THE GOOGOL-TH BIT OF THE ERDŐS–BORWEIN CONSTANT

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Abstract

The Erdős–Borwein constant is a sum over all Mersenne reciprocals, namely

$$E \ := \ \sum_{n \geq 1} \frac{1}{2^n - 1} \ = \ 1.10011011010100000101111111\ldots \text{ (binary)}.$$

Although E is known to be irrational, the nature of the asymptotic distribution of its binary strings remains mysterious. Herein, we invoke nontrivial properties of the classical divisor function to establish that the googol-th bit, i.e., the bit in position 10^{100} to the right of the point is a '1.' Equivalently, the integer

$$\left\lfloor 2^{10^{100}} E \right\rfloor$$

is odd. Methods are also indicated for resolving contiguously the first 2^{43} bits (one full Terabyte) in about one day on modest machinery.

– In memory of longtime comrade, Steven Paul Jobs
1955-2011

1. Preliminaries

Our primary aim is to establish specific binary bits of the Erdős–Borwein constant

$$E \ := \ \sum_{n \geq 1} \frac{1}{2^n - 1} \ = \ 1.10011011010100000101111111\ldots \text{ (binary)}.$$

This is the instance $E = EB(2)$ of the generalization for integer $t > 1$:

$$EB(t) \ := \sum_{n \geq 1} \frac{1}{t^n - 1}.$$

each of which real numbers having been proven irrational. Irrationality was established in 1948 by Erdős [4], and later by P. Borwein [3] via Padé approximants. There is further historical and speculative discussion in [2].

The Erdős irrationality proof is patently number-theoretical. In that same spirit we show how to resolve remote bits of E. It is striking how far "remote" can be in this context. Denoting the binary bits

$$E = e_0.e_1e_2e_3\ldots,$$

we shall establish that

$$e_{10^{100}} \;=\; 1,$$

and note that this bit position is radically farther to the right-of-point than a string of say 10^{80} protons from the visible cosmos – lined up as bits – would reach.[1] It should be mentioned that in 2002 the present author and D. Bailey resolved the googol-th bit of the Stoneham number $\alpha_{2,3}$ (see [2]). Similar ideas are used here for the googol-th bit of E, but this time we need to leverage some nontrivial number theory.

2. The Erdős Paradigm

A number-theoretical approach for extraction of properties of E hinges on the observation

$$E \quad = \quad \sum_{k\geq 1} \frac{d(k)}{2^k}, \tag{1}$$

where $d(k)$ is the classical divisor function—the number of divisors of k, including 1 and k. It is a textbook result [5] that for any positive ϵ, $d(k) = O(k^\epsilon)$, but we shall eventually need precise, effective bounds. Erdős used a clever argument to construct finite chains of integers $n, n+1, n+2, \ldots$ such that $d(n+m)$ is divisible by 2^{m+1}. This leads—after careful bounding of carry-propagation—to the knowledge that arbitrarily long but terminating strings of '0's must appear in the binary expansion, whence E is irrational.

To modify such arguments in order to evaluate remote bits, we require effective bounds on the divisor function. It is a textbook result that $d(n) = O(n^\epsilon)$ for any $\epsilon > 0$, but we require a hard implied big-O constant. First, we have the elementary result

$$d(n) \;=\; 2\left(\sum_{ab=n,\ a\leq b} 1\right) - \delta_{n\in Z^2} < 2\sqrt{n}.$$

[1] The author hereby names this bit $e_{10^{100}} = 1$ the "Jobs bit," as it was resolved right around the time of his passing. Steven Jobs did—beyond his pragmatic eminence—always appreciate such abstract forays.

Then we have results closer to the true asymptotic character of $d(n)$, namely for $n \geq 3$,

$$d(n) \leq n^{\frac{1.5379 \log 2}{\log \log n}},$$

or alternatively

$$d(n) \leq n^{\frac{\log 2}{\log \log n}\left(1+1.9349 \frac{1}{\log \log n}\right)},$$

or even higher-order formulae such as

$$d(n) \leq n^{\frac{\log 2}{\log \log n}\left(1+\frac{1}{\log \log n}+4.7624 \frac{1}{(\log \log n)^2}\right)}.$$

Such results are due to G. Robin and J-L. Nicolas [9] [10] [11], being the fruit of a long-term study on Ramanujan's "highly composite numbers."

