The edge spectrum of the saturation number for small paths

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ABSTRACT

Let H be a simple graph. A graph G is called an H-saturated graph if H is not a subgraph of G, but adding any missing edge to G will produce a copy of H. Denote by SAT(n, H) the set of all H-saturated graphs G with order n. Then the saturation number sat(n, H) is defined as min_{G \in SAT(n, H)} |E(G)|, and the extremal number ex(n, H) is defined as max_{G \in SAT(n, H)} |E(G)|. A natural question is that of whether we can find an H-saturated graph with m edges for any sat(n, H) ≤ m ≤ ex(n, H). The set of all possible values m is called the edge spectrum for H-saturated graphs. In this paper we investigate the edge spectrum for P_1-saturated graphs, where 2 ≤ i ≤ 6. It is trivial for the case of P_2 that the saturated graph must be an empty graph.

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1. Introduction and notation

In this paper we only consider graphs without loops or multiple edges. For terms not defined here see [3]. For a graph G we use G to represent the vertex set V(G) and the edge set E(G) when the meaning is clear from the context. Furthermore, |V(G)| = n, unless otherwise specified. Also, K_p denotes the complete graph on p vertices. A graph G is termed an (n, m) graph if |V(G)| = n and |E(G)| = m.

A fixed graph G is called an H-saturated graph if the graph H is not a subgraph of G, but adding any missing edge to G will produce a copy of H. The collection of all H-saturated graphs of order n is denoted by SAT(n, H), and the saturation number, denoted as sat(n, H), is the minimum number of edges of a graph in the set SAT(n, H). The graphs in SAT(n, H) with the minimum number of edges will be denoted by SAT(n, H). The saturation number was introduced by Erdős, Hajnal, and Moon in [4] in which the authors proved sat(n, K_p) = \left( \frac{p^2}{2} \right) + (n - p + 2)(p - 2) and SAT(n, K_p) = \{ K_{p-2} \lor K_{n-p+2} \}, where \lor is the standard graph joining operation. The maximum number of edges of a graph from SAT(n, H) is the well known Turán extremal number (see [9]), and is usually denoted by ex(n, H). The parameters sat(n, H) and ex(n, H) have been investigated for a range of graphs H. Generalizations to hypergraphs also exist (see [7]).

A natural aim is to find, if possible, an H-saturated graph with m edges for any integer m between the saturation number and extremal number. Barefoot et al. [2] studied the edge spectrum of K_3-saturated graphs and proved the following result.

**Theorem 1.1** ([2]). Let n ≥ 5 and m be nonnegative integers. There is an (n, m) K_3-saturated graph if and only if 2n - 5 ≤ m ≤ \lfloor (n - 1)^2/4 \rfloor + 1 or m = k(n-k) for some positive integer k.

Theorem 1.1 says that a K_3-saturated graph is either a complete bipartite graph or its size falls in the given range and all values in this range are possible.

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Later Amin [1] extended this result from $K_3$-saturated graphs to any complete graph $K_p$ in her Ph.D. thesis, which is the starting point of this paper. In Section 2, we present the known results on saturation numbers and extremal numbers for paths, and then investigate the properties of connected $P_3$-saturated graphs and connected $P_5$-saturated graphs. In Sections 3 and 4 we shall give a complete characterization of the edge spectrum for $P_5$-saturated graphs and $P_6$-saturated graphs respectively.

2. Known results

In [6] Kászonyi and Tuza proved several general results concerning saturated graphs including an upper bound for $sat(n,H)$ for any connected graph $H$ by constructing an $H$-saturated graph.

**Theorem 2.1** ([6]). Saturation numbers for paths:

(a) For $n \geq 3$, $sat(n, P_3) = \lceil n/2 \rceil$.
(b) For $n \geq 4$, $sat(n, P_4) = \begin{cases} n/2 & \text{if } n \text{ is even}, \\ (n + 3)/2 & \text{if } n \text{ is odd}. \end{cases}$
(c) For $n \geq 5$, $sat(n, P_5) = \lceil n^2/6 \rceil$.
(d) Let $a_k = \begin{cases} 3 \cdot 2^{t-1} - 2 & \text{if } k = 2^t, \\ 4 \cdot 2^{t-1} - 2 & \text{if } k = 2^t + 1. \end{cases}$ If $n \geq a_k$ and $k \geq 6$, then $sat(n, P_k) = n - \lfloor n/a_k \rfloor$.

