Rainbow $k$-Connection in Dense Graphs

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Abstract

An edge-coloured path is rainbow if the colours of its edges are distinct. For a positive integer $k$, an edge-colouring of a graph $G$ is rainbow $k$-connected if any two vertices of $G$ are connected by $k$ internally vertex-disjoint rainbow paths. The rainbow $k$-connection number $rc_k(G)$ is defined to be the minimum integer $t$ such that, there exists an edge-colouring of $G$ with $t$ colours which is rainbow $k$-connected. We consider $rc_k(G)$ when $G$ has fixed vertex-connectivity. We also consider $rc_k(G)$ for large complete bipartite and multipartite graphs $G$ with equipartitions. Finally, we determine sharp threshold functions for the properties $rc_k(G) = 2$ and $rc_k(G) = 3$, where $G$ is a random graph. Related open problems are posed.

Keywords: rainbow colouring, vertex-connectivity, random graph

1 Introduction

In this paper, unless otherwise stated, all graphs are finite, simple and undirected. For basic terminology in graph theory, see [1]. An edge-coloured path is rainbow if the colours of its edges are distinct. For $k \in \mathbb{N}$, an edge-colouring of a graph $G$ is rainbow $k$-connected if any two vertices of $G$ are connected by $k$ internally vertex-disjoint rainbow paths. The rainbow $k$-connection number $rc_k(G)$ is defined to be the minimum integer $t$ such that, there exists an edge-colouring of $G$ with $t$ colours which is rainbow $k$-connected. We write $rc(G) = rc_1(G)$. Note that, by Menger’s Theorem [19], a graph is $k$-connected if and only if any two vertices are connected by $k$ internally vertex-disjoint paths. Hence, $rc_k(G)$ will only be defined for $k$-connected graphs $G$.

The function $rc_k(G)$ was introduced by Chartrand et al. [5, 6] in 2008. They studied $rc_k(G)$ for many graphs, notably when $G$ is complete, and complete bipartite and multipartite. They also introduced the strong rainbow connection number $src(G)$, and considered some relationships between $rc(G)$ and $src(G)$. An application to secure data transfer was presented as well. The subject has since attracted considerable interest. These include the study of $rc_k(G)$ when $G$ satisfies some condition on its minimum degree, or forbidden subgraphs, or diameter; or when $G$ is regular. The computational complexity of $rc_k(G)$ has also been studied. Further related functions have been introduced, such as the rainbow vertex connection number $rvr(G)$, and the $k$-rainbow index $rx_k(G)$. See for example, Caro et al. [3], Chartrand et al. [7], and Krivelevich and Yuster [13]. Recently, Li and Sun [17] published a survey on the current status of rainbow connection.

We continue the study of $rc_k(G)$. First, we consider $rc_k(G)$ for graphs $G$ with given vertex-connectivity. The cases $k = 1, 2$ were asked, respectively, by Hajo Broersma (at the IWQuCA workshop

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proved that this is the case, when $f(G)$ is 2-connected. Li and Shi [14] proved that $rc(G) \leq \frac{3(n+1)}{5}$ if $G$ is 3-connected. Chandran et al. [4] proved that, if $G$ has minimum degree $\delta$, then $rc(G) \leq \frac{3n}{\delta+1} + 3$. Hence, if $G$ is $\ell$-connected, then $rc(G) \leq \frac{3n}{\ell+1} + 3$. Here, we prove the following result, in response to the case $k = 2$.

**Theorem 1.1** If $\ell \geq 2$ and $G$ is an $\ell$-connected graph on $n \geq \ell + 1$ vertices, then $rc_2(G) \leq \frac{(\ell+1)n}{\ell}$.

In the case $\ell = 2$, we can do better if $G$ is series-parallel. A 2-connected series-parallel graph is a (simple) graph which can be obtained from a $K_3$, and then repeatedly applying a sequence of operations, each of which is a subdivision, or replacement of an edge by a double edge. These graphs are a well-known sub-family of the 2-connected graphs.

**Theorem 1.2** If $G$ is a 2-connected series-parallel graph on $n \geq 3$ vertices, then $rc_2(G) \leq n$.

Note that $rc_2(C_n) = n$ if $C_n$ is the cycle on $n$ vertices. More generally, Theorem 1.3 below shows that Theorem 1.2 is tight when $G$ is a generalised $\Theta$-graph. That is, $G = \Theta_{q_1,\ldots,q_t}$ is the union of $t \geq 2$ paths with lengths $q_1 \geq \cdots \geq q_t \geq 1$, where $q_{t-1} \geq 2$, and the paths are pairwise internally vertex-disjoint with the same two end-vertices.

**Theorem 1.3** If $G = \Theta_{q_1,\ldots,q_t}$ is a generalised $\Theta$-graph on $n$ vertices, then

\[
rc_2(G) = \begin{cases} n & \text{if } t = 2, \\ n-1 \text{ or } n-2 & \text{if } t \geq 3. \end{cases}
\]

These results naturally lead to the following question.

**Problem 1.4** What is the minimum constant $c > 0$ such that for all 2-connected graphs $G$ on $n$ vertices, we have $rc_2(G) \leq cn$?

By Theorems 1.1 and 1.3, we have $1 \leq c \leq \frac{3}{2}$. Theorem 1.2 suggests that $c = 1$ may possibly be the correct answer.

Theorem 1.2 has an instant corollary. A result of Elmallah and Colbourn [9] says that any 3-connected planar graph contains a 2-connected series-parallel spanning subgraph.

**Corollary 1.5** If $G$ is a 3-connected planar graph on $n \geq 4$ vertices, then $rc_2(G) \leq n$. $\square$

Our next aim is to continue the study of $rc_2(G)$ when $G$ is a complete bipartite or multipartite graph. For $1 \leq n_1 \leq \cdots \leq n_t$ with $t \geq 2$, let $K_{n_1,\ldots,n_t}$ denote the complete multipartite graph with class sizes $n_1,\ldots,n_t$. Chartrand et al. [5] determined $rc(K_{n_1,\ldots,n_t})$ exactly, as follows. If $\sum_{i=1}^{t-1} n_i = m$ and $n_t = n$, then

\[
rc(K_{n_1,\ldots,n_t}) = \begin{cases} n & \text{if } t = 2 \text{ and } n_1 = 1, \\ \min(\lceil \sqrt{m} \rceil, 4) & \text{if } t = 2 \text{ and } 2 \leq n_1 \leq n_2, \\ 1 & \text{if } t \geq 3 \text{ and } n_t = 1, \\ 2 & \text{if } t \geq 3, n_t \geq 2 \text{ and } m > n, \\ \min(\lceil \sqrt{m} \rceil, 3) & \text{if } t \geq 3 \text{ and } m \leq n. \end{cases}
\]

Chartrand et al. [6] also proved that $rc_2(K_{n,n}) = 3$ if $k \geq 2$ and $n = 2k \lceil \frac{1}{2} \rceil$. They asked if for every $k \geq 2$, there is a function $f(k)$ such that for every $n \geq f(k)$, we have $rc_2(K_{n,n}) = 3$. Li and Sun [16] proved that this is the case, when $f(k) = 2k \lceil \frac{1}{2} \rceil$. Both of these results considered explicit colourings. With a random method, we are able to improve the result to $f(k) = 2k + o(k)$, as follows.
Theorem 1.6 Let $0 < \varepsilon < \frac{1}{2}$ and $k \geq \frac{1}{2}(\theta - 1)(1 - 2\varepsilon) + 2$, where $\theta = \theta(\varepsilon)$ is the largest solution of $2x^2 e^{-x^2(x-2)} = 1$. If $n \geq \frac{2k-4}{1-2\varepsilon} + 1$, then $rc_k(K_{n,n}) = 3$.

For example, if we set $\varepsilon = \frac{1}{6}$ so that $\theta \approx 469.94$, this result shows that for $k \geq 159$ and $n \geq 3k - 5$, we have $rc_k(K_{n,n}) = 3$.

On the other hand, how small can the function $f(k)$ be? The next result shows that the best we can hope for is approximately $f(k) \geq \frac{3k}{2}$.

Theorem 1.7 For any 3-colouring of the edges of $K_{n,n}$, there exist $u, v \in V(K_{n,n})$ where the number of internally vertex-disjoint rainbow $u - v$ paths is at most $\frac{2n^2}{3(n-1)}$.

