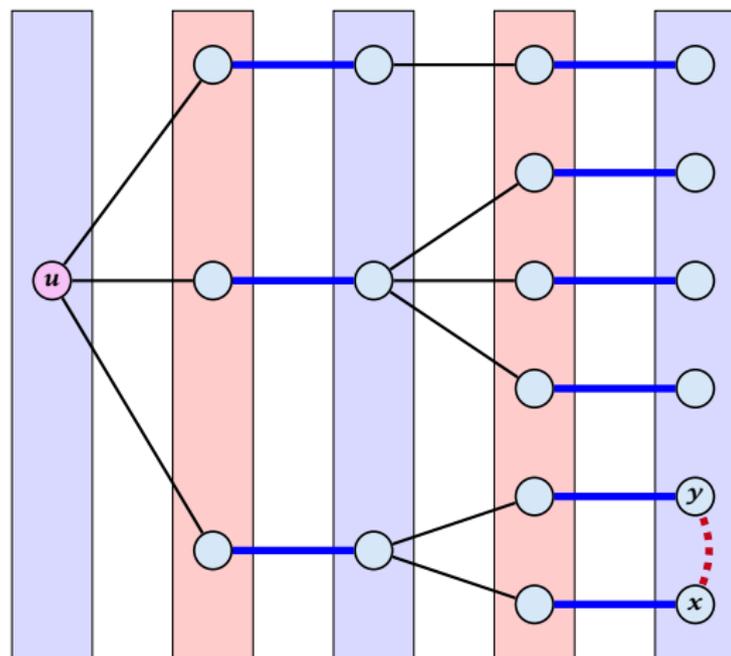


How to find an augmenting path?

Construct an alternating tree.



even nodes

odd nodes

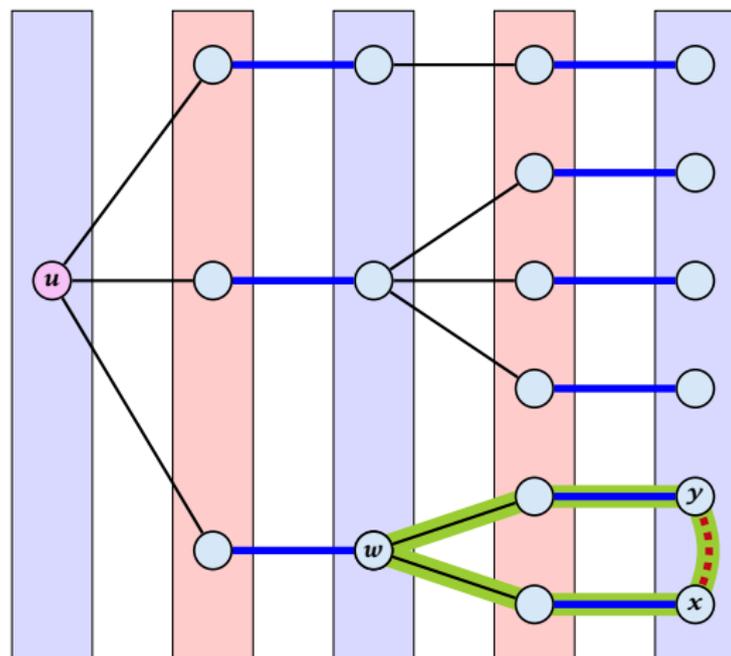
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Flowers and Blossoms

Definition 9

A **flower** in a graph $G = (V, E)$ w.r.t. a matching M and a (free) root node r , is a subgraph with two components:

- ▶ A **stem** is an even length alternating path that starts at the root node r and terminates at some node w . We permit the possibility that $r = w$ (empty stem).
- ▶ A **blossom** is an odd length alternating cycle that starts and terminates at the terminal node w of a stem and has no other node in common with the stem. w is called the **base** of the blossom.

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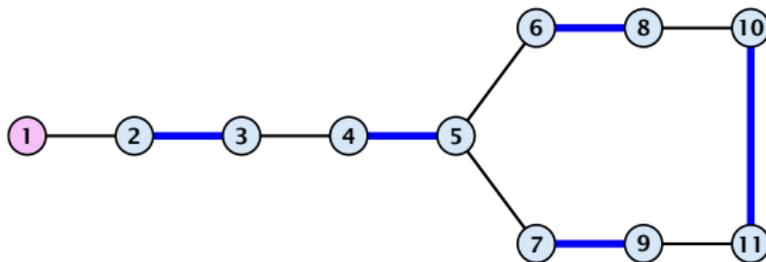
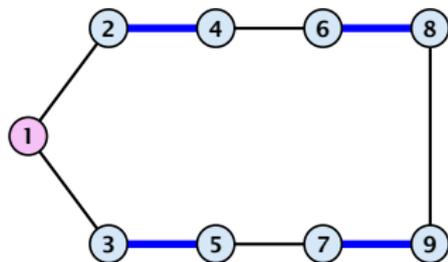
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Properties:

1. A stem spans $2\ell + 1$ nodes and contains ℓ matched edges for some integer $\ell \geq 0$.
2. A blossom spans $2k + 1$ nodes and contains k matched edges for some integer $k \geq 1$. The matched edges match all nodes of the blossom except the base.
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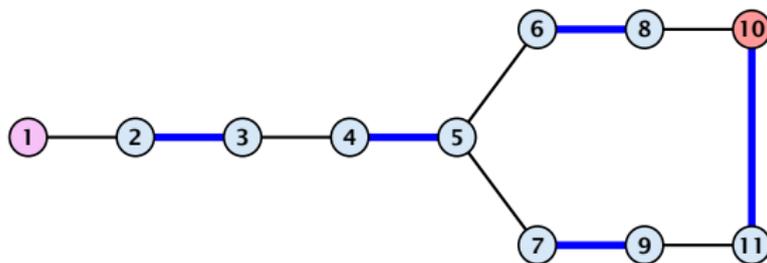
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Shrinking Blossoms

When during the alternating tree construction we discover a blossom B we replace the graph G by $G' = G/B$, which is obtained from G by contracting the blossom B .

- ▶ Delete all vertices in B (and its incident edges) from G .
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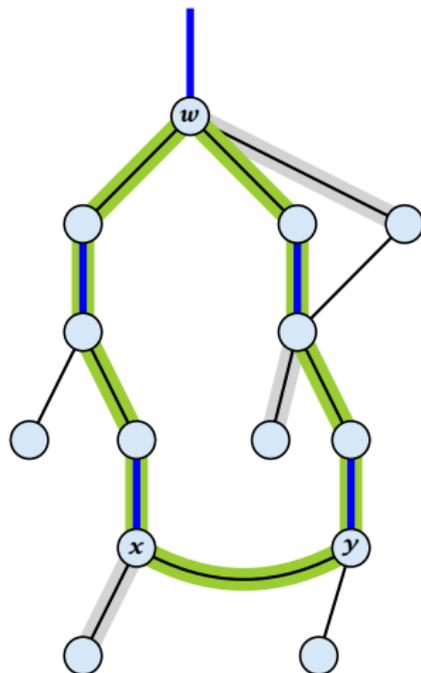
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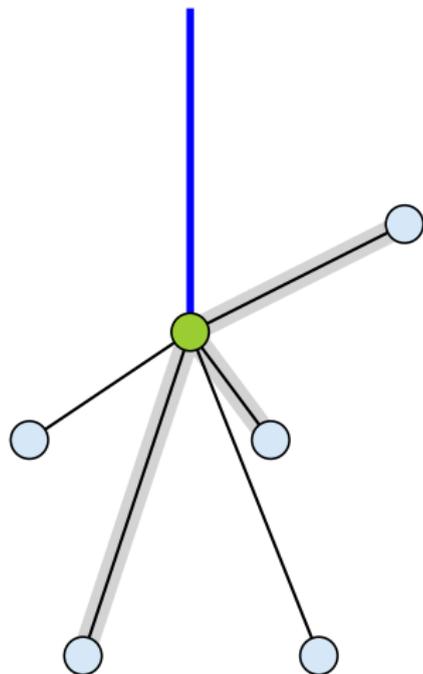
Shrinking Blossoms

- ▶ Edges of T that connect a node u not in B to a node in B become tree edges in T' connecting u to b .
- ▶ Matching edges (there is at most one) that connect a node u not in B to a node in B become matching edges in M' .
- ▶ Nodes that are connected in G to at least one node in B become connected to b in G' .

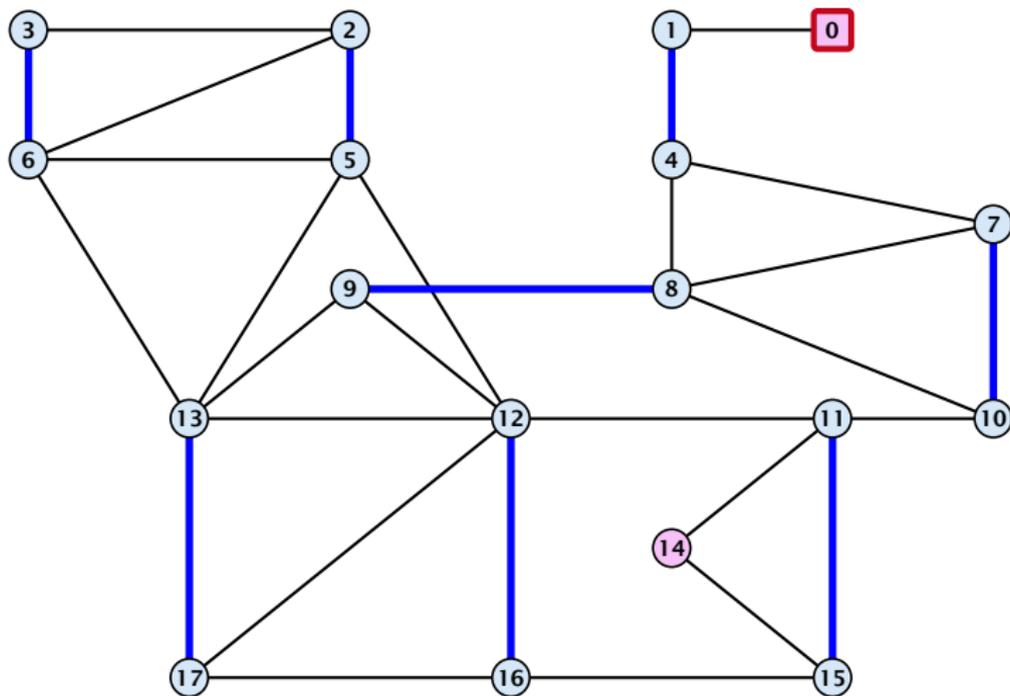


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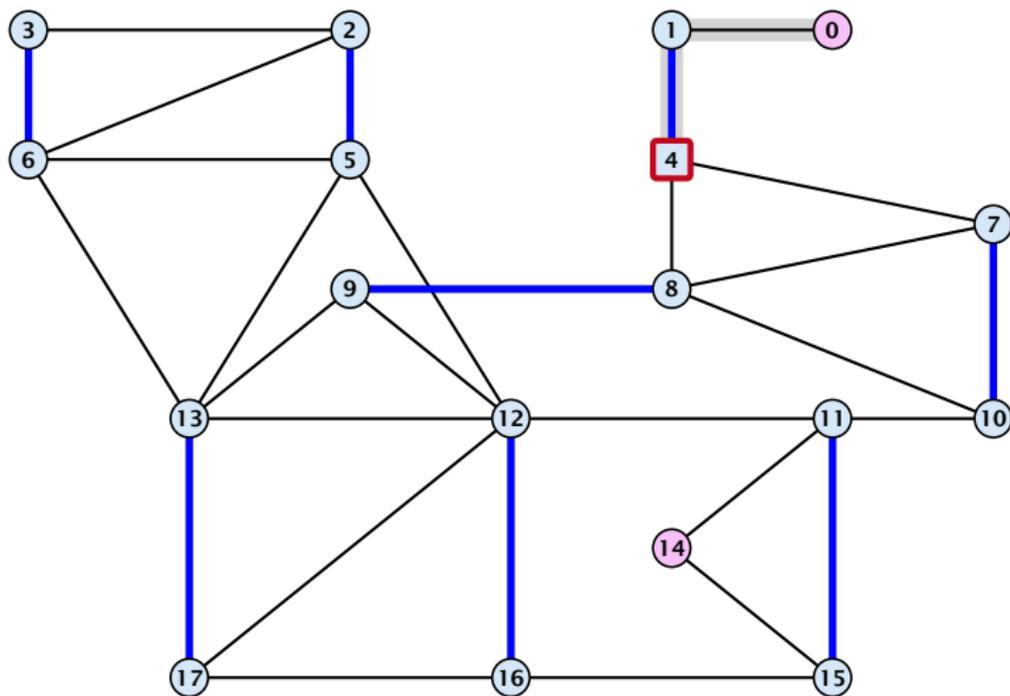
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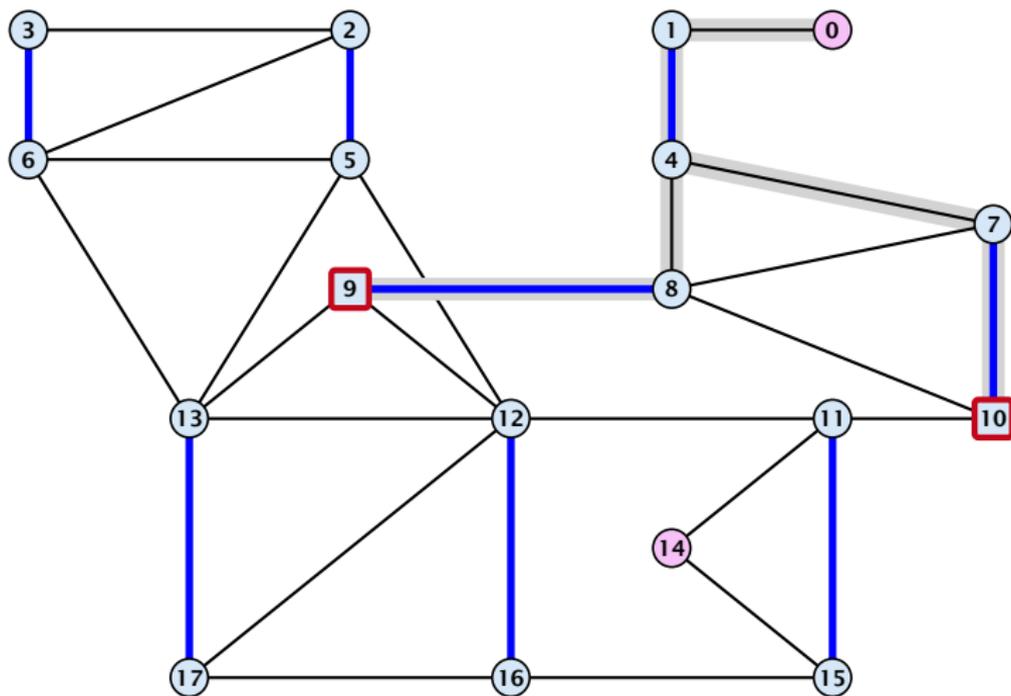
Example: Blossom Algorithm



