

# C&O URA Spring 2017

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## 1 Inertia Bounds

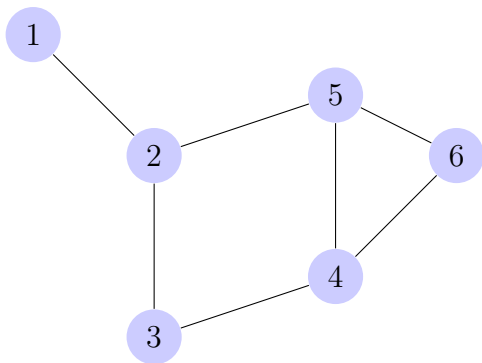
### 1.1 Introduction on Inertia Bounds

#### 1.1 Definition.

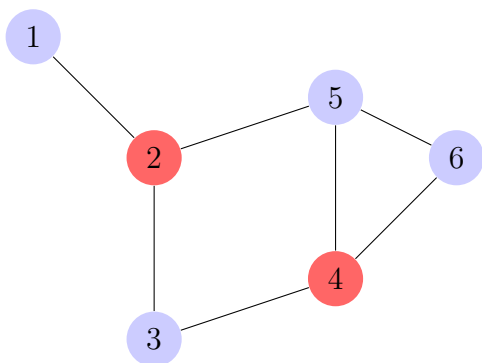
**Independent Set** — An independent set is a set of vertices belonging to a graph in which no two vertices are adjacent.

### 1.1 Example.

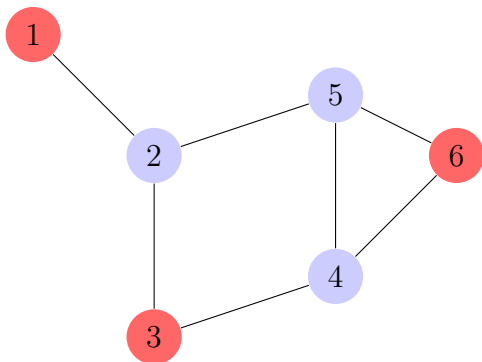
Consider the following graph:



An example of an independent set in this graph is:



However, often the independent set we are most interested in finding is the largest one:



### 1.2 Definition.

**Independence Number** — The independence number of a graph  $G$ , denoted  $\alpha(G)$ , is the size of the largest independent set of  $G$ .

### 1.3 Definition.

**Weight Matrix** — The weight matrix of a graph  $G$ , is a matrix defined by:

$$W_{i,j} = \begin{cases} c_{i,j} & \text{if } v_i \text{ and } v_j \text{ are adjacent} \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

with  $v_i$  a vertex of  $G$  and  $c_{i,j}$ , a constant.

The weight matrix of a graph, is identical to an adjacency matrix, except where there was a 1 in the matrix at entry  $A_{i,j}$  if vertices  $v_i$  and  $v_j$  were adjacent, there is now a constant indicating a weighting for the edge between  $v_i$  and  $v_j$ .

For any graph  $G$ , there exists a bound on  $\alpha(G)$ , known as the Cvetković bound (also referred to as the Interia Bound). This bound provides a relationship between  $\alpha(G)$  and the number of positive, negative, and zero eigenvalues of the weight matrix,  $W$ , associated with  $G$ . The Cvetković bound of  $G$ , is:

$$\alpha(G) \leq \min\{|G| - n_+(W), |G| - n_-(W)\} \quad (2)$$

Where  $n_+(W)$  and  $n_-(W)$  denote the number of positive and negative eigenvalues of  $W$ , respectively.

To prove this, we first need to introduce a result that comes from the Eigenvalue Interlacing Theorem:

#### 1.1 Theorem.

**Corollary of Eigenvalue Interlacing Theorem** — Let  $A$  be an  $n \times n$  real symmetric matrix with eigenvalues  $\lambda_1 \geq \lambda_2 \geq \dots \geq \lambda_n$  and let  $C$  be a  $k \times k$  principal submatrix of  $A$  with eigenvalues  $\tau_1 \geq \tau_2 \geq \dots \geq \tau_k$ . Then  $\lambda_i \geq \tau_i$  for all  $i \in \{1, \dots, k\}$ . [2]

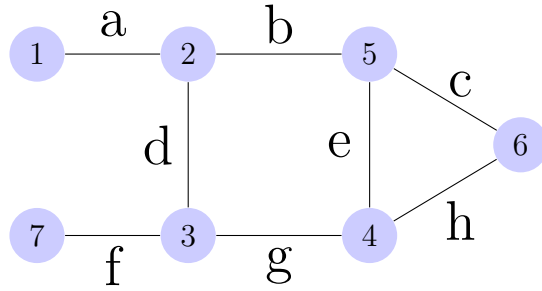
### 1.4 Definition.

