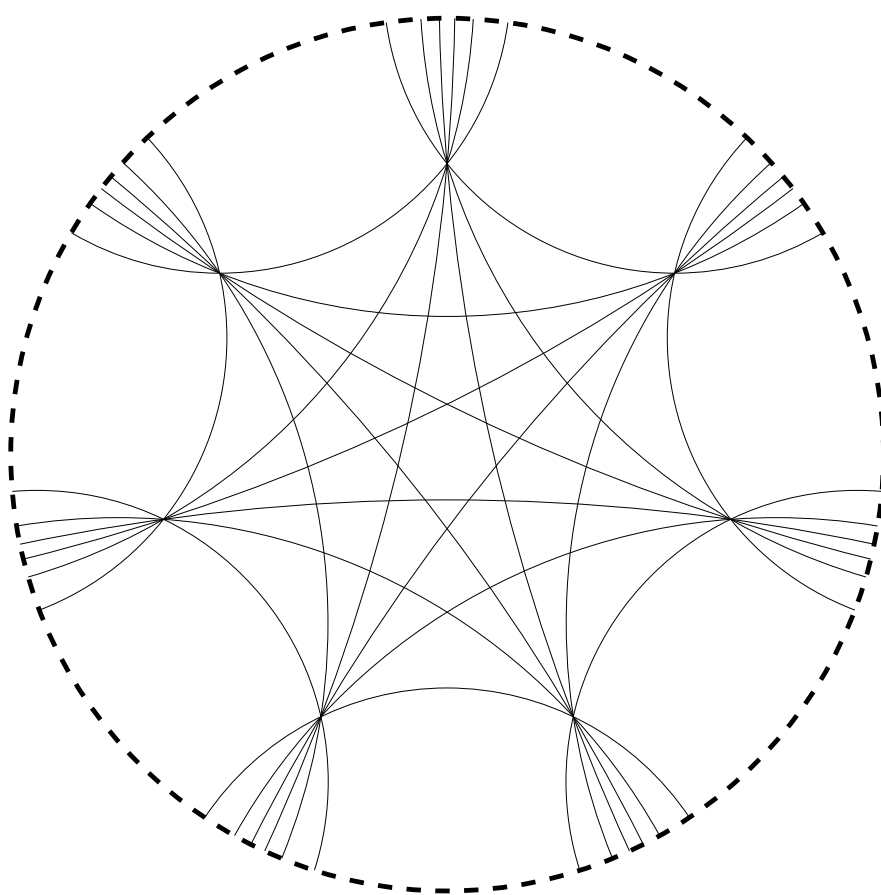


# Elementary Geometrese

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## Contents

### Contents

<b>I</b>	<b>Incidence</b>	<b>1</b>
1	Models and Theories . . . . .	2
2	Incidence Geometry . . . . .	4
3	Parallel Lines . . . . .	7
4	Collineations . . . . .	10
<b>II</b>	<b>Order</b>	<b>11</b>
5	Betweenness . . . . .	12
6	Ordered Geometry . . . . .	15
7	Angles . . . . .	18
<b>III</b>	<b>Neutral Plane Geometry</b>	<b>21</b>
8	Congruence . . . . .	22
9	Plane Geometry . . . . .	25
10	Transversals . . . . .	30
11	Perpendiculars and Tangents . . . . .	35
12	Incircles and Excircles . . . . .	38
<b>IV</b>	<b>Euclidean Planes</b>	<b>41</b>
13	Euclidean Planes . . . . .	42
<b>V</b>	<b>Models</b>	<b>47</b>
14	$\mathbb{R}^2$ – The Cartesian Plane . . . . .	48
15	$\mathbb{H}$ – The Hyperbolic Half Plane . . . . .	55
16	$\mathbb{P}$ – The Poincare Disc . . . . .	62
17	$\mathbb{K}$ – The Klein Disc . . . . .	65
18	$\mathbb{G}$ – The Gans Disc . . . . .	66
	<b>Bibliography</b>	<b>67</b>

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— I —

Incidence

## 1 Models and Theories

One of the goals of this class is to explore the classical theory of geometry as laid out in the famous *Elements of Geometry* by the Greek mathematician Euclid. Before we begin, though, a few words about the distinction between a *theory* and a *model* are in order.

- A **theory** consists of one or more *undefined terms*, which are used in one or more *axioms* or *definitions*, which are then the basis for a list of logical deductions called *theorems*. This may be how you think about geometry as you learned it in high school.
- A **model** is a concrete realization of a theory: a way to associate the undefined terms to “real” objects such that the axioms are satisfied. Models are where we perform calculations and draw pictures.

The correspondence between theories and models is not one-to-one (in either direction). There are theories which have many models, other theories with exactly one model, and yet other theories which have no models at all. Conversely, a given concrete object is likely a model of many different theories, though not all of them will be interesting.

The difference between theory and model turns out to have significant practical applications. In the real world we compute with concrete objects – things like numbers and sets. This is useful, but concrete objects have a tendency to get very messy very quickly. However if some aspects of a concrete object are a model for some theory, we can “throw away” unimportant details and compute more easily at an abstract level. For instance many important theorems about matrices are difficult and tedious to prove if we think of matrices as arrays of numbers but become simple if we think of matrices as linear transformations.

An example of a theory which you may have seen before is Euclid’s postulates for geometry. These are a small number of statements which Euclid took to be obviously true (*axioms* in modern lingo) such as “two points determine a line” and so on. Euclid developed this theory of geometry in a book, called *The Elements*, which went on to become a standard mathematical textbook for many centuries.

The development and proliferation of Euclid’s geometry predates the recognition of the need to carefully distinguish between a theory and its models, and early work did not make this distinction. Euclid seems to have written under the assumption that the universe comes equipped with exactly one geometry – that his theory has only one model. Unfortunately for us, this early confusion led to some problems. First, it turns out that there are many models of geometry, some of which are very strange. We will explore several models of geometry in this text.

The second problem we inherit from Euclid is more serious. Because he conflated his *theory* of geometry with only one particular *model*, and this confusion was not cleared up until much later, and because his book was so influential, Euclid left us with a language problem. The basic terms of geometry – point,

---

line, circle, segment, angle – have multiple meanings. There is the meaning inside Euclid’s *model* of geometry, which corresponds mostly to the bits of geometry we use in college algebra and calculus. But these words have another, more abstract meaning inside Euclid’s *theory* of geometry, and when these terms are used inside other models we can easily get confused. We will look at models of geometry where lines are circles, where points are lines, and where circles are ellipses.

### Theories as Languages

We can think of a theory as a kind of abstract *language*. The undefined terms are the words – nouns, verbs, and so on – while the axioms are the grammar, specifying how the words can be put together into meaningful phrases.

Unlike a natural language, logical theories are very well suited to implementation in software. So, for example, a valid “sentence” expressed in a geometric theory-language can be turned into a drawing by machine. This idea is not new, but it is very powerful.

#### \* \* EXERCISES \* \*

- 1.1. Let  $\alpha, \beta \in \mathbb{R}$  and  $t \in (0, 1)$ .
- (i) If  $\alpha > 0$  and  $\beta > 0$ , then  $\alpha + t(\beta - \alpha) > 0$ .
  - (ii) If  $\alpha > 0$  and  $\beta > 0$ , then  $\alpha + t(\beta - \alpha) < 0$ .
- 1.2. Let  $\alpha, \beta$ , and  $\gamma$  be in  $\mathbb{R}$  such that  $\alpha < \beta < \gamma$ . Show that either  $\beta^2 < \alpha^2$  or  $\beta^2 < \gamma^2$ .
-

## 2 Incidence Geometry

Traditional plane geometry involves many different concepts, including *lines*, *angles*, *congruent*, and many others. In order to manage the complexity this entails, we will build up our geometries one piece at a time starting here with the idea of *collinearity*.

**Def’n 2.1** (Incidence Geometry). Let  $P$  be a set, whose elements we call *points*. A ternary relation  $\langle *, *, * \rangle$  on  $P$  is called a *collinearity relation* if the following properties are satisfied.

IG1. If  $a, b$ , and  $c$  are points such that  $\langle a, b, c \rangle$ , then  $\langle b, a, c \rangle$  and  $\langle a, c, b \rangle$ .

IG2. If  $a$  and  $b$  are points such that  $a \neq b$ , then  $\langle a, b, b \rangle$ .

IG3.  $\langle a, a, a \rangle$  does not hold for any point  $a$ .

IG4. If  $a, b \in P$  are distinct points, there is a point  $c \in P$  such that  $\langle a, b, c \rangle$  does not hold.

IG5. **Exchange Property:** If  $a, b, u$ , and  $v$  are points such that  $a \neq b$ ,  $u \neq v$ ,  $\langle a, b, u \rangle$ , and  $\langle a, b, v \rangle$ , then  $\langle a, u, v \rangle$ .

If such a relation exists we say that  $(P, \langle *, *, * \rangle)$  is an *incidence geometry*. In this case, when  $\langle a, b, c \rangle$  we say that  $a, b$ , and  $c$  are *collinear*.

It is important to remember that the word “collinear” here is an undefined term, and we have to try very hard not to think of ordinary lines and points when using it. (This is part of the theory-model confusion we inherit from history.) The meaning of the word “collinear” is determined precisely by how it is used in the incidence geometry axioms, and only becomes concrete when we specify a particular model. In particular, it does not make sense to draw pictures of the points in an arbitrary incidence geometry!

Although “collinear” is an abstract, undefined term, we’d like for it to behave much like our intuition expects. We want this undefined term to *formalize* our intuition about collinearity. To that end, note that collinearity satisfies some additional basic properties.

**Prop’n 2.2.** Let  $P$  be an incidence geometry. Then we have the following for all points  $a, b$ , and  $c$ .

- (i) If  $\langle a, b, c \rangle$ , then we also have  $\langle b, c, a \rangle$ ,  $\langle c, a, b \rangle$ , and  $\langle c, b, a \rangle$ .
- (ii) If  $a \neq b$ , then  $\langle a, b, a \rangle$  and  $\langle b, a, a \rangle$ .

It may seem strange to define “collinear” before we define “line”; typically we think of points being collinear precisely when there is a unique line contain-



ing all of them. But we can just as easily define lines in terms of collinearity as follows.

**Def'n 2.3** (Line). Let  $P$  be an incidence geometry with distinct points  $a$  and  $b$ . We define the *line* through  $a$  and  $b$  to be the set

$$\overleftrightarrow{ab} = \{c \in P \mid \langle a, b, c \rangle\}.$$

If  $c \in \overleftrightarrow{ab}$ , we say that  $c$  *lies on*  $\overleftrightarrow{ab}$ .

That is, the line through  $a$  and  $b$  is precisely the set of points which are collinear with  $a$  and  $b$ . Remember: it is vital that we not think about drawings of points and lines here. In an arbitrary incidence geometry, “point” and “line” are just *words* which we assume have a particular relationship with one another. Thinking at this level of abstraction may seem unnecessarily difficult at first, but – and it is difficult to overstate this – the abstract way of thinking brings enormous power. Here are some basic properties of lines which can be derived from the properties of collinearity alone.

**Prop'n 2.4.** Let  $P$  be an incidence geometry. Then the following hold for all distinct points  $a$  and  $b$  in  $P$ .

- (i)  $a \in \overleftrightarrow{ab}$  and  $b \in \overleftrightarrow{ab}$ .
- (ii)  $\overleftrightarrow{ab} = \overleftrightarrow{ba}$ .
- (iii) If  $c \in \overleftrightarrow{ab}$  and  $c \neq a$ , then  $\overleftrightarrow{ac} = \overleftrightarrow{ab}$ .
- (iv) If  $u, v \in \overleftrightarrow{ab}$  are distinct points, then  $a, b \in \overleftrightarrow{uv}$ .

Though we will eventually have several examples of incidence geometry, it is crucial when proving theorems that we not rely on any specific model. This is the power of abstraction: any theorem which depends only on properties common to *all* incidence geometries immediately holds in *any* incidence geometry. For example, consider the following theorem.

**Prop'n 2.5** (Line Intersection). Let  $P$  be an incidence geometry with lines  $\ell_1$  and  $\ell_2$ . Then exactly one of the following holds.

- (i)  $\ell_1 = \ell_2$ , and we say  $\ell_1$  and  $\ell_2$  are *coincident*,
- (ii)  $\ell_1 \cap \ell_2 = \emptyset$ , and we say  $\ell_1$  and  $\ell_2$  are *disjoint*, or
- (iii)  $\ell_1 \cap \ell_2 = \{p\}$  for some point  $p$ , and we say  $\ell_1$  and  $\ell_2$  are *incident*.

In the first two cases (coincident or disjoint) we say that  $\ell_1$  and  $\ell_2$  are *parallel*.

*Proof.* Suppose  $\ell_1 \cap \ell_2$  contains at least two points, say  $x$  and  $y$ . Then in fact  $\ell_1 = \overleftrightarrow{xy} = \ell_2$ . So if  $\ell_1 \neq \ell_2$  then  $\ell_1 \cap \ell_2$  contains either exactly one or zero points.  $\square$

This theorem holds in any model of incidence geometry. One problem: we don't have any models of incidence geometry yet! We'll fix this in the next section.

\* \* EXERCISES \* \*

- 2.1. Let  $A = (a_x, a_y)$ ,  $B = (b_x, b_y)$ , and  $C = (c_x, c_y)$  be in  $\mathbb{R}^2$  such that  $A \neq B$ . Show that

$$\det \begin{bmatrix} a_x & a_y & 1 \\ b_x & b_y & 1 \\ c_x & c_y & 1 \end{bmatrix} = 0$$

if and only if  $C = A + t(B - A)$  for some unique  $t \in \mathbb{R}$ . (Hint: Consider the expression  $(c_x - a_x)/(b_x - a_x) = (c_y - a_y)/(b_y - a_y)$ .)

### 3 Parallel Lines

Recall that two lines in an incidence geometry are called *parallel* if they do not meet at a single point. The following question about parallel lines turns out to be interesting.

#### Question

Suppose we have a line  $\ell$  and a point  $p$  in an incidence geometry. How many lines exist which pass through  $p$  and are parallel to  $\ell$ ?

Our intuition says that the answer to this question is clearly 1, and Euclid agreed. It turns out that the parallel lines in our models so far behave in some very different ways.

#### Parallels in $\mathbb{R}^2$

In [Exercise 14.2](#) we found a nice way to characterize whether the lines determined by four cartesian points are parallel: if  $A = (a_x, a_y)$ ,  $B = (b_x, b_y)$ ,  $C = (c_x, c_y)$ , and  $D = (d_x, d_y)$  are points in  $\mathbb{R}^2$  with  $A \neq B$  and  $C \neq D$ , then  $\overleftrightarrow{AB} \parallel \overleftrightarrow{CD}$  if and only if

$$\det \begin{bmatrix} b_x - a_x & d_x - c_x \\ b_y - a_y & d_y - c_y \end{bmatrix} = 0.$$

With this, we can show the following.

**Prop'n 3.1.** If  $\ell = \overleftrightarrow{AB}$  is a line and  $C \notin \ell$  a point in  $\mathbb{R}^2$ , then there is exactly one line passing through  $C$  which is parallel to  $\ell$ .

*Proof.* To see existence, let  $D = C + B - A$ . Now  $D \neq C$  since  $B \neq A$ . Moreover,  $\overleftrightarrow{CD}$  and  $\overleftrightarrow{AB}$  are parallel since

$$\det \begin{bmatrix} b_x - a_x & c_x + b_x - a_x - c_x \\ b_y - a_y & c_y + b_y - a_y - c_y \end{bmatrix} = \det \begin{bmatrix} b_x - a_x & b_x - a_x \\ b_y - a_y & b_y - a_y \end{bmatrix} = 0.$$

To see uniqueness, suppose  $X = (x, y)$  is a point (different from  $C$ ) such that  $\overleftrightarrow{CX}$  is parallel to  $\overleftrightarrow{AB}$ . Then

$$0 = \det \begin{bmatrix} x - c_x & b_x - a_x \\ y - c_y & b_y - a_y \end{bmatrix} = \det \begin{bmatrix} x - c_x & c_x + b_x - a_x - c_x \\ y - c_y & c_y + b_y - a_y - c_y \end{bmatrix}.$$

So  $X$ ,  $C$ , and  $D$  are collinear, and thus  $\overleftrightarrow{CX} = \overleftrightarrow{CD}$ . □

This proof remains valid in the rational plane.

### Parallels in $\mathbb{D}$

Suppose  $\ell$  is a line and  $x$  a point in the unit disc. There are *infinitely many* lines passing through  $x$  which are parallel to  $\ell$ . To see why, remember that  $\ell$  is contained in a line  $\ell_{A,B}$  in the Cartesian Plane. Choose any point  $y$  on this Cartesian line which is not in the unit disk, and let  $\ell_{x,y}$  be the Cartesian line generated by  $x$  and  $y$ . Now  $\ell' = \ell_{x,y} \cap \mathbb{D}$  is parallel to  $\ell$ .

### Parallels in $\mathbb{A}$

It is not too difficult to see that there are *no* pairs of parallel lines in the antipodal sphere; any two different great circles have to intersect.

### Parallels in the Fano plane

In the Fano Plane, no two lines are parallel. In particular, if  $\ell$  is a line and  $x \notin \ell$  a point, there are *no* lines passing through  $x$  which are parallel to  $\ell$ .

Considering these examples, there seem to be (at least) three qualitatively different possibilities for the answer to our Question about parallel lines. This observation is what motivates the following definition.

**Def'n 3.2** (The Parallel Postulates). We say that an incidence geometry  $P$  is

**Elliptic** if there are *no* lines passing through  $x$  and parallel to  $\ell$ , for all lines  $\ell$  and points  $x \notin \ell$ .

**Euclidean** if there is *exactly one* line passing through  $x$  and parallel to  $\ell$ , for all lines  $\ell$  and points  $x \notin \ell$ .

**Hyperbolic** if there are *infinitely many* lines passing through  $x$  and parallel to  $\ell$ , for all lines  $\ell$  and points  $x \notin \ell$ .

With this definition,  $\mathbb{R}^2$  and  $\mathbb{Q}^2$  are Euclidean,  $\mathcal{F}$  and  $\mathbb{A}$  are Elliptic, and  $\mathbb{D}$  and  $\mathbb{H}$  are Hyperbolic. It is important to note that a given incidence geometry need not satisfy **any** of these properties! We will see a strange example of this in the exercises.

### Transitivity of Parallelism

The kinds of “geometries” that arise from our three different Parallel Postulates will be different – perhaps drastically so – as illustrated by the following result.

**Prop'n 3.3.** Suppose  $P$  is a Euclidean incidence geometry, with lines  $\ell_1$ ,  $\ell_2$ , and  $\ell_3$ . If  $\ell_1 \parallel \ell_2$  and  $\ell_2 \parallel \ell_3$ , then  $\ell_1 \parallel \ell_3$ . That is, the relation “is parallel to” is transitive.

*Proof.* If  $\ell_1 \cap \ell_2 = \emptyset$ , then  $\ell_1 \parallel \ell_3$  by definition. Suppose instead that  $\ell_1$  and  $\ell_3$  have *at least one* point in common, say  $p$ . Since  $\ell_1$  is parallel to  $\ell_2$ , note that  $p \notin \ell_2$ . Since  $\mathcal{P}$  is Euclidean, there is exactly one line passing through  $p$  which is parallel to  $\ell_2$ ; call this line  $\ell$ . But now  $\ell_1$  is a line parallel to  $\ell_2$  which passes through  $p$ , so that  $\ell_1 = \ell$ . Likewise,  $\ell_3 = \ell$ . Hence  $\ell_1 = \ell_3$ , and so  $\ell_1 \parallel \ell_3$  as claimed.  $\square$

Note that in a Hyperbolic incidence geometry, this need not be the case. If we have two lines  $\ell_1$  and  $\ell_3$  which pass through a point  $p$  and are parallel to a given line  $\ell_2$ , then  $\ell_1$  and  $\ell_3$  are *not* parallel. And in an Elliptic incidence geometry the transitivity of parallelism is irrelevant: there are no pairs of distinct parallel lines to begin with.

\* \* EXERCISES \* \*

Note that although all of our example incidence geometries happen to be either elliptic, euclidean, or hyperbolic, any given incidence geometry need not be in any of these classes. The next two exercises construct an example.

**Def'n 3.4** (The Two-Pointed Line). Let  $P = \mathbb{R} \cup \{A, B\}$ , where we think of  $A$  and  $B$  simply as symbols not belonging to  $\mathbb{R}$ . We define a ternary relation on  $P$  as follows. Given points  $x, y, z \in P$ , not all equal, we say that  $\langle x, y, z \rangle$  if one of the following holds.

- (i)  $\{x, y, z\} \subseteq \mathbb{R}$ .
- (ii)  $\{x, y, z\} = \{A, \zeta\}$  for some  $\zeta \in \mathbb{R}$ .
- (iii)  $\{x, y, z\} = \{B, \zeta\}$  for some  $\zeta \in \mathbb{R}$ .
- (iv)  $\{x, y, z\} = \{A, B\}$ .

