CS70: Discrete Math and Probability

Fan Ye

June 27, 2016

Today

More graphs

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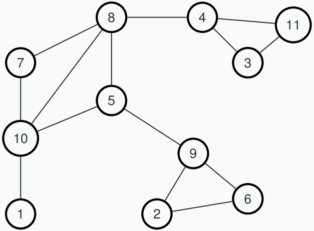
- Connectivity
- Planar graphs
  - 5 coloring theorem

Connectivity



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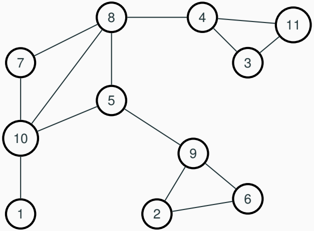

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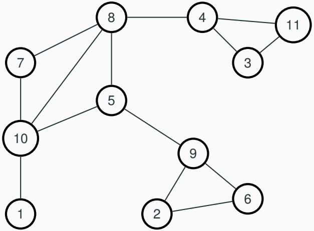

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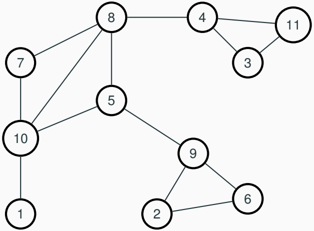

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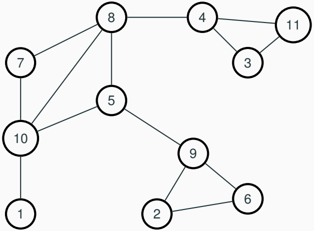

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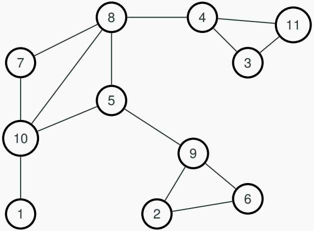

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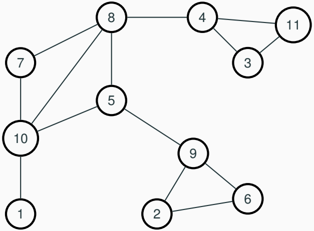

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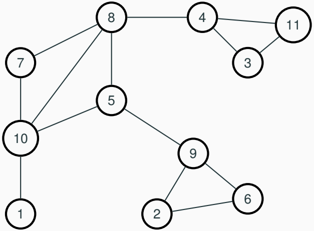

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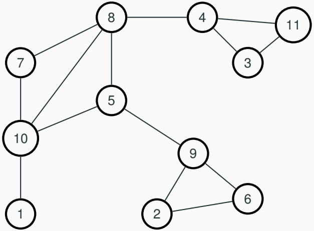

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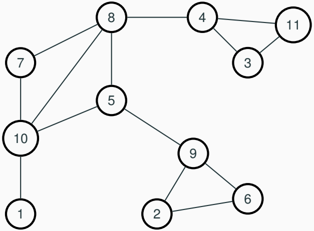

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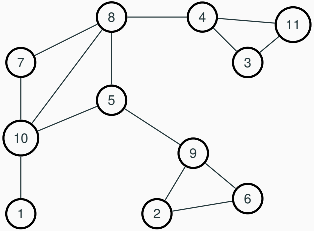

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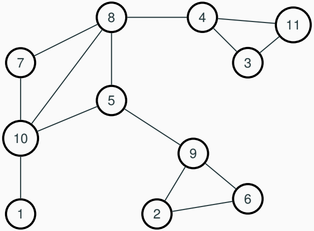

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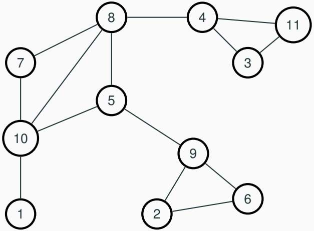

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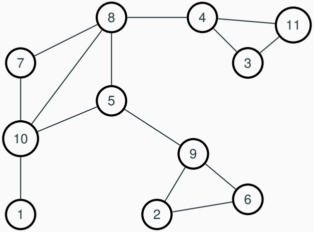
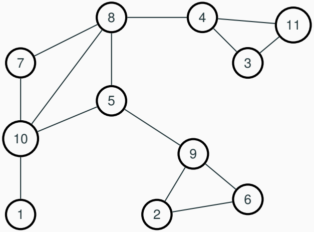


Is graph above connected?

Connected component



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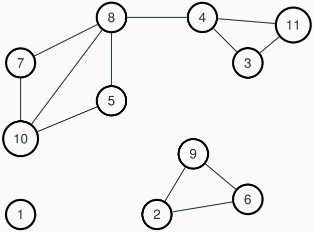
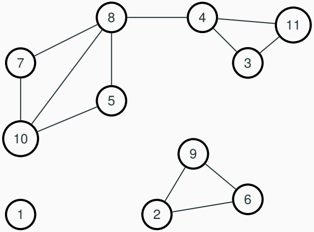


Is graph above connected? Yes!

How about now?

Connected component



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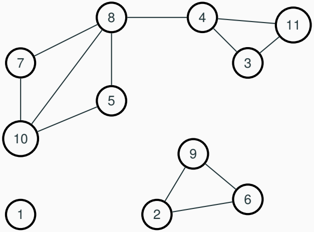

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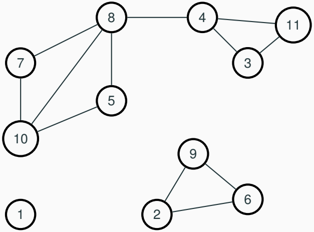
Connected Components?

Connected component

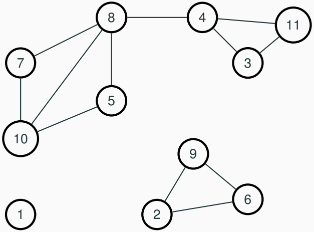


Is graph above connected? Yes!

How about now? No!

Connected Components? $\{1\}, \{10, 7, 5, 8, 4, 3, 11\}, \{2, 9, 6\}$.

Connected component



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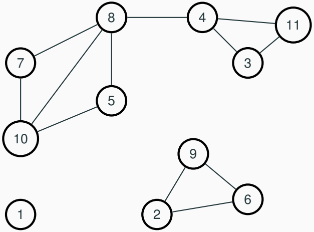
Connected component - maximal set of connected vertices.

Connected component



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Quick Check: Is $\{10, 7, 5\}$ a connected component?

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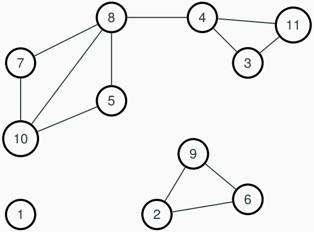

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Finally..back to bridges!

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Definition:

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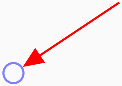

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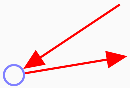

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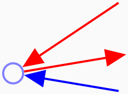

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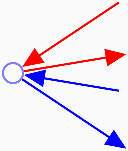

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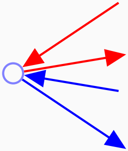

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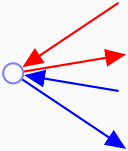

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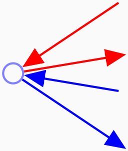

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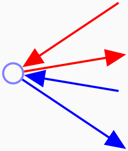

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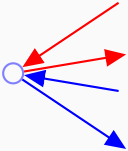

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Proof of if: Even + connected $\implies$ Eulerian Tour.
We will give an algorithm.

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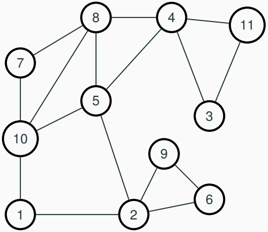

1. Take a walk starting from v (1) on "unused" edges

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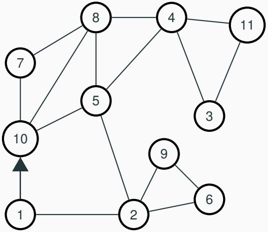

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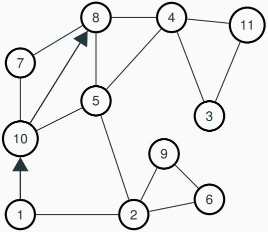

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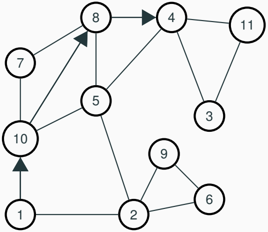

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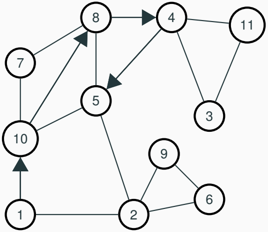

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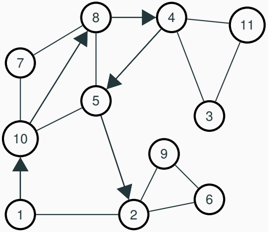

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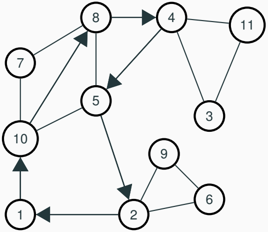

1. Take a walk starting from v (1) on "unused" edges
... till you get back to v.

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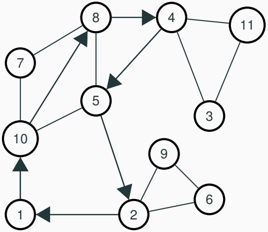

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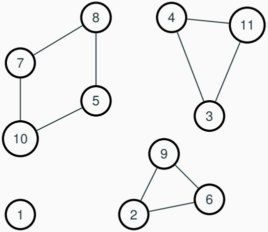
... till you get back to v.
2. Remove tour, C.