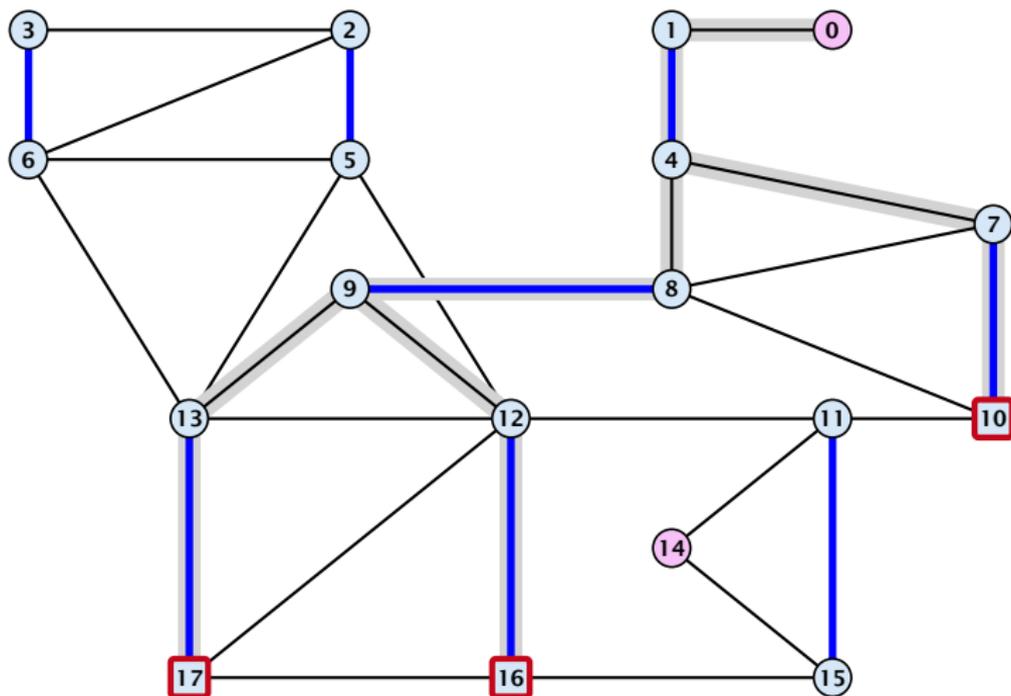
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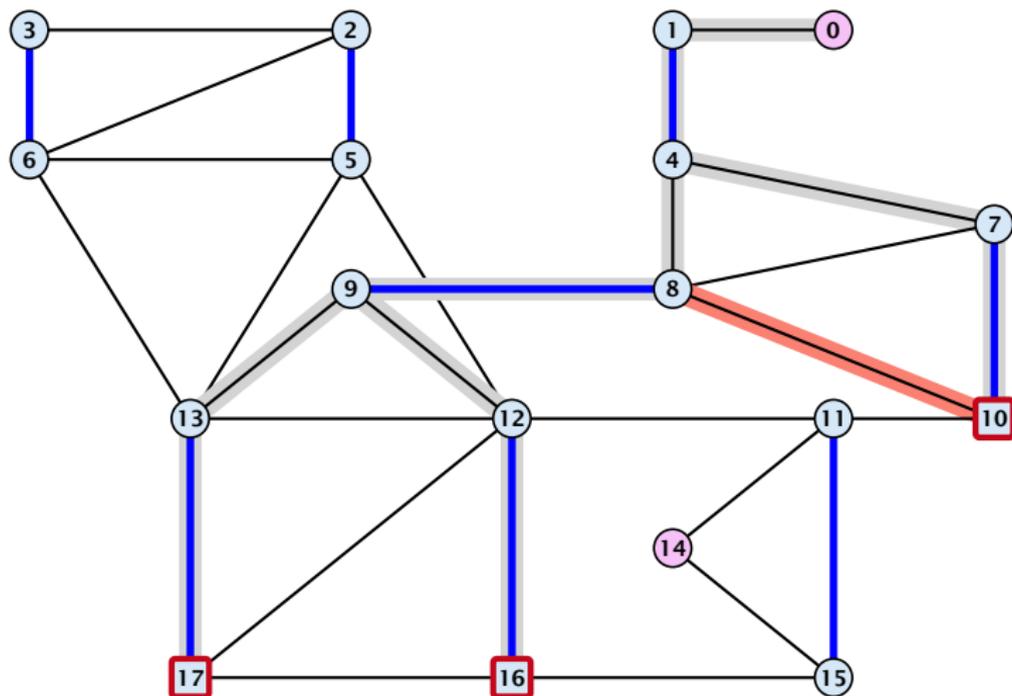
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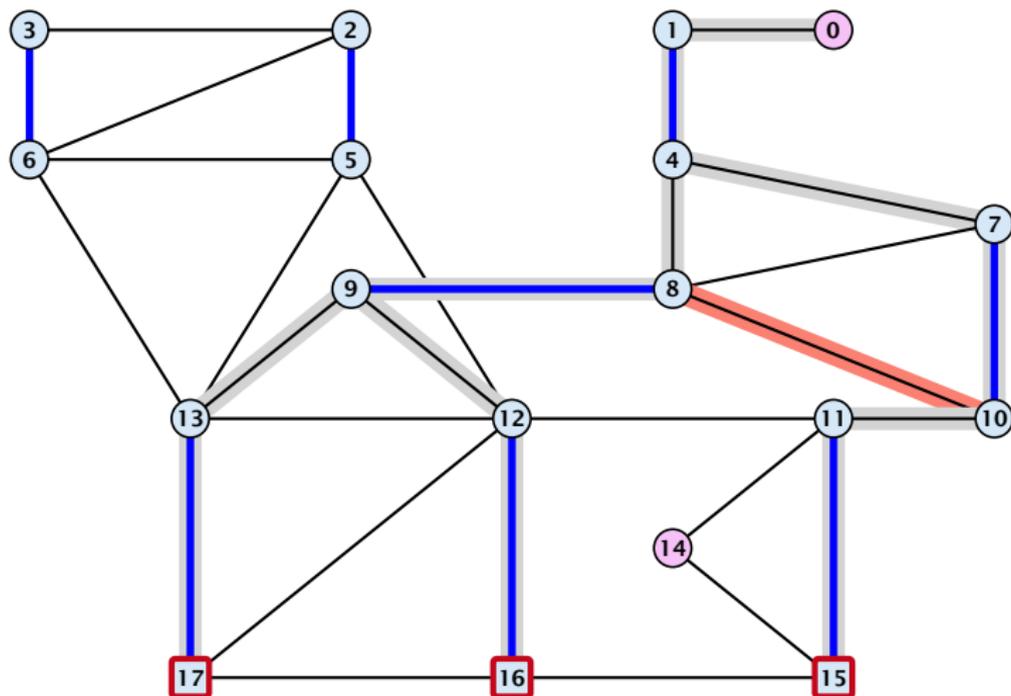
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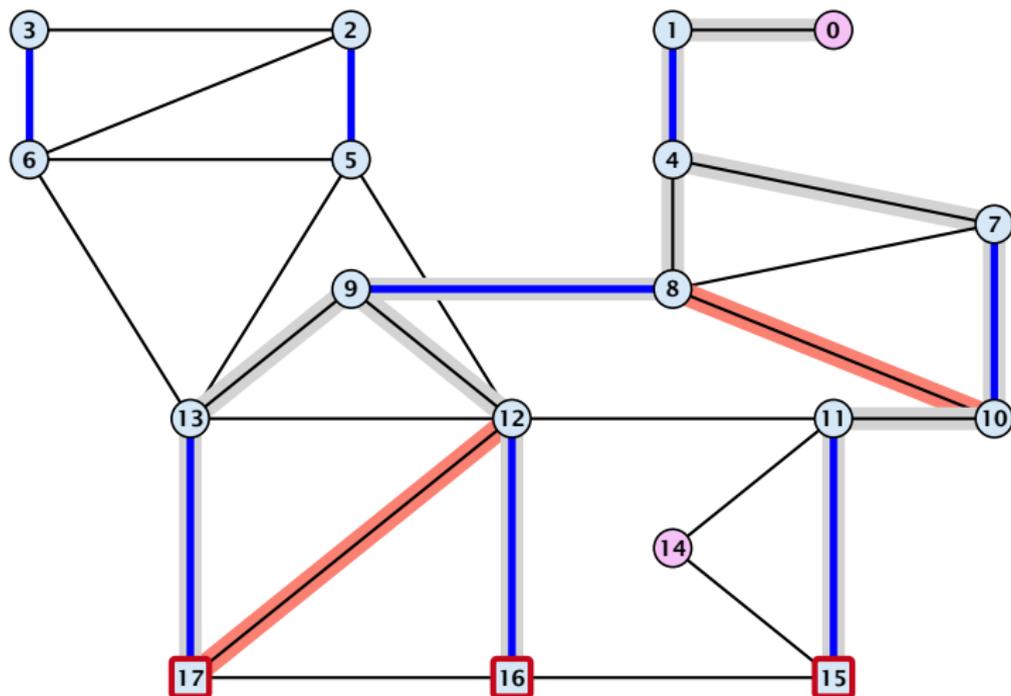
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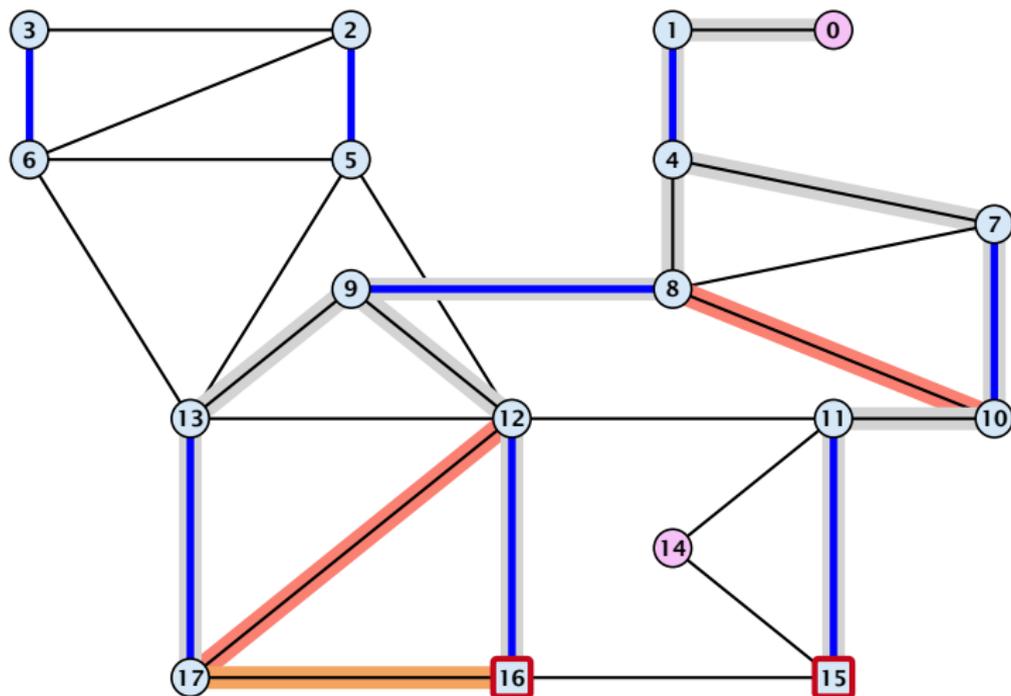
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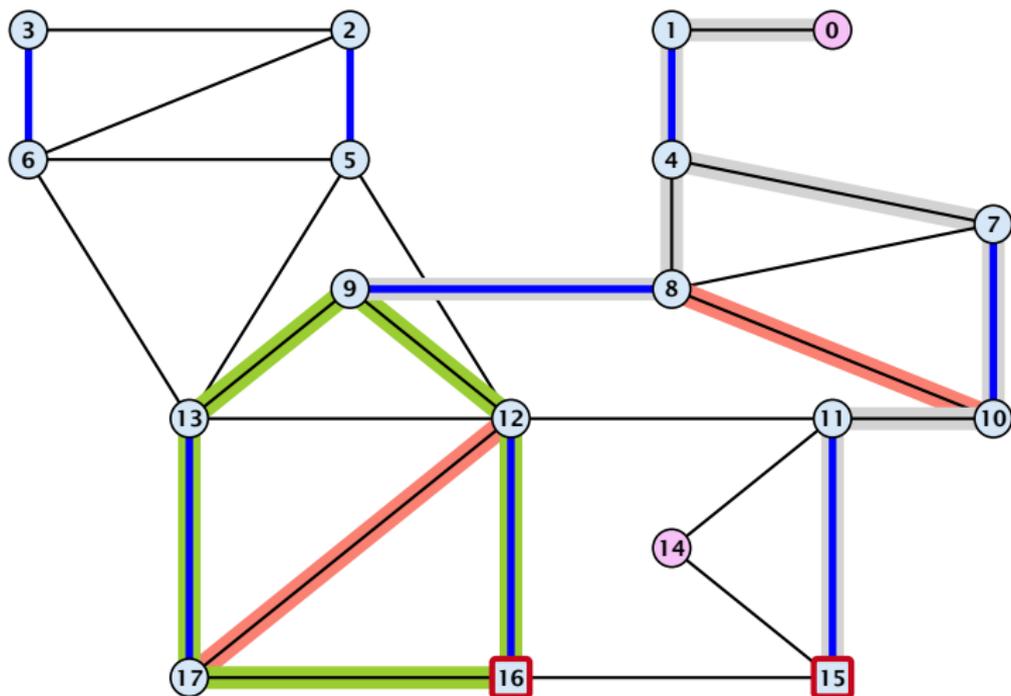