We refer to this structure as the Two-Pointed Line.

- 3.1. Show that the Two-Pointed Line is an incidence geometry.
- 3.2. Show that the Two-Pointed Line is an incidence geometry which is neither elliptic, nor euclidean, nor hyperbolic as follows.
  - (i) Find a line  $\ell$  and a point  $x$  in the Two-Pointed Line such that there is exactly one line passing through  $x$  and parallel to  $\ell$ .
  - (ii) Find a line  $\ell$  and a point  $x$  in the Two-Pointed Line such that there are infinitely many lines passing through  $x$  and parallel to  $\ell$ .

## 4 Collineations

Collinearity relations represent a kind of *abstract structure*. Typically in mathematics, whenever we have a kind of structure, the mappings which *preserve* that structure are interesting. In the case of an incidence geometry such mappings are called *collineations*.

**Def'n 4.1** (Collineation). Suppose we have incidence geometries  $P$  and  $Q$ . A bijective mapping  $\varphi : P \rightarrow Q$  is called a *collineation* if, for all points  $x, y, z \in P$ , whenever  $\langle x, y, z \rangle$  in  $P$ , we also have  $\langle \varphi(x), \varphi(y), \varphi(z) \rangle$  in  $Q$ .

**Prop'n 4.2.** We have the following.

- (i) If  $P$  is an incidence geometry, then the identity map  $1 : P \rightarrow P$  is a collineation.
- (ii) If  $\varphi : P \rightarrow Q$  and  $\psi : Q \rightarrow R$  are collineations, then  $\psi \circ \varphi$  is a collineation.
- (iii) If  $\varphi : P \rightarrow Q$  is a collineation, then  $\varphi^{-1} : Q \rightarrow P$  is a collineation.

### \* \* EXERCISES \* \*

4.1. Let  $\varphi : \mathbb{R}^2 \rightarrow \mathbb{R}^2$  be given by

$$\varphi(X) = MX + B,$$

where  $M$  is an invertible  $2 \times 2$  matrix over  $\mathbb{R}$  and  $B \in \mathbb{R}^2$ . Show that  $\varphi$  is a collineation.

— II —  
Order

## 5 Betweenness

In an incidence geometry we have the ability to detect whether three given points are collinear. However an arbitrary incidence geometry has no notion of “order” for the points on a given line, as we might intuitively expect. For instance, the points  $(0,0)$ ,  $(1,1)$ , and  $(2,2)$  are collinear in  $\mathbb{R}^2$  and we think of  $(1,1)$  as being “between” the other two. But in the Fano plane, does it make sense to order the points on a line? Presently we introduce another piece of technology to an incidence geometry which will allow us to formalize the concept of “betweenness”.

**Def’n 5.1** (Betweenness). Let  $P$  be an incidence geometry. We say that a ternary relation  $[* * *]$  on  $P$  is a *betweenness relation* if the following properties hold.

- B1. If  $[xyz]$ , then  $x$ ,  $y$ , and  $z$  are distinct and  $\langle x, y, z \rangle$ .
- B2. If  $[xzy]$ , then  $[yzx]$ .
- B3. If  $x$ ,  $y$ , and  $z$  are distinct points such that  $\langle x, y, z \rangle$ , then at least one of  $[xyz]$ ,  $[yzx]$ , and  $[zxy]$  is true.
- B4. If  $[xyz]$  and  $[xzw]$ , then  $[xyw]$  and  $[yzw]$ .
- B5. If  $[xyz]$  and  $[yzw]$ , then  $[xyw]$  and  $[xzw]$ .
- B6. **Interpolation Property:** If  $x$  and  $y$  are distinct points, then there exist points  $z_1$ ,  $z_2$ , and  $z_3$  such that  $[z_1xy]$ ,  $[xz_2y]$ , and  $[xyz_3]$ .

If  $[xyz]$ , we say that  $z$  is *between*  $x$  and  $y$ . B1 says that “betweenness” is a refinement of “collinearity”. B2 says that betweenness is symmetric (if we fix the middle point). B3 says that distinct collinear points must be in order somehow, outlawing the bizarre situation where points are collinear but not in order. B4 and B5 are a little more interesting; they are a kind of coherence condition for betweenness. Consider a situation like [Figure 5.1](#). Axiom B4 says that if  $y$  is between  $x$  and  $z$  and  $z$  is between  $x$  and  $w$ , then  $y$  is between  $x$  and  $w$  and  $z$  is between  $y$  and  $w$ . That seems reasonable enough, and B5 says something similar.

As shorthand, if  $x$ ,  $y$ ,  $z$ , and  $w$  are distinct points, we will say  $[xyzw]$  precisely when  $[xyz]$ ,  $[xyw]$ ,  $[xzw]$ , and  $[yzw]$ . More generally, if  $x_1, \dots, x_n$  are distinct points, then  $[x_1x_2 \dots x_n]$  means that  $[x_ix_jx_k]$  for all triples  $(i, j, k)$  with  $1 \leq i < j < k \leq n$ . The next definition will probably look familiar.

**Def’n 5.2** (Segment, Ray). Let  $x$  and  $y$  be points in an incidence geometry  $P$  with a betweenness relation.



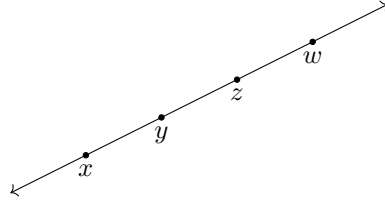


Figure 5.1: The coherence conditions B4 and B5.

(i) The set

$$\overline{xy} = \{z \in P \mid z = x \text{ or } z = y \text{ or } [xzy]\}$$

is called the *segment* with *endpoints*  $x$  and  $y$ . If  $x = y$  we say that the segment  $\overline{xy}$  is *degenerate*. If  $z \in \overline{xy}$  and  $z \neq x$  and  $z \neq y$ , we say that  $z$  is *interior to*  $\overline{xy}$ .

(ii) The set

$$\overrightarrow{xy} = \{z \in P \mid z = x \text{ or } z = y \text{ or } [xzy] \text{ or } [xyz]\}$$

is called the *ray* with *vertex*  $x$  *toward*  $y$ . If  $x = y$  we say that the ray  $\overrightarrow{xy}$  is *degenerate*. If  $z \in \overrightarrow{xy}$  and  $z \neq x$ , we say that  $z$  is *interior to*  $\overrightarrow{xy}$ .

The following properties of segments and rays essentially fall out of the definition.

**Prop'n 5.3.** If  $P$  is an incidence geometry and  $[\dots]$  a betweenness relation on  $P$ , then the following hold.

1.  $\overline{xy} = \overline{yx}$  for all distinct points  $x$  and  $y$ .
2.  $\overline{xy} \subseteq \overrightarrow{xy} \subseteq \overleftarrow{xy}$  for all distinct points  $x$  and  $y$ .
3. If  $\ell$  is a line and  $x$  and  $y$  distinct points, then  $\overline{xy} \cap \ell$  is either  $\overline{xy}$ ,  $\emptyset$ , or  $\{p\}$  for some point  $p$ .
4.  $\overrightarrow{xy} \cap \overrightarrow{yx} = \overline{xy}$  for all distinct points  $x$  and  $y$ .

**Prop'n 5.4** (Line Decomposition). Suppose  $P$  is an incidence geometry with a betweenness relation, and let  $x, y \in P$  be distinct points. Then

$$\overleftrightarrow{xy} = \{z \in P \mid z = x \text{ or } z = y \text{ or } [xzy] \text{ or } [zyx] \text{ or } [xyz] \text{ or } [yxz]\}.$$

Proposition 5.4 is a useful technical result: if we know that a given point  $z$  lies on a line  $\ell_{x,y}$ , then there are five possibilities. The next result is useful for the same reason.

**Prop'n 5.5.** Let  $P$  be an incidence geometry with a betweenness relation and suppose  $x, y, z$ , and  $w$  are points. If  $[xzy]$  and  $[xwy]$ , then either  $[xzw]$  or  $[xwz]$  or  $z = w$ .

We can now define *convexity* in terms of betweenness as follows.

**Def'n 5.6** (Convexity). Let  $P$  be an incidence geometry with a betweenness relation. A non empty set  $S$  of points in  $P$  is called *convex* if it is closed under betweenness in the following sense: if  $x, y \in S$  and  $[xzy]$ , then  $z \in S$ .

\* \* EXERCISES \* \*

- 5.1. Let  $a, b$ , and  $c$  be points such that  $[abc]$ . Then it is not the case that  $[acb]$ .
- 5.2. Suppose  $[abc]$  and  $[abd]$ . Show that either  $c = d$  or  $[bcd]$  or  $[bdc]$ .
- 5.3. Suppose  $S$  is a finite set of points containing at least two distinct elements  $a$  and  $b$ . Then there is a point  $c \in \overleftrightarrow{ab}$  such that  $c \notin S$ .
- 5.4. Suppose  $P$  is an incidence geometry with a betweenness relation. If  $x, y$ , and  $z$  are distinct points such that  $[xyz]$ , then the following hold.
  - (i)  $\overline{xy} \cup \overline{yz} = \overline{xz}$ .
  - (ii)  $\overline{xy} \cap \overline{yz} = \{y\}$ .
  - (iii)  $\overrightarrow{yx} \cap \overrightarrow{yz} = \{y\}$ .
  - (iv)  $\overrightarrow{xy} = \overrightarrow{xz}$ .
  - (v)  $\overrightarrow{xy} \cap \overrightarrow{yz} = \overline{xy}$ .
  - (vi)  $\overrightarrow{yx} \cup \overrightarrow{yz} = \overleftarrow{xz}$ .
- 5.5. Let  $P$  be an incidence geometry with a betweenness relation, and let  $S \subseteq P$ . Show that  $S$  is convex if and only if  $\overline{xy} \subseteq S$  for all distinct points  $x, y \in S$ .
- 5.6. Let  $P$  be an incidence geometry with a betweenness relation and  $x, y \in P$  distinct points. Show that the following sets are convex.
  - (i)  $\overleftarrow{xy}$
  - (ii)  $\overline{xy}$
  - (iii)  $\overrightarrow{xy}$
- 5.7. Let  $P$  be an incidence geometry with a betweenness relation. Show that every line in  $P$  contains infinitely many points.

## 6 Ordered Geometry

The existence of a betweenness relation on an incidence geometry says something very strong. Combined with an additional property – the Line Separation property – such geometries are called *ordered*.

**Def’n 6.1** (Ordered Geometry). Let  $P$  be an incidence geometry with a betweenness relation  $[* * *]$ . We say that  $P$  is an *ordered geometry* if it satisfies the following additional *Line Separation Property*.

LS. For every line  $\ell$  there are two sets,  $\mathcal{H}_{1,\ell}$  and  $\mathcal{H}_{2,\ell}$ , which satisfy the following properties.

- (i)  $\mathcal{H}_{1,\ell}$  and  $\mathcal{H}_{2,\ell}$  are not empty.
- (ii)  $\ell$ ,  $\mathcal{H}_{1,\ell}$ , and  $\mathcal{H}_{2,\ell}$  partition  $P$ .
- (iii)  $\mathcal{H}_{1,\ell}$  and  $\mathcal{H}_{2,\ell}$  are convex.
- (iv) If  $x \in \mathcal{H}_{1,\ell}$  and  $y \in \mathcal{H}_{2,\ell}$ , then  $\overline{xy} \cap \ell = \{p\}$  for some point  $p$ .

The sets  $\mathcal{H}_{1,\ell}$  and  $\mathcal{H}_{2,\ell}$  are called *halfplanes*.

The Line Separation property essentially states that every line divides the plane into two “separate” pieces – we might call these pieces the *sides* of the line. Given a line  $\ell$  and points  $x, y \notin \ell$ , we say that  $x$  and  $y$  are on the *same side* of  $\ell$  if they are both in the same halfplane bounded by  $\ell$ , and otherwise they are on *opposite sides*. See [Figure 6.1](#) for a picture. (But remember that a given ordered geometry might look very different!)

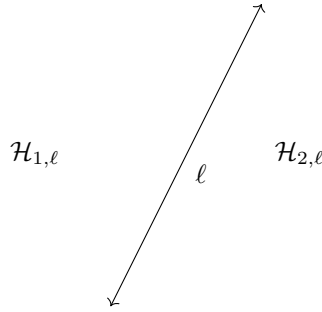


Figure 6.1: The halfplanes bounded by a line.

**Def’n 6.2** (Triangle). Let  $P$  be an incidence geometry, and let  $x$ ,  $y$ , and  $z$  be points. Then the set

$$\triangle xyz = \overline{xy} \cup \overline{yz} \cup \overline{zx}$$

is called the *triangle* with *vertices*  $x$ ,  $y$ , and  $z$ . The segments  $\overline{xy}$ ,  $\overline{yz}$ , and  $\overline{zx}$  are called the *sides* of the triangle, and the lines  $\overleftrightarrow{xy}$ ,  $\overleftrightarrow{yz}$ , and  $\overleftrightarrow{zx}$  are called the *extended sides*. If  $x$ ,  $y$ , and  $z$  are not all distinct, we say that the triangle  $\triangle xyz$  is *degenerate*.

The next result seems intuitive, but must be proven; it states that if a line “enters” a triangle through one side and does not contain any of the triangle’s vertices, then it must “exit” the triangle through one of the other sides. This is called *Pasch’s Axiom* for historical reasons.

**Prop’n 6.3** (Pasch’s Axiom). Let  $x$ ,  $y$ , and  $z$  be distinct noncollinear points in an ordered geometry, and let  $\ell$  be a line such that  $x, y, z \notin \ell$ . Finally, suppose there is a point  $w \in \ell$  such that  $[xwy]$ ; that is,  $\ell$  cuts the side  $\overline{xy}$ . Then precisely one of the following two things happens:

- (i)  $\ell$  cuts  $\overline{yz}$  and does not cut  $\overline{zx}$ , or
- (ii)  $\ell$  cuts  $\overline{zx}$  and does not cut  $\overline{yz}$ .

*Proof.* Since  $P$  is an ordered geometry, it satisfies the Plane Separation property. In particular, the points not on  $\ell$  are partitioned into two convex, nonempty half-planes,  $\mathcal{H}_{1,\ell}$  and  $\mathcal{H}_{2,\ell}$ . Since  $x$  and  $y$  are not on  $\ell$ , without loss of generality we have  $x \in \mathcal{H}_{1,\ell}$  and  $y \in \mathcal{H}_{2,\ell}$ . Since  $z \notin \ell$ , there are two possibilities: either  $z \in \mathcal{H}_{1,\ell}$  or  $z \in \mathcal{H}_{2,\ell}$ . In the first case, we see that  $\ell$  cuts  $\overline{yz}$  and does not cut  $\overline{zx}$ , and in the second case,  $\ell$  cuts  $\overline{zx}$  but not  $\overline{yz}$ .  $\square$

In other words, Pasch’s Axiom states that if a line enters a triangle then it must also exit; see Figure 6.2.

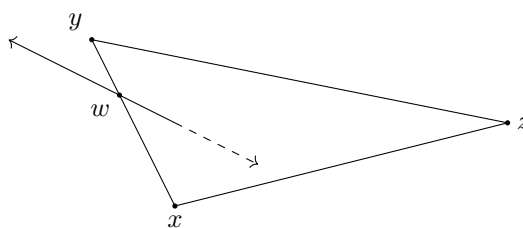


Figure 6.2: The setup of Pasch’s Axiom

**Lemma 6.4.** Let  $\ell$  be a line and  $C \in \ell$  a point in an ordered geometry. Suppose  $A$  and  $B$  are points not on  $\ell$  such that  $[ABC]$ . Then  $A$  and  $B$  are on the same side of  $\ell$ .

*Proof.* Suppose otherwise that  $A$  and  $B$  are on opposite sides of  $\ell$ . By the Line Separation property, and because  $A$  and  $B$  are not on  $\ell$ , the segment  $\overline{AB}$  cuts

$\ell$  at a unique point  $D$ . That is,  $D \in \ell$  and  $[ADB]$ . In particular,  $D$  and  $C$  must be distinct since we have  $[DBC]$ . But note that  $C, D \in \ell$ , so  $\overleftrightarrow{CD} = \ell$ , and also  $C, D \in \overleftrightarrow{AB}$ , so that  $\overleftrightarrow{CD} = \overleftrightarrow{AB}$ . But then  $\overleftrightarrow{AB} = \ell$ , a contradiction. Thus  $A$  and  $B$  must be on the same side of  $\ell$ .  $\square$

\* \* EXERCISES \* \*

- 6.1. Let  $a, b$ , and  $c$  be distinct noncollinear points. Suppose we have points  $d$  and  $e$  such that  $[abd]$  and  $[aec]$ . Then there exists a point  $f$  such that  $[efd]$  and  $[bfc]$ .
- 6.2. Let  $a, b$ , and  $c$  be distinct noncollinear points. Suppose we have points  $d$  and  $e$  such that  $[abd]$  and  $[bec]$ . Then there exists a point  $f$  such that  $[fed]$  and  $[afc]$ .
- 6.3. **Sylvester-Gallai Theorem** If  $S$  is a finite set of points, then there is a line  $\ell$  containing exactly two points from  $S$ . (@@@ Should this be a separate section? See [\[2\]](#))

## 7 Angles

**Def'n 7.1** (Angle). Let  $P$  be an ordered geometry and  $x, o$ , and  $y$  distinct points in  $P$ . Then the set

$$\angle xoy = \overrightarrow{ox} \cup \overrightarrow{oy}$$

is called the *angle* with *vertex*  $o$  and *sides*  $\overrightarrow{ox}$  and  $\overrightarrow{oy}$ . If  $[xoy]$ , then we say the angle is *straight*, and if  $[oxy]$  or  $[oyx]$ , then we say the angle is *flat*.

**Def'n 7.2** (Angle Pairs). Suppose  $x, y, z, w$ , and  $o$  are distinct points in an ordered geometry.

- (i)  $\angle xoy$  and  $\angle yoz$  are called an *adjacent pair*.
- (ii)  $\angle xoy$  and  $\angle yoz$  are called a *linear pair* if  $[xoz]$ .
- (iii)  $\angle xoy$  and  $\angle zow$  are called a *vertical pair* if  $[xoz]$  and  $[yow]$ .

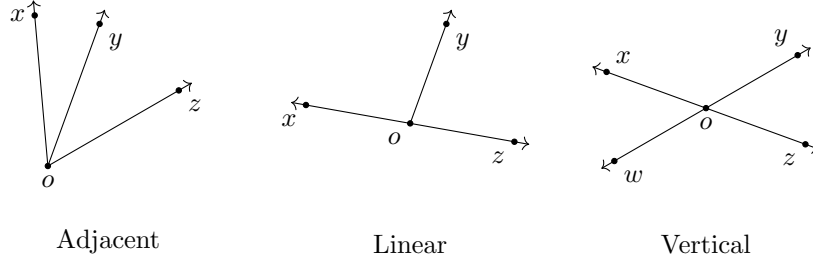


Figure 7.1: Some types of angle pairs.

**Theorem 7.3** (Crossbar Theorem). Suppose  $O, A$ , and  $B$  are noncollinear points in an ordered geometry, and that  $C \in \text{int}\angle AOB$ . Then  $\overrightarrow{OC}$  cuts  $\overline{AB}$  at a unique point  $D$ . (See [Figure 7.2](#).)

*Proof.* By the Interpolation property, there is a point  $P$  on  $\overrightarrow{OA}$  such that  $[POA]$ . Note that  $A$  and  $P$  are on opposite sides of  $\overrightarrow{OB}$ , so that  $P$  and  $C$  are on opposite sides of  $\overrightarrow{OB}$ . (Since  $A$  and  $C$  are on the same side of  $\overrightarrow{OB}$  by definition.) Consider now the triangle  $\triangle PAB$ . Note that the line  $\overrightarrow{OC}$  does not contain  $A, B$ , or  $P$ , since  $C$  is not on  $\overrightarrow{OA}$  or  $\overrightarrow{OB}$  by hypothesis. Moreover,  $\overrightarrow{OC}$  cuts  $\overline{PA}$  at  $O$ . By Pasch's Axiom,  $\overrightarrow{OC}$  must also cut either  $\overline{PB}$  or  $\overline{AB}$ .

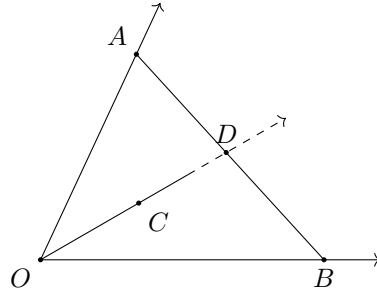


Figure 7.2: The Crossbar Theorem

Suppose  $\overrightarrow{OC}$  cuts  $\overline{PB}$  at a (necessarily unique) point  $Q$ . Note that  $\overrightarrow{OC} = \overrightarrow{QC}$ . Now  $P$  and  $Q$  are on the same side of  $\overrightarrow{OB}$ , so that  $Q$  and  $C$  are on *opposite* sides of  $\overrightarrow{OB}$ . Thus, there is a unique point  $R$  on  $\overrightarrow{OB}$  such that  $[QRC]$ . In particular,  $R \in \overrightarrow{OC}$ . Now we have  $O, R \in \overrightarrow{OC}$  and  $O, R \in \overrightarrow{OB}$ , so that  $\overrightarrow{OC} = \overrightarrow{OB}$ , a contradiction.

