Notes on graph theory

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These notes are frozen in a (very) unfinished state. Currently, only two chapters (beyond the preface) exist, and they too are incomplete (although hopefully readable).

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These are lecture notes on graph theory – the part of mathematics involved with graphs. They are currently work in progress; once finished, they should contain a semester’s worth of material. I have tried to keep the presentation as self-contained and elementary as possible; the reader is nevertheless assumed to possess some mathematical maturity (in particular, to know how to read combinatorial proofs, filling in simple details\(^1\)) and know how to work with modular arithmetic (i.e., congruences between integers modulo a positive integer \(n\)) and summation signs (such as \(\sum_{i=1}^{n}\) and \(\sum_{a \in A}\), where \(n\) is an integer and \(A\) is a finite set)\(^2\). In some chapters, familiarity with matrices (and their products), permutations (and their signs\(^3\)) and polynomials will be required. I hope that the proofs are readable; feel free to contact me (at dgrinber@umn.edu) for any clarifications.

The choice of material surveyed in these notes is idiosyncratic (sometimes even purposefully trying to wander some seldom trodden paths). Some standard material (Eulerian walks, Hamiltonian paths, trees, bipartite matching theory, network flows) is present (at least in the eventual final form of these notes), whereas other popular topics (planar graphs, random graphs, adjacency matrices and spectral

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\(^1\)I believe that the MIT lecture notes [LeLeMe16] are a good source for achieving this mathematical maturity. (Actually, there is some intersection between [LeLeMe16] Chapters 10 and 12] and our notes, but [LeLeMe16] mostly keeps to the basics of graph theory.) Two other resources to familiarize oneself with proofs are [Hammac15] and [Day16]. Generally, most good books about “reading and writing mathematics” or “introductions to abstract mathematics” should convey these skills, although the extent to which they actually do so may differ.

\(^2\)See [Grinbe16] §1.3 for a list of important properties of summation signs.

\(^3\)A summary of the most fundamental results about signs of permutations can be found in [LaNaSc16] §8.1]. These results appear with proofs in [Day16] Chapter 6.B]. For an even more detailed treatment (also including proofs), see [Grimbe16] §4.1–4.3]. Some of the most important properties of signs of permutations are also proven in [Strick13] Appendix B], which also gives one of the best introductions to determinants I have seen in the literature. Another treatment can be found in [Conrad], but this requires some familiarity with group theory.
graph theory) are missing. Some of these omissions have specific reasons (e.g.,
many of the omitted topics would make it much harder to keep the notes self-
contained), whereas others are merely due to my tastes and lack of time.

These notes are accompanying a class on graph theory (Math 5707) I am giving
at the University of Minneapolis in Spring 2017. They contain both the material of
the class (although with no promise of timeliness!) and the homework exercises
(and possibly some additional exercises). Sections marked with an asterisk (*) are
not part of the Math 5707 course.

Various other texts on graph theory are [Bollob79], [Bollob98], [Harary69], [Harju14],
[Balakr97], [Jungni13], [Martin16], [ThuSwa92], [BonMur76], [Ore74], [BehCha71],
[BeChZh15], [BonMur08], [Ruohon13], [Dieste16], [Ore90], [HaHiMo08], [Berge91],
[ChaLes15], [Griffi15], [Wilson96]. (This is a haphazard list; I have barely touched
most of these texts.) Also, texts on combinatorics and on discrete mathematics
(such as [BenWil12], [KelTro15], [PoTaWo83], [Bona11], [Guicha16], or the intro-
ductory [LoPeVe03]) often contain sections on graph theory, since graph theory
is considered to be part of both. Material on graph theory can also be found in
large quantities on mathematical contests for students (such as the International
Mathematical Olympiad) and, consequently, in collections of problems from these
contests, such as the AoPS collection of IMO Shortlist problems [AoPS-ISL]. Fi-
nally, some elementary results in graph theory double as puzzles (or are related
to puzzles), which often has the consequence that they appear on puzzle websites
such as Cut-the-Knot [Bogomoln].

The notes you are reading are under construction, and will remain so for at least
the whole Spring of 2017. Please let me know of any errors and unclarities you
encounter (my email address is dgrinber@umn.edu). Thank you!

1.1. Acknowledgments

Thanks to Victor Reiner and Travis Scrimshaw for helpful conversations.

[Your name could be in here!]

2. Introduction

In this chapter, we shall define a first notion of graphs (“first” because there are
several others to follow) and various basic notions related to it, and prove some
elementary properties thereof. This chapter is meant to give a taste of the whole
theory, although (not unexpectedly) it is not a representative sample.

2.1. Notations and conventions

Before we get to anything interesting, let me get some technicalities out of the way.
Namely, I shall be using the following notations:

4The sourcecode of the notes is also publicly available at https://github.com/darijgr/nogra.
In the following, we use the symbol $\mathbb{N}$ to denote the set \{0,1,2,\ldots\}. (Be warned that some other authors use this symbol for \{1,2,3,\ldots\} instead.)

We let $\mathbb{Q}$ denote the set of all rational numbers; we let $\mathbb{R}$ be the set of all real numbers.

If $X$ and $Y$ are two sets, then we shall use the notation \( X \rightarrow Y, \ x \mapsto E \) (where $x$ is some symbol which has no specific meaning in the current context, and where $E$ is some expression which usually involves $x$) for “the map from $X$ to $Y$ that sends every $x \in X$ to $E$”. For example, \( \mathbb{N} \rightarrow \mathbb{N}, \ x \mapsto x^2 + x + 6 \) means the map from $\mathbb{N}$ to $\mathbb{N}$ that sends every $x \in \mathbb{N}$ to $x^2 + x + 6$. For another example, \( \mathbb{N} \rightarrow \mathbb{Q}, \ x \mapsto \frac{x}{1 + x} \) denotes the map from $\mathbb{N}$ to $\mathbb{Q}$ that sends every $x \in \mathbb{N}$ to $\frac{x}{1 + x}$.

If $S$ is a set, then the powerset of $S$ means the set of all subsets of $S$. This powerset will be denoted by $\mathcal{P}(S)$. For example, the powerset of \{1,2\} is $\mathcal{P}(\{1,2\}) = \{\emptyset, \{1\}, \{2\}, \{1,2\}\}$.

Furthermore, if $S$ is a set and $k$ is an integer, then $\mathcal{P}_k(S)$ shall mean the set of all $k$-element subsets of $S$. (This is empty if $k < 0$.)

2.2. Simple graphs

As already hinted above, there is not one single concept of a “graph”. Instead, there are several mutually related (but not equivalent) concepts of “graph”, which are often kept apart by adorning them with adjectives (e.g., “simple graph”, “directed graph”, “loopless graph”, “loopless weighted undirected graph”, “infinite graph”, etc.) or prefixes (“digraph”, “multigraph”, etc.). Let me first define the simplest one of these:

\[ x \mapsto \frac{x}{1 + x} \]

A word of warning: Of course, the notation \( X \rightarrow Y, \ x \mapsto E \) does not always make sense; indeed, the map that it stands for might sometimes not exist. For instance, the notation \( \mathbb{N} \rightarrow \mathbb{Q}, \ x \mapsto \frac{x}{1 - x} \) does not actually define a map, because the map that it is supposed to define (i.e., the map from $\mathbb{N}$ to $\mathbb{Q}$ that sends every $x \in \mathbb{N}$ to $\frac{x}{1 - x}$) does not exist (since $\frac{x}{1 - x}$ is not defined for $x = 1$). For another example, the notation \( \mathbb{N} \rightarrow \mathbb{Z}, \ x \mapsto \frac{x}{1 + x} \) does not define a map, because the map that it is supposed to define (i.e., the map from $\mathbb{N}$ to $\mathbb{Z}$ that sends every $x \in \mathbb{N}$ to $\frac{x}{1 + x}$) does not exist (for $x = 2$, we have $\frac{x}{1 + x} = \frac{2}{1 + 2} \notin \mathbb{Z}$, which shows that a map from $\mathbb{N}$ to $\mathbb{Z}$ cannot send this $x$ to this $\frac{x}{1 + x}$). Thus, when defining a map from $X$ to $Y$ (using whatever notation), do not forget to check that it is well-defined (i.e., that your definition specifies precisely one image for each $x \in X$, and that these images all lie in $Y$). In many cases, this is obvious or very easy to check (I will usually not even mention this check), but in some cases, this is a difficult task.
Definition 2.2.1. A simple graph is a pair $(V, E)$, where $V$ is a finite set, and where $E$ is a subset of $\mathcal{P}_2(V)$.

Let us unpack this definition first. The word “simple” in “simple graph” (roughly speaking) has the meaning of “with no bells and whistles”; i.e., it says that the notion of “simple graph” is one of the crudest, most primitive notions of a graph known. It does not mean that everything that can be said about simple graphs is simple (this is far from the case, as we will see below). The condition “$E$ is a subset of $\mathcal{P}_2(V)$” in Definition 2.2.1 can be rewritten as “$E$ is a set of 2-element subsets of $V$” (since $\mathcal{P}_2(V)$ is the set of all 2-element subsets of $V$). Thus, a simple graph is a pair consisting of a finite set $V$, and a set of 2-element subsets of $V$. For example, $((\{1, 2, 3\}, \{\{1, 3\}, \{3, 2\}\})$ and $(\{2, 5\}, \{\{2, 5\}\})$ and $(\emptyset, \emptyset)$ are three simple graphs.

Warning 2.2.2. (a) Our Definition 2.2.1 differs from the definition of a “simple graph” in many sources, in that we are requiring $V$ to be finite.

(b) Simple graphs are often just called “graphs”. But then again, some other concepts of graphs (such as multigraphs, which we will encounter further below) are also often just called “graphs”. Thus, the precise meaning of the word “graph” depends on the context in which it appears. For example, Bollobás (in [Bollob79]) uses the word “graph” for “simple graph”, whereas Bondy and Murty (in [BonMur08]) use it for “multigraph with loops allowed” (a concept we will define further below). When reading literature, always check the definitions (and, if these are missing, try to take an educated guess, ruling out options that make some of the claims false).

So far, we have not explained how we should intuitively think of simple graphs, and why they are interesting. We will spend a significant part of these notes answering the latter question; but let us first comment on the former.

Simple graphs can be used to model symmetric relations between different objects. For example, if you have $n$ integers (for some $n \in \mathbb{N}$), then you can define a graph $(V, E)$ for which $V$ is the set of these $n$ integers, and $E$ is the set of all 2-element subsets $\{u, v\}$ of $V$ for which $|u - v| \leq 3$. (Notice that $\{u, u\}$ does not count as a 2-element subset.) For a non-mathematical example, consider an (idealized) group $P$ of (finitely many) people, each two of which are either mutual friends or not. Then, you can define a graph $(P, E)$, where $E$ is the set of all 2-element subsets $\{u, v\}$ of $P$ for which $u$ and $v$ are mutual friends. This graph then models the friendships between the people in the group $P$; in a sense, it is a social network (similar to the ones widespread on the Internet, but much more rudimentary, since it only knows who is a friend of whom).

6We assume that if a person $u$ is a friend of a person $v$, then $v$ is a friend of $u$. We also assume that no person $u$ is a friend of $u$ itself (or, at least, we don’t count this as friendship).

7This kind of “social graphs” has been used for many years as a language for stating theorems about graphs without saying the word “graph” (and without using mathematical notation): Just
The following notations provide a quick way to reference the elements of \( V \) and \( E \) when given a graph \((V,E)\):

**Definition 2.2.3.** Let \( G = (V,E) \) be a simple graph.

(a) The set \( V \) is called the vertex set of \( G \); it is denoted by \( V(G) \). (Notice that the letter “\( V \)” in “\( V(G) \)” is upright, as opposed to the letter “\( V \)” in “\( (V,E) \)” which is italic. These are two different symbols, and have different meanings: The letter \( V \) stands for the specific set \( V \) which is the first component of the pair \( G \), whereas the letter \( V \) is part of the notation \( V(G) \) for the vertex set of any graph. Thus, if \( H = (W,F) \) is another graph, then \( V(H) \) is \( W \), not \( V \).)

The elements of \( V \) are called the vertices (or the nodes) of \( G \).

(b) The set \( E \) is called the edge set of \( G \); it is denoted by \( E(G) \). (Again, the letter “\( E \)” in “\( E(G) \)” is upright, and stands for a different thing than the “\( E \)”.)

The elements of \( E \) are called the edges of \( G \). When \( u \) and \( v \) are two elements of \( V \), we shall often use the notation \( uv \) for \( \{u,v\} \); thus, each edge of \( G \) has the form \( uv \) for two distinct elements \( u \) and \( v \) of \( V \). Of course, we always have \( uv = vu \).

Notice that each simple graph \( G \) satisfies \( G = (V(G), E(G)) \).

(c) Two vertices \( u \) and \( v \) of \( G \) are said to be adjacent (or connected by an edge) if \( uv \in E \) (that is, if \( uv \) is an edge of \( G \)). In this case, the edge \( uv \) is said to connect \( u \) and \( v \); the vertices \( u \) and \( v \) are called the endpoints of this edge. When the graph \( G \) is not obvious from the context, we shall often say “adjacent in \( G \)” instead of just “adjacent”.

Two vertices \( u \) and \( v \) of \( G \) are said to be non-adjacent if they are not adjacent (i.e., if \( uv \notin E \)).

We say that a vertex \( u \) of \( G \) is adjacent to a vertex \( v \) of \( G \) if the vertices \( u \) and \( v \) are adjacent (i.e., if \( uv \in E \)). Similarly, we say that a vertex \( u \) of \( G \) is non-adjacent to a vertex \( v \) of \( G \) if the vertices \( u \) and \( v \) are non-adjacent (i.e., if \( uv \notin E \)).

(d) Let \( v \) be a vertex of \( G \) (that is, \( v \in V \)). Then, the neighbors of \( v \) are the vertices \( u \) of \( G \) that satisfy \( vu \in E \). In other words, the neighbors of \( v \) are the vertices of \( G \) that are adjacent to \( v \). (Of course, these neighbors depend on both \( v \) and \( G \). When \( G \) is not clear from the context, we shall call them the “neighbors of \( v \) in \( G \)” instead of just “neighbors of \( v \”).)

Of course, the relation of adjacency is symmetric\(^8\). The same holds for the relation of non-adjacency.

**Example 2.2.4.** Let \( U \) be the 5-element set \( \{1,2,3,4,5\} \). Let \( E \) be the subset \( \{\{u,v\} \mid u + v \geq 5\} \) of \( \mathcal{P}_2(U) \). This set \( E \) is well-defined, because the sum \( u + v \) of two integers \( u \) and \( v \) depends only on the set \( \{u,v\} \) and not on how this set is written (since \( u + v = v + u \)). (This is important, because if we

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\(^8\)This means the following: Given two vertices \( u \) and \( v \) of a simple graph \( G \), the vertex \( u \) is adjacent to \( v \) if and only if \( v \) is adjacent to \( u \).

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had used the condition \( u - v \geq 3 \) instead of \( u + v \geq 5 \), then the set \( E \) would not be well-defined, because it would not be clear whether \( \{1, 5\} \) should be inside it or not – indeed, if we write \( \{1, 5\} \) as \( \{u, v\} \) with \( u = 5 \) and \( v = 1 \), then \( u - v \geq 3 \) is satisfied, but if we write \( \{1, 5\} \) as \( \{u, v\} \) with \( u = 1 \) and \( v = 5 \), then \( u - v \geq 3 \) is not satisfied.)

Let \( G \) be the simple graph \((U, E)\). Then, \( V(G) = U = \{1, 2, 3, 4, 5\} \) and

\[
E(G) = E = \{ \{u, v\} \in P_2(U) \mid u + v \geq 5 \}
= \{ \{1, 4\}, \{1, 5\}, \{2, 3\}, \{2, 4\}, \{2, 5\}, \{3, 4\}, \{3, 5\}, \{4, 5\} \}. \tag{1}
\]

Thus, \( G \) has \(|V(G)| = |U| = 5\) vertices and \(|E(G)| = |E| = 8\) edges.

Using the shorthand notation \( uv \) for \( \{u, v\} \) (introduced in Definition 2.2.3(b)), the equality (1) rewrites as

\[
E(G) = \{14, 15, 23, 24, 25, 34, 35, 45\}.
\]

The vertices 2 and 4 of \( G \) are adjacent (since \( 24 \in E \)). In other words, 4 is a neighbor of 2. Equivalently, 2 is a neighbor of 4. On the other hand, the vertices 1 and 3 of \( G \) are not adjacent (since \( 13 \notin E \)); thus, 1 is not a neighbor of 3. The neighbors of 1 are 4 and 5.

### 2.3. Drawing graphs

There is a common method to represent graphs visually: Namely, a graph can be drawn as a set of points in the plane and a set of curves connecting some of these points with each other.

More precisely:

**Definition 2.3.1.** A simple graph \( G \) can be visually represented by drawing it on the plane (or on some other surface). To do so, we represent each vertex of \( G \) by a point (at which we put the name of the vertex), and then, for each edge \( uv \) of \( G \), we draw a curve that connects the point representing \( u \) with the point representing \( v \). The positions of the points and the shapes of the curves can be chosen freely, as long as they allow the reader to unambiguously reconstruct the graph \( G \) from the picture. (Thus, for example:

- the points should be distinct and spaced reasonably far apart;
- the curves should not pass through points other than the ones they connect;
- the curves should not be too jagged (and they should certainly be contiguous);
- the curves should intersect in such a way that one can easily see which strand is the continuation of which one.

Various examples of graphs being drawn are given below.)
Example 2.3.2. Let us draw some simple graphs.

(a) The simple graph $\left(\{1, 2, 3\}, \{12, 23\}\right)$ (where we are again using the shorthand notation $uv$ for $\{u, v\}$) can be drawn as follows:

1 —— 2 —— 3.

This is (in a sense) the simplest way to draw this graph: The edges are represented by straight lines (rather than tortuous curves).

There are other options as well. For example, we can draw the same graph as follows:

1 —— 3 —— 2.

Here, we have placed the points representing the vertices 1, 2, 3 differently. As a consequence, we were not able to draw the edge 12 as a straight line, because it would then have overlapped with the vertex 3, which would make the structure of the graph ambiguous (the edge 12 could be mistaken for two edges 13 and 32).

We can just as well draw both edges as curves:

1 —— 3 —— 2.

This drawing still represents the same graph $\left(\{1, 2, 3\}, \{12, 23\}\right)$.

We do not have to place the three vertices all along the same line. We can just as well draw the graph $\left(\{1, 2, 3\}, \{12, 23\}\right)$ as follows:

1
  \(\uparrow\)
  2
    \(\downarrow\)
  3

So far we have drawn our edges in such a way that they did not intersect. But this is not a requirement. We could just as well have represented our graph $\left(\{1, 2, 3\}, \{12, 23\}\right)$ as follows:

1
  \(\uparrow\)
  2
  \(\downarrow\)
  3

This last drawing is, of course, needlessly complicated for such a graph, but it is perfectly legitimate.
(b) Let \( U, E \) and \( G \) be as in Example 2.2.4. Here is one way to draw the graph \( G \):

![Diagram of graph G]

Here is another way to draw the same graph \( G \), with fewer intersections between edges:

![Diagram of graph G]

By appropriately repositioning the points corresponding to the five vertices of \( G \), we can actually get rid of all intersections; namely, we can draw the graph \( G \) as follows:

![Diagram of graph G]

If we reposition the vertices further, we can even achieve a drawing without intersecting curves that uses only straight lines as curves:

![Diagram of graph G]

All of these drawings are equally legitimate; some are more convenient for certain purposes while others are less so.

Let us now show a bad drawing of the graph \( G \) (that is, a drawing that fails the “allow the reader to unambiguously reconstruct the graph \( G \) from the picture”
criterion):

This drawing is bad because of the muddle that happens in the center of the rectangle formed by the vertices 2, 3, 4 and 5. Two curves are touching each other at that center, making the reader wonder whether they are two curves representing the edges 24 and 35 “passing through each other”, or two curves representing the edges 25 and 34 “bouncing off each other”, or both, or maybe even three curves. (The answer is “both”: they represent all four edges 24, 35, 25 and 34. But this is not clear from the drawing.)

(c) Let us draw one further graph: the simple graph \((V=\{1,2,3,4,5\}, E=\mathcal{P}_2(\{1,2,3,4,5\}))\). This is the simple graph whose vertices are 1, 2, 3, 4, 5, and whose edges are all possible two-element sets consisting of its vertices (i.e., each pair of two distinct vertices is adjacent). We shall later (in Definition 2.7.1) refer to this graph as the “complete graph \(K_5\”). Here is a simple way to draw this graph:

This drawing is useful for many purposes; for example, it makes the abstract symmetry of this graph (i.e., the fact that, roughly speaking, its vertices 1, 2, 3, 4, 5 are “equal in rights”) obvious. But sometimes, you might want to draw it differently, to minimize the number of intersecting curves. Here is a drawing with fewer intersections:
In this drawing, we have only one intersection between two curves left. Can we get rid of all intersections?

This is a non-combinatorial question, since it really is about curves in the plane rather than about finite sets and graphs. The answer is “no”. (That is, no matter how you draw this graph in the plane, you will always have at least one pair of curves intersect.) This is a classical result (one of the first theorems in the theory of planar graphs), and proofs of it can be found in various textbooks on graph theory (e.g., [Harary69, Corollary 11.1(d)] or [BonMur08, Theorem 10.2]). These proofs, however, are usually not self-contained; they rely on some basic facts from the topology of the real plane (mostly, the Jordan curve theorem). We shall not study geometrical questions like this in these notes, but instead refer the reader to texts such as [FriFri98] for careful and complete treatments of the topological technicalities. (If you are willing to take certain intuitively obvious topological facts about curves for granted, you can also read the chapters about planar graphs appearing in most books on graph theory.)

**Remark 2.3.3.** When drawing a simple graph $G$, we have so far labelled the points by the names of the vertices that they represent. However, often, the names of the vertices will be unimportant. In such cases, we can just as well label the points by little circles. For example, the simple graph $G$ from Example 2.2.4 can thus be drawn as follows:

![Graph](image)

Of course, from such a drawing, we cannot unambiguously reconstruct the graph, since we do not know which edge connects which vertices. But often, all we want to know about the graph is visible on such a drawing, and the names of the vertices would only be distracting.

### 2.4. A first fact: The Ramsey number $R(3, 3) = 6$

After these definitions, it might be time for a first result. The following classical fact (which is actually the beginning of a deep theory – the so-called Ramsey theory) should neatly illustrate the concepts introduced above:

**Proposition 2.4.1.** Let $G$ be a simple graph with $|V(G)| \geq 6$ (that is, $G$ has at least 6 vertices). Then, at least one of the following two statements holds:

- **Statement 1:** There exist three distinct vertices $a$, $b$ and $c$ of $G$ such that $ab$, $bc$ and $ca$ are edges of $G$.  

• **Statement 2**: There exist three distinct vertices $a, b$ and $c$ of $G$ such that none of $ab$, $bc$ and $ca$ is an edge of $G$.

In other words, Proposition 2.4.1 says that if a graph $G$ has at least 6 vertices, then we can either find three distinct vertices that are mutually adjacent or find three distinct vertices that are mutually non-adjacent (i.e., no two of them are adjacent), or both.

Proposition 2.4.1 can be stated more tersely as follows: “In any graph containing at least six vertices, you can always find three vertices that are mutually adjacent, or three vertices that are mutually non-adjacent”. It is also often restated as follows: “In any group of at least six people, you can always find three that are (pairwise) friends to each other, or three no two of whom are friends” (provided that friendship is a symmetric relation). This follows the old paradigm of restating facts about graphs in terms of people and friendship.

**Example 2.4.2.** Let us show three examples of graphs $G$ to which Proposition 2.4.1 applies, as well as an example to which it does not (because it fails to satisfy the condition $|V(G)| \geq 6$):

(a) Let $G$ be the graph $(V, E)$, where

$$V = \{1, 2, 3, 4, 5, 6\} \quad \text{and} \quad E = \{\{1, 2\}, \{2, 3\}, \{3, 4\}, \{4, 5\}, \{5, 6\}, \{6, 1\}\}.$$ 

(This graph can be drawn in such a way as to look like a hexagon:)

```
       1 ——— 2
       |   |
      6   3
       |   |
       5 ——— 4
```

This graph satisfies Statement 2 of Proposition 2.4.1 for $a = 1$, $b = 3$ and $c = 5$, because its three vertices 1, 3 and 5 are mutually non-adjacent (i.e., none of 13, 35 and 51 is an edge of $G$). It also satisfies Statement 2 of Proposition 2.4.1 for $a = 2$, $b = 4$ and $c = 6$. So in this situation, we witness something slightly stronger than what Proposition 2.4.1 says: There are at least two choices of $a, b$ and $c$ making one of the Statements 1 and 2 valid (and these two choices are not the same up to order). See Exercise 2.4.6 (a) below.

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9by which we mean (of course) that any two distinct ones among these three vertices are adjacent.
(b) Let \( G \) be the simple graph \((V, E)\), where
\[
V = \{-2, -1, 0, 1, 2, 3\} \quad \text{and} \quad E = \{\{u, v\} \in \mathcal{P}_2(V) \mid u \not\equiv v \mod 3\}.
\]
(This graph can be drawn as follows:
\[
\begin{array}{ccc}
0 & -1 & -2 \\
1 & \times & \times \\
& 2 & 3
\end{array}
\]
) This graph satisfies Statement 1 of Proposition 2.4.1 for \( a = 1, b = 2 \) and \( c = 3 \). (Again, other choices of \( a, b \) and \( c \) are also possible.)

(c) Let \( G \) be the graph \((V, E)\), where
\[
V = \{1, 2, 3, 4, 5, 6\} \quad \text{and} \quad E = \{\{1, 2\}, \{2, 3\}, \{3, 4\}, \{4, 5\}, \{5, 6\}, \{6, 1\}, \{1, 3\}\}.
\]
(This graph can be drawn in such a way as to look like a hexagon with one extra diagonal:
\[
\begin{array}{ccc}
1 & 2 \\
\times & \times \\
6 & 3 \\
\times & \times \\
5 & 4 \\
\end{array}
\]
) This graph satisfies Statement 1 of Proposition 2.4.1 for \( a = 1, b = 2 \) and \( c = 3 \). It also satisfies Statement 2 of Proposition 2.4.1 for \( a = 2, b = 4 \) and \( c = 6 \).

(d) Let \( G \) be the graph \((V, E)\), where
\[
V = \{1, 2, 3, 4, 5\} \quad \text{and} \quad E = \{\{1, 2\}, \{2, 3\}, \{3, 4\}, \{4, 5\}, \{5, 1\}\}.
\]
(This graph can be drawn to look like a pentagon:
\[
\begin{array}{ccc}
2 & 3 \\
\times & \times \\
1 & \times & \times \\
\times & \times \\
5 & 4 \\
\end{array}
\]
Proposition 2.4.1 says nothing about this graph, since this graph does not satisfy the assumption of Proposition 2.4.1 (in fact, its number of vertices $|V(G)|$ fails to be $\geq 6$). By itself, this does not yield that the claim of Proposition 2.4.1 is false for this graph. However, it is easy to check that the claim actually is false for this graph: Neither Statement 1 nor Statement 2 hold.

Proof of Proposition 2.4.1 We need to prove that either Statement 1 holds or Statement 2 holds (or both).

Choose any vertex $u \in V(G)$. (This is clearly possible, since $|V(G)| \geq 6 \geq 1$.) Then, $|V(G) \setminus \{u\}| = |V(G)| - 1 \geq 5$ (since $|V(G)| \geq 6$). We are in one of the following two cases:

Case 1: At least 3 vertices in $V(G) \setminus \{u\}$ are adjacent to $u$.

Case 2: At most 2 vertices in $V(G) \setminus \{u\}$ are adjacent to $u$.

Let us consider Case 1 first. In this case, at least 3 vertices in $V(G) \setminus \{u\}$ are adjacent to $u$. Hence, we can find three distinct vertices $p$, $q$, and $r$ in $V(G) \setminus \{u\}$ that are adjacent to $u$. Consider these $p$, $q$, and $r$. If none of $pq$, $qr$ and $rp$ is an edge of $G$, then Statement 2 holds (in fact, we can just take $a = p$, $b = q$ and $c = r$). Thus, if none of $pq$, $qr$ and $rp$ is an edge of $G$, then our proof is complete.\(^{10}\) Thus, we WLOG\(^{11}\) assume that at least one $pq$, $qr$ and $rp$ is an edge of $G$. In other words, we can pick two distinct elements $g$ and $h$ of $\{p, q, r\}$ such that $gh$ is an edge of $G$. Consider these $g$ and $h$.