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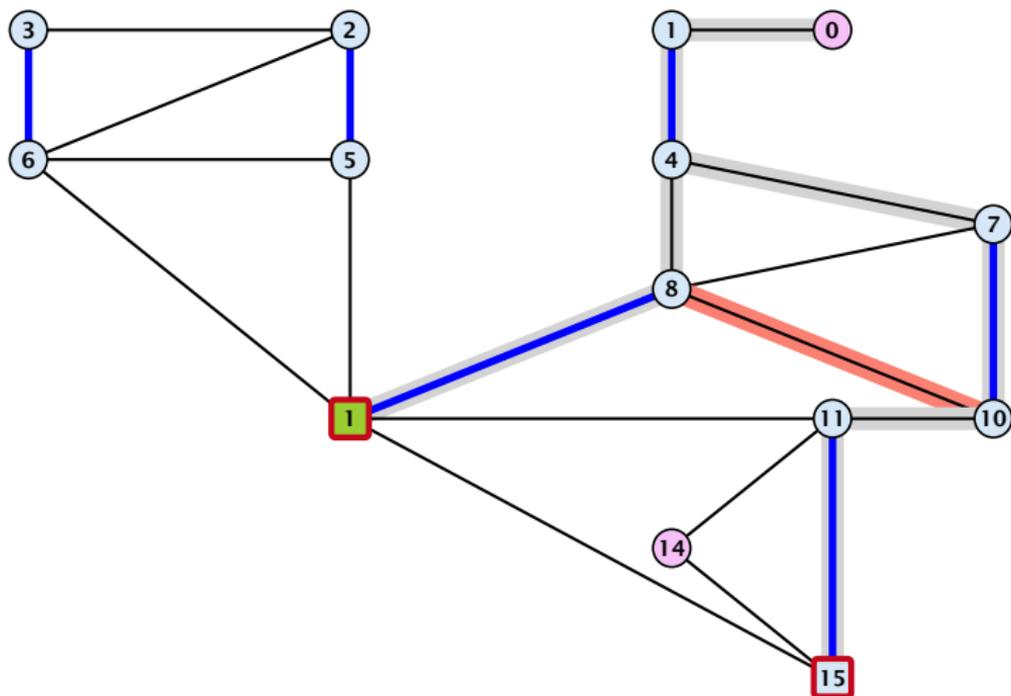
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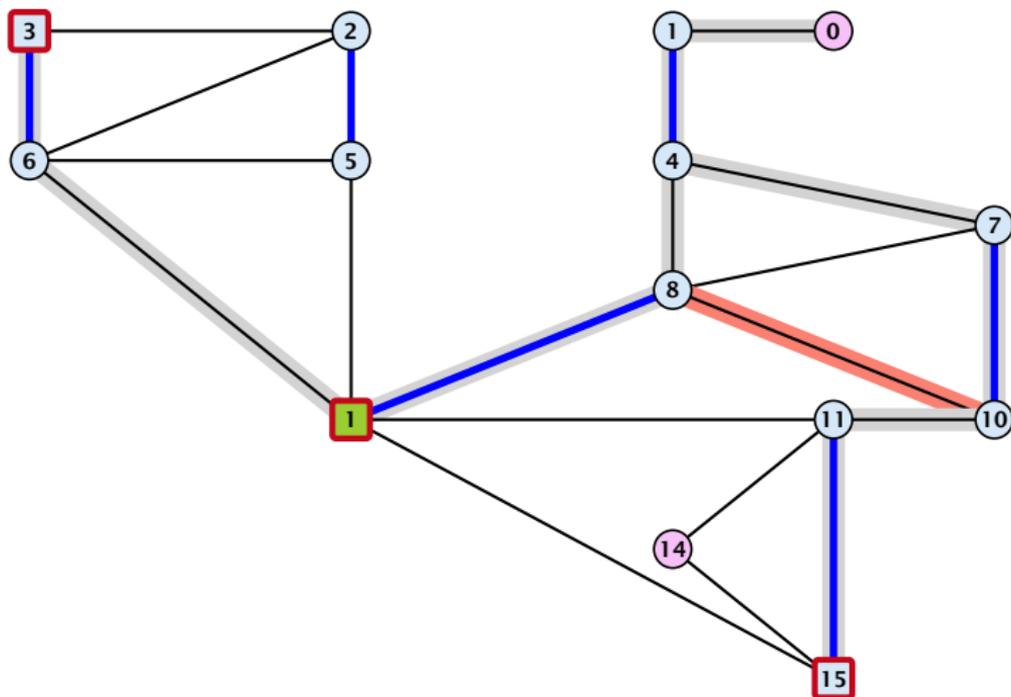
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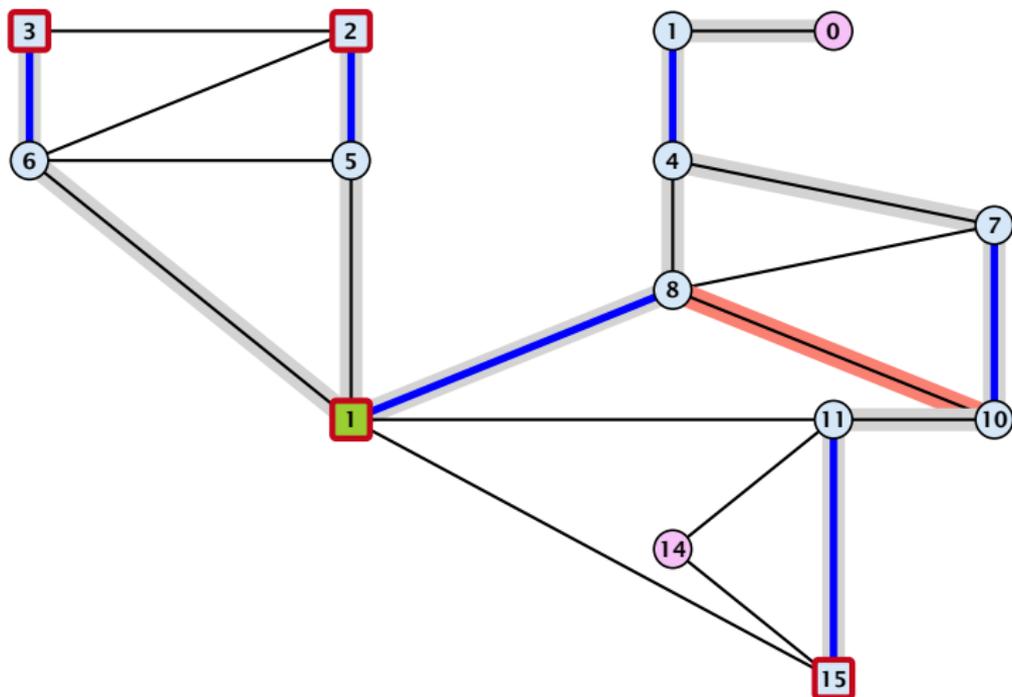
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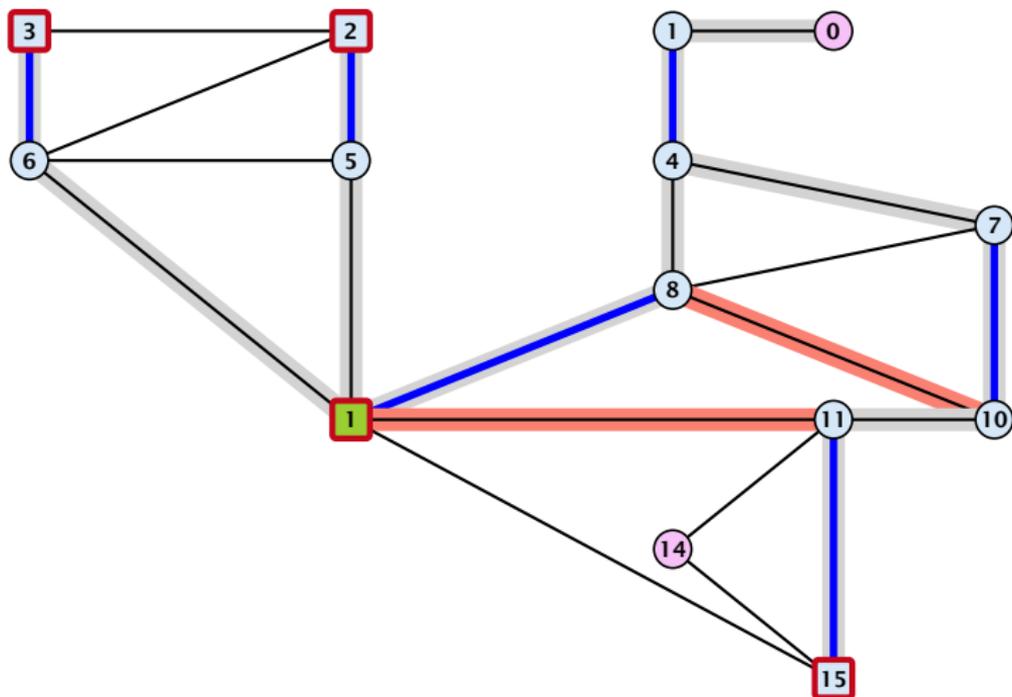
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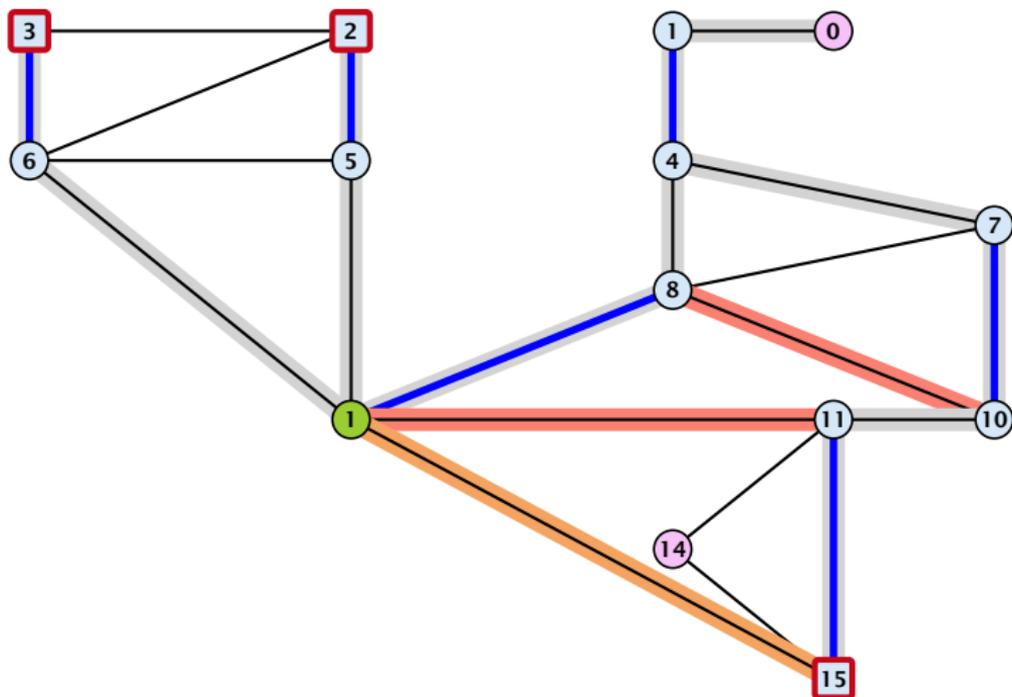
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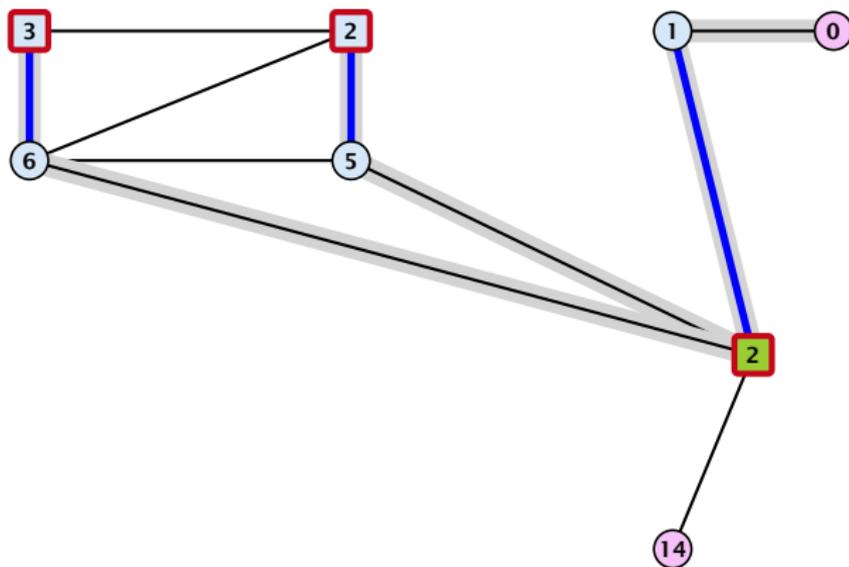
