

## More Equienergetic Signed Graphs

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*Dedicated to Professor Ivan Gutman*

### Abstract

The energy of signed graph is the sum of the absolute values of the eigenvalues of its adjacency matrix. Two signed graphs are said to be equienergetic if they have same energy. In the literature the construction of equienergetic signed graphs are reported. In this paper we obtain the characteristic polynomial and energy of the join of two signed graphs and thereby we give another construction of unbalanced, noncospectral equienergetic signed graphs on  $n \geq 8$  vertices.

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## 1. Introduction

Let  $G$  be a simple undirected graph with  $n$  vertices and  $m$  edges. Let the vertex set of  $G$  be  $V(G) = \{v_1, v_2, \dots, v_n\}$  and edge set be  $E(G) = \{e_1, e_2, \dots, e_m\}$ . A *signed graph* (or *sigraph*) is an ordered pair  $G^s = (G, f)$  where  $G$  is the underlying graph of  $G^s$  and  $f : E(G) \rightarrow \{+1, -1\}$  is the signing function from the edge set  $E(G)$  into the set  $\{+1, -1\}$ . Thus the signed graph  $G^s$  is a graph obtained from the graph  $G$  by assigning positive sign or negative sign to the edges of  $G$ . A signed graph  $G^s$  is called *homogeneous* if its edges are all positive or all negative, otherwise it is called *heterogeneous*. The sign of a cycle is the product of the signs of its edges. A signed graph is said to be *balanced* if all its cycles are positive.

The *adjacency matrix* of a signed graph  $G^s$  is an  $n \times n$  real symmetric matrix

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$A(G^s) = [a_{ij}]$ , where

$$a_{ij} = \begin{cases} 1, & \text{if the edge between the vertices } v_i \text{ and } v_j \text{ is positive} \\ -1, & \text{if the edge between the vertices } v_i \text{ and } v_j \text{ is negative} \\ 0, & \text{otherwise.} \end{cases}$$

The *characteristic polynomial* of  $A(G^s)$  is  $\phi(G^s : \xi) = \det(\xi I - A(G^s))$ , where  $I$  is the identity matrix of order  $n$ . The eigenvalues of the matrix  $A(G^s)$  are denoted by  $\xi_1, \xi_2, \dots, \xi_n$  and their collection is called the *spectra* of  $G^s$ . Since the adjacency matrix of the signed graph  $G^s$  is real and symmetric, its eigenvalues are real. Two signed graphs are said to be *cospectral* if they have same spectra. A signed graph is balanced if and only if it is cospectral with its underlying unsigned graph [1].

The *energy* of a signed graph  $G^s$  denoted by  $\mathcal{E}(G^s)$  is defined as [6]

$$\mathcal{E}(G^s) = \sum_{i=1}^n |\xi_i|. \quad (1)$$

The Eq. (1) is in full analogy to the *ordinary graph energy* [7] defined as the sum of the absolute values of the eigenvalues of the adjacency matrix of  $G$ . For more details about the graph energy one can see the book [10].

The signed graphs  $G_1^s$  and  $G_2^s$  are said to be *equienergetic* if  $\mathcal{E}(G_1^s) = \mathcal{E}(G_2^s)$ . In trivial manner, the cospectral signed graphs are equienergetic. Nayak [11] constructed pairs of equienergetic signed graphs on  $2n$  vertices,  $n \geq 4$ . For odd  $n \geq 5$  and for even  $n \geq 6$ , Bhat and Pirzada [3] constructed the pairs of unbalanced, noncospectral equienergetic signed graphs. If  $G$  is an odd unicyclic graph, then any two signed graphs on  $G$  have the same energy [3]. There are several results on equienergetic graphs [2, 4, 8, 9, 12–14]. In this paper we obtain the characteristic polynomial and energy of the join of two signed graphs and give another construction for unbalanced, noncospectral equienergetic signed graphs on  $n \geq 8$  vertices.

## 2. Spectra and Energy of the Join of Signed Graphs

In Figures 1 and 2, the dotted line represents negative edge and thick line represents positive edge.