**Principal Submatrix** — The principal submatrix of an  $n \times n$  matrix  $A$  is the submatrix obtained where if  $row_i$  is excluded in the submatrix, then  $column_i$  is excluded as well. Note that all principal submatrices of a weight matrix  $W$ , correspond to an induced subgraph in the graph represented by  $W$ .

### 1.2 Example.

The following is an example of a principal submatrix in relation to graph theory.

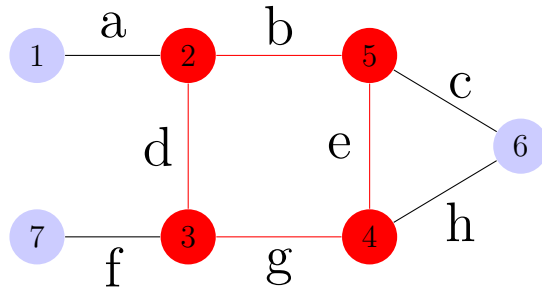
Consider the following graph:



and corresponding weight matrix:

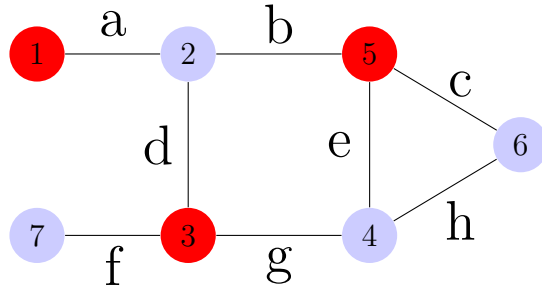
$$\begin{bmatrix} 0 & a & 0 & 0 & 0 & 0 & 0 \\ a & 0 & d & 0 & b & 0 & 0 \\ 0 & d & 0 & g & 0 & 0 & f \\ 0 & 0 & g & 0 & e & h & 0 \\ 0 & b & 0 & e & 0 & c & 0 \\ 0 & 0 & 0 & h & c & 0 & 0 \\ 0 & 0 & f & 0 & 0 & 0 & 0 \end{bmatrix}$$

We can see the following principal submatrix and corresponding induced subgraph:



$$\begin{bmatrix} 0 & a & 0 & 0 & 0 & 0 & 0 \\ a & 0 & d & 0 & b & 0 & 0 \\ 0 & d & 0 & g & 0 & 0 & f \\ 0 & 0 & g & 0 & e & h & 0 \\ 0 & b & 0 & e & 0 & c & 0 \\ 0 & 0 & 0 & h & c & 0 & 0 \\ 0 & 0 & f & 0 & 0 & 0 & 0 \end{bmatrix}$$

As well, we see the following principal submatrix of an independent set of the graph:



$$\begin{bmatrix} 0 & a & 0 & 0 & 0 & 0 & 0 \\ a & 0 & d & 0 & b & 0 & 0 \\ 0 & d & 0 & g & 0 & 0 & f \\ 0 & 0 & g & 0 & e & h & 0 \\ 0 & b & 0 & e & 0 & c & 0 \\ 0 & 0 & 0 & h & c & 0 & 0 \\ 0 & 0 & f & 0 & 0 & 0 & 0 \end{bmatrix}$$

Now to prove the Cvetković Bound:

### 1.2 Theorem.

**Cvetković Bound** — Let  $G$  be a graph on  $n$  vertices, and  $W$  be the weight matrix of  $G$ . Then the following inequality holds:

$$\alpha(G) \leq \min\{|G| - n_+(W), |G| - n_-(W)\} \quad (3)$$

*Proof.* <sup>1</sup> Let  $H$  be the subgraph of  $G$  formed by the vertices in an independent set of size  $s$ . Then  $H$  is an induced subgraph of  $G$  and all eigenvalues of the principal submatrix  $W(H)$  are 0 since the principal submatrix will just be a

