Double Turán Problem

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Overview

Preliminaries

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Question

Given a graph F, how many edges can an n-vertex graph have while containing no copy of F as a subgraph?

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Given a graph F, how many edges can an n-vertex graph have while containing no copy of F as a subgraph?

We call the following quantity the Turán number or extremal number of F:

Definition

$$\mathrm{ex}(n, F) := \max\{e(G) : |V(G)| = n \text{ and } F \not\subseteq G\}$$

Preliminaries

Turán's theorem

The maximum number of edges in an n-vertex graph containing no clique of order $r+1$ is $e(T_r(n))$, with equality only for $T_r(n)$.

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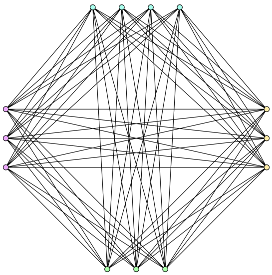

Figure: $T_4(13)$

Preliminaries

Erdős-Stone Theorem, Simonovits' Theorem

Let F be any graph of chromatic number $r + 1 \geq 3$. Then $\mathrm{ex}(n, F) = (1 + o(1))T_r(n)$ as $n \to \infty$.

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Let $G_1, G_2, \ldots, G_m$ be graphs on $[n]$ with $E(F) \not\subseteq E(G_i) \cap E(G_j)$ for distinct $i, j \in [m]$. (Double F-free)

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Question

What is the value of $\phi(m, n, F) = \max \sum_{i=1}^{m} G_i$?

Double Turán Problem

Double Turán problems are closely related to Turán problems for 3-uniform hypergraphs H through link graphs.

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Definition

For $i \in V(H)$, define graph H_i with

$$V(H_i) = V(H) \backslash \{i\} \quad \text{and} \quad E(H_i) = \{\{j, k\} : \{i, j, k\} \in E(H)\}.$$

Example: Octahedron-free 3-uniform hypergraph H

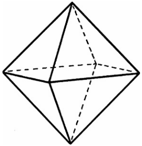

Figure: Octahedron O

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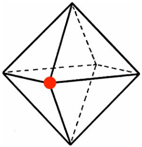

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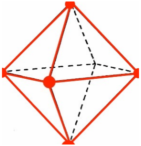

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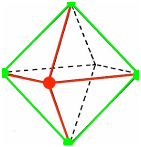

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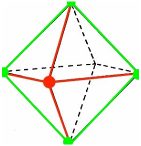

Figure: Octahedron O

H is octahedron-free $\implies$ $H_1, H_2, \ldots, H_n$ are double C_4-free.

$$\boxed{\mathrm{ex}(n, O) \leq \phi(n, n, C_4)}$$

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Let graphs $G_1, G_2, \ldots, G_m$ be induced and double F-free.

Question

What is the value of $\phi^*(m, n, F) = \max \sum_{i=1}^{m} e(G_i)$?

Induced Double Turán Problem

Generalizaed Turán problem

What is the maximum number $\mathrm{ex}(n, F, K_3)$ of triangles in a graph H on $[n]$ with no copy of F as a subgraph?

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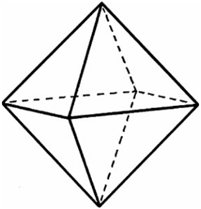
$$V(G_i) = V(G) \quad \text{and} \quad E(G_i) = \{\{j,k\} : \{i,j\},\{j,k\},\{i,k\} \in E(G)\}$$

Ex. Octahedron-free graph G.



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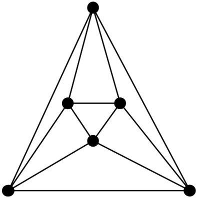

Figure: Octahedron Graph $K_{2,2,2}$

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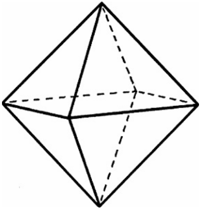

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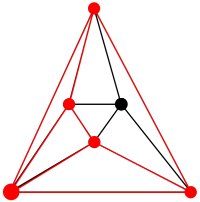

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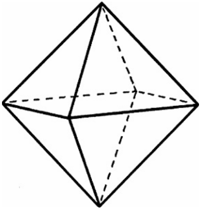

