Chapter 12 and 11.1
Planar graphs, regular polyhedra, and graph colorings

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12.1–12.2. Planar graphs

**Definition**

A *planar embedding* of a graph is a drawing of the graph in the plane without edges crossing.

A graph is *planar* if a planar embedding of it exists.

Consider two drawings of the graph $K_4$:

\[
V = \{1, 2, 3, 4\} \quad E = \{\{1, 2\}, \{1, 3\}, \{1, 4\}, \{2, 3\}, \{2, 4\}, \{3, 4\}\}
\]

The abstract graph $K_4$ is planar because it can be drawn in the plane without crossing edges.
How about $K_5$?

- Both of these drawings of $K_5$ have crossing edges.
- We will develop methods to prove that $K_5$ is not a planar graph, and to characterize what graphs are planar.
Euler’s formula for planar graphs

Euler’s Theorem on Planar Graphs

- Let $G$ be a connected planar graph (drawn without crossing edges).
- Define $V =$ number of vertices
  $E =$ number of edges
  $F =$ number of faces, including the “infinite” face

- Then $V - E + F = 2$.

- Note: this notation conflicts with standard graph theory notation $V =$ set of vertices, $E =$ set of edges.

Example

- $V = 4$
- $E = 6$
- $F = 4$

$V - E + F = 4 - 6 + 4 = 2$
Euler’s formula for planar graphs

- \( V = 10 \)
- \( E = 15 \)
- \( F = 7 \)

\[
V - E + F = 10 - 15 + 7 = 2
\]
A *spanning tree* of a connected graph is a subgraph that’s a tree reaching all vertices. An example is highlighted in red.

We previously saw we could obtain a spanning tree of any connected graph by repeatedly picking any cycle and removing an edge, until there are no cycles remaining.
Proof of Euler’s formula for planar graphs

We will do a proof by induction on the number of edges.

Motivation for the proof:

- Keep removing one edge at a time from the graph while keeping it connected, until we obtain a spanning tree.
- When we delete an edge:
  - $V$ is unchanged.
  - $E$ goes down by 1.
  - $F$ also goes down by 1 since two faces are joined into one.
  - $V - E + F$ is unchanged.
- When we end at a tree, $E = V - 1$ and $F = 1$, so $V - E + F = 2$. 
Proof of Euler’s formula for planar graphs

Let $G$ be a connected graph on $n$ vertices, drawn without crossing edges. We will induct on the number of edges.

**Base case:** The smallest possible number of edges in a connected graph on $n$ vertices is $n - 1$, in which case the graph is a tree:

\[
\begin{align*}
V &= n \\
E &= n - 1 \\
F &= 1 \quad \text{(no cycles, so the only face is the infinite face)}
\end{align*}
\]

\[
V - E + F = n - (n - 1) + 1 = 2
\]
Proof of Euler’s formula for planar graphs

Induction step:

- Let $G$ be a connected planar graph on $n$ vertices and $k$ edges, drawn without edge crossings.
- The base case was $k = n - 1$. Now consider $k \geq n$.
- Assume Euler’s formula holds for connected graphs with $n$ vertices and $k - 1$ edges.
- Remove an edge from any cycle to get a connected subgraph $G'$. $G'$ has $V'$ vertices, $E'$ edges, and $F'$ faces:
  - $V' = V = n$
  - $E' = E - 1 = k - 1$ since we removed one edge.
  - $F' = F - 1$ since the faces on the two sides of the removed edge were different but have been merged together.
- Since $E' = k - 1$, by induction, $G'$ satisfies $V' - E' + F' = 2$.
- Observe that $V' - E' + F' = V - (E - 1) + (F - 1) = V - E + F$, so $V - E + F = 2$ also.
Consider a graph drawn on a sphere.

Poke a hole inside a face, stretch it out from the hole and flatten it onto the plane. (Demo)

The face with the hole becomes the outside or infinite face, while all the other faces are distorted but remain finite.

If a connected graph can be drawn on a surface of a sphere without edges crossing, it’s a planar graph.

The values of $V, E, F$ are the same whether it’s drawn on a plane or the surface of a sphere, so $V - E + F = 2$ still applies.

Figure: http://en.wikipedia.org/wiki/File:Lambert_azimuthal_equal-area_projection_SW.jpg
3D polyhedra w/o holes are topologically equivalent to spheres

Pyramid with a square or rectangular base:

- Poke a pinhole in the base of the pyramid (left). Stretch it out and flatten it into a planar embedding (right). The pyramid base (left) corresponds to the infinite face (right).

