Set theory

From the book: Naive Set Theory by Paul R. Halmos

This set of notes is almost a re-edited version of the original book, but in some places, a unique notation system was used, and there are also specific additions, such as exercise solutions. These notes were written exclusively for myself and may contain errors.

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Contents

1   Axiom of extension

On thing that the development will not include is a definition of sets. The situation is analogous to the familiar axiomatic approach to elementary geometry. That approach does not offer a definition of points and lines; instead it describes what it is that one can do with those objects. The semi-axiomatic point of view adopted here assumes that the reader has the ordinary, human, intuitive (and frequently erroneous) understanding of what sets are; the purpose of the exposition is to delineate some of the many things that one can correctly do with them.

Sets, as they are usually conceived, have *elements* or *members*. An element of a set may be a wolf, a grape, or a pigeon. It is important to know that a set itself may also be an element of some other set. Mathematics is full of examples of sets of sets. A line, for instance, is a set of points; the set of all lines in the plane is a natural example of a set of sets (of points). What may be surprising is not so much that sets may occur as elements, but that for mathematical purposes no other elements need ever be considered.

The principal concept of set theory, the one that in completely axiomatic studies is the principal primitive (undefined) concept, is that of *belonging*. If x belongs to A (x is an element of A, x is *contained* in A), we shall write

$$x \in A.$$

A possible relation between sets, more elementary than belonging, is *equality*. The equality of two sets A and B is universally denoted by the familiar symbol

$$A = B;$$

the fact that A and B are not equal is expressed by writing

$$A \neq B.$$

The most basic property of belonging is its relation to equality, which can be formulated as follows.

> **Axiom of extension.** *Two sets are equal if and only if they have the same elements.*

With greater pretentiousness and less clarity: a set is determined by its extension.

It is valuable to understand that the axiom of extension is not just a logically necessary property of equality but a non-trivial statement about belonging. One way to come to understand the point is to consider a partially analogous situation in which the analogue of the axiom of extension does not hold. Suppose, for instance, that we consider human beings instead of sets, and that, if x and A are human beings, we write $x \in A$ whenever x is an ancestor of A. The analogue of the axiom of extension would say here that if two human beings are equal, then they have the same ancestors (this is the "only if" part, and it is true), and also that if two human beings have the same ancestors, then they are equal (this is the "if" part, and it is false).

If A and B are sets and if every element of A is an element of B, we say that A is a *subset* of B, or B *includes* A, and we write

$$A \subset B$$

or

$$B \supset A.$$

The wording of the definition implies that each set must be considered to be included in itself ($A \subset A$); this fact is described by saying that set inclusion is *reflexive*. (Note that, in the same

sense of the word, equality also is reflexive.) If A and B are sets such that $A \subset B$ and $A \neq B$, the word *proper* is used (proper subset, proper inclusion). If A, B, and C are sets such that $A \subset B$ and $B \subset C$, then $A \subset C$; this fact is described by saying that set inclusion is *transitive*. (This property is also shared by equality.)

If A and B are sets such that $A \subset B$ and $B \subset A$, then A and B have the same elements and therefore, by the axiom of extension, $A = B$. This fact is described by saying that set inclusion is *antisymmetric*. (In this respect set inclusion behaves differently from equality. Equality is *symmetric*, in the sense that if $A = B$, then necessarily $B = A$.) The axiom of extension can, in fact, be reformulated in these terms: if A and B are sets, then a necessary and sufficient condition that $A = B$ is that both $A \subset B$ and $B \subset A$. Correspondingly, almost all proofs of equalities between two sets A and B are split into two parts; first show that $A \subset B$, and then show that $B \subset A$.

Observe that belonging ($\in$) and inclusion ($\subset$) are conceptually very different things indeed. One important difference has already manifested itself above: inclusion is always reflexive, whereas it is not at all clear that belonging is ever reflexive. That is: $A \subset A$ is always true; is $A \in A$ ever true? It is certainly not true of any reasonable set that anyone has ever seen. Observe, along the same lines, that inclusion is transitive, whereas belonging is not. Everyday examples, involving, for instance, super-organizations whose members are organizations, will readily occur to the interested reader.

2   Axiom of specification

All the basic principles of set theory, except only the axiom of extension, are de- signed to make new sets out of old ones. The first and most important of these basic principles of set manufacture says, roughly speaking, that anything intelligent one can assert about the elements of a set specifies a subset, namely, the subset of those elements about which the assertion is true.

Before formulating this principle in exact terms, we look at a heuristic example. Let A be the set of all men. The sentence "x is married" is true for some of the elements x of A and false for others. The principle we are illustrating is the one that justifies the passage from the given set A to the subset (namely, the set of all married men) specified by the given sentence. To indicate the generation of the subset, it is usually denoted by

$$\{x \in A : x \text{ is married}\}.$$

Similarly
$$\{x \in A : x \text{ is not married}\}$$
is the set of all bachelors;
$$\{x \in A : \text{ the father of } x \text{ is Adam}\}$$
is the set that contains Seth, Cain and Abel and nothing else, and

$$\{x \in A : x \text{ is the father of Abel}\}$$

is the set that contains Adam and nothing else. Warning: a box that contains a hat and nothing else is not the same thing as a hat, and, in the same way, the last set in this list of examples is not to be confused with Adam. The analogy between sets and boxes has many weak points, but sometimes it gives a helpful picture of the facts.