Finding a tour!

Proof of if: Even + connected $\implies$ Eulerian Tour.
We will give an algorithm. First by picture.



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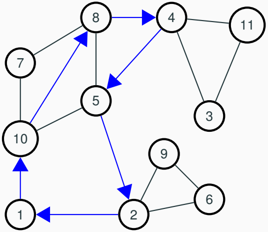

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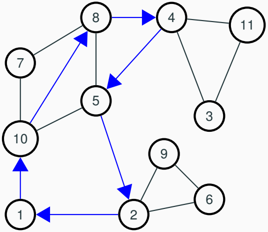

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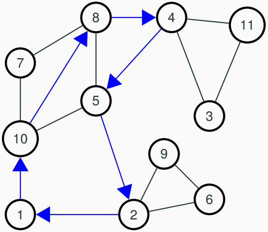

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2. Remove tour, C.
3. Let $G_1, \ldots, G_k$ be connected components.
   Each is touched by C.
      Why? G was connected.

Finding a tour!

Proof of if: Even + connected $\implies$ Eulerian Tour.
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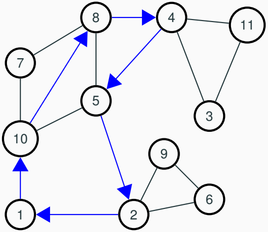

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Finding a tour!

Proof of if: Even + connected $\Longrightarrow$ Eulerian Tour.
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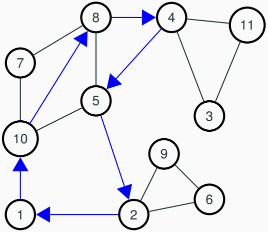

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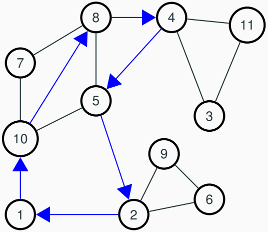
3. Let $G_1, \ldots, G_k$ be connected components.
   Each is touched by C.
   Why? G was connected.
   Let v_i be (first) node in G_i touched by C.
   Example: $v_1 = 1$,

Finding a tour!

Proof of if: Even + connected $\implies$ Eulerian Tour.
We will give an algorithm. First by picture.



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3. Let $G_1, \ldots, G_k$ be connected components.
   Each is touched by C.
      Why? G was connected.
   Let v_i be (first) node in G_i touched by C.
    Example: $v_1 = 1$, $v_2 = 10$,

Finding a tour!

Proof of if: Even + connected $\implies$ Eulerian Tour.
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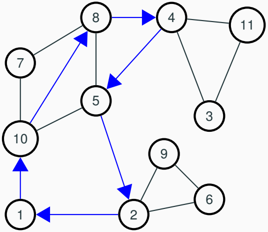

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3. Let $G_1, \ldots, G_k$ be connected components.
   Each is touched by C.
      Why? G was connected.
   Let v_i be (first) node in G_i touched by C.
   Example: $v_1 = 1$, $v_2 = 10$, $v_3 = 4$,

Finding a tour!

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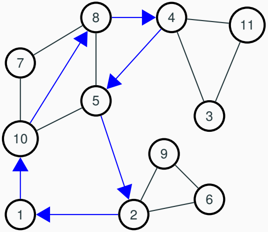

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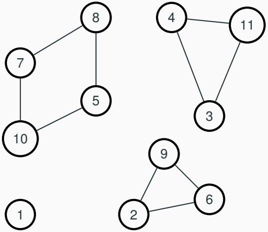
      Why? G was connected.
   Let v_i be (first) node in G_i touched by C.
   Example: $v_1 = 1$, $v_2 = 10$, $v_3 = 4$, $v_4 = 2$.

Finding a tour!

Proof of if: Even + connected $\Longrightarrow$ Eulerian Tour.
We will give an algorithm. First by picture.



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   Let v_i be (first) node in G_i touched by C.
    Example: $v_1 = 1$, $v_2 = 10$, $v_3 = 4$, $v_4 = 2$.
4. Recurse on $G_1, \ldots, G_k$ starting from v_i

Finding a tour!

Proof of if: Even + connected $\implies$ Eulerian Tour.
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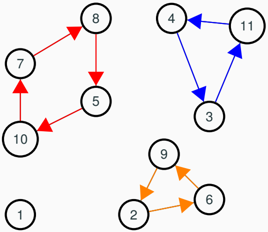

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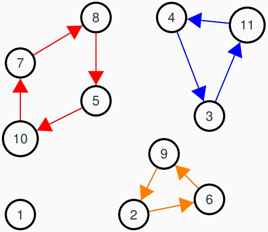

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3. Let $G_1, \ldots, G_k$ be connected components.
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      Why? G was connected.
   Let v_i be (first) node in G_i touched by C.
    Example: $v_1 = 1$, $v_2 = 10$, $v_3 = 4$, $v_4 = 2$.
4. Recurse on $G_1, \ldots, G_k$ starting from v_i
5. Splice together.

Finding a tour!

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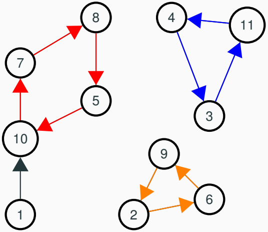

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5. Splice together.
   1,10

Finding a tour!

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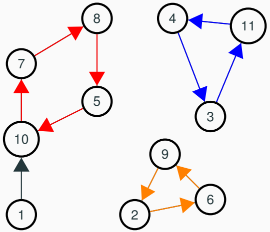

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4. Recurse on $G_1, \ldots, G_k$ starting from v_i
5. Splice together.
   1,10,7,8,5,10

Finding a tour!

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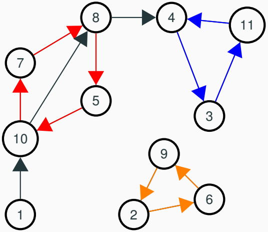

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   1,10,7,8,5,10 ,8,4

Finding a tour!

Proof of if: Even + connected $\implies$ Eulerian Tour.
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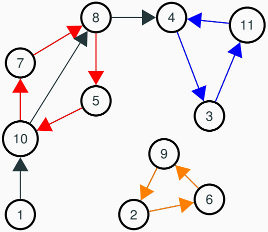

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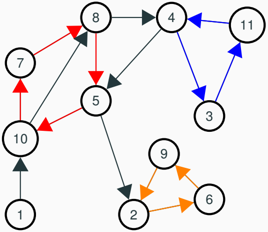

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    Example: $v_1 = 1$, $v_2 = 10$, $v_3 = 4$, $v_4 = 2$.
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5. Splice together.
   1,10,7,8,5,10 ,8,4,3,11,4 5,2

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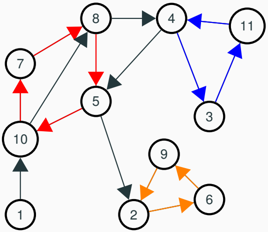

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Finding a tour!

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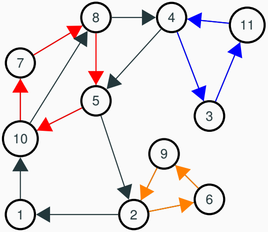

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   1,10,7,8,5,10 ,8,4,3,11,4 5,2,6,9,2 and to 1!

Finding a tour: in general.

1. Take a walk from arbitrary node v, until you get back to v.

Finding a tour: in general.

1. Take a walk from arbitrary node v, until you get back to v.

Claim: Do get back to v!

Finding a tour: in general.

1. Take a walk from arbitrary node v, until you get back to v.

Claim: Do get back to v!
Proof of Claim: Even degree.

Finding a tour: in general.

1. Take a walk from arbitrary node v, until you get back to v.

Claim: Do get back to v!
Proof of Claim: Even degree. If enter, can leave

Finding a tour: in general.

1. Take a walk from arbitrary node v, until you get back to v.

Claim: Do get back to v!
Proof of Claim: Even degree. If enter, can leave except for v.

Finding a tour: in general.

1. Take a walk from arbitrary node v, until you get back to v.

Claim: Do get back to v!
Proof of Claim: Even degree. If enter, can leave except for v. $\square$

Finding a tour: in general.

1. Take a walk from arbitrary node v, until you get back to v.

Claim: Do get back to v!
Proof of Claim: Even degree. If enter, can leave except for v. $\square$

2. Remove cycle, C, from G.

Finding a tour: in general.

1. Take a walk from arbitrary node v, until you get back to v.

Claim: Do get back to v!
Proof of Claim: Even degree. If enter, can leave except for v. $\square$

2. Remove cycle, C, from G.
Resulting graph may be disconnected. (Removed edges!)

Finding a tour: in general.

