

32. Unique Log-Log Slide Rule $50.
wood, ivory, metal
c.1940
Bell Collection
catalogue #: B352.86

33. Dietzgen Redirule $50.
plastic
c.1940
The Computer Museum
catalogue #: X331.84

34. Miniature Slide Rule/Tie Clip $100.
plastic
c.1970
MIT Museum

35. Pilot's Slide Rule $50.
plastic
c.1950
The Computer Museum
catalogue #: X55.82

36. Probability of Destruction Calculator $50.
plastic, metal
c.1960
The Computer Museum
catalogue #: X677.86

37. Harvard Project Physics Multiplication/Division Slide Rule $50.
plastic
c.1960
The Computer Museum
catalogue #: X621.85

38. Curta $500.
metal, plastic
c.1960
The Computer Museum
catalogue #: S#25

39. Leather Case for Curta $100.
Bell Collection

40. HP-41CX $300.
The Computer Museum

41. SHARP Card Calculator EL-900 $30.
The Computer Museum

42. Casio fx-7000G $150.
The Computer Museum

43. HP-12C $70.
The Computer Museum

44. Bowmar MX100 Scientific Brain $200.
metal, plastic
1971
The Computer Museum
catalogue #: X754.86

45. HP-01 Calculator Watch with styllus $1000.
gold, metal, plastic
1977
Hewlett-Packard Company

46. Casio C-80 Calculator Watch $50.
plastic
1980
Casio, Inc.

47. Casio Electronic Calculator TH-10 Crystal Cal $50.
plastic, metal
c.1985
The Computer Museum

48. SL-800 Film Card $50.
plastic, metal
c.1984
The Computer Museum

49. HP-18C Business Consultant $50.
metal, plastic
c.1985
The Computer Museum

50. Casio BC-300 Business Calculator $50.
metal, plastic
c.1986
The Computer Museum

51. SelecTronics PD-100 Personal Directory $50.
metal, plastic
c.1986
The Computer Museum

52. Sharp Sparky WN-30 $100.
plastic
c.1986
The Computer Museum

53. TI-2500 Datamath
plastic
1972
The Computer Museum
catalogue #: X217.83
$100.

54. Wizard of Wine
plastic
c.1984
Bell Collection
$50.

55. Sharp Elsi Mate EL-429
plastic, metal
The Computer Museum
c.1982
$100.

56. CM-601 Casio-Mini Electronic Calculator
plastic, metal
c.1972
Casio, Inc.
$80.

57. HP-35
plastic, metal
1972
The Computer Museum
$500.

58. Sharp EL-805
metal, plastic
1973
The Computer Museum
$100.

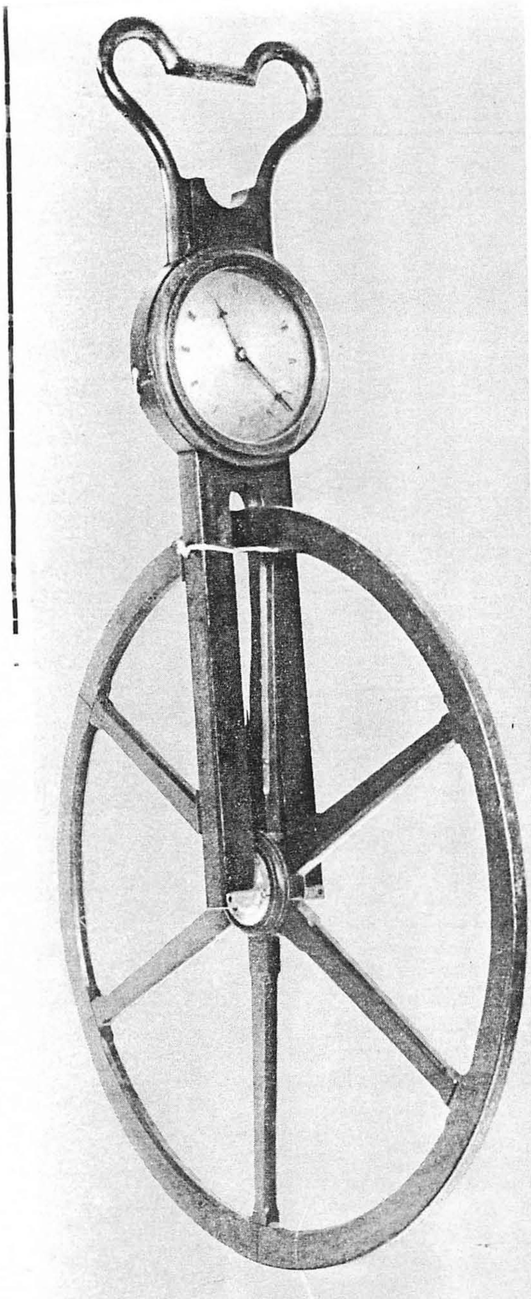
59. HP-65
metal, plastic
1974
The Computer Museum
catalogue #: X752-86
$100.

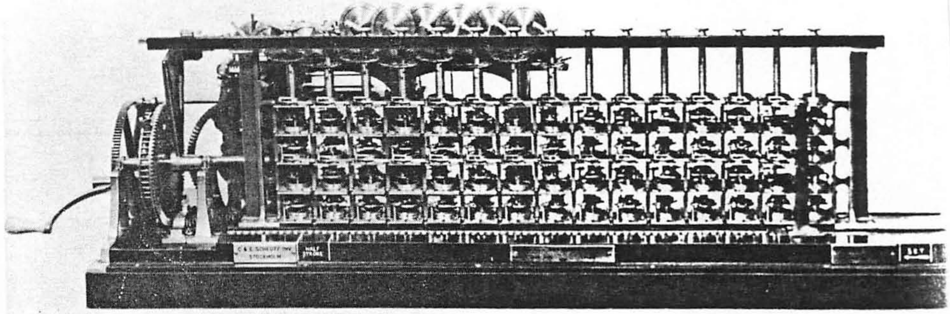
COMPUTERS IN YOUR POCKER
Checklist/page ~~eight~~ nine

60. Novus 650 Mathbox $100.
plastic, metal
c.1975
The Computer Museum
catalogue #: X302.83

61. Sinclair Sovereign $100.
metal, plastic
c.1975
The Computer Museum
catalogue #: X654.86

62. Casio-Mini Card LC-78 $100.
metal, plastic
c.1978
Bell Collection
catalogue #: GB#33.79





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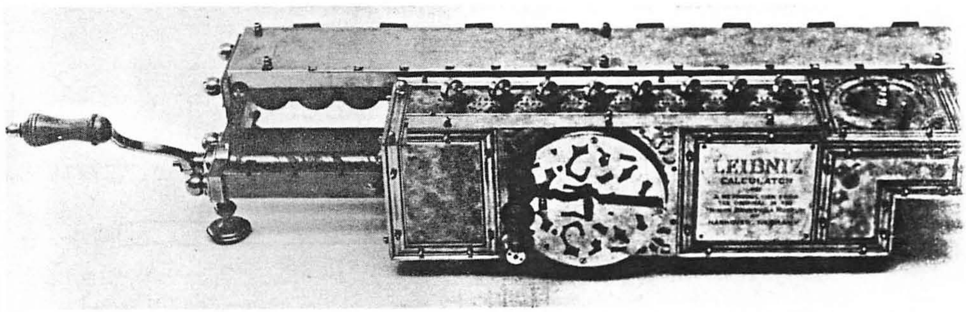

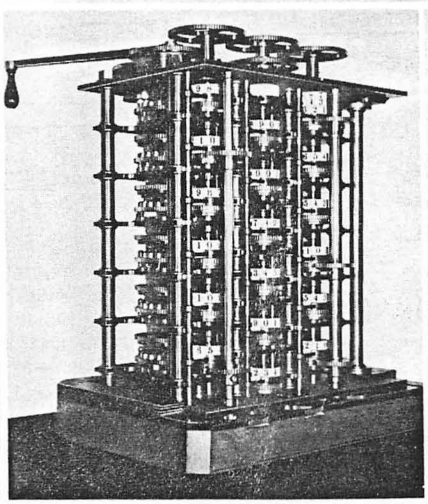

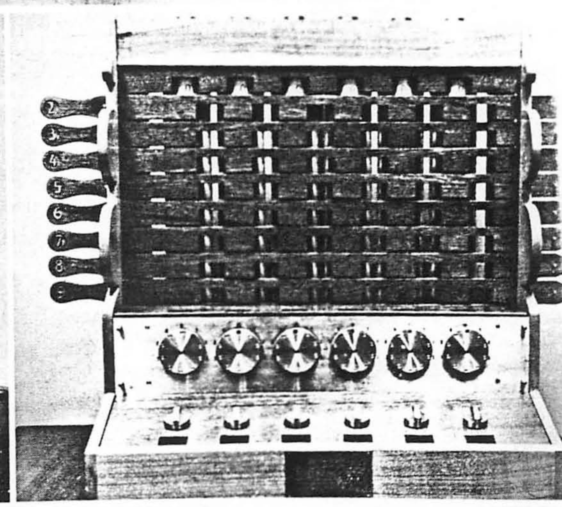

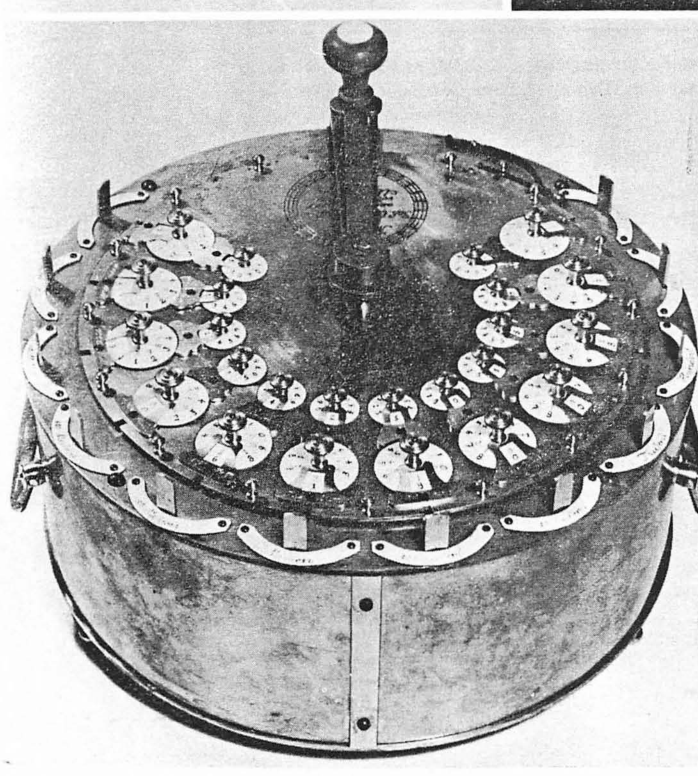

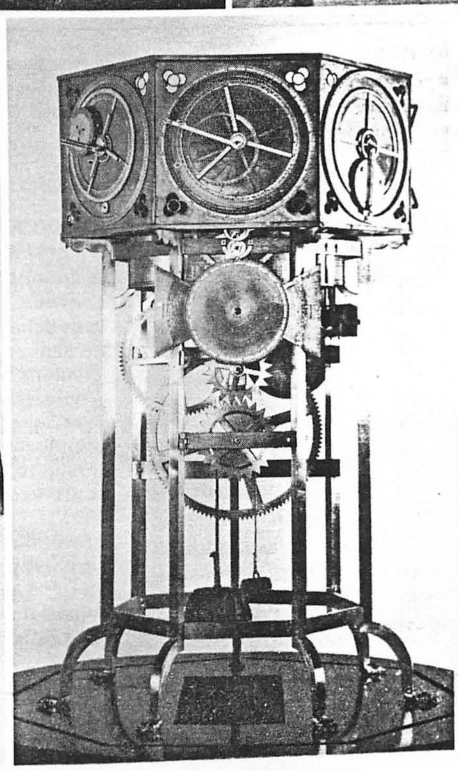

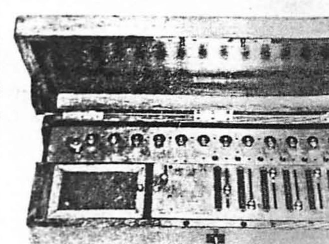

Calculating Machines

Man's attempts to devise aids to calculation are almost as old as man himself.

Derek de Solla Price
Yale University

Calculating machines, the modern electronic marvels that seem to run as deep as a man's mind and much faster, have a history that is almost as old as man himself. It may at first seem paradoxical that anything so exquisitely sophisticated as a combination of the most complex machines that have ever been built and the most abstruse mathematics that have ever been thought could have roots that run back beyond the last few decades or the last few centuries. Yet the truth is that this combination of instrument building and rational mathematical thinking is a continuous thread that runs through the whole of recorded history. It is a thread that links together and dominates the pattern of scientific thought and technological development throughout recorded history, a thread that traces back to perhaps even before man had invented the written word that gives us this record.

Man the Maker, craftsman, and Man the Thinker, the mathematician, are often conceived as opposite poles of human action; we shall show through this history how the coming together of these two extremes has given us so much of the modern world. We shall show that although the most direct product of this combination has been the calculating machine, other offshoots have dominated the growth of pure sciences like mathematics, astronomy, and physics, technologies such as those of clockwork and all sorts of engines, the arts of business and finance, and philosophies and theologies that have

1884 – 1984

A CENTURY OF ELECTRICAL PROGRESS

To commemorate the one-hundredth year of the IEEE, we present this review of the history of pre-electronic calculation. Probably few engineers are aware of the story Derek Price tells here, and so it may be appropriate—especially in this centennial year—to consider the origins of our profession. Computer engineers, as it turns out, have intellectual forebears stretching back to furthest antiquity. In a distant mirror, we see reflections of ourselves. Though we work in metal, oxide, and semiconductor rather than stone, wood, and bronze, the task remains fundamentally the same—science and technique, mind and hand, have joined forces since the earliest times to build instruments for counting and measuring.

Consider this: one day 80 years before the birth of Christ a group of men—today we would call them a design team—met to plan and build a machine that would enable its users to accurately predict celestial motions. Like their distant successors, before they were done they had solved problems—in both elegant and inelegant ways—and produced a working model.

—*Ed.*

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helped man to understand the world and live in it usefully and successfully.

Prehistoric man, primitive man, and the earliest historical records

The coming of the art of writing, about 3000 BC in the ancient river-valley civilizations of Egypt and Mesopotamia, marks the technical boundary between prehistoric and historic man. Two things are, for our purposes, peculiar about this milestone in civilization—first, writing seems a piece of technology extraordinarily late in coming, and second, it seems closely linked to a development of the arts of mathematics that preceded it.

It is late because by that time man had already traveled far along the road of civilization. He had learned to make clothes and utensils, weapons, and tools; he built good houses and well-organized cities. He could tan leather, dye cloth, work stone, and smelt metal and cast it. He could irrigate land, plan for economic plenty and for famine, and invent gods and question them about the future. Even a cursory look at the artifacts of prehistoric men—their tools, pots, jewelry, and the surviving foundations of their cities—will immediately convince one that even at this early age there were fine craftsmen and a deep tradition of handiwork.

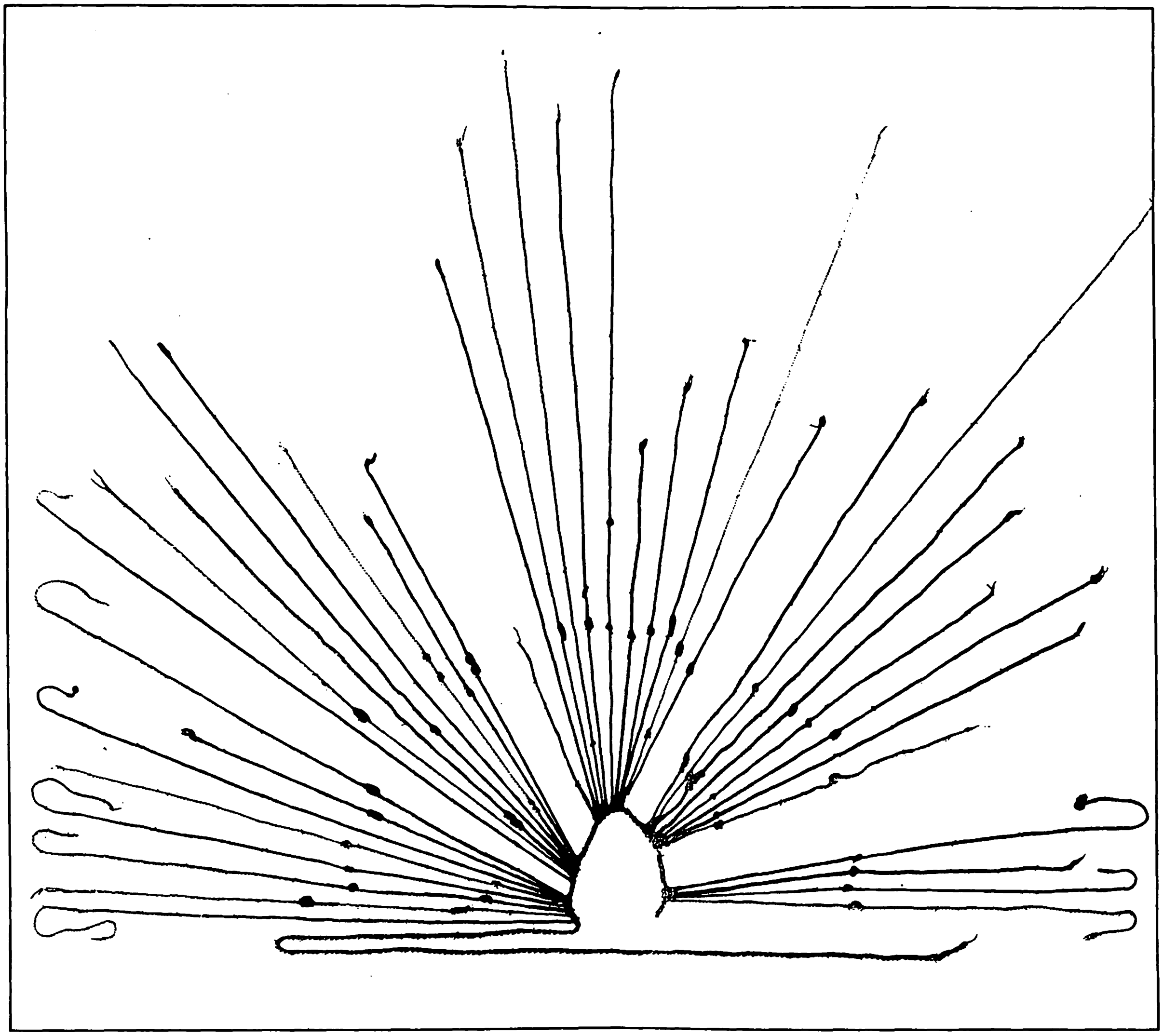
It is peculiarly linked with mathematics because in all cultures we find that a large number of the earliest pieces of writing that have come down to us are accounts listing various numbers of various objects. They specify so many men, women, and children, so many jars of wine and beer and oil, this number of pitchers and plates, that number of bricks and planks, that volume of earth to be dug, this number of hours to be worked, and so on. These "shopping lists" of the temples and the official treasuries are so common that it almost seems as if writing was invented to aid the keeping of such records rather than to record man's thoughts and literature. Certainly we can tell from the earliest lists that by the time they were written down on clay tablets, man had already long practiced the art of keeping accounts, of adding and subtracting and operating with numbers. The earliest signs for numbers are, after all, so much more simple than those for words and other concepts that it seems clear men must have written numbers long before they wrote other things.

These facets of the development of prehistoric and early historic man can still be seen among primitive peoples today. In nearly all preliterate cultures there exist methods, some of them very ingenious, for recording numbers of things and keeping accounts of them. Notches cut on a stick or a bone have been used from the earliest times to represent numbers of people, cattle, or days. Lines drawn in the sand or scratched on a discarded potsherd have served the same purpose. Our modern word "calculate" comes from the diminutive form of the Latin *calx*—a stone—and refers to the ancient practice of using pebbles as counters. In seashore places little shells were used in the same way, and all over the world man has used those natural counters, his fingers, as an aid to calculation. It is odd that the hands that made man a maker and set him higher in the scale of evolution than the highest apes served also as an invaluable tool for the early development of computation. Perhaps it is in the use of fingers for making and for counting that we have our first link in the chain of development uniting the crafts with mathematics.

Notches and scratches, pebbles and shells, lines drawn in the sand, and fingers held together are admittedly simple ways of recording numbers. More complicated techniques soon developed, and several of these depended on that other aspect of man, his skill as an artificer. Jewelry making, that ancient art of adornment, was pressed into use in some communities. In Africa among the Masai tribe the use of decorative necklets and armlets to record each passing year in the life of a woman was found but recently. Another complex art found in parts of the world as diverse as China and Peru was the use of knots in strings as a means of recording numbers. The Peruvian *quipu* is perhaps the most fascinating of all primitive means of handling numbers. It consists of a row of strings gathered at one end along a retaining strand. Each string bears knots of various degrees of complexity; a single ordinary knot stands for a unit, a knot of double convolution for ten, and so on. Colors may signify units of different kinds, and the entire *quipu* is a shorthand aid to memorizing a verbal message. So far as the *quipu* is now understood, it is believed that the numbers represent census figures, either of sheep and cattle for agricultural and tax purposes, or of people for military or social duties.

Thus, at the very onset of recorded history man was in the habit of using objects, natural and artificial, as aids to his already developed ability to count and use the results of such counting for various purposes. With the coming of the great high civilizations of Babylonia, Egypt, China, and India, but above all, of Greece, the functions of counting were to be vastly extended—on one hand, to all the commercial arithmetic and bookkeeping necessary to the new social order; on the other hand, to the needs of the pure mathematics and mathematical astronomy which flourished as the first immortal fruits of intellectual literate civilization. And as these needs grew, so did the technical means of satisfying them, giving a whole new series of artifacts specially designed for dealing with number and mathematics.

But despite this unfolding of sophisticated mathematical hardware, the older and more simple methods lived on and man continued for millenia to count on his fingers or with the aid of pebbles and shells until these became traditional techniques of some depth and scope. In the early nineteenth century Lieutenant Colonel John Warren, an officer in the Indian administration, discovered in the region of Pondicherry, south India, a native calendar maker who recited mnemonic rhymes and laid out black and white shells, by which means he formed a set of tables from which he could accurately compute the occurrence of eclipses. It was later discovered that these tables must have come from the corpus of Seleucid Babylonian astronomy which we know from ancient clay tablets dug out of the sands of Mesopotamia. Thus, having traveled halfway round the world and having been transmitted from one ancient culture to another, ancient mathematical learning had been preserved for two thousand years, without benefit of the written word, by the



THE PERUVIAN QUIPU, as it is now understood, was used to record numbers either of animals for agricultural and tax purposes or of people for military or social duties. It consists of strings gathered along a retaining strand. Each string bears knots of various degrees of complexity; a single knot stands for a unit, a knot of double convolution for ten, and so on. (Photo courtesy Field Museum of Natural History, Chicago.)

primitive technique of laying out seashells. Thus it was that even the most ancient of man's devices to assist him in counting proved vital in transmitting and keeping alive a piece of scientific knowledge.

The first great civilizations

By about 1500 BC, when the art of writing was already firmly established in the civilizations of Egypt and Mesopotamia and was beginning to extend into the early Mediterranean cultures of Crete, new elements had appeared in man's use of numbers. Everywhere the techniques of commercial accounting seem to have been improved to the point that there emerged a new class of scribal craftsmen who appear to have taken special delight in the process of training. School exercises preserved from this period include prototypes of the tedious problems that have plagued elementary arithmetic books ever since—all the familiar baths being filled by several taps and emptied by various-sized drains, all the usual men digging ditches of given dimensions in so many days, all the working out of brackets within brackets within still more brackets. In short, arithmetic had begun to be admired as an exercise in mental gymnastics, and there came into being the first feelings for the pursuit of mathematics for its own sake.