In this paper, we will mainly consider the cases of $P_5$ and $P_6$. By **Theorem 2.1** we have $sat(n, P_6) = \lfloor 9n/10 \rfloor$ for any $n \geq 10$.

Next let us recall a result concerning the Turán extremal number, which was proved by Faudree and Schelp [5] in 1975.

**Theorem 2.2** ([5]). If $G$ is a graph with $|V(G)| = kt + r$, $0 \leq r < k$, containing no path on $k + 1$ vertices, then $|E(G)| \leq t \left( \begin{array}{c} k \\ 2 \end{array} \right) + \left( \begin{array}{c} k \\ 2 \end{array} \right)$ with equality if and only if $G$ is either $(tK_k) \cup K_r$ or $(t - 1)K_k \cup (K_{(k-1)/2} \lor K_{(k+1)/2} + 5k)$ for some $l$, $0 \leq l \leq t$, where $k$ is odd, $t > 0$, and $r = (k \pm 1)/2$.

**Corollary 2.3** ([8]). For all integer $n$, $n \geq 3$.

(a) $ex(n, P_4) = \begin{cases} n & n = 0 \pmod{3} \\ n - 1 & n = 1 \pmod{3} \\ 3n/2 & n = 2 \pmod{3}. \end{cases}$
(b) $ex(n, P_5) = \begin{cases} n/2 & n = 0 \pmod{4} \\ 3n/2 - 2 & n = 2 \pmod{4} \\ 3(n - 1)/2 & n = 1 \pmod{4} \\ n = 3 \pmod{4}. \end{cases}$
(c) $ex(n, P_6) = \begin{cases} 2n & n = 0 \pmod{5} \\ 2n - 2 & n = 1 \pmod{5} \\ 2n - 3 & n = 2 \pmod{5} \\ n = 4 \pmod{5} \end{cases}$.

Considering the fact that for any $P_3$-saturated graph $G$, no two edges can be incident to each other and $G$ contains at most one isolated vertex, therefore, $sat(n, P_3) = ex(n, P_3) = \lceil n/2 \rceil$. As for the case of $P_4$-saturated graphs, the following figures clearly show how we can evolve a $P_4$-saturated graph with the least edges to one with the most edges.

From the **Fig. 1** we can evolve a $P_4$-saturated graph, a perfect matching or a matching union a triangle to one with $n - 1$ edges for any integer $n$. In addition, when $n = 3p$ we can take $G = pK_3$ and find one more $P_4$-saturated graph of size $n$. 

![Fig. 1](image-url) Description of $P_4$-saturated graphs.
3. Edge spectra of $P_5$-saturated graphs

If $G$ is a $P_5$-saturated graph with order less than 5, then $G$ must be a complete graph. Furthermore, the order of the union of any two components of $G$ must be at least 5 since otherwise we can add an edge joining those two components and have no copies of $P_5$ in the resulting graphs. Therefore the structure of every component of a $P_5$-saturated graph becomes important and we have the following lemma concerning it.

**Lemma 3.1.** If $H$ is a connected $P_5$-saturated graph with order at least 5, then each block of $H$ is a clique of order 2 or 3.

**Proof.** If $H$ is 2-connected, i.e. $H$ consists of only one block, $H$ cannot be a complete graph since $H$ is $P_5$-saturated graph. Hence we may take two vertices $u$ and $v$ with $uv \notin E(H)$. There is no circuit with length more than 4 since otherwise a subgraph $P_5$ will be found. Therefore, we can find a circuit of length 4. Considering that $n \geq 5$, there is a vertex $w$ connecting to some vertex on this circuit and forming a path $P_5$. Thus $H$ cannot be 2-connected.