All that is lacking for the precise general formulation that underlies the examples above is a definition of *sentence*. Here is a quick and informal one. There are two basic types of sentences, namely, assertions of belonging,
$$x \in A$$
and assertions of equality,
$$A = B$$

all other sentences are obtained from such *atomic* sentences by repeated applications of the usual logical operators, subject only to the minimal courtesies of grammar and unambiguity. To make the definition more explicit (and longer) it is necessary to append to it a list of the "usual logical operators" and the rules of syntax. An adequate (and, in fact, redundant) list of former contains seven items:

1. *and,*

2. *or (in the sente of "either – or – or both"),*

3. *not,*

4. *if – then – (or implies),*

5. *if and only if,*

6. *for some (or there exists),*

7. *for all.*

As for the rules of sentence construction, they can be described as follows.

- Put "not" before a sentence and enclose the result between parentheses. (The reason for parentheses, here and below, is to guarantee unambiguity. Note, incidentally, that they make all other punctuation marks unnecessary. The complete parenthetical equipment that the definition of sentences calls for is rarely needed. We shall always omit as many parentheses as it seems safe to omit without leading to confusion. In normal mathematical practice, to be followed in this book, several different sizes and shapes of parentheses are used, but that is for visual convenience only.)

- Put "and" or "or" or "if and only if" between two sentences and enclose the result between parentheses.

- Replace the dashes in "if – then –" by sentences and enclose the result in parentheses.

- Replace the dash in "for some –" or in "for all –" by a letter, follow the result by a sentence, and enclose the whole in parentheses.

We are now ready to formulate the major principle of set theory, often referred to by its German name *Aussonderungsaxiom*.

> **Axiom of specification.** *To every set A and to every condition $S(x)$ corresponds a set B whose elements are exactly those elements x of A for which $S(x)$ holds.*

A "condition" here is just a sentence. The symbolism is intended to indicate the letter x if *free* in the sentence $S(x)$; that means that x occurs in $S(x)$ at least once without being introduced by one of the phrases "for some x" or "for all x". It is an immediate consequence of the axiom of extension that the axiom of specification determines the set B uniquely. To indicate the way B is obtained from A and from $S(x)$ it is customary to write

$$B = \{x \in A : S(x)\}.$$

To obtain an amusing and instructive application of the axiom of specification, consider, in the role of $S(x)$, the sentence

$$\text{not } (x \in x).$$

It will be convenient, here and throughout, to write "$x \notin A$" instead of "not $(x \in A)$"; in this notation, the role of $S(x)$ is now played by

$$x \notin x.$$

It follows that, whatever the set A may be, if $B = \{x \in A : x \notin x\}$, then, for all y,

$$y \in B \text{ if and only if } (y \in A \text{ and } y \notin y). \qquad (\star)$$

Can it be that $B \in A$? We proceed to prove that the answer is no. Indeed, if $B \in A$, then either $B \in B$ also (unlikely, but not obviously impossible), or else $B \notin B$. If $B \in B$, then, by $(\star)$, the assumption $B \in A$ yields $B \notin B$ – a contradiction. If $B \notin B$, then, by $(\star)$ again, the assumption $B \in A$ yields $B \in B$ – a contradiction. This completes the proof that is impossible, so that we must have $B \notin A$. The most interesting part of this conclusion is that there exists something (namely B) that does not belong to A. The set A in this argument was quite arbitrary. We have proved, in other words, that

nothing contains everything,

or, more spectacularly

there is no universe.

"Universe" here is used in the sense of "universe of discourse", meaning, in any particular discussion, a set that contains all the objects that enter into that discussion.

In older (pre-axiomatic) approaches to set theory, the existence of universe was takes for granted, and the argument in the preceding paragraph was known as the *Russell's paradox*. The moral is that it is impossible, especially in mathematics, to get something for nothing. To specify a set, it is not enough to pronounce some magic words (which may form a sentence such as "$x \notin z$"); it is necessary also to have at hand a set to whose elements the magic words apply.

3 Unordered pairs

For all that has been said so far, we might have been operating in a vacuum. To give the discussion some substance, let us now officially assume that

there exists a set.

