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The Distribution of Small Gaps Between Successive Primes

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Abstract. For $r \geqq 1$ and large N, a well-known conjecture of Hardy and Littlewood implies that the number of primes $p \leqq N$ such that $p + 2r$ is the least prime greater than p is asymptotic to

$$\int_2^N \left(\sum_{k=1}^{r} \frac{A_{r,k}}{(\log x)^{k+1}} \right) dx,$$

where the $A_{r,k}$ are certain constants. We describe a method for computing these constants. Related constants are given to 10D for $r = 1(1)40$, and some empirical evidence supporting the conjecture is mentioned.

1. Introduction. Let r be a fixed positive integer and N a large integer. Hardy and Littlewood [4] conjectured that the number of primes $p \leqq N$ such that $p + 2r$ is also prime is

$$P_N(r) \sim A_{r,1} \int_2^N \frac{dx}{(\log x)^2}, \tag{1}$$

where

$$A_{r,1} = 2c_2 \prod_{q \mid r} \frac{q-1}{q-2}, \tag{2}$$

$$c_2 = \prod_q \frac{1 - 2/q}{(1 - 1/q)^2} = 0.66016 \cdots \tag{3}$$

is the "twin-prime" constant, and q runs over the odd primes (this convention is adopted throughout). Conjecture (1) has been substantiated empirically and extended by several authors, e.g. [1], [3], [5] and [6].

In this paper, we study the number $Q_N(r)$ of primes $p \leqq N$ such that $p + 2r$ is the *first* prime after p (so $p + 1, p + 2, \cdots, p + 2r - 1$ are composite). In Section 2, we use the principle of inclusion and exclusion to deduce from a conjecture of Hardy and Littlewood that

$$Q_N(r) \sim \int_2^N \left(\sum_{k=1}^{r} \frac{A_{r,k}}{(\log x)^{k+1}} \right) dx, \tag{4}$$

where the constants $A_{r,k}$ are defined by (8) below. Previously, $Q_N(r)$ seems to have been studied only for $r \leqq 4$, although the magnitude of the first prime p followed by $2r - 1$ consecutive composite numbers has been investigated (see [2] and the references given there).

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In Section 3 we discuss the computation of the constants $A_{r,k}$, and related constants $B_{r,k}$ (see Eq. (12)) are given for $r \leqq 40$ in Table 1. Some empirical evidence for conjecture (4) is given in Section 4.

2. Derivation of the Conjecture. If $0 < m_1 < m_2 < \cdots < m_s$, Hardy and Littlewood [4] conjecture that the number of primes $p \leqq N$ such that $p + 2m_i$ is prime for $i = 1, \cdots, s$ is

$$(5) \qquad P_N(m_1, \cdots, m_s) \sim C(m_1, \cdots, m_s) \int_2^N \frac{dx}{(\log x)^{s+1}},$$

where

$$(6) \qquad C(m_1, \cdots, m_s) = 2^s \prod_q (1 - 1/q)^{-(s+1)}(1 - w_{\mathrm{m}}(q)/q)$$

and $w_{\mathrm{m}}(q)$ is the number of distinct residues of $0, m_1, \cdots, m_s$ modulo the odd prime q. (Conjecture (1) is just the special case $s = 1$, $m_1 = r$ of (5).)

From the principle of inclusion and exclusion (see, e.g. [7]),

$$(7) \qquad Q_N(r) = \sum_{s=0}^{r-1} (-1)^s \sum_{0<m_1<\cdots<m_s<r} P_N(m_1, \cdots, m_s, r).$$

From (5), this gives the conjecture (4) if

$$(8) \qquad A_{r,k} = (-1)^{k+1} \sum_{0<m_1<\cdots<m_{k-1}<r} C(m_1, \cdots, m_{k-1}, r).$$

3. Computation of the Constants $A_{r,k}$. Since $w_{\mathrm{m}}(q) = s + 1$ for all $q > m_s$, $C(m_1, \cdots, m_s)$ may easily be found if the Hardy-Littlewood constants

$$(9) \qquad c_k = \prod_{q>k} \frac{1 - k/q}{(1 - 1/q)^k}$$

are known. These may be evaluated by the method of Wrench [10] and Mayoh [8].

