Ramsey numbers of trees

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Outline

Ramsey numbers of trees

Definition

The Ramsey number of a graph G, denoted as $R(G)$, is the smallest integer n such that any red/blue colouring of K_n contains a monochromatic copy of G.

Theorem

- [Gerencsér, Gyárfás, 1967]

$$R(P_k) = \begin{cases} \frac{3k}{2} & \text{if } k \text{ is even,} \\ \frac{3k+1}{2} & \text{if } k \text{ is odd.} \end{cases}$$

- [Harary, 1972]

$$R(K_{1,k}) = \begin{cases} 2k-1 & \text{if } k \text{ is even,} \\ 2k & \text{if } k \text{ is odd.} \end{cases}$$

Burr and Erdős' Conjecture

Conjecture (Burr, Erdős, 1976)

Let T be a tree on n vertices, then

$$R(T) \leq \begin{cases} 2n-3 & \text{if } n \text{ is odd,} \\ 2n-2 & \text{if } n \text{ is even.} \end{cases}$$

Theorem (Zhao, 2016)

Let T be a tree on n vertices with n large, then $R(T) \leq 2n-2$.

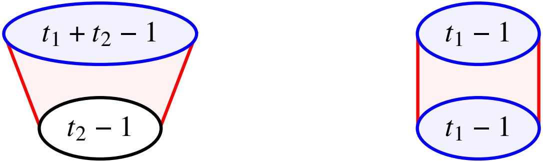
This confirms the conjecture for large even n, but the odd case is still open.

Burr's conjecture

Lemma

Let T be a tree with bipartition classes of sizes $t_1 \geq t_2 \geq 2$, then

$$R(T) \geq R_B(T) := \max\{2t_1, t_1 + 2t_2\} - 1.$$



Conjecture (Burr, 1974)

Let T be a tree with bipartition classes of sizes $t_1 \geq t_2 \geq 2$, then

$$R(T) = R_B(T) = \max\{2t_1, t_1 + 2t_2\} - 1.$$

Counterexamples

Definition

The double star S_{m_1,m_2} is the tree obtained by joining the central vertices of the two stars K_{1,m_1} and K_{1,m_2} with an edge.

Note that if $m_1 \geq m_2$, then

$$R_B(S_{m_1,m_2}) = \max\{2m_1 + 2, m_1 + 2m_2 + 3\} - 1.$$

- [Grossman, Harary, Klawe, 1979]

$$R(S_{3m,m}) = 6m + 2 = R_B(S_{3m,m}) + 1.$$

- [Norin, Sun, Zhao, 2016]

$$R(S_{2m,m}) \geq (4.2 + o(1))m \geq (1.1 + o(1))R_B(S_{2m,m}).$$

Note that double stars have large maximum degrees.

Approximate version

Conjecture (Burr, 1974)

Let T be a tree with bipartition classes of sizes $t_1 \geq t_2 \geq 2$, then

$$R(T) = R_B(T) = \max\{2t_1, t_1 + 2t_2\} - 1.$$

Theorem (Haxell, Łuczak, Tingley, 2002)

For every $\mu > 0$, there exists $c > 0$ such that for every large n and every n-vertex tree T with $\Delta(T) \leq cn$, we have

$$R(T) \leq (1 + \mu) R_B(T).$$

Our Result

Theorem (Montgomery, Pavez-Signé, Y., 2024++)

There exists $c > 0$ such that for every n-vertex tree T with $\Delta(T) \leq cn$ and bipartition classes of sizes $t_1 \geq t_2$, we have

$$R(T) = R_B(T) = \max\{2t_1, t_1 + 2t_2\} - 1.$$

This confirms Burr's conjecture for all trees maximum degree at most cn.

The Haxell, Łuczak, Tingley proof sketch

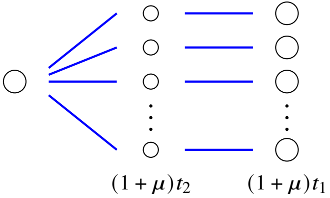
Theorem (Haxell, Łuczak, Tingley, 2002)

For every $\mu > 0$, there exists $c \in (0, 1)$ such that for every large n and every n-vertex tree T with $\Delta(T) \leq cn$ and bipartition classes of sizes $t_1 \geq t_2$, we have

$$R(T) \leq (1 + 2\mu)R_B(T) = (1 + 2\mu)\max\{2t_1, t_1 + 2t_2\}.$$

We may assume $t_1 \leq 2t_2$ by adding additional leaves.