Let $B$ be a block of $H$, then the order of $B$ must be less than 4 since otherwise we may find a circuit of length at least 4 within block $B$, which forms a $P_5$ with any one edge outside $B$. Thus the order of each block in $H$ is either 3 or 2, as we desired. □

Let $H$ be a connected $P_5$-saturated graph. It is trivial for the case $|V(H)| \leq 4$ that $H$ must be a complete graph. Hence we may assume that $|V(H)| \geq 5$. If $H$ contains two triangles $T_1$ and $T_2$, which are connected by a path $Q$, then a path of order at least 5 is naturally contained as a subgraph. Hence $H$ contains at most one triangle. Therefore, by Lemma 3.1 either $G$ is a tree or a graph obtained by adding exactly one edge to a star (see Fig. 2). Then we get the following lemmas.

**Lemma 3.2.** If $H$ is a component of a $P_5$-saturated graph other than $K_4$, then the size of $H$ is either $n' - 1$ or $n'$, where $n' = |V(H)|$.

Let $G$ be a $P_5$-saturated graph and $S_{i_{5}}$ be a graph obtained from the star $S_{i}$ by adding one edge. If we denote by $\alpha_1$ the number of acyclic components of $G$, by $\alpha_2$ the number of $S_{i_{5}}$'s, and by $\alpha_3$ the number of $K_4$'s in $G$, then by applying the above lemma we have the next lemma immediately.

**Lemma 3.3.** If $G \in SAT(n, P_5)$, then $|E(G)| = n - \alpha_1 + 2\alpha_3$, where $\alpha_1, \alpha_3$ are defined above.

The key idea of our method is constructing a new $P_5$-saturated graph from an existing smaller $P_5$-saturated graph. Our main result on $P_5$ is heavily dependent on the following lemmas.

**Lemma 3.4.** Let $m \geq n \geq 5$. There is an $(n, m)$ graph $G$ in $SAT(n, P_5)$ if and only if there exists an $(n + 4, m + 6)$ graph $G'$ in $SAT(n + 4, P_5)$.

**Proof.** It is trivial that $G \in SAT(n, P_5)$ implies $G' = G \cup K_4 \in SAT(n + 4, P_5)$, where $\cup$ is the graph union operation and $V(G') = V(G) \cup V(K_4), E(G') = E(G) \cup E(K_4)$. For the necessity, we assume that $G'$ is an $(n + 4, m + 6)$ graph in SAT($n + 4, P_5$). If there exists a component $K_4$ in $G'$, then $G = G' - K_4$ will be an $(n, m)$ graph in SAT($n, P_5$). Hence, we may suppose that $G''$ contains no $K_4$'s, i.e. $\alpha_3 = 0$. By Lemma 3.3, $m + 6 = |E(G'')| = |E(G'')| - \alpha_1 \leq |V(G'')| = n + 4$, contradicting that $m \geq n$. □

So far we have figured out $P_5$-saturated graphs with $m \geq n$. The next lemma will tell us more information about $P_5$-saturated graphs with fewer edges.

**Lemma 3.5.** Let $n$ be an integer that is at least 5 and $\lceil \frac{5n - 4}{6} \rceil \leq m \leq n - 1$. There exists a $P_5$-saturated $(n, m)$ graph.

**Proof.** If $n = 5$, then $\lceil \frac{5n - 4}{6} \rceil = n - 1 = 4$ and we take $G = K_2 \cup K_3 \in SAT(n, P_5)$. Next we assume that $n > 5$ and write $n = 6k + i$, where $0 \leq i \leq 5$.

First we construct a $P_5$-saturated graph of size $m = \lceil \frac{5n - 4}{6} \rceil$. Let $T_{a,b}$ be a graph obtained from two stars $S_{a}$ and $S_{b}$ by adding an edge joining the two centers (see Fig. 2). We can construct the following graphs: $kT_{2,2}$, $(k - 1)T_{2,2} \cup T_{2,2}$, $kT_{2,2} \cup K_2$, $(k - 1)T_{2,2} \cup T_{2,3} \cup K_2$, $(k - 1)T_{2,2} \cup T_{3,3} \cup K_2$, $(k - 1)T_{2,2} \cup T_{4,3} \cup K_2$ in line with the $i$-values. For example, we can take $G = T_{2,2} \cup T_{4,3} \cup K_2$ if $n = 17$.

