1. Absolute value for the reals.

Definition. (Absolute value of a real number.)

Let r be a real number.

The **absolute value** *of r, which is denoted by $|r|$, is the non-negative real number defined by*

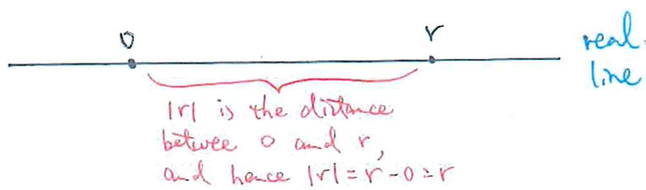
$$|r| = \begin{cases} r & \text{if } r \geq 0 \\ -r & \text{if } r < 0 \end{cases}.$$

Remarks.

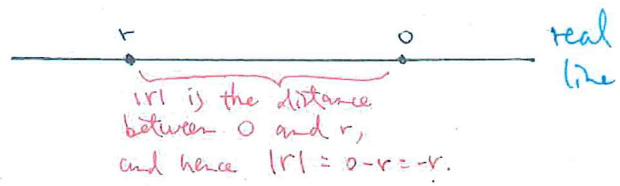
(a) In a less formal manner we may refer to $|r|$ is the **magnitude** of the real number r.

(b) This is the geometric interpretation of the definition: $|r|$ is the distance between the point identified as 0 and the point identified as r on the real line.

(Case 1). Suppose $r \geq 0$. Then:



(Case 2). Suppose $r < 0$. Then:



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Lemma (1).

Let $r \in \mathbb{R}$. The statements below hold:

(a) $r \geq 0$ *iff* $|r| = r$.

(b) $r \leq 0$ *iff* $|r| = -r$.

(c) $r = 0$ *iff* $|r| = 0$.

(d) $-|r| \leq r \leq |r|$.

Proof. Exercise in word game on the definition and the word *iff*.

Lemma (2).

Let $r \in \mathbb{R}$. The statements below hold:

(a) $|r|^2 = r^2$. (b) $|r| = \sqrt{r^2}$.

Remark.

What is the relevance of Lemma (2)?

Here is one example:

(a) Whenever we obtain in a calculation

$$|\text{'blah-blah-blah'}|^2,$$

we may replace this expression by

$$(\text{'blah-blah-blah'})^2,$$

which may be easier to handle.

Lemma (2).

Let $r \in \mathbb{R}$. The statements below hold:

(a) $|r|^2 = r^2$. (b) $|r| = \sqrt{r^2}$.

Proof.

Let $r \in \mathbb{R}$.

(a) We have $r \geq 0$ or $r < 0$.

(Case 1.) Suppose $r \geq 0$. Then $|r| = r$. Therefore $|r|^2 = r^2$.

(Case 2.) Suppose $r < 0$. Then $|r| = -r$. Therefore $|r|^2 = (-r)^2 = r^2$.

Hence, in any case, $|r|^2 = r^2$.

(b) We have verified that $|r|^2 = r^2$. Since $|r| \geq 0$, we have $|r| = \sqrt{|r|^2} = \sqrt{r^2}$.

Lemma (3).

Let $s, t \in \mathbb{R}$. The equality $|st| = |s||t|$ holds.

Proof.

Let $s, t \in \mathbb{R}$. We have $|st|^2 = (st)^2 = s^2t^2 = |s|^2|t|^2 = (|s||t|)^2$. Then $|st| = |s||t|$. (Why?)

Lemma (4).

Let $r, c \in \mathbb{R}$. Suppose $c \geq 0$. Then the statements below hold:

(a) $|r| \leq c$ iff $-c \leq r \leq c$.

(b) $|r| < c$ iff $-c < r < c$.

(c) $|r| \geq c$ iff $(r \leq -c$ or $r \geq c)$.

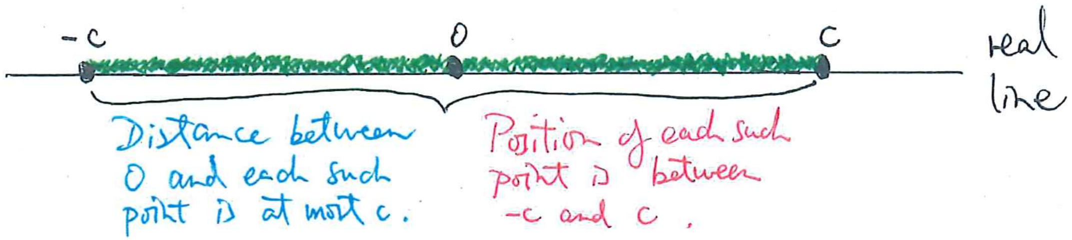
(d) $|r| > c$ iff $(r < -c$ or $r > c)$.

Geometric interpretation? Below is that for (a); how about others?

(a) The two descriptions in blue, red on r, c are the same:

'The distance between $0, r$ as points in the real line is at most c.'

'The position of r in the real line is within the points $-c, c$.'



Lemma (4).

Let $r, c \in \mathbb{R}$. Suppose $c \geq 0$. Then the statements below hold:

(a) $|r| \leq c$ iff $-c \leq r \leq c$.

(b) $|r| < c$ iff $-c < r < c$.

(c) $|r| \geq c$ iff ($r \leq -c$ or $r \geq c$).

(d) $|r| > c$ iff ($r < -c$ or $r > c$).

Proof. Exercise.

Definition. (Absolute value function.)

The function from $\mathbb{R}$ to $\mathbb{R}$ defined by assigning each real number to its absolute value is called the **absolute value function**.

Remark.

