GEOMETRY IN WHICH THE SUM OF THE ANGLES OF EVERY TRIANGLE IS TWO RIGHT ANGLES*

BY

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In his article Die Legendre'schen Sätze über die Winkelsumme im Dreieck,† Dehn has shown what may be stated precisely by the aid of the following abbreviations:

\( H_{-a} \) denotes all those theorems of geometry which are logical consequences of Hilbert's axiom-groups I, II, III, IV, viz., his axioms of association, of order, of parallels, and of congruence respectively.

\( H_{-a-p} \) denotes all those theorems of geometry which are logical consequences of Hilbert's axiom groups, I, II, IV.

\( S \) denotes the assumption that the sum of the angles of every triangle is two right angles.‡

What Dehn has shown is that \( H_{-a} \) does not follow from \( H_{-a-p} \) and \( S \). I wish to show that, nevertheless, if \( H_{-a-p} \) and \( S \) are true of a space, then either this space is a \( H_{-a} \) space or it is possible so to introduce ideal points that the space thus extended will be a \( H_{-a} \) space, these ideal points, moreover, being such that no one of them is between two points of the original space.

One might state this a little more suggestively, if less accurately, as follows: "While the parallel postulate, III, and thus all of that part of Hilbertian Geometry which follows without use of his 'Axiom of ARCHIMEDES' and 'Vollständigkeit Axiom,' can not indeed be proved from his other postulates I, II, IV with III replaced by \( S \), nevertheless it can be shown that a space concerning which these postulates (I, II, IV, \( S \)) are valid must be, if not the whole, then at least a part, of a space in which III also is true."§

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‡ This may be stated precisely as follows: If \( ABC \) is a triangle and \( C \) is between \( B \) and \( E \) then, in the angle \( ACE \), there is a point \( D \) such that \( \angle ACD = \angle BAC \) and \( \angle DCE = \angle ABC \).
§ This result has an interesting connection with our spatial experience. Statements have been made to the effect that, since no human instruments, however delicate, can measure exactly enough to decide in every conceivable case whether the sum of the angles of a triangle is equal to two right angles (unless the difference between this sum and two right angles should exceed
Let us first establish a number of preliminary theorems. The theorems of \( H_{a-p} \) are assumed and I shall take for granted, sometimes without giving exact reference, certain of those definitions and theorems of HILBERT's *Festschrift* which are founded on his axiom groups I, II, IV. Reference will also be made to HALSTED's *Rational Geometry* (R. G.) in case of theorems for which demonstrations without use of HILBERT's III are therein indicated.

For simplicity let us confine ourselves to one plane.

**Theorem I.** If two straight lines, \( a \) and \( b \), are perpendicular to each other at a point \( O \), then every straight line, \( c \), in the plane \( ab \), has a point in common with either \( a \) or \( b \).

**Dem.** This conclusion of course holds if \( c \) coincides with \( a \) or \( b \). If it does not coincide with \( a \) or \( b \), then it has (cf. HILBERT's Theorem 5 and definition following IV, 3 and Theorem 9) a point \( C \) within one of the four right angles into which \( a \) and \( b \) divide the plane \( ab \). There exists a point \( A \) on that ray of this angle which belongs to \( a \) and a point \( B \) on that ray thereof which belongs to \( b \). There is (cf. R. G., art. 47, theorem) a point \( D \) on \( c \) such that \( OD \) is perpendicular to \( c \). On \( c \) there are two points, \( E \) and \( E' \), such that \( DE' = DE = OD \) (cf. HILBERT's IV, 1 and IV, 2). Then (as may be seen with help of \( S \)), the angle \( DOE \) is one half a right angle and the angle \( E'OD \) is one half a right angle. Accordingly the angle \( E'O \) is a right angle. Hence it is easily seen (cf. R. G., arts. 51 and 143) that \( E \) and \( E' \) can not both be within the right angle \( AOB \). Therefore \( c \), which contains both \( E \) and \( E' \), has a point within, and a point without, the angle \( AOB \) and thus must cut either \( OA \) or \( OB \).