The vertex $g$ is one of $p$, $q$ and $r$ (since $g \in \{p, q, r\}$). The vertices $p$, $q$ and $r$ are adjacent to $u$. Hence, the vertex $g$ is adjacent to $u$ (since the vertex $g$ is one of $p$, $q$ and $r$). In other words, $ug$ is an edge of $G$. Similarly, $uh$ is an edge of $G$. In other words, $hu$ is an edge of $G$ (since $hu = uh$).

We have $g \in \{p, q, r\} \subseteq V(G) \setminus \{u\}$ (since $p$, $q$ and $r$ belong to $V(G) \setminus \{u\}$). Hence, $g \neq u$. In other words, $u \neq g$. Similarly, $u \neq h$. Hence, $h \neq u$. Finally, $g \neq h$ (since $g$ and $h$ are distinct). Now, we know that the three vertices $u$, $g$ and $h$ are distinct (since $u \neq g$, $g \neq h$ and $h \neq u$), and have the property that $ug$, $gh$ and $hu$ are edges of $G$. Therefore, Statement 1 holds (in fact, we can just take $a = u$, $b = g$ and $c = h$). Hence, the proof is complete in Case 1.

Let us now consider Case 2. In this case, at most 2 vertices in $V(G) \setminus \{u\}$ are adjacent to $u$. Thus, at least 3 vertices in $V(G) \setminus \{u\}$ are non-adjacent to $u$.\(^{12}\)

---

\(^{10}\)because our goal in this proof is to show that either Statement 1 holds or Statement 2 holds (or both)


\(^{12}\)Proof. Let $k$ be the number of vertices in $V(G) \setminus \{u\}$ that are adjacent to $u$. Let $\ell$ be the number of vertices in $V(G) \setminus \{u\}$ that are non-adjacent to $u$. Then, $k + \ell = |V(G) \setminus \{u\}|$ (since each vertex in $V(G) \setminus \{u\}$ is either adjacent to $u$ or non-adjacent to $u$, but not both at the same time). But $k \leq 2$ (since at most 2 vertices in $V(G) \setminus \{u\}$ are adjacent to $u$). Hence, $k + \ell \leq 2 + \ell = \ell + 2$, so that $\ell + 2 \geq k + \ell = |V(G) \setminus \{u\}| \geq 5$ and thus $\ell \geq 3$. In other words, at least 3 vertices in $V(G) \setminus \{u\}$ are non-adjacent to $u$. Qed.
Hence, we can find three distinct vertices \( p, q \) and \( r \) in \( V(G) \setminus \{u\} \) that are non-adjacent to \( u \). Consider these \( p, q \) and \( r \). If all of \( pq, qr \) and \( rp \) are edges of \( G \), then Statement 1 holds (in fact, we can just take \( a = p, b = q \) and \( c = r \)). Thus, if all of \( pq, qr \) and \( rp \) are edges of \( G \), then our proof is complete. Thus, we WLOG assume that not all of \( pq, qr \) and \( rp \) are edges of \( G \). In other words, at least one of \( pq, qr \) and \( rp \) is not an edge of \( G \). In other words, we can pick two distinct elements \( g \) and \( h \) of \( \{p, q, r\} \) such that \( g h \) is not an edge of \( G \). Consider these \( g \) and \( h \).

The vertex \( g \) is one of \( p, q \) and \( r \) (since \( g \in \{p, q, r\} \)). The vertices \( p, q \) and \( r \) are non-adjacent to \( u \). Hence, the vertex \( g \) is non-adjacent to \( u \) (since the vertex \( g \) is one of \( p, q \) and \( r \)). In other words, \( u g \) is not an edge of \( G \). Similarly, \( u h \) is not an edge of \( G \). In other words, \( u h \) is not an edge of \( G \) (since \( u h = u h \)).

We have \( g \in \{p, q, r\} \subseteq V(G) \setminus \{u\} \) (since \( p, q \) and \( r \) belong to \( V(G) \setminus \{u\} \)). Thus, \( g \neq u \). In other words, \( u \neq g \). Similarly, \( u \neq h \). Finally, \( g \neq h \) (since \( g \) and \( h \) are distinct). Now, we know that the three vertices \( u, g \) and \( h \) are distinct (since \( u \neq g, g \neq h \) and \( h \neq u \)), and have the property that none of \( u g, g h \) and \( u h \) is an edge of \( G \) (since \( u g \) is not an edge of \( G \), since \( g h \) is not an edge of \( G \), and since \( u h \) is not an edge of \( G \)). Therefore, Statement 2 holds (in fact, we can just take \( a = u, b = g \) and \( c = h \)). Hence, the proof is complete in Case 2.

We have now proven Proposition 2.4.1 in each of the two Cases 1 and 2. Thus, the proof of Proposition 2.4.1 is complete. \( \square \)

**Remark 2.4.3.** I have written the above proof in much detail, since it is the first proof in these notes. I could have easily made it much shorter if I had relied on the reader to fill in some details (and in fact, I will rely on the reader in similar situations further below). The proof can further be shortened by noticing that part of the argument for Case 2 was a “mirror version” of the argument for Case 1, with the only difference that “adjacent” is replaced by “non-adjacent” (and vice versa), and “is an edge” is replaced by “is not an edge” (and vice versa).

**Remark 2.4.4.** Let me observe that Proposition 2.4.1 could be proven by brute force as well (using a computer). Indeed, here is how such a proof would proceed: Let \( x_1, x_2, x_3, x_4, x_5, x_6 \) be six distinct vertices of \( G \). (Such six vertices exist, since \( |V(G)| \geq 6 \).) Let \( X = \{x_1, x_2, x_3, x_4, x_5, x_6\} \) be the set of these six vertices.

Notice that the set \( X \) has 6 elements, and thus the set \( P_2(X) \) has \( \binom{6}{2} = 15 \) elements. Let \( F \) be the set of all edges \( uv \) of \( G \) for which both \( u \) and \( v \) belong to \( X \). (In other words, \( F \) is the set of all edges of \( G \) having the form \( x_i x_j \).) Clearly, it suffices to prove Proposition 2.4.1 for the graph \( (X, F) \) instead of \( G \) (because if we have found, for example, three distinct vertices \( a, b \) and \( c \) of \( (X, F) \) such that \( ab, bc \) and \( ca \) are edges of \( (X, F) \), then these \( a, b \) and \( c \) are obviously also three vertices of \( G \) such that \( ab, bc \) and \( ca \) are edges of \( G \)). However, \( F \) is a subset of \( P_2(X) \). Since there are only finitely many subsets of \( P_2(X) \) (in fact, there are \( 2^{15} \) such subsets, since \( P_2(X) \) has 15 elements), we thus see that there are only finitely many choices for \( F \) (when \( X \) is being regarded as fixed). We can check,
for each of these choices, whether the graph \((X,F)\) satisfies Proposition 2.4.1 (Just try each possible choice of three distinct vertices \(a, b\) and \(c\) of this graph \((X,F)\), and check that at least one of these choices satisfies either Statement 1 or Statement 2.) After a huge but finite amount of checking (which you can automate), you will see that Proposition 2.4.1 holds for \((X,F)\). Thus, as we have already mentioned, Proposition 2.4.1 also holds for the original graph \(G\).

Proposition 2.4.1 is the first result in a field of graph theory known as Ramsey theory. I shall not dwell on this field in these notes, but let me make a few more remarks. The first step beyond Proposition 2.4.1 is the following generalization:

**Proposition 2.4.5.** Let \(r\) and \(s\) be two positive integers. Let \(G\) be a simple graph with \(|V(G)| \geq \left(\frac{r+s-2}{r-1}\right)\). Then, at least one of the following two statements holds:

- **Statement 1:** There exist \(r\) distinct vertices of \(G\) that are mutually adjacent (i.e., each two distinct ones among these \(r\) vertices are adjacent).
- **Statement 2:** There exist \(s\) distinct vertices of \(G\) that are mutually non-adjacent (i.e., no two distinct ones among these \(s\) vertices are adjacent).

Applying Proposition 2.4.5 to \(r = 3\) and \(s = 3\), we can recover Proposition 2.4.1.

One might wonder whether the number \(\left(\frac{r+s-2}{r-1}\right)\) in Proposition 2.4.5 can be improved - i.e., whether we can replace it by a smaller number without making Proposition 2.4.5 false. In the case of \(r = 3\) and \(s = 3\), this is impossible, because the number 6 in Proposition 2.4.1 cannot be made smaller\(^{13}\). However, for some other values of \(r\) and \(s\), the value \(\left(\frac{r+s-2}{r-1}\right)\) can be improved. (For example, for \(r = 4\) and \(s = 4\), the best possible value is 18 rather than \(\frac{4+4-2}{4-1} = 20\).)

The smallest possible value is called the Ramsey number \(R(r,s)\), and finding it is a hard computational challenge; for small values of \(r\) and \(s\) it has been found using a computer, but \(R(5,5)\) is still unknown.

Proposition 2.4.5 can be further generalized to a result called Ramsey’s theorem. The idea behind the generalization is to slightly change the point of view, and replace the simple graph \(G\) by a complete graph (i.e., a simple graph in which every two distinct vertices are adjacent) whose edges are colored in two colors (say, blue and red). This is a completely equivalent concept, because the concepts of “adjacent” and “non-adjacent” in \(G\) can be identified with the concepts of “adjacent through a blue edge” (i.e., the edge connecting them is colored blue) and “adjacent

\(^{13}\)Indeed, there is a graph with 5 vertices (namely, the graph \(G\) constructed in Example 2.4.2(d)) that satisfies neither Statement 1 nor Statement 2.
through a red edge”, respectively. Statements 1 and 2 then turn into “there exist \( r \) distinct vertices that are mutually adjacent through blue edges” and “there exist \( s \) distinct vertices that are mutually adjacent through red edges”, respectively. From this point of view, it is only logical to generalize Proposition 2.4.5 further to the case when the edges of a complete graph are colored in \( k \) (rather than two) colors. The corresponding generalization is known as Ramsey’s theorem. We refer to the well-written Wikipedia page [https://en.wikipedia.org/wiki/Ramsey’s_theorem](https://en.wikipedia.org/wiki/Ramsey%27s_theorem) for a treatment of this generalization with proof, as well as a table of known Ramsey numbers \( R(r, s) \) and a self-contained (if somewhat terse) proof of Proposition 2.4.5. Ramsey’s theorem can be generalized further, and many variations of it can be defined, which are usually subsumed under the label “Ramsey theory”.

There are many papers and at least one textbook [GrRoSp90] available on Ramsey theory. For elementary introductions, see the Cut-the-knot page [http://www.cut-the-knot.org/Curriculum/Combinatorics/ThreeOrThree.shtml](http://www.cut-the-knot.org/Curriculum/Combinatorics/ThreeOrThree.shtml) in [Bogomoln], the above-mentioned Wikipedia article, as well as [Harju14, §4.2], [Bollob79, Chapter VI] and [West01, Section 8.3].

### Exercise 2.4.6

Let \( G \) be a simple graph. A **triangle** in \( G \) means a set \( \{a, b, c\} \) of three distinct vertices \( a, b \) and \( c \) of \( G \) such that \( ab, bc \) and \( ca \) are edges of \( G \). An **anti-triangle** in \( G \) means a set \( \{a, b, c\} \) of three distinct vertices \( a, b \) and \( c \) of \( G \) such that none of \( ab, bc \) and \( ca \) is an edge of \( G \). A **triangle-or-anti-triangle** in \( G \) is a set that is either a triangle or an anti-triangle. (Of the three words I have just introduced, only “triangle” is standard.)

(a) Assume that \( |V(G)| \geq 6 \). Prove that \( G \) has at least two triangle-or-anti-triangles. (For comparison: Proposition 2.4.1 shows that \( G \) has at least one triangle-or-anti-triangle.)

(b) Assume that \( |V(G)| = m + 6 \) for some \( m \in \mathbb{N} \). Prove that \( G \) has at least \( m + 1 \) triangle-or-anti-triangles.

### 2.5. Degrees

Next, we introduce the notion of the degree of a vertex of a graph. This is simply the number of edges containing this vertex:

**Definition 2.5.1.** Let \( G = (V, E) \) be a simple graph. Let \( v \in V \) be a vertex of \( G \). Then, the **degree** of \( v \) (with respect to \( G \)) is defined as the number of all edges of \( G \) that contain \( v \). This degree is a nonnegative integer, and is denoted by \( \deg v \). It is also denoted by \( \deg_G v \), when the graph \( G \) is not clear from the context.

---

See [RaWiRa] for a popular view on the philosophy of Ramsey theory (in the wide sense of this word). It should probably be said that mathematicians usually define the word “Ramsey theory” somewhat more restrictively, and not every result of the form “you can find a pattern in any sufficiently large structure” belongs to Ramsey theory; but the rough idea is correct.
Thus,
\[
\deg v = \deg_G v = \begin{cases} 
\text{(the number of all edges of } G \text{ that contain } v) \\
\text{(since the edges of } G \text{ are precisely the } e \in E) \\
\end{cases} 
\]
\[
= \begin{cases} 
\text{(the number of all } e \in E \text{ that contain } v) \\
= |\{e \in E \mid v \in e\}|. 
\end{cases} 
\]

**Example 2.5.2.** Define the sets \(U\) and \(E\) as in Example 2.2.4. Let \(G\) be the graph \((U, E)\). Then, \(\deg 1\) is the number of all edges of \(G\) that contain 1. These edges are 14 and 15; hence, their number is 2. Thus, \(\deg 1 = 2\). Similarly, \(\deg 4 = 4\) (since \(\deg 4\) is the number of all edges of \(G\) that contain 4, but these edges are 14, 24, 34 and 45). Similarly, \(\deg 2 = 3\), \(\deg 3 = 3\) and \(\deg 5 = 4\).

Here are some different characterizations of degrees in a simple graph:

**Proposition 2.5.3.** Let \(G = (V, E)\) be a simple graph. Let \(v \in V\) be a vertex of \(G\). Then,
\[
\deg v = \deg_G v 
\]
\[
= \begin{cases} 
\text{(the number of all neighbors of } v) \\
\text{since } (v, u) \in E \text{ and } v \in u. 
\end{cases} 
\]
\[
= |\{u \in V \mid u \text{ is adjacent to } v\}|. 
\]
\[
= |\{u \in V \mid vu \text{ is an edge of } G\}|. 
\]
\[
= |\{u \in V \mid uv \in E\}|. 
\]

Proposition 2.5.3 is essentially obvious: It follows from observing that each edge of \(E\) that contains \(v\) contains exactly one neighbor of \(v\), and that different such edges contain different neighbors of \(v\). For the mere sake of completeness, let me include a formal proof.

**Proof of Proposition 2.5.3** Both \(\deg v\) and \(\deg_G v\) denote the degree of \(v\). Thus, \(\deg v = \deg_G v\). Hence, (5) is proven.

Let \(U\) be the set of all neighbors of \(v\). Then,
\[
|U| = \begin{cases} 
\text{(the number of all neighbors of } v) \\
\end{cases} 
\]

Let \(E_v\) be the subset \(\{e \in E \mid v \in e\}\) of \(E\). This is the set of all edges \(e \in E\) that contain \(v\).

For each \(u \in U\), we have \(vu \in E_v\). Hence, we can define a map \(\alpha : U \to E_v\) by setting
\[
\alpha(u) = vu \quad \text{for each } u \in U. 
\]

**Proof.** Let \(u \in U\). Thus, \(u\) is a neighbor of \(v\) (by the definition of \(U\)). In other words, \(vu \in E\) (by the definition of a “neighbor”). Furthermore, \(v \in \{v, u\} = vu\). Hence, \(vu\) is an element \(e \in E\) satisfying \(v \in e\) (since \(vu \in E\) and \(v \in vu\)). In other words, \(vu \in \{e \in E \mid v \in e\} = E_v\). Qed.
Consider this map $\alpha$. This map $\alpha$ is injective\footnote{Proof. Let $u_1$ and $u_2$ be two elements of $U$ satisfying $\alpha (u_1) = \alpha (u_2)$. We shall show that $u_1 = u_2$. The definition of $\alpha$ yields $\alpha (u_1) = vu_1 = \{ v, u_1 \}$. Hence, $\{ v, u_1 \} = \alpha (u_1) \in E_v \subseteq E \subseteq P_2 (V)$. Therefore, $\{ v, u_1 \}$ is a two-element set. Hence, $v \neq u_1$. Therefore, $\{ v, u_1 \} \setminus \{ v \} = \{ u_1 \}$. Hence, $\{ u_1 \} = \{ v, u_1 \} \setminus \{ v \} = \alpha (u_1) \setminus \{ v \}$. The same argument (but applied to $u_2$ instead of $u_1$) shows that $\{ u_2 \} = \alpha (u_2) \setminus \{ v \}$. Now, $\{ u_1 \} = \alpha (u_1) \setminus \{ v \} = \alpha (u_2) \setminus \{ v \} = \{ u_2 \}$, so that $u_1 \in \{ u_1 \} = \{ u_2 \}$ and therefore $u_1 = u_2$.} and surjective\footnote{Proof. Let $f \in E_v$. Thus, $f \in E_v = \{ e \in E \mid v \in e \}$. In other words, $f$ is an element of $E$ satisfying $v \in f$. We have $f \in E \subseteq P_2 (V)$. Thus, $f$ is a 2-element subset of $V$. Thus, $|f| = 2$. Since $v \in f$, we have $|f \setminus \{ v \}| = |f| - 1 = 1$ (since $|f| = 2$). Hence, $f \setminus \{ v \}$ is a 1-element set. Therefore, $f \setminus \{ v \} = \{ u \}$ for some $u$. Consider this $u$. Now, $u \in \{ u \} = f \setminus \{ v \} \subseteq f \subseteq V$; thus, $u$ is a vertex of $G$. Moreover, $v \in f$ and thus $f = (f \setminus \{ v \}) \cup \{ v \} = \{ u \} \cup \{ v \} = \{ u, v \} = \{ v, u \} = vu$. Hence, $vu = f \in E$. In other words, $u$ is a neighbor of $v$ (by the definition of “neighbor”). In other words, $u \in U$ (since $U$ is the set of all neighbors of $v$). The definition of $\alpha$ now yields $\alpha (u) = vu = f$. Hence, $f = \alpha (u) \in \alpha (U)$. Now, forget that we fixed $f$. We thus have shown that $f \in \alpha (U)$ for each $f \in E_v$. In other words, $E_v \subseteq \alpha (U)$. In other words, the map $\alpha$ is surjective.}. Hence, the map $\alpha$ is bijective. Thus, we have found a bijective map $\alpha$ from $U$ to $E_v$. Therefore, $|E_v| = |U|$.

But $E_v = \{ e \in E \mid v \in e \}$ and thus $|E_v| = |\{ e \in E \mid v \in e \}| = \deg v$ (by (4)). Hence, $\deg v = |E_v| = |U| = (the number of all neighbors of $v$). This proves (6).

Now,

$$\deg v = \text{(the number of all neighbors of } v)$$

$$= \text{the set of all neighbors of } v$$

$$= \{ u \in V \mid u \text{ is a neighbor of } v \}$$

$$= |\{ u \in V \mid u \text{ is a neighbor of } v \}|$$

$$= |\{ u \in V \mid u \text{ is adjacent to } v \}|$$

(because for any vertex $u \in V$, the condition “$u$ is a neighbor of $v$” is equivalent to the condition “$u$ is adjacent to $v$”). Thus, (7) and (8) are proven.

Furthermore,

$$\deg v = |\{ u \in V \mid u \text{ is a neighbor of } v \}|$$

$$= |\{ u \in V \mid vu \in E \}|$$
Proof of Proposition 2.5.6.

Write the simple graph $G$ (because for any vertex $u \in V$, the condition “$u$ is a neighbor of $v$” is equivalent to the condition “$vu \in E$”). Hence,

$$\deg v = \left| \left\{ u \in V \mid vu \in E \right\} \right| = \left| \left\{ u \in V \mid uv \in E \right\} \right|$$

(because for any vertex $u \in V$, the condition “$uv \in E$” is equivalent to the condition “$vu$ is an edge of $G$”). Thus, we have proven (10) and (9). The proof of Proposition 2.5.3 is thus complete. $\square$

**Remark 2.5.4.** Different sources use different notations for the degree of a vertex $v$ of a simple graph $G$. We call it $\deg v$ (and so do Ore’s [Ore90] and the introductory notes [LeLeMe16]; Ore’s [Ore74] calls it $\rho(v)$; Bollobás’s [Bollob79] and Bondy’s and Murty’s [BonMur08] and [BonMur76] call it $d(v)$.

At this point, we can state a few simple facts about degrees:

**Proposition 2.5.5.** Let $G$ be a simple graph. Let $n = |V(G)|$. Let $v$ be a vertex of $G$. Then, $\deg v \in \{0, 1, \ldots, n-1\}$.

**Proof of Proposition 2.5.5.** Let $U$ be the set of all neighbors of $v$. Then,

$$|U| = (\text{the number of all neighbors of } v)$$

Comparing this with (6), we obtain $|U| = \deg v$.

But $U \subseteq V(G) \setminus \{v\}$. Hence, $|U| \leq |V(G) \setminus \{v\}| = |V(G)| - 1$ (since $v \in V(G)$). Since $|V(G)| = n$, this inequality can be rewritten as $|U| \leq n - 1$. Since $|U|$ is a nonnegative integer, we thus have $|U| \in \{0, 1, \ldots, n-1\}$. Since $|U| = \deg v$, we can rewrite this as $\deg v \in \{0, 1, \ldots, n-1\}$. This proves Proposition 2.5.5. $\square$

**Proposition 2.5.6.** Let $G$ be a simple graph. The sum of the degrees of all vertices of $G$ equals twice the number of edges of $G$. In other words,

$$\sum_{v \in V(G)} \deg v = 2|E(G)|. \quad (11)$$

**Proof of Proposition 2.5.6.** Write the simple graph $G$ in the form $G = (V, E)$. Thus, $V(G) = V$ and $E(G) = E$.

Now, let $N$ be the number of all pairs $(v,e) \in V \times E$ such that $v \in e$. Then, we can express $N$ in the following two ways:

18Proof. Let $u \in U$. Thus, $u$ is a neighbor of $v$ (by the definition of $U$). In other words, $u$ is a vertex of $G$ such that $vu \in E(G)$ (by the definition of “neighbor”). Thus, $vu \in E(G) \subseteq P_2(V(G))$ (since each edge of $G$ is a 2-element subset of $V(G)$). In particular, $vu$ is a 2-element set. Hence, $u \neq v$.

But $u \in V(G)$ (since $u$ is a vertex of $G$). Combining this with $u \neq v$, we obtain $u \in V(G) \setminus \{v\}$.

Now, forget that we fixed $u$. We thus have shown that $u \in V(G) \setminus \{v\}$ for each $u \in U$. In other words, $U \subseteq V(G) \setminus \{v\}$.
We can obtain $N$ by computing, for each $v \in V$, the number of all $e \in E$ satisfying $v \in e$, and then adding up these numbers over all $v \in V$. Thus, we obtain

$$N = \sum_{v \in V} \left( \text{the number of all } e \in E \text{ satisfying } v \in e \right) = \sum_{v \in V} \deg v. \quad (12)$$

We can also obtain $N$ by computing, for each $e \in E$, the number of all $v \in V$ satisfying $v \in e$, and then adding up these numbers over all $e \in E$. Thus, we obtain

$$N = \sum_{e \in E} \left( \text{the number of all } v \in V \text{ satisfying } v \in e \right). \quad (13)$$

But for each $e \in E$, we have

$$(\text{the number of all } v \in V \text{ satisfying } v \in e) = 2$$

Hence, (13) becomes

$$N = \sum_{e \in E} \left( \text{the number of all } v \in V \text{ satisfying } v \in e \right) = \sum_{e \in E} 2 = |E| \cdot 2 \quad (14)$$

(because the sum $\sum_{e \in E} 2$ consists of $|E|$ addends, each of which equals 2).

Comparing (12) with (14), we obtain $\sum_{v \in V} \deg v = |E| \cdot 2 = 2 |E|$. Since $V(G) = V$ and $E(G) = E$, we can rewrite this as $\sum_{v \in V(G)} \deg v = 2 |E(G)|$. Thus, Proposition 2.5.6 is proven.

Remark 2.5.7. The above proof of Proposition 2.5.6 is a classical example of the technique of double-counting: i.e., finding two different expressions for one and the same value (which, in itself, is not of much interest), and then obtaining an equality by comparing these two different expressions. In the above proof, the value was $N$, and the two expressions were (12) and (14).

Proposition 2.5.8. Let $G$ be a simple graph. Then, the number of vertices $v$ of $G$ whose degree $\deg v$ is odd is even.

Proof. Let $e \in E$. Then, $e \in E \subseteq P_2(V)$. In other words, $e$ is a 2-element subset of $V$. Hence, $|e| = 2$ (since $e$ is a 2-element set).

But the $v \in V$ satisfying $v \in e$ are precisely the $v \in e$ (because $e$ is a subset of $V$). Hence, 

$$(\text{the number of all } v \in V \text{ satisfying } v \in e) = (\text{the number of all } v \in e) = |e| = 2,$$

qed.
Proof of Proposition 2.5.8. From (11), we obtain
\[
\sum_{v \in V(G)} \deg v = 2|E(G)| \equiv 0 \mod 2.
\]

Hence,
\[
0 \equiv \sum_{v \in V(G)} \deg v = \sum_{v \in V(G); \deg v \text{ is even}} \deg v + \sum_{v \in V(G); \deg v \text{ is odd}} \deg v \\
\equiv \sum_{v \in V(G); \deg v \text{ is even}} 0 + \sum_{v \in V(G); \deg v \text{ is odd}} 1 \\
= \sum_{v \in V(G); \deg v \text{ is odd}} 1 = |\{v \in V(G) \mid \deg v \text{ is odd}\}| \cdot 1 \\
= |\{v \in V(G) \mid \deg v \text{ is odd}\}| = (\text{the number of vertices } v \text{ of } G \text{ whose degree } \deg v \text{ is odd}) \mod 2.
\]

In other words, the number of vertices \( v \) of \( G \) whose degree \( \deg v \) is odd is even. This proves Proposition 2.5.8. \( \Box \)

As usual, Proposition 2.5.8 can be restated in terms of friendships among people; this restatement takes the following form: “In a group of (finitely many) people, the number of people having an odd number of friends is even”. (Once again, this assumes that friendship is a symmetric relation, and that nobody counts as a friend of his own.)

**Proposition 2.5.9.** Let \( G \) be a simple graph with at least two vertices. Then, there exist two distinct vertices \( v \) and \( w \) of \( G \) having the same degree (that is, having \( \deg v = \deg w \)).

**Proof of Proposition 2.5.9.** Assume the contrary. Then, there exist no two distinct vertices \( v \) and \( w \) of \( G \) having the same degree. Hence, the degrees of all vertices of \( G \) are distinct. In other words, any two distinct vertices \( v \) and \( w \) of \( G \) satisfy
\[
\deg v \neq \deg w. \tag{15}
\]

Let \( n = |V(G)| \). Proposition 2.5.5 shows that \( \deg v \in \{0, 1, \ldots, n-1\} \) for each \( v \in V(G) \). Hence, we can define a map \( d : V(G) \to \{0, 1, \ldots, n-1\} \) by
\[
d(v) = \deg v \quad \text{for each } v \in V(G).
\]

Consider this map \( d \). The map \( d \) is injective.\(^{20}\)

\(^{20}\)Proof. Let \( v \) and \( w \) be two distinct elements of \( V(G) \). Then, \( \deg v \neq \deg w \) (by (15)). But the definition of \( d \) yields \( d(v) = \deg v \) and \( d(w) = \deg w \). Now, \( d(v) = \deg v \neq \deg w = d(w) \).

