29. Pi's Childhood
48. Pi's Adolescence
53. Adulthood of Pi
84. Pi in the Digital Age
118. Computing Individual Digits of π

The Life of π: History and Computation
A Talk for Pi Day or Other Days

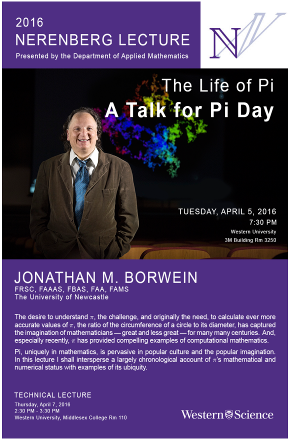
Jonathan M. Borwein FRSC FAA FAAAS

Laureate Professor & Director of CARMA
University of Newcastle
http://carma.newcastle.edu.au/jon/piday-16.pdf

3.14 pm, March 14, 2016 Revised 3.20.16 for *Western* 05.04.16

π

The 2016 Nerenberg Lecture



Dedicated to the memory of Paddy Nerenberg
March 17 1936-1993

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The 2016 Nerenberg Lecture

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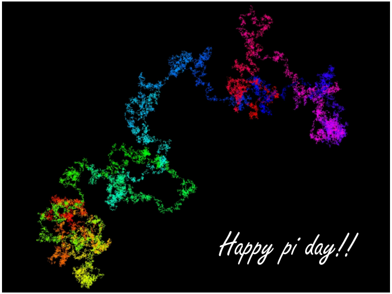

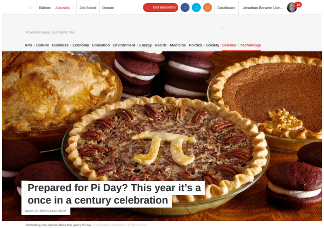

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- Why Pi? From utility to ... normality.
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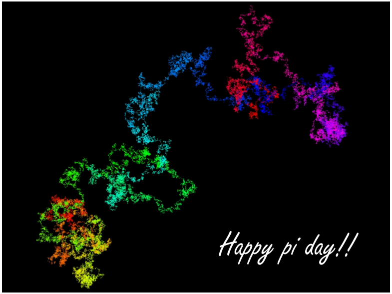

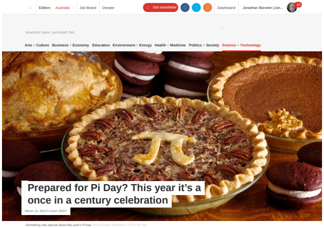

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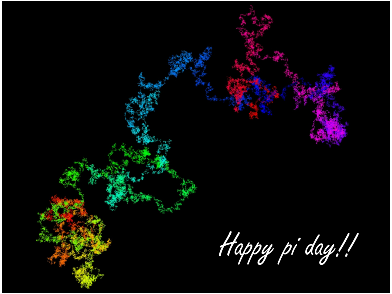

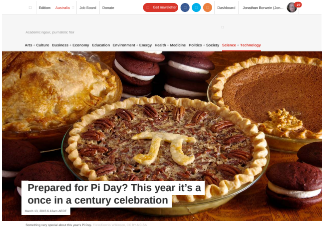

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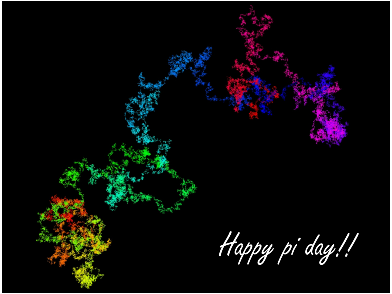

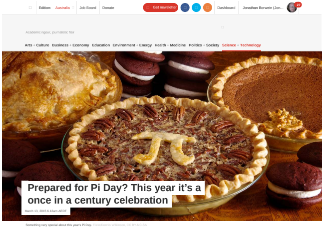

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- Why Pi? From utility to ... normality.
- Recent computations and digit extraction methods.

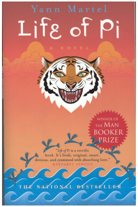
Outline. We will cover Some of:

IBM

1. 29. Pi's Childhood
   - Links and References
   - Babylon, Egypt and Israel
   - Archimedes Method circa 250 BCE
   - Precalculus Calculation Records
   - The Fairly Dark Ages
2. 48. Pi's Adolescence
   - Infinite Expressions
   - Mathematical Interlude, I
   - Geometry and Arithmetic
3. 53. Adulthood of Pi
   - Machin Formulas
   - Newton and Pi
   - Calculus Calculation Records
   - Mathematical Interlude, II
   - Why Pi? Utility and Normality
4. 84. Pi in the Digital Age
   - Ramanujan-type Series
   - The ENIACalculator
   - Reduced Complexity Algorithms
   - Modern Calculation Records
   - A Few Trillion Digits of Pi
5. 118. Computing Individual Digits of π
   - BBP Digit Algorithms
   - Mathematical Interlude, III
   - Hexadecimal Digits
   - BBP Formulas Explained
   - BBP for Pi squared — in base 2 and base 3

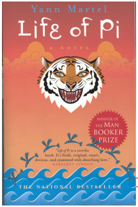
Introduction: Pi is ubiquitous

- The desire to understand π, the challenge, and originally the need, to calculate ever more accurate values of π, the ratio of the circumference of a circle to its diameter, has captured mathematicians — great and less great — for eons.
- And, especially recently, π has provided compelling examples of computational mathematics.



Pi, uniquely in mathematics,
is pervasive in popular culture
and the popular imagination.

In this talk I shall intersperse
a largely chronological account of π's
mathematical and numerical status
with examples of its ubiquity.



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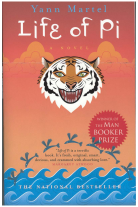

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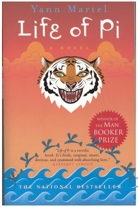

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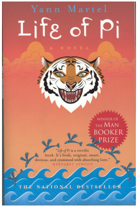

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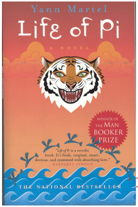

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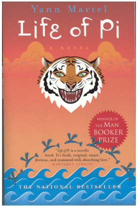

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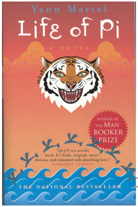
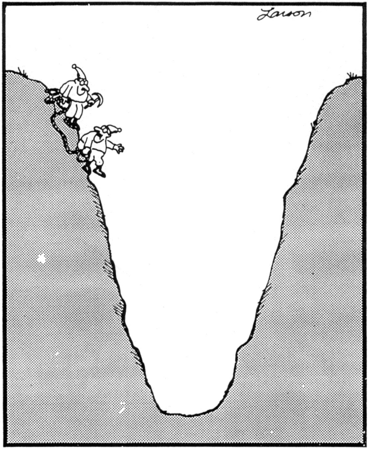


CARMA

The Life of Pi Teaches a Great Deal:

We shall learn that scientists are humans and see a lot:

- of important mathematics;
- of its history and philosophy;
- about the evolution of computers and computation;
- of general history, philosophy and science;
- proof and truth (certainty and likelihood);
- of just plain interesting — sometimes *weird* — stuff.



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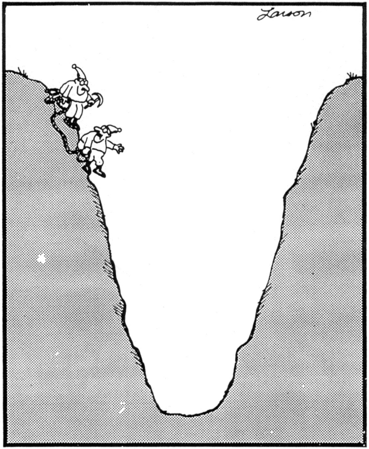

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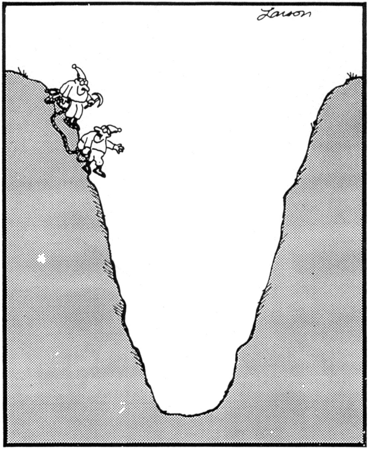

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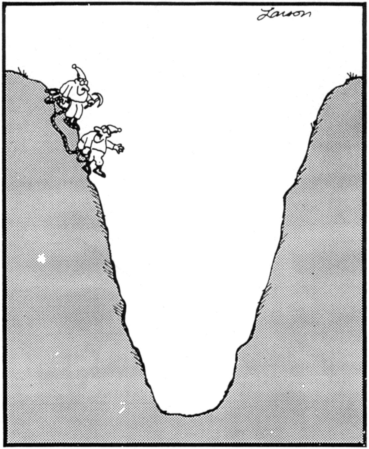

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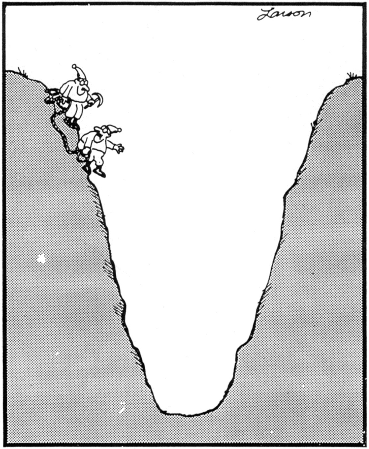

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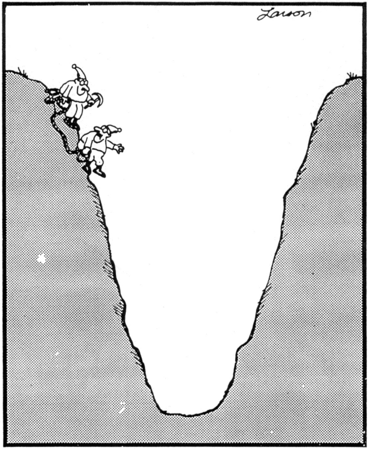

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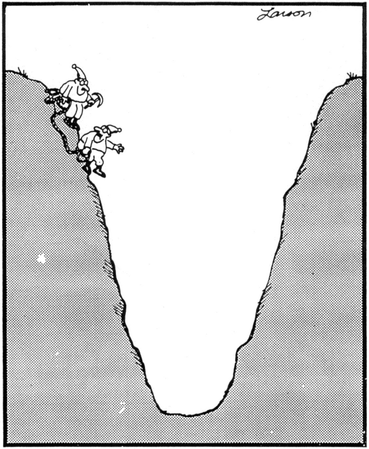

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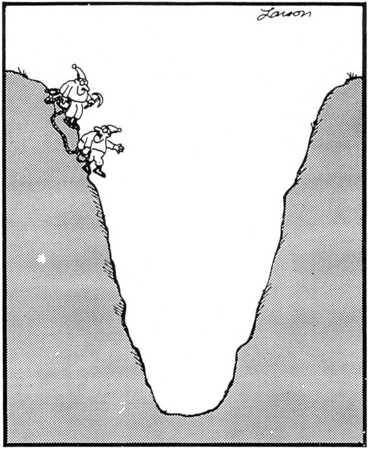

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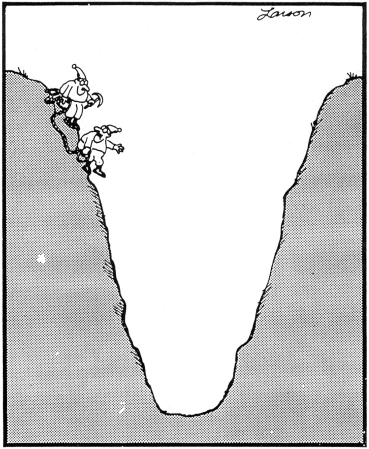

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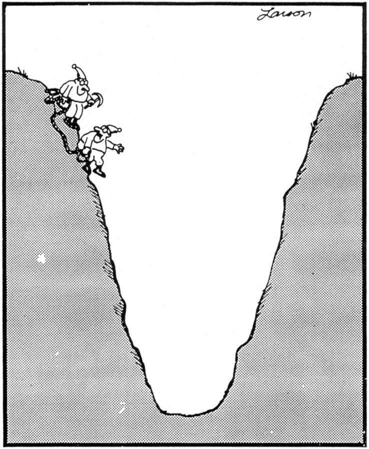

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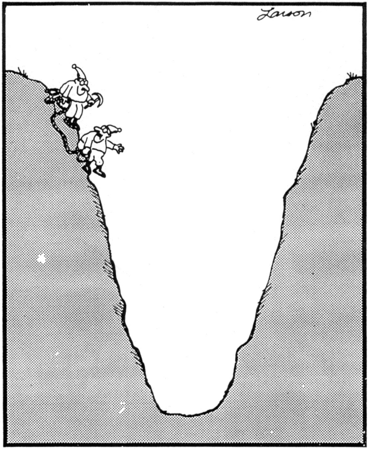

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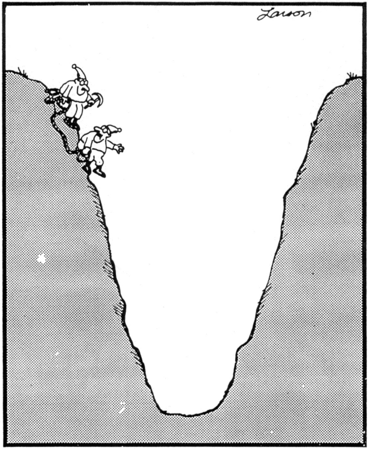

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RMA

Mnemonics for Pi Abound: Piems — Word lengths give digits

toc

"When you're young, it comes naturally, but when you get a little older, you have to rely on mnemonics."

Now I, even I, would celebrate
(3 1 4 1 5 9)
In rhymes inapt, the great
(2 6 5 3 5)
Immortal Syracusan, rivaled nevermore,
Who in his wondrous lore,
Passed on before
Left men for guidance
How to circles mensurate.

– punctuation is always ignored

CARMA

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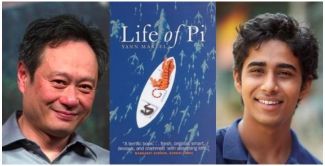
CARMA

Life of Pi (2001): Yann Martel's 2002 Booker Prize novel starts

''My name is
Piscine Molitor Patel
known to all as Pi Patel
For good measure I added
$\pi = 3.14$
and I then drew a large circle
which I sliced in two with a
diameter, to evoke that basic
lesson of geometry.''



2013 Ang Lee's movie version (4 Oscars)

- **1706**. Notation of π introduced by William Jones.
- **1737**. Leonhard Euler (**1707-83**) popularized π.
  - One of the three or four greatest mathematicians of all times:
  - He introduced much of our modern notation: $\int, \Sigma, \phi, e, \Gamma, \ldots$

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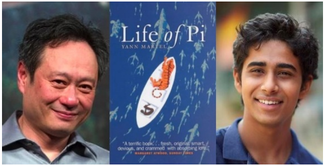

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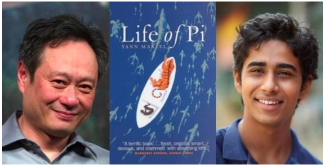

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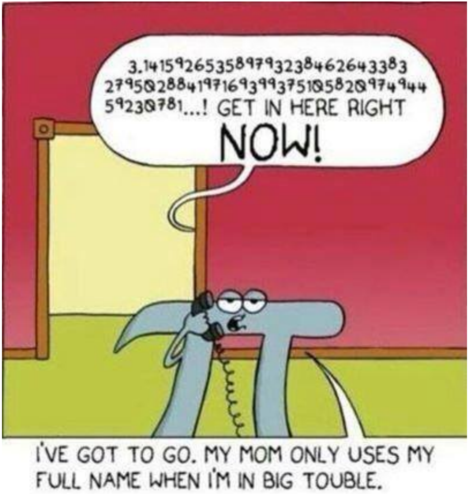
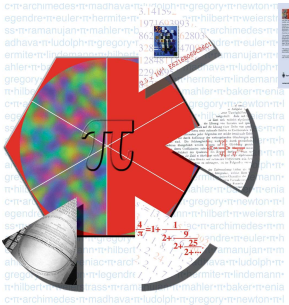
CARMA

Wife of Pi (2013)

Life of Pi (2014)



Pi: the Source Book (1997)



- Berggren, Borwein and Borwein, 3rd Ed, Springer, **2004**. (3,650 years of copyright releases. *E-rights* for Ed. 4 are in process.)
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  - See also www.cecm.sfu.ca/~jborwein/pi_cover.html.

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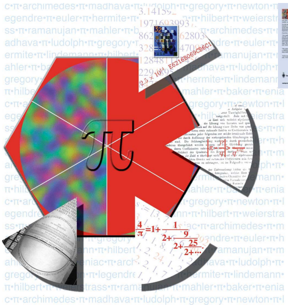

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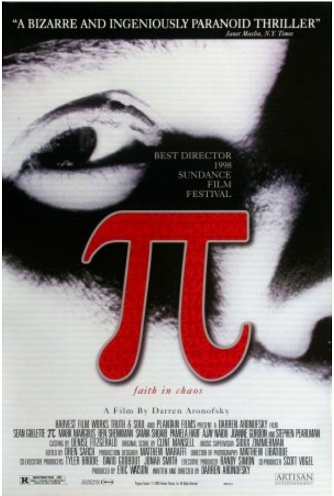
Pi: in The Matrix (1999)

Keanu Reeves, Neo, only has **314** seconds to enter "The Source."
(Do we need Parts 4 and 5?)