Then for the values of $m \in (\lceil \frac{5n - 4}{6} \rceil, n)$, we can build a $P_5$-saturated $(n, m)$ graph by the following process starting with saturated graphs with $\lceil \frac{5n - 4}{6} \rceil$ edges: $T_{a,b} + T_{x,y} \Rightarrow T_{x+a+1, y+b+1}$ or $T_{x,y} + K_2 \Rightarrow T_{x+1, y+1}$. This process is shown in Fig. 3. At the end of this process we shall get a $P_5$-saturated with $n - 1$ edges, namely $T_{a,n-a-2}$. □
Now we are ready to give the edge spectra of $P_5$-saturated graphs and present one of the main theorems. The interval $[A, B] = [\text{sat}(n, P_5), \text{ex}(n, P_5)]$ can be obtained from Theorem 2.1 and Corollary 2.3. We want to determine whether this interval is the spectrum of $P_5$—or are there any missing values within this interval?

It is worth noting here that at each induction process stage we jump four steps. First we give the results for four initial values of $n$, which are listed in the table, and then apply the induction process to get results for the next four $n$ values.

**Theorem 3.1.** Let $n \geq 5$ and $\text{sat}(n, P_5) \leq m \leq \text{ex}(n, P_5)$ be integers. There exists an $(n, m)$ graph $G \in \text{SAT}(n, P_5)$ if and only if $n = 1, 2 \pmod{4}$, or

$$m \notin \left\{ \frac{3n - 5}{2}, \frac{3n - 3}{2}, \frac{3n}{2} - 2, \frac{3n}{2} - 1 \right\}$$

if $n \equiv 0 \pmod{4}$.

**Proof.** The proof of this result follows from Lemma 3.1 through Lemma 3.5 and the next table, by induction on $n$.

<table>
<thead>
<tr>
<th>$n$</th>
<th>$[A, B]$</th>
<th>$\text{SAT}(n, P_5)$</th>
<th>$n$</th>
<th>$[A, B]$</th>
<th>$\text{SAT}(n, P_5)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>[4, 6]</td>
<td>$4: K_1 \cup K_2$</td>
<td>6</td>
<td>[5, 7]</td>
<td>$5: T_{2,2}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$5: S_4^+$</td>
<td></td>
<td></td>
<td>$6: 2K_3$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$6: K_4 \cup K_3$</td>
<td></td>
<td></td>
<td>$7: K_4 \cup K_3$</td>
</tr>
<tr>
<td>7</td>
<td>[6, 9]</td>
<td>$6: T_{2,3}$</td>
<td>8</td>
<td>[6, 12]</td>
<td>$6: T_{2,2} \cup K_3$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$7: 2K_3$</td>
<td></td>
<td></td>
<td>$7: T_{3,3}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$8: \emptyset$</td>
<td></td>
<td></td>
<td>$8: K_3 \cup S_4^+$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$9: K_4 \cup K_3$</td>
<td></td>
<td></td>
<td>$9-11: \emptyset$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$12: 2K_4$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In the above table, the symbol '$\emptyset$' stands for no $(n, m)P_5$-saturated graph existing and $A = \text{sat}(n, P_5)$, $B = \text{ex}(n, P_5)$. The nonexistence of $P_5$-saturated graphs comes from Lemma 3.3 by counting the edges.

The initial results for $n = 5, 6, 7, 8$ are listed in the above table. By the induction hypothesis, suppose that we have the result for $n$; then we shall apply Lemma 3.4 to get a result for $n + 4$. Once we have determined all possible $P_5$-saturated graphs with $n$ vertices, we can also determine the $P_5$-saturated graphs with $n + 4$ vertices according to Lemma 3.4. Therefore we can cover the interval $[\text{sat}(n, P_5) + 6, \text{ex}(n, P_5) + 6]$ which is exactly the interval $[\text{sat}(n, P_5) + 6, \text{ex}(n + 4, P_5)]$. In order to finish the argument that we can determine all integers between $\text{sat}(n + 4, P_5)$ and $\text{ex}(n + 4, P_5)$, we also need to deal with the subinterval $[\text{sat}(n + 4, P_5), \text{sat}(n, P_5) + 5]$, which is fortunately covered by Lemma 3.5 since $\text{sat}(n, P_5) + 5 \leq (n + 4) - 1$ for any integer $n \geq 9$. □

### 4. Edge spectra of $P_6$-saturated graphs

If $G$ is a $P_6$-saturated graph with order less than 6, then $G$ must be a complete graph. Furthermore, the order of the union of any two components of $G$ must be at least 6. Let $B_n$ denote the book graph, the union of $n$ triangles sharing one edge. A $\theta$-graph is the union of three internally disjoint (simple) paths that have the same two distinct end vertices. As we did for the case of $P_5$-saturated graph, we shall pay attention to each connected component of $G$.