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<sup>1</sup>Interesting Graphs and their Colourings, unpublished lecture notes C. Godsil (2004)

zero matrix. Let  $\lambda_i$  denote the  $i$ th largest eigenvalue of  $W$  and  $\tau_i$  denote the  $i$ th largest eigenvalue of  $W(H)$ . Now, by interlacing, we have,

$$\lambda_i \geq \tau_i = 0 \text{ for all } i \in \{1, \dots, s\} \quad (4)$$

and so

$$n - n_-(W) = n_+(W) + n_0(W) \geq s \quad (5)$$

Also, note that by negating  $W$ , the positive eigenvalues become negative eigenvalues and vice versa. Thus,

$$n - n_+(W) = n - n_-(-W), \quad (6)$$

However, the principal submatrix corresponding to  $H$  in  $-W$  is still the zero matrix and thus has all zero eigenvalues. Thus, by interlacing, we get a similar result as above,

$$n - n_+(W) = n - n_-(-W) = n_+(-W) + n_0(-W) \geq s \quad (7)$$

Therefore, both  $n - n_+(W)$  and  $n - n_-(W)$  are greater than or equal to  $s$ . Since  $s$  is the size of the independent set, we can see that letting  $s = \alpha(G)$ , we get:

$$\alpha(G) \leq \min\{|G| - n_+(W), |G| - n_-(W)\} \quad (8)$$

□

## 1.2 Graphs with Tight Inertia Bounds

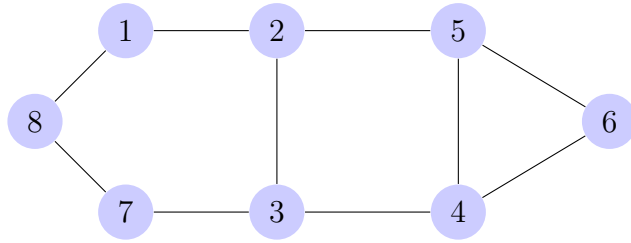
### 1.2.1 Perfect Graphs

#### 1.5 Definition.

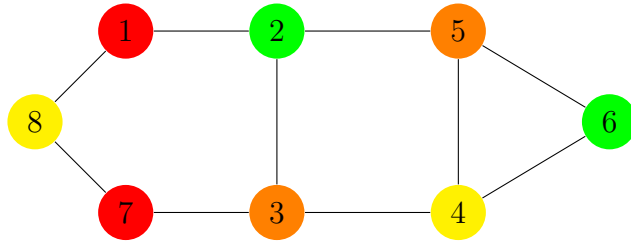
**Chromatic Number** — The chromatic number of a graph,  $\chi(G)$ , is the minimum number of colours needed in a proper colouring of  $G$ . [1]

#### 1.3 Example.

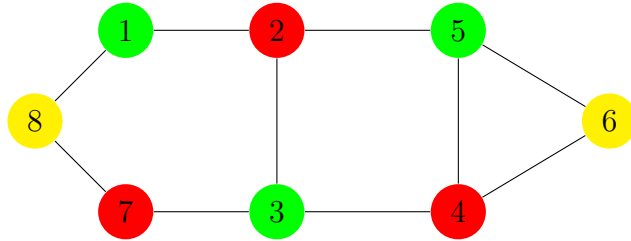
Consider the following graph:



An example of a colouring would be:



However,  $\chi(G)$  for this graph is 3:



#### 1.6 Definition.

**Clique** — An  $m$ -clique in a graph is a complete subgraph on  $m$  vertices. [1]

The clique number,  $\omega(G)$ , is the number of vertices in a maximum clique of  $G$ .

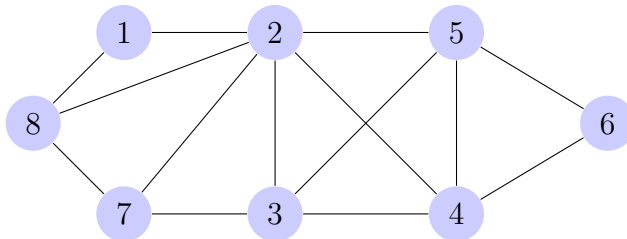
#### 1.7 Definition.

**Clique Cover** — A Clique Cover of the vertex set  $V(G)$  of a graph  $G$  is a set of cliques  $C$ , such that each vertex is in at least one clique in  $C$ .

