On Tensor Product of Graphs, Girth and Triangles

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Abstract. The purpose of this paper is to obtain a necessary and sufficient condition for the tensor product of two or more graphs to be connected, bipartite or eulerian. Also, we present a characterization of the duplicate graph $G \oplus K_2$ to be unicyclic. Finally, the girth and the formula for computing the number of triangles in the tensor product of graphs are worked out.

Keywords: Tensor product, Bipartite graph, Connected graph, Eulerian graph, Girth, Cycle, Path.


1. Introduction

We shall consider only finite, undirected graphs without loops or multiple edges. We follow the terminology of [1]. For a graph $G$, $V(G)$ and $E(G)$ denote the vertex set and edge set of $G$, respectively. For a connected graph $G$, $nG$ is the graph with $n$ components, each being isomorphic to $G$. It is well-known that a graph is bipartite if and only if it contains no odd cycle. We now define the tensor product of two graphs [8] as follows: The tensor product of two graphs $G_1$ and $G_2$ is the graph, denoted by $G_1 \oplus G_2$, with vertex set $V(G_1 \oplus G_2) = V(G_1) \times V(G_2)$, and any two of its vertices $(u_1, v_1)$ and $(u_2, v_2)$ are adjacent, whenever $u_1$ is adjacent to $u_2$ in $G_1$ and $v_1$ is adjacent to $v_2$ in $G_2$.

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Received 03 June 2014; Accepted 06 December 2014
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The graphs $G_1$ and $G_2$ are called factors of the product $G_1 \oplus G_2$. Other popular names for tensor product that have appeared in the literature are Kronecker product, cross product, direct product, conjunction product. Sampathkumar [6] defines the tensor product of a graph $G$ by $K_2$ as the duplicate graph of $G$, and studied its properties and a characterization in great detail. This product is also studied in [5]. Now, we define the two special type of tensor products: $G \oplus nK_2$ and $G \oplus \bigoplus_{i=1}^{n} K_2$ as the generalized duplicate graphs of a graph $G$, for any integer $n \geq 2$, and study their structural properties for our later use.

2. STRUCTURAL PROPERTIES OF THE GENERALIZED DUPLICATE GRAPHS

The following theorem of Weichsel [8] will be useful in the proof of our results.

**Theorem 2.1.** If the connected graphs $G$ and $H$ are bipartite, then $G \oplus H$ has exactly two components.

Next, we present some elementary results of the generalized duplicate graphs for our immediate use.

**Theorem 2.2.** For any connected, bipartite graph $G$, $G \oplus nK_2 = 2nG$ for $n \geq 1$.

**Proof.** For $n = 1$, Theorem 2.1 implies that $G \oplus K_2$ has exactly two components. Furthermore, by using the definition of tensor product, we see that each component of $G \oplus K_2$ is isomorphic to $G$. Therefore, $G \oplus K_2 = 2G$. Moreover, corresponding to $n \geq 1$ copies of $K_2$, $G \oplus nK_2$ certainly contains exactly $2n$ copies of $G$. Thus, $G \oplus nK_2 = 2nG$. □

**Theorem 2.3.** For any connected graph $G$, $G \oplus nK_2$ for $n \geq 1$, is bipartite.

**Proof.** We discuss two cases depending on $G$.

**Case 1.** Suppose $G$ is bipartite. By Theorem 2.2, $G \oplus nK_2 = 2nG$. Since $G$ is bipartite, it follows immediately that $G \oplus nK_2$ is bipartite.

**Case 2.** Suppose $G$ is non-bipartite. Certainly, $G$ contains a cycle $C_m$ for odd $m \geq 3$. Corresponding to each copy of $K_2$ in $G \oplus nK_2$, there are exactly $n$ distinct subgraphs in $G \oplus nK_2$, each isomorphic to $C_m \oplus K_2$. It is shown in [2] that $C_m \oplus K_2$ is isomorphic to $C_{2m}$. For even $m \geq 4$, it is also shown in [2] that $C_m \oplus K_2 = C_m \cup C_m$. This proves that $G \oplus nK_2$ has no odd cycles. Hence, $G \oplus nK_2$ is bipartite. □

**Theorem 2.4.** Let $G$ be a connected, bipartite graph and let $H = \oplus_{i=1}^{n} K_2$. Then $G \oplus H = 2^nG$ for $n \geq 1$.