- Euler’s formula (and other formulas we’ll derive for planar embeddings) apply to polyhedra without holes.

\[ V = 5, \quad E = 8, \quad F = 5, \quad V - E + F = 5 - 8 + 5 = 2 \]
A shape in 2D or 3D is *convex* when the line connecting any two points in it is completely contained in the shape.

A sphere is convex. An indented sphere is not (red line above).

But we can deform the indented sphere to an ordinary sphere, so the graphs that can be drawn on their surfaces are the same.

Convex polyhedra are a special case of 3D polyhedra w/o holes.

The book presents results about graphs on convex polyhedra; more generally, they also apply to 3D polyhedra without holes.
A **torus** is a donut shape. It is not topologically equivalent to a sphere, due to a hole.

Consider a graph drawn on a torus without crossing edges.

Transforming a sphere to a torus requires cutting, stretching, and pasting. Edges on the torus through the cut can’t be drawn there on the sphere. When redrawn on the sphere, they may cross.

So, there may be graphs that can be drawn on the surface of a torus without crossing edges, but which cannot be drawn on the surface of a sphere without crossing edges.
An $m \times n$ grid on a torus has

\[ V = mn, \quad E = 2mn, \quad F = mn \]

\[ V - E + F = mn - 2mn + mn = 0 \]

**Theorem:** for a connected graph on a $g$-holed torus,

\[ V - E + F = 2(1 - g). \quad (g = 0 \text{ for sphere}, \ 1 \text{ for donut, etc.}) \]
More relations on $V, E, F$ in planar graphs
Trace around a face, counting each encounter with an edge.

Face A, has edge encounters A1 through A7, giving $\deg A = 7$.

Face B has edge encounters B1 through B6, including two encounters with one edge ($B5$ and $B6$). So $\deg B = 6$.

$\deg C = 5$. 
The sum of the face degrees is $2E$, since each edge is encountered twice:

$$S = \deg A + \deg B + \deg C = 7 + 6 + 5 = 18$$

$$2E = 2(9) = 18$$

The sum of the vertex degrees is $2E$ for all graphs. Going clockwise from the upper left corner, we have

$$3 + 3 + 2 + 2 + 2 + 3 + 2 + 1 = 18.$$
Faces usually have at least 3 sides, but it is possible to have fewer.

In a simple (no loops, no multiedges) connected graph with at least three vertices, these cases don’t arise, so all faces have face degree at least 3.

Thus, the sum of the face degrees is $S \geq 3F$, so $2E \geq 3F$.

In a bipartite graph, all cycles have even length, so all faces have even degree. Adding bipartite to the above conditions, each face has at least 4 sides. Thus, $2E \geq 4F$, which simplifies to $E \geq 2F$. 
Inequalities between $V, E, F$

**Theorem**

*In a connected graph drawn in the plane without crossing edges:*

1. $V - E + F = 2$

2. Additionally, if $G$ is simple (no multiedges) and if $V \geq 3$, then
   - (a) $3F \leq 2E$
   - (b) $E \leq 3V - 6$
   - (c) $F \leq 2V - 4$

3. If $G$ is simple and bipartite, these bounds improve to
   - (a) $2F \leq E$
   - (b) $E \leq 2V - 4$
   - (c) $F \leq V - 2$

- Part 1 is Euler’s formula. We just showed 2(a) and 3(a).
- We will prove the other parts, and use them to prove certain graphs are not planar.
Inequalities between $V$, $E$, $F$

(a) $3F \leq 2E$  
(b) $E \leq 3V - 6$  
(c) $F \leq 2V - 4$

Let $G$ be a connected simple graph with $V \geq 3$, drawn in the plane without crossing edges.

(a) So far, we showed $V - E + F = 2$ and (a) $3F \leq 2E$.

(b) Thus, $F \leq 2E/3$ and

$$2 = V - E + F \leq V - E + (2E/3) = V - E/3$$

so $2 \leq V - E/3$, or $E \leq 3V - 6$, which is (b).

