A SET OF AXIOMS FOR LINE GEOMETRY*

BY M. G. GABA

1. Introduction. In 1901 Pieri proposed a set of axioms for line geometry in terms of line and intersection.† That Pieri's set of eleven postulates was not independent was shown by Hedrick and Ingold in 1914; they proposed a simpler and more elegant set of but five independent axioms, using the same undefined concepts.‡ Both of these sets are for geometries equivalent to the general three-space geometry established by axioms $A_1, A_2, A_3, E_0, E_1, E_2, E_3$ and $E_3'$ of Veblen and Young.§

In this paper is given a set of six independent axioms in terms of line as an undefined element and an undefined class of one-to-one correspondences among the lines called collineations. There is introduced but one defined term before the complete statement of the axioms. To make a proper projective space it has usually been necessary not only to add a postulate of projectivity but also a sequence of definitions for such concepts as perspectivity, projectivity, etc., to give that postulate content. If to our set a seventh postulate is added, we have a proper projective three-space without the intervention of any additional defined concepts.||

2. Postulates. Our basis is a class of undefined elements, called lines; an undefined class of one-to-one correspondences, or transformations, among the lines, called collineations; and

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* Presented to the Society, Nov. 27, 1920.
† Sui principi che regno la geometria delle rette, Torino Atti, vol. 36 (1901), pp. 335–351.
‡ A set of axioms for line geometry, Transactions of this Society, vol. 15 (1914), pp. 205–214.
|| Another set of postulates equivalent to the set of all seven of the axioms is the first seven given by the author in his paper A set of postulates for general projective geometry, Transactions of this Society, vol. 16 (1915), pp. 51–61.
a class of defined classes of lines, called *fields*. By a one-to-one correspondence among the lines we mean that to every line \( \alpha \) there corresponds one and only one line \( \alpha' \), and no \( \alpha' \) is the correspondent of two distinct lines \( \alpha_1 \) and \( \alpha_2 \). This concept of one-to-one correspondence may be said to belong to the domain of pure logic; we shall therefore not consider it in our basis as an undefined mathematical notion.* We shall define a field as a class of at least three lines such that:

1. every collineation that makes any two distinct lines of the class correspond to two distinct lines of the class leaves the class invariant;
2. a collineation exists that will make any two distinct lines of the class correspond to any two distinct lines of the class;
3. the class has no proper super-class possessing property (2).

Our axioms, whose technical independence is shown by examples given at the end of this paper, are as follows:

1. There exists a line.
2. If \( \alpha \) is a line, there exist five distinct fields containing \( \alpha \).
3. If a collineation \( \tau_1 \) exists such that \( \tau_1 \) makes correspond to the set of lines \( A \) the set of lines \( B \), and if a collineation \( \tau_2 \) exists such that \( \tau_2 \) makes correspond to the set of lines \( A \) the set of lines \( C \), then a collineation \( \tau_3 \) exists such that \( \tau_3 \) makes correspond to the set of lines \( B \) the set of lines \( C \).
4. If no collineation exists that makes correspond to the field \( A \) the field \( B \), and if no collineation exists that makes correspond to the field \( A \) the field \( C \), then a collineation \( \tau \) exists that makes correspond to the field \( B \) the field \( C \).
5. If \( A \) and \( B \) are fields such that a collineation \( \tau \) exists that makes correspond to the field \( A \) the field \( B \), then the fields \( A \) and \( B \) have a line in common.
6. If \( A \), \( B \) and \( C \) are fields such that \( A \) and \( B \) have a line \( \alpha_1 \) in common, and \( B \) and \( C \) have a line \( \alpha_2 \) in common, and \( C \) and

* It is true, of course, that no sharp line of demarcation exists between concepts of pure logic and of mathematics; but an author may choose whether or not he will include a given concept in his own discussion. See Federico Enriques, *Problems of Science*, authorized translation by J. Royce. Open Court Publishing Co., 1914, p. 122.
A have a line $\alpha_3$ in common, then there exists a field $D$ such that $D$ contains the lines $\alpha_1$, $\alpha_2$ and $\alpha_3$.