**Proof.** We proceed by induction on $n$. If $n = 1$, then by Theorem 2.2, $G \oplus H = 2G$. Assume the result holds with at most $n-1$. Consider $G \oplus H = G \oplus \bigoplus_{i=1}^{n} K_2$.
= G ⊕ [⊕_{i=1}^{n-1} K_2 ⊕ K_2] = [G ⊕ (⊕_{i=1}^{n-1} K_2)] ⊕ K_2. By induction hypothesis, we have G ⊕ [⊕_{i=1}^{n-1} K_2] = 2^{n-1}G. Hence,

\[ G ⊕ [⊕_{i=1}^{n} K_2] = 2^{n-1}G ⊕ K_2. \quad (2.1) \]

In view of Theorem 2.2 (with n = 1), G ⊕ K_2 = 2G. Using this in (2.1), we get G ⊕ H = 2^nG.

\[ \square \]

3. Characterization of Connected Tensor Product of Graphs

Now, we obtain a characterization of connected tensor product of arbitrarily many graphs. We see that Weichsel [6] studied the connectedness of the tensor product of two graphs as follows:

**Theorem 3.1.** Let G and H be connected graphs. Then G ⊕ H is connected if and only if either G or H contains an odd cycle.

Now, we present the natural finite extension of Weichsel's Theorem as follows:

**Theorem 3.2.** Let G_k (1 ≤ k ≤ n ; n ≥ 2) be connected graph, and let G = ⊕_{k=1}^{n} G_k. Then G is connected if and only if at most one of G_k’s is bipartite.

**Proof.** Assume that G is connected. We prove by contradiction. If possible, assume that there are at least two distinct graphs G_i and G_j (1 ≤ i, j ≤ n), which are bipartite. By Theorem 2.1, G_i ⊕ G_j contains exactly two components say, F and H. Now, we have G = ⊕_{k=1}^{n} G_k = (F ⊕ M) ∪ (H ⊕ M) , where M = ⊕_{k=1}^{n} G_k (k ≠ i, j). This shows that G is certainly disconnected, and hence we immediately arrive at a contradiction. Thus, it proves that at most one of G_k’s is bipartite.

Conversely, assume that at most one of G_k’s is bipartite. We discuss two cases.

**Case 1.** None of G_k’s is bipartite. Immediately, it follows that each G_k contains an odd cycle.

**Case 2.** Exactly one of G_k’s is bipartite. Without loss of generality, we assume that G_1 is bipartite. The remaining G_i (2 ≤ i ≤ n) is non-bipartite, and hence each such G_i contains an odd cycle.

In either case, by applying Theorem 3.1 and the mathematical induction on the number of factors, the result follows. \[ \square \]

4. Characterization of Bipartite Tensor Product of Graphs

Now, we shall obtain a necessary and sufficient condition for the tensor product of two or more graphs to be bipartite, (which is proposed in [3]).

**Theorem 4.1.** Let G_1 and G_2 be two connected graphs. Then G_1 ⊕ G_2 is bipartite if and only if at least one of G_1 and G_2 is bipartite.
Proof. Suppose $G_1 \oplus G_2$ is bipartite. We claim that at least one of $G_1$ and $G_2$ is bipartite. If this is not so, then both $G_1$ and $G_2$ are non-bipartite. Consequently, there exist two odd cycles $C_m$ (for $m \geq 3$) and $C_n$ (for $n \geq 3$) in $G_1$ and $G_2$, respectively. Without loss of generality, we consider $m \leq n$. Let $C_m : u_1, u_2, \ldots, u_m, u_1$ and let $C_n : v_1, v_2, \ldots, v_m, v_{m+1}, \ldots, v_n, v_1$. Then $C_m \oplus C_n$ contains the cycle $Z$ of length $n$ as follows: $Z : (u_1, v_1), (u_2, v_2), \ldots, (u_m, v_m), (u_{m-1}, v_{m+1}), (u_m, v_{m+2}), (u_{m-1}, v_{m+3}), (u_m, v_{m+4}), \ldots, (u_{m-1}, v_{n-1}), (u_m, v_n), (u_1, v_1)$. So, $G_1 \oplus G_2$ contains the odd cycle $Z$. Hence, $G_1 \oplus G_2$ is non-bipartite. This is a contradiction.

