
STACK NUMBER IS NOT QUEUE-NUMBER BOUNDED

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October 26, 2020

ABSTRACT. We describe a family of graphs in which every member has queue number at most 4, but for every integer s , there is a member of the family whose stack number is greater than s . This resolves open problems of ??? and Blankenship and Oporowski (???).

1 Introduction

STACKS vs QUEUES

LINEAR LAYOUTS, CROSSINGS AND NESTINGS

STACKS AND QUEUES

STACK-NUMBER AND QUEUE-NUMBER

BOUNDED PARAMETERS

IMPORTANT PAPERS [3, 5, 7–9]

IS STACK-NUMBER BOUNDED BY QUEUE-NUMBER?

Heath et al. [7] showed that every 1-queue graph has a 2-stack layout. Heath et al. [7] showed that the ternary hypercubes requires exponentially more stacks than queues. In particular, n -vertex ternary hypercubes have queue-number at most $2\log_3 n$, but stack-number at least $\Omega(n^{1/9-\epsilon})$ for any $\epsilon > 0$. We prove the following theorem, which shows that stack-number is not bounded by queue-number.

Theorem 1. *For every $s \in \mathbb{N}$ there exists a graph G with $\text{qn}(G) \leq 4$ and $\text{sn}(G) > s$.*

IS QUEUE-NUMBER BOUNDED BY STACK-NUMBER?

Heath et al. [7] showed that every 1-stack graph has a 2-queue layout. Dujmović et al. [4] showed that planar graphs have bounded queue-number. In particular, 2-stack graphs have bounded queue-number. It is open whether 3-stack graphs have bounded queue-number. In fact, the case of three stacks is as hard as the general question. Dujmović

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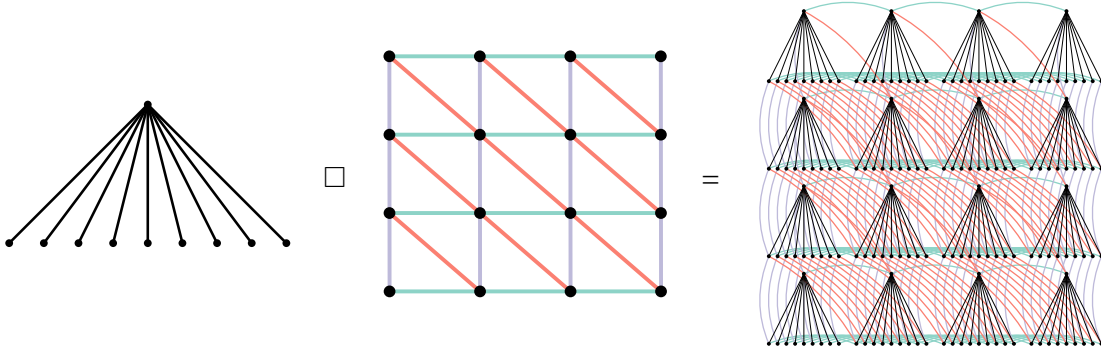


Figure 1: $S_9 \square Q_4$.

and Wood [5] proved that queue-number is bounded by stack-number if and only if 3-stack graphs have bounded queue-number. Moreover, if this is true then stack-number is bounded by a polynomial function of queue-number.

BLANKENSHIP AND OPOROWSKI CONJECTURE [1, 2]

Does anyone know if there is a standard box operator that is typeset like this $S \boxtimes Q$ or $S \boxdot Q$ instead of like this $S \square Q$ or like this $S \sqcap Q$? I tried square and Box.

