The story of π

Robin Wilson

3·14159265358979...

'Tis a favourite project of mine
A new value of π to assign.
I would fix it at 3
For it's simpler, you see,
Than 3·14159...

What is π ?

π is :

- the ratio of the circumference of a circle to its diameter

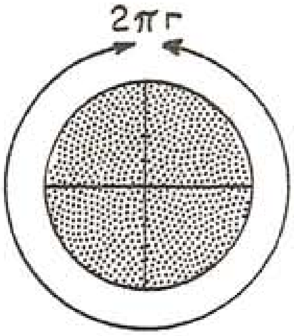
$$C = \pi d = 2\pi r \quad (r = \text{radius})$$

- the area of a circle of radius 1

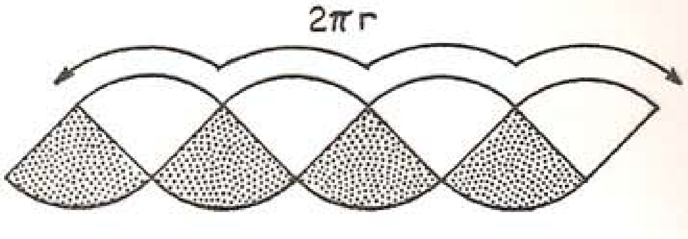
$$A = \pi r^2 = \pi . 1^2 = \pi$$


LET'S SEE... I THINK THE ANSWER IS πr^2
THAT'S INCORRECT.
WHY ??
YOU SAID "PIE ARE SQUARED." WELL, PIES **AREN'T** SQUARED!
ALSO, IT'S BAD GRAMMAR!
THE CORRECT ANSWER IS "PIE IS ROUND"
LOOK, RALPH, "THE FLINTSTONES" IS ON!
11-5

From $2\pi r$ to πr^2

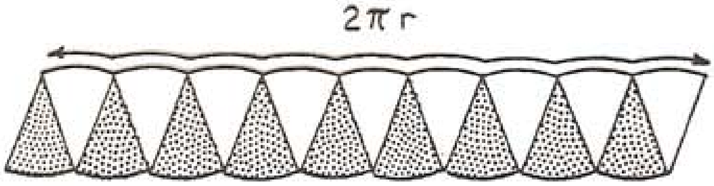


(a)



(b)

(c)



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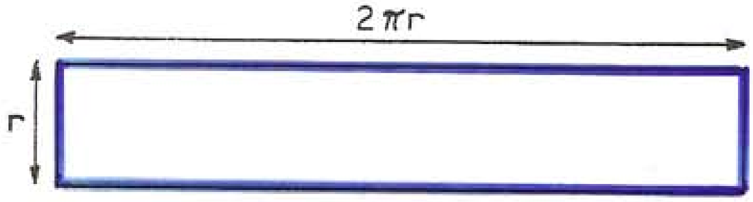


與寄左相消得開方式

三乘方開之得推前術得合

圖解

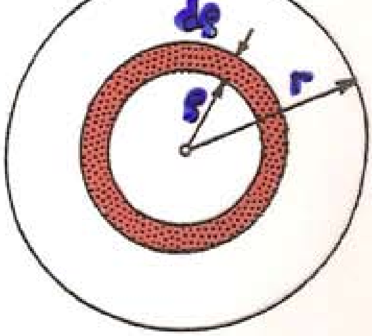
變形

上ノ圓積ノ内ニ黒積十六白積十六共ニ三十二アリ下ノ変形ノ内ニモ黒積十六白積共ニ三十二アリ此故ニ上下トモニ積相同シ

又変形ヲ見ルニ半円径ト半円周ト相乘ナリ故ニ円径ト円周乗スレハ変形ノ積四段ナリ則円積四段ト同シ

今有方錐積三十六歩只云方面長於竪二

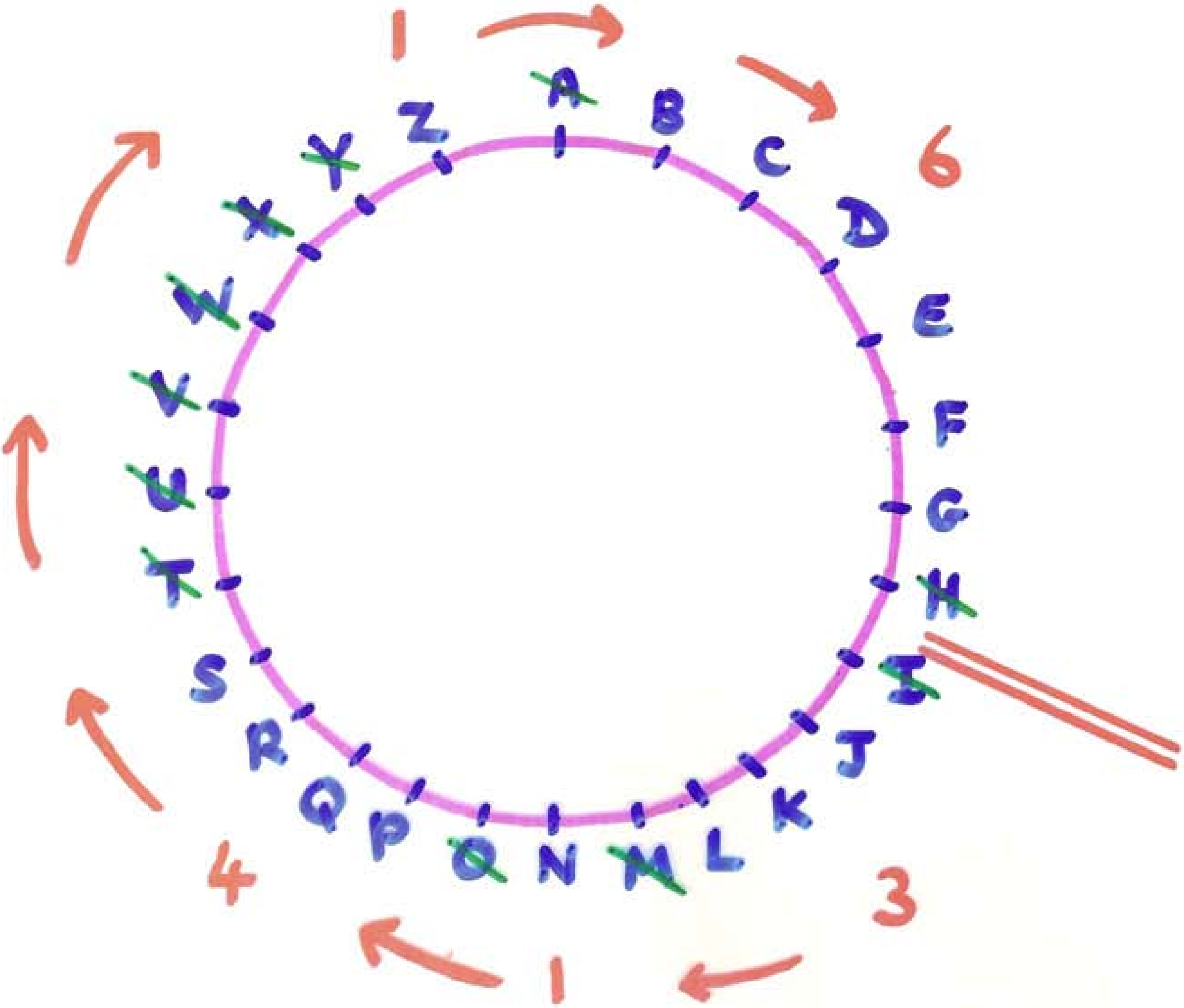
方面竪各幾何



Area $=$

$$\int_0^r 2\pi\rho \, d\rho = \pi r^2$$

An alphabetical method



How I wish I could calculate pi !

