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Direct Product Primality Testing of Graphs is GI-hard

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Abstract

We investigate the computational complexity of the graph primality testing problem with respect to the direct product (also known as Kronecker, cardinal or tensor product). In [1] Imrich proves that both primality testing and a unique prime factorization can be determined in polynomial time for (finite) connected and nonbipartite graphs. The author states as an open problem how results on the direct product of nonbipartite, connected graphs extend to bipartite connected graphs and to disconnected ones. In this paper we partially answer this question by proving that the graph isomorphism problem is polynomial-time many-one reducible to the graph compositeness testing problem (the complement of the graph primality testing problem). As a consequence of this result, we prove that the graph isomorphism problem is polynomial-time Turing reducible to the primality testing problem. Our results show that connectedness plays a crucial role in determining the computational complexity of the graph primality testing problem.

Keywords: Kronecker product, graphs factorization, graphs isomorphism, GI complexity

1. Introduction

Factorization is a fundamental task in mathematics and in many other disciplines including computer science, physics and engineering. The notion of product among mathematical objects not only enables the creation of new objects from smaller ones, but also naturally addresses the more complex task of decomposing an object as the product of simpler components. Factoring a mathematical object is therefore one of the the main methods for understanding its structure.

Integer factorization is by far the most widely known and studied factorization problem; however, many other types of mathematical objects have been extensively studied in order to understand if and how they can be factored. Specifically, graph factorization with respect to several notions of product has been thoroughly investigated both from the theoretical and from the practical point of view.

In this paper we investigate the computational complexity of graph factorization with respect to the direct product (see Definition 2.2) which is one of the most widely studied graph product. Some authors refer to the direct product as the Kronecker, tensor or cardinal product. We will name it direct product and we will denote it by the operator \times according to the notation used in the recent book by Hammack, Imrich and Klavžar [2].

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Direct product is one of the three products (the other two being the Cartesian and Strong products) that satisfies the following fundamental algebraic properties (\simeq stands for "isomorphic to"):

1. Commutativity: $G_1 \times G_2 \simeq G_2 \times G_1$
2. Associativity: $G_1 \times (G_2 \times G_3) \simeq (G_1 \times G_2) \times G_3$
3. Projections from a product to its factors are weak homomorphisms

A fourth product have been considered in the literature, namely the lexicographic product. Lexicographic product does not satisfy properties 1 and 3.

We both consider the primality testing problem and the factorization problem. Informally, primality testing is a decision problem that, given a graph G , answers the question: "is G the product of smaller, nontrivial graphs?". Graph factorization aims at decomposing G into the product of smaller nontrivial graphs (more formal definitions will be given in the next section). Although factorization of general with respect to the direct product is not unique, Imrich [1] proved that if a graph is connected and nonbipartite, then its factorization with respect to the direct product is unique and can be computed in polynomial time. In this paper we address the following question posed by Imrich at the end of his paper.

How do results on the cardinal product of nonbipartite, connected graphs extend to bipartite connected graphs and to disconnected ones ?

We prove (Theorem 4.12) that the graph isomorphism problem reduces to the problem of testing the compositeness of possibly unconnected, nonbipartite graphs. Since the reduction we use is a polynomial time many-one reduction, we show (Corollary 4.13) that testing the primality of a graph is GI -hard. In other words, we prove that testing the primality of a graph in polynomial time would provide a polynomial time algorithm for testing graph isomorphism, which is widely considered to be not feasible, although no formal proof exists. It remains an open question whether testing primality of bipartite, connected graphs can be done in polynomial time

This paper is organized as follows. In section 2 we introduce the notation and definition of terms used in the rest of this work. In section 3 we review the relevant literature related to the graph factorization problem. Section 4 presents the main result of this paper. Finally, conclusions and future research directions are discussed in section 5.

2. Notation and Basic Definitions

In this section we give basic notation and definitions that will be used throughout the paper. An undirected graph $G = (V, E)$ is described as a finite set V of nodes $V = \{v_1, \dots, v_n\}$ and a finite set of edges $E \subseteq \{\{u, v\} \mid u, v \in V\}$, where an edge $e \in E$ is a multiset $e = \{u, v\}$, $u, v \in V$; an edge of the form $\{v, v\}$ denotes a *self-loop*. Given a graph G , $V(G)$ and $E(G)$ denote the set of nodes and edges of G , respectively. We denote by $G_1 \cup G_2$ the disjoint union of graphs G_1 and G_2 , i.e., the graph with node set $V(G_1) \cup V(G_2)$ and edge set $E(G_1) \cup E(G_2)$. Disjoint means that $V(G_1)$ and $V(G_2)$ satisfy $V(G_1) \cap V(G_2) = \emptyset$.

The set of edges of a graph G can be represented also as an adjacency matrix \mathbf{M} . If G has n nodes, \mathbf{M} is a $n \times n$ binary matrix, such that $\mathbf{M}_{ij} = 1$ if and only if $\{v_i, v_j\} \in E$. The adjacency matrix for undirected graphs is symmetric, since every edge $\{v_i, v_j\}$ can also be written as $\{v_j, v_i\}$. As a shorthand notation, we denote with $\mathbf{Adj}(G)$ the adjacency matrix of graph G .

We use the symbol Γ to denote the set of finite, undirected graphs where no self-loops are allowed. The symbol Γ_0 denotes the set of finite, undirected graphs where self-loops are allowed.

An undirected graph G is *connected* iff there exists a path connecting any two nodes $u, v \in V(G)$. G is *bipartite* iff the set of nodes $V(G)$ can be partitioned into two disjoint subsets V_1, V_2 such that each edge $e \in E(G)$ has one endpoint in V_1 and the other in V_2 . We will denote with C, B the set of connected and bipartite graphs, respectively.

Four types of graph products have been investigated in the literature: *Cartesian product*, *Direct product*, *Strong product* and *Lexicographic product*. In all cases, the product of two graphs G_1, G_2 is a new graph G whose set of nodes is the Cartesian product of $V(G_1)$ and $V(G_2)$:

$$V(G) = V(G_1) \times V(G_2) = \{\{u, v\} \mid u \in V(G_1) \wedge v \in V(G_2)\}$$

The edge set $E(G)$ is defined according to the notion of graph product as follows.