**Theorem 2.** If \( O \) lies between \( A \) and \( C \) and also between \( B \) and \( D \), and if \( \triangle AOB \) is a right angle and \( \triangle ABD \equiv \triangle ACD \), then there is a circle passing through \( A \), \( B \), \( C \), and \( D \).†

**Dem.** There exist (cf. R. G., 47, 51 and HILBERT's IV, 4) perpendiculars
LE and MF to AC and BD at their middle points E and F respectively. As LE cannot meet BD (cf. R. G., art. 47), according to Theorem 1 it must meet FM at a point K. Now, by S and Theorem 1, the perpendicular to AB at its middle point must meet either KE or KF. Suppose it meets KF at a point S. Then SD \equiv SB \equiv SA (by definitions of a right angle and of a perpendicular, Hilbert’s Theorem 10, and statement preceding Theorem 13). So there is a circle with S as center passing through A, B, and D. By R. G., art. 57, \( \angle SAD \equiv \angle SDA \) and \( \angle SAB \equiv \angle SBA \). It may then be seen, even without further use of S, that SAD and SAB are acute and hence SA is not perpendicular to AC and therefore, by R. G., art 138, that the circle which passes through A, B, D must have another point P in common with AC also that \( \angle DPA \equiv \angle DBA \) (cf. S and R. G., art. 138); but this, in view of the hypothesis that \( \angle DBA \equiv \angle DCA \), is impossible (cf. R. G., 66) unless P is C. The circle therefore through A, B, and D passes also through C. Similarly if the perpendicular to AB at its middle point met EK it would follow that there would be a circle through A, B, and C, and this circle would necessarily pass through D.

**Convention.** A point O, two straight lines perpendicular to each other at this point, a point I on one of these lines and points Q and S on the other, such that O is between Q and S, are selected once for all and considered as fixed throughout this discussion.

As an aid to the exhibition of an analytic geometry I wish to develop a calculus of those rays (half lines) which start from I towards the O-side of IK where IK is perpendicular to OI. These rays are called “leftward rays.” If a leftward ray cuts QS it is called a “cutting ray.” Small letters of the English alphabet are used to denote cutting rays.

*See R. G., articles 82, 64 and 66.*
If \( M \) is a point of \( QS \), \(|IM|\) means \( IT \) where \( T \) is a point of the ray \( OQ \) such that \( OM \equiv OT \).

The ray \( IO \) is designated by the symbol \( 0 \) (it is a “zero ray”). If \( I' \) is a point on the ray \( OQ \) such that \( OI' \equiv OI \), then the ray \( II' \) is designated by the symbol \( 1 \) (it is a “unit ray”).

Definition 1 (sum of two cutting rays). If \( L \) and \( M \) are two points (or the same point) on \( QS \), ray \( IL + rIM \) means ray \( IN \) where \( N \) is a point of \( QS \) such that \( ON = OL + OM \) in the vector sense.

Definition 2. If \( IM \) and \( IN \) are two leftward rays, then “\( IM > IN \)” means that \( IN \) precedes \( IM \) in the sense \( IS - IO - IQ \); and “\( IM < IN \)” means \( IN > IM \).

Theorem 3. If \( \alpha \) and \( \beta \) are two leftward rays, then of the three statements \( \alpha > \beta \), \( \alpha = \beta \), or \( \alpha < \beta \) one and only one is true. If \( \alpha < \beta \) and \( \beta < \gamma \), then \( \alpha < \gamma \).

Theorem 4. The set of all cutting rays is a commutative group with respect to the operation of addition \((+\)\).