VII. If $A$, $B$, $C$ and $D$ are four distinct fields having a line $\alpha$ in common, and if collineations $\tau_1$, $\tau_2$ and $\tau_3$ exist such that $\tau_1$ makes correspond to the field $A$ the field $B$, $\tau_2$ makes correspond to the field $B$ the field $C$, and $\tau_3$ makes correspond to the field $C$ the field $D$, then every collineation $\tau$ that leaves $A$, $B$ and $C$ invariant also leaves $D$ invariant.

3. Theorems. Theorem 1. If $A$ is a field, then a collineation exists that leaves $A$ invariant.

Let us assume that no collineation exists that leaves $A$ invariant. If now we let fields $B$ and $C$ of Postulate IV be identical with $A$, we are led at once to an absurdity.

Theorem 2. If a collineation $\tau$ exists that makes correspond to the field $A$ the set of lines $B$ (or transforms $A$ into $B$, in notation, $\tau(A) = B$), then a collineation $\tau^{-1}$ exists such that $\tau^{-1}$ makes correspond to the set of lines $B$ the field $A$: $\tau^{-1}(B) = A$.

By hypothesis, a collineation $\tau$ exists such that $\tau(A) = B$, and, by Theorem 1, a collineation $\tau_1$ exists such that $\tau_1(A) = A$. Hence it follows from Postulate III that a collineation $\tau^{-1}$ exists such that $\tau^{-1}(B) = A$.

Theorem 3. If a collineation $\tau_1$ exists such that $\tau_1$ transforms the field $A$ into a set of lines $B$, and a collineation $\tau_2$ exists such that $\tau_2$ transforms the set of lines $B$ into a set of lines $C$, then a $\tau_3$ exists such that $\tau_3$ transforms $A$ into $C$.

By Theorem 2, a collineation $\tau_1^{-1}$ exists such that $\tau_1^{-1}(B) = A$. The existence of $\tau_1^{-1}$ and $\tau_2$, by virtue of Postulate III, implies the existence of a collineation $\tau_3$ such that $\tau_3(A) = C$.

Corollary. The resultant of a sequence of collineations on a field is a collineation.

Theorem 4. Every collineation transforms a field into a field.

Let $\tau$ be any collineation that transforms the field $A$ into a set of lines $B$. Let $\beta_1$, $\beta_2$, $\beta_1'$ and $\beta_2'$ be any four lines of $B$ such that $\beta_1$ and $\beta_2$ are distinct and $\beta_1'$ and $\beta_2'$ are distinct; and let $\alpha_1$, $\alpha_2$, $\alpha_1'$ and $\alpha_2'$ be the four lines of $A$ such that $\tau(\alpha_1, \alpha_2, \alpha_1', \alpha_2') = \beta_1, \beta_2, \beta_1', \beta_2'$. Let $\tau_1$ be any collineation such that $\tau_1(\beta_1, \beta_2) = \beta_1', \beta_2'$. From Theorem 2 and the coroll-
ary of Theorem 3, we know that a collineation \( \tau_2 = \tau^{-1}_1 \tau \) exists such that \( \tau_2(\alpha_1, \alpha_2) = \alpha_1', \alpha_2' \), where \( \alpha_1' \) and \( \alpha_2' \) are lines of \( A \). But since the collineation \( \tau_2 \) makes two lines of the field \( A \) correspond to two lines of \( A \) (which are distinct, since they are the correspondents of pairs of distinct lines), \( \tau_2 \) leaves the field \( A \) invariant. Therefore, since \( \tau^{-1}_1 \tau (A) = A \), \( \tau (A) = B \), and \( \tau^{-1}(B) = A \), we have \( \tau^{-1}_1 \tau (B) = A \), and hence \( \tau_1(B) = B \).