Definition 2.1 (Cartesian product). *The Cartesian product of two graphs G_1, G_2 is denoted as $G = G_1 \square G_2$, where $V(G) = V(G_1) \times V(G_2)$ and*

$$E(G) = \{\{\{x, y\}, \{x', y'\}\} \mid (x = x' \wedge \{y, y'\} \in E(G_2)) \vee (\{x, x'\} \in E(G_1) \wedge y = y')\}$$

Definition 2.2 (Direct product). *The direct product of two graphs G_1, G_2 is denoted as $G = G_1 \times G_2$, where $V(G) = V(G_1) \times V(G_2)$ and*

$$E(G) = \{\{\{x, y\}, \{x', y'\}\} \mid \{x, x'\} \in E(G_1) \wedge \{y, y'\} \in E(G_2)\}$$

The direct product is also known as Kronecker or cardinal product.

Definition 2.3 (Strong product). *The strong product of two graphs G_1, G_2 is denoted as $G = G_1 \boxtimes G_2$, where $V(G) = V(G_1) \times V(G_2)$ and*

$$E(G) = E(G_1 \square G_2) \cup E(G_1 \times G_2)$$

Definition 2.4 (Lexicographic product). *The lexicographic product of two graphs G_1, G_2 is denoted as $G = G_1 \circ G_2$, where $V(G) = V(G_1) \times V(G_2)$ and*

$$E(G) = \{\{\{x, y\}, \{x', y'\}\} \mid \{x, x'\} \in E(G_1) \vee (x = x' \wedge \{y, y'\} \in E(G_2))\}$$

Figure 1 shows the Cartesian, direct, strong and lexicographic product of two graphs G_1, G_2 .

A nontrivial graph $G \in \Gamma_0$ is a graph with more than one node ($|V(G)| > 1$). We say that a graph G is *prime* according to a given graph product \odot if G is nontrivial and $G = G_1 \odot G_2$ implies that either G_1 or G_2 are trivial, i.e., one of them has exactly one node.

It has been shown [3, 2] that the adjacency matrix $\mathbf{Adj}(G_1 \times G_2)$ of the direct product of G_1 and G_2 can be specified in terms of the *Kronecker product* of $\mathbf{Adj}(G_1)$ and $\mathbf{Adj}(G_2)$ (see Lemma 4.6). Given a $n \times m$ matrix \mathbf{A} and a $p \times q$ matrix \mathbf{B} , the Kronecker product $\mathbf{C} = \mathbf{A} \otimes \mathbf{B}$ is a $np \times mq$ matrix obtained from the scalar multiplication between each element of \mathbf{A} and the whole matrix \mathbf{B} :

$$\mathbf{C} = \mathbf{A} \otimes \mathbf{B} = \begin{pmatrix} a_{11}\mathbf{B} & a_{12}\mathbf{B} & \dots & a_{1m}\mathbf{B} \\ a_{21}\mathbf{B} & a_{22}\mathbf{B} & \dots & a_{2m}\mathbf{B} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1}\mathbf{B} & a_{n2}\mathbf{B} & \dots & a_{nm}\mathbf{B} \end{pmatrix} \quad (1)$$

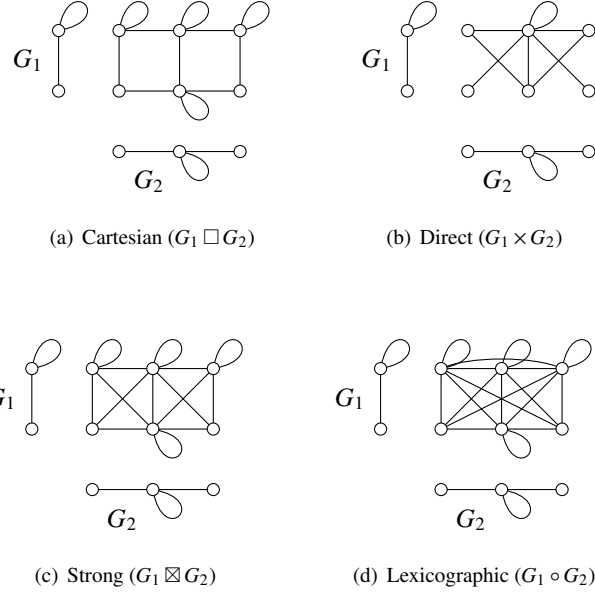


Figure 1: Example of the different types of graph products.

We finally recall the definition of *many-one reducibility* and *Turing reducibility*. Given two sets $S_1, S_2 \subseteq \mathbb{N}$, we say that S_1 is many-one reducible to S_2 , if there exists a total computable function $f : \mathbb{N} \rightarrow \mathbb{N}$ such that [4]

$$n \in S_1 \iff f(n) \in S_2$$

A polynomial time many-one reduction (denoted by \leq_M) is a many-one reduction with the additional constraint that f is computable in polynomial time.

Turing reducibility is a weaker form of many-one reducibility. Informally, S_1 is Turing reducible to S_2 if there exists an oracle for testing membership in S_1 relying on another oracle for testing membership in S_2 [5]. In other words, S_1 is Turing reducible to S_2 if it is possible to answer the question “is $n \in S_1$ ” given the existence of an effective procedure for answering the question “is $m \in S_2$ ” for any $m \in \mathbb{N}$ [4].

S_1 is polynomial-time Turing reducible to S_2 (denoted by $S_1 \leq_T S_2$) if S_1 is Turing reducible to S_2 , with the following two additional constraints:

1. the oracle for testing membership in S_1 makes at most a polynomial number of calls to the oracle for testing membership in S_2 and
2. the overall computational cost of the oracle for testing membership in S_1 (excluding the calls to the oracle for testing membership in S_2) is polynomially bounded.

As a final consideration, throughout the paper we intend graphs to be *finite* and *undirected*, unless otherwise specified. Table 1 summarizes the notation used in this paper.