We can extend this to complete multipartite graphs with equipartitions. Let $K_{t \times n}$ denote the complete multipartite graph with $t \geq 3$ classes of size $n$. For $k \geq 2$, when considering bipartite graphs $K_{n,n}$, we cannot achieve $rc_k(K_{n,n}) = 2$. However, we may hope for $rc_k(K_{t \times n}) = 2$. Using a similar random method, we have the following.

Theorem 1.8 Let $0 < \varepsilon < \frac{1}{2}$, $t \geq 3$, and $k \geq \frac{1}{2}\theta(t - 2)(1 - 2\varepsilon) + 1$, where $\theta = \theta(\varepsilon, t)$ is the largest solution of $\frac{1}{2}t^2x^2 e^{-(t-2)x^2} = 1$. If $n \geq \frac{2k-2}{(t-2)(1-2\varepsilon)}$, then $rc_k(K_{t \times n}) = 2$.

For example, if we set $t = 3$ and $\varepsilon = \frac{1}{6}$ so that $\theta \approx 501.86$, this result shows that for $k \geq 169$ and $n \geq 3k - 3$, we have $rc_k(K_{3 \times n}) = 2$.

Again, going in the other direction, the following result shows that the best lower bound for $n$ would be approximately $n \geq \frac{2k}{t-1}$.

Theorem 1.9 Let $t \geq 3$. For any 2-colouring of the edges of $K_{t \times n}$, there exist $u, v \in V(K_{t \times n})$ where the number of internally vertex-disjoint rainbow $u - v$ paths is at most $\frac{(t-1)n^2}{2(t-1)}$.

The related problem of considering $rc_k(G)$ when $G$ is a complete graph has already been well studied. Obviously, we have $rc(K_n) = 1$ for $n \geq 2$, and $rc_k(K_n) \geq 2$ for $n > k \geq 2$. Chartrand et al. [6] proved that, for $k \geq 2$, if $n \geq (k+1)^2$, then $rc_k(K_n) = 2$. The bound on $n$ was later improved by Li and Sun [15] to $n \geq ck^{3/2} + o(k^{3/2})$ (for some constant $c$), and then by Dellamonica et al. [8] to $n \geq 2k + o(k)$. The latter bound is also asymptotically the best possible.

Our last aim is to study $rc_k(G)$ when $G$ is some random graph model. In this direction, Caro et al. [3] considered $rc(G_{n,p})$, where $G_{n,p}$ is the random graph on $n$ vertices with edge probability $p$. Recall that, if $Q$ is a graph property and $p = p(n)$, then $G_{n,p}$ satisfies $Q$ almost surely (a.s.) if $\mathbb{P}(G_{n,p} \text{ satisfies } Q) \rightarrow 1$ as $n \rightarrow \infty$. A function $f(n)$ is a sharp threshold function for $Q$ if there are constants $c, C > 0$ such that, $G_{n,cf(n)}$ does not satisfy $Q$ a.s., and $G_{n,p}$ satisfies $Q$ a.s. for all $p \geq Cf(n)$. By a result of Bollobás and Thomason [2], every monotone graph property has a sharp threshold function. Since the property $rc(G) \leq 2$ is monotone, it has a sharp threshold function. In this setting, Caro et al. [3] proved that $p = \sqrt{\log n/n}$ is a sharp threshold function for the property $rc(G_{n,p}) \leq 2$. This was generalised by He and Liang [11], who proved that if $d \geq 2$ and $k \leq O(\log n)$, then $p = \frac{(\log n)^{1/d}}{n^{1/d-1}}$ is a sharp threshold function for the property $rc_k(G_{n,p}) \leq d$. Here, we prove the following result.

Theorem 1.10 $p = \sqrt{\log n/n}$ is a sharp threshold function for the property $rc_k(G_{n,p}) \leq 2$ for all $k \geq 1$.

We can consider other random graph models. Let $G_{n,m}$ be the random bipartite graph with class sizes $n$ and $m$, and edge probability $p$. Let $G_{n,M}$ be the random graph on $n$ vertices with $M$ edges, endowed with the uniform probability distribution. We can analogously define sharp threshold functions for these models. Again by the result of Bollobás and Thomason [2], every monotone property for these models has a sharp threshold function. We have the following results.
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Proof of Theorem 2.2.

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- connected graph contains a cycle on at least $\ell \log \sqrt{n}$ vertices is well-known. For example, this is an exercise in [1], Ch. III.6). Now suppose that we have found the graphs $H_i$ for $i = 0, \ldots, t$, where the $H_i$ are connected subgraphs of $G$ with at most $\ell \log \sqrt{n}$ vertices.

Theorem 2.2. We first find subgraphs $H_0 \subset H_1 \subset \cdots \subset H_t \subset G$, for some $t \geq 0$, with $V(H_t) = V(G)$, as follows. Firstly, let $H_0$ be a cycle of $G$ on at least $\ell$ vertices (The fact that any $\ell$-connected graph contains a cycle on at least $\ell$ vertices is well-known. For example, this is an exercise in [1], Ch. III.6). Now suppose that we have found the graphs $H_0, \ldots, H_{t-1}$ for some $i \geq 1$. If $V(H_{t-1}) = V(G)$, then set $H_t = H_{t-1}$. Otherwise, there exists a vertex $v_i \in V(G) \setminus V(H_{t-1})$. By Theorem 2.1, $v_i$ sends $\ell$ paths to $H_{t-1}$, with each pair of paths meeting only at $v_i$, i.e., the union of these $\ell$ paths is a subdivided $K_{1,\ell}$. Let $H_t$ be the union of $H_{t-1}$ with these $\ell$ paths. Repeat this process until it terminates.

We prove inductively that for every $0 \leq i \leq t$, there is an edge-colouring of $H_i$ with at most $\ell \log \sqrt{n}$ colours such that properties (a) to (c) in Theorem 2.2 hold, with $H_i$ in place of $G$. Then, setting $i = t$ implies that Theorem 2.2 holds for $G$.

To proceed, define an edge-colouring of each $H_i$ as follows. Firstly, rainbow colour $H_0$. Then, for $1 \leq i \leq t$, suppose that we have an edge-colouring for $H_{i-1}$, with colours $1, \ldots, m$. The graph $H_i$ is obtained by attaching a subdivided $K_{1,\ell}$ to $H_{i-1}$, where the $\ell$ paths meet at $v_i$. Let the paths be $Q_1, \ldots, Q_{\ell}$, with $e(Q_1) \geq \cdots \geq e(Q_{\ell}) \geq 1$. For the case $\ell = 2$, we may assume that $e(Q_1) \geq e(Q_2) = 1$.
Let $F = Q_1 \cup \cdots \cup Q_\ell$. For each $1 \leq j \leq \ell$, let $w_j \in V(H_{i-1})$ be the other end-vertex of $Q_j$. We call the edges of $Q_j$ incident to $v_i$ and $w_j$ the first edge and last edge of $Q_j$, respectively.

Case 1. $\ell + 1 \leq |V(F)| \leq 2\ell - 1$, $e(Q_1) = |V(F)| - \ell$ and $e(Q_2) = \cdots = e(Q_\ell) = 1$.

Rainbow colour $Q_1$ with colours $m + 1, \ldots, m + |V(F)| - \ell$. In view of $|V(F)| - \ell \leq \ell - 1$, we colour $Q_2, \ldots, Q_\ell$ with colours $m + 1, \ldots, m + |V(F)| - \ell$ in such a way that each colour appears at least once. We have used $|V(F)| - \ell$ new colours in total.

Case 2. $|V(F)| \geq 2\ell$, $e(Q_1) = |V(F)| - \ell$ and $e(Q_2) = \cdots = e(Q_\ell) = 1$.

Rainbow colour $Q_1$ with colours $m + 1, \ldots, m + |V(F)| - \ell$. Colour all of $Q_2, \ldots, Q_\ell$ with colour $m + |V(F)| - \ell + 1$. We have used $|V(F)| - \ell + 1$ new colours in total.

Case 3. $e(Q_2) \geq 2$.