May I have a large container of coffee.

3 · 1 4 1 5 9 2 6 ...

How I need a drink, alcoholic of course, after all these lectures informing Gresham audiences...

3·14159265358979...

ἀει ὁ Θεος ὁ Μεγας γεωμετρει / το κυκλου μηκος ἱνα ὁριση διαμετρω / παρηγαγεν ἀριθμον ἀπεραντον / και ὁν φευ οὐδεποτε ὁλον / θνητοι θα εὑρωσι.

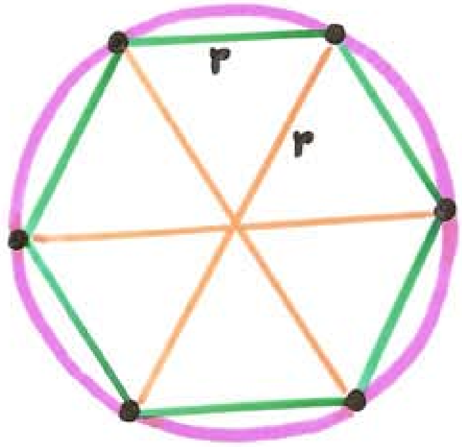
3·14159265358979323846 26...

For

a time I stood pondering on circle sizes. The large
computer mainframe quietly processed all of its assembly code.
Inside my entire hope lay for figuring out an elusive expansion. Value: pi.
Decimals expected soon. I nervously entered a format procedure. The mainframe
processed the request. Error. I, again entering it, carefully retyped. This iteration gave
zero error printouts in all—success. Intently I waited. Soon, roused by thoughts within me,
appeared narrative mnemonics relating digits to verbiage! The idea appeared to exist but only in
abbreviated fashion—little phrases typically. Pressing on I then resolved, deciding firmly about a
sum of decimals to use—likely around four hundred, presuming the computer code soon halted!
Pondering these ideas, words appealed to me. But a problem of zeros did exist. Pondering more, solution
subsequently appeared. Zero suggests a punctuation element. Very novel! My thoughts were culminated.
No periods, I concluded. All residual marks of punctuation = zeros. First digit expansion answer then came
before me. On examining some problems unhappily arose. That imbecilic bug! The printout I possessed
showed four nine as foremost decimals. Manifestly troubling. Totally every number looked wrong. Repairing
the bug took much effort. A pi mnemonic with letters truly seemed good. Counting of all the letters probably
should suffice. Reaching for a record would be helpful. Consequently, I continued, expecting a good final
answer from computer. First number slowly displayed on the flat screen—3. Good. Trailing digits appar-
ently were right also. Now my memory scheme must probably be implementable. The technique was
chosen, elegant in scheme: by self reference a tale mnemonically helpful was ensured. An able title
suddenly existed—"Circle Digits." Taking pen I began. Words emanated uneasily. I desired more
synonyms. Speedily I found my (alongside me) Thesaurus. Rogets is probably an essential in
doing this, instantly I decided. I wrote and erased more. The Rogets clearly assisted
immensely. My story proceeded (how lovely!) faultlessly. The end, above all,
would soon joyfully overtake. So, this memory helper story is incon-
testably complete. Soon I will locate publisher. There a narrative
will I trust immediately appear, producing fame.

The end.

Mesopotamian Value of π (c. 1800 BC)

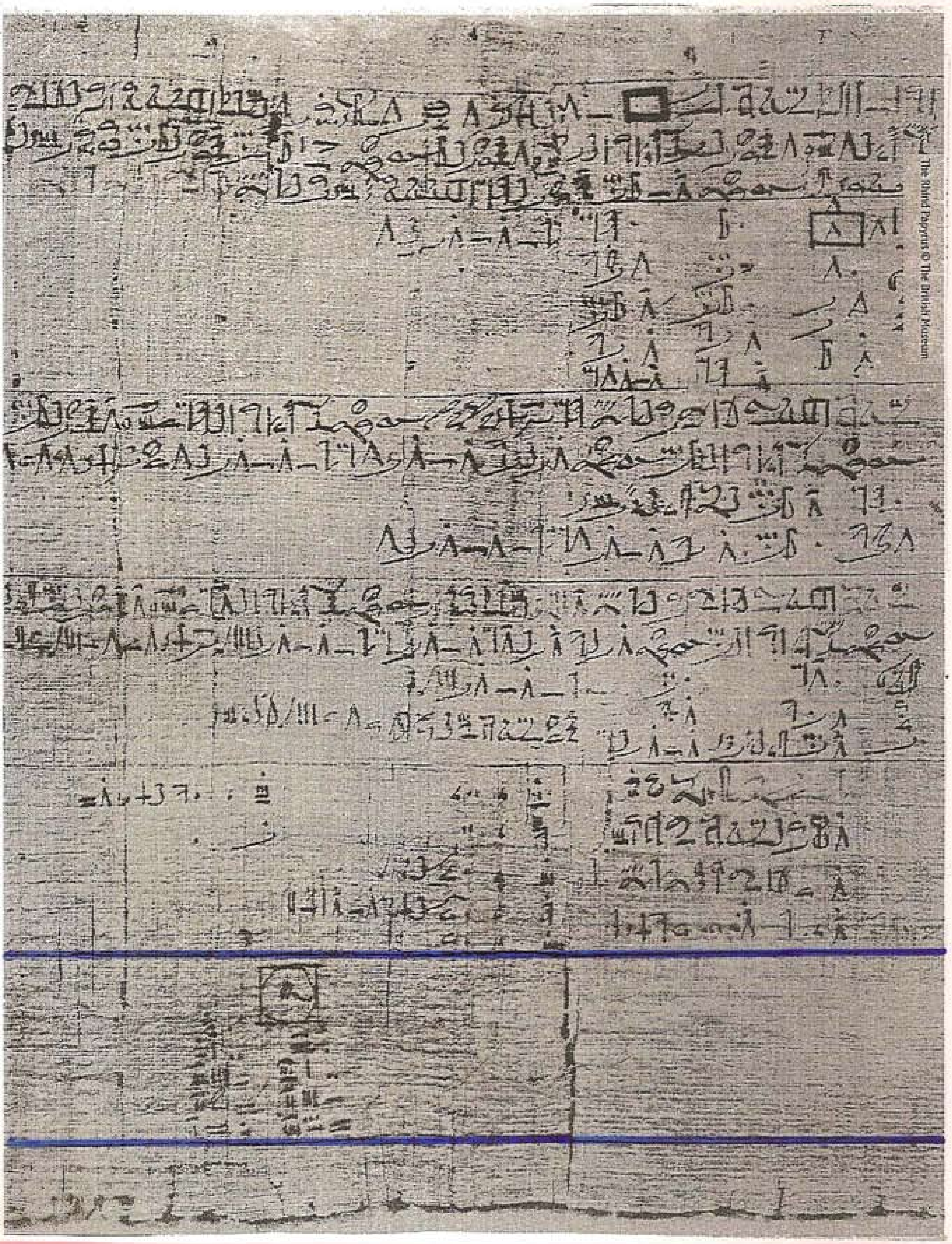


ratio of perimeter of hexagon to circumference of circle = 0; 57, 36 :

$$\frac{6r}{2\pi r} = \frac{3}{\pi} = \frac{57}{60} + \frac{36}{(60)^2}$$

so $\pi = 3\frac{1}{8} = 3.125$

Egyptian Rhind Papyrus

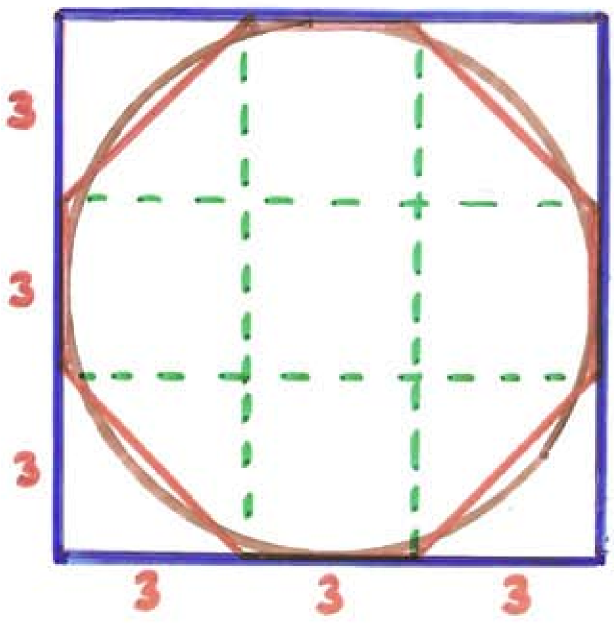


A Problem in Geometry (c. 1650 BC)

Problem 48. Compare the area of a circle and its circumscribing square.