Since later on we shall formulate a deeper and more useful existential assumption, this assumption plays a temporary role only. One consequence of this innocuous seeming assumption is that there exists a set without any elements at all. Indeed, if A is a set, apply the axiom of specification to A with the sentence "$x \neq x$". The result is the set $\{x \in A : x \neq x\}$, and that set, clearly, has no elements. The axiom of extension implies that there can be only one set with no elements. The usual symbol for that set is

$$\emptyset;$$

the set is called *empty set*. The empty set is a subset of every set, or, in other words, $\emptyset \subset A$ for every A. To establish this, we might argue as follows. It is to be proved that every element in $\emptyset$ belongs to A; since there are no elements in $\emptyset$, the condition is automatically fulfilled. The reasoning is correct but perhaps unsatisfying. Since it is a typical example of frequent phenomenon, a condition holding in the "vacuous" sense, a word of advice to the inexperienced reader might be in order. To prove that something is true about the empty set, prove that it cannot be false. How, for instance, could it be false that $\emptyset \subset A$? It could be false only if $\emptyset$ had an element that did not belong to A. Since $\emptyset$ has no elements at all, this is absurd. Conclusion: $\emptyset \subset A$ is not false.

The set theory developed so far is still a pretty poor thing; for all we know there is only one set and that one is empty. Are there enough sets to ensure that every set is an element of some set? Is it true that for any two sets there is a third one that they both belong to? What about three sets, or four, or any number? We need a new principle of set construction to resolve such questions. The following principle is a good beginning.

> **Axiom of pairing.** *For any two sets there exists a set that they both belong to.*

Note that this is just the affirmative answer to the second question above. To reassure worriers, let us hasten to observe that words such as "two", "three", and "four" used above, do not refer to the mathematical concepts bearing those names, which will be defined later; at present such words are merely the ordinary linguistic abbreviations for "something and then something else" repeated an appropriate number of times. Thus, for instance, the axiom of pairing, in unabbreviated form, says that if a and b are sets, then there exists a set A such that $a \in A$ and $b \in A$.

One consequence (in fact an equivalent formulation) of the axiom of pairing is that for any two sets there exists a set that contains both of them and nothing else. Indeed, if a and b are sets, and if A is a set such that $a \in A$ and $b \in A$, then we can apply the axiom of specification to A with the sentence "$x = a$ or $x = b$". The result is the set

$$\{x \in A : x = a \text{ or } x = b\},$$

and that set, clearly, contains just a and b. The axiom of extension implies that there can be only one set with this property. The usual symbol for that set is

$$\{a, b\};$$

the set is called the *pair* (or, by emphatic comparison with a subsequent concept, the *unordered pair*) formed by a and b.

If, temporarily, we refer to the sentence "$x = a$ or $x = b$" as $S(x)$, we may express the axiom of pairing by saying that there exists a set B such that

$$x \in B \text{ if and only if } S(x). \tag{$\star$}$$

The axiom of specification, applied to a set A, asserts the existence of a set B such that

$$x \in B \text{ if and only if } (x \in A \text{ and } S(x)). \tag{$\star\star$}$$

The relation between ($\star$) and ($\star\star$) typifies something that occurs quite frequently. All the remaining principles of set construction are pseudo-special cases of the axiom of specification in the sense which ($\star$) is a pseudo-special case of ($\star\star$). They all assert the existence of a set specified by a certain condition; if it were known in advance that there exists a set containing all t he specified elements, then the existence of a set containing just them would indeed follow as a special case of the axiom of specification.

If a is a set, we may form the unordered pair $\{a, a\}$. That unordered pair is denoted by

$$\{a\}$$

and is called the *singleton* of a; it is uniquely characterized by the statement that it has a as its only element. Thus, for instance, $\emptyset$ and $\{\emptyset\}$ are very different sets; the former has no elements, whereas the latter has the unique element $\emptyset$. To say that $a \in A$ is equivalent to saying that $\{a\} \subset A$.

The axiom of pairing ensures that every set is an element of some set and that any two sets are simultaneously elements of some one and the same set. (The corresponding questions for three and four and more sets will be answered later.) Another pertinent comment is that from the assumptions we have made so far we can infer the existence of very many sets indeed. For examples consider the sets $\emptyset$, $\{\emptyset\}$, $\{\{\emptyset\}\}$, $\{\{\{\emptyset\}\}\}$, etc.; consider the pairs, such as $\{\emptyset, \{\emptyset\}\}$, formed by any two of them; consider the pairs formed by any two such pairs, or else the mixed pairs formed by any singleton and any pair; proceed so on ad infinitum.

Exercise. Are all the sets obtained in this way distinct from one another?

Before continuing our study of set theory, we pause for a moment to discuss a notational matter. It seems natural to denote the set B described in ($\star$) by $\{x : S(x)\}$ in the special case that was there considered

$$\{x : x = a \text{ or } x = b\} = \{a, b\}.$$

We shall use this symbolism whenever it is convenient and permissible to do so. If, that is, $S(x)$ is a condition on x such that the x's that $S(x)$ specifies constitute a set, then we may denote that set by

$$\{x : S(x)\}.$$

In case A is a set and $S(x)$ is ($x \in A$), then it is permissible to form $\{x : S(x)\}$; in fact

$$\{x : x \in A\} = A.$$

If A is a set and $S(x)$ is an arbitrary sentence, it is permissible to form $\{x : xinA \text{ and } S(x)\}$; this set is the same as $\{x \in A : S(x)\}$. As further examples, we note that

$$\{x : x \neq x\} = \emptyset$$

and

$${x : x = a} = {a}.$$

In case $S(x)$ is $(x \notin x)$, or in case $S(x)$ is $(x = x)$, the specified x's do not constitute a set.