Thus, the computation of $A_{r,k}$ from (8) appears to be straightforward. However, the sum in (8) involves $\binom{r-1}{k-1}$ terms, so the evaluation of $A_{r,1}, \cdots, A_{r,r}$ in the obvious way requires the evaluation of 2^{r-1} terms $C(m_1, \cdots, m_{k-1}, r)$. We shall show how this may be reduced to the evaluation of $O(2^{2r/3})$ terms.

It is easy to evaluate $A_{r,k}$ if the integer

$$(10) \qquad T_{r,k} = \sum_{0<m_1<\cdots<m_{k-1}<r} \prod_{q \leqq r+1} (q - w_{\mathrm{m},r}(q))$$

can be evaluated, where $w_{\mathrm{m},r}(q)$ is the number of distinct residues of $0, m_1, \cdots, m_{k-1}$, r modulo the odd prime q. By omitting all the terms with $w_{\mathrm{m},r}(3) = 3$, and using symmetry if $3|r$, we find that

$$(11) \qquad T_{r,k} = K_r \sum_{0<m_1<\cdots<m_{k-1}<r;\, m_i \not\equiv r' \pmod 3} \prod_{5 \leqq q \leqq r+1} (q - w_{\mathrm{m},r}(q)),$$

where

$$K_r = \begin{cases} 1 & \text{if } r \not\equiv 0 \pmod 3 \\ 2 & \text{if } r \equiv 0 \pmod 3 \end{cases},$$

and

$$r' = \begin{cases} 1 & \text{if } r \equiv 2 \pmod 3 \\ 2 & \text{if } r \not\equiv 2 \pmod 3 \end{cases}.$$

Thus, we may compute $T_{r,k}$ by summing

$$\binom{\lfloor 2(r-1)/3 \rfloor}{k-1} \quad \text{instead of} \quad \binom{r-1}{k-1}$$

terms. An additional factor of 2 can be saved by symmetry if r is not divisible by 3.

It is interesting to note that $T_{r,k} = 0$ if k is so large that a cluster of $k - 1$ primes cannot lie between two large primes p and $p + 2r$ (see [9]). Surprisingly, the least such k is not a monotonic function of r, for $T_{10,6} \neq 0$ and $T_{11,6} = 0$.

The constants $A_{r,k}$ for $r \leqq 40$ were found by computing the $T_{r,k}$ as suggested above. Since the $A_{r,k}$ vary greatly in size, it is more convenient to work with

$$(12) \qquad B_{r,k} = \begin{cases} A_{r,1} & \text{if } k = 1 \\ -A_{r,k}/A_{r,k-1} & \text{if } k > 1 \text{ and } A_{r,k-1} \neq 0 \\ 0 & \text{if } k > 1 \text{ and } A_{r,k-1} = 0 \end{cases}.$$

Thus, the integrand in (4) is $B_{r,1}z^2(1 - B_{r,2}z(\cdots(1 - B_{r,r}z)\cdots))$, where $z = 1/(\log x)$.

Table 1 gives the constants $B_{r,k}$, believed to be correctly rounded to 10D, for $1 \leqq k \leqq r \leqq 40$. Values which are omitted are zero.

4. Empirical Evidence for the Conjecture. A "gap of length $2r$" is defined to be an interval $(p, p + 2r)$ where p and $p + 2r$ are successive primes. The number of gaps of length 2, 4, $\cdots$, 80 in an interval (M, N) was compared with the number predicted by conjecture (4) for various M and N in the range $(10^6, 10^{16})$. (For example, $M = 10^6, 10^7, \cdots, 10^{15}$ and $N = M + 10^6$.) The actual and predicted gap distributions agreed closely in all the intervals considered. Detailed results have been deposited in the UMT file of this journal.

