The optimal check weight of an $[\![11, 3, 3]\!]$ stabilizer code is five

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21 September 2026

Abstract

For a stabilizer code, let $\mathrm{W}_{\mathrm{opt}}(n, k, d)$ denote the least achievable maximum generator weight over all generating sets of the stabilizer group. Wei, Han, He, Li and Liu determined $\mathrm{W}_{\mathrm{opt}}(n, 3, 3)$ for all $n \le 10$ and for $n \ge 15$, leaving $\mathrm{W}_{\mathrm{opt}}(11, 3, 3) \in \{4, 5\}$ open. We show that no $[\![11, 3, 3]\!]$ stabilizer code admits eight independent commuting generators of weight at most four, and hence $\mathrm{W}_{\mathrm{opt}}(11, 3, 3) = 5$. The proof is combinatorial and covers degenerate and non-CSS codes. Weight-one and weight-two stabilizer elements reduce the block length; the weight-two elements decompose the qubits into cliques carrying a consistent Pauli label; a symplectic contraction then maps the problem into a smaller symplectic space carrying a lifted weight, on which five necessary counting conditions are imposed and enumerated exhaustively. The enumeration is over multisets of cluster types rather than over generating sets, and terminates in about eighty seconds. A standalone verification program is included.

1 Introduction

Fault-tolerant architectures favour stabilizer codes whose checks are as light as possible, and the extremal question is captured by the *optimal check weight*

$$\mathrm{W}_{\mathrm{opt}}(n, k, d) := \min\{\mathrm{W}(G) : G \text{ a generating set of the stabilizer group of some } [\![n, k, d]\!] \text{ code}\},$$

where $\mathrm{W}(G)$ is the largest weight of a generator in G, and $\mathrm{W}_{\mathrm{opt}} = \infty$ if no such code exists. Wei, Han, He, Li and Liu [1] introduced this quantity, proved general lower bounds, and tabulated it for small parameters. For $k = 3$, $d = 3$ their Eq. (4) gives

$$\mathrm{W}_{\mathrm{opt}}(n, 3, 3) = \infty \ (n \le 7), \qquad 6 \ (n = 8), \qquad 5 \ (n = 9), \qquad 4 \ (n \ge 15),$$

and the caption of their Table 2 records $\mathrm{W}_{\mathrm{opt}}(10, 3, 3) \ge 5$ from their Theorem 4. At $n = 11$ their Table 2 reads "$4 - 5$": their Theorem 4 gives only $\max\{4, \lceil (11n+k+1)/(4(n-k)) \rceil\} = \lceil 125/32 \rceil = 4$, their weight-constrained linear program leaves four, and their Appendix J lists an $[\![11, 3, 3; 5]\!]$ code as not known to be optimal. Their CSS bound $\mathrm{W}^{\mathrm{CSS}}_{\mathrm{opt}}(n, k, d) \ge \lceil (3n + k)/(n - k) \rceil = \lceil 36/8 \rceil = 5$ settles the CSS case, so any weight-four example must be non-CSS.

Theorem 1. *There is no qubit stabilizer code with parameters $[\![11, 3, d]\!]$, $d \ge 3$, whose stabilizer group is generated by eight independent, pairwise commuting Pauli operators each of weight at most four. Consequently* $\mathrm{W}_{\mathrm{opt}}(11, 3, 3) = 5$.

Since $n - k = 8$, the quantum Singleton bound gives $d \le 5$, and [1] record that no $[\![11, 3, 4]\!]$ or $[\![11, 3, 5]\!]$ stabilizer code exists; so $d \ge 3$ is equivalent to $d = 3$ here. The lower bound

$\mathrm{W}_{\mathrm{opt}}(11,3,3) \geq 4$ is their Theorem 4 and the matching construction $[\![9,3,3;5]\!] \otimes [\![2,0]\!]$ is their Appendix J, so Theorem 1 closes the entry.

Our argument in fact yields $\mathrm{W}_{\mathrm{opt}}(n,3,3) \geq 5$ for every $3 \leq n \leq 11$. We stress that only $n = 11$ is new: all of $n \leq 10$ is already contained in [1], as displayed above. We retain the smaller cases because they are obtained uniformly by the same enumeration and therefore serve as a consistency check on the method.