Despite the maxim about never getting something for nothing, it seems a little harsh to be told that certain sets are not really sets and even their names must never be mentioned. Some approaches to set theory try to soften the blow by making systematic use of such illegal sets but just not calling them sets; the customary word is "class". A precise explanation of what classes really are nd how they are used is irrelevant in the present approach. Roughly speaking, a class may be identified with a condition (sentence), or, rather, with the "extension" of a condition.

4   Unions and intersections

If A and B are sets, it is sometimes natural to wish to unite their elements into one comprehensive set. One way of describing such a comprehensive set is to require it to contain all the elements that belong to at least one of the two members of the pair $\{A, B\}$. This formulation suggests a sweeping generalization of itself; surely a similar construction should apply to arbitrary collections of sets and not just to pairs of them. What is wanted, in other words, is the following principle of set construction.

> **Axiom of unions.** For every collection of sets there exists a set that contains all the elements that belong to at least one set of the given collection.

Here it is again: for every collection $\mathcal{C}$ there exists a set U such that if $x \in X$ for some $X \in \mathcal{C}$, then $x \in U$. (Note that "at least one" is the same as "some").

The comprehensive set U described above may be too comprehensive; it may contain elements that belong to none of the sets X in the collection $\mathcal{C}$. This is easy to remedy; just apply the axiom of specification to form the set

$$\{x \in U : x \in X \text{ for some } X \in \mathcal{C}\}.$$

(The condition here is a translation into idiomatic usage of the mathematically more acceptable "for some X ($x \in X$ and $X \in \mathcal{C}$)".) It follows that, for every x, a necessary and sufficient condition that x belong to this set is that x belong to X for some X in $\mathcal{C}$. If we change notation and call the new set U again, then

$$U = \{x : x \in X \text{ for some } X \in \mathcal{C}\}.$$

This set U is called the *union* of the collection $\mathcal{C}$ of sets; note that the axiom of extension guarantees its uniqueness. The simplest symbol for U that is in use at all is not very popular in mathematical circles; it is

$$\bigcup \mathcal{C}.$$

Most mathematicians prefer something like

$$\bigcup \{X : X \in \mathcal{C}\}$$

or

$$\bigcup_{X \in \mathcal{C}} X.$$

Further alternatives are available in certain important cases; they will be described in due course.

For the time begin we restrict our study of the theory of union to the simplest facts only. The simplest fact of all is that

$$\bigcup_{X \in \emptyset} X = \emptyset,$$

and the next simplest fact is that

$$\bigcup_{X \in \{A\}} = A.$$

The proofs are immediate from the definitions.

There is a little more substance in the union of pairs of sets (which is what started this whole discussion anyway). In that case of special notation is used:

$$\bigcup_{X \in \{A,\, B\}} X = A \cup B.$$

The general definition of unions implies in the special case that $x \in A \cup B$ if and only if x belongs to either A or B or both; it follows that

$$A \cup B = \{x : x \in A \text{ or } x \in B\}.$$

Here are some easily proved facts about the unions of pairs.

- $A \cup \emptyset = A$.

   Editor's proof. If $x \in A \cup \emptyset$ then $x \in A$ or $x \in \emptyset$. Since $x \in \emptyset$ is always false, we get $x \in A$, therefore $A \cup \emptyset \subset A$. If $x \in A$, then obviously $x \in A$ or $x \in \emptyset$, therefore $A \subset A \cup \emptyset$. We get $A \subset \emptyset = A$.

- $A \cup B = B \cup A$ (commutativity).

   Editor's proof.
   $$\{x : x \in A \text{ or } x \in B\} = \{x : x \in B \text{ or } x \in A\}.$$

- $A \cup (B \cup C) = (A \cup B) \cup C$ (associativity).

   Editor's proof.
   $$\{x : x \in A \text{ or } (x \in B \text{ or } x \in C)\} = \{x : (x \in A \text{ or } x \in B) \text{ or } x \in C\}.$$

- $A \cup A = A$ (idempotence).

   Editor's proof.
   $$\bigcup_{X \in \{A\}} = A.$$

- $A \subset B$ if and only if $A \cup B = B$.

   Editor's proof. Assume $A \subset B$. From the definition $B \subset A \cup B$. Propose that $A \cup B \subset B$ is false. Then there exists an element $x \in A \cup B$ so that $x \notin B$. This x must be in A, but due to our assumption for every $y \in A$, $y \in B$ is also true. Therefore $A \cup B = B$.