The graph G in Theorem 1 is obtained as follows (See Figure 1): Let S_b denote the star graph with root r and b leaves. For an even positive integer n , let Q_n be the $n \times n$ triangulated grid, defined by $V(Q_n) := \{1, \dots, n\}^2$ and

$$\begin{aligned} E(Q_n) := & \{(x, y)(x + 1, y) : x \in \{1, \dots, n - 1\}, y \in \{1, \dots, n\}\} \\ & \cup \{(x, y)(x, y + 1) : x \in \{1, \dots, n\}, y \in \{1, \dots, n - 1\}\} \\ & \cup \{(x, y + 1)(x + 1, y) : x, y \in \{1, \dots, n - 1\}\} . \end{aligned}$$

We consider the graph $G := S_b \square Q_n$. That is, $V(G) = V(S_b) \times V(Q_n)$ where vertices $(v_1, w_1), (v_2, w_2) \in V(G)$ are adjacent whenever $v_1 = w_1$ and $v_2 w_2 \in E(Q_n)$, or $v_1 w_1 \in E(S_b)$ and $v_2 = w_2$.

2 Queue-Number Upper Bound

To prove that $\text{qn}(G) \leq 4$ in Theorem 1 we need the following definition due to Wood [10]. A queue layout $(\varphi, <)$ is *strict* if for every vertex $u \in V(G)$ and for all neighbours $v, w \in N_G(u)$ with $u < v, w$ or $v, w < u$, we have $\varphi(uv) \neq \varphi(uw)$. Let $\text{sqn}(G)$ be the minimum integer k such that G has a strict k -queue layout. Note that $\text{sqn}(Q_n) \leq 3$: Order the vertices row-by-row and then left-to-right within a row, with vertical edges in one queue, horizontal edges in one queue, and diagonal edges in another queue. Wood [10] proved that $\text{qn}(G \square H) \leq \text{qn}(G) + \text{sqn}(H)$ for all graphs G and H . Of course, S_b has a 1-queue layout (since no two edges are nested for any vertex-ordering). Thus

$$\text{qn}(S_b \square Q_n) \leq 4.$$

ADD TO DISCUSSION LATER: Q_n is planar with a Hamiltonian cycle (assuming n is even), so $\text{sn}(Q_n) \leq 2$

Suggestion:
Replace
 Q_n with
 H (for
Hex)

3 Stack-Number Lower Bound

Consider a hypothetical s -stack layout $(\varphi, <)$ of G where n and b are chosen sufficiently large compared to s as detailed below. We begin with three lemmata that, for sufficiently large b , allow us to find a large subgraph S_d of S_b for which the stack layout $(\varphi, <)$ of $S_d \square Q_n$ is highly structured.

For each node v of S_b , we define π_v as the permutation of $\{1, \dots, n\}^2$ in which (x_1, y_1) appears before (x_2, y_2) if and only if $(v, x_1, y_1) < (v, x_2, y_2)$. The following lemma is an immediate consequence of the Pigeonhole Principle:

Lemma 1. *There exists a permutation π of $\{1, \dots, n\}^2$ and a set L_1 of leaves of S_b of size $b_1 \geq \lceil b/(n^2)! \rceil$ such that $\pi_v = \pi$ for each $v \in L_1$.*

If we cared, we could improve this to $b/2^{cn^2}$ since we only use the weaker property (P3) in the final proof.

For each leaf v in L , let φ_v be the edge colouring of Q_n defined by $\varphi_v(x, y) := \varphi(v, x, y)$. The edges of Q_n are defined as the union of three sets, each of which has size less than n^2 , so Q_n has less than $3n^2$ edges. Therefore are fewer than s^{3n^2} edge colourings of Q_n using s colours. Another application of the Pigeonhole Principle proves the following:

Lemma 2. *There exists a subset $L_2 \subseteq L_1$ of size $b_2 \geq b_1/s^{3n^2}$ and an edge colouring $\varphi_0 : Q_n \rightarrow \{1, \dots, s\}$ such that $\varphi_v = \varphi_0$ for each $v \in L_2$.*

The preceding two lemmata ensure that, for distinct leaves v and w of S_{b_2} , the stack layout of the isomorphic graphs $Q_v := G[\{(v, p) : p \in V(Q)\}]$ and $Q_w := G[\{(w, p) : p \in V(Q)\}]$ is identical. The next lemma is a statement about the relationships between the stack layouts of $S_p := G[\{(v, p) : v \in V(S_{b_2})\}]$ and $S_q := G[\{(v, q) : v \in V(S_{b_2})\}]$ for two distinct $p, q \in V(Q)$. It cannot assert that these two layouts are identical but it does state that they fall into one of two categories.

