

ON \bullet -LINE SIGNED GRAPHS $L_\bullet(S)$

DEEPA SINHA

South Asian University
Akbar Bhawan, Chanakyapuri
New Delhi-110 021, India

e-mail: deepa_sinha2001@yahoo.com

AND

AYUSHI DHAMA

Centre for Mathematical Sciences
Banasthali University
Banasthali-304 022 Rajasthan, India

e-mail: ayushi.dhama2@gmail.com

Abstract

A *signed graph* (or *sigraph* for short) is an ordered pair $S = (S^u, \sigma)$, where S^u is a graph, $G = (V, E)$, called the underlying graph of S and $\sigma : E \rightarrow \{+, -\}$ is a function from the edge set E of S^u into the set $\{+, -\}$. For a sigraph S its \bullet -line sigraph, $L_\bullet(S)$ is the sigraph in which the edges of S are represented as vertices, two of these vertices are defined adjacent whenever the corresponding edges in S have a vertex in common, any such L -edge ee' has the sign given by the product of the signs of the edges incident with the vertex in $e \cap e'$. In this paper we establish a structural characterization of \bullet -line sigraphs, extending a well known characterization of line graphs due to Harary. Further we study several standard properties of \bullet -line sigraphs, such as the balanced \bullet -line sigraphs, sign-compatible \bullet -line sigraphs and \mathcal{C} -sign-compatible \bullet -line sigraphs.

Keywords: sigraph, line graph, \bullet -line sigraph, balance, sign-compatibility, \mathcal{C} -sign-compatibility.

2010 Mathematics Subject Classification: 05C22, 05C75.

1. INTRODUCTION

For standard terminology and notation in graph theory we refer the reader to Harary [8] and West [19], and Zaslavsky [21, 22] for sigraphs. Throughout the paper, we consider finite, undirected graphs with no loops or multiple edges.

A *signed graph* (or *sigraph* for short; see [7]) is an ordered pair $S = (S^u, \sigma)$, where S^u is a graph $G = (V, E)$, called the *underlying graph* of S and $\sigma : E \rightarrow \{+, -\}$ is a function from the edge set E of S^u into the set $\{+, -\}$, called the *signature* of S . The edges of S with positive and negative signs are called *positive edges* and *negative edges*, respectively. In a pictorial representation of a sigraph S , when S is small enough, its positive edges are shown as bold oriented line segments and negative edges as broken line segments. The *positive (negative) degree* of a vertex $v \in V(S)$ denoted by $d^+(v)(d^-(v))$ is the number of positive (negative) edges incident with the vertex v and $d(v) = d^+(v) + d^-(v)$. The edge degree $d_e(e_j)$ of an edge e_j in a sigraph S is the total number of edges adjacent to e_j in S . If the end vertices of the edge e_j are u and v , then *edge-degree* of e_j is defined as the number $d_e(e_j) = d(u) + d(v) - 2$. A vertex is called *pendent* if its degree is one.

A sigraph is *all-positive (all-negative)* if all its edges are positive (negative); further, it is said to be *homogeneous* if it is either all-positive or all-negative and *heterogeneous* otherwise.

A *marked sigraph* is an ordered pair $S_\mu = (S, \mu)$ where $S = (S^u, \sigma)$ is a sigraph and $\mu : V(S) \rightarrow \{+, -\}$ is a function from the vertex set $V(S)$ of S into the set $\{+, -\}$, called a *marking* of S . In particular, a sigraph $S = (S^u, \sigma)$ has a *canonical marking* or *C-marking*, μ_σ , defined for each vertex $v \in V(S)$ by $\mu_\sigma(v) = \prod_{e \in E_v} \sigma(e)$.

The *line graph* $L(G)$ of a graph G is that graph whose vertex set can be put in one-to-one correspondence with the edge set of G , such that two L -vertices of $L(G)$ are adjacent if and only if the corresponding edges of G are adjacent. The edges of the line graph $L(G)$ are called L -edges. The line graphs were first studied by Whitney [20] and the first characterization of line graphs in terms of complete subgraphs was obtained by Krausz [11]. In the literature, we find that different authors gave different name to line graphs; particularly, line graphs are termed as *derivative* (see [14]), *interchange graph* ([13]), *adjoint* ([12]), *derived graph* ([4]) and *covering graph* (see [10]). Harary and Norman [9] finally fixed the terminology by calling it a ‘line graph’. A forbidden subgraph characterization of line graphs was established by Beineke [5]. The following theorem is the well known characterization of a *line graph* given in most of the standard text-books on graph theory (e.g., see Harary [8], Ch. 8, p. 74), originally due to Beineke [4].