Careful application of these sophisticated bounding formulae results in effective bounds, as exemplified in:

Lemma 1. *The divisor function $d(n)$ satisfies $d(n) < 2n^{\delta}$, where the power δ may be interpreted as being n-dependent; for example, one may assign respective δ powers to typical intervals:*

$$n \in \left[1, 10^{10}\right) \to \delta := \frac{1}{2}, \quad n \in \left[10^{10}, 10^{26}\right) \to \delta := \frac{1}{3}, \quad n \in \left[10^{26}, 10^{56}\right) \to \delta := \frac{1}{4},$$

$$n \in \left[10^{56}, 10^{100}\right) \to \delta := \frac{1}{5}, \qquad n \in \left[10^{100}, 10^{112}\right) \to \delta := \frac{5}{29},$$

$$n \in \left[10^{112}, 10^{10^{100}}\right) \to \delta := \frac{1}{6}, \qquad n \geq 10^{10^{100}} \to \delta := \frac{1}{33}.$$

The '2'-factor in the $d(n)$ bound is just for convenience of analysis later; indeed, the prefactor '2' can itself be lowered with more work, or dropped completely for say $n \geq 10^{10}$. This lemma will be used to provide effective bounds on "tail" components of BBP-like series, as we discuss in Section 4.

3. A Variational Approach to the Divisor Function

It is sometimes lucrative to possess a bound on $d(n)$ based on knowledge of the minimum prime factor of n. For example, if n is too large to completely factor – which factoring is the only real hope of calculating $d(n)$ exactly for large n – one may still sieve n for small primes, then apply a factor-dependent bound.

In this regard it is interesting to analyze factorizations without the traditional constraint that powers of primes need be integers. For example, given that n has precisely k prime factors, say (here, $p_1 < p_2 < \cdots p_k$, but not necessarily consecutive primes)

$$n \;=\; \prod_{i=1}^{k} p_i^{t_i},$$

and knowing that the divisor function is

$$d(n) \ = \ \prod (t_i + 1)\,,$$

we might ask: What choice of *real-number* powers t_i maximizes this latter product? An amusing example is $n = 144$, for which the standard factorization is $144 = 2^4 \cdot 3^2$, with divisor function evaluation $d(144) = (4+1)(2+1) = 15$. But there is also the (exact, but nonstandard) factorization

$$144 = 2^{\frac{\log 216}{\log 4}} \cdot 3^{\frac{\log 96}{\log 9}} = 2^{3.877\ldots} \cdot 3^{2.077\ldots}.$$

Moreover one can show that this peculiar pair of noninteger powers atop 2,3 gives the maximum possible power-product, which maximum we shall denote $D(n)$. In our example case,

$$D(144) \ = \ \left(\frac{\log 216}{\log 4} + 1\right)\left(\frac{\log 96}{\log 9} + 1\right) \ = \ 15.0095\ldots$$

and sure enough, $d(144) = 15 < 15.0095$. We can establish a general upper bound $D \geq d(n)$ by proceeding variationally. We borrow here, from mathematical physics, the classical notion of Lagrange multipliers. The idea is to maximize (for $T_i := t_i+1$) the product

$$\bar{D} = \prod T_i$$

subject to the constraint $n = \prod p_i^{T_i - 1}$ in the form

$$0 = C := \log n + \sum_i \log p_i \ - \sum T_i \log p_i.$$

One introduces a Lagrange multiplier λ and proceeds to render stationary (with respect to T_i variations) the unconstrained construct $S \ := \ \bar{D} + \lambda C$. Setting $\partial S / \partial T_i = 0$ for all i, we find, after backsolving for λ in the constraint, a unique maximum $D(n)$:[2]

$$d(n) \ \leq \ D(n) \ = \ \left(\frac{\log n + \sum \log p_i}{k}\right)^k \frac{1}{\prod \log p_i}. \tag{2}$$

There is a similar bounding formula in the excellent survey [7, p. 218]. Our upper bound can be put in the form

$$d(n) \ \leq \ n^{\frac{1}{A} \log \frac{2A}{G}},$$

where A is the arithmetic mean of the sequence $(t_i \log p_i)$ and G is the geometric mean of the sequence $(\log p_i)$.

