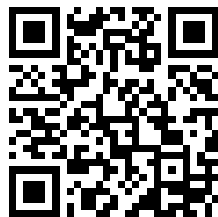
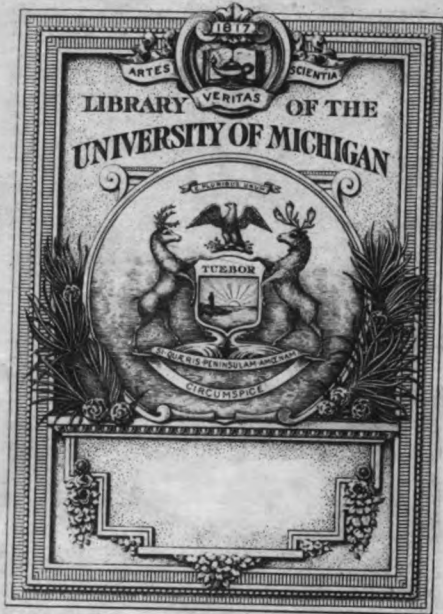

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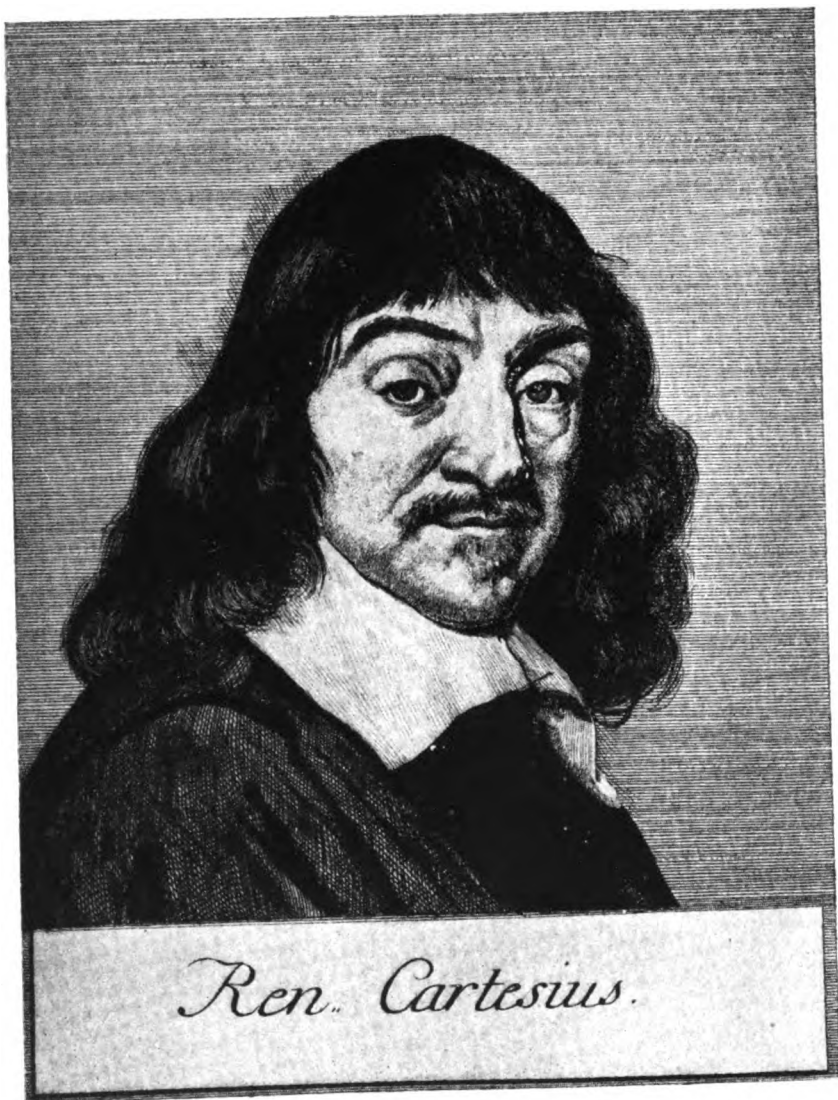
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THE GIFT OF
Prof. Louis C. Karpinski

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THE GEOMETRY OF RENÉ DESCARTES

TRANSLATED FROM THE FRENCH
AND LATIN

BY

DAVID EUGENE SMITH

AND

MARCIA L. LATHAM

WITH A FACSIMILE OF THE FIRST EDITION, 1637

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THE GEOMETRY OF RENÉ DESCARTES

Preface

If a mathematician were asked to name the great epoch-making works in his science, he might well hesitate in his decision concerning the product of the nineteenth century; he might even hesitate with respect to the eighteenth century; but as to the product of the sixteenth and seventeenth centuries, and particularly as to the works of the Greeks in classical times, he would probably have very definite views. He would certainly include the works of Euclid, Archimedes, and Apollonius among the products of the Greek civilization, while among those which contributed to the great renaissance of mathematics in the seventeenth century he would as certainly include *La Géométrie* of Descartes and the *Principia* of Newton.

But it is one of the curious facts in the study of historical material that although we have long had the works of Euclid, Archimedes, Apollonius, and Newton in English, the epoch-making treatise of Descartes has never been printed in our language, or, if so, only in some obscure and long-since-forgotten edition. Written originally in French, it was soon after translated into Latin by Van Schooten, and this was long held to be sufficient for any scholars who might care to follow the work of Descartes in the first printed treatise that ever appeared on analytic geometry. At present it is doubtful if many mathematicians read the work in Latin; indeed, it is doubtful if many except the French scholars consult it very often in the original language in which it appeared. But certainly a work of this kind ought to be easily accessible to American and British students of the history of mathematics, and in a language with which they are entirely familiar.

On this account, The Open Court Publishing Company has agreed with the translators that the work should appear in English, and with such notes as may add to the ease with which it will be read. To this organization the translators are indebted for the publication of the book, a labor of love on its part as well as on theirs.

As to the translation itself, an attempt has been made to give the meaning of the original in simple English rather than to add to the difficulty of the reader by making it a verbatim reproduction. It is believed that the student will welcome this policy, being content to go to the original in case a stricter translation is needed. One of the translators having used chiefly the Latin edition of Van Schooten, and the other the original French edition, it is believed that the meaning which Descartes had in mind has been adequately preserved.

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¹ It should be recalled that the first edition of this work appeared as a kind of appendix to the *Discours de la Methode*, and hence began on page 297. For convenience of reference, the original paging has been retained in the facsimile. A new folio number, appropriate to the present edition, will also be found at the foot of each page. For convenience of reference to the original, this table of contents follows the paging of the 1637 edition.

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BOOK FIRST

The Geometry of René Descartes

BOOK I

PROBLEMS THE CONSTRUCTION OF WHICH REQUIRES ONLY STRAIGHT LINES AND CIRCLES

ANY problem in geometry can easily be reduced to such terms that a knowledge of the lengths of certain straight lines is sufficient for its construction.^[1] Just as arithmetic consists of only four or five operations, namely, addition, subtraction, multiplication, division and the extraction of roots, which may be considered a kind of division, so in geometry, to find required lines it is merely necessary to add or subtract other lines; or else, taking one line which I shall call unity in order to relate it as closely as possible to numbers,^[2] and which can in general be chosen arbitrarily, and having given two other lines, to find a fourth line which shall be to one of the given lines as the other is to unity (which is the same as multiplication); or, again, to find a fourth line which is to one of the given lines as unity is to the other (which is equivalent to division); or, finally, to find one, two, or several mean proportionals between unity and some other line (which is the same

^[1] Large collections of problems of this nature are contained in the following works: Vincenzo Riccati and Girolamo Saladino, *Institutiones Analyticae*, Bologna, 1765; Maria Gaetana Agnesi, *Istituzioni Analitiche*, Milan, 1748; Claude Rabuel, *Commentaires sur la Géométrie de M. Descartes*, Lyons, 1730 (hereafter referred to as Rabuel); and other books of the same period or earlier.

^[2] Van Schooten, in his Latin edition of 1683, has this note: "Per unitatem intellige lineam quandam determinatam, qua ad quamvis reliquarum linearum talem relationem habeat, qualem unitas ad certum aliquem numerum." *Geometria a Renato Des Cartes, una cum notis Florimondi de Beaune, opera atque studio Francisci à Schooten*, Amsterdam, 1683, p. 165 (hereafter referred to as Van Schooten).

In general, the translation runs page for page with the facing original. On account of figures and footnotes, however, this plan is occasionally varied, but not in such a way as to cause the reader any serious inconvenience.

GEOMETRIE.

LIVRE PREMIER.

*Des problemes qu'on peut construire sans
y employer que des cercles & des
lignes droites.*



Tous les Problemes de Geometrie se
peuvent facilement reduire a tels termes,
qu'il n'est besoin par après que de connoi-
stre la longueur de quelques lignes droites,
pour les construire.

Et comme toute l'Arithmetique n'est composée, que
de quatre ou cinq operations, qui sont l'Addition, la
Soustraction, la Multiplication, la Diuision, & l'Extra-
ction des racines, qu'on peut prendre pour vne espece
de Diuision : Ainsi n'at'on autre chose a faire en Geo-
metrie touchant les lignes qu'on cherche, pour les pre-
parer a estre conuës, que leur en adiouter d'autres, ou
en oster, Oubien en ayant vne, que ie nommeray l'vnité.
pour la rapporter d'autant mieux aux nombres, & qui
peut ordinairement estre prise a discretion, puis en ayant
encore deux autres, en trouuer vne quatriesme, qui soit
à l'vne de ces deux, comme l'autre est a l'vnité, ce qui est
le mesme que la Multiplication; oubien en trouuer vne
quatriesme, qui soit a l'vne de ces deux, comme l'vnité

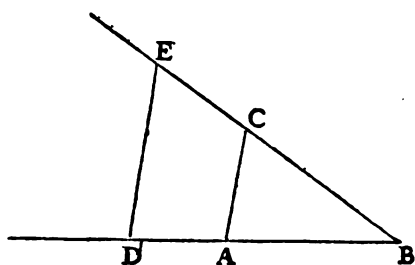
Commẽt
le calcul
d'Ari-
thmeti-
que se
rapporte
aux ope-
rations de
Geome-
trie.

P p

est

est a l'autre, ce qui est le mesme que la Diuision; ou enfin trouuer vne, ou deux, ou plusieurs moyennes proportionnelles entre l'vnité, & quelque autre ligne; ce qui est le mesme que tirer la racine quarrée, ou cubique, &c. Et ie ne craindray pas d'introduire ces termes d'Arithmetique en la Geometrie, affin de me rendre plus intelligible.

La Multi-
plication.

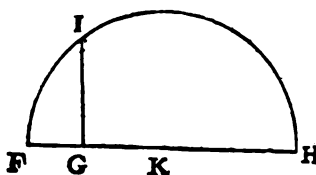


Soit par exemple AB l'vnité, & qu'il faille multiplier BD par BC, ie n'ay qu'a ioinde les points A & C, puis tirer DE parallele a CA, & BE est le produit de cete Multiplication.

La Diui-
sion.

Oubien s'il faut diuifer BE par BD, ayant ioint les points E & D, ie tire AC parallele a DE, & BC est le produit de cete diuision.

L'Extra-
ction de la
racine
quarrée.



Ou s'il faut tirer la racine quarrée de GH, ie luy adiouste en ligne droite FG, qui est l'vnité, & diuisant FH en deux parties esgales au point K, du centre K ie tire

le cercle FKH, puis esleuant du point G vne ligne droite iusques à I, à angles droits sur FH, c'est GI la racine cherchée. Ie ne dis rien icy de la racine cubique, ny des autres, à cause que i'en parleray plus commodement cy après.

Commēt
on peut

Mais souuent on n'a pas besoin de tracer ainsi ces li-
gne

as extracting the square root, cube root, etc., of the given line.^[9] And I shall not hesitate to introduce these arithmetical terms into geometry, for the sake of greater clearness.

For example, let AB be taken as unity, and let it be required to multiply BD by BC. I have only to join the points A and C, and draw DE parallel to CA; then BE is the product of BD and BC.

If it be required to divide BE by BD, I join E and D, and draw AC parallel to DE; then BC is the result of the division.

If the square root of GH is desired, I add, along the same straight line, FG equal to unity; then, bisecting FH at K, I describe the circle FKH about K as a center, and draw from G a perpendicular and extend it to I, and GI is the required root. I do not speak here of cube root, or other roots, since I shall speak more conveniently of them later.

Often it is not necessary thus to draw the lines on paper, but it is sufficient to designate each by a single letter. Thus, to add the lines BD and GH, I call one a and the other b , and write $a + b$. Then $a - b$ will indicate that b is subtracted from a ; ab that a is multiplied by b ; $\frac{a}{b}$ that a is divided by b ; aa or a^2 that a is multiplied by itself; a^3 that this result is multiplied by a , and so on, indefinitely.^[1] Again, if I wish to extract the square root of $a^2 + b^2$, I write $\sqrt{a^2 + b^2}$; if I wish to extract the cube root of $a^3 - b^3 + ab^2$, I write $\sqrt[3]{a^3 - b^3 + ab^2}$, and similarly for other roots.^[1] Here it must be observed that by a^2 , b^3 , and similar expressions, I ordinarily mean only simple lines, which, however, I name squares, cubes, etc., so that I may make use of the terms employed in algebra.^[1]

^[1] While in arithmetic the only exact roots obtainable are those of perfect powers, in geometry a length can be found which will represent exactly the square root of a given line, even though this line be not commensurable with unity. Of other roots, Descartes speaks later.

^[1] Descartes uses a^3 , a^4 , a^5 , a^6 , and so on, to represent the respective powers of a , but he uses both aa and a^2 without distinction. For example, he often has $aabb$, but he also uses $\frac{3a^2}{4b^2}$.

^[1] Descartes writes: $\sqrt{C \cdot a^3 - b^3 + abb}$. See original, page 299, line 9.

^[1] At the time this was written, a^2 was commonly considered to mean the surface of a square whose side is a , and b^3 to mean the volume of a cube whose side is b ; while b^4 , b^5 , ... were unintelligible as geometric forms. Descartes here says that a^2 does not have this meaning, but means the line obtained by constructing a third proportional to 1 and a , and so on.

It should also be noted that all parts of a single line should always be expressed by the same number of dimensions, provided unity is not determined by the conditions of the problem. Thus, a^3 contains as many dimensions as ab^2 or b^3 , these being the component parts of the line which I have called $\sqrt[3]{a^3 - b^3 + ab^2}$. It is not, however, the same thing when unity is determined, because unity can always be understood, even where there are too many or too few dimensions; thus, if it be required to extract the cube root of $a^2b^2 - b$, we must consider the quantity a^2b^2 divided once by unity, and the quantity b multiplied twice by unity.^[7]

Finally, so that we may be sure to remember the names of these lines, a separate list should always be made as often as names are assigned or changed. For example, we may write, $AB=1$, that is AB is equal to 1;^[8] $GH=a$, $BD=b$, and so on.

✓ If, then, we wish to solve any problem, we first suppose the solution already effected,^[9] and give names to all the lines that seem needful for its construction,—to those that are unknown as well as to those that are known.^[10] Then, making no distinction between known and unknown lines, we must unravel the difficulty in any way that shows most natur-

^[7] Descartes seems to say that each term must be of the third degree, and that therefore we must conceive of both a^2b^2 and b as reduced to the proper dimension.

^[8] Van Schooten adds "seu unitati," p. 3. Descartes writes, $AB \propto 1$. He seems to have been the first to use this symbol. Among the few writers who followed him, was Hudde (1633-1704). It is very commonly supposed that $\propto$ is a ligature representing the first two letters (or diphthong) of "square." See, for example, M. Aubry's note in W. W. R. Ball's *Recréations Mathématiques et Problèmes des Temps Anciens et Modernes*, French edition, Paris, 1909, Part III, p. 164.

^[9] This plan, as is well known, goes back to Plato. It appears in the work of Pappus as follows: "In analysis we suppose that which is required to be already obtained, and consider its connections and antecedents, going back until we reach either something already known (given in the hypothesis), or else some fundamental principle (axiom or postulate) of mathematics." *Pappi Alexandrini Collectiones quae supersunt e libris manu scriptis edidit Latina interpellatione et commentariis instruxit Fredericus Hultsch*, Berlin, 1876-1878; vol. II, p. 635 (hereafter referred to as Pappus). See also Commandinus, *Pappi Alexandrini Mathematicae Collectiones*, Bologna, 1588, with later editions.

Pappus of Alexandria was a Greek mathematician who lived about 300 A.D. His most important work is a mathematical treatise in eight books, of which the first and part of the second are lost. This was made known to modern scholars by Commandinus. The work exerted a happy influence on the revival of geometry in the seventeenth century. Pappus was not himself a mathematician of the first rank, but he preserved for the world many extracts or analyses of lost works, and by his commentaries added to their interest.

^[10] Rabuel calls attention to the use of $a, b, c, \dots$ for known, and $x, y, z, \dots$ for unknown quantities (p. 20).

gnes sur le papier, & il suffit de les designer par quelques lettres, chascune par vne seule. Comme pour adiouster la ligne B D a G H, ie nomme l'une a & l'autre b , & escris $a + b$; Et $a - b$, pour soustraire b d' a ; Et ab , pour les multiplier l'une par l'autre; Et $\frac{a}{b}$, pour diuiser a par b ; Et aa , ou a^2 , pour multiplier a par soy mesme; Et a^3 , pour le multiplier encore vne fois par a , & ainsi a l'infini; Et $\sqrt{a^2 + b^2}$, pour tirer la racine quarrée d' $a^2 + b^2$; Et $\sqrt[3]{C. a^3 - b^3 + abb}$, pour tirer la racine cubique d' $a^3 - b^3 + abb$, & ainsi des autres.

vser de
chiffres en
Geome-
trie.

Où il est a remarquer que par a^2 ou b^3 ou semblables, ie ne conçoys ordinairement que des lignes toutes simples, encore que pour me seruir des noms vsités en l'Algebre, ie les nomme des quarrés ou des cubes, &c.

Il est aussy a remarquer que toutes les parties d'une mesme ligne, se doiuent ordinairement exprimer par autant de dimensions l'une que l'autre, lorsque l'vnité n'est point déterminée en la question, comme icy a^3 en contient autant qu' abb ou b^3 dont se compose la ligne que i'ay nommée $\sqrt[3]{C. a^3 - b^3 + abb}$: mais que ce n'est pas de mesme lorsque l'vnité est déterminée, a cause qu'elle peut estre soufentendue par tout ou il y a trop ou trop peu de dimensions: comme s'il faut tirer la racine cubique de $aaabb - b$, il faut penser que la quantité $aaabb$ est diuisée vne fois par l'vnité, & que l'autre quantité b est multipliée deux fois par la mesme.

P p 2

Au

Au reste affin de ne pas manquer a se souuenir des noms de ces lignes, il en faut tousiours faire vn registre separé , à mesure qu'on les pose ou qu'on les change, escriuant par exemple.

$AB \propto 1$, c'est a dire, AB esgal à 1.

$GH \propto a$

$BD \propto b$, &c.

Comme
il faut ve-
nir aux
Equations
qui ser-
uent a re-
soudre les
problem-
es.

Ainsi voulant resoudre quelque problemesme, on doit d'a-
bord le considerer comme desia fait, & donner des noms
a toutes les lignes, qui semblent necessaires pour le con-
struire, aussi bien a celles qui sont inconnues, qu'aux
autres. Puis sans considerer aucune difference entre ces
lignes connues, & inconnues, on doit parcourir la diffi-
culté, selon l'ordre qui montre le plus naturellement
de tous en qu'elle sorte elles dependent mutuellement
les vnes des autres, iusques a ce qu'on ait trouué moyen
d'exprimer vne mesme quantité en deux façons: ce qui
se nomme vne Equation; car les termes de l'vne de ces
deux façons sont esgaux a ceux de l'autre. Et on doit
trouuer autant de telles Equations, qu'on a supposé de li-
gnes, qui estoient inconnues. Oubien s'il ne s'en trouue
pas tant, & que nonobstant on n'omette rien de ce qui est
desiré en la question, cela tesmoigne qu'elle n'est pas en-
tierement determinée. Et lors on peut prendre a discre-
tion des lignes connues, pour toutes les inconnues au-
qu'elles ne correspond aucune Equation. Après cela s'il
en reste encore plusieurs, il se faut seruir par ordre de
chascune des Equations qui restent aussi, soit en la con-
siderant toute seule, soit en la comparant avec les autres,
pour expliquer chascune de ces lignes inconnues; & faire
ainsi

ally the relations between these lines, until we find it possible to express a single quantity in two ways.^[13] This will constitute an equation, since the terms of one of these two expressions are together equal to the terms of the other.

We must find as many such equations as there are supposed to be unknown lines;^[13] but if, after considering everything involved, so many cannot be found, it is evident that the question is not entirely determined. In such a case we may choose arbitrarily lines of known length for each unknown line to which there corresponds no equation.^[14]

If there are several equations, we must use each in order, either considering it alone or comparing it with the others, so as to obtain a value for each of the unknown lines; and so we must combine them until there remains a single unknown line^[14] which is equal to some known line, or whose square, cube, fourth power, fifth power, sixth power, etc., is equal to the sum or difference of two or more quantities,^[15] one of which is known, while the others consist of mean proportionals between unity and this square, or cube, or fourth power, etc., multiplied by other known lines. I may express this as follows:

$$\begin{aligned} z &= b, \\ \text{or } z^2 &= -az + b^2, \\ \text{or } z^3 &= az^2 + b^2z - c^3, \\ \text{or } z^4 &= az^3 - c^3z + d^4, \text{ etc.} \end{aligned}$$

That is, z , which I take for the unknown quantity, is equal to b ; or, the square of z is equal to the square of b diminished by a multiplied by z ; or, the cube of z is equal to a multiplied by the square of z , plus the square of b multiplied by z , diminished by the cube of c ; and similarly for the others.

^[13] That is, we must solve the resulting simultaneous equations.

^[13] Van Schooten (p. 149) gives two problems to illustrate this statement. Of these, the first is as follows: Given a line segment AB containing any point C, required to produce AB to D so that the rectangle AD.DB shall be equal to the square on CD. He lets $AC = a$, $CB = b$, and $BD = x$. Then $AD = a + b + x$, and $CD = b + x$, whence $ax + bx + x^2 = b^2 + 2bx + x^2$ and $x = \frac{b^2}{a - b}$.

^[14] Rabuel adds this note: "We may say that every indeterminate problem is an infinity of determinate problems, or that every problem is determined either by itself or by him who constructs it" (p. 21).

^[14] That is, a line represented by $x, x^2, x^3, x^4, \dots$

^[15] In the older French, "le quarré, ou le cube, ou le quarré de quarré, ou le sur-solide, ou le quarré de cube &c.," as seen on page 11 (original page 302).

Thus, all the unknown quantities can be expressed in terms of a single quantity,^[16] whenever the problem can be constructed by means of circles and straight lines, or by conic sections, or even by some other curve of degree not greater than the third or fourth.^[17]

But I shall not stop to explain this in more detail, because I should deprive you of the pleasure of mastering it yourself, as well as of the advantage of training your mind by working over it, which is in my opinion the principal benefit to be derived from this science. Because, I find nothing here so difficult that it cannot be worked out by any one at all familiar with ordinary geometry and with algebra, who will consider carefully all that is set forth in this treatise.^[18]

^[16] See line 20 on the opposite page.

^[17] Literally, "Only one or two degrees greater."

^[18] In the Introduction to the 1637 edition of *La Géométrie*, Descartes made the following remark: "In my previous writings I have tried to make my meaning clear to everybody; but I doubt if this treatise will be read by anyone not familiar with the books on geometry, and so I have thought it superfluous to repeat demonstrations contained in them." See *Oeuvres de Descartes*, edited by Charles Adam and Paul Tannery, Paris, 1897-1910, vol. VI, p. 368. In a letter written to Mersenne in 1637 Descartes says: "I do not enjoy speaking in praise of myself, but since few people can understand my geometry, and since you wish me to give you my opinion of it, I think it well to say that it is all I could hope for, and that in *La Dioptrique* and *Les Météores*, I have only tried to persuade people that my method is better than the ordinary one. I have proved this in my geometry, for in the beginning I have solved a question which, according to Pappus, could not be solved by any of the ancient geometers.

"Moreover, what I have given in the second book on the nature and properties of curved lines, and the method of examining them, is, it seems to me, as far beyond the treatment in the ordinary geometry, as the rhetoric of Cicero is beyond the a, b, c of children. . . .

"As to the suggestion that what I have written could easily have been gotten from Vieta, the very fact that my treatise is hard to understand is due to my attempt to put nothing in it that I believed to be known either by him or by any one else. . . . I begin the rules of my algebra with what Vieta wrote at the very end of his book, *De emendatione acqutionum*. . . . Thus, I begin where he left off." *Oeuvres de Descartes, publiées par Victor Cousin*, Paris, 1824, Vol. VI, p. 294 (hereafter referred to as Cousin).

In another letter to Mersenne, written April 20, 1646, Descartes writes as follows: "I have omitted a number of things that might have made it (the geometry) clearer, but I did this intentionally, and would not have it otherwise. The only suggestions that have been made concerning changes in it are in regard to rendering it clearer to readers, but most of these are so malicious that I am completely disgusted with them." Cousin, Vol. IX, p. 553.

In a letter to the Princess Elizabeth, Descartes says: "In the solution of a geometrical problem I take care, as far as possible, to use as lines of reference parallel lines or lines at right angles; and I use no theorems except those which assert that the sides of similar triangles are proportional, and that in a right triangle the square of the hypotenuse is equal to the sum of the squares of the sides. I do not hesitate to introduce several unknown quantities, so as to reduce the question to such terms that it shall depend only on these two theorems." Cousin, Vol. IX, p. 143.

ainsi en les demessant, qu'il n'en demeure qu'une seule, esgal a quelque autre, qui soit connue, ou bien dont le quarré, ou le cube, ou le quarré de quarré, ou le surfolide, ou le quarré de cube, &c. soit esgal a ce, qui se produist par l'addition, ou soustraction de deux ou plusieurs autres quantités, dont l'une soit connue, & les autres soient composées de quelques moyennes proportionnelles entre l'unité, & ce quarré, ou cube, ou quarré de quarré, &c. multipliées par d'autres connues. Ce que j'écris en cete sorte.

$$x \propto b. \text{ ou}$$

$$x^2 \propto -a x + b b. \text{ ou}$$

$$x^3 \propto +a x^2 + b b x - c. \text{ ou}$$

$$x^4 \propto a x^3 - c x + d. \text{ \&c.}$$

C'est a dire, x , que ie prens pour la quantité inconnue, est esgalé a b , ou le quarré de x est esgal au quarré de b moins a multiplié par x . ou le cube de x est esgal a a multiplié par le quarré de x plus le quarré de b multiplié par x moins le cube de c . & ainsi des autres.

Et on peut tousiours reduire ainsi toutes les quantités inconnues a une seule, lorsque le Probleme se peut construire par des cercles & des lignes droites, ou aussi par des sections coniques, ou mesme par quelque autre ligne qui ne soit que d'un ou deux degrés plus composée. Mais ie ne m'arestte point a expliquer cecy plus en detail, a cause que ie vous osterois le plaisir de l'apprendre de vous mesme, & l'utilité de cultiuer vostre esprit en vous y exerçant, qui est a mon aui la principale, qu'on puisse

P p 3

tirer:

tirer de cete science. Auffy que ie n y remarque rien de si difficile, que ceux qui seront vn peu versés en la Geometrie commune, & en l'Algebre, & qui prendront garde a tout ce qui est en ce traité, ne puissent trouuer.

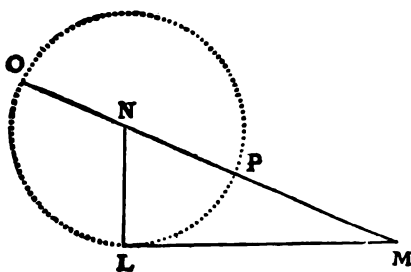
C'est pourquoy ie me contenteray icy de vous avertir, que pourvû qu'en demeslant ces Equations on ne manque point a se servir de toutes les diuisions, qui seront possibles, on aura infalliblement les plus simples termes, auxquels la question puisse estre reduite.

Quels sont les problèmes plans

Et que si elle peut estre resolue par la Geometrie ordinaire, c'est a dire, en ne se seruant que de lignes droites & circulaires tracées sur vne superficie plate, lorsque la derniere Equation aura esté entierement démeslée, il n'y restera tout au plus qu'un quarré inconnu, esgal a ce qui se produist de l'Addition, ou soustraction de sa racine multipliée par quelque quantité connue, & de quelque autre quantité aussi connue

Comment ils se résolvent.

Et lors cete racine, ou ligne inconnue se trouue aysement. Car si r'ay par exemple


$$z^2 \propto a z + b b$$

ie fais le triangle rectan-
gle N L M, dont le co-
sté L M est esgal à b ra-
cine quarrée de la quan-
tité connue bb , & l'au-
tre L N est $\frac{1}{2} a$, la moi-
tié de l'autre quantité

connue, qui estoit multipliée par x que ie suppose estre la
ligne inconnue. puis prolongeant M N la base de ce tri-
angle,

I shall therefore content myself with the statement that if the student, in solving these equations, does not fail to make use of division wherever possible, he will surely reach the simplest terms to which the problem can be reduced.

And if it can be solved by ordinary geometry, that is, by the use of straight lines and circles traced on a plane surface,^[10] when the last equation shall have been entirely solved there will remain at most only the square of an unknown quantity, equal to the product of its root by some known quantity, increased or diminished by some other quantity also known.^[11] Then this root or unknown line can easily be found. For example, if I have $z^2 = az + b^2$,^[12] I construct a right triangle NLM with one side LM, equal to b , the square root of the known quantity b^2 , and the other side, LN, equal to $\frac{1}{2}a$, that is, to half the other known quantity which was multiplied by z , which I supposed to be the unknown line. Then prolonging MN, the hypotenuse^[13] of this triangle, to O, so that NO is equal to NL, the whole line OM is the required line z . This is expressed in the following way:^[14]

$$z = \frac{1}{2}a + \sqrt{\frac{1}{4}a^2 + b^2}.$$

But if I have $y^2 = -ay + b^2$, where y is the quantity whose value is desired, I construct the same right triangle NLM, and on the hypote-

^[10] For a discussion of the possibility of constructions by the compasses and straight edge, see Jacob Steiner, *Die geometrischen Constructionen ausgeführt mittelst der geraden Linie und eines festen Kreises*, Berlin, 1833. For briefer treatments, consult Enriques, *Fragen der Elementar-Geometrie*, Leipzig, 1907; Klein, *Problems in Elementary Geometry*, trans. by Beman and Smith, Boston, 1897; Weber und Wellstein, *Encyclopädie der Elementaren Geometrie*, Leipzig, 1907. The work by Mascheroni, *La geometria del compasso*, Pavia, 1797, is interesting and well known.

^[11] That is, an expression of the form $z^2 = az \pm b$. "Egal a ce qui se produit de l'Addition, ou soustraction de sa racine multiplée par quelque quantité connue, & de quelque autre quantité aussy connue," as it appears in line 14, opposite page.