Theorem 1 [8]. *The following statements are equivalent:*

- (a) $G = (V, E)$ is a line graph.

- (b) The edges of G can be partitioned into some of its complete subgraphs in such a way that no vertex lies in more than two of the subgraphs.
- (c) G does not have $K_{1,3}$ as an induced subgraph, and if two odd triangles have a common edge then the subgraph induced by their vertices is K_4 .
- (d) None of the nine subgraphs shown in Figure 1 is an induced subgraph of G .

A triangle is said to be *odd* if there is a vertex in the graph adjacent to an odd number of vertices of the triangle.

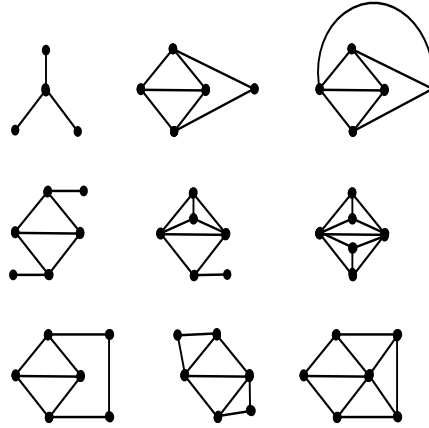


Figure 1. Beineke's nine forbidden subgraphs for a line graph.

The \bullet -line sigraph $L_\bullet(S)$ of a sigraph S is the line graph of $S = (S^u, \sigma)$, with each L -edge ee' ($e, e' \in E(S)$) signed with $\mu_\sigma(e \cap e')$. There are two more notions of a '*signed line graph*' of a given sigraph $S = (S^u, \sigma)$ in the literature, viz., $L(S)$ and $L_\times(S)$, both have $L(S^u)$ as their underlying graph; only the rule to assign signs to the edges of $L(S^u)$ differ. An L -edge ee' in $L(S)$ is negative if and only if both the edges e and e' in S are negative [3] and an L -edge ee' in $L_\times(S)$ has the product $\sigma(e)\sigma(e')$ as its sign [6].

2. BALANCE IN \bullet -LINE SIGRAPHS

The *sign* of a cycle Z in a sigraph S is the product of the signs of all its edges and is denoted by $\theta(Z)$. A cycle in a sigraph S is said to be *positive* (*negative*) if its sign is positive (negative). A sigraph S is said to be *balanced* if and only if all its cycles are positive.

Harary [7] derived the following structural criterion called *partition criterion* for balance in sigraphs.

Theorem 2 [7]. *A sigraph S is balanced if and only if its vertex set $V(S)$ can be partitioned into two subsets V_1 and V_2 , one of them possibly empty, such that every positive edge joins two vertices in the same subset and every negative edge joins two vertices from different subsets.*

The following important lemma on balanced sigraphs is given by Zaslavsky.

Lemma 3 [23]. *A sigraph in which every chordless cycle is positive, is balanced.*

Now, the following theorem gives us the solution for $L_\bullet(S)$ to be balanced.

Theorem 4. *For a sigraph S , $L_\bullet(S)$ is balanced if and only if the following conditions hold:*

- (i) *for every cycle Z in S , Z has even number of negatively marked vertices and*
- (ii) *for $v \in V(S)$, if $d(v) > 2$, then $d^-(v) \equiv 0 \pmod{2}$.*

Proof. *Necessity:* Suppose $L_\bullet(S)$ is balanced. Then, by definition of $L_\bullet(S)$, every L -cycle Z' in $L_\bullet(S)$ contains an even number of negative edges. Suppose there is any cycle in S that has odd number of negatively marked vertices. Then, by the definition of $L_\bullet(S)$, there are odd number of negative L -edges in $L_\bullet(S)$, a contradiction to the hypothesis. Thus, (i) follows. Now, by the definition of $L_\bullet(S)$, any three edges of S incident with v are the L -vertices of an all-negative L -triangle in $L_\bullet(S)$, contrary to the hypothesis. Thus condition (ii) is necessary. Hence, both conditions are necessary.