Let $1 \leq s \leq \frac{1}{2} \ell$ be the largest integer such that $e(Q_1), \ldots, e(Q_{2s}) \geq 2$. For each $1 \leq j \leq s$, colour the first edge of $Q_{2j-1}$ and the last edge of $Q_{2j}$ with colour $m + 2j - 1$, and the last edge of $Q_{2j-1}$ and the first edge of $Q_{2j}$ with colour $m + 2j$. Colour the last edge of $Q_{2s+1}$ and all of $Q_{2s+2}, \ldots, Q_\ell$ (each having length 1) with colour $m + 2s + 1$. Colour the remaining edges of $F$ with further new, distinct colours. We have used $|V(F)| - \ell$ new colours in total.

Repeating inductively, we have a colouring for $H_i$, for every $0 \leq i \leq t$. We prove inductively that for every $0 \leq i \leq t$, the colouring for $H_i$ satisfies all of our requirements. Certainly, for $H_0$, we have used $|V(H_0)| < \frac{(t+1)|V(H_0)|}{t}$ colours, and properties (a) to (c) hold. Now for $1 \leq i \leq t$, suppose that in the colouring for $H_{i-1}$, at most $\frac{(t+1)|V(H_{i-1})|}{t}$ colours are used, and properties (a) to (c) hold. Let $F, Q_1, \ldots, Q_\ell$ be defined as before. Note that $|V(H_{i-1})| = |V(H_i)| - |V(F)| + |V(F)|$. For Cases 1 and 3, since $|V(F)| \geq \ell + 1$, the total number of colours used by $H_i$ is at most $\frac{(t+1)|V(H_{i-1})|}{t} + |V(F)| - \ell < \frac{(t+1)|V(H_i)|}{t}$.

For Case 2, since $|V(F)| \geq 2\ell$, the total number of colours used by $H_i$ is at most $\frac{(t+1)|V(H_{i-1})|}{t} + |V(F)| - \ell + 1 < \frac{(t+1)|V(H_i)|}{t}$.

Next, we show that in Cases 1 to 3, properties (a) to (c) hold for $H_i$. For (a), we are done by the inductive hypothesis if $u, v \in V(H_{i-1})$. Similarly when $\{u\} \cup X \subset V(H_{i-1})$ for (b), and when $X, Y \subset V(H_{i-1})$ for (c). We consider the other possibilities. Since this involves a lengthy case by case analysis, we will only sketch the arguments.

Let $A = V(F) \setminus V(H_{i-1})$, $X = \{x_1, x_2\}$ and $Y = \{y_1, y_2\}$. For two (possibly equal) vertices $x, y \in V(F)$, write $xFy$ for the unique $x - y$ path in $F$. We make the following simple observation, which we will use repeatedly.

**Observation 2.3** For the edge-colouring of $F$ in Cases 1 to 3, the following hold.

(A) For any $x, y \in A$, the path $xFy$ is rainbow.

(B) For any $1 \leq a \leq \ell$ and $x, y \in V(Q_a)$ with $x \in V(yQ_av_i - y)$, there exists $1 \leq b \leq \ell$, $b \neq a$, such that $Q_b$ does not use the colours in the paths $xQ_av_i$ and $yQ_aw_a$. \hfill $\square$

Now, the following arguments apply in each of Cases 1 to 3. Observation 2.3 and the inductive hypothesis will be applied repeatedly, so we abbreviate these to Ob 2.3(A) and $H_{i-1}(a)$, etc. Let $H_i$ be the set of all rainbow subpaths of $H_{i-1}$.

(a) Without loss of generality, we have the following cases. In each case, we find two disjoint rainbow $u - v$ paths in $H_i$.

- $u \in A$ and $v \in V(H_{i-1})$. Let $u \in V(Q_a)$ for some $a$. By Ob 2.3(B), there exists $b \neq a$ such that $uFw_b$ is rainbow. By $H_{i-1}(b)$, there are $w_a - v$ and $w_b - v$ paths $R_1, R_1' \in H$ which meet only at $v$. Take the paths $uQ_aw_a R_1 v$ and $uFw_b R_1' v$.

- $u, v \in A$. If $u, v \in V(Q_a)$ for some $a$, assume that $u \in V(vQ_av_i)$. By Ob 2.3(B) and $H_{i-1}(a)$, there exist $b \neq a$ and a $w_b - w_a$ path $R_2 \in H$ such that $uFw_b R_2 w_a Q_av_i$ is rainbow. Take $uQ_aw_a$ and $uFw_b R_2 w_a Q_av_i$. If $u \in V(Q_a - v_i)$ and $v \in V(Q_b - v_i)$ for some $a \neq b$, then by $H_{i-1}(a)$, there is a $w_a - w_b$ path $R_2' \in H$. Take $uFv$ and $uQ_aw_a R_2' w_b Q_bw_a$ ($uFv$ is rainbow by Ob 2.3(A)).
(b) Without loss of generality, we have the following cases. In each case, we find two rainbow \( u-X \) paths in \( H_i \), meeting only at \( u \).

- \( u \in A \) and \( x_1, x_2 \in V(H_{i-1}) \). This is similar to the first item in (a) above. We apply \( H_{i-1}(c) \) instead of \( H_{i-1}(b) \) to obtain two suitable disjoint rainbow \( u-X \) paths.

- \( x_1 \in A \) and \( u, x_2 \in V(H_{i-1}) \). Let \( x_1 \in V(Q_a) \) for some \( a \). Take \( uR_3w_aQ_ax_1 \) and \( R'_3 \), for some \( R_3, R'_3 \in H \) which meet only at \( u \) (by \( H_{i-1}(b) \)).

- \( u, x_1 \in A \) and \( x_2 \in V(H_{i-1}) \). Let \( u \in V(Q_a) \) for some \( a \). If \( x_1 \in V(uQ_a v_i) \), take \( uF x_1 \) and \( uQ_a w_a R_4 x_2 \), for some \( R_4 \in H \) (by Ob 2.3(A), \( H_{i-1}(a) \)). If \( x_1 \notin V(uQ_a v_i) \), take \( uQ_a x_1 \) and \( uF w_a R'_3 x_2 \) for some \( b \neq a \) and \( R'_3 \in H \) (by Ob 2.3(B), \( H_{i-1}(a) \)).

- \( x_1, x_2 \in A \) and \( u \in V(H_{i-1}) \). If \( x_1, x_2 \in V(Q_a) \) for some \( a \) with \( x_2 \in V(x_1 Q_a v_i) \), take \( uR_3w_aQ_ax_1 \) and \( uR'_3w_aF x_2 \), for some \( b \neq a \) and \( R_3, R'_3 \in H \) meeting only at \( u \) (by Ob 2.3(B), \( H_{i-1}(b) \)). If \( x_1 \in V(Q_a - v_i) \) and \( x_2 \in V(Q_b - v_i) \) for some \( a \neq b \), take \( uR_6w_aQ_ax_1 \) and \( uR'_6w_bQ_b x_2 \), for some \( R_6, R'_6 \in H \) meeting only at \( u \) (by \( H_{i-1}(b) \)).

- \( u, x_1, x_2 \in A \). Assume that \( x_2 \notin V(uF x_1) \). Take \( uF x_1 \) and \( uF x_2 \) if they meet only at \( u \). Otherwise, let \( u \in V(Q_a) \) for some \( a \). If \( u, x_1, x_2 \in V(Q_a) \), then \( x_1 \in V(uQ_a) \). Take \( uQ_a x_1 \) and \( uF w_a R_7w_a Q_a x_2 \) or \( uQ_a w_a R_7w_a F x_2 \), for some \( b \neq a \) and \( R_7 \in H \) (by Ob 2.3(B), \( H_{i-1}(a) \)). If \( x_2 \in V(Q_c) \) for some \( c \neq a \), take \( uF x_1 \) and \( uQ_a w_a R'_7w_cQ_c x_2 \), for some \( R'_7 \in H \) (by Ob 2.3(A), \( H_{i-1}(a) \)).

(c) Without loss of generality, we have the following cases. In each case, we find two disjoint rainbow \( X-Y \) paths in \( H_i \).

- \( x_1 \in A \) and \( x_2, y_1, y_2 \in V(H_{i-1}) \), or \( x_1, x_2 \in A \) and \( y_1, y_2 \in V(H_{i-1}) \). These are similar to the second and fourth items in (b) above, respectively. For both, apply \( H_{i-1}(c) \) instead of \( H_{i-1}(b) \) to obtain two suitable disjoint rainbow \( X-Y \) paths.