1. Take a walk from arbitrary node v, until you get back to v.

Claim: Do get back to v!
Proof of Claim: Even degree. If enter, can leave except for v. $\square$

2. Remove cycle, C, from G.
Resulting graph may be disconnected. (Removed edges!)
Let components be $G_1, \ldots, G_k$.

Finding a tour: in general.

1. Take a walk from arbitrary node v, until you get back to v.

Claim: Do get back to v!
Proof of Claim: Even degree. If enter, can leave except for v. □

2. Remove cycle, C, from G.
Resulting graph may be disconnected. (Removed edges!)
Let components be $G_1, \ldots, G_k$.
Let v_i be first vertex of C that is in G_i.

Finding a tour: in general.

1. Take a walk from arbitrary node v, until you get back to v.

Claim: Do get back to v!
Proof of Claim: Even degree. If enter, can leave except for v. $\square$

2. Remove cycle, C, from G.

Resulting graph may be disconnected. (Removed edges!)
Let components be $G_1, \ldots, G_k$.
Let v_i be first vertex of C that is in G_i.
Why is there a v_i in C?

Finding a tour: in general.

1. Take a walk from arbitrary node v, until you get back to v.

Claim: Do get back to v!
Proof of Claim: Even degree. If enter, can leave except for v. $\square$

2. Remove cycle, C, from G.

Resulting graph may be disconnected. (Removed edges!)
Let components be $G_1, \ldots, G_k$.
Let v_i be first vertex of C that is in G_i.
Why is there a v_i in C?
G was connected $\implies$

Finding a tour: in general.

1. Take a walk from arbitrary node v, until you get back to v.

Claim: Do get back to v!
Proof of Claim: Even degree. If enter, can leave except for v. $\square$

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Resulting graph may be disconnected. (Removed edges!)
Let components be $G_1, \ldots, G_k$.
Let v_i be first vertex of C that is in G_i.
Why is there a v_i in C?
G was connected $\implies$
a vertex in G_i must be incident to a removed edge in C.

Finding a tour: in general.

1. Take a walk from arbitrary node v, until you get back to v.

Claim: Do get back to v!
Proof of Claim: Even degree. If enter, can leave except for v. $\square$

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Let components be $G_1, \ldots, G_k$.
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Why is there a v_i in C?
G was connected $\implies$
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Finding a tour: in general.

1. Take a walk from arbitrary node v, until you get back to v.

Claim: Do get back to v!
Proof of Claim: Even degree. If enter, can leave except for v. $\square$

2. Remove cycle, C, from G.

Resulting graph may be disconnected. (Removed edges!)
Let components be $G_1, \ldots, G_k$.
Let v_i be first vertex of C that is in G_i.
Why is there a v_i in C?
G was connected $\implies$
a vertex in G_i must be incident to a removed edge in C.

Claim: Each vertex in each G_i has even degree

Finding a tour: in general.

1. Take a walk from arbitrary node v, until you get back to v.

Claim: Do get back to v!
Proof of Claim: Even degree. If enter, can leave except for v. $\square$

2. Remove cycle, C, from G.

Resulting graph may be disconnected. (Removed edges!)
Let components be $G_1, \ldots, G_k$.
Let v_i be first vertex of C that is in G_i.
Why is there a v_i in C?
G was connected $\implies$
a vertex in G_i must be incident to a removed edge in C.

Claim: Each vertex in each G_i has even degree and is connected.

Finding a tour: in general.

1. Take a walk from arbitrary node v, until you get back to v.

Claim: Do get back to v!
Proof of Claim: Even degree. If enter, can leave except for v. $\square$

2. Remove cycle, C, from G.

Resulting graph may be disconnected. (Removed edges!)
Let components be $G_1, \ldots, G_k$.
Let v_i be first vertex of C that is in G_i.
Why is there a v_i in C?
G was connected $\Longrightarrow$
a vertex in G_i must be incident to a removed edge in C.

Claim: Each vertex in each G_i has even degree and is connected.
Prf: Tour C has even incidences to any vertex v.

Finding a tour: in general.

1. Take a walk from arbitrary node v, until you get back to v.

Claim: Do get back to v!
Proof of Claim: Even degree. If enter, can leave except for v. $\square$

2. Remove cycle, C, from G.

Resulting graph may be disconnected. (Removed edges!)
Let components be $G_1, \ldots, G_k$.
Let v_i be first vertex of C that is in G_i.
Why is there a v_i in C?
G was connected $\implies$
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Finding a tour: in general.

1. Take a walk from arbitrary node v, until you get back to v.

Claim: Do get back to v!
Proof of Claim: Even degree. If enter, can leave except for v. $\square$

2. Remove cycle, C, from G.

Resulting graph may be disconnected. (Removed edges!)
Let components be $G_1, \ldots, G_k$.
Let v_i be first vertex of C that is in G_i.
Why is there a v_i in C?
G was connected $\implies$
a vertex in G_i must be incident to a removed edge in C.

Claim: Each vertex in each G_i has even degree and is connected.
Prf: Tour C has even incidences to any vertex v. $\square$

3. Find tour T_i of G_i

Finding a tour: in general.

1. Take a walk from arbitrary node v, until you get back to v.

Claim: Do get back to v!
Proof of Claim: Even degree. If enter, can leave except for v. $\square$

2. Remove cycle, C, from G.

Resulting graph may be disconnected. (Removed edges!)
Let components be $G_1, \ldots, G_k$.
Let v_i be first vertex of C that is in G_i.
Why is there a v_i in C?
G was connected $\implies$
a vertex in G_i must be incident to a removed edge in C.

Claim: Each vertex in each G_i has even degree and is connected.
Prf: Tour C has even incidences to any vertex v. $\square$

3. Find tour T_i of G_i starting/ending at v_i.

Finding a tour: in general.

1. Take a walk from arbitrary node v, until you get back to v.

Claim: Do get back to v!
Proof of Claim: Even degree. If enter, can leave except for v. $\square$

2. Remove cycle, C, from G.
Resulting graph may be disconnected. (Removed edges!)
Let components be $G_1, \ldots, G_k$.
Let v_i be first vertex of C that is in G_i.
Why is there a v_i in C?
G was connected $\implies$
a vertex in G_i must be incident to a removed edge in C.

Claim: Each vertex in each G_i has even degree and is connected.
Prf: Tour C has even incidences to any vertex v. $\square$

3. Find tour T_i of G_i starting/ending at v_i. Induction.

Finding a tour: in general.

1. Take a walk from arbitrary node v, until you get back to v.

Claim: Do get back to v!
Proof of Claim: Even degree. If enter, can leave except for v. $\square$

2. Remove cycle, C, from G.

Resulting graph may be disconnected. (Removed edges!)
Let components be $G_1, \ldots, G_k$.
Let v_i be first vertex of C that is in G_i.
Why is there a v_i in C?
G was connected $\Longrightarrow$
a vertex in G_i must be incident to a removed edge in C.

Claim: Each vertex in each G_i has even degree and is connected.
Prf: Tour C has even incidences to any vertex v. $\square$

3. Find tour T_i of G_i starting/ending at v_i. Induction.
4. Splice T_i into C where v_i first appears in C.

Finding a tour: in general.

1. Take a walk from arbitrary node v, until you get back to v.

Claim: Do get back to v!
Proof of Claim: Even degree. If enter, can leave except for v. $\square$

2. Remove cycle, C, from G.

Resulting graph may be disconnected. (Removed edges!)
Let components be $G_1, \ldots, G_k$.
Let v_i be first vertex of C that is in G_i.
Why is there a v_i in C?
G was connected $\implies$
a vertex in G_i must be incident to a removed edge in C.

Claim: Each vertex in each G_i has even degree and is connected.
Prf: Tour C has even incidences to any vertex v. $\square$

3. Find tour T_i of G_i starting/ending at v_i. Induction.
4. Splice T_i into C where v_i first appears in C.

Visits every edge once:
Visits edges in C

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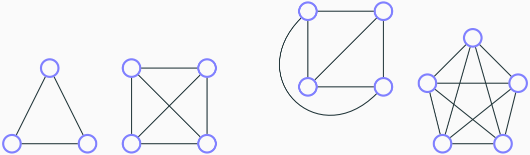
Planar graphs.

A graph that can be drawn in the plane without edge crossings.

Planar graphs.

A graph that can be drawn in the plane without edge crossings.



Planar?

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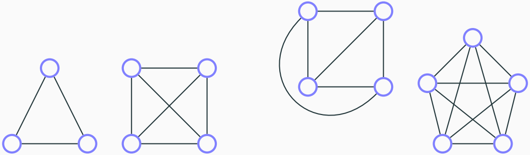

Planar? Yes for Triangle.

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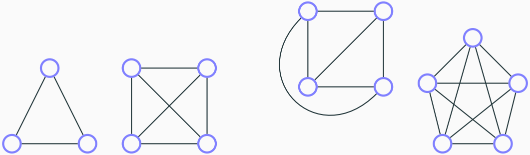

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Four node complete?