Definition 3 (quotient of two cutting rays). If \( L \) and \( M \) are points of the straight line \( QS \) and \( M \) is a point of ray \( OI \) such that \( OM \equiv OM' \) and if \( IN \) is a ray such that \( OIN \equiv OM'L \), if further \( IN \) lies on the \( Q \)- or the \( S \)-side of \( OI \) according as \( M \) and \( N \) are on the same side, or opposite sides, of \( O \), then \( IL/IM = IN \).

Definition 4 (product of two cutting rays), \( ab = c \) if and only if \( c/a = b \).

Theorem 5. If \( a/b = c/b \), then \( a = c \).

Theorem 6. \( b/1 = b \) and \( b \times 0 = 0 \).

Theorem 7. If \( a/b = c/d \), then \( b/a = d/c \).

Theorem 8. If \( A, B, C, D \) are points on \( QS \) and \( A \) and \( B \) are on the same side or opposite sides of \( O \) according as \( C \) and \( D \) are on the same side.
or on opposite sides of O, then the existence of four points A', B', C', D' on a circle and another point O' such that O' is between B' and C', and between A' and D', angle A'O'B is a right angle, OA \equiv O'A', OB \equiv O'B', OC \equiv O'C', and OD \equiv O'D', is a necessary and sufficient condition that IA/IB = IC/ID.

Dem. Use Definition 3 and Theorem 2.

Theorem 9. If a/b = c/d, then a/c = b/d.

Dem. Use Theorem 8.

Theorem 10. If a/b = c/d and a/e = f/d, then b/e = f/c.

Dem.* Consider three cases —

I. Suppose |b| < |e|. Evidently there exist an n such that b/n = e/d, and an x such that b/x = e/c whence also b/e = x/c (see Theorem 9). Now a/f = e/d (see hypothesis and Theorem 9), so that a/f = b/n. Also b/e = n/d (see Theorem 9), therefore n/d = x/c and thus, by Theorem 9, x/n = c/d. But since, by hypothesis, a/b = c/d, we have a/b = x/n. But from a/f = b/n, by Theorem 9, a/b = f/n and thus x/n = f/n; therefore, by Theorem 5, x = f. But as b/e = x/c, it follows finally that b/e = f/c.

II. Suppose e < b. Use similar reasoning to show that e/b = c/f and hence conclude (by use of Theorem 7) that b/e = f/c.

III. Suppose e = b. In this case, by Theorem 5, f = c and by Theorem 9 the theorem is true.

Theorem 11. If ab = x and a'b' = ab, then a/a' = b'/b; and conversely, if ab = x and a/a' = b'/b, then a'b' = ab.

Dem. I. If ab = x and a'b' = ab, then, according to Definition 4, x/a = b and x/a' = b'. According to Theorems 6 and 7 1/b' = a'/x and 1/b = a/x. Hence, by Theorem 10, b'/b = a/a'.

II. If ab = x and a/a' = b'/b, then, by Definition 4 and Theorem 2, x/a = b/1. Hence, by Theorem 7, a/x = 1/b and therefore, by hypothesis and Theorems 10 and 6 and Definition 4, x = a'b'.

Theorem 12. If ab = x, then ba = ab.

Dem. If ab = x, then, by Definition 4 and Theorem 6, x/a = b/1. Hence, by Theorems 9 and 6, x/b = a. Therefore, by Definition 4, ba = x. But since, by hypothesis, ab = x, ba = ab.

Theorem 13. If ab = x, (ab)c = y, and bc = z, then a(bc) = (ab)c.

Dem. According to Theorem 11 this proposition will be established if it is proved that ab/a = bc/c. Now according to Definition 4 and Theorem 6 ab/a = b/1. Likewise bc/c = b/1. So ab/a = bc/c.

Theorem 14. If ab = x, ac = y, then a(b + c) = ab + ac.


* The suggestion of this demonstration I am unable at present to trace to its source.

† i.e., ab is a cutting ray.
Theorem 15. If $|a| < 1$ then for every $b$, $ab$ exists as a cutting ray. For every $c$ there exists $x$ such that $|cx| < 1$.

