

Weak Uniform Distribution for Divisor Functions. II

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Abstract. The author's methods (reference [4]) are developed further to apply to divisor functions σ_i for even values of i . The results of calculations for even values of i in the range $4 \leq i \leq 50$ are tabulated.

1. Introduction. Throughout, the notation and definitions of the author's previous paper [4] will be used. For a full account of the background, see [2].

The function $\sigma_i(x)$ is defined for positive integers i, x by

$$\sigma_i(x) = \sum_{d|x} d^i.$$

An arithmetic function f is defined to be weakly uniformly distributed modulo n (WUD (mod n), for short) if the set

$$\{x \in \mathbf{Z}: x > 0, (f(x), n) = 1\}$$

is infinite and for every pair of integers a_1, a_2 with $(a_1, n) = (a_2, n) = 1$,

$$\begin{aligned} \#\{x: 0 < x < t, f(x) \equiv a_1 \pmod{n}\} &\sim \\ \#\{x: 0 < x < t, f(x) \equiv a_2 \pmod{n}\} & \end{aligned}$$

as $t \rightarrow \infty$.

In [4] the weak uniform distribution properties of σ_i were studied for odd values of i . The algorithm embodied in [4, Lemmas 1-4] and derived from Narkiewicz [2] applies equally well to even values of $i \geq 4$. The improvement contained in [4, Propositions 1 and 2] extends to the even case, and a somewhat weaker version of [4, Proposition 3] can be proved (see Section 3 below).

The result of these calculations is that we find, for even $i \geq 4$, sets K_1, K_2 and K_4 of positive integers such that σ_i is weakly uniformly distributed modulo n if and only if

- (i) n is odd and not divisible by an element of K_1 , or
- (ii) n is even, not divisible by 6 and not divisible by any element of K_2 , or
- (iii) n is divisible by 6 and not divisible by any element of K_4 .

At the end of this paper, tables are given of the sets K_1, K_2 and K_4 for each i in the range $4 \leq i \leq 50$.

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For completeness, we recall the property of σ_2 proved by Narkiewicz and Rayner [3]:

The function σ_2 is WUD (mod n) if and only if either

(i) n is odd and not divisible by 15, or

(ii) n is even, not divisible by 6, and not divisible by 8 or 28, or

(iii) n is divisible by 6, and not divisible by 12, 30, 42, or 66, or

(iv) n is divisible by 8 and not divisible by 40, or

(v) n is divisible by 40 and not divisible by any prime $p \geq 7$ for which the order of 4 modulo p is odd.

Thus, σ_2 does not fit the general pattern described above in respect of moduli divisible by 8, where a more complicated version of [4, Lemma 1] applies. However, as can be seen in the tables of results below, for every even $i \geq 4$, the set $\{15\}$ in (i) is contained in $K_1(i)$, the set $\{8, 28\}$ in (ii) is contained in $K_2(i)$, and the set $\{12, 30, 42, 66\}$ in (iii) is contained in $K_4(i)$. (Note that for $i, k > 2$, and all j , if $i \mid k$, then $K_j(i) \subset K_j(k)$.)

As in [4], the calculations of the present paper depend on properties of a set of primes bounded above by $(i+1)^2$ in the case of K_1 , by $(2i+1)^2$ in the case of K_2 , and by $(4i+1)^2$ in the case of K_4 (see [4, Lemma 4]). In the course of the calculations it became clear that these bounds are too high and that a bound of $5i^{1.5}$ in all three cases would be consistent with the primes actually found. Indeed, something slightly stronger might be true. This is in line with [4, Observation 3]. If such better bounds could actually be proved, it would be easy to carry the calculations considerably further.

2. Values of d . As in [4], let $V_j(x) = 1 + x^i + x^{2i} + \dots + x^{ji}$, let $R_j(n) = \{V_j(a) \bmod n : a \in Z, (aV_j(a), n) = 1\}$, as a subset of the multiplicative group $G(n)$ of residue classes prime to n , let $\Lambda_j(n)$ be the subgroup of $G(n)$ generated by $R_j(n)$, and let $d(n)$ be the least value of $j \geq 1$ for which $R_j(n) \neq \emptyset$.

In order to apply [4, Lemmas 1–4] to the case of even values of $i \geq 4$, we need first to determine the values of $d(n)$ for each i .