Sufficiency: Suppose conditions (i) and (ii) hold for a given sigraph S . We shall show that $L_\bullet(S)$ is balanced. If S is all-positive then, by definition, $L_\bullet(S)$ is also all-positive and hence, it is trivially balanced. Now, suppose that $L_\bullet(S)$ is not balanced. Then, we may assume the negative L -cycle Z'_k is of least possible length with this property. Let it be $(e_1, e_2, \dots, e_k, e_1)$, where each e_i is an L -vertex. Suppose it has a chord $e_i e_j$, then one of the L -cycles $(e_i, e_{i+1}, \dots, e_j, e_i)$ or $(e_j, e_{j+1}, \dots, e_k, e_1, \dots, e_i, e_j)$ is negative, contrary to the least length assumption. So we may assume Z'_k chordless. Now for any graph G , a chordless L -cycle of $L(G)$ must consist either of three L -vertices corresponding to edges of G incident with a single vertex, or of an L -cycle whose L -vertices are the edges of a chordless cycle of G . The result follows. ■

3. SIGN-COMPATIBILITY AND CANONICAL SIGN-COMPATIBILITY OF $L_\bullet(S)$

A sigraph $S = (S^u, \sigma)$ is *sign-compatible* [16] if it has a vertex marking μ such that each edge $e = vw$ has $\sigma(e) = -$ if and only if $\mu(v) = \mu(w) = -$. If the canonical marking μ_σ has this property, then S is said to be *canonically sign-compatible* (or *C-sign-compatible*.)

The conditions for a sigraph S to have these properties are known (Theorems 5, 6 and 8 below). In this section we establish the conditions for a \bullet -line sigraph $L_\bullet(S)$ to have each of these properties.

Theorem 5 [17]. *A sigraph S is sign-compatible if and only if there is a subset W of $V(S)$ whose induced subgraph has for its edge set exactly the negative edges of S .*

Theorem 6 [17]. *A sigraph S is sign-compatible if and only if S does not contain a subgraph isomorphic to either of the two sigraphs, S_1 formed by taking the path $P_4 = (x, u, v, y)$ with both the edges xu and vy negative and the edge uv positive and S_2 formed by taking S_1 and identifying the vertices x and y Figure 2.*

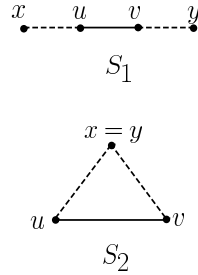


Figure 2. Acharya and Sinha forbidden subgraphs for a sign-compatible sigraph.

Now, we present the condition for a \bullet -line sigraph to be sign-compatible.

Theorem 7. *Let $S = (S^u, \sigma)$ be a canonically-marked sigraph. Then $L_\bullet(S)$ is sign-compatible if and only if S has the following property: Let $e_i, e_j, e_k, e_l \in E(S)$ such that there are vertices v, w, x (not necessarily distinct) with $e_i \cap e_j = v$, $e_k \cap e_l = w$ and $e_l \cap e_j = x$ and $\mu_\sigma(v) = +$. Then, either $\mu_\sigma(w) = +$ or $\mu_\sigma(x) = +$.*

Proof. *Necessity:* Suppose $L_\bullet(S)$ is sign-compatible. Then, by Theorem 6, $L_\bullet(S)$ does not contain a subgraph isomorphic to S_1 or S_2 in Figure 2.

Let e_i and e_j be two adjacent edges in S and v be the common vertex between them and $\mu_\sigma(v) = +$. Now, suppose that e_k is adjacent with e_i and e_l is adjacent with e_j and w and x are common vertices between them respectively. If possible, suppose the condition is false. Then, $\mu_\sigma(v) = +$ and $\mu_\sigma(w) = \mu_\sigma(x) = -$. If $e_k = e_l$ then, by the definition of $L_\bullet(S)$, we have an L -triangle with two negative and one positive L -edges in $L_\bullet(S)$. Thus, we have a subgraph isomorphic to S_2 in Figure 2 in $L_\bullet(S)$, a contradiction to the hypothesis. Now, suppose $e_k \neq e_l$, then we have an L -path $P'_4 = (e_k, e_i, e_j, e_l)$ in $L_\bullet(S)$ such that $e_i e_j$ is a positive L -edge while $e_k e_i$ and $e_j e_l$ are negative L -edges. Thus, we have a subgraph

isomorphic to S_1 in Figure 2 in $L_\bullet(S)$, a contradiction to the hypothesis. Thus, in both the conditions we have a contradiction. Hence, the conditions are necessary.