Conversely, assume that at least one of $G_1$ and $G_2$ is bipartite.

We discuss two cases.

Case 1. Suppose both $G_1$ and $G_2$ are bipartite. Then by Theorem 2.1, $G_1 \oplus G_2$ contains exactly two components, say $H_1$ and $H_2$. Now, we claim that both $H_1$ and $H_2$ are bipartite. On contrary, if one of $H_i$’s is non-bipartite. Without loss of generality, we assume that $H_1$ is non-bipartite. Then $H_1$ contains an odd cycle, say $C : (u_1, v_1), (u_2, v_2), \ldots, (u_n, v_n), (u_1, v_1)$ in $G_1 \oplus G_2$, where $u_i \in V(G_1) \ (1 \leq i \leq n)$, $v_j \in V(G_2) \ (1 \leq j \leq n)$. Certainly, the first co-ordinate vertices $u_1, u_2, \ldots, u_n, u_1$ of the cycle $C$ forms a closed odd walk $W$ in $G_1$. Since every closed odd walk in a graph contains an odd cycle, it follows that the walk $W$ contains an odd cycle in $G_1$. This shows that $G_1$ is not bipartite. But this contradicts the hypothesis that $G_1$ is bipartite. Since each $H_i$ is bipartite, it follows that $G_1 \oplus G_2 = H_1 \cup H_2$ is also bipartite.

Case 2. Suppose one of $G_1$ and $G_2$ is bipartite, and the other is non-bipartite. Assume that $G_1$ is bipartite. Since $G_2$ is non-bipartite, $G_2$ contains an odd cycle. From Theorem 3.1, $G_1 \oplus G_2$ is connected. Next, we claim that $G_1 \oplus G_2$ is bipartite. If this is not so, then $G_1 \oplus G_2$ is non-bipartite, and hence it contains an odd cycle $Z$. By repeating the same argument as in Case 1, we obtain $G_1 \oplus G_2$ is bipartite.

In either case, we see that $G_1 \oplus G_2$ is bipartite.

Next, we obtain the finite extension of the above theorem, and its proof follows by the mathematical induction on the number of factors.

Corollary 4.2. Let $G_k \ (1 \leq k \leq n : n \geq 2)$ be a connected graph, and let $G = \oplus_{k=1}^{n} G_k$. Then $G$ is bipartite if and only if at least one of $G_k$’s is bipartite.

5. Characterization of Eulerian Tensor Product of Graphs

An Euler tour of a graph $G$ is a closed walk in $G$ that traverses each edge of $G$ exactly once. A graph is eulerian if it contains an Euler tour. It is well-known that a connected graph $G$ is eulerian if and only if every vertex in $G$ has an even degree. For any vertex $(u, v)$ in a tensor product $(G \oplus H)$ of two graphs
$G$ and $H$, $\text{deg}(u, v) = \text{deg}(u) \cdot \text{deg}(v)$. Now, we present a characterization of eulerian tensor product of two graphs.

**Theorem 5.1.** Let $G$ and $H$ be connected graphs such that at most one of them is bipartite. Then $G \oplus H$ is eulerian if and only if at least one of $G$ and $H$ is eulerian.