Lemma 3. *There exists a sequence $L_3 := u_1, \dots, u_{b_3}$ with $\{u_1, \dots, u_{b_3}\} \subseteq L_2$ of length $b_3 \geq b_2^{1/2^{n^2-1}}$ such that, for each $p \in V(Q_n)$, $(u_1, p) < (u_2, p) < \dots < (u_{b_3}, p)$ or $(u_1, p) > (u_2, p) > \dots > (u_{b_3}, p)$.*

Proof. Let p_1, \dots, p_{n^2} denote the vertices of Q_n , in any order. Begin with the sequence $S_1 := v_{1,1}, \dots, v_{1,d_1}$ that contains all $d_1 := b_2$ elements of L_2 ordered so that $(v_{1,1}, p_1) < \dots < (v_{1,d_1}, p_1)$. For each $i \in \{2, \dots, n^2\}$, the Erdős-Szekeres Theorem implies that, S_{i-1} contains a subsequence $S_i := v_{i,1}, \dots, v_{i,d_i}$ of length $d_i \geq \sqrt{|S_{i-1}|}$ such that $(v_{i,1}, p_i) < \dots < (v_{i,d_i}, p_i)$ or $(v_{i,1}, p_i) > \dots > (v_{i,d_i}, p_i)$. It is straightforward to verify by induction on i that $d_i \geq b_2^{1/2^{i-1}}$ resulting in a final sequence $S_{n^2} =: L_3$ of length at least $b_2^{1/2^{n^2-1}}$. \square

Reference?

Let $d := b_3$ and let S_d be the the subgraph of S_b induced by $\{r\} \cup \{u_1, \dots, u_d\}$ where u_1, \dots, u_d is the sequence of leaves defined in Lemma 3. Consider the (improper) vertex colouring of Q_n obtained by colouring each vertex $p \in V(Q_n)$ *red* if $(u_1, p) < \dots < (u_d, p)$ and colouring p *blue* if $(u_1, p) > \dots > (u_d, p)$.

Lemma 4. *The graph Q_n contains an n -vertex path R consisting entirely of red vertices or entirely of blue vertices.*

Proof. The dual of Q_n is the board on which the game Hex is played. The well-known *Hex Lemma* states that any colouring of the vertices of Q_n with colours red and blue contains exactly one of the following [6]:

1. a path with endpoints $(x, 1)$ and (x', n) consisting entirely of red vertices, for some $x, x' \in \{1, \dots, n\}$; or
2. a path with endpoints $(1, y)$ and (n, y') consisting entirely of blue vertices, for some $y, y' \in \{1, \dots, n\}$.

In either case, the path contains at least n vertices and therefore has a n -vertex subpath consisting entirely of red vertices or entirely of blue vertices. \square

Without loss of generality, assume that the path $R := p_1, \dots, p_n$ defined by Lemma 4 consists entirely of red vertices, so that $(u_1, p_j) < \dots < (u_d, p_j)$ for each $j \in \{1, \dots, n\}$. Recall that $(\varphi, <)$ is a hypothetical s -stack layout of G and therefore it is also an s -stack layout of the subgraph $X := S_d \square R$. The following result finishes the proof by showing that this is not possible when $n > 2s$ and $d > s2^n$.