Relation to prior and concurrent work. Our Step 1 is Lemma 8 of [1]: weight-one stabilizers split off as one-qubit factors, leaving an active core with the same k, d and check weight and no weight-one stabilizer. The basis-adaptation we use is their Lemma 19(iii): if $L \subset G$ is spanned by stabilizers of weight at most u and $\ell = \dim L$, then G admits a basis whose first ℓ rows have weight at most u and whose remaining rows have weight at most w. Neither is claimed here as new.

The substantive difference lies in the treatment of $L_2(G)$, the span of the stabilizers of weight at most two. Appendix F.2 of [1] uses $\ell = \dim L_2(G)$ as a *counting* parameter: an L_2-adapted basis gives $A := wm - (w-2)\ell - I \geq 0$ (their Eq. (73)), and combining this with column-degree and matching estimates yields their Eq. (80), $\Gamma := (4w+1)m - 12n \geq 0$, whence the $d \geq 3$ bound of their Theorem 4. At $n = 11$, $k = 3$ that bound reads $\lceil 125/32 \rceil = 4$ and therefore does not decide the question; this is exactly why their Table 2 records "$4 - 5$".

We instead use $L_2(G)$ *structurally*. The weight-two stabilizers are shown to decompose the qubits into cliques carrying a single consistent Pauli label (Step 3), which after local Cliffords lets us contract each clique to one coordinate by a symplectic-form-preserving map κ equipped with a lifted weight (Step 4). The residual problem lives in a space of dimension $2\tilde{n}$ rather than $2n$, and the conditions (C1)–(C5) are counting statements about that contracted space. This converts the search from generating sets to multisets of cluster types, and it is what carries the argument past four at $n = 11$.

Concurrently and independently, Wang, Liu, Li, Kubica and Gu [2] study check-weight-constrained codes; their results are asymptotic and do not address the finite $[\![11,3,3]\!]$ weight-four question.

2 Conventions

Pauli operators on n qubits are taken modulo phases and identified with vectors $v = (a,b) \in \mathbb{F}_2^{2n}$ via $X^a Z^b$; $\mathrm{wt}(v) = |\{j : (a_j, b_j) \neq (0,0)\}|$, and two operators commute exactly when the symplectic form $\langle (a,b),(a',b') \rangle = a \cdot b' + b \cdot a'$ vanishes. A stabilizer group with k logical qubits is an isotropic subspace S of dimension $n-k$; $S^\perp$ is its symplectic dual and $d(S) = \min\{\mathrm{wt}(v) : v \in S^\perp \setminus S\}$. Thus $d(S) \geq 3$ iff every v with $1 \leq \mathrm{wt}(v) \leq 2$ either fails to lie in $S^\perp$ or lies in S. Qubit permutations and single-qubit Cliffords (elements of $GL(2,2)$ permuting the three nonzero elements X, Z, Y of $\mathbb{F}_2^2$ at one qubit) preserve weights and the symplectic form, hence isotropy, $S^\perp$ and $d(S)$; we use them freely.

Write *property (W)* for: S has a basis of $n-3$ vectors of weight at most four.

Remark 2. Property (W) is not a restriction relative to $\mathrm{W}_{\mathrm{opt}}$. $\mathrm{W}(G)$ is minimised over *all* generating sets, including redundant ones; but any generating set of weight at most four contains a basis of weight at most four. So $\mathrm{W}_{\mathrm{opt}}(n,3,d) \leq 4$ if and only if some S has property (W).

A *code* below means an isotropic S of dimension $n-3$ with $d(S) \geq 3$; a *counterexample* is a code with property (W). We repeatedly use the Steinitz exchange lemma in the form: if S has a basis of weight-≤ 4 vectors and $U \subseteq S$ is independent, then S has a basis consisting of U together with vectors from that weight-≤ 4 basis. This is the specialisation of [1, Lemma 19(iii)] used below.

3 Proof of Theorem 1

Suppose a counterexample exists and fix one with n minimal, $3 \le n \le 11$.