- From http://www.freakingnews.com/Pi-Day-Pictures--1860.asp

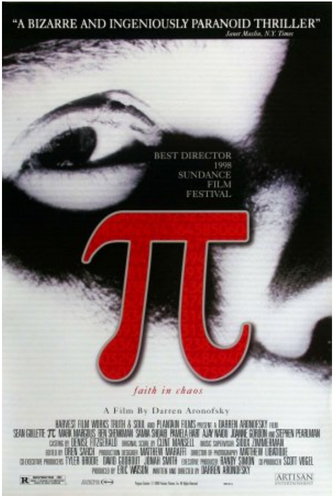
Pi the Movie (1998): a Sundance screenplay winner



Roger Ebert gave the film 3.5 stars out of 4: "Pi is a thriller. I am not very thrilled these days by whether the bad guys will get shot or the chase scene will end one way instead of another. You have to make a movie like that pretty skillfully before I care.

"But I am thrilled when a man risks his mind in the pursuit of a dangerous obsession."

Pi the Movie (1998): a Sundance screenplay winner



Roger Ebert gave the film 3.5 stars out of 4: "Pi is a thriller. I am not very thrilled these days by whether the bad guys will get shot or the chase scene will end one way instead of another. You have to make a movie like that pretty skillfully before I care.

"But I am thrilled when a man risks his mind in the pursuit of a dangerous obsession."

Pi the **URL**

Pi to one MILLION decimal places

3.1415926535897932384626433832795028841971693993751058209749445923078164062862089986280348253421170679
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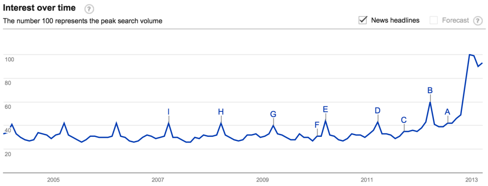
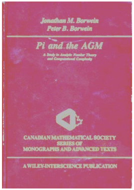
9465764078951269468398352595709825822620522489407726719478268482601476990902640136394437455305068203

- From 3.14159265358979323846264338327950288419716939937510582097494459 2.com/ This **2005 URL** seems to have *disappeared*.

CARMA

2014: πDay turns **26**: Our book Pi and the AGM is **27**





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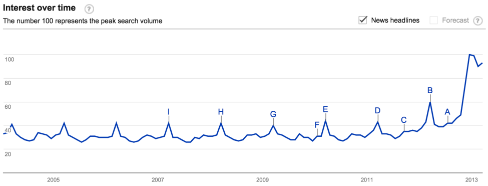

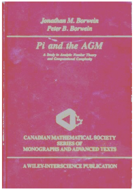

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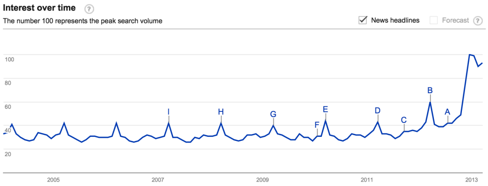

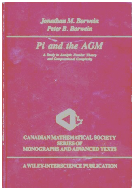

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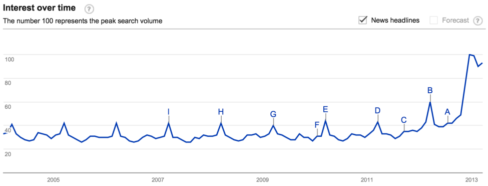

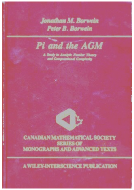

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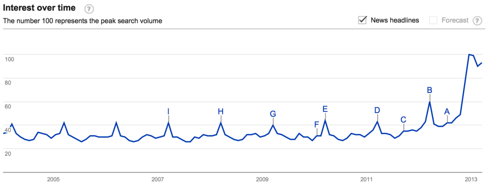

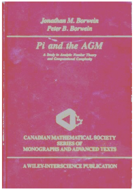

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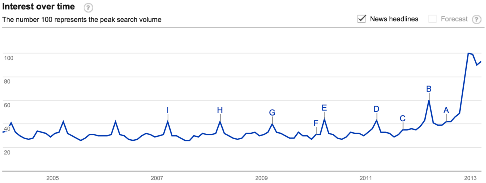

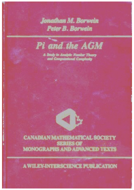

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Google Search for "Pi Day 2013" 345,000 hits (13-3-13)

1. Pi Day
   www.timeanddate.com › Calendar › Holidays

   Pi Day 2013. Thursday, March 14, 2013. Monday, July 22, 2013. Pi Day 2014. Friday, March 14, 2014. Tuesday, July 22, 2014. List of dates for other years **...**

2. News for **"Pi day 2013"**
3. **Celebrate Pi Day 2013 -- with Pie**
   Patch.com - 8 hours ago

   A perfect day for math geeks, Einstein lovers, and admirers of pie.

   4. Celebrate **Pi Day 2013** with Fredericksburg Pizza

   Patch.com - 22 hours ago

   5. **Pi Day 2013**: A Celebration of the Mathematical Constant 3.1415926535...

   Patch.com - 1 day ago

6. Celebrate **Pi Day 2013** -- with Pie - Millburn-Short Hills, NJ Patch
   millburn.patch.com/.../celebrate-**pi-day-2013**-wit... - United States

   9 hours ago – A perfect day for math geeks, Einstein lovers, and admirers of pie.

7. **Pi Day 2013**: A Celebration of the Mathematical Constant **...**
   manassas.patch.com/.../**pi-day-2013**-a-celebration... - United States

   2 days ago – March 14, or 3-14, is Pi Day – a day to celebrate the mathematical constant 3.14. What Pi Day activities do you have planned?

8. **"Pi" Day 2013** - FunCheapSF.com
   sf.funcheap.com › City Guide

   2 days ago – **Pi Day 2013** Any day can be a holiday, so why not look to math for some inspiration. Pi day (March 14th... 3/14... 3.14) seeks to celebrate π **...**

9. **Pi Day 2013** | Facebook
   www.facebook.com/events/181240568664057/

   Thu, 14 Mar - Everywhere, ,

   Celebrate mathematics by celebrating Pi Day! Pi is the ratio of the circumference of a circle to its diameter (3.14159265...) For more info see: http://www.piday.org **...**

10. **Pi Day 2013**: Events, Activities, & History | Exploratorium
    www.exploratorium.edu/learning_studio/pi/

    Welcome to our twenty-fifth annual Pi Day! Help us celebrate this never-ending number (3.14159 . . .) and Einstein's birthday as well. On the afternoon of March ...

Crossword Pi — NYT March 14, 2007

- To solve the puzzle, first note that the clue for 28 `DOWN` is

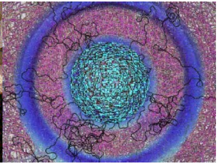
  `March 14, to Mathematicians`,

  to which the answer is `PIDAY`. Moreover, roughly a dozen other characters in the puzzle are π=**PI**.
- For example, the clue for 5 down was `More pleased` with the six character answer `HAP`π`ER`.

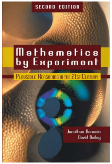
. . . — . . .

Borweins and Plouffe

Pi Art



A Fine Book



Puzzle

(MSNBC Thanksgiving 1997)

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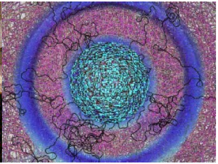

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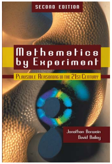


Puzzle

(**MSNBC** Thanksgiving 1997)

The Puzzle (**By Permission**)

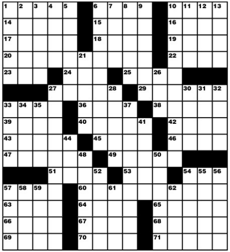
The New York Times Crossword Edited by Will Shortz No. 0314

Across

1 Enlighten
6 A couple CBS spinoffs
10 1972 Broadway musical
14 Metal giant
15 Evict
16 Area
17 Surface again, as a road
18 Pirate or Padre, briefly
19 Camera feature
20 Barracks artwork, perhaps
22 River to the Ligurian Sea
23 Keg necessity
24 "… ___ he drove out of sight"
25 ___ St. Louis, Ill.
27 Preen
29 Greek peak
33 Vice president after Hubert
36 Patient wife of Sir Geraint
38 Action to an ante
39 Gain ___
40 French artist Odilon ___
42 Grape for winemaking
43 Single-dish meal
45 Broad valley
46 See 21-Down
47 Artery inserts
49 Offspring
51 Mexican mouse catcher
53 Medical procedure, in brief
54 "Wheel of Fortune" option
57 Animal with striped legs
60 Editorial
63 It gets bigger at night
64 "Hold your horses!"
65 Idiots
66 Europe/Asia border river
67 Suffix with launder
68 Leaning
69 Brownback and Obama, e.g.: Abbr.
70 Rick with the 1976 #1 hit "Disco Duck"
71 Yegg's targets

Down

1 Mastodon trap
2 "Mefistofele" soprano
3 Misbehave
4 Pen
5 More pleased
6 Treated with disdain
7 Enterprise crewman
8 Rhone feeder
9 Many a webcast
10 Mushroom, for one
11 Unfortunate
12 Nevada's state tree
13 Disney fish
21 Colonial figure with 46-Across
26 Poker champion Ungar
27 Self-medicating excessively
28 March 14, to mathematicians
30 Book part
31 Powder, e.g.
32 007 and others: Abbr.
33 Drains
34 Stove feature
35 Feet per second, e.g.
37 Italian range
41 Prefix with surgery
44 Captain's announcement, for short
48 Tucked away
50 Stealthy fighters
52 Sedative
54 Letter feature
55 Jam
56 Settles in
57 Symphony or sonata
58 Japanese city bombed in W.W. II
59 Beelike
61 Evening, in ads
62 Religious artwork



Puzzle by Peter A. Collins

ANSWER TO PREVIOUS PUZZLE

A	R	F	S	■	A	C	H	E	■	O	R	G	A	N
C	O	R	K	■	T	R	E	X	■	K	E	R	R	Y
O	D	A	Y	■	L	A	I	T	■	S	T	A	T	S
L	E	N	■	R	A	N	D	O	M	■	I	P	S	E
D	O	C	T	O	R	K	I	L	D	A	R	E	■	■
■	■	■	R	A	G	■	■	■	S	I	E	S	T	A
T	Y	R	O	N	E	P	O	W	E	R	■	O	H	M
R	U	E	D	■	■	A	L	I	■	■	I	D	E	S
I	M	P	■	H	O	L	D	T	H	E	M	A	Y	O
B	A	A	B	A	A	■	■	■	O	R	E	■	■	■
■	■	I	R	I	S	H	C	O	U	N	T	I	E	S
P	E	R	I	■	T	I	R	A	D	E	■	D	X	C
A	R	M	E	D	■	T	A	T	I	■	Y	I	P	E
C	L	A	R	E	■	I	T	E	N	■	D	O	W	N

For answers, call 1-900-285-5656, $1.20 a minute; or, with a credit card, 1-800-814-5554.
Annual subscriptions are available for the best of Sunday crosswords from the last 50 years: 1-888-7-ACROSS.
Online subscriptions: Today's puzzle and more than 2,000 past puzzles, nytimes.com/crosswords ($34.95 a year).
Share tips: nytimes.com/puzzleforum. Crosswords for young solvers: nytimes.com/learning/xwords.

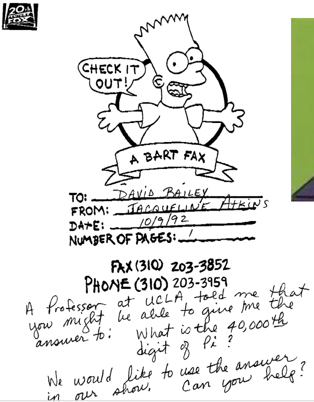
CARMA

The Puzzle Answered

ANSWER TO PREVIOUS PUZZLE

T	E	A	C	H		C	S	I	S		π	P	π	N
A	L	C	O	A		O	U	S	T		Z	O	N	E
R	E	T	O	P		N	L	E	R		Z	O	O	M
π	N	U	P	π	C	T	U	R	E		A	R	N	O
T	A	P		E	R	E		E	A	S	T			
			P	R	I	M	P		M	T	O	S	S	A
S	π	R	O		E	N	I	D		U	P	π	N	G
A	L	A	P		R	E	D	O	N		π	N	O	T
P	O	T	π	E		D	A	L	E		N	E	W	S
S	T	E	N	T	S		Y	O	U	N	G			
			G	A	T	O		M	R	I		S	π	N
O	K	A	π		O	π	N	I	O	N	π	E	C	E
P	U	π	L		W	A	I	T		J	E	R	K	S
U	R	A	L		E	T	T	E		A	T	I	L	T
S	E	N	S		D	E	E	S		S	A	F	E	S

The Simpsons (**Permission refused by Fox**)


CHECK IT OUT!

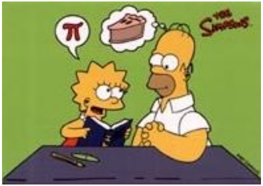
A BART FAX

TO: DAVID BAILEY
FROM: JACQUELINE ATKINS
DATE: 10/9/92
NUMBER OF PAGES: 1

FAX (310) 203-3852
PHONE (310) 203-3959

A Professor at UCLA told me that you might be able to give me the answer to: What is the 40,000th digit of Pi?

We would like to use the answer in our show. Can you help?



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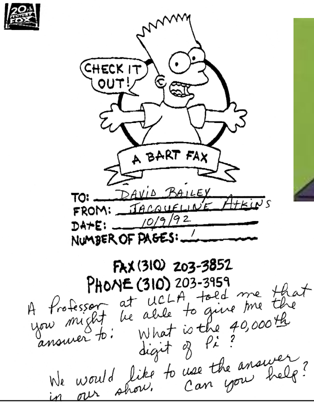
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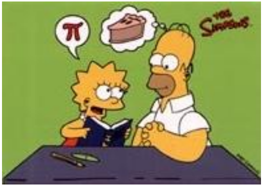

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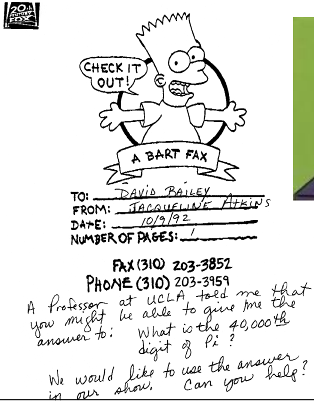
20th Century Fox

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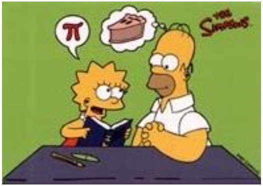

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CARMA

National Pi Day **3.12.2009**: The first successful Pi Law

H.RES.224

Latest Title: Supporting the designation of Pi Day, and for other purposes.
Sponsor: Rep Gordon, Bart [TN-6] (introduced 3/9/2009) Cosponsors (15)
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March 11, 2009 5:01 PM PDT

National Pi Day? Congress makes it official

by Declan McCullagh

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Caption: To celebrate Pi Day 2008, the San Francisco Exploratorium made a Pi string with more than 4,000 colored beads on it, each color representing a digit from 0 to 9.
(Credit: Daniel Terdiman/CNET)

Washington politicians took time from **bailouts** and **earmark-laden** spending packages on Wednesday for what might seem like an unusual act: officially designating a **National Pi Day**.

That's Pi as in ratio-of-a-circle's-circumference-to-diameter, better known as the mathematical constant beginning with 3.14159.

National Pi Day **3.12.2009**: The first successful Pi Law

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CNN Pi Day **3.13.2010**: and Google (in North America)

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On Pi Day, one number 'reeks of mystery'

By Elizabeth Landau, CNN
March 12, 2010 12:36 p.m. ESTMarch 12, 2010 12:36 p.m. EST

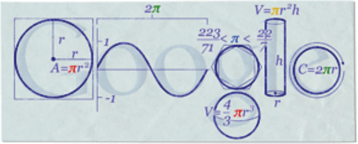
Sunday is Pi Day, on which math geeks celebrate the number representing the ratio of circumference to diameter of a circle.

STORY HIGHLIGHTS

- Pi Day falls on March 14, which is also Albert Einstein's birthday
- The true "randomness" of pi's digits -- 3.14 and so on -- has never been proven
- The U.S. House passed a resolution supporting Pi Day in March 2009

(CNN) -- The sound of meditation for some people is full of deep breaths or gentle humming. For Marc Umile, it's "3.14159265358979..."

Whether in the shower, driving to work, or walking down the street, he'll mentally rattle off digits of pi to pass the time. Holding 10th place in the world for pi memorization -- he typed out 15,314 digits from memory in 2007 -- Umile meditates through one of the most beloved and mysterious numbers in all of mathematics.



Google's homage to 3.14.10

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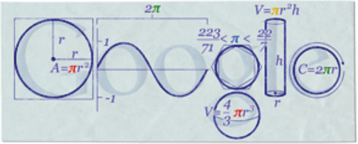

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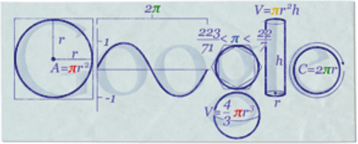

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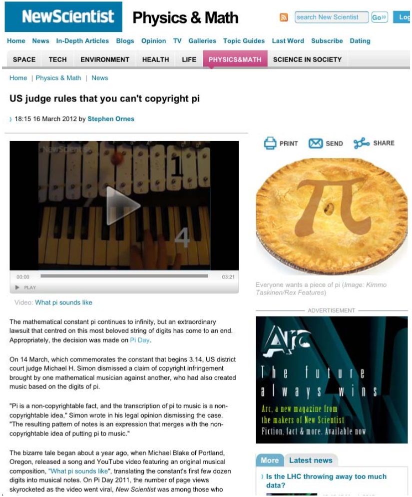
Judge rules "Pi is a non-copyrightable fact" on **3.14.2012**



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US judge rules that you can't copyright pi

18:15 16 March 2012 by Stephen Ornes

Video: What pi sounds like

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Everyone wants a piece of pi (*Image: Kimmo Taskinen/Rex Features*)

The mathematical constant pi continues to infinity, but an extraordinary lawsuit that centred on this most beloved string of digits has come to an end. Appropriately, the decision was made on Pi Day.