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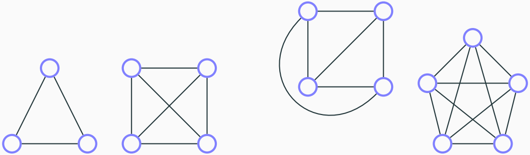

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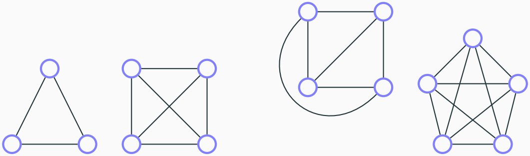

Planar? Yes for Triangle.
Four node complete? Yes.
Five node complete or K_5?

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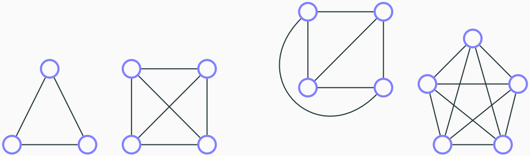

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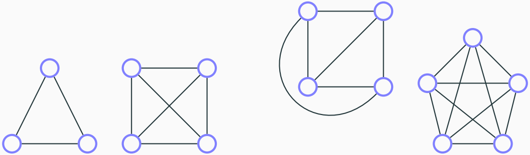

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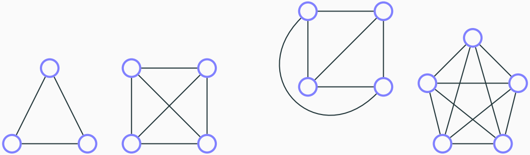

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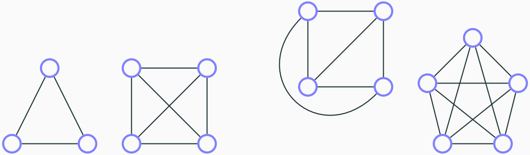

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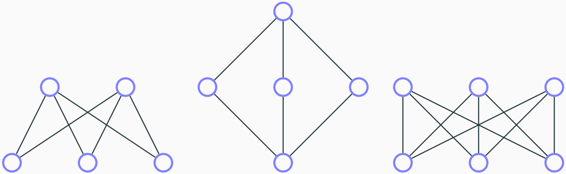

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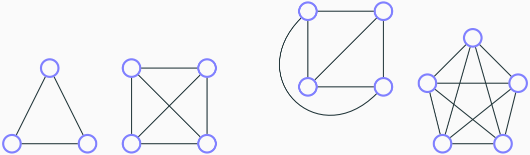

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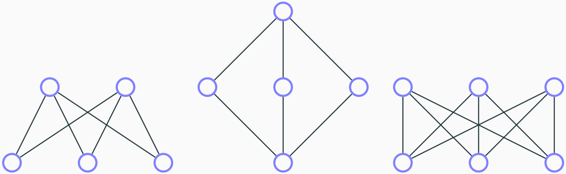

Two to three nodes, bipartite?

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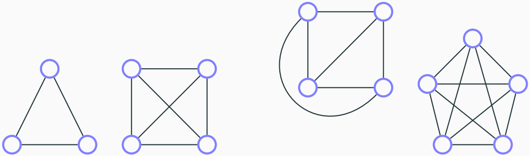

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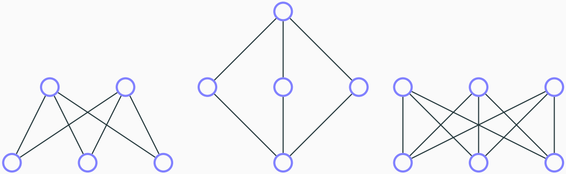

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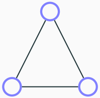
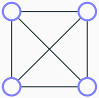
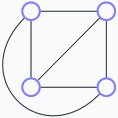
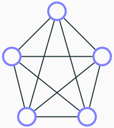

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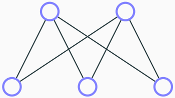
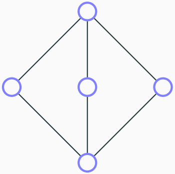
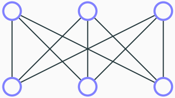

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Three to three nodes, complete/bipartite or $K_{3,3}$.

Planar graphs.

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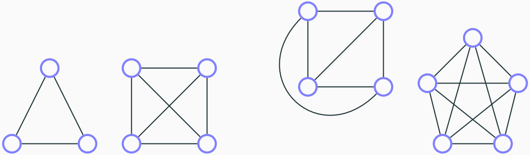

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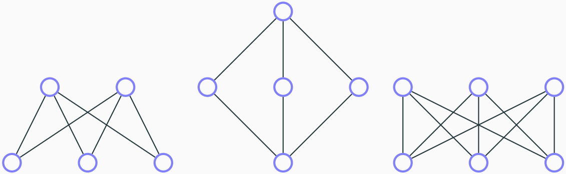

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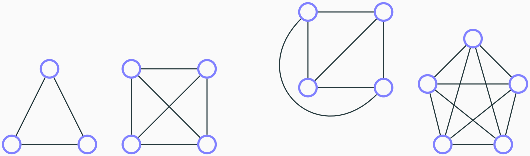

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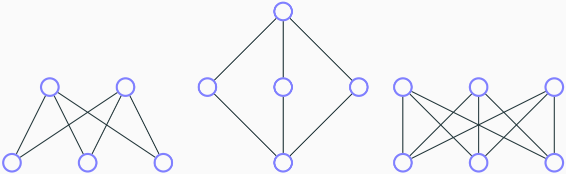

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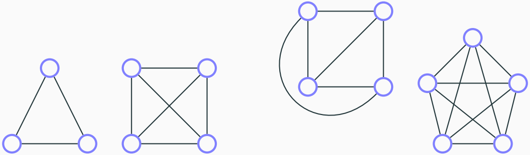

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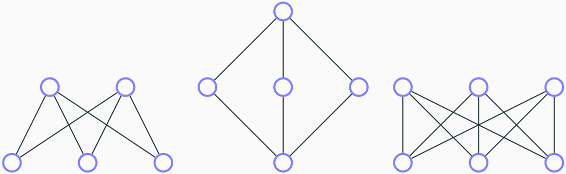

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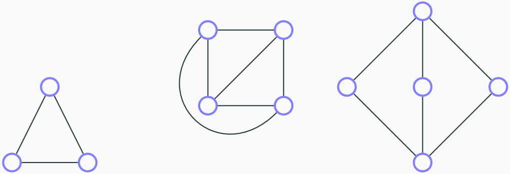

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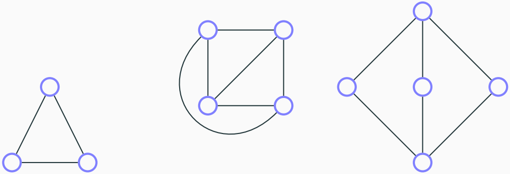
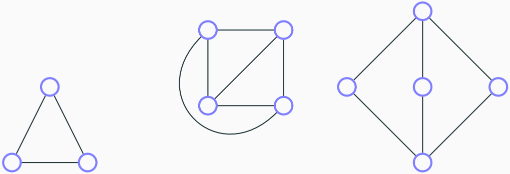


Faces: connected regions of the plane.

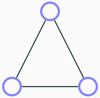
Euler's Formula.

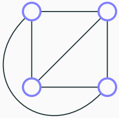


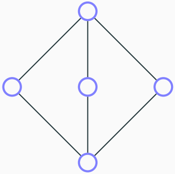
Faces: connected regions of the plane.

How many faces for

Euler’s Formula.





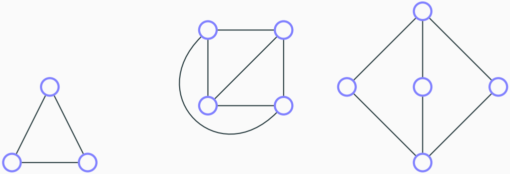


Faces: connected regions of the plane.

How many faces for

triangle?

Euler's Formula.

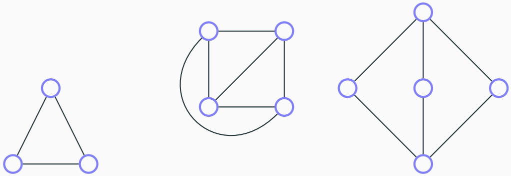


Faces: connected regions of the plane.

How many faces for

triangle? 2

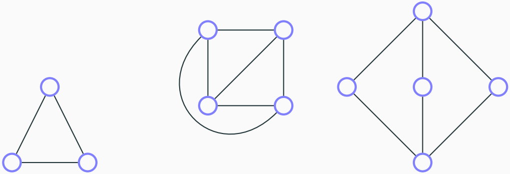
Euler's Formula.



Faces: connected regions of the plane.

How many faces for
- triangle? 2
- complete on four vertices or K_4?

Euler's Formula.



Faces: connected regions of the plane.

How many faces for
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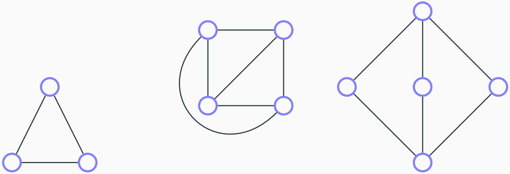


Faces: connected regions of the plane.