Step 1: no weight-one element ([1, Lemma 8]). Let $v \in S$ have weight 1 at qubit i; after a Clifford at i, $v = Z_i$. Every $u \in S$ has $\langle u, v\rangle = a_i(u) = 0$. Let π delete qubit i. For $u, u' \in S$ the qubit-i term of $\langle u, u'\rangle$ is $a_i b'_i + b_i a'_i = 0$, so $\pi(S)$ is isotropic; $\ker(\pi|_S) = \{0, v\}$, so $\dim \pi(S) = (n-1) - 3$. By exchange, S has a basis $\{v, h_2, \dots, h_{n-3}\}$ with $\mathrm{wt}(h_j) \le 4$, and $\{\pi(h_j)\}$ is a weight-≤ 4 basis of $\pi(S)$. If $u' \in \pi(S)^\perp \setminus \pi(S)$ had $\mathrm{wt}(u') \le 2$, inserting $(0,0)$ at qubit i gives u with $\langle u, s\rangle = \langle u', \pi(s)\rangle = 0$ for all $s \in S$ and $u \notin S$, contradicting $d(S) \ge 3$. So $\pi(S)$ is a counterexample on $n-1 \ge 3$ qubits, contradicting minimality.

Step 2: at most one weight-two element per pair. Suppose $v \ne v' \in S$ both have support $\{i, j\}$. Then $v + v' \in S$ is nonzero with support inside $\{i, j\}$, so by Step 1 it has weight two, whence $v_i \ne v'_i$ and $v_j \ne v'_j$. Choosing Cliffords at i, j (the action of $GL(2,2)$ on $\{X, Y, Z\}$ is the full symmetric group) we may take $v = X_i X_j$, $v' = Z_i Z_j$. Every $u \in S$ satisfies $b_i + b_j = 0$ and $a_i + a_j = 0$, so u restricted to $\{i, j\}$ lies in the isotropic $B = \{0, v, v', v + v'\}$. Deleting qubits i, j therefore yields an isotropic $\pi''(S)$ with $\ker(\pi''|_S) = B$ and $\dim \pi''(S) = (n-2) - 3$; exchange and the lifting argument of Step 1 apply verbatim, giving a counterexample on $n - 2 \ge 3$ qubits (Step 2 cannot trigger below $n = 5$), contradicting minimality.

Step 3: clusters. Let W be the graph on qubits whose edges are the supports of the weight-two elements of S (one per edge, by Step 2). If $\{i, j\}$ and $\{j, l\}$ are edges with elements v, v', then $\langle v, v'\rangle = \langle v_j, v'_j\rangle$, which vanishes iff $v_j = v'_j$ (two nonzero elements of $\mathbb{F}_2^2$ are orthogonal iff equal); isotropy forces $v_j = v'_j$, and then $v + v' \in S$ has support $\{i, l\}$, an edge. So every component of W is a clique, and at each vertex j of a nontrivial component all incident edges carry the same nonzero label $L(j)$. Apply at each such j the Clifford sending $L(j) \mapsto Z$. Now every edge element is $Z_a Z_b$, and for each component c of size ≥ 2 the space R_c of even-weight Z-type vectors supported in c lies in S. Let $c_1, \dots, c_{\tilde{n}}$ be the components (*clusters*, singletons included), $R = \sum_c R_c \subseteq S$, $\dim R = n - \tilde{n}$. By Steps 1–2 every element of S of weight ≤ 2 lies in R.