Since \( A \) is a field, a collineation \( \tau_3 \) exists such that \( \tau_3(\bar{\alpha}_1, \bar{\alpha}_2) = \alpha_1', \alpha_2' \), where \( \tau^{-1}(\beta_1, \beta_2) = \bar{\alpha}_1, \bar{\alpha}_2 \). Therefore a collineation \( \tau_4 = \tau \tau_3^{-1} \) exists such that \( \tau_4(\beta_1, \beta_2) = \beta_1', \beta_2' \).

We have shown that properties (1) and (2) of a field are possessed by the set of lines \( B \). Let us now assume that \( B \) has a proper super-class \( B^* \) also possessing property (2). If \( \tau'(B) = A \) and if \( \tau'(B^*) = A^* \), then \( A^* \) is a proper super-class of \( A \). Let \( \alpha_1^*, \alpha_2^* \) and \( \alpha_1^{*'}, \alpha_2^{*'} \) be any two pairs of distinct lines of \( A^* \). Furthermore let \( \beta_1^*, \beta_2^*, \beta_1^{*'}, \beta_2^{*'} \) be those four lines of \( B^* \) such that \( \tau(\alpha_1^*, \alpha_2^*) = \beta_1^*, \beta_2^* \) and \( \tau^{-1}(\beta_1^{*'}, \beta_2^{*'}) = \alpha_1^{*'}, \alpha_2^{*'} \). By our assumption, a \( \tau_5 \) exists such that \( \tau_5(\beta_1^*, \beta_2^*) = \beta_1^{*'}, \beta_2^{*'} \); therefore a \( \tau_6 = \tau^{-1}_5 \tau \) exists. But \( \tau_6(\alpha_1^*, \alpha_2^*) = \alpha_1^{*'}, \alpha_2^{*'} \); hence \( A^* \) possesses property (2) of a field, which is impossible if \( A \) is a field. Therefore our assumption leads to a contradiction; hence \( B \) is a field.

**Theorem 5.** If \( A \) and \( B \) are distinct fields such that a collineation exists transforming \( A \) into \( B \), then \( A \) and \( B \) have at most one line in common.

Let us assume that \( A \) and \( B \) have the two distinct lines \( \gamma_1 \) and \( \gamma_2 \) in common. If the collineation that makes \( A \) go over into \( B \) is \( \tau \), then let \( \tau(\gamma_1, \gamma_2) = \beta_1, \beta_2 \). Since \( \gamma_1, \gamma_2, \beta_1 \) and \( \beta_2 \) are pairs of distinct lines of \( B \), a collineation \( \tau_1 \) exists such that \( \tau_1(\beta_1, \beta_2) = \gamma_1, \gamma_2 \) and \( \tau_1(B) = B \). But \( \tau_1 A = A \), since \( \gamma_1 \) and \( \gamma_2 \) of \( A \) are invariant; and \( \tau_1 B = B \), since \( \tau(A) = B \); therefore our assumption must be wrong.

**Theorem 6.** If \( A \) is a field containing the lines \( \alpha_1 \) and \( \alpha_2 \), then there exists a field \( \bar{A} \) also containing \( \alpha_1 \) and \( \alpha_2 \) and such that no collineation exists that will transform \( A \) into \( \bar{A} \).

