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Searching for binary orientable sequences

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Abstract

An aperiodic binary orientable sequence is a finite sequence of zeros and ones for which, for some integer n, all the subsequences of n consecutive symbols, read either forwards or backwards, are distinct. Analogously, a periodic binary orientable sequence is an infinite periodic sequence of zeros and ones for which, for some integer n, all the subsequences of n consecutive symbols, read either forwards or backwards, are distinct within a single period of the sequence. Such sequences have potential application in position-location applications. For applications, the longer the sequence (or the greater the period in the periodic case) the greater its utility, but yet while constructions are known for such sequences, and upper bounds on their length (or period) exist, the precise maximum length (or period) was previously unknown for anything other than small values of n. In this note the results of LLM-conducted searches for the longest possible aperiodic and periodic binary orientable sequences for $n \leq 16$ are reported. In each case an example of a sequence of the maximum length is also provided, and the maximum possible length is now determined for every $n \leq 16$ for both the periodic and aperiodic cases.

1 Introduction

An aperiodic binary orientable sequence is a finite sequence of zeros and ones for which, for some integer n (the *span*), all the subsequences of n consecutive symbols, read in either direction, are distinct. Analogously, a periodic binary orientable sequence is an infinite periodic sequence of zeros and ones for which, for some integer n (the *span*), all the subsequences of n consecutive symbols, read either forwards or backwards, are distinct within a single period of the sequence.

Such sequences were introduced in the early 1990s [1, 2, 3] in the context of position-location applications. Suppose such a sequence is encoded in

some way in a surface, and suppose that a device capable of reading n consecutive symbols of the encoding wishes to learn where it is and in which direction it is traversing the sequence. Then, because no n-tuple repeats in either direction, reading n consecutive symbols can be used to work out the location in the sequence and the direction in which it is being traversed.

The searches described in this note were performed with the aid of the Claude LLM[1].

2 Definitions

We first give a formal definition of the sequences forming the focus of this note. Note that from here on we do not explicitly say that we are only dealing with the binary case.

Definition 2.1. Suppose $n \geq 2$. A finite sequence of length ℓ, $(a_0, a_1, \ldots, a_{\ell-1})$, where $a_i \in \{0, 1\}$ for every i, is said to be an *aperiodic orientable sequence* of span n if all the $2(\ell - n + 1)$ n-tuples $(a_i, a_{i+1}, \ldots, a_{i+n-1}$ and $(a_{i+n-1}, a_{i+n-2}, \ldots, a_i)$ $(0 \leq i \leq \ell - n)$ are distinct.

Example 2.1. A trivial example for $n = 2$ is (01). For $n = 3$, a simple example is (0011).

A periodic binary orientable sequence can be defined as follows.

Definition 2.2. Suppose $n \geq 2$. An infinite periodic sequence (a_i) $(i \geq 0)$ of period p, where $a_i \in \{0, 1\}$ for every i, is said to be a *periodic orientable sequence* of span n if all the $2p$ n-tuples $(a_i, a_{i+1}, \ldots, a_{i+n-1}$ and $(a_{i+n-1}, a_{i+n-2}, \ldots, a_i)$ $(0 \leq i \leq p - 1)$ are distinct.

3 Previous results

3.1 The 1993 table

The 1993 Burns and Mitchell paper [2, Table 3] tabulates the results of searches for aperiodic orientable sequences, and is reproduced below. Table 1 lists the lengths of the longest known aperiodic orientable sequence for $4 \leq n \leq 16$. For n in the range $4 \leq n \leq 7$ the length given is the length of the longest such sequence, since for these values an exhaustive search was completed.

[1] `https://claude.ai`

Table 1: Existence of aperiodic orientable sequences

Span (n)	Sequence length (ℓ)
4	8
5	14
6	26
7	48
8	108
9	210
10	440
11	872
12	1860
13	3710
14	7400
15	15467
16	31766

3.2 A recursive construction

A 2022 paper [5] describes a simple recursive approach for generating aperiodic orientable sequences. This approach can be used to generate sequences with lengths given in Table 2.

It should be clear by comparing with Table 1 that this method generates maximal length sequences for $n \leq 7$, but not for larger n.