**Definition 2.1.** The positive join of two signed graphs  $G_1^s$  and  $G_2^s$  denoted by  $G_1^s \oplus G_2^s$  is a graph obtained from  $G_1^s$  and  $G_2^s$  by joining each vertex of  $G_1^s$  to all vertices of  $G_2^s$  with positive edges.

**Definition 2.2.** The negative join of two signed graphs  $G_1^s$  and  $G_2^s$  denoted by  $G_1^s \ominus G_2^s$  is a graph obtained from  $G_1^s$  and  $G_2^s$  by joining each vertex of  $G_1^s$  to all vertices of  $G_2^s$  with negative edges.

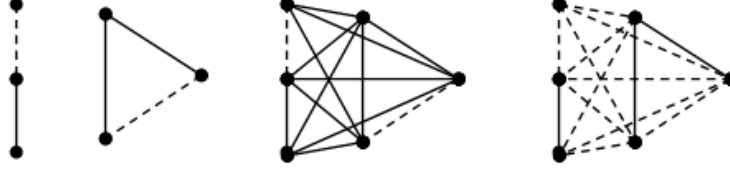


Figure 1: Signed graphs  $G_1^s$  and  $G_2^s$  and their joins  $G_1^s \oplus G_2^s$  and  $G_1^s \ominus G_2^s$ .

Let  $W$  be a subset of the vertex set  $V(G^s)$  of a signed graph  $G^s$  and  $\bar{W} = V(G^s) \setminus W$ . Let  $G'^s$  be the signed graph obtained from  $G^s$  by changing the positive edges to negative edges and negative edges to positive edges between  $W$  and  $\bar{W}$ . We say that  $G'^s$  has been obtained from  $G^s$  by switching with respect to  $W$ . Two signed graphs are said to be switching equivalent if one is obtained from the other by a sequence of switching. The signed graphs  $G_1^s \oplus G_2^s$  and  $G_1^s \ominus G_2^s$  are switching equivalent.

**Theorem 2.3.**  $\phi(G_1^s \oplus G_2^s : \xi) = \phi(G_1^s \ominus G_2^s : \xi)$ .

*Proof.*

$$\begin{aligned} \phi(G_1^s \oplus G_2^s : \xi) &= \det(\xi I - A(G_1^s \oplus G_2^s)) \\ &= \begin{vmatrix} \xi I_{n_1} - A(G_1^s) & -J_{n_1 \times n_2} \\ -J_{n_2 \times n_1} & \xi I_{n_2} - A(G_2^s) \end{vmatrix}, \end{aligned} \tag{2}$$

where  $J$  is the matrix whose all entries are equal to 1. In determinant (2), taking  $-1$  common from first  $n_1$  rows and then from the first  $n_1$  columns we get

$$\begin{aligned} \phi(G_1^s \oplus G_2^s : \xi) &= (-1)^{n_1} (-1)^{n_1} \begin{vmatrix} \xi I_{n_1} - A(G_1^s) & J_{n_1 \times n_2} \\ J_{n_2 \times n_1} & \xi I_{n_2} - A(G_2^s) \end{vmatrix} \\ &= \det(\xi I - A(G_1^s \ominus G_2^s)) \\ &= \phi(G_1^s \ominus G_2^s : \xi). \end{aligned}$$

□

By Theorem 2.3, the signed graphs  $G_1^s \oplus G_2^s$  and  $G_1^s \ominus G_2^s$  are cospectral. Hence  $\mathcal{L}(G_1^s \oplus G_2^s) = \mathcal{L}(G_1^s \ominus G_2^s)$ .

The *positive (negative) degree* of a vertex  $v_i$  in a signed graph  $G^s$  is the number of positive (negative) edges incident to  $v_i$  and is denoted by  $d_i^+$  ( $d_i^-$ ). The degree of a vertex  $v_i$  in  $G^s$  is  $\deg(v_i) = d_i^+ + d_i^-$ . The *net degree* of a vertex  $v_i$  in  $G^s$  is

$d_i^+ - d_i^-$ . A signed graph  $G^s$  is said to be  $k$ -net regular if all its vertices have same net degree equal to  $k$ , that is  $k = d_i^+ - d_i^-$  for  $i = 1, 2, \dots, n$ . The net regularity of signed graph can be either positive or negative or zero.