Now, forget that we fixed \( v \) and \( w \). We thus have shown that if \( v \) and \( w \) are two distinct elements of \( V(G) \), then \( d(v) \neq d(w) \). In other words, the map \( d \) is injective.
Recall the following elementary fact: If $X$ and $Y$ are two finite sets satisfying $|X| = |Y|$, then each injective map from $X$ to $Y$ is bijective.\[^{21}\] Applying this to $X = V(G), Y = \{0, 1, \ldots, n - 1\}$ and $f = d$, we conclude that the map $d$ is bijective (since $V(G)$ and $\{0, 1, \ldots, n - 1\}$ are finite sets satisfying $|V(G)| = n = |\{0, 1, \ldots, n - 1\}|$, and since $d : V(G) \to \{0, 1, \ldots, n - 1\}$ is an injective map). In particular, $d$ is surjective.

Now, $n = |V(G)| \geq 2$ (since $G$ has at least two vertices). Hence, $0 \in \{0, 1, \ldots, n - 1\}$. Since $d$ is surjective, this shows that there exists some vertex $a \in V(G)$ such that $d(a) = 0$. Consider this $a$. The definition of $d$ yields $d(a) = \deg a$, so that $\deg a = d(a) = 0$.

Also, $n - 1 \in \{0, 1, \ldots, n - 1\}$ (since $n \geq 2$). Since $d$ is surjective, this shows that there exists some vertex $b \in V(G)$ such that $d(b) = n - 1$. Consider this $b$. The definition of $d$ yields $d(b) = \deg b$, so that $\deg b = d(b) = n - 1$.

From $n \geq 2$, we obtain $n - 1 \geq 1 > 0$, so that $n - 1 \neq 0$, and thus $\deg a = 0 \neq n - 1 = \deg b$. Hence, $a \neq b$.

Now, let $B$ be the set of all neighbors of $b$. Then,

$$|B| = \text{(the number of all neighbors of } b\text{)}.$$  

Comparing this with

$$\deg b = \text{(the number of all neighbors of } b\text{)} \quad \text{(by (6), applied to } v = b\text{)},$$

we obtain $|B| = \deg b = n - 1$.

\[^{21}\]Here is a quick proof of this fact: Let $X$ and $Y$ be two finite sets satisfying $|X| = |Y|$. Let $f$ be an injective map from $X$ to $Y$. We must show that $f$ is bijective.

The set $Y$ is finite. Hence, the only subset of $Y$ that has as many elements as $Y$ is $Y$ itself.

The set $f(X)$ consists of the images of the elements of $X$ under the map $f$. These images are pairwise distinct (since $f$ is injective), and there are precisely $|X|$ many of them. Hence, $|f(X)| = |X|$. Now, $f(X)$ is a subset of $Y$ that has as many elements as $Y$ (since $|f(X)| = |X| = |Y|$). Therefore, $f(X)$ must be $Y$ itself (since the only subset of $Y$ that has as many elements as $Y$ is $Y$ itself). In other words, $Y = f(X)$. Hence, the map $f$ is surjective. Thus, $f$ is bijective (since $f$ is injective and surjective). This proves the fact that we wanted to prove.
But $B \subseteq V(G) \setminus \{a, b\}$ \footnote{Hence,}

$$|B| \leq |V(G) \setminus \{a, b\}| = |V(G)| - 2 = n - 2 \quad \text{(since } a \neq b)$$

$$= n - 2 < n - 1.$$  

This contradicts $|B| = n - 1$. This contradiction shows that our assumption was wrong. Proposition 2.5.9 is proven. \qed

Degrees of vertices can be used to prove various facts about graphs. For an example, let us show Mantel’s theorem:

**Theorem 2.5.10.** Let $G$ be a simple graph. Let $n = |V(G)|$ be the number of vertices of $G$. Assume that $|E(G)| > n^2/4$. (In other words, assume that $G$ has more than $n^2/4$ edges.) Then, there exist three distinct vertices $a$, $b$ and $c$ of $G$ such that $ab$, $bc$ and $ca$ are edges of $G$.

**Example 2.5.11.** Let $G$ be the graph $(V, E)$, where

$$V = \{1, 2, 3, 4, 5, 6\} \quad \text{and} \quad E = \{\{1, 2\}, \{2, 3\}, \{3, 4\}, \{4, 5\}, \{5, 6\}, \{6, 1\}, \{1, 4\}, \{2, 5\}, \{3, 6\}\}.$$

(This graph can be drawn in such a way as to look like a hexagon with its three longest diagonals:)

![Hexagon with longest diagonals]

\footnote{Proof. Write the graph $G$ in the form $G = (V, E)$. Let $v \in B$. Then, $v$ is a neighbor of $b$ (since $B$ is the set of all neighbors of $b$). In other words, $bv \in E$ (by the definition of “neighbor”). Hence, $bv \in E \subseteq P_2(V)$. Therefore, $bv$ is a 2-element set. Hence, $v \neq b$.

Also, $vb = bv \in E$. Thus, $b$ is a neighbor of $v$. Hence, the vertex $v$ has at least one neighbor (namely, $b$). Now, \footnote{yields} $\deg v = \text{(the number of all neighbors of } v) \geq 1$

(since the vertex $v$ has at least one neighbor), so that $\deg v \geq 1 > 0 = \deg a$ and thus $\deg v \neq \deg a$ and therefore $v \neq a$. Combining this with $v \neq b$, we find $v \notin \{a, b\}$. Hence, $v \in V(G) \setminus \{a, b\}$.

Now, forget that we fixed $v$. We thus have proven that each $v \in B$ satisfies $v \in V(G) \setminus \{a, b\}$. In other words, $B \subseteq V(G) \setminus \{a, b\}$.}
This \( G \) does not satisfy the conditions of Theorem 2.5.10 because its number of edges is \( |E(G)| = |E| = 9 = 6^2/4 \) (whereas Theorem 2.5.10 requires it to be \( > 6^2/4 \)). Therefore, it should come as no surprise that there exist no three distinct vertices \( a, b \) and \( c \) of \( G \) such that \( ab, bc \) and \( ca \) are edges of \( G \). (There is a particularly quick way to convince yourself of this: Observe that if \( u \) and \( v \) are two adjacent vertices of \( G \), then the integer \( u + v \) is odd. Therefore, if there were three distinct vertices \( a, b \) and \( c \) of \( G \) such that \( ab, bc \) and \( ca \) are edges of \( G \), then the integers \( a + b, b + c \) and \( c + a \) would all be odd, and therefore their sum \( (a + b) + (b + c) + (c + a) \) would be odd as well. But this is impossible, since this sum is even (in fact, it equals \( 2(a + b + c) \)). Hence, no such three vertices \( a, b \) and \( c \) exist.)

However, if we add any new edge to \( G \), then the resulting graph \( G' \) satisfies \( |E(G')| = 9 + 1 > 6^2/4 \), and therefore Theorem 2.5.10 can be applied to \( G' \) instead of \( G \). Hence, there exist three distinct vertices \( a, b \) and \( c \) of \( G' \) such that \( ab, bc \) and \( ca \) are edges of \( G' \). Which three vertices they will be depends on which edge we have added. For example, if we have added the edge \( 15 \), then (for example) the three vertices \( a = 1, b = 5 \) and \( c = 6 \) work. Here is a drawing of this \( G' \):

![Diagram of G']

Of course, the converse of Theorem 2.5.10 does not hold. There are many simple graphs \( G \) which do not satisfy the assumption of Theorem 2.5.10 but nevertheless have three distinct vertices \( a, b \) and \( c \) such that \( ab, bc \) and \( ca \) are edges of \( G \). The reader can easily construct such a graph.

For proofs of Theorem 2.5.10, see (for example) the rather well-explained \[Choo16\] (note that the fourth proof is incomplete, as the existence of the maximum \( S^* \) needs to be proven).

**TODO 2.5.12. Proof.**

**Remark 2.5.13.** Let us contrast Proposition 2.4.1 with Theorem 2.5.10. The former guarantees that a graph \( G \) with sufficiently many vertices (namely, at least 6 vertices) must have a triangle or an anti-triangle (where we are using the terminology from Exercise 2.4.6). Theorem 2.5.10 says that any graph \( G \) with sufficiently many edges (namely, more than \( n^2/4 \) edges, where \( n = |V(G)| \)) must have a triangle. These two facts are similar and yet different in nature (e.g., the number 6 in Proposition 2.4.1 is a constant, whereas the \( n^2/4 \) in Theorem 2.5.10
is not). We can also wonder how many edges a graph must have in order to be guaranteed an anti-triangle; this is answered by Exercise 2.5.14 below.

**Exercise 2.5.14.** Let $G$ be a simple graph. Let $n = |V(G)|$ be the number of vertices of $G$. Assume that $|E(G)| < n(n-2)/4$. (In other words, assume that $G$ has less than $n(n-2)/4$ edges.) Prove that there exist three distinct vertices $a, b$ and $c$ of $G$ such that none of $ab$, $bc$ and $ca$ are edges of $G$.

Just as Proposition 2.4.1 is merely the tip of a deep iceberg called Ramsey theory, Theorem 2.5.10 is the beginning of a longer story. The most famous piece of this story is the following fact, known as *Turan’s theorem*:

**Theorem 2.5.15.** Let $r$ be a positive integer. Let $G$ be a simple graph. Let $n = |V(G)|$ be the number of vertices of $G$. Assume that $|E(G)| > \frac{r-1}{r} \cdot \frac{n^2}{2}$. Then, there exist $r+1$ distinct vertices of $G$ that are mutually adjacent (i.e., each two distinct ones among these $r+1$ vertices are adjacent).

Theorem 2.5.10 is the particular case of Theorem 2.5.15 for $r = 2$. See [Jukna11, Chapter 4, Theorem 4.8] for a proof of Theorem 2.5.15.

Results like Theorem 2.5.10 (and sometimes also like Proposition 2.4.5) are commonly regarded as part of a subject called *extremal graph theory*. (The word “extremal” refers to the appearance of bounds, such as the $\frac{r-1}{r} \cdot \frac{n^2}{2}$.) There are textbooks on this subject, such as [Jukna11].

**TODO 2.5.16.** Turan’s theorem: at least state it, and cite a proof. Apparently the WP [https://en.wikipedia.org/wiki/Tur%23A9n%23A9's_theorem](https://en.wikipedia.org/wiki/Tur%23A9n%23A9's_theorem) again?

### 2.6. Graph isomorphisms

Two graphs can be distinct and yet “the same up to the names of their vertices”. For instance, the two graphs $((1,2,3), \{\{1,2\}\})$ and $((1,2,3), \{\{1,3\}\})$ are distinct (since 12 is an edge of the former graph but not of the latter), but if we rename the vertices 2 and 3 of the former graph as 3 and 2, respectively, then it becomes the latter graph. This kind of relation between two graphs is weaker than (literal) equality, but still strong enough to ensure that (roughly speaking) the two graphs have the same properties (as long as the properties don’t refer to specific vertices). Thus, it is worth giving this relation a rigorous definition and a name:

**Definition 2.6.1.** Let $G$ and $H$ be two simple graphs.

(a) A *graph isomorphism* from $G$ to $H$ means a bijection $\phi : V(G) \rightarrow V(H)$ such that for every two vertices $u$ and $v$ of $G$, the following logical equivalence holds:

\[
(\ uv \in E(G)) \iff (\ \phi(u) \ \phi(v) \in E(H)).
\]
(At this point, let me remind you that \( uv \) is shorthand for \( \{u, v\} \), and similarly \( \phi(u) \phi(v) \) is shorthand for \( \{\phi(u), \phi(v)\} \).

When it is clear what we mean, we shall abbreviate “graph isomorphism” as “isomorphism”. We also often write “graph isomorphism \( G \rightarrow H \)” for “graph isomorphism from \( G \) to \( H \).

(b) If there exists a graph isomorphism from \( G \) to \( H \), then we say the graphs \( G \) and \( H \) are isomorphic, and we write \( G \cong H \). Sometimes, the relation \( G \cong H \) itself will be called an “isomorphism” (although it is not a map).

Given this definition, we can now rigorously state the relation between the two graphs \( (\{1, 2, 3\}, \{\{1, 2\}\}) \) and \( (\{1, 2, 3\}, \{\{1, 3\}\}) \) we observed above. Namely, if we denote these two graphs by \( G \) and \( H \), respectively, then the map \( \{1, 2, 3\} \rightarrow \{1, 2, 3\} \) that sends \( 1, 2, 3 \) to \( 1, 3, 2 \) (respectively) is a graph isomorphism from \( G \) to \( H \). Thus, these two graphs are isomorphic. Note that we did not have to pick two graphs with the same vertex set; isomorphisms are often observed between graphs with completely different vertex sets and different definitions. Also, it sometimes happens that there are several isomorphisms between two graphs.

Example 2.6.2. Consider the graph \( G = (V, E) \), where

\[
V = \{1, 2, 3, 4, 5\} \quad \text{and} \quad E = \{\{1, 2\}, \{2, 3\}, \{3, 4\}, \{4, 5\}, \{5, 1\}\}.
\]

(This graph has already been introduced in Example 2.4.2 (d). It can be drawn to look like a pentagon.)

Consider furthermore the graph \( H = (V, F) \), where \( V \) is as before, and where

\[
F = \{\{1, 3\}, \{2, 4\}, \{3, 5\}, \{4, 1\}, \{5, 2\}\}.
\]

(If we draw the vertices \( 1, 2, 3, 4, 5 \in V \) as the five vertices of a pentagon, then the graph \( H \) is the pentagram formed by the diagonals of this pentagon:

![Diagram of a pentagram](image)

The graphs \( G \) and \( H \) are distinct, yet isomorphic. One isomorphism \( G \rightarrow H \) is the bijection \( V \rightarrow V \) sending \( 1, 2, 3, 4, 5 \) to \( 1, 3, 5, 2, 4 \), respectively. Another is the bijection \( V \rightarrow V \) sending \( 1, 2, 3, 4, 5 \) to \( 4, 2, 5, 3, 1 \), respectively. There are 10 isomorphisms in total.)
One way to quickly (visually) observe that two graphs are isomorphic is to draw them in such a way that the drawings look exactly the same but for the names of the vertices. Given such drawings, one can simply “overlay them” to obtain a graph isomorphism. For example, we could have spotted the isomorphism \( G \rightarrow H \) in Example 2.6.2 by drawing the graph \( H \) as follows:

![Graph H]

and overlaying this with the drawing of \( G \) made in Example 2.4.2 (d). (Of course, such drawings are not always easy to find: For example, our first drawing of \( H \) in Example 2.6.2 looked completely different from our drawing of \( G \).

**Example 2.6.3.** The graph \( G \) constructed in Example 2.4.2 (a) is isomorphic to the graph \( G \) constructed in Example 2.4.2 (b), even though this might not be obvious from their definitions. Probably the easiest way to see this is to draw the latter graph \( G \) as follows:

![Graph G]

This drawing makes it clear that it is isomorphic to the former graph (after all, the picture is exactly the same; it’s just that the vertices are different numbers now). Formally speaking, the map sending 1, 2, 3, 4, 5, 6 to 0, 2, \(-2\), 3, \(-1\), 1 (respectively) is a graph isomorphism from the former graph to the latter graph.

Any isomorphism between two graphs is invertible (since, by its definition, it is a bijection). Its inverse, too, is an isomorphism.

**Proposition 2.6.4.** Let \( G \) and \( H \) be two simple graphs. Let \( \phi \) be a graph isomorphism from \( G \) to \( H \). Then, its inverse \( \phi^{-1} \) is a graph isomorphism from \( H \) to \( G \).

**Proof of Proposition 2.6.4.** The map \( \phi \) is a graph isomorphism from \( G \) to \( H \). By the definition of “graph isomorphism”, this means that \( \phi \) is a bijection \( \text{V}(G) \rightarrow \text{V}(H) \) such that for every two vertices \( u \) and \( v \) of \( G \), the following logical equivalence holds:

\[
(uv \in E(G)) \iff (\phi(u)\phi(v) \in E(H)).
\]  
(17)
Now, for every two vertices \( u \) and \( v \) of \( H \), the following equivalence holds:

\[
(uv \in E(H)) \iff \left( \phi^{-1}(u) \phi^{-1}(v) \in E(G) \right)
\]  

(18)

(because we have the following chain of equivalences:

\[
\phi^{-1}(u) \phi^{-1}(v) \in E(G) \\
\iff \left( \phi \left( \phi^{-1}(u) \right) \phi \left( \phi^{-1}(v) \right) \in E(H) \right) =_u =_v \\
\iff (uv \in E(H))
\]  

(17). Thus, \( \phi^{-1} \) is a bijection \( V(H) \to V(G) \) such that for every two vertices \( u \) and \( v \) of \( H \), the equivalence (18) holds. By the definition of “graph isomorphism”, this means precisely that \( \phi^{-1} \) is a graph isomorphism from \( H \) to \( G \). This proves Proposition 2.6.4.

The following fact is similarly easy to check:

**Proposition 2.6.5.** Let \( G \), \( H \) and \( I \) be three simple graphs. Let \( \phi \) be a graph isomorphism from \( G \) to \( H \). Let \( \psi \) be a graph isomorphism from \( H \) to \( I \). Then, the composition \( \psi \circ \phi \) is a graph isomorphism from \( G \) to \( I \).

As we have already alluded to, isomorphic graphs are “equal in all but names”, and thus share all properties that do not depend on the names of vertices. For example, the following holds:

**Proposition 2.6.6.** Let \( G \) and \( H \) be two simple graphs. Let \( \phi \) be a graph isomorphism from \( G \) to \( H \).

(a) For every \( v \in V(G) \), we have \( \deg_G v = \deg_H (\phi(v)) \).

(b) We have \( |E(H)| = |E(G)| \).

**Proof of Proposition 2.6.6.** The map \( \phi \) is a graph isomorphism from \( G \) to \( H \). By the definition of “graph isomorphism”, this means that \( \phi \) is a bijection \( V(G) \to V(H) \) such that for every two vertices \( u \) and \( v \) of \( G \), the following logical equivalence holds:

\[
( uv \in E(G) ) \iff ( \phi(u) \phi(v) \in E(H) ).
\]  

(19)

(a) Fix \( v \in V(G) \). Then, (10) (applied to \( V(G) \) and \( E(G) \) instead of \( V \) and \( E \)) yields \( \deg_G v = |\{ u \in V(G) \mid uv \in E(G) \}| \) (since \( G = (V(G), E(G)) \)). Similarly, (10) (applied to \( H, V(H), E(H) \) and \( \phi(v) \) instead of \( G, V, E \) and \( v \)) yields

\[
\deg_H (\phi(v)) = |\{ u \in V(H) \mid u\phi(v) \in E(H) \}| = |\{ w \in V(H) \mid w\phi(v) \in E(H) \}|.
\]  

(20)
(here, we have renamed the index \( u \) as \( w \)). But recall that \( \phi : V(G) \to V(H) \) is a bijection. Thus, each \( w \in V(H) \) can be written uniquely in the form \( \phi(u) \) for some \( u \in V(G) \). Thus, we can substitute \( \phi(u) \) for \( w \) in \( \{ w \in V(H) \mid w\phi(v) \in E(H) \} \).

We thus find
\[
\{ w \in V(H) \mid w\phi(v) \in E(H) \} = \{ \phi(u) \mid u \in V(G) \text{ and } \phi(u)\phi(v) \in E(H) \}.
\]

Hence, (20) becomes
\[
\deg_H(\phi(v)) = \left\{ \begin{array}{l}
\{ w \in V(H) \mid w\phi(v) \in E(H) \} \\
\equiv \{ \phi(u) \mid u \in V(G) \text{ and } \phi(u)\phi(v) \in E(H) \}
\end{array} \right.
\]
\[
= \left\{ u \in V(G) \mid \phi(u)\phi(v) \in E(H) \right\} \quad \text{(since } \phi \text{ is a bijection)}
\]
\[
= \{ u \in V(G) \mid uv \in E(G) \} = \deg_G v.
\]

This proves Proposition 2.6.6 (a).

(b) Define a map \( \phi' : E(G) \to E(H) \) as follows: Let \( e \in E(G) \). Write the edge \( e \) in the form \( uv \) for two distinct vertices \( u \) and \( v \). Then, \( uv = e \in E(G) \). Thus, (19) shows that \( \phi(u)\phi(v) \in E(H) \). Moreover, this new edge \( \phi(u)\phi(v) \) is independent of the choice of \( u \) and \( v \) (as long as \( e \) is fixed). Hence, we can set \( \phi'(e) = \phi(u)\phi(v) \). Doing so, we obtain a map \( \phi' : E(G) \to E(H) \). This map \( \phi' \) is a bijection. Thus, we have found a bijection from \( E(G) \) to \( E(H) \). Consequently, \( |E(H)| = |E(G)| \). This proves Proposition 2.6.6 (b).

Results similar to Proposition 2.6.6 (saying that isomorphic graphs share the same properties) can be stated easily for any property of graphs you can imagine (as long as the property does not depend on the names of the vertices); the proofs are always straightforward like the one given above (the only idea being to

\[\text{[23]There are two ways of choosing } u \text{ and } v, \text{ since the elements of a 2-element set (like } e) \text{ can be listed in two different orders. We are claiming that the edge } \phi(u)\phi(v) \text{ does not depend on the choice of order. The slickest way of proving this is to rewrite this edge in a form that makes no reference to the choice of } u \text{ and } v \text{ to begin with. Namely: The edge } \phi(u)\phi(v) \text{ can be rewritten as } \{ \phi(x) \mid x \in e \} \text{ because}
\]
\[
\{ \phi(x) \mid x \in e \} = \{ \phi(x) \mid x \in \{u,v\} \} \quad \text{(since } e = uv = \{u,v\} \}
\]
\[
= \{ \phi(u), \phi(v) \} = \phi(u)\phi(v) \}
\]
\[
\), and this is clearly independent of the choice of } u \text{ and } v.
\]
\[\text{[24]Indeed, the inverse map is constructed in the same way as } \phi', \text{ except that } H, G \text{ and } \phi^{-1} \text{ take the roles of } G, H \text{ and } \phi.\]
apply bijectivity of $\phi$ and the equivalence (19) over and over in order to “transfer knowledge” from one graph to the other). I shall not state such results explicitly; instead, I shall merely refer to the overarching idea that isomorphic graphs share the same properties whenever it becomes useful.

One use of graph isomorphisms is to “relabel vertices” in a proof: Instead of proving some property of a given graph $G$, we can just as well prove the same property for a graph isomorphic to $G$ (since isomorphic graphs share the same properties), i.e., a graph obtained from $G$ by renaming its vertices. The vertices can be renamed as we wish; a popular choice is to rename them as $1, 2, \ldots, n$ (where $n = |V(G)|$). Formally speaking, this renaming is possible because of the following fact:

**Proposition 2.6.7.** Let $G$ be a simple graph. Let $S$ be a finite set such that $|S| = |V(G)|$. Then, there exists a simple graph $H$ that is isomorphic to $G$ and has vertex set $V(H) = S$.

**Proof of Proposition 2.6.7.** We have $|S| = |V(G)|$. Thus, there exists a bijection $\phi : V(G) \to S$. Fix such a $\phi$. Define a set $F$ by

$$F = \{ \phi(e) \mid e \in E(G) \} = \{ \phi(u) \phi(v) \mid uv \in E(G) \}$$

(where $\phi(e)$, as usual, denotes the subset $\{ \phi(x) \mid x \in e \}$ of $S$). Now, let $H$ be the simple graph $(S, F)$. Then, $V(H) = S$. Hence, $\phi$ is a bijection $V(G) \to V(H)$. It is straightforward to check that $\phi$ is a graph isomorphism from $G$ to $H$ (indeed, the definition of $F$ was tailored precisely to make the equivalence (16) hold). Thus, $H$ is isomorphic to $G$. As we have already seen, $H$ has vertex set $V(H) = S$. The proof of Proposition 2.6.7 is thus complete.

There is more to say about graph isomorphisms. For example, we can ask how to check whether two given graphs $G$ and $H$ are isomorphic. This is a famous problem in computation, known as the graph isomorphism problem, and has seen recent progress.

A related problem is to count, for a given $n \in \mathbb{N}$, the isomorphism classes of graphs with $n$ vertices. In other words: If we pretend that isomorphic graphs are equal, then how many graphs are there with $n$ vertices? The number is finite, since

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In theory, the problem can be solved by brute force (just check all possible bijections $V(G) \to V(H)$ for being graph isomorphisms); but this is highly inefficient (the number of such bijections becomes forbiddingly large very quickly). In many cases, two non-isomorphic graphs $G$ and $H$ can be “told apart” by some property that holds for one and not the other (e.g., if their numbers of edges differ). But in general, a simple and fast algorithm is not known. The problem is in complexity class NP, and Babai’s work claims to prove a quasipolynomial-time (but very complicated) algorithm. In practice, software written for solving the graph isomorphism problem makes tradeoffs between simplicity and efficiency.
each graph with \( n \) vertices is isomorphic to a graph with vertex set \( \{1, 2, \ldots, n\} \) (this follows from Proposition 2.6.7 applied to \( S = \{1, 2, \ldots, n\} \)), and the number of the latter graphs is clearly finite. Yet, computing this number exactly is hard, and there does not seem to be a closed-form formula. (There is a whole book [HarPal73] written about this. See also [http://oeis.org/A000088](http://oeis.org/A000088) for references and small values.)

### 2.7. Examples of graphs, and basic operations

#### 2.7.1. Complete and empty graphs

Let us next define certain classes of graphs, as well as some specific graphs. These will serve as examples in the first place, but some of them will also reveal themselves to be useful later.

The simplest kinds of simple graphs are the \textit{complete graphs} and the \textit{empty graphs}:

**Definition 2.7.1.** The \textbf{complete graph} on a finite set \( V \) means the simple graph \((V, \mathcal{P}_2(V))\). It is the simple graph with vertex set \( V \) in which each two distinct vertices are adjacent. For each \( n \in \mathbb{N} \), we denote the complete graph on \( \{1, 2, \ldots, n\} \) by \( K_n \). Often, any graph that is isomorphic to \( K_n \) is called "a \( K_n \)" (with the indefinite article, to signify that it isn’t necessarily the exact graph \( K_n \), but can be any graph isomorphic to it).

**Example 2.7.2.** (a) Here is a drawing of the complete graph on the finite set \( \{0, 3, 6\} \):

![Complete Graph](image)

Of course, many other drawings are possible.

(b) The complete graph on the set \( \{1, 2, 3, 4, 5\} \) is the graph \((\{1, 2, 3, 4, 5\}, \mathcal{P}_2(\{1, 2, 3, 4, 5\}))\), which we have drawn in Example 2.3.2.

(c) We are calling this graph \( K_5 \) now, according to Definition 2.7.1.

Note that a simple graph \( G = (V, E) \) is a \( K_n \) (i.e., is isomorphic to \( K_n \)) if and only if it is the complete graph on \( V \) and satisfies \(|V| = n\).

If \( V \) is a finite set, then each vertex \( v \) of the complete graph on \( V \) has degree \( \deg v = |V| - 1 \), because it is adjacent to the \(|V| - 1 \) remaining vertices of the complete graph.

**Definition 2.7.3.** The \textbf{empty graph} on a finite set \( V \) means the simple graph \((V, \emptyset)\). It has no edges; thus, it is the simple graph with vertex set \( V \) in which no two vertices are adjacent.
The empty graphs are, in a sense, the opposite to the complete graphs: In a complete graph, each two distinct vertices are adjacent, whereas in an empty graph, no two vertices are adjacent.

**Example 2.7.4.** Here is a drawing of the empty graph on the finite set \{0, 3, 6\}:

```
 0

3 6
```

**Remark 2.7.5.** Let \( V \) be a finite set. Let \( G \) be the complete graph on this set \( V \). Then, each permutation of \( V \) is a graph isomorphism \( G \to G \). (This is straightforward to check.) The same holds if \( G \) is the empty graph on \( V \) instead of being the complete graph on \( V \).

### 2.7.2. Path and cycle graphs

Next, we define some slightly more interesting graphs:

**Definition 2.7.6.** For each \( n \in \mathbb{N} \), we define the \( n \)-th path graph to be the simple graph

\[
(P_n) = (\{1, 2, \ldots, n\}, \{\{i, i+1\} \mid i \in \{1, 2, \ldots, n-1\}\}).
\]

This graph is denoted by \( P_n \). It has \( n \) vertices and \( n-1 \) edges (unless \( n = 0 \), in which case it has 0 edges). Again, we say that a simple graph is “a \( P_n \)” if it is isomorphic to \( P_n \).