We shall assume \( \alpha_1 \) and \( \alpha_2 \) distinct, since the theorem is true in the case where \( \alpha_1 \) and \( \alpha_2 \) are identical if it is true when \( \alpha_1 \).
and $\alpha_2$ are distinct. By means of Postulate II we know that there exists a field $A_1$ containing the line $\alpha_1$ and distinct from $A$. Let $\tau$ be a collineation such that $\tau(\alpha_1, \alpha_2) = \alpha_2, \alpha_1$. From Theorem 4, we have $\tau(A_1) = A_2$, where $A_2$ is a field containing $\alpha_2$. If $A_1 = A_2$, then $A_1$ is $A$, since $A$ and $A_1$ have the two distinct lines $\alpha_1$ and $\alpha_2$ in common; hence they cannot be transformable into one another without contradicting Theorem 5. Let us now assume $A_1$ and $A_2$ distinct. Since $A_1$ is transformable into $A_2$, fields $A_1$ and $A_2$ have a line $\alpha$ in common. But since $A$ and $A_1$ have the line $\alpha_1$ in common, $A_1$ and $A_2$ the line $\alpha$ in common, and $A_2$ and $A$ the line $\alpha_2$ in common, it follows from Postulate VI that a field $A'$ exists containing $\alpha$, $\alpha_1$ and $\alpha_2$. If $A$ is not transformable into $A'$, then $A'$ is $A$. If $A$ is transformable into $A'$, then $A$ is identical with $A'$ by Theorem 5. In the latter case, however, $A_1$ is not transformable into $A$, since if that were possible, $A$ and $A_1$ would be identical, since they have the lines $\alpha_1$ and $\alpha$ (distinct, since otherwise $A_1 = A_2$) in common. Since $\alpha$, $\alpha_1$ and $\alpha_2$ are distinct lines of the field $A$, a collineation $\tau_1$ exists such that $\tau_1(\alpha_1, \alpha) = \alpha_1, \alpha_2$. The collineation $\tau_1$ transforms the field $A_1$ into a field $A_1'$ containing the lines $\alpha_1$ and $\alpha_2$. But $A$ cannot be transformed into $A_1'$, because, if that were possible, then, by Postulate III, $A_1$ would be transformable into $A$. Hence it follows that $A_1'$ is $A$ in this case.

Theorem 7. Every field belongs to one or to the other of two classes of fields such that collineations exist that will transform any field of one class into any field of the same class, and such that no collineations exist that will transform any field of one class into a field of the other class.

From Theorem 6, we know that two fields $A$ and $\overline{A}$ exist such that no collineation will transform $A$ into $\overline{A}$. Let $[A_i]$ be the class of all fields transformable into $A$, and let $[\overline{A}_i]$ be the class of all fields transformable into $\overline{A}$. Let $B$ be any field. If a collineation $\tau$ exists such that $\tau(B) = A$, then $B$ belongs to $[A_i]$. Suppose $B$ does not belong to $[A_i]$, then since no collineation exists transforming $B$ into $A$, and no collineation exists transforming $\overline{A}$ into $A$, it follows from Theorem 2 and
Postulate IV that a collineation $\tau$ exists such that $\tau(B) = A$; hence $B$ belongs to $[A_i]$. But $B$ cannot belong to both $[A_i]$ and $[A_j]$, for in that case it would follow from Postulate III that $A$ could be transformed into $A$. Any field $A_i$ of the class $[A_i]$ will determine the class, since it is easy to show that if $A_i$ and $A_j$ are both members of the class and hence transformable into $A$, they are transformable into one another. Furthermore, no $A_i$ of $[A_i]$ can be transformed into an $A_j$ of $[A_i]$, since that would make $A_i$ belong to both classes.

We shall call the fields of one of the two classes of fields points, and the fields of the other class planes. We shall use the terminology $\alpha$ is a line on the plane $p$ or $p$ is on $\alpha$ to mean $\alpha$ is a line of $p$; $P$ is a point on the plane $p$ or $p$ on $P$ to mean that $P$ and $p$ have a line in common; $P$ is a point on the line $\alpha$ or $\alpha$ on $P$ to mean that $\alpha$ is a line of $P$. If two lines are on the same plane, they are called copunctal; if two lines are on the same plane, they are called coplanar.

**Theorem 8.** If a point $P$ is on the line $\alpha$ and $\alpha$ is on the plane $p$, then $P$ is on $p$.

Since $P$ and $p$ have the line $\alpha$ in common, the theorem is obvious.

**Theorem 9.** If two lines are copunctal (coplanar), they are coplanar (copunctal).

This theorem is but a restatement of Theorem 6 in the light of subsequent definitions.

**Theorem 10.** If $P_1$ and $P_2$ are distinct points (planes), then there is at least one line on both $P_1$ and $P_2$.

See Postulate V.

**Theorem 11.** If $P_1$ and $P_2$ are distinct points (planes), there is not more than one line on both $P_1$ and $P_2$.