The circle of diameter 9	
1	8 setat
2	16 setat
4	32 setat
8	64 setat

The square of side 9	
1	9 setat
2	18 setat
4	36 setat
8	72 setat
Total	81 setat



$$\text{Area} = \left(d - \frac{d}{9}\right)^2$$

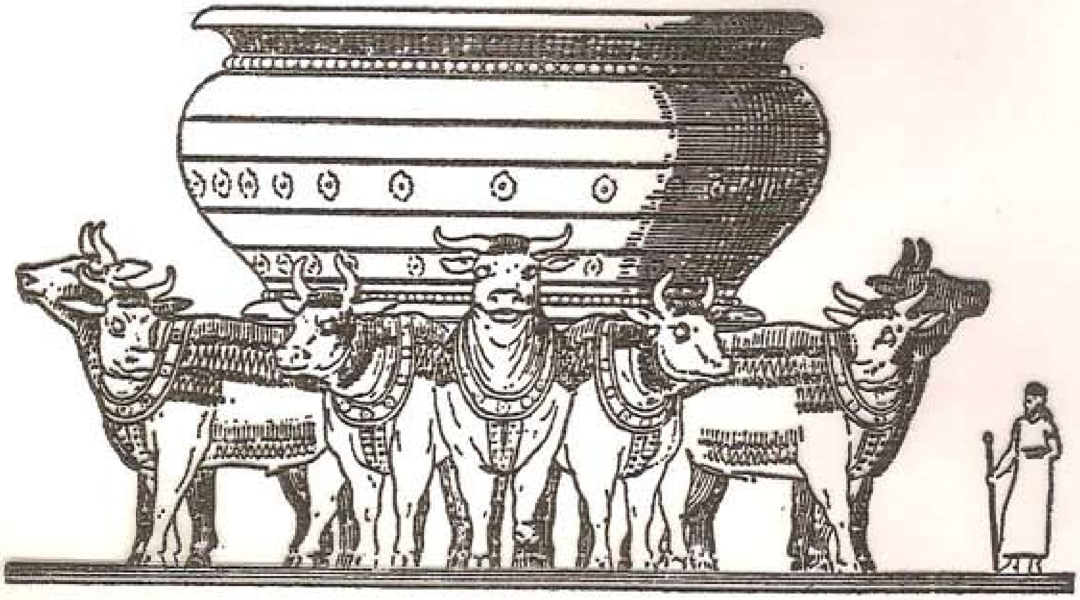
$$= \frac{256}{81} r^2 \simeq 3{\cdot}16\, r^2$$

The Biblical Value (c. 550 BC)

I Kings VII, 23 and II Chronicles IV, 2:

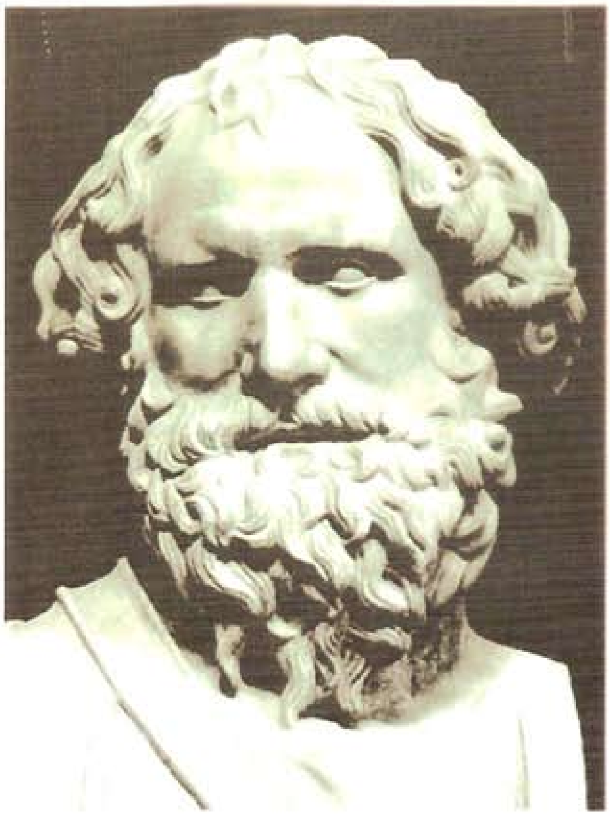
Also, he made a molten sea of ten cubits from brim to brim, round in compass, and five cubits the height thereof; and a line of thirty cubits did compass it round about.

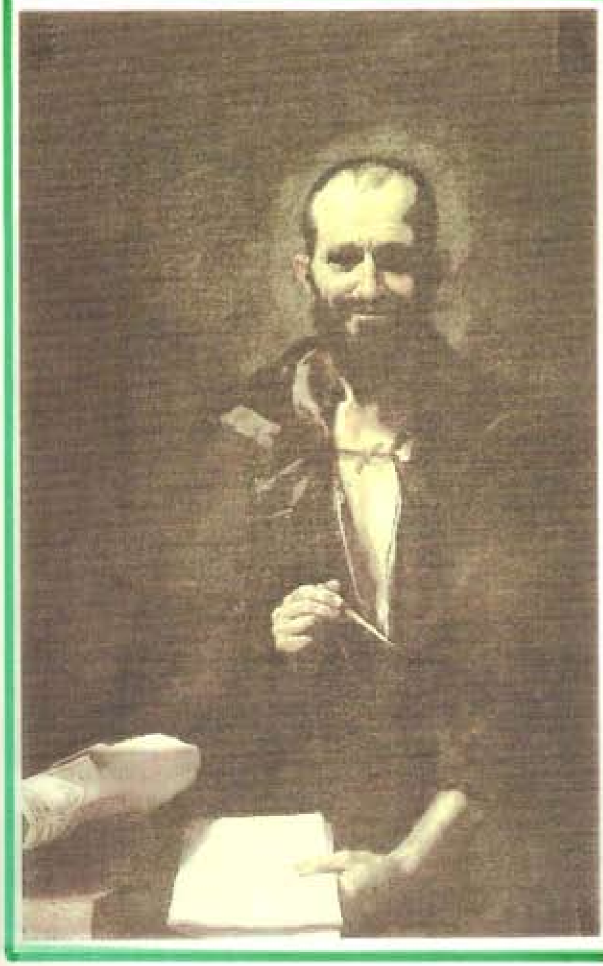
So $\pi = 30/10 = 3$.