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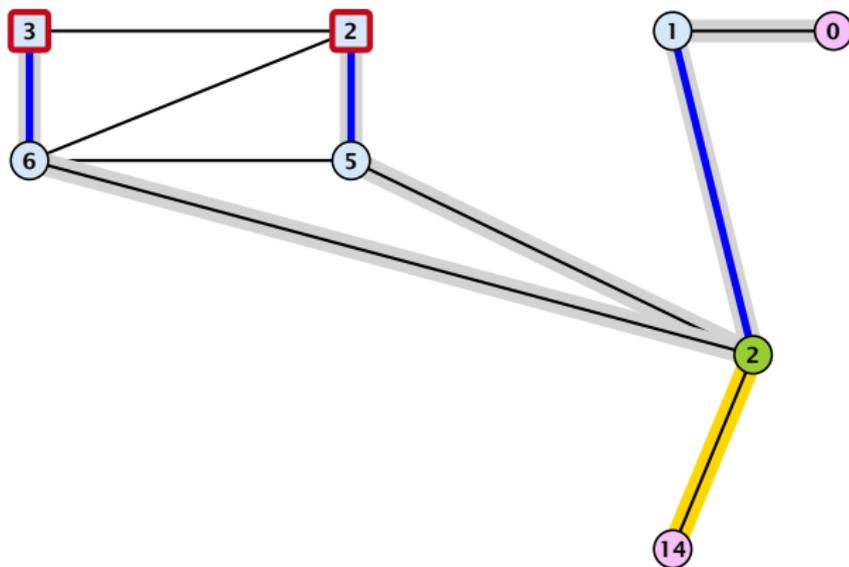
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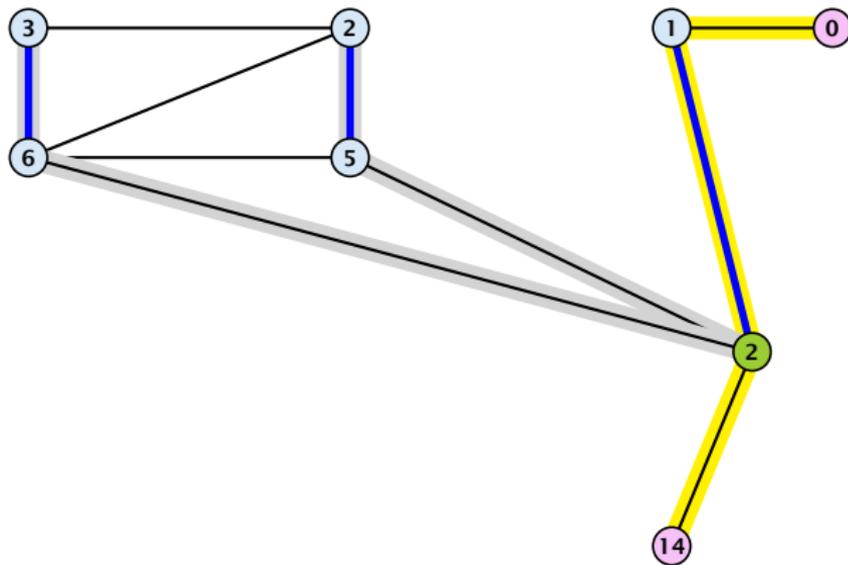
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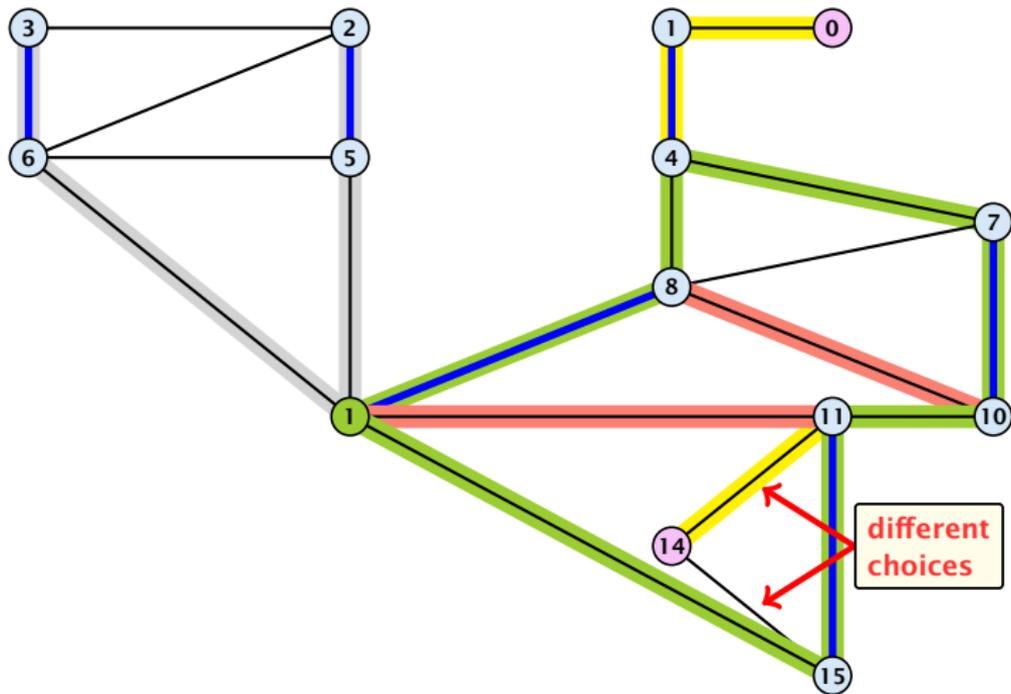
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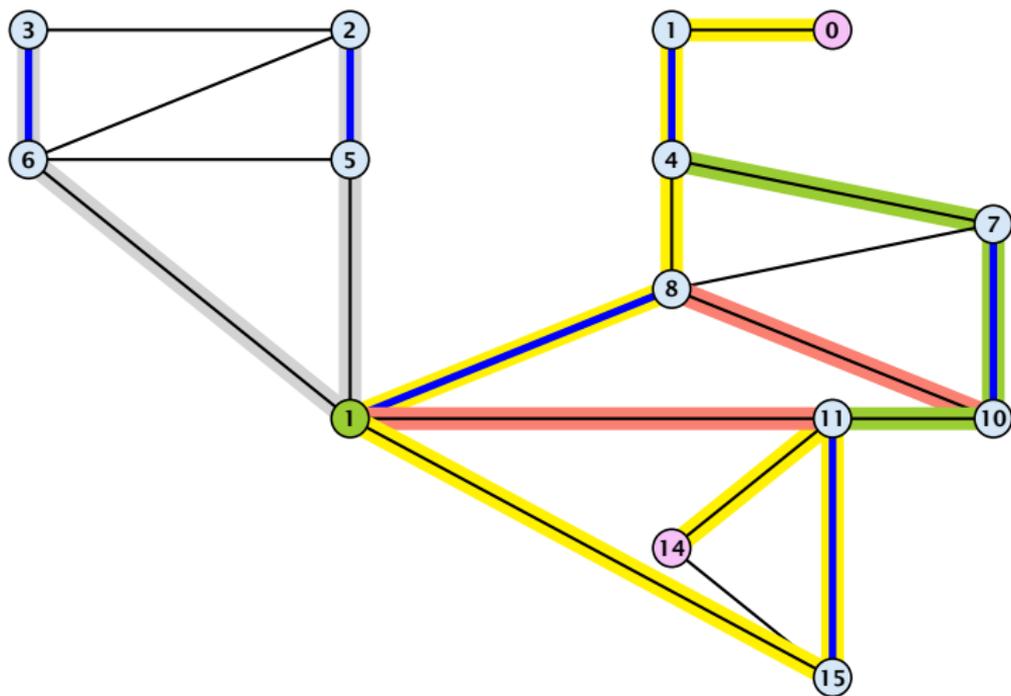
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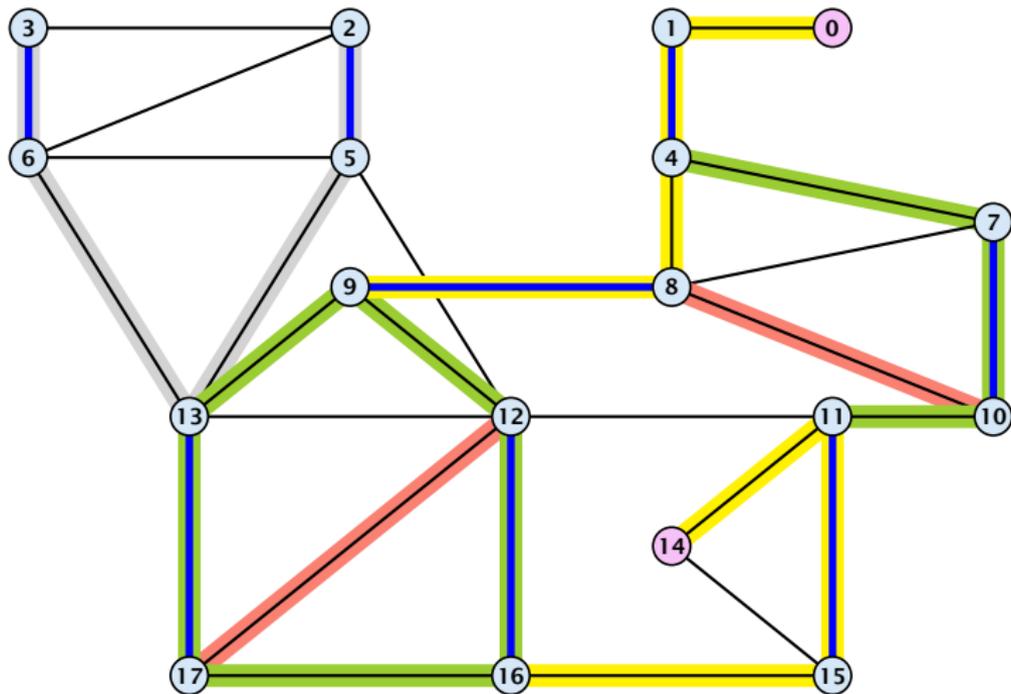
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Correctness