**Lemma 4.1.** Let $H$ be a $(2)$-connected $P_6$-saturated graph of order at least (6). Then $H$ must be a book.

**Proof.** Let $C$ be the longest circuit in $H$. The length of $C$ must be less than 5 since otherwise $P_6$ would be found in a subgraph obtained from $C$ and any other edge touching it. On the other hand, the length of $C$ cannot be less than 4 since $H$ is $2$-connected and every vertex outside of the circuit $C$ is connected to $C$ by two edge-disjoint paths. Therefore $C$ is a circuit of length 4 and we define $C = uvx$ with $e = uv \notin E(H)$ the missing edge in $H$, since otherwise this $K_4$ plus any other vertex would contain a larger circuit in $H$. 

![Fig. 3. The evolution of $P_5$-saturated trees.](image-url)
Considering the fact that every edge in $H$ must have an endpoint in $C$, then the vertex set $H_C = H - C$ is an independent set. Take $w \in H_C$; then $w$ is adjacent to at least two vertices in $C$ from the fact that $H$ is 2-connected, and $w$ cannot be connected to two consecutive vertices in $C$ since otherwise we can find a circuit larger than $C$. Thus $w$ is connected to either $u$ and $v$ or $x$ and $y$. Since we need to avoid the appearance of $P_6$, all vertices from $H_C$ must be connected to either $u$ and $v$ or $x$ and $y$.

$C$ cannot be an induced 4-cycle since no matter how we connect $H_C$ to $C$, we can add a new edge—either $e$ or $f$—back to $H$. Thus $f = xy \in E(H)$, and all vertices in $H_C$ must connect to $x$ and $y$. Therefore the resulting graph is a book graph with common edge $f = xy$. □

**Lemma 4.2.** If $H$ is a connected $P_6$-saturated graph with cut vertices, then each block of $H$ must be a clique. Furthermore, if $H_1$ and $H_2$ are two blocks in $H$, then $|V(H_1)| + |V(H_2)| \leq 6$.

**Proof.** The result is trivial if $H$ is a tree. Let $v$ be the cut vertex and $H_v$ be one of the nontrivial blocks containing $v$ in $H$. If $|H_v| = 3$, then $H_v$ is complete.

Let $|H_v| = 4$; it contains a Hamilton circuit since $H_v$ is 2-connected. Then $H_v$ must be a clique if it is a leaf-block. Hence we may suppose now that $H_v$ is not a leaf-block. And every pair of cut vertices contained in $H_v$ are not joined by a Hamilton path $P_4$ of $H_v$ for otherwise, $H_v$ has a $P_6$. Therefore, $H_v$ has precisely two cut vertices $u$ and $v$ (see Fig. 4(a)) which are not next to each other along the 4-cycle of $H_v$. It is also clear that $H_v$ is not a 4-cycle, for otherwise, $H + uv$ does not have a $P_6$ since $H$ does not. So, $H_v = K_{2,2}$ (see Fig. 4(a)). Now we may add a new edge $e'$ joining $x \in N(v) - V(H_v)$ and $u$ (see Fig. 4(a)) into $H$. But $H + e'$ does not have $P_6$ since $H$ does not. Therefore $H_v$ must be a clique.

Now we may assume that $|H_v| \geq 5$. Following the same arguments as were used to prove Lemma 4.1 (but not the corollary of it), we obtain that the structure of $H_v$ is a book with common edge $e$. If $v \in e$, then all edges connecting neighbors of $v$ not in $H_v$ to $u$ can be added to $H$. In the resulting graph, $v$ is not a cut vertex any more. If $v \not\in e$, then $H$ has the above structure (see Fig. 4(b)) and contains $P_6$ as a subgraph, a contradiction. □

According to the above lemmas, any connected $P_6$-saturated graph with order at least 6 is either a book or one of the following types, where $B_n$ is the book with $n$ triangles sharing one common edge, $F_n$ is obtained from $K_4$ by gluing to the center of star $S_n$, $T_n$ is the union of $n$ triangles obtained by sharing one common vertex and $T'_n$ is obtained from $T_n$ by adding one more edge; $T_{i,j,k}$ is a rooted three-level tree.