Here is a drawing of \( P_4 \):

```
1 —— 2 —— 3 —— 4.
```

Similarly, for each \( n \in \mathbb{N} \), we can draw \( P_n \) by placing \( n \) equally spaced points \( 1, 2, \ldots, n \) on a straight line (in this order) and connecting each point \( i \in \{1, 2, \ldots, n-1\} \) to the next point \( i+1 \).

Path graphs provide a first mildly interesting example of a graph isomorphism:

**Remark 2.7.7.** Let \( n \in \mathbb{N} \). The map

\[
\{1, 2, \ldots, n\} \to \{1, 2, \ldots, n\}, \ i \mapsto n + 1 - i
\]

is an isomorphism \( P_n \to P_n \). This isomorphism is called the *reflection* on the path \( P_n \).
A look at the drawing (21) of $P_4$ should explain why the name “reflection” was chosen for the reflection on the path $P_n$.

**Definition 2.7.8.** For each integer $n > 1$, we define the $n$-th cycle graph to be the simple graph

\[
\{\{1,2,\ldots,n\}, \{i,i+1\} \mid i \in \{1,2,\ldots,n-1\}\} \cup \{\{n,1\}\}
\]

\[
= (\{1,2,\ldots,n\}, \{\{1,2\}, \{2,3\}, \ldots, \{n-1,n\}, \{n,1\}\}).
\]

This graph is denoted by $C_n$. It has $n$ vertices and $\begin{cases} n, & \text{if } n \geq 3; \\ 1, & \text{if } n = 2 \end{cases}$ edges. Again, we say that a simple graph is “a $C_n$” if it is isomorphic to $C_n$.

Here is a drawing of $C_6$:

![Diagram of C6](image)

Similarly, we can draw $C_n$ for each $n > 2$ by drawing an $n$-gon and labelling its vertices by $1,2,\ldots,n$. (Some authors like to use a regular $n$-gon for this purpose, but this is of course irrelevant for the purpose of illustrating the graph.)

Again, cycle graphs have nontrivial isomorphisms to themselves:

**Remark 2.7.9.** Let $n > 1$ be an integer. For each integer $x$, we define $x\%_1 n$ to be the unique element $p \in \{1,2,\ldots,n\}$ that satisfies $p \equiv x \mod n$. For each $k \in \mathbb{Z}$, the map

\[
\{1,2,\ldots,n\} \to \{1,2,\ldots,n\}, \ i \mapsto (i+k) \%_1 n
\]

is an isomorphism $C_n \to C_n$. This isomorphism is called the $k$-rotation on the cycle $C_n$. Note that this $k$-rotation depends only on the remainder of $k$ modulo $n$, not on the integer $k$ itself; in total, we thus have $n$ of these $k$-rotations. Furthermore, there is a reflection on the cycle $C_n$, defined exactly as the reflection on the path $P_n$. This reflection is also a graph isomorphism $C_n \to C_n$. Hence, any composition of this reflection with a $k$-rotation is also a graph isomorphism $C_n \to C_n$ (because of Proposition 2.6.5).

---

\footnote{This map is the permutation of $\{1,2,\ldots,n\}$ that sends the numbers $1,2,\ldots,n$ to $n,n-1,\ldots,1$, respectively.}

\footnote{If $k \in \{0,1,\ldots,n\}$, then this map is the permutation of $\{1,2,\ldots,n\}$ that sends the numbers $1,2,\ldots,n$ to $k+1,k+2,\ldots,n,1,2,\ldots,k$, respectively.}
Again, the names “rotation” and “reflection” reflect the fact that if the cycle graph $C_n$ is drawn as a regular $n$-gon, then the $k$-rotation actually corresponds to rotating the $n$-gon by an angle of $\frac{2\pi k}{n}$ around its center, whereas the reflection corresponds to reflecting the $n$-gon through a certain line.

2.7.3. A few more examples

Here are some further examples of simple graphs, mostly to illustrate certain ideas.

**Example 2.7.10.** Let $n \in \mathbb{N}$. Let $G$ be the graph $(V, E)$, where $V = \{1, 2, \ldots, n\}$ and $E = \{\{i, j\} \in \mathcal{P}_2(V) \mid i \equiv j \mod 3\}$. For example, if $n = 8$, then $G$ can be drawn as follows:

```
1 — 4 — 7
      |
      v
2 — 5 — 8
      |
      v
3 — 6
```

If $n = 9$, then $G$ can be drawn as follows:

```
1 — 4 — 7
      |
      v
2 — 5 — 8
      |
      v
3 — 6 — 9
```

In both cases, we notice that the graph is “disconnected”: It really consists of three smaller graphs, with no edges connecting one to another. We shall make this more rigorous later (in fact, we will formalize the concept of “disconnected” in Subsection 2.8.7, and we will formalize the concept of “consisting of three smaller graphs” in Subsection 2.7.5).

**Example 2.7.11.** If $S$ is a finite set, and if $k \in \mathbb{N}$, then we let $KG_{S,k}$ be the simple graph

$$(\mathcal{P}_k(S), \{\{I, J\} \in \mathcal{P}_2(\mathcal{P}_k(S)) \mid I \cap J = \emptyset\}).$$

The vertices of this graph are the $k$-element subsets of $S$, and two such vertices are adjacent if they (regarded as subsets of $S$) are disjoint. The graph $KG_{S,k}$ is called the $k$-th [Kneser graph](#) of the set $S$. 

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The graph $KG_{\{1,2,3,4,5\},2}$ is known as the **Petersen graph**. Here is one way to draw it:

![Diagram of the Petersen graph]

For $n \in \mathbb{N}$ and $k \in \mathbb{N}$, it is common to denote the Kneser graph $KG_{\{1,2,\ldots,n\},k}$ by $KG_{n,k}$. Thus, the Petersen graph is $KG_{5,2}$.

**Example 2.7.12.** Let $n \in \mathbb{N}$ and $k \in \mathbb{N}$. Define a graph $P_{n,k}$ by

$$P_{n,k} = (\{1,2,\ldots,n\},\{\{i,j\} \in P_2(\{1,2,\ldots,n\}) \mid |i-j| \leq k\}).$$

Thus, the vertices of this graph are $1,2,\ldots,n$, and two distinct vertices $i$ and $j$ are adjacent if and only if they satisfy $|i-j| \leq k$. Hence:

- The graph $P_{n,0}$ is the empty graph on the finite set $\{1,2,\ldots,n\}$. (It is empty because no two distinct vertices $i$ and $j$ satisfy $|i-j| \leq 0$, and thus no two distinct vertices $i$ and $j$ are adjacent.)

- The graph $P_{n,1}$ is the path graph $P_n$ (because two distinct vertices $i$ and $j$ satisfy $|i-j| \leq 1$ if and only if $i$ and $j$ are consecutive integers in some order).

- Whenever $k \geq n-1$, the graph $P_{n,k}$ is the complete graph $K_n$. This is because whenever $k \geq n-1$, any pair of distinct vertices $i$ and $j$ of $P_{n,k}$ satisfies $|i-j| \leq k$.

- Here is how $P_{5,2}$ can be drawn:

1——2——3——4——5.
2.7.4. Subgraphs

**Definition 2.7.13.** Let $G = (V, E)$ be a simple graph.

(a) A **subgraph** of $G$ means a simple graph of the form $H = (W, F)$ with $W \subseteq V$ and $F \subseteq E$. In other words, a subgraph of $G$ means a simple graph whose vertices are vertices of $G$ and whose edges are edges of $G$.

(b) Let $S$ be a subset of $V$. The **induced subgraph of $G$ on the set $S$** denotes the subgraph $(S, E \cap \mathcal{P}_2 (S))$ of $G$. In other words, it denotes the subgraph of $G$ whose vertices are the elements of $S$, and whose edges are precisely those edges of $G$ that connect two vertices in $S$.

(c) An **induced subgraph** of $G$ means a subgraph of $G$ that is the induced subgraph of $G$ on $S$ for some subset $S$ of $V$.

The definition of an induced subgraph readily leads to the following criterion:

**Proposition 2.7.14.** Let $H$ be a subgraph of a simple graph $G$. Then, $G$ is an induced subgraph of $G$ if and only if every edge $uv$ of $G$ whose endpoints $u$ and $v$ both are vertices of $H$ is an edge of $H$.

*Proof sketch for Proposition 2.7.14.* The “only if” part follows immediately from the definition of an “induced subgraph”. The “if” part is almost as obvious (show that $H$ is the induced subgraph of $G$ on $V (H)$). The details are left to the reader.

**Example 2.7.15.** Let $n > 1$ be an integer.

(a) The path graph $P_n$ (defined in Definition 2.7.6) is a subgraph of the cycle graph $C_n$ (defined in Definition 2.7.8), since all vertices of $P_n$ are vertices of $C_n$ and since all edges of $P_n$ are edges of $C_n$. But if $n > 2$, then $P_n$ is not an induced subgraph of $C_n$, because not every edge $uv$ of $C_n$ whose endpoints $u$ and $v$ both are vertices of $P_n$ is an edge of $P_n$. (In fact, the edge $n1$ of $C_n$ is not an edge of $P_n$, although both its endpoints $n$ and $1$ are vertices of $P_n$.)

(b) The path graph $P_{n-1}$ is an induced subgraph of $P_n$ (namely, the induced subgraph of $P_n$ on the set $\{1, 2, \ldots , n-1\}$).

(c) Assume that $n > 3$. Then, $C_{n-1}$ is not a subgraph of $C_n$. Indeed, the edge $(n-1) 1$ of $C_{n-1}$ is not an edge of $C_n$.

**TODO 2.7.16.** Pictures for these examples.

2.7.5. Disjoint unions

**TODO 2.7.17.** Disjoint union of several graphs.

**TODO 2.7.18.** Example of being isomorphic to such a disjoint union: re-use Example 2.7.10.
2.8. Walks and paths

Walks and paths are among the most fundamental notions that can be defined for a graph; a large part of graph theory is concerned with these notions. Let us now introduce them.

2.8.1. Definitions and examples

**Definition 2.8.1.** Let $G$ be a simple graph.

(a) A walk (in $G$) means a finite sequence $(v_0, v_1, \ldots, v_k)$ of vertices of $G$ (with $k \geq 0$) such that all of $v_0v_1, v_1v_2, \ldots, v_{k-1}v_k$ are edges of $G$. (We allow $k$ to be 0, in which case the condition that “$v_0v_1, v_1v_2, \ldots, v_{k-1}v_k$ are edges of $G$” is vacuously true.)

(b) If $w = (v_0, v_1, \ldots, v_k)$ is a walk in $G$, then:

- The vertices of $w$ are defined to be the vertices $v_0, v_1, \ldots, v_k$.
- The edges of $w$ are defined to be the edges $v_0v_1, v_1v_2, \ldots, v_{k-1}v_k$ of $G$;
- The nonnegative integer $k$ is called the length of $w$. (This integer is the number of all edges of $G$, counted with multiplicity. It is 1 smaller than the number of all vertices of $G$, counted with multiplicity.)
- The vertex $v_0$ is said to be the starting point of $w$. We say that the walk $w$ starts at $v_0$ (or, equivalently, begins at $v_0$).
- The vertex $v_k$ is said to be the ending point of $w$. We say that the walk $w$ ends at $v_k$.

(c) A path (in $G$) means a walk (in $G$) whose vertices are distinct. (In other words, a path in $G$ means a walk $(v_0, v_1, \ldots, v_k)$ in $G$ such that $v_0, v_1, \ldots, v_k$ are distinct.)

(e) Let $p$ and $q$ be two vertices of $G$. A walk from $p$ to $q$ (in $G$) means a walk (in $G$) whose starting point is $p$ and whose ending point is $q$. A path from $p$ to $q$ (in $G$) means a path (in $G$) whose starting point is $p$ and whose ending point is $q$.

**Example 2.8.2.** Let $V$ and $E$ be as in Example 2.4.2(c). Let $G$ be the graph $(V, E)$. Then:

- The sequence $(1, 3, 4, 5, 6, 1, 3, 2)$ of vertices of $G$ is a walk (in $G$), since all of $13, 34, 45, 56, 61, 13, \text{ and } 32$ are edges of $G$. This walk is a walk from 1 to 2 (since its starting point is 1, and its ending point is 2). It is not a path (since 1, 3, 4, 5, 6, 1, 3 and 2 are not distinct). The length of this walk is 7.
- The sequence $(1, 2, 4, 3)$ of vertices of $G$ is not a walk (in fact, 12 and 43 are edges of $G$, but 24 is not). Hence, it is not a path either.
• The sequence \((1,3,2)\) of vertices of \(G\) is a walk, but also a path (from 1 to 2). The length of this path is 2.

• The sequence \((1,3,2,1)\) of vertices of \(G\) is a walk (from 1 to 1), but not a path (since 1, 3, 2 and 1 are not distinct). The length of this walk is 3.

• The sequence \((1,2,1)\) of vertices of \(G\) is a walk (from 1 to 1). It is not a path. The length of this walk is 2.

• The sequence \((5)\) of vertices of \(G\) is a walk (from 5 to 5) and a path as well. The length of this path is 0.

• The sequence \((5,4)\) of vertices of \(G\) is a walk (from 5 to 4) and a path as well. The length of this path is 1.

TODO 2.8.3. Pictures for this example.

Exercise 2.8.4. Let \(G\) be a simple graph. Let \(w\) be a path in \(G\). Prove that the edges of \(w\) are distinct. (This may look obvious when you can point to a picture; but we ask you to give a rigorous proof!)

2.8.2. Composing and reverting walks

Let us discuss a few basic properties of paths. First of all, if \(v\) is an vertex of a simple graph \(G\), then the one-element list \((v)\) is a path (in \(G\)) from \(v\) to \(v\). This path has length 0. Hence, there exists a path (of length 0) from each vertex to itself. Furthermore, if \((v_0,v_1,\ldots,v_k)\) is a walk in a simple graph \(G\), and if \(p\) and \(q\) are two elements of \(\{0,1,\ldots,k\}\) satisfying \(p \leq k\), then \((v_p,v_{p+1},\ldots,v_q)\) also is a walk in \(G\). The same statement holds if the word “walk” is replaced by “path” both times. Simple facts like this will be used without further mention. Let us now pass to a few facts which are less obvious (although intuitively clear):

Proposition 2.8.5. Let \(G\) be a simple graph. Let \(u\), \(v\) and \(w\) be three vertices of \(G\). Let \(a = (a_0,a_1,\ldots,a_k)\) be a walk from \(u\) to \(v\). Let \(b = (b_0,b_1,\ldots,b_\ell)\) be a walk from \(v\) to \(w\). Then,

\[
(a_0,a_1,\ldots,a_k,b_1,b_2,\ldots,b_\ell) = (a_0,a_1,\ldots,a_{k-1},b_0,b_1,\ldots,b_\ell) \\
= (a_0,a_1,\ldots,a_{k-1},v,b_1,b_2,\ldots,b_\ell)
\]

is a walk from \(u\) to \(w\).

This walk shall be denoted by \(a * b\).

Proof of Proposition 2.8.5. The list \((a_0,a_1,\ldots,a_k)\) is a walk from \(u\) to \(v\). Hence, all of \(a_0a_1,a_1a_2,\ldots,a_{k-1}a_k\) are edges of \(G\), and we have \(a_0 = u\) and \(a_k = v\).

The list \((b_0,b_1,\ldots,b_\ell)\) is a walk from \(v\) to \(w\). Hence, all of \(b_0b_1,b_1b_2,\ldots,b_{\ell-1}b_\ell\) are edges of \(G\), and we have \(b_0 = v\) and \(b_\ell = w\).
We need to prove three claims:

- **Claim 1**: We have \((a_0, a_1, \ldots, a_k, b_1, b_2, \ldots, b_\ell) = (a_0, a_1, \ldots, a_{k-1}, b_0, b_1, \ldots, b_\ell)\).
- **Claim 2**: We have \((a_0, a_1, \ldots, a_{k-1}, b_0, b_1, \ldots, b_\ell) = (a_0, a_1, \ldots, a_{k-1}, v, b_1, b_2, \ldots, b_\ell)\).
- **Claim 3**: The list \((a_0, a_1, \ldots, a_k, b_1, b_2, \ldots, b_\ell)\) is a walk from \(u\) to \(w\).

**Proof of Claim 1.** The two lists \((a_0, a_1, \ldots, a_k, b_1, b_2, \ldots, b_\ell)\) and \((a_0, a_1, \ldots, a_{k-1}, b_0, b_1, \ldots, b_\ell)\) differ only in their \((k+1)\)-st entry, which is \(a_k\) for the first list and is \(b_0\) for the second list. But since their \((k+1)\)-st entries are also equal (because \(a_k = v = b_0\)), this shows that these two lists are identical. In other words, \((a_0, a_1, \ldots, a_k, b_1, b_2, \ldots, b_\ell) = (a_0, a_1, \ldots, a_{k-1}, b_0, b_1, \ldots, b_\ell)\). Claim 1 is proven.

**Proof of Claim 2.** The two lists \((a_0, a_1, \ldots, a_{k-1}, b_0, b_1, \ldots, b_\ell)\) and \((a_0, a_1, \ldots, a_{k-1}, v, b_1, b_2, \ldots, b_\ell)\) differ only in their \((k+1)\)-st entry, which is \(b_0\) for the first list and is \(v\) for the second list. But since their \((k+1)\)-st entries are also equal (because \(b_0 = v\)), this shows that these two lists are identical. In other words, \((a_0, a_1, \ldots, a_{k-1}, b_0, b_1, \ldots, b_\ell) = (a_0, a_1, \ldots, a_{k-1}, v, b_1, b_2, \ldots, b_\ell)\). Claim 2 is proven.

**Proof of Claim 3.** Recall that all of \(b_0 b_1, b_1 b_2, \ldots, b_{\ell-1} b_\ell\) are edges of \(G\). Since \(b_0 = v = a_k\), this rewrites as follows: All of \(a_k b_1, b_1 b_2, \ldots, b_{\ell-1} b_\ell\) are edges of \(G\). Combining this with the fact that all of \(a_0 a_1, a_1 a_2, \ldots, a_{k-1} a_k\) are edges of \(G\), we obtain the following: All of \(a_0 a_1, a_1 a_2, \ldots, a_{k-1} a_k, a_k b_1, b_1 b_2, \ldots, b_{\ell-1} b_\ell\) are edges of \(G\). Hence, the list \((a_0, a_1, \ldots, a_k, b_1, b_2, \ldots, b_\ell)\) is a walk (by the definition of “walk”). Furthermore, this list is actually a walk from \(u\) to \(w\) (since \(a_0 = u\) and \(b_\ell = w\)). This proves Claim 3.

Thus, all three Claims are proven. Together, they yield Proposition 2.8.5. \(\Box\)

**Proposition 2.8.6.** Let \(G\) be a simple graph. Let \(u\) and \(v\) be two vertices of \(G\). Let \(a = (a_0, a_1, \ldots, a_k)\) be a walk from \(u\) to \(v\).

(a) The list \((a_k, a_{k-1}, \ldots, a_0)\) is a walk from \(v\) to \(u\).

This list shall be denoted by \(\text{rev } a\), and called the **reversal** of \(a\).

(b) If the list \(a\) is a path, then \(\text{rev } a\) is a path as well.

**Proof of Proposition 2.8.6.** The list \((a_0, a_1, \ldots, a_k)\) is a walk from \(u\) to \(v\). Hence, all of \(a_0 a_1, a_1 a_2, \ldots, a_{k-1} a_k\) are edges of \(G\), and we have \(a_0 = u\) and \(a_k = v\).

(a) All of \(a_0 a_1, a_1 a_2, \ldots, a_{k-1} a_k\) are edges of \(G\). In other words,

\[
a_i a_{i+1} \text{ is an edge of } G \quad \text{for each } i \in \{0, 1, \ldots, k-1\}. \tag{23}\]

Now, \(a_{k-j} a_{k-(j+1)}\) is an edge of \(G\) for each \(j \in \{0, 1, \ldots, k-1\}\). In other words, all of \(a_k a_{k-1}, a_{k-1} a_{k-2}, \ldots, a_1 a_0\) are edges of \(G\). In other words, the list

\[
a_k a_{k-1}, a_{k-1} a_{k-2}, \ldots, a_1 a_0\]

is a path from \(u\) to \(v\).

---

\(\text{Proof.}\) Let \(j \in \{0, 1, \ldots, k-1\}\). Then, \(k-1-j \in \{0, 1, \ldots, k-1\}\). Hence, (applied to \(i = k-1-j\)) shows that \(a_{k-1-j} a_{(k-1-j)+1}\) is an edge of \(G\). Since \(a_{k-1-j} a_{(k-1-j)+1} = a_{k-(j+1)} a_{k-j} = a_k a_{k-1} a_{k-2} \ldots a_1 a_0\), this rewrites as follows: \(a_{k-j} a_{k-(j+1)}\) is an edge of \(G\). This completes the proof.
(a_k, a_{k-1}, \ldots, a_0) is a walk. This list is furthermore a walk from \( v \) to \( u \) (since \( a_k = v \) and \( a_0 = v \)). This proves Proposition 2.8.6 (a).

(b) The vertices of the walk \( a \) are \( a_0, a_1, \ldots, a_k \) (since \( a = (a_0, a_1, \ldots, a_k) \)), whereas the vertices of the walk \( \text{rev } a \) are \( a_k, a_{k-1}, \ldots, a_0 \) (since \( \text{rev } a = (a_k, a_{k-1}, \ldots, a_0) \)). Hence, the vertices of the walk \( \text{rev } a \) are the same as the vertices of the walk \( a \), listed in a different order.

Now, assume that \( a \) is a path. Thus, the vertices of the walk \( a \) are distinct (by the definition of “path”). In other words, the vertices of the walk \( \text{rev } a \) are distinct (since the vertices of the walk \( \text{rev } a \) are the same as the vertices of the walk \( a \), listed in a different order). Hence, this walk \( \text{rev } a \) is a path (by the definition of “path”). This proves Proposition 2.8.6 (b).

2.8.3. Reducing a walk to a path

The next result is simple but crucial:

**Proposition 2.8.7.** Let \( G \) be a simple graph. Let \( u \) and \( v \) be two vertices of \( G \). Let 
\[
(a_0, a_1, \ldots, a_k)
\]
be a walk from \( u \) to \( v \). Assume that \( a \) is not a path. Then, there exists a walk from \( u \) to \( v \) whose length is smaller than \( k \).

**Example 2.8.8.** Let \( G \) be the graph \((V, E)\), where
\[
V = \{1, 2, 3, 4, 5, 6\} \quad \text{and} \quad E = \{\{1, 2\}, \{2, 3\}, \{3, 4\}, \{4, 5\}, \{5, 6\}, \{6, 1\}, \{1, 3\}, \{3, 5\}, \{5, 1\}\}.
\]
(This graph can be drawn in such a way as to look like a hexagon with three extra diagonals forming a triangle.) The sequence \((4, 3, 2, 1, 3, 6)\) of vertices of \( G \) is a walk from 4 to 6. But it is not a path, since it passes through the vertex 3 twice (i.e., the vertex 3 appears twice among its vertices). Thus, Proposition 2.8.7 predicts that there exists a walk from 4 to 6 whose length is smaller than 5. And indeed, such a walk can easily be obtained from our walk \((4, 3, 2, 1, 3, 6)\), just by removing the part between the two appearances of the vertex 3 (including one of these two appearances). The result is the walk \((4, 3, 6)\), whose length 2 is indeed smaller than 5.

The same idea (removing a “digression” between two appearances of the same vertex) can be used to prove Proposition 2.8.7 in full generality. This is what we shall do in the proof below.

**Proof of Proposition 2.8.7.** Recall that \((a_0, a_1, \ldots, a_k) = a\) is a walk from \( u \) to \( v \). Hence, 
\( a_0 = u \) and \( a_k = v \).