^[12] Descartes proposes to show how a quadratic may be solved geometrically.

^[13] Descartes says "prolongeant MN la baze de ce triangle," because the hypotenuse was commonly taken as the base in earlier times.

^[14] From the figure $OM \cdot PM = LM^2$. If $OM = z$, $PM = z - a$, and since $LM = b$, we have $z(z - a) = b^2$ or $z^2 = az + b^2$. Again, $MN = \sqrt{\frac{1}{4}a^2 + b^2}$, whence $OM = z = ON + MN = \frac{1}{2}a + \sqrt{\frac{1}{4}a^2 + b^2}$. Descartes ignores the second root, which is negative.

GEOMETRY

nuse MN lay off NP equal to NL. and the remainder PM is y, the desired root. Thus I have

$$y = -\frac{1}{2}a + \sqrt{\frac{1}{4}a^2 + b^2}.$$

In the same way, if I had

$$x^4 = -ax^2 + b^2,$$

PM would be x^2 and I should have

$$x = \sqrt{-\frac{1}{2}a + \sqrt{\frac{1}{4}a^2 + b^2}},$$

and so for other cases.

Finally, if I have $z^2 = az - b^2$, I make NL equal to $\frac{1}{2}a$ and LM equal to b as before; then, instead of joining the points M and N, I draw MQR parallel to LN, and with N as a center describe a circle through L cutting MQR in the points Q and R; then z , the line sought, is either MQ or MR, for in this case it can be expressed in two ways, namely:^[20]

$$z = \frac{1}{2}a + \sqrt{\frac{1}{4}a^2 - b^2},$$

and

$$z = \frac{1}{2}a - \sqrt{\frac{1}{4}a^2 - b^2}.$$

N/

^[20] Since $MR \cdot MQ = \overline{LM}^2$, then if $R = z$, we have $MQ = a - z$, and so $z(a - z) = b^2$ or $z^2 = az - b^2$.

If, instead of this, $MQ = z$, then $MR = a - z$, and again, $z^2 = az - b^2$. Furthermore, letting O be the mid-point of QR,

$$MQ = OM - OQ = \frac{1}{2}a - \sqrt{\frac{1}{4}a^2 - b^2},$$

and

$$MR = MO + OR = \frac{1}{2}a + \sqrt{\frac{1}{4}a^2 - b^2}.$$

Descartes here gives both roots, since both are positive. If MR is tangent to the circle, that is, if $b = \frac{1}{2}a$, the roots will be equal; while if $b > \frac{1}{2}a$, the line MR will not meet the circle and both roots will be imaginary. Also, since $RM \cdot QM = \overline{LM}^2$, $z_1 z_2 = b^2$, and $RM + QM = z_1 + z_2 = a$.

angle, iufques a O, en forte qu'N O foit efgale a N L, la toute O M est x la ligne cherchée. Et elle s'exprime en cete forte

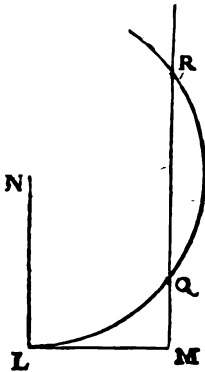
$$x \propto \frac{1}{2} a + \sqrt{\frac{1}{4} a a + b b}.$$

Que si iay $y y \propto - a y + b b$, & qu'y soit la quantité qu'il faut trouuer, ie fais le meſme triangle rectangle N L M, & de ſa baze M N i'oſte N P efgale a N L, & le reſte P M est y la racine cherchée. De façon que iay $y \propto - \frac{1}{2} a + \sqrt{\frac{1}{4} a a + b b}$. Et tout de meſme ſi i'a-uois $x^2 \propto - a x + b$. P M ſeroit x . & i'aurois $x \propto \sqrt{-\frac{1}{2} a + \sqrt{\frac{1}{4} a a + b b}}$: & ainſi des autres.

Enfin ſi i'ay

$$x^2 \propto a x - b b:$$

ie fais N L efgale à $\frac{1}{2} a$, & L M efgale à b cōme deuât, puis, au lieu de ioindre les points M N, ie tire M Q R parallele a L N. & du centre N par L ayant deſcrit vn cercle qui la coupe aux points Q & R, la ligne cherchée x est M Q, oubiẽ M R, car en ce cas elle s'ex-



prime en deux façons, a ſçauoir $x \propto \frac{1}{2} a + \sqrt{\frac{1}{4} a a - b b}$, & $x \propto \frac{1}{2} a - \sqrt{\frac{1}{4} a a - b b}$.

Et ſi le cercle, qui ayant ſon centre au point N, paſſe par le point L, ne coupe ny ne touche la ligne droite M Q R, il n'y a aucune racine en l'Equation, de façon qu'on peut aſſurer que la conſtruction du probleſme propoſé eſt impoſſible.

Au

Au reste ces mesmes racines se peuvent trouver par vne infinité d'autres moyens , & i'ay seulement voulu mettre ceux cy, comme fort simples, afin de faire voir qu'on peut construire tous les Problemes de la Geometrie ordinaire, sans faire autre chose que le peu qui est compris dans les quatre figures que i'ay expliquées. Ce que ie ne croy pas que les anciens aient remarqué. car autrement ils n'eussent pas pris la peine d'en escrire tant de gros liures, ou le seul ordre de leurs propositions nous fait connoistre qu'ils n'ont point eu la vraye methode pour les trouver toutes, mais qu'ils ont seulement ramassé celles qu'ils ont rencontrées.

Exemple
tiré de
Pappus.

Et on le peut voir aussy fort clairement de ce que Pappus a mis au commencement de son septiesme liure, ou après s'estre aresté quelque tems a denommer tout ce qui auoit esté escrit en Geometrie par ceux qui l'auoient precedé, il parle enfin d vne question, qu'il dit que ny Euclide, ny Apollonius, ny aucun autre n'auoient sceu entierement resoudre. & voycy ses mots.

Je cite
plustost la
version la-
tine que le
texte grec
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l'entende
plus ayse-
ment.

Quem autem dicit (Apollonius) in tertio libro locum ad tres, & quatuor lineas ab Euclide perfectum non esse, neque ipse perficere poterat, neque aliquis alius: sed neque paululum quid addere iis, quæ Euclides scripsit, per ea tantum conica, quæ usque ad Euclidis tempora præmonstrata sunt, &c.

Et vn peu après il explique ainsi qu'elle est cete question.

At locus ad tres, & quatuor lineas, in quo (Apollonius) magnifice se iactat, & ostentat, nulla habita gratia ei, qui prius scripserat, est huiusmodi. Si positione datis tribus rectis

And if the circle described about N and passing through L neither cuts nor touches the line MQR, the equation has no root, so that we may say that the construction of the problem is impossible.

These same roots can be found by many other methods,^[28] I have given these very simple ones to show that it is possible to construct all the problems of ordinary geometry by doing no more than the little covered in the four figures that I have explained.^[29] This is one thing which I believe the ancient mathematicians did not observe, for otherwise they would not have put so much labor into writing so many books in which the very sequence of the propositions shows that they did not have a sure method of finding all,^[30] but rather gathered together those propositions on which they had happened by accident.

This is also evident from what Pappus has done in the beginning of his seventh book,^[31] where, after devoting considerable space to an enumeration of the books on geometry written by his predecessors,^[32] he finally refers to a question which he says that neither Euclid nor Apollonius nor any one else had been able to solve completely;^[33] and these are his words:

"Quem autem dicit (Apollonius) in tertio libro locum ad tres, & quatuor lineas ab Euclide perfectum non esse, neque ipse perficere poterat, neque aliquis alius; sed neque paululum quid addere iis, quæ

^[28] For interesting contraction, see Rabuel, p. 23, et seq.

^[29] It will be seen that Descartes considers only three types of the quadratic equation in z , namely, $z^2 + az - b^2 = 0$, $z^2 - az - b^2 = 0$, and $z^2 - az + b^2 = 0$. It thus appears that he has not been able to free himself from the old traditions to the extent of generalizing the meaning of the coefficients, — as negative and fractional as well as positive. He does not consider the type $z^2 + az + b^2 = 0$, because it has no positive roots.

^[30] "Qu'ils n'ont point eu la vraie methode pour les trouver toutes."

^[31] See Note [9].

^[32] See Pappus, Vol. II, p. 637. Pappus here gives a list of books that treat of analysis, in the following words: "Illorum librorum, quibus de loco, ἀναλυόμενος sive resolutio agitur, ordo hic est. Euclidis datorum liber unus, Apollonii de proportionis sectione libri duo, de spatii sectione duo, de sectione determinata duo, de tactionibus duo, Euclidis porismatum libri tres, Apollonii inclinationum libri duo, eiusdem locorum planorum duo, conicorum octo, Aristaei locorum solidorum libri duo." See also the Commandinus edition of Pappus, 1660 edition, pp. 240-252.

^[33] For the history of this problem, see Zeuthen: *Die Lehre von den Kegelschnitten im Alterthum*, Copenhagen, 1886. Also, Adam and Tannery, *Oeuvres de Descartes*, vol. 6, p. 723.

Euclides scripsit, per ea tantum conica, quæ usque ad Euclidis tempora præmonstrata sunt, &c." ^[31]

A little farther on, he states the question as follows:

"At locus ad tres, & quatuor lineas, in quo (Apollonius) magnifice se jactat, & ostentat, nulla habita gratia ei, qui prius scripserat, est hujusmodi.^[32] Si positione datis tribus rectis lineis ab uno & eodem puncto, ad tres lineas in datis angulis rectæ lineæ ducantur, & data sit proportio rectanguli contenti duabus ductis ad quadratum reliquæ: punctum contingit positione datum solidum locum, hoc est unam ex tribus conicis sectionibus. Et si ad quatuor rectas lineas positione datas in datis angulis lineæ ducantur; & rectanguli duabus ductis contenti ad contentum duabus reliquis proportio data sit; similiter punctum datum coni sectionem positione continget. Si quidem igitur ad duas tantum locus planus ostensus est. Quod si ad plures quam quatuor, punctum continget locos non adhuc cognitos, sed lineas tantum dictas; quales autem sint, vel quam habeant proprietatem, non constat: earum unam, neque primam, & quæ manifestissima videtur, composuerunt ostendentes utilem esse. Propositiones autem ipsarum hæc sunt.

"Si ab aliquo puncto ad positione datas rectas lineas quinque ducantur rectæ lineæ in datis angulis, & data sit proportio solidi parallelepipedum rectanguli, quod tribus ductis lineis continetur ad solidum parallelepipedum rectangulum, quod continetur reliquis duabus, & data quapiam linea, punctum positione datam lineam continget. Si autem ad sex, & data sit proportio solidi tribus lineis contenti ad solidum, quod tribus reliquis continetur; rursus punctum continget positione datam lineam. Quod si ad plures quam sex, non adhuc habent dicere, an data sit proportio cujuspiam contenti quatuor lineis ad id quod reliquis continetur,

^[31] Pappus, Vol. II, pp. 677, et seq., Commandinus edition of 1660, p. 251. Literally, "Moreover, he (Apollonius) says that the problem of the locus related to three or four lines was not entirely solved by Euclid, and that neither he himself, nor any one else has been able to solve it completely, nor were they able to add anything at all to those things which Euclid had written, by means of the conic sections only which had been demonstrated before Euclid." Descartes arrived at the solution of this problem four years before the publication of his geometry, after spending five or six weeks on it. See his letters, Cousin, Vol. VI, p. 294, and Vol. VI, p. 224.

^[32] Given as follows in the edition of Pappus by Hultsch, previously quoted: "Sed hic ad tres et quatuor lineas locus quo magnopere gloriatur simul addens ei qui conscripserit gratiam habendam esse, sic se habet."

rectis lineis ab uno & eodem puncto, ad tres lineas in datis angulis rectæ lineæ ducantur, & data sit proportio rectanguli contenti duabus ductis ad quadratum reliquæ: punctum contingit positione datum solidum locum, hoc est unam ex tribus conicis sectionibus. Et si ad quatuor rectas lineas positione datas in datis angulis lineæ ducantur; & rectanguli duabus ductis contenti ad contentum duabus reliquis proportio data sit: similiter punctum datum conicæ sectionem positione continget. Si quidem igitur ad duas tantum locus planus ostensus est. Quod si ad plures quam quatuor, punctum continget locos non adhuc cognitos, sed lineas tantum dictas; quales autem sint, vel quam habeant proprietatem, non constat: earum unam, neque primam, & quæ manifestissima videtur, composuerunt ostendentes utilem esse. propositiones autem ipsarum hæ sunt.

Si ab aliquo puncto ad positione datas rectas lineas quinque ducantur rectæ lineæ in datis angulis, & data sit proportio solidi parallelepipedæ rectanguli, quod tribus ductis lineis continetur ad solidum parallelepipedum rectangulum, quod continetur reliquis duabus, & data quapiam lineæ, punctum positione datam lineam continget. Si autem ad sex, & data sit proportio solidi tribus lineis contenti ad solidam, quod tribus reliquis continetur; rursus punctum continget positione datam lineam. Quod si ad plures quam sex, non adhuc habent dicere, an data sit proportio cuiuspiam contenti quatuor lineis ad id quod reliquis continetur, quoniam non est aliquid contentum pluribus quam tribus dimensionibus.

Ou ie vous prie de remarquer en passant, que le scrupule, que faisoient les anciens d'vser des termes de l'Arithmetique en la Geometrie, qui ne pouuoit proceder,

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que de ce qu'ils ne voyoient pas affés clairement leur rapport, caufoit beaucoup d'obfcurité, & d'embaras, en la façon dont ils s'expliquoient. car Pappus poursuit en cete forte.

Acquiescunt autem his, qui paulo ante talia interpretati sunt. neque unum aliquo pacto comprehensibile significantes quod his continetur. Licebit autē per coniunctas proportionales hæc, & dicere, & demonstrare universe in dictis proportionibus, atque his in hunc modum. Si ab aliquo puncto ad positione datas rectas lineas ducantur rectæ lineæ in datis angulis, & data sit proportio coniuncta ex ea, quam habet una duarum ad unam, & altera ad alteram, & alia ad aliam, & reliqua ad datam lineam, si sint septem; si vero octo, & reliqua ad reliquam: punctum continget positione datæ lineas. Et similiter quotcumque sint impares vel pares multitudine, cum hæc, ut dixi, loco ad quatuor lineas respondeant, nullum igitur posuerant ita ut linea nota sit, &c.

La question donc qui auoit esté commencée a résoudre par Euclide, & pourfuiuite par Apollonius, sans auoir esté acheuée par personne, estoit telle. Ayant trois ou quatre ou plus grand nombre de lignes droites données par position, premierement on demande vn point, duquel on puisse tirer autant d'autres lignes droites, vne sur chascune des données, qui fassent avec elles des angles donnés, & que le rectangle contenu en deux de celles, qui seront ainsi tirées d'un mesme point, ait la proportion donnée avec le quarré de la troisieme, s'il n'y en a que trois; ou bien avec le rectangle des deux autres, s'il y en a quatre; ou bien, s'il y en a cinq, que le parallelepipedé composé de trois ait la proportion donnée avec le parallelepipedé

quoniam non est aliquid contentum pluribus quam tribus dimensionibus." ^[10]

Here I beg you to observe in passing that the considerations that forced ancient writers to use arithmetical terms in geometry, thus making it impossible for them to proceed beyond a point where they could see clearly the relation between the two subjects, caused much obscurity and embarrassment, in their attempts at explanation.

Pappus proceeds as follows:

"Acquiescunt autem his, qui paulo ante talia interpretati sunt; neque unum aliquo pacto comprehensibile significantes quod his continetur. Licebit autem per conjunctas proportionibus hæc, & dicere & demonstrare universe in dictis proportionibus, atque his in hunc modum. Si ab aliquo puncto ad positione datas rectas lineas ducantur rectæ lineæ in datis angulis, & data sit proportio conjuncta ex ea, quam habet una ductarum ad unam, & altera ad alteram, & alia ad aliam, & reliqua ad datam lineam, si sint septem; si vero octo, & reliqua ad reliquam: punctum continget positione datas lineas. Et similiter quotcumque sint

^[11] This may be somewhat freely translated as follows: "The problem of the locus related to three or four lines, about which he (Apollonius) boasts so proudly, giving no credit to the writer who has preceded him, is of this nature: If three straight lines are given in position, and if straight lines be drawn from one and the same point, making given angles with the three given lines; and if there be given the ratio of the rectangle contained by two of the lines so drawn to the square of the other, the point lies on a solid locus given in position, namely, one of the three conic sections.

"Again, if lines be drawn making given angles with four straight lines given in position, and if the rectangle of two of the lines so drawn bears a given ratio to the rectangle of the other two; then, in like manner, the point lies on a conic section given in position. It has been shown that to only two lines there corresponds a plane locus. But if there be given more than four lines, the point generates loci not known up to the present time (that is, impossible to determine by common methods), but merely called 'lines'. It is not clear what they are, or what their properties. One of them, not the first but the most manifest, has been examined, and this has proved to be helpful. (Paul Tannery, in the *Oeuvres de Descartes*, differs with Descartes in his translation of Pappus. He translates as follows: Et on n'a fait la synthèse d' aucune de ces lignes, ni montré qu'elle servit pour ces lieux, pas même pour celle qui semblerait la première et la plus indiquée.) These, however, are the propositions concerning them.

"If from any point straight lines be drawn making given angles with five straight lines given in position, and if the solid rectangular parallelepiped contained by three of the lines so drawn bears a given ratio to the solid rectangular parallelepiped contained by the other two and any given line whatever, the point lies on a 'line' given in position. Again, if there be six lines, and if the solid contained by three of the lines bears a given ratio to the solid contained by the other three lines, the point also lies on a 'line' given in position. But if there be more than six lines, we cannot say whether a ratio of something contained by four lines is given to that which is contained by the rest, since there is no figure of more than three dimensions."

impares vel pares multitudine, cum hæc, ut dixi, loco ad quatuor lineas respondeant, nullum igitur posuerunt ita ut linea nota sit, &c.^[34]

The question, then, the solution of which was begun by Euclid and carried farther by Apollonius, but was completed by no one, is this:

Having three, four or more lines given in position, it is first required to find a point from which as many other lines may be drawn, each making a given angle with one of the given lines, so that the rectangle of two of the lines so drawn shall bear a given ratio to the square of the third (if there be only three); or to the rectangle of the other two (if there be four), or again, that the parallelepiped^[35] constructed upon three shall bear a given ratio to that upon the other two and any given line (if there be five), or to the parallelepiped upon the other three (if there be six); or (if there be seven) that the product obtained by multiplying four of them together shall bear a given ratio to the product of the other three, or (if there be eight) that the product of four of them shall bear a given ratio to the product of the other four. Thus the question admits of extension to any number of lines.

Then, since there is always an infinite number of different points satisfying these requirements, it is also required to discover and trace the curve containing all such points.^[36] Pappus says that when there are only three or four lines given, this line is one of the three conic sections, but he does not undertake to determine, describe, or explain the nature of the line required^[37] when the question involves a greater number of lines. He only adds that the ancients recognized one of them which they had shown to be useful, and which seemed the sim-

^[34] This rather obscure passage may be translated as follows: "For in this are agreed those who formerly interpreted these things (that the dimensions of a figure cannot exceed three) in that they maintain that a figure that is contained by these lines is not comprehensible in any way. This is permissible, however, both to say and to demonstrate generally by this kind of proportion, and in this manner: If from any point straight lines be drawn making given angles with straight lines given in position; and if there be given a ratio compounded of them, that is the ratio that one of the lines drawn has to one, the second has to a second, the third to a third, and so on to the given line if there be seven lines, or, if there be eight lines, of the last to a last, the point lies on the lines that are given in position. And similarly, whatever may be the odd or even number, since these, as I have said, correspond in position to the four lines; therefore they have not set forth any method so that a line may be known." The meaning of the passage appears from that which follows in the text.

^[35] That is, continued product.

^[36] It is here that the essential feature of the work of Descartes may be said to begin.

^[37] See line 19 on the opposite page.

lelepipede composé des deux qui restent, & d'une autre ligne donnée. Ou s'il y en a six, que le parallelepiped composé de trois ait la proportion donnée avec le parallelepiped des trois autres. Ou s'il y en a sept, que ce qui se produist lorsqu'on en multiplie quatre l'une par l'autre, ait la raison donnée avec ce qui se produist par la multiplication des trois autres, & encore d'une autre ligne donnée; Ou s'il y en a huit, que le produit de la multiplication de quatre ait la proportion donnée avec le produit des quatre autres. Et ainsi cete question se peut estendre a tout autre nombre de lignes. Puis a cause qu'il y a tousiours vne infinité de diuers points qui peuuent satisfaire a ce qui est icy demandé, il est aussy requis de connoistre, & de tracer la ligne, dans laquelle ils doiuent tous se trouver. & Pappus dit que lorsqu'il n'y a que trois ou quatre lignes droites données, c'est en vne des trois sections coniques. mais il n'entreprend point de la déterminer, ny de la descrire. non plus que d'expliquer celles ou tous ces points se doiuent trouver, lorsque la question est proposée en vn plus grand nombre de lignes. Seulement il aiouste que les anciens en auoient imaginé vne qu'ils monstroient y estre vtile, mais qui sembloit la plus manifeste, & qui n'estoit pas toutefois la premiere. Ce qui m'a donné occasion d'essayer si par la methode dont ie me sers on peut aller aussy loin qu'ils ont esté.

Et premierement i'ay connu que cete question n'estant proposée qu'en trois, ou quatre, ou cinq lignes, on peut tousiours trouver les points cherchés par la Geometrie simple; c'est a dire en ne se seruant que de la reigle & du

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compas, ny ne faisant autre chose, que ce qui a desia esté dit; excepté seulement lorsqu'il y a cinq lignes données, si elles sont toutes paralleles. Auquel cas, comme aussy lorsque la question est proposée en six, ou 7, ou 8, ou 9 lignes, on peut tousiours trouuer les points cherchés par la Geometrie des solides; c'est a dire en y employant quelqu'une des trois sections coniques. Excepté seulement lorsqu'il y a neuf lignes données, si elles sont toutes paralleles. Auquel cas derechef, & encore en 10, 11, 12, ou 13 lignes on peut trouuer les points cherchés par le moyen d'une ligne courbe qui soit d'un degré plus composée que les sections coniques. Excepté en treize si elles sont toutes paralleles, auquel cas, & en quatorze, 15, 16, & 17 il y faudra employer vne ligne courbe encore d'un degré plus composée que la precedente. & ainsi a l'infini.

Puis iay trouué aussy, que lorsqu'il ny a que trois ou quatre lignes données, les points cherchés se rencontrent tous, non seulement en l'une des trois sections coniques, mais quelquefois aussy en la circonference d'un cercle, ou en vne ligne droite. Et que lorsqu'il y en a cinq, ou six, ou sept, ou huit, tous ces points se rencontrent en quelque vne des lignes, qui sont d'un degré plus composées que les sections coniques, & il est impossible d'en imaginer aucune qui ne soit vtile a cete question; mais ils peuuent aussy derechef se rencontrer en vne section conique, ou en vn cercle, ou en vne ligne droite. Et s'il y en a neuf, ou 10, ou 11, ou 12, ces points se rencontrent en vne ligne, qui ne peut estre que d'un degré plus composée que les precedentes; mais toutes celles
qui

plest, and yet was not the most important.^[38] This led me to try to find out whether, by my own method, I could go as far as they had gone.^[39]

First, I discovered that if the question be proposed for only three, four, or five lines, the required points can be found by elementary geometry, that is, by the use of the ruler and compasses only, and the application of those principles that I have already explained, except in the case of five parallel lines. In this case, and in the cases where there are six, seven, eight, or nine given lines, the required points can always be found by means of the geometry of solid loci,^[40] that is, by using some one of the three conic sections. Here, again, there is an exception in the case of nine parallel lines. For this and the cases of ten, eleven, twelve, or thirteen given lines, the required points may be found by means of a curve of degree next higher than that of the conic sections. Again, the case of thirteen parallel lines must be excluded, for which, as well as for the cases of fourteen, fifteen, sixteen, and seventeen lines, a curve of degree next higher than the preceding must be used; and so on indefinitely.

Next, I have found that when only three or four lines are given, the required points lie not only all on one of the conic sections but sometimes on the circumference of a circle or even on a straight line.^[41]

When there are five, six, seven, or eight lines, the required points lie on a curve of degree next higher than the conic sections, and it is impossible to imagine such a curve that may not satisfy the conditions of the problem; but the required points may possibly lie on a conic section, a circle, or a straight line. If there are nine, ten, eleven, or twelve lines, the required curve is only one degree higher than the preceding, but any such curve may meet the requirements, and so on to infinity.

^[38] See lines 5-10 from the foot of page 23.

^[39] Descartes gives here a brief summary of his solution, which he amplifies later.

^[40] This term was commonly applied by mathematicians of the seventeenth century to the three conic sections, while the straight line and circle were called plane loci, and other curves linear loci. See Fermat, *Isagoge ad Locos Planos et Solidos*, Toulouse, 1679.

^[41] Degenerate or limiting forms of the conic sections.

Finally, the first and simplest curve after the conic sections is the one generated by the intersection of a parabola with a straight line in a way to be described presently.

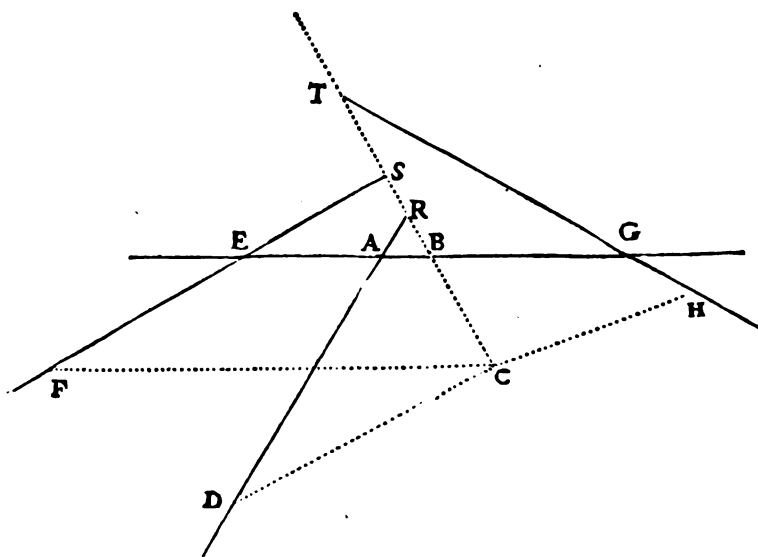
I believe that I have in this way completely accomplished what Pappus tells us the ancients sought to do, and I will try to give the demonstration in a few words, for I am already wearied by so much writing.

Let AB , AD , EF , GHI , ... be any number of straight lines given in position,^[42] and let it be required to find a point C , from which straight lines CB , CD , CF , CH , ... can be drawn, making given angles CBA , CDA , CFE , CHG , ... respectively, with the given lines, and

^[42] It should be noted that these lines are given in position but not in length. They thus become lines of reference or coördinate axes, and accordingly they play a very important part in the development of analytic geometry. In this connection we may quote as follows: "Among the predecessors of Descartes we reckon, besides Apollonius, especially Vieta, Oresme, Cavalieri, Roberval, and Fermat, the last the most distinguished in this field; but nowhere, even by Fermat, had any attempt been made to refer several curves of different orders simultaneously to one system of coördinates, which at most possessed special significance for one of the curves. It is exactly this thing which Descartes systematically accomplished." Karl Fink, *A Brief History of Mathematics*, trans. by Beman and Smith, Chicago, 1903, p. 229.

Heath calls attention to the fact that "the essential difference between the Greek and the modern method is that the Greeks did not direct their efforts to making the fixed lines of a figure as few as possible, but rather to expressing their equations between areas in as short and simple a form as possible." For further discussion see D. E. Smith, *History of Mathematics*, Boston, 1923-25, Vol. II, pp. 316-331 (hereafter referred to as Smith).

Au reste la premiere, & la plus simple de toutes après les sections coniques, est celle qu'on peut descrire par l'interfection d'une Parabole, & d'une ligne droite, en la façon qui sera tantost expliquée. En sorte que ie pense auoir entierement satisfait a ceque Pappus nous dit auoir esté chetché en cecy par les anciens. & ie tascheray d'en mettre la demonstration en peu de mots. car il m'ennuie desja d'en tant escrire.



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& que ce qui est produit par la multiplication d'une partie de ces lignes, soit égal à ce qui est produit par la multiplication des autres, ou bien qu'ils aient quelque autre proportion donnée, car cela ne rend point la question plus difficile.

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exemple.

Premièrement je suppose la chose comme desia faite, & pour me demesler de la confusion de toutes ces lignes, je considere l'une des données, & l'une de celles qu'il faut trouver, par exemple A B, & C B, comme les principales, & auxquelles je tasche de rapporter ainsi toutes les autres. Que le segment de la ligne A B, qui est entre les points A & B, soit nommé x . & que B C soit nommé y . & que toutes les autres lignes données soient prolongées, jusques à ce qu'elles coupent ces deux, aussi prolongées s'il est besoin, & si elles ne leur sont point parallèles. comme vous voyez icy qu'elles coupent la ligne A B aux points A, E, G, & B C aux points R, S, T. Puis à cause que tous les angles du triangle A R B sont donnés, la proportion, qui est entre les costés A B, & B R, est aussi donnée, & je la pose comme de z à b , de façon qu' A B estant x , R B sera $\frac{bx}{z}$, & la toute C R sera $y + \frac{bx}{z}$, à cause que le point B tombe entre C & R; car si R tomboit entre C & B, C R seroit $y - \frac{bx}{z}$; & si C tomboit entre B & R, C R seroit $-y + \frac{bx}{z}$. Tout de même les trois angles du triangle D R C sont donnés, & par conséquent aussi la proportion qui est entre les costés C R, & C D, que je pose comme de z à c : de façon que C R estant $y + \frac{bx}{z}$,

CD

such that the product of certain of them is equal to the product of the rest, or at least such that these two products shall have a given ratio, for this condition does not make the problem any more difficult.

First, I suppose the thing done, and since so many lines are confusing, I may simplify matters by considering one of the given lines and one of those to be drawn (as, for example, AB and BC) as the principal lines, to which I shall try to refer all the others. Call the segment of the line AB between A and B, x , and call BC, y . Produce all the other given lines to meet these two (also produced if necessary) provided none is parallel to either of the principal lines. Thus, in the figure, the given lines cut AB in the points A, E, G, and cut BC in the points R, S, T.

Now, since all the angles of the triangle ARB are known,^[43] the ratio between the sides AB and BR is known.^[44] If we let $AB : BR = z : b$,

since $AB = x$, we have $BR = \frac{bx}{z}$; and since B lies between C and R^[45],

we have $CR = y + \frac{bx}{z}$. (When R lies between C and B, CR is equal to $y - \frac{bx}{z}$, and when C lies between B and R, CR is equal to $-y + \frac{bx}{z}$.)

Again, the three angles of the triangle DRC are known,^[46] and therefore the ratio between the sides CR and CD is determined. Calling this

ratio $z : c$, since $CR = y + \frac{bx}{z}$, we have $CD = \frac{cy}{z} + \frac{bcx}{z^2}$. Then, since

^[43] Since BC cuts AB and AD under given angles.