Step 1: In any red/blue coloured graph G on $(1 + 2\mu)(t_1 + 2t_2)$ vertices, find a monochromatic "HŁT structure" in the reduced graph.

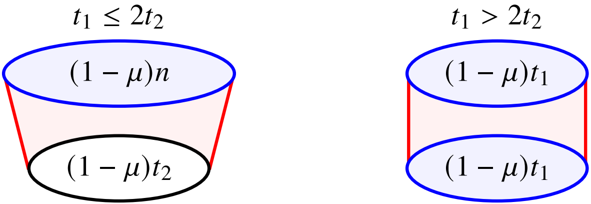


Step 2: Show that T can be embedded into the HŁT structure using regularity.

Our proof sketch

Definition

A red/blue coloured graph/reduced graph is μ-extremal if we can find one of the following approximate extremal constructions as a subgraph.



Stability part: starting with a scaled down HŁT structure in the reduced graph

- either we can find a structure to embed monochromatic T using regularity,
- or the reduced graph, and thus G must be μ-extremal.

Extremal part: embed a monochromatic T into a μ-extremal G.

Outline

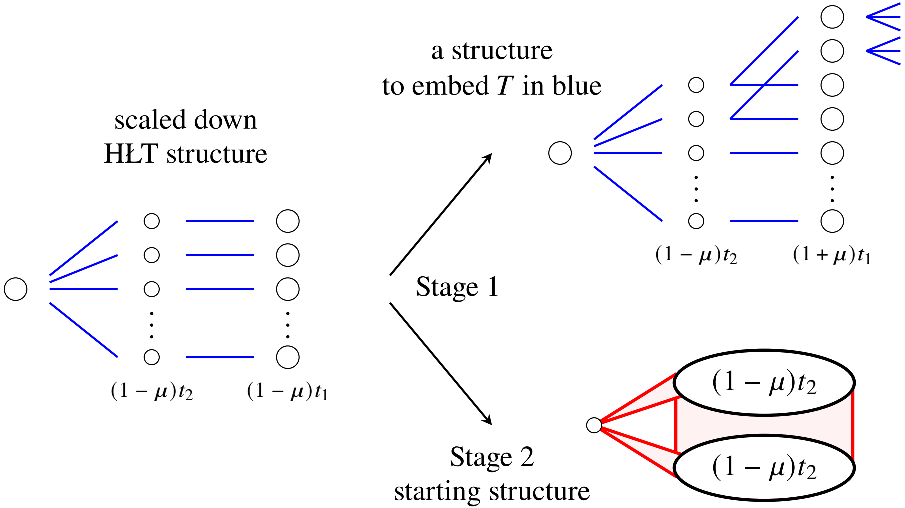
Stability part

Starting with a scaled down HŁT structure in the reduced graph, we move through three stages.

In each stage,

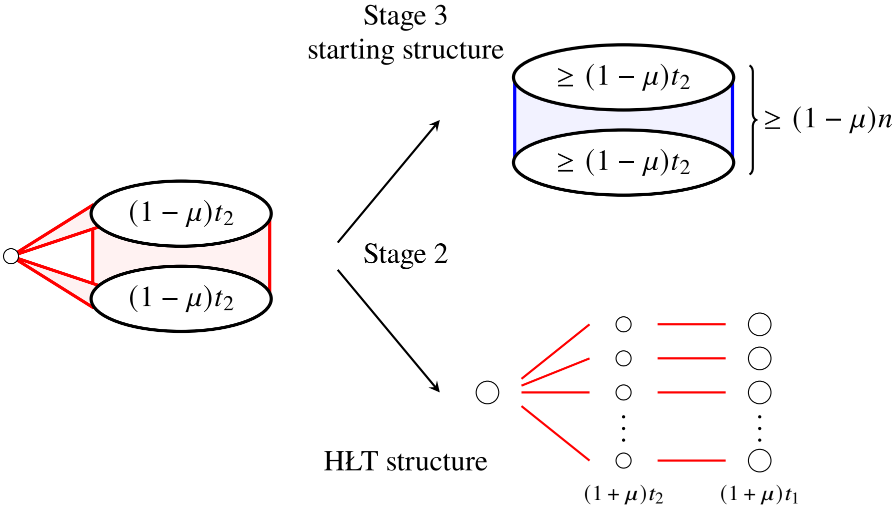
- either we can find a structure to embed monochromatic T using regularity,
- or we find the structure that represents the beginning of the next stage.