   Now assume that $A \cup B = B$. Propose that there exist an element $x \in A$, so that $x \notin B$. By definition $x \in A \cup B$. But $A \cup B \subset B \not\ni x$, so $A \cup B = B$ cannot be true.

Every student of mathematics should prove these things for himself at least once in his life. The proofs are based on the corresponding elementary properties of the logical operator *or*.

An equally simple but quite suggestive fact is that

$$\{a\} \cup \{b\} = \{a,\, b\}.$$

What this suggests is the way to generalize pairs. Specially, we write

$$\{a,\, b,\, c\} = \{a\} \cup \{b\} \cup \{c\}.$$

The equation defines its left side. The right side should by rights have at least one pair of parentheses in it, but, in view of the associative law, their omission can lead to no misunderstanding. Since it is easy to prove that

$$\{a,\, b,\, c\} = \{x : x = a \text{ or } x = b \text{ or } x = c\},$$

we know now that for every three sets there exits a set that contains them and nothing else; it is natural to call that uniquely determined set the (*unordered*) *triple* formed by them. The extension of the notation and terminology thus introduced to more terms (*quadruples*, etc.) is obvious.

The formation of unions has many points of similarity with another set-theoretic operation. If A and B are sets, the *intersection* of A and B is the set

$$A \cap B$$

defined by

$$A \cap B = \{x \in A : x \in B\}.$$

The definition is symmetric in A and B even if it looks otherwise; we have

$$A \cap B = \{x \in B : x \in A\},$$

and, in fact, since $x \in A \cap B$ if and only if x belongs to both A and B, it follows that

$$A \cap B = \{x : x \in A \text{ and } x \in B\}.$$

The basic facts about intersections, as well as their proofs, are similar to the basic facts about union:

- $A \cap \emptyset = \emptyset$,

- $A \cap B = B \cap A$,

- $A \cap (B \cap C) = (A \cap B) \cap C$,

- $A \cap A = A$,

- $A \subset B$ if and only if $A \cap B = A$.

Pairs of sets with an empty intersection occur frequently enough to justify the use of a special word: if $A \cap B = \emptyset$, the sets A and B are called *disjoint*. The same word is sometimes applied to a collection of sets to indicate that any two distinct sets of the collection are disjoint; alternatively we may speak in such a situation of a *pairwise disjoint* collection.

Two useful facts about unions and intersections involve both the operations at the same time:

$$A \cap (B \cup C) = (A \cap B) \cup (A \cap C),$$
$$A \cup (B \cap C) = (A \cup B) \cap (A \cup C).$$

These identities are called the *distributive laws*. By way of a sample of a set-theoretic proof, we prove the second one. If x belongs to the left side, then x belongs either to A or to both B and C; if x is in A, then x is in both $A \cup B$ and $A \cup C$, and if x is in both B and C, then, again x is in both $A \cup B$ and $A \cup C$; it follows that, in any case, x belongs to the right side. This proves that the right side includes the left. To prove the reverse inclusion, just observe that if x belongs to both $A \cup B$ and $A \cup C$, then x belongs either to A or to both B and C.

The formation of the intersection of two sets A and B, or, we might as well say, the formation of the intersection of a pair $\{A, B\}$ of sets, is a special case of a much more general operation. (This is another respect in which the theory of intersections imitates that of unions.) The existence of the general operation of intersection depends on the fact that for each non-empty collection of sets there exists a set that contains exactly those elements that belong to every set

of the given collection. In other words: for each collection $\mathcal{C}$, other than $\emptyset$, there exists a set V such that $x \in V$ if and only if $x \in X$ for every $X \in \mathcal{C}$. To prove this assertion, let A be any particular set in $\mathcal{C}$ (this step is justified by the fact that $\mathcal{C} \neq \emptyset$) and write

$$V = \{x \in A : x \in X \text{ for every } X \in \mathbb{C}\}.$$

(The condition means "for all X (if $X \in \mathcal{C}$, then $x \in X$)".) The dependence of V on the arbitrary choice of A is illusory; in fact

$$V = \{x : x \in X \text{ for every } X \in \mathcal{C}\}.$$

The set V is called the *intersection* of the collection $\mathcal{C}$ of sets; the axiom of extension guarantees its uniqueness. The customary notation is similar to the one for unions:

$$\bigcap\{X : X \in \mathcal{C}\}$$

or

$$\bigcap_{X \in \mathcal{C}} X.$$

> **Exercise.** A necessary and sufficient condition that $(A \cap B) \cup C = A \cap (B \cup C)$ is that $C \subset A$. Observe that the condition has nothing to do with the set B.

Editor's proof. Assume that A, B, C are sets, and $C \subset A$ is true. Let x belong to the left side of the equation; that is, x belongs to both A and B or x belongs to C. Given our assumption, x is in A either way. Since, the set A contains the right side of the equation, we get $(A \cap B) \cup C \subset A \cap (B \cup C)$. Now, let x be contained in the right side of the equation: $x \in (A \cap B) \cup (A \cap C)$. If $x \in A \cup B$, clearly x belongs to the left side. Lastly, if $x \in A \cap C = C$, then again, x belongs to the left side.