- \( x_1, y_1 \in A \) and \( x_2, y_2 \in V(H_{i-1}) \). Take \( x_1 F y_1 \) and \( R_8 \), for some \( R_8 \in H \) (by Ob 2.3(A), \( H_{i-1}(a) \)).

- \( x_1, x_2, y_1 \in A \) and \( y_2 \in V(H_{i-1}) \). Assume that \( x_2 \notin V(x_1 F y_1) \). Let \( x_2 \in V(Q_a) \) for some \( a \). If \( x_1 F y_1 \) and \( x_2 Q_a w_a \) are disjoint, take \( x_1 F y_1 \) and \( x_2 Q_a w_a R_9 y_2 \), for some \( R_9 \in H \) (by Ob 2.3(A), \( H_{i-1}(a) \)). Otherwise, we have \( x_1, y_1 \in V(x_2 Q_a w_a) \). Take \( x_1 Q_a y_1 \) and \( x_2 F w_b R'_9 y_2 \), for some \( b \neq a \) and \( R'_9 \in H \) (by Ob 2.3(B), \( H_{i-1}(a) \)).

- \( x_1, x_2, y_1, y_2 \in A \). Assume that \( x_2, y_2 \notin V(x_1 F y_1) \). Take \( x_1 F y_1 \) and \( x_2 F y_2 \) if they are disjoint. Otherwise, \( x_2 \in V(Q_a) \) and \( y_2 \in V(Q_b) \) for some \( a,b \). If \( a \neq b \) and \( x_2, y_2 \neq v_i \), take \( x_1 F y_1 \) and \( x_2 Q_a w_a R_{10} w_b Q_b y_2 \), for some \( R_{10} \in H \) (by Ob 2.3(A), \( H_{i-1}(a) \)). If \( a = b \), then \( x_1, y_1 \in V(x_2 Q_a y_2) \). Take \( x_1 Q_a y_1 \), and \( x_2 F w_c R'_{10} w_a Q_a y_2 \) or \( x_2 Q_a w_a R'_{10} w_c F y_2 \), for some \( c \neq a \) and \( R'_{10} \in H \) (by Ob 2.3(B), \( H_{i-1}(a) \)).

We have now proved that properties (a) to (c) hold for \( H_i \). This completes the proof of Theorem 2.2, and hence of Theorem 1.1. \( \square \)

Remark. The authors originally found a shorter proof of Theorem 1.1 in the case \( \ell = 2 \). The proof considered an edge-colouring of a minimally 2-connected spanning subgraph of a given 2-connected graph. A sketch of this proof can be found in [10].

Proof of Theorem 1.2. By the definition of a 2-connected series-parallel graph, it is easy to see (and well-known) that \( G \) can be constructed as follows. There are graphs \( G_0 \subset G_1 \subset \cdots \subset G_i = G \) for some \( t \geq 0 \). \( G_0 = Q_0 \) is a cycle. For \( 1 \leq i \leq t \), \( G_i \) is obtained from \( G_{i-1} \) by attaching a path \( Q_i \) of length at least 1 to \( G_{i-1} \), by identifying the end-vertices of \( Q_i \) with two distinct vertices \( x,y \in V(G_{i-1}) \). \( x \) and \( y \) must be the end-vertices of some path \( P \subset Q_j \) for some \( 0 \leq j < i \), and if an end-vertex of some
We have $z \in G$ and orientation for $Q$, and we can think of this as turning $G$ into a directed graph, as follows. Fix $z \in V(G_0)$. Firstly, embed the cycle $G_0$ into the plane and orient it clockwise. Now for $1 \leq i \leq t$ and each $0 \leq j < i$, suppose that we have defined an orientation and a plane embedding for $G_j$, with the exterior cycle of $G_j$ oriented clockwise, and containing $z$. Moreover, for each $1 \leq j < i$ (if $i \geq 2$), assume that the path $Q_j$ is embedded into the exterior face of $G_{j-1}$. If we can embed $Q_i$ into the exterior face of $G_{i-1}$, then we do so, and orient $Q_i$ so that, $z$ remains on the new exterior cycle (of $G_i$), and the cycle remains directed clockwise. In addition, if $z \in V(Q_i)$, then choose the embedding and orientation for $Q_i$ so that $z$ is the tail vertex of $Q_i$. Note that this embedding and orientation of $Q_i$ is unique, up to homotopism.

Otherwise, delete $Q_{i-1}, Q_{i-2}, \ldots$ successively until we reach the first $j$ ($0 \leq j < i - 1$) such that we can embed $Q_i$ into the exterior face of $G_j$. Embed $Q_i$ and orient it in the same way as above. Note that $Q_i$ is embedded into the bounded face created by $Q_{j+1}$ when it was embedded into the exterior face of $G_j$. Hence, we can re-embed and re-orient $Q_{j+1}, \ldots, Q_{i-1}$, in this order, to achieve an embedding and orientation for $G_i$. Finally, re-label $Q_i, Q_{i+1}, \ldots, Q_{i-1}$ with, respectively, $Q_{j+1}, Q_{j+2}, \ldots, Q_i$.

Repeat for each $i$ until we reach $G_i = G$. For $0 \leq i \leq t$, let $H_i$ be the exterior cycle of $G_i$, so that we have $z \in V(H_i)$ for every $i$.

Next, we edge-colour each $G_i$ with $|V(G_i)|$ colours, inductively as follows. Firstly rainbow colour $G_0$, so that $|V(G_0)|$ colours are used. For $1 \leq i \leq t$, suppose that $G_{i-1}$ is coloured with $|V(G_{i-1})|$ colours. $Q_i$ is embedded into the exterior face of $G_{i-1}$. Colour the head edge of $Q_i$ with the colour of the edge of $E(H_{i-1}) \setminus E(H_i)$ incident with the tail edge of $Q_i$. Give the other edges of $Q_i$ new and distinct colours. Then $G_i$ is coloured with $|V(G_i)|$ colours. Note that by induction, $H_i$ is rainbow coloured for every $i$.

We claim that for each $0 \leq i \leq t$, the colouring for $G_i$ is rainbow 2-connected, which implies Theorem 1.2. Proceed by induction. Initially, the colouring for $G_0$ is rainbow 2-connected. For $1 \leq i \leq t$, suppose that the colouring for $G_{i-1}$ is rainbow 2-connected. Let $u, v \in V(G_i)$. We want to find two disjoint rainbow $u-v$ paths in $G_i$. $G_i$ is obtained by embedding $Q_i$ into the exterior face of $G_{i-1}$. If $u, v \in V(G_{i-1})$, then we are done by induction, and if $u, v \in V(H_i)$, then we are also done, since $H_i$ is rainbow coloured.

It remains to consider the case $u \in V(G_{i-1}) \setminus V(H_i)$ and $v \in V(Q_i) \setminus V(G_{i-1})$. For this, we aim to find two rainbow paths from $u$ to $H_i$, meeting only at $u$, with both having ‘almost’ no colours in common with $H_i$. Proceed by deleting $Q_i, Q_{i-1}, Q_{i-2}, \ldots$ until we reach the first $j$ ($0 \leq j < i$) such that $u \in V(H_j)$. Re-embed $Q_{j+1}$. Then $u$ becomes an interior vertex of $G_{j+1}$. Let $Q_{j+1}$ be attached to $H_j$ at $x_1$ and $y_1$, with $x_1$ directed towards $u$, then $y_1$, along $H_j$. Let $\overrightarrow{R_i}$ and $\overrightarrow{S_i}$ be the $x_1-u$ and $u-y_1$ directed paths, respectively. Since $H_j$ is rainbow coloured, so are $\overrightarrow{R_i}$ and $\overrightarrow{S_i}$. Moreover, between $\overrightarrow{R_i} \cup \overrightarrow{S_i}$ and $H_{j+1}$, the only edges that have the same colour are the tail edge of $\overrightarrow{R_i}$ and the head edge of $Q_{j+1}$. Note also that $z \in V(y_1H_{j+1}x_1)$. Now, we prove that for every $1 \leq \ell \leq i - j$, there are distinct $x_\ell, y_\ell \in V(H_{j+\ell})$ such that in $G_{j+\ell}$, the following hold.

(a) There are rainbow $x_\ell - u$ and $u - y_\ell$ directed paths $\overrightarrow{R_\ell}$ and $\overrightarrow{S_\ell}$, meeting only at $u$.