[2]That this solution is a unique maximum over the positive-T_i manifold is not hard to prove—since the product $\bar{D}$ is monotonic in every T_i.

This "variational bound" can be useful when special information about prime factorization of n is in hand. But when the only information is a lower bound on the smallest prime factor p_1, there is a more direct route to a bound on $d(n)$, as follows.[3] Note that d is sub-multiplicative, that is $d(ab) \le d(a)d(b)$ for all a, b (with equality when a, b are coprime). Set $\epsilon := \log 2/\log p_1$. Then, regarding n as $\prod q_1$ with primes q_i not necessarily distinct,

$$\frac{d(n)}{n^\epsilon} \ \le \ \prod_i \frac{d(q_i)}{q_i^\epsilon} \ \le \ \prod_i \frac{2}{p_1^\epsilon} \ = \ \prod_i 1 \ = \ 1.$$

Thus we have

Lemma 2. *For p_1 denoting the smallest prime dividing n, we have $d(n) \ \le \ n^{\frac{\log 2}{\log p_1}}$. In particular, if n has no divisors $< 2^q$, then $d(n) \ \le \ n^{\frac{1}{q}}$.*

Example. If we sieve n by all primes $< 2^{32}$ without finding a factor, then we know $d(n) \le n^{1/32}$. Such a bound can in practice be radically tighter than we glean from Lemma 1.

Another Example. For $n = 10^{50} + 1$, we find that $n = F \cdot C$, where

$$F = 101 \cdot 3541 \cdot 27961 \cdot 60101 \cdot 7019801$$

and C is composite with all prime factors $> 2^{23}$. It follows that

$$d(n) \ = \ d(F)d(C) \ = \ d(F)d(n/F) \ \le \ 2^5 \cdot (n/F)^{1/(23)} \ < \ 549,$$

radically better than the corresponding bound from Lemma 1.

4. Generalized BBP Formula

D. Bailey, P. Borwein, and S. Plouffe invented (1995-1996) a scheme for rapidly establishing remote digits of fundamental constants (see [13]). The now celebrated "BBP" prescription presumes specific base b, then resolves (in our present nomenclature) digit position Q to the right of the point, by determining with sufficient accuracy where $\left(b^{Q-1}E \bmod 1\right)$ lies in $[0, 1)$. Application with base 2 for binary bits of E starts out with the decomposition

$$2^{Q-1}E \ = \ \sum_{k=1}^{Q-1} \frac{2^{Q-1}d(k)}{2^k} \ + \ \sum_{m=0}^{M-1} \frac{d(Q+m)}{2^{m+1}} \ + \ \sum_{m=M}^{\infty} \frac{d(Q+m)}{2^{m+1}}$$

$$= \ R_Q \ + \ S_{Q,M} \ + \ T_{Q,M},$$

[3]The present author is grateful to J-L. Nicolas for this direct, elegant argument [8].

where the $T_{Q,M}$ sum is called the "tail."

The immediate observation – one that lives at the very core of the BBP idea – is that the first sum R_Q is an integer. Most of the work involves the $S_{Q,M}$ sum, while we usually bound T with an appropriate bounding lemma. For the moment, we see that

$$\left(2^{Q-1}E\right) \bmod 1 \;=\; (S_{Q,M} \;+\; T_{Q,m}) \bmod 1,$$

so that the Q-th bit of E (to right-of-point) is '0', '1' respectively, as

$$B_Q \;:=\; S_{Q,M} \bmod 1 \;\;+\;\; T_{Q,M}$$

is in $[0, 1/2), [1/2, 1)$ respectively. Of course, the real trick is to use sufficiently large M to bound $T_{Q,M}$ so tightly that B_Q lies in $[0, 1)$, whence a simple test of $B_Q \geq, < 1/2$ resolves the Q-th bit. To this end, we posit:

Lemma 3. *The tail is bounded by*

$$T_{Q,M} \;<\; \frac{(Q+M)^\delta}{2^M}\frac{1}{1-\frac{1}{2}e^{\delta/(Q+M)}},$$

where δ is taken from Lemma 1 with $n := Q + M$.