Assume that the equation mentioned in the exercise is true. Since A, B, C are arbitrary sets, let B equal the empty set, so we get

$$(A \cap \emptyset) \cup C = A \cap (\emptyset \cup C),$$

or in an equivalent form

$$C = A \cap C.$$

5   Complements are powers

If A and B are sets, the *difference* between A and B, more often known as the *relative complement* of B in A, is the set $A - B$ defined by

$$A - B = \{x \in A : x \notin B\}.$$

Note that in this definition it is not necessary to assume that $B \subset A$. In order to record the basic facts about complementation as simply as possible, we assume nevertheless (in this section only) that all the sets to be mentioned are subsets of one and the same set E and that all complements (unless otherwise mentioned) are formed relative to that E. In such situations (and they are quite common) it is easier to remember the underlying set E than to keep writing it down, and this makes it possible to simplify the notation. An often used symbol for the temporarily absolute (as opposed to relative) complement of A is A'. In terms if this symbol the basic facts about complementation can be stated as follows:

- $(A')' = A$,

- $\emptyset' = E$, $E' = \emptyset$,

- $A \cap A' = \emptyset$, $A \cup A' = E$,

- $A \subset B$ if and only if $B' \subset A'$.

The most important statements about the complements are the so-called *De Morgan laws*:

$$(A \cup B)' = A' \cap B', \quad (A \cap B)' = A' \cup B'.$$

(We shall see presently that the De Morgan laws hold for the unions and intersections of larger collections of sets than just pairs.) These facts about complementation imply that the theorems of set theory usually come in pairs. If in an inclusion or equation involving unions, intersections, and complements of subsets of E we replace each set by its complement, interchange unions and intersections, and reverse all inclusions, the result is another theorem. This fact is sometimes referred to as the *principle of duality* for sets.

Here are some easy exercises on complementation.

- $A - B = A \cap B'$.

  Editor's proof.
  $$\{x \in A : x \notin B\} = \{x \in A : x \in B'\}.$$

- $A \subset B$ if and only if $A - B = \emptyset$.

  Editor's proof. If $A \subset B$, then $A - B = (A \cap B) - B = (A \cap B) \cap B' = A \cap (B \cap B') = A \cap \emptyset = \emptyset$.

  Assume that both $A - B = \emptyset$ and $A \not\subset B$ are true. Then, there exists an element $x \in A$ such that $x \notin B$. By definition
  $$A - B = \{x \in A : x \notin B\} = \emptyset,$$
  a contradiction.

- $A - (A - B) = A \cap B$.

  Editor's proof.

  $A - (A - B) = A - (A \cap B') = A \cap (A \cap B')' = A \cap (A' \cup B) = (A \cap A') \cup (A \cap B) = A \cap B.$

- $A \cap (B - C) = (A \cap B) - (A \cap C)$

    Editor's proof.

    $$(A \cap B) - (A \cap C) = (A \cap B) \cap (A \cap C)' = (A \cap B) \cap (A' \cup C') =$$

    $$(A \cap B \cap A') \cup (A \cap B \cap C') = A \cap B \cap C' = A \cap (B \cap C') \ A \cap (B - C).$$

- $A \cap B \subset (A \cap C) \cup (B \cap C')$.

    Editor's proof. According to the distributive laws we get

    $$(A \cap C) \cup (B \cap C') =$$

    $$\big((A \cap C) \cup B\big) \cap \big((A \cap C) \cup C'\big) =$$

    $$\big((A \cap C) \cup B\big) \cap \big((C' \cup A) \cap (C' \cup C)\big) =$$

    $$\underbrace{\big((A \cap C) \cup B\big)}_{=:P} \cap \underbrace{(C' \cup A)}_{=:Q}.$$

    Let $x \in A \cap B$. With the pre-defined P, Q sets, we get that $x \in P$ and $x \in Q$.

- $(A \cup C) \cap (B \cup C') \subset A \cup B$.

    Editor's proof. According to the distributive laws we get

    $$(A \cup C) \cap (B \cup C') =$$

    $$\big((A \cup C) \cap B\big) \cup \big((A \cup C) \cap C'\big) =$$

    $$\big((A \cup C) \cap B\big) \cup \big((C' \cap A) \cup (C' \cap C)\big) =$$

    $$\underbrace{\big((A \cup C) \cap B\big)}_{=:P} \cup \underbrace{(C' \cap A)}_{=:Q}.$$

    Let $x \in P \cup Q$. If $x \in P$, then $x \in B \subset A \cup B$. On the other way, if $x \in Q$, then $x \in A \subset A \cup B$. Either way, we get that $x \in A \cup B$.