Such intoxication with the style and intrinsic beauty of mathematics was to become an important force in the development of our civilization, one underlying the entire intellectual content of science and philosophy. But at this early stage it was just one more thread in the strand that also contained the purely utilitarian functions of commercial arithmetic and everyday measurement.

Having been liberated by the happy accident of its superior techniques in the writing of numbers, the Old Babylonian civilization of Mesopotamia soon began to reach far beyond the confines of practical application, far beyond mere baths and ditches, until at last its strength in pure mathematics waxed so great that with new sophistication it could tackle the immensely more complicated (although still practical) problems of technical astronomy and refinement of the calendar.

The Egyptians, on the other hand, were less technically able in arithmetic and always retained a strong element of the practical. The Greeks remembered this utilitarian tradition and therefore attributed to the Egyptians the art of the Harpedonaptae, the land measurers who went out each year with measuring ropes and recorders to survey and delimit the lands and fields vacated by the receding flood waters of the Nile.

Perhaps, then, the cumbersome Egyptian methods for dealing with fractions left them masters of the *geometry* that takes its name from land measurement. However, we must bear in mind that geometry in the modern sense did not begin before the Greeks and that the Egyptian practice included no trigonometrical surveying but only the simple calculation of areas from the dimensions of the figures of the fields. Hence, even the apparently utilitarian tradition of the Harpedonaptae employed series after series of "schoolboy problems" in training the scribal craftsmen.

Not all of this most ancient class of mathematics was trivial like the school exercises. It is now impossible to date with any certainty the discovery of all the truly mathematical results that were later systematized and brought into logical order by the Greeks. Unfortunately, the Greek success in producing perfect textbooks like that of Euclid was so complete that they obliterated all that went before.

Undoubtedly the most spectacular of these early evidences of true mathematics is a famous clay tablet, catalogued as Plimpton 322, dating from ca. 1500 BC, the height of the Old Babylonian period, and now in the library of Columbia University. This tablet lists a series of numbers that are associated with the lengths of sides of graduated right-angled triangles which obey the so-called Pythagorean theorem about a thousand years before the birth of Pythagoras. The tablet attests to this theorem being known and used in a way that betokens complete familiarity with all its arithmetical consequences. Furthermore, the numbers in the tablet are expressed in the customary Babylonian fashion, that is, in sexagesimal notation (based on multiples of 60) rather than in our present decimal notation. This sexagesimal system is still preserved in our division of the hour and of the angular degree into minutes and seconds. It is the plainest indication that much of our astronomical heritage, once thought to go no further back than the Greeks, comes instead from this earlier civilization.

Today, thanks to half a century of work by distinguished Assyriologists, we know that more than just the remnants of the sexagesimal system go back to the Babylonians. With the Babylonians we find the beginnings of mathematical astronomy and indeed of the tradition of mathematical interpretation of nature that lies at the heart of modern physics and all our basic sciences. Using purely numerical techniques, without any apparent theory of why things worked the way they did and without any pictorial model of the stars and planets wheeling around, they nevertheless obtained successful results. They could predict virtually all the special astronomical phenomena in which they were interested and they could carry their predictions through long periods of time with amazing accuracy.

We know now that the results of the Babylonian analysis became known in some diluted and perhaps distorted form to the earliest astronomers of Greece, who, however, sought for understanding of the same sort we seek today. They wanted an inner understanding of why things happened the way they did. They wanted a model of the universe. Eventually they achieved exactly this, but a considerable part of their success was owing to the Babylonian numerical constants and analysis which they had taken over and used so effectively.

It is almost as if astronomy got off to an unfair and extraordinarily early start among the sciences by virtue of this curious crossbreeding. The union of Babylonian numerical analysis with the Greek lust for a tangible and visible model of the universe gave man his first huge success in understanding the world in terms of inexorable mathematical reason and in using that understanding to predict and remove the capriciousness that more primitive men had attributed to the whims of the gods. It is the "Greek Miracle" that gave us all the basic philosophy and ways of thought that have pervaded the Western World ever since, but it is the special feature of this miracle having been superimposed upon Babylonian arithmetic and astronomy that has given us the mathematical science now dominating the world.

Scholars of but a generation ago had to presume that most of that which is valuable in our civilization had derived from the Greek Miracle alone. Historians today have revised that estimate, particularly for mathematics. Knowing the extent of the Babylonian development, one might hazard a guess that without it there could have been no Euclid, no Hipparchus, no Archimedes, and none of that special growth of science which has made our culture so different from any other. In this light, then, we might more appropriately speak of the "Babylonian Miracle" as the true formative stage in our mathematics.

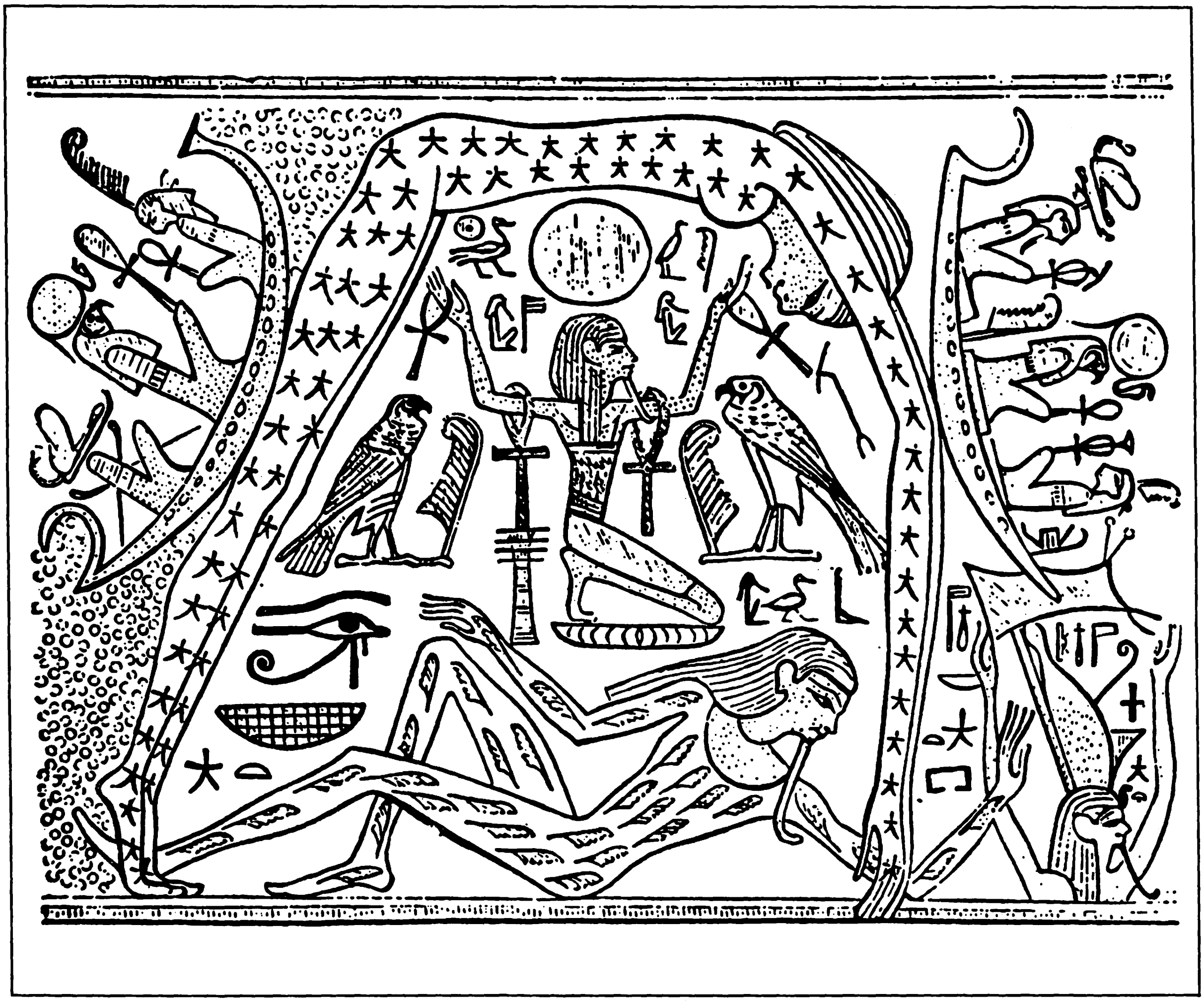
Not only in these two ancient cultures did mathematics and science begin to develop. On the contrary, in nearly all the great centers that have ever been, the ever-visible natural cycles of celestial events dominated and fascinated men so that some knowledge of astronomy was born. Perhaps nowhere else did it reach the heights of Babylonia and Greece, but among other peoples astronomy in its arithmetical or geometrical modes developed in proportion to their abilities to reckon with numbers and visualize the mechanism of the universe. In the ancient American lands of the Aztecs and Mayans, a great arithmetical scheme was built on the basis of the natural cycles and the cycles that encompassed and reencompassed them until it became natural to think in terms of a great universal cycle, at the end of which everything in the world would be restored to its original state. This fascinating notion of a cyclical universe occurred also to the ancient Indian cultures, and again, for different reasons but with the same fascination, in recent times. Symbolizing these cycles to the Aztecs were their great mathematical artifacts, huge stone discs carved elaborately with glyphs corresponding to the succession of days and years. These monumental calendar stones were huge undertakings,

CIRCULAR FORM OF THE AZTEC CALENDAR STONE mirrors that civilization's belief in a great universal cycle. The stone is carved with glyphs corresponding to the succession of days and years. To explain the universe, the Aztecs and Mayans constructed an elaborate arithmetical scheme based on natural cycles. (Photo courtesy Field Museum of Natural History, Chicago.)

magnificent projects which seem to have been central to the ritual and organization of the nation. As primitive mathematical hardware they are impressive, but like stone lions or Easter Island heads they just stand there, finished and static.

In ancient Egypt, contrary to all myths of a powerful secret science, astronomy was more backward than elsewhere. The Egyptians were hindered by a poor technique for expressing numbers, particularly fractions. While the Babylonians could operate with sexagesimal fractions in much the same way as we deal with decimals, the Egyptians had only a notation for unit fractions. They could speak of one fourth-part, and of one fifth-part, but they were unable to reduce 2/5 beyond 1/5 and 1/5, and they could deal with the sum of 1/4 and 1/5 only by means of rote methods so complicated that they made frequent errors.

With this drawback it was natural that Egyptian astronomy never received the complex mathematical treatment that Babylonian and Greek astronomy did. In Egypt, the emphasis seemed more visual, more upon tangible models. Thus there are tombs decorated with star pictures, with zodiacal signs, and with the Sky Goddess supporting the vault of the heavens. There are mummy



EGYPTIAN SKY GODDESS supports the vault of the heavens. In Egypt, mathematical technique never developed to the level of that in Babylonia and Greece. Hence, Egyptian astronomy seemed to depend more on tangible, pictorial models of the universe than on mathematical ones. (Photo courtesy Adler Planetarium, Chicago, D. J. Price Photographic Archives.)

cases decorated with schematic calendars that show the risings of the various constellations in graphic succession throughout the year.

More important to the story of mathematical hardware, it was in Egypt during the second millenium before Christ that there developed the first astronomical instruments of any complexity, a series of sundials and water clocks. The changing direction and length of the shadow of a tree, a stick, or a building can be easily perceived and conveniently used as a measure of the passing of a day and of the change of the days from season to season throughout the year. In primitive tribes today the shadow of a vertical staff is used in this way. Early medieval texts preserve for us the primitive practice of measuring the time of day by noting the length of a man's shadow in terms of the number of times the length of his foot is contained in it. In a couple of obscure Babylonian tablets there are fragments of a scheme that lead us to believe a similar method, arithmetically refined, was also practiced there. But in Egypt, for the first time, one finds more complex instruments to measure the passing shadow and record it. Similarly, the steady drip of water must have been observed as soon as an irate housewife suffered a leaky pot, and presumably the use of this steady flow to measure time came also at an early date. In primitive societies today a leaky bowl is used to control short periods of time—to allocate a sparse flow of precious water in an irrigation channel, for example. In Athenian law courts, each contestant was allowed to speak for a given time measured by a standard pot of water leaking from a little hole at its base.

Here again, in Egypt, more sophisticated methods were developed early. A leaky pot will run quickly when it is full, more slowly as it empties. To counteract this variation, the Egyptians devised a vessel shaped like a modern flowerpot, wide where the flow is more rapid and narrow where it is weak, so that the water level dropped steadily, falling a uniform distance (almost) in uniform time. By marking the interior of the vessel with a uniformly graduated scale, man could now measure the hours of the day, and by having several such scales, one for each month of the year, he could allow for the natural variation that gives long days in summer, short in winter. Not until the end of the Middle Ages was time ordinarily measured in the uniform, constant hours we use today. In all former times the length of daylight and the length of darkness were each divided into twelve, so that when the hours of the day were long, those of the night were short, and vice versa.

It may at first seem as if these devices, sundials, and water clocks correspond to our modern clocks and watches as practical instruments for telling the time. They were more nearly a sort of astronomical peep show, for edification rather than practical utility. It seems likely that in a society with so few such "public clocks" in the temples, telling the time had little practical significance. At any rate, many of the ancient specimens are covered with astronomical inscriptions, which leads one to believe that their role was more scientific than secular.

This role is recurrent throughout the early history of astronomical clocks. The inexorable and immutable laws governing the daily rotation of the heavens and the movements of the planets seem to have inspired man to duplicate them, and these clocks attest not only his understanding but also his skill in making his own microcosm, in following the artifice of the Great Creator. He did not care that the clocks might run a little too fast or too slow; of overriding importance was the making of an artificial universe, or at least that part of it exhibiting the unfailing regularity that was so impressive.

It is, then, in ancient Egypt with its superb technical skills in handicrafts and its apparent love of images and pictorial thinking that we first find such instruments. Yet in this civilization the science of astronomy was hardly begun. We must turn next to the cradle of our own culture, Greece and Rome, and follow the extensive evolution of mathematical hardware there.

Graeco-Roman civilization

From the beginning of Greek history it is clear that Greek culture valued highly the power of the picture and the image. All the justly famous scientific thought and philosophy of the Greek Miracle seems dominated by this capacity to form a clear image and visual model of the world and the interactions within it. Similar in this respect to the more ancient Egyptian civilization, the Greeks possessed the added advantage of that lust for argument and discussion that led to the age of Plato and Socrates.

In the special field of astronomy, later to blaze the trail for a mathematical interpretation of nature, they had one extra advantage, the strength of which has been justly recognized only within the last half century of scholarship. Round about 300 BC, perhaps a little before, they gained access to many of the results of the highly successful and complicated Babylonian astronomy and utilized and intermingled them in their own scientific model of the universe. Thus, by virtue of Babylonian predecessors, the Greeks were able to mix the arithmetical computational approach with the visual image model, a historically unprecedented union of arithmetic and geometry. Out of this melting pot came a virile astronomy in which one could not only compute what was going to happen next, but could also visualize why things would happen in that fashion. This is a line of theory that begins perhaps in the time of Eudoxus (3rd century BC), leads through Hipparchus (2nd century BC), and sees its ultimate development in the great *Mathematical Synthesis* of Ptolemy (2nd century AD), a book that is one of the finest scientific achievements in history. This book dominated scientific thought until the time of Kepler, an interval of about 1400 years. Except for Euclid's *Elements,* it may be said that the *Almagest,* as the Arabs and medieval scholars called Ptolemy's work, lived longer than any other scientific book ever has or probably ever will.

With this exceptional development of the use of mathematics in science it is natural that the Greeks should have been stimulated to new and important advances in mathematical hardware. These took the form of models of this newly understood universe in all sizes and shapes—tangible manifestations that showed the heavens revolving and the natural cycles repeating themselves with appropriate rhythms.

Thus began a new and important line in the growth that led to a proliferation of other mechanical devices such as clocks and, eventually, calculating machines. To trace this line we must follow the rise of Greek technology insofar as it concerns astronomical models and gear wheels, and also the steady improvement and use of the older line of mathematical hardware, the aids to accounting that were used in commerce and government. These two lines, the scientific and the commercial, interweave to produce the history of calculating machines.

Scientific calculators and astronomical models. According to classical tradition, the earliest celestial globes were made by Thales (ca. 600 BC), but virtually nothing is known of this almost mythical beginning. The only surviving example of an ancient globe is the magnificent Farnese Atlas, a work expressing all the artistic imagery attendant upon the earliest astronomical "models." The first concrete evidence of scientific models is attested in the fourth century BC, the golden age of Greek thought, the time of Plato and Aristotle. It is affirmed in the imagery used by Plato in describing the form and structure of the cosmos, and again in mathematical form by his contemporary, Eudoxus, the first Greek astronomer known to have made a geometrical model of the universe. It is not known whether the models of Plato and Eudoxus existed only in their imaginations, but their descriptions are so vivid that one has a strong feeling that material models, of wire and brass and wood, were at hand.

It is abundantly clear that actual models were in use from the third century BC onwards, geometrically constructed sundials from this period have survived, a few hundred of them from the whole classical period. Just as with the Egyptian waterclocks, it seems likely that these sundials were not merely devices for telling the time. Though most of the surviving examples have hour lines marked on their surfaces, these lines are seldom numbered, so one cannot readily tell which hour is indicated. On the other hand, they are often elaborately inscribed with lines representing the equator and the tropics, the solstices and the equinoxes. These sundials must therefore be regarded as beautiful exercises in the cunning use of geometry to model the basic facts of astronomy. They are full of the exuberant use of mathematical tricks and neat devices for their own sake rather than for their utility. In the Greek sundials man achieved a mathematical model that caused the sun to draw its own path in an artificial microcosm of the heavens.

Such sundials were probably the earliest and most primitive models developed by Greek science. Soon they developed into sublimely complicated forms in which a single block of stone could be carved with many different dials, all indicating the same progress of the sun by diverse ingenious arts. These sundials fascinated the Greeks as crossword puzzles and chess problems fascinate us. Again and again in history, in ninth-century Islam, in fourteenth-century Europe, and in the heyday of the seventeenth-century flowering of modern science, this fascination with ingenious dials crops up.

THE FARNESE ATLAS, in the National Museum, Naples, Italy, includes the only surviving example of an ancient globe. According to classical tradition, the earliest celestial globes were made by Thales in about 600 BC. (Photo courtesy Adler Planetarium, Chicago, D. J. Price Photographic Archives.)

Sundials were not the only instruments or models known to the Greeks. Starting slowly in the third century BC, but helped along by the mechanical genius of Archimedes (287 to 212 BC) and by an increasing pace of development in the second century BC, other devices began to appear. Globes and spheres of all sorts were used, and water clocks were developed far beyond the complexity of those of Egypt. Gear wheels, and simple devices employing them, seem to have been used by Archimedes. His writings on the screw are well known, but gears in comparatively well developed form are known only from his later writings.

From Archimedes, too, though again only in later mentions by Cicero and other authors, we know of the making of a wonderful model that not only depicted the arrangements of the stars, the sun, the moon, and all the planets, but showed them in motion, keeping time with their real progress in the heavens. Unfortunately, the awestruck accounts give too little information for us to understand the exact nature of this model. It has often been suggested that it was a complicated geared planetarium, but probably it was merely a water clock in which a string attached to a float and tied round a sphere caused the sphere to rotate and carry round model planets that were stuck to its surface and that were changed by hand from day to day.

Whatever it was, this animated model of Archimedes's clearly stands at the beginning of a long and important tradition. Such astronomical showpieces were more and more elaborate as time passed, from classical times to the Islamic and European middle ages, to the Renaissance, and up to the popular planetariums of our time. From this piece of exhibition artwork there eventually developed the mechanical clock, but it was not until late in the Middle Ages that the little dial on the exhibition that told the time became the main feature and main purpose of the instrument.

Two things must be said about these early astronomical devices and their relation to computing machines. In the first place, they were the first sophisticated scientific instruments, the first of any complexity of construction. Because they stand at the very beginning of all scientific instrumentation, it is important to realize that although one may regard them as little more than scientific toys or sideshows, or at best as mere timekeepers, it is more accurate to think of them as the first true computing machines, the first devices that calculated by making a model of the thing that was to be measured. Today we would call them analog computers.

The second notable thing about these protoclocks, as we shall call them, was their powerful historical effect on the evolution of the particular craft and philosophy that accompanies such special mathematical hardware. The craft of fine mechanics had its beginnings here and later became the whole complex of clock making and scientific instrument making on which depended the rise of experimental science and the mechanics of the industrial revolution. The philosophy was that of the creator as geometer, of the universe as an incredibly complicated machine, and of man as an ingenious mechanism with, possibly, a divine soul that gave him a free will not shared by grosser pieces of clockwork.

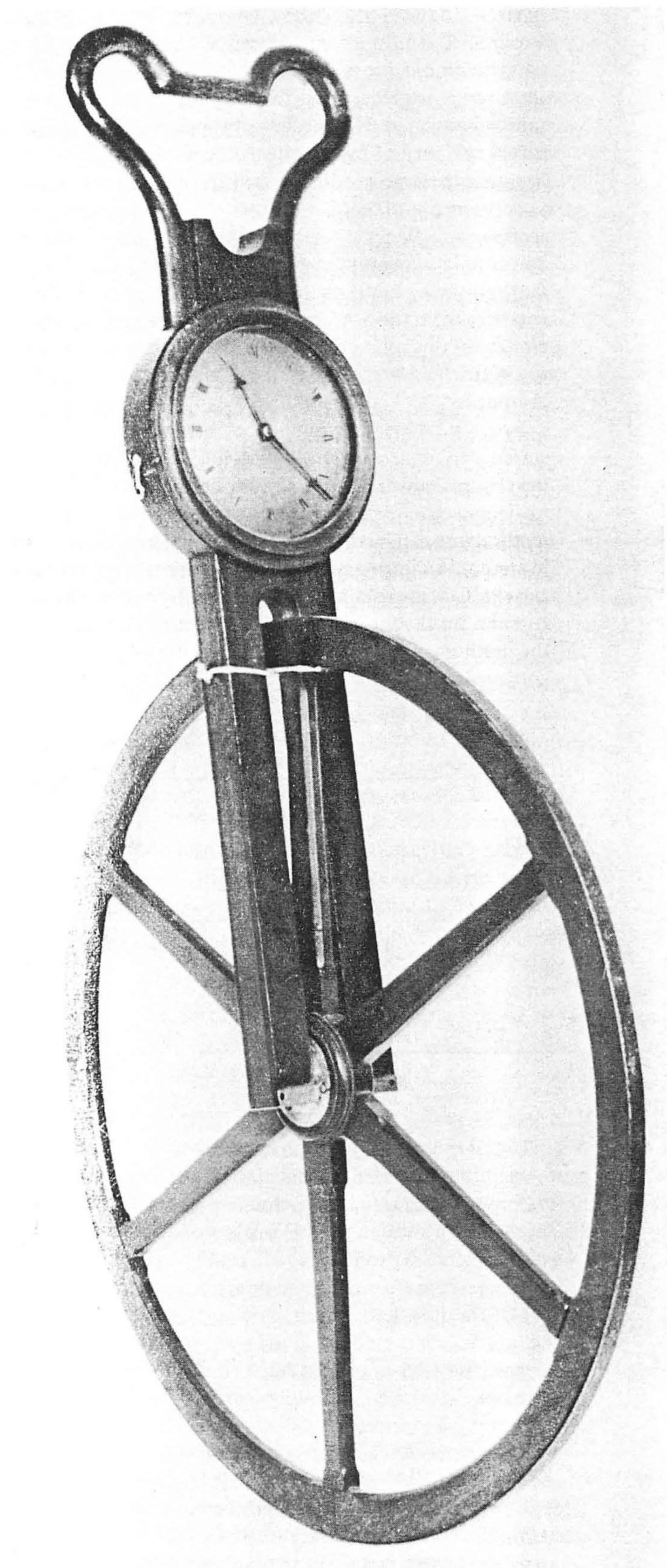
Unfortunately it is almost impossible to follow the growth of Greek technology in the making of these protoclocks. Very few fragments of such devices have come down to us, and it seems clear that this sort of knowledge was not preserved in Greek manuscripts. The only books we have are those that treat mechanics only for the sake of the associated mathematics, and a few precious technical handbooks like those of Hero of Alexandria and Vitruvius. But from such authors we know that there existed an endless variety of semiscientific mechanisms of considerable ingenuity. The texts describe the use of gears in simple reduction trains—the most effective use seems to have been in hodometers, which count the revolutions made by a wheel that is rolled along the ground, and in taximeters, which count the revolutions made by a wagon wheel. From these devices one could measure the distance traveled by means of dials or of little balls made to drop into a gong at each mile or other appropriate interval.