Assume that in G we have a flower w.r.t. matching M . Let r be the root, B the blossom, and w the base. Let graph $G' = G/B$ with pseudonode b . Let M' be the matching in the contracted graph.

Lemma 10

If G' contains an augmenting path P' starting at r (or the pseudo-node containing r) w.r.t. the matching M' then G contains an augmenting path starting at r w.r.t. matching M .

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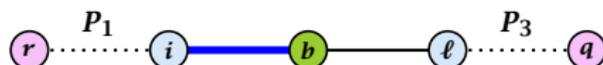
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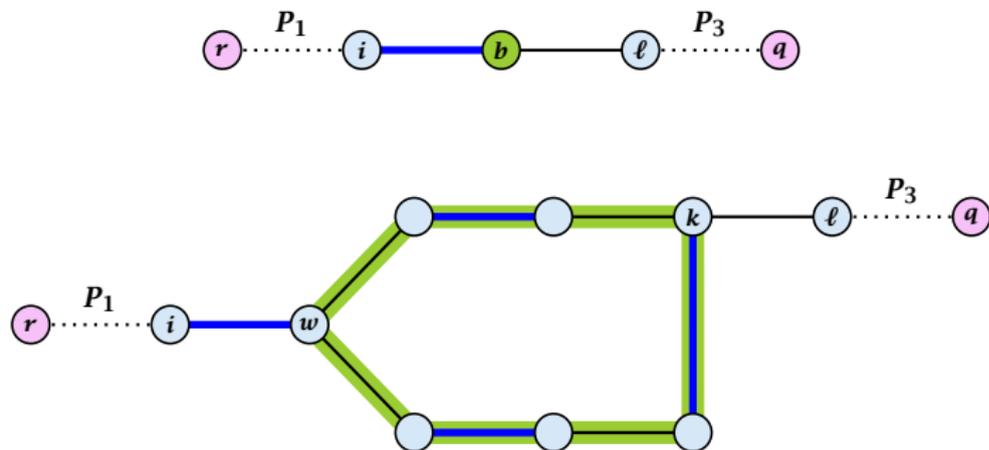
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- ▶ After the expansion ℓ must be incident to some node in the blossom. Let this node be k .
- ▶ If $k \neq w$ there is an alternating path P_2 from w to k that ends in a matching edge.
- ▶ $P_1 \circ (i, w) \circ P_2 \circ (k, \ell) \circ P_3$ is an alternating path.
- ▶ If $k = w$ then $P_1 \circ (i, w) \circ (w, \ell) \circ P_3$ is an alternating path.

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Case 2: empty stem

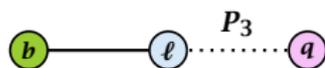
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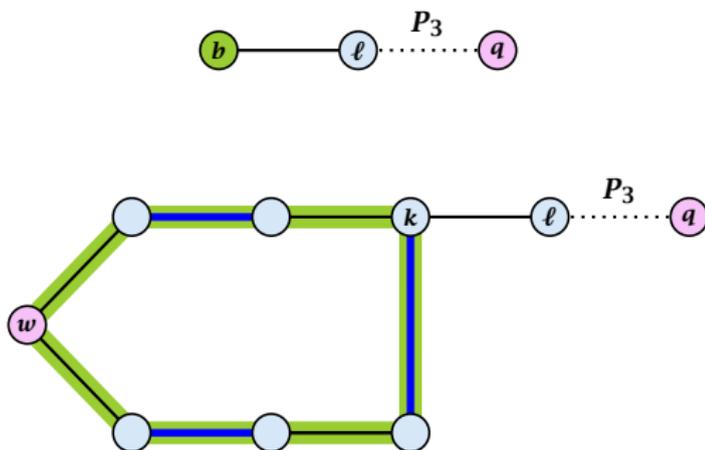


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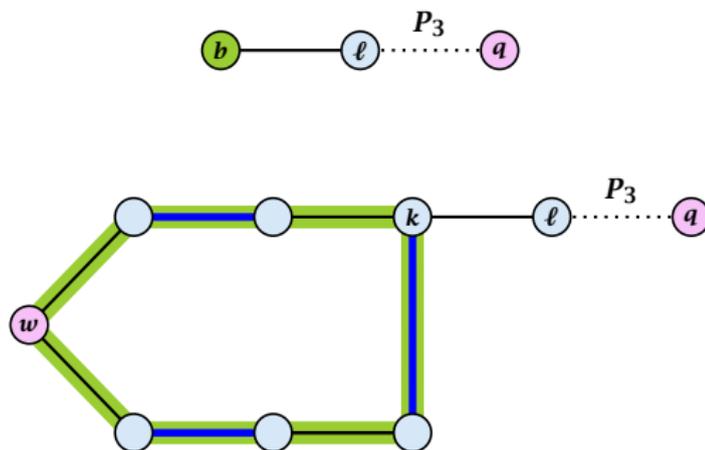


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- ▶ The path $r \circ P_2 \circ (k, l) \circ P_3$ is an alternating path.

Lemma 11

If G contains an augmenting path P from r to q w.r.t. matching M then G' contains an augmenting path from r (or the pseudo-node containing r) to q w.r.t. M' .

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Proof.

- ▶ If P does not contain a node from B there is nothing to prove.
- ▶ We can assume that r and q are the only free nodes in G .

Case 1: empty stem

Let i be the last node on the path P that is part of the blossom.

P is of the form $P_1 \circ (i, j) \circ P_2$, for some node j and (i, j) is unmatched.

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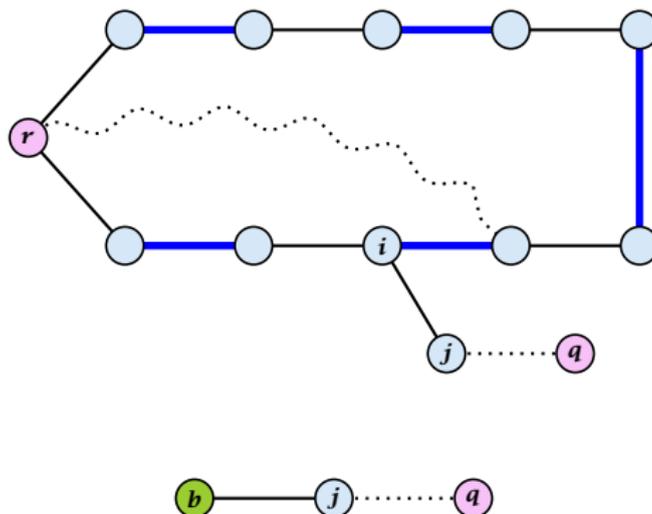
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Correctness

Illustration for Case 1:



Correctness

Case 2: non-empty stem

Let P_3 be alternating path from r to w ; this exists because r and w are root and base of a blossom. Define $M_+ = M \oplus P_3$.

In M_+ , r is matched and w is unmatched.

G must contain an augmenting path w.r.t. matching M_+ , since M and M_+ have same cardinality.

This path must go between w and q as these are the only unmatched vertices w.r.t. M_+ .

For M'_+ the blossom has an empty stem. Case 1 applies.

G' has an augmenting path w.r.t. M'_+ . It must also have an augmenting path w.r.t. M' , as both matchings have the same cardinality.

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Algorithm 54 $\text{search}(r, \text{found})$

- 1: set $\bar{A}(i) \leftarrow A(i)$ for all nodes i
- 2: $\text{found} \leftarrow \text{false}$
- 3: unlabel all nodes;
- 4: give an even label to r and initialize $\text{list} \leftarrow \{r\}$
- 5: **while** $\text{list} \neq \emptyset$ **do**
- 6: delete a node i from list
- 7: examine(i, found)
- 8: **if** $\text{found} = \text{true}$ **then return**

Search for an augmenting path
starting at r .

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$A(i)$ contains neighbours of node i .

We create a copy $\bar{A}(i)$ so that we later
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found is just a Boolean that allows
to abort the search process...

Algorithm 54 $\text{search}(r, \text{found})$

1: set $\bar{A}(i) \leftarrow A(i)$ for all nodes i

2: $\text{found} \leftarrow \text{false}$

3: **unlabel all nodes;**

4: give an even label to r and initialize $\text{list} \leftarrow \{r\}$

5: **while** $\text{list} \neq \emptyset$ **do**

6: delete a node i from list

7: examine(i, found)

8: **if** $\text{found} = \text{true}$ **then return**

In the beginning no node is in the tree.

Algorithm 54 $\text{search}(r, \text{found})$

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6: delete a node i from list

7: examine(i, found)

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Put the root in the tree.

list could also be a set or a stack.

Algorithm 54 $\text{search}(r, \text{found})$

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- 2: $\text{found} \leftarrow \text{false}$
- 3: unlabel all nodes;
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- 6: delete a node i from list
- 7: examine(i, found)
- 8: **if** $\text{found} = \text{true}$ **then return**

As long as there are nodes with
unexamined neighbours...

Algorithm 54 $\text{search}(r, \text{found})$

- 1: set $\bar{A}(i) \leftarrow A(i)$ for all nodes i
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- 5: **while** $\text{list} \neq \emptyset$ **do**
- 6: delete a node i from list
- 7: **examine**(i, found)
- 8: **if** $\text{found} = \text{true}$ **then return**

...examine the next one

Algorithm 54 $\text{search}(r, \text{found})$

- 1: set $\bar{A}(i) \leftarrow A(i)$ for all nodes i
- 2: $\text{found} \leftarrow \text{false}$
- 3: unlabel all nodes;
- 4: give an even label to r and initialize $\text{list} \leftarrow \{r\}$
- 5: **while** $\text{list} \neq \emptyset$ **do**
- 6: delete a node i from list
- 7: examine(i, found)
- 8: **if** $\text{found} = \text{true}$ **then return**

If you found augmenting path
abort and start from next root.

Algorithm 55 examine($i, found$)

```
1: for all  $j \in \bar{A}(i)$  do  
2:   if  $j$  is even then contract( $i, j$ ) and return  
3:   if  $j$  is unmatched then  
4:      $q \leftarrow j$ ;  
5:     pred( $q$ )  $\leftarrow i$ ;  
6:      $found \leftarrow \text{true}$ ;  
7:     return  
8:   if  $j$  is matched and unlabeled then  
9:     pred( $j$ )  $\leftarrow i$ ;  
10:    pred(mate( $j$ ))  $\leftarrow j$ ;  
11:    add mate( $j$ ) to list
```

Examine the neighbours of a node i

Algorithm 55 $\text{examine}(i, \text{found})$

```
1: for all  $j \in \bar{A}(i)$  do  
2:   if  $j$  is even then  $\text{contract}(i, j)$  and return  
3:   if  $j$  is unmatched then  
4:      $q \leftarrow j$ ;  
5:      $\text{pred}(q) \leftarrow i$ ;  
6:      $\text{found} \leftarrow \text{true}$ ;  
7:     return  
8:   if  $j$  is matched and unlabeled then  
9:      $\text{pred}(j) \leftarrow i$ ;  
10:     $\text{pred}(\text{mate}(j)) \leftarrow j$ ;  
11:    add  $\text{mate}(j)$  to list
```

For all neighbours j do...

Algorithm 55 $\text{examine}(i, \text{found})$

```
1: for all  $j \in \bar{A}(i)$  do  
2:   if  $j$  is even then  $\text{contract}(i, j)$  and return  
3:   if  $j$  is unmatched then  
4:      $q \leftarrow j$ ;  
5:      $\text{pred}(q) \leftarrow i$ ;  
6:      $\text{found} \leftarrow \text{true}$ ;  
7:     return  
8:   if  $j$  is matched and unlabeled then  
9:      $\text{pred}(j) \leftarrow i$ ;  
10:     $\text{pred}(\text{mate}(j)) \leftarrow j$ ;  
11:    add  $\text{mate}(j)$  to list
```

You have found a blossom...

Algorithm 55 $\text{examine}(i, \text{found})$

```
1: for all  $j \in \bar{A}(i)$  do  
2:   if  $j$  is even then  $\text{contract}(i, j)$  and return  
3:   if  $j$  is unmatched then  
4:      $q \leftarrow j$ ;  
5:      $\text{pred}(q) \leftarrow i$ ;  
6:      $\text{found} \leftarrow \text{true}$ ;  
7:     return  
8:   if  $j$  is matched and unlabeled then  
9:      $\text{pred}(j) \leftarrow i$ ;  
10:     $\text{pred}(\text{mate}(j)) \leftarrow j$ ;  
11:    add  $\text{mate}(j)$  to list
```

You have found a free node which gives you an augmenting path.

Algorithm 55 $\text{examine}(i, \text{found})$

```
1: for all  $j \in \bar{A}(i)$  do  
2:   if  $j$  is even then  $\text{contract}(i, j)$  and return  
3:   if  $j$  is unmatched then  
4:      $q \leftarrow j$ ;  
5:      $\text{pred}(q) \leftarrow i$ ;  
6:      $\text{found} \leftarrow \text{true}$ ;  
7:     return  
8:   if  $j$  is matched and unlabeled then  
9:      $\text{pred}(j) \leftarrow i$ ;  
10:     $\text{pred}(\text{mate}(j)) \leftarrow j$ ;  
11:    add  $\text{mate}(j)$  to list
```

If you find a matched node that is not
in the tree you grow...

Algorithm 55 $\text{examine}(i, \text{found})$

```
1: for all  $j \in \bar{A}(i)$  do  
2:   if  $j$  is even then  $\text{contract}(i, j)$  and return  
3:   if  $j$  is unmatched then  
4:      $q \leftarrow j$ ;  
5:      $\text{pred}(q) \leftarrow i$ ;  
6:      $\text{found} \leftarrow \text{true}$ ;  
7:     return  
8:   if  $j$  is matched and unlabeled then  
9:      $\text{pred}(j) \leftarrow i$ ;  
10:     $\text{pred}(\text{mate}(j)) \leftarrow j$ ;  
11:    add  $\text{mate}(j)$  to list
```

$\text{mate}(j)$ is a new node from
which you can grow further.