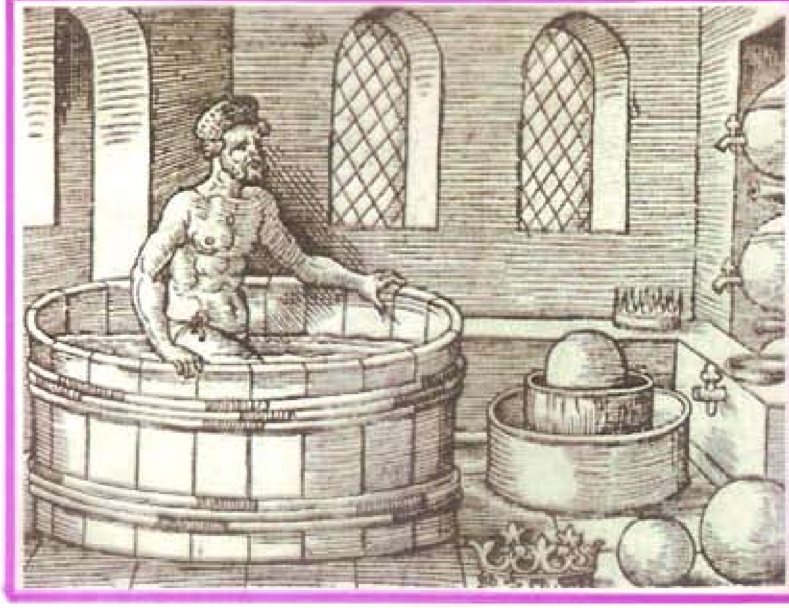


Archimedes

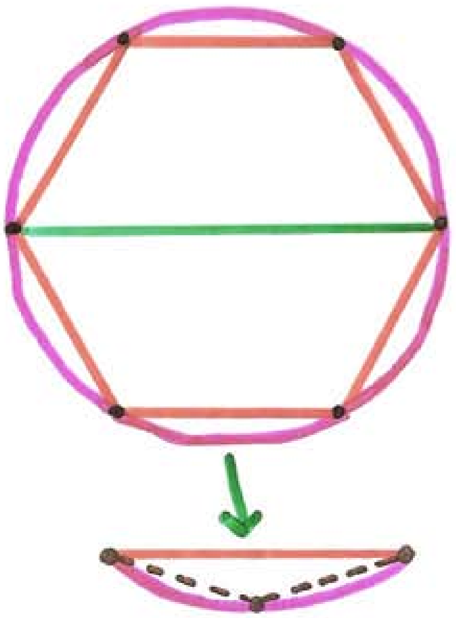
(c. 287 - 212 BC)







The Value of π



perimeter of inscribed 6-gon

< circumference of circle

< perimeter of exscribed 6-gon

double the number of sides:

6, 12, 24, 48, 96.

Archimedes obtained the estimates:

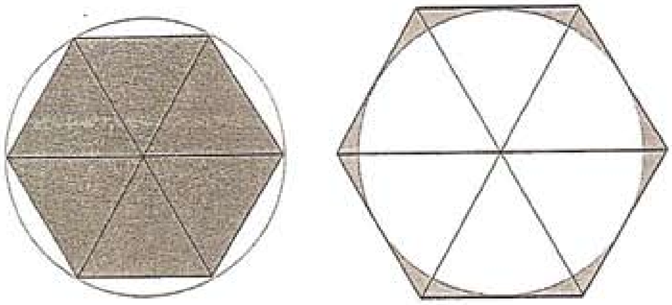
$$3\tfrac{10}{71} < \pi < 3\tfrac{1}{7}$$

3.14084 3.14286

Archimedes' polygons

semi-perimeters

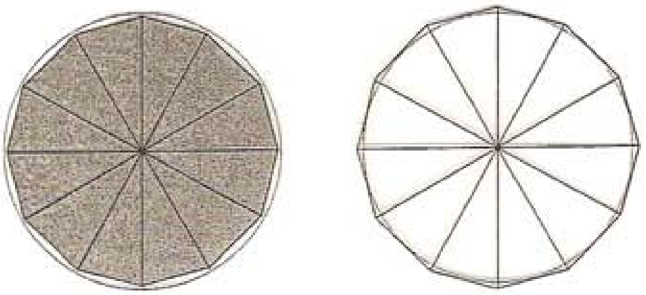
$n = 6$



$l = 3$

$L = 3.464$

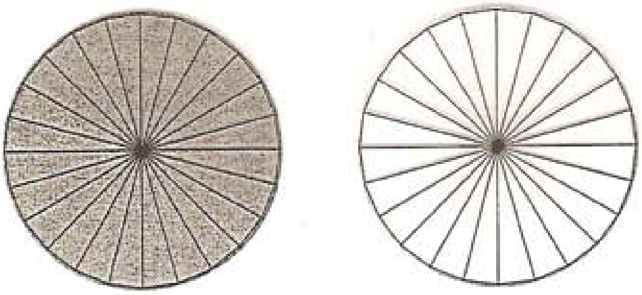
$n = 12$



$l = 3.105$

$L = 3.215$

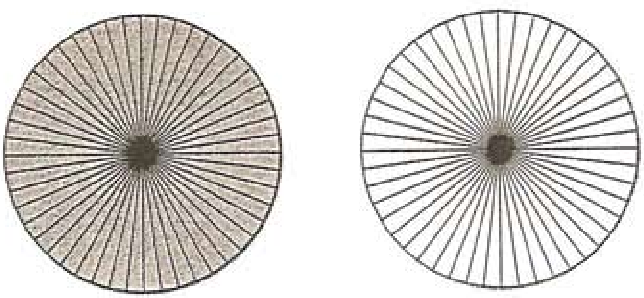
$n = 24$



$l = 3.133$

$L = 3.160$

$n = 48$



$l = 3.139$

$L = 3.146$

Indian values for π

380 AD : $3\frac{177}{1250} = 3.1416\ldots$

Aryabhata (499 AD) :

Add 4 to 100, multiply by 8, and add 62,000.
The result is approximately the circumference of a circle with diameter 20,000.

So $\pi = 62832 \div 20000 = 3.1416$.

Brahmagupta (6th c.) :