The texts also describe automata worked by strings and levers, and complicated dramatic effects produced by water and air pressure. Hero describes an automatic theater that has dancing figures, mechanical birds that sing and flap their wings, temple doors that open by the lighting of a ceremonial fire, slot machines that dispense water or wine on payment of a coin, and trick jugs that pour water or wine at the will of the conjurer. All the basic elements of mechanism were known, but with the sole exception of the protoclocks they seem to have been used for the trivial purpose of an entertaining mechanical magic.

The interest in protoclocks appears to be directly related to the progress of astronomical understanding. The geometrical model of Eudoxus, trailblazing though it was, could not have been of much use in exact calculation and prediction of celestial phenomena. Qualitatively it gave a good picture, but quantitatively it was full of shortcomings. By the time of Hipparchus, thanks to the progress of geometrical techniques and the influx of Babylonian arithmetical methods, astronomy had progressed to the point where it could account accurately, in simple cases, for the motions of the sun, moon, and planets. Eventually, in the elegant and comprehensive scheme of Ptolemy, all the more complicated cases were brought to the mathematical perfection that was to last another 1400 years.

Now, one of the basic problems of mathematical astronomy is that one has to master the techniques of what we now call spherical trigonometry, the calculation of angles and triangles drawn on the surface of a celestial sphere. Then, as now, it was difficult for most people to see three-dimensional problems, and ways were found to reduce the problems to two dimensions. Then, as now, complicated computations involving trigonometric tables, though not difficult in principle, were tedious in practice. Because of these factors it happens that from about the time of Hipparchus onwards, we find considerable use of special methods for drawing astronomical diagrams on a plane instead of a sphere, and for obtaining the result of calculations by measurement of a carefully constructed figure rather than by numerical calculation using tables.

Thus began the series of techniques now known as graphical computation, and no sooner had such methods



A HODOMETER counts the revolutions made by a wheel as it is rolled along the ground; hence, it can be used for land and distance measurement. This nineteenth-century model illustrates the general plan of the device—similar mechanisms were constructed by the Greeks. (Photo courtesy Adler Planetarium, Chicago.)

been introduced than they began to be mechanized. Probably the most important graphical technique, leading to the most sophisticated mechanization, was stereographic projection. This technique was almost certainly known to Hipparchus, though we do not have direct evidence of texts or instruments until rather later. Stereographic projection is used for mapping lines on a sphere onto a plane. To construct a stereographic projection, one places the sphere above the plane so that its south pole is nearest to the plane and its north pole is furthest away, and then views the plane and sphere together from the north pole, the point of projection. All circles on the sphere become circles or straight lines on the plane, and no ovals, ellipses, or other special curves are needed.

For the special purposes of astronomy, the stereographic projection is especially useful, since rotation of the sphere about its poles simply turns the image projected onto the plane by the same amount. Using this method one can have a two-dimensional map of the stars in stereographic projection, and by turning this map one can simulate the rotation of the celestial sphere as the stars rise and set through the night and through the year. All the motions of stars and planets can be shown on a plane and measured by means of appropriate scales.

The Antikythera mechanism is tantalizing evidence that the ancients may have been much further advanced in machine building, and particularly in computer technology, than we think.

Two important ancient instruments were constructed to facilitate and exhibit this elegant means of mapping the universe. In one, the astrolabe, a series of flat discs engraved with stereographic projections and their scales enabled the astronomer to make his calculations graphically; in the other, the anaphoric clock, the main disc of the star map was made to turn automatically by means of a water clock, and the map, seen through a window whose shape corresponded to that of the horizon, gave an impressive public display of the theory of astronomy and the skill of the artificer. By the astrolabe or the anaphoric clock one could know the positions of the stars and their risings and settings even though the night was cloudy; one could tell the positions of the sun at night and of the stars and moon by day. With the astrolabe one could tell the time of day or night from any observed position of sun or stars; from the anaphoric clock one could tell the time without observation at all.

Out of the principle of stereographic projection came these two instruments, the astrolabe, which was to the ancient astronomer what an electronic calculator is to a modern engineer, and the anaphoric clock, which was to the ancients the mightiest and most impressive public demonstration of the most highly developed and most perfect science of the time. Although more than a thousand astrolabes survive, not one dates back to classical antiquity. The fates have dealt less unkindly with the anaphoric clock. In the ancient agora, or marketplace, of Athens, and in the fashionable coastal resort of antiquity at Oropos just south of the capital, there survive foundations and water tanks for buildings that must have housed such monumental clocks. In the Roman Agora at Athens there is also the almost intact Tower of the Winds built by Andronicus Cyrrhestes in the first century BC to house a great water clock. We are sure that the building had other scientific devices, for Varro and Vitruvius describe it as showing astronomical events by means of the clock, by the sundials that were engraved on each of the eight faces of the octagonal tower, and by a large brass weathervane in the shape of a Triton (now lost) that pointed to sculptures personifying the eight winds.

In addition to these remains of the buildings, there survive two fragments of dials from such clocks, both dating from Roman times, perhaps the second century AD. One, from Grand in the Vosges, is only a calendar plate containing a circular series of holes marked with the days and months of the year and intended for the plugging-in of a model sun which was carried round by the clock to show the hours of the day and night. The second piece, found at Salzburg, Austria, has a similar set of holes at its edge but is more elaborately engraved with figures of all the constellations and the ecliptic. The original disc must have been more than five feet in diameter and would have needed a powerful water clock to turn it. (It was from this fragment that an anaphoric clock was reconstructed by IBM to show the function of this most ancient scientific computing device.)

Also preserved from antiquity are the remains of another computing device of quite different character. It comes from the first piece of underwater archaeology, the accidental discovery by Greek sponge fishers in the year 1900 of a wrecked treasure ship from the first century BC. Among the cargo of fine bronze and marble statues was a heavily corroded mass of brass plates and wheels which has been identified as a complex system of gear wheels designed to move pointers over scales engraved with sequences of planetary phenomena. When a main shaft was turned, perhaps by hand, perhaps automatically, the dials indicated the risings and settings of the planets, their stations and retrogradations, and perhaps also the eclipses. Two thousand years under the sea have done so much damage that the machine—now called the Antikythera device, after the name of the island near which it was found—cannot be completely reconstructed. Enough of the inscription survives, however, to make it certain that the device dates from the time of the shipwreck, and that it may well have been the sort of demonstration device housed in the Tower of the Winds or some other monumental water clock. It is enigmatic that this machine is much more intricate in design and exhibits much more skill in workmanship than any other scientific device from antiquity known to us.

Such a device is not mentioned in any known text—it remains tantalizing evidence that tells us the ancients may have been much further advanced in machine building, and particularly in computer technology, than we think.*

Commercial arithmetic and the abacus in classical antiquity. The development of aids to commercial arithmetic took a different line in antiquity from that associated with scientific calculation. Astronomy needed ingenious mathematical constructions and mechanical devices, but the keeping of accounts demanded but little elaboration of the primitive method of laying out pebbles and shells. The chief improvements, indeed almost the only improvements, were in the provision of a specially marked table to keep the piles of pebbles in order, and in the making of a portable miniature table that could be held in the hand and that kept the pebbles handily fitted into grooves so they could not get lost.

Pictorial representations of treasures and accountants sitting at special counting tables are known from a painted vase (the Darius vase, in the Naples National Museum) dating from the fourth century BC, from an Etruscan engraved gem (in the Cabinet des Medailles, Paris), and from a famous Roman mosaic of the Seven Sages which shows not only the counting board but also a globe and sundial. In none of these representations is it clear how the table is designed, but fortunately two excellent and complete specimens have been preserved, one from Salamis and the other from Oropos. In principle they resemble gaming boards (like those used for chess and checkers) which seem to have been known since farthest antiquity.

The Greek counting board comprised essentially a set of symbols for units, tens, hundreds, thousands, etc., and below them a series of parallel lines on which to set out rows of counters corresponding to various amounts of money that were to be added. The examples we have are more complex. Between the symbols for the powers of ten there are others for multiples of five so that the set runs:

five-hundreds
hundreds
fifties
tens
fives
units of drachma

To the right of the unit symbol there are others for obols (sixths of a drachma) and half-, quarter-, and eighth-obols. There are also two other similar sets of symbols so that one can set up two numbers at the same time and work out their product by transferring counting pebbles to the third row of symbols.

The great slabs of marble on which these counting boards have been chiseled must have been set up permanently at some royal treasury or special booth near the marketplace; they could hardly have been carried about. The portable form, now known as the abacus, is represented by three surviving examples, all of the same type. Each consists of a small sheet of iron into which have been cut a number of pairs of slots; each pair consists of a small slot above with a single bead sliding in it and a longer slot below with four beads. The four beads each represent a unit and the single bead represents five, so that, for example, when the single bead is raised and two of the four are also raised, that column represents seven. Such columns are provided for units, tens, hundreds, and so on up to millions, and the appropriate symbol is engraved in the strip between the upper and lower slots. To the right of the units, as in the big marble counting boards, there is a column for obols (with five beads, since six obols make a drachma), and to the right of that again there is a special short slot for fractional parts of an obol.

It might be remarked that the ancient use of fives as extra columns in the marble abacus, and the method of using four beads and one bead in the hand abacus, have been carried through the entire development of the device. The advantage over a row of nine beads or pebbles is obviously that of quicker recognition and manipulation of the numbers. For this reason the Roman system of numerals retained the practice that looks clumsy to our eyes but was very convenient for commercial use on an abacus. It is only when one wishes to multiply and divide (as one rarely did in abacus work) that the Roman system shows its faults. For scientific calculation, the Greeks and Romans continued to use the sexagesimal system of the Babylonians with its adequate multiplication tables, its use of an effective zero, and its place value notation that is so similar to decimals.

The Middle Ages in the Orient, in the Islamic world, and in Europe

To the history of science and technology, the decline of late Roman civilization presents an instructive example. Shunning the effete intellectualism of scientific enquiry for its own sake, the Romans bent their attentions only to those parts of skill and learning that offered a profitable technological application in the cause of state and empire. For some time their achievements in the building of bridges and aqueducts, roads, and plumbing systems were the wonder of the world. But gradually it became clear that there were no fertile new ideas to back the technological applications and produce new technologies. It is an exaggeration to see the decline of Rome in this light alone, for political and economic bankruptcy had many other roots. However, one must allow that a basic scientific effort reaching not much further than dilute encyclopedic gatherings of all that could

*A detailed discussion of both the Tower of the Winds and the Antikythera mechanism appears in "Derek de Solla Price and the Antikythera Mechanism: An Appreciation," also in this issue. See pages 15-21.

—*Ed.*

still be understood and popularized from the grand tradition of Greek science was totally insufficient. The Romans, concentrating on applied technology alone, were unaware that the applied and the theoretical exist in a state of symbiosis, gaining from each other and growing together.

Thus it was that after the decline of Rome, not Roman but Greek science passed to the inheritors of classical culture. For a few centuries the precious remaining fragments of Greek learning were whirled through a tumultuous cycle in that melting pot of people and languages that constituted the civilized world. In the upheaval, Greek science spread to such far-flung parts of the world as India and China and the Sassanian and Byzantine Empires, and eventually to the most receptive culture of Islam, where it took root, grew again, and was eventually handed on to medieval Europe.

Unfortunately, it is in just this exciting period that the historical records are most incomplete, and it is virtually impossible to tell how many of the Oriental contributions were independent and how many were transmissions from West to East or vice versa. For instance, in China in the second century AD, almost the time of Hero of Alexandria, the Buddhist mechanician Chang Heng described a geared taximeter, very like that of Hero, and also a celestial globe that was somehow turned by dripping water so that it would agree with the heavens "like the two halves of a tally."

In India, the earliest astronomical texts contain references to animated astronomical models that turned by themselves in such a manner as to duplicate the eternal and perpetual motion of the heavens. Similar cases of direct transmission, parallel development, and what is sometimes called "stimulus diffusion" occur in tracing the complicated historical development of the numerical systems of the world and of the abacus and other devices of commercial arithmetic. Greek and Arabic alphabetic numerals, Roman numerals, and lastly Hindu numeral forms spread around the world, changing their shapes and styles as they went. A particularly good example of the way such things were transmitted is provided by a brass magic amulet dating from about the eleventh century, recently excavated in Sian, China. The amulet is actually a magic square written in Arabic numerals and is one of the earliest extant examples of this rather curious class of mathematical hardware.

Of more direct interest, perhaps, is the Oriental development of the abacus. The Chinese suan-pan (swan-pan) may well be as ancient as the Roman abacus, but again one cannot tell whether there was direct transmission (in either direction) or parallel development for similar purposes. The Japanese soroban obviously derives from the Chinese instrument it resembles, differing only in the use of a single bead (instead of the suan-pan's two beads) to represent the gatherings of five units in each column. The Western abacus of our own later Middle Ages and the Russian stchoty, which was used in outlying parts until quite recently, probably came from a later transmission from East to West.

In Western Europe, tradition seems to have returned to the original form of the Greek abacus rather than to the portable Roman instruments or their Oriental equivalents. From the rise of mercantilism in the late Middle Ages and early Renaissance we have many pictures of the special counting tables—shop counters—of merchants and moneylenders. The tabletop is divided, perhaps in several places, by inscribed lines headed with symbols for units, tens, hundreds, thousands, etc., and often with additional symbols for subunits of the currency such as shillings and pence for pounds. Special "counters" (rechenpfennige = counting pennies) were minted for use with these tables, and the art of casting accounts became the subject of many treatises in manuscript and later in print. From the evidence provided by such tables that have been preserved, and by pictures and texts, it is clear that they remained in use until the early years of the sixteenth century, when they began to be displaced by the comparatively new art of keeping accounts by means of numerals written on paper and sums worked in the arithmetical techniques that came with the consistent use of modern Hindu-Arabic numerals. The spread of these numerals was surprisingly rapid, especially in scientific circles. When the first great tabular compilation of astronomical information, the Toledo Tables, was transmitted from Moorish Spain to England and France in the twelfth century, all the numbers, though expressed in the usual sexagesimal form, were written in Roman numerals. When the next collection, the Alfonsine Tables, was transmitted from Spain at the end of the thirteenth century, the numerals were all Hindu-Arabic. In the fourteenth and fifteenth centuries these numerals gradually became regularized in use and were transformed into their present forms; the last changes, the turning of the figures 4 and 5 into their present positions, did not happen until the coming of the printed book at the end of the fifteenth century. The change can be followed even in the lifetime of one man, for the dates on the drawings of Albrecht Dürer show the entire transformation.

It was, however, in the area of astronomy and its instruments and protoclocks that calculating devices progressed most during the middle ages of Islam and the West. Just before the rise of intellectual Islam in the seventh and eighth centuries, there had been a stirring of interest in astronomical theory and instruments in the Byzantine Empire. The evidences of scientific work among the Byzantines comprise only a few texts describing the construction and use of the astrolabe, and one splendid surviving example (although this dates from very late in the period).

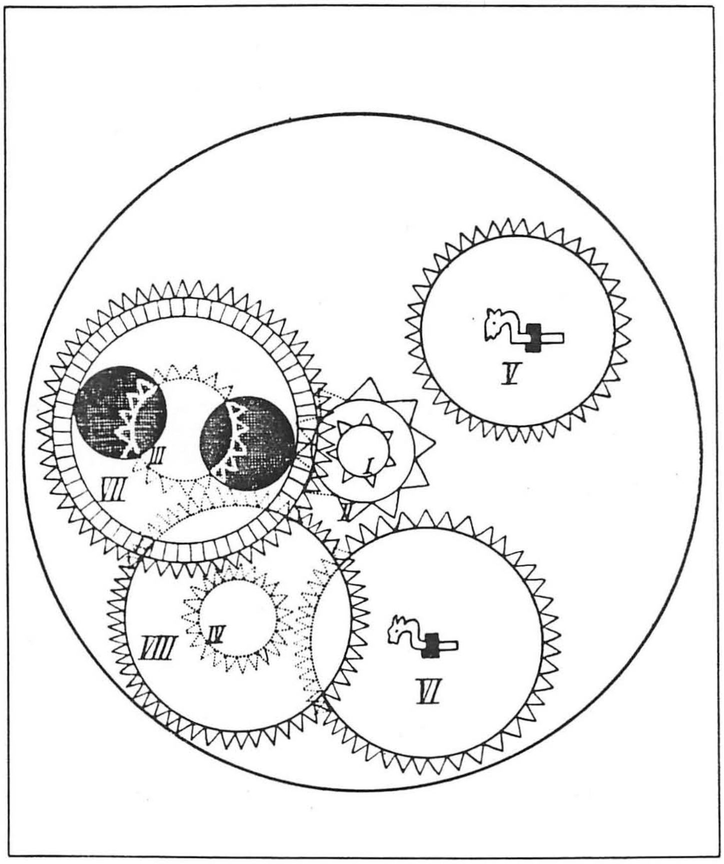
From the beginning of their interest, Moslem scientists evidently took a special pride in treating astronomy not as an abstract mathematical theory so much as a physical description of the cosmos, to be visualized as a model and measured with instruments. The astrolabe became especially popular. Texts describing how to make and use it were among the earliest scientific writings in Arabic. By the eighth century there existed whole dynasties of special craftsmen who made this and similar instruments, improving them with mathematical and artistic embellishments until they became scientific jewels highly prized by scholars and their princely patrons. From signatures and dedications on instruments and from contemporary references we know that astrolabes and other astronomical instruments were often made by a whole team of craftsmen rather than by a single individual; a metalworker, a mathematician, an engraver, and a decorator would work on the same instrument, and all of these men might have sons and apprentices who would grow up in the tradition of the craft. This pattern of collaborative work extended in Islam to the operation of instruments, so that here one finds the first observatories fitted with a great range of instruments and calculating devices and staffed by astronomers, mathematicians, instrument makers, clerks, and students.

Although the astrolabe seems to have been the most ingenious instrument in general use, there was also a large range of sundials, quadrants, globes, and angle-measuring instruments for making observations. Many of them must have been derived from the earlier Greek devices, but in all of them the Moslems made general improvements and adaptations. And new instruments were devised; some, like the Zone Plates made by al-Kashi and others, were designed for graphical computations of trigonometric equations.

The most important development for our purpose was a series of special analog computing devices for calculating the motions of the planets. The first of these appeared early in the eleventh century when the famous astronomer al-Biruni designed a geared machine that showed the places of the sun and moon in the zodiac and indicated the phases of the moon and the age of the (lunar) month. An example of this instrument dating from 1221 AD is preserved on the reverse of an astrolabe made by Muhammad ibn Abi Bakr of Isfahan. It is worth noting that the design of the moon-phase dial is exactly the same as those still found on many grandfather clocks, and that in many detailed points of design this geared astrolabe is in the same tradition as the Antikythera mechanism from first-century BC Greece. Indeed, there is some evidence that the craft was transmitted from Greece to the Islamic world, and from the Islamic world to medieval Europe.

At about the same time, early in the eleventh century, there began to appear a number of designs for other planetary computers, more mathematically intricate so as to follow the motions of planets other than the sun and moon, but without the mechanical sophistication of gearing. The calculations involved in finding the positions of Mercury, Venus, Mars, Jupiter, and Saturn were tedious, and clearly there was much advantage to be gained from the use of these equatorium devices (from equate, to calculate, to make an equation). In principle the equatorium consisted of a brass plate or plates on which geometrical constructions were equipped with movable threads and engraved scales for drawing out each special line position as needed.

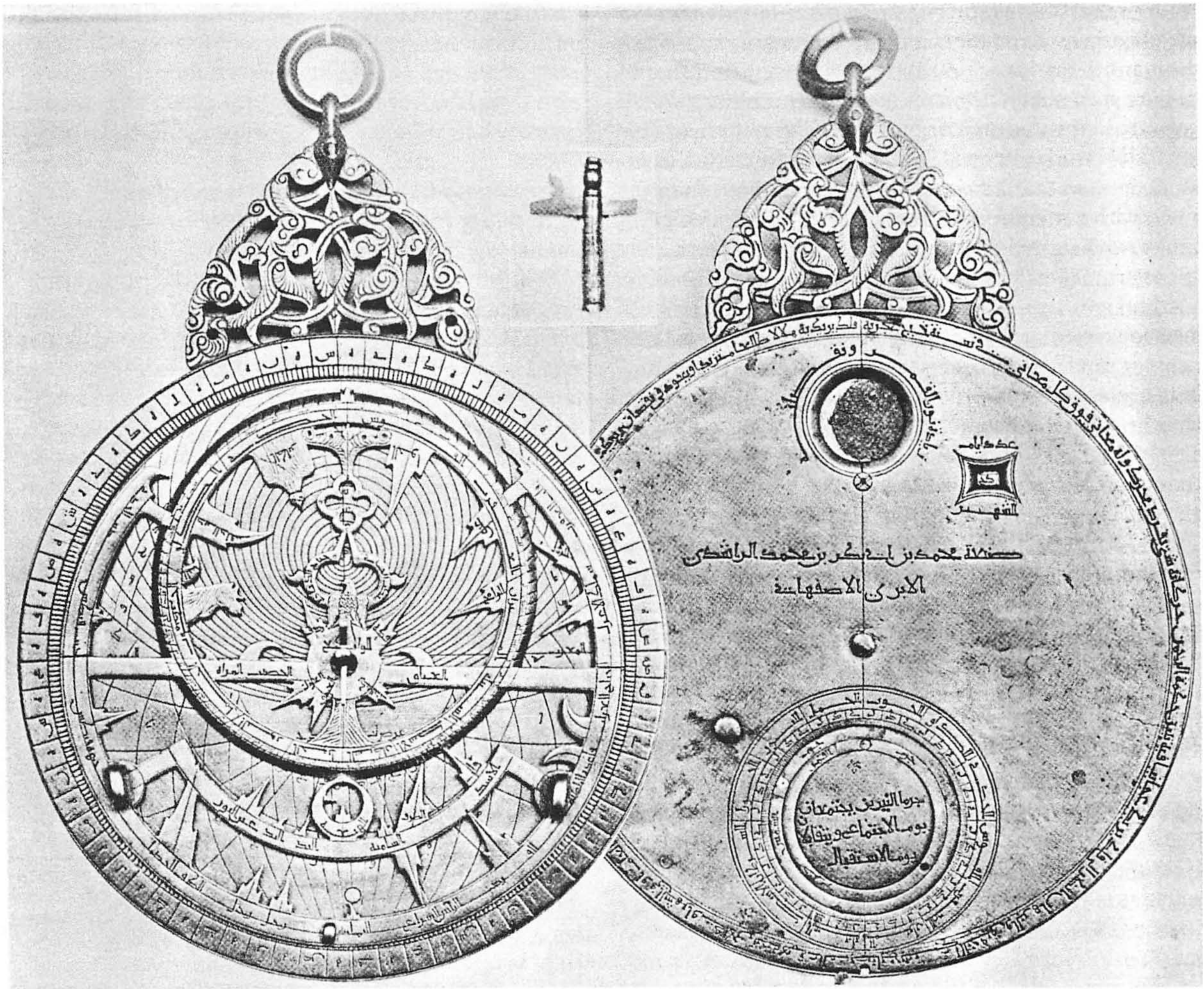
Protoclocks were also developed by the Moslems and elaborated into quite gaudy mechanical peep shows. Several detailed and precise manuscript descriptions and two surviving examples, all from the thirteenth and fourteenth centuries, show that Moslems had taken over all the devices described by Hero and added many improvements. There were water clocks with moving peacocks, monkeys, and elephants; systems for ringing the hours on gongs and bells and indicating them by pointers or by doors that opened to reveal a manikin or



AL-BIRUNI'S GEARED CALENDAR COMPUTER of ca. 1000 AD showed the places of the sun and moon in the zodiac and indicated the phases of the moon and the age of the lunar month. (Drawing courtesy estate of Derek de Solla Price.)

an inscribed tablet; and anaphoric clocks that had turning astrolabic dials to show the places of the stars and planets by night and by day. In the Islamic world, these astronomical devices began to take on something like their modern role as time-telling instruments rather than wonderful models and ingenious embodiments of the cosmos. In the religious practice of Islam it is of cardinal importance to observe the ritual prayers at the exact moments designated throughout the day. Indeed, the chief outward manifestation of the Islamic faith is the colorful call to prayer of the muezzin from his minaret on the mosque; this makes a reliable and accurate timekeeper an essential part of the equipment of each mosque. In a city of many mosques, the guardians of the timekeepers will vie one with another for a record of neither calling before the hour is due nor falling behind the consensus and calling too late. It is for this reason that mosques are richly furnished with clocks and sundials. For a parallel reason cathedral clocks became popular in medieval Europe. During the fourteenth and fifteenth centuries great astronomical clocks were built all over Europe, serving both as astronomical exhibitions and also as timekeepers for the proper execution of the daily round of prayer.