Step 4: contraction. Let $C(R) = R^\perp = \{u : a_a(u) = a_b(u)$ whenever a, b lie in the same cluster$\}$; $S \subseteq C(R)$. Define $\kappa : C(R) \to \mathbb{F}_2^{2\tilde{n}}$ by $\kappa(u)_c = (\bar{a}_c, \bar{b}_c)$ with $\bar{a}_c$ the common value of a on c and $\bar{b}_c = \sum_{a \in c} b_a$. Then $\ker \kappa = R$, κ is surjective, and κ preserves the symplectic form, since the contribution of c to $\langle u, u'\rangle$ is $\bar{a}_c \bar{b}'_c + \bar{b}_c \bar{a}'_c$. Put $\tilde{S} = \kappa(S)$, isotropic of dimension $(n-3) - (n-\tilde{n}) = \tilde{n} - 3 =: r$. By exchange, S has a basis consisting of a basis of R together with $h_1, \dots, h_r$ of weight ≤ 4, and $\tilde{g}_m = \kappa(h_m)$ is a basis of $\tilde{S}$ with $\mathrm{wt}(\tilde{g}_m) \le \#\{\text{clusters meeting } \operatorname{supp} h_m\} \le 4$. Moreover $S^\perp \subseteq C(R)$ and, for $u \in C(R)$, $u \in S^\perp$ iff $\kappa(u) \in \tilde{S}^\perp$; hence $\kappa(S^\perp) = \tilde{S}^\perp$ and $\kappa^{-1}(\tilde{S}) = S + R = S$. Define the *lifted weight* $\tilde{w}(\tilde{u}) = \sum_c \tilde{w}_c(\tilde{u}_c)$ with $\tilde{w}_c(0,0) = 0$, $\tilde{w}_c(0,1) = 1$, $\tilde{w}_c(1,0) = \tilde{w}_c(1,1) = |c|$. Then $\tilde{w}(\tilde{u}) = \min\{\mathrm{wt}(u) : u \in C(R),\ \kappa(u) = \tilde{u}\}$. Consequently

(D1) every $\tilde{u} \in \tilde{S}^\perp \setminus \tilde{S}$ has $\tilde{w}(\tilde{u}) \ge 3$;

(D2) $\tilde{S}$ has no nonzero element with $\tilde{w} \le 2$;

(D3) every nonzero $\tilde{u}$ with $\tilde{w}(\tilde{u}) \le 2$ satisfies $\langle \tilde{u}, \tilde{g}_m\rangle = 1$ for some m.

Step 5: the counting conditions. Let $s(\tilde{u}) = (\langle \tilde{u}, \tilde{g}_m\rangle)_{m=1}^r \in \mathbb{F}_2^r$. For a cluster c let $\tilde{Z}_c, \tilde{X}_c, \tilde{Y}_c$ be the vectors supported on c with c-component $(0,1), (1,0), (1,1)$. Put $G_c = \{m : (\tilde{g}_m)_c \ne 0\}$, $d_c = |G_c|$, and let n_X^c, n_Y^c, n_Z^c count the $m \in G_c$ with $(\tilde{g}_m)_c$ equal to X, Y, Z. Two nonzero elements of $\mathbb{F}_2^2$ have symplectic product 1 iff they differ, so wt $s(\tilde{Z}_c) = n_X^c + n_Y^c$, wt $s(\tilde{X}_c) = n_Y^c + n_Z^c$, wt $s(\tilde{Y}_c) = n_X^c + n_Z^c$.

(C1) By (D3), $s(\tilde{Z}_c) \neq 0$ for every cluster. For a singleton also $s(\tilde{X}_c) \neq 0 \neq s(\tilde{Y}_c)$, so at least two distinct nonzero values occur among $(\tilde{g}_m)_c$, $m \in G_c$; in particular $d_c \geq 2$. For $|c| = 2$, $\tilde{X}_c, \tilde{Y}_c$ have lifted weight two, so $n_Y^c + n_Z^c \geq 1$ and $n_X^c + n_Z^c \geq 1$.

(C2) Let D consist of $s(\tilde{Z}_c)$ for all clusters and $s(\tilde{X}_c), s(\tilde{Y}_c)$ for all singletons ($\tilde{n} + 2n_1$ vectors, n_1 the number of singletons). Any two distinct underlying errors differ by a nonzero vector of lifted weight ≤ 2, so by (D3) their syndromes differ. Hence D consists of pairwise distinct nonzero vectors, and for every $w \geq 1$ at most $\sum_{u=1}^{w} \binom{r}{u}$ members of D have weight $\leq w$ (*profile condition*).

(C3) $\sum_c d_c = \sum_m \mathrm{wt}(\tilde{g}_m) \leq 4r$.