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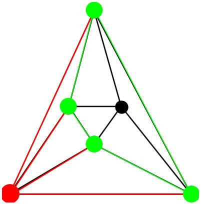

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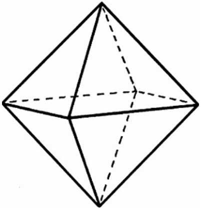

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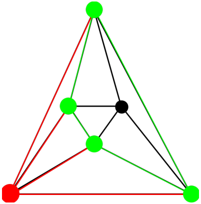

Figure: Octahedron Graph $K_{2,2,2}$

G is $K_{2,2,2}$-free $\implies$ $G_1, G_2, \ldots, G_n$ are induced and double $K_{2,2}$-free.

$$\boxed{\mathrm{ex}(n, K_{2,2,2}, K_3) \leq \phi^*(n, n, K_{2,2})}$$

Main Results

Theorem A

For $m \geq 3$ and non-bipartite F, if n is large enough, then

$$\phi^*(m, n, F) = m \cdot \mathrm{ex}(n, F),$$

with equality only for identical extremal n-vertex F-free graphs.

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Theorem B

For $m, n, r \geq 3$,

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The non-bipartite case for $\phi(m, n, K_r)$ is not as simple.

Intuitively, we might guess

$$\phi(m, n, K_r) = \binom{n}{2} + (m-1)\mathrm{ex}(n, K_r)$$

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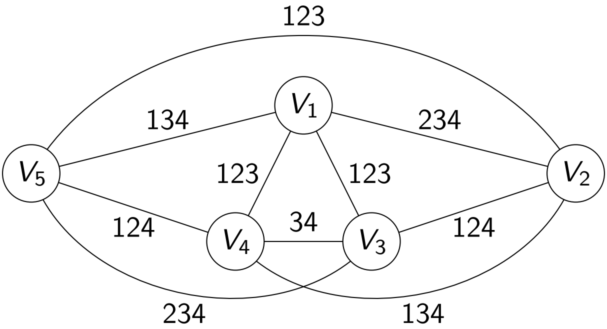

Figure: Example of an $(4, n, 5)$-blowup not containing a double K_3.

Main Results

Let $f(m, n, r)$ denote the maximum possible sum of edges in an double K_r-free (m, n, k)-blowup with $k < R_{\binom{m}{2}}(r)$ ($\binom{m}{2}$-color Ramsey number for K_r).

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Theorem C

For $n \geq 1$,

1. if $r \geq 2$ and $m \geq 1$,

$$\phi(m,n,K_r) = f(m,n,r).$$

2. $$\phi(3,n,K_3) = \binom{n}{2} + \left\lfloor \frac{n^2}{2} \right\rfloor.$$

In particular,

$$\lim_{n\to\infty} \frac{\phi(4,n,K_3)}{\binom{n}{2} + 3\left\lfloor \frac{n^2}{4} \right\rfloor} > 1$$

Main Results

Conjecture

Let F be any non-empty graph and $m, n \geq 1$. Then

$$\phi^*(m, n, F) = \Theta(m \cdot \mathrm{ex}(n, F) + n^2).$$

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By Theorem 1, the conjecture is true when F is non-bipartite.

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$$\phi^*(m, n, F) = \Theta(m \cdot \mathrm{ex}(n, F) + n^2).$$

Since

$$\mathrm{ex}(n, K_{2,2,2}, K_3) \leq \phi^*(n, n, K_{2,2})$$

the conjecture implies

$$\mathrm{ex}(n, K_{2,2,2}, K_3) \leq O(n^2)$$

which solves a conjecture of Mubayi and Verstraete.

Main Results

Theorem D

Let F be a graph. If there exists an extremal F-free n-vertex graph with maximum degree at most $\sqrt{n}/m^2$, then

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If P is a path of length 2 and $m = o(n^{1/4})$,

$$\binom{n}{2} + m - 1 \leq \phi^*(m, n, P) \leq \phi(m, n, P) = \binom{n}{2} + \binom{m}{2}\left\lfloor \frac{n}{2} \right\rfloor.$$

Main Results

Theorem E

Let P be a path with two edges. Then $\phi(n,n,P) = \Omega(n^{5/2})$, whereas $\phi^*(n,n,P) = o(n^{5/2})$, as $n \to \infty$. In particular,

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This shows that $\phi(n, n, P)$ and $\phi^*(n, n, P)$ are very different problems.