Even before this, the whole art and craft of instrument making had spilled over from the Moslem lands into Europe during the great transmissions of learning in the

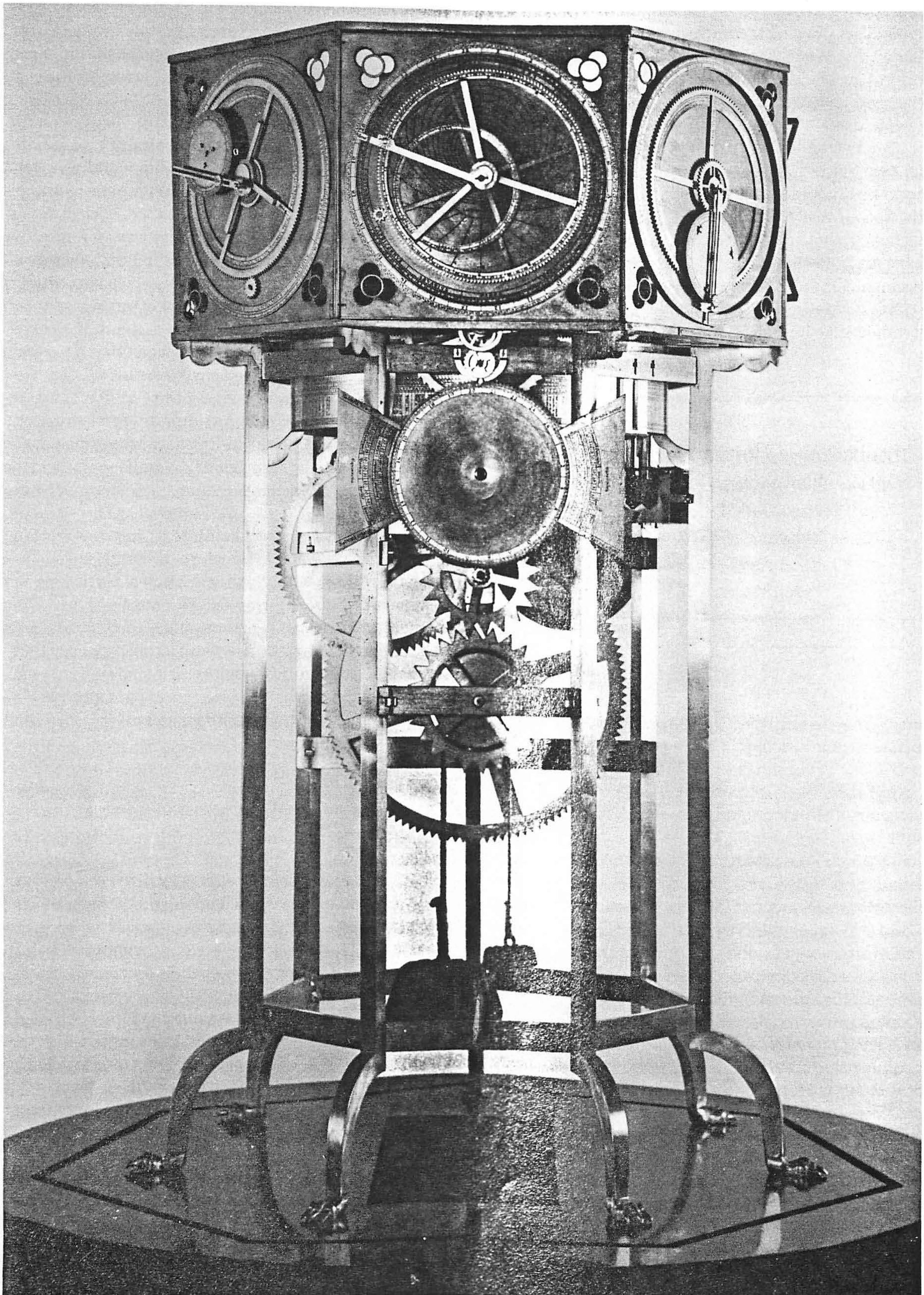


ABI BAKR'S ASTROLABE of 1221/2 AD includes a geared calendar mechanism. The gearing follows the al-Biruni design and contains many features similar to those of the Antikythera mechanism. The instrument is now in the Museum for the History of Science at Oxford University. (Photo courtesy estate of Derek de Solla Price.)

late Middle Ages. From the thirteenth century on, astrolabes had been known and manufactured together with sundials, quadrants, waterclocks, and all the other devices. By the second half of the fourteenth century there was a highly developed craft with its own practitioners, continuous improvement and innovation, and a steadily growing literature. In the 1390's the great English poet Geoffrey Chaucer adapted into English one of the best Arabic texts on the astrolabe and wrote also on the design and construction of a planetary equatorium.

The great astronomical clocks of the cathedrals were undoubtedly the high point in the development of scientific machinery in the Middle Ages. Nobody knows how and when the more precise and reliable weight-driven mechanical escapement replaced the water clock. Some think it might have come from China, where the tradition of globes animated by water power had evolved steadily. By the year 1080 the Chinese had built enormous clock towers in which the automatically moving globes and the manikins that rang gongs and cymbals to announce the hours of the day and the watches of the night were powered by a giant water wheel. This wheel was held in check by a system of rocking levers that bore some resemblance to the verge and foliot escapement of the first European clocks, and the notion could have been transmitted by travelers, perhaps in the late crusades.

Although we do not know just how it evolved, the mechanical clock seems to have reached an impressive maturity with extraordinary rapidity. The earliest clock we know about in any detail also happened to be more complex than any built for centuries after; its array of planetary dials, its complicated assemblies of circular and elliptical gears, its link mechanisms, and its ability to perform careful computation made it one of the most handsome pieces ever constructed. This direct descendent of the Greek anaphoric clock was made by Giovanni de Dondi in Padua in 1364, and although it has since been lost, de Dondi's working drawings have come down to us and



SMITHSONIAN INSTITUTION PHOTO NO. 48667-B

THE DE DONDI CLOCK of 1364 was more complex than any built for centuries after. Its seven main dials showed the motions of the planets and gave results accurate to within a degree or so. Gear teeth in the form of equilateral triangles were employed—such teeth were inefficient, but the form survived in later clockwork. Although the original de Dondi clock has been lost, manuscript descriptions and drawings have permitted reconstructions such as this one in the Smithsonian Institution. (Photo courtesy Smithsonian Institution.)

have permitted the construction of a duplicate. Its seven main dials showing the motions of the planets (the time-telling dial is hardly discernible in the general complication of machinery) accurately portrayed the Ptolemaic theory and gave results generally accurate to within a degree or so.

The de Dondi clock undoubtedly was not the first of its kind but is the earliest we know of in sufficient detail from manuscript evidence. Richard of Wallingford, born the son of a blacksmith and risen to the high post of bishop at the rich Abbey of St. Albans, is reported to have made a wonderful astronomical clock soon after the beginning of the thirteenth century. It is said to have been so full of gearing and so costly and elaborate that only he could keep it running, and only then at an almost prohibitive expense that drew criticism from his superiors and from the king. Richard's clock may have been powered by water; we do not know, for the careful description he left has been lost, and only his lesser works on planetary computers and other astronomical instruments survive.

Leonardo de Vinci's mechanical drawings appear to us as original works of genius—we should remember, however, that Leonardo was also the inheritor of a long-established tradition of instrument making.

De Dondi's clock was followed by many others in the same genre, though none was of such complication until the third in the series of great clocks in Strasbourg Cathedral was built. The first had been contemporary with the device at Padua, but of it only a giant mechanical rooster and a few other pieces survive. The third clock, built in 1542, became the wonder of Europe because of its perfect and complete representation of astronomy and its impressive size and because of the superior workmanship that kept it going without the long periods of breakdown that must have attended most of its predecessors.

By the end of the Middle Ages, therefore, there was in Europe a strong and lively tradition of fine instrument making and skill in the design and production of this special sort of scientific machinery. As a craft it was not widely practiced, for there were only a handful of practitioners alive at any one time. As a skill it may not have been of any great economic importance; only wealthy monarchs and lords could afford to keep such high-class magicians for edification and amusement. Its scientific value was probably slight, for the rise of experimental science and the true appreciation of the role of instruments did not come till the Renaissance was almost over. But as the seed from which would spring the scientific revolution and the mechanics of the industrial revolution, this craft was of decisive importance in the history of man. The skills of these men who made little gear wheels and designed astrolabes and equatorium computers were of the greatest consequence in the explosion of science that was to come.

The great cathedral clocks were also of considerable importance insofar as they excited philosophers, theologians, and other nonscientists with the enormous understanding man had gained in the science of the universe. Their man-made regularity was an impressive argument for the rationality of the universe they modeled. In the school of the astronomer-logicians of Merton College in Oxford, considerable effort was made to deduce a logical and mathematical account of the laws of motion, but at that stage Aristotelian theory was too strong and mathematics too weak for this fundamental task. In Italy, the cosmological poetry of Dante was inspired by Ptolemaic models of the world structure, and the supreme artist-scientist, Leonardo da Vinci, made sketches of planetary gear models closely resembling the clock of de Dondi, sketches that perhaps were made from the instrument itself. Leonardo's mechanical drawings only at first sight appear to be those of a genius working in his ivory tower. It is more accurate to see his mechanical devices only partly as original inventions and to remember that he was deeply fascinated with fine mechanical instruments and machines that depended on a tradition that had come down from classical times through Islam and other cultures, a tradition in which clockwork and astrolabes were all part of the story of man's effort to embody mathematics for pleasure and profit in tangible objects.

Renaissance instruments and computing devices

Two great forces dominated the Renaissance of science: the availability of the printed book and the rise of scientific practitioners. The printed book gave new access to the scientific texts of antiquity and brought them before a different and larger audience than there had been for the precious manuscripts held by the universities and monastic institutions. At the same time the book made easier the spreading of new knowledge around Europe, and the whole pace of learning suddenly quickened. The scientific practitioners were the heirs of the old craftsmen who had made the clocks and astrolabes and quadrants and sundials during the Middle Ages.

With the Reformation, which altered the social pattern of much of Europe, and the rise of the guilds, which regulated and nourished the workers in craft industries, there gradually arose a more secure and massive scientific instrument making industry. In Europe it was first seen on a large scale in Nuremberg, where Regiomontanus settled in 1472 and founded a scientific printing press, an instrument workshop, and an observatory. Instrument making spread to the nearby city-state of Augsburg, and in the sixteenth century and part of the seventeenth, these two cities straddling the great trade route through Europe from Italy to the Low Countries were the chief centers for scientific craftsmanship. There lived the great dynasties of fine metalworkers who made astrolabes and compasses, surveying instruments, and clocks and watches. To them came the professors and the mathematicians, the princes of Europe, and the dealers in books and manuscripts. By the middle of the sixteenth century Tycho Brahe could find only in Augsburg workmen cunning enough to build the new precision instruments he needed for the restoration of astronomy; toward this end in ensuing years he diverted a large part of the wealth of Denmark to the craft guilds of that city.

From about 1540 the crafts began to establish themselves in other centers as local conditions permitted. A most active group grew up in Louvain at the north end of the trade route, where it was inspired by the noted astronomer Gemma Frisius, the cartographer Gerardus Mercator, and the family of Arscenius, nephews of Gemma. In Germany and Flanders, good brass plate was available for the manufacture of instruments, but in England it had to be imported until Queen Elizabeth decided it would improve the safety of the realm if brass cannon could be cast at home. After about 1580, good brass sheet was made in England, and from that date there was a great increase in the making and using of instruments. In England arose other particular developments that gave impetus to the mathematical practitioners. The redistribution of monastic lands under Henry VIII and the golden age of maritime exploration under Elizabeth ushered in a period when surveyors and navigators were much in demand and the country needed every man who could make compasses and survey tools.

Thus by about 1580 there were cities in Europe where flourished dozens of workshops full of craftsmen and apprentices making fine scientific machinery for astronomers and amateurs, surveyors and navigators, and gunners and gaugers. Great ingenuity emerged as artist vied with artist for the production of some instrument like a cannon level with a built-in set of scales that enabled one to compute the range of balls of different weight and calibre. Further advances were made by those who sought to bring the ancient instruments to a new state of perfection; one could not work for Tycho Brahe without finding out what it meant to squeeze the design of a measuring instrument closer and closer to make room for that next decimal place. Another fine example was the noteworthy and almost prophetic improvement made in Augsburg when the old Vitruvian taximeter was adapted so that it could record an entire journey on paper tape. The tape moved steadily forward as the wheels of the carriage turned, and once every few turns a compass needle pressed into the paper to indicate the direction of the carriage at that moment. All one had to do to survey an estate was drive round it, come home, and make a map from the impressions of the needle in the tape. It was another three hundred years before paper tape came into general use in instruments, first for the recording telegraph and later for electronic calculating machines.

The scientific practitioners of the sixteenth and seventeenth centuries are the unsung heroes of the scientific revolution. Few are known beyond their signatures on the instruments they made, their advertisements in scientific books and newspapers of lessons offered in surveying and navigation, and an occasional certificate of marriage or death or of bankruptcy or taxation. For the most part their names are not famous for scientific theories and innovations; the glory has gone to their patrons, the users and designers of instrumental techniques. Nevertheless, much of the steady advance of experimental tools and computing devices was due to their skill and specialized trade, and much of the opportunity for improvement came from the increasing demand for these anonymous practitioners, who gained a marginal living from making maps of estates, charts of the seas, and inventories of wines and oils. It was the gaugers and gunners and such men who used instruments the most and who thereby made them accessible to professors of astronomy and mathematics.

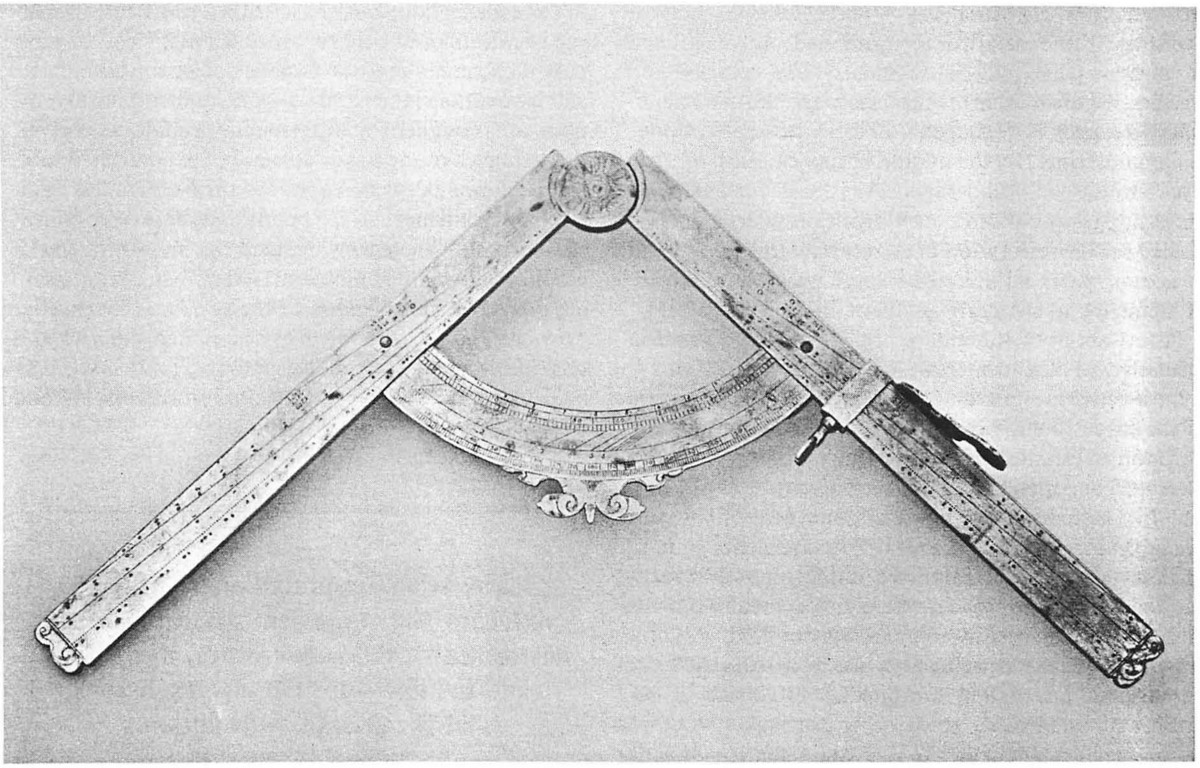
The scientific practitioners of the sixteenth and seventeenth centuries—the instrument makers, surveyors, navigators, and the like—are the unsung heroes of the scientific revolution.

Calculating instruments in the scientific revolution

Just before the dawn of the seventeenth century the art of making technical computations for dialing, gauging, and gunnery became so important and widespread that several instrument makers in several countries began making special ruled scales that were designed to make such measurements and calculations more easy. One of the earliest intruments of this kind was made by Humphrey Cole, a north country Englishman who was the first to apply himself to the craft in London. In the 1580's he made several such scales, including two folding rules on which were engraved all the calibrations needed by a master gunner.

The idea of special scales was in the air all over Europe, and among others it seems to have occurred independently to the young Galileo, who had not yet (ca. 1590) achieved fame from his telescopic observations, theories of mechanics, and discussion of the Copernican doctrine. But he had already tasted that love for scientific instruments that later enabled him to make a telescope on the strength of nothing more than the rumor that such a device had been made in some unknown way by a Dutchman, and to design just before his death the pendulum clock that brought the efficiency of mechanical timekeeping to a new pitch of excellence.

Galileo's calculating instrument was called by him a geometric and military compass, though later it became known as a sector. It was probably the most widely used scientific computing device until it was replaced by the



GALILEO'S COMPASS allowed calculations to be worked on engraved scales. The compass was opened to some fixed angle, and distances on the scales were transferred with a pair of dividers—in this way, simple proportions such as $a/b = c/d$ could be determined. Galileo's instrument later came to be called a *sector*; it was probably the most widely used scientific computing device of the seventeenth and eighteenth centuries. (Photo courtesy Adler Planetarium, Chicago.)

slide rule in about 1800. The sector comprised two bars of brass, ivory, or some other suitable material joined by a hinge so that they could be opened like a folding rule. Along each bar, running radially from the hinge, were engraved scales, with the scales of one bar mirroring those of the other. There were often other scales running along the length of the bars, filling in space that might otherwise have been wasted.

In use the sector was operated in conjunction with a pair of dividers that were used to transfer distances on the scales. The principle is the simple one of similar triangles. The bars were opened to some fixed angle, and the pairs of scales enabled one to work simple proportions such as $a/b = c/d$, so that one could in one step work out any combined multiplication and division such as $a = bc/d$. Furthermore, unlike the slide rule with its logarithmic scales, the sector allowed distances to be added by a mere extra step of the dividers so that one could make calculations such as $bc/(d+e)$. The greatest refinement was that which made it possible to mark the sector with scales other than those for simple numbers. For example, a pair of scales marked with distances proportional to the squares of the natural numbers could be used for computations of the form

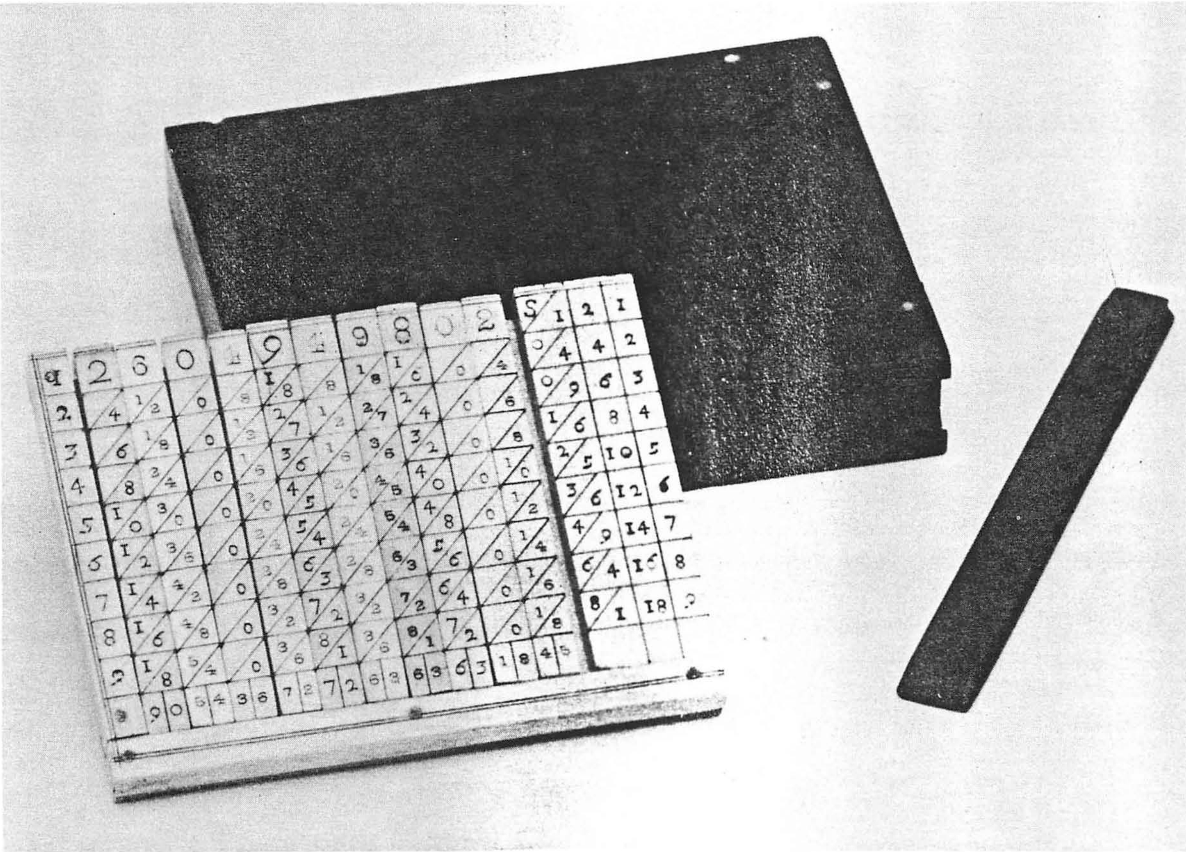
$$a^2/b^2 = c/d,$$

and scales marked in square roots, cubes, and trigonometric and other functions enabled one immediately to compute quite complicated forms of almost any sort.