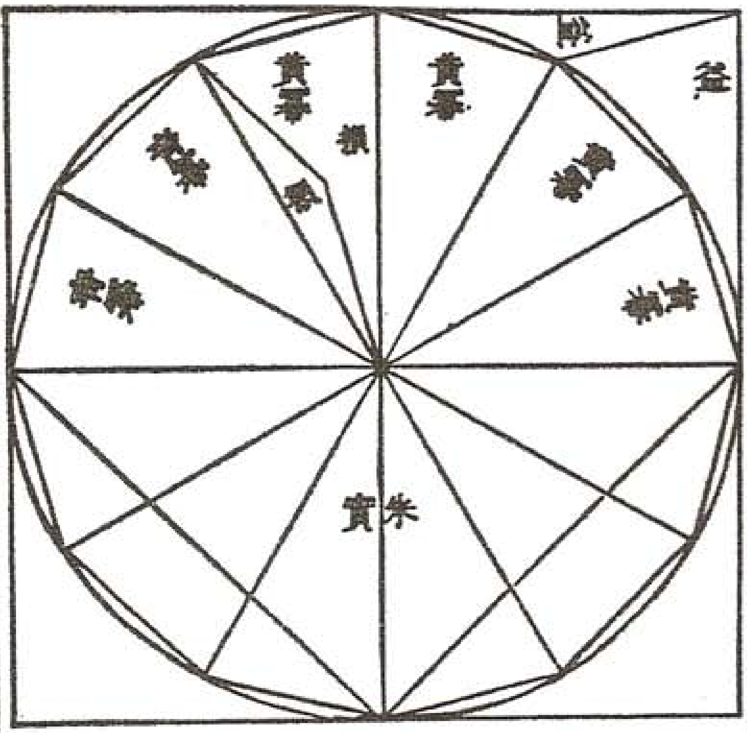
$\pi \sim \sqrt{10} = 3.162\ldots$

Chinese Values for π

訂訛補圖　　微波榭

得徑七周二十二乃祖氏之約率非密率也淳風等以為密率失其實矣徽率與祖氏之約率相較則徽率密於約率

弧田圖



據注意取半圓驗之黃冪令損益相補適滿大方四分之一則青冪適八分之一也合青黃冪為半外方四分之三朱實與黃冪相等舊以十觚之冪為圓冪又以半圓論弧矢立法之疎顯然

Zhang Heng (100 AD): $\pi = \sqrt{10}$

Liu Hui (263 AD): $\pi = 3.14159$ 　　3072

Zu Changzhi (500 AD): $\pi = 3.1415926$ 　　24576

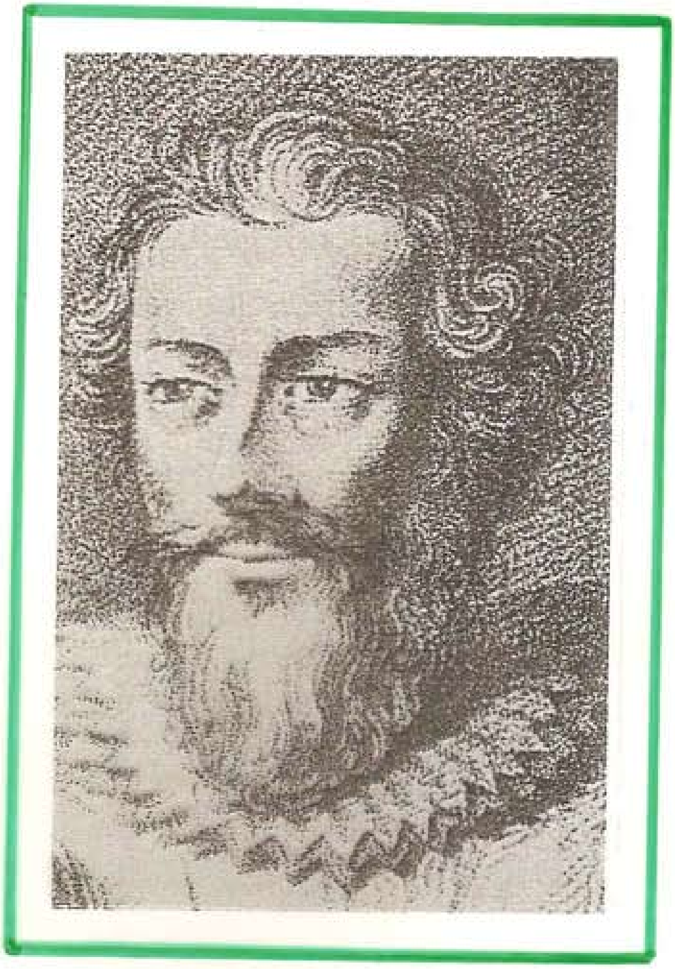
and $\pi \sim 355/113$

Using polygons

Fibonacci (Italy, 1200)	$\pi = 3.141818$	96 sides
al-Kashi (Samarkand, 1430)	14 decimal places	
A. Anthoniszoon (Dutch, 16c.)	$335/113$ ($377/120 > \pi > 333/106$)	
A. van Roomen (Dutch, 1593)	15 decimal places	100 million sides
François Viète	9 decimal places	393216 sides
Ludolph van Ceulen (Dutch 1596, 1615)	20 d.p. 35 d.p.	60×2^{29} sides

FRANÇOIS VIÈTE

(1540 - 1603)



- pioneered improvement in notation – use of letters for unknowns

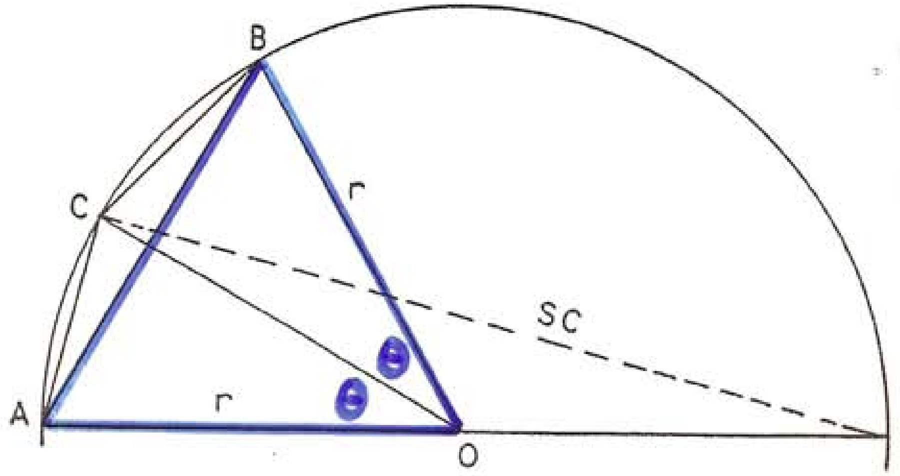
- insisted on 'dimension': e.g. cannot add lines to areas

- computed π to 9 decimal places

- $$\frac{2}{\pi} = \cos\frac{\pi}{4} \cdot \cos\frac{\pi}{8} \cdot \cos\frac{\pi}{16} \cdot \cos\frac{\pi}{32} \cdots$$

$$= \frac{1}{2}\sqrt{2} \times \frac{1}{2}\sqrt{(2+\sqrt{2})} \times \frac{1}{2}\sqrt{2+\sqrt{(2+\sqrt{2})}} \times \cdots$$

Viète's method



A(n) = area of n-sided polygon

$$A(n) = n \times \text{area}(OAB) = n \cdot \tfrac{1}{2} r^2 \sin 2\theta$$

$2\sin\theta\cos\theta$

$$A(2n) = 2n \cdot \tfrac{1}{2} r^2 \sin\theta$$

So $A(n) / A(2n) = \cos\theta$

Also $A(n) / A(4n) = \dfrac{A(n)}{A(2n)} \times \dfrac{A(2n)}{A(4n)}$

$$= \cos\theta \cdot \cos \theta/2$$

$$\frac{A(n)}{A(2^k n)} = \cos\theta \cdot \cos\theta/2 \cdot \cdots \cdot \cos\theta/2^k$$

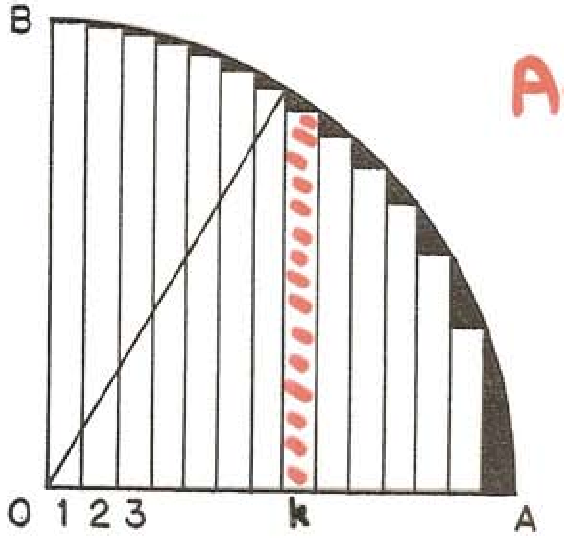
$\downarrow$

πr^2

$n = 4 \quad \theta = 45^\circ, \cos\theta = 1/\sqrt{2}$

$A(4) = 2r^2 \ \ldots$

John Wallis's formula (1655)