If the vertices of \( a \) were distinct, then the walk \( a \) would be a path (by the definition of “path”). Thus, the vertices of \( a \) are not distinct (since \( a \) is not a path. In other words, \( a_0, a_1, \ldots, a_k \) are not pairwise distinct (since the vertices of \( a \) are \( a_0, a_1, \ldots, a_k \)). In other words, there exist two elements \( p \) and \( q \) of \( \{0, 1, \ldots, k\} \) such

```
that \( p < q \) and \( a_p = a_q \). Fix such \( p \) and \( q \). Define a vertex \( x \) of \( G \) by \( x = a_p = a_q \). (This is possible since \( a_p = a_q \).)

Recall that \((a_0,a_1,\ldots,a_k)\) is a walk. Hence, the list \((a_0,a_1,\ldots,a_p)\) is a walk as well. Moreover, this list \((a_0,a_1,\ldots,a_p)\) is a walk from \( u \) to \( x \) (since \( a_0 = u \) and \( a_p = x \)). Denote this walk by \( p \).

Again, recall that \((a_0,a_1,\ldots,a_k)\) is a walk. Hence, the list \((a_q,a_{q+1},\ldots,a_k)\) is a walk as well. Moreover, this list \((a_q,a_{q+1},\ldots,a_k)\) is a walk from \( x \) to \( v \) (since \( a_q = x \) and \( a_k = v \)). Denote this walk by \( q \).

Altogether, we know that \( u, x \) and \( v \) are three vertices of \( G \); we know that \( p = (a_0,a_1,\ldots,a_p) \) is a walk from \( u \) to \( x \); and we know that \( q = (a_q,a_{q+1},\ldots,a_k) \) is a walk from \( x \) to \( v \). Hence, we can apply Proposition 2.8.5 to \( x, v, p, p, a_i, q, k-q \) and \( a_{q+j} \) instead of \( v, w, a, k, a_i, b, \ell \) and \( b_j \). We thus conclude that

\[
(a_0,a_1,\ldots,a_p,a_{q+1},a_{q+2},\ldots,a_k) = (a_0,a_1,\ldots,a_{p-1},a_q,a_{q+1},\ldots,a_k)
\]

is a walk from \( u \) to \( v \). This walk has length smaller than \( k \) (in fact, its length is \((p-1)+2+(k-q-1) = p+q-k < q+k-q = k \)). Hence, there exists a walk from \( u \) to \( v \) whose length is smaller than \( k \) (namely, the walk we have just constructed). This proves Proposition 2.8.7.

From Proposition 2.8.7 we obtain the following corollary:

**Corollary 2.8.9.** Let \( G \) be a simple graph. Let \( u \) and \( v \) be two vertices of \( G \). Let \( k \in \mathbb{N} \). Assume that there exists a walk from \( u \) to \( v \) of length \( k \). Then, there exists a path from \( u \) to \( v \) of length \( \leq k \).

**Example 2.8.10.** Let \( V, E \) and \( G \) be as in Example 2.8.2. Consider the walk \( a = (4,3,2,1,3,4,3,1,5) \) from 4 to 5, having length 8. Corollary 2.8.9 predicts that there exists a path from 4 to 5 of length \( \leq 8 \). This is, of course, obvious (the path \( (4,5) \) works), but let us try to construct such a path from \( a \) by removing “digressions” as we did in Exercise 2.8.8.

- One way to start is by noticing that the vertex 3 appears three times in our walk, and removing the “digression” that the walk makes between the first and the second appearance of 3. The result is the walk \( (4,3,4,3,1,5) \). This latter walk is still not a path, since the vertex 4 appears in it twice. Again, remove the “digression” to obtain the shorter walk \( (4,3,1,5) \). This new walk is a path and has length 3 \( \leq 8 \). So we have found a path from 4 to 5 of length \( \leq 8 \).

- An alternative way to start is by noticing that the vertex 1 appears twice in our walk, and removing the “digression” that the walk makes between its two appearances. The result of this removal is the walk \( (4,3,2,1,5) \), which
is already a path and has length $4 \leq 8$. So we have found a path from 4 to 5 of length $\leq 8$.

- Yet another way to start is by noticing (again) that the vertex 3 appears three times in our walk, and removing the "digression" between its first and third appearances. The result is the path $(4, 3, 1, 5)$.

- There are two other possible ways to start; do you see them?

Note that the different ways to remove "digression" don’t always lead to the same path in the end.

Corollary 2.8.9 can be proved in full generality using this method. Our proof below will do exactly that.

**Proof of Corollary 2.8.9.** The idea behind this proof is the following: Proposition 2.8.7 shows that, whenever we have a walk from $u$ to $v$ that is not a path, we can “shorten it” (i.e., find a shorter walk from $u$ to $v$). Thus, we can start with any walk from $u$ to $v$ of length $k$ (its existence is guaranteed by the hypothesis), and keep “shortening it” until it becomes a path (which has to happen eventually, because we cannot keep shortening it indefinitely). The result will be a path from $u$ to $v$ of length $\leq k$.

This idea can be formalized to give a rigorous proof. The way to formalize it is fairly standard and straightforward, so I am only going to show it now, but leave it to the reader in similar situations that may appear further below.

Our rigorous proof of Corollary 2.8.9 shall proceed by strong induction over $k$. So we fix an integer $\ell \in \mathbb{N}$, and we assume that Corollary 2.8.9 holds whenever $k < \ell$. We then must prove that Corollary 2.8.9 holds when $k = \ell$. (This is the induction step. Note that a strong induction needs no induction base, because the induction step includes the case $\ell = 0$ already.)

We have assumed that Corollary 2.8.9 holds whenever $k < \ell$. In other words, the following claim holds:

**Claim 1:** Let $G$ be a simple graph. Let $u$ and $v$ be two vertices of $G$. Let $k \in \mathbb{N}$ be such that $k < \ell$. Assume that there exists a walk from $u$ to $v$ of length $k$. Then, there exists a path from $u$ to $v$ of length $\leq k$.

Our goal is to prove that Corollary 2.8.9 holds when $k = \ell$. In other words, our goal is to prove the following claim:

**Claim 2:** Let $G$ be a simple graph. Let $u$ and $v$ be two vertices of $G$. Let $k \in \mathbb{N}$ be such that $k = \ell$. Assume that there exists a walk from $u$ to $v$ of length $k$. Then, there exists a path from $u$ to $v$ of length $\leq k$.

**Proof of Claim 2:** We have assumed that there exists a walk from $u$ to $v$ of length $k$. Fix such a walk, and denote it by $a$. Write this walk $a$ in the form $a = (a_0, a_1, \ldots, a_k)$. (This is possible, since $a$ has length $k$.) We are in one of the following two cases:
• **Case 1:** The walk \(a\) is a path.

• **Case 2:** The walk \(a\) is not a path.

Let us consider Case 1 first. In this case, the walk \(a\) is a path. Thus, \(a\) is a path from \(u\) to \(v\) (since \(a\) is a walk from \(u\) to \(v\)), and has length \(\leq k\) (since \(a\) has length \(k\)). Hence, there exists a path from \(u\) to \(v\) of length \(\leq k\) (namely, \(a\)). Thus, Claim 2 is proven in Case 1.

Let us now consider Case 2. In this case, the walk \(a\) is not a path. Hence, Proposition 2.8.7 shows that there exists a walk from \(u\) to \(v\) whose length is smaller than \(k\). Fix such a walk, and denote it by \(b\). Thus, \(b\) is a walk from \(u\) to \(v\) whose length is smaller than \(k\).

Let \(r\) be the length of \(b\). Then, \(r < k\) (since the length of \(b\) is smaller than \(k\)). Hence, \(r < k = \ell\). Now, there exists a walk from \(u\) to \(v\) of length \(r\) (namely, \(b\)). Hence, Claim 1 (applied to \(r\) instead of \(k\)) shows that there exists a path from \(u\) to \(v\) of length \(\leq r\). This path has length \(\leq r < k\); hence, it has length \(\leq k\). Therefore, there exists a path from \(u\) to \(v\) of length \(\leq k\) (namely, the path that we have just constructed). Hence, Claim 2 is proven in Case 2.

Now, we have proven Claim 2 in both possible cases. Therefore, the proof of Claim 2 is complete. In other words, Corollary 2.8.9 holds when \(k = \ell\). This completes the (inductive) proof of Corollary 2.8.9. \(\square\)

### 2.8.4. The equivalence relation \(\simeq_G\)

We can use the concept of paths (and the results proven above) to define a certain equivalence relation on the vertex set of a graph \(G\). First, let us recall what relations and equivalence relations are:

**Definition 2.8.11.** Let \(X\) be a set. A binary relation on \(X\) shall mean a subset of the Cartesian product \(X \times X\). (In other words, it shall mean a set of pairs of elements of \(X\).)

If \(R\) is a binary relation on \(X\), and if \(a\) and \(b\) are two elements of \(X\), then we shall often use the notation \(aRb\) as a synonym for \((a, b) \in R\). This notation is called infix notation. For some relations \(R\), it is usual to always use this notation (i.e., one never writes \((a, b) \in R\), but always writes \(aRb\) instead); in this case, we say that the relation \(R\) is written infix.

Examples of binary relations on the set \(\mathbb{Z}\) are =, \(\leq\), \(<\), \(\geq\), \(>\) and \(\neq\). (These are all written infix: For example, we write \(2 < 4\), but we don’t write \((2, 4) \in <\).)

Now, what is an equivalence relation?

**Definition 2.8.12.** Let \(R\) be a binary relation on a set \(X\). This relation \(R\) shall be written infix throughout this definition.

(a) We say that \(R\) is reflexive if it has the following property: For each \(x \in X\), we have \(xRx\).
(b) We say that $R$ is symmetric if it has the following property: For each $x \in X$ and $y \in X$ satisfying $xRy$, we have $yRx$.

(c) We say that $R$ is transitive if it has the following property: For each $x \in X$, $y \in X$ and $z \in X$ satisfying $xRy$ and $yRz$, we have $xRz$.

(d) We say that $R$ is an equivalence relation if it is reflexive, symmetric and transitive.

We refer to [LeLeMe16, §10.10], or [Hammac15, Chapter 11] (for a particularly detailed treatment), or [Oggier14, Chapter 9], or [Day16, §3.E] for more about equivalence relations. Let us here just briefly mention a few examples:

- Among the six relations $=, \leq, <, \geq, >$ and $\neq$ on the set $\mathbb{Z}$, only the first one ($=$) is an equivalence relation. However, $\leq$ and $\geq$ are reflexive and transitive (but not symmetric), and $<$ and $>$ are transitive. Furthermore, $\neq$ is symmetric.

- For each positive integer $m$, we can define a binary relation $\equiv_m$ on $\mathbb{Z}$ (written infix) by setting
  \[ a \equiv_m b \quad \text{if and only if} \quad a \equiv b \mod m. \]

  This is an equivalence relation (for each $m$).

- Here is a fairly general example: If $X$ and $Y$ are two sets, and if $f : X \to Y$ is any map, then we can define a binary relation $\equiv_f$ on $X$ (written infix) by setting
  \[ a \equiv_f b \quad \text{if and only if} \quad f(a) = f(b). \]

  This is an equivalence relation (for each $f$). The equivalence relation $\equiv_m$ on $\mathbb{Z}$ defined in the previous example is actually a particular case of this $\equiv_f$: Namely, if we define $f : \mathbb{Z} \to \{0, 1, \ldots, m - 1\}$ to be the map that sends each $n \in \mathbb{Z}$ to the remainder obtained when $n$ is divided by $m$, then the relation $f$ becomes identical with $\equiv_m$.

Each simple graph $G$ gives rise to an equivalence relation; here is how it is defined:

**Definition 2.8.13.** Let $G$ be a simple graph. We define a binary relation $\simeq_G$ on the set $V(G)$ (written infix) as follows:

If $u$ and $v$ are two elements of $V(G)$, then we set $u \simeq_G v$ if and only if there exists a walk from $u$ to $v$ in $G$. 
Example 2.8.14. Let $G$ be the simple graph defined in Example 2.4.2 (a). Then, there exists a walk from 1 to 4 in $G$ (for example, the walk $(1,2,3,4)$, or the walk $(1,2,3,2,3,4)$, or the walk $(1,6,5,4)$, or many other walks). In other words, $1 \simeq_G 4$.

It is actually easy to see that $u \simeq_G v$ for any two vertices $u$ and $v$ of $G$. If we want to prove this just using the definition of $\simeq_G$, then we have to construct a walk from $u$ to $v$ for each pair $(u,v)$ of vertices of $G$. However, there is a simpler way to prove this – see Example 2.8.16 below.

The binary relation $\simeq_G$ we just defined is of fundamental importance, although many authors do not define a specific symbol for it. As promised, it is an equivalence relation:

Proposition 2.8.15. Let $G$ be a simple graph. Then, the binary relation $\simeq_G$ (defined in Definition 2.8.13) is an equivalence relation.

Example 2.8.16. Let $G$ be the simple graph defined in Example 2.4.2 (a). Then, there exists a walk from 1 to 2 in $G$ (for example, the walk $(1,2)$). Hence, $1 \simeq_G 2$.

Similarly, $2 \simeq_G 3$, $3 \simeq_G 4$, $4 \simeq_G 5$ and $5 \simeq_G 6$. But Proposition 2.8.15 shows that $\simeq_G$ is an equivalence relation. Hence, from $1 \simeq_G 2 \simeq_G 3 \simeq_G 4 \simeq_G 5 \simeq_G 6$, we immediately conclude that $u \simeq_G v$ for any two vertices $u$ and $v$ of $G$.

Proof of Proposition 2.8.15. We are going to show that the relation $\simeq_G$ is reflexive, symmetric and transitive.

Claim 1: The relation $\simeq_G$ is reflexive.

Proof of Claim 1: Let $x \in V(G)$. Then, $(x)$ is a walk from $x$ to $x$ in $G$. Hence, there exists a walk from $x$ to $x$ in $G$ (namely, $(x)$). In other words, $x \simeq_G x$ (because the definition of $\simeq_G$ reveals that $x \simeq_G x$ holds if and only if there exists a walk from $x$ to $x$ in $G$).

Now, forget that we fixed $x$. We thus have shown that for each $x \in V(G)$, we have $x \simeq_G x$. In other words, the relation $\simeq_G$ is reflexive (by the definition of “reflexive”). This proves Claim 1.

Claim 2: The relation $\simeq_G$ is symmetric.

Proof of Claim 2: Let $x \in V(G)$ and $y \in V(G)$ be such that $x \simeq_G y$.

We have $x \simeq_G y$. In other words, there exists a walk from $x$ to $y$ in $G$ (by the definition of $\simeq_G$). Fix such a walk, and denote it by $a = (a_0,a_1,\ldots,a_k)$.

Thus, $a = (a_0,a_1,\ldots,a_k)$ is a walk from $x$ to $y$ in $G$. Hence, Proposition 2.8.6 (a) (applied to $u = x$ and $v = y$) shows that the list $(a_k,a_{k-1},\ldots,a_0)$ is a walk from $y$ to $x$. Thus, there exists a walk from $y$ to $x$ in $G$ (namely, this list). In other words, $y \simeq_G x$ (by the definition of $\simeq_G$).

Now, forget that we fixed $x$ and $y$. We thus have shown that for each $x \in V(G)$ and $y \in V(G)$ satisfying $x \simeq_G y$, we have $y \simeq_G x$. In other words, the relation $\simeq_G$ is symmetric (by the definition of “symmetric”). This proves Claim 2.
Claim 3: The relation $\simeq_G$ is transitive.

Proof of Claim 3: Let $x \in V(G)$, $y \in V(G)$ and $z \in V(G)$ be such that $x \simeq_G y$ and $y \simeq_G z$.

We have $x \simeq_G y$. In other words, there exists a walk from $x$ to $y$ in $G$ (by the definition of $\simeq_G$). Fix such a walk, and denote it by $a = (a_0, a_1, \ldots, a_k)$.

We have $y \simeq_G z$. In other words, there exists a walk from $y$ to $z$ in $G$ (by the definition of $\simeq_G$). Fix such a walk, and denote it by $b = (b_0, b_1, \ldots, b_\ell)$.

We know that $a = (a_0, a_1, \ldots, a_k)$ is a walk from $x$ to $y$ in $G$, and we also know that $b = (b_0, b_1, \ldots, b_\ell)$ is a walk from $y$ to $z$ in $G$. Hence, Proposition 2.8.5 (applied to $u = x$, $v = y$ and $w = z$) shows that
\[
(a_0, a_1, \ldots, a_k, b_1, b_2, \ldots, b_\ell) = (a_0, a_1, \ldots, a_{k-1}, b_0, b_1, \ldots, b_\ell) = (a_0, a_1, \ldots, a_{k-1}, v, b_1, b_2, \ldots, b_\ell)
\]
is a walk from $x$ to $z$. Thus, there exists a walk from $x$ to $z$ in $G$ (namely, the walk we have just constructed). In other words, $x \simeq_G z$ (by the definition of $\simeq_G$).

Now, forget that we fixed $x$, $y$ and $z$. We thus have shown that for each $x \in V(G)$, $y \in V(G)$ and $z \in V(G)$ satisfying $x \simeq_G y$ and $y \simeq_G z$, we have $x \simeq_G z$. In other words, the relation $\simeq_G$ is transitive (by the definition of “transitive”). This proves Claim 3.

Altogether, we now have shown that the relation $\simeq_G$ is reflexive, symmetric and transitive. In other words, this relation $\simeq_G$ is an equivalence relation (by the definition of an “equivalence relation”). This proves Proposition 2.8.15.

The following proposition gives a few equivalent characterizations for the relation $\simeq_G$ introduced in Definition 2.8.13:

**Proposition 2.8.17.** Let $G$ be a simple graph. Let $u$ and $v$ be two vertices of $G$.

The following seven statements are equivalent:

- **Statement $S_0$:** We have $u \simeq_G v$.
- **Statement $S_1$:** There exists a walk from $u$ to $v$.
- **Statement $S_2$:** There exists a walk from $v$ to $u$.
- **Statement $S_3$:** There exists a walk from one of the two vertices $u$ and $v$ to the other.
- **Statement $S_4$:** There exists a path from $u$ to $v$.
- **Statement $S_5$:** There exists a path from $v$ to $u$.
- **Statement $S_6$:** There exists a path from one of the two vertices $u$ and $v$ to the other.
Proof of Proposition 2.8.17. The definition of the relation $\simeq_G$ shows that $u \simeq_G v$ holds if and only if there exists a walk from $u$ to $v$ in $G$. In other words, Statement $S_0$ holds if and only if Statement $S_1$ holds. This proves the equivalence $S_0 \iff S_1$.

The implication $S_1 \implies S_2$ is easy to prove. The same argument, but with the roles of $u$ and $v$ interchanged, proves the implication $S_2 \implies S_1$. Combining the two implications $S_1 \implies S_2$ and $S_2 \implies S_1$, we obtain the equivalence $S_1 \iff S_2$.

The statement $S_3$ is the disjunction of the two statements $S_1$ and $S_2$. In other words, $S_3 \iff (S_1 \lor S_2)$. But from $S_1 \iff S_2$, we obtain $(S_1 \lor S_2) \iff (S_2 \lor S_2) \iff S_2$. Hence, $S_3 \iff (S_1 \lor S_2) \iff S_2$.

Combining the three equivalences $S_0 \iff S_1$, $S_1 \iff S_2$ and $S_3 \iff S_2$, we obtain the chain of equivalences

$$S_0 \iff S_1 \iff S_2 \iff S_3.$$  \hfill (24)

The implication $S_4 \implies S_1$ holds for obvious reasons (namely, because every path is a walk). But the implication $S_1 \implies S_4$ also holds. Combining the two implications $S_1 \implies S_4$ and $S_4 \implies S_1$, we obtain the equivalence $S_1 \iff S_4$. The same argument (but with the roles of $u$ and $v$ interchanged) proves the equivalence $S_2 \iff S_5$. Thus, $S_1 \iff S_2 \iff S_5$.

The statement $S_6$ is the disjunction of the two statements $S_4$ and $S_5$. In other words, $S_6 \iff (S_4 \lor S_5)$. But from $S_4 \iff S_1$ and $S_5 \iff S_1$, we obtain $(S_4 \lor S_5) \iff (S_1 \lor S_1) \iff S_1$. Hence, $S_6 \iff (S_4 \lor S_5) \iff S_1$.

Because of the three equivalences $S_1 \iff S_4$, $S_1 \iff S_5$ and $S_1 \iff S_6$, we can extend the chain of equivalences (24) to

$$S_0 \iff S_1 \iff S_2 \iff S_3 \iff S_4 \iff S_5 \iff S_6.$$  

Thus, Proposition 2.8.17 is proven. \qed

2.8.5. Dijkstra’s algorithm

\[ \text{TODO 2.8.18. Dijkstra’s algorithm. Use tables of paths to formalize it.} \]
TODO 2.8.19. Proof.

### 2.8.6. Circuits and cycles

**Definition 2.8.20.** Let $G$ be a simple graph.

- *(a)* A **circuit** (in $G$) means a walk $(v_0, v_1, \ldots, v_k)$ in $G$ satisfying $v_k = v_0$.
- *(b)* A **cycle** (in $G$) means a circuit $(v_0, v_1, \ldots, v_k)$ in $G$ such that $k \geq 3$, and such that the vertices $v_0, v_1, \ldots, v_{k-1}$ are distinct.

**Example 2.8.21.** Let $V$ and $E$ be as in Example 2.4.2 (c). Let $G$ be the graph $(V, E)$. Then:

- The sequence $(1, 3, 2, 1, 6, 5, 6, 1)$ of vertices of $G$ is a circuit (in $G$), since it is a walk and satisfies $1 = 1$. But it is not a cycle, since the vertices $1, 3, 2, 1, 6, 5, 6$ are not distinct.
- The sequence $(1, 2, 3, 1)$ of vertices of $G$ is a circuit and a cycle (since the vertices $1, 2, 3$ are distinct).
- The sequence $(1, 2, 1)$ of vertices of $G$ is a circuit, but not a cycle (since it fails the $k \geq 3$ condition in Definition 2.8.20).
- The sequence $(1, 3, 4, 5)$ of vertices of $G$ is not a circuit (since $5 \neq 1$).

TODO 2.8.22. Examples.

TODO 2.8.23. Explain that $(u, v, w)$ and $(v, w, u)$ count as distinct cycles (for us!). Explain that various books define circuits differently, e.g. Diestel:

- Several sources define a cycle not as a list of vertices, but rather as a subgraph isomorphic to $C_k$ for some $k \geq 3$. For example, [Diestel16], [BonMur08] and [West01] do this. This definition is closely related to ours, because when $(v_0, v_1, \ldots, v_k)$ is a cycle of $G$ (in our meaning of this word), then the subgraph

$$\left(\{v_0, v_1, \ldots, v_k\}, \{v_i v_{i+1} \mid i \in \{0, 1, \ldots, k-1\}\}\right)$$

of $G$ is isomorphic to $C_k$. But the two definitions are not literally equivalent, because the cycle $(v_0, v_1, \ldots, v_k)$ (in our sense) cannot be uniquely reconstructed from the subgraph defined by it; indeed, any rotated version $(v_i, v_{i+1}, \ldots, v_{k-1}, v_0, v_1, \ldots, v_{i-1})$ of this cycle (as well as its reflected version $(v_k, v_{k-1}, \ldots, v_0)$) yields the same subgraph.

- [Bollob98] defines a cycle as an equivalence class of what we call “cycle” with respect to reflections and rotations. This ends up equivalent to the convention used in [Diestel16], [BonMur08] and [West01].
• I am not sure how Ore defines cycles in [Ore90] and [Ore74]; but he doesn’t seem to do much with this notion.

• [Harju14] defines cycles in the same way as we do, but erroneously omits the condition $k \geq 3$.

• The definition of cycles in [BehCha71] is equivalent to ours (though circuits are defined slightly differently).

• ...

I haven’t even started discussing the various definitions of “walk”, “path” and “circuit”. Be careful.

TODO 2.8.24. Facts about cycles and circuits:
- Rotating a circuit yields a circuit.
- Rotating a cycle yields a cycle.
- Reversal of a circuit is a circuit.
- Reversal of a cycle is a cycle.
- Edges of a cycle are distinct.
- Each walk with no two identical adjacent edges contains a cycle, unless it is a path.
- If there are two different paths from $u$ to $v$, then there is a cycle.

2.8.7. Connectedness

Definition 2.8.25. Let $G = (V, E)$ be a simple graph. We say that $G$ is connected if $G$ satisfies the following two properties:

• Its vertex set $V$ is nonempty.

• Each two vertices $u \in V$ and $v \in V$ satisfy $u \simeq_G v$.

TODO 2.8.26. Examples. Reuse Example 2.7.10

Definition 2.8.27. Let $G = (V, E)$ be a simple graph. Let $v \in V$. The connected component of $v$ (in $G$) denotes the subset $\{u \in V \mid u \simeq_G v\}$ of $V$. We shall denote this connected component of $v$ by $\text{conncomp}_v$ (or by $\text{conncomp}_G v$, when $G$ is not clear from the context).

A connected component of $G$ means a subset of $V$ that is the connected component of some $v \in V$. (Note that the $v$ is usually not uniquely determined – in fact, several different vertices $v \in V$ often have the same connected component.) Roughly speaking, if $v$ is a vertex of a simple graph $G$, then the connected component of $v$ is the set of all vertices that are reachable from $v$ by walks (i.e., that are ending points of walks that start at $v$).
Example 2.8.28. (a) Let \( G = (V, E) \) be the simple graph defined in Example 2.4.2 (a). Then, we know that (from Example 2.8.14) that \( u \simeq_G v \) for any two vertices \( u \) and \( v \) of \( G \). Hence, for each \( v \in V \), we have
\[
\text{conncomp } v = \left\{ u \in V \mid u \simeq_G v \text{ this always holds} \right\} = \{ u \in V \} = V.
\]
In other words, the connected component of any vertex \( v \) of \( G \) is the whole set \( V \). Thus, \( G \) has only one connected component – namely, \( V \).

(b) Let \( n \in \mathbb{N} \) be such that \( n \geq 3 \). Let \( G = (V, E) \) be the simple graph defined in Example 2.7.10. Then, two vertices \( u \) and \( v \) of \( G \) satisfy \( u \simeq_G v \) if and only if they satisfy \( u \equiv v \mod 3 \). Hence, \( G \) has exactly three connected components:

- The connected component \( \text{conncomp } 1 = \{ u \in V \mid u \equiv 1 \mod 3 \} = \{ 1, 4, 7, \ldots \} \cap V \).
- The connected component \( \text{conncomp } 2 = \{ u \in V \mid u \equiv 2 \mod 3 \} = \{ 2, 5, 8, \ldots \} \cap V \).
- The connected component \( \text{conncomp } 3 = \{ u \in V \mid u \equiv 3 \mod 3 \} = \{ 3, 6, 9, \ldots \} \cap V \).

If we have \( n < 3 \) instead, then some of these connected components are missing (i.e., for \( n = 3 \), there is no \( \text{conncomp } 3 \), and \( G \) has only 2 connected components).

TODO 2.8.29. Connected iff exactly 1 connected component.

Remark about the graph with 0 vertices.
Remark about \( K_n \) and \( E_n \).

TODO 2.8.30. Restate using paths and walks. Equivalence of:

- \( u \simeq_G v \).
- There is a path from \( u \) to \( v \).
- There is a walk from \( u \) to \( v \).
- \( \text{conncomp } u = \text{conncomp } v \).
- \( u \in \text{conncomp } v \).
- \( v \in \text{conncomp } u \).
- \( \text{conncomp } u \cap \text{conncomp } v \neq \emptyset \).

TODO 2.8.31. Each \( v \in V \) lies in exactly one connected component.

TODO 2.8.32. Connected components are connected and maximal at that.

TODO 2.8.33. A graph is isomorphic to the disjoint union of its connected components.
2.9. Questions to ask about graphs

- **TODO 2.9.1.** Connectedness.

- **TODO 2.9.2.** Hamiltonian paths and cycles: Do they exist? How to find them? (We will have partial results, mainly sufficient conditions.)

- **TODO 2.9.3.** Eulerian walks and circuits. (Theory is really nice here, with easy necessary-and-sufficient conditions, but we’ll wait for a better notion of graph.)

- **TODO 2.9.4.** Matchings: how large, how many, structure? (Nice and large theory, still under research; we will see a lot of it but still barely scratch the surface.)

3. Dominating sets

I will next digress to discuss the notion of dominating sets. The reason why I am doing this at this point is not that dominating sets are of any particular fundamental importance (there are arguably more crucial notions in graph theory left to consider), but rather that they neatly illustrate the concepts we have seen so far and provide some experience with graph-theoretical proofs, all that while not requiring any complex theory or advanced techniques.

### 3.1. Definition

**Definition 3.1.1.** Let $G$ be a simple graph. A subset $U$ of $V(G)$ is said to be **dominating** (for $G$) if it has the following property: For every vertex $v \in V(G) \setminus U$, at least one neighbor of $v$ belongs to $U$.

A dominating set of $G$ means a dominating subset of $V(G)$.

**Example 3.1.2.** For this example, let us consider the graph $G = (V,E)$, where

\[