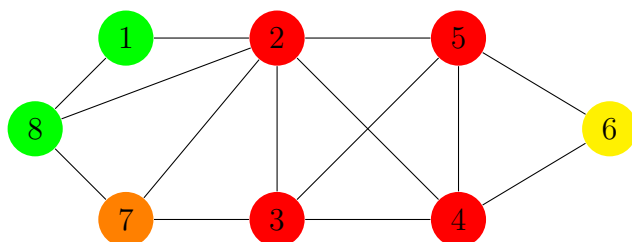
The clique cover number,  $\theta(G)$  is the minimum number of cliques needed in a clique cover of  $G$ . [1]

#### 1.4 Example.

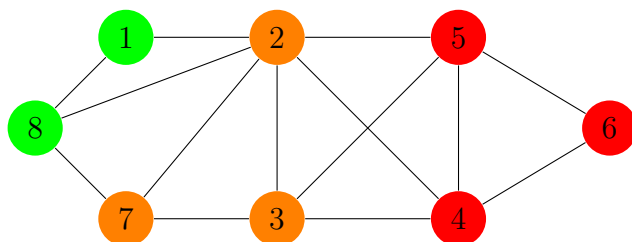
Consider the following graph:



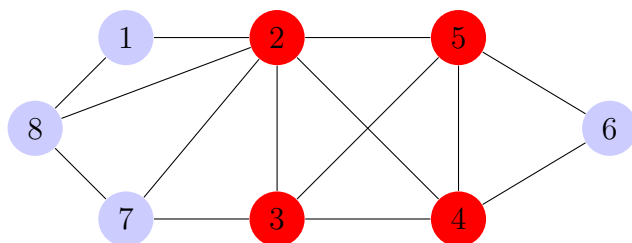
A possible clique covering is:



However, we can find that  $\theta(G)$  is equal to 3 (smallest I could find):



As well, the clique number,  $\omega(G)$ , is 4:



### 1.8 Definition.

**Perfect Graph** — A graph  $G$  is perfect if  $\chi(G) = \omega(G)$  for all induced subgraphs,  $H$ , of  $G$ .



### 1.2.2 Graphs with an Eigensharp decomposition by Stars

### 1.3 Other Bounds on Independence Number

## 2 Algorithm to Find Graphs Lacking a Tight Inertia Bound

### 2.1 Outline of Method

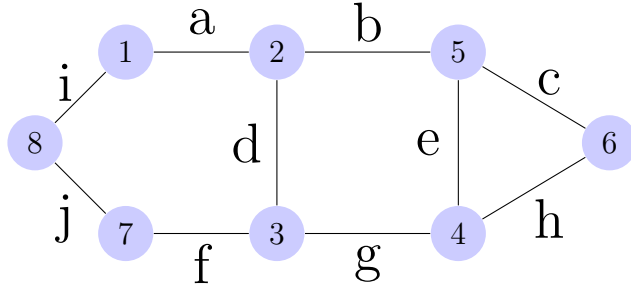
#### 2.1 Definition.

**Optimal Weight Matrix** — A weight matrix,  $W$ , of a graph,  $G$ , is optimal if

$$\alpha(G) = \min\{|G| - n_+(W), |G| - n_-(W)\} \quad (9)$$

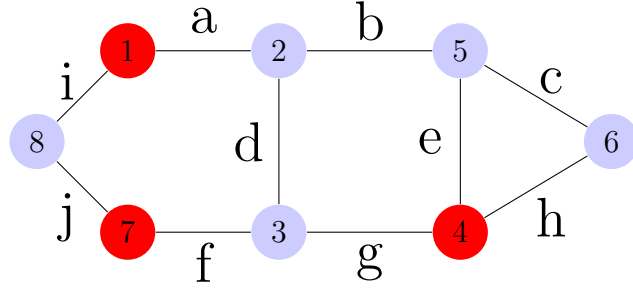
#### 2.1 Example.