**Theorem 2.4.** *Let  $G_i^s$  be a  $k_i$ -net regular signed graph on  $n_i$  vertices,  $i = 1, 2$ . Then the characteristic polynomial of the adjacency matrix of positive join  $G_1^s \oplus G_2^s$  is*

$$\phi(G_1^s \oplus G_2^s : \xi) = \frac{[(\xi - k_1)(\xi - k_2) - n_1 n_2]}{(\xi - k_1)(\xi - k_2)} \phi(G_1^s : \xi) \phi(G_2^s : \xi). \quad (3)$$

*Proof.*

$$\begin{aligned} \phi(G_1^s \oplus G_2^s : \xi) &= \det(\xi I - A(G_1^s \oplus G_2^s)) \\ &= \begin{vmatrix} \xi I_{n_1} - A(G_1^s) & -J_{n_1 \times n_2} \\ -J_{n_2 \times n_1} & \xi I_{n_2} - A(G_2^s) \end{vmatrix} \end{aligned} \quad (4)$$

where  $J$  is the matrix whose all entries are equal to unity.

The determinant (4) can be written as

$$\begin{vmatrix} \xi & -a_{12} & \cdots & -a_{1n_1} & -1 & -1 & \cdots & -1 \\ -a_{21} & \xi & \cdots & -a_{2n_1} & -1 & -1 & \cdots & -1 \\ \vdots & & \vdots & & & & \vdots & \\ -a_{n_1 1} & -a_{n_1 2} & \cdots & \mu & -1 & -1 & \cdots & -1 \\ -1 & -1 & \cdots & -1 & \xi & -a'_{12} & \cdots & -a'_{1n_2} \\ -1 & -1 & \cdots & -1 & -a'_{21} & \xi & \cdots & -a'_{2n_2} \\ \vdots & & \vdots & & & & \vdots & \\ -1 & -1 & \cdots & -1 & -a'_{n_2 1} & -a'_{n_2 2} & \cdots & \xi \end{vmatrix} \quad (5)$$

where  $a_{ij}$  is the  $(i, j)$ -th entry in  $A(G_1^s)$ ,  $i, j = 1, 2, \dots, n_1$  and  $a'_{ij}$  is the  $(i, j)$ -th entry in the matrix  $A(G_2^s)$ ,  $i, j = 1, 2, \dots, n_2$ . Since  $G_i^s$  is a  $k_i$ -net regular signed graph

$$\sum_{j=1}^{n_1} a_{ij} = k_1 \quad \text{for } i = 1, 2, \dots, n_1 \quad (6)$$

and

$$\sum_{j=1}^{n_2} a'_{ij} = k_2 \quad \text{for } i = 1, 2, \dots, n_2. \quad (7)$$

We now perform the number of operations on the determinant (5).

Subtract the row  $(n_1 + 1)$  from the rows  $(n_1 + 2), (n_1 + 3), \dots, (n_1 + n_2)$  of (5)

to obtain (8)

$$\begin{vmatrix} \xi & -a_{12} & \cdots & -a_{1n_1} & -1 & -1 & \cdots & -1 \\ -a_{21} & \xi & \cdots & -a_{2n_1} & -1 & -1 & \cdots & -1 \\ \vdots & & \vdots & & & & \vdots & \\ -a_{n_1 1} & -a_{n_1 2} & \cdots & \mu & -1 & -1 & \cdots & -1 \\ -1 & -1 & \cdots & -1 & \xi & -a'_{12} & \cdots & -a'_{1n_2} \\ 0 & 0 & \cdots & 0 & -a'_{21} - \xi & \xi + a'_{12} & \cdots & -a'_{2n_2} + a'_{1n_2} \\ \vdots & & \vdots & & & & \vdots & \\ 0 & 0 & \cdots & 0 & -a'_{n_2 1} - \xi & -a'_{n_2 2} + a'_{12} & \cdots & \xi + a'_{1n_2} \end{vmatrix} \cdot \quad (8)$$