V = \{1, 2, 3, 4, 5\} \quad \text{and} \quad E = \{\{1, 2\}, \{2, 3\}, \{3, 4\}, \{4, 5\}, \{5, 1\}\}.
\]

(This graph has already been introduced in Example 2.4.2 (d). It can be drawn to look like a pentagon.)

The subset $\{1, 3\}$ of $V$ is dominating (for $G$). (This can be checked directly: We must show that for every vertex $v \in V(G) \setminus \{1, 3\}$, at least one neighbor of $v$ belongs to $\{1, 3\}$. There are three vertices $v \in V(G) \setminus \{1, 3\}$, namely 2, 4 and 5. For $v = 2$, the neighbor 1 of $v$ belongs to $\{1, 3\}$ (and so does the neighbor 3). For $v = 4$, the neighbor 3 of $v$ belongs to $\{1, 3\}$. For $v = 5$, the neighbor 1 of $v$ belongs to $\{1, 3\}$.)

The subset $\{1, 2\}$ of $V$ is **not** dominating (for $G$). (Indeed, the vertex 4 $\in V(G) \setminus \{1, 2\}$ does not have the property that at least one neighbor of 4 belongs to $\{1, 2\}$.)
Every subset of $V$ having at least 3 elements is dominating, whereas no subset of $V$ having at most 1 element is dominating. A 2-element subset can be either dominating or not. (Of course, more complicated graphs exhibit more complex behavior.)

Exercise 3.1.3. Let $n \in \mathbb{N}$. What is the smallest possible size of a dominating set of the cycle graph $C_{3n}$?

Clearly, if $G$ is a simple graph, then its vertex set $V(G)$ is a dominating set. One natural question to ask is how small a dominating set of a graph can be. When the graph $G$ is empty, only the vertex set $V(G)$ itself is dominating. On the other hand, when $G$ is a complete graph on $n \geq 1$ vertices, every nonempty subset of $V(G)$ is dominating. Clearly, the more edges a simple graph has, the more dominating sets it has (in the sense that if we add a new edge, then all sets that are dominating remain dominating, and possibly new dominating sets appear). It is furthermore clear that if a vertex of a simple graph $G$ has no neighbors, then it must belong to each dominating set of $G$ (because otherwise, at least one neighbor of this vertex would need to lie in the dominating set; but this is impossible, since it has no neighbors). Such vertices are said to be isolated.

Definition 3.1.4. Let $G$ be a simple graph. A vertex $v$ of $G$ is said to be isolated if it has no neighbors. (In other words, a vertex $v$ of $G$ is said to be isolated if it belongs to no edge of $G$. In other words, a vertex $v$ of $G$ is said to be isolated if its degree $\deg v$ equals 0.)

Proposition 3.1.5. Let $G = (V, E)$ be a simple graph that has no isolated vertices.

(a) There exist two disjoint dominating subsets $A$ and $B$ of $V$ such that $A \cup B = V$.

(b) There exists a dominating subset of $V$ having size $\leq |V| / 2$.

We will see two proofs of this proposition later, in Subsections 3.5 and 3.6.

Again, Proposition 3.1.5 can be neatly restated in terms of people and friendships.  

Restatement of Proposition 3.1.5 (a): Given a group of people, each of whom has at least one friend (among the others), it is always possible to subdivide the group into two teams such that each person has a friend in the opposite team.

Restatement of Proposition 3.1.5 (b): Given a group of (finitely many) people each of whom has at least one friend (among the others), it is always possible to choose at most $|V| / 2$ people from this group such that everyone who is not chosen has at least one of the chosen ones among his friends.

(As usual, we assume that the group of people is finite, and that the relation of friendship is symmetric.)
Example 3.1.6. (a) Let $V$, $E$ and $G$ be as in Example 3.1.2. Then, Proposition 3.1.5 predicts that there exists a dominating subset of $V$ having size $\leq \frac{|V|}{2} = \frac{5}{2}$. Since the size of a finite set is an integer, this shows that there exists a dominating subset of $V$ having size $\leq 2$ (because any integer that is $\leq 5/2$ must automatically be $\leq 2$). And indeed, such a dominating subset exists (for example, $\{5,3\}$).

(b) Now, let us instead consider the graph $G = (V, E)$, where

$V = \{1, 2, 3, 4, 5\}$ and

$E = \mathcal{P}_2(V)$.

(This is the complete graph $K_5$.) Again, Proposition 3.1.5 predicts that there exists a dominating subset of $V$ having size $\leq \frac{|V|}{2} = \frac{5}{2}$. Again, this entails that there exists a dominating subset of $V$ having size $\leq 2$ (since the size of a finite set is an integer). This is indeed true, but for this particular graph we can even find a dominating subset of $V$ having size 1: for example, the subset $\{1\}$.

3.2. Brouwer’s theorem and the Heinrich-Tittmann formula

Next, we state a surprising recent result by Brouwer ([Brouwe09], from 2009) about the number of dominating sets of a graph:

Theorem 3.2.1. Let $G$ be a simple graph. Then, the number of dominating sets of $G$ is odd.

Brouwer (in [Brouwe09]) gives three proofs of this theorem. We are going to give another. Better yet, we shall prove a more precise result which is even more recent (a preprint [HeiT17] from 2017), due to Heinrich and Tittmann:

Theorem 3.2.2. Let $G = (V, E)$ be a simple graph. Let $n = |V|$. Assume that $n > 0$.

A detached pair shall mean a pair $(A, B)$ of two disjoint subsets $A$ and $B$ of $V$ having the property that there exists no edge $ab \in E$ satisfying $a \in A$ and $b \in B$.

Let $\alpha$ be the number of all detached pairs $(A, B)$ for which both numbers $|A|$ and $|B|$ are even and positive.

Let $\beta$ be the number of all detached pairs $(A, B)$ for which both numbers $|A|$ and $|B|$ are odd.

Then:

(a) The numbers $\alpha$ and $\beta$ are even.

(b) The number of dominating sets of $G$ is $2^n - 1 + \alpha - \beta$.

At this point, let me stress that the word “pair” always means an ordered pair throughout these notes. In particular, in Theorem 3.2.2 a detached pair $(A, B)$ should be distinguished from $(B, A)$, unless they actually are equal (which only happens when both $A$ and $B$ are the empty set).
Theorem 3.2.2 is a restatement of [HeiTit17, Theorem 8]. The proof we shall give below is shorter than the proof in [HeiTit17], but does not lead us through as many interesting intermediate results.

Let us first see how Theorem 3.2.1 can be derived from Theorem 3.2.2:

Proof of Theorem 3.2.1 using Theorem 3.2.2. Write the graph $G$ in the form $G = (V, E)$.

If $|V| = 0$, then Theorem 3.2.1 holds. Hence, for the rest of this proof, we WLOG assume that $|V| = 0$ does not hold.

Let us use the notations of Theorem 3.2.2. From Theorem 3.2.2 (a), we know that $\alpha$ and $\beta$ are even. In other words, $\alpha \equiv 0 \mod 2$ and $\beta \equiv 0 \mod 2$. Furthermore, $n = |V| \neq 0$ (since $|V| = 0$ does not hold), so that $n$ is a positive integer. Thus, $2^n$ is even. In other words, $2^n \equiv 0 \mod 2$. Now, Theorem 3.2.2 (b) shows that the number of dominating sets of $G$ is

$$2^n \equiv 0 \mod 2$$

In other words, the number of dominating sets of $G$ is odd. This proves Theorem 3.2.1.

Thus, it remains to prove Theorem 3.2.2.

3.3. The Iverson bracket

Our proof of Theorem 3.2.2 will rely on a few lemmas. But first, let us introduce a very basic notation, which has nothing to do with graphs specifically but is useful throughout mathematics (particularly combinatorics):

Definition 3.3.1. Let $A$ be a logical statement. (It is not required to be true.) Then, a number $[A] \in \{0, 1\}$ is defined as follows: We set $[A] = \begin{cases} 1, & \text{if } A \text{ is true;} \\ 0, & \text{if } A \text{ is false}. \end{cases}$ This number $[A]$ is called the truth value of $A$. (For example, $[1 + 1 = 2] = 1$ and $[1 + 1 = 3] = 0$. For another example, $[\text{Proposition 2.4.1 holds}] = 1$, because we have proven Proposition 2.4.1.) The notation $[A]$ for the truth value of $A$ is known as the Iverson bracket notation.

Truth values satisfy certain simple rules:

Proposition 3.3.2. (a) If $A$ and $B$ are two equivalent logical statements, then $[A] = [B]$.

(b) If $A$ is any logical statement, then $[\text{not } A] = 1 - [A]$.

$^3$Proof. Assume that $|V| = 0$. Hence, the set $V$ is empty. Thus, the only subset of $V$ is $\emptyset$. This subset $\emptyset$ is dominating (because it is the whole set $V$). Thus, there exists exactly 1 dominating set of $G$ (namely, $\emptyset$). In other words, the number of dominating sets of $G$ is 1. Therefore, this number is odd. Hence, Theorem 3.2.1 is proven (under the assumption that $|V| = 0$.
(c) If $A$ and $B$ are two logical statements, then $[A \land B] = [A] [B]$.
(d) If $A$ and $B$ are two logical statements, then $[A \lor B] = [A] + [B] - [A] [B]$.

**Proposition 3.3.3.** Let $P$ be a finite set. Let $Q$ be a subset of $P$.
(a) Then, $|Q| = \sum_{p \in P} [p \in Q]$.
(b) For each $p \in P$, let $a_p$ be a number (for example, a real number). Then, $\sum_{p \in P} [p \in Q] a_p = \sum_{p \in Q} a_p$.
(c) For each $p \in P$, let $a_p$ be a number (for example, a real number). Let $q \in P$.
Then, $\sum_{p \in P} [p = q] a_p = a_q$.

**Exercise 3.3.4.** (a) Prove Proposition 3.3.2.
(b) Prove Proposition 3.3.3.
Now, let $G$ be a simple graph.
(c) Prove that $\deg v = \sum_{u \in V(G)} \mu uv \in E(G)$ for each vertex $v$ of $G$.
(d) Prove that $2 |E(G)| = \sum_{u \in V(G)} \sum_{v \in V(G)} [uv \in E(G)]$.

The following lemma is fundamental to much of combinatorics (if not to say much of mathematics):

**Lemma 3.3.5.** Let $P$ be a finite set. Then,
$$\sum_{A \subseteq P} (-1)^{|A|} = [P = \emptyset].$$
(The symbol " $\sum_{A \subseteq P}$ " means "sum over all subsets $A$ of $P".
In other words, it means " $\sum_{A \subseteq P}$ ".)

**Proof of Lemma 3.3.5.** If $P = \emptyset$, then Lemma 3.3.5 holds. Hence, for the rest of this proof, we WLOG assume that $P \neq \emptyset$. Thus, there exists at least one element $p$ of $P$. Pick such a $p$.

Proof. Assume that $P = \emptyset$. Then, there exists only one subset of $P$, namely $\emptyset$. Hence, the sum $\sum_{A \subseteq P} (-1)^{|A|}$ has only one addend, namely the addend for $A = \emptyset$. Therefore, this sum simplifies to
$$\sum_{A \subseteq P} (-1)^{|A|} = (-1)^{|\emptyset|} = 1$$
(since $|\emptyset| = 0$). Comparing this with $[P = \emptyset] = 1$ (which holds, since $P = \emptyset$ is true), we obtain $\sum_{A \subseteq P} (-1)^{|A|} = [P = \emptyset]$. Hence, we have shown that Lemma 3.3.5 holds if $P = \emptyset$. 

---
There are two kinds of subsets of $P$: the ones that contain $p$, and the ones that do not. Hence, the sum $\sum_{A \subseteq P} (-1)^{|A|}$ can be decomposed as follows:

$$\sum_{A \subseteq P} (-1)^{|A|} = \sum_{A \subseteq P; \ p \in A} (-1)^{|A|} + \sum_{A \subseteq P; \ p \notin A} (-1)^{|A|}.$$  \hspace{1cm} (25)

But every subset $A$ of $P$ that contains $p$ has the form $B \cup \{p\}$ for a \textbf{unique} subset $B$ of $P$ that does not contain $p$ (namely, for $B = A \setminus \{p\}$). Conversely, of course, if $B$ is a subset of $P$ that does not contain $p$, then $B \cup \{p\}$ will always be a subset of $P$ that contains $p$. Hence, there exists a bijection (i.e., a bijective map) from the set of all subsets of $P$ that do not contain $p$ to the set of all subsets of $P$ that do contain $p$; namely, this bijection sends each subset $B$ of $P$ that does not contain $p$ to $B \cup \{p\}$. Using this bijection, we can rewrite the sum $\sum_{A \subseteq P} (-1)^{|A|}$ as follows:

$$\sum_{A \subseteq P; \ p \in A} (-1)^{|A|} = \sum_{B \subseteq P; \ |B| = 0} (-1)^{|B|} = \sum_{B \subseteq P; \ p \notin B} (-1)^{|B|} + \sum_{A \subseteq P; \ p \notin A} (-1)^{|A|} - \sum_{B \subseteq P; \ p \notin B} (-1)^{|B|}.$$  \hspace{1cm} (25)

(here, we have renamed the summation index $B$ as $A$). Thus, (25) becomes

$$\sum_{A \subseteq P} (-1)^{|A|} = \sum_{A \subseteq P; \ p \in A} (-1)^{|A|} + \sum_{A \subseteq P; \ p \notin A} (-1)^{|A|} = - \sum_{A \subseteq P; \ p \notin A} (-1)^{|A|} + \sum_{A \subseteq P; \ p \notin A} (-1)^{|A|} = 0.$$  \hspace{1cm} (25)

Comparing this with $|P = \emptyset| = 0$ (which holds, since $P = \emptyset$ is false (because we assumed $P \neq \emptyset$)), we obtain $\sum_{A \subseteq P} (-1)^{|A|} = |P = \emptyset|$. Hence, Lemma 3.3.5 is proven.

A different proof of Lemma 3.3.5 can be obtained using the binomial formula and the combinatorial interpretation of binomial coefficients. The main idea of this latter proof is to observe that for each $k \in \{0, 1, \ldots, |P|\}$, exactly $\binom{|P|}{k}$ among the subsets of $P$ have size $k$, and therefore $\sum_{A \subseteq P} (-1)^{|A|}$ can be rewritten as $\sum_{k=0}^{|P|} \binom{|P|}{k} (-1)^k$, which in turn can be simplified (using the binomial formula) to $(1 - 1)^{|P|} = 0^{|P|} =
The following exercise demonstrates an application of Lemma 3.3.5 to (elementary) number theory:

**Exercise 3.3.6.** Let \( \mathbb{N}_+ \) denote the set \( \{1, 2, 3, \ldots\} \). An integer \( n \) is said to be squarefree if it is not divisible by any perfect square apart from 1. (Note that if \( n \) is a positive integer, then \( n \) is squarefree if and only if \( n \) is a product of distinct prime numbers.) We define a map \( \mu : \mathbb{N}_+ \to \{-1, 0, 1\} \) by setting

\[
\mu(n) = \begin{cases} (-1)^{\omega(n)}, & \text{if } n \text{ is squarefree;} \\ 0, & \text{if not} \end{cases}
\]

for each \( n \in \mathbb{N}_+ \), where \( \omega(n) \) denotes the number of distinct prime divisors of \( n \). (For example, \( \mu(6) = (-1)^2 = 1 \), \( \mu(30) = (-1)^3 = -1 \), \( \mu(1) = (-1)^0 = 1 \), and \( \mu(12) = 0 \). The map \( \mu \) is called the (number-theoretical) Möbius function.)

Prove that each \( n \in \mathbb{N}_+ \) satisfies

\[
\sum_{d|n} \mu(d) = [n = 1],
\]

where the sum on the left hand side should be understood as a sum over all positive divisors of \( n \).

**[Hint: Apply Lemma 3.3.5 with \( P \) being the set of all prime factors of \( n \). Relate the subsets of \( P \) to the squarefree divisors of \( n \).]**

**Exercise 3.3.7.** Let \( A \) be a finite set. Let \( A_1, A_2, \ldots, A_m \) be some subsets of \( A \). Prove that

\[
|\{U \subseteq A \mid U \cap A_i \neq \emptyset \text{ for all } i \in \{1, 2, \ldots, m\}\}| \\
\equiv \left| \left\{ J \subseteq \{1, 2, \ldots, m\} \mid \bigcup_{j \in J} A_j = A \right\} \right| \pmod{2}.
\]

**[Hint: Set \( I = \{1, 2, \ldots, m\} \). Compute the double sum**

\[
\sum_{U \subseteq A} \sum_{J \subseteq I} (-1)^{|I|} (-1)^{|J|} \left[ U \subseteq A \setminus \bigcup_{j \in I} A_j \right]
\]

**in two different ways (once by interchanging the summations, and once again by rewriting**

\[
U \subseteq A \setminus \bigcup_{j \in I} A_j
\]

**as \( |J \subseteq \{i \in I \mid U \cap A_i = \emptyset\}| \)). Notice that powers of**

\(-1\) **can be discarded when working modulo 2.**

\]
3.4. Proving the Heinrich-Tittmann formula

In this section, we shall finally prove Theorem 3.2.2. Instead of presenting the
proof as a monolithic piece of work, I shall distribute most of it into a series of easy
lemmas (some of which are of independent interest).

Throughout this section, we consider a simple graph \( G = (V, E) \). The notion of
a “detached pair” is to be understood as in Theorem 3.2.2.

Lemma 3.4.1. Let \( B \) be a subset of \( V \). Then,

\[
\sum_{A \subseteq V: (A, B) \text{ is a detached pair}} (-1)^{|A|} = \begin{cases} 1 & \text{[B is dominating]} \end{cases}.
\]

Proof of Lemma 3.4.1. Let \( B' \) be the set of all vertices \( v \in V \setminus B \) such that at least one
neighbor of \( v \) belongs to \( B \). Then, for each subset \( A \) of \( V \), the following equivalence holds:

\[
((A, B) \text{ is a detached pair}) \iff (A \subseteq V \setminus (B \cup B'))
\]

We shall prove the \( \iff \) and \( \implies \) directions of the equivalence (26) separately:

\( \implies \): Assume that \( (A, B) \) is a detached pair. We must show that \( A \subseteq V \setminus (B \cup B') \).

We know that \( (A, B) \) is a detached pair. By the definition of a “detached pair”, this means
that \( A \) and \( B \) are two disjoint subsets of \( V \) having the property that there exists no edge \( ab \in E \)
satisfying \( a \in A \) and \( b \in B \).

We have \( A \subseteq V \setminus B \) (since \( A \) and \( B \) are disjoint).

We claim that \( A \cap B' = \emptyset \). Indeed, assume the contrary. Thus, the set \( A \cap B' \) is nonempty.
Hence, there exists some \( v \in A \cap B' \). Fix such a \( v \). From \( v \in A \cap B' \subseteq B' \), we conclude that \( v \) is a vertex in \( V \setminus B \) such that at least one neighbor of \( v \) belongs to \( B \) (by the definition of \( B' \)). In
particular, at least one neighbor of \( v \) belongs to \( B \). Let \( w \) be such a neighbor. Then, \( vw \in E \) (since \( w \) is a neighbor of \( v \)). Notice also that \( v \in A \cap B' \subseteq A \) and \( w \in B \). Now, recall that there exists no edge \( ab \in E \) satisfying \( a \in A \) and \( b \in B \). This contradicts the fact that \( vw \) is such an edge
(since \( vw \in E \), \( v \in A \) and \( w \in B \)). This contradiction shows that our assumption was wrong.
Hence, \( A \cap B' = \emptyset \). Thus, \( A \subseteq V \setminus B' \).

Combining \( A \subseteq V \setminus B \) with \( A \subseteq V \setminus B' \), we find

\[
A \subseteq (V \setminus B) \cap (V \setminus B') = V \setminus (B \cup B')
\]

Hence, the \( \implies \) direction of the equivalence (26) is proven.

\( \iff \): Assume that \( A \subseteq V \setminus (B \cup B') \). We must then show that \( (A, B) \) is a detached pair.

First of all, we have \( A \subseteq V \setminus (B \cup B') \subseteq V \setminus B \) (since \( B \cup B' \subseteq B \)). Thus, the sets \( A \) and \( B \) are disjoint.

Next, I claim that there exists no edge \( ab \in E \) satisfying \( a \in A \) and \( b \in B \). Indeed, assume the
contrary. Thus, there exists an edge \( ab \in E \) satisfying \( a \in A \) and \( b \in B \). Consider such an edge.
Then, \( b \) is a neighbor of \( a \) (since \( ab \in E \)) and belongs to \( B \). Hence, at least one neighbor of \( a \)
deals to \( B \) (namely, the neighbor \( b \)). The element \( a \) is a vertex in \( V \setminus B \) (since \( a \in A \subseteq V \setminus B \))
such that at least one neighbor of \( a \) belongs to \( B \). In other words, \( a \) belongs to \( B' \) (by the
definition of \( B' \)). Thus, \( a \in B' \subseteq B \cup B' \). But from \( a \in A \subseteq V \setminus (B \cup B') \), we obtain \( a \notin B \cup B' \).
This contradicts \( a \in B \cup B' \). This contradiction shows that our assumption was wrong. Hence,
we have shown that there exists no edge \( ab \in E \) satisfying \( a \in A \) and \( b \in B \). Since the subsets \( A \)
On the other hand, the following equivalence holds:

\[(V \setminus (B \cup B') = \emptyset) \iff (B \text{ is dominating})\]  \hfill (27)

Now, we can use the equivalence (26) to rewrite the summation sign \[\sum_{A \subseteq V; \text{ (A,B) is a detached pair}}{(A,B)}\] as \[\sum_{A \subseteq V \setminus (B \cup B')}{(A,B)}\]. This latter summation sign can be further simplified to \[\sum_{A \subseteq V \setminus (B \cup B')}{(A,B) \text{ is a detached pair}}\].

(since every subset \(A\) of \(V \setminus (B \cup B')\) is clearly a subset of \(V\) as well). Hence, we can replace the summation sign \[\sum_{A \subseteq V; \text{ (A,B) is a detached pair}}{(A,B)}\] by \[\sum_{A \subseteq V \setminus (B \cup B')}{(A,B)}\]. In particular,

\[\sum_{A \subseteq V; \text{ (A,B) is a detached pair}}{(-1)^{|A|}}\]

\[= \sum_{A \subseteq V \setminus (B \cup B')}{(-1)^{|A|}}\]

\[= [V \setminus (B \cup B') = \emptyset] \quad (\text{by Lemma 3.3.5 applied to } P = V \setminus (B \cup B'))\]

\[= [B \text{ is dominating}]\]

(by the equivalence (27)). This proves Lemma 3.4.1. \(\Box\)

Lemma 3.4.1 has the following consequence:

and \(B\) of \(V\) are disjoint, this shows that \((A, B)\) is a detached pair (by the definition of a “detached pair”). This proves the \(\iff\) direction of the equivalence (26).

Hence, both directions of (26) are proven.

\[\text{Proof of (27).} \text{ Again, we are going to separately prove the } \implies \text{ and } \iff \text{ directions of the equivalence (26).}\]

\[\implies: \text{ Assume that } V \setminus (B \cup B') = \emptyset. \text{ We must show that } B \text{ is dominating.}\]

Let \(v \in V(G) \setminus B\). Thus, \(v \in V(G)\) and \(v \not\in B\). We have \(v \in V(G) = V \subseteq B \cup B'\) (since \(V \setminus (B \cup B') = \emptyset\)). Combined with \(v \not\in B\), we obtain \(v \in (B \cup B') \setminus B \subseteq B'\). According to the definition of \(B'\), this means that \(v\) is a vertex in \(V \setminus B\) such that at least one neighbor of \(v\) belongs to \(B\). In particular, we thus have shown that at least one neighbor of \(v\) belongs to \(B\).

Now, forget that we fixed \(v\). We thus have proven that for every vertex \(v \in V(G) \setminus B\), at least one neighbor of \(v\) belongs to \(B\). In other words, the set \(B\) is dominating (because this is how we defined “dominating sets”). This proves the \(\implies\) direction of the equivalence (27).

\[\iff: \text{ Assume that } B \text{ is dominating. We must prove that } V \setminus (B \cup B') = \emptyset.\]

We know that \(B\) is dominating. In other words, for every vertex \(v \in V(G) \setminus B\), at least one neighbor of \(v\) belongs to \(B\) (because this is what “dominating” means). In other words, for every \(v \in V \setminus B\), at least one neighbor of \(v\) belongs to \(B\) (since \(V \setminus B = V\)).

Now, let \(v \in V \setminus B\) be arbitrary. As we have just seen, we then know that at least one neighbor of \(v\) belongs to \(B\).

Let \(v \in V \setminus B\). Thus, \(v\) is a vertex in \(V \setminus B\) such that at least one neighbor of \(v\) belongs to \(B\). This means that \(v \in B'\) (by the definition of \(B'\)).

Now, forget that we fixed \(v\). We thus have shown that \(v \in B'\) for each \(v \in V \setminus B\). In other words, \(V \setminus (B \cup B') = (V \setminus B) \setminus B' = \emptyset\) (since \(V \setminus B \subseteq B'\)). Thus, the \(\iff\) direction of the equivalence (27) is proven.
Corollary 3.4.2. Let $B$ be a subset of $V$. Then,

$$\sum_{\substack{A \subseteq V; \\ A \neq \emptyset; \\ (A, B) \text{ is a detached pair}}} (-1)^{|A|} = [B \text{ is dominating}] - 1.$$ 

Proof of Corollary 3.4.2. The pair $(\emptyset, B)$ is a detached pair. Hence, the sum

$$\sum_{\substack{A \subseteq V; \\ (A, B) \text{ is a detached pair}}} (-1)^{|A|}$$

has an addend for $A = \emptyset$. If we split off this addend from this sum, we obtain

$$\sum_{\substack{A \subseteq V; \\ (A, B) \text{ is a detached pair}}} (-1)^{|A|} = (-1)^{|\emptyset|} + \sum_{\substack{A \subseteq V; \\ A \neq \emptyset; \\ (A, B) \text{ is a detached pair}}} (-1)^{|A|}.$$

Hence,

$$\sum_{\substack{A \subseteq V; \\ (A, B) \text{ is a detached pair}; \\ A \neq \emptyset}} (-1)^{|A|} = \sum_{\substack{A \subseteq V; \\ (A, B) \text{ is a detached pair}}} (-1)^{|A|} - (-1)^{|\emptyset|} = \sum_{\substack{A \subseteq V; \\ A \neq \emptyset}} (-1)^{|A|} = [B \text{ is dominating}] - 1.$$

Thus,

$$\sum_{\substack{A \subseteq V; \\ A \neq \emptyset; \\ (A, B) \text{ is a detached pair}}} (-1)^{|A|} = \sum_{\substack{A \subseteq V; \\ A \neq \emptyset; \\ (A, B) \text{ is a detached pair}}} (-1)^{|A|} = [B \text{ is dominating}] - 1.$$

This proves Corollary 3.4.2.

Lemma 3.4.3. Let $A$ and $B$ be two subsets of $V$. Then, $(A, B)$ is a detached pair if and only if $(B, A)$ is a detached pair.

Proof. The sets $\emptyset$ and $B$ are two disjoint subsets of $V$ (disjoint because $\emptyset \cap B = \emptyset$) having the property that there exists no edge $ab \in E$ satisfying $a \in \emptyset$ and $b \in B$ (this is vacuously true, since there exists no $a \in \emptyset$). In other words, $(\emptyset, B)$ is a detached pair (by the definition of a “detached pair”).
Proof of Lemma 3.4.3. We have the following chain of logical equivalences:

\[(B, A) \text{ is a detached pair} \quad \iff \quad (B \text{ and } A \text{ are two disjoint subsets of } V \text{ having the property that there exists no edge } ab \in E \text{ satisfying } a \in B \text{ and } b \in A)\]

(by the definition of “detached pair”)

\[(B \text{ and } A \text{ are two disjoint subsets of } V \text{ having the property that there exists no edge } ba \in E \text{ satisfying } b \in B \text{ and } a \in A)\]

(here, we renamed \(a\) and \(b\) as \(b\) and \(a\), respectively)

\[(A \text{ and } B \text{ are two disjoint subsets of } V \text{ having the property that there exists no edge } ba \in E \text{ satisfying } a \in A \text{ and } b \in B)\]

(since \(B\) and \(A\) are disjoint if and only if \(A\) and \(B\) are disjoint)

\[(A \text{ and } B \text{ are two disjoint subsets of } V \text{ having the property that there exists no edge } ab \in E \text{ satisfying } a \in A \text{ and } b \in B)\]

(since \(ba = ab\))

\[\iff ((A, B) \text{ is a detached pair})\]

(by the definition of “detached pair”).

This proves Lemma 3.4.3. \(\square\)

Next comes another general lemma about cardinalities of sets:

Lemma 3.4.4. Let \(S\) be a finite set. Let \(\sigma : S \to S\) be a map such that \(\sigma \circ \sigma = \text{id}_S\). (Such a map is called an involution on \(S\).)

Let \(F = \{i \in S \mid \sigma(i) = i\}\). (The elements of \(F\) are known as the fixed points of \(\sigma\).) Then, \(|F| \equiv |S| \mod 2\).

Proof of Lemma 3.4.4. In a nutshell, the proof of Lemma 3.4.4 is very simple: We have \(\sigma \circ \sigma = \text{id}_S\); in other words, we have \(\sigma(\sigma(i)) = i\) for each \(i \in S\). Each \(i \in S \setminus F\) satisfies \(\sigma(i) \neq i\). Thus, we can assign to each element \(i \in S \setminus F\) the two-element subset \(\{i, \sigma(i)\}\) \(\subseteq S\). This assignment has the property that the two-element subset assigned to \(\sigma(i)\) is the same as the one assigned to \(i\) (since \(\{\sigma(i), \sigma(\sigma(i))\} = \{\sigma(i), i\}\)). Thus, each two-element subset that gets assigned at all is assigned to exactly two elements of \(S \setminus F\) (namely, the subset assigned to \(i\) is assigned to \(i\) and \(\sigma(i)\), and to no other elements of \(S \setminus F\)). As a consequence, the elements of \(S \setminus F\) are paired up (each pair consisting of two elements to which the same subset is assigned). Correspondingly, \(|S \setminus F|\) is even. Thus, \(|S| - |F| = |S \setminus F|\) is even, so that \(|F| \equiv |S| \mod 2\).