Unfortunately, Galileo did not reap the benefit of this invention he had set store by. Although he employed an instrument maker who lived in his house and produced many copies of the sector that were presented to likely patrons and the learned of the country, he soon became embroiled in a priority dispute of the kind that plagued the lives of pioneers in the scientific revolution. Another man claimed the invention as his own, and the resulting storm of calumny and bitter rivalry quite overshadowed all potential gains. The sector, however, reinvented several times and improved by each maker adding special scales of his own devising, became a standard instrument. It was issued as late as 1900 in navigation and drawing instrument sets made for the British Navy.

In the early decades of the seventeenth century the world saw the invention or discovery of that powerful aid to computation, the logarithm, made twice by independent workers. One of the inventors was Jubst Bürgi, clock maker at the court of Rudolph II, Holy Roman emperor and patron of all scientific and pseudoscientific artisans. Bürgi devised in 1611 and published nine years later a table that we would now call a table of antilogarithms of integers. His publication was in part forestalled by the appearance in 1614 of a book by John Napier, Laird of Merchiston, a work so influential that it went through six editions in as many years.

In 1617, when logarithms had already begun to revolutionize astronomical calculations, Napier devised yet another popular aid to computation, the little rods now known as "Napier's Bones," each of which bore a



NAPIER'S BONES, devised by John Napier in 1617, consisted of small rods, each of which bore a multiplication table for a particular digit. With a set of these bones, one could pick those corresponding to a given number of many digits, lay them side by side, and read off the result of multiplying the given number by any other digit. In this illustration, one can determine the result of multiplying 26,049 by 7, for example. The answer, 182,343, is read from the diagonals, working right to left and carrying where appropriate: 3/8+6/9+2/2+0/4+4/1 yields 3/4/3/2/8/1. (Photo courtesy IBM Archives, Armonk, New York.)

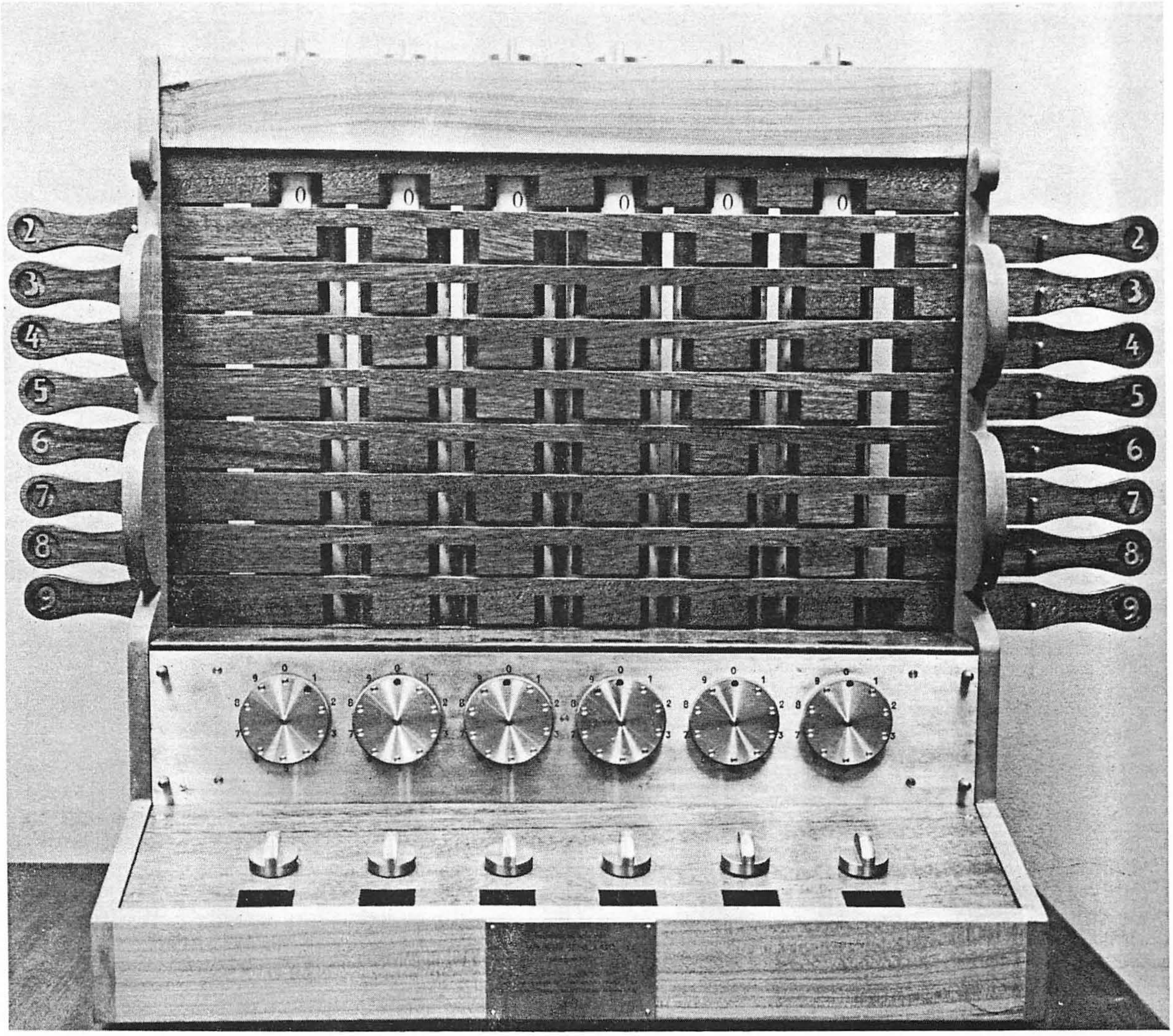
multiplication table for some particular digit. With a stock of such bones one could pick those corresponding to a given number of many digits, lay them side by side, and read off the result of multiplying the given number by any other digit. In this way multiplications could be performed in an almost automatic fashion without the mental labor of remembering and applying the multiplication table. At a later period special bones were added that made possible the semiautomatic calculation of squares and square roots on the same principle.

Hardly had Napier's Bones been invented than another striking advance was made. Edmund Gunter, a mathematical instrument maker of London, produced in 1620 a scale engraved with numbers and divided proportionally to the logarithms of those numbers. With such a scale one could use a pair of dividers (as with the sector) to multiply and divide numbers by adding and subtracting the distances along the scale. By 1622, William Oughtred, another mathematical practitioner and teacher, had applied Gunter's scale to a circle, with the dividers pivoted at the middle—he called it a "circle of proportion," and in fact it was in modern terms a circular slide rule.

Like the sector, the slide rule was reinvented and improved many times. Scales were set up as circles and spirals, as pairs of straight lines, and as quadruple arrays. Special scales of all sorts were added and slide rules were produced for special purposes of astronomy and navigation and for gauging the strengths of spirits, the weight of metals, and the reactions of chemistry. The earliest known example of the basic modern type with a single strip sliding in a slot is preserved in London and was made by the otherwise unknown Robert Bissaker in 1654.

Along with this activity in the art of scientific calculation there began to be a renewed interest in that of commercial arithmetic, which till then had remained satisfied with ciphering with modern numerals on paper rather than on counting boards. The new commercial arithmetic had swept through the trade centers of Holland, Frankfurt, Lyons, and London, and it took merchants and their clerks some time to adjust to the new facility of decimal notation and written numbers.

Probably the first simple step toward the mechanization of commercial arithmetic was taken by William Pratt, who published in 1617 a book called the *Arithmeticall Jewell,* into the cover of which was bound a little ivory table with brass sliders that one could push around with a stylus so that operations in arithmetic could be performed without writing numerals. The Jewell was an elementary device that contained no gear wheels or moving parts other than those which indicated the numbers and fractions. It was a cumbersome little piece, probably more difficult to work than the old counting board, but



SCHICKARD'S CALCULATING CLOCK of 1623 was probably the first true mechanical calculator. It could multiply two numbers by means of a system of rods and gears and an automatic carrying mechanism. Its uneven gear teeth, however, made it sluggish and unreliable. Descriptions of the machine were only recently discovered; the device pictured here is a modern reconstruction. (Photo courtesy IBM Archives, Armonk, New York.)

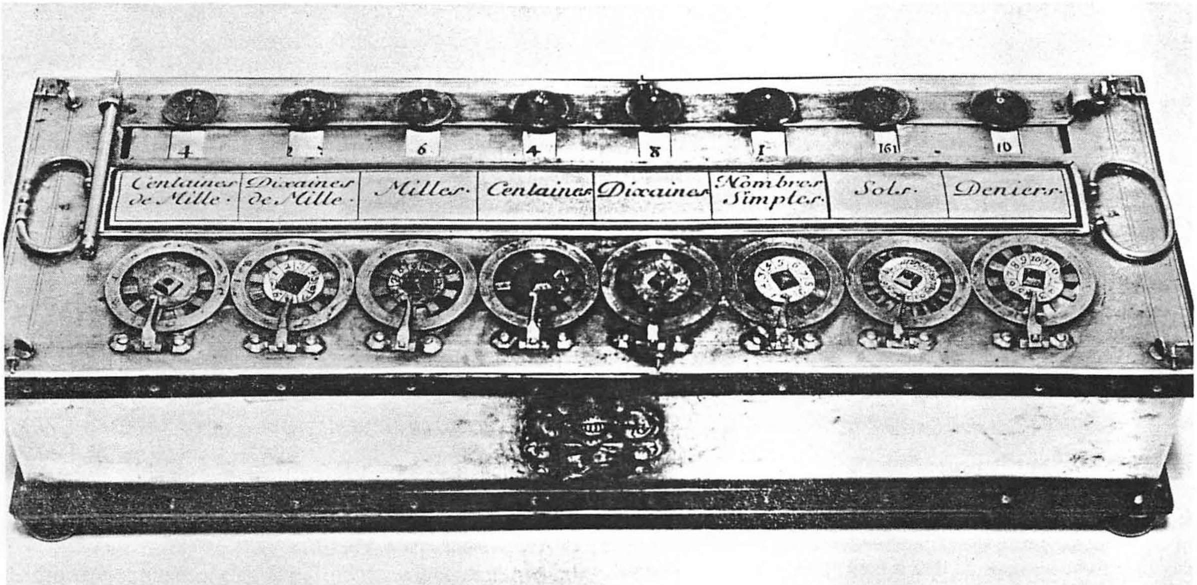
its invention signified a mounting interest in all forms of calculation, and the practitioners were losing no chance to make ingenious devices that would satisfy the public demand. No less a person than Thomas Harriott, navigator and man of court, posed for his portrait with an example of the Jewell before him.

The coming of true mechanical calculation

By the middle of the seventeenth century the art of designing and building aids to computation was, as we have seen, in a particularly active ferment. This was the heyday of the scientific revolution, when social forces were gathering for the foundation of the first great national academies of science, when important mathematical techniques were being developed, and when new types of scientific instruments were allowing man to perform observations and experiments in glorious and inspiring profusion. Clock making was by then a particularly highly developed craft, and the status of the great astronomical clocks of the cathedrals of Strasbourg, Prague, and dozens of other places was by now so marked that Boyle was drawn to the mechanical philosophy after having been suitably impressed with the spectacle at Strasbourg. Hundreds of seventeenth-century theologians were beginning to espouse the philosophy later so well expressed by William Paley, the theory of the universe and everything within it as a highly complicated mechanism, with God as the master clockmaker, the author and initiator of this mechanical masterpiece.

At this crucial point around the middle of the century a crucial step was taken, a step that brought together scientific calculation and its clockwork on the one hand and commercial ciphering and its counting boards on the other. This step was actually taken not once, but many times in many ways.

The first example of this joining of the scientific and commercial seems to have been a calculator made in 1623 by Wilhelm Schickard, professor of mathematics in Tü-



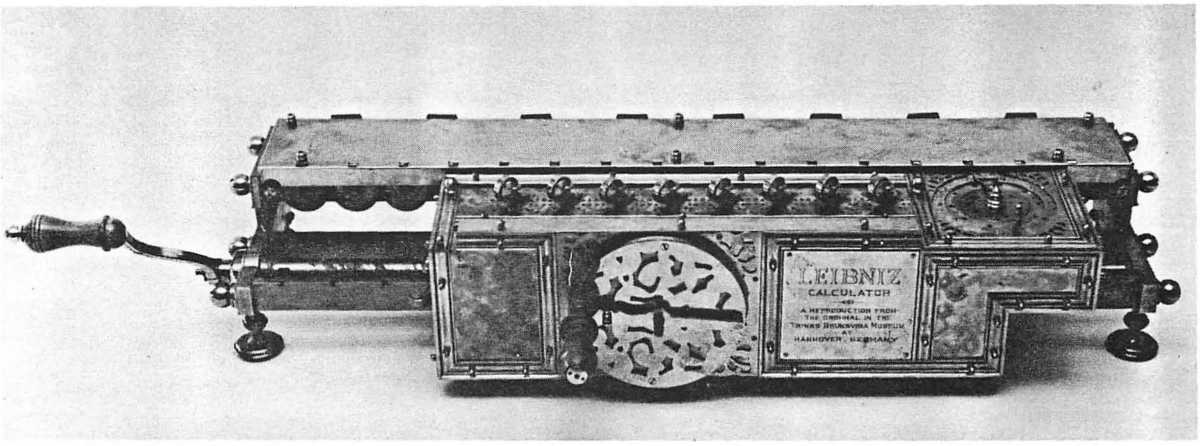
PASCAL'S CALCULATOR worked by means of a series of toothed wheels on which given numbers could be set in turn. These wheels communicated their totals by register wheels linked to them. The heart of the machine was a device for carrying tens. Pascal devised his first calculator in 1642, when he was 19, and made additional models thereafter. The one shown here includes two special wheels for handling sums of money—*sous* and *deniers.* Note that 20 divisions are provided for *sous* and 12 for *deniers.* (Photo courtesy IBM Archives, Armonk, New York.)

bingen. He called it a "Rechenuhr," a calculating clock, and described it in a letter to the great astronomer, Johannes Kepler. The machine was apparently not very satisfactory in its action since its gear teeth were uneven and sluggish and sometimes caused it to miss a count or make two counts instead of one. Nevertheless, it deserves a place as the first true digital computer, theoretically able to multiply two numbers by purely mechanical means—by a system of rods and gears and an automatic carrying mechanism for moving tens to the next highest column. So far as is known, this device had no influence on any other later machine designer—Schickard and all his family died of the plague in 1635, and Kepler apparently did not make use of the information contained in the letter that is now the only evidence that this machine was ever devised. Possibly this or some other similar machine became known in principle, for Johann Ciermans, in *Disciplinae Mathematicae,* a book published in 1640, mentions the existence of a machine with wheels for mechanical multiplication and division, but gives no details from which to identify or further describe it.

The next and most famous step was taken by Blaise Pascal (1623-1662), mathematician, scientist, philosopher, theologian, and master of prose. In 1642, when he was 19, he devised a completely automatic adding machine that worked by means of a series of toothed wheels on which given numbers could be set in turn. These wheels communicated their total by register wheels linked to them. The wheels could be turned in both directions so that both additions and subtractions could be handled. The heart of the machine, the most difficult feature, was the device for carrying tens to the next column; unfortunately, it appears that even with the best workmanship obtainable, the ratchet system employed was not satisfactory in use. It is said that Pascal originally designed and made the machine to help his father keep accounts in his tax office, and that once this was done his interest remained keen and he built several additional devices, each of them different. Some had a capacity of six digits, others of eight; some dealt with numbers only, others had special wheels to handle sums of money, in which case one needed 12 and 20 divisions to the wheel for handling *sous* and *deniers.* In 1647, five years after the first machine had been made, Pascal obtained the privilege of patent for his device, which thereafter, being well known by virtue of its inventor's fame, was many times adapted and used. It was given a complete description in Diderot's *Encyclopédie,* 1751, and became traditionally accepted as the first of the new line of geared digital computers.

A series of three calculating machines, one of them rather like that of Pascal but apparently developed independently, was invented in the 1660's by Sir Samuel Morland, Master of Mechanics to Charles II. The first of these, invented in 1663 and made in the following year by Henry Sutton, noted instrument maker, and Samuel Knibb, clock maker, was an analog calculator for trigonometrical problems. Finely graduated scales and protractors could be arranged to form a triangle, the sides and angles of which could then be measured. As an added refinement the device could be set to work as a Galilean sector, and in this way multiplications and divisions could be performed graphically. Another model of the same general design was made by John Mark, apprentice to Sutton, in 1670.

Moreland's second machine was similar to that of Pascal. It was invented in 1666 and made for him by Humphrey Adamson, a skilled craftsman who was one of the first makers of the pendulum clock designed by Huygens. This machine used little wheels, each of which had a simple projection that turned a companion wheel



LEIBNIZ CALCULATOR of 1694 had two essential elements—a collection of pin wheels arranged for adding, and a system of stepped cogwheels that allowed any number of teeth from none to nine to engage with the adding section. This latter element was designed to be movable so that it could be slid to follow decimal places in multiplication. As was the case with other seventeenth-century designs, the concept of this machine was ahead of the instrument making capabilities of its day. (Photo courtesy IBM Archives, Armonk, New York.)

at each revolution so as to carry the tens; the carrying was not automatic, however, for the operator had to remember to add the extra digits indicated on the auxiliary dials. Like Pascal's, this adding machine was specially designed for adding sums of money, with wheels provided for shillings (up to 19) and pence (up to 11). As with so many other inventions, a priority dispute arose—Robert Hooke, the mechanical genius of the Royal Society, declared this device to have been stolen from his work. And Samuel Pepys, with his usual candor, recorded in his diary for January 1668, that Lord Sandwich had just acquired one of Morland's machines for "casting up sums of £.s.d. [pounds, shillings, and pence] which is very pretty but not very useful."

A description of the third calculator, which Morland claimed to have invented earlier, was not published till 1673 when it had already been forestalled by the altogether superior device invented by Leibniz. Morland independently applied himself to the obviously central problem of mechanical calculation, that of making a digital machine that would multiply automatically. He achieved only part of that automation, using an arrangement similar to that of Napier's Bones, a series of small discs that could be picked out and set by hand. Again it was a pretty idea, but not quite perfect enough to be useful.

A fundamental new design for a multiplying computer was devised by Gottfried Wilhelm Leibniz (1646-1716), who shares with Newton the honor of having laid the mathematical foundations of both differential and integral calculus. Perhaps it is not entirely coincidental that both Pascal and Leibniz were philosophers, theologians, and mathematicians as well as incidental inventors of important calculating devices. Besides their immediate motivations—Pascal and his father's office work, Leibniz and the tedious calculations of the new mathematics—they were both deeply immersed in the renaissance of the ancient tradition. The Cartesian theories, the rise of the technical arts, and several other factors had put new emphasis upon the old idea of the glory of manufacturing automata to replicate the structure of the universe and the mechanisms of man and beast. Hence, what was more natural than to attempt a machine to replicate one of man's highest intellectual achievements, mathematics? In many ways this attempt was a crucial experiment that tried to show that at least some mathematics could be performed automatically, without the need of divine understanding.

Leibniz invented the machine in 1671 at the age of 25, but only two machines seem to have been made, and those not until 1694 and 1706, respectively (only the first has been preserved). The machine had two essential elements—the first, a collection of pin wheels arranged for adding, was similar in principle to Pascal's arrangement; the second, a new feature of stepped cogwheels, could be moved so as to allow any number of teeth from none to nine to engage with the adding section. The second element was movable so that it could be slid to follow decimal places in the multiplication.

Although the machine of Leibniz represented the final achievement of a completely automatic machine capable of all arithmetical operations, it was not a practical solution. In spite of lavish expenditure, the technology of fine instrument making could not yet reach the precision that was essential, and machines like those of Pascal and Morland remained little more than pretty toys. It was more than a century before the advanced machine design of the nascent industrial revolution could make effective the basic achievement of the ingenious mechanics of the seventeenth century.

The coming of practical calculating machines

By the beginning of the eighteenth century, the physical sciences in general and calculating machines in particular had cleared their first decisive hurdles and settled down to a less eventful progression. Important advances there certainly were, but in many fields one senses something of a lull between the intense pace of the scientific revolution in the seventeenth century and the equally intense pace of the industrial revolution in the nineteenth century.

The seventeenth century had seen all the crucial steps taken in bringing together the diverse traditions from which had sprung the concept of the calculating machine. There were the concepts of commercial arithmetic on the one hand and of mathematical science on the other; there were the idea of automata and the special craft of the instrument maker. The art of the metalworker had triumphed, but in principle only. Perhaps the learned world was by this time convinced that machines could be made to calculate. However, if machine calculation was to be more than a philosophic triumph, it would have to be shown that machine and man could work successfully together. The calculator would have to become something more than a pretty toy; it would have to be an engine fit for commercial use and for mathematical research.

The story of eighteenth-century calculating devices is, for the most part, one of experiments which ran through all the possible variations on the inventions of Pascal, Morland, and Leibniz; it is one of all the ingenious art of the instrument maker brought to bear on the noble end of mechanized calculation. A world that had but recently experienced the Newtonian theories, which had cut like a knife through past problems and had revealed the inexorably determined causal laws of universal mechanics, could take readily to the concept of a machine whose very soul was mathematical.

Mechanic after mechanic built his chosen form of machine, expecting fondly to have created a device that would free man from the drudgery of arithmetic. Again and again the experiment was successful only in the eyes of the inventor, for the demands of precision engineering proved always to be beyond the craft techniques of custom-built instruments and clocks. Thus, although there were repeated attempts to make a calculating machine that was not merely theoretically sound but practical as well, they all missed the mark. By the end of the eighteenth century, the general ambition was inclining toward the theoretical perfection of the machine so that it could undertake more and more complicated mathematical and mechanical functions. Only when this love of mechanization had run its course did interest revert to practicality in commerce.

If one considers the simple adding machine as designed by Pascal and, in an inferior form, by Morland, one may note a continuous series of adaptations of principle, and of rather ineffective improvements in mechanical design. In 1678, Grillet in France combined such an adding machine with a set of Napier's Bones that could be rotated on cylinders; the apparatus had no loose parts and could be carried in the pocket. Then, in 1725, Lepine attempted to improve the Pascal machine by modifying its most troublesome element, the device for carrying tens. This was followed in 1730 by at least three attempts by Hillerin de Boistissandeau to remedy the same fault and to minimize the friction that was another disturbing ailment of this class of machine.