LEMMA 1. *Let m, n be positive integers. Then $R_j(n)$ is the image of $R_j(mn)$ under the mapping induced by $x \bmod mn \rightarrow x \bmod n$.*

COROLLARY 1. $\Lambda_j(n)$ is the image of $\Lambda_j(mn)$.

COROLLARY 2. *The following statements are equivalent:*

(i) $R_j(n) \neq \emptyset$;

(ii) *For all primes p which divide n , $R_j(p) \neq \emptyset$.*

COROLLARY 3. *Let $4 \mid i$ and $30 \mid n$. Then $R_4(n) = \emptyset$.*

Proof. (Corollary 3) $G(30)$ is an abelian group of exponent 4; the only value of $x^i \bmod 30$ is 1, and so $V_4(x) = 5$ for all x . Hence, $R_4(30) = \emptyset$, and the result follows from Lemma 1.

LEMMA 2. *For any prime p , if, for all $x \in G(p)$, $x^i = 1$, then $R_{p-1}(p) = \emptyset$. If there exists $x \in G(p)$ with $x^i \neq 1$, then $R_{p-1}(p) = \{1\}$.*

Proof. In the second case, calculating in the field of p elements, $V_{p-1}(x) = (1 - (x^i)^p)/(1 - x^i) = 1$.

COROLLARY. *Let q be the least prime for which $(q-1)$ does not divide i . Then $d \leq q-1$.*

Proof. Lemma 1, Corollary 3 shows that it is enough to prove that for all p dividing n we have $R_{q-1}(p) \neq \emptyset$. For $p \neq q$ we have $q \in R_{q-1}(p)$; for $p = q$, Lemma 2 gives $R_{q-1}(p) = \{1\}$.

(This Corollary is due to Narkiewicz [1, Lemma 1].)

PROPOSITION 1. *Let i be even.*

(i) *if n is odd then $d(n) = 1$;*

(ii) *if n is even and not divisible by 6, then $d(n) = 2$;*

(iii) *if n is divisible by 6 and not divisible by 30, then $d(n) = 4$.*

Proof. In case (i), $2 \in R_1(n)$; in case (ii), $3 \in R_2(n)$; and in case (iii), $R_2(6) = \emptyset$ and so, by Lemma 1, $R_2(n) = \emptyset$. Now $5 \in R_4(n)$.

PROPOSITION 2. *Let $30 \mid n$, and let i be even. Then σ_i is not WUD (mod n).*

Proof. Note that $d = d(n)$ is even and ≥ 4 .

Firstly, if $i \equiv 2 \pmod{4}$, numerical calculation shows $R_4(30) = \{11\}$, so that $d = 4$ and $\Lambda_4(30)$ is cyclic. Since $G(30)$ is not cyclic, $R_4(30)$ does not generate $G(30)$. Secondly, if $i \equiv 0 \pmod{4}$, then in $G(30)$, $x^4 = 1$ for all x , so that $R_d(30) = \{d+1\}$. Thus $\Lambda_d(30)$ is cyclic, and (again) $R_d(30)$ does not generate $G(30)$.

In either case, it follows from [4, Lemma 1] that σ_i is not WUD (mod n).

3. Squares of Primes. Here the objective is to show that, in [4, Lemma 3], and in the calculation of the sets k_j it is only necessary to consider squares of primes in a few cases (see the Corollary to Proposition 4 below).

Let q denote an odd prime, and (as in [4]) define the homomorphisms $\phi: G(q^2) \rightarrow G(q)$ and $\phi(x \bmod q^2) = x \bmod q$ and $\psi: G(q) \rightarrow G(q^2)$ by $\psi(x \bmod q) = x^q \bmod q^2$.

PROPOSITION 3. *Let q be an odd prime not dividing the integer i . Let $R_j(q)$ and $R_j(q^2)$ be calculated using the polynomial V_j , where $j = 1, 2$, or 4 . Then there is a nontrivial character on $G(q^2)$ constant on $R_j(q^2)$ if and only if there is a nontrivial character on $G(q)$ constant on $R_j(q)$. Moreover, for $j = 1$ and 2 , the values of the nontrivial character on $G(q^2)$ are $(q-1)$ th roots of unity and take the same value on $R(q^2)$ as the values of the nontrivial character on $G(q)$ does on $R(q)$.*