Lemma 5. *The graph X contains a set of edges of size at least $\min\{d/2^n, n/2\}$ that are pairwise crossing with respect to $<$.*

Proof. We will define two sequences of nested sets $A_1 \supseteq \dots \supseteq A_n$ of leaves of S_d so that each A_i satisfies the following conditions:

- (C1) A_i contain $d_i \geq d/2^{i-1}$ leaves of S_d .
- (C2) Each leaf $v \in A_i$ defines an i -element vertex set $Z_{i,v} := \{(v, p_j) : j \in \{1, \dots, i\}\}$. For any distinct $v, w \in A_i$, $Z_{i,v}$ and $Z_{i,w}$ are *separated* with respect to $<$, i.e., $Z_{i,v} < Z_{i,w}$ or $Z_{i,v} > Z_{i,w}$.

Before defining A_1, \dots, A_n we first show how the existence of the set A_n implies the lemma. To avoid triple-subscripts, let $d' := d_n \geq d/2^n$. The set A_n defines vertex sets $Z_{n,v_1} < \dots < Z_{n,v_{d'}}$. Refer to Figure 2. Recall that r is the root of S_b so it is adjacent to each of $v_1, \dots, v_{d'}$ in S_b . Therefore, for each $j \in \{1, \dots, n\}$ and each $i \in \{1, \dots, d'\}$, the edge $(r, p_j)(v_i, p_j)$ is in X . Therefore, (r, p_j) is adjacent to an element of each of $Z_{n,v_1}, \dots, Z_{n,v_{d'}}$.

Since $Z_{n,v_1}, \dots, Z_{n,v_{d'}}$ are separated with respect to $<$, when viewed from afar, this situation looks like a complete bipartite graph $K_{n,d'}$ with the root vertices $L := \{(r, p_j) : j \in \{1, \dots, n\}\}$ in one part and the groups $R := Z_{n,v_1} \cup \dots \cup Z_{n,v_{d'}}$ in the other part. Any linear ordering of $K_{n,d'}$ has a large set of pairwise crossing edges so, intuitively, the graph induced by $L \cup R$ should also have a large set of pairwise crossing edges. Lemma 6, below, formalizes this and shows that this graph has a set of at least $\min\{d', n\}/2$ pairwise crossing edges.

All that remains is to define the sets $A_1 \supseteq \dots \supseteq A_n$ that satisfy (C1) and (C2). The set A_1 contains all the leaves of S_d . For each $i \in \{2, \dots, n\}$, the set A_i is defined as follows: Let Z_1, \dots, Z_r denote the sets $\{(v, p_j) : j \in \{1, \dots, i-1\}\}$ for $v \in A_{i-1}$ ordered so that $Z_1 < \dots < Z_r$.

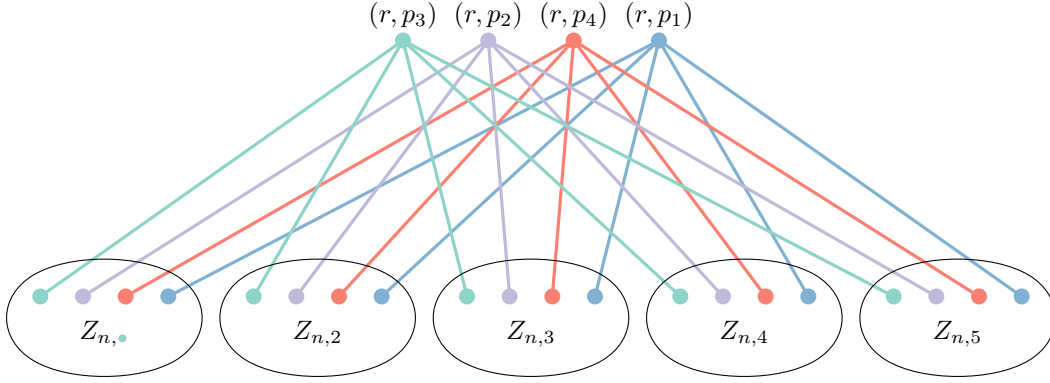


Figure 2: The sets $Z_{n,1}, \dots, Z_{n,d'}$ ($n = 4$, $d' = 5$).