Consider the following graph,  $G$ , with corresponding weight matrix  $W$ :

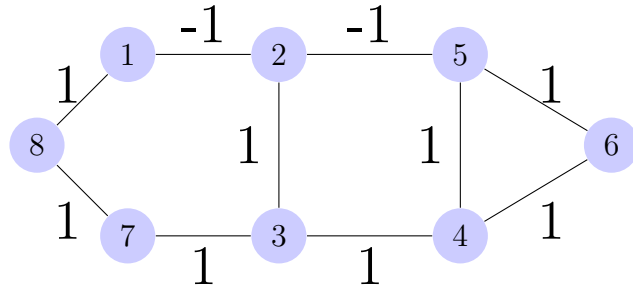


$$\begin{bmatrix} 0 & a & 0 & 0 & 0 & 0 & 0 & i \\ a & 0 & d & 0 & b & 0 & 0 & 0 \\ 0 & d & 0 & g & 0 & 0 & f & 0 \\ 0 & 0 & g & 0 & e & h & 0 & 0 \\ 0 & b & 0 & e & 0 & c & 0 & 0 \\ 0 & 0 & 0 & h & c & 0 & 0 & 0 \\ 0 & 0 & f & 0 & 0 & 0 & 0 & j \\ i & 0 & 0 & 0 & 0 & 0 & j & 0 \end{bmatrix}$$

We can see the independent number of  $G$  is 3:



Now, let  $G$  have the following weighting:



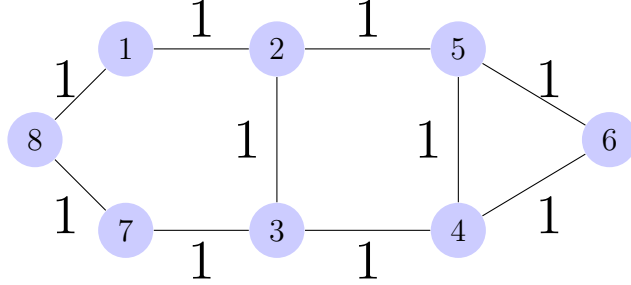
$$\begin{bmatrix} 0 & -1 & 0 & 0 & 0 & 0 & 0 & 1 \\ -1 & 0 & 1 & 0 & -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 1 & 1 & 0 & 0 \\ 0 & -1 & 0 & 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}$$

Finding the eigenvalues of  $W$ , we find there are 3 positive eigenvalues and 5 negative eigenvalues. Thus, we see for this weight matrix we have:

$$\begin{aligned} \alpha(G) &= \min\{|G| - n_+(W), |G| - n_-(W)\} \\ &= \min\{8 - 3, 8 - 5\} \\ &= \min\{5, 3\} \\ &= 3 \end{aligned} \tag{10}$$

Therefore, this is an optimal weight matrix of  $G$ .

Now consider the following weighting for the same graph:



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

Finding the eigenvalues of this weight matrix, we find there are 4 positive eigenvalues and 4 negative eigenvalues. Thus, we see we get:

$$\begin{aligned} \alpha(G) &= 3 \neq \min\{|G| - n_+(W), |G| - n_-(W)\} \\ &= \min\{8 - 4, 8 - 4\} \\ &= \min\{4, 4\} \\ &= 4 \end{aligned} \tag{11}$$

Therefore, we see that the previous weighting was not optimal for  $G$ .

### 2.1 Lemma.

If a graph,  $G$ , with weight matrix  $W$ , has two induced subgraphs,  $S_1$  and  $S_2$ , such that  $S_1$  has  $\alpha(G) + 1$  positive eigenvalues under the weighting of  $W$ , and  $S_2$  has  $\alpha(G) + 1$  negative eigenvalues under the weighting of  $W$ , then  $W$  is not optimal

*Proof.*

□

## 2.2 Preliminary Tests to Determine if the Graph may be Suitable

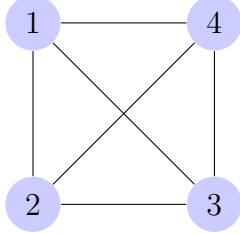
### 2.2.1 Test for $\alpha$ -Critical

#### 2.2 Definition.

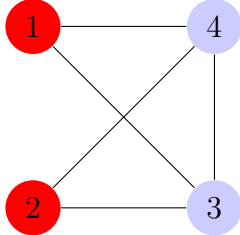
**$\alpha$ -Critical** — A graph,  $G$ , is  $\alpha$ -critical if  $\alpha(G) < \alpha(G - e)$  for all edges  $e$ .

#### 2.2 Example.

Consider the following graph  $G$ :



we see that  $\alpha(G) = 1$ . But since this graph is complete, we see that if we delete any edge, we can get an independent set of size 2 by making the set include the two vertices that were connected by the edge we deleted. For example:



Thus,  $G$  is  $\alpha$ -critical.

