What Drives an Aliquot Sequence?

By Richard K. Guy* and J. L. Selfridge

To D. H. Lehmer, on his 70th birthday, in gratitude for much inspiration, encouragement and computation

Abstract. The concept of the “driver” of an aliquot sequence is discussed. It is shown that no driver can be expected to persist indefinitely. A definition of driver is given which leads to just 5 drivers apart from the even perfect numbers.

If we examine the sequence 30, 42, 54, 66, 78, 90, ... we notice that each term is the sum of the aliquot parts (divisors other than the number itself) of its predecessor. Various authors have been struck by the peculiar charm and regularity displayed by these aliquot sequences. It is easy to show that every such sequence starting with a number less than 138 either contains 1 and terminates, or contains a perfect number and repeats.

Catalan’s conjecture [1] was restated by Dickson [3] to the effect that every aliquot sequence will either terminate or become periodic; e.g., the amicable pair 220, 284 has period 2. Later Poulet [8] found that 12496 starts a sequence with period 5 and that 14316 has period 28. He and Lehmer struggled with the sequence starting with 138.

More formally, let \( s(n) = \sigma(n) - n \), where \( \sigma(n) \) is the sum of the divisors of \( n \), and let \( n : 0 = n \), \( n : k + 1 = s(n : k) \). Lehmer showed that the 138 sequence has a maximum

\[
179\,931\,895\,322 = 138 : 117 = 2 \cdot 61 \cdot 929 \cdot 1587569
\]

and that \( 138 : 177 = 1 \).

The next difficulty arose with the 276 sequence. Each term from 2716 = 276 : 8 = \( 2^2 \cdot 7 \cdot 37 \) is divisible by \( 2^2 \cdot 7 \), and since any multiple of the perfect number 28 is abundant, the terms increase monotonically. Notice that in our little sequence starting with 30 the terms have the same property with respect to 6. Paxson [7] computed \( (p \) denotes a prime cofactor) \[
5641 \, 4000 \, 09252 = 276 \, : \, 67 = 2^2 \cdot 7 \cdot p
\]

and Henri Cohen [2] extended the calculation to

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2133 148752623 068133100 = 276 : 118 = 2^{2\times3}5^27\cdot p.

Stimulated by this, Lehmer persevered until he reached the term 276 : 169 = 2^{2\times7}p, where p is a prime congruent to 1, mod 4, so that

7 421365124 006306789 124764410 = 276 : 170 = 2\cdot5\cdot7\cdot13\cdot829\cdot848557\cdot p

suddenly lost the "driver" 28. The succeeding terms, all being congruent to ± 2, mod 12, decrease steadily from 276 : 172 to the term 276 : 226 = 2p, where again p is a prime congruent to 1, mod 4, and

351121 244430380 = 276 : 227 = 2^{2\times5}\cdot131\cdot48539\cdot2760991.

Lehmer has computed a further 200 terms which show an erratic upward tendency. The extent of our present knowledge [5], [6] is

107100047 962427456 048833497 403019424 = 276 : 433 = 2^{3\times3}\cdot199\cdot c

where c is a 31-digit composite number with no small factors. Lehmer also verified that, apart from 396 = s(276) = s(306), all sequences starting with numbers less than 552 are bounded.

On the other hand, we have found [4], [5], [6] that of the sequences starting with numbers less than 10^4, there are 751 which contain a term exceeding 10^24; and we have conjectured that an infinite number of aliquot sequences are unbounded. Our aim here is to outline some of the characteristics of the "driver" phenomenon which support this view. Good examples of driver dominated sequences are

628628 = 552 : 26 = 2^{2\times7}\cdot11\cdot13\cdot157

35149477 396986268 016618868 344127020 = 552 : 181 = 2^3\cdot5^2\cdot7^2\cdot c,

3985 297814226 = 564 : 83 = 2\cdot3\cdot211\cdot3147944561

2422 499075303 417661059 252663526 = 564 : 265 = 2\cdot3^2\cdot23\cdot89\cdot c,

11400 = 5250 : 3 = 2^3\cdot3\cdot5\cdot19

4 553462993 488753886 439512520 = 5250 : 72 = 2^3\cdot3\cdot5\cdot c,

8154 = 8154 : 0 = 2\cdot3^3\cdot151

4615096 670497664 245830510 = 8154 : 201 = 2\cdot3^6\cdot5\cdot43\cdot c,

1503680 = 8904 : 13 = 2^6\cdot5^2\cdot37\cdot127

3200141 507007701 992846912 = 8904 : 166 = 2^6\cdot89\cdot127\cdot c,

44144 = 9852 : 11 = 2^4\cdot31\cdot89

5149877 193773848 066488144 = 9852 : 146 = 2^4\cdot3\cdot11\cdot31\cdot c.