(b) Among all edges of $\overrightarrow{R_\ell} \cup \overrightarrow{S_\ell}$ and $H_{j+\ell}$, the only possible edges with the same colour are the tail edge of $\overrightarrow{R_\ell}$ and the head edge of $x_\ell H_{j+\ell} y_\ell$. Hence, the directed cycle $x_\ell R_\ell u S_\ell y_\ell H_{j+\ell} x_\ell$ is rainbow.

(c) If $a$ and $b$ are internal vertices of $x_\ell H_{j+\ell} y_\ell$ and $y_\ell H_{j+\ell} x_\ell$ respectively, then for all $0 \leq m \leq j + \ell$, we have $\{a, b\} \not\subseteq V(Q_m)$.

(d) $z \in V(y_\ell H_{j+\ell} x_\ell)$. 

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We proceed inductively. For $\ell = 1$, (a) to (d) all hold. For $2 \leq \ell \leq i - j$, suppose that they hold for $G_{j+\ell-1}$. We have the vertices $x_{\ell - 1}, y_{\ell - 1}$, and by (a), the directed paths $\overrightarrow{R_{\ell - 1}}, \overrightarrow{S_{\ell - 1}}$. By (d), let $\overrightarrow{T_1}, \overrightarrow{T_2}$ and $\overrightarrow{T_3}$ be the $x_{\ell - 1} \rightarrow y_{\ell - 1}, y_{\ell - 1} \rightarrow z$ and $z \rightarrow x_{\ell - 1}$ directed paths along $H_{j+\ell-1}$. Embed and orient $Q_{j+\ell}$ as before. Let $x$ and $y$ be the tail and head vertices of $Q_{j+\ell}$, respectively. By (c), $x$ and $y$ must both belong to $\overrightarrow{T_1}$ or $\overrightarrow{T_2} \cup \overrightarrow{T_3}$, since $G_{j+\ell}$ is a 2-connected series-parallel graph. We consider two cases. Note that the following arguments apply even if we have $z \in \{x_{\ell - 1}, y_{\ell - 1}\}$.

- $x, y \in V(\overrightarrow{T_1})$, or $x, y \in V(\overrightarrow{T_2} \cup \overrightarrow{T_3})$.

We have $x_{\ell - 1}, y_{\ell - 1} \in V(H_{j+\ell})$. Set $x_{\ell} = x_{\ell - 1}, y_{\ell} = y_{\ell - 1}, \overrightarrow{R_{\ell}} = \overrightarrow{R_{\ell - 1}}$ and $\overrightarrow{S_{\ell}} = \overrightarrow{S_{\ell - 1}}$. Clearly $G_{j+\ell}$ satisfies (a), (c) and (d). For (b), note that $\overrightarrow{R_{\ell}} \cup \overrightarrow{S_{\ell}} = \overrightarrow{R_{\ell - 1}} \cup \overrightarrow{S_{\ell - 1}}$, and to get from the set of colours of $H_{j+\ell-1}$ to that of $H_{j+\ell}$, we remove some colours of $H_{j+\ell-1}$ and add some new colours, unused in $G_{j+\ell-1}$. Hence, among the edges of $\overrightarrow{R_{\ell}} \cup \overrightarrow{S_{\ell}}$ and $H_{j+\ell}$, the only ones that can have the same colour will still be the tail edge of $\overrightarrow{R_{\ell}}$ and the head edge of $x_{\ell}H_{j+\ell-1}y_{\ell}$. They will actually have different colours if $x, y \in V(\overrightarrow{T_1})$, $y = y_{\ell - 1}$, and $x, y$ are non-adjacent in $H_{j+\ell-1}$.

- $x \in V(\overrightarrow{T_3})$, $y \in V(\overrightarrow{T_2} \cup \overrightarrow{T_3})$ and $\{x, y\} \neq \{x_{\ell - 1}, y_{\ell - 1}\}$.

Here, $x_{\ell - 1}, y_{\ell - 1}$ can possibly be interior vertices of $G_{j+\ell}$. Along $\overrightarrow{H_{j+\ell-1}}$, $y_{\ell - 1}$ is directed towards $y, z, x_{\ell - 1}$, in this order. Let $x_{\ell} = x, y_{\ell} = y$. Then $G_{j+\ell}$ clearly satisfies (c) and (d). Let $\overrightarrow{R_{\ell}} = xH_{j+\ell-1}x_{\ell-1}R_{\ell-1}u, \overrightarrow{S_{\ell}} = uS_{\ell-1}y_{\ell-1}H_{j+\ell-1}y_{\ell}$. We have $\overrightarrow{R_{\ell}}, \overrightarrow{S_{\ell}}$ are rainbow, since $\overrightarrow{R_{\ell}} \cup \overrightarrow{S_{\ell}} \subset x_{\ell-1}R_{\ell-1}uS_{\ell-1}y_{\ell-1}H_{j+\ell-1}x_{\ell-1}$, the latter of which is rainbow by (b) for $G_{j+\ell-1}$. Hence, $G_{j+\ell}$ satisfies (a). For (b), note that $H_{j+\ell} = xQ_{j+\ell}yH_{j+\ell-1}x$. Again by (b) for $G_{j+\ell-1}$, $\overrightarrow{R_{\ell}} \cup \overrightarrow{S_{\ell}}$ has no colours in common with $yH_{j+\ell-1}x$. Also, by the construction of the colouring of $Q_{j+\ell}$, among the edges of $\overrightarrow{R_{\ell}} \cup \overrightarrow{S_{\ell}}$ and $\overrightarrow{Q_{j+\ell}}$, the only ones that can have the same colour are the tail edge of $\overrightarrow{R_{\ell}}$ and the head edge of $Q_{j+\ell} = xH_{j+\ell-1}y_{\ell}$. They will actually have different colours if $x = x_{\ell - 1}$ and $x_{\ell - 1}, y_{\ell - 1}$ are non-adjacent in $H_{j+\ell-1}$. This proves (b) for $G_{j+\ell}$.

Hence, properties (a) to (d) hold for $G_i$. By (a), we have the vertices $x_i, y_i \in V(H_i)$ and the directed paths $\overrightarrow{R_i}, \overrightarrow{S_i}$. If $v \in V(x_iH_iy_i) \setminus \{x_i, y_i\}$, take $u \overrightarrow{R_i}x_i\overrightarrow{H_i}v$ and $u \overrightarrow{S_i}y_i\overrightarrow{H_i}v$. If $v \in V(y_iH_ix_i)$, take $u \overrightarrow{R_i}x_i\overrightarrow{H_i}v$ and $u \overrightarrow{S_i}y_i\overrightarrow{H_i}v$. By (b), we have two disjoint rainbow $u - v$ paths in $G_i$, in both cases. The induction on $i$ is complete, and Theorem 1.2 follows. □

**Proof of Theorem 1.3.** Let $Q_1, \ldots, Q_t$ be the $t$ paths, and $x, y$ be their common end-vertices. The case $t = 2$ is clear ($G$ is a cycle). Now, let $t \geq 3$.

Firstly, since $c(G - y) = n - 2$, if we colour $G$ with fewer than $n - 2$ colours, then for some $u, v \in \Gamma(y) \setminus \{x\}$, the unique $u - v$ path $P$ in $G - y$ is not rainbow. But in $G$, there is only one pair of disjoint $u - v$ paths, and $P$ is one of the paths. Hence, $rc_2(G) \geq n - 2$.

Secondly, colour $G$ as follows. For $1 \leq i \leq t - 1$, colour the edges of $Q_i$ incident to $x$ and $y$ with colours $i$ and $i + 1$ (modulo $t - 1$) respectively. Colour the other edges with further distinct colours. Then we have used $n - 1$ colours for $G$, and this colouring is rainbow 2-connected, since $t \geq 3$. Hence, $rc_2(G) \leq n - 1$. □

### 3 Complete Bipartite and Multipartite Graphs

In this section, we prove Theorems 1.6 to 1.9. We will only sketch the proofs of Theorems 1.8 and 1.9, since these are similar to the proofs of Theorems 1.6 and 1.7.