Adding the columns  $(n_1 + 2), (n_1 + 3), \dots, (n_1 + n_2)$  to the column  $(n_1 + 1)$  of (8) and using Eq. (7) we arrive at the determinant (9):

$$\begin{vmatrix} \xi & -a_{12} & \cdots & -a_{1n_1} & -n_2 & -1 & \cdots & -1 \\ -a_{21} & \xi & \cdots & -a_{2n_1} & -n_2 & -1 & \cdots & -1 \\ \vdots & & \vdots & & & & \vdots & \\ -a_{n_1 1} & -a_{n_1 2} & \cdots & \xi & -n_2 & -1 & \cdots & -1 \\ -1 & -1 & \cdots & -1 & \xi - k_2 & -a'_{12} & \cdots & -a'_{1n_2} \\ 0 & 0 & \cdots & 0 & 0 & \xi + a'_{12} & \cdots & -a'_{2n_2} + a'_{1n_2} \\ \vdots & & \vdots & & & & \vdots & \\ 0 & 0 & \cdots & 0 & 0 & -a'_{n_2 2} + a'_{12} & \cdots & \xi + a'_{1n_2} \end{vmatrix} \quad (9)$$

which is equal to (10):

$$\begin{vmatrix} \xi & -a_{12} & \cdots & -a_{1n_1} & -n_2 \\ -a_{21} & \xi & \cdots & -a_{2n_1} & -n_2 \\ \vdots & & \vdots & & \\ -a_{n_1 1} & -a_{n_1 2} & \cdots & \xi & -n_2 \\ -1 & -1 & \cdots & -1 & \xi - k_2 \end{vmatrix} |B| \quad (10)$$

where

$$|B| = \begin{vmatrix} \xi + a'_{12} & -a'_{23} + a'_{13} & \cdots & -a'_{2n_2} + a'_{1n_2} \\ -a'_{32} + a'_{12} & \xi + a'_{13} & \cdots & -a'_{3n_2} + a'_{1n_2} \\ \vdots & & \vdots & \\ -a'_{n_2 2} + a'_{12} & -a'_{n_2 3} + a'_{13} & \cdots & \xi + a'_{1n_2} \end{vmatrix} \cdot \quad (11)$$

The first determinant in (10) is of order  $(n_1 + 1)$ . Subtract the first row from

the rows  $2, 3, \dots, n_1$ , in (10) to obtain (12):

$$\begin{vmatrix} \xi & -a_{12} & \cdots & -a_{1n_1} & -n_2 \\ -a_{21} - \xi & \xi + a_{12} & \cdots & -a_{2n_1} + a_{1n_1} & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ -a_{n_11} - \xi & -a_{n_12} + a_{12} & \cdots & \xi + a_{1n_1} & 0 \\ -1 & -1 & \cdots & -1 & \xi - k_2 \end{vmatrix} |B|. \quad (12)$$

Adding columns  $2, 3, \dots, n_1$  to the first column of (12) and using Eq. (6) we get (13):

$$\begin{vmatrix} \xi - k_1 & -a_{12} & \cdots & -a_{1n_1} & -n_2 \\ 0 & \xi + a_{12} & \cdots & -a_{2n_1} + a_{1n_1} & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & -a_{n_12} + a_{12} & \cdots & \xi + a_{1n_1} & 0 \\ -n_1 & -1 & \cdots & -1 & \xi - k_2 \end{vmatrix} |B|. \quad (13)$$

Expand it along the first column to obtain (14):

$$\{(\xi - k_1) \Delta_1 - (-1)^{n_1} (n_1) \Delta_2\} |B| \quad (14)$$

where

$$\Delta_1 = \begin{vmatrix} \xi + a_{12} & -a_{23} + a_{13} & \cdots & -a_{2n_1} + a_{1n_1} & 0 \\ -a_{32} + a_{12} & \xi + a_{13} & \cdots & -a_{3n_1} + a_{1n_1} & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ -a_{n_12} + a_{12} & -a_{n_13} + a_{13} & \cdots & \xi + a_{1n_1} & 0 \\ -1 & -1 & \cdots & -1 & \xi - k_2 \end{vmatrix}$$

and

$$\Delta_2 = \begin{vmatrix} -a_{12} & -a_{13} & \cdots & -a_{1n_1} & -n_2 \\ \xi + a_{12} & -a_{23} + a_{13} & \cdots & -a_{2n_1} + a_{1n_1} & 0 \\ -a_{32} + a_{12} & \xi + a_{13} & \cdots & -a_{3n_1} + a_{1n_1} & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ -a_{n_12} + a_{12} & -a_{n_13} + a_{13} & \cdots & \xi + a_{1n_1} & 0 \end{vmatrix}.$$