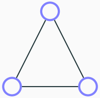
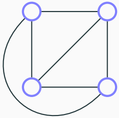
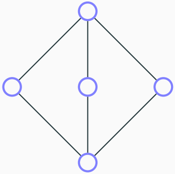
How many faces for

triangle? 2

complete on four vertices or K_4? 4

bipartite, complete two/three or $K_{2,3}$?

Euler's Formula.

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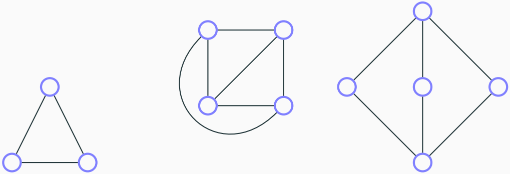

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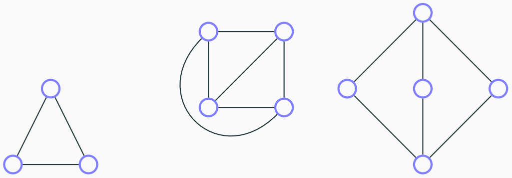

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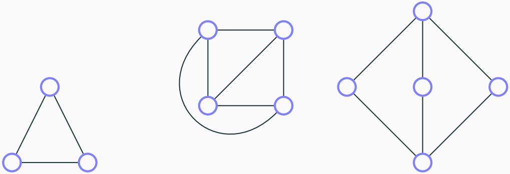

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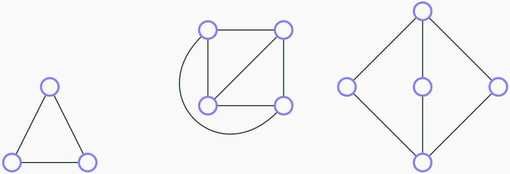

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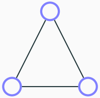
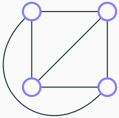
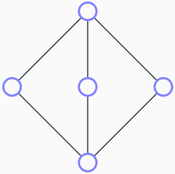

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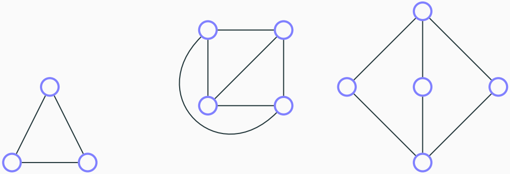

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Triangle: $3 + 2 = 3 + 2$!

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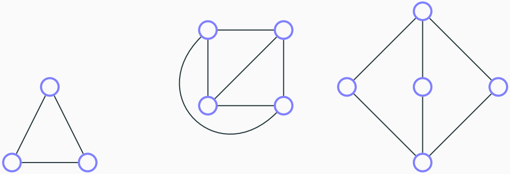

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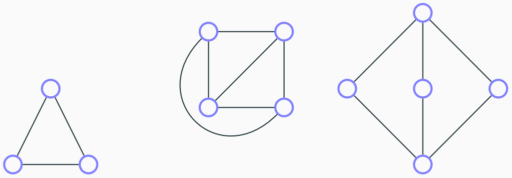
K_4:



Faces: connected regions of the plane.

How many faces for

triangle? 2

complete on four vertices or K_4? 4

bipartite, complete two/three or $K_{2,3}$? 3

v is number of vertices, e is number of edges, f is number of faces.

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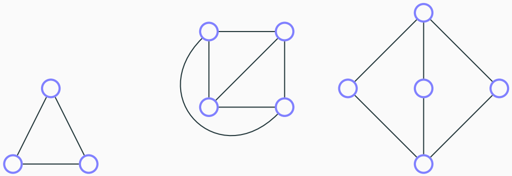
Euler's Formula.



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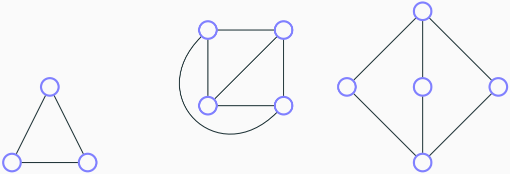

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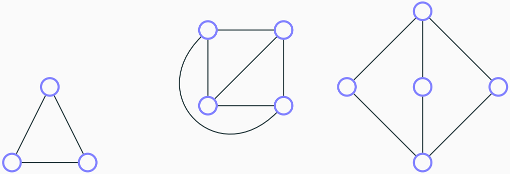

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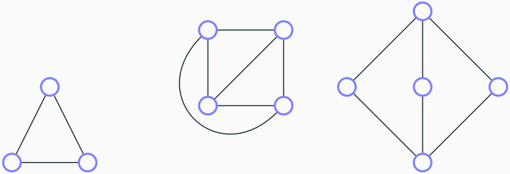

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Examples = 3!

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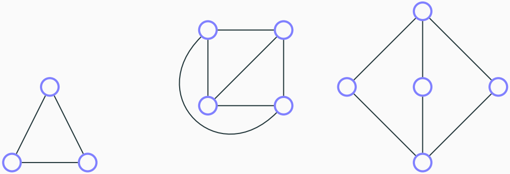

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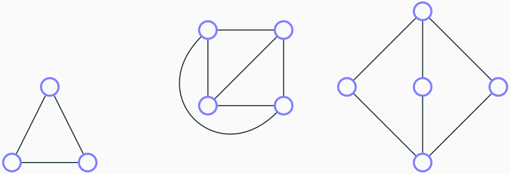

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Euler and Polyhedron.

Greeks knew formula for polyhedron.

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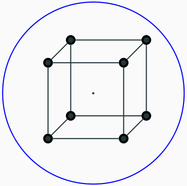

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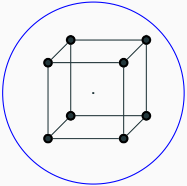

Faces?

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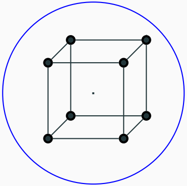

Faces? 6. Edges?

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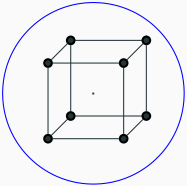

Faces? 6. Edges? 12.

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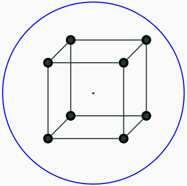

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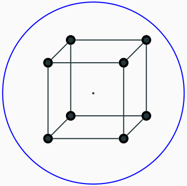

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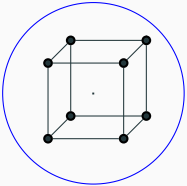

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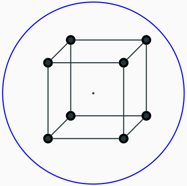

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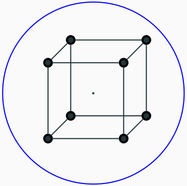

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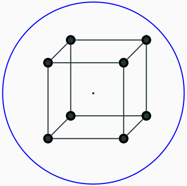

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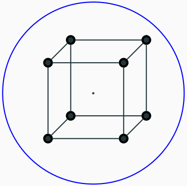

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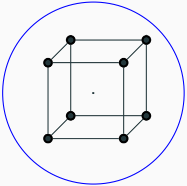

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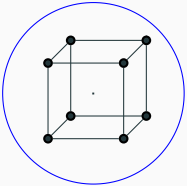

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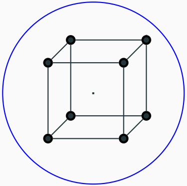

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Polyhedron without holes

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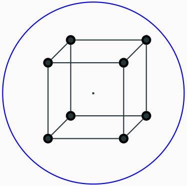

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Polyhedron without holes $\equiv$

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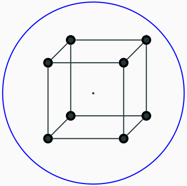

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Polyhedron without holes $\equiv$ Planar graphs.

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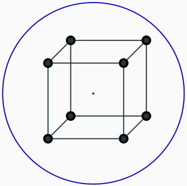

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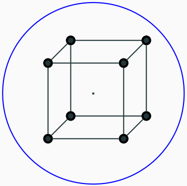
Polyhedron without holes $\equiv$ Planar graphs.

Surround by sphere.

Euler and Polyhedron.

Greeks knew formula for polyhedron.



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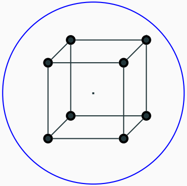
Polyhedron without holes $\equiv$ Planar graphs.

Surround by sphere.
Project from point inside polytope onto sphere.

Euler and Polyhedron.

Greeks knew formula for polyhedron.



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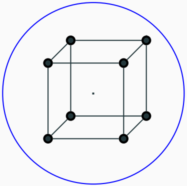
Polyhedron without holes $\equiv$ Planar graphs.

Surround by sphere.
Project from point inside polytope onto sphere.
Sphere

Euler and Polyhedron.

Greeks knew formula for polyhedron.



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Polyhedron without holes $\equiv$ Planar graphs.

Surround by sphere.
Project from point inside polytope onto sphere.
Sphere $\equiv$ Plane!

Euler and Polyhedron.

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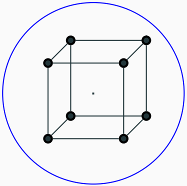

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Project from point inside polytope onto sphere.
Sphere $\equiv$ Plane! Topologically.