If $|a| < |b|$ and $bx$ exists as a cutting ray, then $|ax| < |bx|$. Given $d$, $e$, $k$, $e \neq 0$, $k \neq 0$, then there exist $d'$, $e'$ such that $|d'| < |k|$, $|e'| < |k|$, and $d/e = d'/e'$.

Theorem 16. If $|a|, |b|, |c|, |d|$ are all less than 1, and if $a/b = e$ and $c/d = f$, then $a/b + c/d = (ad + bc)/bd$.

Dem. According to hypothesis and Definition 4, $a = be$, $c = df$; and by hypothesis and Theorems 15, 12, 13, and 14, $ad + bc = (be)d + b(df) = d(be) + b(df) = (db)e + (bd)f = bd(e + f)$. This gives, by the use of Definition 4, $(ad + bc)/bd = e + f = a/b + c/d$.

Theorem 17. If $|a|, |b|, |c|, |d|$ are all less than 1, $a/b = e$, $c/d = f$ and $ef = y$, then $ac/bd = ef$.

Dem. By hypothesis and Definition 4, $c = df$, $a = be$ and, by hypothesis and Theorem 15, $ac = (be)(df)$. Hence, by hypothesis, Theorems 15, 12, and 13, $ac = (bd)(ef)$, and from this, by Definition 4, $ac/bd = ef$.

Theorem 18. If $|a|, |b|, |c|, |d|, |a'|, |b'|, |c'|, |d'|$ are all less than 1, and if $a/b = a'/b'$, $c/d = c'/d'$, then $(ad + bc)/bd = (a'd' + b'c')/b'd'$.

Dem. By hypothesis and Theorems 15 and 11, $ab' = ba'$ and $cd' = dc'$. Hence (see Theorem 15) $(ab')(cd') = (ba')(dd')$ and $(cd')(bb') = (dc')(bb')$. Hence, by Theorems 12, 13, and 14, $(ad)(b'd') + (bc)(b'd') = bd(a'd') + (bd)(b'c')$ and thus, by Theorems 12 and 14, $(ad + bc)b'd' = bd(a'd' + b'c')$; therefore by Theorem 11, $(ad + bc)/bd = (a'd' + b'c')/b'd'$.

Theorem 19. If $|a|, |b|, |c|, |d|, |a'|, |b'|, |c'|, |d'|$ are all less than 1 and $a/b = a'/b'$ and $c/d = c'/d'$, then $ac/bd = ac'/bd'$.

Dem. According to Theorems 15 and 11, $ab' = ba'$, $cd' = dc'$, whence follows (see Theorem 15), $(ab')(cd') = (ba')(dc')$. Hence, by Theorems 15, 12, and 13, $(ac)(b'd') = bd(a'c')$ and thus, by Theorem 11, $ac/bd = ac'/b'd'$.

Definition 5. If either there is no $e$ such that $a/b = e$ or there is no $f$ such that $c/d = f$, then $a/b \times c/d$ means $a'c'/b'd'$ and $a/b + c/d$ means $a'd' + b'c'/b'd'$ where $a'$, $b'$, $c'$, $d'$ are in absolute value less than 1, and $a/b = a'/b'$ and $c/d = c'/d'$.

Theorem 20. $a/b \times c/d = a'c'/b'd'$ and $a/b + c/d = a'd' + b'c'/b'd'$ where $a'$, $b'$, $c'$, $d'$ are all less than 1 in absolute value and $a'/b' = a/b$ and $c'/d' = c/d$.

Dem. See Theorems 16 and 17 and Definition 5.

Lemma. If $a'b$, $a'c$ and $(a'b)c$ are cutting rays, then $a'b/a'c = b/c$.

Dem. $(a'b)c = (ba')c$ by hypothesis and Theorem 12, $= b(a'c)$ by Theorem 13, $= (a'c)b$ by Theorem 12.

Hence, by Theorem 11, $a'b/a'c = b/c$. 