(c) $3F \leq 2E$ also gives $E \geq 3F/2$ and

$$2 = V - E + F \leq V - (3F/2) + F = V - F/2$$

so $2 \leq V - F/2$, or $F \leq 2V - 4$, which is (c).
Inequalities between $V, E, F$ for a simple bipartite graph

(a) $2F \leq E$  \hspace{1cm} (b) $E \leq 2V - 4$  \hspace{1cm} (c) $F \leq V - 2$

Let $G$ be a connected simple bipartite graph with $V \geq 3$, drawn in the plane without crossing edges.

(a) For this case, we showed $V - E + F = 2$ and (a) $2F \leq E$.

(b) Thus, $F \leq E/2$ and
\[ 2 = V - E + F \leq V - E + (E/2) = V - E/2 \]
so $2 \leq V - E/2$, or $E \leq 2V - 4$, which is (b).

(c) $2F \leq E$ also gives
\[ 2 = V - E + F \leq V - 2F + F = V - F \]
so $2 \leq V - F$, or $F \leq V - 2$, which is (c).
Characterizing planar graphs
The complete bipartite graph $K_{m,n}$ has

- Vertices $V = A \cup B$ where $|A| = m$ and $|B| = n$, and $A \cap B = \emptyset$.
- Edges $E = \{ \{a, b\} : a \in A \text{ and } b \in B \}$
  All possible edges with one vertex in $A$ and the other in $B$.
- In total, $m + n$ vertices and $mn$ edges.
$K_5$ and $K_{3,3}$ are not planar

$K_5$ is not planar
- $V = 5$
- $E = \binom{5}{2} = 10$
- This violates $E \leq 3V - 6$ since $3V - 6 = 15 - 6 = 9$ and $10 \not\leq 9$.

$K_{3,3}$ is not planar
- $V = 6$
- $E = 3 \cdot 3 = 9$
- This is a bipartite graph, so if it has a planar embedding, it satisfies $E \leq 2V - 4$.
- However, $2V - 4 = 2(6) - 4 = 8$, and $9 \not\leq 8$. 
Suppose that we can turn graph $G$ into graph $H$ by repeatedly applying these two operations:

- Split an edge $AB$ into two edges $AV$ and $VB$ by adding a vertex $V$ somewhere in the middle (not incident with any other edge).
- Let $V$ be a vertex of degree 2. Replace two edges $AV$ and $VB$ by one edge $AB$ and delete vertex $V$.

Then $G$ and $H$ are homeomorphic (a.k.a. edge equivalent).

The left graph is homeomorphic to $K_5$ (on the right):

- Apply the 2nd operation above to every black vertex to get $K_5$.
- Repeatedly apply the 1st operation to $K_5$ to get the left graph.
Characterizing planar graphs

**Theorem (Kuratowski’s Theorem)**

$G$ is planar iff it does not have a subgraph homeomorphic to $K_5$ or $K_{3,3}$.

- **Necessity**: If $G$ is planar, so is every subgraph. But if $G$ has a subgraph homeomorphic to $K_5$ or $K_{3,3}$, the subgraph is not planar.
- **Sufficiency**: The proof is too advanced.
- The graph shown above has a subgraph (shown in red) homeomorphic to $K_5$, and thus, it is not a planar graph.
More properties of planar graphs
Theorem

A connected, simple, planar graph has a vertex with degree at most 5.

Proof:

- The sum of vertex degrees in any graph equals $2E$.

- Assume by way of contradiction that all vertices have degree $\geq 6$. Then the sum of vertex degrees is $\geq 6V$.

- So $2E \geq 6V$, so $E \geq 3V$.

- This contradicts $E \leq 3V - 6$, so some vertex has degree $\leq 5$. 
Start with a planar embedding of a graph $G$ (shown in black).

Draw a red vertex inside each face, including the “infinite face.”

For every edge $e$ of $G$:
  - Let $a, b$ be the red vertices in the faces on the two sides of $e$.
  - Draw a red edge $\{a, b\}$ crossing $e$.

Remove the original graph $G$ to obtain the red graph $H$.

$H$ is a dual graph of $G$. (It is “a” dual graph instead of “the” dual graph, since it may depend on how $G$ is drawn.)

If $G$ is connected, then $G$ is also a dual graph of $H$ — just switch the roles of the colors!
**Dual graph**

- **Graph G**
- **Constructing dual graph**
- **Dual graph H**

- $G$ and $H$ have the same number of edges:
  - Each edge of $G$ crosses exactly one edge of $H$ and vice-versa.