Proof. For $j = 1$, this is [4, Proposition 1], and for $j = 2$, this is [4, Proposition 2]. In these cases, it was shown in [4] that, given a nontrivial character χ on $G(q^2)$ taking a constant value a on R_j , the corresponding character on $G(q)$ was $\chi \circ \psi$ taking the value a^q on $R_j(q)$. Since $\chi \circ \psi$ is nontrivial, the values of χ cannot be q th roots of unity. Moreover, if the values of χ are qt th roots of unity, then χ^t will be a nontrivial character constant on $R(q^2)$ with values which are qt th roots of unity, and we have just seen that this cannot happen. Hence the values of χ on $G(q^2)$ are all $(q-1)$ th roots of unity; since then $a^q = a$, the characters χ and $\chi \circ \psi$ take the same values on $R(q^2)$ and $R(q)$, respectively.

Now suppose $j \geq 4$, and write $V = V_j$, and let χ be a nontrivial character on $G(q^2)$ constant on $R_j(q^2)$. Then $\chi \circ \psi \circ \phi$ is again a character constant on $R_j(q^2)$,

so that $\chi \circ \psi$ is a character on $G(q)$ constant on $R_j(q)$ which will be nontrivial unless $\ker \chi$ contains the subgroup of $G(q^2)$ of order $(q - 1)$. Since q is prime and χ is nontrivial, the only case which occurs is that in which $\ker \chi$ is the subgroup of order $q - 1$. Since all of $R_j(q^2)$ is contained in a single coset of this subgroup, it follows that $R_j(q^2)$ has fewer than q elements. From Taylor's theorem,

$$V(x + qy) \equiv V(x) + qyV'(x) \pmod{q^2},$$

so that, if $V'(x)$ is not congruent to 0 modulo q , then there are q elements of $R_j(q^2)$ mapped by ϕ onto the element $V(x) \pmod{q}$ of $R_j(q)$. Since this cannot happen, it follows that, whenever $V(x) \pmod{q} \in R_j(q)$ (i.e., $V(x)$ does not vanish modulo q), we have $V'(x) \equiv 0 \pmod{q}$. Differentiation of the equation $(1 - x^j)V(x) = 1 - x^{j+1}$ gives $V(x) \equiv (j + 1)x^{j+1} \pmod{q}$ whenever $V'(x) \equiv 0 \pmod{q}$, so that $V(x)$ is always in the $(j + 1)$ coset of the subgroup of squares in $G(q)$, i.e., the quadratic character of $G(q)$ is constant on $R_j(q)$. This completes the proof of Proposition 3.

As a consequence, we can find all primes q for which there is a character mod q^2 constant on $R_j(q^2)$ by merely finding those primes for which there is a character mod q constant on $R_j(q)$. Further, for $j = 1$ and 2 , if σ_i is not WUD (mod m), and m has a factor p^2 , then σ_i is not WUD (mod m/p).

COROLLARY. *Let i be even or j be even. Let there be a nontrivial character χ on $G(q^2)$ taking the constant value 1 on $R_j(q^2)$. Then there is a nontrivial character on $G(q)$ taking the constant value 1 on $R_j(q)$.*

Proof. The character is $\chi \circ \psi$ with the required property, unless $\ker \chi$ is the subgroup of $G(q^2)$ of order $q - 1$. In this case, the elements of $R_j(q)$ are given by those nonzero values of $V_j(x) \pmod{q}$ arising from those values of x which satisfy $V_j'(x) \equiv 0 \pmod{q}$, and we have $V_j(x) \equiv (j + 1)x^{ij} \pmod{q}$. Firstly, let $j \equiv -1 \pmod{q}$. Then all values of $V_j(x)$ are congruent to zero modulo q , so that $R_j(q) = \emptyset$. Secondly, let $j \equiv 0 \pmod{q}$. Then all values of $V_j(x)$ are congruent to a square modulo q (since ij is even), and the quadratic character on $G(q)$ takes the constant value 1 on $R_j(q)$. Finally, let j be different from -1 and 0 modulo q . Then $j + 1 \in R_j(q)$, since $j + 1 = V(j)$. However, $V_j'(1) = ij(j + 1)/2$, which is nonzero mod q , so that there are q distinct elements of $R_j(q^2)$ mapped onto $j + 1 \pmod{q}$ by ϕ , which is impossible because cosets of $\ker \chi$ have at most $q - 1$ elements.