Sufficiency: Suppose the condition in the statement of the theorem holds for a sigraph S . We want to show that $L_\bullet(S)$ is sign-compatible. Suppose to the contrary that $L_\bullet(S)$ contains a subsigraph isomorphic to S_1 or S_2 .

Case I: Suppose $L_\bullet(S)$ contains a subsigraph, say P_4' , isomorphic to S_1 . Let $P_4' = (e_i, e_j, e_k, e_l)$ be such that $e_i e_j$ and $e_k e_l$ are negative L -edges and $e_j e_k$ is a positive L -edge in $L_\bullet(S)$. Then, by the definition of $L_\bullet(S)$, there exists a vertex between e_j and e_k in $L_\bullet(S)$ such that it is positively marked in S and the common vertices between e_i, e_j and e_k, e_l are marked negatively in S , a contradiction to the hypothesis. Thus, $L_\bullet(S)$ does not contain a subsigraph isomorphic to S_1 .

Case II: Now, let $L_\bullet(S)$ contain a subsigraph isomorphic to S_2 . Then this L -triangle is either due to the edges of a triangle or due to a vertex $v \in V(S)$ in S with $d(v) \geq 3$. Let Z' be an L -triangle in $L_\bullet(S)$ which is isomorphic to S_2 .

Case II(a): If all the vertices of Z' are due to the adjacent edges of a single triangle Z in S , then by the definition of $L_\bullet(S)$, we have a triangle Z in S such that its two vertices are marked negatively while one vertex is marked positively, a contradiction to the hypothesis.

Case II(b): Now, since this triangle is not due to any triangle of S , therefore Z' must contain an L -vertex, say e_p , which corresponds to an edge e_p incident with a vertex v with $d(v) \geq 3$ in S . Then either $\mu_\sigma(v) = +$ or $\mu_\sigma(v) = -$. Then, by the definition of $L_\bullet(S)$, such L -triangle is either all-positive or all-negative, a contradiction to the hypothesis. Hence, in all the conditions $L_\bullet(S)$ does not contain a subsigraph isomorphic to S_2 . Hence, by Theorem 6, $L_\bullet(S)$ is sign-compatible. ■

The following characterization of the \mathcal{C} -sign-compatible sigraph is given by the authors in [18]. This theorem is useful for our further investigation of \mathcal{C} -sign-compatible $L_\bullet(S)$.

Theorem 8 [18]. *A sigraph $S = (S^u, \sigma)$ is \mathcal{C} -sign-compatible if and only if the following conditions hold in S :*

- (i) *for every vertex $v \in V(S)$ either $d^-(v) = 0$ or $d^-(v) \equiv 1 \pmod{2}$, and*
- (ii) *for every positive edge $e_k = v_i v_j$ in S , $d^-(v_i) = 0$ or $d^-(v_j) = 0$.*

Now, the following theorem determines the condition for $L_\bullet(S)$ to be \mathcal{C} -sign-compatible.

Theorem 9. *For a given sigraph $S = (S^u, \sigma)$, $L_\bullet(S)$ is \mathcal{C} -sign-compatible if and only if the following conditions hold in S :*

- (a) for each edge e of S , the number of edges that are adjacent with e and incident with a negative vertex that is also adjacent with e , is zero or odd, and
- (b) for every positively marked vertex in S , say v_i , if there are two negatively marked vertices, say v_j and v_k , adjacent with v_i , then there is no other vertex adjacent with v_j or there is no other vertex adjacent with v_k .

Proof. *Necessity:* Let \bullet -line sigraph $L_\bullet(S)$ be \mathcal{C} -sign-compatible. Then, conditions (i) and (ii) of Theorem 8 hold for $L_\bullet(S)$.

Let θ denote the signature of $L_\bullet(S)$. Thus, for any edge $e = vw$ of S , the L -vertex e of $L_\bullet(S)$ has $\mu_\theta(e)$ equal to the number of edges of S that are adjacent with e and incident with v (if v is negative) or w (if w is negative). If this number is even and positive, then $L_\bullet(S)$ is not \mathcal{C} -sign-compatible. Hence condition (a) is necessary.