Proof. We have, with $r := \frac{1}{2}e^{\delta/(Q+M)}$,

$$T_{Q,M} \;=\; \sum_{m \geq M} \frac{d(Q+m)}{2^{m+1}} \;<\; \sum_{m \geq M} \frac{(Q+m)^\delta}{2^m} \;<\; \frac{(Q+M)^\delta}{2^M}(1 + r + r^2 + \cdots). \quad \square$$

Note that this lemma's tail bound can be cut dramatically if one has a few "lucky sievings," as per Lemma 2. That is, if prime factors of $Q + M$ are sufficiently large, or in some sense sparse, one may peel off the first tail term then start a bound at index $M + 1$, and so on.

5. Resolution of the Googol-th Bit

Using the apparatus of the previous section, we can find remote bits of E as in Table 1, with the count M of S-summands growing roughly logarithmically in Q. As an example table entry, the googol-th bit ($Q = 10^{100}$) involves divisor-function values as recorded in the Appendix.

All one has to do to find, say, a multibit word starting at position Q is to force the tail T to be sufficiently small. For $Q = 10^{100}$, taking $M = 94$ terms of S results in the resolution of an entire 32-bit word starting at the googol-th position. We have—from the post-googol factor tabulations in the Appendix—an exact value

$$S_{Q,94} = \frac{6435549334824119260427382656685}{1237940039285380274899124224},$$

Q	e_Q	M
10^{10}	0	21
10^{20}	0	37
10^{30}	0	39
10^{40}	1	49
10^{50}	0	49
10^{60}	0	53
10^{70}	0	61
$\vdots$	$\vdots$	$\vdots$
10^{100}	1	60

Table 1: Resolution of e_Q, the Q-th bit of E (meaning in the Q-th position to the right-of-point). The number M counts the necessary summands for the $S_{Q,M}$ term from Section 4; thus, M evaluations of the divisor function $d(Q+m)$ are used. (But Lemma 2 can accelerate this process in certain circumstances.)

while from Lemmas 1 and 3 we have $T_{Q,94} \; < \; 2 \cdot 10^{-11}$, so that in binary we know rigorously that

$$S_{Q,94} \bmod 1 + T_{Q,94} \;\; = \;\; 0.1001100001101001000001000110110010\ldots,$$

where – as claimed – the first bit to the right-of-point, being the googol-th bit itself, is '1.'

6. The Contiguous Terabyte has "Too Many '1s"

Thanks to the work of D. Mitchell, a program has been created to calculate contiguous bits from the $Q = 1$ bit (just to the right of point, the 0-th bit being the leading '1' to left-of-point) through the $Q = 2^{43}$ bit. That means we now know more than the first 8 trillion bits, and have logged populations for certain bases.

As to the method, the formula

$$E \;\; = \;\; \sum_{m \ge 1} \frac{1}{2^{m^2}} \frac{2^m + 1}{2^m - 1}$$

turns out to be efficient in a programming scenario. Rewriting,

$$E = \sum_{m \ge 1} \frac{1}{2^{m^2}} \left(1 + \frac{2}{2^m} + \frac{2}{2^{2m}} + \cdots \right),$$

we see that we can initialize each m^2-th bit to 1, than add '2's along arithmetic progressions.[4] With adroit use of threading, memory and eventual disk-writing, Mitchell was able to create the "contiguous Terabyte" in about one day.[5] As an integrity check, the remote-bits method of Sections 4, 5 was used to check the first 1 billion random bit positions in the contiguous Terabyte. In addition, several million random bit positions were likewise checked.

The discovered population counts are tabulated below. Note that in every base $2^{\beta=1,2,3,4}$ all digit populations listed add up to $2^{43}/\beta = 8796093022208/\beta$; that is, we count only nonoverlapping β-bit digits.