Hence  $\overrightarrow{OC}$  must cut  $\overline{AB}$  at a unique point; say  $D$ . Now  $D$  and  $A$  are on the same side of  $\overrightarrow{OB}$ , and so  $C$  and  $D$  are on the same side of  $\overrightarrow{OB}$ ; in particular, we cannot have  $[DOC]$ . So in fact  $\overrightarrow{OC}$  cuts  $\overline{AB}$  at a unique point.  $\square$

**Def'n 7.4** (Angle Interior). Suppose  $x$ ,  $o$ , and  $y$  are noncollinear points in an ordered geometry. Note that the lines  $\overleftrightarrow{ox}$  and  $\overleftrightarrow{oy}$  each divide  $P$  into half-planes. Let  $H_1$  be the  $y$  half-plane of  $\overleftrightarrow{ox}$ , and let  $K_1$  be the  $x$  half-plane of  $\overleftrightarrow{oy}$ . We define the *interior* of  $\angle xoy$  to be the set

$$\text{int}\angle xoy = H_1 \cap K_1.$$

If  $x$ ,  $y$ , and  $o$  are collinear, then the interior of  $\angle xoy$  is not defined.





— III —

Neutral Plane Geometry

## 8 Congruence

Intuitively, we want to say that two sets of points in a geometry are “congruent” if they have the same size and shape. But what exactly do “size” and “shape” mean? Rather than defining congruence once and for all, we will instead define two primitive forms of congruence on segments and angles. Then congruence for more complicated sets can be defined in terms of the primitives.

**Def’n 8.1** (Segment Congruence). Let  $P$  be an ordered geometry, and suppose we have an equivalence relation on pairs of points, denoted  $(*, *) \cong_s (*, *)$ . We call  $(*, *) \cong_s (*, *)$  a *segment congruence* if the following properties are satisfied.

SC1.  $(x, x) \cong_s (y, z)$  if and only if  $y = z$  for all points  $x, y$ , and  $z$ .

SC2.  $(x, y) \cong_s (y, x)$  for all points  $x$  and  $y$ .

SC3. If  $z \in \overrightarrow{xy}$  such that  $(x, z) \cong_s (x, y)$ , then  $z = y$ .

In this case,  $(*, *) \cong_s (*, *)$  is well-defined on the set of *segments* in  $P$ , where we write  $\overline{xy} \equiv \overline{ab}$  to mean  $(x, y) \cong_s (a, b)$ .

The first property handles the “trivial” case, the second makes the relation well-defined on segments, and the third ensures that it differentiates between segments on the same ray which share an endpoint.

**Def’n 8.2** (Angle Congruence). Let  $P$  be an ordered geometry, and suppose we have an equivalence relation on triples of points, denoted  $(*, *, *) \cong_a (*, *, *)$ . We call  $(*, *, *) \cong_a (*, *, *)$  an *angle congruence* if the following properties are satisfied.

AC1. If  $[a_1 b_1 c_1]$  and  $a_2, b_2$ , and  $c_2$  are points, then  $(a_1, b_1, c_1) \cong_a (a_2, b_2, c_2)$  if and only if  $[a_2 b_2 c_2]$  if and only if  $(b_1, a_1, c_1) \cong_a (b_2, a_2, c_2)$ .

AC2. If  $a, b, o, x$ , and  $y$  are points such that  $o \notin \{a, b, x, y\}$ ,  $x \in \overrightarrow{oa}$ , and  $y \in \overrightarrow{ob}$ , then  $(a, o, b) \cong_a (x, o, y)$  and  $(a, o, b) \cong_a (y, o, x)$ .

AC3. If  $a, b$ , and  $o$  are distinct noncollinear points and  $x$  is on the  $b$ -side of  $\overleftrightarrow{oa}$  such that  $(a, o, b) \cong_a (a, o, x)$ , then  $x \in \overrightarrow{ob}$ .

In this case,  $(*, *, *) \cong_a (*, *, *)$  is an equivalence relation on the set of *angles* in  $P$ , and we write  $\angle aob \equiv \angle xpy$  to mean  $(a, o, b) \cong_a (x, p, y)$ .

Much like the properties of segment congruence, the first property handles the trivial cases, the second makes the relation well-defined on angles, and the third ensures that it differentiates between angles on one half-plane which share a vertex.

**Def'n 8.3** (Congruence Geometry). Let  $P$  be an ordered geometry. If  $P$  has a segment congruence and an angle congruence, we say that  $P$  is a *congruence geometry*.

We can define congruence of many different kinds of figures in terms of segment and angle congruence. For instance...

**Def'n 8.4** (Triangle Congruence). Let  $a, b$ , and  $c$  be distinct points, and let  $x, y$ , and  $z$  be distinct points. We say that  $\triangle abc$  is *congruent* to  $\triangle xyz$ , denoted  $\triangle abc \equiv \triangle xyz$ , if

$$\overline{ab} \equiv \overline{xy}, \quad \overline{bc} \equiv \overline{yz}, \quad \text{and} \quad \overline{ca} \equiv \overline{zx}$$

and

$$\angle abc \equiv \angle xyz, \quad \angle bca \equiv \angle yzx, \quad \text{and} \quad \angle cab \equiv \angle zxy.$$

**Def'n 8.5.** Let  $a, b$ , and  $c$  be distinct points.

- (i) We say that the triangle  $\triangle abc$  is *equilateral* if  $\overline{ab} \equiv \overline{bc} \equiv \overline{ca}$ .
- (ii) We say that the triangle  $\triangle abc$  is *isocles* if two of its sides are congruent to each other.

**Def'n 8.6** (Supplementary Angles). We say that angles  $\angle aob$  and  $\angle xpy$  are *supplementary* if there is a linear pair,  $\angle uqv$  and  $\angle vqw$ , such that  $\angle aob \equiv \angle uqv$  and  $\angle xpy \equiv \angle vqw$ . In this case we say that  $\angle xpy$  is a *supplement* of  $\angle aob$ .

**Prop'n 8.7.** Let  $P$  be a congruence geometry.

- (i) If two angles form a linear pair, then they are supplementary.
- (ii) Every angle has a supplement.

**Def'n 8.8** (Circle). Let  $P$  be a congruence geometry and let  $o, a \in P$  be points. The set

$$\bigcirc oa = \{x \in P \mid \overline{ox} \equiv \overline{oa}\}$$

is called the *circle* with *center*  $o$  and *passing through*  $a$ . If  $o = a$ , we say the circle  $\bigcirc oa$  is *degenerate*.

**Def'n 8.9** (Radius, Diameter, Chord). Let  $o$  and  $a$  be distinct points in a congruence geometry, and let  $C = \bigcirc oa$ .

- (i) If  $u \in C$ , then the segment  $\overline{ou}$  is called a *radius* of  $C$ .
- (ii) If  $u$  and  $v$  are distinct points on  $C$ , then the segment  $\overline{uv}$  is called a *chord* of  $C$ .
- (iii) A chord  $\overline{uv}$  of  $C$  is called a *diameter* if  $[uov]$ .

**Def'n 8.10** (Circle Interior and Exterior). Let  $o, a, b$  be points with  $o \neq a$ . We say that  $b$  is *interior to* the circle  $\bigcirc oa$  if either  $b = o$  or there is a point  $z \in \bigcirc oa$  such that  $[obz]$ . We say that  $b$  is *exterior to* the circle  $\bigcirc oa$  if there is a point  $z \in \bigcirc oa$  such that  $[ozb]$ .

\* \* EXERCISES \* \*

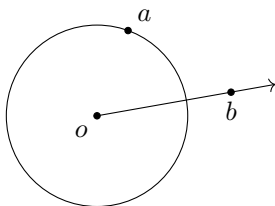
- 8.1. Show that triangle congruence is an equivalence relation.
- 8.2. Let  $\alpha$ ,  $\beta$ , and  $\gamma$  be angles in a congruence geometry such that  $\alpha$  and  $\beta$  are supplementary and  $\beta \equiv \gamma$ . Show that  $\alpha$  and  $\gamma$  are supplementary.
- 8.3. Let  $\alpha$  and  $\beta$  be angles in a congruence geometry such that  $\alpha$  and  $\beta$  are supplementary and  $\alpha$  is right. Show that  $\beta$  is right.
- 8.4. Show that no flat angle is congruent to any straight angle.

## 9 Plane Geometry

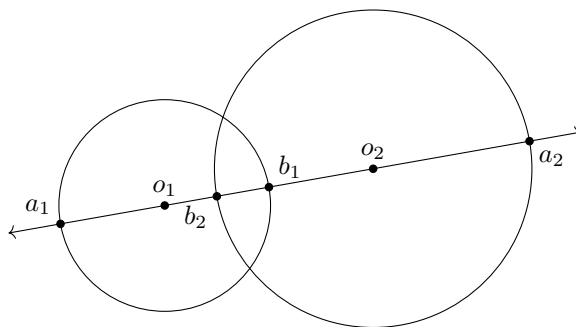
**Def'n 9.1** (Plane Geometry). Let  $P$  be an ordered geometry with a segment congruence and an angle congruence. We say that  $P$  is a *plane geometry* if the following properties are satisfied.

**PG1. Angle-Side Congruence.** Suppose  $a_1, b_1$ , and  $c_1$  are distinct points and  $a_2, b_2$ , and  $c_2$  are distinct points such that  $\overline{b_1a_1} \equiv \overline{b_2a_2}$  and  $\overline{b_1c_1} \equiv \overline{b_2c_2}$ . Then  $\overline{a_1c_1} \equiv \overline{a_2c_2}$  if and only if  $\angle a_1b_1c_1 \equiv \angle a_2b_2c_2$ .

**PG2. Circle Cut.** If  $o, a$ , and  $b$  are points such that  $a \neq o$  and  $b \neq o$ , then there is a point  $c \in \overrightarrow{ob}$  such that  $\overline{oc} \equiv \overline{oa}$ .



**PG3. Interleaved Diameters.** Let  $C_1$  and  $C_2$  be circles centered at distinct points  $o_1$  and  $o_2$ , respectively. Further suppose we have diameters  $\overline{a_1b_1}$  of  $C_1$  and  $\overline{a_2b_2}$  of  $C_2$  such that  $[a_1o_1a_2]$  and  $[a_1o_2a_2]$ . Then  $C_1 \cap C_2$  is nonempty if and only if  $[a_1b_2b_1a_2]$ , and in this case  $C_1 \cap C_2$  consists of exactly two points which are on opposite sides of  $\overleftrightarrow{o_1o_2}$ .



Each of these properties says something which is (hopefully!) fairly intuitive. Angle-Side Congruence provides an essential link between segment congruence and angle congruence, which are otherwise unrelated. The Circle Cut and Interleaved Diameters properties allow us to construct points on the intersection of a circle with a central ray and of two circles, respectively. (Without these we have no way to construct points on circles!)

We finally have enough technology to start doing some more recognizable geometry. For the remainder of this chapter  $P$  is a plane geometry. First, we give two shortcut results for determining when two triangles are congruent.

**Prop'n 9.2** (SSS Theorem). If two nondegenerate triangles can be labeled such that corresponding sides are congruent, then the triangles are congruent.

More precisely, let  $a_1, b_1$ , and  $c_1$  be distinct points and  $a_2, b_2$ , and  $c_2$  be distinct points. If  $\overline{a_1b_1} \equiv \overline{a_2b_2}$ ,  $\overline{b_1c_1} \equiv \overline{b_2c_2}$ , and  $\overline{c_1a_1} \equiv \overline{c_2a_2}$ , then  $\triangle a_1b_1c_1 \equiv \triangle a_2b_2c_2$ .

*Proof.* We have  $\angle a_1b_1c_1 \equiv \angle a_2b_2c_2$ ,  $\angle b_1c_1a_1 \equiv \angle b_2c_2a_2$ , and  $\angle c_1a_1b_1 \equiv \angle c_2a_2b_2$  using the Angle-Side Congruence property three times.  $\square$

**Prop'n 9.3** (SAS Theorem). If two nondegenerate triangles can be labeled such that two corresponding sides, and the angles between, are congruent, then the triangles are congruent.

More precisely, let  $a_1, b_1$ , and  $c_1$  be distinct points, and  $a_2, b_2$ , and  $c_2$  be distinct points. If  $\overline{a_1b_1} \equiv \overline{a_2b_2}$ ,  $\overline{b_1c_1} \equiv \overline{b_2c_2}$ , and  $\angle a_1b_1c_1 \equiv \angle a_2b_2c_2$ , then  $\triangle a_1b_1c_1 \equiv \triangle a_2b_2c_2$ .

*Proof.* We have  $\overline{a_1c_1} \equiv \overline{a_2c_2}$  by Angle-Side Congruence, and then SSS applies.  $\square$

**Cor. 9.4** (Pons Asinorum). If  $\triangle abc$  is isocles with  $\overline{ab} \equiv \overline{bc}$ , then  $\angle bac \equiv \angle bca$ .

*Proof.* We have two triangles,  $\triangle bac$  and  $\triangle bca$ , such that  $\overline{bc} \equiv \overline{ba}$ ,  $\overline{ba} \equiv \overline{bc}$ , and  $\angle cba \equiv \angle abc$ . By SAS we have  $\triangle bac \equiv \triangle bca$ , and thus  $\angle bac \equiv \angle bca$  as needed.  $\square$

**Cor. 9.5.** Every triangle which is equilateral is also equiangular; all three interior angles are congruent.

*Proof.* Follows from two applications of Pons Asinorum.  $\square$

**Cor. 9.6** (Segment Addition). Suppose  $[a_1b_1c_1]$  and  $[a_2b_2c_2]$ . If any two of  $\overline{a_1b_1} \equiv \overline{a_2b_2}$ ,  $\overline{b_1c_1} \equiv \overline{b_2c_2}$ , and  $\overline{a_1c_1} \equiv \overline{a_2c_2}$  hold, then so does the third.

*Proof.* Note that  $\angle a_1b_1c_1 \equiv \angle a_2b_2c_2$ ,  $\angle b_1c_1a_1 \equiv \angle b_2c_2a_2$ , and  $\angle c_1a_1b_1 \equiv \angle c_2a_2b_2$  by AC1. The result then follows from three applications of SAS.  $\square$

**Construction 9.7** (Antipode). Given distinct points  $a$  and  $b$ , there is a unique point  $c$  such that  $[abc]$  and  $\overrightarrow{ab} \equiv \overrightarrow{bc}$ . We say that  $c$  is an *antipode* of  $a$  through  $b$ .

*Proof.* First we show existence. Using the Interpolation property, there is a point  $u$  such that  $[uba]$ . Now using Circle Cut, there is a point  $c \in \overrightarrow{bu} \cap \overrightarrow{ba}$ . Note that  $[abc]$ , and we have  $\overrightarrow{bc} \equiv \overrightarrow{ba}$  as needed. Next we show uniqueness. Suppose  $d$  is a point such that  $[abd]$  and  $\overrightarrow{ab} \equiv \overrightarrow{bd}$ . But then  $d \in \overrightarrow{bc}$ , and in fact  $c = d$  by AC4.  $\square$

**Construction 9.8** (Equilateral triangle with a given side). Given distinct points  $a$  and  $b$ , there exist two and only two points  $c_1$  and  $c_2$ , on opposite sides of  $\overleftrightarrow{ab}$ , such that  $\triangle abc_1$  and  $\triangle abc_2$  are equilateral. In fact, we have  $\triangle abc_1 \equiv \triangle abc_2$ .

*Proof.* First, construct the antipode  $h$  of  $b$  through  $a$ , and construct the antipode  $k$  of  $a$  through  $b$ . Note that  $[habk]$ , and that  $\overrightarrow{ah} \equiv \overrightarrow{ab}$  and  $\overrightarrow{bk} \equiv \overrightarrow{ba}$ ; that is,  $a$  is a midpoint of  $\overline{hb}$  and  $b$  a midpoint of  $\overline{ak}$ , so that  $a$  is the center of  $\odot ab$  with diameter  $\overline{hb}$  and  $b$  is the center of  $\odot ba$  with diameter  $\overline{ak}$ . Thus the Interleaved Diameters property applies, and we have two points  $c_1, c_2 \in \odot ab \cap \odot ba$  which are in opposite halfplanes of  $\overleftrightarrow{ab}$ . Note that  $\overrightarrow{ac_1} \equiv \overrightarrow{ab} \equiv \overrightarrow{bc_1}$ , and thus  $\triangle abc_1$  is equilateral. Similarly,  $\triangle abc_2$  is equilateral. Moreover, we see that  $\triangle abc_1 \equiv \triangle abc_2$  by the SSS Theorem.  $\square$

**Lemma 9.9** (Betweenness Transfer). Let  $a_1, b_1, c_1, a_2, b_2$ , and  $c_2$  be points such that  $[a_1b_1c_1]$ ,  $b_2 \in \overrightarrow{a_2c_2}$ ,  $\overrightarrow{a_1b_1} \equiv \overrightarrow{a_2b_2}$ , and  $\overrightarrow{a_1c_1} \equiv \overrightarrow{a_2c_2}$ . Then  $[a_2b_2c_2]$ .

*Proof.* Note that  $a_1, b_1$ , and  $c_1$  are distinct. Since  $\overrightarrow{a_1b_1} \equiv \overrightarrow{a_2b_2}$ ,  $a_2$  and  $b_2$  are distinct. If  $b_2 = c_2$ , then we have  $\overrightarrow{a_1b_1} \equiv \overrightarrow{a_1c_1}$ , so that  $b_1 = c_1$  by S3 – a contradiction. So  $b_2$  and  $c_2$  are distinct. Because  $b_2 \in \overrightarrow{a_2c_2}$ , there are two possibilities: either  $[a_2c_2b_2]$  or  $[a_2b_2c_2]$ .

Suppose  $[a_2c_2b_2]$ . Now  $\angle c_2a_2b_2 \equiv \angle c_1a_1b_1$  (both angles are flat), and by SAS we have  $\triangle c_1a_1b_1 \equiv \triangle c_2a_2b_2$ . In particular, we have  $\angle a_1b_1c_1 \equiv \angle a_2b_2c_2$ ; a contradiction, as in this case  $\angle a_1b_1c_1$  is straight while  $\angle a_2b_2c_2$  is flat. Thus  $[a_2b_2c_2]$  as claimed.  $\square$

**Construction 9.10** (Segment Copy Theorem). Let  $a$  and  $b$  be points, and let  $o$  and  $t$  be distinct points. Then there is a unique point  $x$  on  $\overrightarrow{ot}$  such that  $\overrightarrow{ox} \equiv \overrightarrow{ab}$ .

*Proof.* If  $a = b$ , note that  $x = t$  satisfies the theorem. Suppose now that  $a \neq b$ . Now at least one of  $a$  and  $b$  has to be distinct from  $o$ ; without loss of generality, suppose  $a \neq o$ . Construct a point  $z$  such that  $\triangle aoz$  is equilateral; now  $\overrightarrow{za} \equiv \overrightarrow{zo}$ . Using the Interpolation property, construct a point  $h$  such that  $[zah]$ , and using the Circle Cut property, construct a point  $u$  on  $\overrightarrow{ah}$  such that  $\overrightarrow{au} \equiv \overrightarrow{ab}$ . Again using Circle Cut, construct a point  $v$  on  $\overrightarrow{zo}$  such that  $\overrightarrow{zv} \equiv \overrightarrow{zu}$ . By Lemma 9.9 we have  $[zov]$ . Now  $\overrightarrow{za} \equiv \overrightarrow{zo}$  and  $\overrightarrow{zu} \equiv \overrightarrow{zv}$ , thus  $\overrightarrow{au} \equiv \overrightarrow{ov}$ . Again using Circle Cut, construct a point  $x$  on  $\overrightarrow{ot}$  such that  $\overrightarrow{ox} \equiv \overrightarrow{ov}$ . Then we have  $\overrightarrow{ox} \equiv \overrightarrow{ov} \equiv \overrightarrow{au} \equiv \overrightarrow{ab}$  as needed. Uniqueness follows from SC3.  $\square$

**Lemma 9.11.** Suppose  $a_1, b_1, c_1, d_1, a_2, b_2, c_2$ , and  $d_2$  are points such that  $\overrightarrow{a_1c_1} \equiv \overrightarrow{a_2c_2}$ ,  $\overrightarrow{b_1d_1} \equiv \overrightarrow{b_2d_2}$ ,  $\overrightarrow{a_1d_1} \equiv \overrightarrow{a_2d_2}$ ,  $[a_1b_1c_1d_1]$ ,  $c_2 \in \overrightarrow{a_2d_2}$ , and  $b_2 \in d_2a_2$ . Then  $[a_2b_2c_2d_2]$ .