Now, suppose there is a positively marked vertex v_i in S and two negatively marked vertices v_j and v_k such that v_j and v_k are adjacent with v_i . Suppose v_j and v_k are adjacent with some vertices. Then, one possibility is that v_j and v_k are adjacent with each other. In this case, we have an L -triangle $(v_i v_j, v_j v_k, v_k v_i, v_i v_j)$ with one positive L -edge $v_i v_j v_k v_i$ and two negative L -edges in $L_\bullet(S)$. So there exists a positive L -edge in $L_\bullet(S)$ such that it does not satisfy condition (ii) of Theorem 8. Thus, by Theorem 8, $L_\bullet(S)$ is not \mathcal{C} -sign-compatible, a contradiction to the hypothesis. Hence, v_j and v_k are not adjacent with each other in $L_\bullet(S)$.

Now, suppose v_l is a vertex adjacent with v_j and v_m is a vertex adjacent with v_k respectively in S . Then, by the definition of $L_\bullet(S)$, we have an L -path $p_4 = (v_l v_j, v_j v_i, v_i v_k, v_k v_m)$ in $L_\bullet(S)$ such that L -edge $v_j v_i v_i v_k$ is a positive edge while L -edges $v_l v_j v_j v_i$ and $v_i v_k v_k v_m$ are negative edges. Thus, again there exists a positive L -edge in $L_\bullet(S)$ such that it does not satisfy condition (ii) of Theorem 8. So by the same argument as above, we get a contradiction to the hypothesis. Hence, condition (b) is necessary.

Sufficiency: Suppose conditions (a) and (b) hold for a given sigraph S . We shall show that $L_\bullet(S)$ is \mathcal{C} -sign-compatible. Suppose on contrary that $L_\bullet(S)$ is not \mathcal{C} -sign-compatible. Then, by Theorem 8 condition (i) or condition (ii) is not satisfied for $L_\bullet(S)$.

Suppose condition (i) of Theorem 8 is not satisfied for $L_\bullet(S)$ i.e., there is an L -vertex $e \in V(L_\bullet(S))$ such that neither $d^-(e) = 0$ nor $d^-(e) \equiv 1 \pmod{2}$. This shows that there are even number of edges adjacent with e in S such that these edges are incident with vertices with negative marking, a contradiction to condition (a).

Now, suppose condition (ii) of Theorem 8 is not satisfied i.e., for any positive edge $k = ee'$ there are negative L -edges on e and e' in $L_\bullet(S)$. Suppose this positive L -edge lies on an L -path $P'_4 = (e_i, e_j, e_k, e_l)$ such that $e_j e_k$ is a positive L -edge while $e_i e_j$ and $e_k e_l$ are negative L -edges in $L_\bullet(S)$. Then, by the definition

of $L_\bullet(S)$, we have a path $p_5 = (u, v, w, x, y)$ in S such that $e_i = uv$, $e_j = vw$, $e_k = wx$ and $e_l = xy$. Clearly, $e_j e_k$ is a positive L -edge in $L_\bullet(S)$ so, by the definition of $L_\bullet(S)$, common vertex w between e_j and e_k is surely positively marked in S . Similarly, $e_i e_j$ and $e_k e_l$ are negative L -edges in $L_\bullet(S)$, so their common vertices v and x , respectively, receive negative mark in S . Thus, for a positively marked vertex w in S , two negative vertices v and x are adjacent with w in S . Also, u and y are adjacent with v and x in S , a contradiction to (a).

This positive L -edge can be in a triangle also. Let Z' be such L -triangle in $L_\bullet(S)$. Now, this L -triangle is either due to the edges of a triangle of S or due to a triangle $v \in V(S)$ in S with $d(v) \geq 3$.

Case I: If all the vertices of Z' are due to the adjacent edges of a single triangle Z in S , then by the definition of $L_\bullet(S)$, we have triangle Z in S with one and two negatively marked vertices in S . Thus, again we have a contradiction to (a).

Case II: Now, since this L -triangle is not due to any triangle of S , therefore Z' must contain an L -vertex, say e_p , such that it is incident with a vertex $v \in V(S)$ with $d(v) \geq 3$ in S . Then, by the definition of $L_\bullet(S)$, either such L -triangle is all-positive or all-negative. So there is no such positive L -edge in $L_\bullet(S)$. Hence, by Theorem 8, $L_\bullet(S)$ is \mathcal{C} -sign-compatible. This completes the proof. ■

4. EXISTENTIAL CHARACTERIZATION OF $L_\bullet(S)$

In this section we establish the characterization of the \bullet -line sigraph. While the characterization problem has been solved for ‘line sigraph’ (i.e., sigraph S for which there exists a sigraph H such that $L(H) \cong S$) as in [2], the same remains to be solved for the \times -line sigraph’ (i.e., sigraph S for which there exists a sigraph H such that $L_\times(H) \cong S$) as well as for the ‘ \bullet -line sigraph’ (i.e., sigraph S for which there exists a sigraph H such that $L_\bullet(H) \cong S$).