Let $G$ be a $P_6$-saturated graph (Fig. 5). Denote by $a$, $b$, $c$, $\alpha$, $\beta_1$, $\beta_2$, $\gamma$, $\delta$ the numbers of components isomorphic to the various structures $K_3$, $K_4$, $K_5$, $F_i$, $T_j$, $T'_n$, trees and books in $G$ for the remainder of this section. For any graph $G$, we denote by $r(G) = |E(G)| - |V(G)|$ the rank of $G$. Thus $r(K_4) = r(F_i) = 2$, $r(K_5) = 5$.

**Lemma 4.3.** Let $m = 2n - 4$ and $n \geq 10$ be positive integers. There exists an $(n, m)$ graph in SAT($n$, $P_6$) if and only if $n \equiv 1, 3 (mod\ 5)$.

**Proof.** Let $n \equiv 1 (mod\ 5)$ and $m = 2n - 4$. We can construct an $(n, m)$ graph $G = F_2 \cup \alpha K_5$, where $\alpha = (n - 6)/5$. Then $|V(G)| = 5\alpha + 6$ and $|E(G)| = 10\alpha + 8 = 2n - 4$. If $n \equiv 3 (mod\ 5)$, we build an $(n, m)$ graph $G = 2K_4 \cup \alpha K_5$, where $\alpha = (n - 8)/5$. Then $|V(G)| = 5\alpha + 8$ and $|E(G)| = 10\alpha + 12 = 2n - 4$.

Next we shall prove by contradiction that there is no $(n, m)$ graph in SAT($n$, $P_6$) with $m = 2n - 4$ if $n \not\equiv 1, 3 (mod\ 5)$. Suppose $G$ is such a graph with components $H_1, H_2, \ldots, H_l$ and $h_1 \leq h_2 \leq \cdots \leq h_l$, where $h_i = |H_i|$. If $h_1 = 1$, then each
The constraint would be for every . Therefore we have , a contradiction. If , the remaining components of would be either or a book . Then we have

\[ n = 2 + 4b + 5c + \sum_{i=1}^{a} |V(F_i)| + \sum_{j=1}^{\delta} |V(B_j)| \]

and

\[ m = 1 + 6b + 10c + \sum_{i=1}^{a} (|V(F_i)| + 2) + \sum_{j=1}^{\delta} (2|V(B_j)| - 3), \]

where \(|V(F_i)|, |V(B_j)| \geq 6\). Hence \(4 = 2n - m = 3 + 2b + \sum_{i=1}^{a} (|V(F_i)| - 2) + 3\delta\). Simplifying this we have

\[ 2b + \sum_{i=1}^{a} (|V(F_i)| - 2) + 3\delta = 1. \]

It is easy to see that there is no integer solution to this equation.

So far we may suppose that \(h_1 \geq 3\), and the remaining components of are , , , , , trees , and books . By counting the number of vertices and edges of each component, we obtain

\[ n = 3a + 4b + 5c + \sum_{i=1}^{a} |V(F_i)| + \sum_{j=1}^{\beta_1} |V(T_j)| + \sum_{j'=1}^{\beta_2} |V(T'_{j'})| + \sum_{k=1}^{\gamma} |V(T^{(k)})| + \sum_{l=1}^{\delta} |V(B_l)| \]

and

\[ m = 3a + 6b + 10c + \sum_{i=1}^{a} (|V(F_i)| + 2) + \sum_{j=1}^{\beta_1} \frac{3(|V(T_j)| - 1)}{2} + \sum_{j'=1}^{\beta_2} \left( \frac{3|V(T'_{j'})|}{2} - 2 \right) + \sum_{k=1}^{\gamma} (|V(T^{(k)})| - 1) + \sum_{l=1}^{\delta} (2|V(B_l)| - 3), \]

where \(|V(F_i)|, |V(T_j)|, |V(T'_{j'})|, |V(B_l)| \geq 6\) and \(|V(T^{(k)})| \geq 10\). Then we have