^[44] Since the ratio of the sines of the opposite angles is known.

^[45] In this particular figure, of course.

^[46] Since CB and CD cut AD under given angles.

the lines AB, AD, and EF are given in position, the distance from A to E is known. If we call this distance k , then $EB = k + x$; although $EB = k - x$ when B lies between E and A, and $\cancel{EB} = -k + x$ when E lies between A and B. Now the angles of the triangle ESB being given, the ratio of BE to BS is known. We may call this ratio $z : d$.

Then $BS = \frac{dk + dx}{z}$ and $CS = \frac{zy + dk + dx}{z}$.^[47] When S lies between B and C we have $CS = \frac{zy - dk - dx}{z}$, and when C lies between B and S we have $CS = \frac{-zy + dk + dx}{z}$. The angles of the triangle FSC are known, and hence, also the ratio of CS to CF, or $z : e$. Therefore, $CF = \frac{czy + dek + dex}{z^2}$. Likewise, AG or l is given, and $BG = l - x$. Also, in triangle BGT, the ratio of BG to BT, or $z : f$, is known. Therefore, $BT = \frac{fl - fx}{z}$ and $CT = \frac{zy + fl - fx}{z}$. In triangle TCH, the ratio of TC to CH, or $z : g$, is known,^[48] whence $CH = \frac{gzy + fgl - fgx}{z^2}$.

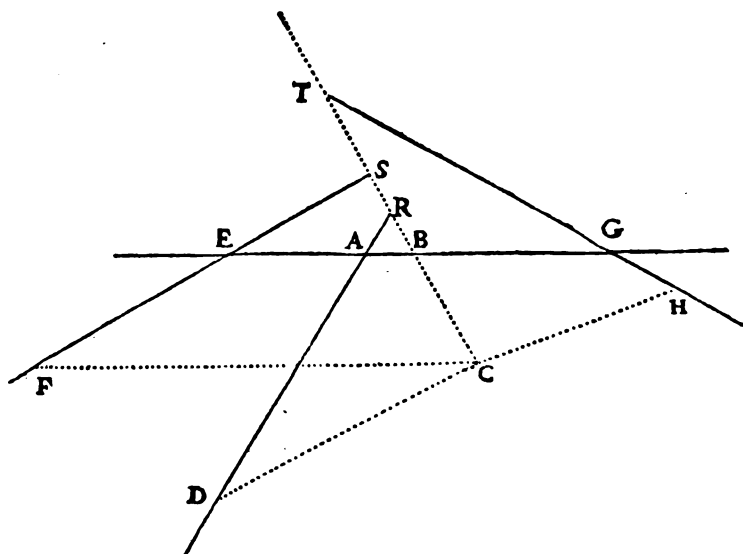
^[47] We have

$$\begin{aligned} CS &= y + BS \\ &= y + \frac{dk + dx}{z} \\ &= \frac{zy + dk + dx}{z}, \end{aligned}$$

and similarly for the other cases considered below.

The translation covers the first eight lines on the original page 312 (page 32 of this edition).

^[48] It should be noted that each ratio assumed has z as antecedent.



CD fera $\frac{cy}{x} + \frac{bcx}{x^2}$. Après cela pourceque les lignes AB, AD, & EF sont données par position, la distance qui est entre les points A & E est aussi donnée, & si on la nomme K, on aura E B egal à $k + x$; mais ce seroit $k - x$, si le point B tomboit entre E & A; & $-k + x$, si E tomboit entre A & B. Et pourceque les angles du triangle ESB sont tous donnés, la proportion de BE à BS est aussi donnée, & ie la pose comme z à d , si bien que BS est $\frac{dk + dx}{z}$, & la toute CS est $\frac{zy + dk + dx}{z}$; mais ce seroit $\frac{zy - dk - dx}{z}$, si le point S tomboit entre B & C; & ce seroit $\frac{-zy + dk + dx}{z}$, si C tomboit entre B & S. De plus les trois angles du triangle FSC sont donnés, & en suite la pro-

proportion de CS à CF , qui soit comme de z à e , & la toute CF fera $\frac{ez y + dek + dex}{zz}$. En mesme façon AG que ie nomme l est donnée, & BG est $l - x$, & a cause du triangle BGT la proportion de BG à BT est aussi donnée, qui soit comme de z à f . & BT fera $\frac{fl - fx}{z}$, & $CT \propto \frac{zy + fl - fx}{z}$. Puis derechef la proportion de TC à CH est donnée, a cause du triangle TCH , & la posant comme de z à g , on aura $CH \propto \frac{+gz y + fgl - fgx}{zz}$.

Et ainsi vous voyés, qu'en tel nombre de lignes données par position qu'on puisse auoir, toutes les lignes tirées dessus du point C a angles donnés suivant la teneur de la question, se peuvent tousiours exprimer chascune par trois termes, dont l'un est composé de la quantité inconnue y , multipliée, ou diuisée par quelque autre connue; & l'autre de la quantité inconnue x , aussi multipliée ou diuisée par quelque autre connuë, & le troisieme d'une quantité toute connuë. Excepté seulement si elles sont paralleles; ou bien a la ligne AB , auquel cas le terme composé de la quantité x sera nul; ou bien a la ligne CB , auquel cas celui qui est composé de la quantité y sera nul; ainsi qu'il est trop manifeste pour que ie m'arreste a l'expliquer. Et pour les signes $+$, & $-$, qui se ioignent à ces termes, ils peuvent estre changés en toutes les façons imaginables.

Puis vous voyés aussi, que multipliant plusieurs de ces lignes l'une par l'autre, les quantités x & y , qui se trouuent dans le produit, n'y peuvent auoir que chascune autant de dimensions, qu'il y a eu de lignes, a l'expli-

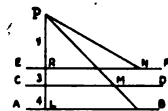
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And thus you see that, no matter how many lines are given in position, the length of any such line through C making given angles with these lines can always be expressed by three terms, one of which consists of the unknown quantity y multiplied or divided by some known quantity; another consisting of the unknown quantity x multiplied or divided by some other known quantity; and the third consisting of a known quantity.^[49] An exception must be made in the case where the given lines are parallel either to AB (when the term containing x vanishes), or to CB (when the term containing y vanishes). This case is too simple to require further explanation.^[50] The signs of the terms may be either $+$ or $-$ in every conceivable combination.^[51]

You also see that in the product of any number of these lines the degree of any term containing x or y will not be greater than the number of lines (expressed by means of x and y) whose product is found. Thus, no term will be of degree higher than the second if two lines be multiplied together, nor of degree higher than the third, if there be three lines, and so on to infinity.

^[49] That is, an expression of the form $ax+by+c$, where a, b, c , are any real positive or negative quantities, integral or fractional (not zero, since this exception is considered later).

^[50] The following problem will serve as a very simple illustration: Given three parallel lines AB, CD, EF, so placed that AB is distant 4 units from CD, and CD is distant 3 units from EF; required to find a point P such that if PL, PM, PN



be drawn through P, making angles of 90° , 45° , 30° , respectively, with the parallels. Then $\overline{PM}^2 = \overline{PL} \cdot \overline{PN}$.

Let $PR = y$, then $PN = 2y$, $PM = \sqrt{2}(y+3)$, $PL = y+7$. If $\overline{PM}^2 = \overline{PN} \cdot \overline{PL}$, we have $\left[\sqrt{2}(y+3) \right]^2 = 2y(y+7)$, whence $y = 9$. Therefore, the point P lies on the line XY parallel to EF and at a distance of 9 units from it. Cf. Rabuel, p. 79.

^[51] Depending, of course, upon the relative positions of the given lines.

Furthermore, to determine the point C, but one condition is needed, namely, that the product of a certain number of lines shall be equal to, or (what is quite as simple), shall bear a given ratio to the product of certain other lines. Since this condition can be expressed by a single equation in two unknown quantities,^[62] we may give any value we please to either x or y and find the value of the other from this equation. It is obvious that when not more than five lines are given, the quantity x , which is not used to express the first of the lines can never be of degree higher than the second.^[63]

Assigning a value to y , we have $x^2 = \pm ax \pm b^2$, and therefore x can be found with ruler and compasses, by a method already explained.^[64] If then we should take successively an infinite number of different values for the line y , we should obtain an infinite number of values for the line x , and therefore an infinity of different points, such as C, by means of which the required curve could be drawn.

This method can be used when the problem concerns six or more lines, if some of them are parallel to either AB or BC, in which case

^[62] That is, an indeterminate equation. "De plus, à cause que pour déterminer le point C, il n'y a qu'une seule condition qui soit requise, à sçavoir que ce qui est produit par la multiplication d'un certain nombre de ces lignes soit égal, ou (ce qui n'est de rien plus mal-aisé) ait la proportion donnée, à ce qui est produit par la multiplication des autres; on peut prendre à discretion l'une des deux quantitez inconnuës x ou y , & chercher l'autre par cette Equation." Such variations in the texts of different editions are of no moment, but are occasionally introduced as matters of interest.

^[63] Since the product of three lines bears a given ratio to the product of two others and a given line, no term can be of higher degree than the third, and therefore, than the second in x .

^[64] See pages 13, et seq.

cation desquelles elles seruent, qui ont esté ainsi multipliées: en sorte qu'elles n'auront iamais plus de deux dimensions, en ce qui ne sera produit que par la multiplication de deux lignes; ny plus de trois, en ce qui ne sera produit que par la multiplication de trois, & ainsi a l'infini.

De plus, a cause que pour determiner le point C, il n'y a qu'une seule condition qui soit requise, à sçavoir que ce qui est produit par la multiplication d'un certain nombre de ces lignes soit esgal, ou (ce qui n'est de rien plus malayse) ait la proportion donnée, à ce qui est produit par la multiplication des autres; on peut prendre a discretion l'une des deux quantités inconnues x ou y , & chercher l'autre par cete Equation. en laquelle il est evident que lorsque la question n'est point proposée en plus de cinq lignes, la quantité x qui ne sert point a l'expression de la premiere peut tousiours n'y auoir que deux dimensions. de façon que prenant une quantité connue pour y , il ne restera que xx ou $+$ ou $- ax +$ ou $- bb$. & ainsi on pourra trouuer la quantité x avec la règle & le compas, en la façon tantost expliquée. Mesme prenant successiuelement infinies diuerses grandeurs pour la ligne y , on en trouuera aussi infinies pour la ligne x , & ainsi on aura une infinité de diuers points, tels que celui qui est marqué C, par le moyen desquels on descrira la ligne courbe demandée.

Il se peut faire aussi, la question estant proposée en six, ou plus grand nombre de lignes; s'il y en a entre les données, qui soient paralleles a BA, ou BC, que l'une des deux quantités x ou y n'ait que deux dimensions en

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l'Equation, & ainsi qu'on puisse trouuer le point C avec la reigle & le compas. Mais au contraire si elles sont toutes paralleles , encore que la question ne soit proposée qu'en cinq lignes, ce point C ne pourra ainsi estre trouué, a cause que la quantité x ne se trouuant point en toute l'Equation, il ne sera plus permis de prendre vne quantité connue pour celle qui est nommée y , mais ce sera elle qu'il faudra chercher. Et pource quelle aura trois dimensions, on ne la pourra trouuer qu'en tirant la racine d'une Equation cubique. ce qui ne se peut generalement faire sans qu'on y employe pour le moins vne section conique. Et encore qu'il y ait iusques a neuf lignes données, pourvû qu'elles ne soient point toutes paralleles, on peut tousiours faire que l'Equation ne monte que iusques au quarré de quarré. au moyen dequoy on la peut aussy tousiours resoudre par les sections coniques, en la façon que i'expliqueray cy après. Et encore qu'il y en ait iusques a treize, on peut tousiours faire qu'elle ne monte que iusques au quarré de cube. en suite de quoy on la peut resoudre par le moyen d'une ligne, qui n'est que d'un degré plus composée que les sections coniques, en la façon que i'expliqueray aussy cy après. Et cecy est la premiere partie de ce que i'auois icy a demonstrier, mais avant que ie passe a la seconde il est besoin que ie dise quelque chose en general de la nature des lignes courbes.

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either x or y will be of only the second degree in the equation, so that the point C can be found with ruler and compasses.

On the other hand, if the given lines are all parallel even though a question should be proposed involving only five lines, the point C cannot be found in this way. For, since the quantity x does not occur at all in the equation, it is no longer allowable to give a known value to y . It is then necessary to find the value of y .^[65] And since the term in y will now be of the third degree, its value can be found only by finding the root of a cubic equation, which cannot in general be done without the use of one of the conic sections.^[66]

And furthermore, if not more than nine lines are given, not all of them being parallel, the equation can always be so expressed as to be of degree not higher than the fourth. Such equations can always be solved by means of the conic sections in a way that I shall presently explain.^[67]

Again, if there are not more than thirteen lines, an equation of degree not higher than the sixth can be employed, which admits of solution by means of a curve just one degree higher than the conic sections by a method to be explained presently.^[68]

This completes the first part of what I have to demonstrate here, but it is necessary, before passing to the second part, to make some general statements concerning the nature of curved lines.

^[65] That is, to solve the equation for y .

^[66] See page 84.

^[67] See page 107.

^[68] This line of reasoning may be extended indefinitely. Briefly, it means that for every two lines introduced the equation becomes one degree higher and the curve becomes correspondingly more complex.

BOOK SECOND

Geometry

BOOK II

ON THE NATURE OF CURVED LINES

THE ancients were familiar with the fact that the problems of geometry may be divided into three classes, namely, plane, solid, and linear problems.^[90] This is equivalent to saying that some problems require only circles and straight lines for their construction, while others require a conic section and still others require more complex curves.^[90] I am surprised, however, that they did not go further, and distinguish between different degrees of these more complex curves, nor do I see why they called the latter mechanical, rather than geometrical.^[91] If we say that they are called mechanical because some sort of instrument^[92] has to be used to describe them, then we must, to be consistent,

^[90] Cf. Pappus, Vol. I, p. 55, Proposition 5, Book III: "The ancients considered three classes of geometric problems, which they called plane, solid, and linear. Those which can be solved by means of straight lines and circumferences of circles are called plane problems, since the lines or curves by which they are solved have their origin in a plane. But problems whose solutions are obtained by the use of one or more of the conic sections are called solid problems, for the surfaces of solid figures (conical surfaces) have to be used. There remains a third class which is called linear because other 'lines' than those I have just described, having diverse and more involved origins, are required for their construction. Such lines are the spirals, the quadratrix, the conchoid, and the cissoid, all of which have many important properties." See also Pappus, Vol. I, p. 271.

^[91] Rabel (p. 92) suggests dividing problems into classes, the first class to include all problems that can be constructed by means of straight lines, that is, curves whose equations are of the first degree; the second, those that require curves whose equations are of the second degree, namely, the circle and the conic sections, and so on.

^[92] Cf. *Encyclopédie ou Dictionnaire Raisonné des Sciences, des Arts et des Metiers, par une Société de gens de lettres, mis en ordre et publiées par M. Diderot, et quant à la Partie Mathématique par M. d'Alembert*, Lausanne and Berne, 1780. In substance as follows: "Mechanical is a mathematical term designating a construction not geometric, that is, that cannot be accomplished by geometric curves. Such are constructions depending upon the quadrature of the circle.

The term, mechanical curve, was used by Descartes to designate a curve that cannot be expressed by an algebraic equation." Leibniz and others call them transcendental.

^[92] "Machine."

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De la nature des lignes courbes.

LEs anciens ont fort bien remarqué , qu'entre les Problèmes de Geometrie, les vns sont plans , les autres solides, & les autres lineaires, c'est a dire, que les vns peuvent estre construits , en ne traçant que des lignes droites, & des cercles; au lieu que les autres ne le peuvent estre, qu'on n'y employe pour le moins quelque section conique; ni enfin les autres , qu'on n'y employe quelque autre ligne plus composée. Mais ie m'estonne de ce qu'ils n'ont point outre cela distingué diuers degrés entre ces lignes plus composées , & ie ne sçauois comprendre pourquoy ils les ont nommées mechaniques, plustost que Geometriques. Car de dire que ç'ait esté, a cause qu'il est besoin de se seruir de quelque machine pour les descrire, il faudroit reietter par mesme raison les cercles & les lignes droites; vû qu'on ne les décrit sur le papier qu'avec vn compas, & vne reigle, qu'on peut aussy nommer des machines. Ce n'est pas non plus, a cause que les instrumens, qui seruent a les tracer, estant plus composés que la reigle & le compas , ne peuvent estre si iustes; car il faudroit pour cete raison les reietter des Mechaniques, où la iustesse des ouurages qui sortent de la main est désirée; plustost que de la Geometrie , où c'est seulement la iustesse du raisonnement qu'on recherche,

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che,

che, & qui peut sans doute estre aussi parfaite touchant ces lignes, que touchant les autres. Je ne diray pas aussi, que ce soit a cause qu'ils n'ont pas voulu augmenter le nombre de leurs demandes, & qu'ils se sont contentés qu'on leur accordast, qu'ils pussent joindre deux points donnés par vne ligne droite, & descrire vn cercle d'un centre donné, qui passast par vn point donné. car ils n'ont point fait de scrupule de supposer outre cela, pour traiter des sections coniques, qu'on pust couper tout cône donné par vn plan donné. & il n'est besoin de rien supposer pour tracer toutes les lignes courbes, que ie pretens icy d'introduire, sinon que deux ou plusieurs lignes pussent estre menées l'une par l'autre, & que leurs intersections en marquent d'autres; ce qui ne me paroist en rien plus difficile. Il est vray qu'ils n'ont pas aussi entierement receu les sections coniques en leur Geometrie, & ie ne veux pas entreprendre de changer les noms qui ont esté approuvés par l'usage; mais il est, ce me semble, tres clair, que prenant comme on fait pour Geometrique ce qui est precis & exact, & pour Mechanique ce qui ne l'est pas; & considerant la Geometrie comme vne science, qui enseigne generalement a connoistre les mesures de tous les cors, on n'en doit pas plustost exclure les lignes les plus composées que les plus simples, pourvû qu'on les puisse imaginer estre descrites par vn mouvement continu, ou par plusieurs qui s'entresuiuent & dont les derniers soient entierement réglés par ceux qui les precedent. car par ce moyen on peut tousiours auoir vne connoissance exacte de leur mesure. Mais peutestre que ce qui a empesché les anciens Geometres de recevoir

reject circles and straight lines, since these cannot be described on paper without the use of compasses and a ruler, which may also be termed instruments. It is not because the other instruments, being more complicated than the ruler and compasses, are therefore less accurate, for if this were so they would have to be excluded from mechanics, in which accuracy of construction is even more important than in geometry. In the latter, exactness of reasoning alone^[65] is sought, and this can surely be as thorough with reference to such lines as to simpler ones.^[66] I cannot believe, either, that it was because they did not wish to make more than two postulates, namely, (1) a straight line can be drawn between any two points, and (2) about a given center a circle can be described passing through a given point. In their treatment of the conic sections they did not hesitate to introduce the assumption that any given cone can be cut by a given plane. Now to treat all the curves which I mean to introduce here, only one additional assumption is necessary, namely, two or more lines can be moved, one upon the other, determining by their intersection other curves. This seems to me in no way more difficult.^[67]

It is true that the conic sections were never freely received into ancient geometry,^[68] and I do not care to undertake to change names confirmed by usage; nevertheless, it seems very clear to me that if we make the usual assumption that geometry is precise and exact, while mechanics is not;^[69] and if we think of geometry as the science which furnishes a general knowledge of the measurement of all bodies, then we have no more right to exclude the more complex curves than the simpler ones, provided they can be conceived of as described by a continuous motion or by several successive motions, each motion being completely determined by those which precede; for in this way an exact knowledge of the magnitude of each is always obtainable.

^[65] An interesting question of modern education is here raised, namely, to what extent we should insist upon accuracy of construction even in elementary geometry.

^[66] Not only ancient writers but later ones, up to the time of Descartes, made the same distinction; for example, Vieta. Descartes's view has been universally accepted since his time.

^[67] That is, in no way less obvious than the other postulates.

^[68] Because the ancients did not believe that the so-called constructions of the conic sections on a plane surface could be exact.

^[69] Since it is not possible to construct an ideal line, plane, and so on.

Probably the real explanation of the refusal of ancient geometers to accept curves more complex than the conic sections lies in the fact that the first curves to which their attention was attracted happened to be the spiral,^[68] the quadratrix,^[69] and similar curves, which really do belong only to mechanics, and are not among those curves that I think should be included here, since they must be conceived of as described by two separate movements whose relation does not admit of exact determination. Yet they afterwards examined the conchoid,^[70] the cissoid,^[71] and a few others which should be accepted; but not knowing much about their properties they took no more account of these than of the others. Again, it may have been that, knowing as they did only a little about the conic sections,^[72] and being still ignorant of many of the possibilities of the ruler and compasses, they dared not yet attack a matter of still greater difficulty. I hope that hereafter those who are clever enough to make use of the geometric methods herein suggested will find no great difficulty in applying them to plane or solid problems. I therefore think it proper to suggest to such a more extended line of investigation which will furnish abundant opportunities for practice.

Consider the lines AB, AD, AF, and so forth (page 46), which we may suppose to be described by means of the instrument YZ. This instrument consists of several rulers hinged together in such a way that YZ being placed along the line AN the angle XYZ can be increased or decreased in size, and when its sides are together the points B, C, D, E, F, G, H, all coincide with A; but as the size of the angle is increased,

^[68] See Heath, *History of Greek Mathematics* (hereafter referred to as Heath), Cambridge, 2 vols., 1921. Also Cantor, *Vorlesungen über Geschichte der Mathematik*, Leipzig, Vol. I (2), p. 263, and Vol. II (1), pp. 765 and 781 (hereafter referred to as Cantor).

^[69] See Heath, I, 225; Smith, Vol. II, pp. 300, 305.

^[70] See Heath, I, 235, 238; Smith, Vol. II, p. 298.

^[71] See Heath, I, 264; Smith, Vol. II, p. 314.

^[72] They really knew much more than would be inferred from this statement. In this connection, see Taylor, *Ancient and Modern Geometry of Conics*, Cambridge, 1881.

voir celles qui estoient plus composées que les sections coniques, c'est que les premieres qu'ils ont considerées, ayant par hasard esté la Spirale, la Quadratrice, & semblables, qui n'appartiennent veritablement qu'aux Mechaniques, & ne sont point du nombre de celles que ie pense deuoir icy estre receues, a cause qu'on les imagine descrites par deux mouuemens separes, & qui n'ont entre eux aucun rapport qu'on puisse mesurer exactement, bienqu'ils ayent après examiné la Conchoide, la Cissoïde, & quelque peu d'autres qui en sont, toutefois a cause qu'ils n'ont peuteestre pas assez remarqué leurs propriétés, ils n'en ont pas fait plus d'estat que des premieres. Oubien c'est que voyant, qu'ils ne connoissoient encore, que peu de choses touchant les sections coniques, & qu'il leur en restoit mesme beaucoup, touchant ce qui se peut faire avec la reigle & le compas, qu'ils ignoroient, ils ont creu ne deuoir point entamer de matiere plus difficile. Mais pourceque j'espere que d'orenavant ceux qui auront l'adresse de se seruir du calcul Geometrique icy proposé, ne trouueront pas assez de quoy s'arester touchant les problemes plans, ou solides; ie croy qu'il est a propos que ie les inuite a d'autres recherches, où ils ne manqueront iamais d'exercice.

Voyés les lignes A B, A D, A F, & semblables que ie suppose auoir esté descrites par l'ayde de l'instrument Y Z, qui est composé de plusieurs reigles tellement iointes, que celle qui est marquée Y Z estant arestée sur la ligne A N, on peut ouurir & fermer l'angle X Y Z; & que lorsqu'il est tout fermé, les points B, C, D, F, G, H sont tous assemblés au point A ; mais qu'a mesure qu'on

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the ruler BC, fastened at right angles to XY at the point B, pushes toward Z the ruler CD which slides along YZ always at right angles. In like manner, CD pushes DE which slides along YX always parallel to BC; DE pushes EF; EF pushes FG; FG pushes GH, and so on. Thus we may imagine an infinity of rulers, each pushing another, half of them making equal angles with YX and the rest with YZ.

Now as the angle XYZ is increased the point B describes the curve AB, which is a circle; while the intersections of the other rulers, namely, the points D, F, H describe other curves, AD, AF, AH, of which the latter are more complex than the first and this more complex than the circle. Nevertheless I see no reason why the description of the first^[73] cannot be conceived as clearly and distinctly as that of the circle, or at least as that of the conic sections; or why that of the second, third,^[74] or any other that can be thus described, cannot be as clearly conceived of as the first; and therefore I see no reason why they should not be used in the same way in the solution of geometric problems.^[75]

^[73] That is, AD.

^[74] That is, AF and AH.

^[75] The equations of these curves may be obtained as follows: (1) Let $YA = YB = a$, $YC = x$, $CD = y$, $YD = z$; then $z : x = x : a$, whence $z = \frac{x^2}{a}$. Also $z^2 = x^2 + y^2$; therefore the equation of AD is $x^4 = a^2(x^2 + y^2)$. (2) Let $YA = YB = a$, $YE = x$, $EF = y$, $YF = z$. Then $z : x = x : YD$, whence $YD = \frac{x^2}{z}$. Also

$$x : YD = YD : YC, \text{ whence } YC = \frac{x^4}{z^2} \div x = \frac{x^3}{z^2}.$$

But $YD : YC = YC : a$, and therefore

$$\frac{ax^2}{z} = \left(\frac{x^3}{z^2}\right)^2, \text{ or } z = \sqrt[3]{\frac{x^4}{a}}.$$

Also, $z^2 = x^2 + y^2$. Thus we get, as the equation of AF,

$$\sqrt[3]{\frac{x^8}{a^2}} = x^2 + y^2, \text{ or } x^8 = a^2(x^2 + y^2)^3.$$

(3) In the same way, it can be shown that the equation of AH is

$$x^{12} = a^2(x^2 + y^2)^5.$$

See Rabuel, p. 107.

I could give here several other ways of tracing and conceiving a series of curved lines, each curve more complex than any preceding one,^[76] but I think the best way to group together all such curves and then classify them in order, is by recognizing the fact that all points of those curves which we may call "geometric," that is, those which admit of precise and exact measurement, must bear a definite relation^[77] to all points of a straight line, and that this relation must be expressed by means of a single equation.^[78] If this equation contains no term of higher degree than the rectangle of two unknown quantities, or the square of one, the curve belongs to the first and simplest class,^[79] which contains only the circle, the parabola, the hyperbola, and the ellipse; but when the equation contains one or more terms of the third or fourth degree^[80] in one or both of the two unknown quantities^[81] (for it requires two unknown quantities to express the relation between two points) the curve belongs to the second class; and if the equation contains a term of the fifth or sixth degree in either or both of the unknown quantities the curve belongs to the third class, and so on indefinitely.

^[76] "Qui seroient de plus en plus composées par degrez à l'infini." The French quotations in the footnotes show a few variants in style in different editions.

^[77] That is, a relation exactly known, as, for example, that between two straight lines in distinction to that between a straight line and a curve, unless the length of the curve is known.

^[78] It will be recognized at once that this statement contains the fundamental concept of analytic geometry.

^[79] "Du premier & plus simple genre," an expression not now recognized. As now understood, the order or degree of a plane curve is the greatest number of points in which it can be cut by any arbitrary line, while the class is the greatest number of tangents that can be drawn to it from any arbitrary point in the plane.

^[80] Grouped together because an equation of the fourth degree can always be transformed into one of the third degree.

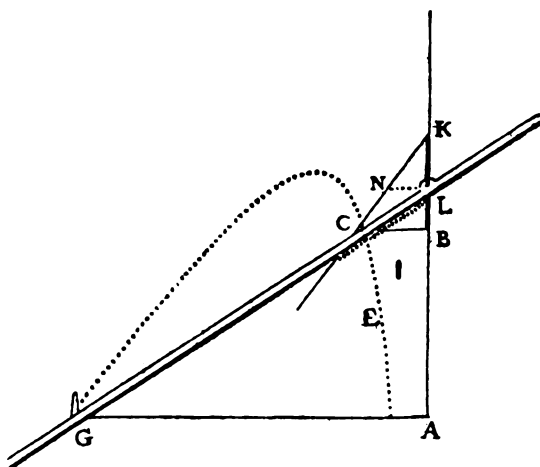
^[81] Thus Descartes includes such terms as x^2y , x^2y^2 , . . . as well as x^3 , y^4

du moins que des sections coniques; ny ce qui peut empêcher, qu'on ne conçoive la seconde, & la troisieme, & toutes les autres, qu'on peut descrire, aussy bien que la premiere; ny par consequent qu'on ne les recoive toutes en mesme façon, pour servir aux speculations de Geometrie.

Je pourrois mettre icy plusieurs autres moyens pour tracer & concevoir des lignes courbes, qui seroient de plus en plus composées par degrés a l'infini. mais pour comprendre ensemble toutes celles, qui sont en la nature, & les distinguer par ordre en certains genres; ie ne sçache rien de meilleur que de dire que tous les points, de celles qu'on peut nommer Geometriques, c'est a dire qui tombent sous quelque mesure précise & exacte, ont necessairement quelque rapport a tous les points d'une ligne droite, qui peut estre exprimé par quelque equation, en tous par vne mesme. Et que lorsque cete equation ne monte que iusques au rectangle de deux quantités indeterminées, ou bien au quarré d'une mesme, la ligne courbe est du premier & plus simple genre, dans lequel il ny a que le cercle, la parabole, l'hyperbole, & l'Ellipse qui soient comprises. mais que lorsque l'equation monte iusques a la trois ou quatrieme dimension des deux, ou de l'une des deux quantités indeterminées, car il en faut deux pour expliquer icy le rapport d'un point a un autre, elle est du second; & que lorsque l'equation monte iusques a la 5 ou sixieme dimension, elle est du troisieme; & ainsi des autres a l'infini.

Comme si ie veux sçavoir de quel genre est la ligne E C, que i' imagine estre descrite par l'intersection de la reigle

La façon de distinguer toutes les lignes courbes en certains genres. Et de connoître le rapport qu'ont tous leurs points a ceux des lignes droites.



reigle GL , & du plan rectiligne $CNKL$, dont le costé KN est indefiniement prolongé vers C , & qui estant meu sur le plan de dessous en ligne droite, c'est a dire en telle sorte que son diametre KL se trouue tousiours appliqué sur quelque endroit de la ligne BA prolongée de part & d'autre, fait mouvoir circulairement cete reigle GL autour du point G , a cause quelle luy est tellement iointe quelle passe tousiours par le point L . Je choisis vne ligne droite, comme AB , pour rapporter a ses diuers points tous ceux de cete ligne courbe EC , & en cete ligne AB ie choisis vn point, comme A , pour commencer par luy ce calcul. Je dis que ie choisis & l'un & l'autre, a cause qu'il est libre de les prendre tels qu'on veut. car encore qu'il y ait beaucoup de choix pour rendre l'equation plus courte, & plus aysée, toutefois en quelle façon qu'on les prene, on peut tousiours faire que la ligne paroisse de mesme genre, ainsi qu'il est aysé a demonstrier.