At the end of Stage 3, we conclude that the reduced graph is extremal, and hence so is the original graph G.

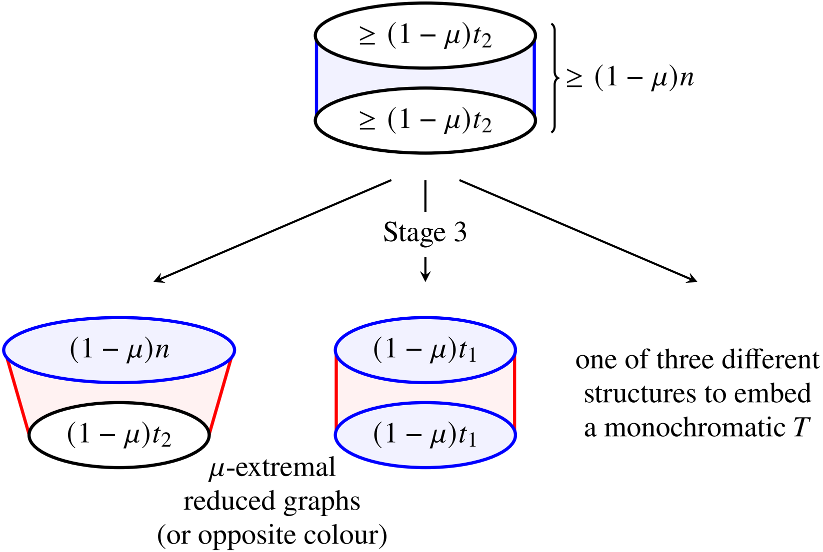


scaled down
HŁT structure
$(1-\mu)t_2$
$(1-\mu)t_1$
a structure
to embed T in blue
$(1-\mu)t_2$
$(1+\mu)t_1$
Stage 1
Stage 2
starting structure
$(1-\mu)t_2$
$(1-\mu)t_2$

Stage 2


Stage 3
starting structure
$\geq (1-\mu)t_2$
$\geq (1-\mu)t_2$
$\geq (1-\mu)n$
$(1-\mu)t_2$
$(1-\mu)t_2$
Stage 2
HŁT structure
$(1+\mu)t_2$
$(1+\mu)t_1$

Stage 3

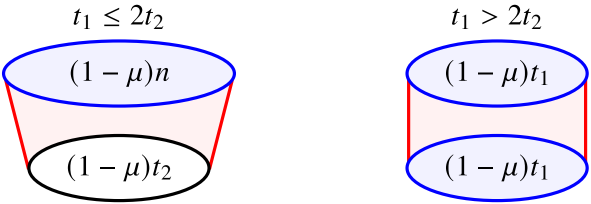


$\geq (1-\mu)t_2$
$\geq (1-\mu)t_2$
$\geq (1-\mu)n$
Stage 3
$(1-\mu)n$
$(1-\mu)t_2$
$(1-\mu)t_1$
$(1-\mu)t_1$
one of three different structures to embed a monochromatic T
μ-extremal reduced graphs (or opposite colour)

Outline

Extremal part

It follows from the Stability part that if a graph G on $R_B(T)$ vertices does not contain a monochromatic T, then G must be μ-extremal, with each vertex having at most μn neighbours in the wrong colour.



We show that we can find still a monochromatic T in any μ-extremal graph. Absorption type arguments relying on a random embedding technique.

Dichotomy between leaves and bare paths

Definition

A path P in a tree T is a bare path if all vertices in P has degree exactly 2.