\[ 4 = 2n - m = 3a + 2b + \sum_{i=1}^{a} (|V(F_i)| - 2) + \sum_{j=1}^{\beta_1} \frac{|V(T_j)|}{2} + 3 + \sum_{j'=1}^{\beta_2} \left( \frac{|V(T'_{j'})|}{2} + 2 \right) + \sum_{k=1}^{\gamma} (|V(T^{(k)})| + 1) + 3\delta \]

which implies that \(\beta_1 = \beta_2 = \gamma = 0\), and \(\alpha \leq 1\). Plugging into the above equation we obtain \(4 = 2b + 3(a + \delta) + \alpha(|V(F)| - 2)\). The integer solution to this equation is either \(\alpha = 1\), \(|V(F)| = 6\), \(a = b = \delta = 0\) or \(b = 2\), \(a = \delta = \alpha = 0\).

The first case implies that is with six vertices and eight edges, a contradiction. For the latter case, is the union of two ’s and some ’s, implying that \(n = 8 + 5c\), contradicting the assumption that \(n \neq 1, 3 \pmod{5}\). □

By a similar argument we have the following lemma.

**Lemma 4.4.** If is an integer and divisible by (5), then there is no \((n, m)\) graph in \(\text{SAT}(n, P_9)\) with \(m = 2n - 2\) or \(m = 2n - 1\).

**Proof.** We prove this by contradiction. Suppose is such an \((n, m)\) graph in \(\text{SAT}(n, P_9)\) with \(2n - m \in \{1, 2\}\). Then \(h_1 \geq 2\). If \(h_1 = 2\), then \(2n - m = 3 + 2b + \sum_{i=1}^{a} (|V(F_i)| - 2) + 3\beta \geq 3\), a contradiction. Hence we may assume that \(h_1 \geq 3\). Arguing as we did in the previous lemma we have

\[ 2n - m = 3a + 2b + \sum_{i=1}^{a} (|V(F_i)| - 2) + \sum_{j=1}^{\beta_1} \frac{|V(T_j)|}{2} + 3 + \sum_{j'=1}^{\beta_2} \left( \frac{|V(T'_{j'})|}{2} + 2 \right) + \sum_{k=1}^{\gamma} (|V(T^{(k)})| + 1) + 3\delta. \]

The constraint \(2n - m \in \{1, 2\}\) implies that \(b = 1, a = \alpha = \beta_1 = \beta_2 = \gamma = \delta = 0\) and hence is the union of and some ’s. Therefore we have \(n = 4 + 5c\), contradicting the fact that \(5|n\). □

**Lemma 4.5.** Let be an integer that is at least \((15); then there is a \(P_9\)-saturated \((n, m)\) graph for all \(\lceil \frac{9n}{10} \rceil \leq m \leq n + 5\).

**Proof.** For those values of in \([n, n+5]\), we can construct \(P_9\)-saturated graphs as follows: \(T_{2,2,n-14}, K_2 \cup F_{n-6}, F_{n-4}, K_2 \cup K_4 \cup F_{n-10}, K_4 \cup F_{n-8}, B_4 \cup F_{n-10}\). Let \(n = 10k + i\), where \(i = 0, 1, \ldots, 9\). We can construct an \((n, m)\) graph in \(\text{SAT}(n, P_9)\) as follows: \(C_0 = (k - 1)T_{2,2,2} \cup T_{2,2,2,2+i}, \) and then \(m = |E(G)| = 9(k - 1) + 9i = 9k + i = \lceil \frac{9n}{10} \rceil\). Next we shall define an operation as follows: \(T_{a,b,c} + T_{x,y,z} \Rightarrow T_{x,y,z+a+b+c+4}\). Under this operation we build a new \(P_9\)-saturated graph \(T_{x,y,z+a+b+c+4}\) from a given \(P_9\)-saturated graph \(T_{a,b,c} \cup T_{x,y,z}\) with one more edge. Continuing this process starting from \(C_0\), we can end this process with \(T_{2,2,n-8}\), which has \(n - 1\) edges. Hence we find \(P_9\)-saturated graphs with \(m\) edges for \(\lceil \frac{9n}{10} \rceil \leq m \leq n - 1\). □
Combining Lemma 4.1 through 4.5 we shall get the next main theorem concerning the edge spectrum of \( P_6 \). But this time we jump five steps at each induction process stage.