#### 2.2 Lemma.

If  $G$  is  $\alpha$ -critical, and  $W$  an optimal weight matrix of  $G$ , then  $w_{i,j} \neq 0$  for all  $i, j \in E(G)$

*Proof.* Assume for the sake of contradiction, that for some  $i, j \in E(G)$ , we have  $w_{i,j} = 0$ . Then, we know  $\alpha(G - e_{i,j}) > \alpha(G)$  because  $G$  is  $\alpha$ -critical. Thus:

$$\alpha(G) < \alpha(G - e_{i,j}) \leq \min\{|G| - n_+(W), |G| - n_-(W)\}$$

Thus, we see that the inertia bound is not tight for  $G$ , so  $W$  is not an optimal weight matrix of  $G$ , which is a contradiction.  $\square$

Due to the complexity of needing to consider edges that could potentially be zero in the weight matrix, it is easier to consider graphs that are restricted to only non-zero edge weights in its optimal weight matrix. Thus, it makes sense to only consider  $\alpha$ -critical graphs, because of Lemma 2.2 ensuring that all  $\alpha$ -critical graphs have non-zero weight matrices.



## 2.2.2 Determining Each Triangle Must Have the Same Sign

## 2.3 Graphs Currently Found

Graph	Vertices	$\alpha$	Degree	Circulant	Strongly Regular	Arc Transitive
<sup>1</sup>	16	4	5	No	No	No
<sup>2</sup>	16	2	10	No	(16,10,6,6)	Yes
<sup>3</sup>	17	3	8	[1,2,4,8]	(17,8,3,4)	Yes
<sup>4</sup>	19	4	6	[1,7,8]	No	Yes
<sup>5</sup>	20	2	13	No	No	No
<sup>6</sup>	20	2	13	[1,3,4,7,8,9,10]	No	No
<sup>7</sup>	22	3	11	[1,2,3,5,10,11]	No	No
<sup>8</sup>	24	3	12	No	No	No
<sup>9</sup>	24	3	12	No	No	No
<sup>10</sup>	24	4	9	No	No	No
<sup>11</sup>	24	4	10	[1,2,4,8,9]	No	No
<sup>12</sup>	24	4	9	No	No	No
<sup>13</sup>	24	3	12	No	No	No
<sup>14</sup>	24	4	9	No	No	No
<sup>15</sup>	24	4	9	No	No	No
<sup>16</sup>	24	2	16	No	No	No
<sup>17</sup>	24	2	16	No	No	No
<sup>18</sup>	24	2	16	[1,2,3,4,6,7,8,10]	No	No
<sup>19</sup>	24	2	16	No	No	No