Symbol	Description
Γ	The set of finite, undirected graphs, without self-loops
Γ_0	The set of finite, undirected graphs, self-loops allowed
C, \bar{C}	The set of connected/unconnected, undirected graphs
B, \bar{B}	The set of bipartite/nonbipartite, undirected graphs
$\text{Adj}(G)$	The adjacency matrix of graph G
\mathbf{I}_n	The $n \times n$ identity matrix
$\mathbf{0}_n$	The $n \times n$ zero matrix
\times	The direct graph product operator
\square	The Cartesian graph product operator
\boxtimes	The strong graph product operator
\circ	The lexicographic graph product operator
\otimes	The Kronecker matrix product operator
\simeq	The graphs isomorphism operator
\leq_M	Polynomial many-one reducibility
\leq_T	Polynomial Turing reducibility
\cup	Disjoint union of graphs

Table 1: Summary of notation.

3. Related works

In this section we list the main results on graph factorization that are strictly related to the work presented in this paper. The interested reader may find a comprehensive review of the theory of graph factorization in the recent book by Hammack, Imrich and Klavžar [2].

Direct product. Prime factorization of connected, nonbipartite graphs in Γ_0 is unique up to isomorphism and the order of the factors, and can be computed in polynomial time [1].

Cartesian product. Prime factorization of connected graphs is unique up to isomorphism and the order of the factors [6, 7]. Prime factorization is not unique in the class of possibly disconnected simple graphs. Following Sabidussi’s approach, Feigenbaum et al. [8] derived a polynomial-time algorithm that computes the prime factors of a connected graph. A different polynomial-time algorithm for connected graphs has been independently discovered by Winkler [9].

Strong product. Prime factorization of connected graphs is unique up to reordering and isomorphism of factors and it can be computed in polynomial time [1].

Lexicographic product. Determining whether a connected graph is prime is at least as difficult as the graph isomorphism problem [10].

An interesting observation relating graph factorization and graph isomorphism problem can be found at the end of page of [2, p. 229]. The authors claim that, if X is the disjoint union of graphs G and H , then $G \simeq H$ if and only if $X = D_2 \square G = D_2 \boxtimes G = D_2 \circ G$ where D_2 denotes the graph with two nodes and two self-loops. They conclude that “testing whether a disconnected graph is decomposable with respect to any of these three products is at least as hard as the

Graph type	Product type			
	Direct	Cartesian	Strong	Lexicographic
Connected and nonbipartite	P [1]	P [8, 9]	P [11]	•
Connected	•	P [8, 9]	P [11]	GI-Hard [10]
Unconnected and nonbipartite	GI-Hard (our results)	•	•	•
Nonbipartite	GI-Hard (our results)	•	•	•

Table 2: Complexity of the graph factorization problem for different types of graphs considered in the literature (connected, unconnected, nonbipartite) and different notions of graph product (direct, Cartesian, strong and lexicographic product); **P** stands for polynomially time solvable. Table cells reported in light gray can be easily inferred from another cells in the same column depending on the relation between the corresponding classes of graphs. For instance, a polynomial-time solvable problem for connected graphs is polynomial-time solvable within a restricted class of graphs (e.g., connected and nonbipartite). Dots denote the cases that, to our knowledge, have not yet been explored.

graph isomorphism problem”. They do not give a formal proof of their claim and in particular they do not explain how they get rid of the case in which X is the disjoint union of two non isomorphic graphs G_1 and G_2 and, at the same time, X admits as a factor a graph with two nodes that is not isomorphic to D_2 . In that case the decomposability test would lead to erroneously declare $G_1 \simeq G_2$. Moreover, if X admits more than one factorization, also computing a single factorization could not be enough for testing isomorphism.

In Section 4 we show (see Figures 3 and 4) that when the direct product is used, both these cases may occur.

4. Main Results

In this section we prove that testing whether two graphs G_1, G_2 are isomorphic is not harder than testing whether an undirected graph $G \in \Gamma_0$ is \times -composite, i.e., G admits nontrivial factors with respect to the direct product decomposition. More formally, we show that graph isomorphism problem is polynomially many-one reducible to the problem of testing \times -compositeness of graphs.

Before starting, we formally define the following three decision problems in terms of their admissible inputs and related outputs.

Definition 4.1 (GI[S]). Let S be any set of graphs. **GI[S]** is defined as follows.

Input: $G_1, G_2 \in S$

Output: YES if G_1 is isomorphic to G_2 , NO otherwise.

Definition 4.2 (Primality[S]). Let S be any set of graphs. **Primality[S]** is defined as follows.

Input: $G \in S$

Output: YES if G is prime with respect to the direct product, NO otherwise.

Definition 4.3 (Compositeness[S]). Let S be any set of graphs. **Compositeness[S]** is defined as follows.

Input: $G \in S$

Output: YES if G is composite with respect to the direct product, NO otherwise.

Definition 4.4 (GI-hard problem). A decision problem \mathcal{P} is GI-hard if and only if

$$GI[\text{general graphs}] \leq_T \mathcal{P}$$

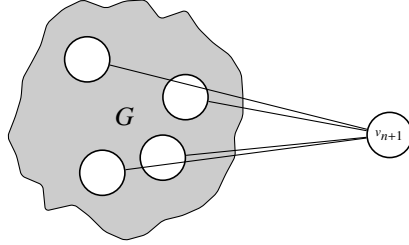


Figure 2: Construction of $\text{Ext}(G)$

We also prove the following

Lemma 4.5. *Graph isomorphism on general graphs is polynomial-time Turing-reducible to graph isomorphism on connected graphs:*

$$\mathbf{GI}[\text{general graphs}] \leq_{\mathbf{T}} \mathbf{GI}[C]$$

Proof. We show that, if we have an oracle that can decide whether two connected graphs $G_1, G_2 \in C$ are isomorphic, we can decide whether two general (i.e., not necessarily connected) graphs are isomorphic by calling the oracle a polynomial number of times, plus a polynomially bounded amount of additional work

Given a general, undirected graph G with n nodes, we define a new graph $\text{Ext}(G)$ as:

$$\begin{aligned} V(\text{Ext}(G)) &:= V(G) \cup v_{n+1} \\ E(\text{Ext}(G)) &:= E(G) \cup \{v_1, v_{n+1}\} \cup \dots \cup \{v_n, v_{n+1}\} \end{aligned}$$

where v_1, \dots, v_n are the nodes of G and v_{n+1} is a new node. Basically, $\text{Ext}(G)$ is obtained by extending G with a new node v_{n+1} that is connected to all other nodes (see Figure 2). $\text{Ext}(G)$ can be built in polynomial time and is connected by construction.