On 14 March, which commemorates the constant that begins 3.14, US district court judge Michael H. Simon dismissed a claim of copyright infringement brought by one mathematical musician against another, who had also created music based on the digits of pi.

"Pi is a non-copyrightable fact, and the transcription of pi to music is a non-copyrightable idea," Simon wrote in his legal opinion dismissing the case. "The resulting pattern of notes is an expression that merges with the non-copyrightable idea of putting pi to music."

The bizarre tale began about a year ago, when Michael Blake of Portland, Oregon, released a song and YouTube video featuring an original musical composition, "What pi sounds like", translating the constant's first few dozen digits into musical notes. On Pi Day 2011, the number of page views skyrocketed as the video went viral, *New Scientist* was among those who

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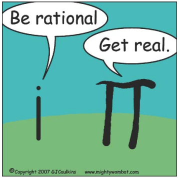

Two of many cartoons

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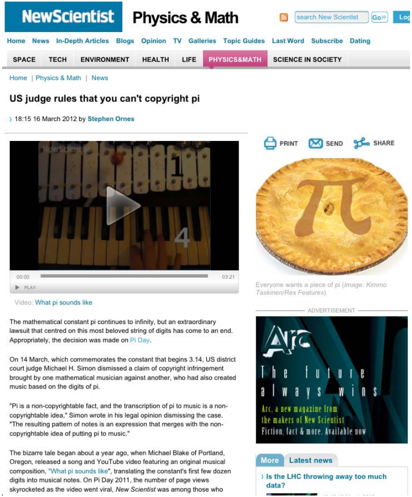
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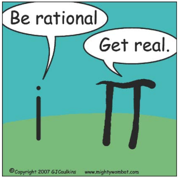

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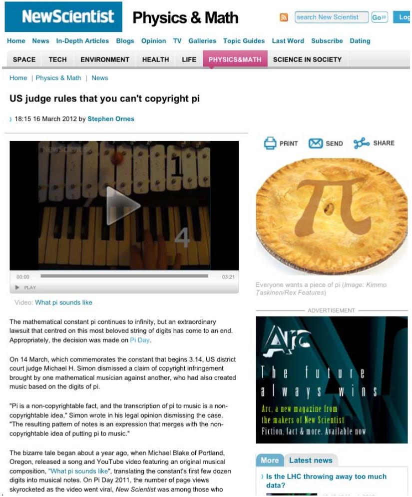

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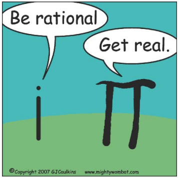

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Google (29-1-13) and US Gov't (14-8-12) still both love π

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Hackers slug Aussies with trojans in ATO, air ticket spam

9 iPhone and iPad apps that invade your privacy, and 1 that doesn't

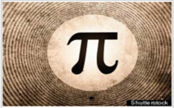
Rising cyberthreats set backdr latest cybersecurity bill

Google rounds up Pwnie prize to $π million for Chrome OS hacks

Google shoves Chrome OS in to the hacker spotlight.

U.S. Population Reaches 314,159,265, Or Pi Times 100 Million: Census

The Huffington Post | By Bonnie Kavoussi
Posted: 08/14/2012 4:03 pm Updated: 08/14/2012 5:55 pm



Pi.

The U.S. population has reached a nerdy and delightful milestone.

Shortly after 2:29 p.m. on Tuesday, August 14, 2012, the U.S. population was exactly 314,159,265, or Pi (π) times 100 million, the U.S. Census Bureau reports.

Pi (π) is a unique number in multiple ways. For one, it is the ratio of a circle's circumference to its diameter. It is also an irrational number, meaning it goes on forever without ever repeating itself. Are you remembering how much you loved geometry class? You can check out Pi to one million places here.

Contestants will be offered $110,000 for a successful exploit delivered by a web page that achieves a browser or system level compromise "in guest mode or as a logged-in user". A $150,000 prize will be offered for a "compromise with device persistence -- guest to guest with interim reboot, delivered via a web page".

Hackers will need to demonstrate their attacks against a Wifi-only model of Samsung's Series 5 550 Chromebook running the latest stable version of Chrome OS. The current beta Chrome OS version

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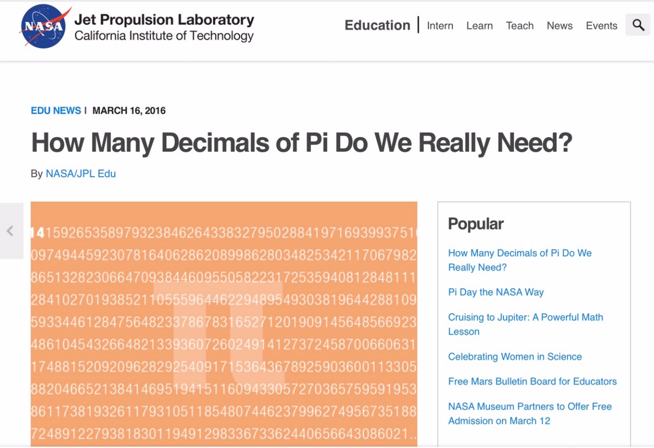
3.14.16 blog.pizzahut.com...the century's best approximation

Pizza restaurant company recognizes unique holiday by releasing three mathematical equations created by Conway, offers 3.14 years of free Pizza Hut 'pie' to first consumers to solve each problem

PLANO, Texas, March 10, 2016 /PRNewswire/ -- Nobody knows "pie" like Pizza Hut, but this March 14, Pizza Hut is dropping the "e" in honor of Pi – 3.14 – everyone's favorite irrational number.

In partnership with acclaimed mathematical genius John H. Conway, distinguished professor of pure and applied mathematics emeritus, Princeton University, and in honor of "National Pi Day" on March 14, Pizza Hut will release three math problems on its Hut Life blog (blog.pizzahut.com) with a unique challenge to consumers and mathematic wizards everywhere: be the first person to solve and submit the correct answer to any one of the problems for a chance to receive 3.14 years of free pizza from Pizza Hut. Varying in level of difficulty from high school to PhD level, all three problems will be released at 8 a.m. ET.

3.14.16 ... 39 digits will do NASA



http://www.jpl.nasa.gov/edu/news/2016/3/16/how-many-decimals-of-pi-do-we-really-need/

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Each year brings more π-trivia and serious stuff

1. September 2014. *Pencil, Paper and Pi* or where Shanks computation went wrong

   http://www.americanscientist.org/issues/pub/2014/5/pencil-paper-and-pi

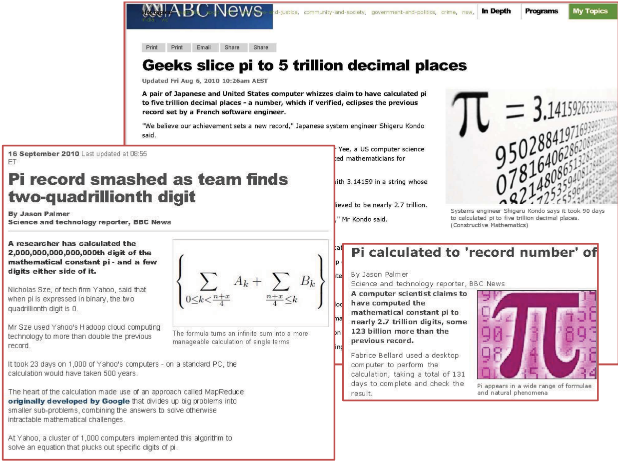
2. March 2015. J.M. Borwein and Scott T. Chapman, "I Prefer Pi: A Brief History and Anthology of Articles in the American Mathematical Monthly." **122** (2015), 195–216.

3. 22.10.14. A mile of Pi on one piece of paper

   http://www.youtube.com/watch?v=0r3cEKZiLmg&feature=youtu.be

π Records *Always* Make The News

More later



ABC News

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Geeks slice pi to 5 trillion decimal places

Updated Fri Aug 6, 2010 10:26am AEST

A pair of Japanese and United States computer whizzes claim to have calculated pi to five trillion decimal places - a number, which if verified, eclipses the previous record set by a French software engineer.

"We believe our achievement sets a new record," Japanese system engineer Shigeru Kondo said.

Systems engineer Shigeru Kondo says it took 90 days to calculated pi to five trillion decimal places. (Constructive Mathematics)

16 September 2010 Last updated at 08:55 ET

Pi record smashed as team finds two-quadrillionth digit

By Jason Palmer
Science and technology reporter, BBC News

A researcher has calculated the 2,000,000,000,000,000th digit of the mathematical constant pi - and a few digits either side of it.

Nicholas Sze, of tech firm Yahoo, said that when pi is expressed in binary, the two quadrillionth digit is 0.

Mr Sze used Yahoo's Hadoop cloud computing technology to more than double the previous record.

$$\left\{\sum_{0\le k<\frac{n+x}{4}} A_k + \sum_{\frac{n+x}{4}\le k} B_k\right\}$$

The formula turns an infinite sum into a more manageable calculation of single terms

It took 23 days on 1,000 of Yahoo's computers - on a standard PC, the calculation would have taken 500 years.

The heart of the calculation made use of an approach called MapReduce **originally developed by Google** that divides up big problems into smaller sub-problems, combining the answers to solve otherwise intractable mathematical challenges.

At Yahoo, a cluster of 1,000 computers implemented this algorithm to solve an equation that plucks out specific digits of pi.

Pi calculated to 'record number' of

By Jason Palmer
Science and technology reporter, BBC News

A computer scientist claims to have computed the mathematical constant pi to nearly 2.7 trillion digits, some 123 billion more than the previous record.

Fabrice Bellard used a desktop computer to perform the calculation, taking a total of 131 days to complete and check the result.

Pi appears in a wide range of formulae and natural phenomena

- By now you get the idea: π is everywhere ... also volumes, areas, lengths, probabilities, everywhere.

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30. Links and References

1. The Pi Digit site: `http://carma.newcastle.edu.au/bbp`
2. Dave Bailey's Pi Resources: `http://crd.lbl.gov/~dhbailey/pi/`
3. The Life of Pi: `http://carma.newcastle.edu.au/jon/pi-2012.pdf`.
4. Experimental Mathematics: `http://www.experimentalmath.info/`.
5. Dr Pi's brief Bio: `http://carma.newcastle.edu.au/jon/bio_short.html`.

. . . — . . .

1. D.H. Bailey and J.M. Borwein, "On Pi Day 2014, Pi's normality is still in question." *American Mathematical Monthly*, **121** March (2014), 191–204. (and H*uffington Post* 3.14.14 Blog)
2. D.H. Bailey, and J.M. Borwein, *Mathematics by Experiment: Plausible Reasoning in the 21st Century,* AK Peters Ltd, Ed 2, 2008, ISBN: 1-56881-136-5. See `http://www.experimentalmath.info/`
3. J.M. Borwein, "Pi: from Archimedes to ENIAC and beyond," in *Mathematics and Culture,* Einaudi, 2006. Updated 2012: `http://carma.newcastle.edu.au/jon/pi-2012.pdf`.
4. J.M. & P.B. Borwein, and D.A. Bailey, "Ramanujan, modular equations and pi or how to compute a billion digits of pi," *MAA Monthly*, **96** (1989), 201–219. Reprinted in *Organic Mathematics*, `www.cecm.sfu.ca/organics`, 1996, *CMS/AMS Conference Proceedings*, **20** (1997), ISSN: 0731-1036.
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6. Jonathan M. Borwein and Peter B. Borwein, *Selected Writings on Experimental and Computational Mathematics*, PsiPress. October 2010.[1]
7. L. Berggren, J.M. Borwein and P.B. Borwein, *Pi: a Source Book,* Springer-Verlag, (1997), (2000), (2004). Fourth Edition, in Press.

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The Infancy of Pi: Babylon, Egypt and Israel

2000 BCE. Babylonians used the approximation $3\frac{1}{8} = 3.125$.

1650 BCE. Rhind papyrus: a circle of diameter *nine* has the area of a square of side *eight*:

$$\pi = \frac{256}{81} = 3.1604\ldots$$

- **Pi** is the only topic from the earliest strata of mathematics being actively researched today.

Some argue ancient Hebrews used $\pi = 3$:

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. (I Kings 7:23; 2 Chron. 4:2)

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CARMA

The Infancy of Pi: Babylon, Egypt and Israel

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There are two Pi(es): Did they tell you?

Archimedes of Syracuse (c.**287 – 212 BCE**) was first to show that the "two Pi's" are one in *Measurement of the Circle* (c.**250 BCE**):

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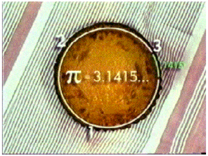
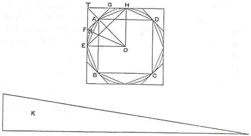


The area of any circle is equal to a right-angled triangle in which one of the sides about the right angle is equal to the radius, and the other to the circumference, of the circle.

Let $ABCD$ be the given circle, K the triangle described.



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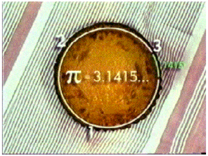

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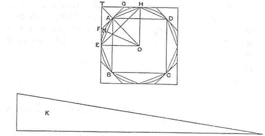

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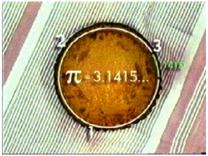

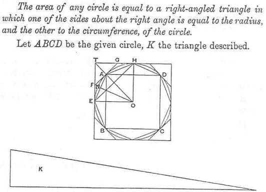
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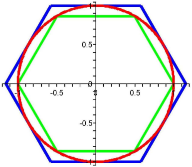

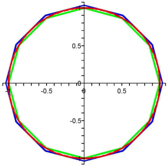

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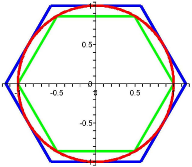

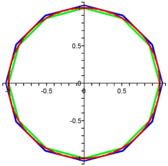

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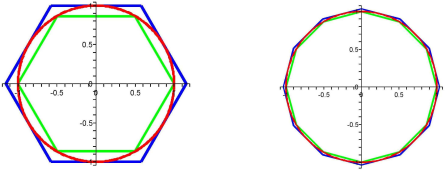

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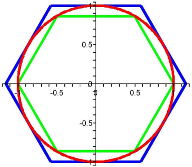

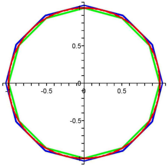

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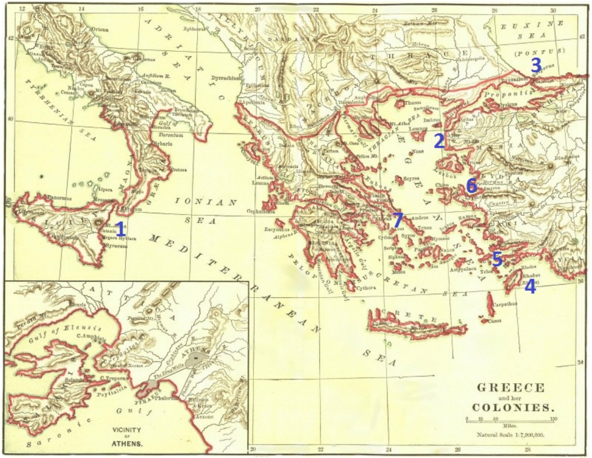

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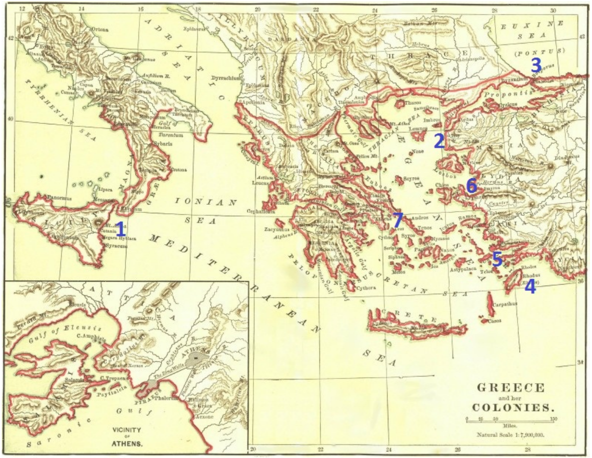

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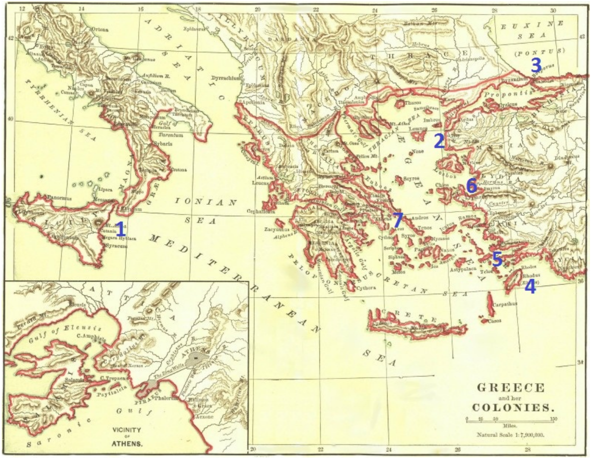

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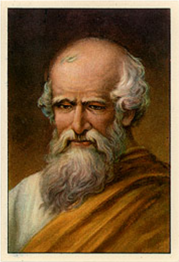
Archimedes from *The Method*

"... certain things first became clear to me by a mechanical method, although they had to be proved by geometry afterwards because their investigation by the said method did not furnish an actual proof. But it is of course easier, when we have previously acquired, by the method, some knowledge of the questions, to supply the proof than it is to find it without any previous knowledge."



Let's be Clear: π Really is not $\frac{22}{7}$

Even *Maple* or *Mathematica* 'knows' this since

$$0 < \int_0^1 \frac{(1-x)^4 x^4}{1+x^2}\, dx = \frac{22}{7} - \pi, \qquad (1)$$

though it would be prudent to ask 'why' it can perform the integral and 'whether' to trust it?

Assume we trust it. Then the integrand is strictly positive on $(0,1)$, and the answer in (1) is an area and so strictly positive, despite millennia of claims that π is $22/7$.