PROPOSITION 4. *Let i be even. Let p be an odd prime greater than 3 such that p does not divide i and such that there is a character modulo p^a constant on $R_j(p^a)$ with $a = 1$ or 2 . Let t be an integer not divisible by p , and if $t \neq 1$, such that also p is not a divisor of the order of $G(t)$. Let $R_j(pt)$ generate $G(pt)$. Then $R_j(p^2t)$ generates $G(p^2t)$.*

Proof. The case $t = 1$ is the Corollary to Proposition 3. By Lemma 1, $R_j(p)$ generates $G(p)$ and $R_j(t)$ generates $G(t)$; by the Corollary to Proposition 3, $R_j(p^2)$ generates $G(p^2)$. Now suppose $R_j(p^2t)$ does not generate $G(p^2t)$. Then there is a character χ_1 on $G(p^2)$ taking a constant value $\alpha \neq 1$ on $R_j(p^2)$ and another character χ_2 on $G(t)$ taking a constant value α^{-1} on $R_j(t)$. Suppose e is the least exponent for which $\alpha^e = 1$. Then $e > 1$ and $e \mid p(p - 1)$ and e divides the order of $G(t)$. Now p does not divide the order of $G(t)$, so that $e \mid (p - 1)$, and $\chi_1 \circ \psi$ is

a character of $G(p)$ taking the constant value α on $R_j(t)$. Hence $R_j(pt)$ does not generate $G(pt)$, contrary to hypothesis. This completes the proof of Proposition 4.

COROLLARY. *When constructing products m of primes and squares of primes to test as in [4, Lemma 2] (see Section 4, stage 4 below), it is unnecessary to consider the square of an odd prime p unless p is a divisor of i or a divisor of $s - 1$, where s is any other prime divisor of m . Further, for $j = 1$ or $j = 2$ it is unnecessary to consider the square of p unless $p \mid i$.*

Proof. For $j = 4$ this follows from Proposition 4. For $j = 1, 2$ this follows from consideration of the characters described in the proof of Proposition 3.

4. Calculations. Suppose that i is even and ≥ 4 . The algorithm described in [4] can be carried out with the benefit of Propositions 1 to 4, and is then as follows.

Let $j = 1$ or 2 or 4.

Stage 1. Determine the set H_j of all primes less than $(1 + ij)^2$, excluding 2 in the case $j = 1$, and excluding 3 in the case $j = 2$.

Stage 2. Determine the set I_j consisting of all p in H_j together with p^2 (whenever $p \in H_j$ and $p \mid i$) and 8 (whenever $2 \in H_j$).

Stage 3. Determine the set J_j of all n in I_j for which there is a nontrivial character of $G(n)$ constant on $R_j(n)$.

Stage 4. Determine the set K_j of all integers $n = \prod q_i$ for which $R_j(n)$ does not generate $G(n)$, where all the q_i are distinct, and for each i , either $q_i \in J_j$ or $q_i = p^2$ where $p \in H_j \cap J_j$ and $p \mid (q_j - 1)$ for some $j \neq i$, and furthermore, for $j = 2$, n is even and for $j = 4$, n is divisible by 6.

Then σ_i will fail to be WUD (mod m) if and only if

- (i) m is odd and divisible by an element of K_1 , or
- (ii) m is even, not divisible by 6, but divisible by an element of K_2 , or
- (iii) m is divisible by 6 and not divisible by 30, but divisible by an element of K_4 , or
- (iv) m is divisible by 30 (Proposition 2).

We can incorporate case (iv) in case (iii) by including the integer 30 in each of the sets K_4 in the tables below, and can remove as redundant from each K_d any integer properly divisible by another element of the same K_d .

Calculations of K_1, K_2 and K_4 for $4 \leq i \leq 200$ have been carried out in the University of Liverpool Computer Laboratory, and the results for $i \leq 50$ are given below. The general pattern for $50 < i \leq 200$ is similar, with no additional features appearing.

During the course of the calculations for K_4 it was observed that whenever the prime $p \geq 5$ was such that there was a nontrivial character on $G(p)$ constant on $R_4(p)$, then σ_i failed to be WUD (mod $6p$). Thus it was never necessary to test for WUD (mod $6p^2$), etc., so that the calculations became lighter.