If two general graphs G_1 and G_2 are isomorphic, then it immediately follows that $\text{Ext}(G_1)$ and $\text{Ext}(G_2)$ are isomorphic as well.

Conversely, let us assume that $\text{Ext}(G_1)$ and $\text{Ext}(G_2)$ are isomorphic. This implies that G_1 and G_2 have the same number of nodes n , and both $\text{Ext}(G_1)$ and $\text{Ext}(G_2)$ have $(n + 1)$ nodes. By construction, $\text{Ext}(G_1)$ and $\text{Ext}(G_2)$ have exactly one node of degree n , namely, the new node(s) v_{n+1} . Therefore, every isomorphism between $\text{Ext}(G_1)$ and $\text{Ext}(G_2)$ must define a bijection that maps the new node of $\text{Ext}(G_1)$ to the new node of $\text{Ext}(G_2)$. The bijection can be restricted to $V(G_1)$ and $V(G_2)$ of the original graphs, implying that they are isomorphic as well. \square

From Definition 4.4 and Lemma 4.5 we get, by transitivity, that a decision problem P is \mathbf{GI} -hard if and only if

$$\mathbf{GI}[C] \leq_{\mathbf{T}} P$$

The following observation highlights the strong relation between the direct product of graphs and the Kronecker product of their adjacency matrices.

Lemma 4.6 ([3, 2]). *Let G_1 and G_2 be graphs. Then*

$$\mathbf{Adj}(G_1 \times G_2) = \mathbf{P}^\top (\mathbf{Adj}(G_1) \otimes \mathbf{Adj}(G_2)) \mathbf{P},$$

where \mathbf{P} is a suitable permutation matrix.

Proof. This lemma can be proved with the following observation [2]. Eq. 1 shows that the Kronecker product of two matrices \mathbf{A} and \mathbf{B} has a block structure so that the rows of $\mathbf{A} \otimes \mathbf{B}$ can be indexed by an ordered pair (i, j) that corresponds to the j -th row of \mathbf{B} in the i -th row block. If we let $V(G_1) = \{g_1, \dots, g_m\}$ and $V(G_2) = \{h_1, \dots, h_n\}$, then $G_1 \otimes G_2$ has adjacency matrix $\mathbf{Adj}(G_1) \otimes \mathbf{Adj}(G_2)$ with the node ordering $(g_1, h_1), \dots, (g_1, h_n), (g_2, h_1), \dots, (g_2, h_n), \dots, (g_m, h_1), \dots, (g_m, h_n)$. The use of a permutation matrix \mathbf{P} makes the result independent from the node ordering. \square

In the following lemma we prove that two graphs G_1 and G_2 are isomorphic if and only if there exists a permutation matrix \mathbf{P} that transforms the adjacency matrix of the disjoint union of G_1 and G_2 into the Kronecker product of the identity matrix \mathbf{I}_2 and a suitable binary matrix \mathbf{B} .

Lemma 4.7. *Let $G_1, G_2 \in \mathcal{C}$ be undirected, connected graphs with n nodes. Let $\mathbf{M}_1 = \mathbf{Adj}(G_1)$ and $\mathbf{M}_2 = \mathbf{Adj}(G_2)$. Let \mathbf{M} denote the adjacency matrix of the disjoint union $G = G_1 \cup G_2$. Without loss of generality, we may write \mathbf{M} as*

$$\mathbf{M} = \begin{pmatrix} \mathbf{M}_1 & \mathbf{0}_n \\ \mathbf{0}_n & \mathbf{M}_2 \end{pmatrix} \quad (2)$$

Then, G_1 and G_2 are isomorphic ($G_1 \simeq G_2$) if and only if there exists a $2n \times 2n$ permutation matrix \mathbf{P} and a $n \times n$ binary matrix \mathbf{B} such that

$$\mathbf{P}^\top \mathbf{M} \mathbf{P} = \mathbf{I}_2 \otimes \mathbf{B} \quad (3)$$

where \mathbf{I}_2 denotes the 2×2 identity matrix.

Proof. (\implies) We first prove that if G_1 and G_2 are isomorphic, then Eq. (3) holds. If $G_1 \simeq G_2$ then there exists a $n \times n$ permutation matrix \mathbf{Q} that transforms the adjacency matrix \mathbf{M}_2 of G_2 in the adjacency matrix \mathbf{M}_1 of G_1 :

$$\mathbf{M}_1 = \mathbf{Q}^\top \mathbf{M}_2 \mathbf{Q} \quad (4)$$

Let us define

$$\mathbf{P} = \begin{pmatrix} \mathbf{I}_n & \mathbf{0}_n \\ \mathbf{0}_n & \mathbf{Q} \end{pmatrix} \quad (5)$$

It follows that

$$\begin{aligned} \mathbf{P}^\top \mathbf{M} \mathbf{P} &= \begin{pmatrix} \mathbf{I}_n & \mathbf{0}_n \\ \mathbf{0}_n & \mathbf{Q}^\top \end{pmatrix} \begin{pmatrix} \mathbf{M}_1 & \mathbf{0}_n \\ \mathbf{0}_n & \mathbf{M}_2 \end{pmatrix} \begin{pmatrix} \mathbf{I}_n & \mathbf{0}_n \\ \mathbf{0}_n & \mathbf{Q} \end{pmatrix} && \text{by (5) and (2)} \\ &= \begin{pmatrix} \mathbf{M}_1 & \mathbf{0}_n \\ \mathbf{0}_n & \mathbf{Q}^\top \mathbf{M}_2 \mathbf{Q} \end{pmatrix} \\ &= \begin{pmatrix} \mathbf{M}_1 & \mathbf{0}_n \\ \mathbf{0}_n & \mathbf{M}_1 \end{pmatrix} && \text{by (4)} \\ &= \mathbf{I}_2 \otimes \mathbf{M}_1 \end{aligned}$$

(\Leftarrow) We prove that if Eq. (3) holds, then G_1, G_2 are isomorphic.