Après

Suppose the curve EC to be described by the intersection of the ruler GL and the rectilinear plane figure CNKL, whose side KN is produced indefinitely in the direction of C, and which, being moved in the same plane in such a way that its side^[89] KL always coincides with some part of the line BA (produced in both directions), imparts to the ruler GL a rotary motion about G (the ruler being hinged to the figure CNKL at L).^[90] If I wish to find out to what class this curve belongs, I choose a straight line, as AB, to which to refer all its points, and in AB I choose a point A at which to begin the investigation.^[91] I say "choose this and that," because we are free to choose what we will, for, while it is necessary to use care in the choice in order to make the equation as short and simple as possible, yet no matter what line I should take instead of AB the curve would always prove to be of the same class, a fact easily demonstrated.^[92]

^[89] "Diametre."

^[90] The instrument thus consists of three parts, (1) a ruler AK of indefinite length, fixed in a plane; (2) a ruler GL, also of indefinite length, fastened to a pivot, G, in the same plane, but not on AK; and (3) a rectilinear figure BKC, the side KC being indefinitely long, to which the ruler GL is hinged at L, and which is made to slide along the ruler GL.

^[91] That is, Descartes uses the point A as origin, and the line AB as axis of abscissas. He uses parallel ordinates, but does not draw the axis of ordinates.

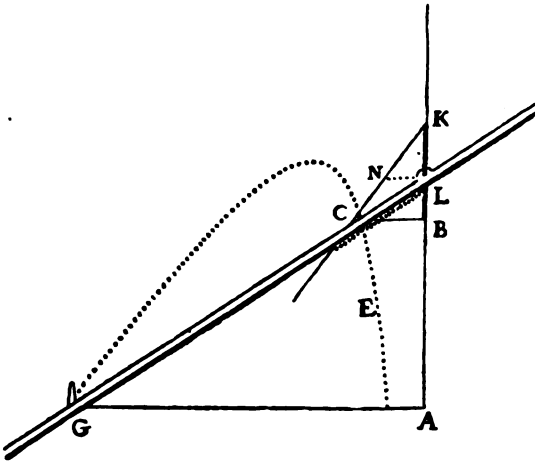
^[92] That is, the nature of a curve is not affected by a transformation of coördinates.

Then I take on the curve an arbitrary point, as C, at which we will suppose the instrument applied to describe the curve. Then I draw through C the line CB parallel to GA. Since CB and BA are unknown and indeterminate quantities, I shall call one of them y and the other x . To the relation between these quantities I must consider also the known quantities which determine the description of the curve, as GA, which I shall call a ; KL, which I shall call b ; and NL parallel to GA, which I shall call c . Then I say that as NL is to LK, or as c is to b , so CB, or y , is to BK, which is therefore equal to $\frac{b}{c}y$. Then BL is equal to $\frac{b}{c}y - b$, and AL is equal to $x + \frac{b}{c}y - b$. Moreover, as CB is to LB, that is, as y is to $\frac{b}{c}y - b$, so AG or a is to LA or $x + \frac{b}{c}y - b$. Multiplying the second by the third, we get $\frac{ab}{c}y - ab$ equal to

$$xy + \frac{b}{c}y^2 - by,$$

which is obtained by multiplying the first by the last. Therefore, the required equation is

$$y^2 = cy - \frac{cx}{b}y + ay - ac.$$



Après cela prenant vn point a discretion dans la courbe, comme C, sur lequel ie suppose que l'instrument qui sert a la descire est appliqué, ie tire de ce point C. la ligne CB parallele a GA, & pourceque CB & BA sont deux quantités indeterminées & inconnuës , ie les nomme l'une y & l'autre x. mais affin de trouuer le rapport de l'une à l'autre, ie considere aussy les quantités connuës qui determinent la description de cete ligne courbe, comme GA que ie nomme a, KL que ie nomme b, & NL parallele a GA que ie nomme c. puis ie dis, comme NL est à LK, ou c à b, ainsi CB, ou y, est à BK, qui est par consequent $\frac{b}{c} y$: & BL est $\frac{b}{c} y - b$, & AL est $x + \frac{b}{c} y - b$. de plus comme CB est à LB, ou y à $\frac{b}{c} y - b$, ainsi a, ou GA, est à LA, ou $x + \frac{b}{c} y - b$. de façon que mul-

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multipliant la seconde par la troisieme on produit $\frac{a^b}{c}y - ab$, qui est esgale à $xy + \frac{b}{c}yy - by$ qui se produit en multipliant la premiere par la derniere. & ainsi l'equation qu'il falloit trouver est .

$$yy \propto cy - \frac{cx}{b}y + ay - ar.$$

de laquelle on connoist que la ligne EC est du premier genre , comme en effect elle n'est autre qu'une Hyperbole.

Que si en l'instrument qui sert a la descrire on fait qu'au lieu de la ligne droite CNK, ce soit cete Hyperbole, ou quelque autre ligne courbe du premier genre, qui termine le plan CNKL; l'interfection de cete ligne & de la reigle GL descrira, au lieu de l'Hyperbole EC, vne autre ligne courbe, qui sera du second genre. Comme si CNK est vu cercle, dont L soit le centre, on descrira la premiere Conchoide des anciens; & si c'est vne Parabole dont le diametre soit KB, on descrira la ligne courbe, que j'ay tantost dit estre la premiere, & la plus simple pour la question de Pappus, lorsqu'il n'y a que cinq lignes droites donnees par position. Mais si au lieu d'une de ces lignes courbes du premier genre, c'en est vne du second, qui termine le plan CNKL, on en descrira par son moyen vne du troisieme, ou si c'en est vne du troisieme, on en descrira vne du quatrieme, & ainsi a l'infini. comme il est fort aysé a connoistre par le calcul. Et en quelque autre façon, qu'on imagine la description d'une ligne courbe, pourvu qu'elle soit du nombre de celles que je nomme Geometriques, on pourra tousiours trouver

From this equation we see that the curve EC belongs to the first class, it being, in fact, a hyperbola.^[60]

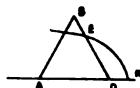
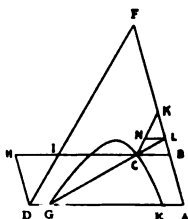
If in the instrument used to describe the curve we substitute for the rectilinear figure CNK this hyperbola or some other curve of the first class lying in the plane CNKL, the intersection of this curve with the ruler GL will describe, instead of the hyperbola EC, another curve, which will be of the second class.

Thus, if CNK be a circle having its center at L, we shall describe the first conchoid of the ancients,^[61] while if we use a parabola having KB as axis we shall describe the curve which, as I have already said, is the first and simplest of the curves required in the problem of Pappus, that is, the one which furnishes the solution when five lines are given in position.^[62]

^[60] Cf. Briot and Bouquet, *Elements of Analytical Geometry of Two Dimensions*, trans. by J. H. Boyd, New York, 1896, p. 143.

The two branches of the curve are determined by the position of the triangle CNKL with respect to the directrix AB. See Rabuel, p. 119.

Van Schooten, p. 171, gives the following construction and proof: Produce AG to D, making $DG = EA$. Since E is a point of the curve obtained when GL coincides with GA, L with A, and C with N, then $EA = NL$. Draw DF parallel to KC. Now let GCE be a hyperbola through E whose asymptotes are DF and FA. To prove that this hyperbola is the curve given by the instrument described above, produce BC to cut DF in I, and draw DH parallel to AF



meeting BC in H. Then $KL : LN = DH : HI$. But $DH = AB = x$, so we may write $b : c = x : HI$, whence $HI = \frac{cx}{b}$, $IB = a + c - \frac{cx}{b}$, $IC = a + c - \frac{cx}{b} - y$.

But in any hyperbola $IC \cdot BC = DE \cdot EA$, whence we have $(a + c - \frac{cx}{b} - y)y = ac$,

or $y^2 = cy - \frac{cxy}{b} + ay - ac$. But this is the equation obtained above, which is

therefore the equation of a hyperbola whose asymptotes are AF and FD.

Van Schooten, p. 172, describes another similar instrument: Given a ruler AB pivoted at A, and another BD hinged to AB at B. Let AB rotate about A so that D moves along LK; then the curve generated by any point E of BE will be an ellipse whose semi-major axis is $AB + BE$ and whose semi-minor axis is $AB - BE$.

^[61] See notes 59 and 70.

^[62] For a discussion of the elliptic, parabolic, and hyperbolic conchoids see Rabuel, pp. 123, 124.

If, instead of one of these curves of the first class, there be used a curve of the second class lying in the plane CNKL, a curve of the third class will be described; while if one of the third class be used, one of the fourth class will be obtained, and so on to infinity.^[90] These statements are easily proved by actual calculation.

Thus, no matter how we conceive a curve to be described, provided it be one of those which I have called geometric, it is always possible to find in this manner an equation determining all its points. Now I shall place curves whose equations are of the fourth degree in the same class with those whose equations are of the third degree; and those whose equations are of the sixth degree^[91] in the same class with those whose equations are of the fifth degree^[92] and similarly for the rest. This classification is based upon the fact that there is a general rule for reducing to a cubic any equation of the fourth degree, and to an equation of the fifth degree^[93] any equation of the sixth degree, so that the latter in each case need not be considered any more complex than the former.

It should be observed, however, with regard to the curves of any one class, that while many of them are equally complex so that they may be employed to determine the same points and construct the same problems, yet there are certain simpler ones whose usefulness is more limited. Thus, among the curves of the first class, besides the ellipse, the hyperbola, and the parabola, which are equally complex, there is also found the circle, which is evidently a simpler curve; while among those of the second class we find the common conchoid, which is described by means of the circle, and some others which, though less

^[90] Rabuel (p. 125), illustrates this, substituting for the curve CNKL the semi-cubical parabola, and showing that the resulting equation is of the fifth degree, and therefore, according to Descartes, of the third class. Rabuel also gives (p. 119), a general method for finding the curve, no matter what figure is used for CNKL. Let $GA = a$, $KL = b$, $AB = x$, $CB = y$ and $KB = z$; then $LB = z - b$, and $AL = x + z - b$. Now $GA : AL = CB : BL$, or $a : x + z - b = y : z - b$, whence $z = \frac{xy - by + ab}{a - y}$.

This value of z is independent of the nature of the figure CNKL. But given any figure CNKL it is possible to obtain a second value for z from the nature of the curve. Equating these values of z we get the equation of the curve.

^[91] "Celles dont l'équation monte au quarré de cube."

^[92] "Celles dont elle ne monte qu'au sursolide."

^[93] "Au sursolide."

uer vne equation pour déterminer tous ses poins en cete sorte.

Au reste ie mets les lignes courbes qui font monter cete equation iusques au quarré de quarré , au mesme genre que celles qui ne la font monter que iusques au cube. & celles dont l'equation monte au quarré de cube, au mesme genre que celles dont elle ne monte qu'au surfolide. & ainsi des autres. Dont la raison est, qu'il y a reigle generale pour reduire au cube toutes les difficultés qui vont au quarré de quarré , & au surfolide toutes celles qui vont au quarré de cube , de façon qu'on ne les doit point estimer plus composées.

Mais il est a remarquer qu'entre les lignes de chaque genre, encore que la plus part soient esgalement composées , en sorte qu'elles peuuent seruir a déterminer les mesmes poins, & construire les mesmes problemes, il y en a toutefois aussi quelques vnes, qui sont plus simples, & qui n'ont pas tant d'estendue en leur puissance. comme entre celles du premier genre outre l'Ellipse l'Hyperbole & la Parabole qui sont esgalement composées, le cercle y est aussi compris, qui manifestement est plus simple, & entre celles du second genre il y a la Conchoïde vulgaire, qui a son origine du cercle; & il y en a encore quelques autres, qui bien qu'elles n'ayent pas tant d'estendue que la plus part de celles du mesme genre, ne peuuent toutefois estre mises dans le premier.

Or après auoir ainsi reduit toutes les lignes courbes a certains genres , il m'est aysé de poursuire en la demonstration de la responce, que i'ay tantost faite a la question de Pappus. Car premierement ayant fait voir cy

S f 2

dessus, Suite de l'explication de la question de Pappus mise au liure precedent

deffus , que lorsqu'il n'y a que trois ou 4 lignes droites données, l'equation qui sert a determiner les poins cherchés, ne monte que iusques au quarré; il est euident, que la ligne courbe ou se trouuent ces poins, est necessairement quelqu'une de celles du premier genre: a cause que cete mesme equation explique le rapport, qu'ont tous les poins des lignes du premier genre a ceux d'une ligne droite. Et que lorsqu'il n'y a point plus de 8 lignes droites données, cete equation ne monte que iusques au quarré de quarré tout au plus, & que par consequent la ligne cherchée ne peut estre que du second genre, ou au deffous. Et que lorsqu'il n'y a point plus de 12 lignes données, l'equation ne monte que iusques au quarré de cube, & que par consequent la ligne cherchée n'est que du troisieme genre, ou au deffous. & ainsi des autres. Et mesme a cause que la position des lignes droites données peut varier en toutes sortes, & par consequent faire charger tant les quantités connues, que les signes $+$ & $-$ de l'equation, en toutes les façons imaginables; il est euident qu'il n'y a aucune ligne courbe du premier genre, qui ne soit vtile a cete question, quand elle est proposée en 4 lignes droites; ny aucune du second qui n'y soit vtile, quand elle est proposée en huit; ny du troisieme, quand elle est proposée en douze: & ainsi des autres. En forte qu'il n'y a pas vne ligne courbe qui tombe sous le calcul & puisse estre receüe en Geometrie, qui n'y soit vtile pour quelque nombre de lignes.

Solution
de-cete
question
quandelle
n'est pro-
posée
qu'en 3
ou 4 li-
gnes.

Mais il faut icy plus particulierement que ie determine, & donne la façon de trouuer la ligne cherchée; qui sert en chasque cas, lorsqu'il ny a que 3 ou 4 lignes droites

complicated^[100] than many curves of the same class, cannot be placed in the first class.^[99]

Having now made a general classification of curves, it is easy for me to demonstrate the solution which I have already given of the problem of Pappus. For, first, I have shown that when there are only three or four lines the equation which serves to determine the required points^[100] is of the second degree. It follows that the curve containing these points must belong to the first class, since such an equation expresses the relation between all points of curves of Class I and all points of a fixed straight line. When there are not more than eight given lines the equation is at most a biquadratic, and therefore the resulting curve belongs to Class II or Class I. When there are not more than twelve given lines, the equation is of the sixth degree or lower, and therefore the required curve belongs to Class III or a lower class, and so on for other cases.

Now, since each of the given lines may have any conceivable position, and since any change in the position of a line produces a corresponding change in the values of the known quantities as well as in the signs + and — of the equation, it is clear that there is no curve of Class I that may not furnish a solution of this problem when it relates to four lines, and that there is no curve of Class II that may not furnish a solution when the problem relates to eight lines, none of Class III when it relates to twelve lines, etc. It follows that there is no geometric curve whose equation can be obtained that may not be used for some number of lines.^[101]

It is now necessary to determine more particularly and to give the method of finding the curve required in each case, for only three or

^[99] "Pas tant d'étendue." Cf. Rabuel, p. 113. "Pas tant d'étendue en leur puissance."

^[100] Various methods of tracing curves were used by writers of the seventeenth century. Among these there were not only the usual method of plotting a curve from its equation and that of using strings, pegs, etc., as in the popular construction of the ellipse, but also the method of using jointed rulers and that of using one curve from which to derive another, as for example the usual method of describing the cissoid. Cf. Rabuel, p. 138.

^[101] That is, the equation of the required locus.

^[102] "En sorte qu'il n'y a pas une ligne courbe qui tombe sous le calcul & puisse être receuë en Geometrie, qui n'y soit utile pour quelque nombre de lignes."

four given lines. This investigation will show that Class I contains only the circle and the three conic sections.

Consider again the four lines AB, AD, EF, and GH, given before, and let it be required to find the locus generated by a point C, such that, if four lines CB, CD, CF, and CH be drawn through it making given angles with the given lines, the product of CB and CF is equal to the product of CD and CH. This is equivalent to saying that if

$$CB = y,$$

$$CD = \frac{czy + bcx}{z^2},$$

$$CF = \frac{ezy + dek + dcx}{z^2},$$

and

$$CH = \frac{gzy + fgl - fgx}{z^2}.$$

then the equation is

$$y^2 = \frac{(cfglz - dckz^2)y - (dez^2 + cfgz - bcgz)xy + bcfglx - bcfgx^2}{ez^3 - cgz^2}.$$

A geometric diagram illustrating the construction of a circle tangent to three lines. A horizontal line contains points E, A, B, G. A line from F passes through A to D. A line from H passes through G to C. A circle is tangent to these three lines at points R, S, and T. Other points include M, L, N, K, and a central dot.

c'est a dire ayant fait $CB \propto y$, $CD \propto \frac{c^2 y + b c x}{z z}$
 $CF \propto \frac{c^2 y + d e k + d e x}{z z}$ & $CH \propto \frac{g z y + f g l - f g x}{z z}$ l'equatiõ est

$$\left. \begin{array}{l} y y \propto \frac{-d e k x z}{+ c f g l z} \end{array} \right\} y \frac{-d e z x x}{- c f g z x} \left\{ y \frac{+ b c f g l x}{- b c f g x x} \right\}$$

$$\frac{+ b c g z x}{+ b c g z x}$$

e z z z -- g z z.
Sf 3

all

au moins en supposant $e z$ plus grand que $e g$, car s'il estoit moindre, il faudroit changer tous les signes $+$ & $--$. Et si la quantité y se trouuoit nulle, ou moindre que rien en cete equation, lorsqu'on a supposé le point C en l'angle D A G, il faudroit le supposer aussy en l'angle D A E, ou E A R, ou R A G, en changeant les lignes $+$ & $--$ selon qu'il seroit requis a cet effect. Et si en toutes ces 4 positions la valeur d' y se trouuoit nulle, la question seroit impossible au cas proposé. Mais supposons la icy estre possible, & pour en abreger les termes, au lieu des quantités $\frac{c f g l z -- d e R z z}{e z -- e g z z}$ escriuons $2 m$, & au lieu de $\frac{d e z z + c f g z -- b c g z}{e z -- e g z z}$ escriuons $\frac{2 n}{z}$; & ainsi nous au-

rons
 $y y \propto 2 m y -- \frac{2 n}{z} x y \frac{+ b c f g l x -- b c f g x x}{e z -- e g z z}$, dont la racine est

$y \propto m -- \frac{n x}{z} + \sqrt{m m -- \frac{2 m n x}{z} + \frac{n n x x + b c f g l x -- b c f g x x}{e z -- e g z z}}$
 & derechef pour abreger, au lieu de $-- \frac{2 m n}{z} + \frac{b c f g l}{e z -- e g z z}$ escriuons o , & au lieu de $\frac{n n -- b c f g}{e z -- e g z z}$

escriuons $\frac{p}{m}$. car ces quantités estant toutes données, nous les pouons nommer comme il nous plaist. & ainsi nous auons

$y \propto m -- \frac{n}{z} x + \sqrt{m m + o x -- \frac{p}{m} x x}$, qui doit estre la longueur de la ligne B C, en laissant A B, ou x indeterminée.

It is here assumed that ez is greater than cg ; otherwise the signs + and — must all be changed.^[97] If y is zero or less than nothing in this equation,^[98] the point C being supposed to lie within the angle DAG , then C must be supposed to lie within one of the angles DAE , EAR , or RAG , and the signs must be changed to produce this result. If for each of these four positions y is equal to zero, then the problem admits of no solution in the case proposed.

Let us suppose the solution possible, and to shorten the work let us write $2m$ instead of $\frac{cflgz - dehz^2}{ez^3 - cgz^2}$, and $\frac{2n}{z}$ instead of $\frac{dez^2 + cfgz - bcga}{ez^3 - cgz^2}$. Then we have

$$y^2 = 2my - \frac{2n}{z}xy + \frac{bcfglx - bcgax^2}{ez^3 - cgz^2},$$

of which the root^[99] is

$$y = m - \frac{nx}{z} + \sqrt{m^2 - \frac{2mnx}{z} + \frac{n^2x^2}{z^2} + \frac{bcfglx - bcgax^2}{ez^3 - cgz^2}}.$$

Again, for the sake of brevity, put $-\frac{2mn}{z} + \frac{bcfgl}{ez^3 - cgz^2}$ equal to o , and

$\frac{n^2}{z^2} - \frac{bcfg}{ez^3 - cgz^2}$ equal to $\frac{p}{m}$; for these quantities being given, we can

represent them in any way we please.^[100] Then we have

$$y = m - \frac{n}{z}x + \sqrt{m^2 + ox + \frac{p}{m}x^2}.$$

This must give the length of the line BC , leaving AB or x undeter-

^[97] When ez is greater than cg , then $ez^3 - cgz^2$ is positive and its square root is therefore real.

^[98] Descartes uses "moindre que rien" for "negative."

^[99] Descartes mentions here only one root; of course the other root would furnish a second locus.

^[100] In a letter to Mersenne (Cousin, Vol. VII, p. 157), Descartes says: "In regard to the problem of Pappus, I have given only the construction and demonstration without putting in all the analysis; . . . in other words, I have given the construction as architects build structures, giving the specifications and leaving the actual manual labor to carpenters and masons."

mined. Since the problem relates to only three or four lines, it is obvious that we shall always have such terms, although some of them may vanish and the signs may all vary.^[101]

After this, I make KI equal and parallel to BA, and cutting off on BC a segment BK equal to m (since the expression for BC contains $+m$; if this were $-m$, I should have drawn IK on the other side of AB,^[102] while if m were zero, I would not have drawn IK at all). Then I draw IL so that $IK : KL = z : n$; that is, so that if IK is equal to x , KL is equal to $\frac{n}{z}x$. In the same way I know the ratio of KL to IL, which I may call $n : a$, so that if KL is equal to $\frac{n}{z}x$, IL is equal to $\frac{a}{z}x$. I take the point K between L and C, since the equation contains $-\frac{n}{z}x$; if this were $+\frac{n}{z}x$, I should take L between K and C;^[103] while if $\frac{n}{z}x$ were equal to zero, I should not draw IL.

This being done, there remains the expression

$$LC = \sqrt{m^2 + ox + \frac{p}{m}x^2},$$

from which to construct LC. It is clear that if this were zero the point

^[101] Having obtained the value of BC algebraically, Descartes now proceeds to construct the length BC geometrically, term by term. He considers BC equal to $BK + KL + LC$, which is equal to $BK - LK + LC$ which in turn is equal to

$$m - \frac{n}{z}x + \sqrt{m^2 + ox + \frac{p}{m}x^2}.$$

^[102] That is, take I on CB produced.

^[103] That is, on KB produced. C is not yet determined.

qui est entre KL , & IL , que ie pose comme entre n & a :
 sibienque KL estant $\frac{n}{z}x$, IL est $\frac{a}{z}x$; Et ie fais que le
 point K soit entre L & C , a cause qu'il y a icy -- $\frac{n}{z}x$;
 au lieu que j'aurois mis L entre K & C , si j'eusse eu + $\frac{n}{z}x$;
 & ie n'eusse point tiré cete ligne IL , si $\frac{n}{z}x$ eust esté nulle.

Or cela fait, il ne me reste plus pour la ligne LC , que
 ces termes, $LC \propto \sqrt{mm + ox - \frac{p}{m}xx}$. d'où ie voy
 que s'ils estoient nuls, ce point C se trouueroit en la li-
 gne droite IL ; & que s'ils estoient tels que la racine s'en
 pust tirer, c'est a dire que mm & $\frac{p}{m}xx$ estant marqués
 d'un mesme signe + ou --, oo fust esgal à $4pm$, ou bien
 que les termes mm & ox , ou ox & $\frac{p}{m}xx$ fussent nuls, ce
 point C se trouueroit en vne autre ligne droite qui ne se-
 roit pas plus malaysée a trouuer qu' IL . Mais lorsque
 cela n'est pas, ce point C est tousiours en l'une des trois
 sections coniques, ou en vn cercle, dont l'un des dia-
 metres est en la ligne IL , & la ligne LC est l'une de cel-
 les qui s'appliquent par ordre à ce diametre; ou au con-
 traire LC est parallele au diametre, auquel celle qui est
 en la ligne IL est appliquée par ordre. A sçauoir si le ter-
 me $\frac{p}{m}xx$, est nul cete section conique est vne Parabole;
 & s'il est marqué du signe +, c'est vne Hyperbole; &
 enfin s'il est marqué du signe -- c'est vne Ellipse. Excepté
 seulement si la quantité aam est esgale à pzz & que l'an-
 gle ILC soit droit: auquel cas on a vn cercle au lieu
 d'une

C would lie on the straight line IL;^[104] that if it were a perfect square, that is if m^2 and $\frac{p}{m}x^2$ were both $+$ ^[105] and o^2 was equal to $4pm$, or if m^2 and ox , or ox and $\frac{p}{m}x^2$, were zero, then the point C would lie on another straight line, whose position could be determined as easily as that of IL.^[106]

If none of these exceptional cases occur,^[107] the point C always lies on one of the three conic sections, or on a circle having its diameter in the line IL and having LC a line applied in order to this diameter,^[108] or, on the other hand, having LC parallel to a diameter and IL applied in order.

In particular, if the term $\frac{p}{m}x^2$ is zero, the conic section is a parabola; if it is preceded by a plus sign, it is a hyperbola; and, finally, if it is preceded by a minus sign, it is an ellipse.^[109] An exception occurs when

^[104] The equation of IL is $y = m - \frac{n}{z}x$.

^[105] There is considerable diversity in the treatment of this sentence in different editions. The Latin edition of 1683 has "Hoc est, ut, mm & $\frac{p}{m}xx$ signo + notalis." The French edition, Paris, 1705, has "C'est à dire que mm et $\frac{p}{m}xx$ étant marquez d'un même signe + ou —." Rabuel gives "C'est à dire que mm and $\frac{p}{m}xx$ étant marquez d'un même signe +." He adds the following note: "Il y a dans les Editions Françoises de Leyde, 1637, et de Paris, 1705, 'un meme signe + ou —', ce qui est une faute d'impression." The French edition, Paris, 1886, has "Étant marqués d'un meme signe + ou —."

^[106] Note the difficulty in generalization experienced even by Descartes. Cf. Briot and Bouquet, p. 72.

^[107] "Mais lorsque cela n'est pas." In each case the equation giving the value of y is linear in x and y , and therefore represents a straight line. If the quantity under the radical sign and $\frac{n}{z}x$ are both zero, the line is parallel to AB. If the quantity under the radical sign and m are both zero, C lies in AL.

^[108] "An ordinate." The equivalent of "ordination application" was used in the 16th century translation of Apollonius. Hutton's Mathematical Dictionary, 1796, gives "applicate," "Ordinate applicate," was also used.

^[109] Cf. Briot and Bouquet, p. 143.

a^2m is equal to px^2 and the angle ILC is a right angle,^[130] in which case we get a circle instead of an ellipse.^[131]

If the conic section is a parabola, its latus rectum is equal to $\frac{oz}{a}$ and its axis always lies along the line IL.^[132] To find its vertex, N, make IN equal to $\frac{am^2}{oz}$, so that the point I lies between L and N if m^2 is positive and ox is positive; and L lies between I and N if m^2 is positive and ox negative; and N lies between I and L if m^2 is negative and ox positive. It is impossible that m^2 should be negative when the terms are arranged as above. Finally, if m^2 is equal to zero, the points N and I must coincide. It is thus easy to determine this parabola, according to the first problem of the first book of Apollonius^[133].

If, however, the required locus is a circle, an ellipse, or a hyperbola,^[134] the point M, the center of the figure, must first be found. This

^[130] Rabuel (p. 167) adds "If $a^2m = px^2$ or if $m = p$ the hyperbola is equilateral."

^[131] In this case the triangle ILK is a right triangle, whence $\overline{IK}^2 = \overline{LK}^2 + \overline{IC}^2$; but by hypothesis IL : IK : KL = $a : z : n$; then $a^2 + n^2 = z^2$. Now the equation of the curve is

$$y = m - \frac{n}{z} + x\sqrt{m^2 + oz - \frac{p}{m}x^2},$$

and therefore the term in x^2 is

$$\left(\frac{n^2}{z^2} + \frac{p}{m}\right)x^2;$$

and if $a^2m = px^2$, then $\frac{p}{m} = \frac{a^2}{z^2}$, and this term in x^2 becomes $\frac{a^2+n^2}{z^2}x^2 = x^2$.

Therefore, the coefficients of x^2 and y^2 are unity and the locus is a circle.

^[132] This may be seen as follows: From the figure, and by the nature of the parabola $\overline{LC}^2 = \overline{LN} \cdot p$ and $\overline{LN} = \overline{IL} + \overline{IN}$. Let $\overline{IN} = \phi$; then since $\overline{IL} = \frac{a}{z}x$, we have $\overline{LN} = \frac{a}{z}x + \phi$ and $\overline{LC} = y - m + \frac{n}{z}x$; whence $(y - m + \frac{n}{z}x)^2 = (\frac{a}{z}x + \phi)p$. But $(y - m + \frac{n}{z}x)^2 = m^2 + oz$ from the equation of the parabola; therefore $\frac{a}{z}xp + \phi p = m^2 + oz$. Equating coefficients, we have $\frac{a}{z}p = o$; $p = \frac{oz}{a}$; $\phi p = m^2$; $\phi \frac{oz}{a} = m^2$; $\phi = \frac{am^2}{oz}$.

^[133] *Apollonii Pergaei Quae Graece exstant* edidit I. L. Heiberg, Leipzig, 1891. Vol. I, p. 159, Liber I, Prop. LII. Hereafter referred to as Apollonius. This may be freely translated as follows: To describe in a plane a parabola, having given the parameter, the vertex, and the angle between an ordinate and the corresponding abscissa.

^[134] Central conics are thus grouped together by Descartes, the circle being treated as a special form of the ellipse, but being mentioned separately in all cases.