*Proof.* We have  $[a_2c_2d_2]$  by Betweenness Transfer and  $\overrightarrow{c_1d_1} \equiv \overrightarrow{c_2d_2}$  by Segment Addition. Similarly,  $[a_2b_2d_2]$  and  $\overrightarrow{a_1b_1} \equiv \overrightarrow{a_2b_2}$ . Now  $[a_2b_2c_2]$  by Betweenness Transfer. Thus  $[a_2b_2c_2d_2]$  as needed.  $\square$

**Construction 9.12** (Angle Copy Theorem). Let  $a, o, b$  be distinct non-collinear points and let  $p$  and  $x$  be distinct points. There exist two points  $y_1$  and  $y_2$ , on opposite sides of  $\overleftrightarrow{px}$ , such that  $\angle xpy_1 \equiv \angle xpy_2 \equiv \angle aob$ .

*Proof.* First copy segment  $\overrightarrow{ob}$  onto  $\overleftrightarrow{px}$  at the point  $u$ , then copy the segment  $\overrightarrow{ba}$  onto the ray  $\overrightarrow{up}$  at the point  $v$ . Now copy  $\overrightarrow{oa}$  onto  $\overleftrightarrow{px}$  at the point  $w$ . Note that  $\overrightarrow{oa} \equiv \overrightarrow{pw}$ ,  $\overrightarrow{ob} \equiv \overrightarrow{pu}$ , and  $\overrightarrow{ba} \equiv \overrightarrow{uv}$ . Moreover, the intersection  $\odot oa \cap \odot ba$  is nonempty, as it contains  $a$ . By the Interleaved Diameters property,  $\odot pw \cap \odot uv$  contains two points  $z_1$  and  $z_2$  on opposite sides of  $\overleftrightarrow{px}$ . By the SSS Theorem, we have  $\triangle puz_1 \equiv \triangle oba \equiv \triangle puz_2$ , and thus  $\angle upz_1 \equiv \angle aob \equiv \angle upz_2$  as needed.  $\square$

**Prop'n 9.13** (ASA Theorem). Let  $a_1, b_1$ , and  $c_1$  be distinct noncollinear points, and let  $a_2, b_2$ , and  $c_2$  be distinct points. If  $\angle a_1b_1c_1 \equiv \angle a_2b_2c_2$ ,  $\overrightarrow{b_1c_1} \equiv \overrightarrow{b_2c_2}$ , and  $\angle b_1c_1a_1 \equiv \angle b_2c_2a_2$ , then  $\triangle a_1b_1c_1 \equiv \triangle a_2b_2c_2$ .

*Proof.* Copy  $\overrightarrow{b_2a_2}$  onto  $\overrightarrow{b_1a_1}$  at  $d$ . Note that  $d$  and  $a_1$  are on the same side of  $\overleftrightarrow{b_1c_1}$ . Moreover, we have  $\triangle db_1c_1 \equiv \triangle a_2b_2c_2$  by SAS, and so  $\angle b_1c_1d \equiv \angle b_2c_2a_2 \equiv \angle b_1c_1a_1$ . By AC4, we have  $d \in \overrightarrow{c_1a_1}$ . Now  $d$  is on both  $\overrightarrow{b_1a_1}$  and  $\overrightarrow{c_1a_1}$ , and since  $a_1, b_1$ , and  $c_1$  are not collinear, we must have  $d = a_1$ . So we have  $\triangle a_1b_1c_1 \equiv \triangle a_2b_2c_2$  as claimed.  $\square$



**Lemma 9.14.** If  $[aoc]$  and if  $b$  and  $d$  are points on the same side of  $\overleftrightarrow{ac}$  such that  $\angle boc \equiv \angle aob$  and  $\angle doc \equiv \angle aod$ , then  $\angle boc \equiv \angle doc$ .

*Proof.* Note that we can assume that  $\overline{ao} \equiv \overline{oc}$ ; if not, use Circle Cut to construct  $c'$  on  $\overrightarrow{oc}$  with this property. Since  $\angle boc$  is right, we then have  $\angle aob \equiv \angle boc$  by definition; thus  $\triangle aob \equiv \triangle cob$  by SAS. In particular, we have  $\angle bao \equiv \angle bco$ . Now there are three possibilities for  $d$ : either  $d$  is on  $\overleftrightarrow{ob}$ ,  $d$  is on the  $a$ -side of  $\overleftrightarrow{ob}$ , or  $d$  is on the  $c$ -side of  $\overleftrightarrow{ob}$ . Suppose  $d$  is on the  $c$ -side of  $\overleftrightarrow{ob}$ ; the  $a$ -side case is similar. By the Crossbar Theorem,  $\overrightarrow{od}$  cuts  $\overline{bc}$  at an interior point  $w$ . Now  $\triangle aow \equiv \triangle cow$  again using SAS. But now we have  $\angle wao \equiv \angle wco \equiv \angle bao$ . By AC4, then, we have  $w \in \overleftrightarrow{ab}$  and  $w \in \overleftrightarrow{bc}$ ; thus  $w = b$ . In this case we have  $d \in \overleftrightarrow{ob}$ , a contradiction. Thus  $d \in \overleftrightarrow{ob}$ , and we have  $\angle boc \equiv \angle doc$ .  $\square$

## 10 Transversals

**Prop'n 10.1** (Supplements are unique).

- (i) Suppose that  $\angle a_1 o_1 b_1$  and  $\angle b_1 o_1 c_1$  are a linear pair, and that  $\angle a_2 o_2 b_2$  and  $\angle b_2 o_2 c_2$  are a linear pair. If  $\angle a_1 o_1 b_1 \equiv \angle a_2 o_2 b_2$ , then  $\angle b_1 o_1 c_1 \equiv \angle b_2 o_2 c_2$ .



- (ii) Suppose  $\alpha$ ,  $\beta$ , and  $\gamma$  are angles such that  $\alpha$  and  $\beta$  are supplementary and  $\alpha$  and  $\gamma$  are supplementary. Then  $\alpha \equiv \gamma$ .

*Proof.*

- (i) Suppose we have two such linear pairs. Without loss of generality, we can suppose that

$$\overline{o_1 a_1} \equiv \overline{o_1 b_1} \equiv \overline{o_1 c_1} \equiv \overline{o_2 a_2} \equiv \overline{o_2 b_2} \equiv \overline{o_2 c_2}.$$

(If they aren't, we can use Circle Cut and the Segment Copy construction to find such points.) Now  $\triangle b_1 o_1 a_1 \equiv \triangle b_2 o_2 a_2$  by SAS, so that  $\angle b_1 a_1 o_1 \equiv \angle b_2 a_2 o_2$ . Now  $\overline{a_1 c_1} \equiv \overline{a_2 c_2}$ , so that  $\triangle b_1 a_1 c_1 \equiv \triangle b_2 a_2 c_2$  by SAS. So  $\overline{b_1 c_1} \equiv \overline{b_2 c_2}$ , and thus  $\triangle b_1 o_1 c_1 \equiv \triangle b_2 o_2 c_2$  by SSS. Thus  $\angle b_1 o_1 c_1 \equiv \angle b_2 o_2 c_2$  as needed.

- (ii) Follows from the definition of supplementary. □

**Cor. 10.2.** If angles  $\alpha$  and  $\beta$  are a vertical pair, then  $\alpha \equiv \beta$ .

*Proof.* If  $\angle aob$  and  $\angle cod$  are a vertical pair, with  $[boc]$  and  $[aod]$ , then both  $\angle aob$  and  $\angle cod$  are supplementary to  $\angle aoc$ . □

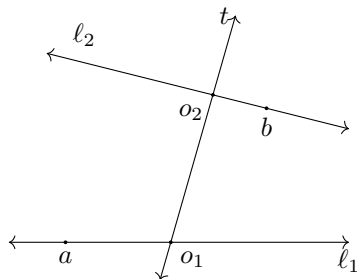
**Def'n 10.3.** An angle is called *right* if it is supplementary to itself.

**Cor. 10.4.** Any two right angles are congruent.

*Proof.* Suppose angles  $\alpha$  and  $\beta$  are right. We can copy  $\beta$  to an angle  $\beta'$  in the configuration of 9.14. Since supplements are congruent, 9.14 applies. □

**Def'n 10.5** (Transversal). Suppose we have three lines  $\ell_1$ ,  $\ell_2$ , and  $t$  in a plane geometry. We say that  $t$  is a *transversal* of  $\ell_1$  and  $\ell_2$  if  $t$  cuts both  $\ell_1$  and  $\ell_2$  at unique points, and these points are distinct.

Suppose  $t$  is a transversal of  $\ell_1$  and  $\ell_2$ , cutting these lines at  $o_1$  and  $o_2$ , respectively as shown.

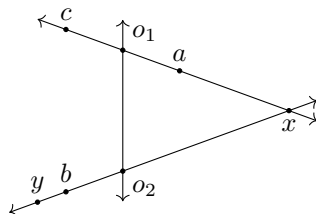


If  $a$  is on  $\ell_1$  and  $b$  is on  $\ell_2$  such that  $a$  and  $b$  are on opposite sides of  $t$ , then we say that  $\angle ao_1o_2$  and  $\angle bo_2o_1$  are *alternate interior angles* of this transversal.

Every transversal has two pairs of alternate interior angles.

**Prop'n 10.6** (AIA Theorem). If two lines  $\ell_1$  and  $\ell_2$  are cut by a transversal  $t$  so that a pair of alternate interior angles are congruent, then  $\ell_1$  and  $\ell_2$  are parallel.

*Proof.* Suppose  $t$  meets  $\ell_1$  and  $\ell_2$  at points  $o_1$  and  $o_2$  respectively, and that  $a$  and  $b$  are on  $\ell_1$  and  $\ell_2$ , respectively, and on opposite sides of  $t$ , such that  $\angle ao_1o_2 \equiv \angle bo_2o_1$ . Now suppose by way of contradiction that  $\ell_1$  and  $\ell_2$  are *not* parallel; rather, they meet at a point  $x$  which (WLOG) is on the  $a$ -side of  $t$ . Let  $c$  be on  $\ell_1$  such that  $[ao_1c]$ . Copy  $\overrightarrow{o_1x}$  onto  $\overrightarrow{o_2b}$  at the point  $y$ . Note that  $\overrightarrow{o_1x} \equiv \overrightarrow{o_2y}$ ,  $\overrightarrow{o_1o_2} \equiv \overrightarrow{o_2o_1}$ , and  $\angle xo_1o_2 \equiv \angle yo_2o_1$ ; by **SAS** we thus have  $\triangle xo_1o_2 \equiv \triangle yo_2o_1$ . In particular,  $\angle o_2o_1y \equiv \angle o_1o_2x$ .



Note that  $\angle xo_2o_1$  and  $\angle o_1o_2y$  are supplementary, and  $\angle o_1o_2y \equiv \angle ao_1o_2$  by hypothesis, so that  $\angle ao_1o_2$  and  $\angle xo_2o_1$  are supplementary. Since  $\angle xo_2o_1 \equiv \angle yo_1o_2$ , we have that  $\angle ao_1o_2$  and  $\angle yo_1o_2$  are supplementary. But also  $\angle ao_1o_2$

and  $\angle o_2 o_1 c$  are supplementary. Thus  $\angle o_2 o_1 y \equiv \angle o_2 o_1 c$ . By AC4, we have that  $o_1$ ,  $c$ , and  $y$  are collinear, so that  $y \in \ell_1$ . But now  $\ell_1$  and  $\ell_2$  have two points in common –  $x$  and  $y$  – which are necessarily distinct as they are on opposite halfplanes of  $t$ . So we have  $\ell_1 = \ell_2$ , a contradiction.

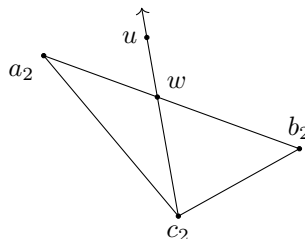
Thus  $\ell_1$  and  $\ell_2$  must be parallel.  $\square$

**Cor. 10.7.** A triangle formed by three distinct noncollinear points cannot have two interior angles which are both right.

*Proof.* Such a triangle would violate the [AIA Theorem](#) since right angles are self-supplementary, and any two right angles are congruent.  $\square$

**Prop'n 10.8** (AAS Theorem). Suppose we have distinct noncollinear points  $a_1$ ,  $b_1$ , and  $c_1$  and distinct noncollinear points  $a_2$ ,  $b_2$ , and  $c_2$  such that  $\angle c_1 a_1 b_1 \equiv \angle c_2 a_2 b_2$ ,  $\angle a_1 b_1 c_1 \equiv \angle a_2 b_2 c_2$ , and  $\overline{b_1 c_1} \equiv \overline{b_2 c_2}$ . Then  $\triangle a_1 b_1 c_1 \equiv \triangle a_2 b_2 c_2$ .

*Proof.* Copy  $\overline{b_1 a_1}$  onto  $\overline{b_2 a_2}$  at the point  $w$ . Note that  $w \neq b_2$ , since  $a_1 \neq b_1$ . Note also that  $\triangle w b_2 c_2 \equiv \triangle a_1 b_2 c_2$  by [SAS](#), so that  $\angle b_1 a_1 c_1 \equiv \angle b_2 w c_2$ . Suppose now that  $w$  and  $a_2$  are distinct points; say  $[b_2 w a_2]$ . (The case  $[b_2 a_2 w]$  is very similar.) In this case  $\overleftrightarrow{a_2 c_2}$  and  $\overleftrightarrow{w c_2}$  are lines cut by a transversal  $\overleftrightarrow{a_2 b_2}$ .



Moreover, if we let  $u$  be a point such that  $[u w c_2]$ , then  $\angle u w a_2$  and  $\angle b_2 w c_2$  are vertical, hence congruent, and so we have  $\angle u w a_2 \equiv \angle b_2 a_2 c_2$ . But now by the [AIA Theorem](#),  $\overleftrightarrow{a_2 c_2}$  and  $\overleftrightarrow{w c_2}$  must be parallel – a contradiction since they meet at  $c_2$ . So in fact  $a_2$  and  $w$  are the same point, and thus  $\triangle a_1 b_1 c_1 \equiv \triangle a_2 b_2 c_2$  by [SAS](#).  $\square$

Note that the AAS Theorem is slightly less general than the triangle congruence theorems we've seen so far: it does not apply to triangles whose vertices are collinear, while the SSS and SAS Theorems do.

**Prop'n 10.9** (HL Theorem). Suppose we have distinct noncollinear points  $a_1$ ,  $b_1$ , and  $c_1$  and distinct noncollinear points  $a_2$ ,  $b_2$ , and  $c_2$  such that  $\angle b_1 c_1 a_1$  and  $\angle b_2 c_2 a_2$  are right and  $\overline{a_1 b_1} \equiv \overline{a_2 b_2}$  and  $\overline{b_1 c_1} \equiv \overline{b_2 c_2}$ . Then

$$\triangle a_1 b_1 c_1 \equiv \triangle a_2 b_2 c_2.$$

*Proof.* Copy  $\overline{c_2 a_2}$  onto the ray opposite  $\overrightarrow{c_1 a_1}$  at the point  $d$ . Now  $\angle b_1 c_1 d$  is a right angle, since it is supplementary to  $\angle a_1 c_1 b_1$ . By **SAS**, we have  $\triangle a_2 c_2 b_2 \equiv \triangle d c_1 b_1$ , and thus  $\overline{b_1 d} \equiv \overline{b_2 a_2} \equiv \overline{b_1 a_1}$ . Now  $\triangle a_1 b_1 d$  is isosceles with  $\overline{b_1 a_1} \equiv \overline{b_1 d}$ , so that  $\angle b_1 a_1 c_1 = \angle b_1 a_1 d \equiv \angle b_1 d a_1 \equiv \angle b_2 a_2 c_2$  using Pons Asinorum. By **AAS**, we have  $\triangle a_1 b_1 c_1 \equiv \triangle a_2 b_2 c_2$  as needed.  $\square$

**Construction 10.10** (Angle Bisector). Let  $a$ ,  $o$ , and  $b$  be distinct non-collinear points. There exists a unique line  $\ell$ , containing  $o$ , such that if  $u \in \ell$  is different from  $o$  then  $\angle aou \equiv \angle bou$ . This line is called the *bisector* of  $\angle aob$ .

*Proof.* WLOG, we can assume that  $\overrightarrow{oa} \equiv \overrightarrow{ob}$ ; if not, construct such a point on  $\overrightarrow{ob}$  using Circle Cut. Since the intersection of  $\odot ao$  and  $\odot bo$  contains a point not on  $\overrightarrow{ab}$ , by Interleaved Diameters there is a second point  $u$  on the opposite side of  $\overrightarrow{ab}$  such that  $\overline{au} \equiv \overline{bu}$ . Let  $\ell = \overleftrightarrow{ou}$ . Note that  $\triangle aou \equiv \triangle bou$  by **SSS**, so that  $\angle aou \equiv \angle bou$ .

Now let  $v$  be a point in  $\overleftrightarrow{ou}$  distinct from  $o$ . Certainly if  $v \in \overrightarrow{ou}$  then  $\angle voa \equiv \angle vob$ . If instead we have  $[vou]$ , then  $\angle voa \equiv \angle vob$ , since these are supplementary to congruent angles.

To see uniqueness, note that any such line must contain  $o$  and  $u$  and thus be equal to  $\overleftrightarrow{ou}$ .  $\square$

**Cor. 10.11.** The points  $a$  and  $b$  are on opposite sides of the bisector of  $\angle aob$ . In particular, the bisector of  $\angle aob$  contains points which are interior to  $\angle aob$ .

*Proof.* Suppose otherwise, and let  $u \neq o$  be a point on the bisector. Then  $\angle uoa$  and  $\angle uob$  are congruent angles on the same halfplane of a ray, so that  $a$ ,  $b$ , and  $o$  are collinear – a contradiction. Now by the Line Separation property there is a point  $w$  between  $a$  and  $b$  which is on the bisector; this point is interior to  $\angle aob$  by **Lemma 6.4** as needed.  $\square$

**Construction 10.12** (Segment Midpoint). Let  $a$  and  $b$  be distinct points. There is a unique point  $m$  such that  $[amb]$  and  $\overline{am} \equiv \overline{bm}$ . This point is called the *midpoint* of  $\overline{ab}$ .

*Proof.* Construct a point  $o$  such that  $\triangle aob$  is equilateral, and construct the bisector of  $\angle aob$ . By the Crossbar Theorem, this bisector must cut  $\overline{ab}$  at an interior point, say  $m$ . Now  $\triangle oam \equiv \triangle obm$  by **SAS**, and thus  $\overline{am} \equiv \overline{bm}$  as needed. Note that  $m$  is unique by the uniqueness of congruent segments on a ray.  $\square$

## \* \* EXERCISES \* \*

- 10.1. Show that no right angle is also flat or straight.

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## 11 Perpendiculars and Tangents

We say that two lines are *perpendicular* if they form a right angle.

**Construction 11.1** (Foot of a point). Let  $x$  and  $y$  be distinct points and  $p$  a point not on  $\overleftrightarrow{xy}$ . There is a unique point  $f \in \overleftrightarrow{xy}$  such that  $\overleftrightarrow{xy}$  and  $\overleftrightarrow{pf}$  are perpendicular. We say that  $f$  is the *foot* of  $p$  on  $\overleftrightarrow{xy}$ .

*Proof.* First we show existence. Note that  $\odot xp \cap \odot yp$  is not empty (as it contains  $p$ ), and by Interleaved Diameters there is a second point  $o$  in the intersection of these circles which is on the opposite side of  $\overleftrightarrow{xy}$ . By the Plane Separation property,  $\overleftrightarrow{xy}$  and  $\overleftrightarrow{op}$  meet at a unique point  $f$ . Note that  $f$  must be different from either  $x$  or  $y$ ; WLOG, suppose  $f \neq x$ . Now  $\triangle oxy \equiv \triangle pxy$  by SSS, so that  $\angle pxf \equiv \angle ofx$ . Then  $\triangle pxf \equiv \triangle ofx$  by SAS. Then  $\angle pfx \equiv \angle ofx$ ; that is,  $\angle pfx$  is congruent to its supplement. Thus  $\ell$  and  $\overleftrightarrow{pf}$  are perpendicular.

To see uniqueness, note that if  $p$  has two distinct feet  $f_1$  and  $f_2$  on  $\ell$  then  $p$ ,  $f_1$ , and  $f_2$  form a triangle with two internal right angles, contradicting 10.7.  $\square$

**Construction 11.2** (Normal at a point). Let  $\ell$  be a line and  $p \in \ell$  a point in a plane geometry. There is a unique line  $t$  containing  $p$  which is perpendicular to  $\ell$ . We say that  $t$  is the *normal line* of  $\ell$  at  $p$ .

*Proof.* Let  $x$  be a point on  $\ell$  different from  $p$ , and copy  $\overline{px}$  to the opposite side of  $p$  at a point  $y$  by Circle Separation. Note that  $p$  is the midpoint of  $\overline{xy}$ . Construct a point  $z$  such that  $\triangle xyz$  is equilateral. Now  $\triangle zxp \equiv \triangle zyp$  by SSS, so that  $\angle zpx \equiv \angle zpy$ , and thus  $\overleftrightarrow{pz}$  is perpendicular to  $\ell$ .