Proof of Theorem B

Theorem B

Let $m, n, r \geq 3$. Then

$$\phi^*(m, n, K_r) = m \cdot e(T_{r-1}(n)),$$

with equality for induced K_r-free graphs $G_1, G_2, \ldots, G_m$ only if $G_1 = G_2 = \cdots = G_m = T_{r-1}(n)$.

Proof Roadmap

- Step 1: Reduce to the case of smaller m
- Step 2: Further reduce to an optimization problem
- Step 3: Solve the optimization problem

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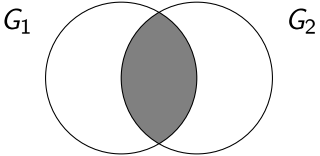

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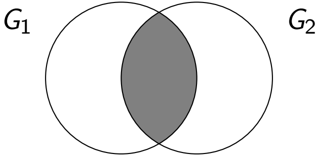

The intersection of G_1, G_2 (gray area) is double K_r-free.

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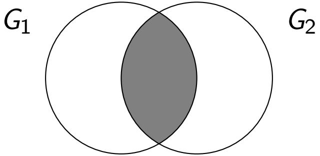

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Observation

If G_1, G_2 intersects in t vertices, Then

$$e(G_1) + e(G_2) \leq \binom{n-t}{2} + (n-t)t + 2\mathrm{ex}(t, F)$$

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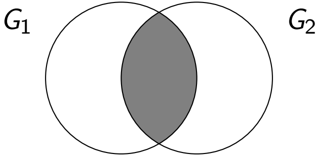

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$\implies$ we are done if the unique maximum on t is at $t = n$.

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Proof of Theorem D: Upper Bound

Theorem D

Let F be a graph. If there exists an extremal F-free n-vertex graph with maximum degree at most $\sqrt{n}/m^2$, then

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Let E_S be the set of edges in exactly $\{G_i\}_{i \in S}$.

$$\implies \sum_{i=1}^{m} e(G_i) = \sum_{S \subseteq [m]} |S||E_S| \leq \binom{n}{2} + \sum_{S \subseteq [m], |S| \geq 2} (|S| - 1)|E_S|.$$

Proof of Theorem D: Upper Bound

$$\sum_{\substack{S\subseteq[m]\\|S|\geq 2}}(|S|-1)|E_S| = \sum_{\substack{S\subseteq[m],\\|S|=2}}\sum_{T\supseteq S}\frac{(|T|-1)|E_T|}{\binom{|T|}{2}} \leq \sum_{\substack{S\subseteq[m],\\|S|=2}}\sum_{T\supseteq S}|E_T|,$$

as each $T \in [m]$ with $|T| \geq 2$ is counted $\binom{|T|}{2}$ times.

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$$\implies \sum_{\substack{S \subseteq [m] \\ |S| \geq 2}} (|S| - 1)|E_S| \leq \sum_{\substack{S \subseteq [m], \\ |S| = 2}} \sum_{T \supseteq S} |E_T| \leq \binom{m}{2} \mathrm{ex}(n, F)$$

This proves the upper bound.

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IDEA: start with any embedding and iteratively decrease overlapping edges

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$\implies (u, v, i)$-swap perserves graph isomorphism.

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$\implies |N(u) \cup N(N(u))| \leq \triangle + \triangle(\triangle - 1) \leq n/4$

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$\implies \exists v \notin N(u) \cup N(N(u))$, so $N(u) \cap N(v) = \emptyset$.

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Suppose there exists $\{u, w\} \in E(H_i) \cap E(H_j)$

$|N(u)| \leq M \cdot \triangle \leq n^{1/2}/2$

$\implies |N(u) \cup N(N(u))| \leq \triangle + \triangle(\triangle - 1) \leq n/4$

$\implies \exists v \notin N(u) \cup N(N(u))$, so $N(u) \cap N(v) = \emptyset$.

$\implies (u, v, i)$-swap makes $\{u, w\}$ not overlapping!

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Keep swapping until no overlapping edges left