Euler and Polyhedron.

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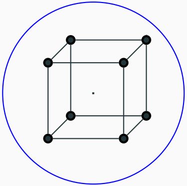

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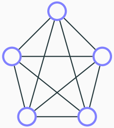
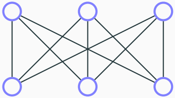
Polyhedron without holes $\equiv$ Planar graphs.

Surround by sphere.
Project from point inside polytope onto sphere.
Sphere $\equiv$ Plane! Topologically.

Euler proved formula thousands of years later!

Euler and planarity of K_5 and $K_{3,3}$





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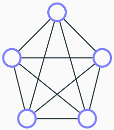

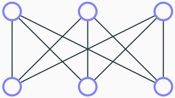

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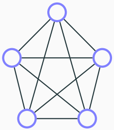

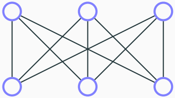

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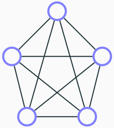
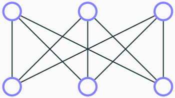
Each face is adjacent to at least three edges.

Euler and planarity of K_5 and $K_{3,3}$

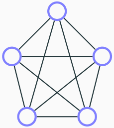


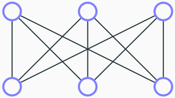


Euler: $v + f = e + 2$ for connected planar graph.

Each face is adjacent to at least three edges. $\geq 3f$ face-edge adjacencies.

Euler and planarity of K_5 and $K_{3,3}$

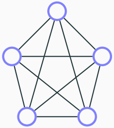


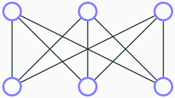


Euler: $v + f = e + 2$ for connected planar graph.

Each face is adjacent to at least three edges. $\geq 3f$ face-edge adjacencies.
Each edge is adjacent to (at most) two faces.

Euler and planarity of K_5 and $K_{3,3}$





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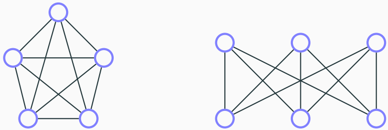

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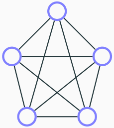

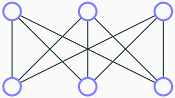

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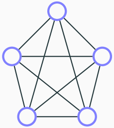
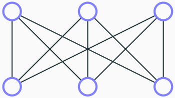
Euler: $v + \frac{2}{3}e \geq e + 2$

Euler and planarity of K_5 and $K_{3,3}$





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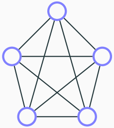

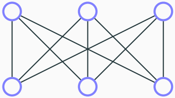

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K_5

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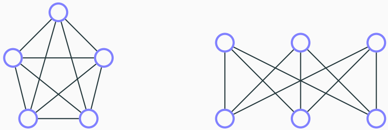

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K_5 Edges?

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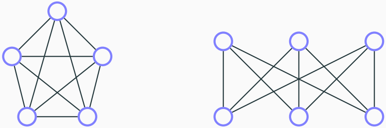

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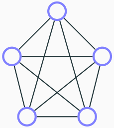

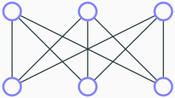

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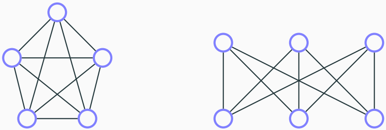

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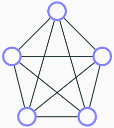

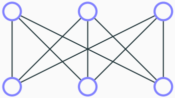

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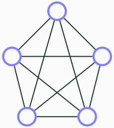

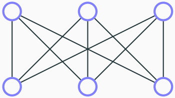

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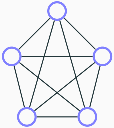

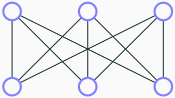

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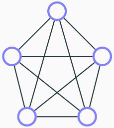
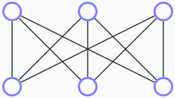

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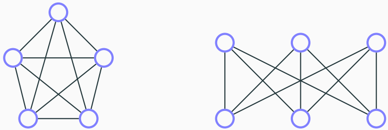

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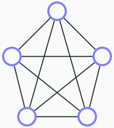

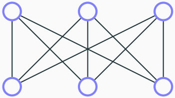

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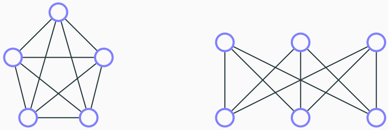

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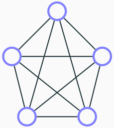

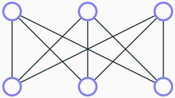

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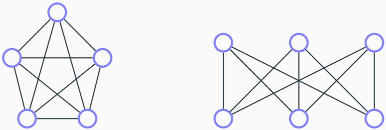

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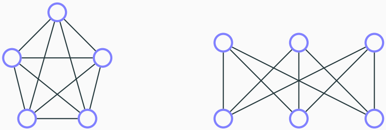

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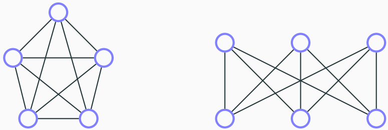

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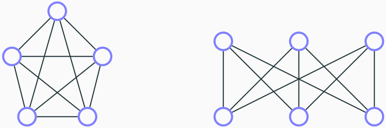

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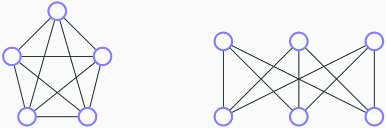

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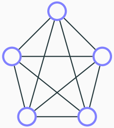

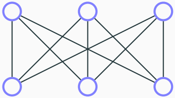

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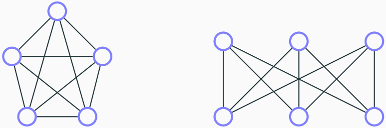

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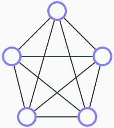

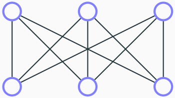

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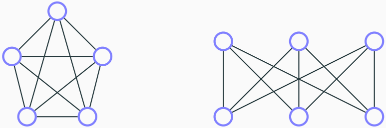

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$K_{3,3}$? Edges? 9. Vertices. 6. $9 \leq 3(6)-6$? Sure!
But no cycles that are triangles. Face is of length ≥ 4.
.... $4f \leq 2e$.
Euler: $v+\frac{1}{2}e \geq e+2 \implies e \leq 2v-4$

$9 \not\leq 2(6)-4$. $\implies$ $K_{3,3}$ is not planar!

Tree.

A tree is a connected acyclic graph.

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To tree or not to tree!

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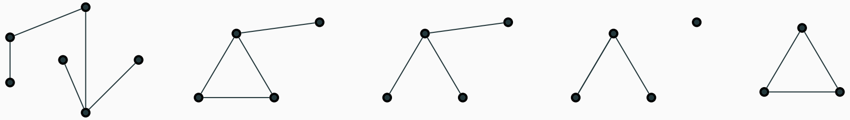

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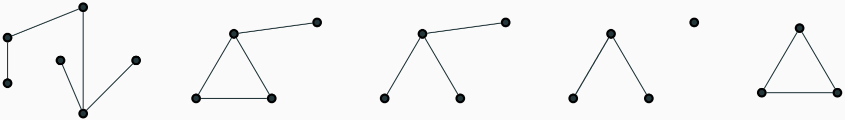

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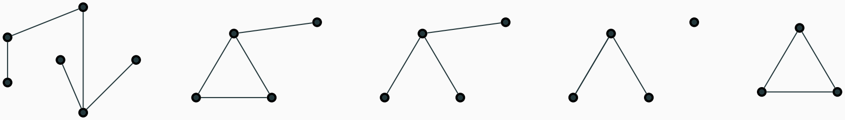

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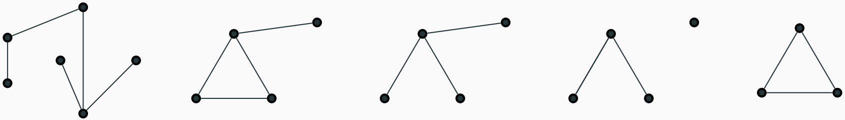

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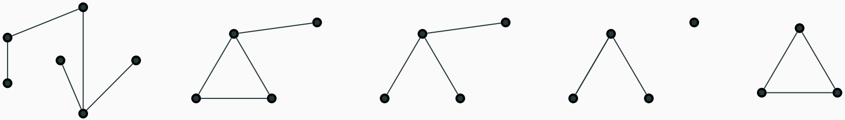

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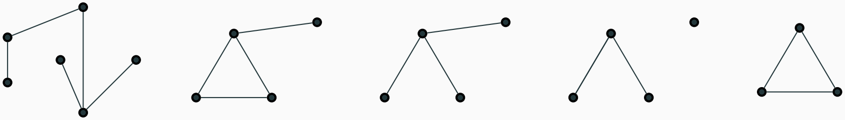

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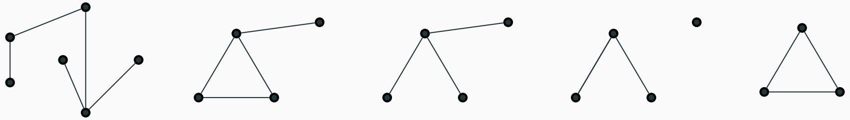

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Faces?