See Theorem 5.

Points (planes) which are on the same line are said to be collinear; points (planes) which are not on the same line are said to be non-collinear.

**Theorem 12.** If $P_1$, $P_2$ and $P_3$ are three non-collinear points (planes), then there is one and only one plane (point) $p$ such that $P_1$, $P_2$ and $P_3$ are on $p$. 
Let the line common to $P_1$ and $P_2$ be $\alpha_3$, the line common to $P_2$ and $P_3$ be $\alpha_1$, and the line common to $P_3$ and $P_1$ be $\alpha_2$. By Postulate VI a field exists containing $\alpha_1$, $\alpha_2$ and $\alpha_3$. If this field is a point (plane), then $P_1$, $P_2$ and $P_3$ coincide, contrary to the hypothesis that they are non-collinear and hence distinct. The field is therefore a plane (point). There can be but one such plane (point). Since $\alpha_1$ and $\alpha_2$ are distinct (otherwise $P_1$, $P_2$ and $P_3$ are collinear), they determine the plane (point) $p$. Let $\alpha'$ be a line of $P_1$ in $p'$, $\alpha_2'$ a line of $P_2$ in $p'$, and $\alpha_3'$ a line of $P_3$ in $p'$; hence $P_1$, $P_2$ and $P_3$ are on the plane (point) $p'$. If $\alpha'$ and $\alpha_2'$ coincide, then $\alpha' = \alpha_2' = \alpha_3$. Since $\alpha_1'$ and $\alpha_2'$ are coplanar (copunctal), they must be coplanar (copunctal). If $\alpha_1'$ and $\alpha_2'$ are distinct, they determine a point (plane) $P_3'$. Now $P_3'$ cannot be on $\alpha_3$ since that would make $\alpha_1'$ and $\alpha_2'$ coincide. By the part of the theorem already proved, a plane (point) $p''$ exists such that $P_1$, $P_2$ and $P_3'$ are on $p''$. But $p''$ contains $\alpha_1'$ and $\alpha_2'$; therefore $p''$ is $p'$. Hence the plane (point) $p'$ contains $\alpha_3$. In like fashion it can be shown that $p'$ contains $\alpha_1$ and $\alpha_2$; hence $p'$ is $p$.

**Corollary 1.** If $P_1$ and $P_2$ are distinct points (planes), and if $P_1$ and $P_2$ are both on the plane (point) $p$, then the line $\alpha$ common to $P_1$ and $P_2$ is on $P$.

**Corollary 2.** If $P$ is a point (plane) and $\alpha$ is a line such that $P$ is not on $\alpha$, then there is one and only one plane (point) determined by $P$ and $\alpha$.

**Theorem 13.** If $P_1$, $P_2$, $P_3$ are three points (planes) not on the same line, and $\alpha$ is a line joining $P_2$ and $P_3$, the class $[P_i]$ of all points (planes) such that every point (plane) of $[P_i]$ is collinear with $P_1$ and some point (plane) on $\alpha$, is such that every point (plane) of $[P_i]$ is on the plane (point) $p$ determined by $P$ and $\alpha$, and every point (plane) on the plane (point) $p$ is a point (plane) of $[P_i]$.

Let $P_i$ be a point (plane) collinear with $P_1$, and $\bar{P}_i$ a point (plane) on $\alpha$. $\bar{P}_i$ is on $p$, since $\bar{P}_i$ is on $\alpha$, by Theorem 8. Let the line determined by $P_1$ and $P_i$ be $\alpha_i$. Then $\alpha_i$ is on $p$ by Corollary 1, Theorem 12. But $P_i$ is on $\alpha_i$; therefore $P_i$ is on $p$. 

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Let $P'$ be any point (plane) of $p$. $P_1$ and $P'$ determine a line $\alpha'$ (unless $P'$ is $P_1$, in which case $P'$ obviously belongs to $[P_1]$). The lines $\alpha'$ and $\alpha$ are distinct since $\alpha$ is not on $P_1$, and they are copunctal (coplanar) since both lines are on $p$. Hence $\alpha$ and $\alpha'$ determine a point (plane) $P'$. Hence $P'$ is collinear with $P_1$, and $P'$ a point (plane) on $\alpha$; consequently $P'$ belongs to $[P_1]$.