**Proof of Theorem 1.6.** Let $M$ be a perfect matching of $K_{n,n}$. Colour the edges of $M$ with colour 1, and randomly and independently colour the other edges with colours 2 and 3. Label the pairs of vertices in $K_{n,n}$ with $1,2,\ldots,m$, where $m = \binom{2n}{2}$. Let $E_i$ be the event that the $i$th pair does not
have $k$ disjoint rainbow paths connecting them. If $\mathbb{P}(\bigcup_{i=1}^{n} E_i) < 1$, then a suitable 3-colouring of $K_{n,n}$ exists, and Theorem 1.6 follows.

We bound $\mathbb{P}(E_i)$ for each $i$. First, let $E_i$ correspond to a pair of vertices $u, v$ in the same class of $K_{n,n}$. Then, every rainbow $u - v$ path must have length 2. Let $P_i$ be the set of all $u - v$ paths of length 2. Two paths in $P_i$ are already rainbow (using edges of $M$). The probability that each of the other paths being rainbow is $\frac{1}{2}$, and these probabilities are independent. Let $X$ be the number of rainbow $u - v$ paths of length 2, other than the two using edges of $M$. We have $X \sim \text{Bi}(n-2, \frac{1}{2})$, and $E_i$ is the event that $X \leq k - 3$. Using the Chernoff bound (see, for example, [12] Ch. 2.1; note that $k - 3 < \frac{1}{2}(n - 2)$, so the bound applies), and that $n \geq \frac{2k-4}{\epsilon^2} + 1$ implies $\frac{1}{4}(\frac{n-2k+4}{n-2})^2 \geq \epsilon^2$,

$$\mathbb{P}(E_i) = \mathbb{P}(X \leq k - 3) = \mathbb{P}
\left(X \leq \frac{1}{2}(n-2) \left(1 - \frac{n - 2k + 4}{n - 2}\right)\right)
< \exp\left(-\frac{1}{2} \cdot \frac{1}{2}(n-2) \left(\frac{n - 2k + 4}{n - 2}\right)^2\right) \leq e^{-\epsilon^2(n-1)}.
$$

Next, let $E_i$ correspond to a pair of vertices $u, v$ in different classes. Then, one of the rainbow $u - v$ paths is the edge $uv$, and any other such path must have length 3. Choose a set $P'_i$ of $n - 1$ disjoint $u - v$ paths of length 3, each using exactly one edge of $M$. The probability that each path of $P'_i$ being rainbow is $\frac{1}{2}$, and these probabilities are independent. Let $X$ be the number of rainbow $u - v$ paths in $P'_i$, so that $X \sim \text{Bi}(n-1, \frac{1}{2})$. A similar calculation (note that $k - 2 < \frac{1}{2}(n - 1)$ and $\frac{1}{4}(\frac{n-2k+3}{n-2})^2 \geq \epsilon^2$) gives

$$\mathbb{P}(E_i) \leq \mathbb{P}(X \leq k - 2) = \mathbb{P}
\left(X \leq \frac{1}{2}(n-1) \left(1 - \frac{n - 2k + 3}{n - 1}\right)\right) < e^{-\epsilon^2(n-1)}.
$$

Therefore, $\mathbb{P}(E_i) < e^{-\epsilon^2(n-2)}$ for all $i$. By the union bound, $\mathbb{P}(\bigcup_{i=1}^{n} E_i) < 2n^2e^{-\epsilon^2(n-2)}$. On $[0, \infty)$, the function $2x^2e^{-\epsilon^2(x-2)}$ is eventually decreasing, and tends to 0 as $x \to \infty$. If $\theta = \theta(\epsilon)$ is the largest solution of $2x^2e^{-\epsilon^2(x-2)} = 1$, then we have $\mathbb{P}(\bigcup_{i=1}^{n} E_i) < 1$ for $n \geq \theta$. Hence, the result holds for $n \geq \frac{2k-4}{\epsilon^2} + 1$ with $k \geq \frac{1}{2}(\theta - 1)(1 - 2\epsilon) + 2$.

**Proof of Theorem 1.7.** Let $A$ and $B$ be the classes of $K_{n,n}$. We prove that there exist $u, v \in A$ which will work for the theorem. For $u, v \in A$, any rainbow $u - v$ path must have length 2. Let $Z(\{u, v\})$ be the number of monochromatic $u - v$ paths of length 2. Note that $\sum_{u,v \in A} Z(\{u, v\}) = \sum_{b \in B} Y(b)$, where $Y(b)$ is the number of monochromatic paths of length 2 with middle vertex $b$. For $b \in B$ and $i \in \{1, 2, 3\}$, let $d_i(b)$ be the number of edges of colour $i$ at $b$. Then, by the convexity of $\frac{1}{2}$ (for $x \in \mathbb{R}$),

$$\mathbb{E}Z = \frac{1}{2} \sum_{u,v \in A} Z(\{u, v\}) = \frac{1}{2} \sum_{b \in B} Y(b) = \frac{1}{2} \sum_{b \in B} \left(\binom{d_1(b)}{2} + \binom{d_2(b)}{2} + \binom{d_3(b)}{2}\right)
\geq \frac{1}{2} \sum_{b \in B} 3 \left(\frac{1}{3}(d_1(b) + d_2(b) + d_3(b))\right) = \frac{1}{2} \cdot 3n \left(\frac{1}{3}n\right) = \frac{n^2 - 3n}{3(n-1)}.
$$

Hence, there exist $u, v \in A$ such that the number of rainbow $u - v$ paths is at most $n - \frac{n^2 - 3n}{3(n-1)} = \frac{2n^2}{3(n-1)}$.

**Proof of Theorem 1.8.** Colour the edges of $K_{t \times n}$ randomly and independently with 2 colours. Label the vertices $v_1, v_2, \ldots, v_n$, and let $E_{i,j}$ be the event that there are less than $k$ rainbow $v_i - v_j$ paths. Let $X$ be the number of rainbow $v_i - v_j$ paths of length 2.

First, let $v_i$ and $v_j$ be in the same partite set. Then $v_i$ and $v_j$ share $(t - 1)n$ neighbours, so $\mathbb{P}(E_{i,j}) = \mathbb{P}(X \leq k - 1)$, where $X \sim \text{Bi}(t-1)n, \frac{1}{2})$. By the Chernoff bound (note that $k - 1 < \frac{1}{2}(t-1)n$, and $n \geq \frac{2k-2}{(t-2)(t-2\epsilon)}$ implies $\frac{1}{4}(\frac{(t-1)n-2k+2}{(t-1)n})^2 \geq \epsilon^2$),

$$\mathbb{P}(E_{i,j}) = \mathbb{P}
\left(X \leq \frac{1}{2}(t-1)n \left(1 - \frac{(t-1)n-2k+2}{(t-1)n}\right)\right) < e^{-(t-1)^2\epsilon^2n}.$$
Next, let \( v_i \) and \( v_j \) be in different partite sets. Then \( v_i \) and \( v_j \) share \((t-2)n\) neighbours. But now, \( v_i v_j \) is an edge, so \( \mathbb{P}(E_{i,j}) = \mathbb{P}(X \leq k - 2) \), where \( X \sim \text{Bi}((t-2)n, \frac{1}{2}) \). As before (note that \( k - 2 < \frac{1}{2}(t-2)n \) and \( \frac{1}{4} \left( \frac{t-1}{(t-2)n} - 2k + 4 \right)^2 \geq \varepsilon^2 \)),

\[
\mathbb{P}(E_{i,j}) = \mathbb{P} \left( X \leq \frac{1}{2}(t-2)n \left( 1 - \frac{(t-1)n - 2k + 4}{(t-2)n} \right) \right) < e^{-(t-2)\varepsilon^2 n}.
\]

We have \( \mathbb{P}(\bigcup_{i,j} E_{i,j}) < \frac{1}{2}t^2n^2e^{-(t-2)\varepsilon^2 n} \). If \( \theta = \theta(\varepsilon, t) \) is the largest solution of \( \frac{1}{2}t^2x^2e^{-(t-2)\varepsilon^2 x} = 1 \), then \( \mathbb{P}(\bigcup_{i,j} E_{i,j}) < 1 \) for \( n \geq \theta \). Hence, the result holds for \( n \geq \frac{2k-2}{(t-2)(1-2\varepsilon)} \) with \( k \geq \frac{1}{2}\theta(t-2)(1-2\varepsilon)+1 \).