- Accidentally, $22/7$ is one of the early continued fraction approximation to π. These commence:

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

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Archimedes Method circa **1800 CE**

As discovered — by Schwabb, Pfaff, Borchardt, Gauss — in the 19th century, this becomes a simple recursion:

Algorithm (Archimedes)

Set $a_0 := 2\sqrt{3}, b_0 := 3$. Compute

$$a_{n+1} = \frac{2a_n b_n}{a_n + b_n} \qquad (H)$$

$$b_{n+1} = \sqrt{a_{n+1} b_n} \qquad (G)$$

These tend to π, error decreasing by a *factor of four* at each step.

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Proving π is not $\frac{22}{7}$

In this case, the indefinite integral provides immediate reassurance. We obtain

$$\int_0^{t} \frac{x^4(1-x)^4}{1+x^2}\,dx = \frac{1}{7}t^7 - \frac{2}{3}t^6 + t^5 - \frac{4}{3}t^3 + 4t - 4\arctan(t)$$

as differentiation easily confirms, and the fundamental theorem of calculus **proves** (1). **QED**

One can take this idea a bit further. Note that

$$\int_0^1 x^4(1-x)^4\,dx = \frac{1}{630}. \qquad (2)$$

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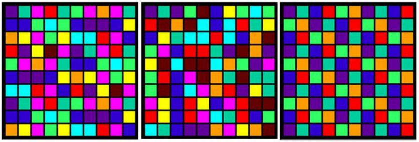
CARMA

... Going Further

Hence

$$\frac{1}{2}\int_0^1 x^4(1-x)^4\,dx < \int_0^1 \frac{(1-x)^4x^4}{1+x^2}\,dx < \int_0^1 x^4(1-x)^4\,dx.$$



Archimedes: 223/71 < π < 22/7

Combine this with (1) and (2) to derive:

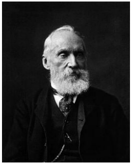
$$223/71 < 22/7 - 1/630 < \pi < 22/7 - 1/1260 < 22/7$$

and so re-obtain Archimedes' famous

$$\mathbf{3\frac{10}{71}} < \pi < \mathbf{3\frac{10}{70}}. \quad (3)$$

Never Trust Secondary References

- See Dalziel in *Eureka* (1971), a Cambridge student journal.
- Integral (1) was on the 1968 *Putnam*, an early 60's Sydney exam, and traces back to **1944** (Dalziel).

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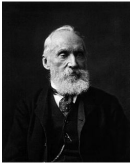


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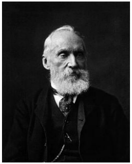


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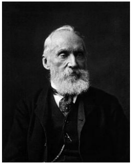


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Kuhnian 'Paradigm Shifts' and Normal Science

Variations of Archimedes' method were used for all calculations of π for **1800** years — well beyond its 'best before' date.

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CARMA

Precalculus π Calculations

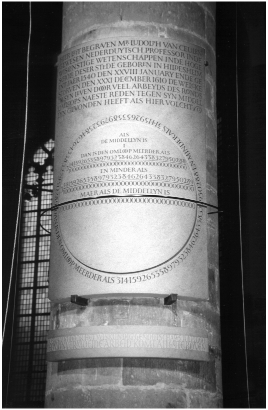
IBM

Name	Year	Digits
Babylonians	2000? BCE	1
Egyptians	2000? BCE	1
Hebrews (1 Kings 7:23)	550? BCE	1
Archimedes	250? BCE	3
Ptolemy	150	3
Liu Hui	263	5
Tsu Ch'ung Chi	480?	7
Al-Kashi	1429	14
Romanus	1593	15
Van Ceulen (**Ludolph's number***)	1615	35

* Used 2^{62}-gons for 39 places/35 correct — published posthumously.

CARMA

Ludolph's Rebuilt Tombstone in Leiden

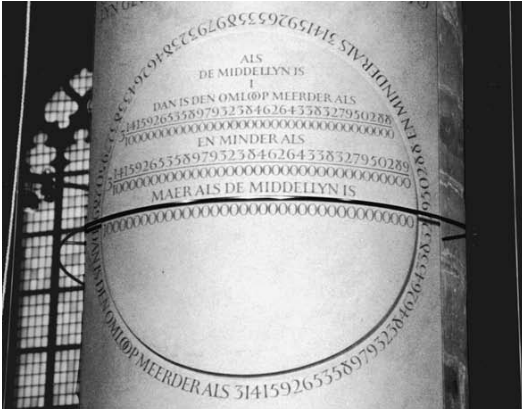


Ludolph van Ceulen (1540-1610)

- Destroyed several centuries ago; the plans remained.

CARMA

Ludolph's Reconsecrated Tombstone in Leiden



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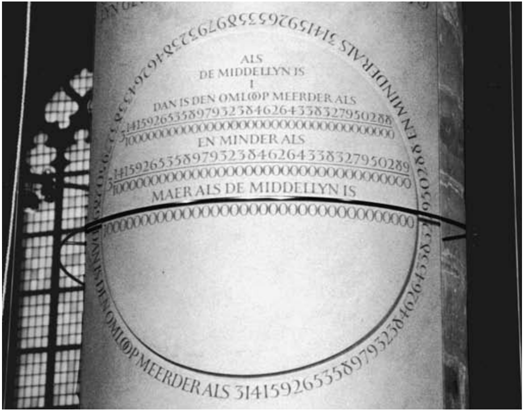

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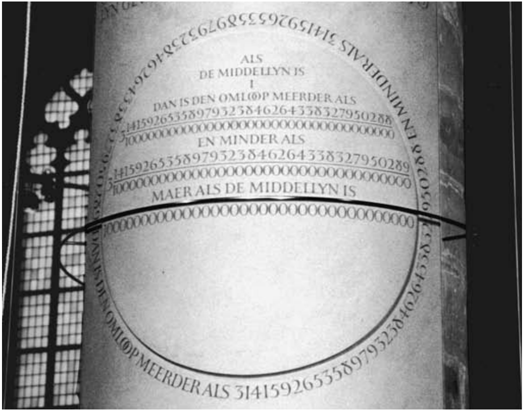

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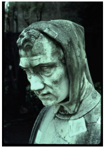

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- Still underestimated, this greatly enhanced arithmetic and mathematics in general, and computing π in particular.
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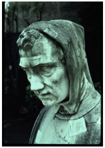

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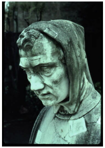

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Google Buys (Pi-3) $\times$ 100,000,000 Shares

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49. Pi's (troubled) Adolescence

1579. Modern mathematics dawns in *Viéte's product*

$$\frac{\sqrt{2}}{2}\,\frac{\sqrt{2+\sqrt{2}}}{2}\,\frac{\sqrt{2+\sqrt{2+\sqrt{2}}}}{2}\cdots=\frac{2}{\pi} \tag{4}$$

— considered to be the *first truly infinite formula* — and in the *first continued fraction* given by Lord Brouncker (**1620-1684**):

$$\frac{2}{\pi}=\cfrac{1}{1+\cfrac{9}{2+\cfrac{25}{2+\cfrac{49}{2+\cdots}}}}$$

Wallis Product

Eqn. (4) was based on John Wallis' (**1613-1706**) 'interpolated' product:

$$\frac{1\cdot 3}{2\cdot 2}\cdot\frac{3\cdot 5}{4\cdot 4}\cdot\frac{5\cdot 7}{6\cdot 6}\cdots=\prod_{k=1}^{\infty}\frac{4k^2-1}{4k^2}=\frac{2}{\pi} \tag{5}$$

which led to discovery of the *Gamma function* and much more.

- Christiaan Huygens (**1629-1695**) did not believe (5) before he checked it numerically.

It's a clue.
A never repeating or ending chain, the total timeless catalogue,
elusive sequences, sum of the universe.
This riddle of nature begs:
Can the totality see no pattern, revealing order as reality's disguise?

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Formula (5) follows from Euler's product formula for π,

$$\frac{\sin(\pi x)}{x} = c \prod_{n=1}^{\infty} \left(1 - \frac{x^2}{n^2}\right) \tag{6}$$

with $x = 1/2$, or by integrating $\int_0^{\pi/2} \sin^{2n}(t)\, dt$ by parts.

One may divine (6) — as Euler did — by *considering* $\sin(\pi x)$ *as an 'infinite' polynomial* and obtaining a product in terms of the roots $0, \{1/n^2\}$. Euler argued that, like a polynomial, $c = \pi$ is the value at 0.

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CATEGORY: By the numbers. **CLUE:** The phrase "**How I want a drink, alcoholic of course**" is often used to help memorize this. **ANSWER:** **What is Pi?** **FINAL SCORES:**

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(New champion: \$14,200)
Stacey: \$11,400 - \$3,001 = \$8,399 (What is no clue!?)
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CARMA

Pi's Adult Life with Calculus

TOC

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- It was instantly exploited to find formulas for π.

One early use comes from the arctan integral and series:[3]

$$\begin{aligned}\tan^{-1} x &= \int_0^x \frac{dt}{1+t^2} = \int_0^x (1 - t^2 + t^4 - t^6 + \cdots)\, dt \\ &= x - \frac{x^3}{3} + \frac{x^5}{5} - \frac{x^7}{7} + \frac{x^9}{9} - \cdots\end{aligned}$$

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Madahava–Gregory–Leibniz formula

Formally $x := 1$ gives the Gregory–Leibniz formula (**1671–74**)

$$\frac{\pi}{4} = 1 - \frac{1}{3} + \frac{1}{5} - \frac{1}{7} + \frac{1}{9} - \frac{1}{11} + \cdots$$

- Naively, this is useless — hundreds of terms produce two digits.
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- By contrast, Euler's (1738) trigonometric identity

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An even faster formula, found earlier by John Machin — Brook Taylor's teacher — lies in the identity

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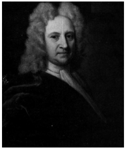
Machin    Taylor

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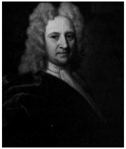
Machin    Taylor

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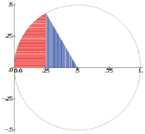
Newton discovered a different (disguised $\arcsin$) formula. He considered the area A of the red region to the right:



Now $A := \int_0^{1/4} \sqrt{x - x^2}\, dx$ equals the circular sector, $\pi/24$, less the triangle, $\sqrt{3}/32$. His new binomial theorem gave:

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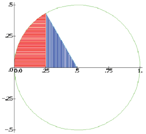

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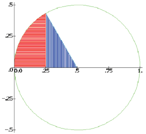

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Newton used his formula to find **15 digits** of π.

- As noted, he 'apologized' for "having no other business at the time." A standard **1951** MAA chronology said, condescendingly, "*Newton never tried to compute* π."

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Calculus π Calculations: and an IBM 7090

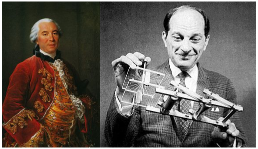
SKIP IBM

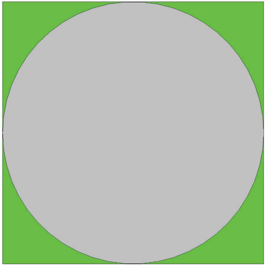
Name	Year	Digits
Sharp (and Halley)	1699	71
Machin	1706	100
Strassnitzky and Dase	1844	200
Rutherford	1853	440
W. Shanks	1874	(707) 527
Ferguson (**Calculator**)	1947	808
Reitwiesner et al. (**ENIAC**)	1949	2,037
Genuys	1958	10,000
D. Shanks and Wrench (**IBM**)	1961	100,265
Guilloud and Bouyer	1973	1,001,250

CARMA

Why a Serial God Should Not Play Dice

Buffon (1707-78) & Ulam (1909-84)





Share the count to speed the process

An early vegetarian (who misused needles) next to the inventor of Monte Carlo methods.

1. Draw a unit square and inscribe a circle within: the area of the circle is $\frac{\pi}{4}$.

2. Uniformly scatter objects of uniform size throughout the square (e.g., grains of rice or sand): they *should* fall inside the circle with probability $\frac{\pi}{4}$.

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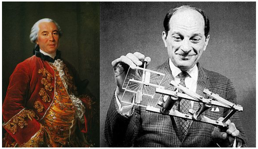

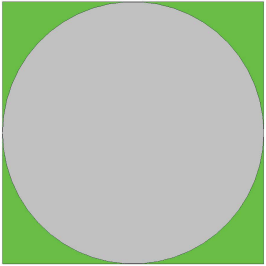

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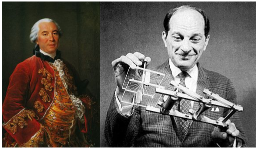

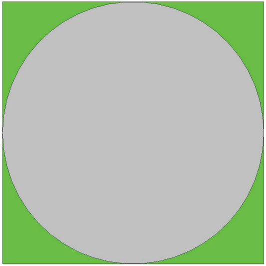

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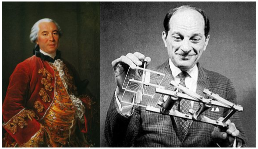

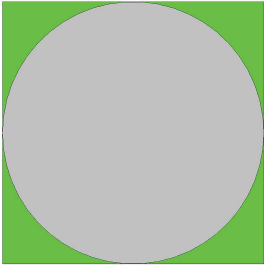

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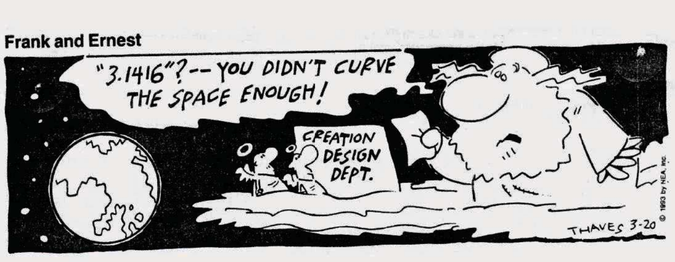
Monte Carlo Methods

- This is a Monte Carlo estimate **(MC)** for π.
- **MC** simulation: slow ($\sqrt{n}$) convergence — but great in parallel on *Beowulf clusters*.
- Used in Manhattan project … the atomic-bomb predates digital computers!



Gauss (1777-1855), Johan Dase and William Shanks



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SKIP

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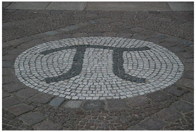

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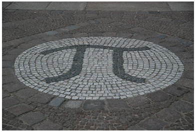

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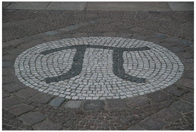

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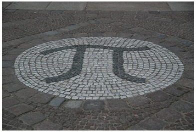

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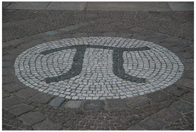

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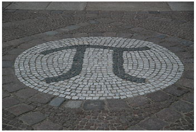

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William Shanks (1812-82): "A Human Computer" (1853)

CONTRIBUTIONS TO MATHEMATICS,

COMPRISING CHIEFLY

THE

RECTIFICATION OF THE CIRCLE

TO 607 PLACES OF DECIMALS.

BY

WILLIAM SHANKS,

HOUGHTON-LE-SPRING, DURHAM.

LONDON:
G. BELL, 186, FLEET-STREET; MACMILLAN & Co., CAMBRIDGE;
ANDREWS, DURHAM.

1853.

PRINTED FOR THE AUTHOR.

TOWARDS the close of the year 1850, the Author first formed the design of rectifying the Circle to upwards of 300 places of decimals. He was fully aware, at that time, that the accomplishment of his purpose would add little or nothing to his fame as a Mathematician, though it might as a Computer; nor would it be productive of anything in the shape of pecuniary recompense at all adequate to the labour of such lengthy computations. He was anxious to fill up scanty intervals of leisure with the achievement of something original, and which, at the same time, should not subject him either to great tension of thought, or to consult books. He is aware that works on nearly every branch of Mathematics are being published almost weekly, both in Europe and America; and that it has therefore become no easy task to ascertain what really is original matter, even in the pure science itself. Beautiful speculations, especially in both Plane and Curved

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A few of the higher powers of 2, as far as 2^{721}, having been obtained in the calculation of $\tan^{-1}\frac{1}{5}$, conclude the volume.

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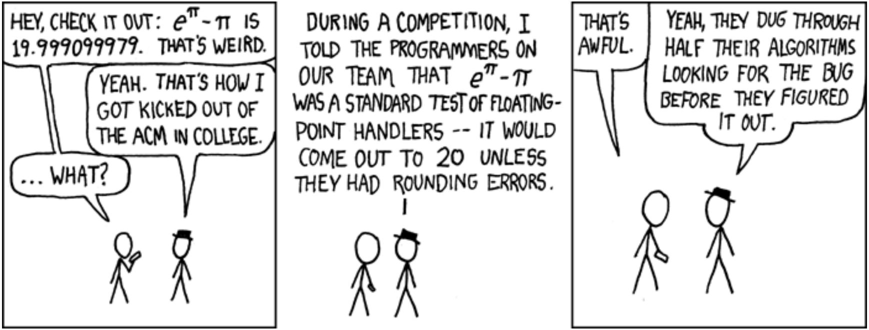

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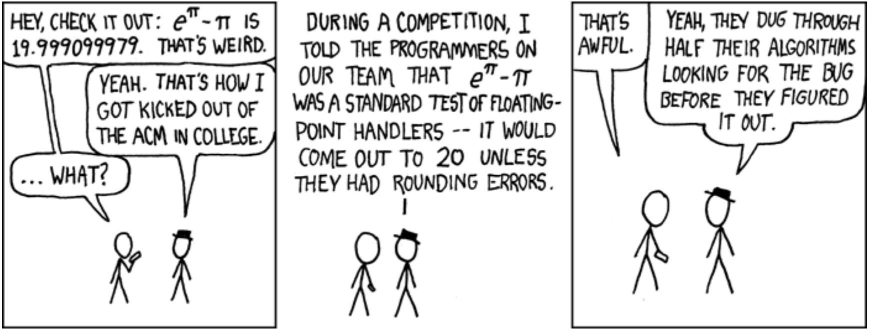

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Number Theoretic Consequences

Lambert (1728-77)

Legendre (1752-1833)

Lindemann (1852-1939)

- Irrationality of π was established by Lambert (**1766**) and then Legendre. Using the continued fraction for $\arctan(x)$

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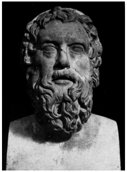
The Three Construction Problems of Antiquity

The other two are doubling the cube and trisecting the angle



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- It cannot, because lengths of lines that can be constructed using ruler and compasses (constructible numbers) are necessarily algebraic, and squaring the circle is equivalent to constructing the value of π.
- Aristophanes (**448-380 BCE**) 'knew' this and derided all 'circle-squarers' in his play The Birds of **414** BCE.