Observe that the transformation $\mathbf{P}^\top \mathbf{M} \mathbf{P}$ consists of relabeling the nodes of G according to the permutation matrix \mathbf{P} . Let us define this relabeling as the bijection $\pi : \{1, 2, \dots, 2n\} \rightarrow \{1, 2, \dots, 2n\}$. Therefore, $\pi(i) = j$ if and only if the node i of G is relabeled as j . Note also that $\mathbf{P}^\top \mathbf{M} \mathbf{P}$ is symmetric, since it represents the adjacency matrix of an undirected graph.

Since we are assuming that G_1 is connected, then there always exists a path from node i to node j , $1 \leq i, j \leq n$. Thus, should the permutation contain a mapping such that $\pi(i) \leq n$ and $\pi(j) > n$, the relabeled adjacency matrix $\mathbf{P}^\top \mathbf{M} \mathbf{P}$ would contain at least one 1 in the upper-right quadrant and (by symmetry) in the lower-left one. However, this contradicts the hypothesis (3), since the upper right and lower left quadrants of $\mathbf{I}_2 \otimes \mathbf{B}$ are the zero matrix $\mathbf{0}_n$. The same considerations apply to G_2 .

Thus, from Eq. (3) we observe that π maps the sets $\{1, 2, \dots, n\}$ and $\{n+1, n+2, \dots, 2n\}$ into themselves, and therefore \mathbf{P} must have a block structure:

$$\mathbf{P} = \begin{pmatrix} \mathbf{P}_1 & \mathbf{0}_n \\ \mathbf{0}_n & \mathbf{P}_2 \end{pmatrix} \quad (6)$$

Let G_3 be the undirected graph such that $\text{Adj}(G_3) = \mathbf{B}$. Combining (6) and (3) we can conclude that $G_1 \simeq G_3$ and $G_2 \simeq G_3$, because the adjacency matrices $\mathbf{M}_1, \mathbf{M}_2$ can be transformed into \mathbf{B} via the permutation matrices $\mathbf{P}_1, \mathbf{P}_2$, respectively. By transitivity we conclude $G_1 \simeq G_2$. \square

Lemma 4.7 ensures that the adjacency matrix of the disjoint union of two isomorphic graphs may always be written as $\mathbf{I}_2 \otimes \mathbf{B}$; note that \mathbf{I}_2 is the adjacency matrix of D_2 , the graph with two nodes and two self-loops. Unfortunately, simply testing primality of the disjoint union $X = G_1 \cup G_2$ of two graphs G_1 and G_2 is not enough for deciding whether G_1 and G_2 are isomorphic or not. In fact, as mentioned at the end of Section 3, the graph X could admit as a factor a graph with two nodes different from D_2 . For example, Figure 4 shows a graph X such that

- X is the disjoint union of two non isomorphic graphs (connected and having the same number of nodes and edges) and
- X admits as a factor a graph with two nodes that is different from D_2 .

Moreover, the idea of factorizing $X = G_1 \cup G_2$ to check whether D_2 is a factor (or, equivalently, $G_1 \simeq G_2$) might fail due to the fact that X could admit two different factorizations F_1 and F_2 where F_1 contains D_2 while F_2 does not. Figure 3 shows an example of a graph X such that

- X is the disjoint union of two isomorphic graphs (both connected and with a prime number of nodes)
- X admits two distinct factorizations F_1 and F_2 where F_1 contains D_2 while F_2 does not.

In order to prove the main result of this paper, we define a class of graphs Θ as follows.

Definition 4.8 (Class Θ). *A graph $G = (V, E)$ with n nodes and m edges belongs to the class $\Theta \subset \Gamma_0$ if and only if:*

P1 G is undirected, connected and not bipartite ($G \in C \cap \overline{B}$);

P2 The number of nodes n is prime;

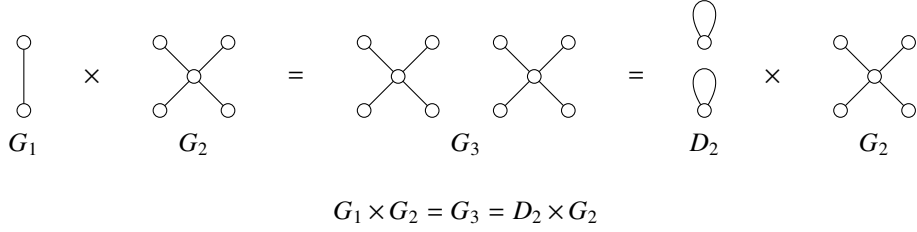


Figure 3: G_2 is a connected graph with a prime number of nodes. G_3 is the disjoint union of two copies of G_2 . G_3 has two different factorizations, namely, $G_1 \times G_2$ and $D_2 \times G_2$.

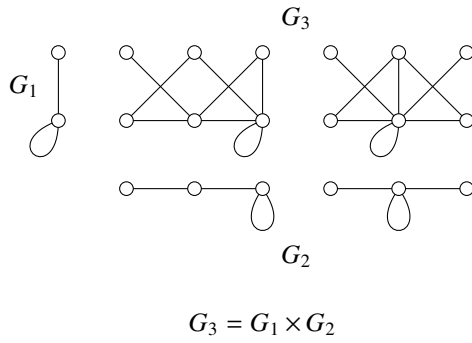


Figure 4: G_3 is the disjoint union of two connected graphs with the same number of nodes and edges. G_3 is the direct product of G_1 and G_2 . G_3 has G_1 as a factor, which differs from D_2 by two nodes. G_3 has not D_2 as a factor.

P3 The number s of self-loops is strictly less than the number of edges, i.e., $s < m$;

P4 $(2m - s)$ is not divisible by 2;

P5 $(2m - s)$ is not divisible by 3;

In the following theorem we give a polynomial time many-one reduction from $\mathbf{GI}[\Theta]$ to $\mathbf{Compositeness}[\Theta]$. A consequence of this result is that the existence of a polynomial-time algorithm to determine whether a given graph in Θ is composite with respect to the direct product would imply the existence of a polynomial-time algorithm for the graph isomorphism problem between any two graphs in Θ .