**Proof of Theorem 1.9.** Let \( A \) be a class of \( K_{1,n} \) and \( B = V(K_{1,n}) \setminus A \). For \( u, v \in A \), any rainbow \( u-v \) path must have length \( 2 \). Let \( Z(\{u,v\}) \) be the number of monochromatic \( u-v \) paths of length 2. Then, by similar calculation as in Theorem 1.7,

\[
\mathbb{E}Z = \left( \frac{1}{2} \right) \sum_{u,v \in A} Z(\{u,v\}) \geq \left( \frac{1}{2} \right) \cdot 2(t-1)n \left( \frac{n^2}{2} \right) = \frac{(t-1)(n^2 - 2n)}{2(n-1)}.
\]

Hence, there exist \( u, v \in A \) such that the number of rainbow \( u-v \) paths is at most \( (t-1)n - \frac{(t-1)(n^2 - 2n)}{2(n-1)} = \frac{(t-1)n^2}{2(n-1)} \).

\[\square\]

### 4 Random Graphs

We first prove Theorem 1.10. We recall the result for \( rc(G_{n,p}) \) by Caro et al.

**Theorem 4.1 ([3])** \( p = \sqrt{\log n/n} \) is a sharp threshold function for the property \( rc(G_{n,p}) \leq 2 \).

The proof of Theorem 1.10 will be similar to that of Theorem 4.1. A key result used in the proof of Theorem 4.1 is Theorem 4.2 below. We generalise this in Theorem 4.3.

**Theorem 4.2 ([3])** For any non-complete graph \( G \) on \( n \) vertices, with minimum degree \( \delta(G) \geq \frac{n}{2} + \log_2 n \), we have \( rc(G) = 2 \).

**Theorem 4.3** For all \( k \geq 2 \) and \( \varepsilon > 0 \), there exists an integer \( N = N(k, \varepsilon) \) so that, for all graphs \( G \) on \( n \geq N \) vertices with minimum degree \( \delta(G) \geq \frac{n}{2} + (1+\varepsilon) \log_2 n \), we have \( rc_k(G) = 2 \).

**Proof.** Colour the edges of \( G \) with 2 colours, randomly and independently. Let \( u, v \in V(G) \), and \( E \) be the event that we do not have \( k \) disjoint rainbow \( u-v \) paths. We have \( |\Gamma(u) \cap \Gamma(v)| \geq t \), where \( t = 2(1+\varepsilon) \log_2 n \) (we may assume that \( t \in \mathbb{N} \)). Let \( P \) be a set of \( t \) \( u-v \) paths of length \( 2 \), and \( X \) be the number of rainbow paths in \( P \). For \( P \in P \), \( \mathbb{P}(P \text{ is not rainbow}) = \frac{1}{2} \), so \( X \sim \text{Bi}(t, \frac{1}{2}) \). For \( 0 \leq \ell \leq t \),

\[
\mathbb{P}(X \leq \ell) = \left( \frac{1}{2} \right)^t \sum_{\ell=0}^{t} {t\choose \ell} \leq \left( \frac{1}{2} \right)^t (1 + t)^t.
\]

For fixed \( k \geq 2 \) and \( \varepsilon > 0 \), \( \lim_{n \to \infty} \frac{(1+2(1+\varepsilon) \log_2 n)^{k-1}}{n^{\varepsilon}} = 0 \), so

\[
\mathbb{P}(E) \leq \mathbb{P}(X \leq k - 1) \leq \left( \frac{1}{2} \right)^{2(1+\varepsilon) \log_2 n} (1 + 2(1+\varepsilon) \log_2 n)^{k-1} = o\left( \frac{1}{n^2} \right).
\]

There are \( \binom{n}{2} \) pairs \( u, v \), so from the union bound, with positive probability, each pair of vertices in \( G \) has at least \( k \) disjoint rainbow paths connecting them. Hence, there exists a 2-colouring of \( G \) which is rainbow \( k \)-connected.

**Proof of Theorem 1.10.** By Theorem 4.1, it suffices to consider \( k \geq 2 \), and to show that there is a constant \( C > 0 \) such that, for \( p = C\sqrt{\log n/n} \), we have \( rc_k(G_{n,p}) = 2 \) a.s. By Theorem 4.3 with \( \varepsilon = 1 \), it suffices to show that any two vertices of \( G_{n,p} \) have at least \( 4 \log_2 n \) common neighbours, a.s. In the proof of Theorem 4.1 [3], it was shown that there is a constant \( C' > 0 \) such that, for \( p = C' \sqrt{\log n/n} \),
any two vertices of $G_{n,p}$ have at least $2\log_2 n$ common neighbours, a.s. Here, we take a larger constant for $C$.

Next, we prove Theorem 1.11. We first prove Theorem 4.4, which is the analogue of Theorem 4.3 for bipartite graphs. The version for $k = 1$ was also proved by Caro et al. 

**Theorem 4.4.** Let $c = 1/\log^3 9/4$. For all $k \geq 2$ and $\varepsilon > 0$, there exists an integer $N = N(k, \varepsilon)$ so that, for all bipartite graphs $G$ on $n \geq N$ vertices, any two vertices of the same class have at least $2c(1+\varepsilon)\log n$ common neighbours, we have $rc_k(G) = 3$.

**Theorem 4.5 ([3]).** Let $c = 1/\log^2 9/4$. If $G$ is a non-complete bipartite graph on $n$ vertices, and any two vertices in the same class have at least $2c\log n$ common neighbours, then $rc(G) = 3$.

**Proof of Theorem 4.4.** Colour the edges of $G$ with 3 colours, randomly and independently. Let $u, v \in V(G)$, $t = 2c(1+\varepsilon)\log n$ (assume that $t \in \mathbb{N}$), and $E$ be the event that we do not have $k$ disjoint rainbow $u - v$ paths.

First, let $u$ and $v$ be in the same class, so $|\Gamma(u) \cap \Gamma(v)| \geq t$. Let $\mathcal{P}$ be a set of $t$ $u - v$ paths of length 2, and $X$ be the number of rainbow paths in $\mathcal{P}$. For $P \in \mathcal{P}$, $\mathbf{P}(P$ is not rainbow) $= \frac{1}{2}$, so $X \sim \text{Bi}(t, \frac{1}{2})$. For $0 \leq \ell \leq t$, $\mathbf{P}(X \leq \ell) = \sum_{r=0}^{\ell} (\frac{1}{2})^{t-r} (\frac{1}{2})^{r} \leq (\frac{1}{2})^{t} (1 + t)^{-1}$. For fixed $k \geq 2$ and $\varepsilon > 0$, $\mathbf{P}(E) \leq \mathbf{P}(X \leq k-1) \leq (\frac{1}{2})^{t} (1 + 2c(1+\varepsilon)\log n)^{k-1} = o(\frac{1}{n^{\varepsilon}})$.

Next, let $u$ and $v$ be in different classes. We claim that there is a set $\mathcal{P}'$ of $t - 1$ disjoint $u - v$ paths of length 3. Let $B = \Gamma(u) \setminus \{v\}$, and note that $|B| \geq t - 1$. For each vertex $x \in B$, let $A_x = (\Gamma(x) \cap \Gamma(u)) \setminus \{u\}$, and note that $|A_x| \geq t - 1$. For the sets $A_x$, take a system of distinct representatives $\{y_x\}_{x \in B}$. Then we can take $\mathcal{P}' = \{uxy : v \in B\}$.

Let $X$ be the number of paths of $\mathcal{P}'$ which are not rainbow. For $P \in \mathcal{P}'$, $\mathbf{P}(P$ is not rainbow) $= \frac{7}{9}$, so $X \sim \text{Bi}(t-1, \frac{7}{9})$. For $0 \leq \ell \leq t - 1$, $\mathbf{P}(X \leq \ell) = \sum_{r=0}^{\ell} (\frac{7}{9})^{t-r} (\frac{2}{9})^{r} \leq (\frac{7}{9})^{t} (1 + t)^{-1}$. As before, $\mathbf{P}(E) \leq \mathbf{P}(X \leq k - 1) = o(\frac{1}{n^{\varepsilon}})$.

There are $\binom{t}{2}$ pairs $u, v$, so applying the union bound, there exists an edge-colouring of $G$ with 3 colours which is rainbow $k$-connected.