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Theorem 21. If \( b \) and \( d \) are different from 0 and \( a \) and \( c \) are any cutting rays, then there exist \( x \) and \( y \) (\( y \neq 0 \)) such that \( a/b + x/y = c/d \). If \( a/b + x/y = c/d \) and \( a/b + w/z = c/d \), then \( x/y = w/z \).

Dem. Use Lemma and Theorems 15, 4, 20, 11.

Theorem 22. If \( a, b, \) and \( d \) are different from 0 and \( c \) is any cutting ray, then there exist \( x \) and \( y \) such that \( a/b \times x/y = c/d \). If \( a/b \times x/y = c/d \) and \( a/b \times w/z = c/d \), then \( x/y = w/z \).

Dem. I. By Theorem 15 there exist \( a', b', c', d' \) all less than 1 in absolute value, such that \( a/b = a'/b' \), \( c/d = c'/d' \). By Theorems 15, 20, 13, 11, and Lemma, \( a/b \times b'c'/a'd' = a(b'c')/b(a'd') = (ab')c'/(ba')d' = c'/d' \).

II. Suppose \( a/b \times x/y = c/d \) and \( a/b \times w/z = c/d \). By Theorem 15 there exist \( a', b', c', d', x', y', w', z' \), all less than 1 in absolute value, such that \( a/b = a'/b' \), \( c/d = c'/d' \), \( x/y = x'/y' \), \( w/z = w'/z' \). By hypothesis and Theorem 20, \( a'x'/b'y' = c'/d' \) and \( a'w'/b'z' = c'/d' \). Hence, by Theorems 15, 11, 12, 13, \( (a'd')x' = (b'c')y' \) and \( (a'd')w' = (b'c')z' \). Hence, by Theorems 12 and 11, \( x'/y' = b'c'/a'd' = w'/z' \). Hence \( x/y = w/z \).

Convention. Any Greek letter denotes \( a/b \) where \( a \) and \( b \) are cutting rays.

Theorem 23. The set of all \( a's \) is a number system for which Hilbert's Theorems 1-16 of §13 of his Grundlagen der Geometrie hold true with respect to +, \( \times \), and \( > \) as defined in this paper.*

Dem. Hilbert's Theorems 1-12 may be proved by use of my Theorems 20, 6, 4, 21, 22, 12, 15, 14, 13, and Lemma to Theorem 22. His Theorems 13-16 may be proved with the use of my Theorems 1-12 in connection with Definitions 1-5.

Definition 6. The length of a segment \( AB \) means the ray \( IT \) where \( T \) is a point on the ray \( OQ \) such that \( AB \equiv OT \).

The length of \( AB \) is denoted by \( e(AB) \).

Lemma I. If in the triangles \( ABC, A'B'C', \angle A = \angle A', \angle B = \angle B', \angle C = \angle C', \) then

\[
\frac{e(AB)}{e(A'B')} = \frac{e(B'C')}{e(B'C')} = \frac{e(CA)}{e(C'A')}.
\]

Dem. Use Definitions 6 and 3, Theorem 23, etc., in connection with Theorem 22 of Hilbert's Grundlagen der Geometrie.

Lemma II. If \( BAC \) is a right angle, then \( e^2(AB) + e^2(AC) = e^2(BC) \).

Dem. There is (cf. R. G., Art. 47) a point \( D \) on \( BC \) such that \( AD \) is perpendicular to \( BC \). \( D \) is between \( B \) and \( C \). Otherwise (as may easily be seen, cf. R. G., Art. 66, etc.), either \( AD \) and \( AC \) or \( AD \) and \( AB \) could not meet on the \( A \) side of \( BC \). According to \( S \), \( \angle ACB = \angle BAD \)

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*See Definitions 1-5.
\( \angle CAD = \angle ABC \). It follows by Lemma I, Theorem 23 and Definitions 6 and 1, that
\[
e^2(AB) + e^2(AC) = e(BD)e(BC) + e(CD)e(BC)
= \{ e(BD) + e(CD) \} e(BC) = e^2(BC).
\]