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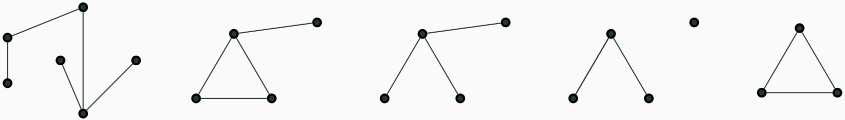

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Faces? 1.

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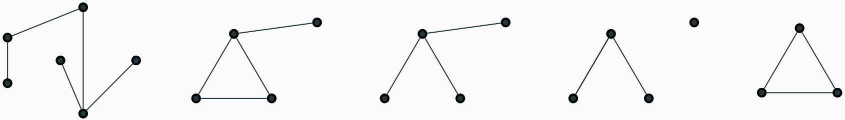

Yes. No. Yes. No. No.

Faces? 1. 2.

Tree.

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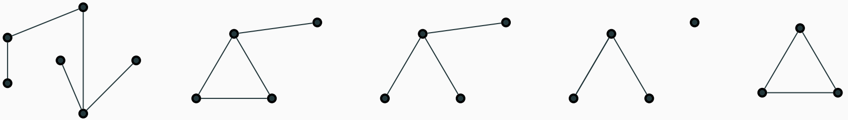

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Faces? 1. 2. 1.

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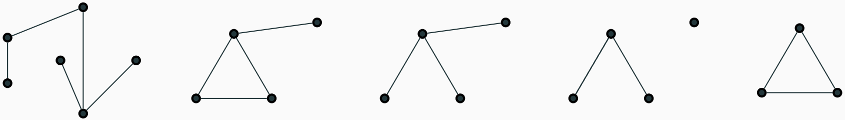

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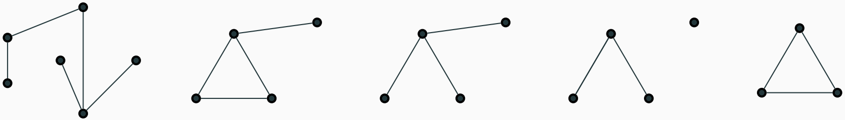

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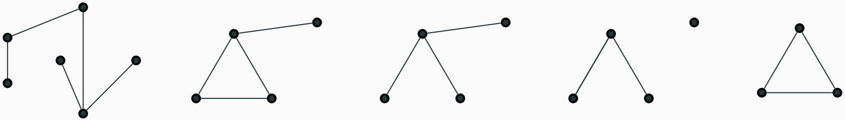

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Faces?   1. 2. 1. 1. 2.
Vertices/Edges.

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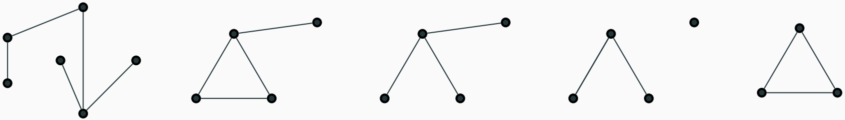

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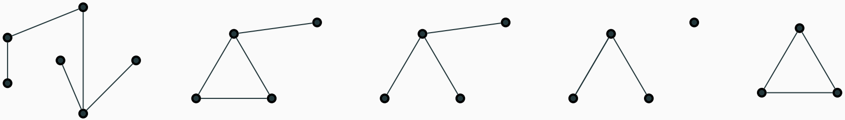

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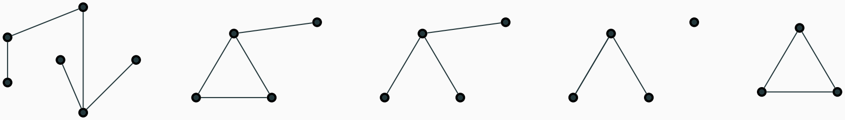

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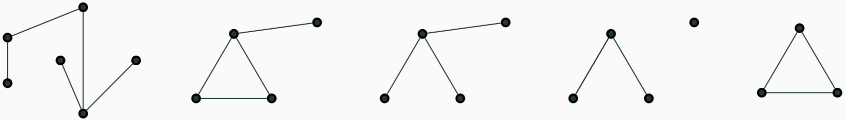

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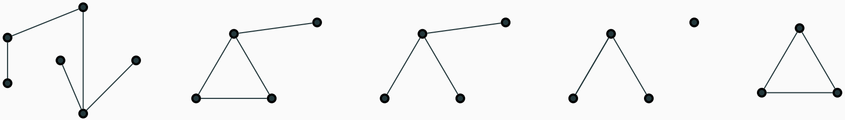

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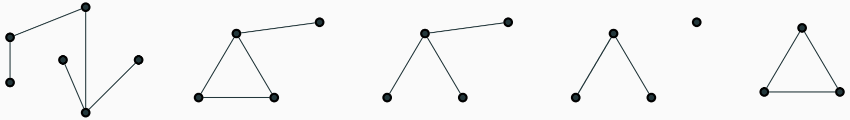

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Euler's formula.

Euler: Connected planar graph has $v + f = e + 2$.

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Proof sketch:

Euler's formula.

Euler: Connected planar graph has $v+f=e+2$.

Proof sketch: Induction on e.

Euler's formula.

Euler: Connected planar graph has $v + f = e + 2$.

Proof sketch: Induction on e.
Base:

Euler's formula.

Euler: Connected planar graph has $v + f = e + 2$.

Proof sketch: Induction on e.
Base: $e = 0$,

Euler's formula.

Euler: Connected planar graph has $v+f=e+2$.

Proof sketch: Induction on e.
Base: $e=0$, $v=f=1$.

Euler's formula.

Euler: Connected planar graph has $v + f = e + 2$.

Proof sketch: Induction on e.
Base: $e = 0$, $v = f = 1$.
Induction Step:

Euler's formula.

Euler: Connected planar graph has $v+f=e+2$.

Proof sketch: Induction on e.
Base: $e=0$, $v=f=1$.
Induction Step:
If it is a tree.

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Proof sketch: Induction on e.
Base: $e=0$, $v=f=1$.
Induction Step:
If it is a tree. Done.

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Proof sketch: Induction on e.
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Induction Step:
  If it is a tree. Done.
  If not a tree.

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Base: $e=0$, $v=f=1$.
Induction Step:
If it is a tree. Done.
If not a tree.
Find a cycle.

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Proof sketch: Induction on e.
Base: $e=0$, $v=f=1$.
Induction Step:
  If it is a tree. Done.
  If not a tree.
    Find a cycle. Remove edge.

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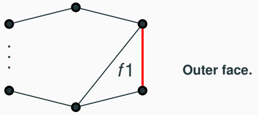

Joins two faces.

Euler's formula.

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Base: $e=0$, $v=f=1$.
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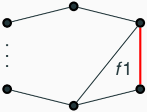


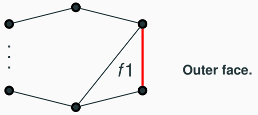
Outer face.

Joins two faces.
New graph: v-vertices.

Euler's formula.

Euler: Connected planar graph has $v + f = e + 2$.

Proof sketch: Induction on e.
Base: $e = 0$, $v = f = 1$.
Induction Step:
If it is a tree. Done.
If not a tree.
Find a cycle. Remove edge.



Joins two faces.
New graph: v-vertices. $e - 1$ edges.

Euler's formula.

Euler: Connected planar graph has $v + f = e + 2$.

Proof sketch: Induction on e.
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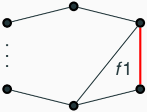
Induction Step:
If it is a tree. Done.
If not a tree.
Find a cycle. Remove edge.



Outer face.

Joins two faces.
New graph: v-vertices. $e - 1$ edges. $f - 1$ faces.

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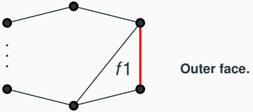

Joins two faces.
New graph: v-vertices. $e-1$ edges. $f-1$ faces. Planar.

Euler's formula.

Euler: Connected planar graph has $v+f=e+2$.

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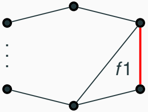

Outer face.

  Joins two faces.
  New graph: v-vertices. $e-1$ edges. $f-1$ faces. Planar.
  $v+(f-1)=(e-1)+2$ by induction hypothesis.

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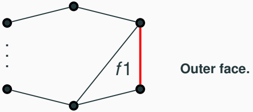

Joins two faces.
New graph: v-vertices. $e - 1$ edges. $f - 1$ faces. Planar.
$v + (f - 1) = (e - 1) + 2$ by induction hypothesis.
Therefore $v + f = e + 2$.

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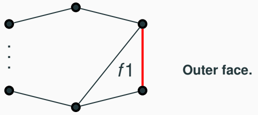

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New graph: v-vertices. $e-1$ edges. $f-1$ faces. Planar.
$v+(f-1)=(e-1)+2$ by induction hypothesis.
Therefore $v+f=e+2$. $\square$

Graph Coloring.