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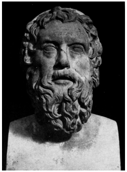


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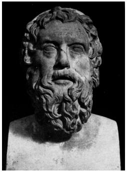

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The Irrationality of π, II

Ivan Niven's 1947 proof that π is irrational. Let $\pi = a/b$, the quotient of positive integers. We define the polynomials

$$f(x) = \frac{x^n(a-bx)^n}{n!}$$

$$F(x) = f(x) - f^{(2)}(x) + f^{(4)}(x) - \cdots + (-1)^n f^{(2n)}(x)$$

the positive integer being specified later. Since $n!f(x)$ has integral coefficients and terms in x of degree not less than n, $f(x)$ and its derivatives $f^{(j)}(x)$ have integral values for $x = 0$; also for $x = \pi = a/b$, since $f(x) = f(a/b - x)$. By elementary calculus we have

$$\begin{aligned} & \frac{d}{dx}\{F'(x)\sin x - F(x)\cos x\} \\ = \quad & F''(x)\sin x + F(x)\sin x = f(x)\sin x \end{aligned}$$

The Irrationality of π, II

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$$\begin{aligned}\int_0^\pi f(x)\sin x dx &= [F'(x)\sin x - F(x)\cos x]_0^\pi \\ &= F(\pi)+F(0). \qquad (10)\end{aligned}$$

Now $F(\pi)+F(0)$ is an *integer*, since $f^{(j)}(0)$ and $f^{(j)}(\pi)$ are integers. But for $0 < x < \pi$,

$$0 < f(x)\sin x < \frac{\pi^n a^n}{n!},$$

so that the integral in (10) is *positive but arbitrarily small* for n sufficiently large. Thus (10) is false, and so is our assumption that π is rational. **QED**

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Richard Parker (L) and Pi Molitor
Ang Lee's 2012 film Life of Pi

> I am a person who believes in form, in harmony of order. Where we can, we must give things a meaningful shape. For example — I wonder — could you tell my jumbled story in exactly one hundred chapters, not one more, not one less? I'll tell you, that's one thing I hate about my nickname, the way that number runs on forever. It's important in life to conclude things properly. Only then can you let go.

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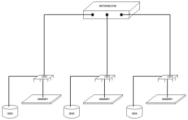
Summation. Why Pi? "Pi is Mount Everest."

What motivates modern computations of π — given that irrationality and transcendence of π were settled a century ago?

- One motivation is the raw challenge of harnessing the stupendous power of modern computer systems.



Programming is quite hard — especially on large, distributed memory computer systems: load balancing, communication needs, etc.

Substantial practical spin-offs accrue:

- Accelerating computations of π sped up the fast Fourier transform (FFT) — heavily used in science and engineering.
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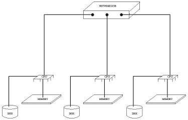

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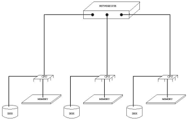

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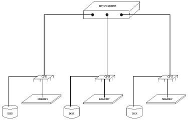

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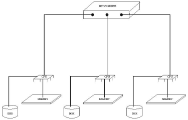

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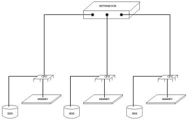

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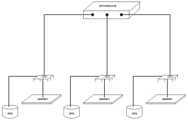

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CARMA

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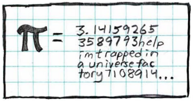

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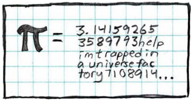

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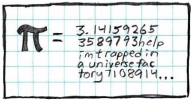

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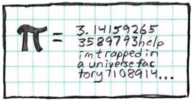

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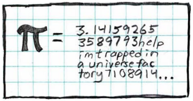

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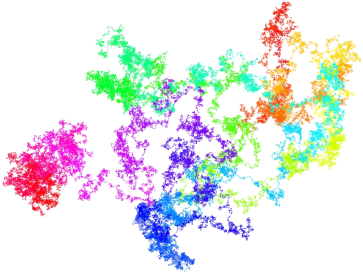
Pi Seems Normal: Things we sort of know about Pi

A walk on a billion hex digits of Pi with *box dimension* 1.85343...



- A 100Gb 100 billion step walk is at http://carma.newcastle.edu.au/walks/
- A Poisson inter-arrival time model applied to 15.925 trillion bits gives: probability Pi is not normal $< 1/10^{3600}$.

D. Bailey, J. Borwein, C. Calude, M. Dinneen, M. Dumitrescu, and A. Yee, "An empirical approach to the normality of pi." *Exp. Math.* **21**(4) (2012), 375–384. DOI 10.1080/10586458.2012.665333.

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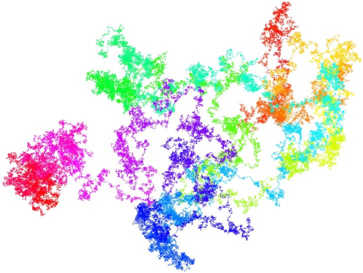

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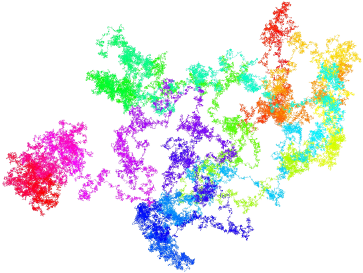

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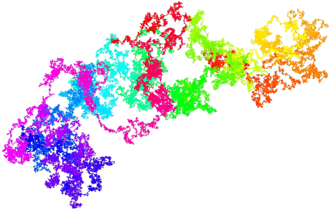
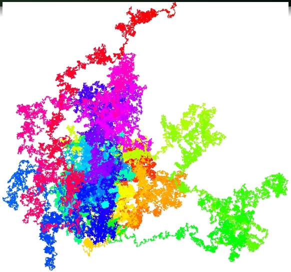
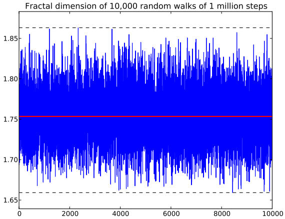
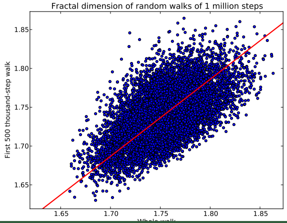
Pi Seems Normal: Some million bit comparisons





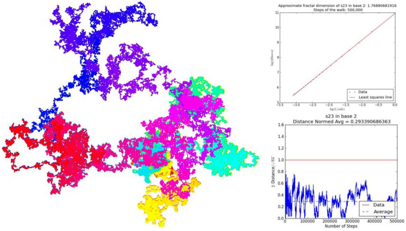
Euler's constant and a pseudo-random number

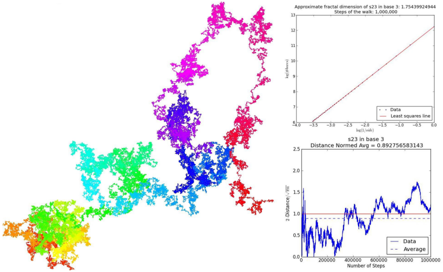




Pi Seems Normal: Comparisons to Stoneham's number $\sum_{k\geq 1} 1/(3^k 2^{3^k})$, I

In base 2 Stoneham's number is provably normal. It may be normal base 3.





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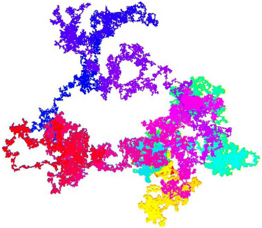
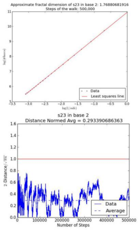
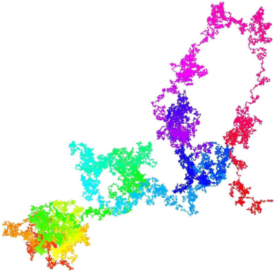
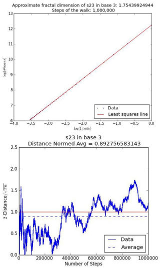


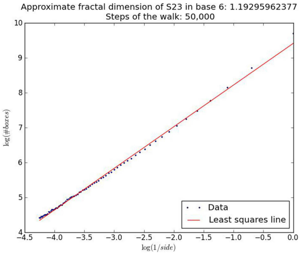


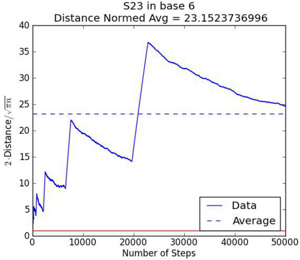




Pi Seems Normal: Comparisons to Stoneham's number, II

Stoneham's number is provably abnormal base 6 (too many zeros).





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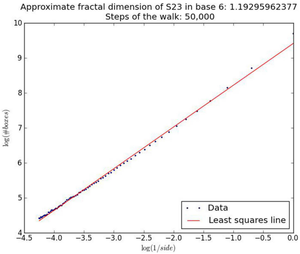

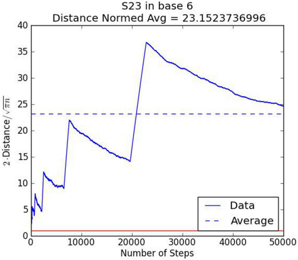

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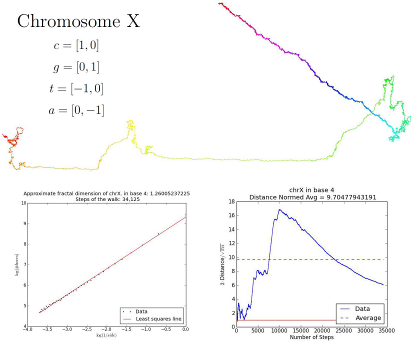
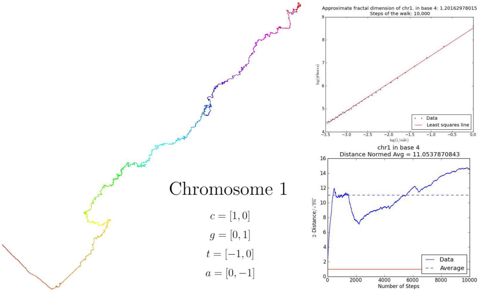
Pi Seems Normal: Comparisons to Human Genomes — we are base 4 no's





The X Chromosome (34K) and Chromosome One (10K).

CARMA

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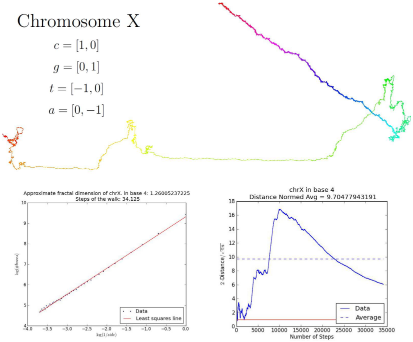

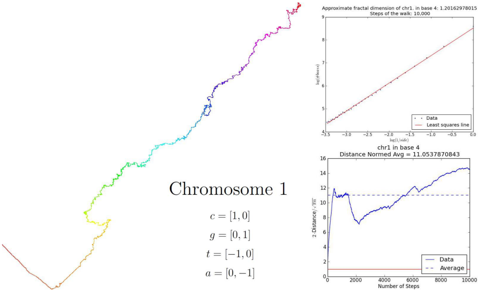

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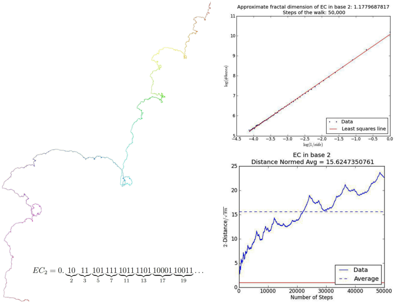
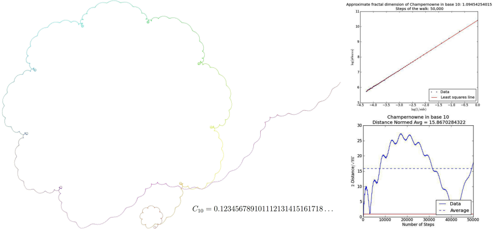
Pi Seems Normal: Comparisons to other provably normal numbers



$EC_2 = 0.\underbrace{10}_{2}\underbrace{11}_{3}\underbrace{101}_{5}\underbrace{111}_{7}\underbrace{1011}_{11}\underbrace{1101}_{13}\underbrace{10001}_{17}\underbrace{10011}_{19}\ldots$



$C_{10} = 0.123456789101112131415161718\ldots$

Erdös-Copeland number (base 2) and Champernowne number (base 10).

All pictures are thanks to Fran Aragon and Jake Fountain
http://www.carma.newcastle.edu.au/numberwalks.pdf

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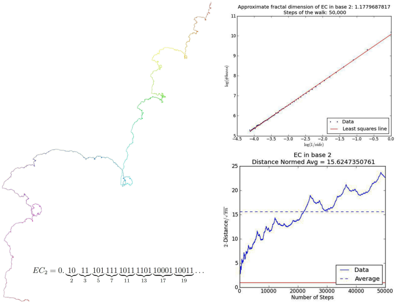

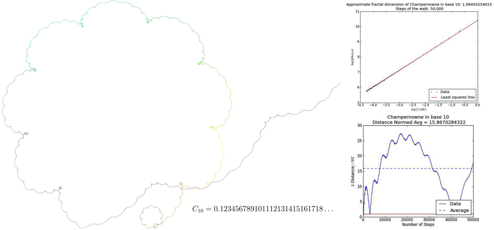

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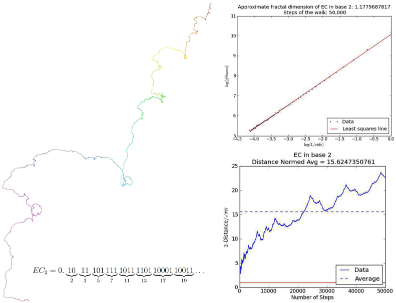

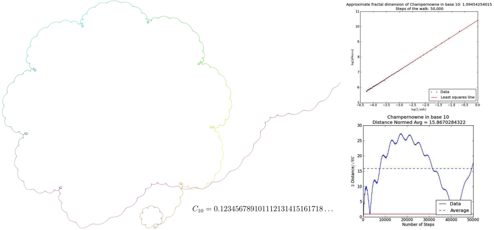

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Pi is Still Mysterious: Things we don't know about Pi

We do not 'know' (in the sense of being able to prove) whether ....

- The simple continued fraction for Pi is unbounded.
  - Euler found the **292**.
- There are infinitely many sevens in the decimal expansion of Pi.
- There are infinitely many ones in the ternary expansion of Pi.
- There are equally many zeroes and ones in the binary expansion of Pi.
- Or pretty much anything I have not told you.

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

$$e = 2 + \cfrac{1}{1 + \cfrac{1}{2 + \cfrac{1}{1 + \cfrac{1}{1 + \cfrac{1}{4 + \cfrac{1}{1 + \cfrac{1}{1 + \cfrac{1}{6 + \cfrac{1}{1 + \ldots}}}}}}}}}$$

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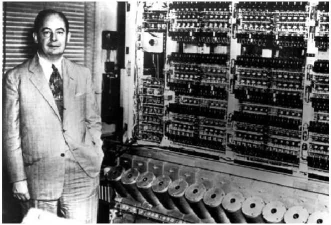
Decimal Digit Frequency: and "Johnny" von Neumann

IBM ▸ SKIP

1st von Neumann architecture machine



JvN (1903-57) at the Institute for Advanced Study

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

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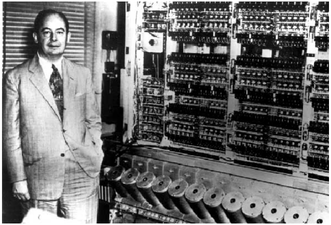

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8	100000791469
9	99999854780
Total	**1000000000000**

CARMA

Hexadecimal Digit Frequency: and Richard Crandall (Apple HPC)

0	62499881108
1	62500212206
2	62499924780
3	62500188844
4	62499807368
5	62500007205
6	62499925426
7	62499878794
8	62500216752
9	62500120671
A	62500266095
B	62499955595
C	62500188610
D	62499613666
E	62499875079
F	62499937801

(1947–2012)

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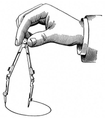
Changing Cognitive Tastes



Why in antiquity π was not *measured* to greater accuracy than $22/7$ (with rope)?

It reflects not an inability, but rather a very different mindset to a modern (Baconian) experimental one — see Francis Bacon's *De augmentis scientiarum* (1623).

- Gauss and Ramanujan did not exploit their identities for π.
  - An algorithm, as opposed to a closed form, was unsatisfactory to them — especially Ramanujan. He preferred

$$\frac{3}{\sqrt{163}}\log(640320) \approx \pi \qquad \text{and} \qquad \frac{3}{\sqrt{67}}\log(5280) \approx \pi$$

correct to 15 and 9 decimal places respectively.