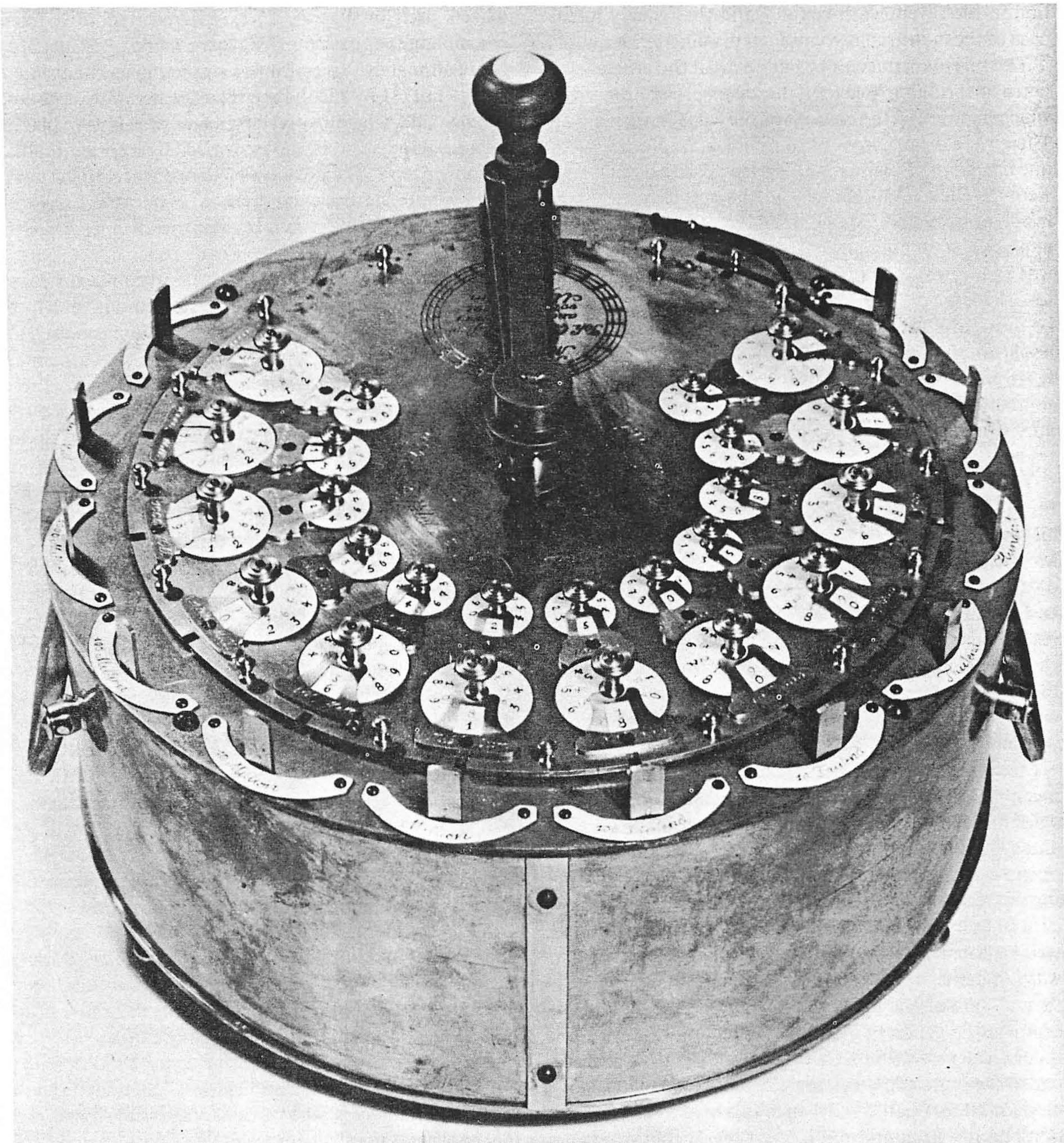
Another modification, devised by C. L. Gersten of Giessen in 1720 but not published till 1735, substituted a linear array of numbers working a rack for the pin wheels used by Pascal. In this it reverted to a form resembling the first abortive device made by Schickard. More ultimately successful was a carrying mechanism invented in 1751 by Jacob Pereire, a teacher of deaf mutes. He devised a scheme whereby register wheels were placed on a single axis and tens were carried by a spring-loaded peg made to project sideways from one wheel to the next. This is still the basic mechanism of most mechanical counters such as those that register the distance traveled by a car.

The Leibniz machine also resulted in a constant stream of improvements and innovations in methods of effecting multiplication by repeated addition. On his most successful machine Leibniz had used the device of a stepped gear so arranged that by sliding the gear sideways there could be engaged during a revolution any number of teeth from none to nine. Another way of doing the same thing, also proposed by Leibniz, was through the use of an adjustable pin wheel from which teeth projected or not according to which number from none to nine was to mesh with the neighboring counting mechanism.

The adjustable pin wheel was used in a multiplying machine built by G. Poleni in 1709, but this calculator proved not much better than Leibniz's. A third method, still more complicated, for varying the number of teeth engaging at each turn of the counter was proposed by the eminent mechanician Jacob Leupold in 1727, though he died before the design could be embodied in a machine. Leupold's principle was to disengage the gear wheel when the required number of teeth had meshed with the counter. He effected this in a particularly elegant fashion by means of a little rack of nine teeth which could be brushed past the counter wheels and raised so as to press against them for a greater or shorter distance according to the required number of teeth. Even though Leupold never made this machine, the publication of his proposal in a popular and important book on mechanical devices drew considerable attention to the art of designing machines to perform mathematical marvels, and it must be reckoned as a most influential piece of work.

The next consequential improvement of the Leibniz-type machine was made by Charles, Viscount Mahon (later Earl Stanhope), who was also responsible for several other advances in calculator technology. In 1775 and 1777 he made two machines, the first using the stepped gear principle of Leibniz, and the second being a more complicated variant of the Leupold scheme in which the cogs were disengaged after the required number of teeth had passed. Although neither machine embodied basically new mechanical systems, their rugged construction made them considerably more reliable than any hitherto. Thanks to the lapse of time, there had been an opportunity for technical skill to catch up with the inventive capacity that before had always outstripped it.

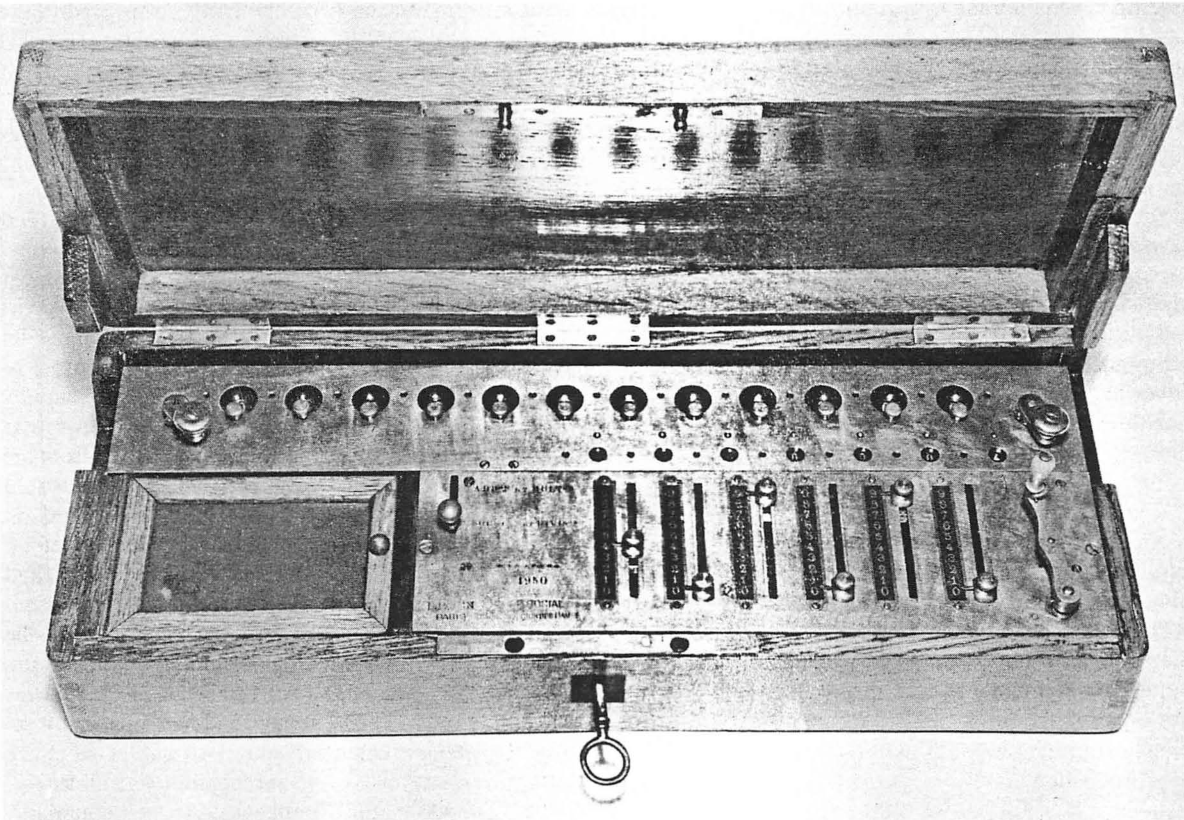
Stanhope, as a wealthy amateur and man of science with catholic tastes, was able to enjoy the services of James Bullock, one of the best mechanics of the day, and when the job was done could move on to other things. Thus, although his machines showed that mechanical multiplication could be achieved in a fairly reliable way, they were not pursued into general popularity. Stanhope later turned his attention to a different sort of apparatus



HAHN'S CALCULATOR was one of an early group of machines built on sound mechanical principles. Hahn made his first calculator in 1770-76, and he and his son improved upon the design thereafter. A fourth model using the stepped cylinder principle of Leibniz proved capable of giving consistently correct results with numbers of up to twelve digits. After Hahn's death, members of his family continued making the machines until about 1820. The calculator pictured here was made by Hahn's brother-in-law, Schuster, in 1792. (Photo courtesy IBM Archives, Armonk, New York.)

that was also a landmark in mathematical machines. He devised and published a description of a simple demonstrator that mechanized logical relations and showed by a pair of scales at right angles to one another the effects of combining two probabilities. There had been other visualizations of logical relations before this (compare, for example, the circles used by Euler to demonstrate overlapping classes), but Stanhope's Demonstrator marked the beginning of a new attitude toward computers; they were to be considered not just simple arithmetical machines but mechanical embodiments of more generalized mathematicological processes. Stanhope's two calculating machines came eventually into the possession of Charles Babbage, who was to continue this tradition and bring it (at least on paper) to the very apex of perfection; in many ways his work proceeded from the sound mechanical basis laid down by Stanhope.

In Germany, too, a multiplying calculator based on sound mechanical principles had been made before the end of the eighteenth century. The first step toward this success was taken in 1770-76 by Mathieu Hahn, Vicar of Echterdingen, who made at great expense a circular



DE COLMAR'S ARITHMOMETER was the first calculator put into general commercial production. It was manufactured from the early 1850's well into the present century. The Arithmometer employed the Leibniz stepped gear, which is used with a system of counting gears with automatic carrying. The secret of its accuracy was probably the use of many springs and other contrivances to destroy the momentum of the moving parts so that they would not carry beyond their intended point. (Photo courtesy IBM Archives, Armonk, New York.)

machine similar in appearance to that of Leupold. Later, improved models were built by Hahn and his son until a fourth model using the stepped cylinder principle of Leibniz proved capable of giving consistently correct results with numbers of up to twelve digits. While these improvements were being made, another German engineer, J. H. Muller of Giessen, armed only with a knowledge of the published external appearance of Hahn's machine, set out to design a similar but improved version, which he constructed in 1783.

It is curious that upon the attainment of mechanical reliability the science of calculating machines seems to have regressed momentarily, as if it was gathering strength for a final burst of mechanical ingenuity that would put the design in such a form that it could be manufactured commercially and made generally available for the first time. This great step was taken by the Chevalier Charles Xavier Thomas de Colmar (1785-1870) in 1820, though the first patent models were not made before about 1850. Soon afterwards the machine was put into general commercial production that continued well into the present century.

This machine, which at last achieved the success of general use, was based on the Leibniz stepped gear, which it used in conjunction with a simple system of counting gears with automatic carrying. The secret of its success was probably the use of many springs and other contrivances to destroy the momentum of the moving parts so that they would not carry beyond their intended point. Such carrying was a frequent failing of earlier machines.

De Colmar's Arithmometer, as it was called, by its very success constituted a branchpoint in the evolution of calculating machines. Until that time, although commercial success and scientific usefulness had been the twin goals, design and construction had always rested in the hands of scientists, mathematicians, and mechanicians imbued with the ancient obsession of mechanizing the mathematics of the world around them. Now, with the coming of the industrial revolution, the agents changed in character. Formerly scientists had worked with skilled artisans who made only scientific instruments; now, the calculating machine was just one of several ambitions cherished by that class of ingenious inventors which saw the birth of the steam engine, of interchangeable parts, of power tools, and of other evidences of a burgeoning industrialism that was making nations richer than ever before.

Scientists and mathematicians were still most concerned with the perfection of the device, but now they had at their disposal all the skills of professional machinists accustomed to high precision, reproducibility, and other techniques for successful commercial mass production.

With the Arithmometer of de Colmar, which capitalized on these gains, the road divided. Although there developed a main trend toward the perfection of a cheap and reliable machine for commercial use, a second line of development emerged and became distinct. Accepting that the basic utilitarian calculating machine had arrived in principle if not in fact, scientists and visionaries could now dream of a machine that would not only perform the simple mechanical operations of arithmetic but reach further, into the complexity of mathematical thought that seemed so peculiarly human. Perhaps in doing this they were merely looking at the same problem that had confronted both the first makers of astronomical protoclocks and the philosophers Pascal and Leibniz. Now, with the minor goal having been achieved or nearly achieved, the stakes had been raised and the designers of computing machines began to envisage that the whole of mathematical thought—perhaps even *all* human thought—might one day be encompassed by a machine. The would-be inventor of such a machine might well be fascinated by the concept. From his thought alone might grow the design of an engine that would outthink the best human minds.

Thus, during the remainder of the nineteenth century, one group took a step back to the simpler adding machine and eventually made it a common article of office furniture, while the other group—though it continued for a while to move the multiplying calculator toward the mass production that would make it a general aid to scientists—bent its efforts toward mathematical machines of different content. In this last class we must next consider the prodigious Charles Babbage.

The mathematical engines of Babbage and Scheutz

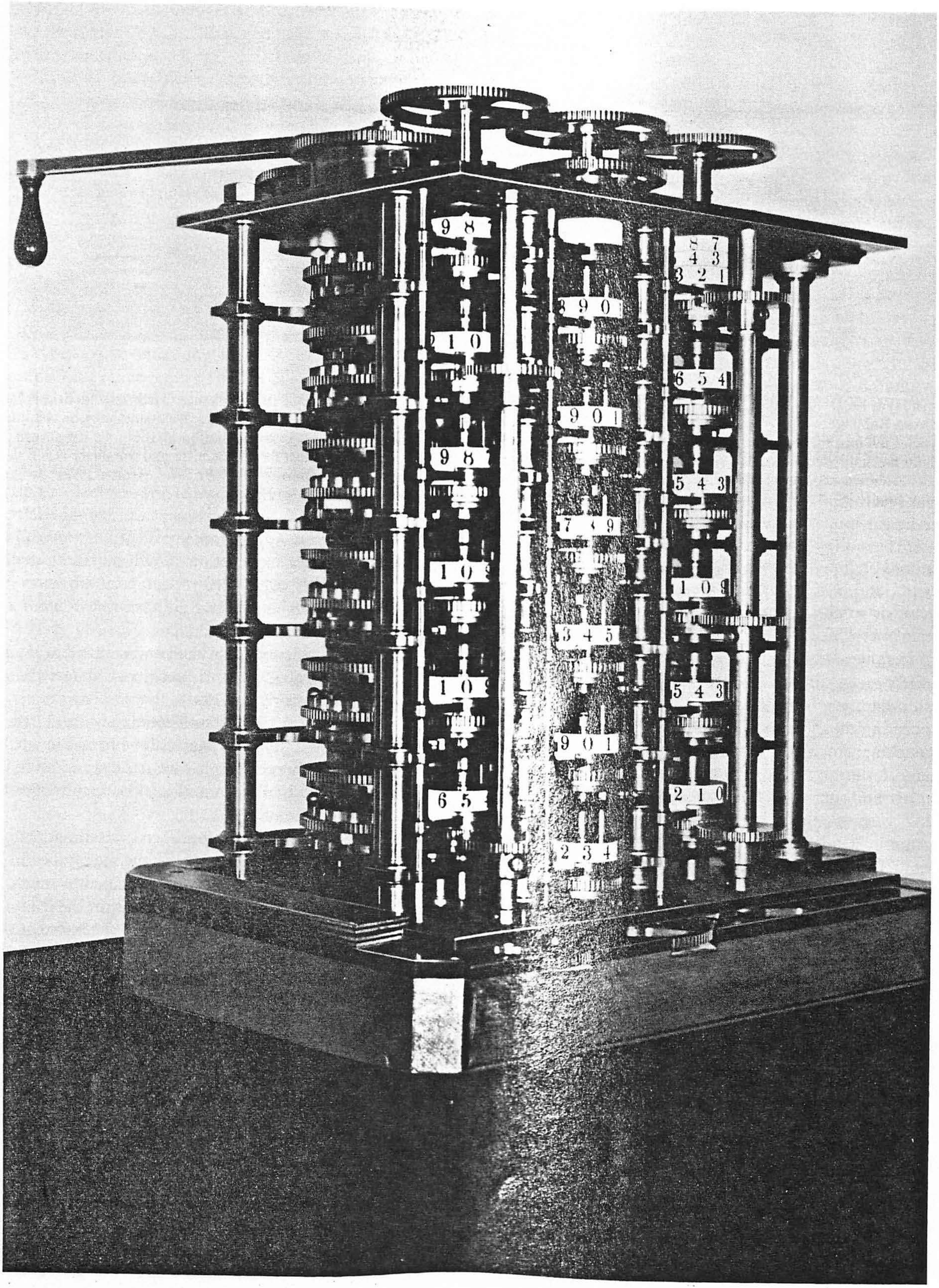
Charles Babbage (1792-1871) had the misfortune to invent the modern computer in an age when there were only painstakingly constructed gear wheels grinding too slowly to perform the mighty task he envisaged. He was a remarkable prophet of the techniques of operational research. He had the additional misfortune to be a believer in government support of science at a time when government still took fright at the thought of spending hundreds, let along thousands, of pounds on a project that did not promise a fairly rapid return. It was his experience to deal with a government that took umbrage every time he abandoned a design that had cost years of work to begin a new line that promised to be more efficient; it was an experience that made a once convivial fellow into an embittered old man, an experience that left a wondrous machine only partly built.

Babbage was born in Devonshire of a tolerably wealthy family whose fortune was eventually expended upon his passion for the calculating engine. This passion, according to the earlier and more reliable of his two autobiographical accounts, developed around 1822, some five years after he had left Cambridge, where he had received his training as a mathematician in company with such distinguished colleagues as John Herschel and George Peacock. These three had founded the notorious Analytic Society of Cambridge to combat the dot-age of Leibniz and support the de-ism of Newton— these two terms referring to the two rival symbolisms used in the differential calculus. According to the account, Herschel and Babbage were laboriously correcting some tables that had been computed professionally for the Royal Astronomical Society. At one point, weary of the errors, Babbage expostulated, "I wish to God these calculations had been executed by steam." "It is quite possible," replied Herschel, innocently setting Babbage on the road he was to follow so long and so far.

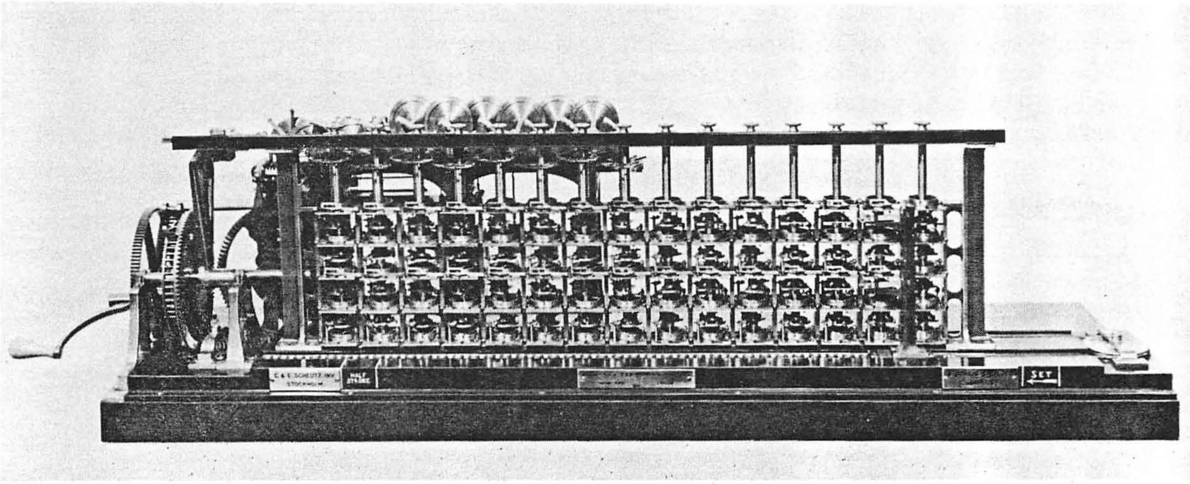
Thinking over the idea, Babbage became convinced that it should be possible to make machinery that could compute by successive differences and set type automatically so that tables could be printed without the errors produced by the intervention of an operator. He rapidly published papers describing his idea, and within a year he had extracted a rather noncommittal promise from the Chancellor of the Exchequer that the government would support for three years work leading to the production of such a machine. He worked for four years, ended up with only a series of scrapped and incomplete rejects, and then, on his doctor's advice, abandoned his work and went on a tour of Europe. Coming back in 1828, he sought and found further support and set about making more parts for his Difference Engine, as he called his machine. Alas, by 1833 Babbage had had a fiery quarrel with Clement, his engineer, and after a work stoppage lasting a year they parted, apparently not very amicably. While work was stopped Babbage conceived a new sort of machine that would transcend the Difference Engine and all other mathematical machinery. It was conceived in an exciting new fashion, for it would use a principle that we now call programming. The basic notion of this Analytical Engine was the use of a series of punched cards to tell the machine what operations to perform at any stage in the successive calculations. Such punched cards had been first designed by Falcon for textile machinery in 1728, had been brought to a peak of impressive perfection in the Jacquard loom, and had already been used by Vaucanson in his daring construction of a mechanical duck and other automata that performed in a most lifelike fashion, running through a series of operations in a long and complex cycle that almost seemed to involve free will and thought. Inspired by this new idea, Babbage went again to the Treasury seeking funds for his Analytical Engine, which he thought it well within his capabilities to devise.

From 1834 to 1842 he argued the case, but the government proved unwilling to expend any more money after the £17,000 it had already put into the first effort. Enraged, Babbage worked on, but in 1848 he made yet another major change of course, going back to a second model of the Difference Engine and unsuccessfully offering this new wonder of the drawing board to a singularly unenthusiastic Treasury.

Fortunately, in 1834 a copy of one of Babbage's articles on the Difference Engine fell into the hands of a far less temperamental mechanician who was inspired by them. A rich Stockholm printer, George Scheutz, and his son, with some financial assistance from their government and National Academy, set about building such a machine and brought it to a successful conclusion without the sort of distraction that Babbage's own fertility of mind im-



THE DIFFERENCE ENGINE was conceived by Charles Babbage in 1822. He worked on it fitfully until about 1833, when he had a fiery quarrel with his engineer, and work on the machine stopped. Babbage then conceived the Analytical Engine, a new design that would transcend the Difference Engine and all other mathematical machinery. The new machine would include a "mill" for performing operations on numbers and a "store" for holding them, and would be operated by sequences of instructions on punched cards. Babbage transferred his efforts to this new concept and worked on it until 1848, when he again changed course and returned to a second model of the Difference Engine. Babbage failed to bring any of his machines to successful completion; the machinery pictured here is a portion of the Difference Engine. (Photo courtesy IBM Archives, Armonk, New York.)