(C4) For $m \neq m'$ put $a_{mm'} = \#\{c : (\tilde{g}_m)_c, (\tilde{g}_{m'})_c \text{ both nonzero and different}\}$. Then $\langle \tilde{g}_m, \tilde{g}_{m'} \rangle = a_{mm'} \bmod 2$, so $a_{mm'}$ is even; with $\mathrm{anti}_c = n_X^c n_Y^c + n_Y^c n_Z^c + n_Z^c n_X^c$ we get $\sum_c \mathrm{anti}_c = \sum_{m<m'} a_{mm'}$, which is even (*parity condition*).

(C5) Call $\{m, m'\}$ *tight* if for some singleton c, $e_m + e_{m'} \in \{s(\tilde{Z}_c), s(\tilde{X}_c), s(\tilde{Y}_c)\}$ and $(\tilde{g}_m)_c \neq (\tilde{g}_{m'})_c$. See Lemma 3 for the count σ_c of such errors at c. Let N_{11} be the number of clusters of size ≥ 2 with $n_X^c = n_Y^c = 1$. Then

$$\sum_c \mathrm{anti}_c \;\geq\; 2\Big(\sum_{\text{singletons } c} \sigma_c + N_{11} \Big) \qquad (\textit{refined condition}).$$

Lemma 3. *Fix a singleton c and let (α, β, γ) be the multiplicities of the three nonzero values X, Y, Z among $\{(\tilde{g}_m)_c : m \in G_c\}$, so $d_c = \alpha + \beta + \gamma$. For a nonzero $P \in \mathbb{F}_2^2$ the syndrome of the error P at c has weight $d_c - \mathrm{mult}(P)$ and support G_c minus those generators equal to P at c. It is a weight-two vector whose two generators differ at c precisely when*

$$d_c - \mathrm{mult}(P) = 2 \quad \textit{and the other two multiplicities are both } 1.$$

Let σ_c be the number of nonzero $P \in \mathbb{F}_2^2$ satisfying this. Here P ranges over all three *nonzero values, including a value carried by no generator, i.e.* $\mathrm{mult}(P) = 0$ *is allowed. In particular a singleton of type $(\alpha, \beta, \gamma) = (1, 1, 0)$ has $\sigma_c = 1$, realised by the value P carried by neither generator.*

Proof. All three errors $\tilde{X}_c, \tilde{Y}_c, \tilde{Z}_c$ at a singleton have lifted weight one and therefore lie in D, whatever the generators carry; so the count is over all three values. The displayed criterion is immediate from $\mathrm{wt}\, s = d_c - \mathrm{mult}(P)$ together with the requirement that the two surviving generators carry *different* values at c, which for a weight-two syndrome says exactly that the other two multiplicities are 1 and 1. For type $(1, 1, 0)$ and P the absent value, $\mathrm{mult}(P) = 0$, $d_c = 2$, and the two generators carry the two distinct present values, so the pair is tight. □

Remark 4. Lemma 3 is load-bearing. If σ_c is (incorrectly) restricted to values present among the generators, the sieve below leaves 13 surviving configurations at $n = 11$ instead of none. Likewise the N_{11} term cannot be dropped: without it, 3 configurations survive at $n = 11$.

Proof of (C5). Because the members of D are pairwise distinct, each tight pair arises from exactly one singleton and one error there, and distinct tight pairs give distinct vectors $e_m + e_{m'}$; hence the number of tight pairs is $\sum_c \sigma_c$. For a cluster c of size ≥ 2 with $n_X^c = n_Y^c = 1$, the set $A_c = \{m : (\tilde{g}_m)_c \in \{X, Y\}\}$ is a pair differing at c, with $e_m + e_{m'} = s(\tilde{Z}_c) \in D$; were it tight, that vector would also be the syndrome of an error at a singleton, a second member of D, contradicting distinctness. So the N_{11} pairs are non-tight, and distinct clusters give distinct members of D hence distinct pairs. Let $\mathcal{P} = \{\{m, m'\} : a_{mm'} > 0\}$; all tight and all N_{11} pairs lie in $\mathcal{P}$, and each has $a_{mm'} \geq 2$ since $a_{mm'}$ is positive and even by (C4). Therefore $\sum_c \mathrm{anti}_c = \sum_{\mathcal{P}} a_{mm'} \geq 2(\sum_c \sigma_c + N_{11})$. □