Uniqueness follows from the uniqueness of angles on a half-plane, since all right angles are congruent.  $\square$

**Def'n 11.3** (Perpendicular Bisector). If  $x$  and  $y$  are two points, then the (unique) line perpendicular to  $\overleftrightarrow{xy}$  at the midpoint of  $\overline{xy}$  is called the *perpendicular bisector* of  $\overline{xy}$ .

**Prop'n 11.4.** Let  $x$  and  $y$  be distinct points. Then  $z$  is on the perpendicular bisector of  $x$  and  $y$  if and only if  $\overline{xz} \equiv \overline{yz}$ .

### Intersections of Lines and Circles

**Prop'n 11.5.** In a plane geometry, a line and a circle can have at most two points in common.

*Proof.* Let  $\ell$  be a line and  $\odot oa$  a circle which have at least three points in common; say  $x$ ,  $y$ , and  $z$ . Suppose WLOG that  $[xyz]$ . Note that  $o$  cannot also be on  $\ell$ , as in this case  $z$  cannot be distinct from both  $x$  and  $y$  by the uniqueness of congruent segments on rays. Now  $\angle oxy \equiv \angle oxy$ ,  $\angle oyx \equiv \angle ozy$ , and  $\angle oxz \equiv \angle ozx$  by Pons Asinorum. In particular,  $\angle oxy$  is right, so that  $\triangle oxy$  has two right interior angles – a contradiction.  $\square$

**Def’n 11.6** (Tangent, Secant). Let  $\ell$  be a line and  $C$  a circle in a plane geometry. We say that  $\ell$  is *tangent to  $C$*  if  $\ell$  and  $C$  have exactly one point in common. Suppose this point is  $t$ ; in this case we say that  $\ell$  is tangent to  $C$  at  $t$ . Similarly, we say that  $\ell$  is a *secant* of  $C$  if  $\ell$  and  $C$  have exactly two distinct points in common.

**Prop’n 11.7.** Let  $\ell$  be a line and  $C$  a circle with center  $o$  in a plane geometry. Then  $\ell$  is tangent to  $C$  if and only if  $o$  is not on  $\ell$  and the foot of  $o$  on  $\ell$  is on  $C$ .

*Proof.* Suppose  $\ell$  is tangent to  $C$  at  $p$ . If  $o \in \ell$ , then  $\ell \cap C$  contains a second point by Circle Separation; so in fact  $o$  is not on  $\ell$ . Let  $f$  be the foot of  $o$  on  $\ell$ . If  $f \neq p$ , then  $o$ ,  $f$ , and  $p$  are noncollinear and form a triangle. Now construct the antipode of  $p$  through  $f$  at  $q$ . Note that  $\triangle opf \equiv \triangle oqf$  by SAS, so that  $\overline{op} \equiv \overline{oq}$ . In particular,  $q$  is a second point in the intersection of  $\ell$  and  $C$ , a contradiction. Thus  $f = p$  as needed.

Conversely, suppose  $\ell$  does not contain  $o$  and that the foot  $f$  of  $o$  on  $\ell$  is on  $C$ . Suppose BWOC that there is a second point  $g \in \ell \cap C$ . Now  $o$ ,  $f$ , and  $g$  are noncollinear, and  $\overline{of} \equiv \overline{og}$ , and  $\angle ofg$  is right (by the definition of foot). So  $\angle ogf$  is right by Pons Asinorum, a contradiction since no triangle can have two interior angles which are both right. So  $C \cap \ell$  contains exactly one point as needed.  $\square$

**Construction 11.8** (Tangent at a point). Let  $C$  be a circle with center  $o$  and let  $p$  be a point on  $C$ . There exists a line  $\ell$  which is tangent to  $C$  at  $p$ .

*Proof.* Construct the line  $\ell$  which is perpendicular to  $\overleftrightarrow{op}$  at  $p$ . Then  $o$  is not on  $\ell$ , and  $p$  is the foot of  $o$  on  $\ell$ . So  $\ell$  is tangent to  $C$  at  $p$ .  $\square$

**Construction 11.9** (Second cut of line and circle). Let  $\ell$  be a line and  $C$  a circle with center  $o$  in a plane geometry such that  $\ell$  is not tangent to  $C$ . Suppose  $p \in \ell \cap C$ . We may construct the second point in  $\ell \cap C$ .



*Proof.* If  $o$  is on  $\ell$ , use Circle Separation. If  $o$  not on  $\ell$ , construct the foot  $f$  of  $o$  on  $\ell$ . Using Circle Separation, copy  $fp$  onto the opposite side of  $f$  from  $p$  at the point  $q$ . Note that  $\triangle ofp \equiv \triangle ofq$  by SAS, so that  $\overline{op} \equiv \overline{oq}$ ; thus  $q \in \ell \cap C$  as needed.  $\square$

## Comparing Segments

**Def'n 11.10.** Let  $\overline{ab}$  and  $\overline{cd}$  be segments in a plane geometry. We say that  $\overline{ab} \leq \overline{cd}$  if there is a point  $x \in \overline{cd}$  such that  $\overline{ab} \equiv \overline{cx}$ .

### Prop'n 11.11.

1. If  $\overline{a_1b_1} \equiv \overline{a_2b_2}$ ,  $\overline{c_1d_1} \equiv \overline{c_2d_2}$ , and  $\overline{a_1b_1} \leq \overline{c_1d_1}$ , then  $\overline{a_2b_2} \leq \overline{c_2d_2}$ .
2. If  $\overline{ab} \leq \overline{cd}$  and  $\overline{cd} \leq \overline{ef}$ , then  $\overline{ab} \leq \overline{ef}$ .
3. If  $[abc]$ , then  $\overline{ab} \leq \overline{ac}$ . If  $[abcd]$ , then  $\overline{bc} \leq \overline{ad}$ .
4. If  $\overline{ab} \leq \overline{cd}$  and  $\overline{cd} \leq \overline{ab}$ , then  $\overline{ab} \equiv \overline{cd}$ .

*Proof.*

There is a point  $x \in \overline{c_1d_1}$  such that  $\overline{a_1b_1} \equiv \overline{c_1x}$ . Now copy  $\overline{c_1x}$  onto  $\overline{c_2d_2}$  at the point  $y$ ; note that  $[c_2yd_2]$ , so that  $y \in \overline{c_2d_2}$ . Now  $\overline{a_2b_2} \equiv \overline{c_2y}$  as needed.

There exists a point  $x \in \overline{cd}$  such that  $\overline{ab} \equiv \overline{cx}$ , and a point  $y \in \overline{ef}$  such that  $\overline{cd} \equiv \overline{ey}$ . Now copy  $\overline{cx}$  onto  $\overline{ey}$  at the point  $z$ ; note that  $[ezy]$ ; in particular,  $\overline{ab} \equiv \overline{ez}$ .

Clear.

There exists a point  $x \in \overline{cd}$  such that  $\overline{cx} \equiv \overline{ab}$ . Now either  $x = c$ ,  $x = d$ , or  $[cxd]$ . If  $x = c$ , then  $b = a$ , and  $d = c$ , so that  $\overline{ab} \equiv \overline{cd}$ . Suppose  $[cxd]$ . There is a point  $y \in \overline{ab}$  such that  $\overline{cy} \equiv \overline{ab}$ ; but now  $[aby]$ , a contradiction. So we have  $x = d$  as needed.  $\square$

## 12 Incircles and Excircles

**Prop'n 12.1.** Let  $a$ ,  $o$ , and  $b$  be distinct points. A point  $p$  not on  $\overleftrightarrow{ad}$  or  $\overleftrightarrow{bo}$  is on the bisector of  $\angle aob$  if and only if  $\overline{px} \equiv \overline{py}$ , where  $x$  is the foot of  $p$  on  $\overleftrightarrow{da}$  and  $y$  is the foot of  $p$  on  $\overleftrightarrow{ob}$ .

*Proof.* Suppose  $p$  has this property. Now  $\triangle opx$  and  $\triangle opy$  are right, with  $\overline{px} \equiv \overline{py}$  and  $\overline{op} \equiv \overline{op}$ . By the HL Theorem,  $\triangle opx \equiv \triangle opy$ , and thus  $\angle xop \equiv \angle yop$ . So  $p$  is on the bisector of  $\angle aob$ .

Conversely, suppose  $p$  is on the bisector of  $\angle aob$ , and let  $x$  be the foot of  $p$  on  $\overleftrightarrow{da}$  and  $y$  the foot of  $p$  on  $\overleftrightarrow{ob}$ . Now  $\triangle xop \equiv \triangle yop$  by AAS, so that  $\overline{px} \equiv \overline{py}$ .  $\square$

**Construction 12.2** (Incircle Theorem). Let  $a$ ,  $b$ , and  $c$  be distinct non-collinear points. Then we have the following.

- (i) The bisectors of the interior angles of  $\triangle abc$  are concurrent at a point  $o$ , called the *incenter* of the triangle, which is interior to  $\triangle abc$ .
- (ii) The feet of  $o$  on the sides of  $\triangle abc$  lie on a circle, called the *incircle* of  $\triangle abc$ , which is centered at  $o$  and tangent to the sides of  $\triangle abc$ .

*Proof.* Construct the bisector of  $\angle bac$ . By the Crossbar Theorem this ray cuts  $\overline{bc}$  at a point, say  $h$ . Now construct the bisector of  $\angle abc$ ; again by the Crossbar Theorem this ray cuts  $\overline{ah}$  at a point, say  $o$ . Note that  $o$  is interior to  $\triangle abc$ . Let  $x$ ,  $y$ , and  $z$  be the feet of  $o$  on  $\overleftrightarrow{ac}$ ,  $\overleftrightarrow{ab}$ , and  $\overleftrightarrow{bc}$ , respectively. Since  $o$  is on the bisectors of  $\angle bac$  and  $\angle abc$ , we have  $\overline{ox} \equiv \overline{oy}$  using the AAS Theorem on  $\triangle oxa$  and  $\triangle oya$ . Similarly,  $\overline{oy} \equiv \overline{oz}$ . Thus  $\overline{ox} \equiv \overline{oz}$ , and so  $o$  is also on the bisector of  $\angle BCA$  by 12.1. Thus the bisectors of the interior angles of  $\triangle abc$  are concurrent at  $o$ .

Now  $x$ ,  $y$ , and  $z$  are the feet of  $o$  on the sides of  $\triangle abc$ , and we've seen that  $\overline{ox} \equiv \overline{oy} \equiv \overline{oz}$ . Thus the circle  $\odot ox$  contains  $x$ ,  $y$ , and  $z$ , and moreover is tangent to the sides of  $\triangle abc$  at  $x$ ,  $y$ , and  $z$ .  $\square$

**Construction 12.3** (Excicle Theorem). Let  $a$ ,  $b$ , and  $c$  be distinct non-collinear points. Then we have the following.

- (i) The bisector of the interior angle at  $a$  and the exterior angles at  $b$  and  $c$  are concurrent at a point  $o$ , called the *excenter* of  $\triangle abc$  at  $a$ .
- (ii) The feet of  $o$  on the (extended) sides of  $\triangle abc$  lie on a circle, called the *excicle* of  $\triangle abc$  at  $a$ , which is centered at  $o$  and tangent to the sides of  $\triangle abc$ .

*Proof.* Essentially the same as the proof of the Incircle Theorem.  $\square$

To every triangle we can associate four special circles: the incircle, and one excircle for each vertex. These circles are tangent to all three (extended) sides of the triangle.

**Prop'n 12.4.** Any circle which is tangent to all three (extended) sides of a triangle is either the incircle or one of the excircles.

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— IV —

Euclidean Planes

### 13 Euclidean Planes

Recall that an incidence geometry is called *euclidean* if, given any line  $\ell$  and any point  $p$  not on  $\ell$ , there is exactly one line passing through  $p$  which is parallel to  $\ell$ . So far we have avoided using any assumptions about the uniqueness of parallel lines, and have been able to prove a good number of interesting results. We will now specialize to the Euclidean case for a while.

**Prop'n 13.1** (Converse of the Alternate Interior Angles Theorem). In a Euclidean plane geometry, if two parallel lines are cut by a transversal, then alternate interior angles formed by the cut are congruent.

*Proof.* (copy angle, use AIA, use uniqueness.) □

**Prop'n 13.2.** If  $\ell$  and  $m$  are parallel and  $m$  and  $t$  are parallel, then  $\ell$  and  $t$  are parallel.

*Proof.* We can assume that  $\ell$  and  $t$  are distinct (if equal, they are parallel). Suppose BWOC that  $\ell$  and  $t$  meet at the unique point  $x$ . Since  $\ell$  and  $m$  are parallel,  $x$  is not on  $m$ . By the Euclidean property, there is a unique line  $s$  containing  $x$  which is parallel to  $m$ . But both  $\ell$  and  $t$  satisfy this condition, and they are distinct - a contradiction. □

**Cor. 13.3.** If  $\ell_1$  and  $\ell_2$  are parallel and  $m$  is incident to  $\ell_1$ , then  $m$  is incident to  $\ell_2$ .

**Prop'n 13.4.** If  $\ell_1$  and  $m$  are perpendicular, and if  $\ell_1$  and  $\ell_2$  are parallel, then  $\ell_2$  and  $m$  are perpendicular.

*Proof.* If  $\ell_1 = \ell_2$  there's nothing to do. Otherwise  $m$  is a transversal and the result follows from the converse of the AIA theorem. □

**Prop'n 13.5.** If  $\ell_1$  and  $\ell_2$  are parallel,  $m_1$  and  $\ell_1$  are perpendicular, and  $m_2$  and  $\ell_2$  are perpendicular, then  $m_1$  and  $m_2$  are parallel.

*Proof.*  $\ell_2$  and  $m_1$  are perpendicular by the converse of AIA, and then  $m_1$  and  $m_2$  are parallel by AIA. □

**Construction 13.6.** Let  $a$ ,  $b$ , and  $c$  be distinct noncollinear points. Then the perpendicular bisectors of  $\overline{ab}$ ,  $\overline{bc}$ , and  $\overline{ca}$  are concurrent at a point  $o$ , called the *circumcenter* of  $a$ ,  $b$ , and  $c$ . Moreover,  $\odot oa$  contains all of  $a$ ,  $b$ ,

and  $c$  and is unique with this property; this circle is called the *circumcircle* of  $\triangle abc$ .

*Proof.* Let  $\ell$  be the perpendicular bisector of  $\overline{ab}$  and let  $m$  be the perpendicular bisector of  $\overline{bc}$ . Now  $\ell$  and  $m$  must be incident at a unique point  $o$ , since otherwise  $\overleftrightarrow{ab}$  and  $\overleftrightarrow{bc}$  are parallel (which they aren't, as they meet at the unique point  $b$  (since  $a$ ,  $b$ , and  $c$  are not collinear)). Recall that all points  $x$  on the perpendicular bisector of  $\overline{ab}$  have the property that  $\overline{ax} \equiv \overline{bx}$ . So we have  $\overline{ao} \equiv \overline{bo} \equiv \overline{co}$ . Thus  $o$  is also on the perpendicular bisector of  $\overline{ca}$ , and moreover  $\odot oa$  contains  $a$ ,  $b$ , and  $c$ .

To see uniqueness, note that the center of any circle containing all of  $a$ ,  $b$ , and  $c$  must be on the perpendicular bisectors of  $\overline{ab}$ ,  $\overline{bc}$ , and  $\overline{ca}$ .  $\square$

### Prop'n 13.7.

- (i) Opposite angles of a parallelogram are congruent.
- (ii) Opposite sides of a parallelogram are congruent.
- (iii) The diagonals of a parallelogram bisect each other.

*Proof.* For the angles, use AIA and converse of AIA. For the sides, construct a diagonal and use AAS. For the diagonals, use converse of AIA and ASA.  $\square$

**Prop'n 13.8** (Thales' Theorem). Suppose  $a$  and  $b$  are the opposite endpoints of a diameter of a circle centered at  $o$ , and that  $c$  is a point on this circle distinct from  $a$  and  $b$ . Then  $\angle acb$  is right. Moreover,  $\angle cab$  is congruent to the bisector of  $\angle cob$ .

*Proof.* Construct the second point  $d$  on the intersection of  $\odot oa$  and  $\overleftrightarrow{bc}$  using Circle Cut. Now  $\overline{ac} \equiv \overline{bd}$  using SAS, and similarly  $\overline{cb} \equiv \overline{ad}$ . Now  $\triangle abc \equiv \triangle bad$  by SSS, so that  $\angle cba \equiv \angle dab$ . Thus  $\overleftrightarrow{bc}$  and  $\overleftrightarrow{ad}$  are parallel by AIA. Now  $\triangle bac \equiv \triangle dca$  by SSS, so that  $\angle bca \equiv \angle dac$ . Now  $\angle dac$  and  $\angle bca$  are supplementary by the converse of AIA. So  $\angle bca$  is right.

Now let  $m$  be the point on  $\overline{bc}$  such that  $\overleftrightarrow{om}$  bisects  $\angle cob$ . (Use crossbar.) We have  $\angle ocb \equiv \angle ocb$  by Pons Asinorum, so that  $\angle omc \equiv \angle omb$  by ASA. Thus  $\angle cmo$  is right. By AIA,  $\overleftrightarrow{om}$  is parallel to  $\overleftrightarrow{ac}$ . By the converse of AIA,  $\angle oca \equiv \angle com$ , and  $\angle cao \equiv \angle com$  by Pons Asinorum.  $\square$

**Prop'n 13.9** (Converse of Thales' Theorem). Let  $a$ ,  $b$ , and  $c$  be distinct noncollinear points and let  $m$  be the midpoint of  $\overline{ab}$ . If  $\angle acb$  is right, then  $c$  lies on  $\odot ma$ .

*Proof.* Construct the antipode  $d$  of  $c$  through  $m$ . Now  $\overline{bc} \equiv \overline{ad}$  by SAS, and similarly  $\overline{ac} \equiv \overline{bd}$ . So  $\triangle abc \equiv \triangle bad$  by SSS. Now  $\overleftrightarrow{bc}$  is parallel to  $\overleftrightarrow{ad}$  by AIA, and so  $\angle cad \equiv \angle acb$  using the converse of AIA. Now  $\triangle cad \equiv \triangle acb$  by SAS, so that  $\overline{ab} \equiv \overline{cd}$ . Thus  $\overline{am} \equiv \overline{cm}$ .  $\square$

(Here we used a lemma that if two segments are congruent, then their midsegments are congruent.)

**Construction 13.10** (Tangent through an exterior point.). Given a circle  $\odot oa$  and a point  $b$  exterior to this circle, there exist two lines which are tangent to  $\odot oa$  and which pass through  $b$ .

*Proof.* Construct the midpoint  $m$  of  $\overline{bo}$ , and construct circle centered at  $m$  and passing through  $o$ . By the Interleaved Diameters axiom,  $\odot mo \cap \odot oa$  contains exactly two points,  $x$  and  $y$ . Note that  $\angle oxb$  and  $\angle oyb$  are inscribed on the diameter of a circle, and thus are right; so  $\overleftrightarrow{bx}$  and  $\overleftrightarrow{by}$  are tangent to  $\odot oa$ .

Suppose now that there is a third point  $z$  on  $\odot oa$ , different from  $x$  and  $y$ , such that  $\angle ozb$  is right. By the HL Theorem, we have  $\triangle oxb \equiv \triangle oyb \equiv \triangle ozb$ . In particular,  $\angle xob \equiv \angle yob \equiv \angle zob$ . But now  $z$  is on either the  $x$  side or the  $y$  side of  $\overleftrightarrow{ob}$  (it cannot be on  $\overleftrightarrow{ob}$  since that line is not tangent to  $\odot oa$ ). By the uniqueness of angles on a half-plane, either  $x = z$  or  $y = z$ .  $\square$

**Prop'n 13.11** (Inscribed Angle Theorem). Let  $a$ ,  $b$ , and  $o$  be distinct noncollinear points with  $\overline{ao} \equiv \overline{bo}$ . If  $c$  is a point on  $\odot oa$  such that  $c$  and  $o$  are on the same side of  $\overleftrightarrow{ab}$ , then  $\angle acb$  is congruent to a bisector of  $\angle aob$ . In particular, any two such points form congruent angles.

*Proof.* (@@@)  $\square$

## Altitudes and the Orthocenter

**Def'n 13.12.** Let  $a$ ,  $b$ , and  $c$  be distinct noncollinear points, and let  $f$  be the foot of  $a$  on  $\overleftrightarrow{bc}$ . Then  $\overline{af}$  is called an *altitude* of  $\triangle abc$ .

**Prop'n 13.13** (Orthocenter Theorem). Let  $a$ ,  $b$ , and  $c$  be distinct noncollinear points. Then the lines containing the three altitudes of  $\triangle abc$  are concurrent at a point  $o$ , called the *orthocenter* of  $\triangle abc$ .