Area of kth strip is

$$\frac{1}{n}\sqrt{1-\left(\frac{k}{n}\right)^2}$$

So $$\frac{\pi}{4} = \lim_{n\to\infty} \sum_{k=0}^{n} \frac{1}{n}\sqrt{1-(k/n)^2}$$

$$\frac{\pi}{4} = \int_0^1 \sqrt{1-x^2}\,dx$$

Leading to:

$$\boxed{\frac{\pi}{4} = \frac{2.4.4.6.6.8.\cdots}{3\;3.5.5.7.7.\cdots}}$$

Continued fractions

$$\frac{4}{\pi} = 1 + \cfrac{1^2}{2 + \cfrac{3^2}{2 + \cfrac{5^2}{2 + \cfrac{7^2}{2 + \cfrac{9^2}{2 + \cdots}}}}}$$

W. Brouncker (1660s)

$$1, \frac{3}{2}, \frac{15}{13}, \frac{105}{76}, \frac{945}{789}, \ldots$$

$$\pi = 3 + \cfrac{1}{7 + \cfrac{1}{15 + \cfrac{1}{1 + \cfrac{1}{292 + \cfrac{1}{1 + \cfrac{1}{1 + \cdots}}}}}}$$

J. Lambert (1767)

$$3, \frac{22}{7}, \frac{333}{106}, \frac{355}{113}, \frac{103993}{33102}, \ldots$$

π is irrational (not a fraction)

Johann Heinrich Lambert (1767)

If x is a rational number (other than 0), then $\tan x$ cannot be rational.

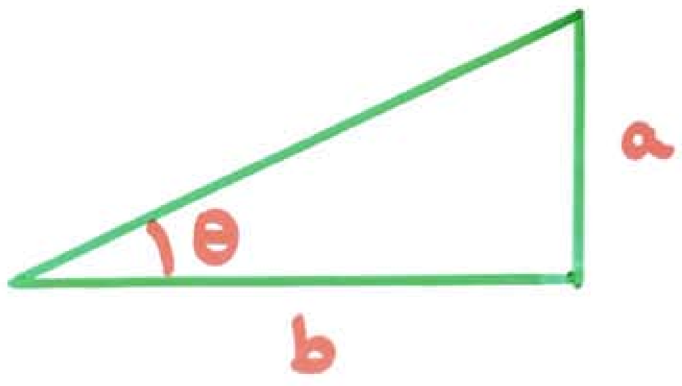
So:

If $\tan x$ is rational, then x must be irrational (or 0).

But $\tan(\pi/4) = 1$, which is rational:

so $\pi/4$ (and hence π) is irrational.

The $\tan^{-1}$ function

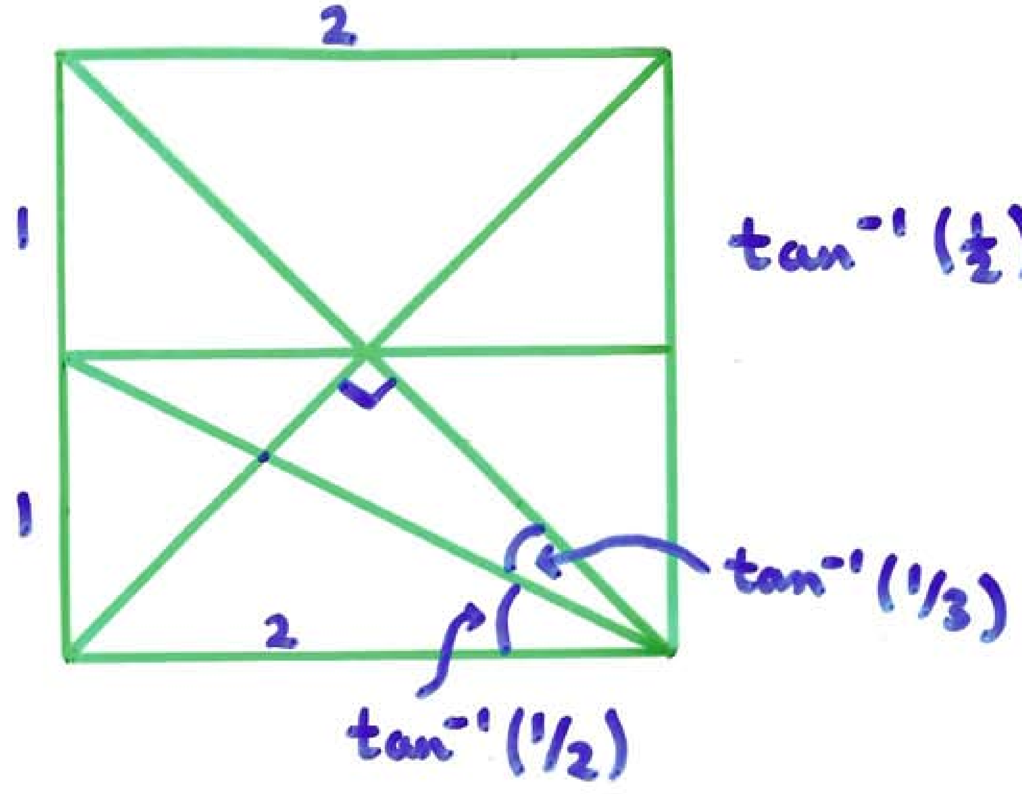


$\tan\theta = a/b$

$\theta = \tan^{-1}(a/b)$

$\tan \pi/4 = 1$, so $\tan^{-1}(1) = \pi/4$

$\tan \pi/6 = 1/\sqrt{3}$, so $\tan^{-1}(1/\sqrt{3}) = \pi/6$



$\tan^{-1}(\frac{1}{2}) + \tan^{-1}(1/3)$

$= \pi/4$

$$\boxed{\tan^{-1}x + \tan^{-1}y = \tan^{-1}\left(\frac{x+y}{1-xy}\right)}$$

The series for $\tan^{-1} x$

$$\tan^{-1} x = x - \frac{x^3}{3} + \frac{x^5}{5} - \frac{x^7}{7} + \cdots$$

(J. Gregory)

so, with $x = 1$:

$$\pi/4 = 1 - \frac{1}{3} + \frac{1}{5} - \frac{1}{7} + \cdots \qquad \text{(Leibniz)}$$

This converges very slowly: 300 terms for two decimal digits of π.

$$\frac{\pi}{4} = \tan^{-1}\left(\frac{1}{2}\right) + \tan^{-1}\left(\frac{1}{3}\right)$$

$$= \left\{ \frac{1}{2} - \frac{(1/2)^3}{3} + \frac{(1/2)^5}{5} - \frac{(1/2)^7}{7} + \cdots \right\}$$

$$+ \left\{ \frac{1}{3} - \frac{(1/3)^3}{3} + \frac{(1/3)^5}{5} - \frac{(1/3)^7}{7} + \cdots \right\}$$

which converges much faster.

Better series ...

$$\frac{\pi}{4} = 4\tan^{-1}\left(\frac{1}{5}\right) - \tan^{-1}\left(\frac{1}{239}\right)$$ John Machin (1706)

$$= 4\left\{\frac{1}{5} - \frac{(1/5)^3}{3} + \frac{(1/5)^5}{5} - \dots\right\}$$

$$- \left\{\frac{1}{239} - \frac{(1/239)^3}{3} + \frac{(1/239)^5}{5} - \dots\right\}$$

100 places

Euler (1764)

$$\frac{\pi}{4} = 4\tan^{-1}\left(\frac{1}{5}\right) - \tan^{-1}\left(\frac{1}{70}\right) + \tan^{-1}\left(\frac{1}{99}\right)$$

200

Loney (1893)

$$\frac{\pi}{4} = 3\tan^{-1}\left(\frac{1}{4}\right) + \tan^{-1}\left(\frac{1}{20}\right) + \tan^{-1}\left(\frac{1}{1985}\right)$$

528

Gauss

$$\frac{\pi}{4} = 12\tan^{-1}\left(\frac{1}{18}\right) + 8\tan^{-1}\left(\frac{1}{57}\right) - 5\tan^{-1}\left(\frac{1}{239}\right)$$