Algorithm 56 contract(i, j)

- 1: trace pred-indices of i and j to identify a blossom B
- 2: create new node b and set $\bar{A}(b) \leftarrow \cup_{x \in B} \bar{A}(x)$
- 3: label b even and add to *list*
- 4: update $\bar{A}(j) \leftarrow \bar{A}(j) \cup \{b\}$ for each $j \in \bar{A}(b)$
- 5: form a circular double linked list of nodes in B
- 6: delete nodes in B from the graph

Contract blossom identified by
nodes i and j

Algorithm 56 $\text{contract}(i, j)$

- 1: trace pred-indices of i and j to identify a blossom B
- 2: create new node b and set $\bar{A}(b) \leftarrow \cup_{x \in B} \bar{A}(x)$
- 3: label b even and add to *list*
- 4: update $\bar{A}(j) \leftarrow \bar{A}(j) \cup \{b\}$ for each $j \in \bar{A}(b)$
- 5: form a circular double linked list of nodes in B
- 6: delete nodes in B from the graph

Get all nodes of the blossom.

Time: $\mathcal{O}(m)$

Algorithm 56 contract(i, j)

- 1: trace pred-indices of i and j to identify a blossom B
- 2: create new node b and set $\bar{A}(b) \leftarrow \cup_{x \in B} \bar{A}(x)$
- 3: label b even and add to *list*
- 4: update $\bar{A}(j) \leftarrow \bar{A}(j) \cup \{b\}$ for each $j \in \bar{A}(b)$
- 5: form a circular double linked list of nodes in B
- 6: delete nodes in B from the graph

Identify all neighbours of b .

Time: $\mathcal{O}(m)$ (how?)

Algorithm 56 $\text{contract}(i, j)$

- 1: trace pred-indices of i and j to identify a blossom B
- 2: create new node b and set $\bar{A}(b) \leftarrow \cup_{x \in B} \bar{A}(x)$
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- 5: form a circular double linked list of nodes in B
- 6: delete nodes in B from the graph

Every node that was adjacent to a node
in B is now adjacent to b

Algorithm 56 $\text{contract}(i, j)$

- 1: trace pred-indices of i and j to identify a blossom B
- 2: create new node b and set $\bar{A}(b) \leftarrow \cup_{x \in B} \bar{A}(x)$
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- 5: form a circular double linked list of nodes in B
- 6: delete nodes in B from the graph

Only for making a blossom expansion easier.

Algorithm 56 $\text{contract}(i, j)$

- 1: trace pred-indices of i and j to identify a blossom B
- 2: create new node b and set $\bar{A}(b) \leftarrow \cup_{x \in B} \bar{A}(x)$
- 3: label b even and add to *list*
- 4: update $\bar{A}(j) \leftarrow \bar{A}(j) \cup \{b\}$ for each $j \in \bar{A}(b)$
- 5: form a circular double linked list of nodes in B
- 6: delete nodes in B from the graph

Only delete links from nodes not in B to B .
When expanding the blossom again we can
recreate these links in time $\mathcal{O}(m)$.

Analysis

- ▶ A contraction operation can be performed in time $\mathcal{O}(m)$. Note, that any graph created will have at most m edges.
- ▶ The time between two contraction-operation is basically a BFS/DFS on a graph. Hence takes time $\mathcal{O}(m)$.
- ▶ There are at most n contractions as each contraction reduces the number of vertices.
- ▶ The expansion can trivially be done in the same time as needed for all contractions.
- ▶ An augmentation requires time $\mathcal{O}(n)$. There are at most n of them.
- ▶ In total the running time is at most

$$n \cdot (\mathcal{O}(mn) + \mathcal{O}(n)) = \mathcal{O}(mn^2) .$$

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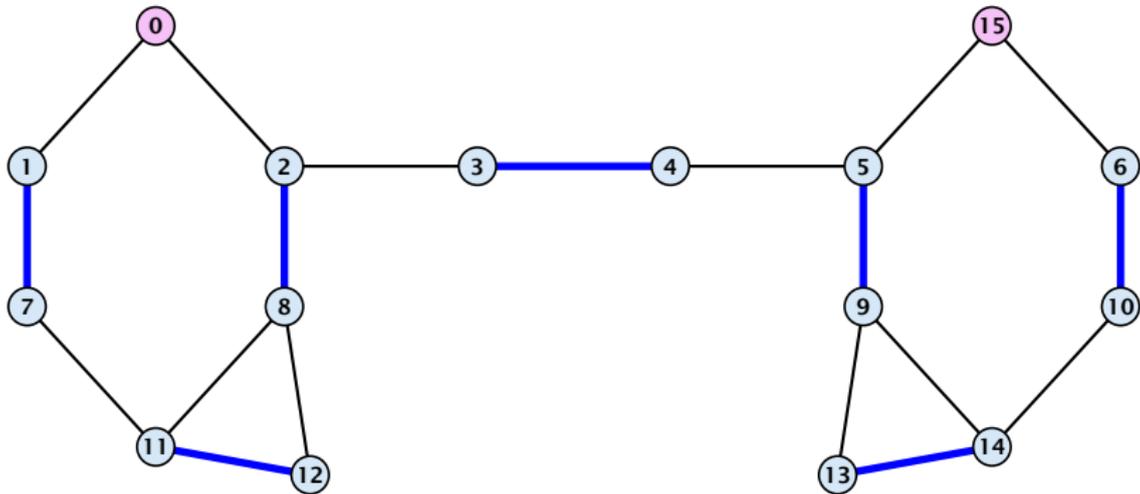
$$n \cdot (\mathcal{O}(mn) + \mathcal{O}(n)) = \mathcal{O}(mn^2) .$$

Analysis

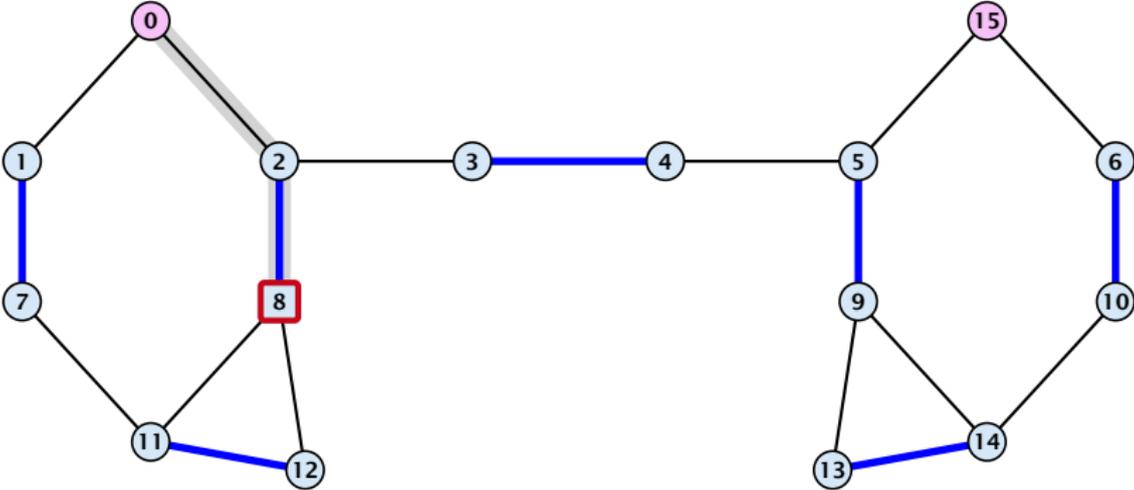
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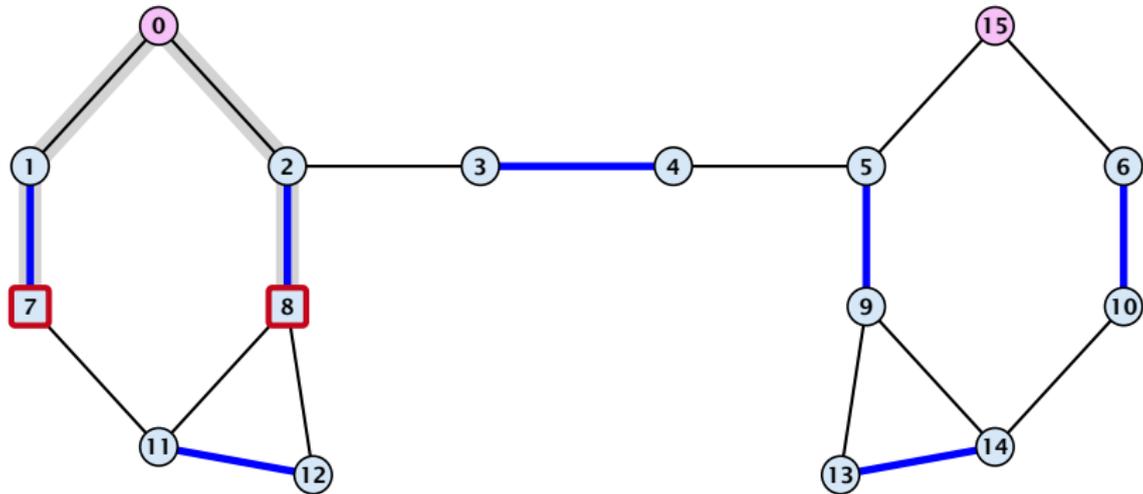
Example: Blossom Algorithm