SCHEUTZ DIFFERENCE ENGINE was successfully developed from Babbage's ideas. In 1834, a copy of one of Babbage's articles fell into the hands of George Scheutz, a Stockholm printer and mechanician. Inspired by Babbage's plans, Scheutz and his son, Edward, set about building a machine. They completed a working model in 1837; by 1843 they had successfully constructed a version that automatically printed results. Their final model, which incorporated all prior improvements, was completed in 1853; it won a gold medal at a Paris exhibition in 1855. To the surprise of the makers, their most fervent admirer and supporter was Babbage himself. (Photo courtesy IBM Archives, Armonk, New York.)

posed on him. They made their first trial model in wood, wire, and pasteboard in 1834, and by 1837 the son had built a working version in metal. In 1840 they had a machine which worked to five digits and calculated first differences. In 1842 this capability was extended to third differences, and by 1843 an automatically printing version had been successfully made. A final version incorporating all the improvements was ready by 1853. The machine won a gold medal at a Paris exhibition in 1855, and to the surprise of the makers their most fervent admirer and supporter was Babbage himself. In the following year the machine was bought for $5000 by an American businessman, who presented it to the newly built Dudley Observatory in Albany, New York.

The difference engines of Babbage and Scheutz provided a new sort of automation of mathematics. Previous devices had enabled man to mechanize only single operations—addition and subtraction in machines of the Pascal type, multiplication and division in those of the Leibniz variety. With the difference engines came the new concept of a continuous series of operations, of the taking of differences that could be used to automatically build up a printed table for almost any mathematical (regular analytical) function that one could wish to tabulate.

The Analytical Engine, only a part of which was put together before Babbage's death in 1871, had much greater versatility than the difference engines. The heart of the machine, or rather its brain, consisted of two sets of perforated cards used in a fashion similar to that in which were used the cards of a Jacquard loom, which wove a complicated, predetermined pattern fed into the machine by levers that "felt" the holes in the cards and moved the shuttles accordingly. In the analytical engine one set of cards acted as mill, programming the machine to go through operations of addition, subtraction, multiplication, and division in a prearranged sequence, while the other set of cards was a store for numbers to be acted upon by these operations. With this technique, the machine not only could perform and print differences, but it could solve any succession of algebraic equations capable of numerical solution.

The whole operation was checked and counterchecked in several ways to guard against accidental defects and malfunctions, and for this reason the whole assembly became almost impossibly complicated. However, the ideas were so sound that they may still be found in electronic computers, but gear wheels were too slow and too heavy, too plagued by inertia and backlash, to be used in such fearsome arrays.

Again, however, the stakes had been raised and success achieved—in principle. Some of the techniques invented by Babbage and Scheutz and embodied by means of the machinist's new skills remained within the useful tradition. They contributed much toward the later commercial perfection of the mechanical computing machines which became standard equipment on scientists' work benches a century later. But the grand concept would have to wait for the development of new electronic skills capable of achieving those ends for which mere metal wheels and bars were too inert, imperfect, and tedious.

The modern accounting machine and typewriter

The story of the calculating machine in the commercial office began at the same time as that of the office typewriter. Both machines utilized the concept of the keyboard, long familiar from musical instruments. This familiarity enabled operators to easily and effectively work their machines—the keyboard was obviously the most convenient input device for both a writing machine and a calculating engine.

Although the concept was simple, the mechanical difficulties were considerable. In the first place, it took much ingenuity to devise linkages and mechanisms that would give the right effect. The first steps had been taken in 1714 by an Englishman, Henry Mill, who obtained a patent for a nonkeyboard device (details unknown) to print letters one by one. More than a century later, in 1829, a similar invention by William Burt of Detroit had pieces of type arranged on a wheel; letters could be selected and printed one at a time. For the calculating machine a whole tradition was already in existence, but input was provided by turning wheels rather than pushing keys.

The first steps toward the keyboard seem to have been taken through calculators rather than through typewriters. As so often happens, when the idea came it came almost simultaneously in many countries and to many people. Priority seems to belong to D. D. Parmelee, who patented his first key-driven adding machine in 1850; the keys not only set the numbers to be added but provided the motive power for performing the operation. Parmelee was followed during the next few decades by dozens more of inventors, many working independently of one another. They always found that the rapid motion of so many parts caused overshooting through inertia. Unfortunately, an office adding machine was a device in which one could not countenance frequent errors—what advantage was there to a thinking machine more fallible than a second-rate accounting clerk?

Although the adding machine proved disappointing in its early years, it seems to have stimulated the development of the typewriter, which, though started later, reached commercial production first. The big step was taken by C. Latham Sholes, a Wisconsin editor, politician, inventor, and enthusiast for most diverse things and causes, and by his promoter friend, James Densmore. In 1867 they devised the first "literary piano," a machine modeled partly on an automatic numbering machine and partly on the action of a telegraphic key. Rapidly producing one more effective model after another and capitalizing on the exploding capabilities of America's new machine age, they reached commercial exploitation by 1872. Long before the decade of the 1870's had ended, the typewriter had taken virtually its modern form. As with earlier devices, and as was so common in the nineteenth century, the next phase was jealous patent litigation to gain control of a device so eminently profitable, and to this end several new principles of operation were contrived and alternate devices manufactured.

Now the tables turned, and the commercial success of the office typewriter contributed to that of the accounting machine. The prime idea apparently came to a young machinist, Dorr E. Felt, just before Thanksgiving 1884. He had been operating a planing machine with an action in which a ratchet wheel could be moved automatically by one, two, three, or four teeth at a time; this ratchet was similar in design to the roller ratchet of a typewriter, by means of which the space between lines could be automatically varied. Using his holiday to make the now famous prototype contrived out of a macaroni box, a few meat skewers, some elastic bands, and much whittled wood, Felt proved that it was a workable device for causing keys to operate an adding machine. By 1887 the device, now much improved, could be patented by Felt (at the age of 24—a typical story for the times of young inventor made good), and shortly afterward his machine became the Comptometer—a companion in offices to the typewriter and a commercial success of like magnitude.

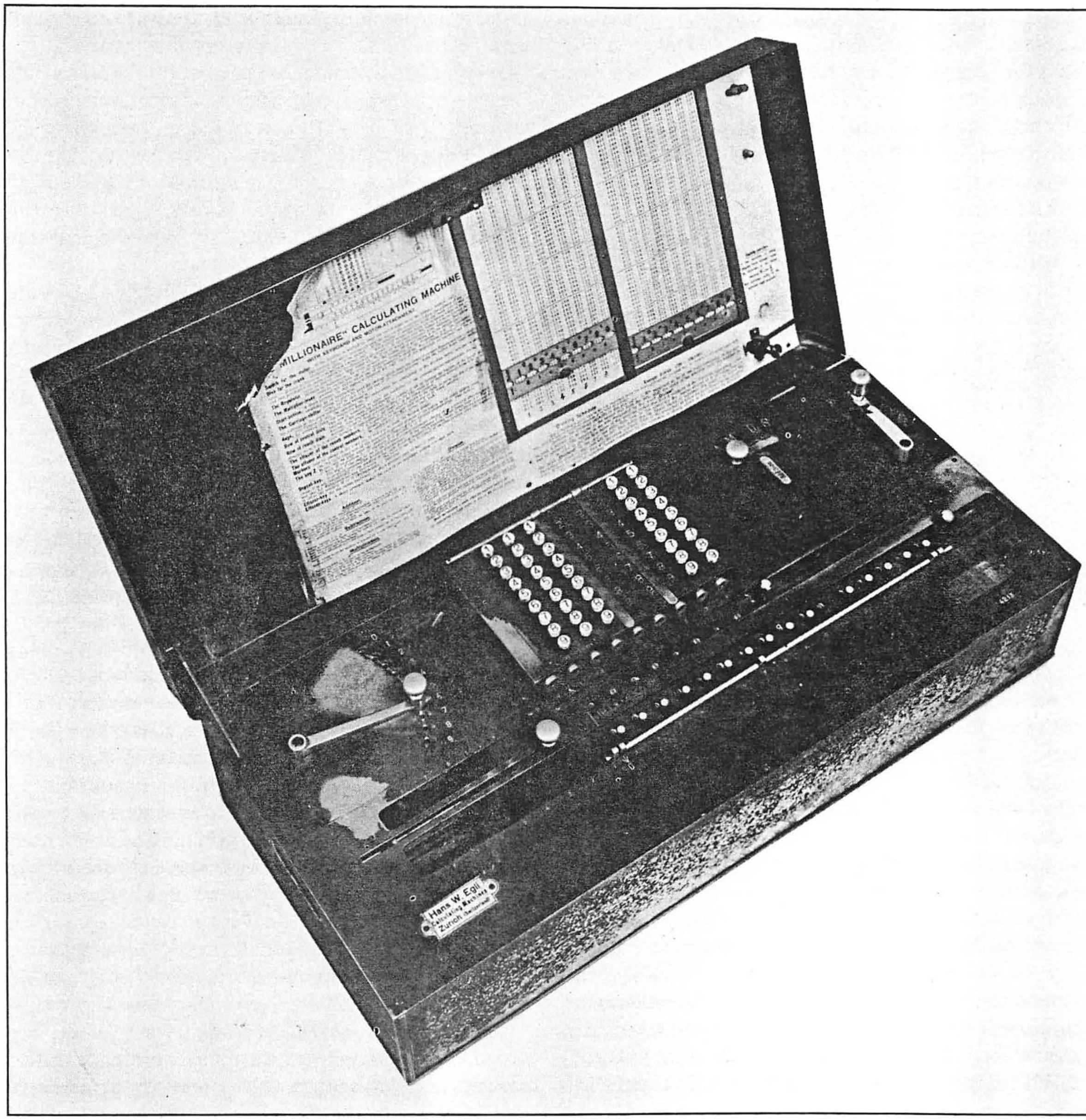
Now that keyboard operation had lent convenience, and modern machine-shop production had removed the bugbear of inertial overshooting, the way was clear to further improvement on a commercial basis. In the 1880's there came an interesting combination of the typewriter and the calculator, the first successful machine that printed the results of computations and thereby relieved the human operator of still more of his chores. Further combination of the two types of machine yielded what has since become the tabulating machine and the tabulator-typewriter.

Improvement in another direction enabled the Swiss worker, Otto Steiger, to extend enormously the mathematical usefulness of calculators by means of a built-in multiplication table, an innovation already worked out in principle by Bollee. His versatile calculator, called the "Millionaire," was capable not only of addition and subtraction but of multiplication and division too (though the latter could be done only somewhat tediously). It became another great commercial success and found a place in many laboratories and engineering shops. Thus, by the end of the nineteenth century commercial success had been [illegible] for every type of calculator except the soph[illegible]thematical thinking machine envisaged by Ba[illegible]commercial use, for simple mathematical comp[illegible] normal reading, and for printing and tabula[illegible] basic problems had been successfully overcome[illegible] was, if anything, an excess of commercial [illegible] that led to a vast number of minor varia[illegible]nd [illegible]mproved" versions.

Development of nondigital calculating devices

In the one remaining area of sophisticated scientific calculation there began in the late nineteenth century a marked trend toward experiment with devices outside the tradition of Pascal and Leibniz. In many ways a return was made to the principle of geometrical devices and analog computers that had originated with the first astronomical models.

One type of geometrical calculator, the slide rule, had a history of development reaching back to the seventeenth century, having been developed almost immediately after the device of logarithms came into widespread use. The earliest forms of slide rule had been without a slider, so to speak. Dividers were used to transfer distances on a plain logarithmic scale engraved on a ruler. Next a circular scale, inscribed around the perimeter of a disc and having the dividers pivoted at its center, was used. Soon afterwards the slide rule took on almost its present form, progressing with slight improvement to eventual mass production and the present day. But not until about 1900 did the modern slide rule completely displace the sector as the prime device for all occasions—on shipboard, for example, where rapid and approximate computation with mathematical formulas was employed, the sector remained in use until about that time.

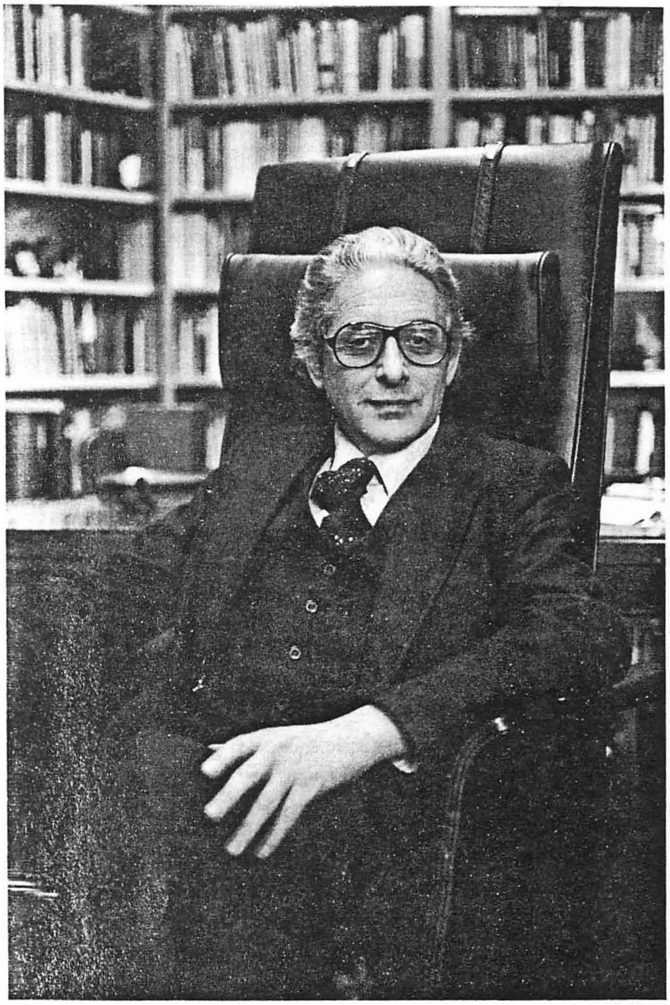


THE MILLIONAIRE included the innovation of a built-in multiplication table. This versatile late-nineteenth-century calculator, designed by the Swiss worker, Otto Steiger, was capable of multiplication and division as well as of addition and subtraction. It was a great commercial success and found a place in many laboratories and engineering shops. (Photo courtesy IBM Archives, Armonk, New York.)

More typical of the late nineteenth century were the invention and proliferation of a large variety of instruments that depended for their working order on precise geometrical linkages. There were all kinds of pantographs and other linkages for copying diagrams to scale; there were planimeters of ingenious construction for measuring the areas of curves and for graphically integrating functions. Most complicated of all, perhaps, were the harmonic analyzers such as those which had been invented by Michelson and Stratton in the United States and by Lord Kelvin in Britain. They were used for what would otherwise have been a most tedious computation—that of the Fourier components which determined tables of the tides. Seen in retrospect, these machines represented a search for some special means of doing mathematical work beyond the compass of the relatively simple digital computers then available. As calculators became faster, more efficient, and more complicated, they swallowed up the jobs for which there had been special pleading, leaving room only for such simple and relatively inexpensive devices as the slide rule. With the complicated analyzers, mechanical technology had been successfully taken to its limit; now it was time for a new art to fulfill the dream of Babbage and produce the device that would work mathematics with all the adaptability of the human brain but with all the precision of machinery. It would be for the new electronic age to achieve that rapidity of operation that could not be attained by historical model making and mere mechanical technology. ■

IEEE Micro 4 (1984)

Derek de Solla Price and the Antikythera Mechanism: An Appreciation



Derek de Solla Price
1922-1983

L. Robert Morris*
Carleton University and
DSPS Inc., Ottawa

Derek Price was born in Leyton, near London, England, in 1922. He was educated at the local state schools, where he displayed an early mathematical and scientific inclination derived in some measure from a diet of science fiction magazines. He received a bachelor's degree in physics and math from the University of London in 1942 and—in addition to pursuing wartime research into the optics of molten metals—taught and pursued thesis work toward a PhD in physics, also at the University of London. Price's postdoctoral work included publication of four papers—three in physics and one in math, a patent on an optical pyrometer, a year at Princeton, and three years of teaching at Raffles College, University of Malaya, Singapore.

In 1948, that university acquired a complete set of the *Philosophical Transactions of the Royal Society* covering the years 1665 through 1850. An unanticipated discovery concerning these volumes led Price to the formulation and publication, in 1950, of the law of exponential growth of scientific literature. Because the university library had not yet been built, Price had temporarily taken custody of the volumes. "I placed them into neat chronological piles against the bedroom wall," he recalled, ". . . [and] noticed that [they] made a beautiful exponential curve. . . ."

Price entered Cambridge in 1950 to embark upon study for a second doctorate—in the history of science. During his tenure there, he acted as honorary curator of the Whipple Museum of Antique Scientific Instruments and collaborated on a book on the history of medieval Chinese clockwork. (His thesis area was history of instruments.) One of his discoveries during this time was a holograph by Chaucer on the construction of a planetary calculating instrument. After completing his Cambridge PhD, Price consulted with a group at the Smithsonian Institution in the planning of their Museum of History and Technology.

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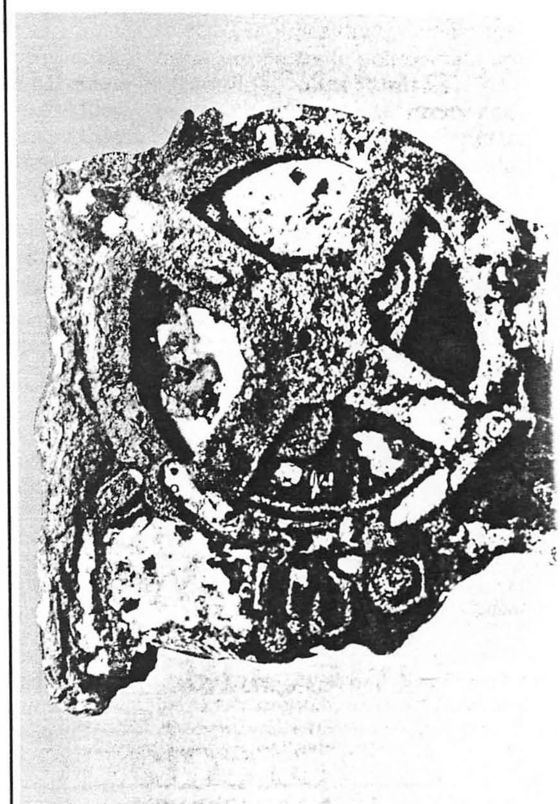
In June 1959, Price contributed the cover article, "An Ancient Greek Computer," to *Scientific American.*[1] He described, and attempted a preliminary reconstruction of, a mechanism—now in the National Archeological Museum in Athens—found by divers near the island of Antikythera, northwest of Crete, in 1900. "Corroded and crumbling from 2000 years under the sea, its dials, gear wheels, and inscribed plates present the historian with a tantalizing problem . . . [which may cause] revision of many of our estimates of Greek science," Price observed.

Price described the provenance of the device—how a party of Dodecanese sponge fishers had found the wreck of an ancient ship, some 200 feet down, before Easter 1900—and remarked that the calcified fragments of corroded bronze had originally been thought to be pieces of broken statuary. He justified the dating of the wreck to 65 BC and noted how the inscriptions had quickly identified the mechanism as an astronomical device.

The Antikythera mechanism consisted of a box about 16 × 32 × 9 centimeters in size, with dials on the outside and a very complex assembly of gear wheels inside. Doors hinged to the box served to protect the dials, and on the surfaces of the box, doors, and dials were Greek inscriptions describing the operation of the instrument. Price noted in the article that "nothing like this instrument is preserved elsewhere . . . [and] from all we know of science and technology in the Hellenistic age we should have felt that such a device could not exist." Although gears had appeared in other Greek devices, they had functioned simply as ratio changers. The 20 gear wheels of the Antikythera mechanism, ". . . including a very sophisticated assembly . . . mounted eccentrically on a turntable . . . [which] probably functioned as a sort of epicyclic or differential gear system . . . ," was unprecedented.

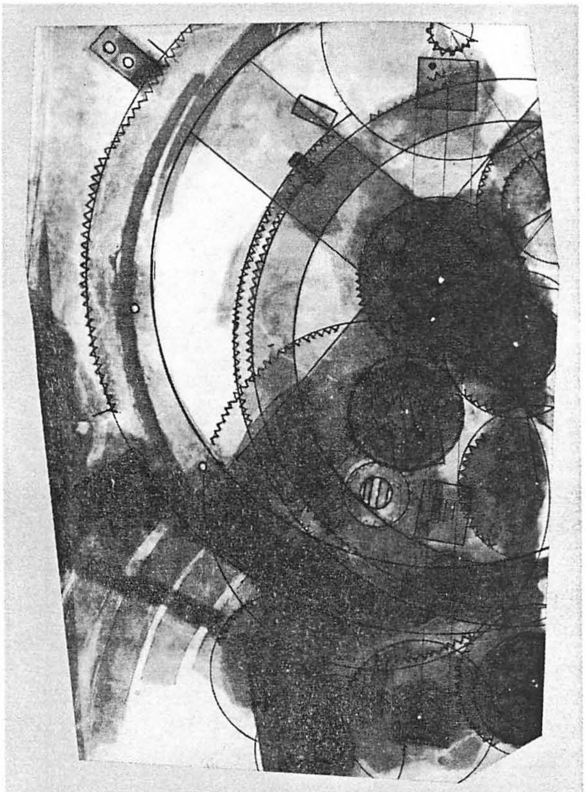
The system input was via a crown-gear wheel (see A in the figure on page 20) which moved a large, four-spoked driving wheel (B). This wheel in turn drove two trains of gears (E1-E5, K2-K1 and C1-C2, D1-D2, B4, $E2_i$-$E2_{ii}$), each of which eventually led to the "epicyclic" turntable (via J). A number of shafts rotated dial pointers such that when the input axle was turned, the pointers all moved at various speeds around their dials. There were three dials, one at the front of the case and two at the rear. The front dial displayed the signs of the zodiac on a fixed scale, and a movable slip ring showed the months of the year. Thus, Price suggested, this dial showed the annual motion of the sun in the zodiac and—indirectly—the risings and settings of bright stars and constellations throughout the year. The more complex rear dials comprised an upper dial with four slip rings and a lower dial with three slip rings. In the article, Price could only suggest that lunar phases and moonrise and set times might have been indicated on the lower dial and planetary risings and settings on the upper. He thought that the device could have been an analog representation of the heavens. He also noted that clocks started as astronomical showpieces that also happened to indicate the time and that eventually the timekeeping functions took over. Thus, he suggested, "the Antikythera mechanism is . . . the venerable progenitor of all of our present plethora of scientific hardware." Price later commented that

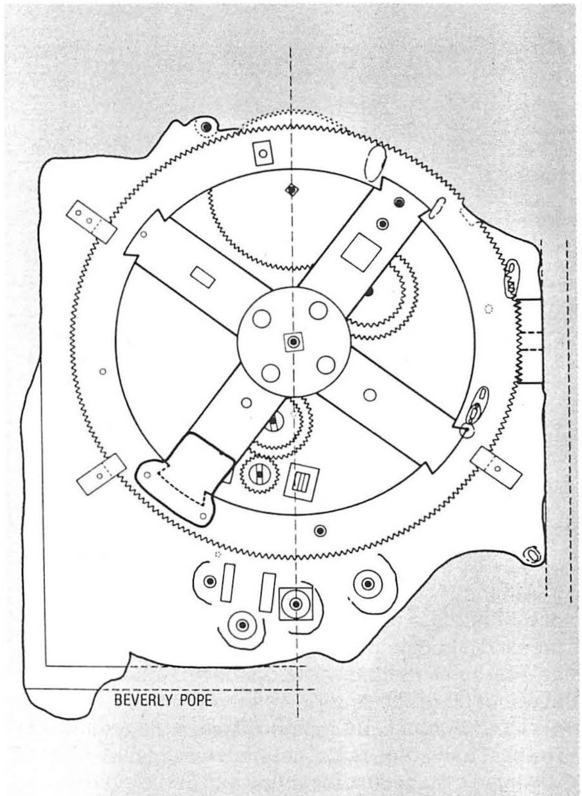


THE ANTIKYTHERA MECHANISM was recovered from t sea as a single corroded mass but broke into several fragments af drying out. The main fragment (left) shows the effects of two miller in salt water. It should be noted that the photo was taken *after* t fragment had been cleaned. Working with the cleaned fragmen Derek Price attempted a reconstruction of the mechanism. He w able to work out the joins of the fragments and deduce the gener

"there were some only too ready to believe that the con plexity of the device . . . put it so far beyond the sco of Hellenistic technology that it could only have bee designed and created by alien astronauts . . . visiting o civilization."