CARMA

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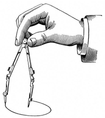

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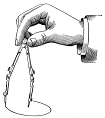

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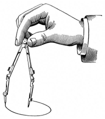

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Changing Cognitive Tastes: Truth without Proof

Gourevich used integer relation computer methods to find the Ramanujan-type series — discussed below — in (11):

$$\frac{4}{\pi^3} \stackrel{?}{=} \sum_{n=0}^{\infty} r(n)^7 (1 + 14n + 76n^2 + 168n^3) \left(\frac{1}{8}\right)^{2n+1} \tag{11}$$

where $r(n) := \frac{1}{2} \cdot \frac{3}{4} \cdot \cdots \cdot \frac{2n-1}{2n}$.

- I can "discover" it using **30**-digit arithmetic. and check it to **1,000** digits in **0.75** sec, **10,000** digits in **4.01** min with two naive command-line instructions in *Maple*.
  - No one has any inkling of how to prove it.
  - I "know" the beautiful identity is true — it would be more remarkable were it eventually to fail.
  - It may be true for no good reason — it might just have no proof and be a very concrete Gödel-like statement.

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Pi in High Culture (1993)

The admirable number pi:
three point one four one.
All the following digits are also initial,
five nine two because it never ends.
It can't be comprehended *six five three five* at a glance,
eight nine by calculation,
seven nine or imagination,
not even *three two three eight* by wit, that is, by comparison
four six to anything else
two six four three in the world.
The longest snake on earth calls it quits at about forty feet.
Likewise, snakes of myth and legend, though they may hold out a bit longer.
The pageant of digits comprising the number pi
doesn't stop at the page's edge.
It goes on across the table, through the air,
over a wall, a leaf, a bird's nest, clouds, straight into the sky,
through all the bottomless, bloated heavens.

Oh how brief - a mouse tail, a pigtail - is the tail of a comet!
How feeble the star's ray, bent by bumping up against space!
While here we have *two three fifteen three hundred nineteen*
my phone number your shirt size the year
nineteen hundred and seventy-three the sixth floor
the number of inhabitants sixty-five cents
hip measurement two fingers a charade, a code,
in which we find *hail to thee, blithe spirit, bird thou never wert*
alongside *ladies and gentlemen, no cause for alarm*,
as well as *heaven and earth shall pass away*,
but not the number pi, oh no, nothing doing,
it keeps right on with its rather remarkable *five*,
its uncommonly fine *eight*,
its far from final *seven*,
nudging, always nudging a sluggish eternity
to continue.

1996 Nobel Wislawa Szymborska (2-7-1923 1-2-2012)

CARMA

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Newton Method Illustrated in Maple for 1/7

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> restart:Digits:=100:N:=x->x+x*(1-7*x);
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$$N := x \to x + x\,(1 - 7\,x)$$

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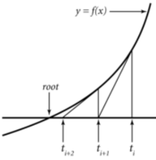

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1. Newton's method is self-correcting and quadratically convergent.
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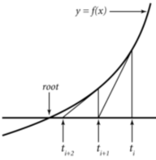

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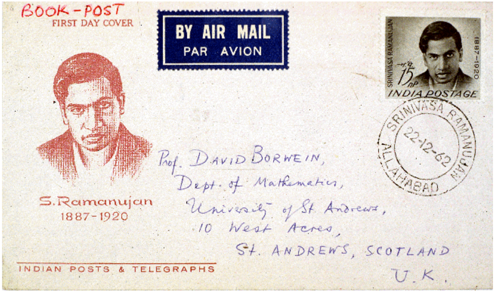

Ramanujan's Seventy-Fifth Birthday Stamp.

- Truly new infinite series formulas were discovered by the self-taught Indian genius Srinivasa Ramanujan around **1910**.
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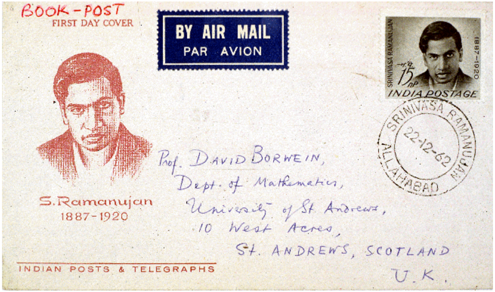

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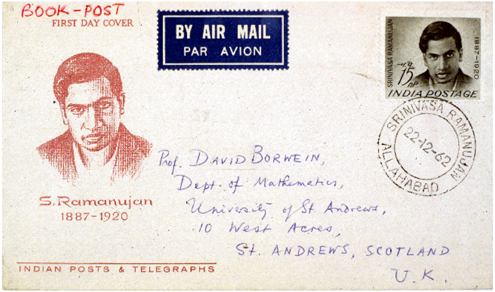

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Ramanujan Series for $1/\pi$ See "Ramanujan at 125", *Notices* 2012-13

One of these series is the remarkable:

$$\frac{1}{\pi} = \frac{2\sqrt{2}}{9801}\sum_{k=0}^{\infty}\frac{(4k)!\,(\mathbf{1103}+26390k)}{(k!)^4 396^{4k}} \qquad (12)$$

- Each term adds an additional **eight** correct digits.

◇ **1985**. 'Hacker' Bill Gosper used (12) to compute **17 million digits** of (the continued fraction for) π; and so the first proof of (12) !

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$$\frac{1}{\pi} = 12\sum_{k=0}^{\infty}\frac{(-1)^k\,(6k)!(13591409+545140134k)}{(3k)!\,(k!)^3\,640320^{3k+3/2}} \qquad (13)$$

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allows one to compute the billionth binary digit of $1/\pi$, or the like, *without computing the first half* of the series.

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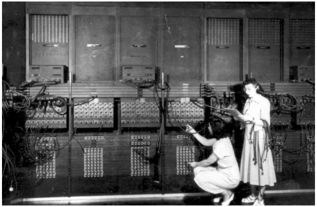

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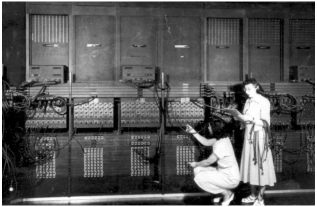

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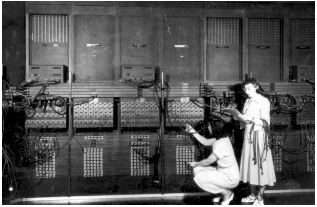

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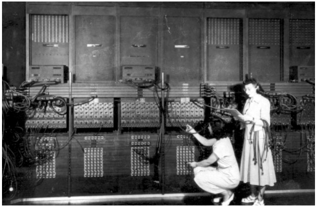

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$$x \sum_{n=0}^{\infty} \frac{(n!)^2\, 4^n}{(2\,n+1)!\, (x^2+1)^{n+1}} \quad = \quad \arctan\left(\frac{1}{x}\right).$$

As $10\left(18^2+1\right) = 57^2+1 = 3250$ we may rewrite the formula

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

used by Shanks and Wrench in **1961** for **100,000** digits, and by Guilloud and Boyer in **1973** for a million digits of Pi in the efficient form

$$\pi = 864 \sum_{n=0}^{\infty} \frac{(n!)^2\, 4^n}{(2\,n+1)!\, \mathbf{325}^{n+1}} + 1824 \sum_{n=0}^{\infty} \frac{(n!)^2\, 4^n}{(2\,n+1)!\, \mathbf{3250}^{n+1}} - 20\arctan\left(\frac{1}{239}\right)$$

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Shanks (the 2nd) and Wrench: "A Million Decimals?" (1961)

Calculation of π to 100,000 Decimals

By Daniel Shanks and John W. Wrench, Jr.

1. Introduction. The following comparison of the previous calculations of π performed on electronic computers shows the rapid increase in computational speeds which has taken place.

Author		Machine	Date	Precision	Time
Reitwiesner	[1]	ENIAC	1949	2037D	70 hours
Nicholson & Jeenel	[2]	NORC	1954	3089D	13 min.
Felton	[3]	Pegasus	1958	10000D	33 hours
Genuys	[4]	IBM 704	1958	10000D	100 min.
Unpublished	[5]	IBM 704	1959	16167D	4.3 hours

All these computations, except Felton's, used Machin's formula:

(1) $$\pi = 16 \tan^{-1} \tfrac{1}{5} - 4 \tan^{-1} \tfrac{1}{239}.$$

Other things being equal, that is, assuming the use of the same machine and the same program, an increase in precision by a factor f requires f times as much memory, and f^2 times as much machine time. For example, a hypothetical computation of π to 100,000D using Genuys' program would require 167 hours on an IBM 704 system and more than 38,000 words of core memory. However, since the latter is not available, the program would require modification, and this would extend the running time. Further, since the probability of a machine error would be more than 100 times that during Genuys' computation, prudence would require still other program modifications, and, therefore, still more machine time.

5. A Million Decimals? Can π be computed to 1,000,000 decimals with the computers of today? From the remarks in the first section we see that the program which we have described would require times of the order of *months*. But since the memory of a 7090 is too small, by a factor of ten, a modified program, which writes and reads partial results, would take longer still. One would really want a computer 100 times as fast, 100 times as reliable, and with a memory 10 times as large. No such machine now exists.

There are, of course, many other formulas similar to (1), (2), and (5), and other programming devices are also possible, but it seems unlikely that any such modification can lead to more than a rather small improvement.

Are there *entirely different* procedures? This is, of course, possible. We cite the following: compute $1/\pi$ and then take its reciprocal. This sounds fantastic, but, in fact, it can be faster than the use of equation (2). One can compute $1/\pi$ by Ramanujan's formula [8]:

(6) $$\frac{1}{\pi} = \frac{1}{4}\left(\frac{1123}{882} - \frac{22583}{882^3}\,\frac{1}{2}\cdot\frac{1\cdot 3}{4^2} + \frac{44043}{882^5}\,\frac{1\cdot 3}{2\cdot 4}\cdot\frac{1\cdot 3\cdot 5\cdot 7}{4^2\cdot 8^2} - \cdots\right).$$

The first factors here are given by $(-1)^k(1123 + 21460k)$. A binary value of $1/\pi$ equivalent to 100,000D, can be computed on a 7090 using equation (6) in 6 hours instead of the 8 hours required for the application of equation (2).* To reciprocate this value of $1/\pi$ would take about 1 hour. Thus, we can reduce the time required by (2) by an hour. But unfortunately we lose our overlapping check, and, in any case, this small gain is quite inadequate for the present question.

One could hope for a theoretical approach to this question of optimization—a theory of the "*depth*" of numbers—but no such theory now exists. One can guess that e is not as "deep" as π,† but try to prove it!

Such a theory would, of course, take years to develop. In the meantime—say, in 5 to 7 years—such a computer as we suggested above (100 times as fast, 100 times as reliable, and with 10 times the memory) will, no doubt, become a reality. At that time a computation of π to 1,000,000D will not be difficult.

* We have computed $1/\pi$ by (6) to over 5000D in less than a minute.

† We have computed e on a 7090 to 100,265D by the obvious program. This takes 2.5 hours instead of the 8-hour run for π by (2).

CARMA

Shanks (the 2nd) and Wrench: "A Million Decimals?" (1961)

Calculation of π to 100,000 Decimals

By Daniel Shanks and John W. Wrench, Jr.

1. Introduction. The following comparison of the previous calculations of π performed on electronic computers shows the rapid increase in computational speeds which has taken place.

Author		Machine	Date	Precision	Time
Reitwiesner	[1]	ENIAC	1949	2037D	70 hours
Nicholson & Jeenel	[2]	NORC	1954	3089D	13 min.
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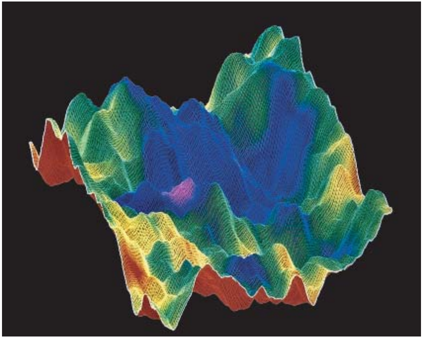
CARMA

The First Million Digits of π



A *random walk* on π (courtesy David and Gregory Chudnovsky)

- See Richard Preston's: "The Mountains of Pi", *New Yorker*, March 2, **1992** (AAAS-Westinghouse Award for Science Journalism);
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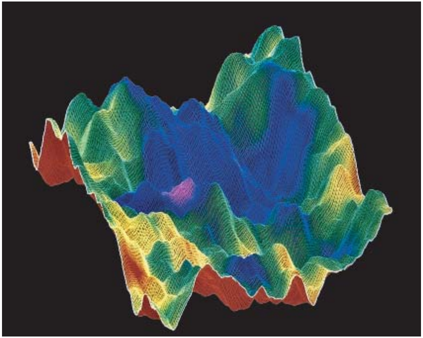

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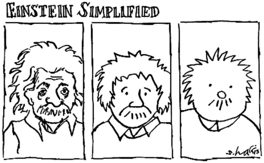
Reduced Complexity Methods

These series are much faster than classical ones, *but* the number of terms needed *still* increases linearly with the number of digits.

Twice as many digits correct requires twice as many terms of the series.



1976. Richard Brent of **ANU-CARMA** and Eugene Salamin independently found a reduced complexity algorithm for π.

– It takes $O(\log N)$ operations for N digits.

– Uses arithmetic-geometric mean iteration (AGM) and other elliptic integral ideas due to Gauss and Legendre circa **1800**.

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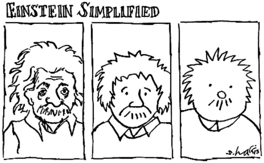

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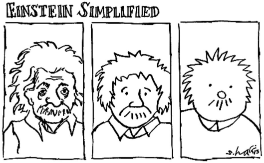

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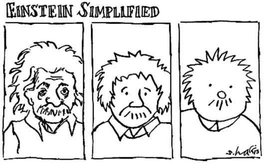

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A Reduced Complexity Algorithm

Algorithm (Brent-Salamin AGM iteration)

Set $a_0 = 1, b_0 = 1/\sqrt{2}$ and $s_0 = 1/2$. Calculate

$$a_k = \frac{a_{k-1} + b_{k-1}}{2} \quad (A) \qquad b_k = \sqrt{a_{k-1} b_{k-1}} \quad (G)$$

$$c_k = a_k^2 - b_k^2, \qquad s_k = s_{k-1} - 2^k c_k$$

$$\text{and compute} \quad p_k = \frac{2a_k^2}{s_k}. \tag{15}$$

Then p_k converges quadratically to π.

- Each step doubles the correct digits — successive steps produce 1, 4, 9, 20, 42, 85, 173, 347 and 697 digits of π.
  - 25 steps compute π to **45 million** digits. But, steps must be performed to the desired precision.

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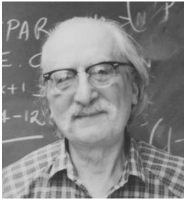
CARMA

Four Famous Pi Guys: Salamin, Kanada, Bailey and Gosper in 1987

- To appear in Donald Knuth's book of mathematics pictures.

And Some Others: Niven, Shanks (1917-96), Brent, Zudilin (⟳)



CARMA

The Borwein Brothers

1985. Peter and I discovered algebraic algorithms of all orders:

Algorithm (Cubic Algorithm)

Set $a_0 = 1/3$ and $s_0 = (\sqrt{3} - 1)/2$. Iterate

$$r_{k+1} = \frac{3}{1 + 2(1 - s_k^3)^{1/3}}, \qquad s_{k+1} = \frac{r_{k+1} - 1}{2}$$

and $$a_{k+1} = r_{k+1}^2 a_k - 3^k(r_{k+1}^2 - 1).$$

Then $1/a_k$ converges cubically to π.

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CARMA

A Fourth Order Algorithm

Algorithm (Quartic Algorithm)

Set $a_0 = 6 - 4\sqrt{2}$ and $y_0 = \sqrt{2} - 1$. Iterate

$$y_{k+1} = \frac{1-(1-y_k^4)^{1/4}}{1+(1-y_k^4)^{1/4}} \quad \text{and}$$

$$a_{k+1} = a_k(1+y_{k+1})^4 - 2^{2k+3}y_{k+1}(1+y_{k+1}+y_{k+1}^2).$$

Then $1/a_k$ converges quartically to π

- Using **4** $\times$ 'plus' **1** $\div$ 'plus' **2** $1/\sqrt{\cdot}$ = **19** full precision $\times$ per step. So **20 steps** costs out at around **400** full precision multiplications.

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CARMA

Modern Calculation Records: and IBM Blue Gene/L at Argonne

IBM

Name	Year	Correct Digits
Miyoshi and Kanada	1981	2,000,036
Kanada-Yoshino-Tamura	1982	16,777,206
Gosper	1985	17,526,200
Bailey	Jan. 1986	29,360,111
Kanada and Tamura	Sep. 1986	33,554,414
Kanada and Tamura	Oct. 1986	67,108,839
Kanada et. al	Jan. 1987	134,217,700
Kanada and Tamura	Jan. 1988	201,326,551
Chudnovskys	May 1989	480,000,000
Kanada and Tamura	Jul. 1989	536,870,898
Kanada and Tamura	Nov. 1989	1,073,741,799
Chudnovskys	Aug. 1991	2,260,000,000
Chudnovskys	May 1994	4,044,000,000
Kanada and Takahashi	Oct. 1995	6,442,450,938
Kanada and Takahashi	Jul. 1997	51,539,600,000
Kanada and Takahashi	Sep. 1999	206,158,430,000
Kanada-Ushiro-Kuroda	Dec. 2002	1,241,100,000,000
Takahashi	Jan. 2009	1,649,000,000,000
Takahashi	April. 2009	2,576,980,377,524
Bellard	Dec. 2009	2,699,999,990,000
Kondo and Yee	Aug. 2010	**5,000,000,000,000**
Kondo and Yee	Oct. 2011	**10,000,000,000,000**
Kondo and Yee	Dec. 2013	**12,200,000,000,000**

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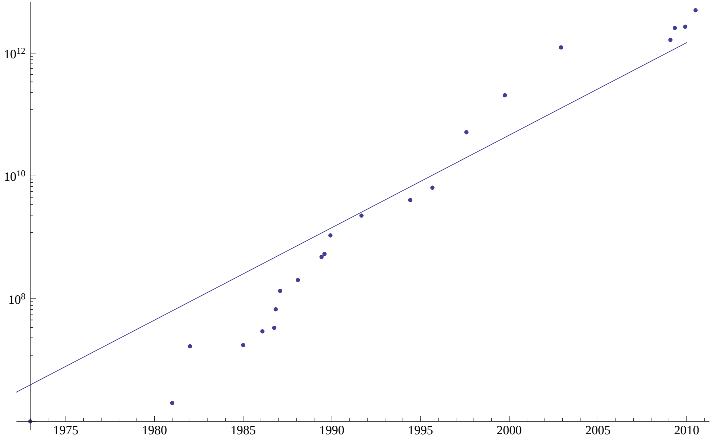
Moore's Law Marches On



Computation of π since 1975 plotted vs. Moore's law predicted increase

An Amazing Algebraic Approximation to π

The **transcendental number** $\boxed{\pi}$ and the **algebraic number** $1/a_{20}$ actually agree for more than **1.5 trillion decimal places**.