By Property (C2), this is always possible. Label the vertices of A_{i-1} as v_1, \dots, v_r so that $(v_1, p_{i-1}) < \dots < (v_r, p_{i-1})$. (This is equivalent to naming them so that $(v_j, p_{i-1}) \in Z_j$ for each $j \in \{1, \dots, r\}$.) We define the set $A_i := \{v_{2k+1} : k \in \{0, \dots, \lfloor (r-1)/2 \rfloor\}\} = \{v_j \in A_{i-1} : j \text{ is odd}\}$. This completes the definition of A_1, \dots, A_n .

All that remains is to verify that A_i satisfies (C1) and (C2). We do this by induction on i . The base case $i = 1$ is trivial so we assume from this point on that $i \in \{2, \dots, n\}$. To see that A_i satisfies (C1) just observe that $|A_i| = \lceil r/2 \rceil \geq r/2 = |A_{i-1}|/2 \geq d/2^{i-1}$. All that remains is to show that A_i satisfies (C2).

For each $j \in \{i-1, i\}$, let $Q_j := Q_n[\{(v, p_j) : v \in A_{i-1}\}]$. Recall that, for each $v \in A_{i-1}$, the edge $e_v := (v, p_{i-1})(v, p_i)$ is in X . We have the following properties:

- (P1) By Lemma 2, $\varphi(e_v) = \varphi_0(p_{i-1}, p_i)$ for each $v \in A_{i-1}$.
- (P2) By the application of Lemma 4, $(v, p_{i-1}) < (w, p_{i-1})$ if and only if $(v, p_i) < (w, p_i)$ for each $v, w \in A_{i-1}$.
- (P3) By Lemma 1, $(v, p_{i-1}) < (v, p_i)$ for every $v \in A_{i-1}$ or $(v, p_{i-1}) > (v, p_i)$ for every $v \in A_{i-1}$.

We claim that these three conditions imply that the vertex sets Q_{i-1} and Q_i interleave perfectly with respect to $<$. More precisely:

Claim 1. $(v_1, p_{i-1+t}) < (v_1, p_{i-t}) < (v_2, p_{i-1+t}) < (v_2, p_{i-t}) \dots < (v_r, p_{i-1+t}) < (v_r, p_{i-t})$ for some $t \in \{0, 1\}$.

Proof of Claim 1. By (P3) we may assume, without loss of generality, that $(v, p_{i-1}) < (v, p_i)$ for each $v \in A_{i-1}$, in which case we are trying to prove the claim for $t = 0$. It is sufficient, therefore to show that $(v_j, p_i) < (v_{j+1}, p_{i-1})$ for each $j \in \{1, \dots, r-1\}$. For the sake of contradiction, suppose $(v_j, p_i) > (v_{j+1}, p_{i-1})$ for some $j \in \{1, \dots, r-1\}$. By definition $(v_j, p_{i-1}) < (v_{j+1}, p_{i-1})$ so, by (P2) $(v_j, p_i) < (v_{j+1}, p_i)$. Therefore

$$(v_j, p_{i-1}) < (v_{j+1}, p_{i-1}) < (v_j, p_i) < (v_{j+1}, p_i) .$$

Therefore the edges $(v_j, p_{i-1})(v_j, p_i)$ and $(v_{j+1}, p_{i-1})(v_{j+1}, p_i)$ cross with respect to $<$. But this is a contradiction since, by (P1), $\varphi((v_j, p_{i-1})(v_j, p_i)) = \varphi((v_{j+1}, p_{i-1})(v_{j+1}, p_i)) = \varphi_0(p_{i-1}, p_i)$. This contradiction completes the proof of Claim 1. \square

Tiny notation conflict here: Q_n, Q_i, Q_{i-1} .