Theorem 4.9.

$$\mathbf{GI}[\Theta] \leq_M \mathbf{Compositeness}[\Theta]$$

Proof. Let \mathcal{A} be an algorithm for testing compositeness for graphs in Θ . The following algorithm solves the isomorphism problem for graphs in Θ relying on a single call to \mathcal{A} , therefore providing a polynomial time many-one reduction from $\mathbf{GI}[\Theta]$ to $\mathbf{Compositeness}[\Theta]$.

Θ -GRAPH-ISOMORPHISM (G_1, G_2)

```

1  if  $|V(G_1)| \neq |V(G_2)|$  or  $|E(G_1)| \neq |E(G_2)|$ 
2      return NO
3   $G = G_1 \cup G_2$  // graphs disjoint union
4  return  $\mathcal{A}(G)$ 

```

Let us prove that Θ -GRAPH-ISOMORPHISM is correct. To this end, we consider two cases:

G is prime. Let $G_1, G_2 \in \Theta$ and $\mathbf{M} = \mathbf{Adj}(G_1 \cup G_2)$. According to Lemma 4.7 and 4.6, if G is prime we can conclude that G_1 and G_2 are not isomorphic, since if they were, there should exist a permutation matrix \mathbf{P} and a suitable adjacency matrix \mathbf{B} such that $\mathbf{P}^T \mathbf{M} \mathbf{P} = \mathbf{I}_2 \otimes \mathbf{B}$ and then $G_1 \cup G_2$ would be composite.

G is composite. Let $G_1, G_2 \in \Theta$ and $\mathbf{M} = \mathbf{Adj}(G_1 \cup G_2)$. Let $n = |V(G_1)| = |V(G_2)|$ be the number of nodes of either G_1 or G_2 . Since $G_1 \in \Theta$, n is prime (**P2**). Consequently, the number of nodes of $G = G_1 \cup G_2$ is $2n$ and its adjacency matrix \mathbf{M} has size $2n \times 2n$. Therefore, the only possible factorization of \mathbf{M} is $\mathbf{M} = \mathbf{A} \otimes \mathbf{B}$, where \mathbf{A} has size 2×2 and \mathbf{B} has size $n \times n$. Additionally, since $G_1, G_2 \in \Theta$, their adjacency matrices have exactly $2m - s$ nonzero elements each, where $m = |E(G_1)| = |E(G_2)|$ is the number of edges of either G_1 or G_2 and s is the number of self-loops. Let us consider each possible configuration of the matrix \mathbf{A} :

$$\begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix} \quad \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \quad \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} \quad \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix} \quad \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} \quad \begin{pmatrix} 1 & 1 \\ 0 & 0 \end{pmatrix} \quad \begin{pmatrix} 1 & 0 \\ 1 & 0 \end{pmatrix} \quad \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

$$\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \quad \begin{pmatrix} 0 & 1 \\ 0 & 1 \end{pmatrix} \quad \begin{pmatrix} 0 & 0 \\ 1 & 1 \end{pmatrix} \quad \begin{pmatrix} 0 & 1 \\ 1 & 1 \end{pmatrix} \quad \begin{pmatrix} 1 & 0 \\ 1 & 1 \end{pmatrix} \quad \begin{pmatrix} 1 & 1 \\ 0 & 1 \end{pmatrix} \quad \begin{pmatrix} 1 & 1 \\ 1 & 0 \end{pmatrix} \quad \begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix}$$

Since G_1 and G_2 are undirected, G is undirected as well, so its adjacency matrix \mathbf{M} must be symmetric. From 4.7 we deduce that \mathbf{A} must be symmetric, since \mathbf{B} is a nonzero matrix. Therefore, we exclude all configurations of matrix \mathbf{A} that are not symmetric.

$$\begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix} \quad \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \quad \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} \quad \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix} \quad \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} \quad \begin{pmatrix} 1 & 1 \\ 0 & 0 \end{pmatrix} \quad \begin{pmatrix} 1 & 0 \\ 1 & 0 \end{pmatrix} \quad \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

$$\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \quad \begin{pmatrix} 0 & 1 \\ 0 & 1 \end{pmatrix} \quad \begin{pmatrix} 0 & 0 \\ 1 & 1 \end{pmatrix} \quad \begin{pmatrix} 0 & 1 \\ 1 & 1 \end{pmatrix} \quad \begin{pmatrix} 1 & 0 \\ 1 & 1 \end{pmatrix} \quad \begin{pmatrix} 1 & 1 \\ 0 & 1 \end{pmatrix} \quad \begin{pmatrix} 1 & 1 \\ 1 & 0 \end{pmatrix} \quad \begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix}$$

Since G_1 and G_2 are connected, the degrees of all their nodes must be strictly greater than zero. Therefore, \mathbf{A} must contain more than a single nonzero element as, conversely, the resulting matrix \mathbf{M} would have at least n unconnected nodes with zero degree. Therefore, we exclude all configurations of \mathbf{A} that have less than two nonzero elements.

$$\begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix} \quad \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \quad \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} \quad \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix} \quad \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} \quad \begin{pmatrix} 1 & 1 \\ 0 & 0 \end{pmatrix} \quad \begin{pmatrix} 1 & 0 \\ 1 & 0 \end{pmatrix} \quad \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

$$\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \quad \begin{pmatrix} 0 & 1 \\ 0 & 1 \end{pmatrix} \quad \begin{pmatrix} 0 & 0 \\ 1 & 1 \end{pmatrix} \quad \begin{pmatrix} 0 & 1 \\ 1 & 1 \end{pmatrix} \quad \begin{pmatrix} 1 & 0 \\ 1 & 1 \end{pmatrix} \quad \begin{pmatrix} 1 & 1 \\ 0 & 1 \end{pmatrix} \quad \begin{pmatrix} 1 & 1 \\ 1 & 0 \end{pmatrix} \quad \begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix}$$