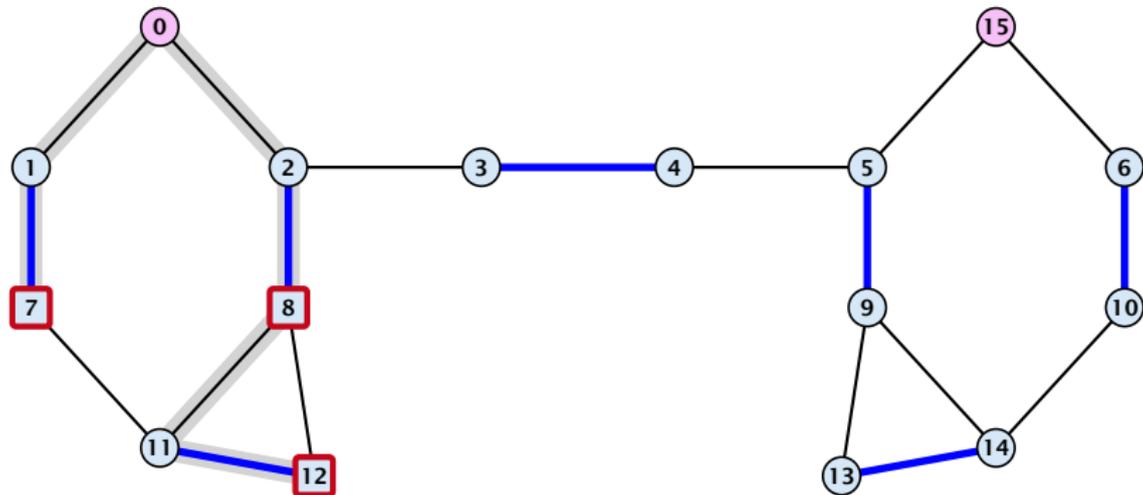
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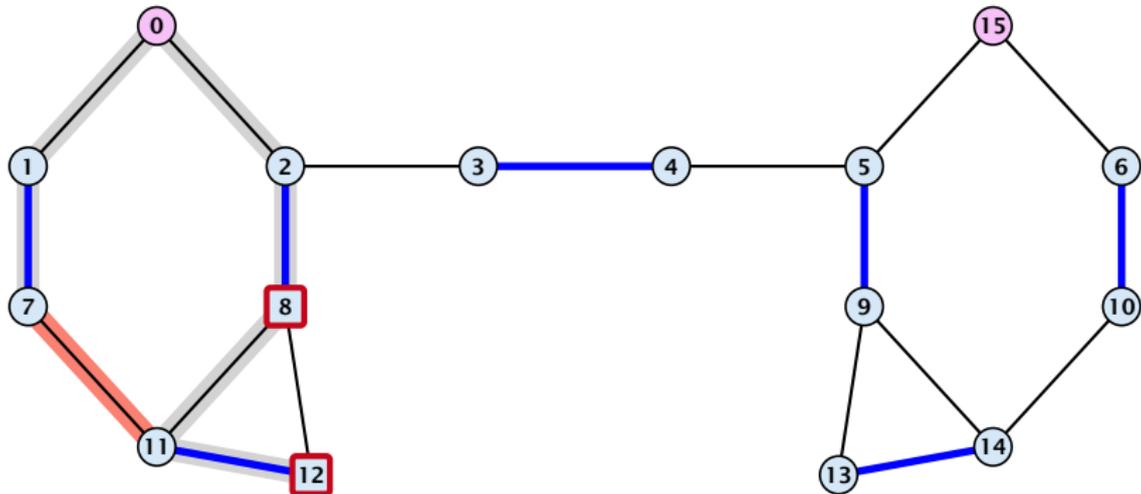
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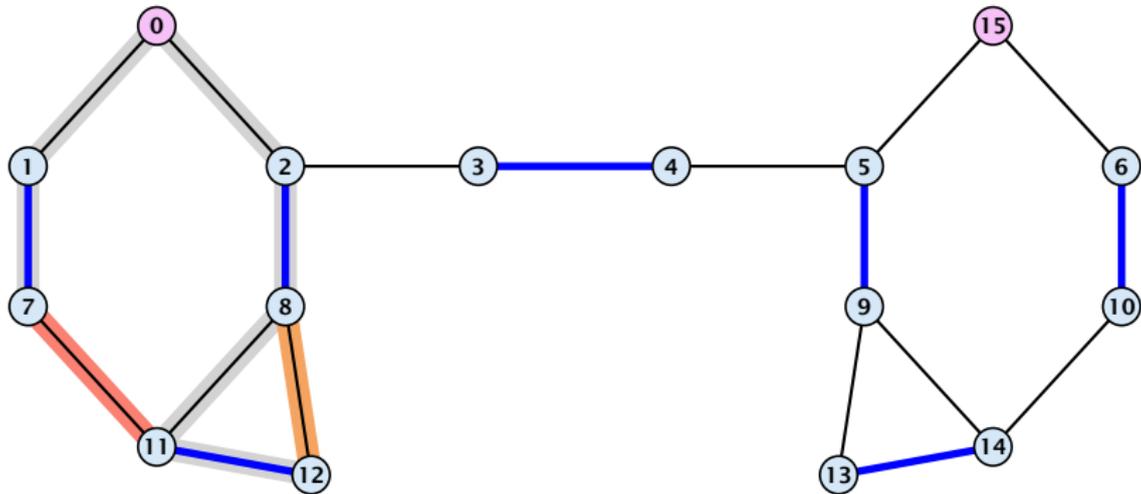
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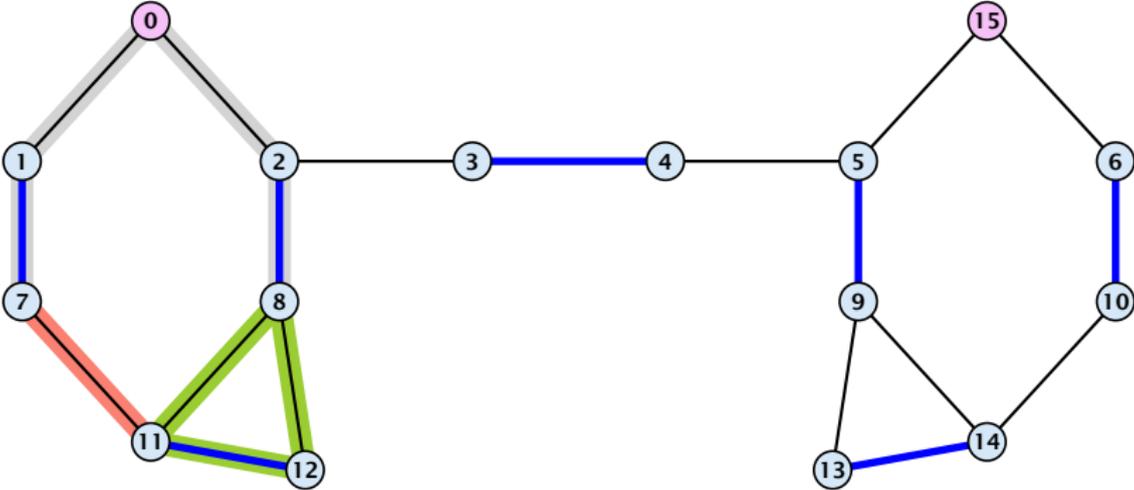
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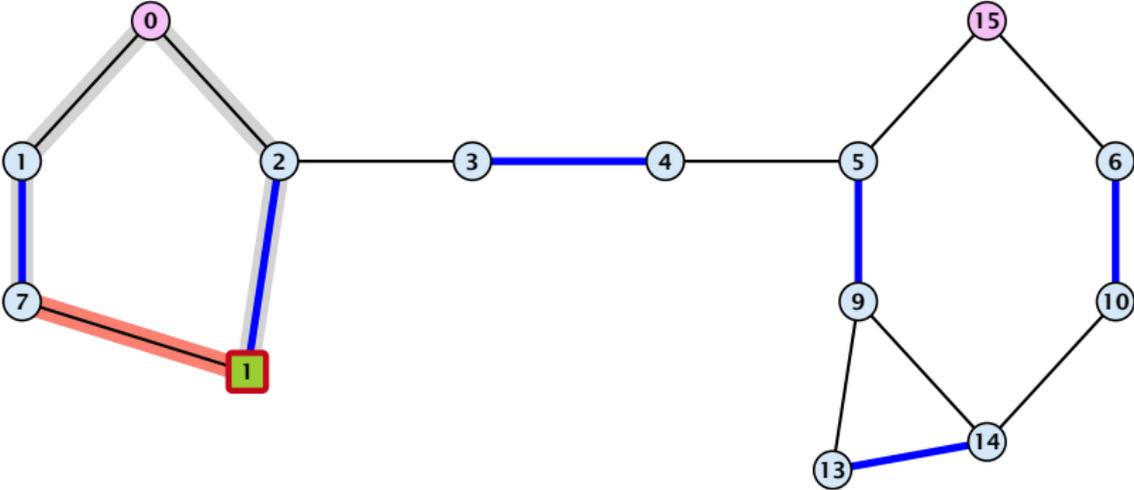
Example: Blossom Algorithm



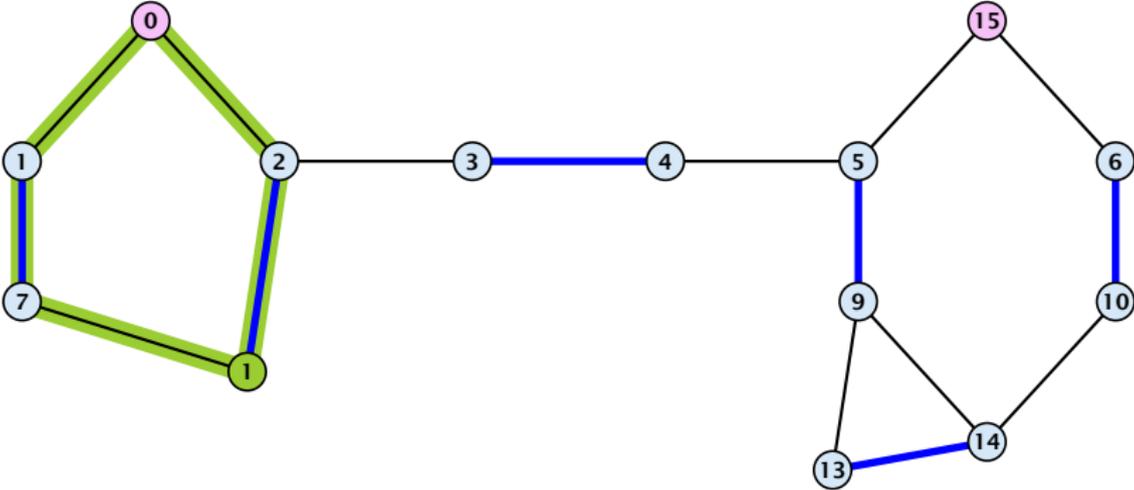
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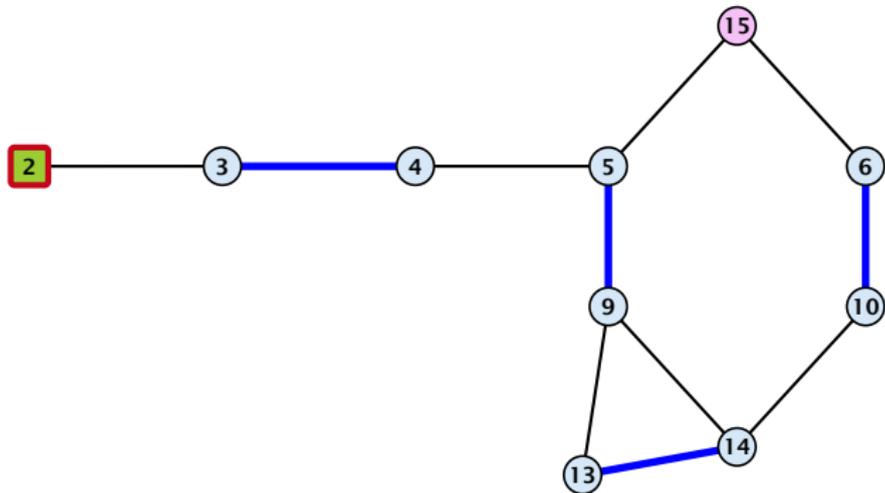
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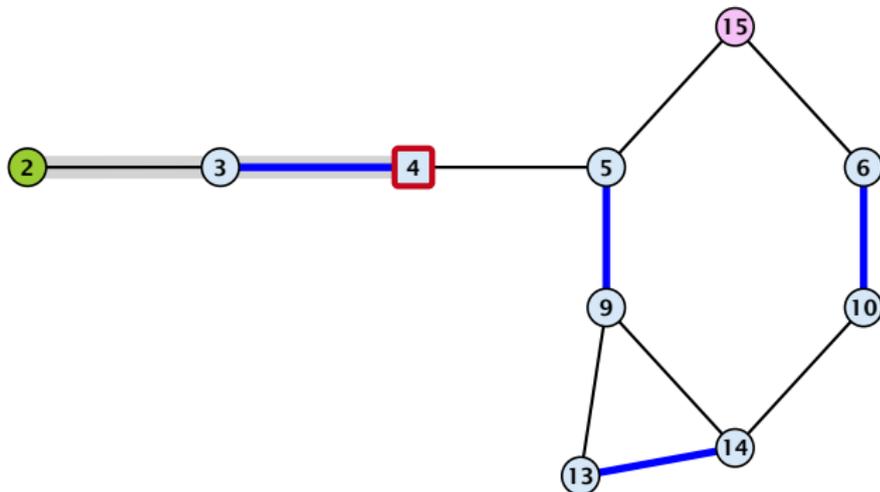
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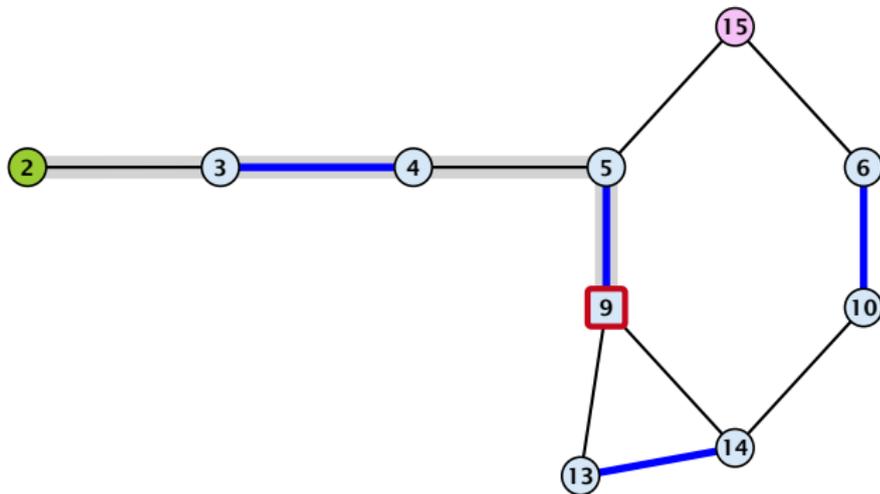
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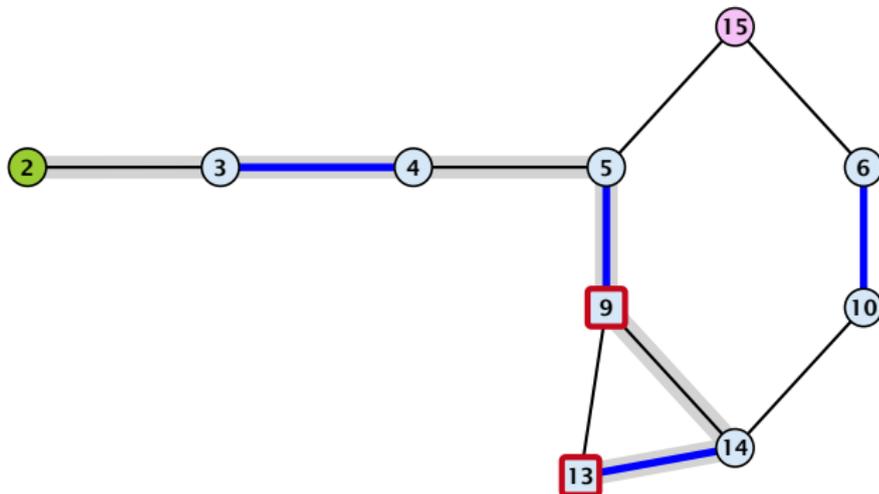
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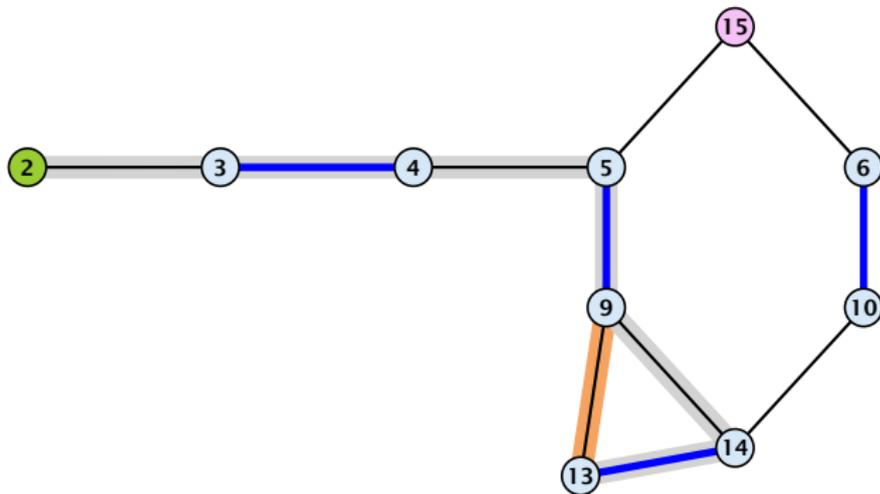
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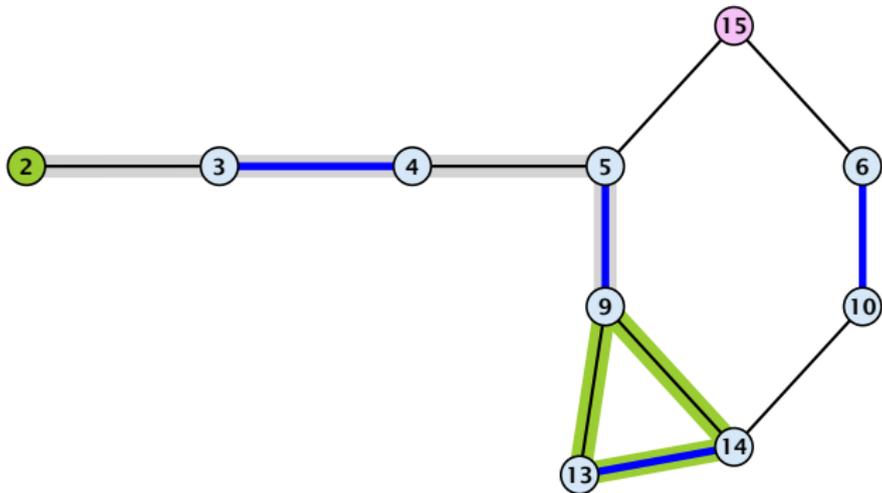
Example: Blossom Algorithm