<sup>1</sup>Otr@PKoE?T.iOoOG.dg\_m

<sup>2</sup>O~~em]uj[vmsZTUrfFwN~

<sup>3</sup>P}qtSeLUbaKeQZJabfGmmG~G

<sup>4</sup>R}ecZ@OH?oW~@gOWcL.p?hkHL?GuG

<sup>5</sup>S~~~vVjjve}vmxymLG~Oi~Qm{jfxjNw{z{

<sup>6</sup>S~~~vnZjvUtvimj'~nibtTP}{ffwk~wR~{

<sup>7</sup>Uv~LnbgfeDShP\G}HuXmePrSemapSxqJWG|ZCVhvw

<sup>8</sup>Wunneyzx~W]OwBPferoK~S{OlogtIoyPlPFMIjWPUvaGu~

<sup>9</sup>WvrlvjZj~c\\_wBTRcroK~K{HLpGtPo[ikpImQHrWaUn'Cv^

<sup>10</sup>WvvdIjPb.c[LEHPiH?PsE.GAsWKcwBXhGDgOFXWIBV@CZT

<sup>11</sup>W}mKmIbqD.JJMMBYa}\_{??ucC{YKeHKXPadVXOmqqbqEDMp

<sup>12</sup>W}nS|QeoOq\_nWS]?KcPQUdG@\_TBG.ug@ei?jCgCwY\_?J~

<sup>13</sup>W}{}VNbMtdyWkic?zg|gevHT.TfGo~bPK|xHkJJMolozdq\s

<sup>14</sup>W}~SvAbp@IcjDgEaj?@BKPCgBbXP@oCz?BLdE@KwGu[?EFZ

<sup>15</sup>W~nELU\'aKkXTJ]?@cGUB@KgBSX?wG\_sS'DUCGyWO'?@M^

<sup>16</sup>W~~~vnnv|~}gzH}'za|J^ef|~wBJNis1f5n^@^nwez~'V^~

<sup>17</sup>W~~~vnn{vT{nvFnFo^}~Dnw\{^AF|hFz[YZ~DT~wX^~n{B~

<sup>18</sup>W~~~vnn{vXyjqqnFs^}~Knw\[^QF|hiz|iznCt~wX^~n{B~

<sup>19</sup>W~~~vvu|^\\jvivTvtTyj\_~|}ibyiiF}[b{~C{~wU^~f~~





### 2.3.1 Graphs Created from Deleting a Vertex

Graph	Created From	Vertices	$\alpha$	Regular	Circulant	Strongly Regular	Arc Transitive
1	1	15	4	No	No	No	No
2	2	15	2	No	No	No	No
3	3	16	3	No	No	No	No
4	4	18	4	No	No	No	No
5	6	19	2	No	No	No	No
6	7	21	3	No	No	No	No
7	8	23	3	No	No	No	No
8	9	23	3	No	No	No	No
9	10	23	4	No	No	No	No
10	11	23	4	No	No	No	No
11	12	23	4	No	No	No	No
12	13	23	3	No	No	No	No
13	14	23	4	No	No	No	No
14	15	23	4	No	No	No	No
15	16	23	2	No	No	No	No
16	17	23	2	No	No	No	No
17	18	23	2	No	No	No	No
18	19	23	2	No	No	No	No
19	4	17	4	No	No	No	No
20	5	18	2	No	No	No	No
21	9	22	4	No	No	No	No
22	11	22	4	No	No	No	No
23	15	22	2	No	No	No	No
24	18	22	2	No	No	No	No
25	19	16	4	No	No	No	No
26	21	21	4	No	No	No	No
27	24	21	2	No	No	No	No

<sup>1</sup>Ntr@PKoE?T iOoOG\_dg

<sup>2</sup>N~~em]uj[vmsZTUrfFw

<sup>3</sup>O}qtSeLUbaKeQZJabfGmm

<sup>4</sup>Q}ecZ@OH?oW@gOWcI\_p?hkHL?

<sup>5</sup>R~~vnZjvUtvimj~nibtTP}{ffwk~w

<sup>6</sup>Tv~LnbgfeDShP\G}HuXmePrSemapSxqJWG|Z

<sup>7</sup>Vunneyzx~W]OwBPfcroK~S{OlogtIoyPIPFMIjWPUv\_

<sup>8</sup>VvrlvjZj~c\\_wBTRcroK~K{HLpGtPo]jplmQHRWaUn\_

<sup>9</sup>VvdtIJpB\_c[LEHPiH?PsE\_GAsWKcwBXhGDgOFXWIBV?

<sup>10</sup>V}mKmIbqD\_JJMMBYa]\_{??ucC{YKeHKXPadVXOmQqbq?

<sup>11</sup>V}nS|QeoOq\_nWS]?KcPQUPDgU@\_TBG\_ug@ei?jCgCwY\_

<sup>12</sup>W}}VNBmtdyWkic?zg]gevHT\_TfGo~bPK|xHkJJMolozdq\s

<sup>13</sup>V}~SvAbp@IcjDgEaj?@BKPCgBbXP@oCz?BLdE@KwGu[?

<sup>14</sup>V~nELU\'aKkXTJ]?@cGUB@KgBSX?wG\_sS'DUCgyWO'}?

<sup>15</sup>V~~~vnnv|~}gzH}'za|J^ef]~wBJNisn[bn^@^nwez~\_

<sup>16</sup>V~~~vnn{vT{nvFnFo^}~Dnw\{^AF|hFz|YZ~DT~wX^~

## 3 Other Useful Information

### 3.1 Cayley Graphs

#### 3.1 Definition.

Cayley Graph —

## References

- [1] Randall J Elzinga. *The Minimum Witt Index of a Graph*. PhD thesis, Queens University, 2007.
- [2] John Sinkovic. A graph for which the inertia bound is not tight. *arXiv preprint arXiv:1609.02826*, 2016.