Que si la ligne demãdée est vn cercle, ou vne ellipse, ou vne Hyperbole, il faut premierement chercher le point M, qui en est le centre, & qui est tousiours en la ligne droite IL, ou on le trouue en prenant $\frac{ao m}{2 p r}$ pour IM. en sorte que si la quantité o est nulle, ce centre est iustement au point I. Et si la ligne cherchée est vn cercle, ou vne Ellipse; on doit prendre le point M du mesme costé que le point L, au respect du point I, lorsqu'on a $+ o x$; & lorsqu'on a $-- o x$, on le doit prendre de l'autre. Mais tout au contraire en l'Hyperbole, si on a $-- o x$, ce centre M doit estre vers L; & si on a $+ o x$, il doit estre de l'autre costé. Après cela le costé droit de la figure doit estre

$\sqrt{\frac{o o x x}{a a} + \frac{4 m p x x}{a a}}$ lorsqu'on a $+ m m$, & que la ligne cherchée est vn cercle, ou vne Ellipse; ou bien lorsqu'on a $-- m m$, & que c'est vne Hyperbole. & il doit estre

$\sqrt{\frac{o o x x}{a a} - \frac{4 m p x x}{a a}}$ si la ligne cherchée estant vn cercle, ou vne Ellipse, on a $-- m m$; ou bien si estant vne Hyperbole & la quantité $o o$ estant plus grande que $4 m p$, on a $+ m m$. Que si la quantité $m m$ est nulle, ce costé droit

est $\frac{o x}{a}$, & si $o x$ est nulle, il est $\sqrt{\frac{4 m p x x}{a a}}$. Puis pour le costé traversant, il faut trouuer vne ligne; qui soit a ce costé droit, cõme $a a m$ est à $p x x$, à sçauoir si ce costé droit est

$\sqrt{\frac{o o x x}{a a} + \frac{4 m p x x}{a a}}$ le trauerfant est $\sqrt{\frac{a a o o m m}{p p x x} + \frac{4 a a m}{p x x}}$;

Et en tous ces cas le diametre de la section est en la ligne IM, & LC est l'une de celles qui luy est appliquée par ordre. Sibienque faisant MN esgale a la moitié du costé trauer-

will always lie on the line IL and may be found by taking IM equal to $\frac{aom}{2pz}$.^[115] If o is equal to zero M coincides with I. If the required locus is a circle or an ellipse, M and L must lie on the same side of I when the term ox is positive and on opposite sides when ox is negative. On the other hand, in the case of the hyperbola, M and L lie on the same side of I when ox is negative and on opposite sides when ox is positive.

The latus rectum of the figure must be

$$\sqrt{\frac{o^2 z^2}{a^2} + \frac{4mpz^2}{a^2}}$$

if m^2 is positive and the locus is a circle or an ellipse, or if m^2 is negative and the locus is a hyperbola. It must be

$$\sqrt{\frac{o^2 z^2}{a^2} - \frac{4mpz^2}{a^2}}$$

if the required locus is a circle or an ellipse and m^2 is negative, or if it is an hyperbola and o^2 is greater than $4mp$, m^2 being positive.

But if m^2 is equal to zero, the latus rectum is $\frac{oz}{a}$; and if oz is equal to zero^[116], it is

$$\sqrt{\frac{4mpz^2}{a^2}}$$

For the corresponding diameter a line must be found which bears the ratio $\frac{a^2 m}{pz^2}$ to the latus rectum; that is, if the latus rectum is

$$\sqrt{\frac{o^2 z^2}{a^2} + \frac{4mpz^2}{a^2}}$$

the diameter is

$$\sqrt{\frac{a^2 o^2 m^2}{p^2 z^2} + \frac{4a^2 m^3}{pz^2}}$$

In every case, the diameter of the section lies along IM, and LC is one of its lines applied in order.^[117] It is thus evident that, by making MN equal to half the diameter and taking N and L on the same side of M,

[115] Cf. Briot and Bouquet, p. 156.

[116] Some editions give, incorrectly, ox for oz .

[117] See note 108.

the point N will be the vertex of this diameter.^[118] It is then a simple matter to determine the curve, according to the second and third problems of the first book of Apollonius.^[119]

When the locus is a hyperbola^[120] and m^2 is positive, if o^2 is equal to zero or less than $4pm$ we must draw the line MOP from the center M parallel to LC, and draw CP parallel to LM, and take MO equal to

$$\sqrt{m^2 - \frac{o^2 m}{4p}};$$

while if ox is equal to zero, MO must be taken equal to m . Then considering O as the vertex of this hyperbola, the diameter being OP and the line applied in order being CP, its latus rectum is

$$\sqrt{\frac{4a^4 m^4}{p^2 z^4} - \frac{a^4 o^2 m^3}{p^3 z^4}}$$

and its diameter^[121] is

$$\sqrt{4m^2 - \frac{o^2 m}{p}}.$$

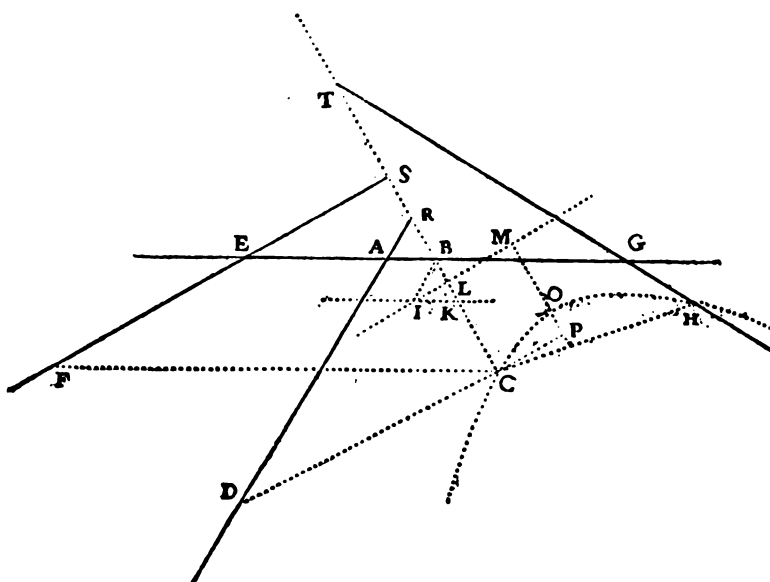
^[118] If the equation contains $-m^2$ and $+nx$, then n^2 must be greater than $4mp$, otherwise the problem is impossible.

^[119] Cf. Apollonius, Vol. I, p. 173, Lib. I, Prop. LV: To describe a hyperbola, given the axis, the vertex, the parameter, and the angle between the axes. Also see Prop. LVI: To describe an ellipse, etc.

^[120] Cf. Letters of Descartes, Cousin, Vol. VIII, p. 142.

^[121] "Côté traversant."

traverfant & le prenant du mesme costé du point M, qu'est le point L, on a le point N pour le sommet de ce diametre. en suite dequoy il est aysé de trouver la section par le second & 3 prob. du 1^{er}. liu. d'Apollonius.



Mais quand cete section estant vne Hyperbole, on à $+mm$; & que la quantité oo est nulle ou plus petite que $4pm$, on doit tirer du centre M la ligne MOP parallele a LC, & CP parallele à LM: & faire MO esgale a $\sqrt{mm - \frac{oo m}{4p}}$; ou bien la faire esgale à m si la quantité oo est nulle. Puis considerer le point O, cōme le sommet de cete Hyperbole; dont le diametre est OP, & CP la

T t 2

ligne

ligne qui luy est appliquée par ordre, & son costé droit est

$$\sqrt{\frac{4a^4m^4}{p^2p^2z^4} - \frac{a^4o^4m^4}{p^2z^4}}, \text{ \& son costé trauersant est } \sqrt{4mm - \frac{o^4m}{p}}$$

Excepté quand o est nulle. car alors le costé droit est $\frac{2aam}{pzz}$, & le trauersant est $2m$. & ainsi il est aysé de la trouuer par le 3 prob. du 1^{er}. liu. d'Apollonius.

Demor-
stration
de tout ce
qui vient
d'estre
expliqué.

Et les demonstres de tout cecy sont euidentes. car composant vn espace des quantités que iay assignées pour le costé droit, & le trauersant, & pour le segment du diametre NL, ou OP, suiuant la teneur de l'11, du 12, & du 13 theoremes du 1^{er}. liure d'Apollonius, on trouuera tous les mesmes termes dont est composé le quarré de la ligne CP, ou CL, qui est appliquée par ordre a ce diametre. Comme en cet exemple ostant IM, qui est

$$\frac{aom}{ap\gamma}, \text{ de NM, qui est } \frac{am}{2p\gamma} \sqrt{oo + 4mp}, \text{ iay IN, a laquelle aionstant IL, qui est } \frac{a}{z}x, \text{ iay NL, qui est } \frac{a}{\gamma}x - \frac{aom}{2p\gamma}$$

$$+ \frac{am}{2pz} \sqrt{a.a + 4mp}, \text{ \& cecy estant multiplié par } \frac{x}{a} \sqrt{oo + 4mp}, \text{ qui est le costé droit de la figure, il vient}$$

$$x \sqrt{oo + 4mp} - \frac{o^4m}{2p} \sqrt{a.a + 4mp} + \frac{mo^4}{2p} + 2mm.$$

pour le rectangle. duquel il faut oster vn espace qui soit au quarré de NL comme le costé droit est au trauersant.

$$\text{\& ce quarré de NL est } \frac{aa}{zz}xx - \frac{aom}{pzz}x$$

$$+ \frac{aam}{pzz\gamma}x \sqrt{oo + 4mp} + \frac{aaoom\gamma}{2ppzz} + \frac{aam}{pzz} \\ = \frac{aom}{2ppzz}$$

An exception must be made when ox is equal to zero, in which case the latus rectum is $\frac{2a^2m^2}{pz^2}$ and the diameter is $2m$. From these data the curve can be determined in accordance with the third problem of the first book of Apollonius.^[120]

The demonstrations of the above statements are all very simple, for, forming the product^[121] of the quantities given above as latus rectum, diameter, and segment of the diameter NL or OP , by the methods of Theorems 11, 12, and 13 of the first book of Apollonius, the result will contain exactly the terms which express the square of the line CP or CL , which is an ordinate of this diameter.

In this case take IM or $\frac{aom}{2pz}$ from NM or from its equal

$$\frac{am}{2pz} \sqrt{o^2 + 4mp}.$$

To the remainder IN add IL or $\frac{a}{z}x$, and we have

$$NL = \frac{a}{z}x - \frac{aom}{2pz} + \frac{am}{2pz} \sqrt{o^2 + 4mp}.$$

Multiplying this by

$$\frac{z}{a} \sqrt{o^2 + 4mp},$$

the latus rectum of the curve, we get

$$x \sqrt{o^2 + 4mp} - \frac{om}{2p} \sqrt{o^2 + 4mp} + \frac{mo^2}{2p} + 2m^2$$

for the rectangle, from which is to be subtracted a rectangle which is to the square of NL as the latus rectum is to the diameter. The square of NL is

$$\frac{a^2}{2^2} x^2 - \frac{a^2 om}{pz^2} x + \frac{a^2 m}{pz^2} x \sqrt{o^2 + 4mp} + \frac{a^2 o^2 m^2}{2p^2 z^2} + \frac{a^2 m^2}{pz^2} - \frac{a^2 om^2}{2p^2 z^2} \sqrt{o^2 + 4mp}.$$

[120] See note 113.

[121] "Composant un espace."

Divide this by a^2m and multiply the quotient by pz^2 , since these terms express the ratio between the diameter and the latus rectum. The result is

$$\frac{p}{m}x^2 - ox + x\sqrt{o^2 + 4mp} + \frac{o^2m}{2p} - \frac{om}{2p}\sqrt{o^2 + 4mp} + m^2.$$

This quantity being subtracted from the rectangle previously obtained, we get

$$\overline{CL}^2 = m^2 + ox - \frac{p}{m}x^2.$$

It follows that CL is an ordinate of an ellipse or circle applied to NL, the segment of the axis.

Suppose all the given quantities expressed numerically, as EA=3, AG=5, AB=BR, BS= $\frac{1}{2}$ BE, GB=BT, CD= $\frac{3}{2}$ CR, CF=2CS, CH= $\frac{2}{3}$ CT, the angle ABR=60°; and let CB.CF=CD.CH. All these quantities must be known if the problem is to be entirely determined. Now let AB= x , and CB= y . By the method given above we shall obtain

$$y^2 = 2y - xy + 5x - x^2;$$

$$y = 1 - \frac{1}{2}x + \sqrt{1 + 4x - \frac{3}{4}x^2};$$

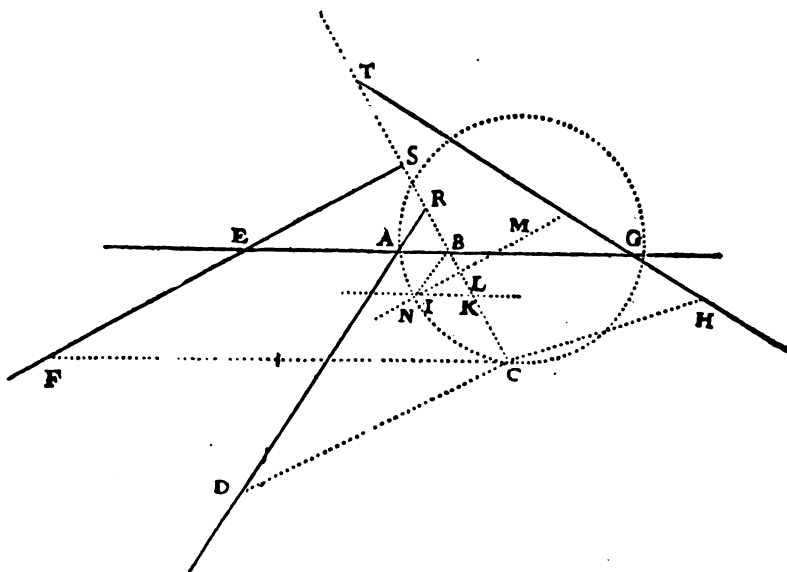
whence BK must be equal to 1, and KL must be equal to one-half KI; and since the angle IKL = angle ABR = 60° and angle KIL (which is one-half angle KIB or one-half angle IKL) is 30°, the angle ILK is a right angle. Since IK=AB= x , KL= $\frac{1}{2}x$, IL= $x\sqrt{\frac{3}{4}}$, and the quantity represented by z above is 1, we have $a = \sqrt{\frac{3}{4}}$, $m = 1$, $o = 4$, $p = \frac{3}{4}$, whence IM= $\sqrt{\frac{16}{3}}$, NM= $\sqrt{\frac{19}{3}}$; and since a^2m (which is $\frac{3}{4}$) is equal to pz^2 , and

$-\frac{a a o m m}{2 p p x x} \sqrt{00 + 4 m p}$ qu'il faut diuifer par $a a m$ & multiplier par $p x x$, a cause que ces termes expliquent la proportion qui est entre le costé trauerfant & le droit, & il vient $\frac{p}{m} x x -- o x + x \sqrt{00 + 4 m p} + \frac{o o m}{2 p}$ $-\frac{o m}{2 p} \sqrt{00 + 4 m p} + m m$. cequ'il faut oster du rectangle precedent, & on trouue $m m + o x -- \frac{p}{m} x x$ pour le quarre de C L, qui par consequent est vne ligne appliquée par ordre dans vne Ellipse, ou dans vn cercle, au segment du diametre N L.

Et si on vent expliquer toutes les quantités données par nombres, en faisant par exemple $E A \propto 3$, $A G \propto 5$, $A B \propto B R$, $B S \propto \frac{1}{2} B E$, $G B \propto B T$, $C D \propto \frac{1}{2} C R$, $C F \propto 2 C S$, $C H \propto \frac{2}{3} C T$, & que l'angle A B R soit de 60 degrés, & enfin que le rectangle des deux C B, & C F, soit esgal au rectangle des deux autres C D & C H, car il faut auoir toutes ces choses affin que la question soit entierement determinée. & avec cela supposant $A B \propto x$, & $C B \propto y$, on trouue par la façon cy dessus expliquée $y y \propto 2 y -- x y + 5 x -- x x$ & $y \propto 1 -- \frac{1}{2} x + \sqrt{1 + 4 x -- \frac{3}{4} x x}$: si bien que B K doit estre 1, & K L doit estre la moitié de K I, & pourceque l'angle I K L ou A B R est de 60 degrés, & K I L qui est la moitié de K I B ou I K L, de 30, I L K est droit. Et pourceque I K ou A B est nomme x , K L est $\frac{1}{2} x$, & I L est $x \sqrt{\frac{3}{4}}$, & la quantité qui estoit tantost nommée x est 1, celle qui estoit a est $\sqrt{\frac{3}{4}}$, celle qui estoit m est 1, celle qui estoit o est 4, & celle qui estoit p est $\frac{3}{4}$, de façon qu'on a $\sqrt{\frac{16}{3}}$

Tit 3.

pour.



pour IM, & $\sqrt{1\frac{1}{2}}$ pour NM, & pourceque *aam* qui est $\frac{3}{4}$ est icy esgal à *pqx* & que l'angle IL C est droit, on trouue que la ligne courbe NC est vn cercle. Et on peut facilement examiner tous les autres cas en mesme sorte.

**Quels
sont les
lieux
plans, &
solides: &
la facon
de les
trouver.**

Au reste a cause que les equations, qui ne montent que iusques au quarre, sont toutes comprises en ce que ie viens d'expliquer; non seulement le problemes des anciens en 3 & 4 lignes est icy entierement acheué; mais aussy tout ce qui appartient à ce qu'ils nommoient la composition des lieux solides; & par consequent aussy a celle des lieux plans, a cause qu'ils sont compris dans les solides. Car ces lieux ne sont autre chose, sinon que lors qu'il est question de trouuer quelque point auquel il manque

the angle ILC is a right angle, it follows that the curve NC is a circle. A similar treatment of any of the other cases offers no difficulty.

Since all equations of degree not higher than the second are included in the discussion just given, not only is the problem of the ancients relating to three or four lines completely solved, but also the whole problem of what they called the composition of solid loci, and consequently that of plane loci, since they are included under solid loci.^[136] For the solution of any one of these problems of loci is nothing more than the finding of a point for whose complete determination one con-

^[136] Since plane loci are degenerate cases of solid loci. The case in which neither x^2 nor y^2 but only xy occurs, and the case in which a constant term occurs, are omitted by Descartes. The various kinds of solid loci represented by the equation $y = \pm m \pm \frac{n}{z}x \pm \frac{n^2}{x} \pm \sqrt{\pm m^2 \pm ox \pm \frac{p}{m}x}$ may be summarized as follows:

(1) If all the terms of the right member are zero except $\frac{n^2}{x}$, the equation represents an hyperbola referred to its asymptotes. (2) If $\frac{n^2}{x}$ is not present, there are several cases, as follows: (a) If the quantity under the radical sign is zero or a perfect square, the equation represents a straight line; (b) If this quantity is not a perfect square and if $\frac{p}{m}x^2 = 0$, the equation represents a parabola; (c) If it is not a perfect square and if $\frac{p}{m}x^2$ is negative, the equation represents a circle or an ellipse; (d) If $\frac{p}{m}x^2$ is positive, the equation represents a hyperbola. Rabuel, p. 248.

dition is wanting, the other conditions being such that (as in this example) all the points of a single line will satisfy them. If the line is straight or circular, it is said to be a plane locus; but if it is a parabola, a hyperbola, or an ellipse, it is called a solid locus. In every such case an equation can be obtained containing two unknown quantities and entirely analogous to those found above. If the curve upon which the required point lies is of higher degree than the conic sections, it may be called in the same way a supersolid locus,^[138] and so on for other cases. If two conditions for the determination of the point are lacking, the locus of the point is a surface, which may be plane, spherical, or more complex. The ancients attempted nothing beyond the composition of solid loci, and it would appear that the sole aim of Apollonius in his treatise on the conic sections was the solution of problems of solid loci.

I have shown, further, that what I have termed the first class of curves contains no others besides the circle, the parabola, the hyperbola, and the ellipse. This is what I undertook to prove.

^[138] "Un lieu sursolide."

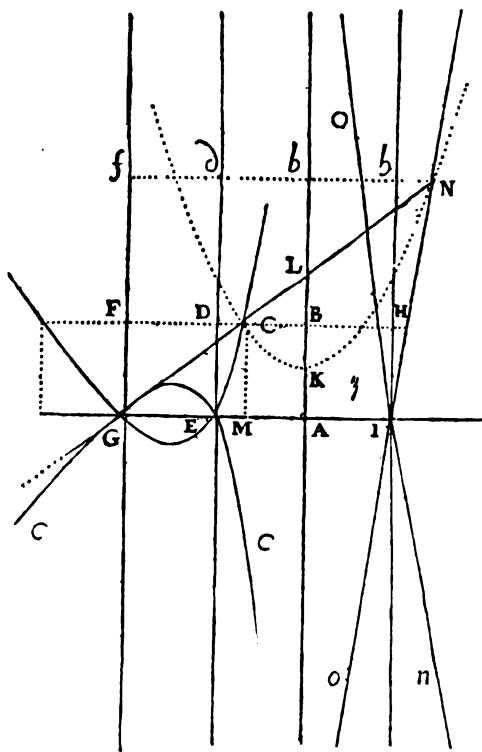
manque vne condition pour estre entierement determiné, ainsi qu'il arrive en cete exemple, tous les poins d'une mesme ligne peuvent estre pris pour celuy qui est demandé. Et si cete ligne est droite, ou circulaire, on la nomme vn lieu plan. Mais si c'est vne parabole, ou vne hyperbole, ou vne ellipse, on la nomme vn lieu solide. Et toutefois & quantes que cela est, on peut venir a vne Equation qui contient deux quantités inconnues, & est pareille a quelqu'une de celles que ie viens de resoudre. Que si la ligne qui determine ainsi le point cherché, est d'un degré plus composée que les sections coniques, on la peut nommer, en mesme façon, vn lieu sur solide, & ainsi des autres. Et s'il manque deux conditions a la determination de ce point, le lieu ou il se trouue est vne superficie, laquelle peut estre tout de mesme ou plate, ou spherique, ou plus composée. Mais le plus haut but qu'ayent eu les anciens en ceté matiere a esté de parvenir a la composition des lieux solides: Et il semble que tout ce qu'Apollonius a escrit des sections coniques n'a esté qu'à dessein de la chercher.

De plus on voit icy que ce que iay pris pour le premier genre des lignes courbes, n'en peut comprendre aucunes autres que le cercle, la parabole, l'hyperbole, & l'ellipse. qui est tout ce que i'auois entrepris de prouver.

Que si la question des anciens est proposée en cinq lignes, qui soient toutes paralleles; il est evident que le point cherché sera tousiours en vne ligne droite. Mais si elle est proposée en cinq lignes, dont il y en ait quatre qui soient paralleles, & que la cinquieme les coupe a angles droits, & mesme que toutes les lignes tirées du point

Quelle est la premiere & la plus simple de toutes les lignes courbes qui servent en la question des anciens quand elle est proposée en cinq lignes.

point cherché les rencontrent auffy a angles droits, & enfin que le parallelepipedé composé de trois. des lignes ainfi tirées sur trois de celles qui font paralleles, soit esgal au parallelepipedé composé des deux lignes tirées l'une sur la quatriefme de celles qui font paralleles & l'autre sur celle qui les coupe a angles droits, & d'une troisieme ligne donnée. ce qui est ce semble le plus simple cas qu'on puisse imaginer après le precedent ; le point cherché fera en la ligne courbe, qui est descrite par le mouuement d'une parabole en la façon cy dessus expliquée.



Soient

SECOND BOOK

If the problem of the ancients be proposed concerning five lines, all parallel, the required point will evidently always lie on a straight line. Suppose it be proposed concerning five lines with the following conditions:

(1) Four of these lines parallel and the fifth perpendicular to each of the others ;

(2) The lines drawn from the required point to meet the given lines at right angles ;

(3) The parallelepiped^[126] composed of the three lines drawn to meet three of the parallel lines must be equal to that composed of three lines, namely, the one drawn to meet the fourth parallel, the one drawn to meet the perpendicular, and a certain given line.

This is, with the exception of the preceding one, the simplest possible case. The point required will lie on a curve generated by the motion of a parabola in the following way:

^[126] That is, the product of the numerical measures of these lines.

Let the required lines be AB, IH, ED, GF, and GA, and let it be required to find the point C, such that if CB, CF, CD, CH, and CM be drawn perpendicular respectively to the given lines, the parallelepiped of the three lines CF, CD, and CH shall be equal to that of the other two, CB and CM, and a third line AI. Let $CB=y$, $CM=x$, AI or AE or $GE=a$; whence if C lies between AB and DE, we have $CF=2a-y$, $CD=a-y$, and $CH=y+a$. Multiplying these three together we get $y^3-2ay^2-a^2y+2a^3$ equal to the product of the other three, namely to axy .

I shall consider next the curve CEG, which I imagine to be described by the intersection of the parabola CKN (which is made to move so that its axis KL always lies along the straight line AB) with the ruler GL (which rotates about the point G in such a way that it constantly lies in the plane of the parabola and passes through the point L). I take KL equal to a and let the principal parameter, that is, the parameter corresponding to the axis of the given parabola, be also equal to a , and let $GA=2a$, CB or $MA=y$, CM or $AB=x$. Since the triangles GMC and CBL are similar, GM (or $2a-y$) is to MC (or x) as CB (or y) is to BL, which is therefore equal to $\frac{xy}{2a-y}$. Since KL is a , BK is $a - \frac{xy}{2a-y}$ or $\frac{2a^2-ay-xy}{2a-y}$. Finally, since this same BK is a segment of the axis of the parabola, BK is to BC (its ordinate) as BC is to a (the latus rectum), whence we get $y^3-2ay^2-a^2y+2a^3=axy$, and therefore C is the required point.

Soient par exemple les lignes cherchées $AB, IH, ED, GF, \& GA$. & qu'on demande le point C , en sorte que tirant $CB, CF, CD, CH, \& CM$ a angles droits sur les données, le parallelepipedes des trois $CF, CD, \& CH$ soit esgal a celuy des 2 autres $CB, \& CM$, & d'une troi-fiesme qui soit AI . Je pose $CB \propto y$. $CM \propto x$. AI , ou AE , ou $GE \propto a$, de façon que le point C estant entre les lignes $AB, \& DE$, iay $CF \propto 2a - y$, $CD \propto a - y$. & $CH \propto y + a$ & multipliant ces trois l'une par l'autre, iay $y^3 - 2ayy - aay + 2a^3$ esgal au produit des trois autres qui est axy . Après cela ie considere la ligne cour-be CEG , que i' imagine estre descrite par l'interfection, de la Parabole CKN , qu'on fait mouvoir en telle sorte que son diametre KL est tousiours sur la ligne droite AB , & de la reigle GL qui tourne cependant autour du point G en telle sorte quelle passe tousiours dans le plan de cete Parabole par le point L . Et ie fais $KL \propto a$, & le costé droit principal, c'est a dire celuy qui se rapporte a l'aissieu de cete parabole, aussy esgal à a , & $GA \propto 2a$, & CB ou $MA \propto y$, & CM ou $AB \propto x$. Puis a cause des triangles semblables $GMC, \& CBL$, GM qui est $2a - y$, est à MC qui est x , comme CB qui est y , est à BL qui est par consequent $\frac{xy}{2a - y}$. Et pourceque LK est a , BK est $a - \frac{xy}{2a - y}$, ou bien $\frac{2aa - ay - xy}{2a - y}$. Et enfin pourceque ce mes-me BK estant vn segment du diametre de la Parabole, est à BC qui luy est appliquée par ordre, comme cel-lecy est au costé droit qui est a , le calcul monstre que $y^3 - 2ayy - aay + 2a^3$, est esgal à axy . & par conse-

V v
quent

SECOND BOOK

The point C can be taken on any part of the curve CEG or of its adjunct $cEGc$, which is described in the same way as the former, except that the vertex of the parabola is turned in the opposite direction; or it may lie on their counterparts^[127] NIo and nIO , which are generated by the intersection of the line GL with the other branch of the parabola KN .

Again, suppose that the given parallel lines AB , IH , ED , and GF are not equally distant from one another and are not perpendicular to GA , and that the lines through C are oblique to the given lines. In this case the point C will not always lie on a curve of just the same nature. This may even occur when no two of the given lines are parallel.

^[127] "En leurs contreposées."

Next, suppose that we have four parallel lines, and a fifth line cutting them, such that the parallelepiped of three lines drawn through the point C (one to the cutting line and two to two of the parallel lines) is equal to the parallelepiped of two lines drawn through C to meet the other two parallels respectively and another given line. In this case the required point lies on a curve of different nature,^[129] namely, a curve such that, all the ordinates to its axis being equal to the ordinates of a conic section, the segments of the axis between the vertex and the ordinates^[130] bear the same ratio to a certain given line that this line bears to the segments of the axis of the conic section having equal ordinates.^[130]

I cannot say that this curve is less simple than the preceding ; indeed, I have always thought the former should be considered first, since its description and the determination of its equation are somewhat easier.

I shall not stop to consider in detail the curves corresponding to the other cases, for I have not undertaken to give a complete discussion of the subject ; and having explained the method of determining an infinite number of points lying on any curve, I think I have furnished a way to describe them.

It is worthy of note that there is a great difference between this method^[131] in which the curve is traced by finding several points upon

^[129] The general equation of this curve is $axy - xy^2 + 2a^2x = a^2y - ay^2$. Rabuel, p. 270.

^[130] That is, the abscissas of points on the curve.

^[130] The thought, expressed in modern phraseology, is as follows : The curve is of such nature that the abscissa of any point on it is a third proportional to the abscissa of a point on a conic section whose ordinate is the same as that of the given point, and a given line. Cf. Rabuel, pp. 270, et seq.

^[131] That is, the method of analytic geometry.

tirées du point C vers elles, ce point C ne laisseroit pas de se trouver toujours en vne ligne courbe, qui seroit de cete mesme nature. Et il s'y peut aussy trouver quelquefois, encore qu'aucune des lignes données ne soient paralleles. Mais si lorsqu'il y en a 4 ainsi paralleles, & vne cinquiesme qui les traaverse: & que le parallelepiped de trois des lignes tirées du point cherché, l'une sur cete cinquiesme, & les 2 autres sur 2 de celles qui sont paralleles; soit esgale a celuy, des deux tirées sur les deux autres paralleles, & d'une autre ligne donnée. Ce point cherché est en vne ligne courbe d'une autre nature, a sçavoir en vne qui est telle, que toutes les lignes droites appliquées par ordre a son diametre estant esgales a celles d'une section conique, les segmens de ce diametre, qui sont entre le sommet & ces lignes, ont mesme proportion a vne certaine ligne donnée, que cete ligne donnée a aux segmens du diametre de la section conique, auxquels les pareilles lignes sont appliquées par ordre. Et ie ne sçauois veritablement dire que cete ligne soit moins simple que la precedente, laquelle iay creu toute-fois deuoir prendre pour la premiere, a cause que la description, & le calcul en sont en quelque façon plus faciles.

Pour les lignes qui seruent aux autres cas, ie ne m'arrestay point a les distinguer par especes. car ie n'ay pas entrepris de dire tout; & ayant expliqué la façon de trouver vne infinité de poins par ou elles passent, ie pense auoir assez donné le moyen de les descrire.

Mesme il est a propos de remarquer, qu'il y a grande difference entre cete façon de trouver plusieurs poins

V v 2

pour

Quelles
sont les
lignes
courbes
qu'on de-
crit en
trouuant
plusieurs
de leurs
poins, qui
peuuent
estre re-
ceues en
Geome-
trie.

pour tracer vne ligne courbe, & celle dont on se sert pour la spirale, & ses semblables. car par cete derniere on ne trouue pas indifferẽment tous les poins de la ligne qu'on cherche, mais seulement ceux qui peuuent estre determinés par quelque mesure plus simple, que celle qui est requise pour la composer, & ainsi a proprement parler on ne trouue pas vn de ses poins. c'est a dire pas vn de ceux qui luy sont tellement propres, qu'ils ne puissent estre trouués que par elle: Au lieu qu'il ny a aucun point dans les lignes qui seruent a la question proposée, qui ne se puisse rencontrer entre ceux qui se determinent par la façon tantost expliquée. Et pourceque cete façon de tracer une ligne courbe, en trouuant indifferẽment plusieurs de ses poins, ne s'estend qu'a celles qui peuuent aussi estre descrites par vn mouuement regulier & continu, on ne la doit pas entierement reietter de la Geometrie.