*Proof.* Construct the feet  $f_a$ ,  $f_b$ , and  $f_c$  of  $a$ ,  $b$ , and  $c$  on  $\overline{bc}$ ,  $\overline{ac}$ , and  $\overline{ab}$ , respectively. Let  $\ell_a$  be the (unique) line passing through  $a$  and parallel to  $\overleftrightarrow{bc}$ ; similarly, construct lines  $\ell_b$  and  $\ell_c$  passing through  $b$  and  $c$  and parallel to  $\overleftrightarrow{ac}$  and  $\overleftrightarrow{ab}$ . Note that  $\ell_a$  and  $\ell_b$  are incident at a point  $c'$ . Similarly,  $\ell_a$



and  $\ell_c$  are incident at  $b'$  and  $\ell_b$  and  $\ell_c$  are incident at  $a'$ . Note that  $\overline{c'a}$  and  $\overline{bc}$  are opposite sides of a parallelogram, and thus congruent; similarly we have  $\overline{ab'} \equiv \overline{bc}$ . In particular,  $\overleftrightarrow{af_a}$  is the perpendicular bisector of  $\overline{b'c'}$ . Similarly,  $\overleftrightarrow{bf_b}$  is the perpendicular bisector of  $\overline{a'c'}$  and  $\overleftrightarrow{cf_c}$  the perpendicular bisector of  $\overline{a'b'}$ . That is, the lines containing the altitudes of  $\triangle abc$  are the perpendicular bisectors of the sides of  $\triangle a'b'c'$ , and thus are concurrent.  $\square$

### Medians and the Centroid

**Prop'n 13.14.** Let  $a$ ,  $b$ , and  $c$  be distinct noncollinear points. Let  $m$  be the midpoint of  $\overline{ab}$ , and let  $n$  be the midpoint of  $\overline{ac}$ . Finally, let  $\ell$  be the line parallel to  $\overleftrightarrow{ab}$  through  $n$  and  $t$  the line parallel to  $\overleftrightarrow{ac}$  through  $m$ . Then  $\ell$  and  $t$  meet at the midpoint of  $\overline{bc}$  and  $\overleftrightarrow{mn}$  is parallel to  $\overleftrightarrow{bc}$ .

*Proof.* Let  $p$  be the point of intersection of  $\ell$  and  $t$ . Now  $\angle mna \equiv \angle nmp$  by the converse of AIA; similarly  $\angle nma \equiv \angle mnp$ . Then  $\triangle amn \equiv \triangle pnm$  by ASA. In particular we have  $\overline{mp} \equiv \overline{an}$  and  $\overline{np} \equiv \overline{am}$ . Next, using the converse of AIA and the Vertical Angles theorem, we have  $\angle man \equiv \angle bmp$  and  $\angle man \equiv \angle pnc$ . By SAS we have  $\triangle bmp \equiv \triangle man \equiv \triangle pnc$ . Using AIA, then, we have that  $\overleftrightarrow{bp}$  and  $\overleftrightarrow{pc}$  are both parallel to  $\overleftrightarrow{mn}$ ; by the uniqueness of parallel lines through a point, in fact  $b$ ,  $p$ , and  $c$  are collinear, and we see that  $p$  is the midpoint of  $\overline{bc}$  as needed.  $\square$

**Lemma 13.15.** Let  $a$ ,  $b$ , and  $c$  be distinct collinear points, and  $a$ ,  $e$ , and  $d$  distinct collinear points such that  $e$  is the midpoint of  $\overline{ad}$ . Then  $\overleftrightarrow{be}$  is parallel to  $\overleftrightarrow{cd}$  if and only if  $\overline{ab} \equiv \overline{bc}$ .

*Proof.* Follows from the previous result.  $\square$

**Cor. 13.16.** Let  $a$ ,  $b$ , and  $c$  be distinct noncollinear points. Then the medians of  $\triangle abc$  are concurrent at a point  $o$ , called the *centroid* of  $\triangle abc$ .

*Proof.* Let  $m$  be the midpoint of  $\overline{ab}$  and  $n$  the midpoint of  $\overline{ac}$ . By the previous proposition,  $\overleftrightarrow{mn}$  is parallel to  $\overleftrightarrow{bc}$ . Now let  $o$  be the point of concurrency of  $\overline{bn}$  and  $\overline{cm}$ , and using the Crossbar Theorem let  $t$  be the point on  $\overline{bc}$  which is also on  $\overline{ao}$ . We need to show that  $t$  is the midpoint of  $\overline{bc}$ . To this end, construct the line parallel to  $\overleftrightarrow{bm}$  through  $c$ , and let  $h$  be the point where this line cuts  $\overleftrightarrow{ao}$ . By the previous lemma,  $o$  is the midpoint of  $\overline{ah}$ . Again using the previous lemma,  $\overleftrightarrow{bh}$  is parallel to  $\overleftrightarrow{cn}$ . In particular,  $b$ ,  $h$ ,  $c$ ,  $o$  form a parallelogram whose diagonals meet at  $t$ . Thus  $t$  is the midpoint of  $\overline{bc}$ .  $\square$

**Prop'n 13.17** (Centroid Trisection).

**Prop'n 13.18** (Euler Line). Let  $a$ ,  $b$ , and  $c$  be distinct noncollinear points. Then the orthocenter, centroid, and circumcenter of  $\triangle abc$  are collinear. The line containing these three points is called the *euler line* of  $\triangle abc$ .

*Proof.* Let  $o$  be the orthocenter and  $d$  the centroid of  $\triangle abc$ . Let  $m$  be the midpoint of  $\overline{od}$ , and construct the antipode of  $m$  through  $d$  at  $p$ . We claim that  $p$  lies on the perpendicular bisector of  $\overline{bc}$ . To this end, let  $m_a$  be the midpoint of  $\overline{bc}$ . Note that  $\overline{md} \equiv \overline{dp}$  by construction. Now construct the parallel to  $\overleftrightarrow{ao}$  through  $m$ , cutting  $\overleftrightarrow{ad}$  at  $h$ . By the lemma, since  $\overline{om} \equiv \overline{md}$  we have  $\overline{ah} \equiv \overline{hd}$ . By the Centroid Trisection theorem we have  $\overline{hd} \equiv \overline{dm_a}$ . Note that  $\angle hdo \equiv \angle m_a dp$ , and by SAS,  $\triangle hdo \equiv \triangle m_a dp$ . Thus  $\angle mhd \equiv \angle m_a pd$ . By AIA, we have  $\overleftrightarrow{pm_a}$  parallel to  $\overleftrightarrow{hm}$ , so that  $\overleftrightarrow{pm_a}$  is the perpendicular bisector of  $\overline{bc}$ . That is,  $p$  lies on the perpendicular bisector of  $\overline{bc}$ . Similar reasoning shows that  $p$  lies on the perpendicular bisectors of  $\overline{ab}$  and  $\overline{ac}$  as well; thus  $p$  is the circumcenter of  $\triangle abc$ . In particular, the orthocenter, centroid, and circumcenter of  $\triangle abc$  are collinear.  $\square$

**Prop'n 13.19** (9 Point Circle). Let  $a$ ,  $b$ , and  $c$  be distinct noncollinear points, and let  $o$  be the orthocenter of  $\triangle abc$ . Then the following points all lie on a common circle:

- (i) The midpoints  $m_a$ ,  $m_b$ , and  $m_c$  of  $\overline{bc}$ ,  $\overline{ac}$ , and  $\overline{ab}$ ,
- (ii) The feet  $h_a$ ,  $h_b$ , and  $h_c$  of  $a$  on  $\overleftrightarrow{bc}$ ,  $b$  on  $\overleftrightarrow{ac}$ , and  $c$  on  $\overleftrightarrow{ab}$ , and
- (iii) The midpoints  $n_a$ ,  $n_b$ , and  $n_c$  of  $\overline{ao}$ ,  $\overline{bo}$ , and  $\overline{co}$ .

*Proof.* Note that  $\overleftrightarrow{m_b m_c}$  is parallel to  $\overleftrightarrow{bc}$ , which is parallel to  $\overleftrightarrow{n_b n_c}$  using [Lemma 13.15](#). Similarly, we have  $\overleftrightarrow{n_b m_c}$  parallel to  $\overleftrightarrow{ao}$  parallel to  $\overleftrightarrow{n_c m_b}$ . Since  $\overleftrightarrow{bc}$  is perpendicular to  $\overleftrightarrow{ao}$ , in fact  $m_c$ ,  $m_b$ ,  $n_c$ , and  $n_b$  form a rectangle. Thus  $m_c$ ,  $m_b$ ,  $n_c$ , and  $n_b$  lie on a common circle having diameters  $\overline{m_b n_b}$  and  $\overline{m_c n_c}$ . By similar reasoning,  $m_c$ ,  $m_a$ ,  $n_c$ , and  $n_a$  lie on a common circle having diameters  $\overline{m_a n_a}$  and  $\overline{m_c n_c}$ . Because every segment is the diameter of a unique circle, in fact all six points  $m_i$  and  $n_i$  lie on a common circle. By the converse of Thales' Theorem,  $h_a$ ,  $h_b$ , and  $h_c$  also lie on this circle as claimed.  $\square$

— V —

Models

## 14 $\mathbb{R}^2$ – The Cartesian Plane

Our definition of incidence geometry is a kind of **theory**, and a theory is only really useful if it has at least one **model**. So before we develop our theory of geometry further we'll spend the next few sections constructing some models. Remember that the words “point”, “collinear”, and “line” are context dependent – what they mean depends on the model – and so we may find ourselves using these words in unintuitive ways.

We'll start with a model of incidence geometry with which you are probably already familiar: the cartesian plane. To define this or any model it's enough to specify (1) what our points are and (2) what it means for three points to be collinear. At risk of giving away the punchline, in this model points are pairs of real numbers and lines are what you expect.

**Prop'n 14.1** (Cartesian Plane). Define a ternary relation on  $\mathbb{R}^2$  as follows. Given  $A = (a_x, a_y)$ ,  $B = (b_x, b_y)$ , and  $C = (c_x, c_y)$  in  $\mathbb{R}^2$ , we say that  $\langle A, B, C \rangle$  if and only if  $A$ ,  $B$ , and  $C$  are not all equal and

$$\det \begin{bmatrix} a_x & a_y & 1 \\ b_x & b_y & 1 \\ c_x & c_y & 1 \end{bmatrix} = 0.$$

This relation makes the set  $\mathbb{R}^2$  an incidence geometry, which we call the *cartesian plane*.

*Proof.* IG1, IG2, and IG3 can be verified directly, and we can see that IG4 holds by considering the points  $(0,0)$ ,  $(0,1)$ , and  $(1,0)$ . So it suffices to show that IG5 holds. To this end suppose we have  $A$ ,  $B$ ,  $U$ , and  $V$ . Expanding and rearranging the known determinants, we have

$$(b_x - a_x)(u_y - a_y) = (b_y - a_y)(u_x - a_x)$$

and

$$(b_x - a_x)(v_y - a_y) = (b_y - a_y)(v_x - a_x).$$

If  $a_x = b_x$ , then we see that  $u_x = a_x = v_x$  and thus  $\langle A, U, V \rangle$ . Similarly, if  $a_y = b_y$ , we see that  $u_y = a_y = v_y$  and so  $\langle A, U, V \rangle$ . Finally, suppose we have  $a_x \neq b_x$  and  $a_y \neq b_y$ . Now we have

$$\frac{u_y - a_y}{u_x - a_x} = \frac{b_y - a_y}{b_x - a_x} = \frac{v_y - a_y}{v_x - a_x}.$$

Equating the first and last of these expressions we see that  $\langle A, U, V \rangle$ .  $\square$

This might seem like a strange way to define “collinearity”, but it is easy to compute, and by expanding the determinant we can see that the lines in this geometry are precisely the solutions of linear equations.

**Cor. 14.2** (Lines in  $\mathbb{R}^2$ ). Let  $A = (a_x, a_y)$  and  $B = (b_x, b_y)$  be distinct cartesian points. Then  $\overleftrightarrow{AB}$  is the set of all points  $X = (x, y)$  which satisfy the equation

$$(b_y - a_y)x - (b_x - a_x)y + a_y b_x - a_x b_y = 0.$$

That equation may look familiar as the standard form equation of a line. You might have noticed that our proof of 14.1 used nothing more than the arithmetic on  $\mathbb{R}$ . This means that the result still holds if we replace  $\mathbb{R}$  by any object  $F$  where we have an arithmetic which behaves like that of  $\mathbb{R}$ . Such objects are called *fields*, and there are many examples, including the field  $\mathbb{Q}$  of rational numbers and the field  $\mathbb{C}$  of complex numbers. So we immediately get some additional models as well.

**Cor. 14.3.** The sets  $\mathbb{Q}^2$  and  $\mathbb{C}^2$  are incidence geometries, which we call the *rational plane* and the *complex plane*, respectively.

Note that lines in  $\mathbb{Q}^2$  look much like lines in  $\mathbb{R}^2$  except that they are filled with “holes”; any point on a line in  $\mathbb{R}^2$  which has an irrational coordinate is not on the corresponding line in  $\mathbb{Q}^2$ . Lines in  $\mathbb{C}^2$  are stranger still.

## Betweenness

In this section we will establish that the cartesian plane is an ordered geometry. To do this, we need to specify (1) how to detect when one point is between two others, and (2) the halfplanes for each line.

**Prop’n 14.4.** Given points  $A$ ,  $B$ , and  $C$  in  $\mathbb{R}^2$ , we say  $[ACB]$  if  $A \neq B$  and the equation  $C = A + t(B - A)$  has a solution  $t \in (0, 1)$ . Then this  $[\ast \ast \ast]$  is a betweenness relation on  $\mathbb{R}^2$ .

*Proof.*

B1. Suppose  $[ACB]$ . Now  $A \neq B$  by definition, and we have  $C = A + t(B - A)$  for some  $t \in (0, 1)$ . If  $C = A$ , then  $(0, 0) = t(B - A)$ , so that  $B = A$ ; a contradiction. If  $C = B$ , then  $(0, 0) = (t - 1)(B - A)$ , so that  $B = A$ ; a contradiction. So  $A$ ,  $B$ , and  $C$  are distinct. Now  $A$ ,  $B$ , and  $C$  are collinear because

$$\det \begin{bmatrix} a_x & a_y & 1 \\ b_x & b_y & 1 \\ c_x & c_y & 1 \end{bmatrix} = \det \begin{bmatrix} a_x & a_y & 1 \\ b_x & b_y & 1 \\ a_x + t(b_x - a_x) & a_y + t(b_y - a_y) & 1 \end{bmatrix} = 0.$$

B2. If  $C = A + t(B - A)$  where  $t \in (0, 1)$ , then (rearranging) we also have  $C = B + (1 - t)(A - B)$  with  $1 - t \in (0, 1)$  as needed.

- B3. Suppose  $A$ ,  $B$ , and  $C$  are distinct such that  $\langle A, B, C \rangle$ . Using [Exercise 2.1](#), we have  $C = A + t(B - A)$  for some real number  $t$ . Note that  $t \neq 0$  and  $t \neq 1$  since in the first case we would have  $C = A$  and in the second,  $C = B$ . There are then three possibilities for  $t$ . If  $t \in (0, 1)$ , then  $[ACB]$  by definition. If  $t > 1$ , then “solving for  $B$ ” we have  $B = A + \frac{1}{t}(C - A)$ , and since  $1/t \in (0, 1)$ , we have  $[ABC]$ . If  $t < 0$ , then we have  $A = C + \frac{-t}{1-t}(B - C)$ , and since  $\frac{-t}{1-t} \in (0, 1)$ , we have  $[CAB]$ .
- B4. Suppose  $[ABC]$  and  $[ACD]$ ; say we have  $B = A + t(C - A)$  and  $C = A + s(D - A)$  where  $s, t \in (0, 1)$ . Now  $B = A + ts(D - A)$ , and since  $st \in (0, 1)$ , we have  $[ABD]$ . Similarly, we have  $C = B + \frac{s-ts}{1-ts}(D - B)$ , and since  $\frac{s-ts}{1-ts} \in (0, 1)$ , we have  $[BCD]$  as needed.
- B5. Suppose  $[ABC]$  and  $[BCD]$ ; say we have  $B = t(C - A)$  and  $C = B + s(D - B)$  where  $s, t \in (0, 1)$ . Now  $C = A + \frac{s}{1-t+st}(D - A)$ , and we also have  $\frac{s}{1-t+st} \in (0, 1)$ . (To see this, note that  $0 < (1-s)(1-t)$  and rearrange to get  $s < 1 - t + st$ .) Thus  $[BCD]$ . Next note that  $B = A + \frac{ts}{1-t+ts}(D - A)$ , and since  $\frac{ts}{1-t+ts} \in (0, 1)$ , we have  $[ABD]$  as needed.
- B6. Let  $A$  and  $B$  be distinct points. Given a real number  $t$ , let  $C = A + t(B - A)$ . If  $t \in (0, 1)$ , then  $[ACB]$  by definition. If  $t > 1$ , then  $B = A + \frac{1}{t}(C - A)$  with  $\frac{1}{t} \in (0, 1)$  and we have  $[ABC]$ . If  $t < 0$ , then  $A = C + \frac{-t}{1-t}(B - C)$  with  $\frac{-t}{1-t} \in (0, 1)$  and we have  $[CAB]$ .  $\square$

Next, we'd like to show that  $\mathbb{R}^2$  is an ordered geometry by showing that it has the Line Separation property. First, we need the following technical lemma about the intersection of a segment and a line in  $\mathbb{R}^2$ .

**Lemma 14.5.** Let  $A = (a_x, a_y)$  and  $B = (b_x, b_y)$  be distinct points in  $\mathbb{R}^2$ , and let  $U = (u_x, u_y)$  and  $V = (v_x, v_y)$  be distinct points not on  $\overleftrightarrow{AB}$ . Then  $\overline{UV} \cap \overleftrightarrow{AB}$  consists of a single point if and only if

$$\det \begin{bmatrix} a_x & a_y & 1 \\ b_x & b_y & 1 \\ u_x & u_y & 1 \end{bmatrix} \quad \text{and} \quad \det \begin{bmatrix} a_x & a_y & 1 \\ b_x & b_y & 1 \\ v_x & v_y & 1 \end{bmatrix}$$

have opposite signs.

*Proof.* Note that  $\overline{UV} \cap \overleftrightarrow{AB}$  contains exactly one point if and only if the equation  $U + t(V - U) = A + u(B - A)$  has a unique solution  $(t, u)$ . In fact, by comparing coordinates we can rewrite this equation in matrix form as

$$\begin{bmatrix} t \\ -u \end{bmatrix} = \begin{bmatrix} v_x - u_x & b_x - a_x \\ v_y - u_y & b_y - a_y \end{bmatrix}^{-1} \begin{bmatrix} a_x - u_x \\ a_y - u_y \end{bmatrix}.$$

(This matrix is invertible by [Exercise 14.2](#).) Comparing entries, we have

$$t = \frac{(b_y - a_y)(a_x - u_x) - (b_x - a_x)(a_y - u_y)}{(v_x - u_x)(b_y - a_y) - (v_y - u_y)(b_x - a_x)}.$$

Now by definition the unique point in  $\overleftrightarrow{UV} \cap \overleftrightarrow{AB}$  is more specifically on the segment  $\overline{UV}$  if and only if  $t \in (0, 1)$ .

There are now two possibilities, depending on whether the denominator of  $t$  is positive or negative. If the denominator of  $t$  is positive, we can see that  $t \in (0, 1)$  if and only if

$$\det \begin{bmatrix} a_x & a_y & 1 \\ b_x & b_y & 1 \\ u_x & u_y & 1 \end{bmatrix} > 0 > \det \begin{bmatrix} a_x & a_y & 1 \\ b_x & b_y & 1 \\ v_x & v_y & 1 \end{bmatrix},$$

and if the denominator of  $t$  is negative, then  $t \in (0, 1)$  if and only if

$$\det \begin{bmatrix} a_x & a_y & 1 \\ b_x & b_y & 1 \\ u_x & u_y & 1 \end{bmatrix} < 0 < \det \begin{bmatrix} a_x & a_y & 1 \\ b_x & b_y & 1 \\ v_x & v_y & 1 \end{bmatrix}$$

as needed. □

We are now prepared to show the following.

**Prop'n 14.6.** For each line  $\ell = \overleftrightarrow{AB}$  in  $\mathbb{R}^2$ , we define two halfplanes as follows.

$$\begin{aligned} \mathcal{H}_{1,\ell} &= \left\{ (x, y) \mid \det \begin{bmatrix} a_x & a_y & 1 \\ b_x & b_y & 1 \\ x & y & 1 \end{bmatrix} > 0 \right\} \\ \mathcal{H}_{2,\ell} &= \left\{ (x, y) \mid \det \begin{bmatrix} a_x & a_y & 1 \\ b_x & b_y & 1 \\ x & y & 1 \end{bmatrix} < 0 \right\}. \end{aligned}$$

With halfplanes defined this way for all lines,  $\mathbb{R}^2$  satisfies the Line Separation Property and thus is an ordered geometry.