- π and $1/a_{21}$ agree for more than **six trillion decimal places.**

1984. I found these on a **16K** upgrade of an 8K double-precision TRS80-100 Radio Shack portable.

- **1986**. A **29 million** digit calculation at NASA Ames — just after the shuttle disaster — uncovered CRAY hardware and software faults.
  - Took 6 months to convince Seymour Cray; then ran on every *CRAY* before it left the factory.
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$$y_1 = \frac{1 - \sqrt[4]{1 - {y_0}^4}}{1 + \sqrt[4]{1 - {y_0}^4}}, a_1 = a_0 (1 + y_1)^4 - 2^3 y_1 \left(1 + y_1 + {y_1}^2\right)$$

$$y_2 = \frac{1 - \sqrt[4]{1 - {y_1}^4}}{1 + \sqrt[4]{1 - {y_1}^4}}, a_2 = a_1 (1 + y_2)^4 - 2^5 y_2 \left(1 + y_2 + {y_2}^2\right)$$

$$y_3 = \frac{1 - \sqrt[4]{1 - {y_2}^4}}{1 + \sqrt[4]{1 - {y_2}^4}}, a_3 = a_2 (1 + y_3)^4 - 2^7 y_3 \left(1 + y_3 + {y_3}^2\right)$$

$$y_4 = \frac{1 - \sqrt[4]{1 - {y_3}^4}}{1 + \sqrt[4]{1 - {y_3}^4}}, a_4 = a_3 (1 + y_4)^4 - 2^9 y_4 \left(1 + y_4 + {y_4}^2\right)$$

$$y_5 = \frac{1 - \sqrt[4]{1 - {y_4}^4}}{1 + \sqrt[4]{1 - {y_4}^4}}, a_5 = a_4 (1 + y_5)^4 - 2^{11} y_5 \left(1 + y_5 + {y_5}^2\right)$$

$$y_6 = \frac{1 - \sqrt[4]{1 - {y_5}^4}}{1 + \sqrt[4]{1 - {y_5}^4}}, a_6 = a_5 (1 + y_6)^4 - 2^{13} y_6 \left(1 + y_6 + {y_6}^2\right)$$

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$$y_8 = \frac{1 - \sqrt[4]{1 - {y_7}^4}}{1 + \sqrt[4]{1 - {y_7}^4}}, a_8 = a_7 (1 + y_8)^4 - 2^{17} y_8 \left(1 + y_8 + {y_8}^2\right)$$

$$y_9 = \frac{1 - \sqrt[4]{1 - {y_8}^4}}{1 + \sqrt[4]{1 - {y_8}^4}}, a_9 = a_8 (1 + y_9)^4 - 2^{19} y_9 \left(1 + y_9 + {y_9}^2\right)$$

$$y_{10} = \frac{1 - \sqrt[4]{1 - {y_9}^4}}{1 + \sqrt[4]{1 - {y_9}^4}}, a_{10} = a_9 (1 + y_{10})^4 - 2^{21} y_{10} \left(1 + y_{10} + {y_{10}}^2\right)$$

$a_0 = 6 - 4\sqrt{2}$, $y_0 = \sqrt{2} - 1$

$$y_1 = \frac{1 - \sqrt[4]{1 - {y_0}^4}}{1 + \sqrt[4]{1 - {y_0}^4}}, a_1 = a_0 (1 + y_1)^4 - 2^3 y_1 \left(1 + y_1 + {y_1}^2\right)$$

$$y_2 = \frac{1 - \sqrt[4]{1 - {y_1}^4}}{1 + \sqrt[4]{1 - {y_1}^4}}, a_2 = a_1 (1 + y_2)^4 - 2^5 y_2 \left(1 + y_2 + {y_2}^2\right)$$

$$y_3 = \frac{1 - \sqrt[4]{1 - {y_2}^4}}{1 + \sqrt[4]{1 - {y_2}^4}}, a_3 = a_2 (1 + y_3)^4 - 2^7 y_3 \left(1 + y_3 + {y_3}^2\right)$$

$$y_4 = \frac{1 - \sqrt[4]{1 - {y_3}^4}}{1 + \sqrt[4]{1 - {y_3}^4}}, a_4 = a_3 (1 + y_4)^4 - 2^9 y_4 \left(1 + y_4 + {y_4}^2\right)$$

$$y_5 = \frac{1 - \sqrt[4]{1 - {y_4}^4}}{1 + \sqrt[4]{1 - {y_4}^4}}, a_5 = a_4 (1 + y_5)^4 - 2^{11} y_5 \left(1 + y_5 + {y_5}^2\right)$$

$$y_6 = \frac{1 - \sqrt[4]{1 - {y_5}^4}}{1 + \sqrt[4]{1 - {y_5}^4}}, a_6 = a_5 (1 + y_6)^4 - 2^{13} y_6 \left(1 + y_6 + {y_6}^2\right)$$

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$$y_8 = \frac{1 - \sqrt[4]{1 - {y_7}^4}}{1 + \sqrt[4]{1 - {y_7}^4}}, a_8 = a_7 (1 + y_8)^4 - 2^{17} y_8 \left(1 + y_8 + {y_8}^2\right)$$

$$y_9 = \frac{1 - \sqrt[4]{1 - {y_8}^4}}{1 + \sqrt[4]{1 - {y_8}^4}}, a_9 = a_8 (1 + y_9)^4 - 2^{19} y_9 \left(1 + y_9 + {y_9}^2\right)$$

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CARMA

$$y_{11} = \frac{1-\sqrt[4]{1-{y_{10}}^4}}{1+\sqrt[4]{1-{y_{10}}^4}}, a_{11} = a_{10}\left(1+y_{11}\right)^4 - 2^{23} y_{11}\left(1+y_{11}+{y_{11}}^2\right)$$

$$y_{12} = \frac{1-\sqrt[4]{1-{y_{11}}^4}}{1+\sqrt[4]{1-{y_{11}}^4}}, a_{12} = a_{11}\left(1+y_{12}\right)^4 - 2^{25} y_{12}\left(1+y_{12}+{y_{12}}^2\right)$$

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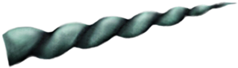
- Since **1988** used, with Salamin-Brent, by Kanada's Tokyo team. Including: π to **200 billion** decimal digits in **1999** ... and records in **2009**.



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- In **1997** the *first occurrence of the sequence* **0123456789** was found (late) in the decimal expansion of π starting at the $\mathbf{17,387,594,880}$-th digit after the decimal point.
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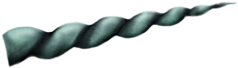

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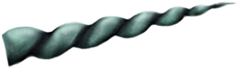

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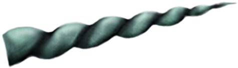

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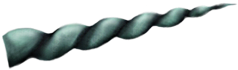

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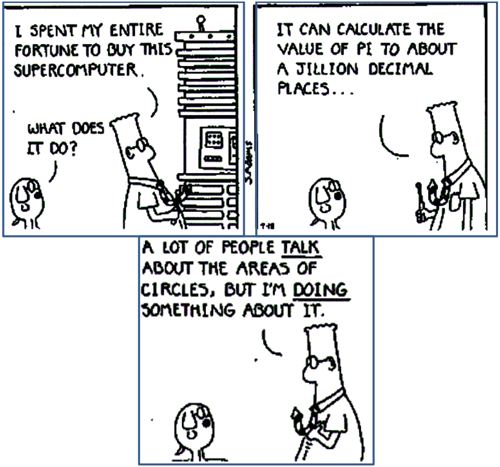
Billions and Billions



Star Trek

Kirk asks:

> *"Aren't there some mathematical problems that simply can't be solved?"*

And Spock 'fries the brains' of a rogue computer by telling it:

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Pi the Song: from the album Aerial

2005 Influential Singer-songwriter *Kate Bush* sings "Pi" on Aerial.

Sweet and gentle and sensitive man
With an obsessive nature and deep fascination
for numbers
And a complete infatuation
with the calculation of Pi
Chorus: Oh he love, he love, he love
He does love his numbers
And they run, they run, they run him
In a great big circle
In a circle of infinity

"a sentimental ode to a mathematician, audacious in both subject matter and treatment. The chorus is the number sung to many, many decimal places." [**150** – wrong after 50] — Observer Review

CARMA

Back to the Future

2002. Kanada computed π to over **1.24 trillion decimal digits**. His team first computed π in **hex** (base 16) to **1,030,700, 000,000** places, using good old Machin type relations:

$$\pi = 48\tan^{-1}\frac{1}{49} + 128\tan^{-1}\frac{1}{\mathbf{57}} - 20\tan^{-1}\frac{1}{\mathbf{239}} + 48\tan^{-1}\frac{1}{110443}$$

(Takano, pop-song writer **1982**)

$$\pi = 176\tan^{-1}\frac{1}{\mathbf{57}} + 28\tan^{-1}\frac{1}{\mathbf{239}} - 48\tan^{-1}\frac{1}{682} + 96\tan^{-1}\frac{1}{12943}$$

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CARMA

Yasumasa Kanada

3.141592653589793238462643383279502884197169399375105820974944592307816406286208998628034825342117068

$\leftrightsquigarrow$

11.00100100001111110110101010001000100001011010001100001000110100110001001100011001100010100010111000

- The decimal expansion was checked by converting it back to hex.
  - Base conversion require pretty massive computation.
- **Six times** as many digits as before: hex and decimal ran **600** hrs on same 64-node Hitachi — at roughly **1 Tflop/sec** (2002).
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- First in hexadecimal using the Chudnovsky series;
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This took **131 days** but he only used a single 4-core workstation with a lot of storage and even more human intelligence!

- For full details of this feat and of Takahashi's most recent computation one can look at Wikipedia

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  /wiki/Chronology_of_computation_of_pi

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Shiguro Kendo and Alex Yee: What is the Limit?

- August **2010**. On a home built **$18,000** machine, Kondo (hardware engineer, below) and Yee (undergrad software) nearly doubled this to **5,000,000,000,000** places. The last 30 are

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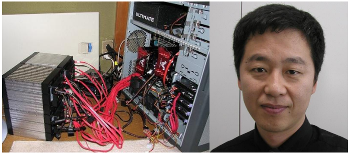

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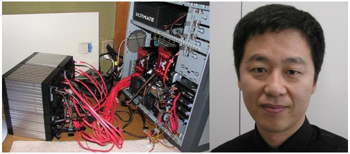

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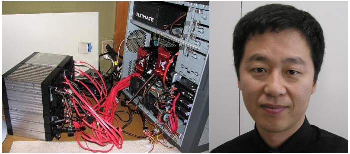

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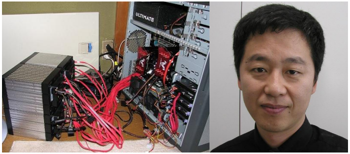

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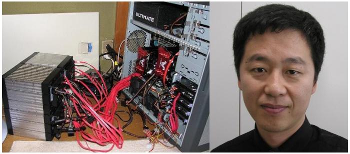

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Two New Pi Guys: Alex Yee and his Elephant

♠ The elephant may have provided extra memory?

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Two New Pi Guys: Mario Livio (JPL) in 01-31-2013 *HuffPost*

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Astrophysicist, Space Telescope Science Institute

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There is probably no number in mathematics (with the possible exception of 0) that is more celebrated than the one equal to the ratio of a circle's circumference to its diameter. This number is denoted by the Greek letter π (pi). Pi is approximately equal to 3.14159, but its decimal representation neither ends nor settles into a repeating pattern. In fact, on Oct. 16, 2011, Alexander J. Yee and Shigeru Kondo completed the task of using a custom-built computer (shown in Fig. 1) for 371 days, to calculate π to 10 trillion digits! To appreciate this accuracy, let me note that if we wanted to express the radius of the observable universe in terms of the radius of the hydrogen atom, about 40 digits would have sufficed.

Figure 1. The computer used by Alexander Yee and Shigeru Kondo to calculate π to 10 trillion digits (reproduced by permission from Alexander Yee)

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Computing Individual Digits of π

TOC IBM

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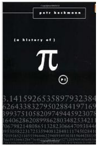

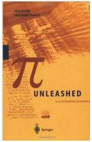

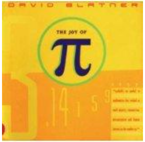

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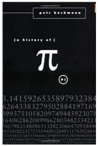

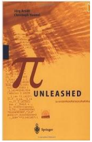

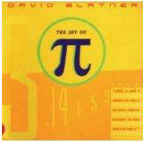

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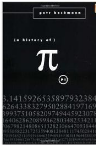

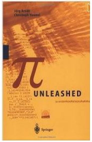

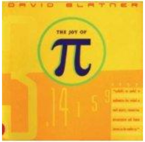

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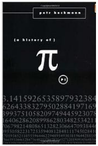

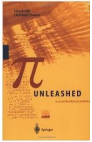

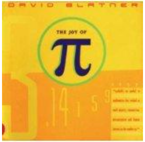

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Prior to **1996**, most folks thought to compute the d-th digit of π, you had to generate the (order of) the entire first d digits.

- **This is not true**, at least for hex (base 16) or binary (base 2) digits of π. In **1996**, P. Borwein, Plouffe, and Bailey found an algorithm for individual hex digits of π. It produces:

- a modest-length string hex or binary digits of π, beginning at an any position, *using no prior bits*;
  1. is implementable on any modern computer;
  2. requires no multiple precision software;
  3. requires very little memory; and has
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What BBP Is? Reverse Engineered Mathematics

This is based on the following then new formula for π:

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

- The millionth hex digit (four millionth binary digit) of π can be found in under **30** secs on a fairly new computer in Maple (not C++) and the billionth in **10** hrs.

Equation (16) was discovered numerically using integer relation methods over months in our Vancouver lab, **CECM**. It arrived in the coded form:

$$\pi = 4\,{}_2F_1\left(1, \frac{1}{4}; \frac{5}{4}, -\frac{1}{4}\right) + 2\tan^{-1}\left(\frac{1}{2}\right) - \log 5$$

where ${}_2F_1(1, 1/4; 5/4, -1/4) = 0.955933837\ldots$ is a Gauss hypergeometric function.

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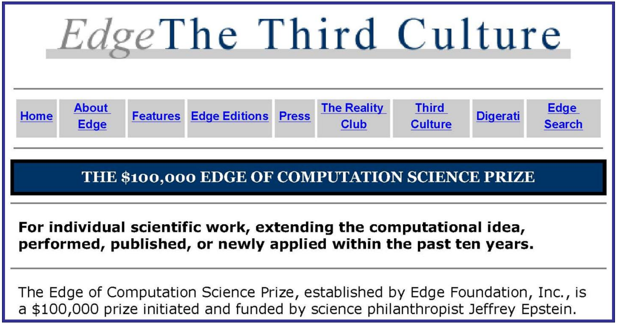
Edge of Computation Prize Finalist



- BBP was the only mathematical finalist (of about 40) for the first **Edge of Computation Science Prize**
  - Along with founders of Google, Netscape, Celera and many brilliant thinkers, ...
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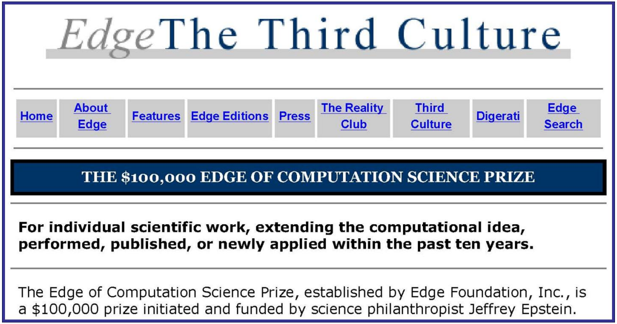

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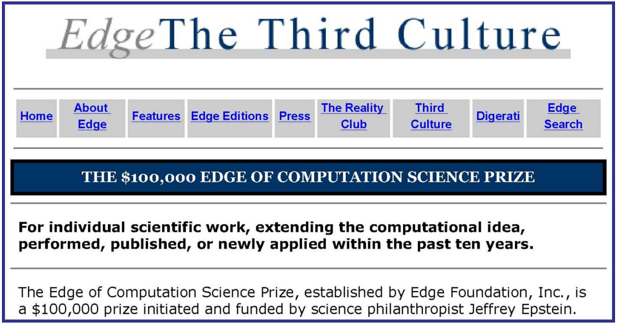

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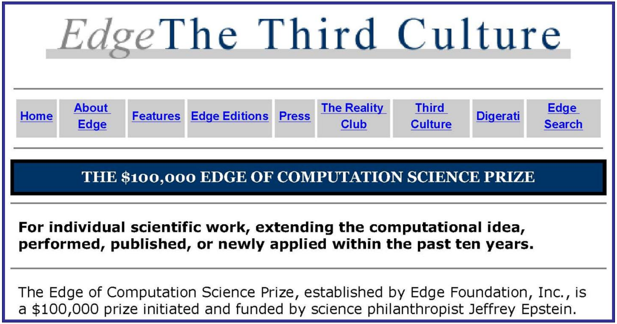

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BBP Formula Database http://carma.newcastle.edu.au/bbp