Quelles
sont aussi
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Et on n'en doit pas reietter non plus, celle ou on se sert d'un fil, ou d'une chorde repliée, pour determiner l'egalité ou la difference de deux ou plusieurs lignes droites qui peuuent estre tirées de chaque point de la courbe qu'on cherche, a certains autres poins, ou sur certaines autres lignes a certains angles. ainsi que nous auons fait en la Dioptrique pour expliquer l'Ellipse & l'Hyperbole. car encore qu'on n'y puisse recevoir aucunes lignes qui semblent a des chordes, c'est a dire qui deuiennent tantost droites & tantost courbes, a cause que la proportion, qui est entre les droites & les courbes, n'estant pas connue, & mesme ie croy ne le pouuant estre par les hommes, on ne pourroit rien conclure de là qui fust

it, and that used for the spiral and similar curves.^[122] In the latter not any point of the required curve may be found at pleasure, but only such points as can be determined by a process simpler than that required for the composition of the curve. Therefore, strictly speaking, we do not find any one of its points, that is, not any one of those which are so peculiarly points of this curve that they cannot be found except by means of it. On the other hand, there is no point on these curves which supplies a solution for the proposed problem that cannot be determined by the method I have given.

But the fact that this method of tracing a curve by determining a number of its points taken at random applies only to curves that can be generated by a regular and continuous motion does not justify its exclusion from geometry. Nor should we reject the method^[123] in which a string or loop of thread is used to determine the equality or difference of two or more straight lines drawn from each point of the required curve to certain other points,^[124] or making fixed angles with certain other lines. We have used this method in "La Dioptrique"^[125] in the discussion of the ellipse and the hyperbola.

On the other hand, geometry should not include lines that are like strings, in that they are sometimes straight and sometimes curved, since the ratios between straight and curved lines are not known, and I believe cannot be discovered by human minds,^[126] and therefore no conclusion based upon such ratios can be accepted as rigorous and exact.

^[122] That is, transcendental curves, called by Descartes "mechanical" curves.

^[123] Cf. the familiar "mechanical descriptions" of the conic sections.

^[124] As for example, the foci, in the description of the ellipse.

^[125] This work was published at Leyden in 1637, together with Descartes's *Discours de la Methode*.

^[126] This is of course concerned with the problem of the rectification of curves. See Cantor, Vol. II (1), pp. 794 and 807, and especially p. 778. This statement, "ne pouvant être par les hommes" is a very noteworthy one, coming as it does from a philosopher like Descartes. On the philosophical question involved, consult such writers as Bertrand Russell.

Nevertheless, since strings can be used in these constructions only to determine lines whose lengths are known, they need not be wholly excluded.

When the relation between all points of a curve and all points of a straight line is known,^[127] in the way I have already explained, it is easy to find the relation between the points of the curve and all other given points and lines; and from these relations to find its diameters, axes, center and other lines^[128] or points which have especial significance for this curve, and thence to conceive various ways of describing the curve, and to choose the easiest.

By this method alone it is then possible to find out all that can be determined about the magnitude of their areas,^[129] and there is no need for further explanation from me.

^[127] Expressed by means of the equation of the curve.

^[128] For example, the equations of tangents, normals, etc.

^[129] For the history of the quadrature of curves, consult Cantor, Vol. II (1), pp. 758, et seq., Smith, *History*, Vol. II, p. 302.

fust exact & assuré. Toutefois a cause qu'on ne se sert de chordes en ces constructions, que pour déterminer des lignes droites, dont on connoist parfaitement la longueur, cela ne doit point faire qu'on les reiette.

Or de cela seul qu'on sçait le rapport, qu'ont tous les poins d'une ligne courbe a tous ceux d'une ligne droite, en la façon que iay expliquée; il est ayisé de trouver aussi le rapport qu'ils ont a tous les autres poins, & lignes données: & en suite de connoistre les diametres, les aissieux, les centres, & autres lignes, ou poins, a qui chascune ligne courbe aura quelque rapport plus particulier, ou plus simple, qu'aux autres: & ainsi d'imaginer diuers moyens pour les descrire, & d'en choisir les plus faciles. Et mesme on peut aussi par cela seul trouver quasi tout ce qui peut estre déterminé touchant la grandeur de l'espace quelles comprennent, sans qu'il soit besoin que l'en donne plus d'ouverture. Et enfin pour ce qui est de toutes les autres propriétés qu'on peut attribuer aux lignes courbes, elles ne dependent que de la grandeur des angles qu'elles font avec quelques autres lignes. Mais lorsqu'on peut tirer des lignes droites qui les coupent a angles droits, aux poins ou elles sont rencontrées par celles avec qui elles font les angles qu'on veut mesurer, ou, ce que ie prens icy pour le mesme, qui coupent leurs contingentes; la grandeur de ces angles n'est pas plus malayisée a trouver, que s'ils estoient compris entre deux lignes droites. C'est pourquoy ie croyray avoir mis icy tout ce qui est requis pour les elemens des lignes courbes, lorsque j'auray generalement donné la façon de tirer des lignes droites, qui tombent a angles droits sur

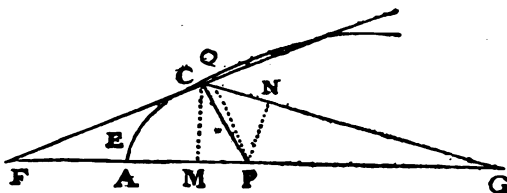
Que pour
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coupent
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a angles
droits.

Vv. 3

tels

tels de leurs points qu'on voudra choisir. Et i'ose dire que c'est cecy le problême le plus vtile, & le plus general non seulement que ie sçache, mais mesme que i'aye iamais désiré de sçavoir en Geometrie.

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trouver
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courbes
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ou leurs
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gentes, a
angles
droits.



Soit C E
la ligne courbe,
& qu'il faille ti-
rer vne ligne
droite par le
point C, qui fa-

ce avec elle des angles droits. Je suppose la chose desia faite, & que la ligne cherchée est C P; laquelle ie prolonge iusques au point P, ou elle rencontre la ligne droite G A, que ie suppose estre celle aux points de laquelle on rapporte tous ceux de la ligne C E: en sorte que faisant M A ou C B $\propto y$, & C M, ou B A $\propto x$, iay quelque equation, qui explique le rapport, qui est entre x & y . Puis ie fais P C $\propto s$, & P A $\propto v$, ou P M $\propto v - y$, & a cause du triangle rectangle P M C iay ss , qui est le quar-
ré de la baze esgal à $xx + vv - 2vy + yy$, qui sont les quarrés des deux costés. c'est a dire iay $x \propto \sqrt{ss - vv + 2vy - yy}$, ou bien $y \propto v + \sqrt{ss - xx}$, & par le moyen de cete equation, i'oste de l'autre equation qui m'explique le rapport qu'ont tous les points de la courbe C E a ceux de la droite G A, l'une des deux quantités indeterminées x ou y . ce qui est aisé a faire en mettant partout $\sqrt{ss - vv + 2vy - yy}$ au lieu d' x , & le quarré de cete somme au lieu d' xx , & son cube au lieu d' x^3 , & ainsi des autres, si c'est x que ie veuille oster; ou bien

Finally, all other properties of curves depend only on the angles which these curves make with other lines. But the angle formed by two intersecting curves can be as easily measured as the angle between two straight lines, provided that a straight line can be drawn making right angles with one of these curves at its point of intersection with the other.^[140] This is my reason for believing that I shall have given here a sufficient introduction to the study of curves when I have given a general method of drawing a straight line making right angles with a curve at an arbitrarily chosen point upon it. And I dare say that this is not only the most useful and most general problem in geometry that I know, but even that I have ever desired to know.

Let CE be the given curve, and let it be required to draw through C a straight line making right angles with CE. Suppose the problem solved, and let the required line be CP. Produce CP to meet the straight line GA, to whose points the points of CE are to be related.^[141] Then, let $MA=CB=y$; and $CM=BA=x$. An equation must be found expressing the relation between x and y .^[142] I let $PC=s$, $PA=v$, whence $PM=v-y$. Since PMC is a right triangle, we see that s^2 , the square of the hypotenuse, is equal to $x^2+v^2-2vy+y^2$, the sum of the squares of the two sides. That is to say, $x = \sqrt{s^2-v^2+2vy-y^2}$ or $y = v + \sqrt{s^2-x^2}$. By means of these last two equations, I can eliminate one of the two quantities x and y from the equation expressing the relation between the points of the curve CE and those of the straight line GA. If x is to be eliminated, this may easily be done by replacing x wherever it occurs by $\sqrt{s^2-v^2+2vy-y^2}$, x^2 by the square of this expression, x^3 by its cube, etc., while if y is to be eliminated, y must be replaced by $v + \sqrt{s^2-x^2}$, and $y^2, y^3, \dots$ by the square of this expres-

^[140] That is, the angle between two curves is defined as the angle between the normals to the curve at the point of intersection.

^[141] That is, the line GA is taken as one of the coordinate axes.

^[142] This will be the equation of the curve. See also the figure on page 97.

sion, its cube, and so on. The result will be an equation in only one unknown quantity, x or y .

For example, if CE is an ellipse, MA the segment of its axis of which CM is an ordinate, r its latus rectum, and q its transverse axis,^[143] then by Theorem 13, Book I, of Apollonius,^[144] we have

$x^2 = ry - \frac{r}{q}y^2$. Eliminating x^2 the resulting equation is

$$s^2 - v^2 + 2vy - y^2 = ry - \frac{r}{q}y^2, \quad \text{or} \quad y^2 + \frac{qry - 2qvy + qv^2 - qs^2}{q-r} = 0.$$

In this case it is better to consider the whole as constituting a single expression than as consisting of two equal parts.^[145]

If CE be the curve generated by the motion of a parabola (see pages 47, et seq.) already discussed, and if we represent GA by b , KL by c , and the parameter of the axis KL of the parabola by d , the equation

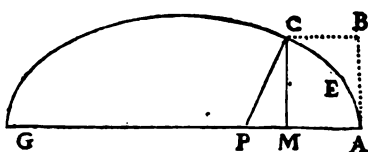
^[143] "Le traversant."

^[144] Apollonius, p. 49: "Si conus per axem plano secatur autem alio quoque plano, quod cum utroque latere trianguli per axem posita concurrat, sed neque basi conici parallelum ducitur neque e contrario et si planum, in quo est basis conici, planumque secans concurrunt in recta perpendiculari aut ad basim trianguli per axem positi aut ad eam productam quælibet recta, quæ a sectione conici communi sectioni planorum parallela ducitur ad diametrum sectiones sumpta quadrata æqualis erit spatio adplicato rectæ cuidam, ad quam diametrus sectionis rationem habet, quam habet quadratum rectæ a vertice conici diametro sectionis parallelæ ductæ usque ad basim trianguli ad rectangulum comprehensum rectis ab ea ad latera trianguli abscissis, latitudinem rectam ab ea e diametro ad verticem sectionis abscissam et figura deficiens simili similiterque posita rectangulo a diametro parametroque comprehenso; vocetur autem talis sectio ellipsis." Cf. *Apollonius of Perga*, edited by Sir T. L. Heath, Cambridge, 1896, p. 11.

^[145] That is, to transpose all the terms to the left member.

bien si c'est y , en mettant en son lieu $x + \sqrt{ss - xx}$, & le quarré, ou le cube, &c. de cete somme, au lieu d' yy , ou y^3 &c. De façon qu'il reste tousiours après cela vne equation, en laquelle il ny a plus qu'une seule quantité indéterminée, x , ou y .

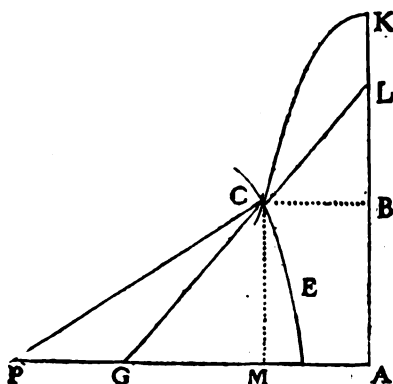
Comme si CE est vne Ellipse, & que MA soit le segment de son diametre, auquel CM soit appliquée par ordre, & qui ait r pour son costé droit, & q pour le tra-



uerfant, on à par le 13 th. du 1 liu. d'Apollonius.

$xx \propto ry - \frac{r}{q} yy$, d'on ostant xx , il reste $ss - vv + 2vy - yy \propto ry - \frac{r}{q} yy$. ou bien,

$yy \frac{xy - 2vy + qv - q^2}{q - r}$ esgal a rien. car il est mieux en cet endroit de considerer ainsi ensemble toute la somme, que d'en faire vne partie esgale a l'autre.



Tout de mesme si CE est la ligne courbe descrite par le mouvement d'une Parabole en la façon cy dessus expliquée, & qu'on ait posé b pour GA, c pour KL, & d pour le costé droit du diametre KL en la parabole: l'equation qui explique le rapport qui

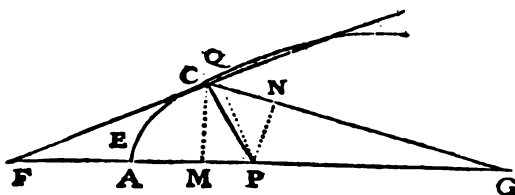
qui est entre x & y , est $y^3 - byy - cdy + bcd + dxy \propto a$.

d'où ostant x , on a $y^3 - byy - cdy + bcd + dy$
 $\sqrt{ss - vv + 2vy - yy}$. & remetrant en ordre ces
termes par le moyen de la multiplication, il vient

$$y^6 - 2by^4 + bb^2 y^2 + dd^2 y^2 - 2ddv y + dd^2 vv \} y^4 + 4bcd y^2 - 2ddv y + dd^2 vv \} y^3 - 2bccddy + bbccdd \propto a.$$

Et ainsi des autres.

Mesme encore que les points de la ligne courbe ne se rapportassent pas en la façon que iay ditte a ceux d'une ligne droite, mais en toute autre qu'on scauroit imaginer, on ne laisse pas de pouoir tousiours auoir vne telle equation. Comme si $Q E$ est vne ligne, qui ait tel rapport aux trois points F , G , & A , que les lignes droites tirées de chascun de ses points comme C , iusques au point F , surpassent la ligne $F A$ d'une quantité, qui ait certaine



proportiō donnée a vne autre quantité dont GA surpassé les lignes tirées des mesmes

points iusques à G . Faisons $GA \propto b$, $AF \propto c$, & prenant à discretion le point C dans la courbe, que la quantité dont CF surpassé FA , soit à celle dont GA surpassé GC , commè d à e , en sorte que si cete quantité qui est indeterminée se nomme x , FC est $c + x$, & GC est $b - \frac{e}{d}x$.

Puis posant $MA \propto y$, GM est $b - y$, & FM est $c + y$, & a cause du triangle rectangle CMG , ostant le quarré de

expressing the relation between x and y is $y^3 - by^2 - cdy + bcd + dxy = 0$.
Eliminating x , we have

$$y^3 - by^2 - cdy + bcd + dy\sqrt{s^2 - v^2 + 2vy} - y^2 = 0.$$

Arranging the terms according to the powers of y by squaring,^[146] this becomes

$$y^6 - 2by^5 + (b^2 - 2cd + d^2)y^4 + (4bcd - 2d^2v)y^3 \\ + (c^2d^2 - d^2s^2 + d^2v^2 - 2b^2cd)y^2 - 2bc^2d^2y + b^2c^2d^2 = 0,$$

and so for the other cases. If the points of the curve are not related to those of a straight line in the way explained, but are related in some other way,^[147] such an equation can always be found.

Let CE be a curve which is so related to the points F, G, and A, that a straight line drawn from any point on it, as C, to F exceeds the line FA by a quantity which bears a given ratio to the excess of GA over the line drawn from the point C to G.^[148] Let $GA = b$, $AF = c$, and taking an arbitrary point C on the curve let the quantity by which CF exceeds FA be to the quantity by which GA exceeds GC as d is to e . Then if we let z represent the undetermined quantity, $FC = c + z$ and $GC = b - \frac{e}{d}z$. Let $MA = y$, $GM = b - y$, and $FM = c + y$. Since CMG is a right triangle, taking the square of GM from the square of GC we have

[146] "En remettant en ordre ces termes par moyen de la multiplication."

[147] "Mais en toute autre qu'on saurait imaginer."

[148] That is the ratio of $CF - FA$ to $GA - CG$ is a constant.

left the square of CM, or $\frac{e^2}{d^2}z^2 - \frac{2be}{d}z + 2by - y^2$. Again, taking the square of FM from the square of FC we have the square of CM expressed in another way, namely: $z^2 + 2cz - 2cy - y^2$. These two expressions being equal they will yield the value of y or MA, which is

$$\frac{d^2z^2 + 2cd^2z - e^2z^2 + 2bdez}{2bd^2 + 2cd^2}.$$

Substituting this value for y in the expression for the square of CM, we have

$$\overline{\text{CM}}^2 = \frac{bd^2z^2 + ce^2z^2 + 2bcd^2z - 2bcdez}{bd^2 + cd^2} - y^2.$$

If now we suppose the line PC to meet the curve at right angles at C, and let PC= s and PA= v as before, PM is equal to $v-y$; and since PCM is a right triangle, we have $s^2 - v^2 + 2vy - y^2$ for the square of CM. Substituting for y its value, and equating the values of the square of CM, we have

$$z^2 + \frac{2bcd^2z - 2bcdez - 2cd^2vz - 2bdevz - bd^2s^2 + bd^2v^2 - cd^2s^2 + cd^2v^2}{bd^2 + ce^2 + e^2v - d^2v} = 0$$

for the required equation.

Such an equation having been found⁽¹⁴⁰⁾ it is to be used, not to determine x , y , or z , which are known, since the point C is given, but to find v or s , which determine the required point P. With this in view, observe that if the point P fulfills the required conditions, the circle about P as center and passing through the point C will touch but not cut the curve CE; but if this point P be ever so little nearer to or farther from A than it should be, this circle must cut the curve not only

⁽¹⁴⁰⁾ Three such equations have been found by Descartes, namely those for the ellipse, the parabolic conchoid, and the curve just described.

de G M du quarré de G C, on a le quarré de C M, qui est $\frac{ce}{dd}zz -- \frac{2be}{d}z + 2by -- yy$. puis ostant le quarré de F M du quarré de F C, on a encore le quarré de C M en d'autres termes, a sçavoir $zz + 2cz -- 2cy -- yy$, & cester mes estant esgaux aux precedens, ils font connoistre y, ou M A, qui est $\frac{ddzz + 2cddz -- cezz + 2bdez}{2bdd + 2cd}$, & substituant cete somme au lieu d'y dans le quarré de C M, on trouue qu'il s'exprime en ces termes.

$$\frac{bddz + cezz + 2bddz -- 2bedz}{bdd + cd} -- yy.$$

Puis supposant que la ligne droite P C rencontre la courbe a angles droits au point C, & faisant P C $\propto s$, & P A $\propto v$ comme deuant, P M est $v -- y$; & a cause du triangle rectangle P C M, on a $ss -- vv + 2vy -- yy$ pour le quarré de C M, ou derechef ayant au lieu d'y substitué la somme qui luy est esgale, il vient

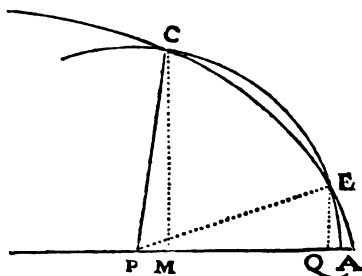
$$zz + \frac{2bddz -- 2bedz -- 2cddvz -- 2bdevz -- bddss + bddvv -- bdd + cee -- ce v -- dd v}{-- cddss + cddvv} \propto 0 \text{ pour l'equation que nous cherchions.}$$

Or après qu'on à trouué vne telle equation, au lieu de s'en seruir pour connoistre les quantités x , ou y , ou z , qui sont desia données, puisque le point C est donné, on la doit employer a trouuer v , ou s , qui determinent le point P, qui est demandé. Et a cet effect il faut considerer, que si ce point P est tel qu'on le desire, le cercle dont il sera le centre, & qui passera par le point C, y touchera la ligne courbe C E, sans la couper: mais que si ce point P, est tant soit peu plus proche, ou plus esloigné du point

X x

A, qu'il

A, qu'il ne doit, ce cercle coupera la courbe, non seulement au point C, mais aussi nécessairement en quelque autre. Puis il faut aussi considérer, que lorsque ce cercle coupe la ligne courbe CE, l'équation par laquelle on cherche la quantité x , ou y , ou quelque autre semblable, en supposant PA & PC estre connues, contient nécessairement deux racines, qui sont inégales. Car par exemple si ce cercle coupe la courbe aux points C & E, ayant tiré EQ parallèle à CM, les noms des quantités indéterminées x & y , conviendront aussi bien aux lignes EQ, & QA, qu'à CM, & MA; puis PE est égale à PC, à cause du cercle, si bien que cherchant les lignes



EQ & QA, par PE & PA qu'on suppose comme données, on aura la même équation, que si on cherchoit CM & MA par PC, PA. d'où il suit évidemment, que la valeur d' x , ou d' y , ou de

telle autre quantité qu'on aura supposée, fera double en cette équation, c'est à dire qu'il y aura deux racines inégales entre elles; & dont l'une sera CM, l'autre EQ, si c'est x qu'on cherche; ou bien l'une sera MA, & l'autre QA, si c'est y . & ainsi des autres. Il est vrai que si le point E ne se trouve pas du même côté de la courbe que le point C; il n'y aura que l'une de ces deux racines qui soit vraie, & l'autre sera renversée, ou moindre que rien: mais plus ces deux points, C, & E, sont proches l'un de l'autre, moins il y a de différence entre ces deux racines;

SECOND BOOK

at C but also in another point. Now if this circle cuts CE, the equation involving x and y as unknown quantities (supposing PA and PC known) must have two unequal roots. Suppose, for example, that the circle cuts the curve in the points C and E. Draw EQ parallel to CM. Then x and y may be used to represent EQ and QA respectively in just the same way as they were used to represent CM and MA; since PE is equal to PC (being radii of the same circle), if we seek EQ and QA (supposing PE and PA given) we shall get the same equation that we should obtain by seeking CM and MA (supposing PC and PA given). It follows that the value of x , or y , or any other such quantity, will be two-fold in this equation, that is, the equation will have two unequal roots. If the value of x be required, one of these roots will be CM and the other EQ; while if y be required, one root will be MA and the other QA. It is true that if E is not on the same side of the curve as C, only one of these will be a true root, the other being drawn in the opposite direction, or less than nothing.^[180] The nearer together the points C and E are taken however, the less differ-

^[180] "Et l'autre sera renversée ou moindre que rien."

ence there is between the roots ; and when the points coincide, the roots are exactly equal, that is to say, the circle through C will touch the curve CE at the point C without cutting it.

Furthermore, it is to be observed that when an equation has two equal roots, its left-hand member must be similar in form to the expression obtained by multiplying by itself the difference between the unknown quantity and a known quantity equal to it;^[151] and then, if the resulting expression is not of as high a degree as the original equation, multiplying it by another expression which will make it of the same degree. This last step makes the two expressions correspond term by term.

For example, I say that the first equation found in the present discussion,^[152] namely

$$y^2 + \frac{qry - 2qvy + qv^2 - qs^2}{q - r},$$

must be of the same form as the expression obtained by making $e=y$ and multiplying $y-e$ by itself, that is, as $y^2 - 2ey + e^2$. We may then compare the two expressions term by term, thus: Since the first term, y^2 , is the same in each, the second term,^[153] $\frac{qry - 2qvy}{q - r}$, of the first is equal to $-2ey$, the second term of the second; whence, solving for v , or PA, we have $v = e - \frac{r}{q}e + \frac{1}{2}r$; or, since we have assumed e equal to y , $v = y - \frac{r}{q}y + \frac{1}{2}r$. In the same way, we can find s from the third term,

^[151] That is, the left-hand member will be the square of the binomial $x - a$ when $x = a$.

^[152] See page 96. The original has "first equation," not "first member of the equation."

^[153] That is, the second term in y .

$e^2 = \frac{qv^2 - qs^2}{q - r}$; but since v completely determines P , which is all that is required, it is not necessary to go further.^[154]

In the same way, the second equation found above,^[155] namely,

$$y^6 - 2by^5 + (b^2 - 2cd + d^2)y^4 + (4bcd - 2d^2v)y^3 + (c^2d^2 - 2b^2cd + d^2v^2 - d^2s^2)y^2 - 2bc^2d^2y + b^2c^2d^2,$$

must have the same form as the expression obtained by multiplying

$$y^2 - 2ey + e^2 \text{ by } y^4 + fy^3 + g^2y^2 + h^3y + k^4,$$

that is, as

$$y^6 + (f - 2e)y^5 + (g^2 - 2ef + e^2)y^4 + (h^3 - 2eg^2 + e^2f)y^3 + (k^4 - 2eh^3 + e^2g^2)y^2 + (e^2h^3 - 2ek^4)y + e^2k^4.$$

From these two equations, six others may be obtained, which serve to determine the six quantities f , g , h , k , v , and s . It is easily seen that to whatever class the given curve may belong, this method will always furnish just as many equations as we necessarily have unknown quantities. In order to solve these equations, and ultimately to find v , which is the only value really wanted (the others being used only as means of finding v), we first determine f , the first unknown in the above expression, from the second term. Thus, $f = 2e - 2b$. Then in the last terms we can find k , the last unknown in the same expression, from

^[154] That is, to construct PC we may lay off $AP = v$ and join P and C . If instead we use the value of e , taking C as center and a radius $CP = e$, we construct an arc cutting AG in P , and join P and C . Rabuel, p. 309. To apply Descartes's method to the circle, for example, it is only necessary to observe that all parameters and diameters are equal, that is, $q = r$; and therefore the equation

$v = y - \frac{r}{q}y + \frac{1}{2}r$ becomes $v = \frac{1}{2}q = \frac{1}{2}$ diameter. That is, the normal passes

through the center and is a radius of the circle. Rabuel, p. 313.

^[155] See page 99. As before, Descartes uses "second equation" for "first member of the second equation."

which $k^4 = \frac{b^2 c^2 d^2}{e^2}$. From the third term we get the second quantity

$$g^2 = 3e^2 - 4be - 2cd + b^2 + d^2.$$

From the next to the last term we get h , the next to the last quantity, which is^[184]

$$h^3 = \frac{2b^3 c^2 d^2}{e^2} - \frac{2bc^3 d^2}{e^2}.$$

In the same way we should proceed in this order, until the last quantity is found.

Then from the corresponding term (here the fourth) we may find v , and we have

$$v = \frac{2e^3}{d^2} - \frac{3be^2}{d^2} + \frac{b^2 e}{d^2} - \frac{2ce}{d} + e + \frac{2bc}{d} + \frac{bc^2}{e^2} - \frac{b^3 c^2}{e^3};$$

or putting y for its equal e , we get

$$v = \frac{2y^3}{d^2} - \frac{3by^2}{d^2} + \frac{b^2 y}{d^2} - \frac{2cy}{d} + y + \frac{2bc}{d} + \frac{bc^2}{y^2} - \frac{b^3 c^2}{y^3},$$

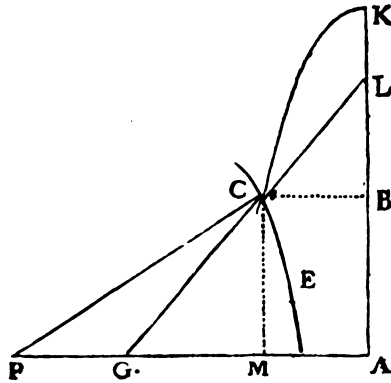
for the length of AP.

^[185] Found from.

Puis par le troisieme terme il faut chercher g la seconde quantité, & on a $gg \propto 3 ee - 4 be - 2 cd + bb + dd$.

Puis par le penultiesme il faut chercher h la penultiesme quantité, qui est $h \propto \frac{2bbccdd}{e^3} - \frac{2bccdd}{ee}$. Et ainsi il faudroit continuer suivant ce mesme ordre iusques a la derriere, s'il y en auoit d'avantage en cete somme ; car c'est chose qu'on peut tousiours faire en mesme façon.

Puis par le terme qui suit en ce mesme ordre, qui est icy le quatriesme, il faut chercher la quantité v , & on a



$$v \propto \frac{2e^3}{dd} - \frac{3bee}{dd} + \frac{bbe}{dd} - \frac{2ce}{d} + e + \frac{2bc}{d} + \frac{bcc}{ee} - \frac{bbcc}{e^3}.$$

ou mettant y au lieu d' e qui luy est esgal on a

$$v \propto \frac{2y^3}{dd} - \frac{3byy}{dd} + \frac{bb y}{dd} - \frac{2cy}{d} + y + \frac{2bc}{d} + \frac{bcc}{yy} - \frac{bbcc}{y^3}.$$

pour la ligne A P.

Et ainsi la troisieme equation, qui est

$$Xx \propto 3$$

zz-

Again, the third^[107] equation, namely,

$$z^2 + \frac{2bcd^2z - 2bcdez - 2cd^2vz - 2bdevz - bd^2s^2 + bd^2v^2 - cd^2s^2 + cd^2v^2}{bd^2 + ce^2 + e^2v - d^2v},$$

is of the same form as $z^2 - 2fz + f^2$ where $f = z$, so that $-2f$ or $-2z$ must be equal to

$$\frac{2bcd^2 - 2bcde - 2cd^2v - 2bdev}{bd^2 + ce^2 + e^2v - d^2v},$$

whence

$$v = \frac{bcd^2 - bcde + bd^2z + ce^2z}{cd^2 + bde - e^2z + d^2z}.$$

Therefore, if we take AP equal to the above value of v , all the terms of which are known, and join the point P thus determined to C, this line will cut the curve CE at right angles, which was required. I see no reason why this solution should not apply to every curve to which the methods of geometry are applicable.^[108]

It should be observed regarding the expression taken arbitrarily to raise the original product to the required degree, as we just now took

$$y^4 + fy^3 + g^2y^2 + h^3y + k^4,$$

that the signs $+$ and $-$ may be chosen at will, without producing different values of v or AP.^[109] This is easily found to be the case, but if I should stop to demonstrate every theorem I use, it would require a

^[107] First member of the third equation.

^[108] Let us apply this method to the problem of constructing a normal to a parabola at a given point. As before, $s^2 = x^2 + v^2 - 2vy + y^2$. If we take as the equation of the parabola $x^2 = ry$, and substitute, we have

$$s^2 = ry + v^2 - 2vy + y^2 \quad \text{or} \quad y^2 + (r - 2v)y + v^2 - s^2 = 0.$$

Comparing this with $y^2 - 2cy + e^2 = 0$, we have $r - 2v = -2e$; $v^2 - s^2 = e^2$; $v = \frac{r}{2} + e$. Since $e = y$, $v = \frac{r}{2} + y$. Let $AM = y$, and $v = AP$; then $AM - AP = MP =$ one-half the parameter. Rabuel, p. 314.