**Theorem 24.** Given \( \alpha, \beta \) there exists \( \gamma \) such that \( \gamma^2 = \alpha^2 + \beta^2 \).

**Dem.** This theorem is evidently true for the case in which \( \alpha \) or \( \beta = 0 \). If \( \alpha \) and \( \beta \) are different from 0, then by Theorems 6 and 15 there exist \( a, b, c, d \), all less than 1 in absolute value, such that \( \alpha = a/b, \beta = c/d \). By Theorem 23 \( \alpha^2 + \beta^2 = [(ad)^2 + (bc)^2]/(bd)^2 \). But, by Theorem 15 and Definition 6, \( ad \) and \( bc \) are lengths of segments. Hence there exists a right-angled triangle \( BAC \) such that the length of \( AB \) is \( ad \) and the length of \( AC \) is \( bc \). According to Lemma 2, \( e^2(BC) = (ad)^2 + (bc)^2 \). Therefore, by Theorem 23, \( \alpha^2 + \beta^2 = e^2(BC)/(bd)^2 = \left[ e(BC) / bd \right]^2 \).

**Convention.** Two straight lines \( OX \) and \( OY \) perpendicular to each other are selected as axes of coordinates. If \( P \) is any point and \( D \) and \( E \) are the feet of the perpendiculars from \( P \) to \( OX \) and \( OY \) respectively, then \( x_P \) means 0, \( e(PE) \), or \( -e(PE) \) according as \( P \) is on \( OY \), on the \( X \)-side of \( OY \), or on the non-\( X \)-side of \( OY \), and \( y_P \) means 0, \( e(PD) \), or \( -e(PD) \), according as \( P \) is on \( OX \), on the \( Y \)-side of \( OX \), or on the non-\( Y \)-side of \( OX \).

As a result of this convention we have the theorem:

**Theorem 25.** Every point \( P \) is represented by one and only one sensed pair of coordinates \( (x_P, y_P) \) and every sensed pair of cutting rays represents one and only one point.

**Theorem 26.** Given a straight line \( AB \), there exist \( \alpha, \beta, \gamma \) (\( \alpha, \beta \) not both 0) such that the \( x \) and \( y \) of every point on \( AB \) satisfy the equation \( \alpha x + \beta y + \gamma = 0 \).

**Dem.** Use \( S \), Theorems 1 and 23, lemma I, Definitions 6 and 1, also R. G., articles 47 and 49, and HILBERT’s axiom IV, 4, Axiom IV, 1, Theorem 11, etc.

**Theorem 27.** If \( B \) is between \( A \) and \( C \) and \( x_A \neq x_B \), then \( x_A < x_B < x_C \) or \( x_A > x_B > x_C \). If \( B \) is between \( A \) and \( C \) and \( x_A = x_B \), then \( y_A > y_B > y_C \) or \( y_A < y_B < y_C \).

**Dem.** Use Theorems 1 and 23, R. G., 47, and HILBERT’s Theorem 5 et seq.

**Theorem 28.** The length \( e(AB) \) equals \( \sqrt{(x_A-x_B)^2+(y_A-y_B)^2} \) and thus the relation \( e(AB) = e(A'B') \) is a necessary and sufficient condition for the equality
\[
(x_A - x_B)^2 + (y_A - y_B)^2 = (x_A' - x_B')^2 + (y_A' - y_B')^2.
\]