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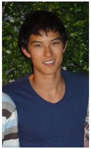

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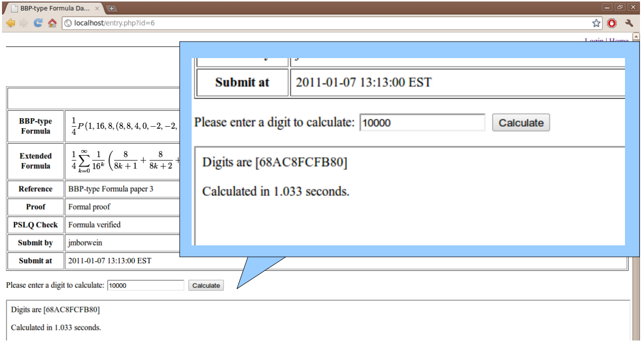

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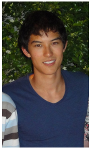

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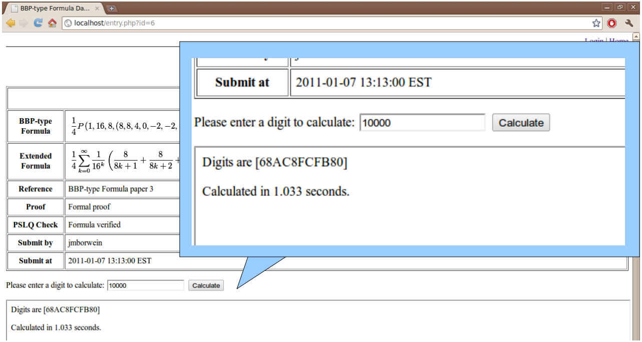

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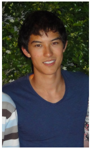

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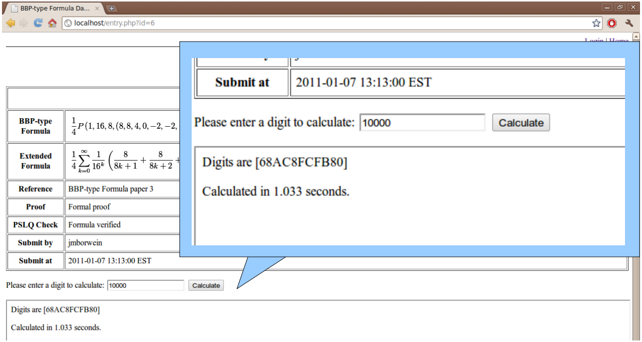

Mathematical Interlude: III. (Maple, Mathematica and Human)

Proof of (16). For $0 < k < 8$,

$$\int_0^{1/\sqrt{2}} \frac{x^{k-1}}{1-x^8}\,dx = \int_0^{1/\sqrt{2}} \sum_{i=0}^{\infty} x^{k-1+8i}\,dx = \frac{1}{2^{k/2}} \sum_{i=0}^{\infty} \frac{1}{16^i(8i+k)}.$$

Thus, one can write

$$\sum_{i=0}^{\infty} \frac{1}{16^i}\left(\frac{4}{8i+1} - \frac{2}{8i+4} - \frac{1}{8i+5} - \frac{1}{8i+6}\right) = \int_0^{1/\sqrt{2}} \frac{4\sqrt{2} - 8x^3 - 4\sqrt{2}x^4 - 8x^5}{1-x^8}\,dx,$$

which on substituting $y := \sqrt{2}x$ becomes

$$\int_0^1 \frac{16\,y - 16}{y^4 - 2\,y^3 + 4\,y - 4}\,dy = \int_0^1 \frac{4y}{y^2-2}\,dy - \int_0^1 \frac{4y-8}{y^2-2y+2}\,dy = \pi.$$

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QED

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

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QED

Mathematical Interlude: III. (Maple, Mathematica and Human)

Proof of (16). For $0 < k < 8$,

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Tuning BBP Computation

- **1997**. Fabrice Bellard of INRIA computed 152 bits of π starting at the trillionth position;
  - in 12 days on 20 workstations working in parallel over the Internet.

Bellard used the following variant of (16):

$$\pi = 4\sum_{k=0}^{\infty}\frac{(-1)^k}{4^k(2k+1)} - \frac{1}{64}\sum_{k=0}^{\infty}\frac{(-1)^k}{1024^k}\left(\frac{32}{4k+1}+\frac{8}{4k+2}+\frac{1}{4k+3}\right) \quad (17)$$

This frequently-used formula is a little faster than (16).

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Hexadecimal Digits

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2000. He then found the quadrillionth binary digit is **0**.

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Position	Hex Digits
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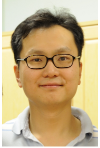
Everything Doubles Eventually



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Abstract

We present a new record on computing specific bits of π, the mathematical constant, and discuss performing such computations on Apache Hadoop clusters. The new record represented in hexadecimal is

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which has **256 bits** ending at the $2,000,000,000,000,000,252^{th}$ bit position. The position of the first bit is $1,999,999,999,999,997$ and the value of the two quadrillionth bit is 0.

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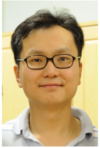

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August 27, 2012 Ed Karrel found 25 hex digits of π starting *after* the 10^{15} position

- They are $353CB3F7F0C9ACCFA9AA215F2$
- Using BBP on *CUDA* (too 'hard' for Blue Gene)
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OCTOPI

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BBP Formulas Explained

Base-b BBP numbers are constants of the form

$$\alpha = \sum_{k=0}^{\infty} \frac{p(k)}{q(k)b^k}, \tag{18}$$

where $p(k)$ and $q(k)$ are integer polynomials and $b = 2, 3, \ldots$.

- I illustrate why this works in binary for $\log 2$. We start with:

$$\log 2 = \sum_{k=0}^{\infty} \frac{1}{k2^k} \tag{19}$$

as discovered by Euler.

- We wish to compute digits *beginning* at position $d + 1$.
- Equivalently, we need $\{2^d \log 2\}$ ($\{\cdot\}$ is the fractional part).

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CARMA

BBP Formula for $\log 2$

We can write

$$\begin{aligned} \{2^d \log 2\} &= \left\{\left\{\sum_{k=0}^{d} \frac{2^{d-k}}{k}\right\} + \left\{\sum_{k=d+1}^{\infty} \frac{2^{d-k}}{k}\right\}\right\} \\ &= \left\{\left\{\sum_{k=0}^{d} \frac{\mathbf{2^{d-k} \bmod k}}{k}\right\} + \left\{\sum_{k=d+1}^{\infty} \frac{\mathbf{2^{d-k}}}{\mathbf{k}}\right\}\right\}. \end{aligned} \quad (20)$$

- The key: the numerator in (20), $2^{d-k} \bmod k$, can be found rapidly by binary exponentiation, performed modulo k. So,

$$3^{17} = ((((3^2)^2)^2)^2) \cdot 3$$

uses only **5** multiplications, not the usual **16**. Moreover, $3^{17} \bmod 10$ is done as $3^2 = 9; 9^2 = 1; 1^2 = 1; 1^2 = 1; 1 \times 3 = 3$

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Catalan's Constant G: and BBP for G in Binary

The simplest number not proven irrational is

$$G := 1 - \frac{1}{3^2} + \frac{1}{5^2} - \frac{1}{7^2} + \cdots, \qquad \frac{\pi^2}{12} = 1 + \frac{1}{3^2} + \frac{1}{5^2} + \frac{1}{7^2} + \cdots$$

2009. G is calculated to **31.026** billion digits. Records often use:

$$G = \frac{3}{8}\sum_{n=0}^{\infty} \frac{1}{\binom{2n}{n}(2n+1)^2} + \frac{\pi}{8}\log(2+\sqrt{3}) \text{ (Ramanujan)} \tag{21}$$

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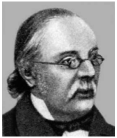

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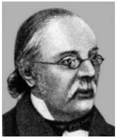

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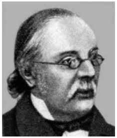

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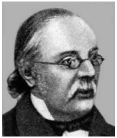

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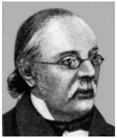

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A Better Formula for G

A **16** term formula in concise BBP notation is:

$$\begin{aligned} G &= P\left(2, \mathbf{4096}, 24, \vec{v}\right) \qquad \text{where} \\ \vec{v} &:= (6144, -6144, -6144, 0, -1536, -3072, -768, 0, -768, \\ &\quad -384, 192, 0, -96, 96, 96, 0, 24, 48, 12, 0, 12, 6, -3, 0) \end{aligned}$$

It takes almost exactly **8/9**th the time of **18** term formula for G.

- This makes for a very cool calculation
- Since we can not prove G is irrational, *Who can say what might turn up*?

CARMA

What About Base Ten?

- The first integer logarithm with no known binary BBP formula is $\log 23$ (since $23 \times 89 = 2^{10} - 1$).

Searches conducted by numerous researchers for base-ten formulas have been unfruitful. Indeed:

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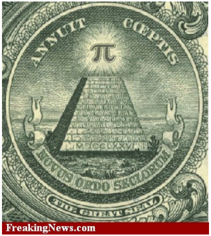
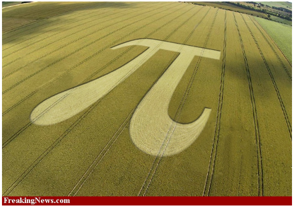
Pi Photo-shopped: a 2010 PiDay Contest





"Noli Credere Pictis"

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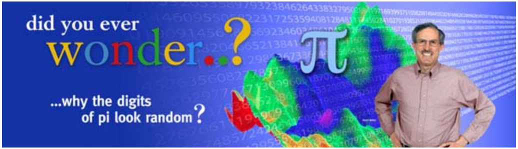
π^2 in Binary and Ternary

Bailey and Pi on a bus. Only in Berkeley?



Thanks to Dave Broadhurst, a ternary BBP formula exists for π^2 (unlike π):

$$\pi^2 = \frac{2}{27}\sum_{k=0}^{\infty}\frac{1}{3^{6k}} \times \left\{\frac{243}{(12k+1)^2} - \frac{405}{(12k+2)^2} - \frac{81}{(12k+4)^2} - \frac{27}{(12k+5)^2} - \frac{72}{(12k+6)^2} - \frac{9}{(12k+7)^2} - \frac{9}{(12k+8)^2} - \frac{5}{(12k+10)^2} + \frac{1}{(12k+11)^2}\right\}$$

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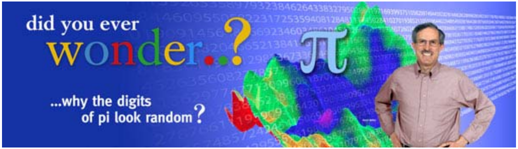

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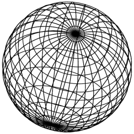
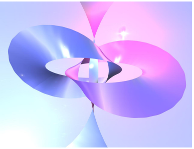
$$\pi^2 = \frac{9}{8}\sum_{k=0}^{\infty}\frac{1}{2^{6k}}\left\{\frac{16}{(6k+1)^2}-\frac{24}{(6k+2)^2}-\frac{8}{(6k+3)^2}-\frac{6}{(6k+4)^2}+\frac{1}{(6k+5)^2}\right\}$$

- We do not fully understand why π^2 allows BBP formulas in two distinct bases.





- $4\pi^2$ is the area of a sphere in three-space (L).
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  - So in binary we are computing these fundamental physical constants.

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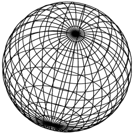

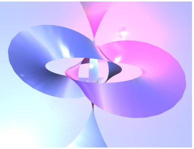

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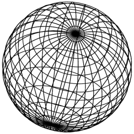

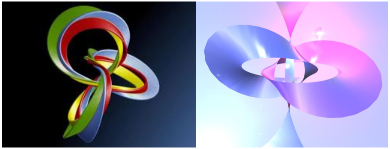

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IBM's New Record Results

Algorithm (What We Did)

Dave Bailey, Andrew Mattingly (L) and Glenn Wightwick (R) of IBM Australia, and I, have obtained and (nearly) confirmed:

1. **106** digits of π^2 base **2** at the **ten trillion**th place base **64**
2. **94** digits of π^2 base **3** at the **ten trillion**th place base **729**
3. **150** digits of G base **2** at the **ten trillion**th place base **4096**

on a 4-rack BlueGene/P system at IBM's Benchmarking Centre in Rochester, Minn, USA.

The 3 Records Use Over 1380 CPU Years (135 rack days)

An enormous amount of delicate computation: **1380 years** is a long time. Suppose a spanking new IBM single-core PC went back **1381 years**.

- It would find itself in **632 CE**.
- The year that Mohammed died, and the Caliphate was established. If it then calculated π nonstop:
  - Through the Crusades, black plague, Moguls, Renaissance, discovery of America, Gutenberg, Reformation, invention of steam, Napoleon, electricity, WW2, the transistor, fiber optics,...
- With no breaks or break-downs:
- It would have finished in **2012**.

August 2013, *Notices of the AMS*
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IBM's New Results: π^2 base **2**

Algorithm (10 trillionth digits of π^2 in base 64 — in 230 years)

1. The calculation took, on average, **253529** seconds per thread. It was broken into 7 "partitions" of **2048** threads each. For a total of $7 \cdot 2048 \cdot 253529 = 3.6 \cdot 10^9$ CPU seconds.

2. On a single Blue Gene/P CPU it *would* take **115 years**!

   Each rack of BG/P contains 4096 threads (or cores). Thus, we used $\frac{7 \cdot 2048 \cdot 253529}{4096 \cdot 60 \cdot 60 \cdot 24} =$ **10.3** "rack days".

3. The verification run took the same time (within a few minutes): **106 base 2 digits** are in agreement.

```
base-8 digits = 75|601145053032364757245000057432627545303630524163506634|573227604
                   601145053032364757245000057432627545303630524163506634|22021056612
```

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IBM's New Results: π^2 base **3**

Algorithm (10 trillionth digits of π^2 in base 729 — in **414** years)

1. The calculation took, on average, **795773** seconds per thread. It was broken into 4 "partitions" of **2048** threads each. For a total of $4 \cdot 2048 \cdot 795773 = 6.5 \cdot 10^9$ CPU seconds.
2. On a single Blue Gene/P CPU it *would* take **207 years**!

   Each rack of BG/P contains 4096 threads (or cores). Thus, we used $\frac{4 \cdot 2048 \cdot 795773}{4096 \cdot 60 \cdot 60 \cdot 24} =$ **18.4** "rack days".
3. The verification run took the same time (within a few minutes): **94 base 3 digits** are in agreement.

```
base-9 digits = 001|12264485064548583177111135210162856048323453468|10565567|635862
                    12264485064548583177111135210162856048323453468|04744867|134524345
```

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IBM's New Results: G base 2

Algorithm (10 trillionth digits of G in base **4096** — in **735** years)

1. The calculation took, on average, **707857** seconds per thread. It was broken into 8 "partitions" of **2048** threads each. For a total of $8 \cdot 2048 \cdot 707857 = 1.2 \cdot 10^{10}$ CPU seconds.
2. On a single Blue Gene/P CPU it *would* take **368 years**!

   Each rack of BG/P contains 4096 threads (or cores). Thus, we used $\frac{8\cdot 2048\cdot 707857}{4096\cdot 60\cdot 60\cdot 24} =$ **32.8** "rack days".
3. The verification run will take the same time (within a few minutes): **xxx base 2 digits** will be in agreement.

```
base-8 digits = 0176|3470505377477705112261337162012525732721732452260001775457 27
                    xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx|xxxx
```

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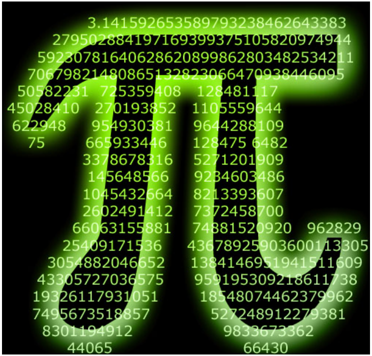
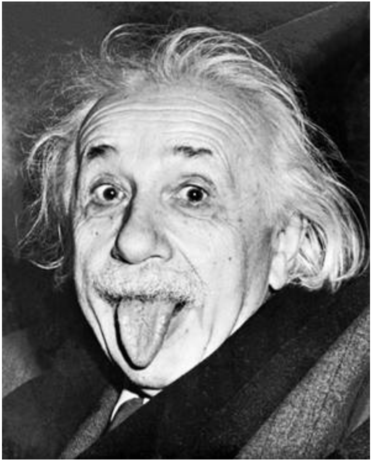
Thank You, One and All, and Happy Birthday, Albert





Albert Einstein 3.14.1879 – 18.04.1955

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143. Links and References

1. The Pi Digit site: `http://carma.newcastle.edu.au/bbp`
2. Dave Bailey's Pi Resources: `http://crd.lbl.gov/~dhbailey/pi/`
3. The Life of Pi: `http://carma.newcastle.edu.au/jon/pi-2010.pdf`.
4. Experimental Mathematics: `http://www.experimentalmath.info/`.
5. Dr Pi's brief Bio: `http://carma.newcastle.edu.au/jon/bio_short.html`.

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1. D.H. Bailey and J.M. Borwein, "On Pi Day 2014, Pi's normality is still in question." *American Mathematical Monthly*, **121** March (2014), 191–204 (and Huffington Post 3.14.14 Blog)
2. D.H. Bailey, and J.M. Borwein, *Mathematics by Experiment: Plausible Reasoning in the 21st Century,* AK Peters Ltd, 2003, ISBN: 1-56881-136-5. See `http://www.experimentalmath.info/`
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4. J.M. & P.B. Borwein, and D.A. Bailey, "Ramanujan, modular equations and pi or how to compute a billion digits of pi," *MAA Monthly*, **96** (1989), 201–219. Reprinted in *Organic Mathematics*, `www.cecm.sfu.ca/organics`, 1996, *CMS/AMS Conference Proceedings*, **20** (1997), ISSN: 0731-1036.
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