As noted in Section 1 above, in the calculations of K_1, K_2 and K_4 the upper bounds in stage 1 of the algorithm are much higher than necessary, and a bound of $5i^{1.5}$ would not lead to smaller sets J_d in the range of calculations attempted. The indications are that this bound should apply at least for values of i up to 1225.

It is an unsettled problem to prove that these two observations are true in general.

TABLES OF RESULTS

The sets $K_1(i)$. For odd m , σ_i is not WUD (mod m) if and only if m is divisible by an element of $K_1(i)$.

i	$K_1(i)$
4	15
6	7 15 39 57 65 95 247
8	15 17
10	15 33 41 55
12	7 15 39 57 65 95 183 247 305 793 1159
14	15 87 129 145 215 1247
16	15 17
18	7 15 39 57 65 95 111 185 247 481 703
20	15 33 41 55
22	15 23 201 335
24	7 15 17 39 57 65 73 95 183 247 305 793 1159
26	15 159 265
28	15 87 113 129 145 215 1247
30	7 15 31 33 39 41 55 57 65 95 143 183 209 247 305 671 793 1159
32	15 17 97 193
34	15 137 239
36	7 15 39 57 65 73 95 109 111 183 185 247 305 481 703 793 1159 2257
38	15
40	15 17 33 41 55
42	7 15 39 43 57 65 87 95 127 145 247 337 377 551 1137 1895 4927 7201 10991
44	15 23 89 201 335
46	15 47 417 695
48	7 15 17 39 57 65 73 95 97 183 247 305 793 1159 3033 4381
50	15 33 41 55 151 303 505 1111

The sets $K_2(i)$. For even m not divisible by 6, σ_i is not WUD (mod m) if and only if m is divisible by an element of $K_2(i)$.

i	$K_2(i)$
4	8 20 26 28 70
6	8 26 28 76 266
8	8 20 26 28 70 164 194 410 574
10	8 22 28 82 124 434
12	8 20 26 28 70 74 76 146 190 266
14	8 28 172 602
16	8 20 26 28 68 70 164 170 194 238 410 574 1394
18	8 26 28 74 76 146 266 362
20	8 20 22 26 28 70 82 122 124 310 434
22	8 28 46 134
24	8 20 26 28 70 74 76 146 164 190 194 266 410 574 1558
26	8 28 316 1106
28	8 20 26 28 70 116 172 290 406 430 602 2494
30	8 22 26 28 76 82 122 124 266 302 434 1178
32	8 20 26 28 68 70 164 170 194 238 386 410 574 1394
34	8 28 206 818
36	8 20 26 28 70 74 76 146 190 218 266 362 866
38	8 28 914
40	8 20 22 26 28 70 82 122 124 194 310 434 482
42	8 26 28 76 172 266 508 602 674 1634 1778 4826 10922
44	8 20 26 28 46 70 134
46	8 28 94 556 1946
48	8 20 26 28 68 70 74 76 146 164 170 190 194 238 266 386 410 574 646 1394 1558 4718 12806
50	8 22 28 82 124 302 434

The sets $K_4(i)$. For m divisible by 6, σ_i is not WUD (mod m) if and only if m is divisible by an element of $K_4(i)$.

i	$K_4(i)$
4	12 30 42 66
6	12 30 42 66 78 186 366
8	12 30 42 66 246
10	12 30 42 66 186 246 366
12	12 30 42 66 78 186 366
14	12 30 42 66 174 258 426
16	12 30 42 66 102 246
18	12 30 42 66 78 114 186 366 654
20	12 30 42 66 186 246 366 606 1446
22	12 30 42 66 138 402 534
24	12 30 42 66 78 186 246 366
26	12 30 42 66 786
28	12 30 42 66 174 258 426
30	12 30 42 66 78 186 246 366 906 1086 1446 3246
32	12 30 42 66 102 246
34	12 30 42 66 618 2454
36	12 30 42 66 78 114 186 222 366 654 1086
38	12 30 42 66 1146 1374
40	12 30 42 66 186 246 366 606 1446 2406
42	12 30 42 66 78 174 186 258 366 426 762 1266 2022 2526
44	12 30 42 66 138 402 534
46	12 30 42 66 282
48	12 30 42 66 78 102 186 246 366 1446
50	12 30 42 66 186 246 366 606 1506 3606 4206 7806

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