Despite the tenacity of these drivers, none is expected to live for ever.

We notice that any prime divisor p of n will appear in s(n) just if p divides σ(n) and will appear to the same power in s(n) if a higher power divides σ(n). If p divides both n and σ(n) to the same power, p will divide s(n) to at least that power and to a higher power with probability 1/(p - 1), i.e.,
always when $p = 2$. In fact, the prime 2 will continue to be present unless $n$ is a square or twice a square, and continue to be absent unless $n$ is a square. This fact, more than any other, seems to dominate the discussion of the behavior of aliquot sequences.

A very rough argument in favor of our conjecture goes like this: on the average the value of $\sigma(n) - n$ is greater than $n$ if $n$ is even, and less than $n$ if $n$ is odd. If in the long run other effects are small compared to the persistence of parity, one would expect that most large even sequences are unbounded and that most odd sequences are bounded.

More precisely, since the average order, $\alpha$, of $s(n)/n$, taken over even values of $n$, is greater than one so long as the terms remain even, we expect $n : r$ to be $n\alpha'$. The probability that this is a square, or twice a square, is $c_1/\sqrt{n\alpha'}$, so that the probability that any future term is odd is $c_2/\sqrt{n}$, which tends to 0 as $n \to \infty$.

One might ask if a sequence could be shown to be unbounded by displaying a driver which persisted indefinitely. This would only occur if certain prime factors of $n$ would always continue to appear to the same or higher powers in $s(n)$. The prime 2 in fact should keep the same power throughout, since the nature of the driver changes radically when the power of 2 changes. If each of a set of primes divides $\sigma(n)$ to a higher power than it divides $n$, then we would have achieved the goal. We prove that this cannot happen.

**Theorem 1.** For any divisor $v$, $v > 1$, of $n$, there is some prime divisor of $v$ which does not divide $\sigma(v)/v$.

**Proof.** Let $v = 2^{a_1}p_1^{a_1} \cdots p_r^{a_r}$ with $a_1, \ldots, a_r > 0$, so that

$$\sigma(v) = (2^{a_1+1} - 1) \frac{p_1^{a_1+1} - 1}{p_1 - 1} \cdots \frac{p_r^{a_r+1} - 1}{p_r - 1}.
$$

If $p_1 \cdots p_r$ divides $\sigma(v)/v$, then

$$p_1 \cdots p_r \leq \frac{\sigma(v)}{v} < \frac{p_1}{p_1 - 1} \cdots \frac{p_r}{p_r - 1},
$$

i.e. $(p_1 - 1) \cdots (p_r - 1) < 2$ and $v$ has no odd prime divisors. Moreover, since $\sigma(2^d)$ is odd, $2 \not| v$.

Note that we can prove this without the requirement that the power of 2 be higher in $\sigma(v)$ than in $v$.

A precise definition of driver is desired at this point, but we would like our definition to avoid fragile structures, such as

$$2^73^65\cdot 17\cdot 23\cdot 137\cdot 547\cdot 1093$$

which crumples when the power of 3 changes. In addition to the even perfect numbers one would normally include in a list of drivers, any products of prime powers which have a reasonable expectation of persistence, such as $2^33\cdot 5$, $2^53\cdot 7$ and $2^93\cdot 11\cdot 31$. 

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Each of these divides the sum of its divisors and hence divides the sum of its aliquot parts.

For example, if \( n = 2^9 \cdot 3 \cdot 11 \cdot 31 \cdot m \), where \( (m, 2^{11} - 2) = 1 \), then \( o(n) = 2^9 \cdot 3 \cdot 11 \cdot 31 \cdot o(m) \), where \( o(m) \) is even when \( m \) is not a square. Then \( s(n) = 2^9 \cdot 3 \cdot 11 \cdot 31 \cdot m' \) where \( (m', 6) = 1 \) and the chance of \( m' \) being divisible by 11 or 31 is small, and of its being a square is negligible. For similar reasons \( 2^3 \cdot 5 \) and \( 2^5 \cdot 7 \) are persistent.

A further remarkable driver is the number 2. When \( n = 2m \) and \( (m, 6) = 1 \), \( o(n) = 3a(m) \) and \( s(n) = 2m' \), where \( (m', 6) = 1 \) provided that \( 4 \mid o(m) \). Neglecting squares, \( 4 \mid o(m) \) unless \( m \) is a prime congruent to 1, mod 4. Similar considerations hold for \( 2^3 \).