As a typical example, results for the interval $(10^6, 10^9)$ are given in Table 2. For $r = 1, 2, \cdots, 40$, the table gives the actual number of gaps of length $2r$, and the number predicted from

$$(13) \qquad \int_{10^6}^{10^9} \left(\sum_{k=1}^{r} \frac{A_{r,k}}{(\log x)^{k+1}} \right) dx.$$

In $(10^6, 10^9)$, there are 50769035 gaps, and

$$(14) \qquad \int_{10^6}^{10^9} \frac{dx}{\log x} \simeq 50770607.4.$$

TABLE 1

The constants $B_{r,k}$ for $r = 1(1)40$ (values omitted are zero)

r	k	$B_{r,k}$
1	1	1.3203236317
2	1	1.3203236317
3	1	2.6406472634
	2	2.1648090870
4	1	1.3203236317
	2	4.3296181741
	3	0.7261756149
5	1	1.7604315089
	2	4.8708204458
	3	0.9682341532
6	1	2.6406472634
	2	7.5768318046
	3	2.0747874712
	4	0.4881403766
7	1	1.5843883580
	2	9.0200378627
	3	2.7110556291
	4	0.7845113196
8	1	1.3203236317
	2	10.8240454352
	3	3.4856429517
	4	1.2203509416
	5	0.2845598501
9	1	2.6406472634
	2	12.4476522505
	3	4.2097137097
	4	1.6108632428
	5	0.4656433910
10	1	1.7604315089
	2	15.8301664490
	3	5.7597518859
	4	2.5248640170
	5	1.0244154603
	6	0.2600013387
11	1	1.4670262574
	2	15.3430844044
	3	5.5503309283
	4	2.3653954168
	5	0.8429475787
12	1	2.6406472634
	2	18.4008772398
	3	7.0705502451
	4	3.3815938634
	5	1.6080940365
	6	0.6066697903
13	1	1.4403530528
	2	20.7370670462
	3	8.1550214623
	4	4.0633477298
	5	2.1093164691
	6	1.0254787648
	7	0.3885721249
14	1	1.5843883580
	2	20.8588375574
	3	8.1825131838
	4	4.0589157778
	5	2.0866554914
	6	0.9897331926
	7	0.3495093187
15	1	3.5208630178
	2	24.4961678255
	3	9.9210862934
	4	5.1517209912
	5	2.8451655917
	6	1.5366370101
	7	0.7430478393
	8	0.2639864981
16	1	1.3203236317
	2	27.4930754054
	3	11.3952967179
	4	6.1214210653
	5	3.5632266426

TABLE 1 (*continued*)

r	k	$B_{r,k}$
16	6	2.1006626920
	7	1.1950083565
	8	0.6157145513
	9	0.2444874923
17	1	1.4083452071
	2	27.7245360198
	3	11.4984742518
	4	6.1729997100
	5	3.5819776177
	6	2.0946244877
	7	1.1705496702
	8	0.5824231949
	9	0.2198886873
18	1	2.6406472634
	2	30.0425246784
	3	12.6122048727
	4	6.8853036007
	5	4.0940729018
	6	2.4873794831
	7	1.4840852989
	8	0.8373344927
	9	0.4234899981
	10	0.1658772706
19	1	1.3979897277
	2	31.9331890432
	3	13.4561073779
	4	7.3677263519
	5	4.3825468884
	6	2.6448059150
	7	1.5377429643
	8	0.7999341181
	9	0.3061670870
20	1	1.7604315089
	2	33.0230029036
	3	14.0212494141
	4	7.7552428532
	5	4.6798483508
	6	2.8876803489
	7	1.7450477061
	8	0.9833612019
	9	0.4731308341
20	10	0.1513663376
21	1	3.1687767161
	2	36.3539740286
	3	15.6509822856
	4	8.8131644369
	5	5.4466534309
	6	3.4737488749
	7	2.2032572055
	8	1.3409356167
	9	0.7429532570
	10	0.3357930107
	11	0.0896365942
22	1	1.4670262574
	2	38.5221012010
	3	16.7436006742
	4	9.5502460845
	5	6.0071544989
	6	3.9277664665
	7	2.5837231927
	8	1.6635481779
	9	1.0125375871
	10	0.5464248161
	11	0.2174507624
23	1	1.3831961856
	2	39.9075175164
	3	17.3771078681
	4	9.9252611046
	5	6.2469956507
	6	4.0820403447
	7	2.6778338225
	8	1.7129792116
	9	1.0284516322
	10	0.5388263843
	11	0.1992045198
24	1	2.6406472634
	2	41.6087903720
	3	18.2211462744
	4	10.4857133121
	5	6.6675963762
	6	4.4204962521
	7	2.9630734223