**Proof of Theorem 1.11.** For the first part, we prove that for $C_1 > 6$, if $p \geq C_1 \sqrt{\log n/n}$, then $rc_k(G_{n,n,p}) = 3$, a.s. By Theorem 4.5, and Theorem 4.4 with $\varepsilon = 1$, it suffices to show that any two vertices in the same class of $G_{n,n,p}$ have at least $4c\log(2n)$ common neighbours, a.s., where $c = 1/\log^2 9/4$. Fix two vertices $u, v$ in one class. For a vertex $w$ in the other class, the probability that $w$ is a common neighbour of $u$ and $v$ is $C_2^2 \log n/n$. If $X$ be the number of common neighbours of $u$ and $v$, then $X \sim \text{Bi}(n, C_2^2 \log n/n)$ and $\mathbb{E}X = C_2^2 \log n$. By Chernoff’s inequality, $\mathbf{P}(X \leq \frac{1}{3} C_2^2 \log n) \leq \exp(-\frac{1}{8} C_2^2 \log n) = o(\frac{1}{n}).$ There are $\binom{t}{2}$ pairs $u, v$. By the union bound, every pair of vertices in the same class of $G_{n,n,p}$ have at least $\frac{1}{3} C_2^2 \log n > 4c\log(2n)$ common neighbours in the other class, a.s.

For the second part, we prove that for $0 < C_2 < \frac{1}{2}$, $G_{n,n,p}$ has diameter at least 4 a.s., if $p = C_2 \log n/n$. Let $A, B$ be two disjoint sets in one class, with $|A| = |B| = \frac{n}{2}$ (assume that $\frac{n}{2} \in \mathbb{N}$). Let $A = \{a_1, \ldots, a_{n/2}\}$ and $B = \{b_1, \ldots, b_{n/2}\}$. The probability of the event $E_i$ that a pair $a_i, b_i$ have a common neighbour in the same class is $1 - \left(1 - \frac{C_2^2 \log n}{n}\right)^n$. The events $E_i$ are independent, so the probability that all pairs $a_i, b_i$ have a common neighbour is $\left(1 - \left(1 - \frac{C_2^2 \log n}{n}\right)^n\right)^{n/2} = o_n(1)$. Hence, there is a pair of vertices in one class with no common neighbour, a.s., so they have distance at least 4 between them.

We finish with the proof of Theorem 1.12, which is similar to the previous proofs.

**Proof of Theorem 1.12.** For the first part, we prove that for $C_1 > 3$, if $M \geq C_1 \sqrt{n^3 \log n}$, then $rc_k(G_{n,M}) = 2$, a.s. By Theorem 4.2, and Theorem 4.3 with $\varepsilon = 1$, it suffices to show that any two vertices of $G_{n,M}$ have at least $4\log_2 n$ common neighbours, a.s. Let $N = \binom{M}{2}$, and fix two vertices $u, v$. For another vertex $w$, the probability that $w$ is a common neighbour of $u$ and $v$ is $\binom{M-2}{N}/\binom{M}{N} = \binom{M-2}{N}/\binom{M}{N} = \frac{M-2}{M-1} \frac{N}{N-1}$. If $X$ is the number of common neighbours of $u$ and $v$, then $X \sim \text{Bi}(n-2, \frac{M-2}{M-1} \frac{N}{N-1})$ and $\mathbb{E}X = (n-2) \frac{M-2}{M-1} \frac{N}{N-1} \geq 2C_1^2 \log n$. By Chernoff’s inequality, $\mathbf{P}(X \leq C_1^2 \log n) \leq \exp(-\frac{1}{8} C_1^2 \log n) = o(\frac{1}{n^{\varepsilon}})$.
exp(-\frac{1}{32}EX) \leq \exp(-\frac{1}{4}C^2 \log n) = o(\frac{1}{n^2})}. There are \binom{n}{2}^2 pairs u, v. By the union bound, every pair of vertices in \(G_{n,M}\) have at least \(C^2 \log n > 4 \log_2 n\) common neighbours, a.s.

For the second part, we prove that if \(0 < C_2 < \frac{1}{5}\), then \(G_{n,M}\) has diameter at least 3 a.s., if \(M = C_2 \sqrt{n^3 \log n}\). Let \(A, B\) be two disjoint sets of vertices, with \(|A| = |B| = n^{1/2}\) (assume that \(n^{1/2} \in \mathbb{N}\)). The probability that \(A \cup B\) is an independent set is

\[
\binom{N-2n^{1/2}}{N/M} = \frac{(N - 2n^{1/2}) - C_2 \sqrt{n^3 \log n} + 1) \cdots (N - C_2 \sqrt{n^3 \log n})}{(N - (2n^{1/2} + 1) \cdots N} = 1 - o_n(1).
\]

Let \(A = \{a_1, \ldots, a_{n^{1/2}}\}, B = \{b_1, \ldots, b_{n^{1/2}}\}\). The probability of the event \(E_i\) that a pair \(a_i, b_i\) have a common neighbour is \(1 - (1 - \frac{M(M-1)}{N(N-1)})^{n-2n^{1/2}}\). The events \(E_i\) are independent, so the probability that all pairs \(a_i, b_i\) have a common neighbour is

\[
\left(1 - \left(1 - \frac{M(M-1)}{N(N-1)}\right)^{n-2n^{1/2}}\right)^{n^{1/2}} \leq \left(1 - \left(1 - \frac{M(M-1)}{N(N-1)}\right)^n\right)^{n^{1/2}} = o_n(1),
\]

since \(M = C_2 \sqrt{n^3 \log n}\) and \(0 < C_2 < \frac{1}{5}\).

It follows that there is a non-adjacent pair \(a_i, b_i\) with no common neighbour a.s., and such a pair has distance at least 3 between them. \(\Box\)

## 5 Open Problems

In this section, we pose some open problems which are related to the results of this paper.

We can ask the following extension of Problem 1.4: If \(1 \leq k \leq \ell\), derive a sharp upper bound on \(r_{ck}(G)\) for every \(\ell\)-connected graph \(G\). A result of Mader [18] implies that any minimally \(k\)-connected graph on \(n\) vertices has at most \(kn\) edges. If \(G\) is \(\ell\)-connected on \(n\) vertices, then by considering a minimally \(k\)-connected spanning subgraph of \(G\), we have \(r_{ck}(G) \leq kn\). Therefore, we ask the following question.

**Problem 5.1** Let \(1 \leq k \leq \ell\). Find the least constant \(c = c(k, \ell)\), where \(0 < c \leq k\), such that for all \(\ell\)-connected graphs \(G\) on \(n\) vertices, we have \(r_{ck}(G) \leq cn\).

We have already asked the question of whether or not do we have \(c(2, 2) = 1\).

For Theorems 1.6 and 1.7, if \(k \geq 2\), we still do not know the best function \(f(k)\) such that, if \(n \geq f(k)\), then \(r_{ck}(K_{n,n}) = 3\) (unlike the analogous situation for complete graphs). We only know that the answer lies between \(\frac{3k}{2}\) and \(2k + o(k)\).

**Problem 5.2** For \(k \geq 2\), is there a constant \(\frac{3}{2} \leq c < 2\) such that, if \(n \geq ck\), then \(r_{ck}(K_{n,n}) = 3\)?

In relation to Theorems 1.6 and 1.8, for complete bipartite and multipartite graphs \(G\), all known results for \(r_{ck}(G)\) with \(k \geq 2\) only concern those graphs with equipartitions.

**Problem 5.3** For \(k, t \geq 2\) and \(n_1 \leq \cdots \leq n_t\), is there a function \(f(k, t)\) such that, if \(n_1 \geq f(k, t)\), then

\[
r_{ck}(K_{n_1, \ldots, n_t}) = \begin{cases} 3 & \text{if } t = 2, \\ 2 & \text{if } t \geq 3? \end{cases}
\]

The case \(t = 2\) was asked by Chartrand et al. [6]. It is surprising that this particular case of Problem 5.3 is still open, since complete bipartite graphs are very basic graphs.

Finally, for random graphs, we can obviously ask the following.

**Problem 5.4** For \(d \geq 2\), determine a sharp threshold function for the property \(r_{ck}(G) \leq d\), where \(G\) is another random graph model.

In particular, an answer for random regular graphs would be interesting.
References


[13] M. Krivelevich, and R. Yuster, The rainbow connection of a graph is (at most) reciprocal to its minimum degree, J. Graph Th. 63(3) (2009), 185-191.