If \( n = 2^3 \cdot 5 \cdot m \), we find it convenient to regard \( 2^3 \cdot 5 \) as the driver even when \( (m, 15) \neq 1 \) (and similarly for other drivers) so that the only crucial exponent is that of 2. That is, we draw the line to exclude some possibilities which tempt us on account of their stability, but which rely for this on considerations secondary to the factorization of \( o(2^a) = 2^{a+1} - 1 \). Some further examples which are thus excluded are \( 2^3 \cdot 3 \cdot 13 \), \( 2^5 \cdot 3 \cdot 13 \), \( 2^5 \cdot 3 \cdot 5 \), and \( 2^5 \cdot 3 \cdot 5 \cdot 7 \).

Define a guide to be \( 2^a \), together with a subset of the prime factors of \( o(2^a) \).

A driver is defined as a number \( 2^a v \) with \( a > 0, v \) odd, \( v \mid o(2^a) \) and \( 2^{a-1} \mid o(v) \). This last requirement is included so that the power of the prime 2 will tend to persist at least as well as it does for the driver 2 itself, for which the condition is trivially satisfied.

**Theorem 2.** The only drivers are \( 2 \), \( 2^3 \), \( 2^3 \cdot 5 \), \( 2^5 \cdot 7 \), \( 2^9 \cdot 11 \cdot 31 \), and the even perfect numbers.

**Proof.** Let \( 2^a v \) be a driver, so that \( v \mid 2^{a+1} - 1, 2^{a-1} \mid o(v) \). If \( 2^{a+1} - 1 = v \) is a Mersenne prime, the driver is an even perfect number. If \( v = 1, 2^{a-1} \mid o(v) = 1, a = 1 \) and we have the “downdriver” 2. Henceforth we assume that \( v > 1 \), and that \( o(2^a) = 2^{a+1} - 1 = p_1^{a_1} \cdots p_r^{a_r} \) is composite, so that \( v = p_1^{b_1} \cdots p_r^{b_r} \), \( 0 \leq b_i \leq a_i \), \( 1 \leq i \leq r \) and not all the \( b_i \) are zero.

Define the deficiency of the factor \( p_i^{b_i} \) of \( v \) to be \( 2^{d_i} \mid p_i^{a_i} \), where \( 2^{d_i} \) is the highest power of 2 in any \( o(p_i^{b_i}) \), \( 0 \leq j \leq b_i \). The product of the deficiencies of the factors of \( v \) is greater than 1/4, since otherwise

\[
2^{a+1} > 2^{a+1} - 1 = \prod_{i=1}^{r} p_i^{a_i} \geq 4 \prod_{i=1}^{r} 2^{d_i},
\]

so that \( 2^{a-1} \mid \prod_{i=1}^{r} 2^{d_i} \) and \( 2^{a-1} \mid \prod_{i=1}^{r} o(p_i^{b_i}) = o(v) \).

The product of the deficiencies of the Mersenne primes, \( 2^q - 1, q \in \{2, 3, 5, 7, 13, \ldots \} \) is at most

\[
\frac{4 \cdot 8 \cdot 32 \cdot 128}{3 \cdot 7 \cdot 31 \cdot 127} \ldots < \frac{4 \cdot 8 \cdot 32 \cdot 64}{3 \cdot 7 \cdot 31 \cdot 63} < \frac{8}{5}.
\]
If the prime 7 is missing, this product is less than 7/5; if 3 does not occur, the product is less than 6/5.

The deficiency of \( p_i^{a_i} \) is at most \( 2^{h_i}(p_i + 1)/p_i^{a_i} \), where \( h_i = \lceil \log_2(b_i + 1) \rceil - 1 \), and is strictly less than this unless \( p_i \) is a Mersenne prime. So \( a_i < 4 \) for each \( i \), since otherwise the deficiency of the corresponding factor \( p_i^{a_i} \) is at most \( 2(3 + 1)/3^4 \), and the product of all deficiencies would be less than \((8/81)(6/5) < 1/4\). If \( a_i = 2 \) or 3 for any \( p_i \geq 5 \), the product of the deficiencies would be less than

\[
\max \left\{ \frac{2}{5^2} \cdot \frac{8}{5}, \frac{8}{7^2}, \frac{7}{5} \right\} < \frac{1}{4},
\]

so, with the possible exception of 3, we may assume that \( 2^{a+1} - 1 \) contains no repeated factors.