**Theorem 14.** If $P_1$, $P_2$, $P_3$ are points (planes) not all on the same line, and $P_4$ and $P_5$ ($P_4 \neq P_5$) are points (planes) such that $P_2$, $P_3$, $P_4$ are on a line and $P_1$, $P_3$, $P_5$ are on a line, there is a point (plane) $P_6$ such that $P_1$, $P_2$, $P_6$ are on a line and also $P_4$, $P_5$, $P_6$ are on a line.

Since the points (planes) $P_1$, $P_2$ and $P_3$ are non-collinear, they determine a plane (point) $p$. The three lines $\alpha_1$ common to $P_2$ and $P_3$, $\alpha_2$ common to $P_1$ and $P_3$, and $\alpha_3$ common to $P_1$ and $P_2$, are on $p$ by Corollary 1, Theorem 12. Since $P_4$ is on $\alpha_1$, and $P_5$ is on $\alpha_2$, $P_4$ and $P_5$ are also on $p$. Hence the line $\alpha$ common to $P_4$ and $P_5$ is on $p$, and consequently $\alpha$ is copunctal (coplanar) with $\alpha_1$. If $\alpha$ and $\alpha_1$ are distinct, they determine a point (plane) which is $P_6$. If $\alpha$ and $\alpha_1$ coincide, then any point (plane) on $\alpha$ will serve as a $P_6$.

**Theorem 15.** If $\alpha_1$ and $\alpha_2$ are lines, then $\alpha_1$ and $\alpha_2$ are on the same number of points (planes).

Since collineations exist that transform any point (plane) into any point (plane) and any line in a point (plane) into any other in the same point (plane), a collineation $\tau$ exists that transforms $\alpha_1$ into $\alpha_2$. Every point (plane) on $\alpha_1$ is transformed by $\tau$ into a point (plane) on $\alpha_2$, and every point (plane) on $\alpha_2$ comes from a point (plane) on $\alpha_1$. Hence $\alpha_1$ and $\alpha_2$ are on the same number of points (planes).

**Theorem 16.** All points (planes) are not on the same line.

Let us assume that every point (plane) is on a line $\alpha$. Let $\tau$ be a collineation that transforms $\alpha$ into a distinct line $\alpha'$. If we transform every point (plane) by $\tau$, we get all the points (planes) again, since distinct fields transform into distinct fields. But all points (planes) now contain $\alpha'$ as well as $\alpha$. Therefore it follows that there is but one point (plane) $P$. 

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Every line is in $P$, since, by Theorem 6, every line is in a point (plane). No other field can exist, since, if it did, it would be a proper sub-class of $P$, contrary to the definition of field. But if there is only one field, Postulate II is contradicted. Hence our original assumption is false and the theorem proved.

**Theorem 17.** If $\alpha$ is a line, then the number of planes on $\alpha$ is the same as the number of points on $\alpha$.

Since, by Theorem 16, all planes are not on $\alpha$, there exists a line $\bar{\alpha}$ non-coplanar with $\alpha$. Every point on $\bar{\alpha}$ determines, with the line $\alpha$, a different plane, since if two distinct points $\bar{P}_1$ and $\bar{P}_2$ on $\bar{\alpha}$ and $\alpha$ were on the same plane, the lines $\bar{\alpha}$ and $\alpha$ would be coplanar. Hence there are at least as many planes on $\alpha$ as there are points on $\bar{\alpha}$. Likewise every plane on $\alpha$ determines, with the line $\bar{\alpha}$, a different point. Hence there are at least as many points on $\alpha$ as there are planes on $\bar{\alpha}$. Since, by Theorem 15, the number of points on $\alpha$ and on $\bar{\alpha}$ are equal, and since the number of planes on $\alpha$ must equal the number of points on $\bar{\alpha}$, it follows that $\alpha$ is on the same number of points as $\alpha$ is on planes.