3.3 Constructions for periodic sequences

Most of the prior work in this general area has focussed on the *periodic* case, and the two cases are closely related as the following remark shows.

Remark 3.1. Any $p + n - 1$ consecutive symbols of a periodic orientable sequence form an aperiodic orientable sequence. That is, any method of construction for a periodic orientable sequence automatically yields aperiodic sequences.

A number of recent papers have considered construction methods, and period bounds, for periodic sequences, including [4, 5]. Table 3 lists the periods of the orientable sequences constructed by Gabrić and Sawada [4], together with the length of the aperiodic orientable sequence which can be derived from it.

For further information on orientable sequences and their generation see Sawada's excellent web page: `https://debruijnsequence.org/db/orientable`

Table 2: A family of aperiodic orientable sequences

Span (n)	Sequence length (ℓ)
2	2
3	4
4	8
5	14
6	26
7	48
8	92
9	178
10	350
...	...
$2r$	$2^{2r-2} + (2^{2r-2} - 1)/3 + 2r - 1$
$2r+1$	$2^{2r-1} + (2^{2r-1} - 2)/3 + 2r$

4 Searches

4.1 Aperiodic sequences

Claude used two methods of search: exhaustive search (for $n \leq 7$) and integer programming ($8 \leq n \leq 16$), as follows.

- *Exhaustive search.* This employed a depth-first extension, one bit at a time, pruning only when the windows used so far plus the number of unused non-palindromic reversal pairs cannot reach the best length found. Complementation symmetry was used (first bit 0); nothing else was pruned, so every sequence of maximal length is enumerated.

- *Integer programming.* In this approach windows (n-tuples) were treated as edges $\mathbf{w} : (w_0, w_1, \ldots, w_{n-2}) \to (w_1, w_2, \ldots, w_{n-1})$ of the de Bruijn digraph with vertices all $(n-1)$-tuples, and where an aperiodic orientable sequence is a trail that includes no palindromic edges and involves at most one edge from each pair $\{\mathbf{w}, \mathbf{w}^R\}$, where the superscripted R denotes the reverse n-tuple. The integer programming setup involves binary variables $x_{\mathbf{w}}$, one per non-palindromic n-tuple $\mathbf{w}$, with $x_{\mathbf{w}} + x_{\mathbf{w}^R} \leq 1$; for every vertex $\mathbf{u}$, the out-degree minus the in-degree equals $\sigma_{\mathbf{u}} - \tau_{\mathbf{u}}$ with binary $\sigma_{\mathbf{u}}$, $\tau_{\mathbf{u}}$ and $\sum \sigma_{\mathbf{u}} \leq 1$ and $\sum \tau_{\mathbf{u}} \leq 1$. The integer programming goal is to maximise $\sum x_{\mathbf{w}}$. This omits the requirement that the chosen edges be connected, so its optimum value is an upper bound on $\ell - n + 1$ (as is also any bound proved by the solver). When the optimal edge set is connected it is an Eulerian trail,

Table 3: The Gabrić-Sawada sequences

Span (n)	Period (p)	Aperiodic sequence length ($\ell = p + n - 1$)
5	6	10
6	16	21
7	36	42
8	92	99
9	174	182
10	416	425
11	844	854
12	1844	1855
13	3700	3712
14	7694	7707
15	15394	15408
16	31483	31498
17	63135	63151
18	128639	128656
19	257272	257290
20	519160	519179

i.e. an aperiodic orientable sequence attaining the bound, which proves maximality[2]. The problem was solved using the HiGHS solver[3], seeded with a heuristic solution. For $n = 14$ the solver could not close the final gap of one edge directly, and so the problem was split into cases. Since the complement and the reverse of an aperiodic orientable sequence are also aperiodic orientable sequences, it can be assumed that the start vertex $\mathbf{a}$ and end vertex $\mathbf{b}$ of the trail satisfy $w_h(\mathbf{a}) \leq \mathrm{wt}(\mathbf{b})$ and $w_h(\mathbf{a}) + \mathrm{wt}(\mathbf{b}) \leq 13$, where w_h denotes Hamming weight. Separate integer programs, each requiring at least 7752 edges, were then solved for the case of a closed trail, for each value of $w_h(\mathbf{a}) \in \{1, 2, \ldots, 6\}$, and for $\mathbf{a} = 0^{13}$ combined with each value of $w_h(\mathbf{b}) \in \{0, 1, \ldots, 13\}$. All 21 were shown to be infeasible, establishing that 7764 is the maximum length. As a check, the same model was used to reproduce the exhaustive search values for $4 \leq n \leq 7$. As a further check, the same searches were carried out using the SCIP solver[4], with the same re-