TABLE 1 (*continued*)

r	k	$B_{r,k}$
24	8	1.9613859814
	9	1.2496708257
	10	0.7375923983
	11	0.3737970930
	12	0.1307666522
25	1	1.7604315089
	2	44.4259414830
	3	19.6478400115
	4	11.4435289614
	5	7.3859456123
	6	4.9901941363
	7	3.4285605747
	8	2.3470128849
	9	1.5694239568
	10	0.9991223480
	11	0.5797444199
	12	0.2779751671
	13	0.0773583678
26	1	1.4403530528
	2	45.5513844929
	3	20.1021552452
	4	11.6727241289
	5	7.5016123702
	6	5.0370857637
	7	3.4292205066
	8	2.3145847402
	9	1.5125764268
	10	0.9245068977
	11	0.4938397071
	12	0.1894277144
27	1	2.6406472634
	2	47.3706617010
	3	21.0944825152
	4	12.3891416646
	5	8.0793108307
	6	5.5302801907
	7	3.8641962264
	8	2.7052770199
	9	1.8661755593
	10	1.2435276562
	11	0.7763137851
	12	0.4271256883
27	13	0.1729604958
28	1	1.5843883580
	2	49.7793339545
	3	22.2516291007
	4	13.1317161092
	5	8.6175937443
	6	5.9494259004
	7	4.2078174539
	8	2.9992575087
	9	2.1274078880
	10	1.4833716834
	11	1.0014969256
	12	0.6388395411
	13	0.3646341816
	14	0.1558821625
29	1	1.3692245069
	2	49.7351293969
	3	22.2010534736
	4	13.0749059856
	5	8.5538846663
	6	5.8779731882
	7	4.1277954713
	8	2.9100995690
	9	2.0292305179
	10	1.3777494229
	11	0.8927963590
	12	0.5361400447
	13	0.2829661211
	14	0.1112806842
30	1	3.5208630178
	2	53.4568780418
	3	24.0119086856
	4	14.2465572306
	5	9.4040165228
	6	6.5333739503
	7	4.6514933053
	8	3.3376210785
	9	2.3821089677
	10	1.6694186696
	11	1.1314474006
	12	0.7264160913
	13	0.4281428785

TABLE 1 (*continued*)

r	k	$B_{r,k}$	r	k	$B_{r,k}$
30	14	0.2187972637	33	11	1.5642788142
	15	0.0799007719		12	1.0853435243
				13	0.7167409804
31	1	1.3658520328		14	0.4387634196
	2	57.0564427867		15	0.2379412131
	3	25.7883873035		16	0.1004264844
	4	15.4134377102			
	5	10.2643380469	34	1	1.4083452071
	6	7.2079466964		2	61.9919072207
	7	5.2002014685		3	28.2142671194
	8	3.7939887877		4	16.9990534791
	9	2.7661319314		5	11.4265453826
	10	1.9930796451		6	8.1130495630
	11	1.4012127006		7	5.9309308916
	12	0.9442903513		8	4.3972048990
	13	0.5922053004		9	3.2707071778
	14	0.3249621929		10	2.4178440362
	15	0.1294626296		11	1.7589282962
				12	1.2438306194
32	1	1.3203236317		13	0.8398533041
	2	56.0765841791		14	0.5252330428
	3	25.2955005318		15	0.2854048569
	4	15.0822774906		16	0.1108625403
	5	10.0134861920			
	6	7.0047474948	35	1	2.1125178107
	7	5.0282652653		2	62.7958185378
	8	3.6439356759		3	28.6092743854
	9	2.6321755336		4	17.2585563381
	10	1.8716152565		5	11.6189657616
	11	1.2903211212		6	8.2658057455
	12	0.8438892387		7	6.0577632487
	13	0.5049928034		8	4.5059818778
	14	0.2585874366		9	3.3663563583
	15	0.0987505835		10	2.5036711044
				11	1.8373213753
33	1	2.9340525149		12	1.3167529951
	2	59.3116309805		13	0.9093775214
	3	26.8938829613		14	0.5943929626
	4	16.1336371765		15	0.3596437584
	5	10.7902210471		16	0.1989064249
	6	7.6158335959		17	0.0993281933
	7	5.5282304118			
	8	4.0639911464	36	1	2.6406472634
	9	2.9918723175		2	66.2111617092
	10	2.1839746041		3	30.2766540599