- # faces of $G = $ # vertices of $H$ and
  - # faces of $H = $ # vertices of $G$:
    - Bijections: vertices of either graph $\leftrightarrow$ faces of the other.

<table>
<thead>
<tr>
<th></th>
<th>$G$</th>
<th>$H$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V$</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>$E$</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>$F$</td>
<td>6</td>
<td>8</td>
</tr>
</tbody>
</table>
12.2. Classifying regular polyhedra
Classifying regular polyhedra

- A *polyhedron* is a 3D solid whose surface consists of polygons. As a graph, no loops and no multiple edges.
- All faces have $\geq 3$ edges and all vertices are in $\geq 3$ edges.
- To be 3D, there must be $\geq 4$ vertices, $\geq 4$ faces, and $\geq 6$ edges.
- A *regular polyhedron* has these symmetries:
  - All faces are regular $\ell$-gons for the same $\ell \geq 3$.
  - All vertices have the same degree ($r \geq 3$).
  - All edges have the same length.
  - All pairs of adjacent faces have the same angle between them.
Suppose all vertices have the same degree \( r \geq 3 \) and all faces are \( \ell \)-gons (same \( \ell \geq 3 \) for all faces).

The sum of vertex degrees is \( r \cdot V = 2E \), so \( V = \frac{2E}{r} \).

The sum of face degrees is \( \ell \cdot F = 2E \), so \( F = \frac{2E}{\ell} \).

Plug these into \( V - E + F = 2 \):

\[
\frac{2E}{r} - E + \frac{2E}{\ell} = 2 \quad \quad E \cdot \left( \frac{2}{r} - 1 + \frac{2}{\ell} \right) = 2 \quad \quad E = \frac{2}{\frac{r}{2} + \frac{2}{\ell} - 1}
\]

We have to find all integers \( r, \ell \geq 3 \) for which \( V, E, F \) are positive integers, and then check if polyhedra with those parameters exist.
Suppose all vertices have the same degree \( r \geq 3 \) and all faces are \( \ell \)-gons (same \( \ell \geq 3 \) for all faces).

Compute \((V, E, F)\) using \( E = \frac{2}{\frac{2}{r} + \frac{2}{\ell} - 1} \), \( V = \frac{2E}{r} \), \( F = \frac{2E}{\ell} \):

E.g., \( r = 3 \) and \( \ell = 4 \) gives

\[
E = \frac{2}{\frac{2}{3} + \frac{2}{4} - 1} = \frac{2}{1/6} = 12
\]

\[
V = \frac{2(12)}{3} = 8
\]

\[
F = \frac{2(12)}{4} = 6
\]

What shape is it?
Classifying regular polyhedra
What range of vertex degree ($r$) and face degree ($\ell$) are permitted?

First method
- We have $r \geq 3$.
  Since some vertex has degree $\leq 5$, all do, so $r$ is 3, 4, or 5.
- Vertices and faces are swapped in the dual graph, so $\ell$ is 3, 4, or 5.

Second method: analyze formula of $E$
- $E$ is a positive integer, so its denominator must be positive:
  \[
  \frac{2}{r} + \frac{2}{\ell} - 1 > 0
  \]
  We have $r, \ell \geq 3$.
- If both $r, \ell \geq 4$, the denominator of $E$ is $\leq \frac{2}{4} + \frac{2}{4} - 1 = 0$, which is invalid. So $r$ and/or $\ell$ is 3.
- If $r = 3$, then the denominator of $E$ is $\frac{2}{3} + \frac{2}{\ell} - 1 = \frac{2}{\ell} - \frac{1}{3}$.
  To be positive requires $\ell \leq 5$.
- Similarly, if $\ell = 3$ then $r \leq 5$. 
Classifying regular polyhedra

- Suppose all vertices have the same degree $r \in \{3, 4, 5\}$ and all faces are $\ell$-gons (same $\ell \in \{3, 4, 5\}$ for all faces).

- Compute $(V, E, F)$ using $E = \frac{2}{\frac{2}{r} + \frac{2}{\ell} - 1}$, $V = \frac{2E}{r}$, $F = \frac{2E}{\ell}$:

<table>
<thead>
<tr>
<th>$(V, E, F)$</th>
<th>$\ell = 3$</th>
<th>$\ell = 4$</th>
<th>$\ell = 5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r = 3$</td>
<td>(4, 6, 4)</td>
<td>(8, 12, 6)</td>
<td>(20, 30, 12)</td>
</tr>
<tr>
<td>$r = 4$</td>
<td>(6, 12, 8)</td>
<td>Division by 0</td>
<td>(−10, −20, −8)</td>
</tr>
<tr>
<td>$r = 5$</td>
<td>(12, 30, 20)</td>
<td>(−8, −20, −10)</td>
<td>(−4, −10, −4)</td>
</tr>
</tbody>
</table>

- If $V, E, F$ are not all positive integers, it can’t work (shown in pink).