[2] In all the cases examined the optimum of the relaxed integer program was attained by a single trail, so the maximum length of an aperiodic orientable sequence of span n equals $n - 1$ plus the largest number of edges in a near-balanced (with one start and one end vertex) subgraph of the de Bruijn graph that uses at most one edge of each reversal pair.

[3] `https://highs.dev/`

[4] `https://scipopt.org/`

sults, except that for $n = 14$ SCIP confirmed 20 of the 21 cases; the remaining case ($\mathbf{a} = 0^{13}$, $\mathbf{b} = 1^{13}$) could not be completed in the time available.

The results of the computer searches performed by Claude are summarised in Table 4. The following observations can be made regarding the entries in the table.

- The searches confirm the correctness of the claim made in [1, 2] that the values in Table 1 are indeed the lengths of the longest possible sequences for $n \leq 7$.
- The searches also revealed the number of distinct maximal length sequences for $4 \leq n \leq 7$, namely 2 ($n = 4$), 2 ($n = 5$), 22 ($n = 6$), and 3294 ($n = 7$), where the complement and reverse of a sequence are regarded as distinct. If two sequences that are equal after complementation or reversal are deemed equivalent, then the number of equivalence classes is 1 ($n = 4$), 1 ($n = 5$), 6 ($n = 6$), and 829 ($n = 7$)
- The Table 1 value is maximal for $n = 8$ (108) and $n = 9$ (210).
- For every n from 10 to 16 a longer sequence exists than the one in Table 1. In every case the new lengths are largest possible.
- The status field indicates that the length listed has been found to be longest possible (*maximal*), and how this was established, i.e. via exhaustive search or integer programming (as outlined above).
- Every sequence listed in Section 5.1 was checked again to verify that it satisfies the orientable property.

4.2 Periodic sequences

The integer programming approach of Section 4.1 works equally well for periodic orientable sequences. A periodic orientable sequence of span n and period p corresponds to a closed walk of p edges in the de Bruijn digraph which involves no palindromic edge and includes at most one edge of each pair $\{\mathbf{w}, \mathbf{w}^R\}$. The integer programming model is therefore the same as before except that every vertex is balanced, i.e. $\sigma_{\mathbf{u}} = \tau_{\mathbf{u}} = 0$ for every $\mathbf{u}$, and the goal is again to maximise $\sum x_{\mathbf{w}}$. As in the aperiodic case, this omits the requirement that the chosen edges be connected, so its optimum value is an upper bound on the period; whenever the optimal edge set is connected it is an Eulerian circuit, i.e. a periodic orientable sequence attaining the bound. In every case examined the optimum was achieved by a connected edge set.

Table 4: Search results

n	ℓ in Table 1	max. length found	status
4	8	8	maximal (exhaustive and ILP)
5	14	14	maximal (exhaustive and ILP)
6	26	26	maximal (exhaustive and ILP)
7	48	48	maximal (exhaustive and ILP)
8	108	108	maximal (ILP)
9	210	210	maximal (ILP)
10	440	444	maximal (ILP)
11	872	882	maximal (ILP)
12	1860	1878	maximal (ILP)
13	3710	3752	maximal (ILP)
14	7400	7764	maximal (ILP)
15	15467	15534	maximal (ILP)
16	31766	31810	maximal (ILP)

The results are summarised in Table 5, which also repeats the periods of the Gabrić-Sawada sequences from Table 3 and the maximum aperiodic lengths from Table 4. The following observations can be made.