The expression (14) can be rewritten as

$$\begin{aligned} & \{(\xi - k_1)(\xi - k_2) |A| - (-1)^{n_1} (n_1) (-1)^{1+n_1} (-n_2) |A|\} |B| \\ & = \{(\xi - k_1)(\xi - k_2) - n_1 n_2\} |A| |B| \end{aligned} \quad (15)$$

where

$$|A| = \begin{vmatrix} \xi + a_{12} & -a_{23} + a_{13} & \cdots & -a_{2n_1} + a_{1n_1} \\ -a_{32} + a_{12} & \xi + a_{13} & \cdots & -a_{3n_1} + a_{1n_1} \\ \vdots & \vdots & \vdots & \vdots \\ -a_{n_12} + a_{12} & -a_{n_13} + a_{13} & \cdots & \xi + a_{1n_1} \end{vmatrix}. \quad (16)$$

The determinant (16) can be written as

$$|A| = \frac{1}{(\xi - k_1)} \begin{vmatrix} \xi - k_1 & -a_{12} & -a_{13} & \cdots & -a_{1n_1} \\ 0 & \xi + a_{12} & -a_{23} + a_{13} & \cdots & -a_{2n_1} + a_{1n_1} \\ 0 & -a_{32} + a_{12} & \xi + a_{13} & \cdots & -a_{3n_1} + a_{1n_1} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & -a_{n_1 2} + a_{12} & -a_{n_1 3} + a_{13} & \cdots & \xi + a_{1n_1} \end{vmatrix}. \tag{17}$$

From Eq. (6) the sum of the  $i$ -th row in (17) is  $\xi + a_{i1}$  for  $i = 2, 3, \dots, n_1$ . Therefore, by subtracting the columns  $2, 3, \dots, n_1$  of (17) from the first column, we obtain (18):

$$|A| = \frac{1}{(\xi - k_1)} \begin{vmatrix} \xi & -a_{12} & -a_{13} & \cdots & -a_{1n_1} \\ -\xi - a_{21} & \xi + a_{12} & -a_{23} + a_{13} & \cdots & -a_{2n_1} + a_{1n_1} \\ -\xi - a_{31} & -a_{32} + a_{12} & \xi + a_{13} & \cdots & -a_{3n_1} + a_{1n_1} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ -\xi - a_{n_1 1} & -a_{n_1 2} + a_{12} & -a_{n_1 3} + a_{13} & \cdots & \xi + a_{1n_1} \end{vmatrix}. \tag{18}$$

Add the first row of (18) to the rows  $2, 3, \dots, n_1$  to obtain (19):

$$\begin{aligned} |A| &= \frac{1}{(\xi - k_1)} \begin{vmatrix} \xi & -a_{12} & -a_{13} & \cdots & -a_{1n_1} \\ -a_{21} & \xi & -a_{23} & \cdots & -a_{2n_1} \\ -a_{31} & -a_{32} & \xi & \cdots & -a_{3n_1} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ -a_{n_1 1} & -a_{n_1 2} & -a_{n_1 3} & \cdots & \xi \end{vmatrix} \\ &= \frac{1}{(\xi - k_1)} \phi(G_1^s : \xi). \end{aligned} \tag{19}$$

In a similar manner we can show that from (11),

$$|B| = \frac{1}{(\xi - k_2)} \phi(G_2^s : \xi). \tag{20}$$

Substituting (19) and (20) back into (15) gives Eq. (3). □

**Theorem 2.5.** *Let  $G_i^s$  be a  $k_i$ -net regular signed graph on  $n_i$  vertices,  $i = 1, 2$ . Then*

$$\mathcal{E}(G_1^s \oplus G_2^s) = \mathcal{E}(G_1^s) + \mathcal{E}(G_2^s) - (k_1 + k_2) + \sqrt{(k_1 - k_2)^2 + 4n_1 n_2}.$$

