GRAPH EXPONENTIATION AND NEIGHBORHOOD RECONSTRUCTION

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Abstract

Any graph $G$ admits a neighborhood multiset $N(G) = \{N_G(x) \mid x \in V(G)\}$ whose elements are precisely the open neighborhoods of $G$. We say $G$ is neighborhood reconstructible if it can be reconstructed from $N(G)$, that is, if $G \cong H$ whenever $N(G) = N(H)$ for some other graph $H$. This note characterizes neighborhood reconstructible graphs as those graphs $G$ that obey the exponential cancellation $G^{K_2} \cong H^{K_2} \Longrightarrow G \cong H$.

Keywords: neighborhood reconstructible graphs, graph exponentiation.

2010 Mathematics Subject Classification: 05C60, 05C76.

Our graphs are finite and may have loops, but not parallel edges. The open neighborhood of a vertex $x$ of a graph $G$ is $N_G(x) := \{y \in V(G) \mid xy \in E(G)\}$. Notice that $x \in N_G(x)$ if and only if $xx \in E(G)$, that is, there is a loop at $x$.

To any graph $G$ there is an associated neighborhood multiset $N(G) = \{N_G(x) \mid x \in V(G)\}$ whose elements are the open neighborhoods of $G$. It is possible that $N(G) = N(H)$ but $G \not\cong H$. Figure 1 shows the simplest instance of this. Here $G \not\cong H$ but $N(G) = \{\{0\}, \{1\}\} = N(H)$. Figure 2 shows a more complex and interesting example.

$N_G(0) = \{1\} = N_H(1) \quad N_G(1) = \{0\} = N_H(0)$

Figure 1. Two non-isomorphic graphs with the same neighborhood multiset.

1Supported by Simons Collaboration Grant for Mathematicians 523748.
A graph $G$ is called neighborhood reconstructible if $\mathcal{N}(G) = \mathcal{N}(H)$ implies $G \cong H$ for any graph $H$ with $V(H) = V(G)$. Figure 2 shows that the Petersen graph is not neighborhood reconstructible. Aigner and Triesch [1] attribute the neighborhood reconstruction problem to Sós [9]. They note that deciding if a graph is neighborhood reconstructible is NP-complete.

Given graphs $G$ and $K$, the graph exponential $G^K$ is the graph whose vertex set is the set of all functions $V(K) \to V(G)$, where two functions $f, g$ are adjacent precisely if $f(x)g(y) \in E(G)$ for all $xy \in E(K)$. (See [6, 8].) If $V(K) = \{v_1, \ldots, v_n\}$, then a function $f : V(K) \to V(G)$ can be identified with an $n$-tuple $f = (x_1, \ldots, x_n) \in V(G)^n$ signifying $f(v_i) = x_i$.

We are interested exclusively in $G^{K_2}$. Note $V(G^{K_2}) = V(G) \times V(G)$, and two functions $(x_1, x_2)$ and $(y_1, y_2)$ are adjacent if and only if $x_1y_2 \in E(G)$ and $x_2y_1 \in E(G)$. That is,

$$E(G^{K_2}) = \{(x_1, x_2)(y_1, y_2) \mid x_1y_2 \in E(G) \text{ and } x_2y_1 \in E(G)\}.$$ 

See Figure 3, which shows that $G^K \cong H^K$ does not necessarily imply $G \cong H$.

$$\begin{pmatrix} 1 \\ 0 \end{pmatrix} K_2 = \begin{pmatrix} (0,1) & (1,1) \\ (0,0) & (1,0) \end{pmatrix} \quad \begin{pmatrix} 0 \\ 1 \end{pmatrix} K_2 = \begin{pmatrix} (0,1) & (1,1) \\ (0,0) & (1,0) \end{pmatrix}$$

Figure 3. Two exponentials $G^{K_2}$ and $H^{K_2}$. This shows $G^K \cong H^K$ may not imply $G \cong H$.

Actually, the conditions under which $G^K \cong H^K$ implies $G \cong K$ are not fully understood today. (The issue is further complicated by the fact that there are at least two definitions of graph exponentiation; compare [4].) This note links one instance of this exponential cancellation to neighborhood reconstruction. Our
main result is that $G$ is neighborhood reconstructible if and only if $G^{K_2} \cong H^{K_2}$ implies $G \cong H$ for all graphs $H$. To understand why we might expect this, consider Proposition 1 below, whose proof is almost automatic. (Figures 1 and 3 illustrate Proposition 1.)

**Proposition 1.** If $G$ and $H$ are two graphs on the same vertex set and $\mathcal{N}(G) = \mathcal{N}(H)$, then $G^{K_2} \cong H^{K_2}$.

**Proof.** Say $\mathcal{N}(G) = \mathcal{N}(H)$. As $G$ and $H$ have the same neighborhood multiset, there is a bijection $\varphi : V(G) \to V(H)$ for which $N_G(x) = N_H(\varphi(x))$ for each $x \in V(G)$. (Such map $\varphi$ is unique if no two vertices of $G$ have the neighborhood; otherwise there is more than one $\varphi$.) The bijection $\lambda : V(G^{K_2}) \to V(H^{K_2})$ where $\lambda(x, y) = (\varphi(x), y)$ is an isomorphism. Indeed,

\[
(x, y)(u, v) \in E(G^{K_2}) \iff v \in N_G(x) \text{ and } y \in N_G(u) \\
\iff v \in N_H(\varphi(x)) \text{ and } y \in N_H(\varphi(u)) \\
\iff (\varphi(x), y)(\varphi(u), v) \in E(H^{K_2}) \\
\iff \lambda(x, y)\lambda(u, v) \in E(H^{K_2}).
\]

We will use this proposition in the proof of our main result. We will also need the direct product of graphs: $G \times H$ is the graph whose vertex set is the set Cartesian product $V(G \times H) = V(G) \times V(H)$, and whose edges are

\[
E(G \times H) = \{(x, y)(x', y') \mid xx' \in E(G) \text{ and } yy' \in E(H)\}.
\]

See Chapter 8 of [2] for a survey of the direct product.