- The maximum period of a periodic orientable sequence is now known for every n with $5 \leq n \leq 16$. For $n = 4$ the model shows that no periodic orientable sequence exists.
- The Gabrić-Sawada construction achieves the maximum period for $5 \leq n \leq 8$, but not for $9 \leq n \leq 16$. Nevertheless it comes close: for $n = 16$ its period is about 99.1% of the maximum.
- The longest aperiodic orientable sequences are strictly longer than those derived from periodic sequences of maximal period: for every n with $5 \leq n \leq 16$, the maximum aperiodic length exceeds $p + n - 1$ (where p is the maximum period) by between 4 and 19.
- All the values were established using the HiGHS solver. As a check, the computations were repeated using the SCIP solver, which confirmed the maximum period for $5 \leq n \leq 15$; for $n = 16$ SCIP found a sequence of period 31776 and proved an upper bound of 31777 within the time available.
- Every sequence listed in Section 5.2 was checked again to verify that it is a periodic orientable sequence with the stated period.

Table 5: Maximum periods of periodic orientable sequences (GS: Gabrić-Sawada period; max. ℓ: maximum aperiodic length from Table 4)

n	GS p	max. p	$p+n-1$	max. ℓ	optimality proved by
5	6	6	10	14	HiGHS, SCIP
6	16	16	21	26	HiGHS, SCIP
7	36	36	42	48	HiGHS, SCIP
8	92	92	99	108	HiGHS, SCIP
9	174	194	202	210	HiGHS, SCIP
10	416	426	435	444	HiGHS, SCIP
11	844	860	870	882	HiGHS, SCIP
12	1844	1856	1867	1878	HiGHS, SCIP
13	3700	3728	3740	3752	HiGHS, SCIP
14	7694	7738	7751	7764	HiGHS, SCIP
15	15394	15504	15518	15534	HiGHS, SCIP
16	31483	31776	31791	31810	HiGHS

5 Examples

For compactness, each sequence is given in hexadecimal, read left to right, where each hex digit stands for four consecutive bits (most significant bit first). The final digit is padded with zero bits on the right. The sequences are also given in binary for small values of n.

5.1 Aperiodic sequences

An example of an aperiodic binary orientable sequence is given below for every n satisfying $4 \leq n \leq 16$ of length equal to the value in Table 4.

$n = 4$, $\ell = 8$ **(unique if complementing and reversing are taken into account).** Binary: `00010111`
Hex: `17`

$n = 5$, $\ell = 14$ **(unique if complementing and reversing are taken into account).** Binary: `00001101001111`
Hex: `0D3C`

$n = 6$, $\ell = 26$**.** Binary: `00000100110111000101011111`
Hex: `04DC57C`

$n = 7$, $\ell = 48$. Binary: 000000100110000101011001110100011110110100111111
Hex: 026159D1ED3F

$n = 8$, $\ell = 108$. Binary: 111111101110000101001100010000011011101010100011110100111000110101111100100101011011001000101110011010000000
Hex: FEE14C41BAA3D38D7C95B22E680

$n = 9$, $\ell = 210$. 00CE32BCBB6647B05BE6B9E04FD22E1269B8B10A77A1AA5A8C3FC

$n = 10$, $\ell = 444$. 0057BB6AEE7F7835BF2B9A096E45B1C27B3D7452C9C5F32D7051F62C3BEB31563287C94E9223A19CBB08D3C4DC7A6C042A6A20C818955FF

$n = 11$, $\ell = 882$. 002F5CB7F20BBF0EDF44B291EA7BB3FD0AC943AB754DCA8B1F9DF281336F4E36D27A5AF3EB0AB598B511B8BC2E05B2FD9A7EA0D35DC8A63BD91CF1D201CCAD8461E5CE4C4F347D8CED10A3C1968667B5C41C574C92F82C87CC08986F18AAC52C486093A36752EC04270D09581EFFC

$n = 12$, $\ell = 1878$. 0017956F52CF5C7FD6E5BE2DE4C713F62FC6F71C8DDF83A7D9FABBEDD4FF41591F0DF5EF0AB1E8F7712EF494BC08BEAA9919BD158B5D9ABD0AE7F70F5491E725C6DE3EB3BE6A737053E7B270A6EDAD35D518DC9F5027C67833B203E617C272FED6673A279B2ED47E5A2E9D2A8A77996D58704C5C334E2A12B80C665235E234C36D12CAFE20D72A5381A5D44D8AF2177683D82E496E30858A63476050DD1C23AB58D80B50C1B4A3C3164AC01058398A0914832B675D03B9E9EFA687F2500E3CA6AB904451D0ED9506225443664232E64D616C913BAFDF043C90EB6202AB48688E7D2064428B38D26134DFFC