Step 6: enumeration. Every quantity in (C1)–(C5) depends only on the multiset of *cluster types*: for a singleton, the sorted multiplicities $(\alpha \geq \beta \geq \gamma)$ of the three nonzero values — all three enter symmetrically, since no Clifford was fixed at a singleton in Step 3 and the residual freedom is the full S_3 on $\{X, Y, Z\}$; for a cluster of size ≥ 2, the triple (n_X, n_Y, n_Z) with $n_X \geq n_Y$, since X and Y enter symmetrically in $|A_c|$, anti_c, the size-two condition and N_{11}, while Z is distinguished by the normalisation of Step 3. The accompanying program enumerates, for each n, every partition of n into cluster sizes, sets $r = \tilde{n} - 3$, enumerates every multiset of admissible types (patterns satisfying (C1) with $d_c \leq r$) whose total incidence satisfies (C3), and applies (C2), (C4), (C5) in turn.

Proposition 5. *For every $3 \leq n \leq 11$ no multiset of cluster types satisfies (C1)–(C5).*

The cumulative survivor counts are

n	(C3)	(C2)	(C4)	(C5)
3–5	0	0	0	0
6	1	0	0	0
7	11	0	0	0
8	97	0	0	0
9	717	0	0	0
10	4692	6	4	0
11	28032	244	114	0
12	155364	3236	1614	191

The value at $n = 12$, together with 4088, 45881 and 370512 survivors at $n = 13, 14, 15$, shows the sieve is far from vacuous, so the zeros at $n \leq 11$ are a genuine consequence of the conditions and not an artefact of over-pruning. Nothing is claimed about $n \geq 12$.

Proof of Theorem 1. A minimal counterexample with $3 \leq n \leq 11$ yields, through Steps 1–5, a multiset of cluster types for its n satisfying (C1)–(C5), which Proposition 5 excludes. Hence no counterexample exists; for $n = 11$ this is the negation of the statement, and with Remark 2, $\mathrm{W}_{\mathrm{opt}}(11, 3, 3) \geq 5$. The $[\![9, 3, 3; 5]\!] \otimes [\![2, 0]\!]$ code of [1, App. J] gives $\mathrm{W}_{\mathrm{opt}}(11, 3, 3) \leq 5$. □

Degenerate and non-CSS codes are included throughout: Steps 1–5 make no CSS or nondegeneracy assumption, and degeneracy is precisely what the clusters encode.

4 Verification

The file `checker.py` is standalone — it uses only the Python standard library, needs no network, no other file and no arguments — and prints the table above together with positive controls: the conditions are verified on genuine distance-three codes ($3 \times [\![5, 1, 3]\!]$, the Steane code, repetition-extended codes with clusters of sizes two and three, and 75 random distance-three $[\![7, k, 3]\!]$ codes containing $Z_0 Z_1$). A condition failing a positive control would be a condition that is not necessary. Expected output is in `expected_stdout.txt`; see `VERIFY.md`. Reproduction establishes only that the program computes what is described; the necessity of (C1)–(C5) must be checked against Steps 1–5.

AI assistance and review status

AI tools were used to develop the argument of Sections 3, to write the verification program, to assist exposition, and to conduct internal adversarial reviews. The manuscript follows the

evidence-tracking guidance of Scientific Agent Skills [5]. These activities are disclosed as AI assistance, not as external refereeing or formal proof verification.

Two independent adversarial reviews were performed by AI in isolated contexts; each re-implemented the enumeration of Section 3 from the written argument alone and reproduced every counter of the table in Section 4. Both reviewers initially misread the convention of Lemma 3, which is why that convention is stated there as a lemma with proof and quantified in Remark 4; a reader checking this paper should begin there. **No independent human expert has examined this argument, and no novelty certification by a human is recorded.** The problem record [4] was still listed as unsolved when this manuscript was prepared.

The written argument, not the program, supports the theorem: the program checks a finite enumeration and supplies no substitute for the necessity of (C1)–(C5).

References

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