TABLE 1 (*continued*)

r	k	$B_{r,k}$	r	k	$B_{r,k}$
36	4	18.3409094425	38	13	1.3131389130
	5	12.4068962334		14	0.9365319820
	6	8.8754487506		15	0.6404963934
	7	6.5470947651		16	0.4138510165
	8	4.9080453851		17	0.2463430835
	9	3.7017107962		18	0.1194900846
	10	2.7858957162			
	11	2.0757081630	39	1	2.8807061055
	12	1.5176476093		2	70.6997065950
	13	1.0766924356		3	32.5107597334
	14	0.7293724865		4	19.8218855636
	15	0.4597244627		5	13.5097785123
	16	0.2563308030		6	9.7499560283
	17	0.1085109086		7	7.2677697292
				8	5.5171282455
37	1	1.3580471640		9	4.2251859714
	2	66.9782027174		10	3.2405820808
	3	30.6782419268		11	2.4727472369
	4	18.6201628208		12	1.8643285785
	5	12.6242292479		13	1.3774162158
	6	9.0546344932		14	0.9861397380
	7	6.6995839806		15	0.6724449317
	8	5.0398868987		16	0.4235592577
	9	3.8161157582		17	0.2304613130
	10	2.8843429973		18	0.0876237466
	11	2.1584604606			
	12	1.5839990281	40	1	1.7604315089
	13	1.1250993393		2	73.6107429917
	14	0.7576010703		3	33.9328292881
	15	0.4653031637		4	20.7460643325
	16	0.2382708022		5	14.1837340795
	17	0.0741063531		6	10.2726763283
				7	7.6886927466
38	1	1.3979897277		8	5.8644776442
	2	69.4720528395		9	4.5166169192
	3	31.9135466028		10	3.4879437671
	4	19.4347144701		11	2.6845126281
	5	13.2275487026		12	2.0469957441
	6	9.5306429383		13	1.5364440188
	7	7.0904008520		14	1.1267004833
	8	5.3697954268		15	0.8001365673
	9	4.1005791410		16	0.5450067101
	10	3.1340488773		17	0.3529451420
	11	2.3813915965		18	0.2139492394
	12	1.7866244753		19	0.1062961616

By summing (13) over $r = 1, \cdots, 40$ and subtracting from (14), the predicted number of gaps of length greater than 80 is 473076.4, and the actual number is 473186.

Table 2 shows that (13) predicts quite well the number of gaps of various lengths in $(10^6, 10^9)$. Although the right sides of (1) and (4) are asymptotically equal, the higher terms in (4) are important for approximating $Q_N(r)$. It is interesting to note that in $(10^6, 10^9)$ there are less gaps (observed and predicted) for $r = 31$ than for $r = 32$, although $A_{31,1} = 1.36 \cdots > A_{32,1} = 1.32 \cdots$. Thus, the higher terms in (13) are significant.

TABLE 2

Actual and predicted gap distribution in $(10^6, 10^9)$

r	Actual	Predicted	r	Actual	Predicted
1	3416337	3417060.1	21	953980	954689.0
2	3416536	3417060.1	22	389432	389057.1
3	6076242	6077407.1	23	334565	335337.0
4	2689540	2688560.2	24	577051	577893.6
5	3477688	3477436.8	25	327960	327323.5
6	4460952	4460654.7	26	245727	245799.1
7	2460332	2461360.3	27	410614	410578.1
8	1843216	1842845.7	28	211409	211469.0
9	3346123	3347229.6	29	181894	182398.0
10	1821641	1823424.2	30	371743	372007.3
11	1567507	1567220.8	31	115542	115837.8
12	2364792	2362746.8	32	118927	118681.6
13	1118410	1118419.0	33	216739	216467.5
14	1218009	1218441.9	34	88383	88116.0
15	2176077	2176130.5	35	125542	125688.7
16	683346	682871.2	36	126650	126786.7
17	718974	718118.6	37	62514	62578.8
18	1170757	1169307.2	38	55107	55325.4
19	548416	547688.6	39	105300	105390.3
20	648356	648539.8	40	53519	53578.4

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