Lemma (Krivelevich, 2010)

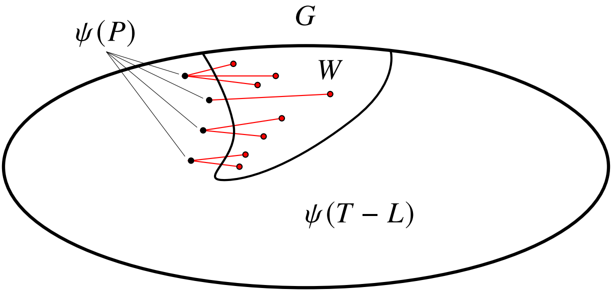
Let T be a tree on n vertices, then

- either T contains at least ℓ leaves,
- or T contains at least $\frac{n}{s+1} - 2\ell$ bare paths of length s.

Generalised Hall's matching condition

Lemma

Let G be a bipartite graph with bipartition $A \cup B$ and let $(f_a)_{a \in A}$ be a tuple of non-negative integers indexed by elements of A.
Suppose that $|N(S)| \geq \sum_{a \in S} f_a$ for all $S \subset A$. Then, there exists a disjoint collection of f_a neighbours for all $a \in A$ in B.



Tree splitting

Lemma (Montgomery, 2019)

Let T be a tree and let $Q \subset V(T)$.
Then, T can be decomposed into subtrees T_1 and T_2 with a unique common vertex such that $|Q \cap T_1| \geq \frac{1}{3}|Q|$ and $|Q \cap T_2| \geq \frac{1}{3}|Q|$.

Corollary

Let T be a tree with n vertices.
Then, T can be decomposed into subtrees T_1 and T_2 with a unique common vertex such that $\frac{n}{3} \leq |T_1|, |T_2| \leq \frac{2n}{3}$.

Corollary

Let $\gamma \ll \alpha \ll 1$ be suitably chosen constants. Let T be a tree with n vertices containing a set L of $n/100$ leaves.
Then, there is a subtree T_1 of T with $|T_1| \leq \alpha n$ and $|T_1 \cap L| \geq \gamma n$.

Random embedding method: Idea

Lemma (Montgomery, Pavez-Signé, Y., 2024++)

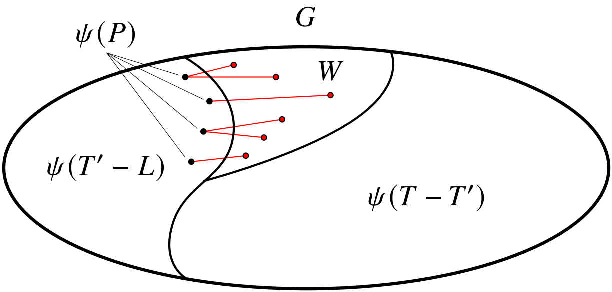
Let G be a graph with $|G| = n + \lfloor \frac{d}{100} \rfloor$ and $\delta(G) \geq (1-\mu)n$.
Suppose T is a tree with $|T| = n$, and T contains a subtree T' such that

- $|T'| \leq \alpha n$,
- T' contains a set L of $\lambda n \gg \mu n$ leaves in T,
- every parent of leaves in L in has at most $d \ll \mu n$ children in L.

Then G contains a copy of T.

- Embed $T' - L$ randomly.
- Embed the rest of $T - L$ greedily.
- Randomness ensures a generalised Hall's matching condition holds, so we can attach the leaves to finish a copy of T.

Random embedding method: Sketch



- $w \in W$ is good if the set of $p \in P$ such that $\psi(p)$ is a neighbours of w together have at least $\frac{1}{2}|L|$ neighbours in L.
- The set B of bad vertices in W has size at most $\frac{d}{100}$ by Azuma.

Generalised Hall's matching condition holds between $\psi(P)$ and $W \setminus B$, which allows us to embed L.

Random embedding method: Remarks

Lemma (Montgomery, Pavez-Signé, Y., 2024++)

Let G be a graph with $|G| = n + \lfloor \frac{d}{100} \rfloor$ and $\delta(G) \geq (1-\mu)n$.
Suppose T is a tree with $|T| = n$, and T contains a subtree T' such that

- $|T'| \leq \alpha n$,
- T' contains a set L of $\lambda n \gg \mu n$ leaves in T,
- every parent of leaves in L in has at most $d \ll \mu n$ children in L.