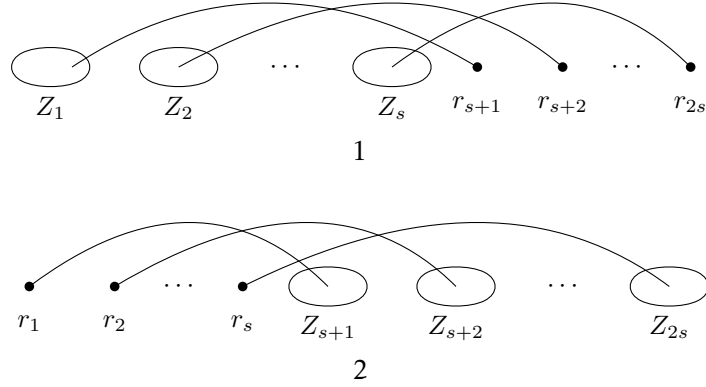


Figure 3: The two cases in the proof of Lemma 6.

Now, apply Claim 1 and assume without loss of generality that $t = 0$, so that

$$(v_1, p_{i-1}) < (v_1, p_i) < (v_2, p_{i-1}) < (v_2, p_i) \cdots < (v_r, p_{i-1}) < (v_r, p_i) .$$

For each $j \in \{1, \dots, r-2\}$, $(v_{j+1}, p_{i-1}) \in Z_{j+1} < Z_{j+2}$, so $(v_j, p_i) < (v_{j+1}, p_{i-1}) < Z_{j+2}$. Therefore $Z_j \cup \{(v_j, p_i)\} < Z_{j+2}$. By a symmetric argument, $Z_j \cup \{(v_j, p_i)\} > Z_{j-2}$ for each $j \in \{2, \dots, r\}$. Finally, since $(v_j, p_i) < (v_{j+2}, p_i)$ for each odd $j \in \{1, \dots, r\}$, we have $Z_j \cup \{(v_j, p_i)\} < Z_{j+2} \cup \{(v_{j+2}, p_i)\}$ for each odd $j \in \{1, \dots, r-2\}$. Thus A_i satisfies (C2) since the sets $Z_1 \cup \{(v_1, p_i)\}, Z_3 \cup \{(v_3, p_i)\}, \dots, Z_{2\lfloor (r-1)/2 \rfloor + 1} \cup \{(v_{2\lfloor (r-1)/2 \rfloor + 1}, p_i)\}$ are precisely the sets $Z_{i,1}, \dots, Z_{i,d_i}$ determined by our choice of A_i . \square

Lemma 6. Let G be any graph, let $<$ be any linear ordering of $V(G)$, let $Z_1 < \dots < Z_{2s}$ be subsets of $V(G)$, and let $r_1 < \dots < r_{2s}$ be vertices of G such that, for each $i, j \in \{1, \dots, 2s\}$, G contains an edge $r_i z_j$ with $z_j \in Z_j$. Then G contains a set of s edges that are pairwise crossing with respect to $<$.

Proof. At least one of the following two cases applies (see Figure 3):

1. $Z_s < r_{s+1}$ in which case the graph between r_{s+1}, \dots, r_{2s} and Z_1, \dots, Z_s has a set of s pairwise-crossing edges.
2. $r_s < Z_{s+1}$ in which case the graph between r_1, \dots, r_s and Z_{s+1}, \dots, Z_{2s} has a set of s pairwise-crossing edges. \square

4 Open Problems

Recall that every 1-queue graph has a 2-stack layout [7] and we proved that there are 4-queue graphs with unbounded stack-number. The following questions remain open: Do 2-queue graphs have bounded stack-number? Do 3-queue graphs have bounded stack-number?

Is $\text{sn}(T \square H)$ bounded for every tree T and outerplanar graph H with bounded degree?

Is $\text{sn}(T \boxtimes P)$ bounded for every tree T and path P ?

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