Hence, for any given isolate-free sigraph S , consider the sigraph equation

$$(1) \quad L_\bullet(H) \cong S$$

where any sigraph H satisfying (1) (i.e., a ‘solution’ of (1)) will be called an L_\bullet -root of S [1]. By the definition of \bullet -line sigraph it is clear that

$$L_\bullet(S^u) \cong L(S^u),$$

so Theorem 1 is a characterization of \bullet -line graphs also. We have the following important observation by Sampatkumar, which is useful in the upcoming theorem.

Remark 10 [15]. *Every canonically marked sigraph contains an even number of negative vertices.*

Now, we give two following lemmas which are essential for the characterization of \bullet -line graphs.

Lemma 11. *Let S be a connected graph and let U be any even subset of $V(S)$. Then there is a signature σ for S such that $\mu_\sigma(v) = -$ if and only if $v \in U$.*

Proof. Let $|U| = 2k$. If $k = 0$ then we have the all-positive signature; now inductively suppose the statement true for even subsets of size $2, 4, \dots, 2(k-1)$. Let u, v be any two elements of U . By the inductive hypothesis there is a signature σ such that $\mu_\sigma(w) = -$ if and only if $w \in U - \{u, v\}$ (or w could be anything other than u or v). There is a path from u to v ; change the sign of every edge on the path, giving a signature τ . It is clear that $\mu_\tau(w) = -$ if and only if $w \in U$. ■

Lemma 12. *Let $S = (S^u, \sigma)$ be the \bullet -line graph of sigraph $T = (T^u, \tau)$ and extend T^u to a graph \hat{T}^u by adding a new vertex t and an edge $e = st$, where $s \in V(T^u)$ (so that t is pendent). Now extend σ to a signature $\hat{\sigma}$ on $L(S^u)$ as follows. The new L -edges are e_1e, e_2e, \dots, e_de where the e_i are the edges of T^u incident with s ; give all these the same sign (either $+$ or $-$). Then $\hat{S} = (\hat{S}^u, \hat{\sigma})$ is a \bullet -line graph.*

Proof. Extend τ to a signature on \hat{T}^u , by appropriately signing st so that the canonical marking $\hat{\mu}(s)$ of $V(T)$ agrees with the $\hat{\sigma}(e_i e)$. ■

Now, the following theorem gives us the solution of (1).

Theorem 13. *A given connected sigraph $S = (S^u, \sigma)$ is a \bullet -line graph if and only if following conditions hold in S :*

- (1) S^u is a line graph and the edges of S can be partitioned into complete subsignographs in such a way that no vertex lies in more than two of the subsignographs and each such complete subsignograph is homogeneous.
- (2) if each vertex of S belongs to exactly two of these subsignographs, then the number of all-negative complete sigraphs is even.

Proof. *Necessity:* We are given a sigraph S . Suppose S is a \bullet -line sigraph. Then there exists a sigraph T , such that $S^u \cong L_\bullet(T^u)$, so that S^u is a line graph. Thus, by Theorem 1, the edges of S^u can be partitioned into complete subsignographs such that no vertex lies in more than two of these. The vertices of any such subsignograph \mathcal{Q} are the L -vertices of $L_\bullet(T^u)$ corresponding to the edges of T^u incident with some vertex v of T^u , and therefore the edges of \mathcal{Q} are L -edges of $L_\bullet(T^u)$ signed

with $\mu_\sigma(v)$. Thus these complete subsigraphs are homogeneous, and condition (1) is satisfied.

Next, suppose all the vertices in S lie in exactly two such subsigraphs and number of all-negative subsigraphs is odd. By the definition of \bullet -line sigraph, it is clear that there are odd number of negatively marked vertices in the L_\bullet -root of S , a contradiction to the Remark 10. Hence, by contradiction, (2) holds.