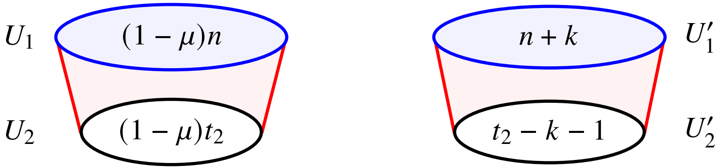
Then G contains a copy of T.

- If $d \ll \frac{n}{\log n}$, just $|G| = n$ is sufficient, so we can embed spanning trees.
- Still works if a set of at most $10\mu n$ vertices only have degree $\beta n \gg \lambda n$.
- There is an analogous bipartite version.
- A variant where there is a set of αn vertices with a higher degree $n - C$, and $\lfloor \frac{C}{100} \rfloor$ spare vertices.
- Very flexible. Can use randomness to guarantee many other conditions satisfied by the embedding, e.g. certain vertices go into a certain set.

Extremal part: $t_1 \leq 2t_2$ cleaning

Assume that $t_1 \leq 2t_2$, so G contains $t_1 + 2t_2 - 1 = n + t_2 - 1$ vertices in total.

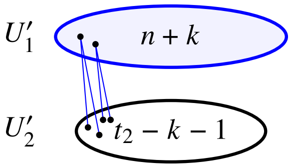
Cleaning: For each remaining vertex, add it to U_1 if it has at least βn blue neighbours in U_1, and add it to U_2 otherwise.

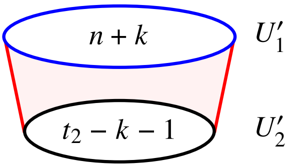


Extremal part: $t_1 \leq 2t_2$ and $d \ll \frac{n}{\log n}$

If $k \geq 0$, we can find a blue T in U_1' with the random embedding method.
If $k \leq -1$, then

- either several vertices in U_1 have at least $-k$ blue neighbours in U_2':
  Embed T in blue in U_1' with the random embedding method, except that $-k$ leaves are embedded into U_2'.
- or most vertices in U_1 have at least t_2 red neighbours in U_2':
  Embed T in red between U_1 and U_2' greedily.

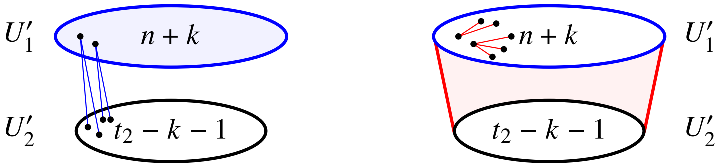




Extremal part: $t_1 \leq 2t_2$ and $d \gg \frac{n}{\log n}$

$t_1 \leq 2t_2$ and $d \gg \frac{n}{\log n}$: Random embedding method requires spare vertices. Tradeoff between conditions required to embed in blue and red.

- If several vertices in U_1' have higher blue degree $n - C$:
  Use a variant of the random embedding method to embed T in blue.
- Otherwise, there are enough red edges in U_1':
  Embed T in red mostly greedily, but "flip" enough vertices to create space in U_2'.



Extremal part: $t_1 > 2t_2$ cleaning

Assume now that $t_1 > 2t_2$, so G contains $2t_1 - 1$ vertices in total.

We first run a similar cleaning process:

Extremal part: $t_1 > 2t_2$ brief sketches

- If T can be decomposed into T_1, T_2 with a unique common vertex v, such that $\frac{n}{3} + 2\mu n \le |T_1|, |T_2| \le \frac{2n}{3} - 2\mu n$, and there is a vertex in U_1' with at least cn blue edges to U_2', then we can greedily embed in blue.
- If T has a subtree T_1 with a set L of λn leaves in the t_1 side, and all of its parents have at most $d \ll \frac{n}{\log n}$ children in L, then we can use random embedding method to embed in red.
- Otherwise, more involved arguments...