If you found this insufficiently rigorous (or unclear), here is a rigorous version of
this proof: For each $i \in S \setminus F$, we have $\{i, \sigma(i)\} \in \mathcal{P}_2(S)$  In other words, for each $i \in S \setminus F$, there exists a unique $K \in \mathcal{P}_2(S)$ satisfying $\{i, \sigma(i)\} = K$ (namely, $K = \{i, \sigma(i)\}$).

But

$$|S \setminus F| = (\text{the number of } i \in S \setminus F) = \sum_{K \in \mathcal{P}_2(S)} \text{(the number of } i \in S \setminus F \text{ satisfying } \{i, \sigma(i)\} = K) \quad (28)$$

(because for each $i \in S \setminus F$, there exists a unique $K \in \mathcal{P}_2(S)$ satisfying $\{i, \sigma(i)\} = K$).

On the other hand, for each $K \in \mathcal{P}_2(S)$, we have

$$\text{(the number of } i \in S \setminus F \text{ satisfying } \{i, \sigma(i)\} = K) \equiv 0 \mod 2 \quad (29)$$

\[\text{Proof.} \quad \text{Let } i \in S \setminus F. \text{ Thus, } i \in S \text{ and } i \notin F. \text{ If we had } \sigma(i) = i, \text{ then we would have } i \in F \text{ (by the definition of } F), \text{ which would contradict } i \notin F. \text{ Hence, we do not have } \sigma(i) = i. \text{ Thus, we have } \sigma(i) \neq i. \text{ Hence, } \{i, \sigma(i)\} \text{ is a 2-element set. Since } \{i, \sigma(i)\} \subseteq S \text{ (because both } i \text{ and } \sigma(i) \text{ are elements of } S), \text{ this shows that } \{i, \sigma(i)\} \text{ is a 2-element subset of } S. \text{ In other words, } \{i, \sigma(i)\} \in \mathcal{P}_2(S), \text{ qed.}

\[\text{Proof of } (29) \text{. Let } K \in \mathcal{P}_2(S). \text{ If there exists no } i \in S \setminus F \text{ satisfying } \{i, \sigma(i)\} = K, \text{ then } (29) \text{ is true (because in this case, we have } \text{(the number of } i \in S \setminus F \text{ satisfying } \{i, \sigma(i)\} = K) = 0 \equiv 0 \mod 2. \text{ Hence, we WLOG assume that there does exist some } i \in S \setminus F \text{ satisfying } \{i, \sigma(i)\} = K. \text{ Fix such an } i, \text{ and denote it by } j. \text{ Thus, } j \text{ is an element of } S \setminus F \text{ and satisfies } \{j, \sigma(j)\} = K.

\text{Set } k = \sigma(j). \text{ Thus, } \sigma(k) = \sigma(\sigma(j)) = (\sigma \circ \sigma)(j) = \text{id}_S(j) = j \text{ and therefore } \left\{k, \sigma(k)\right\} = \left\{j, \sigma(j)\right\} = K. \text{ Furthermore, from } j \in S \setminus F, \text{ we obtain } j \in S \text{ and } j \notin F. \text{ If we had } \sigma(j) = j, \text{ then we would have } j \in F \text{ (by the definition of } F), \text{ which would contradict } j \notin F. \text{ Hence, we do not have } \sigma(j) = j. \text{ Thus, we have } \sigma(j) \neq j. \text{ Hence, } j \neq \sigma(j) = k. \text{ In other words, } j \text{ and } k \text{ are distinct.}

\text{If } i \in S \setminus F \text{ satisfies } \{i, \sigma(i)\} = K, \text{ then } i \text{ must be either } j \text{ or } k \text{ (because } i \in \{i, \sigma(i)\} = K = \left\{j, \sigma(j)\right\} = \left\{j, k\right\}.

\text{If we had } k \in F, \text{ then we would have } \sigma(k) = k \text{ (by the definition of } F), \text{ which would contradict } \sigma(k) = j \neq k. \text{ Hence, we do not have } k \in F. \text{ Thus, } k \notin F. \text{ Combining this with } k \in S, \text{ we find } k \in S \setminus F. \text{ Hence, } j \text{ and } k \text{ are two elements of } S \setminus F. \text{ Furthermore, } j \text{ and } k \text{ are two } i \in S \setminus F \text{ satisfying } \{i, \sigma(i)\} = K \text{ (since } j \text{ is an element of } S \setminus F \text{ satisfying } \{j, \sigma(j)\} = K, \text{ and since } k \text{ is an element of } S \setminus F \text{ satisfying } \{k, \sigma(k)\} = K). \text{ Furthermore, } j \text{ and } k \text{ are the } \text{only} \text{ such } i \text{ (because we have shown that if } i \in S \setminus F \text{ satisfies } \{i, \sigma(i)\} = K, \text{ then } i \text{ must be either } j \text{ or } k). \text{ Therefore, we conclude that there are exactly two } i \in S \setminus F \text{ that satisfy } \{i, \sigma(i)\} = K \text{ (namely, } j \text{ and } k \text{ (because } j \text{ and } k \text{ are distinct)). Hence, } (\text{the number of } i \in S \setminus F \text{ satisfying } \{i, \sigma(i)\} = K) = 2 \equiv 0 \mod 2. \text{ This completes the proof of } (29).
Now, (28) becomes
\[ |S \setminus F| = \sum_{K \in \mathcal{P}_2(S)} \text{(the number of } i \in S \setminus F \text{ satisfying } \{i, \sigma(i)\} = K) \equiv 0 \pmod{2} \]
\[ \equiv \sum_{K \in \mathcal{P}_2(S)} 0 = 0 \pmod{2}. \]

Since \( |S \setminus F| = |S| - |F| \) (because \( F \subseteq S \)), this rewrites as \( |S| - |F| \equiv 0 \pmod{2} \). In other words, \( |S| \equiv |F| \pmod{2} \). This proves Lemma 3.4.4. \( \square \)

Here is a particular case of Lemma 3.4.4:

**Corollary 3.4.5.** Let \( S \) be a finite set. Let \( \sigma : S \to S \) be a map such that \( \sigma \circ \sigma = \text{id}_S \).
Assume that each \( i \in S \) satisfies \( \sigma(i) \neq i \). Then, \( |S| \) is even.

**Proof of Corollary 3.4.5.** Let \( F = \{ i \in S | \sigma(i) = i \} \). Lemma 3.4.4 yields \( |F| \equiv |S| \pmod{2} \).

But each \( i \in S \) satisfies \( \sigma(i) \neq i \). In other words, no \( i \in S \) satisfies \( \sigma(i) = i \). In other words, \( \{ i \in S | \sigma(i) = i \} = \emptyset \). Thus, \( F = \{ i \in S | \sigma(i) = i \} = \emptyset \). Hence, \( |F| = |\emptyset| = 0 \). But from \( |F| \equiv |S| \pmod{2} \), we obtain \( |S| \equiv |F| = 0 \pmod{2} \). In other words, \( |S| \) is even. Hence, Corollary 3.4.5 is proven. \( \square \)

Now, it is time to get rid of part (a) of Theorem 3.2.2.

**Lemma 3.4.6.** Let \( \alpha \) and \( \beta \) be defined as in Theorem 3.2.2. Then, \( \alpha \) and \( \beta \) are even.

**Proof of Lemma 3.4.6.** Let us first show that \( \beta \) is even.

Indeed, let \( S \) be the set of all detached pairs \( (A, B) \) for which both numbers \( |A| \) and \( |B| \) are odd. Then, the definition of \( \beta \) can be rewritten as \( \beta = |S| \). Clearly, \( S \) is a finite set.

For every \( (A, B) \in S \), we have \( (B, A) \in S \). \( \square \) Hence, we can define a map \( \sigma : S \to S \) by setting
\[ \sigma(A, B) = (B, A) \quad \text{for all } (A, B) \in S. \]

Consider this \( \sigma \). It is easy to see that \( \sigma \circ \sigma = \text{id}_S \). \( \square \)

**Proof.** Let \( (A, B) \in S \). Thus, \( (A, B) \) is a detached pair for which both numbers \( |A| \) and \( |B| \) are odd (by the definition of \( S \)). Hence, \( A \) and \( B \) are two subsets of \( V \) (since \( (A, B) \) is a detached pair). But Lemma 3.4.3 shows that \( (A, B) \) is a detached pair if and only if \( (B, A) \) is a detached pair. Hence, \( (B, A) \) is a detached pair (since \( (A, B) \) is a detached pair). Furthermore, both numbers \( |B| \) and \( |A| \) are odd. Thus, \( (B, A) \) is a detached pair for which both numbers \( |B| \) and \( |A| \) are odd. In other words, \( (B, A) \in S \) (by the definition of \( S \)), qed.

**Proof.** For every \( (A, B) \in S \), we have
\[ (\sigma \circ \sigma)(A, B) = \sigma(\sigma(A, B)) = \sigma(B, A) = (A, B) \]
Each \( i \in S \) satisfies \( \sigma (i) \neq i \). Hence, Corollary 3.4.5 shows that \( |S| \) is even. In other words, \( \beta \) is even (since \( \beta = |S| \)).

The same argument (with the obvious change\(^{42}\)) shows that \( \alpha \) is even. This completes the proof of Lemma 3.4.6. \( \square \)

We will spend the rest of this section manipulating sums in various artful ways. These manipulations will culminate in a proof of Theorem 3.2.2(b); they also provide examples of techniques that are useful throughout mathematics.

**Lemma 3.4.7.** We have
\[
\sum_{(A,B) \text{ is a detached pair; } \; A \neq \emptyset; \; B \neq \emptyset} \left( (-1)^{|A|} + (-1)^{|B|} \right) = 2 \sum_{(A,B) \text{ is a detached pair; } \; A \neq \emptyset; \; B \neq \emptyset} (-1)^{|A|}.
\]

**Proof of Lemma 3.4.7** First of all,
\[
\sum_{(A,B) \text{ is a detached pair; } \; A \neq \emptyset; \; B \neq \emptyset} \left( (-1)^{|A|} + (-1)^{|B|} \right) = \sum_{(A,B) \text{ is a detached pair; } \; A \neq \emptyset; \; B \neq \emptyset} (-1)^{|A|} + \sum_{(A,B) \text{ is a detached pair; } \; A \neq \emptyset; \; B \neq \emptyset} (-1)^{|B|}. \tag{30}
\]

(by the definition of \( \sigma \)). In other words, the map \( \sigma \circ \sigma \) sends each \( (A,B) \in S \) to itself. Hence, \( \sigma \circ \sigma = \text{id}_S \).

\(^{41}\)Proof. Let \( i \in S \). We must prove that \( \sigma (i) \neq i \).

We have \( i \in S \). In other words, \( i \) is a detached pair \( (A,B) \) for which both numbers \( |A| \) and \( |B| \) are odd (by the definition of \( S \)). Consider this \( (A,B) \). The number \( |B| \) is odd and is a nonnegative integer. Hence, this number \( |B| \) is positive (because any odd nonnegative integer is positive). Thus, the set \( B \) is nonempty. In other words, \( B \neq \emptyset \).

But \( (A,B) \) is a detached pair. In other words, \( A \) and \( B \) are two disjoint subsets of \( V \) having the property that there exists no edge \( ab \in E \) satisfying \( a \in A \) and \( b \in B \) (by the definition of a “detached pair”). Now, \( A \cap B = \emptyset \) (since \( A \) and \( B \) are disjoint). If we had \( A = B \), then we would have \( A \cap B = B \cap B = B \neq \emptyset \), which would contradict \( A \cap B = \emptyset \). Hence, we cannot have \( A = B \). Thus, \( A \neq B \).

If we had \( (A,B) = (B,A) \), then we would have \( A = B \), which would contradict \( A \neq B \). Hence, we cannot have \( (A,B) = (B,A) \). Therefore, \( (A,B) \neq (B,A) \).

But \( i = (A,B) \), and thus \( \sigma (i) = \sigma (A,B) = (B,A) \) (by the definition of \( \sigma \)). Now, \( i = (A,B) \neq (B,A) = \sigma (i) \). In other words, \( \sigma (i) \neq i \), qed.

\(^{42}\)For example, “odd” has to be replaced by “even and positive”.

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Let us now rewrite the second sum on the right hand side of this equation:

\[
\sum_{(A,B) \text{ is a detached pair; } A \neq \emptyset; B \neq \emptyset} (-1)^{|B|} = \sum_{(B,A) \text{ is a detached pair; } B \neq \emptyset; A \neq \emptyset} (-1)^{|A|}
\]

(here, we have renamed the summation index \((A, B)\) as \((B, A)\))

\[
\sum_{(B,A) \text{ is a detached pair; } A \neq \emptyset; B \neq \emptyset} (-1)^{|A|} = \sum_{(A,B) \text{ is a detached pair; } A \neq \emptyset; B \neq \emptyset} (-1)^{|A|}
\]

(because the condition “\((B, A)\) is a detached pair” under the summation sign is equivalent to the condition “\((A, B)\) is a detached pair” (by Lemma \ref{3.4.3}). Hence, \eqref{30} becomes

\[
\sum_{(A,B) \text{ is a detached pair; } A \neq \emptyset; B \neq \emptyset} \left((-1)^{|A|} + (-1)^{|B|}\right)
\]

\[
= \sum_{(A,B) \text{ is a detached pair; } A \neq \emptyset; B \neq \emptyset} (-1)^{|A|} + \sum_{(A,B) \text{ is a detached pair; } A \neq \emptyset; B \neq \emptyset} (-1)^{|B|}
\]

\[
= \sum_{(A,B) \text{ is a detached pair; } A \neq \emptyset; B \neq \emptyset} (-1)^{|A|} + \sum_{(A,B) \text{ is a detached pair; } A \neq \emptyset; B \neq \emptyset} (-1)^{|A|}
\]

\[
= 2 \sum_{(A,B) \text{ is a detached pair; } A \neq \emptyset; B \neq \emptyset} (-1)^{|A|}.
\]

This proves Lemma \ref{3.4.7}.

\[\square\]

**Lemma 3.4.8.** Let \(n = |V|\). Assume that \(n > 0\). Let \(\delta\) be the number of dominating sets of \(G\). Then,

\[
\sum_{(A,B) \text{ is a detached pair; } A \neq \emptyset; B \neq \emptyset} (-1)^{|A|} = \delta - (2^n - 1).
\]

**Proof of Lemma 3.4.8** We first observe that the set \(V\) has \(2^{|V|}\) subsets. In other words, the set \(V\) has \(2^n\) subsets (since \(|V| = n\)). Thus, the sum \(\sum_{B \subseteq V} 1\) has \(2^n\) addends. Since
each of these addends equals 1, we conclude that this sum equals $2^n \cdot 1 = 2^n$. In other words,
\[ \sum_{B \subseteq V} 1 = 2^n. \] (31)

On the other hand, each subset $B$ of $V$ is either dominating or not. Hence,
\[
\sum_{B \subseteq V} [B \text{ is dominating}] = \sum_{B \subseteq V; B \text{ is dominating}} 1 + \sum_{B \subseteq V; B \text{ is not dominating}} 0 = \sum_{B \subseteq V; B \text{ is dominating}} 1.
\]

But the number of dominating sets of $G$ is $\delta$. In other words, the number of dominating subsets $B \subseteq V$ is $\delta$. Hence, the sum $\sum_{B \subseteq V; B \text{ is dominating}} 1$ has $\delta$ addends. Since each of these addends equals 1, we thus see that this sum equals $\delta \cdot 1 = \delta$. In other words,
\[ \sum_{B \subseteq V; B \text{ is dominating}} 1 = \delta. \]

Hence,
\[ \sum_{B \subseteq V} [B \text{ is dominating}] = \sum_{B \subseteq V; B \text{ is dominating}} 1 = \delta. \] (32)

The subset $\emptyset$ of $V$ is not dominating. Hence, $[\emptyset \text{ is dominating}] = 0$.

Each detached pair $(A, B)$ consists of two subsets $A$ and $B$ of $V$ (by the definition

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43Proof. Assume the contrary. Thus, the subset $\emptyset$ of $V$ is dominating.

The set $V$ is nonempty (since $|V| = n > 0$). Thus, there exists some $q \in V$. Consider this $q$.

But the set $\emptyset$ is dominating. In other words, for every vertex $v \in V (G) \setminus \emptyset$, at least one neighbor of $v$ belongs to $\emptyset$. Applying this to $v = q$, we conclude that at least one neighbor of $q$ belongs to $\emptyset$ (since $q \in V = V (G) = V (G) \setminus \emptyset$). Hence, at least some object belongs to $\emptyset$. In other words, $\emptyset$ is nonempty. This is absurd. This contradiction shows that our assumption is false, qed.
of a “detached pair”). Hence,

\[
\sum_{(A, B) \text{ is a detached pair}; A \neq \emptyset; B \neq \emptyset} (-1)^{|A|} = \sum_{B \subseteq V; B \neq \emptyset} \sum_{A \subseteq V; A \neq \emptyset} (-1)^{|A|}
\]

\[
= \sum_{B \subseteq V; B \neq \emptyset} (-1)^{|A|} = |B \text{ is dominating}|-1 \quad \text{(by Corollary 3.4.2)}
\]

\[
= \sum_{B \subseteq V; B \neq \emptyset} (\lfloor B \text{ is dominating} \rfloor - 1).
\]

But the sum \( \sum_{B \subseteq V} (\lfloor B \text{ is dominating} \rfloor - 1) \) has an addend for \( B = \emptyset \). If we split off this addend, we find

\[
\sum_{B \subseteq V} (\lfloor B \text{ is dominating} \rfloor - 1) = \sum_{B \subseteq V; B \neq \emptyset} (\lfloor B \text{ is dominating} \rfloor - 1)
\]

\[
= -1 + \sum_{B \subseteq V; B \neq \emptyset} (\lfloor B \text{ is dominating} \rfloor - 1).
\]

Thus,

\[
\sum_{B \subseteq V; B \neq \emptyset} (\lfloor B \text{ is dominating} \rfloor - 1) = \sum_{B \subseteq V} (\lfloor B \text{ is dominating} \rfloor - 1) + 1
\]

\[
= \sum_{B \subseteq V} \lfloor B \text{ is dominating} \rfloor - \sum_{B \subseteq V} 1
\]

\[
= \sum_{B \subseteq V} \lfloor B \text{ is dominating} \rfloor - \sum_{B \subseteq V} 1 + 1 = \delta - 2^n + 1.
\]

Thus, (33) becomes

\[
\sum_{(A, B) \text{ is a detached pair}; A \neq \emptyset; B \neq \emptyset} (-1)^{|A|} = \sum_{B \subseteq V; B \neq \emptyset} (\lfloor B \text{ is dominating} \rfloor - 1) = \delta - 2^n + 1 = \delta - (2^n - 1).
\]

This proves Lemma 3.4.8
Let us now finally step to the proof of Theorem 3.2.2.

**Proof of Theorem 3.2.2** (a) Theorem 3.2.2 (a) is precisely Lemma 3.4.6, which has already been proven.

(b) Let $\delta$ be the number of dominating sets of $G$.

We shall compute the sum $\sum_{(A,B) \text{ is a detached pair}; \ A \neq \emptyset; \ B \neq \emptyset} \left((-1)^{|A|} + (-1)^{|B|}\right)$ in two different ways, and then compare the results.

The first way relies on Lemma 3.4.7 and on Lemma 3.4.8: From Lemma 3.4.7, we obtain

$$\sum_{(A,B) \text{ is a detached pair}; \ A \neq \emptyset; \ B \neq \emptyset} \left((-1)^{|A|} + (-1)^{|B|}\right) = 2 \sum_{(A,B) \text{ is a detached pair}; \ A \neq \emptyset; \ B \neq \emptyset} (-1)^{|A|} = \delta - (2^n - 1) \quad \text{(by Lemma 3.4.8)}$$

$$= 2 \left(\delta - (2^n - 1)\right). \quad (34)$$

Now, let us try another way. We observe that each detached pair $(A,B)$ satisfies one and only one of the following four conditions:

1. The number $|A|$ is even, and the number $|B|$ is even.
2. The number $|A|$ is even, and the number $|B|$ is odd.
3. The number $|A|$ is odd, and the number $|B|$ is even.
4. The number $|A|$ is odd, and the number $|B|$ is odd.

Accordingly, the sum on the left hand side of (34) can be split into four smaller
sums:

\[
\sum_{(A,B) \text{ is a detached pair}; \ A \neq \emptyset; \ B \neq \emptyset} \left( (-1)^{|A|} + (-1)^{|B|} \right)
\]

\[
= \sum_{(A,B) \text{ is a detached pair}; \ A \neq \emptyset; \ B \neq \emptyset; \ |A| \text{ is even}; \ |B| \text{ is even}} \left( \frac{(-1)^{|A|}}{=1} + \frac{(-1)^{|B|}}{=1} \right) \quad \text{(since } |A| \text{ is even) \ (since } |B| \text{ is even)}
\]

\[
+ \sum_{(A,B) \text{ is a detached pair}; \ A \neq \emptyset; \ B \neq \emptyset; \ |A| \text{ is even}; \ |B| \text{ is odd}} \left( \frac{(-1)^{|A|}}{=1} + \frac{(-1)^{|B|}}{=-1} \right) \quad \text{(since } |A| \text{ is even) \ (since } |B| \text{ is odd)}
\]

\[
+ \sum_{(A,B) \text{ is a detached pair}; \ A \neq \emptyset; \ B \neq \emptyset; \ |A| \text{ is odd}; \ |B| \text{ is even}} \left( \frac{(-1)^{|A|}}{=-1} + \frac{(-1)^{|B|}}{=1} \right) \quad \text{(since } |A| \text{ is odd) \ (since } |B| \text{ is even)}
\]

\[
+ \sum_{(A,B) \text{ is a detached pair}; \ A \neq \emptyset; \ B \neq \emptyset; \ |A| \text{ is odd}; \ |B| \text{ is odd}} \left( \frac{(-1)^{|A|}}{=-1} + \frac{(-1)^{|B|}}{=-1} \right) \quad \text{(since } |A| \text{ is odd) \ (since } |B| \text{ is odd)}
\]

\[
= \sum_{(A,B) \text{ is a detached pair}; \ A \neq \emptyset; \ B \neq \emptyset; \ |A| \text{ is even}; \ |B| \text{ is even}} \left( 1 + 1 \right) + \sum_{(A,B) \text{ is a detached pair}; \ A \neq \emptyset; \ B \neq \emptyset; \ |A| \text{ is odd}; \ |B| \text{ is odd}} \left( 1 + (-1) \right)
\]

\[
+ \sum_{(A,B) \text{ is a detached pair}; \ A \neq \emptyset; \ B \neq \emptyset; \ |A| \text{ is even}; \ |B| \text{ is odd}} \left( (-1) + 1 \right) + \sum_{(A,B) \text{ is a detached pair}; \ A \neq \emptyset; \ B \neq \emptyset; \ |A| \text{ is odd}; \ |B| \text{ is even}} \left( (-1) + (-1) \right)
\]

\[
= 2 + \sum_{(A,B) \text{ is a detached pair}; \ A \neq \emptyset; \ B \neq \emptyset; \ |A| \text{ is even}; \ |B| \text{ is even}} 0 + \sum_{(A,B) \text{ is a detached pair}; \ A \neq \emptyset; \ B \neq \emptyset; \ |A| \text{ is odd}; \ |B| \text{ is odd}} \left( -2 \right)
\]
\[
\sum_{(A, B) \text{ is a detached pair; } \begin{array}{c}
A \neq \emptyset; B \neq \emptyset; \\
|A| \text{ is even; } |B| \text{ is even}
\end{array}} 2 + \sum_{(A, B) \text{ is a detached pair; } \begin{array}{c}
A \neq \emptyset; B \neq \emptyset; \\
|A| \text{ is odd; } |B| \text{ is odd}
\end{array}} (-2). \tag{35}
\]

We shall now analyze the two sums on the right hand side of (35) more closely. Let us begin with the first sum. For any subset \(A\) of \(V\), the condition \(|A| = \emptyset\) is equivalent to the condition \(|A| \text{ is positive}\) (because clearly, the finite set \(A\) is distinct from \(\emptyset\) if and only if its size \(|A|\) is positive). Likewise, for any subset \(B\) of \(V\), the condition \(B \neq \emptyset\) is equivalent to the condition \(|B| \text{ is positive}\). Combining the preceding two sentences, we conclude that the conditions \(|A| = \emptyset\) and \(B \neq \emptyset\) under the summation sign \(\sum\) are equivalent to the conditions \(|A| \text{ is positive} \) and \(|B| \text{ is positive}\), respectively. Hence, we can rewrite this summation sign as \(\sum\). Thus,

\[
\sum_{(A, B) \text{ is a detached pair; } \begin{array}{c}
A \neq \emptyset; B \neq \emptyset; \\
|A| \text{ is even; } |B| \text{ is even}
\end{array}} 2 = \sum_{(A, B) \text{ is a detached pair; } \begin{array}{c}
A \neq \emptyset; B \neq \emptyset; \\
|A| \text{ is even; } |B| \text{ is even}
\end{array}} 2 = \sum_{(A, B) \text{ is a detached pair; } \begin{array}{c}
A \neq \emptyset; B \neq \emptyset; \\
|A| \text{ is even and positive; } |B| \text{ is even and positive}
\end{array}} 2. \tag{36}
\]

But the sum \(\sum_{(A, B) \text{ is a detached pair; both numbers } |A| \text{ and } |B| \text{ are even and positive}} 2\) has exactly \(\alpha\) terms (since the number of all detached pairs \((A, B)\) for which both numbers \(|A|\) and \(|B|\) are even and positive is \(\alpha\)), and thus equals \(\alpha \cdot 2\) (since each of its \(\alpha\) terms equals 2). Thus, \(\sum_{(A, B) \text{ is a detached pair; both numbers } |A| \text{ and } |B| \text{ are even and positive}} 2 = \alpha \cdot 2 = 2\alpha\). Hence, (36) becomes

\[
\sum_{(A, B) \text{ is a detached pair; both numbers } |A| \text{ and } |B| \text{ are even and positive}} 2 = \sum_{(A, B) \text{ is a detached pair; both numbers } |A| \text{ and } |B| \text{ are even and positive}} 2 = 2\alpha. \tag{37}
\]

Let us now attack the second sum. We have

\[
\sum_{(A, B) \text{ is a detached pair; } \begin{array}{c}
A \neq \emptyset; B \neq \emptyset; \\
|A| \text{ is odd; } |B| \text{ is odd}
\end{array}} (-2) = \sum_{(A, B) \text{ is a detached pair; both numbers } |A| \text{ and } |B| \text{ are odd and positive}} (-2). \tag{38}
\]

(Indeed, this can be proven in the same way as we proved (36), except that we must replace every word “even” by “odd”, and every appearance of 2 by −2.)
But if \((A, B)\) is a detached pair, then the condition “both numbers \(|A|\) and \(|B|\) are odd and positive” is equivalent to the simpler condition “both numbers \(|A|\) and \(|B|\) are odd”. Hence, the summation sign
\[
\sum_{(A, B) \text{ is a detached pair; both numbers } |A| \text{ and } |B| \text{ are odd}} (-2)
\]
can be rewritten as
\[
\sum_{(A, B) \text{ is a detached pair; both numbers } |A| \text{ and } |B| \text{ are odd}} (-2) = \sum_{(A, B) \text{ is a detached pair; both numbers } |A| \text{ and } |B| \text{ are odd}} (-2) .
\]
But the sum
\[
\sum_{(A, B) \text{ is a detached pair; both numbers } |A| \text{ and } |B| \text{ are odd}} (-2)
\]
of all detached pairs \((A, B)\) for which both numbers \(|A|\) and \(|B|\) are odd is \(\beta\), and thus equals \(\beta \cdot (-2)\) (since each of its \(\beta\) terms equals \(-2\)). Thus,
\[
\sum_{(A, B) \text{ is a detached pair; both numbers } |A| \text{ and } |B| \text{ are odd}} (-2) = \beta \cdot (-2) = -2\beta .
\]
Hence, (38) becomes
\[
\sum_{(A, B) \text{ is a detached pair; both numbers } |A| \text{ and } |B| \text{ are odd}} (-2) = \sum_{(A, B) \text{ is a detached pair; both numbers } |A| \text{ and } |B| \text{ are odd}} (-2) = -2\beta .
\]
Now, (35) becomes
\[
\sum_{(A, B) \text{ is a detached pair; } A \neq \emptyset; B \neq \emptyset; |A| \text{ is even; } |B| \text{ is even}} \left(-1\right)^{|A|} \left(-1\right)^{|B|}
= \sum_{(A, B) \text{ is a detached pair; } A \neq \emptyset; B \neq \emptyset; |A| \text{ is even; } |B| \text{ is even}} 2 + \sum_{(A, B) \text{ is a detached pair; } A \neq \emptyset; B \neq \emptyset; |A| \text{ is odd; } |B| \text{ is odd}} (-2)
\]
\[
= 2\alpha + (-2\beta) = 2(\alpha - \beta).
\]

\^[44]Proof. Let \((A, B)\) be a detached pair. Thus, \(A\) and \(B\) are two subsets of \(V\) (by the definition of “detached pair”), and thus are two finite sets. Hence, \(|A|\) and \(|B|\) are nonnegative integers. Therefore, if \(|A|\) and \(|B|\) are odd, then \(|A|\) and \(|B|\) are automatically positive (because if a nonnegative integer is odd, then it is automatically positive). Therefore, the condition “both numbers \(|A|\) and \(|B|\) are odd and positive” is equivalent to the simpler condition “both numbers \(|A|\) and \(|B|\) are odd”. Qed.
Comparing this with (34), we find
\[ \frac{2}{2} \left( \delta - (2^n - 1) \right) = 2 \left( \alpha - \beta \right). \]
Cancelling 2 from this equality, we obtain \( \delta - (2^n - 1) = \alpha - \beta \). Solving this equation for \( \delta \), we find \( \delta = 2^n - 1 + \alpha - \beta \).

Now, recall that \( \delta \) is the number of dominating sets of \( G \). Hence, the number of dominating sets of \( G \) is \( \delta = 2^n - 1 + \alpha - \beta \). This proves Theorem 3.2.2(b). \( \square \)

3.5. Distances in graphs; first proof of Proposition 3.1.5

TODO 3.5.1. Write this proof up. Note that it has several steps: First, splitting into connected components, and then (WLOG assuming \( G \) to be connected) the actual argument using distances.

3.6. Independent sets; second proof of Proposition 3.1.5

Now, let us prove Proposition 3.1.5 using the concept of independent sets. This concept (which is actually more fundamental than that of dominating sets) is easily defined:

**Definition 3.6.1.** Let \( G = (V, E) \) be a simple graph. A subset \( S \) of \( V \) is said to be independent (with respect to \( G \)) if and only if no two distinct elements of \( S \) are adjacent.

An independent set of \( G \) means a subset of \( V \) that is independent (with respect to \( G \)).

Independent sets are often called stable sets.

If \( G = (V, E) \) is a simple graph, then each subset \( S \) of \( V \) that has size \( |S| \leq 1 \) is automatically independent (since it has no two distinct elements). A subset \( S \) of \( V \) that has size \( |S| = 2 \) is independent if and only if its two elements are non-adjacent. A subset \( S \) of \( V \) that has size 3 is the same as an anti-triangle of \( G \), as defined in Exercise 2.4.6 above. Here is a concrete example:

**Example 3.6.2.** Let \( V, E \) and \( G \) be as in Example 2.4.2(c). Then, the subset \( \{2, 4, 6\} \) of \( V \) is independent (since no two distinct elements of this subset are adjacent), whereas the subset \( \{1, 3, 5\} \) is not independent (since the two distinct elements 1 and 3 of this subset are adjacent).

TODO 3.6.3. explain that independent sets are induced subgraphs isomorphic to the empty graph.

The following property of independent set is almost trivial:
Lemma 3.6.4. Let $G = (V, E)$ be a simple graph. Let $S$ be an independent set of $G$. Let $v \in V$. Assume that no neighbor of $v$ belongs to $S$. Then, $S \cup \{v\}$ also is an independent set of $G$.