If \( 3^2 \mid 2^{a+1} - 1, 6 \mid a + 1, 3^2 \mid 2^{a+1} - 1 \) and then \( 7 \mid v \), for otherwise the product of the deficiencies is at most \((1/7)(7/5) < 1/4\). If \( 3^2 \mid v \) or \( 3 \nmid v \), the product is less than \((1/9)(6/5) < 1/4\), while if \( 3^3 \mid v, 3^3 \mid 2^{a+1} - 1, 18 \mid a + 1, 3^3 \cdot 19 \cdot 73 \mid 2^{a+1} - 1 \) and the product is much less than \( 1/4 \). So \( 3 \nmid v \) and if \( a = 5 \) we have the driver \( 2^5 \cdot 3 \cdot 7 \). We cannot have \( a \) larger, since \( 2^{a+1} - 1 \) would contain, in addition to \( 3^2 \), some factor congruent to 1, mod 4, and the product of the deficiencies would be less than

\[
\frac{4}{9} \cdot \frac{2}{5} \cdot \frac{6}{5} < \frac{1}{4}.
\]

We also notice that \( 2^{a+1} - 1 \) contains at most one non-Mersenne prime factor, i.e., factor of the form \( 2^c u - 1 \), \( u \) odd, \( u \geq 3, c \geq 1 \), since the deficiency of such a factor is \( 2^c/(2^c u - 1) \), which is at most \( 2/5 \) (\( u = 3, c = 1 \)), or otherwise at most \( 4/11 \) (\( u = 3, c = 2 \)), and

\[
\frac{2}{5} \cdot \frac{4}{11} \cdot \frac{8}{5} < \frac{1}{4}.
\]

It remains to consider \( 2^{a+1} - 1 = (2^q_1 - 1)(2^q_2 - 1)\cdots(2^c u - 1) \), where \( 2 < q_1 < q_2 < \cdots \). If \( u \geq 7 \), the product of the deficiencies is less than \((2/13)(8/5) < 1/4\), so \( u = 3 \) or 5. If \( c = 1, u = 3 \) (since \( 2^5 - 1 \) is not prime), \( 2^c u - 1 = 5, 5 \mid 2^{a+1} - 1, 4 \mid a + 1, 15 \mid 2^{a+1} - 1 \). If \( a = 3 \) we have the drivers \( 2^3 \cdot 3 \cdot 5 \) and \( 2^3 \cdot 3 \). If \( a \geq 7 \), there is another prime divisor of \( 2^{a+1} - 1 \) which is congruent to 1, mod 4, and the product of the deficiencies is at most

\[
\max \left\{ \frac{2}{5}, \frac{2}{13}, \frac{8}{5^2}, \frac{1}{5}, \frac{8}{5} \right\} < \frac{1}{4},
\]

So we have \( c \geq 2, q_1 \geq 2, u = 3 \) or 5, and, since we have dealt with \( 1 \leq a \leq 4 \), \( a \geq 5 \). Considerations modulo \( 2^{\min(c,q_1)+1} \) show that

\[
-1 \equiv (2^q_1 - 1)(-1)\cdots(2^c u - 1), \mod 2^{\min(c,q_1)+1}.
\]

So \( \pm 1 \equiv 2^q_1 + 2^c u - 1 \), the choice of sign is minus, the number of Mersenne primes is even (and not zero) and \( q_1 = c \). Now \( 2^q_1 u \cdot 2^q_1 2^q_2 \cdots > 2^{a+1} \), so
\[3 + 2q_1 + q_2 + \cdots > \log_2u + 2q_1 + q_2 + \cdots > a + 1 \geq q_1q_2\cdots\]
since \(2^q - 1\) divides \(2^{a+1} - 1\) just if \(q \mid a + 1\), and the \(q_i\) are distinct primes. This is clearly a contradiction if the number of \(q_i\) is 4 or more, so there are just two \(q_i\): \(3 + 2q_1 + q_2 > q_1q_2\), \((q_1 - 1)(q_2 - 2) < 5\), \(q_1 = 2 = c\) and \(q_2 = 3\) or 5. Only the latter gives a solution; \(u = 3\) and \(2^9 \cdot 3 \cdot 11 \cdot 31\) is a driver.

The theorem is proved.

Table 1 exhibits some drivers, \(d\), and guides, \(g\), and the effect on the power of two, \(2^a\), when \(n = dm\) or \(gm\), \((d, m)\) or \((g, m) = 1\) and \(m = s\), a square or \(m = ps\) where \(p\) is a prime congruent to 1, mod 4. The odd prime factors of \(d\) or \(g\) always divide \(s(n)\); for a driver \(2^a \parallel s(n)\) with the exceptions noted. If \((d, m) > 1\), the situation is more complicated.