*Proof.* It is enough to show that the Line Separation property is satisfied. But first, we need to verify that our halfplanes are well-defined; that is, they do not depend on the choice of line generators. (@@@)

Certainly  $\mathcal{H}_{1,\ell}$ ,  $\mathcal{H}_{2,\ell}$ , and  $\ell$  partition  $\mathbb{R}^2$  by the trichotomy property of  $<$ . To see that both halfplanes are nonempty we consider three cases: if  $a_x = b_x$ , then  $(a_x + 1, 0)$  and  $(a_x - 1, 0)$  are in opposite halfplanes; if  $a_y = b_y$ , then  $(0, a_y + 1)$  and  $(0, a_y - 1)$  are in opposite halfplanes; and if  $a_x \neq b_x$  and  $a_y \neq b_y$  then  $(a_x, b_y)$  and  $(b_x, a_y)$  are in opposite halfplanes. By [Lemma 14.5](#), if  $U \in \mathcal{H}_{1,\ell}$

and  $V \in \mathcal{H}_{2,\ell}$ , then  $\overline{UV} \cap \overleftrightarrow{AB}$  consists of a unique point. All that remains is to show that  $\mathcal{H}_{1,\ell}$  and  $\mathcal{H}_{2,\ell}$  are convex.

To see that  $\mathcal{H}_{1,\ell}$  is convex, let  $U, V \in \mathcal{H}_{1,\ell}$ . By definition, we have

$$\det \begin{bmatrix} a_x & a_y & 1 \\ b_x & b_y & 1 \\ u_x & u_y & 1 \end{bmatrix} > 0 \text{ and } \det \begin{bmatrix} a_x & a_y & 1 \\ b_x & b_y & 1 \\ v_x & v_y & 1 \end{bmatrix} > 0.$$

Now suppose  $[UWV]$ ; then again by definition we have  $t \in (0, 1)$  such that  $W = U + t(V - U)$ . Then

$$\begin{aligned} & \det \begin{bmatrix} a_x & a_y & 1 \\ b_x & b_y & 1 \\ w_x & w_y & 1 \end{bmatrix} \\ &= \det \begin{bmatrix} a_x & a_y & 1 \\ b_x & b_y & 1 \\ u_x + t(v_x - u_x) & u_y + t(v_y - u_y) & 1 + t(1 - 1) \end{bmatrix} \\ &= \det \begin{bmatrix} a_x & a_y & 1 \\ b_x & b_y & 1 \\ u_x & u_y & 1 \end{bmatrix} + t \left( \det \begin{bmatrix} a_x & a_y & 1 \\ b_x & b_y & 1 \\ v_x & v_y & 1 \end{bmatrix} - \det \begin{bmatrix} a_x & a_y & 1 \\ b_x & b_y & 1 \\ u_x & u_y & 1 \end{bmatrix} \right) \\ &> 0 \end{aligned}$$

using [Exercise 1.1](#), and because the determinant is multilinear. So we have  $W \in \mathcal{H}_{1,\ell}$ , and thus  $\mathcal{H}_{1,\ell}$  is convex. A similar argument shows that  $\mathcal{H}_{2,\ell}$  is convex.  $\square$

The proofs of Propositions [14.4](#) and [14.6](#) remain valid if we replace  $\mathbb{R}^2$  by  $\mathbb{Q}^2$ , so that the Rational Plane is also an ordered geometry. However we cannot replace  $\mathbb{R}^2$  by  $\mathbb{C}^2$ , because the order relation  $<$  does not make sense in the complex numbers.

## Congruence

Remember: to show that an ordered geometry is a congruence geometry, we need to specify (1) how to detect when two segments are congruent and (2) how to detect when two angles are congruent. In this section we will establish segment and angle congruences in the cartesian plane.

We define two helper functions,  $N$  and  $M$ , as follows. Given  $A, B \in \mathbb{R}^2$ , we define

$$N(A, B) = (b_x - a_x)^2 + (b_y - a_y)^2.$$

Given  $A, B, O \in \mathbb{R}^2$ , we define

$$M(A, O, B) = (a_x - o_x)(b_x - o_x) + (a_y - o_y)(b_y - o_y).$$



**Prop'n 14.7.** The following hold for all cartesian points  $A$  and  $B$ .

- (i)  $N(A, B) \geq 0$ , with equality if and only if  $A = B$ .
- (ii)  $N(A, B) = N(B, A)$ .
- (iii)  $M(A, O, B) = M(B, O, A)$ .
- (iv) If  $C$  is a point such that  $A$ ,  $B$ , and  $C$  are distinct and  $\langle A, B, C \rangle$ , then

$$\frac{M(A, B, C)^2}{N(A, B)N(C, B)} = 1.$$

**Prop'n 14.8.**  $\mathbb{R}^2$  is a congruence geometry under the following relations.

- (i) Given points  $A$ ,  $B$ ,  $X$ , and  $Y$  in  $\mathbb{R}^2$ , we say that  $(A, B) \cong_s (X, Y)$  if

$$N(A, B) = N(X, Y).$$

- (ii) Given points  $A$ ,  $O$ ,  $B$ ,  $X$ ,  $P$ , and  $Y$  in  $\mathbb{R}^2$  such that  $A \neq O$ ,  $B \neq O$ ,  $X \neq P$ , and  $Y \neq P$ , we say that  $(A, O, B) \cong_a (X, P, Y)$  if  $M(A, O, B)$  and  $M(X, P, Y)$  have the same sign and

$$\frac{M(A, O, B)^2}{N(A, O)N(B, O)} = \frac{M(X, P, Y)^2}{N(X, P)N(Y, P)}.$$

*Proof.* Certainly both  $(*, *) \cong_s (*, *)$  and  $(*, *, *) \cong_a (*, *, *)$  are equivalence relations.

SC1. Note that  $N(A, A) = 0 = N(B, B)$  for all points  $A$  and  $B$  by 14.7(i).

SC2. We have  $N(A, B) = N(B, A)$  for all points  $A$  and  $B$  by 14.7(ii)

SC3. Suppose we have  $C \in \overrightarrow{AB}$  such that  $(A, C) \cong_s (A, B)$ . By Exercise 14.6, we have  $C = A + t(B - A)$  for some real number  $t > 0$ . Comparing coordinates, then, we have  $c_x - a_x = t(b_x - a_x)$  and  $c_y - a_y = t(b_y - a_y)$ . Expanding the definition of segment congruence, and noting that  $A \neq B$ , we see that  $t^2 = 1$ . Since  $t$  is positive, in fact  $t = 1$ , and thus  $C = B$  as needed.

AC1. (@@@)

AC2. (@@@)

AC3. (@@@)

AC4. (@@@)

□

## \* \* EXERCISES \* \*

- 14.1. Prove Corollary 14.2.
- 14.2. **A parallel criterion in  $\mathbb{R}^2$ .** Let  $A = (a_1, a_2)$ ,  $B = (b_1, b_2)$ ,  $C = (c_1, c_2)$ , and  $D = (d_1, d_2)$  be points in the cartesian plane with  $A \neq B$  and  $C \neq D$ . Show that  $\overleftrightarrow{AB}$  and  $\overleftrightarrow{CD}$  are parallel if and only if

$$\det \begin{bmatrix} b_1 - a_1 & d_1 - c_1 \\ b_2 - a_2 & d_2 - c_2 \end{bmatrix} = 0.$$

- 14.3. **A collinearity criterion in  $\mathbb{R}^2$ .** Let  $A = (a_x, a_y)$ ,  $B = (b_x, b_y)$ , and  $C = (c_x, c_y)$  be points in  $\mathbb{R}^2$  such that  $A \neq C$  and  $B \neq C$ . Show that  $A$ ,  $B$ , and  $C$  are collinear if and only if

$$\det \begin{bmatrix} a_x - c_x & b_x - c_x \\ a_y - c_y & b_y - c_y \end{bmatrix} = 0.$$

- 14.4. **The Unit Disc** Let  $\mathbb{D} = \{(x, y) \in \mathbb{R}^2 \mid x^2 + y^2 < 1\}$ ; these are points in the cartesian plane which are inside the unit circle. Given points  $A$ ,  $B$ , and  $C$  in  $\mathbb{D}$ , we say they are collinear in  $\mathbb{D}$  if they are collinear in  $\mathbb{R}^2$ . Verify that this relation makes  $\mathbb{D}$  an incidence geometry, which we call the *unit disc*.
- 14.5. Fix  $(\alpha, \beta) \in \mathbb{R}^2$ , and define a mapping  $\varphi : \mathbb{R}^2 \rightarrow \mathbb{R}^2$  by  $\varphi(x, y) = (x + \alpha, y + \beta)$ . Show that  $\varphi$  is a collineation.
- 14.6. Let  $A, B, C$  be points in the cartesian plane with  $A \neq B$ . Show that  $C \in \overrightarrow{AB}$  if and only if  $C = A + t(B - A)$  for some  $t \in (0, \infty)$ .
-

## 15 $\mathbb{H}$ – The Hyperbolic Half Plane

We will now construct an odd model of incidence geometry. For this example, our set of points is  $\mathbb{H} = \{(x, y) \mid x, y \in \mathbb{R} \text{ and } y > 0\}$  – the “upper half plane”. Suppose we have two such points  $A = (a_x, a_y)$  and  $B = (b_x, b_y)$ . If  $a_x \neq b_x$ , then we define the *hyperbolic ideal point* of  $A$  and  $B$  is the number

$$H_{A,B} = \frac{b_x^2 + b_y^2 - a_x^2 - a_y^2}{2(b_x - a_x)}.$$

Intuitively, the ideal point is the  $x$ -coordinate of the point on the cartesian  $x$ -axis which is “equidistant” from  $A$  and  $B$ . More precisely, we have the following.

**Lemma 15.1.** Let  $A = (a_x, a_y)$  and  $B = (b_x, b_y)$  be points in  $\mathbb{H}$  such that  $a_x \neq b_x$ . Then we have the following.

- (i) The ideal point  $H_{A,B}$  is the unique solution  $z$  of the following equation.

$$(a_x - z)^2 + a_y^2 = (b_x - z)^2 + b_y^2.$$

- (ii)  $H_{A,B} = H_{B,A}$ .

Take care that  $H_{A,B}$  only exists if  $A$  and  $B$  have distinct  $x$ -coordinates. We use the ideal point to define a collinearity relation on  $\mathbb{H}$  as follows.

**Prop’n 15.2.** Define a ternary relation  $\langle *, *, * \rangle$  on  $\mathbb{H}$  as follows. Given points  $A = (a_x, a_y)$ ,  $B = (b_x, b_y)$ , and  $C = (c_x, c_y)$  in  $\mathbb{H}$ , we say that  $\langle A, B, C \rangle$  if one of the following holds.

- (i)  $a_x = b_x$  and  $a_y = b_y$  and  $C \neq A$ .
- (ii)  $a_x = b_x$  and  $a_y \neq b_y$  and  $c_x = a_x$ .
- (iii)  $a_x \neq b_x$  and  $(c_x - H_{A,B})^2 + c_y^2 = (a_x - H_{A,B})^2 + a_y^2$ .

This is a collinearity relation on the set  $\mathbb{H}$ , which we call the *hyperbolic half plane*.

*Proof.*

IG2. Suppose  $A \neq B$ . If  $a_x = b_x$ , then we must have  $a_y \neq b_y$ . Then  $\langle A, B, B \rangle$  since  $b_x = a_x$ . If instead we have  $a_x \neq b_x$ , then  $\langle A, B, B \rangle$  using 15.1(i).

IG3. Note that  $\langle A, A, A \rangle$  does not hold, because in this case we have  $a_x = a_x$  and  $a_y = a_y$  but  $A = A$ .

IG4. Let  $A = (0, 1)$ ,  $B = (0, 2)$ , and  $C = (1, 1)$ . Now  $\langle A, B, C \rangle$  does not hold, because we have  $a_x = b_x$  and  $a_y \neq b_y$  but  $c_x \neq a_x$ .

IG1. Suppose  $\langle A, B, C \rangle$ . First we will show that  $\langle B, A, C \rangle$  by considering the three possibilities in the definition of  $\langle *, *, * \rangle$ . If  $a_x = b_x$  and  $a_y = b_y$  and  $C \neq A$ , then we have  $b_x = a_x$  and  $b_y = a_y$  and  $C \neq B$ , so that  $\langle B, A, C \rangle$ . If  $a_x = b_x$  and  $a_y \neq b_y$  and  $c_x = a_x$ , then we have  $b_x = a_x$  and  $b_y \neq a_y$  and  $c_x = b_x$ , so that  $\langle B, A, C \rangle$ . Suppose now that  $a_x \neq b_x$  and

$$(c_x - H_{A,B})^2 + c_y^2 = (a_x - H_{A,B})^2 + a_y^2.$$

Now we have

$$\begin{aligned} (c_x - H_{B,A})^2 + c_y^2 &= (c_x - H_{A,B})^2 + c_y^2 \\ &= (a_x - H_{A,B})^2 + a_y^2 \\ &= (b_x - H_{A,B})^2 + b_y^2 \\ &= (b_x - H_{B,A})^2 + b_y^2 \end{aligned}$$

so that  $\langle B, A, C \rangle$ .

Next we show that  $\langle A, C, B \rangle$ , again by considering the three possibilities. If  $a_x = b_x$  and  $a_y = b_y$  and  $C \neq A$  then we have  $\langle C, A, B \rangle$  by IG2, and in the previous paragraph we saw that we can swap the first two slots in  $\langle *, *, * \rangle$ , so that  $\langle A, C, B \rangle$ . Suppose  $a_x = b_x$  and  $a_y \neq b_y$  and  $c_x = a_x$ . Now if  $c_y = a_y$ , then we have  $a_x = c_x$  and  $a_y = c_y$  and  $B \neq A$ , so that  $\langle A, C, B \rangle$ . If instead we have  $c_y \neq a_y$ , then we have  $a_x = c_x$  and  $a_y \neq c_y$  and  $b_x = a_x$ , so that  $\langle A, C, B \rangle$ . Finally, suppose that  $a_x \neq b_x$  and

$$(c_x - H_{A,B})^2 + c_y^2 = (a_x - H_{A,B})^2 + a_y^2.$$

If  $a_x = c_x$ , then we have  $a_y = c_y$  since  $a_y, c_y > 0$ . Since  $b_x \neq a_x$ , we have  $\langle A, C, B \rangle$ . Suppose instead that  $a_x \neq c_x$ . By [Lemma 15.1](#), we have  $H_{A,C} = H_{A,B}$ . Thus

$$(b_x - H_{A,C})^2 + b_y^2 = (a_x - H_{A,C})^2 + a_y^2,$$

and thus  $\langle A, C, B \rangle$ .

IG5. Suppose we have points  $A \neq B$  and  $U \neq V$  such that  $\langle A, B, U \rangle$  and  $\langle A, B, V \rangle$ . If  $a_x = b_x$ , then we have  $u_x = a_x$  and  $v_x = a_x$ . Now  $u_x = v_x$  and so  $u_y \neq v_y$  and  $a_x = u_x$ , so that  $\langle U, V, A \rangle$ , and thus  $\langle A, U, V \rangle$  by IG1. Suppose instead that  $a_x \neq b_x$ . Then we have

$$(u_x - H_{A,B})^2 + u_y^2 = (a_x - H_{A,B})^2 + a_y^2$$

and

$$(v_x - H_{A,B})^2 + v_y^2 = (a_x - H_{A,B})^2 + a_y^2.$$

If  $a_x = u_x$ , then  $u_y = a_y$  and  $V \neq A$ , so that  $\langle A, U, V \rangle$ . If  $a_x \neq u_x$  we have  $H_{A,U} = H_{A,B}$ , so that

$$(v_x - H_{A,U})^2 + v_y^2 = (a_x - H_{A,U})^2 + a_y^2$$

and thus  $\langle A, U, V \rangle$ . □

Showing that  $\mathbb{H}$  is an incidence geometry is a bit tedious, but it only has to be done once, and immediately all of our theorems about incidence geometries hold. A good question to ask is this: what are the lines in  $\mathbb{H}$ ? It turns out that the lines in this model come in two flavors, which we will call Type I and Type II.

**Cor. 15.3** (Lines in  $\mathbb{H}$ ). Let  $A, B \in \mathbb{H}$  be distinct points.

(i) If  $a_x = b_x$  we say  $\overleftrightarrow{AB}$  is of *Type I*. In this case we have

$$\overleftrightarrow{AB} = \{(x, y) \in \mathbb{H} \mid x = a_x\}.$$

(ii) If  $a_x \neq b_x$  we say  $\overleftrightarrow{AB}$  is of *Type II*. In this case we have

$$\overleftrightarrow{AB} = \{(x, y) \in \mathbb{H} \mid (x - H_{A,B})^2 + y^2 = (a_x - H_{A,B})^2 + a_y^2\}.$$

Viewed as sets in the cartesian plane, the Type I lines in  $\mathbb{H}$  are vertical half lines, and the Type II lines in  $\mathbb{H}$  are semicircles centered on the  $x$ -axis. In fact the cartesian center of a Type II line is the point  $(H_{A,B}, 0)$ .

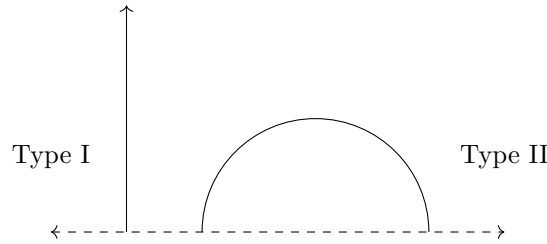


Figure 15.1: Lines in  $\mathbb{H}$ .

### Betweenness

In this section we establish that the hyperbolic half plane is an ordered geometry.

**Prop'n 15.4.** Define a ternary relation  $***$  on  $\mathbb{H}$  as follows. Given  $A = (a_x, a_y)$ ,  $B = (b_x, b_y)$ , and  $C = (c_x, c_y)$ , we say that  $[ACB]$  if  $\langle A, C, B \rangle$  and one of the following holds.

(i)  $a_x = b_x$  and  $\min(a_y, b_y) < c_y < \max(a_y, b_y)$ .

(ii)  $a_x \neq b_x$  and  $\min(a_x, b_x) < c_x < \max(a_x, b_x)$ .

This relation is a betweenness on  $\mathbb{H}$ .

*Proof.*

B1. Suppose  $[ABC]$ . Now  $\langle A, B, C \rangle$  by definition. Moreover, either  $a_x, b_x$ , and  $c_x$  or  $a_y, b_y$ , and  $c_y$  are all distinct, so that  $A, B$ , and  $C$  are distinct.

B2. Follows because  $=$  and  $\neq$  are symmetric and we can permute the arguments of  $\langle *, *, * \rangle$ ,  $\min(*, *)$ , and  $\max(*, *)$ .

B3. Suppose  $A, B$ , and  $C$  are distinct and  $\langle A, B, C \rangle$ . Suppose  $a_x = b_x$ . Then by the definition of collinearity in  $\mathbb{H}$ , we have  $c_x = a_x$ . Since  $A, B$ , and  $C$  are distinct,  $a_y, b_y$ , and  $c_y$  must be distinct. Since the order on  $\mathbb{R}$  is total, there are six possibilities. If  $a_y < b_y < c_y$ ,  $a_y < c_y < b_y$ , or  $c_y < a_y < b_y$ , we have  $[ABC]$ ,  $[ACB]$ , or  $[CAB]$ , respectively. If  $b_y < a_y < c_y$ ,  $b_y < c_y < a_y$ , or  $c_y < b_y < a_y$ , we have  $[BAC]$ ,  $[BCA]$ , or  $[CBA]$ , respectively; using B2 we then have  $[CAB]$ ,  $[ACB]$ , or  $[ABC]$ , respectively.

Suppose instead that  $a_x \neq b_x$ . We can see that because  $A, B$ , and  $C$  are distinct,  $a_x, b_x$ , and  $c_x$  must also be distinct. As in the previous paragraph, since the order on  $\mathbb{R}$  is total there are six possibilities, and in each case either  $[CAB]$ ,  $[ACB]$ , or  $[ABC]$ .

B4. Suppose we have  $[ABC]$  and  $[ACD]$ . Note that  $\langle A, B, C \rangle$  and  $\langle A, C, D \rangle$ , and that  $A, B$ , and  $C$  are distinct, and  $A, C$ , and  $D$  are distinct. If  $a_x = b_x$ , then we also have  $c_x = d_x = a_x$ . Now

$$\min(a_y, c_y) < b_y < \max(a_y, c_y) \text{ and } \min(a_y, d_y) < c_y < \max(a_y, d_y).$$

There are four possibilities. If  $a_y < b_y < c_y$  and  $a_y < c_y < d_y$ , then we have  $[ABD]$  and  $[BCD]$ . If  $c_y < b_y < a_y$  and  $d_y < c_y < a_y$ , then we have  $[DBA]$  and  $[DCB]$ , and by B2,  $[ABD]$  and  $[BCD]$ . The other two possibilities lead to contradictions.

Suppose instead that  $a_x \neq b_x$ ; a similar analysis of  $a_x, b_x, c_x$ , and  $d_x$  shows that  $[ABD]$  and  $[BCD]$ .

B5. Similar to the proof for B4.