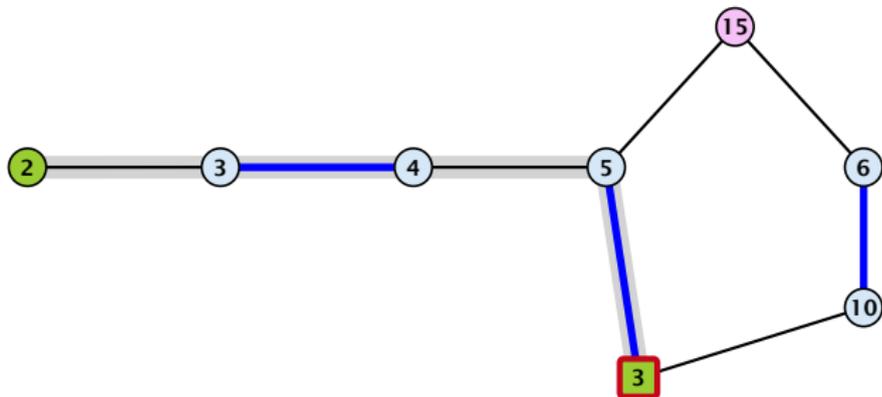
Example: Blossom Algorithm



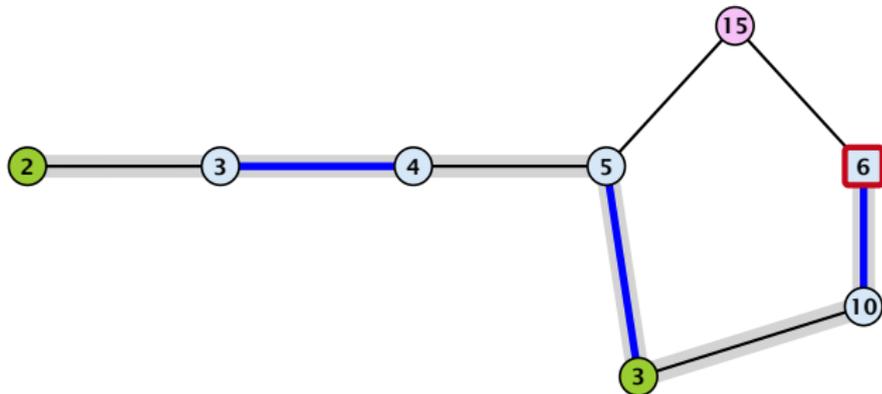
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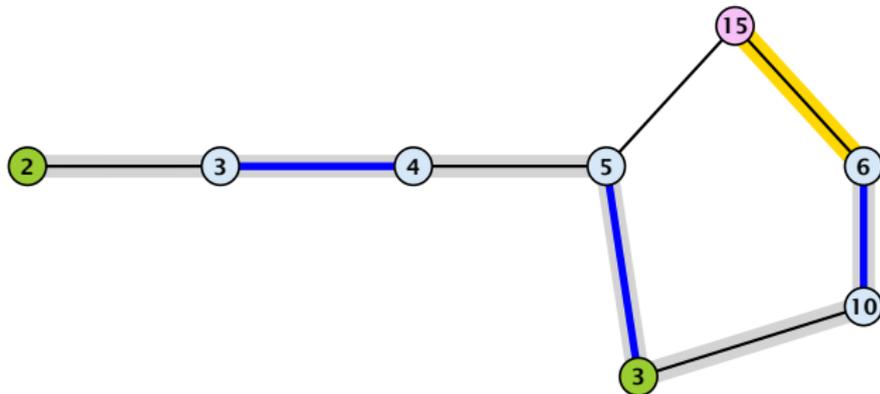
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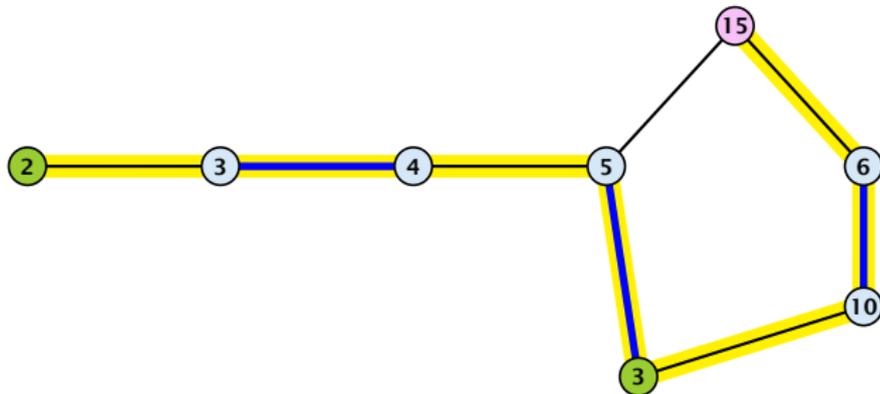
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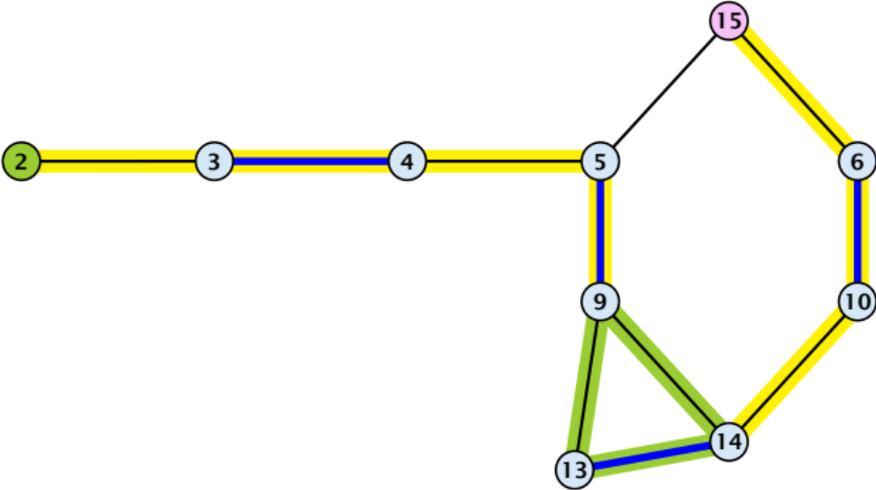
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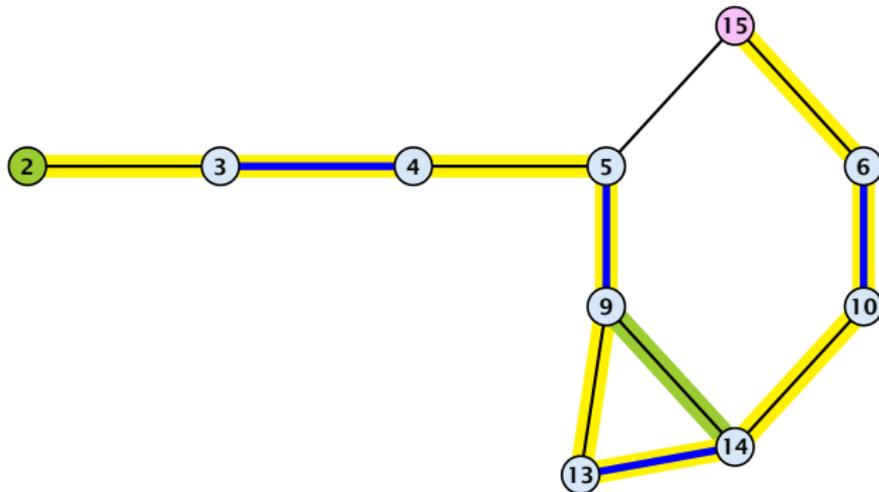
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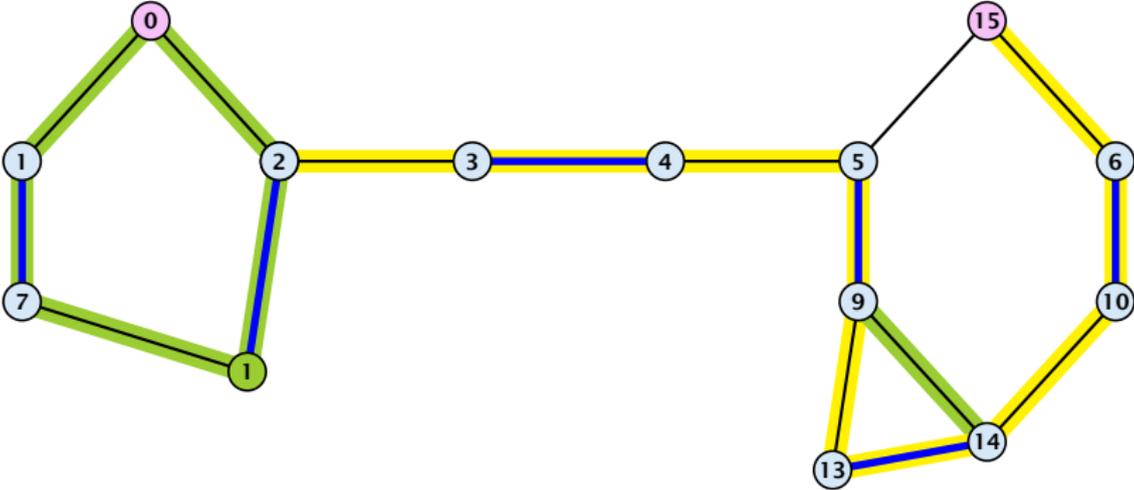
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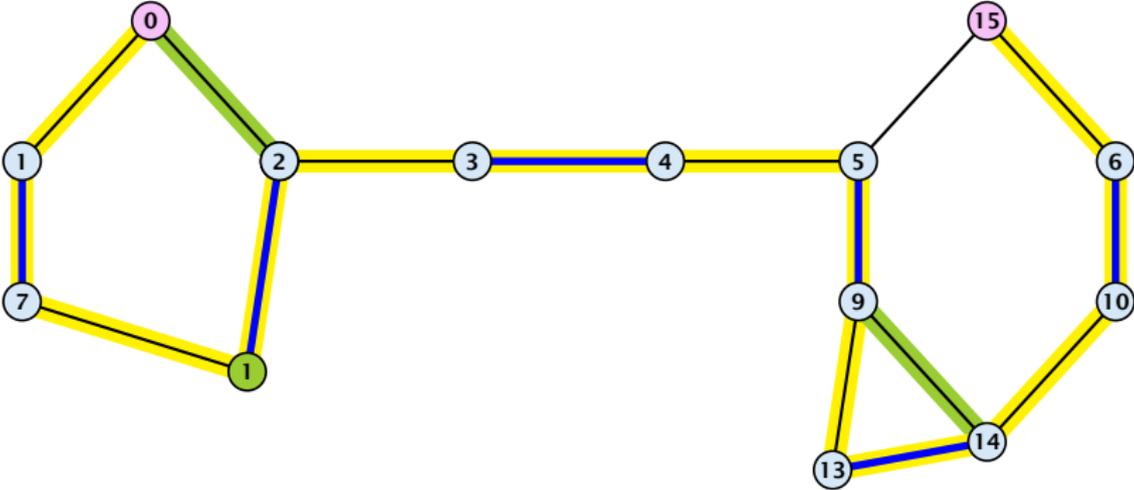
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