**Theorem 18.** There are at least three points (planes) on every line.

By Postulate II, every line is on at least five fields; and, since the number of planes and points on a line is the same, the theorem follows immediately.

**Theorem 19.** All points (planes) are not on the same plane (point).

Let $p$ be any plane (point). Since there is more than one plane (point), there exists a line $\alpha$ not on $p$. If two points (planes) of $\alpha$ were on $p$, then $\alpha$ would be on $p$. Hence at most one of the points (planes) of $\alpha$ can be on $p$.

4. **Comparison with Ordinary Geometry.** Let us now compare our geometry with the general three-space geometry of Veblen and Young.* If we identify our lines as lines, collineations as projectivities, and fields as either points or planes in the Veblen-Young geometry, then our axioms are theorems in

*Loc. cit.
their geometry. Incidentally, the consistency of our axioms is thus established.

On the other hand, let the undefined line of Veblen and Young be our line; their undefined point, our point; and their on our on. Consider their assumptions of alignment A:

$A_1$. If $A$ and $B$ are distinct points, there is at least one line on both $A$ and $B$.

$A_2$. If $A$ and $B$ are distinct points, there is not more than one line on both $A$ and $B$.

$A_3$. If $A$, $B$, $C$ are points not all on the same line, and $D$ and $E$ ($D \neq E$) are points such that $B, C, D$ are on a line and $C, A, E$ are on a line, there is a point $F$ such that $A, B, F$ are on a line and also $D, E, F$ are on a line.

We see that, except for notation, $A_1$ is our Theorem 10, $A_2$ is Theorem 11, and $A_3$ is Theorem 14. The plane defined by Veblen and Young is equivalent to our plane, by virtue of Theorem 13.

The assumptions of extension, substituting for the usual $E_3'$ an equivalent axiom also given by Veblen and Young, are as follows:

$E_0$. There are at least three points on every line.

$E_1$. There exists at least one line.

$E_2$. All points are not on the same line.

$E_3$. All points are not on the same plane.

$E_3'$. Any two distinct planes have a line in common.

$E_0$ is our Theorem 18; $E_1$ is Postulate I; $E_2$ is Theorem 16; $E_3$ is Theorem 19; and $E_3'$ is Theorem 10. We have therefore proved that our geometry is equivalent to that of Veblen and Young.

The assumption of projectivity is as follows:

$P$. If a projectivity leaves each of three distinct points of a line invariant, it leaves every point of the line invariant.

It is evident that $P$ is a rephrasing of Postulate VII in terms of point.

5. Independence Examples.—1. No lines exist. Hence neither collineations nor fields exist.

—2. Lines are all the lines of a projective three-space and
an extra line not in that three-space. Collineations are all the projectivities on the lines of the three-space, but in addition leave the extra line invariant. Fields are therefore the points and planes of the three-space.

—3. Lines are all the lines of a projective finite three-space. Collineations are all the projectivities on the three-space and an extra transformation \( \tau \), such that \( \tau \) transforms every line \( \alpha \) into a line \( \alpha' \) skew to \( \alpha \). Fields are therefore the points and planes of the three-space.

—4. Lines are all the lines of two projective three-spaces having no line in common. Collineations are all the projectivities on the two three-spaces such that each of the three-spaces is left invariant. Fields are therefore the points and planes of the two three-spaces.

—5. Lines are all the lines of two projective three-spaces having no line in common. Collineations are all the projectivities on the two three-spaces such that each of the three-spaces is left invariant, or such that the two three-spaces are interchanged. Fields are therefore the points and planes of the two three-spaces.

—6. Lines are all the lines of a euclidean plane. Collineations are all the projectivities such that parallel lines are transformed into parallel lines. Fields are therefore pencils of lines.

—7. Lines are all the lines of an improperly projective three-space. Collineations are all the projectivities in such a three-space. Fields are therefore the points and planes of that three-space.