Proof of Lemma 3.6.4. We have $V(G) = V$ (since $G = (V, E)$). Furthermore, recall that $S$ is an independent set of $G$. In other words, the subset $S$ of $V$ is independent. In other words, no two distinct elements of $S$ are adjacent (by the definition of “independent”).

Clearly, $S \cup \{v\}$ is a subset of $V$ (since $S \subseteq V$ and $v \in V$).

Assume (for the sake of contradiction) that some two distinct elements of $S \cup \{v\}$ are adjacent. Fix two such elements, and denote them by $p$ and $q$. Hence, $p$ and $q$ are two distinct elements of $S \cup \{v\}$, and are adjacent. We have $p \neq q$ (since $p$ and $q$ are distinct). Hence, at least one of the elements $p$ and $q$ must be distinct from $v$ (because otherwise, both $p$ and $q$ would be equal to $v$, which would yield that $p = q$, but this would contradict $p \neq q$). In other words, $p$ is distinct from $v$, or $q$ is distinct from $v$ (or both). Hence, we WLOG assume that $p$ is distinct from $v$ (since otherwise, we can simply switch $p$ with $q$). Then, $p \neq v$. Combining this with $p \in S \cup \{v\}$, we obtain $p \in (S \cup \{v\}) \setminus \{v\} \subseteq S$. Hence, $q = v$.

Now, $p$ is a neighbor of $q$ (since $p$ and $q$ are adjacent). In other words, $p$ is a neighbor of $v$ (since $q = v$). Hence, at least one neighbor of $v$ belongs to $S$ (namely, the neighbor $p$). This contradicts the fact that no neighbor of $v$ belongs to $S$.

This contradiction proves that our assumption (that some two distinct elements of $S \cup \{v\}$ are adjacent) was false. Hence, no two distinct elements of $S \cup \{v\}$ are adjacent. In other words, the subset $S \cup \{v\}$ of $V$ is independent (by the definition of “independent”). In other words, $S \cup \{v\}$ is an independent set of $G$. This proves Lemma 3.6.4.

We shall now consider two specific classes of independent sets: the maximum and the maximal ones. These are not the same, and the contrast between them is rather important to understand. Let us define the two classes:

Definition 3.6.5. Let $G = (V, E)$ be a simple graph.

(a) A maximum independent set of $G$ means a subset of $V$ that is independent and has the highest possible size among all independent sets. In other words, a maximum independent set of $G$ means a subset $S$ of $V$ that is independent and that has the property that every independent subset $T$ of $V$ satisfies $|T| \leq |S|$.

(b) A maximal independent set of $G$ means a subset of $V$ that is independent and that cannot be written as a proper subset of any independent subset of $V$. In other words, a maximal independent set of $G$ means a subset of $V$ that

45Proof. Assume the contrary. Thus, $q \neq v$. Combining this with $q \in S \cup \{v\}$, we obtain $q \in (S \cup \{v\}) \setminus \{v\} \subseteq S$. Now, $p$ and $q$ are two distinct elements of $S$ (since $p \in S$, $q \in S$ and $p \neq q$), and are adjacent. Hence, there are two distinct elements of $S$ that are adjacent (namely, $p$ and $q$). This contradicts the fact that no two distinct elements of $S$ are adjacent. This contradiction proves that our assumption was wrong, qed.
is independent and that has the property that no independent subset \( T \) of \( V \) satisfies \( S \subseteq T \).

Thus, roughly speaking, a maximum independent set is an independent set having maximum size (among the independent sets), whereas a maximal independent set is an independent set that cannot be extended to a larger independent set by adding new elements.

Notice that a simple graph often will have several maximum independent sets (after all, the requirement to have maximum size does not uniquely determine the set; it merely uniquely determines the size), and also several maximal independent sets.

It is easy to see that each maximum independent set of a simple graph \( G \) is automatically a maximal independent set of \( G \) as well. However, the opposite is not true, as the following example shows:

**Example 3.6.6.** Let \( V, E \) and \( G \) be as in Example 2.4.2 (c). Then, the subset \( \{2, 4, 6\} \) of \( V \) is independent, and is a maximum independent set of \( G \) (indeed, it is easy to check that each independent set of \( G \) has size \( \leq 3 \)). The subset \( \{1, 5\} \) is also independent, and is a maximal independent set of \( G \) (indeed, it is easy to check that no independent subset \( T \) of \( V \) satisfies \( \{1, 5\} \subseteq T \), because each of the remaining vertices 2, 3, 4, 6 of \( G \) is connected to at least one of 1 and 5 and therefore cannot be in an independent set together with 1 and 5), but not a maximum independent set of \( G \) (since the independent set \( \{2, 4, 6\} \) has greater size).

You might wonder how to compute a maximum independent set or a maximal independent set of a simple graph \( G = (V, E) \). Obviously, one way to do so is to catalogue all subsets of \( V \), then check which of them are independent, and then check which of them are maximum independent sets and which are maximal independent sets. This algorithm, while theoretically doable, is massively inefficient, since the number of subsets of \( V \) grows exponentially with \( |V| \). Are there fast algorithms? This is a more interesting question, and the answers for maximum and for maximal independent sets are completely different:

- There are, most likely, no quick algorithms to find a maximum independent set of a simple graph \( G = (V, E) \). Indeed, this problem is NP-hard. There are better algorithms than checking all subsets of \( V \), but no algorithm of polynomial time in \( |V| \) is possible (unless \( P = NP \)).

- Finding a maximal independent set of a simple graph \( G = (V, E) \) is easy: Start with the empty set (which is clearly independent), and keep adding new elements to it while keeping the subset independent until it is no longer possible. Once it is no longer possible, your independent subset is a maximal

\[\text{It is easy to check whether adding a given new vertex } v \text{ to a given independent set } S \text{ keeps the set independent (in fact, we just need to check that } v \text{ is not adjacent to any of the elements of } S).\]
independent set. This is a polynomial-time algorithm. We shall formalize this algorithm (and prove its correctness) further below (in Proposition 3.6.9).

Now, let us show a simple yet crucial fact about maximal independent sets:

**Lemma 3.6.7.** Let $G = (V, E)$ be a simple graph. Let $S$ be an independent subset of $V$. Then, $S$ is a maximal independent set of $G$ if and only if $S$ is dominating.

**Proof of Lemma 3.6.7.** We have $V(G) = V$ (since $G = (V, E)$). Furthermore, recall that the subset $S$ of $V$ is independent. In other words, no two distinct elements of $S$ are adjacent (by the definition of “independent”).

Now, let us make the following two claims:

1. **Claim 1:** If $S$ is a maximal independent set of $G$, then $S$ is dominating.
2. **Claim 2:** If $S$ is dominating, then $S$ is a maximal independent set of $G$.

**Proof of Claim 1:** Assume that $S$ is a maximal independent set of $G$. We must prove that $S$ is dominating.

We know that $S$ is a maximal independent set of $G$. In other words, $S$ is a subset of $V$ that is independent and that cannot be written as a proper subset of any independent subset of $V$.

Let $v \in V(G) \setminus S$ be a vertex. Thus, $v \in V(G)$ and $v \notin S$. From $S \subseteq V$ and $v \in V(G) = V$, we conclude that $S \cup \{v\}$ is a subset of $V$. This subset $S \cup \{v\}$ of $V$ is not independent. Hence, at least one neighbor of $v$ belongs to $S$.

Now, forget that we have fixed $v$. We thus have shown that for every vertex $v \in V(G) \setminus S$, at least one neighbor of $v$ belongs to $S$. In other words, the subset $S$ of $V$ is dominating (by the definition of “dominating”). This proves Claim 1.

**Proof of Claim 2:** Assume that $S$ is dominating. We must prove that $S$ is a maximal independent set of $G$.

Assume (for the sake of contradiction) that $S$ can be written as a proper subset of some independent subset of $V$. Let $I$ be this independent subset. Thus, $S$ is a proper subset of $I$. In particular, $S \subseteq I$. But $I \setminus S \neq \emptyset$ (since $S$ is a proper subset of $I$). Hence, there exists some $i \in I \setminus S$. Consider such an $i$. Combining $i \in I \setminus S \subseteq I \subseteq V = V(G)$ with $i \notin S$ (since $i \in I \setminus S$), we obtain $i \in V(G) \setminus S$.

The subset $I$ of $V$ is independent. In other words, no two distinct elements of $I$ are adjacent (by the definition of “independent”).

**Proof.** Assume the contrary. Thus, the subset $S \cup \{v\}$ of $V$ is independent. But $S$ is a proper subset of $S \cup \{v\}$ (since $v \notin S$). Hence, $S$ can be written as a proper subset of some independent subset of $V$ (namely, of the independent subset $S \cup \{v\}$). This contradicts the fact that $S$ cannot be written as a proper subset of any independent subset of $V$. This contradiction proves that our assumption was wrong, qed.

**Proof.** Assume the contrary. Thus, no neighbor of $v$ belongs to $S$. Hence, Lemma 3.6.4 shows that $S \cup \{v\}$ also is an independent set of $G$ (since $v \in V(G) = V$). In other words, the subset $S \cup \{v\}$ of $V$ is independent. This contradicts the fact that the subset $S \cup \{v\}$ of $V$ is not independent. This contradiction proves that our assumption was wrong, qed.
But the subset \( S \) of \( V \) is dominating. In other words, for every vertex \( v \in V(G) \setminus S \), at least one neighbor of \( v \) belongs to \( S \) (by the definition of “dominating”). Applying this to \( v = i \), we find that at least one neighbor of \( i \) belongs to \( S \) (since \( i \in V(G) \setminus S \)). Let \( j \) be this neighbor. Thus, \( j \in S \). Also, the vertices \( i \) and \( j \) are adjacent (since \( j \) is a neighbor of \( i \)). Hence, the vertices \( i \) and \( j \) are distinct. Also, \( i \) and \( j \) are elements of \( I \) (since \( i \in I \) and \( j \in S \subseteq I \)). Thus, there exist two distinct elements of \( I \) that are adjacent (namely, \( i \) and \( j \)). This contradicts the fact that no two distinct elements of \( I \) are adjacent. This contradiction proves that our assumption (that \( S \) can be written as a proper subset of some independent subset of \( V \)) is wrong. Hence, \( S \) cannot be written as a proper subset of any independent subset of \( V \). Thus, \( S \) is a subset of \( V \) that is independent and that cannot be written as a proper subset of any independent subset of \( V \). In other words, \( S \) is a maximal independent set of \( G \) (by the definition of maximal independent sets). This proves Claim 2.
Combining Claim 1 and Claim 2, we conclude that \( S \) is a maximal independent set of \( G \) if and only if \( S \) is dominating. This proves Lemma 3.6.7.

Let us now rigorously state the algorithm for finding a maximal independent set:

**Algorithm 3.6.8.** Input: a simple graph \( G = (V, E) \).
Output: a maximal independent set \( S \) of \( G \).

1. Define a subset \( S \) of \( V \) by \( S = \emptyset \).
2. While there exists some \( v \in V \setminus S \) such that no neighbor of \( v \) belongs to \( S \), do the following:
   - Choose one such \( v \), and add this \( v \) to \( S \). (Clearly, the new \( S \) is still a subset of \( V \).)
3. Output the subset \( S \) of \( V \).

(Note that in each iteration of the while-loop in Step 2 of Algorithm 3.6.8, we only add one \( v \) to \( S \), even if there exist several candidates. Then, we go back to the beginning of the while-loop, and we check again whether there exists some \( v \in V \setminus S \) such that no neighbor of \( v \) belongs to \( S \).)

**Proposition 3.6.9.** Algorithm 3.6.8 always terminates, and the subset \( S \) that it outputs is indeed a maximal independent set of \( G \).

We shall show the proof of Proposition 3.6.9 in all detail due to it being a neat introductory example of reasoning about algorithms; nevertheless, the proof is almost evident.

**Proof of Proposition 3.6.9.** We will prove the following claims:
Claim 1: During each iteration of the while-loop in Algorithm 3.6.8 the size $|S|$ increases by 1.

Claim 2: Algorithm 3.6.8 always terminates.

Claim 3: Consider one single iteration of the while-loop in Algorithm 3.6.8. If the subset $S$ is independent before this iteration, then $S$ is also independent after the iteration.

Claim 4: The subset $S$ stays independent throughout the execution of Algorithm 3.6.8.

Claim 5: The subset $S$ that is outputted by Algorithm 3.6.8 is a maximal independent set of $G$.

Clearly, Claim 2 and Claim 5 combined will yield Proposition 3.6.9 (once they are proven). The other three claims are merely auxiliary results.

Let us now prove the five claims:

Proof of Claim 1. Consider one single iteration of the while-loop in Algorithm 3.6.8. Let $S_{\text{old}}$ be the value of $S$ at the beginning of this iteration, and let $S_{\text{new}}$ be the value of $S$ at the end of this iteration. Thus, $S_{\text{new}}$ is obtained from $S_{\text{old}}$ by adding the element $v$ that was chosen during this particular iteration of the while-loop (because what happens to $S$ during an iteration of the while-loop is that the element $v$ is being added to $S$). In other words, we have $S_{\text{new}} = S_{\text{old}} \cup \{v\}$. But remember how the element $v$ was chosen at the beginning of the iteration: It was chosen to be an element of $V \setminus S$ such that no neighbor of $v$ belongs to $S$. Thus, $v$ is an element of $V \setminus S_{\text{old}}$ such that no neighbor of $v$ belongs to $S_{\text{old}}$. In particular, $v$ is an element of $V \setminus S_{\text{old}}$. Hence, $v \notin S_{\text{old}}$. But from $S_{\text{new}} = S_{\text{old}} \cup \{v\}$, we obtain $|S_{\text{new}}| = |S_{\text{old}} \cup \{v\}| = |S_{\text{old}}| + 1$ (since $v \notin S_{\text{old}}$). In other words, the size $|S|$ has increased by 1 during our iteration.

We thus have shown that during each iteration of the while-loop in Algorithm 3.6.8, the size $|S|$ increases by 1. This proves Claim 1.

Proof of Claim 2. Let us show that the while-loop in Algorithm 3.6.8 (more precisely, in its Step 2) cannot go on forever.

Throughout the execution of the algorithm, $S$ remains a subset of $V$. Hence, $|S|$ remains a nonnegative integer smaller or equal to $|V|$ throughout the execution of the algorithm. Therefore, $|S|$ cannot keep increasing by 1 forever (since it would eventually surpass $|V|$ this way). But Claim 1 shows that $|S|$ increases by 1 during each iteration of the while-loop in Algorithm 3.6.8. Therefore, the while-loop in Algorithm 3.6.8 cannot go on forever (since $|S|$ cannot keep increasing by 1 forever). Hence, Algorithm 3.6.8 must eventually terminate (since the only part of Algorithm 3.6.8 that could possibly go on forever is the while-loop). This proves Claim 2.

Proof of Claim 3. Let $I$ be a single iteration of the while-loop in Algorithm 3.6.8. We must show that if the subset $S$ is independent before the iteration $I$, then $S$ is also independent after the iteration $I$. 

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Let $S_{\text{old}}$ be the value of $S$ at the beginning of this iteration $I$, and let $S_{\text{new}}$ be the value of $S$ at the end of this iteration $I$.

Assume that the subset $S_{\text{old}}$ of $V$ is independent. In other words, $S_{\text{old}}$ is an independent set of $G$. Now, $S_{\text{new}}$ is obtained from $S_{\text{old}}$ by adding the element $v$ that was chosen during this particular iteration of the while-loop (because what happens to $S$ during an iteration of the while-loop is that the element $v$ is being added to $S$). In other words, we have $S_{\text{new}} = S_{\text{old}} \cup \{v\}$.

The element $v$ was chosen to be an element of $V \setminus S$ such that no neighbor of $v$ belongs to $S$ at the beginning of the iteration $I$. Hence, $v$ is an element of $V \setminus S_{\text{old}}$ such that no neighbor of $v$ belongs to $S_{\text{old}}$. Thus, we have $v \in V \setminus S_{\text{old}} \subseteq V$, and no neighbor of $v$ belongs to $S_{\text{old}}$. Hence, Lemma 3.6.4 (applied to $S_{\text{old}}$ instead of $S$) shows that $S_{\text{old}} \cup \{v\}$ also is an independent set of $G$. In other words, $S_{\text{new}}$ is an independent set of $G$ (since $S_{\text{new}} = S_{\text{old}} \cup \{v\}$). In other words, the subset $S_{\text{new}}$ of $V$ is independent.

Now, forget our assumption that the subset $S_{\text{old}}$ of $V$ is independent. We thus have shown that if the subset $S_{\text{old}}$ of $V$ is independent, then the subset $S_{\text{new}}$ of $V$ is independent. In other words, if the subset $S$ is independent before the iteration $I$, then $S$ is also independent after the iteration $I$. This proves Claim 3.

**Proof of Claim 4.** The empty set $\emptyset$ is clearly independent. Hence, the subset $S$ of $V$ is independent when it is first defined in Algorithm 3.6.8 (because it is first defined to be the empty set $\emptyset$). Then, throughout the while-loop in Algorithm 3.6.8, it remains independent (because of Claim 3). Therefore, $S$ stays independent throughout Algorithm 3.6.8. This proves Claim 4.

**Proof of Claim 5.** Consider the subset $S$ that is outputted by Algorithm 3.6.8. This subset $S$ is independent (by Claim 4), i.e., is an independent set of $G$.

Notice that $G = (V, E)$, hence $V(G) = V$. We have $S \subseteq V = V(G)$.

Furthermore, looking back at Algorithm 3.6.8 we see that the subset $S$ gets outputted immediately after the while-loop is escaped. Thus, the condition of the while-loop cannot be satisfied for this subset $S$ (because otherwise, the while-loop would not be escaped at this point). In other words, there exists no $v \in V \setminus S$ such that no neighbor of $v$ belongs to $S$. In other words, for every $v \in V \setminus S$, at least one neighbor of $v$ belongs to $S$. In other words, for every $v \in V(G) \setminus S$, at least one neighbor of $v$ belongs to $S$ (because $V = V(G)$). In other words, the subset $S$ of $V(G)$ is dominating (by the definition of “dominating”). But Lemma 3.6.7 shows that $S$ is a maximal independent set of $G$ if and only if $S$ is dominating. Thus, $S$ is a maximal independent set of $G$ (since $S$ is dominating). This proves Claim 5.

Now, all five claims are proven. Proposition 3.6.9 follows from Claim 2 and Claim 5.

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**Lemma 3.6.10.** Let $G = (V, E)$ be a simple graph that has no isolated vertices. Let $S$ be an independent set of $G$. Then, the subset $V \setminus S$ of $V$ is dominating.

**Proof of Lemma 3.6.10.** We have $G = (V, E)$, thus $V(G) = V$. But $S$ is an independent set of $G$, hence an independent subset of $V$. In other words, no two distinct elements of $S$ are adjacent (by the definition of “independent”).
Proof of Proposition 3.1.5.

(a) Consider such a set, and denote it by $S$ (since $S$ is a maximal independent set of $G$). Let $v \in S$ such that $v$ has no neighbors. Thus, the vertex $v$ of $G$ is isolated (because the vertex $v$ of $G$ is isolated if and only if $v$ has no neighbors). Therefore, the graph $G$ has at least one isolated vertex. This contradicts the fact that $G$ has no isolated vertices. This contradiction proves that our assumption was false, qed.

(b) Proposition 3.1.5(a) shows that there exist two disjoint dominating subsets $A$ and $B$ of $V$ such that $A \cup B = V$. Consider such $A$ and $B$. We WLOG assume that $|A| \geq |B|$ (since otherwise, we can simply switch $A$ with $B$). But since the sets $A$ and $B$ are disjoint, we have $|A \cup B| = |A| + |B|$. Now, from $V = A \cup B$, we obtain

$$|V| = |A \cup B| = |A| + |B| \geq |B| + |B| = 2|B|, \quad \geq |B|$$

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49 Proof. Assume the contrary. Thus, the vertex $v$ has no neighbors. Hence, the vertex $v$ of $G$ is isolated (because the vertex $v$ of $G$ is isolated if and only if $v$ has no neighbors). Therefore, the graph $G$ has at least one isolated vertex. This contradicts the fact that $G$ has no isolated vertices. This contradiction proves that our assumption was false, qed.

50 Proof. Assume the contrary. Thus, $u \in S$. Now, $u$ and $v$ are two elements of $S$ (since $u \in S$ and $v \in S$) and are distinct (since $u$ and $v$ are adjacent). Hence, some two distinct elements of $S$ are adjacent (namely, $u$ and $v$). This contradicts the fact that no two distinct elements of $S$ are adjacent. This contradiction proves that our assumption was false, qed.

51 First proof. Such a set can be obtained by Algorithm 3.6.8 (because Proposition 3.6.9 shows that this algorithm outputs a maximal independent set of $G$).

Second proof. We have the following two observations:

- There exists at least one independent set of $G$. (In fact, the subset $\emptyset$ of $V$ is clearly independent.)
- There are only finitely many independent sets of $G$. (In fact, each independent set of $G$ is a subset of $V$, and there are only finitely many subsets of $V$.)

From these two observations, we can conclude that there exists an independent set of $G$ having maximum size. In other words, there exists a maximum independent set of $G$. But since each maximum independent set of $G$ is a maximal independent set of $G$ (this is easy to show), we can thus conclude that there exists a maximal independent set of $G$. 

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Let $v \in V(G) \setminus (V \setminus S)$ be a vertex. Thus, $v \in V(G) \setminus (V \setminus S) = V \setminus (V \setminus S) = S$ (since $S \subseteq V$). Furthermore, the vertex $v$ of $G$ has a neighbor. Fix such a neighbor, and denote it by $u$. Thus, $u$ and $v$ are adjacent (since $u$ is a neighbor of $v$). We have $u \not\in S$ (since otherwise, we can simply switch $A$ with $B$). Hence, $u \in V \setminus S$ (since $u \in V$ and $u \not\in S$). Recall also that $u$ is a neighbor of $v$. Thus, at least one neighbor of $v$ belongs to $V \setminus S$ (namely, the neighbor $u$).

Now, forget that we fixed $v$. We thus have shown that for every vertex $v \in V(G) \setminus (V \setminus S)$, at least one neighbor of $v$ belongs to $V \setminus S$. In other words, the subset $V \setminus S$ of $V$ is dominating (by the definition of “dominating”). This proves Lemma 3.6.10.

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Proof of Proposition 3.1.5 (a) There exists a maximal independent set of $G$. Consider such a set, and denote it by $S$. Lemma 3.6.7 shows that $S$ is a maximal independent set of $G$ if and only if $S$ is dominating. Thus, $S$ is dominating (since $S$ is a maximal independent set of $G$). But Lemma 3.6.10 shows that the subset $V \setminus S$ of $V$ is dominating. Clearly, the sets $S$ and $V \setminus S$ are disjoint subsets of $V$. Furthermore, $S \cup (V \setminus S) = V$ (since $S \subseteq V$). Hence, there exist two disjoint dominating subsets $A$ and $B$ of $V$ such that $A \cup B = V$ (namely, $A = S$ and $B = V \setminus S$). This proves Proposition 3.1.5(a).

(b) Proposition 3.1.5(a) shows that there exist two disjoint dominating subsets $A$ and $B$ of $V$ such that $A \cup B = V$. Consider such $A$ and $B$. We WLOG assume that $|A| \geq |B|$ (since otherwise, we can simply switch $A$ with $B$). But since the sets $A$ and $B$ are disjoint, we have $|A \cup B| = |A| + |B|$. Now, from $V = A \cup B$, we obtain

$$|V| = |A \cup B| = |A| + |B| \geq |B| + |B| = 2|B|,$$

which proves Proposition 3.1.5(b).

---

49 Proof. Assume the contrary. Thus, the vertex $v$ has no neighbors. Hence, the vertex $v$ of $G$ is isolated (because the vertex $v$ of $G$ is isolated if and only if $v$ has no neighbors). Therefore, the graph $G$ has at least one isolated vertex. This contradicts the fact that $G$ has no isolated vertices. This contradiction proves that our assumption was false, qed.

50 Proof. Assume the contrary. Thus, $u \in S$. Now, $u$ and $v$ are two elements of $S$ (since $u \in S$ and $v \in S$) and are distinct (since $u$ and $v$ are adjacent). Hence, some two distinct elements of $S$ are adjacent (namely, $u$ and $v$). This contradicts the fact that no two distinct elements of $S$ are adjacent. This contradiction proves that our assumption was false, qed.

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so that $|B| \leq |V|/2$. In other words, the subset $B$ of $V$ has size $\leq |V|/2$. Hence, there exists a dominating subset of $V$ having size $\leq |V|/2$ (namely, the subset $B$). This proves Proposition 3.1.5 (b).

\section{4. Hamiltonian paths}

\begin{itemize}
  \item \textbf{TODO 4.0.1}. Continue from here...
  \end{itemize}

[...]
[to be continued]

\section*{References}

\begin{itemize}
  \item [AoPS-ISL]  Art of Problem Solving (forum), \textit{IMO Shortlist} (collection of threads), http://www.artofproblemsolving.com/community/c3223_imo_shortlist
  \item [BenWil12]  Edward A. Bender and S. Gill Williamson, \textit{Foundations of Combinatorics with Applications}. http://cseweb.ucsd.edu/~gill/FoundCombSite/
  \item [Bogomoln]  Alexander Bogomolny, \textit{Cut the Knot} (website devoted to educational applets on various mathematical subjects), http://www.cut-the-knot.org/Curriculum/index.shtml#combinatorics.
\end{itemize}
https://sites.google.com/site/cgriffin229/.


[Guicha16] David Guichard, *An Introduction to Combinatorics and Graph Theory*,
https://www.whitman.edu/mathematics/cgt_online/cgt.pdf

http://www.people.vcu.edu/~rhammack/BookOfProof/


http://users.utu.fi/harju/graphtheory/graphtheory.pdf


https://www.quantamagazine.org/20170105-graph-isomorphism-retraction/


[Petrov15] Fedor Petrov, mathoverflow post #198679 (Flooding a cycle digraph via chip-firing: $n^{k-1} + n^{k-2} + \cdots + 1$ bound (a Norway 1998-99 problem generalized)), MathOverflow, http://mathoverflow.net/q/198679


https://neil-strickland.staff.shef.ac.uk/courses/MAS201/


See http://www.math.illinois.edu/~dwest/igt/ for updates and corrections.

See https://archive.org/details/IntroductionToGraphTheory for the 3rd edition.