Now, suppose there are some vertices in S such that these are not in two such subsigraphs. While making the L_\bullet -root of S by the help of these subsets, it is clear that there are some pendent vertices in the L_\bullet -root of S . Since the vertices are pendent in L_\bullet -root of S , so there are not any other edges incident with these vertices in the L_\bullet -root of S . By the definition of $L_\bullet(S)$, these vertices are not giving any contribution to the signing of any complete subsigraphs in the \bullet -line sigraph. Thus, by including or excluding these vertices the number of negatively marked vertices, in L_\bullet -root of S , is even. So the number of all-negative homogeneous complete subsigraphs is either even or odd according to the number of pendent vertices and their canonical marking in the L_\bullet -root of S .

Sufficiency: Suppose S is a sigraph satisfying the conditions. We shall show that S is the \bullet -line sigraph, that is, there exists a sigraph T such that $S \cong L_\bullet(T)$.

Let T^u be the graph such that $S^u = L(T^u)$. We wish to find a signature τ on T^u such that μ_τ is the canonical marking of $V(T^u)$ giving the required signature of S^u . Assume, first that there is an even number of all-negative complete subsigraphs in the partitioning of $E(S)$. Let U be the corresponding set of vertices of T^u . By Lemma 11, there is a signature τ on T^u such that μ_τ is negative exactly on U . Finally, if T^u has a pendent vertex t , then by Lemma 12 there is a complete sigraph whose sign may be chosen independently. This completes the proof. ■

Note: If a sigraph S is disconnected then S is a \bullet -line sigraph if and only if its every component satisfies the conditions of Theorem 13 separately.

Corollary 14. *Every homogeneous complete sigraph K_n is a \bullet -line sigraph.*

Proof. Suppose we are given a homogeneous complete sigraph. It is easy to see that L_\bullet -root for K_n^u is star $K_{1,n}^u$. Thus, K_n^u is a line graph. Thus, the conditions of Theorem 13 are satisfied. Hence, every homogeneous complete sigraph K_n is a \bullet -line sigraph. ■

Corollary 15. *Every path sigraph P_n is a \bullet -line sigraph.*

Proof. Suppose we are given a path sigraph P_n . It is easy to see that L_\bullet -root for P_n^u is P_{n+1}^u . Thus, P_n^u is a line graph. We can partition P_n into $(n-1)$ K_2 complete subsigraphs in such a way that no vertex lies in more than two of the subsigraphs and each such K_2 is homogeneous. Since there are pendent vertices in P_n , number of such complete subsigraph may be even or odd. So both the

conditions of Theorem 13 are satisfied. Hence, every path sigraph P_n is a \bullet -line sigraph. ■

Corollary 16. *A cycle C_n is a \bullet -line sigraph if it contains even number of negative edges.*

Proof. Suppose we are given a cycle C_n . It is easy to see that the L_\bullet -root for C_n^u is C_n^u . Thus, C_n^u is a line graph. We can partition C_n into $n/2$ K_2 complete subsigraphs in such a way that no vertex lies in more than two of the subsigraphs and each such K_2 is homogeneous. Since there are no pendent vertices in C_n and there is an even number of negative edges in C_n , the number of such complete subsigraphs K_2 is even. So both the conditions of Theorem 13 are satisfied. Hence, every cycle sigraph C_n is a \bullet -line sigraph. ■

Corollary 17. *Every balanced cycle C_n is a \bullet -line sigraph.*

Proof. The result is trivial by Lemma 3 and Corollary 16. ■

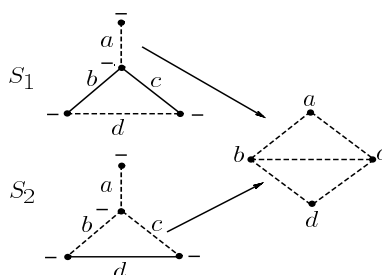


Figure 3. Showing a \bullet -line sigraph and its two L_\bullet -root sigraphs.

Note: We know that if there are odd (even) number of negative edges incident with any vertex, then due to its canonical marking $\mu_\sigma(v) = -$ ($\mu_\sigma(v) = +$). Therefore, for a given \bullet -line sigraph its L_\bullet -root sigraphs is not unique. The pictorial presentation of this is shown in Figure 3. Hence, the following problem is open.

Problem 18. Characterize \bullet -line sigraphs having exactly one L_\bullet -root sigraph up to isomorphism.