**Proof.** Suppose $G$ is eulerian, and it contains an odd cycle. Then by Theorem 4.1, $G \oplus H$ is connected. Since $G$ is eulerian, $\text{deg}(u)$ is even for all vertices $u$ in $G$. Consequently, for any vertex $v$ of $H$, the pair $(u, v)$ is a vertex in $G \oplus H$, and $\text{deg}(u, v) = \text{deg}(u) \cdot \text{deg}(v)$, which is an even degree, because $\text{deg}(u)$ is even, and $\text{deg}(v) \geq 1$. This implies that $G \oplus H$ is eulerian.

Conversely, assume that $G \oplus H$ is eulerian. By definition, $G \oplus H$ is certainly connected. Again by Theorem 4.1, one of $G$ and $H$ contains an odd cycle. To complete the proof, we claim that at least one of $G$ and $H$ is eulerian.

The finite extension of Theorem 5.1 is the following result, and its proof directly follows by the induction on the number of factors.

**Corollary 5.2.** Let $G_k$ $(1 \leq k \leq n; n \geq 2)$ be a connected graph such that at most one of $G_k$’s is bipartite, and let $G = \oplus_{k=1}^{n} G_k$. Then $G$ is eulerian if and only if at least one of $G_k$’s is eulerian.

6. **Characterization of Unicyclic Duplicate Graph**

A **unicyclic graph** is a connected graph which contains exactly one cycle. Next, we obtain a characterization of unicyclic duplicate graph $G \oplus K_2$.

**Theorem 6.1.** A non-bipartite graph $G$ is unicyclic if and only if the duplicate graph $G \oplus K_2$ is unicyclic.

**Proof.** Suppose a non-bipartite graph $G$ is unicyclic. Then $G$ contains exactly one odd cycle $C$. Hence by Theorem 4.1, $G \oplus K_2$ is connected. Let $C : u_1, u_2, \ldots, u_{2k+1}, u_1$ for $k \geq 1$. Next, we show that $G \oplus K_2$ is unicyclic. For this, let us consider $V(K_2) = \{v_1, v_2\}$. It is easy to see that the subgraph induced by $C \oplus K_2$ in $G \oplus K_2$ is certainly isomorphic to an even cycle $C_{2(2k+1)}$, where $C_{2(2k+1)} : (u_1, v_1), (u_2, v_2), (u_3, v_1), \ldots, (u_{2k-1}, v_1), (u_{2k}, v_2), (u_{2k+1}, v_1), (u_{2k}, v_2), (u_{2k+1}, v_1), (u_1, v_2), (u_{2k+1}, v_1), (u_2, v_1), (u_{2k}, v_2), \ldots, (u_{2k-1}, v_2), (u_{2k}, v_1)$, $(u_{2k+1}, v_2), (u_1, v_1)$. Since $G$ is unicyclic, it follows that $G \oplus K_2$ has no cycles other than $C_{2(2k+1)}$. If this is not so, then there exists another cycle $J$ in $G \oplus K_2$, which is different from $C_{2(2k+1)}$. Consequently, the first co-ordinates...
of the vertices of the cycle $J$, which are in pairs, will form another cycle $C'$ in $G$. Since $J \neq C_{2(2k+1)}$ in $G \oplus K_2$, it follows $C \neq C'$ in $G$. This is a contradiction to the fact that $G$ is unicyclic. Therefore, $G \oplus K_2$ is unicyclic.

Conversely, suppose that $G \oplus K_2$ is unicyclic. Let $Z$ be the only one cycle in $G \oplus K_2$. By Theorem 2.3 (with $n = 1$), $G \oplus K_2$ is bipartite. Hence, $Z$ is a unique even cycle. Clearly, we notice that the first co-ordinate vertices of $G$ in $Z$ forms an odd cycle $C$ in $G$. Since $G \oplus K_2$ is unicyclic, it follows that $C$ is the unique cycle in $G$. Moreover, since $G \oplus K_2$ is connected, it implies that $G$ is connected. Therefore, $G$ is unicyclic. □

7. The Girth and Triangles in Tensor Product Graphs

The girth of a graph $G$, denoted by $g(G)$, is the length of a shortest cycle in $G$, if any. Otherwise, it is undefined if $G$ is a forest. It is clear that the girth of a graph $G$ is the minimum of the girths of its components. Firstly, we determine the girth of the generalized duplicate graphs.