Even though the fragments of the machine had bee cleaned prior to Price's research in the 1950's, the corr sion and calcification had been so extensive that ar reconstruction beyond that described in the 1959 artic proved impossible. Then, in 1971, Price made breakthrough. He read that radiography could be use to see through the products of corrosion and calcific tion. With the aid of Dr. Ch. Karakalos, he was eve tually able to obtain a series of fine x-radiographs of t gears. The result was that the missing links in the ge trains were revealed, and Price could proceed with a mu more detailed reconstruction.[2] Especially important w the clarification of the structure of the differential tur table, which demonstrated that the Antikythe mechanism functioned as a *portable, solar/lunar cale drical analog computer*, certainly the first known cor puter (albeit fixed-program) in history. The function



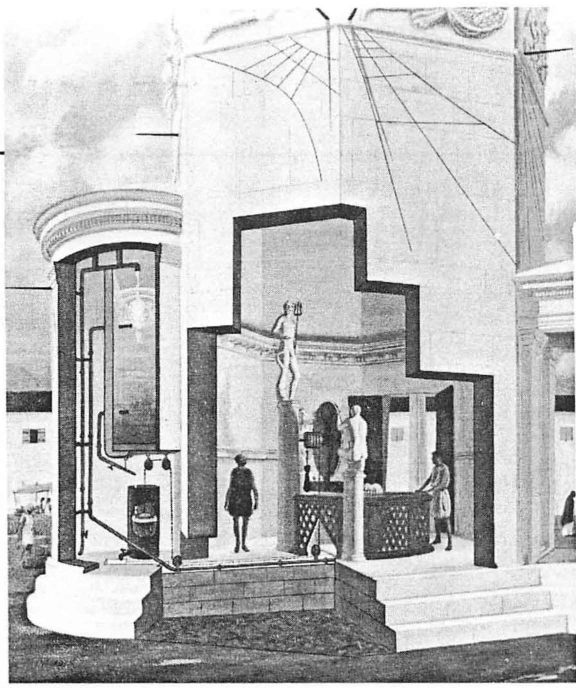


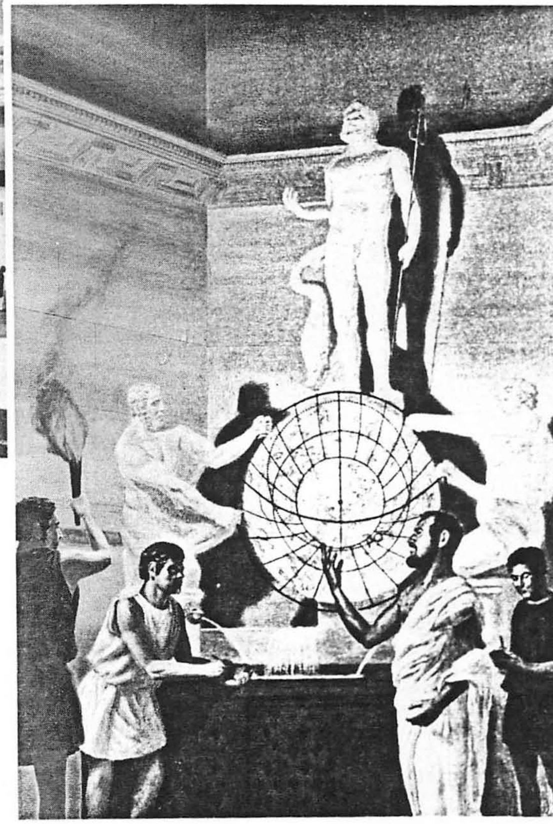
function of the machine but, because of the corrosion, could not obtain a detailed reconstruction. Later, he discovered that radiography provided a means to "see into" heavily corroded and calcified objects, and he arranged to have radiographs of the fragments made. The radiograph of the main fragment (center) shows the sort of structural detail that had been hidden. Here, wheels, gear teeth, pivots, and brackets were clear enough to be traced out in ink and later incorporated in a detailed schematic drawing (right). The structural information provided by the radiographs enabled Price to work out an almost-complete reconstruction and functional description of the mechanism. (Photo, radiograph, and drawing courtesy estate of Derek de Solla Price.)

the differential gear apparently was to compute the *difference* between the sidereal motions of the sun and moon against the backdrop of fixed stars and thereby derive a phase-of-moon indication. Thus, conventional ratio gear trains operating separately off the crown-gear yielded analog inputs to the differential turntable that were proportional to the sun and moon positions as seen from earth; the differential subtracted these inputs to yield the lunar phase. (When sun and moon have the same zodiacal position, then—regardless of their absolute positions—the moon is new; similarly, when sun and moon are 180 degrees apart, the moon is full.) Price concluded that "the differential turntable is certainly the most spectacular feature of the Antikythera device because of its extreme sophistication and lack of any historical precedent." He suggested that the mechanism is the earliest example of what we now term "high technology."

Derek de Solla Price was appointed Avalon Professor of the History of Science at Yale University in 1962. In addition to research into the history of scientific instruments and medieval astronomy, he worked in the areas of science policy, bibliometrics, and citation analysis. He published over three hundred papers and six books, including *Science Since Babylon* and *Little Science, Big Science.* He was the first President of the International Council for Science Policy Studies. In 1976, Price received the Leonardo da Vinci Medal, the major award of the Society for the History of Technology, and in 1981, the John Desmond Bernal Award, in recognition of outstanding contributions, given by the Society for Social Studies of Science. The Royal Swedish Academy of Sciences elected him a Foreign Member for Distinguished Service to Scientific Research in 1983.

Although Price's major contribution to the history of science (and computers) was his 20-year quest to illuminate the Antikythera mechanism, his work in establishing and analyzing the Science Citation Index (what he called "knowledge engineering") has been of more immediate impact. For example, his analysis of the output of researchers, showing that half the total output of papers in any discipline comes from a small elite of highly productive authors whose number is equal to ap-





The Tower of the Winds

Athens' Tower of the Winds, located in the Agora, or marketplace, near the Acropolis, is one of the best-preserved buildings of classical antiquity. Resembling an octagonal marble canister, the structure was built in about 50 BC by Andronicus Cyrrhestes, a Macedonian astronomer, during the Roman occupation of Greece. Each face is surmounted by a carved relief of a winged demigod representing one of the eight winds; a sundial customized for each side's orientation was located beneath the carving. The roof was topped by a bronze wind vane—in the form of Triton, son of Poseidon—which pointed to the image of the wind that was blowing.

It was the Greeks' belief in the existence of the eight winds and in the octagonal symmetry of the universe that *dictated* the structure's form.

Inside the tower was a *horologion,* or hour indicator, powered by a constant-pressure water source. The power source was reset each day by draining a tank. The centerpiece of the mechanism was an engraved bronze disc which effected a model of the heavens by revolving clockwise behind a stationary grid of hour lines. Engraved upon the disk were mythological figures of the constellations, including the signs of the zodiac. An ellipse of perforations on the disc traced the apparent annual solar path through the heavens—the ecliptic—and a sun marker was manually moved along the perforations to indicate the solar position in the heavens on the current day. The clock's "hour hand" was thus the solar image, whose position relative to the grid was constantly changed by the water-controlled mechanism driving the disc. The exhibition was overseen by a trident-bearing statue of Poseidon.

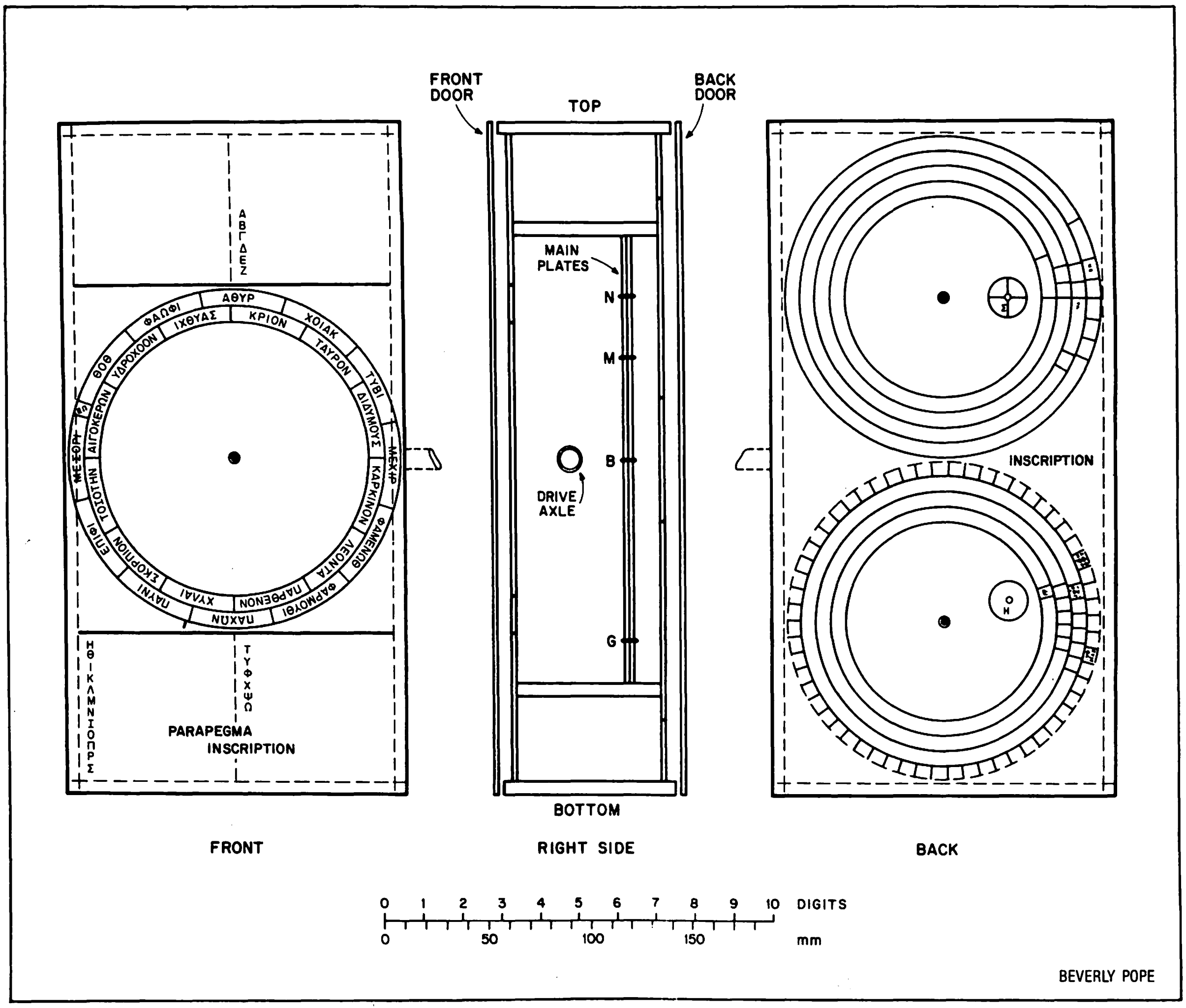
The tower showed the time via the sundials and the horologion, and the date via the length of the shadows on the sundial faces. It thus served as both clock and calendar.

—*L. Robert Morris*

proximately the square root of the entire group, seems to be an inviolable law of technical literature.[3] And his recent contention that the Babylonians were the first "programmers," that their tablets of mathematical astronomy read exactly like a computer program printout, promises further revelations of ancient technical sophistication.[4]

One other of Price's projects deserves note. He reconstructed an ancient Greek water clock that had been housed in Athens' Tower of the Winds, an extremely well-preserved structure dating from about 50 BC. (The tower features prominently on this issue's cover—see also the interior views, above.) Under a grant from the National Geographic Society, Price and his fellow researcher, Joseph V. Noble of the Metropolitan Museum of Art, deduced the general plan of the clock from the grooves, holes, and stains its fittings had left in the tower's floor. The project was "akin to re-creating the workings of a suburban kitchen in an empty room, using the relative positions of electric sockets, pipe holes, and rectangular floor stains as evidence," Price remarked in a *National Geographic* article describing the work.[5]

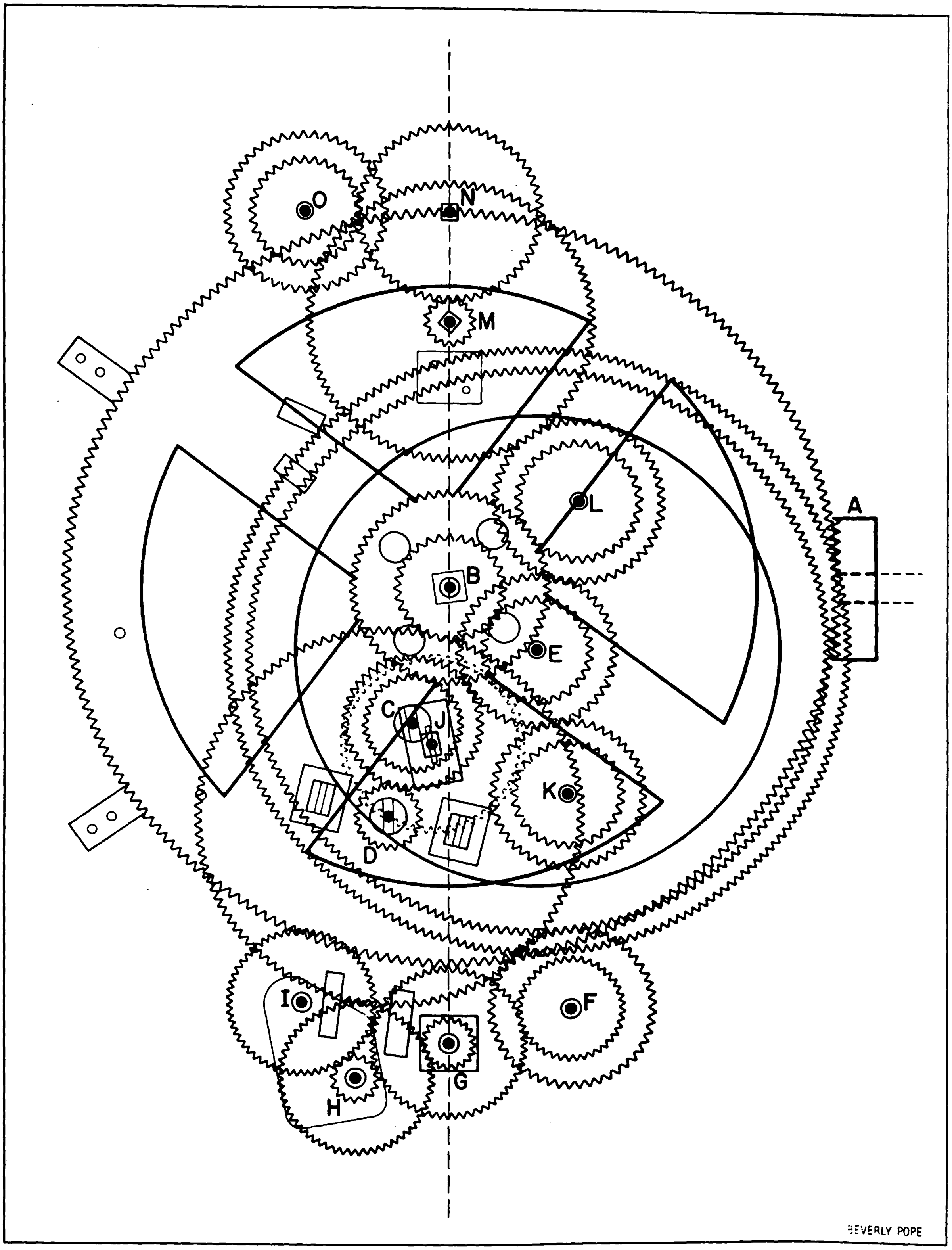
I first contacted Derek Price in 1978 to obtain permission to use a diagram of the Antikythera mechanism's



RECONSTRUCTION OF THE DIAL PLATES AND CASING of the Antikythera mechanism shows the dimensions of the original device—about 6.5 × 12.5 × 3.5 inches. The instrument was designed to be held or stood vertically and operated with a crank. The dial plates and internal gearing were made of bronze; the casing, of which very little has survived, was constructed of wood. Door plates covered the front and rear dial plates—both the door and dial plates bore inscriptions containing information used in the operation of the device. The front dial consisted of a fixed inner ring with 12 divisions for the 12 constellations of the zodiac and a movable outer ring with divisions for the months of the year. A marker was attached to the dial to indicate the place in the year. Thus, the dial showed the annual motion of the sun in the zodiac and—indirectly—the risings and settings of bright stars and constellations throughout the year. The back dials comprised an upper dial with four movable rings and a lower dial with three movable rings. The upper dial indicated risings and settings of planets; the lower dial provided a phase-of-moon indication and moonrise and set times. The side view shows four pivots, N, M, B, and G, which correspond to the pivots indicated in the figure on page 20. (Drawing courtesy estate of Derek de Solla Price.)

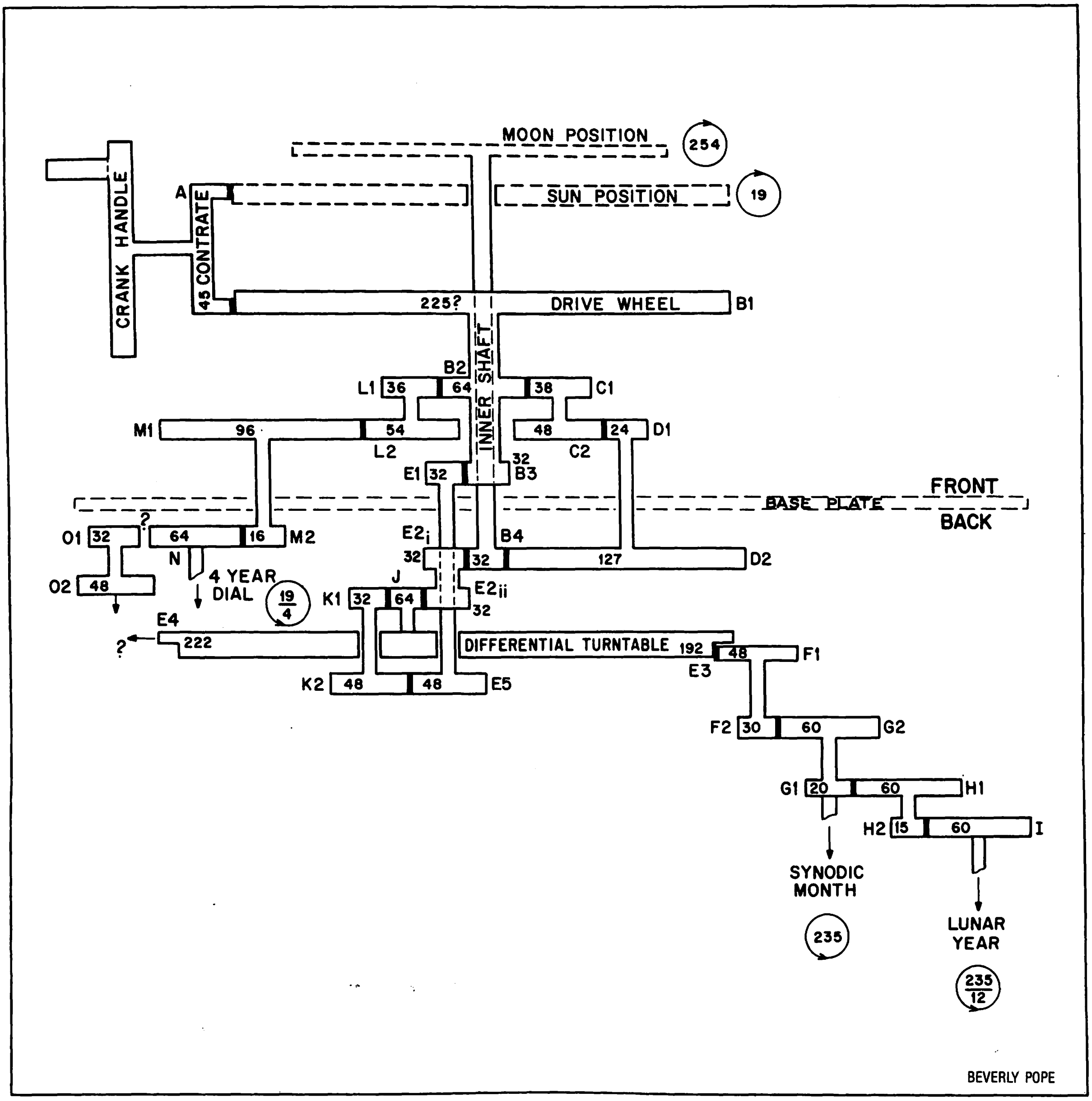
gears on the cover of a minicomputer system text I had coauthored.[6] My editor at first protested, maintaining that this would suggest a mechanical engineering text, but I noted that the Antikythera mechanism, besides being the first computer, was also a minicomputer. (The dimensions of the Antikythera cabinet were remarkably close to those of the TRS-80 Model 100 Portable Computer!) Also, using a block diagram compiler, ANIM8, I had constructed an animated version of the gears for a stroke-vector graphics system. (Price had a mechanical reconstruction on his desk.) I spoke to Derek Price again early in 1983, asking if he would be willing to write an article for *IEEE Micro*. He then revealed the existence of the article we are presenting here, hitherto unpublished and his first (and only) for a computer-related journal. When I asked him why the Antikythera mechanism was not more prominent in the article, he said that most people were fairly familiar with it. This is obviously not the case in the computer area, and we hope that this note and his article will help remedy the situation.

During a recent holiday in Greece, my wife and I made a point to visit the Athens museum, only to find the gears hidden from public view due to gallery renovations. With special permission, we were able to view the fragments of the world's first known computing mechanism. Upon our return to Canada, I immediately phoned Price's office, hoping to persuade him to spearhead an attempt to convince the Greek government to allow the "dormant" gears to be put on show temporarily in the new Massachusetts computer museum. I then learned that Derek de Solla Price had died suddenly while visiting family in England, on September 3, 1983. With his pass-



GENERAL PLAN OF ALL GEARING illustrates the complexity of the Antikythera mechanism and the detailed nature of Price's final reconstruction. The part labeled "A" was a crown, or contrate, wheel that was attached to the crank; it engaged the main drive wheel at a right angle. (Drawing courtesy estate of Derek de Solla Price.)

ing, we lose an original contributor to the history of calculating machines. In this, the IEEE's centennial year, it is particularly appropriate to consider the twin threads of mathematics and craftsmanship that tie us to the machine designers and builders of centuries past. And it is particularly fortunate that in these pages we have Professor Price—scientist, historian, decipherer of ancient machines—to trace those threads for us. ■



SECTIONAL DIAGRAM OF THE GEARING SYSTEM shows the relationships among the various gear trains. The contrate wheel and crank are at upper left; the main drive wheel is at upper center and is labeled "B1." The number inside the diagram of each wheel indicates the number of gear teeth on that wheel—45 for the contrate, for example. (Drawing courtesy estate of Derek de Solla Price.)

Acknowledgments

Publication of Price's manuscript would not have been possible without the cooperation of Ann Leskowitz, administrative assistant in the Department of the History of Science at Yale University. We are also indebted to a number of individuals who assisted us in obtaining the illustrations used in Price's article—these include Roderick and Marjorie Webster, curators of the History of Astronomy Collections of the Adler Planetarium, Chicago; Uta Merzbach, curator of the Division of Mathematics of the Smithsonian Institution, Washington; Robert E. Pokorak of the IBM Archives, Armonk, New York; and Barbara Shattuck of the National Geographic Society, Washington.

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