1000000

New values for π

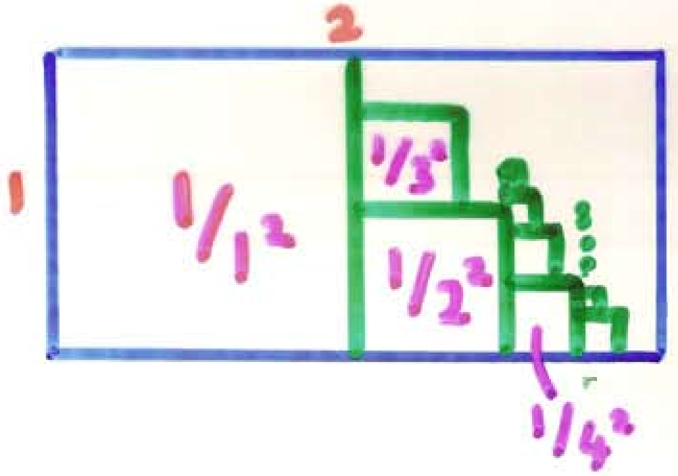
1706	Machin	100 places
1719	De Lagny	127 places
1794	Vega	140 places
1855	Richter	500 places
1874	Shanks	707 places (wrong from 527th ...)
1946/7	Ferguson	808 places

Euler's Basel Problem (1730)

What is the value of :

$$1 + \frac{1}{4} + \frac{1}{9} + \frac{1}{16} + \cdots \quad ?$$

$$\left[\frac{1}{1^2} + \frac{1}{2^2} + \frac{1}{3^2} + \frac{1}{4^2} + \cdots\right]$$



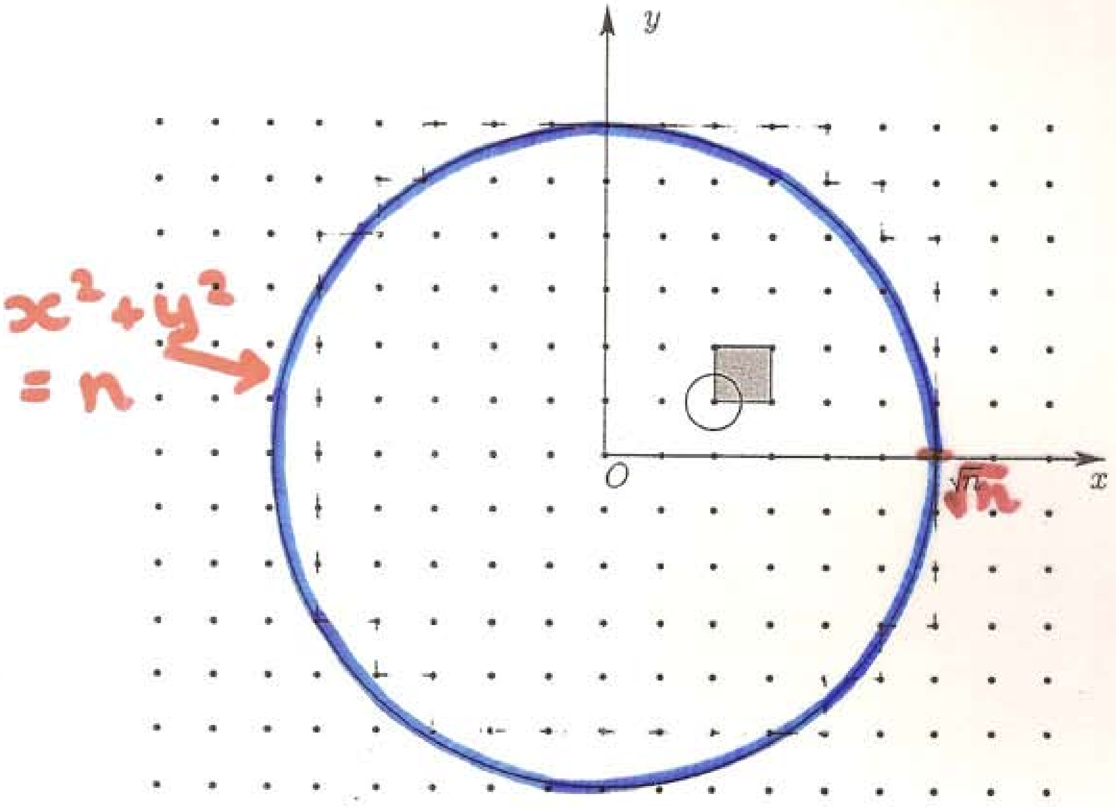
answer is less than 2

$$\frac{1}{1^2} + \frac{1}{2^2} + \frac{1}{3^2} + \cdots = \frac{\pi^2}{6}$$

$$\frac{1}{1^4} + \frac{1}{2^4} + \frac{1}{3^4} + \cdots = \frac{\pi^4}{90}$$

$$\frac{1}{1^6} + \frac{1}{2^6} + \frac{1}{3^6} + \cdots = \frac{\pi^6}{945} \quad \cdots$$

Gauss's Circle Problem



Let $r(n)$ be the number of ways of writing n as the sum of two squares:

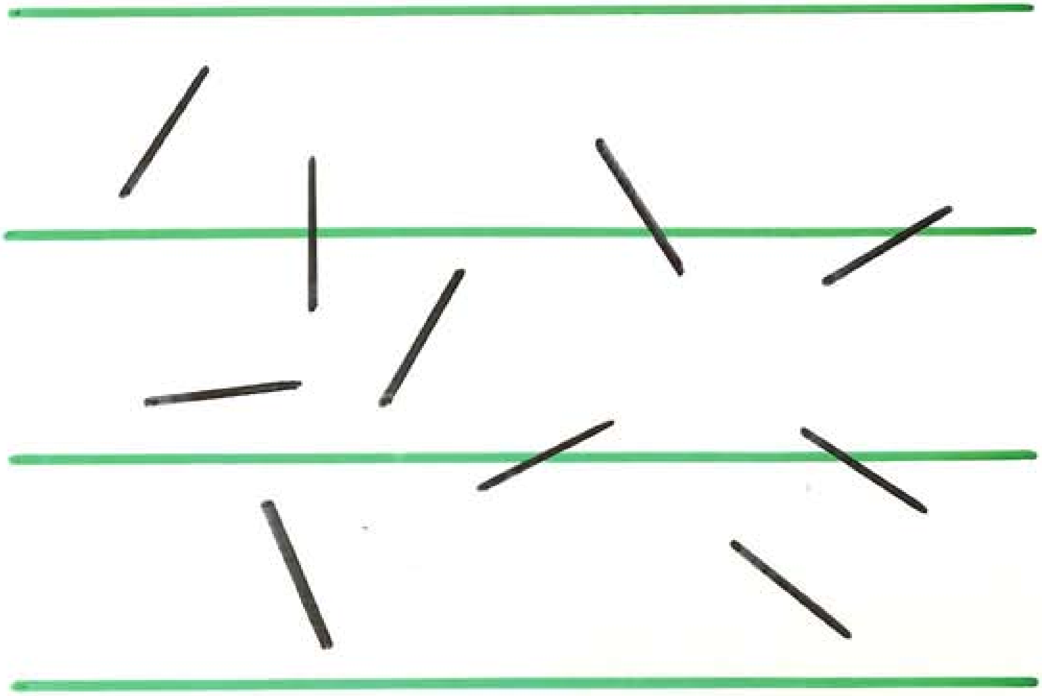
$r(5) = 8$: $\quad 5 = (\pm 2)^2 + (\pm 1)^2 = (\pm 1)^2 + (\pm 2)^2$

$r(7) = 0 \qquad r(250) = 16 \qquad r(251) = 0$

$r(n)$ is very erratic: look at averages

$$\frac{r(1) + r(2) + \cdots + r(n)}{n} \to \pi \quad \text{as } n \to \infty$$

Buffon's needle experiment (1777)



L = length of needle

a = distance between lines

$$\left.\begin{array}{l}\text{probability of}\\ \text{crossing a line}\end{array}\right\} = \frac{2L}{\pi a}$$

(Here, $\frac{1}{2} = \dfrac{2 \times 4}{\pi \times 5}$, so $\pi = \frac{16}{5} = 3 \cdot 2$.)