*Proof.* From Theorem 2.4,

$$\phi(G_1^s \oplus G_2^s : \xi) = \frac{[(\xi - k_1)(\xi - k_2) - n_1 n_2]}{(\xi - k_1)(\xi - k_2)} \phi(G_1^s : \xi) \phi(G_2^s : \xi),$$

which gives that

$$(\xi - k_1)(\xi - k_2)\phi(G_1^s \oplus G_2^s : \xi) = [(\xi - k_1)(\xi - k_2) - n_1 n_2]\phi(G_1^s : \xi)\phi(G_2^s : \xi).$$

Let

$$P_1(\xi) = (\xi - k_1)(\xi - k_2)\phi(G_1^s \oplus G_2^s : \xi)$$

and

$$P_2(\xi) = [(\xi - k_1)(\xi - k_2) - n_1 n_2]\phi(G_1^s : \xi)\phi(G_2^s : \xi).$$

The roots of  $P_1(\xi) = 0$  are  $k_1, k_2$  and the eigenvalues of  $G_1^s \oplus G_2^s$ . Therefore the sum of the absolute values of the roots of  $P_1(\xi) = 0$  is

$$k_1 + k_2 + \mathcal{E}(G_1^s \oplus G_2^s). \quad (21)$$

The roots of  $P_2(\xi) = 0$  are the eigenvalues of  $G_1^s$ , eigenvalues of  $G_2^s$  and

$$\frac{1}{2} \left[ (k_1 + k_2) \pm \sqrt{(k_1 + k_2)^2 - 4(k_1 k_2 - n_1 n_2)} \right].$$

Therefore the sum of the absolute values of the roots of  $P_2(\xi) = 0$  is

$$\begin{aligned} \mathcal{E}(G_1^s) + \mathcal{E}(G_2^s) + \left| \frac{1}{2} \left[ (k_1 + k_2) + \sqrt{(k_1 + k_2)^2 - 4(k_1 k_2 - n_1 n_2)} \right] \right| \\ + \left| \frac{1}{2} \left[ (k_1 + k_2) - \sqrt{(k_1 + k_2)^2 - 4(k_1 k_2 - n_1 n_2)} \right] \right|. \end{aligned} \quad (22)$$

Since  $P_1(\xi) = P_2(\xi)$ , equating (21) and (22), we get

$$\begin{aligned} \mathcal{E}(G_1^s \oplus G_2^s) &= \mathcal{E}(G_1^s) + \mathcal{E}(G_2^s) - (k_1 + k_2) \\ &+ \left| \frac{1}{2} \left[ (k_1 + k_2) + \sqrt{(k_1 + k_2)^2 - 4(k_1 k_2 - n_1 n_2)} \right] \right| \\ &+ \left| \frac{1}{2} \left[ (k_1 + k_2) - \sqrt{(k_1 + k_2)^2 - 4(k_1 k_2 - n_1 n_2)} \right] \right|. \end{aligned} \quad (23)$$

Since  $k_1 k_2 \leq (n_1 - 1)(n_2 - 1) < n_1 n_2$ , the Eq. (23) reduces to

$$\begin{aligned} \mathcal{E}(G_1^s \oplus G_2^s) &= \mathcal{E}(G_1^s) + \mathcal{E}(G_2^s) - (k_1 + k_2) + \sqrt{(k_1 + k_2)^2 - 4(k_1 k_2 - n_1 n_2)} \\ &= \mathcal{E}(G_1^s) + \mathcal{E}(G_2^s) - (k_1 + k_2) + \sqrt{(k_1 - k_2)^2 + 4n_1 n_2}. \end{aligned}$$

□

**Corollary 2.6.** *If  $H_1^s$  and  $H_2^s$  are non cospectral, equienergetic net regular signed graphs on  $n$  vertices and of same net regularity, then for any net regular signed graph  $G^s$ ,  $\mathcal{E}(H_1^s \oplus G^s) = \mathcal{E}(H_2^s \oplus G^s)$ .*



The complete graph  $K_p$  is a net regular signed graph on  $p$  vertices with net regularity  $p - 1$  and  $\mathcal{E}(K_p) = 2(p - 1)$  [5].