<table>
<thead>
<tr>
<th>Driver or guide</th>
<th>(a)</th>
<th>(m = s), a square</th>
<th>(m = ps \equiv 1) (mod 4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(d) 2</td>
<td>1</td>
<td>0 \downarrow</td>
<td>(\geq 2) \uparrow</td>
</tr>
<tr>
<td>(d) 2 \cdot 3</td>
<td>1</td>
<td>1 \downarrow</td>
<td>1 \downarrow</td>
</tr>
<tr>
<td>(g) 2</td>
<td>2</td>
<td>0 \downarrow</td>
<td>1 \downarrow</td>
</tr>
<tr>
<td>(d) 2^2</td>
<td>2</td>
<td>2 \downarrow</td>
<td>2 \downarrow</td>
</tr>
<tr>
<td>(g) 2^3</td>
<td>3</td>
<td>0 \downarrow</td>
<td>1 \downarrow</td>
</tr>
<tr>
<td>(d) 2^3 \cdot 5</td>
<td>3</td>
<td>2 \downarrow</td>
<td>(\geq 4) \uparrow</td>
</tr>
<tr>
<td>(g) 2^3 \cdot 7</td>
<td>3</td>
<td>1 \downarrow</td>
<td>2 \downarrow</td>
</tr>
<tr>
<td>(d) 2^4</td>
<td>4</td>
<td>0 \downarrow</td>
<td>1 \downarrow</td>
</tr>
<tr>
<td>(d) 2^4 \cdot 31</td>
<td>4</td>
<td>4 \downarrow</td>
<td>4 \downarrow</td>
</tr>
<tr>
<td>(g) 2^5</td>
<td>5</td>
<td>2 \downarrow</td>
<td>3 \downarrow</td>
</tr>
<tr>
<td>(g) 2^5 \cdot 7</td>
<td>5</td>
<td>3 \downarrow</td>
<td>4 \downarrow</td>
</tr>
<tr>
<td>(d) 2^6 \cdot 127</td>
<td>5</td>
<td>(\geq 6) \uparrow</td>
<td>5 \uparrow</td>
</tr>
<tr>
<td>(d) 2^9 \cdot 3 \cdot 11 \cdot 31</td>
<td>9</td>
<td>(\geq 10) \uparrow</td>
<td>9 \uparrow</td>
</tr>
</tbody>
</table>

The signs \(\downarrow, \uparrow\) indicate that the driver or guide changes "downward" or "upward".

We are examining the statistical and probabilistic evidence concerning boundedness and unboundedness of aliquot sequences in collaboration with M. C. Wunderlich. The probabilistic model is a Markov process. An aliquot sequence is in one of a finite number of states; one of a finite set of drivers and guides is in control, or none of them is. We can calculate the expected "life" of a sequence in one of these states and the expected number of terms in which the driver is retained. "Break probabilities" between pairs of states can also be calculated; for example, that from the \(2^3 \cdot 5\) driver to the 2 driver is zero since direct transition is impossible.

We conclude with a table showing the numbers of sequences starting below \(10^3\) and below \(10^4\) which surpass various bounds. The number of distinct sequences at each bound is also given.
WHAT DRIVES AN ALIQUOT SEQUENCE?

Table 2. Numbers of sequences surpassing given bounds

<table>
<thead>
<tr>
<th>bound</th>
<th>$10^{12}$</th>
<th>$10^{15}$</th>
<th>$10^{18}$</th>
<th>$10^{21}$</th>
<th>$10^{24}$</th>
<th>$10^{27}$</th>
<th>$10^{30}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>starting below $10^{3}$</td>
<td>19</td>
<td>17</td>
<td>16</td>
<td>13</td>
<td>13</td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td>distinct</td>
<td>10</td>
<td>8</td>
<td>7</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>starting below $10^{4}$</td>
<td>896</td>
<td>820</td>
<td>803</td>
<td>761</td>
<td>751</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>distinct</td>
<td>113</td>
<td>106</td>
<td>104</td>
<td>100</td>
<td>98</td>
<td>?</td>
<td>?</td>
</tr>
</tbody>
</table>

We expect to fill in the missing entries in due course, but much computation is needed. As remarked in [5], [6] considerable help from Lehmer's sieve was necessary to push all the sequences beyond $10^{24}$.

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