**Theorem 7.1.** Let $G$ be a connected graph with $g(G) = k$. For any positive integer $n \geq 1$, we have

$$g(G \oplus n K_2) = g(G \oplus [ \oplus_{i=1}^{n} K_2]) = \begin{cases} k & \text{if } G \text{ is bipartite}, \\ \min\{2p, q\} & \text{otherwise}, \end{cases}$$

where $C_p$ and $C_q$ are the minimal odd and even cycles in a non-bipartite graph $G$, respectively.

**Proof.** First, we discuss the result when $n = 1$.

**Case 1.** Assume $G$ is bipartite. From Theorem 2.2 (with $n = 1$), we have for the duplicate graph $G \oplus K_2 = 2G$. Consequently, $g(G \oplus K_2) = k$.

**Case 2.** Suppose $G$ is not bipartite. Then $G$ contains an odd cycle. Let $C_p$ for $p \geq 3$, be a minimal odd cycle in $G$.

Now, there are two possibilities to discuss:

**2.1.** If $G$ is free-from even cycles, then $C_p \oplus K_2$ contains an even cycle $C_{2p}$ in $G \oplus K_2$.

**2.2.** If $G$ contains a minimal even cycle $C_q$, $q \geq 4$, then $C_q \oplus K_2 = 2C_q$ appears in $G \oplus K_2$.

From the above possibilities, it follows that $g(G \oplus K_2)$ is the minimum of $2p$ and $q$. Thus, $g(G \oplus K_2) = \min\{2p, q\}$.

Finally, consider the result when $n \geq 2$. The result follows immediately if we proceed as above by applying Theorem 2.2 or 2.4 repeatedly. □

Next, we derive a formula (which is proposed in [4]) for computing the number of triangles in the tensor product of two graphs. For this, firstly we establish the following lemma.
Lemma 7.2. Let $G_k$ $(1 \leq k \leq n ; n \geq 2)$ be a connected graph. Then the product $\oplus_{k=1}^n G_k$ contains a triangle if and only if each $G_k$ contains a triangle.

Proof. Now, we discuss the case when $n = 2$. Suppose $G_1 \oplus G_2$ contains a triangle $T$, and let $(a_1, b_1), (a_2, b_2)$ and $(a_3, b_3)$ be any three vertices of $T$. By definition, $(a_1, b_1)(a_2, b_2), (a_2, b_2)(a_3, b_3)$ and $(a_3, b_3)(a_1, b_1)$ are the edges of $T$ in $G_1 \oplus G_2$ if and only if the edges: $a_1a_2, a_2a_3$ and $a_3a_1$ constitute a triangle $T_1$ in $G_1$ and also the edges: $b_1b_2, b_2b_3$ and $b_3b_1$ constitute a triangle $T_2$ in $G_2$. But this is so if and only if both $G_1$ and $G_2$ have triangles $T_1$ and $T_2$, respectively. Finally, we discuss the case when $n \geq 3$. The result follows immediately if we proceed by applying induction on the number of factors. \hfill $\square$

Theorem 7.3. Let $G_i$ $(1 \leq i \leq 2)$ be a connected graph having the number of triangles $n_i$. Then the product $G_1 \oplus G_2$ contains $6n_1n_2$ triangles.

Proof. First, let us compute the actual number of triangles in the product $T_1 \oplus T_2$, when $T_i$ is any triangle in $G_i$ (for $i = 1, 2$). It is easy to see that there are exactly 6 distinct triangles in $T_1 \oplus T_2$. But each $G_i$ contains $n_i$ triangles. Consequently, the product $G_1 \oplus G_2$ contains $6n_1n_2$ triangles, and there are no more other triangles because of Lemma 7.2. \hfill $\square$

The immediate consequence of the above theorem is the following corollary.

Corollary 7.4. Let $G_k$ $(1 \leq k \leq n ; n \geq 2)$ be a connected graph having the number of triangles $n_k$. Then the product $\oplus_{k=1}^n G_k$ contains $6^{n-1}(\Pi_{k=1}^n n_k)$ triangles.