^[109] It will be observed that Descartes did not consider a coefficient, as a , in the general sense of a positive or a negative quantity, but that he always wrote the sign intended. In this sentence, however, he suggests some generalization.

much larger volume than I wish to write. I desire rather to tell you in passing that this method, of which you have here an example, of supposing two equations to be of the same form in order to compare them term by term and so to obtain several equations from one, will apply to an infinity of other problems and is not the least important feature of my general method.^[100]

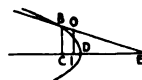
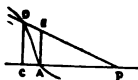
I shall not give the constructions for the required tangents and normals in connection with the method just explained, since it is always easy to find them, although it often requires some ingenuity to get short and simple methods of construction.

^[100] The method may be used to draw a normal to a curve from a given point, to draw a tangent to a curve from a point without, and to discover points of inflexion, maxima, and minima. Compare Descartes's Letters, Cousin, Vol. VI, p. 421. As an illustration, let it be required to find a point of inflexion on the first cubical parabola. Its equation is $y^3 = a^2x$. Assume that D is a point of inflexion, and let $CD = y$, $AC = x$, $PA = s$, and $AE = r$. Since triangle PAE is similar to triangle PCD we have $\frac{y}{x+s} = \frac{r}{s}$, whence $x = \frac{sy - rs}{r}$. Substituting in

the equation of the curve, we have $y^3 - \frac{a^2sy}{r} + a^2s = 0$. But if D is a point of inflexion this equation must have three equal roots, since at a point of inflexion there are three coincident points of section. Compare the equation with

$$y^3 - 3ey^2 + 3e^2y - e^3 = 0.$$

Then $3e^2 = 0$ and $e = 0$. But $e = y$, and therefore $y = 0$. Therefore the point of inflexion is $(0, 0)$. Rabuel, p. 321.



It will be of interest to compare the method of drawing tangents given by Fermat in *Methodus ad disquirendam maximam et minimam*, Toulouse, 1679, which is as follows: It is required to draw a tangent to the parabola BD from a

point O without. From the nature of the parabola $\frac{CD}{DI} > \frac{BC^2}{OI^2}$, since O is without the

curve. But by similar triangles $\frac{BC^2}{OI^2} = \frac{CE^2}{IE^2}$. Therefore $\frac{CD}{DI} > \frac{CE^2}{IE^2}$. Let $CE = a$,

$CI = e$, and $CD = d$; then $DI = d - e$, and $\frac{d}{d - e} > \frac{a^2}{(a - e)^2}$; whence

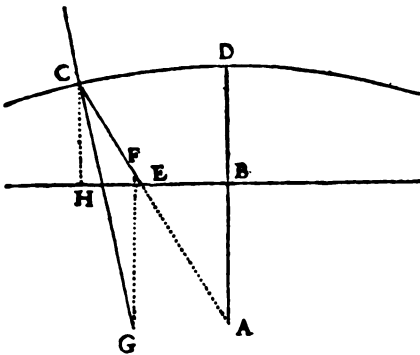
$$de^2 - 2ade > -a^2e.$$

Dividing by e , we have $de - 2ad > -a^2$. Now if the line BO becomes tangent to the curve, the point B and O coincide, $de - 2ad = -a^2$, and e vanishes; then $2ad = a^2$ and $a = 2d$ in length. That is $CE = 2CD$.

fais quelque mention, ie serois contraint d'escrire vn volume beaucoup plus gros que ie ne desire. Mais ie veux bien en passant vous auertir que l'inuention de supposer deux equations de mesme forme, pour comparer separément tous les termes de l'une a ceux de l'autre, & ainsi en faire naistre plusieurs d'une seule, dont vous aués vû icy vn exemple, peut seruir a vne infinité d'autres Problemes, & n'est pas l'une des moindres de la methode dont ie me sers.

Ie n'adiouste point les constructions, par lesquelles on peut descrire les contingentes ou les perpendiculaires cherchées, en suite du calcul que ie viens d'expliquer, a cause qu'il est tousiours aysé de les trouuer: Bienque souuent on ait besoin d'un peu d'adresse, pour les rendre courtes & simples.

Comme par exemple, si D C'est la premiere conchoi-



de des anciens, dont A soit le pole, & BH la regle: en sorte que toutes les lignes droites qui regardent vers A, & sont comprises entre la courbe CD, & la droite BH, comme

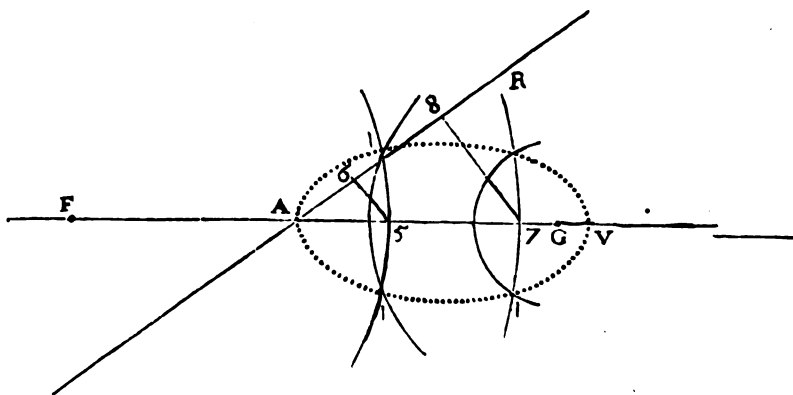
Exemple de la construction de ce probleme en la conchoide.

me DB & CE, soient esgales: Et qu'on veuille trouuer la ligne CG qui la coupe au point C a angles droits. On pourroit en cherchant, dans la ligne BH, le point par où cete ligne CG doit passer, selon la methode icy expli-

expliquée, s'engager dans vn calcul autant ou plus long qu'aucun des precedens: Et toutefois la construction, qui deuroit après en estre deduite, est fort simple. Car il ne faut que prendre $C F$ en la ligne droite $C A$, & la faire esgale à $C H$ qui est perpendiculaire sur $H B$: puis du point F tirer $F G$, parallele à $B A$, & esgale à $E A$: au moyen de quoy on a le point G , par lequel doit passer $C G$ la ligne cherchée.

Explica-
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que.

Au reste affin que vous sçachiées que la consideration des lignes courbes icy proposée n'est pas sans vſage, & qu'elles ont diuerſes propriétés, qui ne cedent en rien a celles des sections coniques, ie veux encore adiouter icy l'explication de certaines Ouales, que vous verrez estre tres vtils pour la Theorie de la Catoptrique, & de la Dioptrique. Voycy la facon dont ie les descris.



Premierement ayant tiré les lignes droites $F A$, & $A R$, qui s'entrecouppent au point A , sans qu'il importe a quels angles, ie prens en l'vne le point F a discretion, c'est a dire plus ou moins esloigné du point A selon que
ie

Given, for example, CD , the first conchoid of the ancients (see page 113). Let A be its pole and BH the ruler, so that the segments of all straight lines, as CE and DB , converging toward A and included between the curve CD and the straight line BH are equal. Let it be required to find a line CG normal to the curve at the point C . In trying to find the point on BH through which CG must pass (according to the method just explained), we would involve ourselves in a calculation as long as, or longer than any of those just given, and yet the resulting construction would be very simple. For we need only take CF on CA equal to CH , the perpendicular to BH ; then through F draw FG parallel to BA and equal to EA , thus determining the point G , through which the required line CG must pass.

To show that a consideration of these curves is not without its use, and that they have diverse properties of no less importance than those of the conic sections I shall add a discussion of certain ovals which you will find very useful in the theory of catoptrics and dioptrics. They

may be described in the following way: Drawing the two straight lines FA and AR (p. 114) intersecting at A under any angle, I choose arbitrarily a point F on one of them (more or less distant from A according as the oval is to be large or small). With F as center I describe a circle cutting FA at a point a little beyond A, as at the point 5. I then draw the straight line 56^[161] cutting AR at 6, so that A6 is less than A5, and so that A6 is to A5 in any given ratio, as, for example, that which measures the refraction,^[162] if the oval is to be used for dioptrics. This being done, I take an arbitrary point G in the line FA on the same side as the point 5, so that AF is to GA in any given ratio. Next, along the line A6 I lay off RA equal to GA, and with G as center and a radius equal to R6 I describe a circle. This circle will cut the first one in two points 1, 1,^[163] through which the first of the required ovals must pass.

Next, with F as center I describe a circle which cuts FA as little nearer to or farther from A than the point 5, as, for example, at the point 7. I then draw 78 parallel to 56 and with G as center and a radius equal to R8 I describe another circle. This circle will cut the one through 7 in the points 1, 1^[164] which are points of the same oval. We can thus find as many points as may be desired, by drawing lines parallel to 78 and describing circles with F and G as centers.

^[161] The confusion resulting from the use of Arabic figures to designate points is here apparent.

^[162] That is, the ratio corresponding to the index of refraction.

^[163] "Au point 1."

^[164] "Au point 1."

ie veux faire ces Ouales plus ou moins grandes , & de ce point F comme centre ie defcris vn cercle , qui passe quelque peu au delà du point A, comme par le point 5, puis de ce point 5 ie tire la ligne droite 5 6, qui coupe l'autre au point 6, en sorte qu' A 6 soit moindre qu' A 5, selon telle proportion donnée qu'on veut, a sçauoir selon celle qui mesure les Refractions si on s'en veut seruir pour la Dioptrique. Après cela ie prens aussy le point G, en la ligne F A, du costé où est le point 5, a discretion, c'est a dire en faisant que les lignes A F & G A ont entre elles telle proportion donnée qu'on veut. Puis ie fais R A esgal à G A en la ligne A 6. & du centre G descriuant vn cercle, dont le rayon soit esgal à R 6, il coupe l'autre cercle de part & d'autre au point 1, qui est l'un de ceux par où doit passer la premiere des Ouales cherchées. Puis derechef du centre F ie defcris vn cercle, qui passe vn peu au deça, ou au delà du point 5, comme par le point 7, & ayant tiré la ligne droite 7 8 parallele a 5 6, du centre G ie defcris vn autre cercle, dont le rayon est esgal a la ligne R 8. & ce cercle coupe celuy qui passe par le point 7 au point 1, qui est encore l'un de ceux de la mesme Ouale. Et ainsi on en peut trouuer autant d'autres qu'on voudra , en tirant derechef d'autres lignes paralleles à 7 8, & d'autres cercles des centres F, & G.

Pour la seconde Ouale il n'y a point de difference , sinon qu'au lieu d' A R il faut de l'autre costé du point A prendre A S esgal à A G, & que le rayon du cercle descrit du centre G, pour couper celuy qui est descrit du centre F & qui passe par le point 5, soit esgal a la

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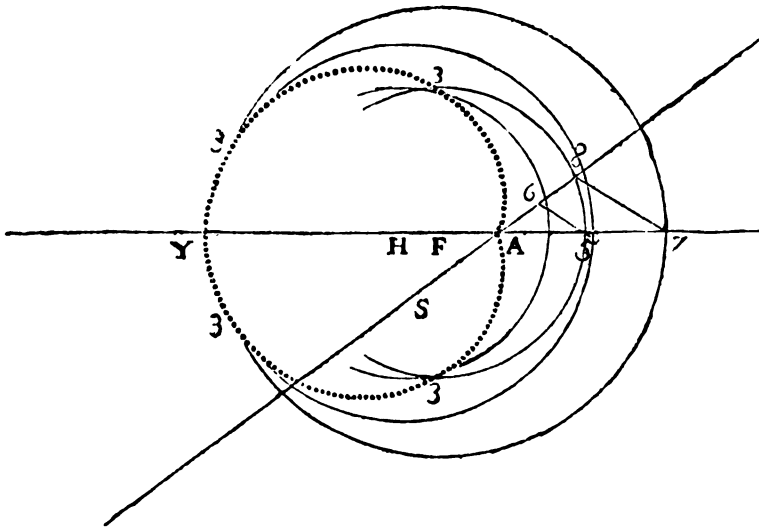
In the construction of the second oval the only difference is that instead of AR we must take AS on the other side of A, equal to AG, and that the radius of the circle about G cutting the circle about F and passing through 5 must be equal to the line S6; or if it is to cut the circle through 7 it must be equal to S8, and so on. In this way the circles intersect in the points 2, 2, which are points of this second oval A2X.

To construct the third and fourth ovals (see page 121), instead of AG I take AH on the other side of A, that is, on the same side as F. It should be observed that this line AH must be greater than AF, which in any of these ovals may even be zero, in which case F and A coincide. Then, taking AR and AS each equal to AH, to describe the third oval,

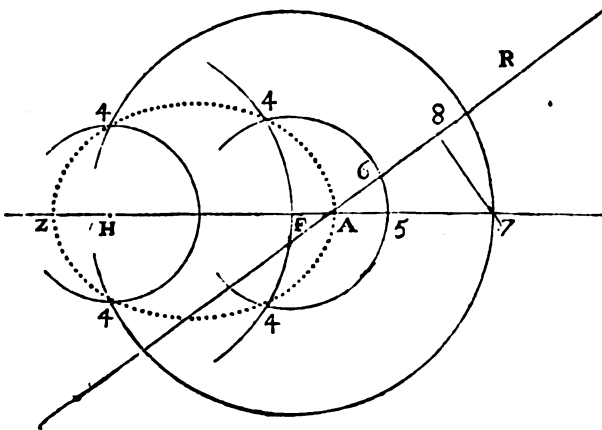
A3Y, I draw a circle about H as center with a radius equal to S6 and cutting in the point 3 the circle about F passing through 5, and another with a radius equal to S8 cutting the circle through 7 in the point also marked 3, and so on.

Finally, for the fourth oval, I draw circles about H as center with radii equal to R6, R8, and so on, and cutting the other circles in the points marked 4.^[106]

^[106] In all four ovals AF and AR or AF and AS intersect at A under any angle. F may coincide with A, and otherwise its distance from A determines the size of the oval. The ratio A5 : A6 is determined by the index of refraction of the material used. In the first two ovals, if A does not coincide with F it lies between F and G, and the ratio AF : AG is arbitrary. In the last two, if F does not coincide with A it lies between A and H, and the ratio AF : AH is arbitrary. In the first oval AR = AG and the points R, 6, 8 are on the same side of A. In the second oval AS = AG and S is on the opposite side of A from 6, 8. In the third oval AS = AH and S is on the opposite side of A from 6, 8. In the fourth oval AR = AH and R, 6, 8 are on the same side of A. Rabuel, p. 342.



esgal à S 6, qui coupe au point 3 celui du centre F, qui passe par le point 5; & vn autre dont le rayon est esgal a S 8, qui coupe celui qui passe par le point 7, au point aussy marqué 3; & ainsi des autres. Enfin pour la dernière

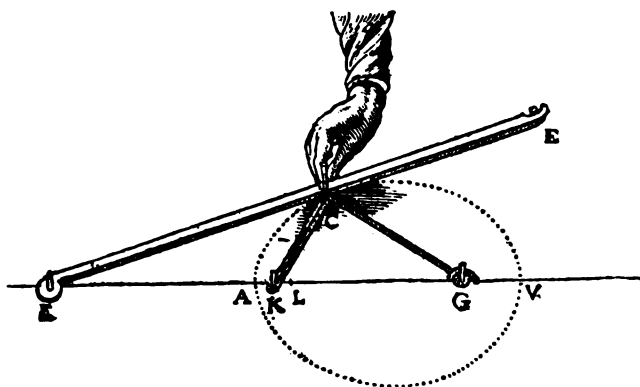


Yy 2

ouale

ouale ie fais des cercles du centre H , dont les rayons sont esgaux aux lignes R 6, R 8, & semblables, qui coupent les autres cercles aux points marqués 4.

On pourroit encore trouuer vne infinité d'autres moyens pour descrire ces mesmes ouales. comme par exemple, on peut tracer la premiere AV, lorsqu'on suppose les lignes FA & AG estre esgales, si on diuise la toute FG au point L, en forte que FL soit a LG, com-



me A 5 à A 6. c'est à dire qu'elles ayent la proportion, qui mesure les refractions. Puis ayant diuisé AL en deux parties esgales au point K, qu'on face tourner vne reigle, comme FE, autour du point F, en pressant du doigt C, la chorde EC, qui estant attachée au bout de cete reigle vers E, se replie de C vers K, puis de K derechef vers C, & de C vers G, ou son autre bout soit attaché, en forte que la longueur de cete chorde soit composée de celle des lignes GA plus AL plus FE moins AF. & ce fera le mouuement du point C, qui descripta cete ouale, a l'imitation de cequi a esté dit en la Dioptrique, de l'Ellipse, &

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There are many other ways of describing these same ovals. For example, the first one, AV (provided we assume FA and AG equal) might be traced as follows: Divide the line FG at L so that $FL : LG = A5 : A6$, that is, in the ratio corresponding to the index of refraction. Then bisecting AL at K, turn a ruler FE about the point F, pressing with the finger at C the cord EC, which, being attached at E to the end of the ruler, passes from C to K and then back to C and from C to G, where its other end is fastened. Thus the entire length of the cord is composed of $GA + AL + FE - AF$, and the point C will describe the first oval in a way similar to that in which the

ellipse and hyperbola are described in *La Dioptrique*.^[106] But I cannot give any further attention to this subject.

Although these ovals seem to be of almost the same nature, they nevertheless belong to four different classes, each containing an infinity of sub-classes, each of which in turn contains as many different kinds as does the class of ellipses or of hyperbolas; the sub-classes depending upon the value of the ratio of A5 to A6. Then, as the ratio of AF to AG, or of AF to AH changes, the ovals of each sub-class change in kind, and the length of AG or AH determines the size of the oval.^[107]

If A5 is equal to A6, the ovals of the first and third classes become straight lines; while among those of the second class we have all possible hyperbolas, and among those of the fourth all possible ellipses.^[108]

In the case of each oval it is necessary further to consider two portions having different properties. In the first oval the portion toward A (see page 114) causes rays passing through the air from F to converge towards G upon meeting the convex surface 1A1 of a lens whose index of refraction, according to dioptrics, determines such ratios as that of A5 to A6, by means of which the oval is described.

^[106] See the notes on pages 10, 55, 112.

^[107] Compare the changes in the ellipse and hyperbola as the ratio of the length of the transverse axis to the distance between the foci changes.

^[108] These theorems may be proved as follows: (1) Given the first oval, with $A5 = A6$; then $RA = GA$; $FP = F5$; $GP = R6 = AR - R6 = GA - A5 = G5$. Therefore $FP + GP = F5 + G5$. That is, the point P lies on the straight line FG. (2) Given the second oval, with $A5 = A6$; then $F2 = F5 = FA + A5$; $G2 = S6 = SA + A6 = SA + A5$; $G2 - F2 = SA - FA = GA - FA = C$. Therefore 2 lies on a hyperbola whose foci are F and G, and whose transverse axis is $GA - FA$. The proof for the third oval is analogous to (1) and that for the fourth to (2).

It may be noted that the first oval is the same curve as that described on page 98. For $FP = F5$, whence $FP - AF = A5$, and $AR = AG$; $GP = R6$; $AG - GP = A6$. If then $A5 : A6 = d : e$ we have, as before,

$$FP - AF : AG - GP = d : e.$$

& de l'Hyperbole. mais ie ne veux point m'arester plus long tems sur ce fuiet.

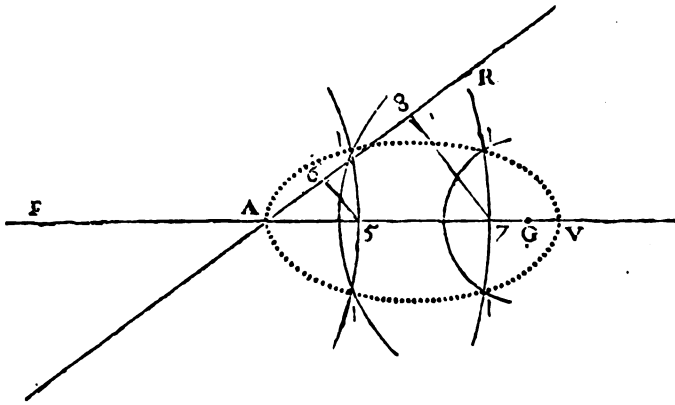
Or encore que toutes ces ouales semblent estre quasi de mesme nature, elles sont neanmoins de 4 diuers genres, chascun desquels contient sous soy vne infinité d'autres genres, qui derechef contiennent chascun autant de diuerses especes, que fait le genre des Ellipses, ou celuy des Hyperboles. Car selon que la proportion, qui est entre les lignes A 5, A 6, ou semblables, est differente ; le genre subalterne de ces ouales est different. Puis selon que la proportion, qui est entre les lignes A F, & A G, ou A H, est changée, les ouales de chasque genre subalterne changent d'espece. Et selon qu' A G, ou A H est plus ou moins grande, elles sont diuerses en grandeur. Et si les lignes A 5 & A 6 sont esgales, au lieu des ouales du premier genre ou du troisieme, on ne descrit que des lignes droites; mais au lieu de celles du second on a toutes les Hyperboles possibles; & au lieu de celles du dernier toutes les Ellipses.

Outre cela en chascune de ces ouales il faut considerer deux parties, qui ont diuerses propriétés; a sçauoir en la premiere, la partie qui est vers A, fait que les rayons, qui estant dans l'air viennent du point F, se retournent tous vers le point G, lorsqu'ils rencontrent la superficie convexe d'un verre, dont la superficie est 1 A 1, & dans lequel les refractions se font telles, que suivant ce qui a esté dit en la Dioptrique, elles peuvent toutes estre mesurées par la proportion, qui est entre les lignes A 5 & A 6, ou semblables, par l'ayde desquelles on a descrit cete ouale.

Les propriétés de ces ouales touchant les reflexions, & les refractions.

Y y 3

Mais



Mais la partie, qui est vers V, fait que les rayons qui viennent du point G se reflexchiroient tous vers F, s'ils y rencontroient la superficie concaue d'un miroir, dont la figure fust 1 V 1, & qui fust de telle matiere qu'il diminuast la force de ces rayons, selon la proportion qui est entre les lignes A 5 & A 6: Car de ce qui a esté demonstté en la Dioptrique, il est evident que cela posé, les angles de la reflexion seroient inefgaux, aussy bien que sont ceux de la refraction, & pourroient estre mesurés en mesme sorte.

En la seconde ouale la partie 2 A 2 sert encore pour les reflexions dont on suppose les angles estre inefgaux. car estant en la superficie d'un miroir composé de mesme matiere que le precedent, elle feroit tellement reflexchir tous les rayons, qui viendroient du point G, qu'ils sembleroient après estre reflexchis venir du point F. Et il est a remarquer, qu'ayant fait la ligne A G beaucoup plus

But the portion toward V causes all rays coming from G to converge toward F when they strike the concave surface of a mirror of the shape of 1V1 and of such material that it diminishes the velocity of these rays in the ratio of A5 to A6, for it is proved in dioptrics that in this case the angles of reflection will be unequal as well as the angles of refraction, and can be measured in the same way.

Now consider the second oval. Here, too, the portion 2A2 (see page 118) serves for reflections of which the angles may be assumed unequal. For if the surface of a mirror of the same material as in the case of the first oval be of this form, it will reflect all rays from G, making them seem to come from F. Observe, too, that if the line AG

is considerably greater than AF , such a mirror will be convex in the center (toward A) and concave at each end; for such a curve would be heart-shaped rather than oval. The other part, $X2$, is useful for refracting lenses; rays which pass through the air toward F are refracted by a lens whose surface has this form.

The third oval is of use only for refraction, and causes rays traveling through the air toward F (page 121) to move through the glass toward H , after they have passed through the surface whose form is $A3Y3$, which is convex throughout except toward A , where it is slightly concave, so that this curve is also heart-shaped. The difference between the two parts of this oval is that the one part is nearer F and farther from H , while the other is nearer H and farther from F .

Similarly, the last of these ovals is useful only in the case of reflection. Its effect is to make all rays coming from H (see the second figure on page 121) and meeting the concave surface of a mirror of the same material as those previously discussed, and of the form $A4Z4$, converge towards F after reflection.

The points F , G and H may be called the "burning points"^[166] of these ovals, to correspond to those of the ellipse and hyperbola, and they are so named in dioptrics.

I have not mentioned several other kinds of reflection and refraction that are effected^[170] by these ovals; for being merely reverse or opposite effects they are easily deduced.

^[166] That is, the foci, from the Latin *focus*, "hearth." The word *focus* was first used in the geometric sense by Kepler, *Ad Vitellionem Paralipomena*, Frankfurt, 1604. Chap. 4, Sect. 4.

^[170] "Reglées."

plus grande que AF , ce miroir seroit conuexe au milieu, vers A , & concaue aux extrêmitéz: car telle est la figure de cete ligne, qui en cela represente plutoſt vn coeur qu'une ouale.

Mais son autre partie X_2 sert pour les refractions, & fait que les rayons, qui estant dans l'air tendent vers F , se detournent vers G , en trauerſant la superficie d'un verre, qui en ait la figure.

La troisieme ouale sert toute aux refractions, & fait que les rayons, qui estant dans l'air tendent vers F , se vont rendre vers H dans le verre, après qu'ils ont trauerſé sa superficie, dont la figure est A_3Y_3 , qui est conuexe par tout, excepté vers A où elle est vn peu concaue, en forte qu'elle a la figure d'un coeur auſſy bien que la precedente. Et la difference qui est entre les deux parties de cete ouale, consiste en ce que le point F est plus proche de l'une, que n'est le point H ; & qu'il est plus eſloigné de l'autre, que ce meſme point H .

En meſme façon la derniere ouale sert toute aux reflexions, & fait que si les rayons, qui viennent du point H , rencontroient la superficie concaue d'un miroir de meſme matiere que les precedens, & dont la figure fuſt A_4Z_4 , ils se reflexchiroient tous vers F .

De façon qu'on peut nommer les poins F , & G , ou H les poins bruſlans de ces ouales, a l'exemple de ceux des Ellipses, & des Hyperboles, qui ont eſté ainſi nommés en la Dioptrique.

I'omet quantité d'autres refractions, & reflexions, qui ſont reiglées par ces meſmes ouales: car n'estant que les conuerſes, ou les contraires de celles cy, elles en
peuvent

SECOND BOOK

I must not, however, fail to prove the statements already made. For this purpose, take any point C on the first part of the first oval, and draw the straight line CP normal to the curve at C. This can be done by the method given above,^[171] as follows:

Let $AG=b$, $AF=c$, $FC=c+z$. Suppose the ratio of d to e , which I always take here to measure the refractive power of the lens under consideration, to represent the ratio of A5 to A6 or similar lines used to describe the oval. Then

$$GC = b - \frac{e}{d}z,$$

whence

$$AP = \frac{bcd^2 - bcde + bd^2z + ce^2z}{bde + cd^2 + d^2z - e^2z}.$$

From P draw PQ perpendicular to FC, and PN perpendicular to GC.^[172] Now if $PQ : PN = d : e$, that is, if $PQ : PN$ is equal to the same ratio as that between the lines which measure the refraction of the convex glass AC, then a ray passing from F to C must be refracted toward G upon entering the glass. This follows at once from dioptrics.

^[171] See page 115.

^[172] Here PQ is the sine of the angle of incidence and PN is the sine of the angle of refraction. The ray FC is reflected along CG.

Now let us determine by calculation if it be true that $PQ : PN = d : e$. The right triangles PQF and CMF are similar, whence it follows that $CF : CM = FP : PQ$, and $\frac{FP \cdot CM}{CF} = PQ$. Again, the right triangles PNG and CMG are similar, and therefore $\frac{GP \cdot CM}{CG} = PN$. Now since the multiplication or division of two terms of a ratio by the same number does not alter the ratio, if $\frac{FP \cdot CM}{CF} : \frac{GP \cdot CM}{CG} = d : e$, then, dividing each term of the first ratio by CM and multiplying each by both CF and CG, we have $FP \cdot CG : GP \cdot CF = d : e$. Now by construction,

$$FP = c + \frac{bcd^2 - bcde + bd^2z + ce^2z}{cd^2 + bde - e^2z + d^2z},$$

or

$$FP = \frac{bcd^2 + c^2d^2 + bd^2z + cd^2z}{cd^2 + bde - e^2z + d^2z},$$

and

$$CG = b - \frac{e}{d}z.$$

Then

$$FP \cdot CG = \frac{b^2cd^2 + bc^2d^2 + b^2d^2z + bcd^2z - bcdez - c^2dez - bdez^2 - cdez^2}{cd^2 + bde - e^2z + d^2z}.$$

Then

$$GP = b - \frac{bcd^2 - bcde + bd^2z + ce^2z}{cd^2 + bde - e^2z + d^2z};$$

or

$$GP = \frac{b^2de + bcde - be^2z - ce^2z}{cd^2 + bde - e^2z + d^2z};$$

and $CF = c + z$. So that

$$GP \cdot CF = \frac{b^2cde + bc^2dc + b^2dez + bcdcz - bce^2z - c^2e^2z - be^2z^2 - ce^2z^2}{cd^2 + bde - e^2z + d^2z}.$$

blables, d'où il suit que CF est à CM , comme FP est à PQ ; & par conséquent que FP , estant multipliée par CM , & diuisée par CF , est esgale à PQ . Tout de mesme les triangles rectangles PNG , & CMG sont semblables; d'où il suit que GP , multipliée par CM , & diuisée par CG , est esgale à PN . Puis à cause que les multiplications, ou diuisions, qui se font de deux quantités par vne mesme, ne changent point la proportion qui est entre elles; si FP multipliée par CM , & diuisée par CF , est à GP multipliée aussi par CM & diuisée par CG ; comme d est à e , en diuisant l'une & l'autre de ces deux sommes par CM , puis les multipliant toutes deux par CF , & derechef par CG , il reste FP multipliée par CG , qui doit estre à GP multipliée par CF , comme d est à e .

Or par la construction FP est $c \frac{bcdd - bcdx + bddx + ceex}{bde + cdd + ddz - eex}$

ou bien $FP \propto \frac{bcdd + cdd + bddx + cddx}{bde + cdd + ddz - eex}$ & CG est

$b - \frac{e}{d} x$ sibienque multipliant FP par CG il vient

$$\frac{bbcd + bcdd + bddx + bcdx - bcdx - ccdx - bcdx - cdxz}{bde + cdd + ddz - eex}$$

Puis GP est $b \frac{bcdd + bcdx - bddx - ceex}{bde + cdd + ddz - eex}$ ou bien

$GP \propto \frac{bbde + bcde - beex - ceex}{bde + cdd + ddz - eex}$ & CF est $c + x$;

sibienque multipliant GP par CF , il vient

$$\frac{bbcd + bcde - beex - ceex + bbde + bcde - beex - ceex}{bde + cdd + ddz - eex}$$

Et pourceque la premiere de ces sommes diuisée par d , est la mesme que la seconde diuisée par e , il est manifeste, que FP multipliée par CG est à GP multipliée par CF ;

Z z

c'est

c'est à dire que PQ est à PN , comme d est à e , qui est tout ce qu'il falloit demonstrier.