Acknowledgement

The authors express gratitude to Dr. B.D. Acharya, who attracted the authors to the characterization problem and to find other related properties of \bullet -line sigraphs. Also, his paper *Signed intersection graphs* [1] gave a way to solve the problems.

REFERENCES

- [1] B.D. Acharya, *Signed intersection graphs*, J. Discrete Math. Sci. Cryptogr. **13** (2010) 553–569.
doi:10.1080/09720529.2010.10698314
- [2] M. Acharya and D. Sinha, *Characterizations of line sigraphs*, Nat. Acad. Sci. Lett. **28** (2005) 31–34.
Extended abstract in: Electron. Notes Discrete Math. **15** (2003) 12.
- [3] M. Behzad and G.T. Chartrand, *Line coloring of signed graphs*, Elem. Math. **24**(3) (1969) 49–52.
- [4] L.W. Beineke, *Derived graphs and digraphs*, in: Beiträge zur Graphentheorie, H. Sachs, H. Voss and H. Walter (Ed(s)), (Teubner, Leipzig, 1968) 17–33.
- [5] L.W. Beineke, *Characterizations of derived graphs*, J. Combin. Theory (B) **9** (1970) 129–135.
doi:10.1016/S0021-9800(70)80019-9
- [6] M.K. Gill, Contribution to some topics in graph theory and its applications (Ph.D. Thesis, Indian Institute of Technology, Bombay, 1983).
- [7] F. Harary, *On the notion of balance of a signed graph*, Michigan Math. J. **2** (1953) 143–146.
doi:10.1307/mmj/1028989917
- [8] F. Harary, Graph Theory (Addison-Wesley Publ. Comp., Reading, Massachusetts, 1969).
- [9] F. Harary and R.Z. Norman, *Some properties of line digraphs*, Rend. Circ. Mat. Palermo (2) Suppl. **9** (1960) 161–168.
- [10] R.L. Hemminger and L.W. Beineke, *Line graphs and line digraphs*, in: Selected Topics in Graph Theory, L.W. Beineke and R.J. Wilson (Ed(s)), (Academic Press Inc., 1978) 271–305.
- [11] J. Krausz, *Démonstration nouvelle d’une théorème de Whitney sur les réseaux*, Mat. Fiz. Lapok **50** (1943) 75–89.
- [12] V.V. Menon, *On repeated interchange graphs*, Amer. Math. Monthly **73** (1966) 986–989.
doi:10.2307/2314503
- [13] O. Ore, Theory of Graphs (Amer. Math. Soc. Colloq. Publ. 38, Providence, 1962).
- [14] G. Sabidussi, *Graph derivatives*, Math. Z. **76** (1961) 385–401.
doi:10.1007/BF01210984
- [15] E. Sampathkumar, *Point-signed and line-signed graphs*, Karnatak Univ. Graph Theory Res. Rep. No.1 (1973) (also see Abstract No. 1 in: Graph Theory Newsletter **2**(2) (1972), National Academy Science Letters **7** (1984) 91–93).
- [16] D. Sinha, New frontiers in the theory of signed graph (Ph.D. Thesis, University of Delhi, Faculty of Technology, 2005).

- [17] D. Sinha and A. Dhama, *Sign-compatibility of some derived signed graphs*, Indian J. Math. **55** (2013) 23–40.
- [18] D. Sinha and A. Dhama, *Canonical-sign-compatibility of some signed graphs*, J. Combin. Inf. Syst. Sci. **38** (2013) 129–138.
- [19] D.B. West, *Introduction to Graph Theory* (Prentice-Hall of India Pvt. Ltd., 1996).
- [20] H. Whitney, *Congruent graphs and the connectivity of graphs*, Amer. J. Math. **54** (1932) 150–168.
doi:10.2307/2371086
- [21] T. Zaslavsky, *A mathematical bibliography of signed and gain graphs and allied areas*, 7th Edition, Electron. J. Combin. (1998) #DS8.
- [22] T. Zaslavsky, *Glossary of signed and gain graphs and allied areas*, Second Edition, Electron. J. Combin. (1998) #DS9.
- [23] T. Zaslavsky, *Signed analogs of bipartite graphs*, Discrete Math. **179** (1998) 205–216.
doi:10.1016/S0012-365X(96)00386-X

Received 25 September 2013

Revised 7 April 2014

Accepted 9 April 2014