For a positive integer $k$, the direct power $G^k$ is $G \times \cdots \times G$ ($k$ factors). Any square $G^2$ admits a mirror automorphism $\mu : G^2 \to G^2$ of order 2, where $\mu(x, y) = (y, x)$. From the definitions it is immediate that

\[
(x, y)(u, v) \in E(G^2) \text{ if and only if } (x, y)\mu(u, v) \in E(G^{K_2}),
\]

\[
(x, y)(u, v) \in E(G^{K_2}) \text{ if and only if } \mu(x, y)(u, v) \in E(G^2).
\]

Recall the following two results (by Lovász) concerning direct powers and products. (They are Theorems 2 and 5, respectively, in [7].)

**Proposition 2.** If $G^k \cong H^k$ for a positive integer $k$, then $G \cong H$.

**Proposition 3.** If $G \times K \cong H \times K$, then there is an isomorphism $G \times K \to H \times K$ of form $(x, y) \mapsto (\lambda(x, y), y)$ for some map $\lambda : G \times K \to H$.

Actually, we will only need a weaker instance of Proposition 3, one that is easy to prove from scratch. If $G \times K_2 \cong H \times K_2$, then there exists an isomorphism $G \times K_2 \to H \times K_2$ of form $(x, y) \mapsto (\lambda(x, y), y)$. 


We are ready for our main theorem.

**Theorem 4.** A graph $G$ is neighborhood reconstructible if and only if the exponential cancellation law $G^{K_2} \cong H^{K_2} \Rightarrow G \cong H$ holds for any graph $H$.

**Proof.** Say the exponential cancellation law $G^{K_2} \cong H^{K_2} \Rightarrow G \cong H$ holds. Let $\mathcal{N}(G) = \mathcal{N}(H)$ for a graph $H$ with $V(H) = V(G)$. Proposition 1 yields $G^{K_2} \cong H^{K_2}$, whence $G \cong H$. Thus $G$ is neighborhood reconstructible.

Conversely, suppose $G$ is neighborhood reconstructible. Say $G^{K_2} \cong H^{K_2}$ for some graph $H$. We must show $G \cong H$.

Put $V(K_2) = \{0, 1\}$. Take an isomorphism $\varphi : G^{K_2} \to H^{K_2}$. Using (1) and (2), observe that

$$(x, y)(u, v) \in E(G^{2}) \iff (x, y)\mu(u, v) \in E(G^{K_2})$$

$$\iff \varphi(x, y)\varphi\mu(u, v) \in E(H^{K_2})$$

$$\iff \mu\varphi(x, y)\varphi\mu(u, v) \in E(H^{2}).$$

From this we get an isomorphism $\Theta : G^{2} \times K_2 \to H^{2} \times K_2$ defined as

$$\Theta((x, y), \varepsilon) = \begin{cases} (\varphi\mu(x, y), \varepsilon) & \text{if } \varepsilon = 0, \\ (\mu\varphi(x, y), \varepsilon) & \text{if } \varepsilon = 1. \end{cases}$$

From $G^{2} \times K_2 \cong H^{2} \times K_2$ we get $G^{2} \times K_2 \times K_2 \cong H^{2} \times K_2 \times K_3$, yielding $(G \times K_2)^2 \cong (H \times K_2)^2$. By Proposition 2 we have $G \times K_2 \cong H \times K_2$. Then Proposition 3 guarantees an isomorphism $\theta : G \times K_2 \to H \times K_2$ having form

$$\theta(x, \varepsilon) = \begin{cases} (\lambda_0(x), \varepsilon) & \text{if } \varepsilon = 0, \\ (\lambda_1(x), \varepsilon) & \text{if } \varepsilon = 1. \end{cases}$$

for two bijections $\lambda_0, \lambda_1 : V(G) \to V(H)$, which (by definition of the direct product) necessarily satisfy $xy \in E(G)$ if and only if $\lambda_0(x)\lambda_1(y) \in E(H)$.

Now form a graph $H'$ on $V(G)$ whose edges are precisely $\lambda_1^{-1}(u)\lambda_1^{-1}(v)$ for each $uv \in E(H)$. Thus $\lambda_1^{-1} : H \to H'$ is an isomorphism.

We claim that $N_G(x) = N_{H'}(\lambda_1^{-1}\lambda_0(x))$ for each $x \in V(G) = V(H')$. Note $y \in N_G(x)$ if and only if $xy \in E(G)$, if and only if $\lambda_0(x)\lambda_1(y) \in E(H)$, if and only if $\lambda_1^{-1}\lambda_0(x)\lambda_1^{-1}\lambda_1(y) \in E(H')$, if and only if $\lambda_1^{-1}\lambda_0(x)y \in E(H')$, if and only if $y \in N_{H'}(\lambda_1^{-1}\lambda_0(x))$. Thus indeed $N_G(x) = N_{H'}(\lambda_1^{-1}\lambda_0(x))$.

Consequently $\mathcal{N}(G) = \mathcal{N}(H')$, so $G \cong H'$ because $G$ is neighborhood reconstructible. But $H' \cong H$, so $G \cong H$. 

The present note is a sequel to [3], which characterizes neighborhood reconstructible graphs as those graphs $G$ which obey the cancellation law $G \times K \cong H \times K \Rightarrow G \cong K$ for all graphs $H$ and $K$. 

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Acknowledgment

The author thanks the referee for a prompt response.

References


Received 3 September 2018
Accepted 27 October 2018