Let us now consider the number b of nonzero elements in \mathbf{B} . Should \mathbf{A} have three nonzero elements, the resulting number of nonzero elements in \mathbf{M} would be $3b$, which is divisible by 3. Moreover, the number of nonzero elements of \mathbf{M} is equal to the number of nonzero elements of the adjacency matrices of G_1 and G_2 :

$$3b = 2(2m - s)$$

Since $G_1, G_2 \in \Theta$, we know that the number of nonzero elements $(2m - s)$ in their adjacency matrices must not be divisible by 3 (**P5**). Thus, $2(2m - s)$ must not be divisible by 3 either, contradicting (4). We conclude that \mathbf{A} can not contain three nonzero elements.

$$\begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 1 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

$$\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} 0 & 1 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 0 & 0 \\ 1 & 1 \end{pmatrix} \begin{pmatrix} 0 & 1 \\ 1 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 1 & 1 \end{pmatrix} \begin{pmatrix} 1 & 1 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix}$$

Similarly, should the matrix \mathbf{A} have four nonzero elements, the number of nonzero elements in \mathbf{M} would be $4b$; from the same reasoning above, we get:

$$4b = 2(2m - s)$$

However, from **P4** we have that $(2m - s)$ is not divisible by 2, and therefore $2(2m - s)$ is not divisible by 4. We conclude that \mathbf{A} can not have four nonzero elements.

$$\begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 1 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

$$\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} 0 & 1 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 0 & 0 \\ 1 & 1 \end{pmatrix} \begin{pmatrix} 0 & 1 \\ 1 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 1 & 1 \end{pmatrix} \begin{pmatrix} 1 & 1 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix}$$

Finally, we point out that since G_1 and G_2 are not bipartite (**P1**), G is not bipartite as well. Should $\mathbf{A} = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$, matrix $\mathbf{M} = \mathbf{A} \otimes \mathbf{B}$ would represent a bipartite graph, where the first n nodes are only connected to the other n nodes. Therefore, \mathbf{A} can not be in that form.

$$\begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 1 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

$$\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} 0 & 1 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 0 & 0 \\ 1 & 1 \end{pmatrix} \begin{pmatrix} 0 & 1 \\ 1 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 1 & 1 \end{pmatrix} \begin{pmatrix} 1 & 1 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix}$$

We conclude that $\mathbf{A} = \mathbf{I}_2$. Thus, according to Lemma 4.7, G_1 and G_2 are isomorphic. □

Theorem 4.9 shows that, within the class Θ , there exists an intimate relation between graph primality with respect to the direct product and graph isomorphism. In what follows we will extend Theorem 4.9 to the class of graph Γ_0 by describing a polynomial-time, isomorphism-preserving transformation that maps any connected graph $G \in C$ into a graph in Θ . Before doing so, we need to prove a small technical lemma.

Lemma 4.10. *For each $n \in \mathbb{Z}$ there exists $d \in \{0, 1, 2, 3\}$ such that $(n + d)$ is not divisible by two nor by three; formally, $(n + d) \bmod 2 \neq 0$ and $(n + d) \bmod 3 \neq 0$.*

Proof. Let us denote with $\llbracket n \rrbracket_k$ the equivalence class of all integers that are congruent to n modulo k (also called residual class): $\llbracket n \rrbracket_k = \{\dots, n - 2k, n - k, n, n + k, n + 2k, \dots\}$. The lemma can then be rephrased as: for each $n \in \mathbb{Z}$ there exists $d \in \{0, 1, 2, 3\}$ such that $(n + d) \notin (\llbracket 0 \rrbracket_2 \cup \llbracket 0 \rrbracket_3)$. The following table shows all possible values of d for any combination of residual classes modulo 2 and modulo 3 that n may belong to.

n	$\llbracket 0 \rrbracket_3$	$\llbracket 1 \rrbracket_3$	$\llbracket 2 \rrbracket_3$
$\llbracket 0 \rrbracket_2$	$d = 1$	$d = 1, 3$	$d = 3$
$\llbracket 1 \rrbracket_2$	$d = 2$	$d = 0$	$d = 0, 2$

For example, if $n \in \llbracket 1 \rrbracket_2 \cap \llbracket 0 \rrbracket_3$, then $(n + 2) \in \llbracket 1 \rrbracket_2 \cap \llbracket 2 \rrbracket_3$, which means that $(n + 2)$ is not divisible by 2 nor by 3. To build the table, one might observe that:

$$\llbracket n + d \rrbracket_2 = \begin{cases} \llbracket n \rrbracket_2 & \text{if } d \in \{0, 2\} \\ \llbracket n + 1 \rrbracket_2 & \text{if } d \in \{1, 3\} \end{cases} \quad \llbracket n + d \rrbracket_3 = \begin{cases} \llbracket n \rrbracket_3 & \text{if } d \in \{0, 3\} \\ \llbracket n + 1 \rrbracket_3 & \text{if } d = 1 \\ \llbracket n + 2 \rrbracket_3 & \text{if } d = 2 \end{cases}$$

□

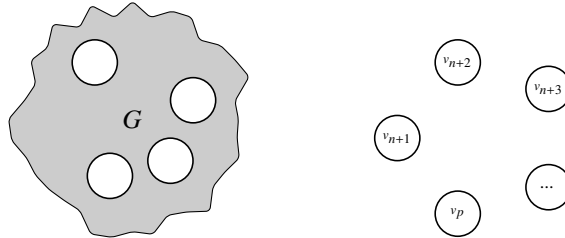
Theorem 4.11. *There exists a mapping $f : C \rightarrow \Theta$ such that for every two connected graphs $G_1, G_2 \in C$ with the same number of nodes and edges, $G_1 \simeq G_2$ if and only if $f(G_1) \simeq f(G_2)$. Furthermore, $f(G)$ can be computed in polynomial time with respect to the size of G .*

Proof. Given a connected graph $G \in C$, let us define $G' = f(G)$ as follows. Let $m = |E(G)|$ and $n = |V(G)|$. According to the Bertrand-Chebyshev theorem [12], for any integer $q > 1$ there exists a prime in $\{q + 1, \dots, 2q - 1\}$, and such prime can be found in polynomial time [13]. Therefore, there is a prime p such that $2n < p < 4n$.

The vertex set of G' is defined as

$$V(G') := V(G) \cup \{v_{n+1}, v_{n+2}, \dots, v_p\}$$

where $v_{n+1}, v_{n+2}, \dots, v_p$ are new nodes.