- We found five possible values of $(V, E, F)$ with graph theory. Use geometry to actually find the shapes (if they exist).
Classifying regular polyhedra

<table>
<thead>
<tr>
<th>Shape</th>
<th>Tetrahedron</th>
<th>Cube</th>
<th>Octahedron</th>
<th>Dodecahedron</th>
<th>Icosahedron</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r =$ vertex degree</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>$\ell =$ face degree</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>$V =$ # vertices</td>
<td>4</td>
<td>8</td>
<td>6</td>
<td>20</td>
<td>12</td>
</tr>
<tr>
<td>$E =$ # edges</td>
<td>6</td>
<td>12</td>
<td>12</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>$F =$ # faces</td>
<td>4</td>
<td>6</td>
<td>8</td>
<td>12</td>
<td>20</td>
</tr>
</tbody>
</table>

- These are known as the **Platonic solids**.
- The cube and octahedron are dual graphs.
- The dodecahedron and icosahedron are dual graphs.
- The tetrahedron is its own dual.
Octahedron and cube are dual

- Can draw either one inside the other. Place a dual vertex at the center of each face.
- In 3D, this construction shrinks the dual, vs. in 2D, it did not.
11.1 and 12.3. Graph colorings
Let $G$ be a graph and $C$ be a set of colors, e.g.,

$$C = \{\text{black, white}\} \quad C = \{a, b\} \quad C = \{1, 2\}$$

A **proper coloring** of $G$ by $C$ is to assign a color from $C$ to every vertex, such that in every edge $\{v, w\}$, the vertices $v$ and $w$ have different colors.

$G$ is **$k$-colorable** if it has a proper coloring with $k$ colors (e.g., $C = [k]$).
A *bipartite graph* is a graph in which:

- The set of vertices can be split as $V = A \cup B$, where $A \cap B = \emptyset$.
- Every edge has the form $\{a, b\}$ where $a \in A$ and $b \in B$.

A graph is bipartite if and only if it is 2-colorable: set $A$ = black vertices, $B$ = white vertices.
The **chromatic number**, $\chi(G)$, of a graph $G$ is the minimum number of colors needed for a proper coloring of $G$.

Color this with as few colors as possible:
Color this with as few colors $a, b, c, d, e, \ldots$ as possible

We’ve shown it’s 3-colorable, so $\chi(G) \leq 3$.

It has a triangle as a subgraph, which requires 3 colors.
Other vertices may require additional colors, so $\chi(G) \geq 3$.

Combining these gives $\chi(G) = 3$.

A triangle is $K_3$.
More generally, if $G$ has $K_m$ as a subgraph, then $\chi(G) \geq m$. 
Coloring maps

Color states so that neighboring states have different colors. This map uses 4 colors for the states.

Assume each state is a contiguous region. Michigan isn’t. All of its regions have to be colored the same, which could increase the number of colors required, but we can artificially fill in Lake Michigan to make Michigan contiguous.

Also assume the states form a contiguous region. Alaska and Hawaii are isolated, and just added onto the map separately.
A proper coloring of the faces of a graph \( \leftrightarrow \) a proper coloring of the vertices of its dual graph

The regions/states/countries of the map are faces of a graph, \( G \).
Place a vertex inside each region and form the dual graph, \( H \).
A proper coloring of the vertices of \( H \) gives a proper coloring of the faces of \( G \).
Theorem (Four Color Theorem)

Every planar graph has a proper coloring with at most four colors.

- Map makers have believed this for centuries, but it was not proven.
- This was the first major theorem to be proved using a computer program (Kenneth Appel and Wolfgang Haken, 1976).
- The original proof had 1936 cases! Their program determined the cases and showed they are all 4-colorable.
- The proof was controversial because it was the first proof that was impractical for any human to verify.
- Over the years, people have found errors in the proof, but they have been fixed, and the result still stands. The number of cases has been cut down to 633.