In symbols we may denote this function by $|\cdot|$, and express its 'formula of definition' as '$x \longmapsto |x|$ for each $x \in \mathbb{R}$', or equivalently as

$$|x| = \begin{cases} x & \text{if } x \geq 0 \\ -x & \text{if } x < 0 \end{cases}$$

We may also express the 'formula of definition' of the function $|\cdot|$ as '$|x| = \sqrt{x^2}$ for any $x \in \mathbb{R}$'.

2. **Triangle Inequality on the real line.**

Lemma (5).
Suppose x, y are real numbers.
Then $x^2 + y^2 \geq 2xy$.
Equality holds iff $x = y$.

Proof. Suppose x, y are real numbers.
We have $(x^2 + y^2) - 2xy = (x - y)^2$.

(a) Since x, y are real, $x - y$ is real.
Then $(x - y)^2 \geq 0$.
Therefore $x^2 + y^2 \geq 2xy$.

(b) i. Suppose $x = y$.
Then $(x^2 + y^2) - 2xy = (x - y)^2 = (x - x)^2 = 0$.
Therefore $x^2 + y^2 = 2xy$.

ii. Suppose $x^2 + y^2 = 2xy$.
Then $0 = (x^2 + y^2) - 2xy = (x - y)^2$.
Therefore $x - y = 0$. Hence $x = y$.

Theorem (6). (Triangle Inequality on the real line.)

Suppose u, v are real numbers. Then $|u+v| \le |u|+|v|$. Equality holds iff $uv \ge 0$.

(a) (b)

Proof.

Suppose u, v are real numbers.

Then

$$(|u|+|v|)^2 - |u+v|^2$$

$$= (|u|+|v|)^2 - (u+v)^2$$

$$= (|u|^2+|v|^2+2|u||v|) - (u^2+v^2+2uv)$$

$$= 2(|u||v| - uv)$$

$$= 2(|uv| - uv)$$

[Lemma(2) applied.]

[Lemma(3) applied.]

(a) We have $uv \le |uv|$.

Then $(|u|+|v|)^2 \ge |u+v|^2$. (why?)

Since $|u+v| \ge 0$ and $|u|+|v| \ge 0$, we have $|u+v| \le |u|+|v|$.

(b)(i). Suppose $uv \ge 0$.

Then $|uv| = uv$ (by definition).

Therefore

$$(|u|+|v|)^2 - |u+v|^2 = 2(|uv| - uv) = 0.$$

Hence $|u+v| = |u|+|v|$. (why?)

(ii) Suppose $|u+v| = |u|+|v|$.

Then

$$0 = (|u|+|v|)^2 - |u+v|^2 = 2(|uv| - uv).$$

Therefore $|uv| = uv$

Hence $uv \ge 0$ (by Lemma(1).).

Remark. Alternative argument?

Corollary (7). (Corollary to Triangle Inequality on the real line.)

Suppose s, t are real numbers. Then $\big|\,|s| - |t|\,\big| \le |s-t|$. Equality holds iff $st \ge 0$.

3. **Appendix: Triangle Inequality on the plane.**

Theorem (6) can be regarded as a special case of Theorem (8).

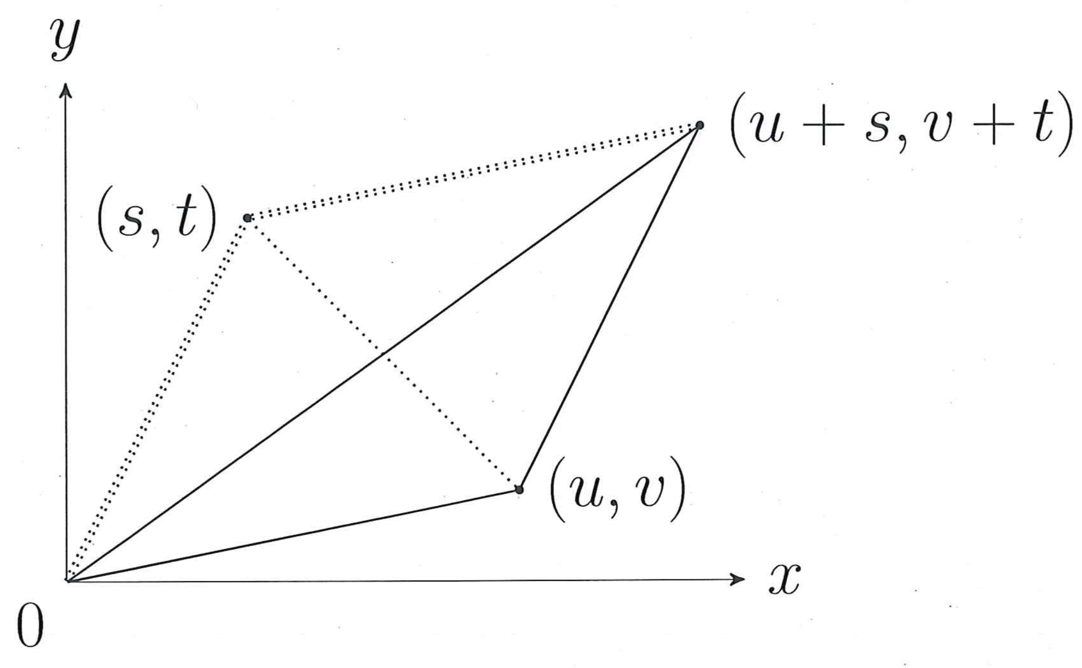
Theorem (8). (Triangle Inequality on the plane.)

Suppose u, v, s, t are real numbers.

Then $\sqrt{(u+s)^2 + (v+t)^2} \leq \sqrt{u^2+v^2} + \sqrt{s^2+t^2}$.

Equality holds iff ($ut = vs$ and $us \geq 0$ and $vt \geq 0$).

Remark. This is the geometric interpretation of Theorem (7) on the coordinate plane:



Proof. Postponed.