**Theorem 4.1.** Let \( n \geq 10 \) be an integer. There is a \( P_6 \)-saturated \((n, m)\) graph with \((n, m) \neq (11, 14)\) if and only if \( m \) is in the following interval:

\[
\text{sat}(n, P_6) = [11, 21], \quad \text{ex}(n, P_6) = [12, 24]
\]

where the triangle “\( \triangle \)” means the existence of a \( P_6 \)-saturated \((n, m)\) graph only for \( n \geq 15 \), and a blue dot stands for a missing value.

**Proof.** The proof is by induction on \( n \) based on the following table, where \( A = \text{sat}(n, P_6) \) and \( B = \text{ex}(n, P_6) \). The initial results for \( 10 \leq n \leq 14 \) are listed in the table. One exception in this table is \( n = 11, m = 14 \). There is no such kinds of \( P_6 \)-saturated graphs, but for the next induction set we do have a \((16, 24)\)-graph \( 4K_4 \), which is a \( P_6 \)-saturated graph. For the base case of the induction process, it is easy to check the graph listed in the table, while for those not listed in the table we can count all possible combinations of basic structures of \( P_6 \)-saturated graphs for the corresponding \((n, m)\)-values.

By the induction hypothesis, suppose we have the result for \( n \leq 14 \). By adding a complete graph \( K_5 \), we may get some partial results for \( n + 5 \). For the missing values on the interval \([A, B]\), we shall refer to Lemma 4.3 up to Lemma 4.5. So far we have covered the interval \([\text{sat}(n, P_6) + 10, B]\) since \( \text{ex}(n, P_6) + 10 = B \). The remaining interval \([A, \text{sat}(n, P_6) + 9]\) will be covered by Lemma 4.6 since \( \text{sat}(n, P_6) + 9 \leq (n + 5) + 5 = n + 10 \) for any integer \( n \).

<table>
<thead>
<tr>
<th>( n )</th>
<th>([A, B])</th>
<th>( \text{SAT}(n, P_6) )</th>
<th>( n )</th>
<th>([A, B])</th>
<th>( \text{SAT}(n, P_6) )</th>
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<tbody>
<tr>
<td>10</td>
<td>[9, 20]</td>
<td></td>
<td>11</td>
<td>[10, 20]</td>
<td></td>
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<tr>
<td>11</td>
<td>[11, 21]</td>
<td>9: ( T_{2,2,2} ), ( K_2 \cup F_4 ), ( F_6 ), ( T_4 ), ( K_2 \cup B_6 ), ( K_4 \cup F_4 ), ( B_8 ), ( 2K_5 )</td>
<td>12</td>
<td>[12, 23]</td>
<td>10: ( T_{2,2,3} ), ( K_2 \cup F_5 ), ( B_9 ), ( 2K_5 \cup K_1 )</td>
</tr>
<tr>
<td>12</td>
<td>[11, 21]</td>
<td>11: ( T_{3,3,3} ), ( 4K_5 ), ( F_6 \cup K_2 ), ( F_8 ), ( K_2 \cup K_4 \cup K_2 ), ( K_4 \cup F_4 ), ( F_2 \cup B_4 ), ( K_3 \cup K_4 \cup K_5 ), ( 2K_5 \cup K_2 )</td>
<td>13</td>
<td>[12, 23]</td>
<td>12: ( T_{3,3,3} ), ( K_2 \cup F_7 ), ( 4K_5 ), ( F_9 ), ( K_4 \cup F_5 ), ( K_2 \cup B_9 ), ( K_4 \cup B_7 ), ( 2K_4 \cup K_5 ), ( K_3 \cup 2K_5 )</td>
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<tr>
<td>14</td>
<td>[13, 19]</td>
<td>13: ( 2K_4 ), ( K_2 \cup F_8 ), ( F_{10} ), ( T_5 ), ( K_3 \cup T_5 ), ( T_6 )</td>
<td>14</td>
<td>[20, 26]</td>
<td>14: ( 2K_4 ), ( K_2 \cup F_5 ), ( F_{10} ), ( T_5 ), ( 2K_4 \cup K_4 ), ( B_{12} ), ( 2K_5 \cup K_4 )</td>
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References