B6. (@@@)

□

**Prop'n 15.5.** Given a line  $\ell = \overleftrightarrow{AB}$  in  $\mathbb{H}$ , we define halfplanes  $\mathcal{H}_{1,\ell}$  and  $\mathcal{H}_{2,\ell}$  as follows.

(i) If  $a_x = b_x$ , then

$$\mathcal{H}_{1,\ell} = \{(x, y) \in \mathbb{H} \mid x < a_x\}$$

$$\mathcal{H}_{2,\ell} = \{(x, y) \in \mathbb{H} \mid x > a_x\}$$

(ii) If  $a_x \neq b_x$ , then

$$\mathcal{H}_{1,\ell} = \{(x, y) \in \mathbb{H} \mid (x - H_{A,B})^2 + y^2 < (a_x - H_{A,B})^2 + a_y^2\}$$

$$\mathcal{H}_{2,\ell} = \{(x, y) \in \mathbb{H} \mid (x - H_{A,B})^2 + y^2 > (a_x - H_{A,B})^2 + a_y^2\}$$

With halfplanes defined this way for all lines,  $\mathbb{H}$  satisfies the Line Separation Property and thus is an ordered geometry.

*Proof.* First we need to verify that these half planes are well-defined as functions of  $\ell$ ; that is, they do not depend on the points used to generate  $\ell$ . To see this, suppose we have distinct points  $U$  and  $V$  such that  $\ell = \overleftrightarrow{UV}$ . If  $a_x = b_x$ , then in fact  $u_x = a_x$ , and we have  $\{(x, y) \in \mathbb{H} \mid x < a_x\} = \{(x, y) \in \mathbb{H} \mid x < u_x\}$  and  $\{(x, y) \in \mathbb{H} \mid x > a_x\} = \{(x, y) \in \mathbb{H} \mid x > u_x\}$  as needed. If  $a_x \neq b_x$ , then we have  $(u_x - H_{A,B})^2 + u_y^2 = (a_x - H_{A,B})^2 + a_y^2$ , and using [Exercise 15.2](#) we have  $H_{U,V} = H_{A,B}$ . Thus

$$(u_x - H_{U,V})^2 + u_y^2 = (a_x - H_{A,B})^2 + a_y^2$$

as needed.

Certainly  $\ell$ ,  $\mathcal{H}_{1,\ell}$ , and  $\mathcal{H}_{2,\ell}$  partition  $\mathbb{H}$ . To see that  $\mathcal{H}_{1,\ell}$  and  $\mathcal{H}_{2,\ell}$  are not empty, choose  $y_1$  and  $y_2$  such that  $y_1^2 < (a_x - H_{A,B})^2 + a_y^2 < y_2^2$ ; then  $(H_{A,B}, y_1) \in \mathcal{H}_{1,\ell}$  and  $(H_{A,B}, y_2) \in \mathcal{H}_{2,\ell}$ .

Next we show that  $\mathcal{H}_{1,\ell}$  is convex; the proof that  $\mathcal{H}_{2,\ell}$  is convex is very similar. To this end, let  $U, V \in \mathcal{H}_{1,\ell}$  be distinct and suppose  $[UWV]$ . First suppose that  $a_x = b_x$ . If  $u_x = v_x$  then we have  $w_x = u_x < a_x$  so that  $W \in \mathcal{H}_{1,\ell}$ . If  $u_x \neq v_x$  then we have  $w_x < \max(u_x, v_x) < a_x$  and thus  $W \in \mathcal{H}_{1,\ell}$ . So  $\mathcal{H}_{1,\ell}$  is convex in this case. Next suppose that  $a_x \neq b_x$ . If  $u_x = v_x$  then we have  $w_x = u_x = v_x$ . Without loss of generality, suppose  $\max(u_y, v_y) = u_y$ ; then we have

$$(w_x - H_{A,B})^2 + w_y^2 < (u_x - H_{A,B})^2 + u_y^2 < (a_x - H_{A,B})^2 + a_y^2,$$

and thus  $W \in \mathcal{H}_{1,\ell}$ . If  $u_x \neq v_x$  and  $H_{U,V} = H_{A,B}$ , then we have

$$(w_x - H_{A,B})^2 + w_y^2 = (u_x - H_{A,B})^2 + u_y^2 < (a_x - H_{A,B})^2 + a_y^2,$$

and thus  $W \in \mathcal{H}_{1,\ell}$ . Suppose then that  $u_x \neq v_x$  and  $H_{U,V} \neq H_{A,B}$ . Since  $\langle U, V, W \rangle$ , we have  $(w_x - H_{U,V})^2 + w_y^2 = (u_x - H_{U,V})^2 + u_y^2$ , which can be rearranged as

$$(w_x - H_{A,B})^2 + w_y^2 + 2(H_{U,V} - H_{A,B})(u_x - w_x) = (u_x - H_{A,B})^2 + u_y^2.$$

A similar equality holds for  $V$ . And since  $U$  and  $V$  are in  $\mathcal{H}_{1,\ell}$ , we have the system of inequalities

$$\begin{aligned} (w_x - H_{A,B})^2 + w_y^2 + 2(H_{U,V} - H_{A,B})(u_x - w_x) &< (a_x - H_{A,B})^2 + a_y^2 \\ (w_x - H_{A,B})^2 + w_y^2 + 2(H_{U,V} - H_{A,B})(v_x - w_x) &< (a_x - H_{A,B})^2 + a_y^2. \end{aligned}$$

Note that either  $2(H_{U,V} - H_{A,B})(u_x - w_x)$  or  $2(H_{U,V} - H_{A,B})(v_x - w_x)$  must be negative, since we have  $w_x < \max(u_x, v_x)$ . So  $W \in \mathcal{H}_{1,\ell}$  as needed, and  $\mathcal{H}_{1,\ell}$  is convex.

Finally, suppose we have  $U \in \mathcal{H}_{1,\ell}$  and  $V \in \mathcal{H}_{2,\ell}$ . We need to show that there is a point  $W \in \overline{UV} \cap \overleftrightarrow{AB}$ . If  $a_x = b_x$ , then  $u_x < a_x < v_x$ . Note that by [Exercise 1.2](#) we can say without loss of generality that  $(a_x - H_{U,V})^2 < (u_x - H_{U,V})^2$ . Now let  $w_x = a_x$  and

$$w_y = \sqrt{(u_x - H_{U,V})^2 + u_y^2 - (a_x - H_{U,V})^2}.$$

We can see that  $W = (w_x, w_y)$  is the unique point on both  $\overline{UV}$  and  $\overleftrightarrow{AB}$ .

Suppose now that  $a_x \neq b_x$ . If  $u_x = v_x$ , then (@@@)

Finally suppose  $u_x \neq v_x$ ; without loss of generality, say  $u_x < v_x$  (the case  $v_x < u_x$  is similar). By [Exercise 15.2](#), we have  $H_{U,V} \neq H_{A,B}$ . Note that  $\overline{UV} \cap \overleftrightarrow{AB}$  is the solution(s) of the following system of equations:

$$\begin{cases} (x - H_{A,B})^2 + y^2 = (a_x - H_{A,B})^2 + a_y^2 \\ (x - H_{U,V})^2 + y^2 = (u_x - H_{U,V})^2 + u_y^2 \\ u_x < x < v_x. \end{cases}$$

We can solve the first two equations for  $x$  as

$$w_x = \frac{a_x^2 + a_y^2 - u_x^2 - u_y^2 + 2(u_x H_{U,V} - a_x H_{A,B})}{2(H_{U,V} - H_{A,B})}.$$

Note that

$$(u_x - H_{A,B})^2 + u_y^2 < (a_x - H_{A,B})^2 + a_y^2 < (v_x - H_{A,B})^2 + v_y^2$$

because  $U \in \mathcal{H}_{1,\ell}$  and  $V \in \mathcal{H}_{2,\ell}$ . Now

$$\begin{aligned} (u_x - H_{A,B})^2 + u_y^2 &< (a_x - H_{A,B})^2 + a_y^2 < \\ &(v_x - H_{U,V})^2 + v_y^2 - H_{U,V}^2 + 2v_x(H_{U,V} - H_{A,B}) + H_{A,B}^2 \end{aligned}$$

and thus

$$\begin{aligned} (u_x - H_{A,B})^2 + u_y^2 &< (a_x - H_{A,B})^2 + a_y^2 < \\ &(u_x - H_{U,V})^2 + u_y^2 - H_{U,V}^2 + 2v_x(H_{U,V} - H_{A,B}) + H_{A,B}^2 \end{aligned}$$



which rearranges as

$$u_x < \frac{a_x^2 + a_y^2 - u_x^2 - u_y^2 + 2(u_x H_{U,V} - a_x H_{A,B})}{2(H_{U,V} - H_{A,B})} < v_x.$$

(In the last step, we used [Exercise 15.4](#).) (@@@)

□

\* \* EXERCISES \* \*

- 15.1. Prove [Lemma 15.1](#).
- 15.2. **A parallel criterion in  $\mathbb{H}$**  Suppose  $A$ ,  $B$ ,  $C$ , and  $D$  are points in  $\mathbb{H}$  such that  $a_x \neq b_x$  and  $c_x \neq d_x$ . Show that  $\overleftrightarrow{AB}$  and  $\overleftrightarrow{CD}$  are parallel if and only if  $H_{A,B} = H_{C,D}$ .
- 15.3. **A collinearity criterion in  $\mathbb{H}$**  Suppose  $A$ ,  $B$ , and  $C$  are points in  $\mathbb{H}$  such that  $a_x$ ,  $b_x$ , and  $c_x$  are distinct. Show that  $\langle A, B, C \rangle$  if and only if  $H_{A,C} = H_{A,B}$ .
- 15.4. Let  $A, B, U, V \in \mathbb{H}$  such that  $A \neq B$  and  $U \neq V$ , and suppose we have

$$(u_x - H_{A,B})^2 + u_y^2 < (v_x - H_{A,B})^2 + v_y^2.$$

Show that  $u_x < v_x$  if and only if  $H_{A,B} < H_{U,V}$ .

## 16 $\mathbb{P}$ – The Poincare Disc

We will now construct an alternative collinearity relation on the unit disc. For this example, our set of points is  $\mathbb{P} = \{(x, y) \in \mathbb{R}^2 \mid x^2 + y^2 < 1\}$ . Given points  $A = (a_x, a_y)$  and  $B = (b_x, b_y)$  in  $\mathbb{P}$ , we define the abbreviation

$$D_{A,B} = \det \begin{bmatrix} a_x & a_y \\ b_x & b_y \end{bmatrix}.$$

If  $D_{A,B} \neq 0$ , we define the *poincare ideal point* of  $A$  and  $B$  to be

$$P_{A,B} = \frac{1}{2} \begin{bmatrix} a_x & a_y \\ b_x & b_y \end{bmatrix}^{-1} \begin{bmatrix} a_x^2 + a_y^2 + 1 \\ b_x^2 + b_y^2 + 1 \end{bmatrix}.$$

**Lemma 16.1.** Let  $A, B \in \mathbb{P}$  such that  $D_{A,B} \neq 0$ . Then we have the following.

- (i)  $P_{B,A} = P_{A,B}$ .
- (ii) The ideal point  $P_{A,B}$  is the unique solution  $(x, y)$  to the following system of equations.

$$\begin{cases} x^2 + y^2 = (a_x - x)^2 + (a_y - y)^2 + 1 \\ x^2 + y^2 = (b_x - x)^2 + (b_y - y)^2 + 1 \end{cases}$$

We can use the poincare ideal point to define a collinearity relation on  $\mathbb{P}$  as follows.

**Prop'n 16.2.** Define a ternary relation on  $\mathbb{P}$  as follows. Given  $A = (a_x, a_y)$ ,  $B = (b_x, b_y)$ , and  $C = (c_x, c_y)$  in  $\mathbb{P}$ , we say that  $\langle A, B, C \rangle$  if one of the following holds.

- (i) Exactly two of  $A$ ,  $B$ , and  $C$  are equal.
- (ii)  $A$ ,  $B$ , and  $C$  are distinct and  $D_{A,B} = D_{A,C} = D_{B,C} = 0$ .
- (iii)  $A$ ,  $B$ , and  $C$  are distinct and  $D_{A,B}$ ,  $D_{A,C}$ , and  $D_{B,C}$  are nonzero and  $P_{A,B} = P_{A,C} = P_{B,C}$ .

This is a collinearity relation on the set  $\mathbb{P}$ , which we call the *poincare disc*.

*Proof.*

IG2. Let  $A, B \in \mathbb{P}$  be distinct. Then  $\langle A, B, B \rangle$  holds by definition.

IG3. Note that  $\langle A, A, A \rangle$  does not hold for any  $A$  by definition.

- IG4. Let  $A = (0, 0)$ ,  $B = (1, 0)$ , and  $C = (0, 1)$ . Now  $A$ ,  $B$ , and  $C$  are distinct, but we have  $D_{A,B} = 0$   $D_{B,C} = 1 \neq 0$ . So  $\langle A, B, C \rangle$  does not hold.
- IG1. Suppose we have  $\langle A, B, C \rangle$ . If exactly two of  $A$ ,  $B$ , and  $C$  are equal, then we also have  $\langle B, A, C \rangle$  since exactly two of  $B$ ,  $A$ , and  $C$  are equal, and  $\langle A, C, B \rangle$  since exactly two of  $A$ ,  $C$ , and  $B$  are equal. Suppose then that  $A$ ,  $B$ , and  $C$  are distinct. Certainly then  $B$ ,  $A$ , and  $C$  are distinct, as are  $A$ ,  $C$ , and  $B$ . If  $D_{A,B} = D_{A,C} = D_{B,C} = 0$ , then  $D_{B,A} = D_{B,C} = D_{A,C} = 0$ , so that  $\langle B, A, C \rangle$ , and  $D_{A,C} = D_{C,B} = D_{C,B} = 0$  so that  $\langle A, C, B \rangle$ . Finally, suppose we have  $D_{A,B}$ ,  $D_{A,C}$ , and  $D_{B,C}$  nonzero and  $P_{A,B} = P_{A,C} = P_{B,C}$ . Then  $D_{B,A}$ ,  $D_{B,C}$ , and  $D_{A,C}$  are nonzero and  $P_{B,A} = P_{B,C} = P_{A,C}$ , so that  $\langle B, A, C \rangle$ , and likewise  $D_{A,C}$ ,  $D_{A,B}$ , and  $D_{C,B}$  are nonzero and  $P_{A,C} = P_{A,B} = P_{C,B}$ , so that  $\langle A, C, B \rangle$  as claimed.
- IG5. Suppose we have  $A \neq B$  and  $U \neq V$  such that  $\langle A, B, U \rangle$  and  $\langle A, B, V \rangle$ . If  $U = B$ , then we have  $\langle A, U, V \rangle$ ; similarly, if  $V = B$  then  $\langle A, V, U \rangle$ , so that by IG1,  $\langle A, U, V \rangle$ . Suppose then that  $U \neq B$  and  $V \neq B$ . If  $U = A$ , then  $\langle A, U, V \rangle$  by definition; similarly, if  $V = A$  then  $\langle A, U, V \rangle$ . Suppose then that  $U \neq A$  and  $V \neq A$ . Now  $A$ ,  $B$ ,  $U$ , and  $V$  are all distinct. There are two possibilities for  $D_{A,B}$ : either zero or nonzero.

If  $D_{A,B} = 0$ , then in fact we have  $D_{A,U} = D_{B,U} = 0$  and  $D_{A,V} = D_{B,V} = 0$ . Now since  $A \neq B$ , one of  $A$  or  $B$  must be nonzero; suppose without loss of generality it is  $A$ . Then either  $a_x$  or  $a_y$  must be nonzero; suppose it is  $a_x$  – the argument for  $a_y$  is similar. We have  $a_x u_y = a_y u_x$ , so that  $v_x a_x u_y = v_x a_y u_x$ , and thus  $v_x a_x u_y = v_y a_x u_x$ . Since  $a_x \neq 0$ , we have  $v_x u_y = v_y u_x$ , so that  $D_{U,V} = 0$ . Thus  $\langle A, U, V \rangle$  as needed.

Suppose instead that  $D_{A,B} \neq 0$ . Then  $D_{A,U}$ ,  $D_{B,U}$ ,  $D_{A,V}$ , and  $D_{B,V}$  are all nonzero, and we have  $P_{A,B} = P_{A,U} = P_{B,U} = P_{A,V} = P_{B,V}$ . Suppose first that  $D_{U,V} = 0$ . In this case, we have  $V = kU$  for some constant  $k$ , since  $U \neq 0$ . Now we have

$$(u_x - x)^2 + (u_y - y)^2 = (ku_x - x)^2 + (ku_y - y)^2.$$

Expanding this equation and supposing  $k \neq 1$  we solve for  $k$  as

$$k = 2 \frac{u_x x + u_y y}{u_x^2 + u_y^2} - 1.$$

But note that  $2(u_x x + u_y y) = u_x^2 + u_y^2 + 1$ , so that in fact  $k = 1/(u_x^2 + u_y^2)$ . But now

$$v_x^2 + v_y^2 = 1/(u_x^2 + u_y^2) > 1,$$

a contradiction. So in fact we have  $k = 1$ , and thus  $V = U$ , a contradiction. So we must have  $D_{U,V} \neq 0$ . Now by 16.1(ii), we have  $P_{U,V} = P_{A,U} = P_{A,V}$ , and thus  $\langle A, U, V \rangle$  as needed.  $\square$

As with the hyperbolic half plane, showing that the Poincare disc is an incidence geometry is a bit tedious. But this only has to be done once, and all our incidence geometry theorems immediately apply.

**Prop'n 16.3** (Lines in  $\mathbb{P}$ ). Let  $A, B \in \mathbb{P}$  be distinct points, and without loss of generality suppose  $A \neq 0$ .

(i) If  $D_{A,B} = 0$ , we say that  $\overleftrightarrow{AB}$  is of *Type I*. In this case we have

$$\overleftrightarrow{AB} = \left\{ (x, y) \in \mathbb{P} \mid \det \begin{bmatrix} a_x & a_y \\ x & y \end{bmatrix} = 0 \right\}$$

(ii) If  $D_{A,B} \neq 0$ , we say that  $\overleftrightarrow{AB}$  is of *Type II*. In this case we have

$$\overleftrightarrow{AB} = \{ (x, y) \in \mathbb{P} \mid (x - h)^2 + (y - k)^2 = t \},$$

where  $(h, k) = P_{A,B}$  and  $t = (a_x - h)^2 + (a_y - k)^2$ .

\* \* EXERCISES \* \*

16.1. Consider the map  $\varphi$  on  $\mathbb{H}$  given by

$$\varphi(x, y) = \left( \frac{2x}{x^2 + (y+1)^2}, \frac{x^2 + y^2 - 1}{x^2 + (y+1)^2} \right).$$

- (i) Show that  $\varphi : \mathbb{H} \rightarrow \mathbb{P}$ .
- (ii) Show that  $\varphi$  is bijective.
- (iii) Show that  $\varphi$  is a collineation.

## 17 $\mathbb{K}$ – The Klein Disc

We define the *klein ideal point* of  $A$  and  $B$  to be

$$K_{A,B} = \frac{1}{2} \begin{bmatrix} a_x & a_y \\ b_x & b_y \end{bmatrix}^{-1} \begin{bmatrix} a_x^2 + a_y^2 - 1 \\ b_x^2 + b_y^2 - 1 \end{bmatrix}.$$

## 18 $\mathbb{G}$ – The Gans Disc

This model appears in an article by Adolf Mader [\[1\]](#), who attributes it to David Gans.

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## Index

- alternate interior angles, 31
- altitude
  - of a triangle, 44
- angle, 18
  - adjacent pair, 18
  - flat, 18
  - linear pair, 18
  - straight, 18
  - vertical pair, 18
- antipode, 27
- betweenness, 12
- bisector, 33
- cartesian plane, 48
- centroid, 45
- chord, 24
- circle, 23
- circumcenter, 42
- circumcircle, 43
- coincident lines, 5
- collinearity, 4
- collineation, 10
- congruence
  - of angles, 22
  - of segments, 22
  - of triangles, 23
- congruence geometry, 23
- convex, 14
- degenerate
  - triangle, 16
- diameter, 24
- disjoint lines, 5
- equilateral, 23
- excenter, 38
- excircle, 38
- extended sides (of a triangle), 16
- foot, 35
- halfplane, 15
- hyperbolic half plane, 55
- hyperbolic ideal point, 55
- incenter, 38
- incidence geometry, 4
- incident lines, 5
- incircle, 38
- interior
  - of a ray, 13
  - of a segment, 13
  - of an angle, 19
- isocles, 23
- line, 5
- midpoint, 33
- normal line, 35
- orthocenter, 44
- parallel lines, 6
- perpendicular, 35
- perpendicular bisector, 35
- poincare disc, 62
- poincare ideal point, 62
- radius, 24
- ray, 13

segment, [13](#)

side

    of an angle, [18](#)

sides (of a triangle), [16](#)

supplementary angles, [23](#)

transversal, [31](#)

unit disc, [54](#)

vertex

    of an angle, [18](#)

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