If A and B are sets, the *symmetric difference* (or *Boolean sum*) of A and B is the set $A + B$ defined by

$$A + B = (A - B) \cup (B - A).$$

This operation is commutative ($A + B = B + A$) and associative ($A + (B + C) = (A + B) + C$), and is such that $A + \emptyset = A$ and $A + A = \emptyset$.

This may be the right time to straighten out a trivial but occasionally puzzling part of the theory of intersections. Recall, to begin with, that intersections were defined for non-empty collections only. The reason is that the same approach to the empty collection does not define a set. Which x's are specified by the sentence

$$x \in X \text{ for every } X \in \emptyset?$$

As usual for questions about $\emptyset$ the answer is easier to see for the corresponding negative question. Which x's do *not* satisfy the stated condition? If it is not true that $x \in X$ for every $X \in \emptyset$, then there must exist an X in $\emptyset$ such that $x \notin X$; since, however, there do not exist any X's in $\emptyset$ at all, this is absurd. Conclusion: no x fails to satisfy the stated condition, or, equivalently, every x does satisfy it. In other words, the x's that the condition specifies exhaust the (nonexistent) universe. There is no profound problem here; it is merely a nuisance to be forced always to

be making qualifications and exceptions because some set somewhere along some construction might turn out to be empty. There is nothing to be done about this; it is just a fact of life.

If we restrict our attention to subsets of a particular set E, as we have temporarily agreed to do, then the unpleasantness described in the preceding paragraph appears to go away. The point is that in that case we can define the intersection of a collection $\mathcal{C}$ (of subsets of E) to be the set

$$\{x \in E : x \in X \text{ for every } X \in \mathcal{C}\}.$$

This is nothing revolutionary; for each non-empty collection, the new definition agrees with the old one. The difference is in the way the old and the new definitions treat the empty collection; according to the new definition

$$\bigcap_{X \in \emptyset} X = E.$$

(For which elements x of E can it be false that $x \in X$ for every $X \in \emptyset$?) The difference is just a matter of language. A little reflection reveals that the "new" definition offered for the intersection of a collection $\mathbb{C}$ of subsets E is really the same as he old definition of the intersection of the collection $\mathcal{C} \cup \{E\}$, and the latter is never empty.

We have been considering subsets of a set E; do those subsets themselves constitute a set? The following principle guarantees that the answer is yes.

> **Axiom of powers.** *For each set there exists a collection of sets that contains among its elements all the subsets of the given set.*

In other words, if E is a set, then there exists a set (collection) $\mathcal{P}$ such that if $X \subset E$, then $X \in \mathcal{P}$.

The set $\mathcal{P}$ described above maybe larger than wanted; it may contain elements other than the subsets of E. This is easy to remedy; just apply the axiom of specification to form the set $\{X \in \mathcal{P} : X \subset E\}$. (Recall that "$X \subset E$" says the same thing as "for all x (if $x \in X$ then $x \in E$)".) Since, for every X, a necessary and sufficient condition that X belongs to this set is that X be a subset of E, it follows that if we change notation and call this set $\mathcal{P}$ again, then

$$\mathcal{P} = \{X : X \subset E\}.$$

The set $\mathcal{P}$ is called the *power set* of E; the axiom the extension guarantees its uniqueness. The dependence of $\mathcal{P}$ on E is denoted by writing $\mathcal{P}(E)$ instead of just $\mathcal{P}$.

Because the the set $\mathcal{P}(E)$ is very big in comparison with E; it is not easy to give examples. If $E = \emptyset$, the situation is clear enough; the set $\mathcal{P}(\emptyset)$ is the singleton $\{\emptyset\}$. The power sets of singletons and pairs are also easily describable; we have

$$\mathcal{P}(\{a\}) = \{\emptyset, \{a\}\}$$

and

$$\mathcal{P}(\{a, b\}) = \{\emptyset, \{a\}, \{b\}, \{a\,b\}\}.$$

The power set of a triple has eight elements. The reader can probably guess (and is hereby challenged to prove) the generalization that includes all these statements: the power set of a finite set with, say, n elements has 2^n elements. (Of course concepts like "finite" and "2^n" have no official standing for us yet; this should not prevent them from being unofficially understood.)

Editor's proof. Let us have a number $n \in \mathbf{N}$, and a set A with length n. May we denote the sets in $\mathcal{P}(A)$ of length $i \in \{1, \ldots, n\}$ with the symbol A^i. Then

$$|\mathcal{P}(A)| = \sum_{i=0}^{n} |A^i| = \sum_{i=0}^{n} \binom{n}{i}.$$

According to the binomial theorem

$$\sum_{i=0}^{n} \binom{n}{i} = \sum_{i=0}^{n} \binom{n}{i} \cdot 1^{n-i} \cdot 1^{i} = (1+1)^n = 2^n.$$

The occurrence of n as an exponent (the n-th power of 2) has something to do with the reason why a power set bears its name.