$n = 13$, $\ell = 3752$. FFF3ECF1F561BFA7ECCB7CBBD3BDBF96EBF6C3D7D2DEC7331E2AFC74AE631D1F479F929DD81F8C80F3A29D0DE95723A16E3C179784B3FA9FF6815E3943DBAB4154D4B6A3F7C6E2A13FDCFE2DE31384F7BB863E7A9B79E689BBE6B959EE6ED129BEB7E1AF36E9BDFA4F1A7C3B5A599EC5EFA9533CB97540F99DBE8B2D7794A1896AA8DD65C5E2CC073141FFA33752766B7A8E7719F8926DA76900BF517AE97987DC8BF38EFCDC24EBE17C8A666D374A659D950761D4E0F432FC1A5CE64FBCE0B6F8874E79381EC175192C30796A7AE177306E7A227A674C9567136AF7033EB323E49985669ED53C8D49176A63925EA9872FBA877DA85EDB075BBA47947BB712BD64E93570169C42D643FD68DB90DD01269518DB3793789FAC5C83868788B5043E3832D2906CA30CD851D5435B3AD63356E7579236873930D8D0A2D272C89304CAEB02C15C6CF9053F0A90B2B04237EE8E421B5D181A3BC3FBC1214D366869D44C47F990CE5565808F5B700D5780430F207871AE221A80638B430297FB208EEB9F4D251C281341989A8A58C2511A62D97A07484D8A56C7A454EC4C233C22C764A1562B1FD0980289194FA8456BD9C3A20FB1974207120451A4462C991092D812B54584882E081735883103280C148D1A097C009CD000

$n = 14$, $\ell = 7764$. 0006BBD3E0D5977559BD37EBEA97FF3B5FDB96F7D8DABEFF09ED975FEE17377FD679D5DFD3D8FE0E9E73A3733FE856FD3B393D7F3743F97CA7568F4397AF8F762B75

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$n = 15$, $\ell = 15534$. FFFDFBA59DDA3A75830FA6BC85166E9D18F43F8F6FBF9F33DFF3AB2
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5.2 Periodic sequences

For each n with $5 \leq n \leq 16$, one period of a periodic orientable sequence of maximum period is given below, using the same hexadecimal convention as in Section 5.1.

$n = 5$, $p = 6$. Binary: 001101
Hex: 34

$n = 6$, $p = 16$. Binary: 0001011001010111
Hex: 1657

$n = 7$, $p = 36$. Binary: 000011101000110010110011110110101001
Hex: 0E8CB3DA9

$n = 8$, $p = 92$. Binary: 000001010010011110101100111000110110101010001111101110100010011000100001110110010010111001011
Hex: 0527ACE36A8FBA2621D95CB

$n = 9$, $p = 194$. 024D3A263BD423D9761E56956651AE17E6DF219C5B9E9182C

$n = 10$, $p = 426$. 0195DB57B14B78BF2FBB3937CEE8AAE6368C8EC1354E99FD470D96B30BCD38F293DC2B1D07C8B284BADC87AE0C49605882A4435F114

$n = 11$, $p = 860$. 00C3F4783473AF2FF05EC5BDCF487DA9BE84FC55DF9BCD0ED96BF609C6EF23674D46AA63BE61772BC75B19CBA94093B4FA8B49981D18416207C9581722F0AE1E7F7898A45386E652F8D3AB3822C92E285B614D321AECD6A0CBD6443896193C62423B203DBA599E54466D2AD

$n = 12$, $p = 1856$. 0056C5FE4E75DBCB8E6DAAFDF63EF3498DD2C986BA735BB857BB0F8F
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92E6451A70917486F706CF165A3B9A2F8590F127876C8D85C42ED3313956B68609D80B72F0A0
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$n = 13$, $p = 3728$. 003B9B7E6FF9F5DAFF72F99DF528AD14C5668EFDA64D5D8FFD3F5CFE
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$n = 14$, $p = 7738$. 001A46F3B5EAD88C8CED3BED777CDAFA7ADBFBAFEC7F02F797713BBD
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