**Dem.** Use lemma 2 in connection with convention preceding Theorem 25.
Theorem 29. The existence of \( \alpha, \beta, \gamma, \delta \) satisfying the relations

\[
\begin{align*}
x_{A'} &= \frac{\alpha}{\sqrt{\alpha^2 + \beta^2}} x_A - \frac{\beta}{\sqrt{\alpha^2 + \beta^2}} y_A + \gamma, \\
x_{B'} &= \frac{\alpha}{\sqrt{\alpha^2 + \beta^2}} x_B - \frac{\beta}{\sqrt{\alpha^2 + \beta^2}} y_B + \gamma, \\
y_{A'} &= \frac{\beta}{\sqrt{\alpha^2 + \beta^2}} x_A + \frac{\alpha}{\sqrt{\alpha^2 + \beta^2}} y_A + \delta, \\
y_{B'} &= \frac{\beta}{\sqrt{\alpha^2 + \beta^2}} x_B + \frac{\alpha}{\sqrt{\alpha^2 + \beta^2}} y_B + \delta,
\end{align*}
\]

is a necessary and sufficient condition for the congruence \( AB \equiv A'B' \).

In view of Theorems 23–27 and Theorem 29 it may be easily seen that one could proceed in a manner similar to that indicated by HILBERT in § 9 of his Grundlagen der Geometrie and show that all of his axioms hold true of our geometry, were it not for one obstacle, namely that there is not necessarily a perfect one-to-one correspondence between the set of all points and the set of all sensed pairs of \( \alpha \)'s. If \( \alpha \) is not a cutting ray then \((\alpha, \beta)\) does not correspond to a point in manner indicated in Theorem 25.

It is natural then to fill up this gap by means of the following definitions:

Definition 7. Every sensed pair \((\alpha, \beta)\) is called an ideal point and "ideal point" means such a sensed pair; \( \alpha \) and \( \beta \) are called its co-ordinates.

Definition 8.* An ideal straight line means the set of all existent points, real and ideal, whose co-ordinates satisfy an equation of the form \( ax + \beta y + \gamma = 0 \).

Definition 9. If of the points \( A, B, C \) at least one is ideal then \( ABC \) means \( x_A > x_B > x_C \) or \( x_A < x_B < x_C \) unless \( x_A = x_B \), in which case \( ABC \) means \( y_A > y_B > y_C \) or \( y_A < y_B < y_C \).

Definition 10. If one of the points \( A, A', B, B' \) is ideal then "\( AB \equiv A'B' \)" means there exist \( \alpha, \beta, \gamma, \delta \) satisfying the relations

\[
\begin{align*}
x_{A'} &= \frac{\alpha}{\sqrt{\alpha^2 + \beta^2}} x_A - \frac{\beta}{\sqrt{\alpha^2 + \beta^2}} y_A + \gamma, \\
x_{B'} &= \frac{\alpha}{\sqrt{\alpha^2 + \beta^2}} x_B - \frac{\beta}{\sqrt{\alpha^2 + \beta^2}} y_B + \gamma, \\
y_{A'} &= \frac{\beta}{\sqrt{\alpha^2 + \beta^2}} x_A + \frac{\alpha}{\sqrt{\alpha^2 + \beta^2}} y_A + \delta, \\
y_{B'} &= \frac{\beta}{\sqrt{\alpha^2 + \beta^2}} x_B + \frac{\alpha}{\sqrt{\alpha^2 + \beta^2}} y_B + \delta,
\end{align*}
\]

* In this definition and in what follows, small letters of the English alphabet are not always used, according to earlier convention, to designate cutting rays exclusively.

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In view of Theorems 25, 26, 27, 29 and the corresponding Definitions 6, 7, 8, 9 it is evident that our real and ideal points and straight lines form a system which, with respect to order, congruence and association, is related to our set of \( \alpha \)'s as Hilbert's geometry of \$9 \$ of his Festschrift is related to his number system of that paragraph, and moreover in view of Theorems 28 and 24 it is evident that the set of \( \alpha \)'s satisfy with respect to the operations of addition (+), multiplication (\( \times \)), and the relation \( > \), sufficient conditions to enable us to proceed according to the method indicated by Hilbert to prove that our geometry satisfies his axioms of groups I–IV. It remains to be shown that no ideal point is between two real points. This may be proved by use of Definitions 7 and 1 and Theorem 23.

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