If $\mathcal{C}$ is a collection of subsets of a set E (that is, $\mathcal{C}$ is a subcollection of $\mathcal{P}(E)$), then write

$$\mathcal{D} = \{X \in \mathcal{P}(E) : X' \in \mathcal{C}\}.$$

(To be certain that the condition used in the definition of $\mathcal{D}$ is a sentence in the precise technical sense, it must be rewritten in something like the form

$$\text{for some } Y \Big(Y \in \mathcal{C} \text{ and for all } x \big(x \in X \text{ if and only if } (x \in E \text{ and } x \notin Y) \big) \Big).$$

Similar comments often apply when we wish to use defined abbreviations instead of logical and set-theoretic primitives only. The translation rarely requires any ingenuity and we shall usually omit it.) It is customary to denote the union and the intersection of the collection $\mathcal{D}$ by the symbols

$$\bigcup_{X \in \mathcal{C}} X' \quad \text{and} \quad \bigcap_{X \in \mathcal{C}} X'.$$

In this notation the general forms of the De Morgan laws become

$$\left(\bigcup_{X \in \mathcal{C}} X \right)' = \bigcap_{X \in \mathcal{C}} X'$$

and

$$\left(\bigcap_{X \in \mathcal{C}} X \right)' = \bigcup_{X \in \mathcal{C}} X'.$$

The proofs of these equations are immediate consequences of the appropriate definitions.

Exercise. Prove that $\mathcal{P}(E) \cap \mathcal{P}(F) = \mathcal{P}(E \cap F)$.

Editor's proof. Let $X \in \mathcal{P}(E) \cap \mathcal{P}(F)$. Then $X \subset E$ and $X \subset F$, therefore $X \subset E \cap F$, thus $X \in \mathcal{P}(E \cap F)$. Now, let $X \in \mathcal{P}(E \cap F)$, we get $X \subset E \cap F$, that is $X \subset E$ and $X \subset F$, therefore $X \in \mathcal{P}(E) \cap \mathcal{P}(F)$.

Exercise. Prove that $\mathcal{P}(E) \cup \mathcal{P}(F) \subset \mathcal{P}(E \cup F)$.

Editor's proof. Let $X \in \mathcal{P}(E) \cup \mathcal{P}(F)$. That means either $X \subset E$ or $X \subset F$ is true. Since $X \subset E \cup F$, we get $X \in \mathcal{P}(E \cup F)$.

These assertions can be generalized to

$$\bigcap_{X \in \mathcal{C}} \mathcal{P}(X) = \mathcal{P}\left(\bigcap_{X \in \mathcal{C}} X\right)$$

and

$$\bigcup_{X \in \mathcal{C}} \mathcal{P}(X) \subset \mathcal{P}\left(\bigcup_{X \in \mathcal{C}} X\right).$$

Further elementary facts:

$$\bigcap_{X \in \mathcal{P}(E)} X = \emptyset,$$

and

$$\text{if } E \subset F, \text{ then } \mathcal{P}(E) \subset \mathcal{P}(F).$$

A curious question concerns the commutativity of the operators $\mathcal{P}$ and $\cup$.

Exercise. Show that E is always equal to

$$\bigcup_{X \in \mathcal{P}(E)} X$$

(that is $E = \bigcup \mathcal{P}(E)$), but that the result of applying $\mathcal{P}$ and $\bigcup$ to E in the other order is a set that includes E as a subset, typically a proper subset.

Editor's proof. Let $x \in E$. Since $E \subset E$ ($E \in \mathcal{P}(E)$), we get

$$x \in \bigcup_{X \in \mathcal{P}(E)} X.$$

Now let

$$x \in \bigcup_{X \in \mathcal{P}(E)} X.$$

An equivalent formulation is the following: x belongs to the preceding set if and only if there exists a set $A \subset E$ so that $x \in A$. The first half of the exercise is proved.

Before proving the next statement, let us observe the following: given a set A, and one of its element $a \in A$, then $a \in \mathcal{P}(a)$; given another element $b \in A$, we again, get $b \in \mathcal{P}(b)$. The statements $a, b \in \mathcal{P}(a \cup b)$ are also true. This can be generalized the following way

$$A \subset \mathcal{P}\left(\bigcup_{x \in A} x\right).$$

In order to prove the last bit ("typically a proper subset"), first lets use the notation $\mathcal{X}$ instead of E. We may notice that there may be a set X in $\mathcal{X}$ such that X contains an element x whose singleton $\{x\}$ does not belong to the "big" set $\mathcal{X}$.

However when we apply the union operator to the set $\mathcal{X}$:

$$\bigcup_{X \in \mathcal{X}} X,$$

we get a new set that contains x. After using the power operator:

$$\mathcal{P}\left(\bigcup_{X \in \mathcal{X}} X\right),$$

the singleton $\{x\}$ will be part of the resulting set, since

$$\{x\} \subset \bigcup_{X \in \mathcal{X}} X.$$