Corollary 7.5. The number of triangles in $K_m \oplus K_n$ is $\frac{1}{6} \cdot mn(m-1)(n-1)(m-2)(n-2)$.

Proof. We know that the number of triangles in $K_p = pC_3$. Therefore from Theorem 7.3, the number of triangles in $K_m \oplus K_n$ is $6(mC_3)(nC_3) = \frac{1}{6} \cdot mn(m-1)(n-1)(m-2)(n-2)$. \hfill $\square$

Finally to determine the girth of the tensor product of graphs, we need to establish the following lemma.

Lemma 7.6. Let $G_k$ $(1 \leq k \leq n ; n \geq 2)$ be a connected, triangle-free graph such that each $G_k$ contains an induced subgraph isomorphic to $P_3$. Then $g(\oplus_{k=1}^n G_k) = 4$.

Proof. We discuss the case when $n = 2$. Let $a_i$ $(1 \leq i \leq 3)$ and $b_i$ $(1 \leq i \leq 3)$ be the vertices of a subgraph isomorphic to $P_3$ in $G_1$ and $G_2$, respectively. Then the subgraph $\{a_1, a_2, a_3\} \oplus \{b_1, b_2, b_3\}$ is isomorphic to $P_3 \oplus P_3$ in $G_1 \oplus G_2$. It is easy to see that $P_3 \oplus P_3 = K_{1,4} \cup C_4$. Immediately, a 4-cycle $C_4$ appears as a subgraph in $G_1 \oplus G_2$. However from Lemma 7.2, there is no triangle in $G_1 \oplus G_2$. Consequently, $C_4$ is the smallest cycle in $G_1 \oplus G_2$. 

[DOI: 10.7508/ijmsi.2015.01.011]
Therefore, \( g(G_1 \oplus G_2) = 4 \).

When \( n \geq 3 \), the result follows easily if we proceed by induction on the number of factors. \( \square \)

The following result gives the girth of tensor product of arbitrarily many graphs.

**Theorem 7.7.** Let \( G_k \) (\( 1 \leq k \leq n; \ n \geq 2 \)) be a connected graph of order \( \geq 3 \). Then \( g(\bigoplus_{k=1}^{n} G_k) \) is either 3 or 4.

**Proof.** We discuss three cases when \( n = 2 \).

**Case 1.** Suppose both \( G_1 \) and \( G_2 \) have triangles. By Lemma 7.2, \( G_1 \oplus G_2 \) contains a triangle. Hence, \( g(G_1 \oplus G_2) = 3 \).

**Case 2.** Suppose one of \( G_1 \) and \( G_2 \) is triangle-free. Without loss of generality, we assume that \( G_1 \) contains a triangle, and \( G_2 \) has an induced subgraph isomorphic to \( P_3 \). It is easy to check that \( K_3 \oplus P_3 \) contains a 4-cycle \( C_4 \). Consequently, this \( C_4 \) appears in \((G_1 \oplus G_2)\). However again by Lemma 7.2, \( G_1 \oplus G_2 \) is triangle-free. This implies that \( C_4 \) is the smallest cycle in \( G_1 \oplus G_2 \). Therefore, \( g(G_1 \oplus G_2) = 4 \).

**Case 3.** Suppose \( G_1 \) and \( G_2 \) are triangle-free. Then each \( G_1 \) and \( G_2 \) contains an induced subgraph isomorphic to \( P_3 \). From Lemma 7.6, \( g(G_1 \oplus G_2) = 4 \).

From the above cases, it follows that \( g(G_1 \oplus G_2) = 3 \) or 4.

When \( n \geq 3 \), it is not difficult to prove the result if we proceed by induction on the number of factors. \( \square \)

**Acknowledgments**

The authors are indebted to the referee for useful suggestions and comments. The first author research supported by SAP-UGC/ FIST-DST and the second author research was supported by UGC-BSR Research Fellowship, New Delhi, Government of India, India.

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