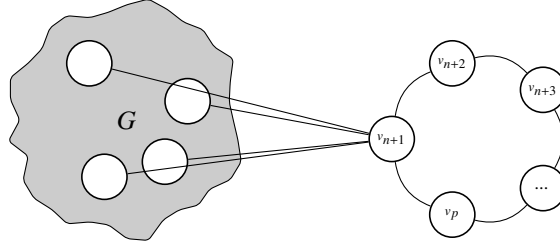


The edge set $E(G')$ is constructed incrementally from $E(G)$, as follows. Let

$$C_f := \{\{x, v_{n+1}\} \mid x \in V(G)\}$$

$$C_c := \{\{v_{n+1}, v_{n+2}\}, \{v_{n+2}, v_{n+3}\}, \dots, \{v_p, v_{n+1}\}\}$$

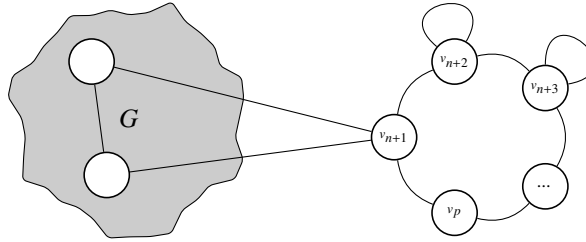
that is, C_f is a set of new edges that connect each node in $V(G)$ to the first newly created node v_{n+1} , and C_c is a set of new edges that form a cycle within the new nodes. Since we have chosen p such that $2n < p < 4n$, the length of the cycle in C_c is greater than n .



We finally add a number s of self-loops within the new nodes in order to meet conditions **P4** and **P5**. Lemma 4.10 guarantees that s is at most 3. Thus:

$$C_s := \begin{cases} \emptyset & \text{if } s = 0 \\ \{\{v_{n+2}, v_{n+2}\}\} & \text{if } s = 1 \\ \{\{v_{n+2}, v_{n+2}\}, \{v_{n+3}, v_{n+3}\}\} & \text{if } s = 2 \\ \{\{v_{n+2}, v_{n+2}\}, \{v_{n+3}, v_{n+3}\}, \{v_{n+4}, v_{n+4}\}\} & \text{if } s = 3 \end{cases}$$

The edge set $E(G')$ is therefore defined as $E(G') := E(G) \cup C_f \cup C_c \cup C_s$.



Observe that, since G is connected, the edge subset C_f induces at least one odd cycle (specifically, at least one cycle of length three), and therefore G' is not bipartite (a graph is bipartite if and only if it has no odd cycles [14]). Therefore we conclude that $G' \in \Theta$.

We now prove that $G_1 \simeq G_2 \iff f(G_1) \simeq f(G_2)$.

(\implies) Assume $G_1 \simeq G_2$. Then, the isomorphism can be trivially extended to $f(G_1)$ and $f(G_2)$ since these graphs are obtained from G_1, G_2 by adding an identical structure.

(\impliedby) Assume $f(G_1) \simeq f(G_2)$. The only possible isomorphisms are those that map one of the cycles C_c to the corresponding one on the other graph. Since in the transformation we have chosen $p > 2n$, the cycle length of C_c is larger than n , and therefore is larger than any simple cycle in G_1 (or G_2). Consequently, the isomorphism between $f(G_1)$ and $f(G_2)$ can be restricted to an isomorphism between G_1 and G_2 . \square

Theorem 4.11 allows us to assert the main result of this paper, that is the relation between primality test and graphs isomorphism.

Theorem 4.12.

$$GI[C] \leq_M \text{Compositeness}[\overline{C} \cap \overline{B}]$$

Proof. Assume that there exists an algorithm \mathcal{A} that solves the **Compositeness** $[\overline{C} \cap \overline{B}]$ decision problem. Specifically, $\mathcal{A}(G)$ returns YES if the unconnected, nonbipartite graph $G \in \overline{C} \cap \overline{B}$ is composite with respect to the direct product, NO otherwise. Then, the following algorithm solves the **GI** $[C]$ decision problem, providing a polynomial time many-one reduction from **GI** $[C]$ to **Compositeness** $[\overline{C} \cap \overline{B}]$.

GRAPH-ISOMORPHISM(G_1, G_2)

```

1  if  $|V(G_1)| \neq |V(G_2)|$  or  $|E(G_1)| \neq |E(G_2)|$ 
2      return NO
3   $G_3 = f(G_1)$  // Theorem 4.11
4   $G_4 = f(G_2)$  // Theorem 4.11
5   $G = G_3 \cup G_4$  // disjoint union of graphs
6  return  $\mathcal{A}(G)$ 

```

Indeed, by Theorem 4.11, G_1 is isomorphic to G_2 if and only if $f(G_1)$ is isomorphic to $f(G_2)$. Since both $f(G_1)$ and $f(G_2)$ belong to Θ , then by Theorem 4.9, $G = G_3 \cup G_4$ is decomposable if and only if G_3 is isomorphic to G_4 . \square

Note that **Compositeness** $[\overline{C} \cap \overline{B}]$ remains *GI*-hard even if we relax either the *undirected* or the *nonbipartite* constraints, as the resulting class of graphs would be larger than the one which was considered throughout our discussion.

Corollary 4.13. *Primality* $[\overline{C} \cap \overline{B}]$ is *GI*-hard or, equivalently,

$$GI[C] \leq_T \text{Primality}[\overline{C} \cap \overline{B}]$$

Proof. The proof follows directly from the proof of Theorem 4.12 by negating the result provided by the oracle \mathcal{A} . \square

5. Conclusions

In this paper we proved that primality testing of unconnected, nonbipartite graphs with respect to direct product is at least as hard as deciding graph isomorphism. The same result also applies to the computation of a prime factorization of a graph. This result answer a long standing open question posed in [1] and shows the crucial role played by connectedness in decomposing a graph.

It would be of some interest to investigate the reversed question, i.e., whether deciding graph isomorphism is at least as hard as primality testing. Another interesting research direction is the design and implementation of efficient heuristics for computing a prime factorization or its approximation of large, possibly unconnected and/or weighted graphs knowing that a polynomial time algorithm for computing such a prime factorization is unlikely to exist.

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