Given $G = (V, E)$, a coloring of a G assigns colors to vertices V where for each edge the endpoints have different colors.

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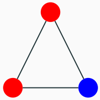

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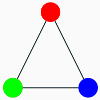

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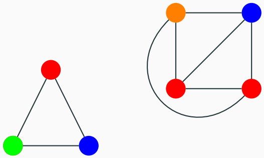

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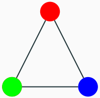

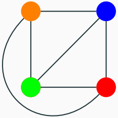

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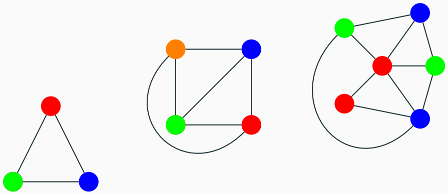

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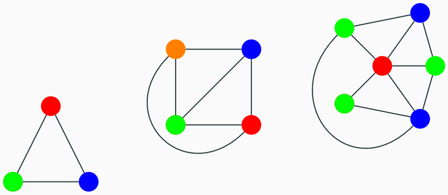

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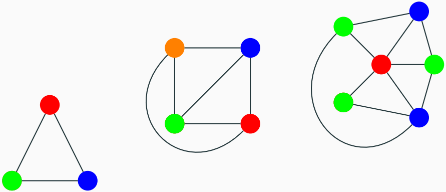

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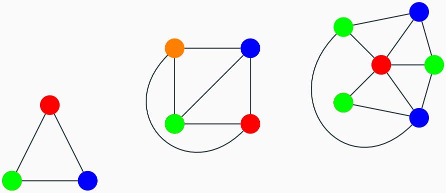
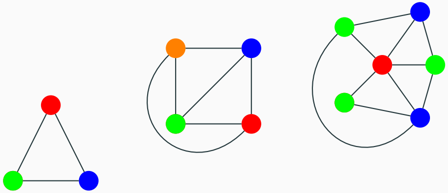


Notice that the last one, has one three colors.

Graph Coloring.

Given $G = (V, E)$, a coloring of a G assigns colors to vertices V where for each edge the endpoints have different colors.



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Fewer colors than number of vertices.

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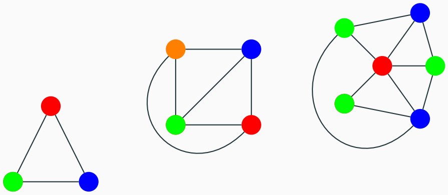

Notice that the last one, has one three colors.
  Fewer colors than number of vertices.
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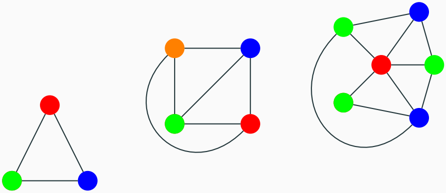

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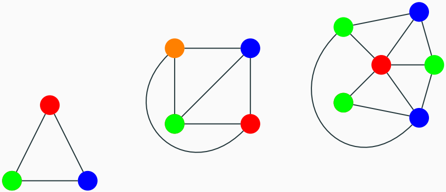

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Interesting things to do.

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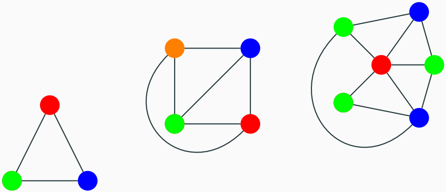

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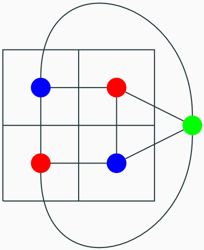
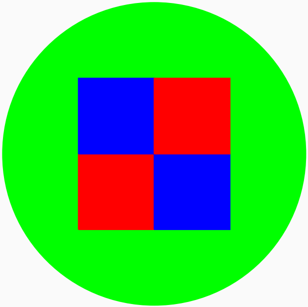
Interesting things to do. Algorithm!

Planar graphs and maps.

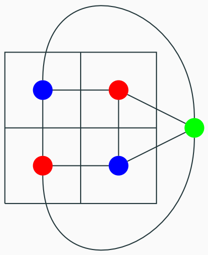
Planar graph coloring $\equiv$ map coloring.

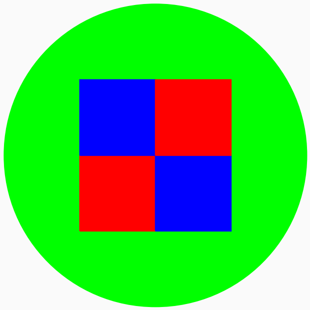




Planar graphs and maps.

Planar graph coloring $\equiv$ map coloring.





Four color theorem is about planar graphs!

Six color theorem.

Theorem: Every planar graph can be colored with six colors.

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Proof:

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Proof:
Recall: $e \leq 3v - 6$ for any planar graph.

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Total degree: $2e$

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Total degree: $2e$
Average degree: $\leq \frac{2e}{v}$

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Recall: $e \leq 3v - 6$ for any planar graph.
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Total degree: $2e$
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Inductively color remaining graph.

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Color is available for v since only five neighbors...

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Again with the degree 5 vertex.

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Proof:
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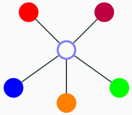

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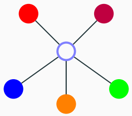

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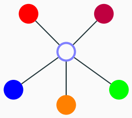

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Switch green to blue in component.

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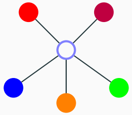

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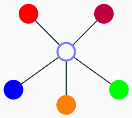

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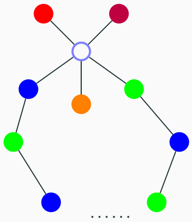

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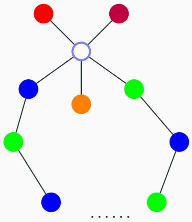

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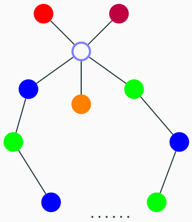

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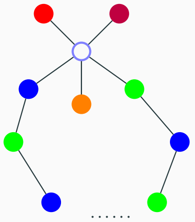

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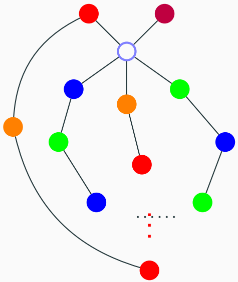

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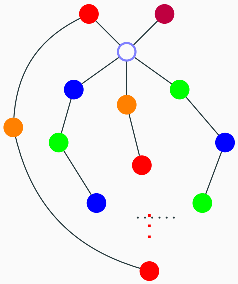

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Planar.

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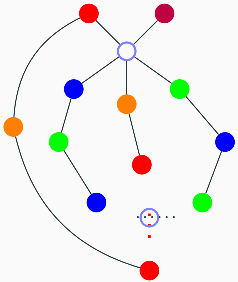

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Planar. $\implies$ paths intersect at a vertex!

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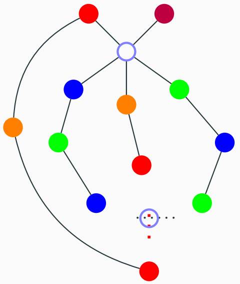

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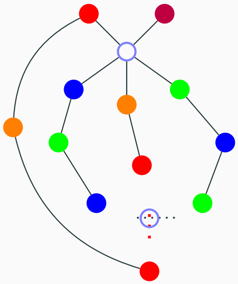

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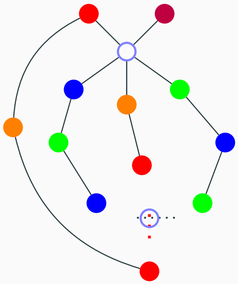

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What color is it?
  Must be blue or green to be on that path.

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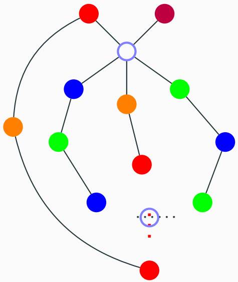

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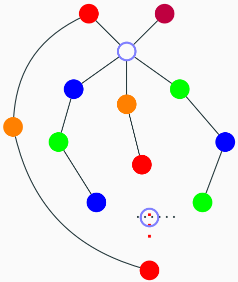

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What color is it?
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Contradiction.

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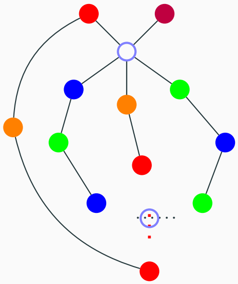

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What color is it?
Must be blue or green to be on that path.
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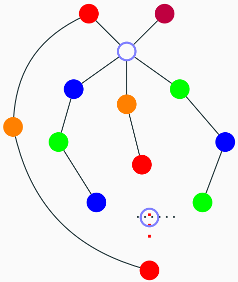
Contradiction. Can recolor one of the neighbors.
And recolor "center" vertex.

Theorem: Every planar graph can be colored with five colors.

Preliminary Observation: Connected components of vertices with two colors in a legal coloring can switch colors.

Proof:
Again with the degree 5 vertex. Again recurse.



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Four Color Theorem

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Proof:

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Proof: Not Today!

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