Legislating for π

State legislature of Indiana (1897)

Edwin J. Goodman M.D. proposed a bill:

A bill for an act introducing a new mathematical truth and offered as a contribution to education to be used only by the State of Indiana free of cost by paying any royalties whatever on the same, provided it is accepted and adopted by the official action of the legislature in 1897.

→ House Committee on Swamp Lands

→ Committee on Education: bill passed

Be it enacted by the General Assembly of the State of Indiana: It has been found that the circular area is to the quadrant of the circumference, as the area of an equilateral rectangle is to the square on one side. The diameter employed as the linear unit according to the present rule in computing the circle's area is entirely wrong...

→ Committee on temperance

Mathematics professor C. A. Waldo (Purdue)

Enter the Computer

1949	ENIAC	2037	70 hours
1955	NORC	3089	13 mins
1957	Pegasus	10021	33 hours
1958	IBM 704	10000	1 hr, 40 mins
1961	IBM 7090	20000	39 mins
1961	Shanks/Wrench	100265	~8 hours
1967	CDC 6600	500000	28 hours
1989	Chudnovskys	1 billion	
2002	Kanada	1 trillion	

π to 5000 decimal places

3.1415926535 8979323846 2643383279 5028841971 6939937510 5820974944 5923078164 0628620899 8628034825 3421170679
8214808651 3282306647 0938446095 5058223172 5359408128 4811174502 8410270193 8521105559 6446229489 5493038196
4428810975 6659334461 2847564823 3786783165 2712019091 4564856692 3460348610 4543266482 1339360726 0249141273
7245870066 0631558817 4881520920 9628292540 9171536436 7892590360 0113305305 4882046652 1384146951 9415116094
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Some bizarre results

Ramanujan (1914)

$$\frac{1}{\pi} = \sum_{n=0}^{\infty} \binom{2n}{n}^3 \frac{42n+5}{2^{12n+4}}$$

$$\frac{1}{\pi} = \frac{2\sqrt{2}}{9801} \sum_{n=0}^{\infty} \frac{(4n)!}{(n!)^4} \times \frac{(1103+26390n)}{(4\times 99)^{4n}}$$

Borweins and Chudnovskys:

$$\frac{1}{\pi} = 12 \sum_{n=0}^{\infty} \frac{(-1)^n \, (6n)! \, (13591409+545140134n)}{(n!)^3 \, (3n)! \, (640320^3)^{n+1/2}}$$

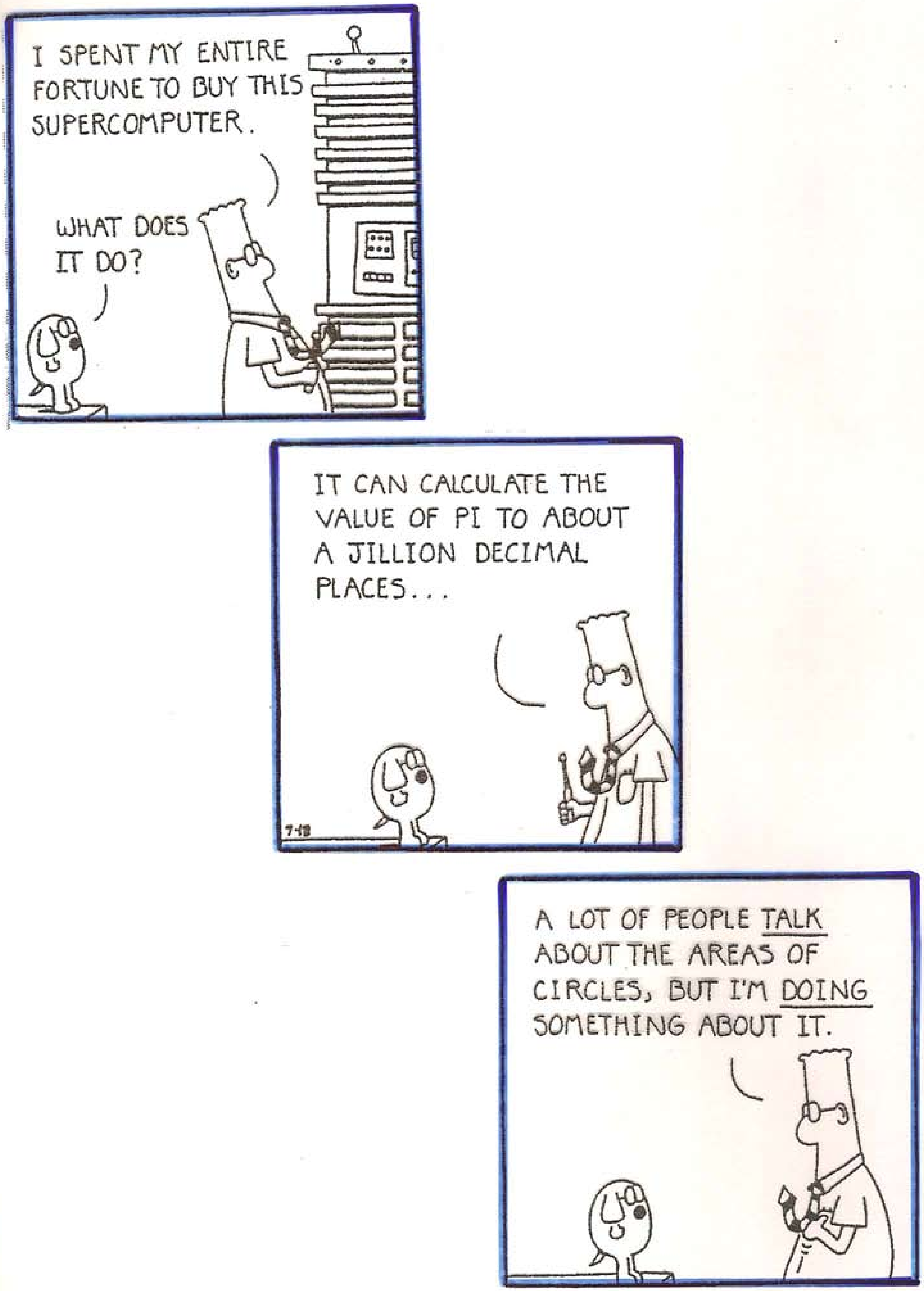
$$\pi = \sum_{n=0}^{\infty} \frac{1}{16^n} \left\{ \frac{4}{8n+1} - \frac{2}{8n+4} - \frac{1}{8n+5} - \frac{1}{8n+6} \right\}$$

Why calculate so many digits?

- to enable us to look for patterns
- to test the accuracy of a new computer

The first trillion digits of π

digit	occurrences
0	99999485134
1	99999945664
2	100000480057
3	99999787805
4	100000357857
5	99999671008
6	99999807503
7	99999818723
8	100000791469
9	99999854780
	1000000000000


I SPENT MY ENTIRE FORTUNE TO BUY THIS SUPERCOMPUTER.
WHAT DOES IT DO?
IT CAN CALCULATE THE VALUE OF PI TO ABOUT A JILLION DECIMAL PLACES...
A LOT OF PEOPLE TALK ABOUT THE AREAS OF CIRCLES, BUT I'M DOING SOMETHING ABOUT IT.