It is remarkable that the binary-bit counts for $0, 1$—respectively

$$4359105565638, 4436987456570$$

are so disparate. Indeed, a random coin-toss game should have, after some 8 trillion tosses, perhaps the first *four* digits in agreement. Of course, observing there are "too many '1's" in the contiguous Terabyte is merely suggestive of possible anomalies in the bit statistics of E.

```
Base 2 (binary)
0 : 4359105565638
1 : 4436987456570

Base 4 (quaternary)
0 : 1080561684345
1 : 1106903007230
2 : 1091079189718
3 : 1119502629811

Base 8 (octal)
0 : 359190664177
1 : 361815499829
2 : 361805068965
3 : 371183479256
4 : 361917190569
5 : 368575859354
6 : 370698715770
7 : 376844529482
```

[4]Of course, one takes every arithmetic progression beyond $Q = 2^{43}$ to guard against carry-interference. In this Terabyte case we guarded with 256 extra bits.

[5]Meaning about 24 real-time hours on an 8-core Mac Pro; still, a single desktop machine not a supercomputer warehouse! By contrast, the isolated googolth-bit resolution takes a few minutes—most of the work in that case being factorizations for post-googol integers (see Appendix).

```
Base 16 (hexadecimal)
0  : 134567994085
1  : 132761862795
2  : 131164175459
3  : 135827739295
4  : 135994852874
5  : 139494161026
6  : 140042450578
7  : 142316547830
8  : 137111036682
9  : 135761702456
A  : 134046630124
B  : 138527844259
C  : 138566029070
D  : 141037268645
E  : 140378720036
F  : 141424240338
```

7. Open Problems

- What Erdős actually showed in 1948 was that out of the first N bits of E, there *must* be a '0'-string of length at least $c \log^{\alpha} N$ for some absolute constant c with $\alpha := 1/10$. Can this power α be increased? On the notion of randomness, is it legitimate to call a sequence random if it *must* contain strings of this type, for any N? (Certainly there are "coin-flip" games—real points expanded in binary—having bounded '0'-run length over the entire, infinite string.) Put another way: What is the probability measure for real numbers, in binary, that have this Erdős "string property" for a given α? (There are heuristic arguments that $\alpha = 1$ is a barrier, in the sense that we expect longest '0'-runs out of N bits to be of length $O(\log N)$ [6].) Incidentally, in the contiguous Terabyte, the first 2^{43} bits of E, the longest run of '0's has length 47, with longest run of '1's having length 41.
- What is the 10^{1000}-th bit of E? The present author knows of no way to answer this without at least *some* factorizations of 1000-decimal numbers.
- What about 2-normality of E? Can one even show that 1/2 of the bits of E are 1's? The present author does not even know how to show that the string '11' appears infinitely often in E. In regard to 2-normality, see [2].
- What is the googolplex-th bit of E? This is equivalent to asking whether the integer $\left\lfloor 2^{10^{10^{100}}} E \right\rfloor$ is even or odd, to yield respectively '0/1.' Actually, we

may never know this bit—certainly, factoring of numbers in the googolplex region is problematic!

- It is interesting to contemplate the true complexity of $d(n)$. Evidently, since primes p (uniquely) enjoy $d(p) = 2$, complete knowledge of $d(n)$ is at least as hard as primality proving. But what about factoring? A cryptographic RSA number $N = pq$ (product of two primes) has, trivially, $d(N) = 4$. So factoring can be quite unlike knowing $d(N)$ if there be certain extra information about N. In this regard, see [12] and references therein.

- For the constant

$$EB(10) \ := \ \sum_{k\geq 1} \frac{1}{10^k - 1}$$

there is some suspicion of statistical anomalies, at least so for the first billion decimal digits (see [1] where, as an example of statistical anomaly, it is proved that $\alpha_{2,3}$ is not 6-normal). It would be good to extend the present treatment in regard to $EB(10)$.