**Corollary 2.7.** *Let  $G^s$  be a  $k$ -net regular signed graph on  $n$  vertices. Then*

$$\mathcal{E}(G^s \oplus K_p) = \mathcal{E}(G^s) + p - 1 - k + \sqrt{(p - 1 - k)^2 + 4np}.$$

The totally disconnected graph  $\overline{K_p}$  is a net regular signed graph on  $p$  vertices with net regularity 0 and  $\mathcal{E}(\overline{K_p}) = 0$  [5].

**Corollary 2.8.** *Let  $G^s$  be a  $k$ -net regular signed graph on  $n$  vertices. Then*

$$\mathcal{E}(G^s \oplus \overline{K_p}) = \mathcal{E}(G^s) - k + \sqrt{k^2 + 4np}.$$

Any ordinary regular graph  $H$  of degree  $r$  is a net regular signed graph with net regularity  $r$ .

**Corollary 2.9.** *Let  $H$  be an  $r$ -regular ordinary graph on  $n_1$  vertices and  $G^s$  be a  $k$ -net regular signed graph on  $n_2$  vertices. Then*

$$\mathcal{E}(H \oplus G^s) = \mathcal{E}(H) + \mathcal{E}(G^s) - (r + k) + \sqrt{(r - k)^2 + 4n_1n_2}.$$

### 3. Construction of Equienergetic Signed Graphs

Consider the signed graphs  $H_a^s$  and  $H_b^s$  as shown in the Figure 2.

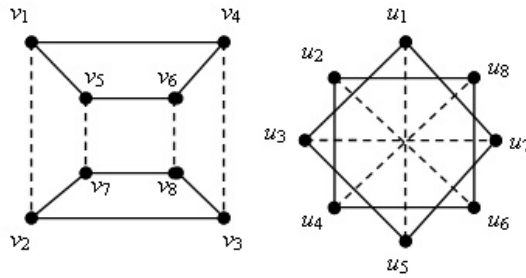


Figure 2: Signed graphs  $H_a^s$  and  $H_b^s$ .

By direct computation,

$$\phi(H_a^s : \xi) = (\xi - 1)^6(\xi + 3)^2 \tag{24}$$

and

$$\phi(H_b^s : \xi) = (\xi - 3)(\xi - 1)^3(\xi + 1)^3(\xi + 3). \tag{25}$$

Both  $H_a^s$  and  $H_b^s$  are net regular signed graphs on 8 vertices and of net regularity 1 and  $\mathcal{E}(H_a^s) = \mathcal{E}(H_b^s) = 12$ .

Let  $H^s$  be any  $k$ -net regular signed graph on  $p \geq 1$  vertices. Then by Theorem 2.5,

$$\mathcal{E}(H_a^s \oplus H^s) = \mathcal{E}(H_b^s \oplus H^s) = \mathcal{E}(H^s) + 11 - k + \sqrt{(1-k)^2 + 32p}.$$

Thus,  $H_a^s \oplus H^s$  and  $H_b^s \oplus H^s$  are equienergetic signed graphs. By Eqs. (24) and (25),  $H_a^s$  and  $H_b^s$  are non cospectral, so by Theorem 2.4,  $H_a^s \oplus H^s$  and  $H_b^s \oplus H^s$  are also non cospectral. Further  $H_a^s \oplus H^s$  and  $H_b^s \oplus H^s$  are heterogeneous, unbalanced signed graphs possessing equal number of vertices  $n = 8 + p$ ,  $p = 0, 1, \dots$

## 4. Conclusion

From Corollary 2.6 it is easy to construct a pair of non cospectral, equienergetic signed graphs. In particular by the construction given in Section 3, it is easy to obtain a pair of non cospectral, heterogeneous, unbalanced, equienergetic  $n$ -vertex signed graphs for  $n \geq 8$ .

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