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8. Appendix: Post-Googol Divisors and Factors

```
d(10^100)  =  10201
(d(10^100+1), d(10^100+2),..., d(10^100+200))  =
(256, 64, 128, 96, 32, 128, 16, 768, 8, 24576, 64, 24, 48, 64, 16, 80,
64, 32, 64, 768, 32, 8, 16, 128, 12, 192, 8, 192, 32, 96, 32, 768, 4,
16, 96, 24, 16, 192, 8, 512, 8, 128, 128, 96, 32, 16, 64, 160, 64, 192,
8, 24, 24, 128, 128, 512, 256, 32, 16, 192, 64, 48, 16, 896, 512, 128,
256, 48, 64, 32, 48, 8, 256, 32, 576, 48, 8, 32, 32, 1920, 64, 32, 32,
96, 128, 64, 24, 4096, 12, 16, 32, 384, 16, 32, 64, 384, 64, 4096, 4,
288, 256, 32, 64, 64, 32, 256, 24, 48, 16, 256, 4, 80, 128, 256, 512,
144, 32, 128, 64, 256, 32, 256, 32, 24, 256, 512, 16, 128, 64, 64, 384,
48, 32, 24, 16, 96, 16, 128, 16, 192, 16, 512, 384, 320, 16, 128, 16,
96, 64, 96, 4, 640, 128, 16, 16, 24, 64, 256, 32, 192, 24, 384, 4, 96,
8, 512, 32, 64, 32, 384, 64, 48, 64, 32, 192, 160, 16, 32, 256, 48, 128,
32, 16, 256, 2048, 128, 32, 144, 8, 128, 128, 896, 16, 128, 64, 96, 48,
16, 8, 1536)
```

```
10^100+1 = 73.137.401.1201.1601.1676321.5964848081.
            1296944190290577505513857711845642744990757009476567578215372915271968 01
10^100+2 = 2.3.4832936419.5025493293281.1061431139892014340488875721.
            6464979402011013241687574830622406864012978402059 3
10^100+3 = 7.157.769.2593.4888946572366141.2200309359940584892261 33.
            4242036622639156527888055237578804493024993216233097
10^100+4 = 2^2.20794121.319929089.406288107529.5918277534160279189665941011889.
            1562846321861029648354357361984048909038 09
10^100+5 = 3.5.127.570527.9200868376117164262739684518876954703 20
                             9497971776676688390514959123739106672139895228883723
10^100+6 = 2.859493.2698836149.46606393157.201991350982876187.
            6930035321787863868408416051.3303980117998549980200318 2831
10^100+7 = 557.294001.6908913964859.8838655616713081384235006409 05
                             1132181948832801178384207854273111302870957443689
10^100+8 = 2^3.3^2.113.593.48673.8181960160259.32930456993518040815814175510134 27.
            15804877474670386224821814037114289709866 89
10^100+9 = 3221.426362206609.728166297212893998092178252925291701 13
                             1895221015099208343986527943941226915328263778 1
```

```
10^100+10 = 2.5.7.11^2.13.19.23.4093.8779.52579.599144041.7093127053.183411838171.
            141122524877886182282233539317796144938305111168717
10^100+11 = 3.7549.9604831.170862023971269597381883 9.15972037776884529561552 01.
            16845880550367127868901238960308061187 57
10^100+12 = 2^2.43.79.7359434795407712687665587282896673535472475
                    71386517515454813070356196644097733294083014424492199
10^100+13 = 17.29^2.173.687282158304630200628747266365592320781.
            588266218930313741304202156907675299648983684567 2351533
10^100+14 = 2.3.61.320355733.6029721445642558523.
            1414455095865246309606228934558018968908797094381419270388765180563 4231
10^100+15 = 5.211.7938203515098092034640534069030726139283094 9801.
            119405769425714490171006230771951087269574666783273
10^100+16 = 2^4.241.6486935848076218529.19152505976856146588269 93193.
            208736196265400028175308137031943022654796390562313
10^100+17 = 3^3.7.18617.25903.10971813871758633469374645226 47388
                    790495510837594855265276660125591723007363461909143 61603
10^100+18 = 2.907.59246083817.52963207955625452232593144663 0827.
            175682614675517925123451219617166344582046244425465993
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10^100+164 = 2^2.3.7.11.14552688897681160359740467096331204097734569.
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