Et sçachés, que cete mesme demonstration s'estend a tout ce qui a esté dit des autres refractions ou reflexions, qui se font dans les ouales proposées, sans qu'il y faille changer aucune chose, que les signes $+$ & $-$ du calcul. c'est pourquoy chascun les peut aysement examiner de soy mesme, sans qu'il soit besoin que ie m'y arreste.

Mais il faut maintenant, que ie satisfasse a ce que iay omis en la Dioptrique, lorsqu'après auoir remarqué, qu'il peut y auoir des verres de plusieurs diuerses figures, qui font aussi bien l'un que l'autre, que les rayons venans d'un mesme point de l'obiet, s'assemblent tous en un autre point après les auoir trauerfés. & qu'entre ces verres, ceux qui sont fort conuexes d'un costé, & concaues de l'autre, ont plus de force pour brasser, que ceux qui sont esgalement conuexes des deux costés. au lieu que tout au contraire ces derniers sont les meilleurs pour les lunettes. ie me suis contenté d'expliquer ceux, que i'ay crû estre les meilleurs pour la pratique, en supposant la difficulté que les artisans peuuent auoir a les tailler. C'est pourquoy, afin qu'il ne reste rien a souhaiter touchant la theorie de cete science, ie doy expliquer encore icy la figure des verres, qui ayant l'une de leurs superficies autant conuexe, ou concaue, qu'on voudra, ne laissent pas de faire que tous les rayons, qui viennent vers eux d'un mesme point, ou paralleles, s'assemblent après en un mesme point; & celle des verres qui font le semblable, estant esgalement conuexes des deux costés, ou bien la

conue-

The first of these products divided by d is equal to the second divided by e , whence it follows that $PQ : PN = FP . CG : GP . CF = d : e$, which was to be proved. This proof may be made to hold for the reflecting and refracting properties of any one of these ovals, by proper changes of the signs plus and minus; and as each can be investigated by the reader, there is no need for further discussion here.^[178]

It now becomes necessary for me to supplement the statements made in my *Dioptrique*^[179] to the effect that lenses of various forms serve equally well to cause rays coming from the same point and passing through them to converge to another point; and that among such lenses those which are convex on one side and concave on the other are more powerful burning-glasses than those which are convex on both sides; while, on the other hand, the latter make the better telescopes.^[179] I shall describe and explain only those which I believe to have the greatest practical value, taking into consideration the difficulties of cutting. To complete the theory of the subject, I shall now have to describe

^[178] To obtain the equation of the first oval we may proceed as follows: Let $AF = c$; $AG = b$; $FC = c + z$; $GC = b - \frac{e}{d}z$. Let $CM = x$, $AM = y$. $FM = c + y$; $GM = b - y$. Draw PC normal to the curve at any point C . Let $AP = v$. Then $CF^2 = CM^2 + FM^2$. Also, $c^2 + 2cz + z^2 = x^2 + c^2 + 2cy + y^2$, whence

$$z = -c + \sqrt{x^2 + c^2 + 2cy + y^2}.$$

Also, $CG^2 = CM^2 + GM^2$, whence

$$b^2 - 2\frac{be}{d}z + \frac{e^2}{d^2}z^2 = x^2 + b^2 - 2by + y^2.$$

Substituting in this equation the value of z obtained above, squaring, and simplifying, we obtain:

$$\left[(d^2 - e^2)x^2 + (d^2 - e^2)y^2 - 2(e^2c + bd^2)y - 2ec(ec - bd) \right]^2 \\ = 4c^2(bd + ec)^2(x^2 + c^2 + 2cy + y^2). \quad \text{Rabuel, p. 348.}$$

^[179] Descartes: *La Dioptrique*, published with *Discours de la Methode*, Leyden, 1637. See also Cousin, vol. III, p. 401.

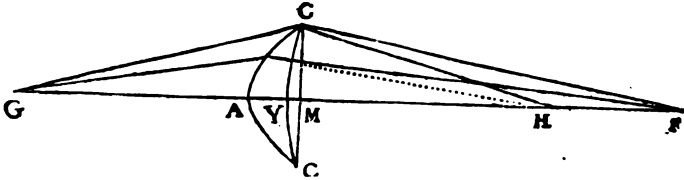
^[179] "Lunetes." The laws of reflection were familiar to the geometers of the Platonic school, and burning-glasses, in the form of spherical glass shells filled with water, or balls of rock crystal are discussed by Pliny, *Hist. Nat.* xxxvi, 67 (25) and xxxvii, 10. Ptolemy, in his treatise on Optics, discussed reflection, refraction, and plane and concave mirrors.

again the form of lens which has one side of any desired degree of convexity or concavity, and which makes all the rays that are parallel or that come from a single point converge after passing through it; and also the form of lens having the same effect but being equally convex on both sides, or such that the convexity of one of its surfaces bears a given ratio to that of the other.

In the first place, let G , Y , C , and F be given points, such that rays coming from G or parallel to GA converge at F after passing through a concave lens. Let Y be the center of the inner surface of this lens and C its edge, and let the chord CMC be given, and also the altitude of the arc CYC . First we must determine which of these ovals can be used for a lens that will cause rays passing through it in the direction of H (a point as yet undetermined) to converge toward F after leaving it.

There is no change in the direction of rays by means of reflection or refraction which cannot be effected by at least one of these ovals; and it is easily seen that this particular result can be obtained by using either part of the third oval, marked $3A3$ or $3Y3$ (see page 121), or the part of the second oval marked $2X2$ (see page 118). Since the same method applied to each of these, we may in each case take Y

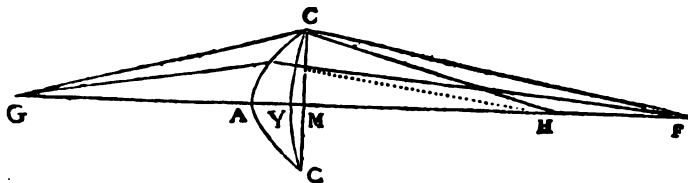
convexité de l'une de leurs superficies ayant la proportion donnée à celle de l'autre.



Poſons pour le premier cas, que les points G, Y, C, & F Comme on peut faire vn verre au-tant con-uexe ou concaue, en l'une de ſes ſuperficiés, qu'on voudra, qui raf-ſemble a vn point donné, tous les rayons qui viennent d'un autre point donné.
 eſtant donnés, les rayons qui viennent du point G, ou bien
 qui ſont paralleles à GA ſe doiuent aſſembler au point
 F, après auoir trauerſé vn verre ſi concaue, qu'Y eſtant
 le milieu de ſa ſuperficie interieure, l'extremité en ſoit
 au point C, enſorte que la chorde CM C, & la fleche
 YM de l'arc CY C, ſont données. La queſtion va là,
 que premierement il faut conſiderer, de laquelle des
 ouales expliquées, la ſuperficie du verre Y C, doit auoir
 la figure, pour faire que tous les rayons, qui eſtant de-
 dans tendent vers vn meſme point, comme vers H, qui
 n'eſt pas encore connu, s'aillent rendre vers vn autre, a
 ſçauoir vers F, après en eſtre ſortis. Car il n'y a aucun
 effect touchant le rapport des rayons changé par refle-
 xion, ou refraction d'un point a vn autre, qui ne puiſſe
 eſtre cauſé par quelqu'une de ces ouales. & on voit
 ayſement que ceruycy le peut eſtre par la partie de la
 troiſieſme Ouale, qui a tantost eſté marquée 3 A 3, ou
 par celle de la meſme, qui a eſté marquée 3 Y 3, ou enfin
 par la partie de la ſeconde qui a eſté marquée 2 X 2. Et
 pourceque ces trois tombent icy ſous meſme calcul, on-
 doit tant pour l'une, que pour l'autre prendre Y pour
 leur

Zz 2

leur sommet, C pour l'un des points de leur circonférence, & F pour l'un de leurs points brûlans ; après quoy il ne reste plus à chercher que le point H, qui doit estre l'autre point brûlant. Et on le trouue en considerant, que la difference, qui est entre les lignes F Y & F C, doit estre a celle, qui est entre les lignes H Y & H C, comme d est à e, c'est a dire, comme la plus grande des lignes qui mesurent les refractions du verre proposé est à la moindre ; ainsi qu'on peut voir manifestement de la description de ces ouales. Et pourceque les lignes F Y & F C sont données, leur difference l'est aussi, & en suite celle qui est entre H Y & H C ; pourceque la proportion qui est entre ces deux differences est donnée. Et de plus a cause que Y M est donnée, la difference qui est entre M H, & H C, l'est aussi ; & enfin pourceque C M est donnée, il ne reste plus qu'à trouuer M H le costé du triangle



rectangle C M H, dont on a l'autre costé C M, & on a aussi la difference qui est entre C H la base, & M H le costé demandé. d'où il est aysé de le trouuer. car si on prend k pour l'excès de C H sur M H, & n pour la longueur de la ligne C M, on aura $\frac{n^2}{2k} - \frac{1}{2} k$ pour M H. Et après auoir ainsi le point H, s'il se trouue plus loin du point Y, que

(see pages 137 and 138), as the vertex, C as a point on the curve,^[176] and F as one of the foci. It then remains to determine H, the other focus. This may be found by considering that the difference between FY and FC is to the difference between HY and HC as d is to e ; that is, as the longer of the lines measuring the refractive power of the lens is to the shorter, as is evident from the manner of describing the ovals.

Since the lines FY and FC are given we know their difference; and then, since the ratio of the two differences is known, we know the difference between HY and HC.

Again, since YM is known, we know the difference between MH and HC, and therefore CM. It remains to find MH, the side of the right triangle CMH. The other side of this triangle, CM, is known, and also the difference between the hypotenuse, CH and the required side, MH. We can therefore easily determine MH as follows:

Let $k = CH - MH$ and $n = CM$; then $\frac{n^2}{2k} - \frac{1}{2}k = MH$, which determines the position of the point H.

^[176] "Circonference."

If HY is greater than HF , the curve CY must be the first part of the third class of oval, which has already been designated by 3A3.

But suppose that HY is less than FY . This includes two cases: In the first, HY exceeds HF by such an amount that the ratio of their difference to the whole line FY is greater than the ratio of e , the smaller of the two lines that represent the refractive power, to d , the larger; that is, if $HF=c$, and $HY=c+h$, then dh is greater than $2ce+eh$. In this case CY must be the second part 3Y3 of the same oval of the third class.

In the second case dh is less than or equal to $2ce+eh$, and CY is the second part 2X2 of the oval of the second class.

Finally, if the points H and F coincide, $FY=FC$ and the curve YC is a circle.

It is also necessary to determine CAC , the other surface of the lens. If we suppose the rays falling on it to be parallel, this will be an ellipse having H as one of its foci, and the form is easily determined. If, however, we suppose the rays to come from the point G , the lens must have the form of the first part of an oval of the first class, the two foci of which are G and H and which passes through the point C . The point A is seen to be its vertex from the fact that the excess of GC over GA is to the excess of HA over HC as d is to e . For if k represents the difference between CH and HM , and x represents AM , then $x-k$ will represent the difference between AH and CH ; and if g represents the difference between GC and GM , which are given, $g+x$

que n'en est le point F, la ligne C Y doit estre la premiere partie de l'ouale du troisieme genre, qui a tantost esté nommée 3 A 3; Mais si H Y est moindre que F Y, ou bien elle surpasse H F de tant, que leur difference est plus grande a raison de la route F Y, que n'est e la moindre des lignes qui mesurent les refractions comparée avec d la plus grande, c'est a dire que faisant $H F \propto c$, & $H Y \propto c + h$, $d h$ est plus grande que $2 c e + e h$, & lors C Y doit estre la seconde partie de la mesme ouale du troisieme genre, qui a tantost esté nommée 3 Y 3; Ou bien $d h$ est esgale, ou moindre que $2 c e + e h$, & lors C Y doit estre la seconde partie de l'ouale du second genre qui a cy dessus esté nommée 2 X 2. Et enfin si le point H est le mesme que le point F, ce qui n'arriue que lorsque F Y & F C sont esgales cete ligne Y C est vn cercle.

Aprés cela il faut chercher C A C l'autre superficie de ce verre, qui doit estre vne Ellipse, dont H soit le point brulant; si on suppose que les rayons qui tombent dessus soiēt paralleles, & lors il est aysé de la trouuer. Mais si on suppose qu'ils vienēt du point G, ce doit estre la premiere partie d'une ouale du premier genre, dont les deux points brulans soiēt G & H, & qui passe par le point C: d'où on trouue le point A pour le sommet de cete ouale, en considerāt, que G C doit estre plus grāde que G A, d'une quantité, qui soit a celle dont H A surpasse H C, comme d à e . car ayant pris k pour la difference, qui est entre C H, & H M, si on suppose x pour A M, on aura $x - k$, pour la difference qui est entre A H, & C H; puis si on prend g pour celle, qui est entre G C, & G M, qui sont données, on aura $g + x$ pour celle, qui est entre G C, & G A; &

Z z 3

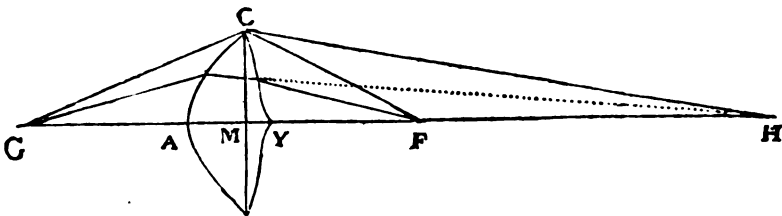
pour-

Comme
on peut
faire un
verre, qui
ait le mes-
me effect
que le
preceder.
& que la
convexi-
té del'vne
de ses su-
perficie
ait la pro-
portion
donnée
avec celle
del'autre.

pourceque cete derniere $g+x$ est à l'autre $x-k$, com-
me d est à e . on à $ge+ex \propto dx - dk$, ou bien $\frac{ge+dk}{d-e}$
pour la ligne x , ou AM , par laquelle on determine le
point A qui estoit cherché.

Posons maintenant pour l'autre cas, qu'on ne donne
que les points G, C , & F , avec la proportion qui est entre
les lignes AM , & YM , & qu'il faille trouver la figure du
verre ACY , qui face que tous les rayons, qui viennent
du point G s'assemblent au point F .

On peut derechef icy se servir de deux ouales dont
l'une, AC , ait G & H pour ses points bruslans; & l'autre,



CY , ait F & H pour les siens. Et pour les trouver, premie-
rement supposant le point H qui est commun a toutes
deux estre connu, ie cherche AM par les trois points
 G, C, H , en la façon tout maintenant expliquée; a sçavoir
preuant k pour la difference, qui est entre CH , & HM ,
& g pour celle qui est entre GC & GM : & AC estant
la premiere partie de l'Ouale du premier genre, iay
 $\frac{ge+dk}{d-e}$ pour AM : puis ie cherche aussi MY par les trois
points F, C, H , en sorte que CY soit la premiere partie
d'une ouale du troisieme genre; & prenant y pour MY ,
&

will represent the difference between GC and GA; and since $g+x : x-k=d : e$, we have $ge+ex=dx-dk$, or $AM=x=\frac{ge+dk}{d-e}$, which enables us to determine the required point A.

Again, suppose that only the points G, C, and F are given, together with the ratio of AM to YM; and let it be required to determine the form of the lens ACY which causes all the rays coming from the point G to converge to F.

In this case, we can use two ovals, AC and CY, with foci G and H, and F and H respectively. To determine these, let us suppose first that H, the focus common to both, is known. Then AM is determined by the three points G, C, and H in the way just now explained; that is if k represents the difference between CH and HM, and g the difference between GC and GM, and if AC be the first part of the oval of the first class, we have $AM=\frac{ge+dk}{d-e}$.

We may then find MY by means of the three points F, C, and H. If CY is the first part of an oval of the third class and we take y for MY and f for the difference between CF and FM, we have the dif-

ference between CF and FY equal to $f+y$; then let the difference between CH and HM equal k , and the difference between CH and HY equal $k+y$. Now $k+y : f+y = e : d$, since the oval is of the third class, whence $MY = \frac{fe-dk}{d-e}$. Therefore, $AM+MY=AY = \frac{ge+fe}{d-e}$, whence it follows that on whichever side the point H may lie, the ratio of the line AY to the excess of $GC+CI$ over GF is always equal to the ratio of e , the smaller of the two lines representing the refractive power of the glass, to $d-e$, the difference of these two lines, which gives a very interesting theorem.^[177]

The line AY being found, it must be divided in the proper ratio into AM and MY, and since M is known the points A and Y, and finally the point H, may be found by the preceding problem. We must first find whether the line AM thus found is greater than, equal to, or less than $\frac{ge}{d-e}$. If it is greater, AC must be the first part of one of the third class, as they have been considered here. If it is smaller, CY must be the first part of an oval of the first class and AC the first part

^[177] "Qui est un assez beau théorème."

& f pour la difference, qui est entre CF , & FM , i'ay
 $f+y$, pour celle qui est entre CF , & FY : puis ayant de-
 fia k pour celle qui est entre CH , & HM , i'ay $k+y$ pour
 celle qui est entre CH , & HY , que ie scay deuoir estre
 à $f+y$ comme e est à d , a cause de l'Ouale du troisieme
 genre, d'où ie trouue que y ou MY est $\frac{fe--dk}{d--e}$ puis ioi-
 gnant ensemble les deux quantités trouuées pour AM , &
 MY , ie trouue $\frac{ge+fe}{d--e}$ pour la toute AY ; D'où il suit que
 de quelque costé que soit supposé le point H , cete ligne
 AY est tousiours composée d'une quantité, qui est a cel-
 le dont les deux ensemble GC , & CF surpassent la tou-
 te GF , Comme e , la moindre des deux lignes qui seruent
 a mesurer les réfractions du verre proposé, est à $d--e$, la
 difference qui est entre ces deux lignes: cequi est vn as-
 sés beau theoresme. Or ayant ainsi la toute AY , il la
 faut couper selon la proportion que doiuent auoir ses
 parties AM & MY ; au moyen de quoy pource qu'on a
 desia le point M , on trouue aussy les points A & Y ; & en
 suite le point H , par le problemesme precedent. Mais au-
 parauant il faut regarder, si la ligne AM ainsi trouuée est
 plus grande que $\frac{ge}{d--e}$ ou plus petite, ou esgale. Car si elle
 est plus grande, on apprend de là que la courbe AC doit
 estre la premiere partie d'une ouale du premier genre; &
 CY la premiere d'une du troisieme, ainsi qu'elles ont
 esté icy supposées: au lieu que si elle est plus petite, cela
 montre que c'est CY , qui doit estre la premiere partie
 d'une ouale du premier genre; & que AC doit estre la
 premiere d'une du troisieme: Enfin si AM est esgale à
 $\frac{ge}{d--e}$

^{8e}
d -- e les deux courbes A C & C Y doivent estre deux hyperboles.

On pourroit estendre ces deux problemes a vne infinité d'autres cas, que ie ne m'arestre pas a deduire, à cause qu'ils n'ont eu aucun vsage en la Dioptrique.

On pourroit aussi passer outre, & dire, lorsque l'une des superficies du verre est donnée, pouruû qu'elle ne soit que toute plate, ou composée de sections coniques, ou de cercles; comment on doit faire son autre superficie, afin qu'il transmette tous les rayons d'un point donné, a un autre point aussi donné. car ce n'est rien de plus difficile que ce que ie viens d'expliquer; ou plutost c'est chose beaucoup plus facile, à cause que le chemin en est ouuert. Mais j'ayme mieux, que d'autres le cherchent, afin que s'ils ont encore un peu de peine à le trouuer, cela leur face d'autant plus estimer l'inuention des choses qui sont icy demonstrees.

Commẽt
on peut
appliquer
ce qui a
esté dit
icy des
lignes
courbes
descrites
sur vne
superficie
plate, à
celles qui
se descri-
uent dãs vn
espace qui
a trois di-
mensions.

Au reste ie n'ay parlé en tout cecy, que des lignes courbes, qu'on peut descrire sur vne superficie plate; mais il est aysé de rapporter ce que i'en ay dit, à toutes celles qu'on scauroit imaginer estre formées, par le mouuement regulier des points de quelque cors, dans un espace qui a trois dimensions. A scauoir en tirant deux perpendiculaires, de chascun des points de la ligne courbe qu'on veut considerer, sur deux plans qui s'entrecouppent a angles droits, l'une sur l'un, & l'autre sur l'autre. car les extremités de ces perpendiculaires descriuent deux autres lignes courbes, vne sur chascun de ces plans, desquelles on peut, en la façon cy dessus expliquée, determiner tous les

of one of the third class. Finally, if AM is equal to $\frac{ge}{d-e}$, the curves AC and CY must both be hyperbolas.

These two problems can be extended to an infinity of other cases which I will not stop to deduce, since they have no practical value in dioptrics.

I might go farther and show how, if one surface of a lens is given and is neither entirely plane nor composed of conic sections or circles, the other surface can be so determined as to transmit all the rays from a given point to another point, also given. This is no more difficult than the problems I have just explained; indeed, it is much easier since the way is now open; I prefer, however, to leave this for others to work out, to the end that they may appreciate the more highly the discovery of those things here demonstrated, through having themselves to meet some difficulties.

In all this discussion I have considered only curves that can be described upon a plane surface, but my remarks can easily be made to apply to all those curves which can be conceived of as generated by the regular movement of the points of a body in three-dimensional space.^[179] This can be done by dropping perpendiculars from each point of the curve under consideration upon two planes intersecting at right angles, for the ends of these perpendiculars will describe two other curves, one in each of the two planes, all points of which may be determined in the way already explained, and all of which may be related to those of a straight line common to the two planes; and by means of these the points of the three-dimensional curve will be entirely determined.

^[179] This is the hint which Descartes gives of the possibility of the extension of his theory to solid geometry. This extension was effected largely by Parent (1666-1716), Clairaut (1713-1765), and Van Schooten (d. 1661).

We can even draw a straight line at right angles to this curve at a given point, simply by drawing a straight line in each plane normal to the curve lying in that plane at the foot of the perpendicular drawn from the given point of the three-dimensional curve to that plane and then drawing two other planes, each passing through one of the straight lines and perpendicular to the plane containing it; the intersection of these two planes will be the required normal.

And so I think I have omitted nothing essential to an understanding of curved lines.

les points, & les rapporter a ceux de la ligne droite , qui est commune a ces deux plans , au moyen dequoy ceux de la courbe, qui a trois dimensions , sont entierement determinés. Mesme si on veut tirer vne ligne droite, qui coupe cete courbe au point donné a angles droits . il faut seulement tirer deux autres lignes droites dans les deux plans, vne en chascun, qui couppent a angles droits les deux lignes courbes, qui y sont, aux deux points , où tombent les perpendiculaires qui viennent de ce point donné. car ayant esleué deux autres plans , vn sur chascune de ces lignes droites, qui coupe a angles droits le plan où elle est, on aura l'interfection de ces deux plans pour la ligne droite cherchée. Et ainsi ie pense n'auoir rien omis des elemens, qui sont necessaires pour la connoissance des lignes courbes.

BOOK THIRD

Geometry

BOOK III

ON THE CONSTRUCTION OF SOLID AND SUPERSOLID PROBLEMS

WHILE it is true that every curve which can be described by a continuous motion should be recognized in geometry, this does not mean that we should use at random the first one that we meet in the construction of a given problem. We should always choose with

L A

G E O M E T R I E.

LIVRE TROISIÈME.

*De la construction des Problemes , qui
sont Solides, ou plusque Solides.*

EN C O R E que toutes les lignes courbes, qui peuvent
estre descrites par quelque mouvement regulier,
doivent estre receuës en la Geometrie , ce n'est pas a di-
re qu'il soit permis de se servir indifferemment de la pre-
miere qui se rencontre, pour la construction de chaque

De quel-
les lignes
courbes
on peut
se servir,
en la con-
struction
de chaque
proble-
me.

A a a

pro-
me.

THIRD BOOK

care the simplest curve that can be used in the solution of a problem, but it should be noted that the simplest means not merely the one most easily described, nor the one that leads to the easiest demonstration or construction of the problem, but rather the one of the simplest class that can be used to determine the required quantity.

For example, there is, I believe, no easier method of finding any number of mean proportionals,^[179] nor one whose demonstration is clearer, than the one which employs the curves described by the instrument XYZ, previously explained.^[180] Thus, if two mean proportionals between YA and YE be required, it is only necessary to describe

^[179] For the history of this problem, see Heath, *History*, Vol. I, p. 244, et seq.

^[180] See page 46.

a circle upon YE as diameter cutting the curve AD in D, and YD is then one of the required mean proportionals. The demonstration becomes obvious as soon as the instrument is applied to YD, since YA (or YB) is to YC as YC is to YD as YD is to YE.

Similarly, to find four mean proportionals between YA and YG, or six between YA and YN, it is only necessary to draw the circle YFG, which determines by its intersection with AF the line YF, one of the four mean proportionals; or the circle YHN, which determines by its intersection with AH the line YH, one of the six mean proportionals, and so on.

But the curve AD is of the second class, while it is possible to find two mean proportionals by the use of the conic sections, which are curves of the first class.^[181] Again, four or six mean proportionals can be found by curves of lower classes than AF and AH respectively. It would therefore be a geometric error to use these curves. On the other hand, it would be a blunder to try vainly to construct a problem by means of a class of lines simpler than its nature allows.^[182]

Before giving the rules for the avoidance of both these errors, some general statements must be made concerning the nature of equations.

An equation consists of several terms, some known and some unknown, some of which are together equal to the rest; or rather, all of which taken together are equal to nothing; for this is often the best form to consider.^[183]

^[181] If we let x and y represent the two mean proportionals between a and b we have $a : x = x : y = y : b$, whence $x^2 = ay$; $y^2 = bx$, and $xy = ab$. Therefore x and y may be found by determining the intersections of two parabolas or of a parabola and a hyperbola.

^[182] Cf. Pappus, Book IV, Prop. 31, Vol. I, p. 273. See also Guisnée, *Application de l'Algèbre à la Géométrie*, Paris, 1733, p. 28, and L'Hospital, *Traité Analytique des Sections Coniques*, Paris, 1707, p. 400.

^[183] The advantage of this arrangement had been recognized by several writers before Descartes.

pe la courbe A D au point D, Y D est l'une des moyennes proportionnelles cherchées. Dont la demonstration se voit a l'œil par la seule application de cet instrument sur la courbe A D. car comme Y A, ou Y B, qui luy est esgale a Y D, & Y D a Y E.

ie pour trouver quatre moyennes propres Y A & Y G; ou pour en trouver six en il ne faut que tracer le cercle Y F G, qui au point F, determine la ligne droite Y F, ces quatre proportionnelles; ou Y H N, H au point H, determine Y H l'une des autres.

que la ligne courbe A D est du second on peut trouver deux moyennes proportionnelles coniques, qui sont du premier; & si l'on peut trouver quatre ou six moyennes, par des lignes qui ne sont pas de genres ne sont A F, & A H, ce seroit vne faute en ne de les y employer. Et c'est vne faute osté de se travailler inutilement a vouloir quelque problemes par vn genre de lignes ne sa nature ne permet.

ue ie puisse icy donner quelques reigles, De la nature des Equations. l'une & l'autre de ces deux fautes, il faut que l'on se choise en general de la nature des Equations;

c'est a dire des sommes composées de plusieurs termes partie connus, & partie inconnus, dont les vns sont esgaux aux autres, ou plustost qui considerés tous ensemble sont esgaux a rien. car ce fera souuent le meilleur de les considerer en cete sorte.

A a a 2

Scachés

Combien
il peut y
auoir de
racines
en chasc
Equatiõ

Scachés donc qu'en chascque Equation, autant que la quantité inconnue a de dimensions, autant peut il y auoir de diuerses racines, c'est a dire de valeurs de cete quantité. car par exemple si on suppose x esgale a 2; ou bien $x - 2$ esgal a rien ; & derechef $x \propto 3$; ou bien $x - 3 \propto 0$; en multipliant ces deux equations $x - 2 \propto 0$, & $x - 3 \propto 0$, l'une par l'autre, on aura $xx - 5x + 6 \propto 0$, ou bien $xx \propto 5x - 6$, qui est vne Equation en laquelle la quantité x vaut 2 & tout ensemble vaut 3. Que si derechef on fait $x - 4 \propto 0$, & qu'on multiplie cete somme par $xx - 5x + 6 \propto 0$, on aura $x^3 - 9xx + 26x - 24 \propto 0$, qui est vne autre Equation en laquelle x ayant trois dimensions a aussi trois valeurs, qui sont 2, 3, & 4.

Quelles
sont les
fausses ra-
cines.

Mais souuent il arriue, que quelques vnes de ces racines sont fausses, ou moindres que rien. comme si on suppose que x designe aussi le defect d'une quantité, qui soit 5, on a $x + 5 \propto 0$, qui estant multipliée par $x^3 - 9xx + 26x - 24 \propto 0$ fait

$$x^4 - 4x^3 - 19xx + 106x - 120 \propto 0$$

pour vne equation en laquelle il y a quatre racines, a sçauoir trois vraies qui sont 2, 3, 4, & vne fausse qui est 5.

Cóment
on peut
diminuer
lenombre
des di-
mensions
d'une E-
quation
lorsqu'on
connoist
quel-
qu'une de
ses raci-
nes.

Et on voit euidemment de cecy, que la somme d'une equation, qui contient plusieurs racines, peut tousiours estre diuisée par vn binôme composé de la quantité inconnue, moins la valeur de l'une des vraies racines, laquelle que ce soit; ou plus la valeur de l'une des fausses. Au moyen de quoy on diminue d'autant ses dimensions.

Et reciproquement que si la somme d'une equation

ne

Every equation can have^[184] as many distinct roots (values of the unknown quantity) as the number of dimensions of the unknown quantity in the equation.^[185] Suppose, for example, $x = 2$ or $x - 2 = 0$, and again, $x = 3$, or $x - 3 = 0$. Multiplying together the two equations $x - 2 = 0$ and $x - 3 = 0$, we have $x^2 - 5x + 6 = 0$, or $x^2 = 5x - 6$. This is an equation in which x has the value 2 and at the same time^[186] x has the value 3. If we next make $x - 4 = 0$ and multiply this by $x^2 - 5x + 6 = 0$, we have $x^3 - 9x^2 + 26x - 24 = 0$ another equation, in which x , having three dimensions, has also three values, namely, 2, 3, and 4.

It often happens, however, that some of the roots are false^[187] or less than nothing. Thus, if we suppose x to represent the defect^[188] of a quantity 5, we have $x + 5 = 0$ which, multiplied by $x^3 - 9x^2 + 26x - 24 = 0$, yields $x^4 - 4x^3 - 19x^2 + 106x - 120 = 0$, an equation having four roots, namely three true roots, 2, 3, and 4, and one false root, 5.^[189]

It is evident from the above that the sum^[190] of an equation having several roots is always divisible by a binomial consisting of the unknown quantity diminished by the value of one of the true roots, or plus the value of one of the false roots. In this way,^[191] the degree of an equation can be lowered.

On the other hand, if the sum of the terms of an equation^[192] is not divisible by a binomial consisting of the unknown quantity plus or

^[184] It is worthy of note that Descartes writes "can have" ("peut-il y avoir"), not "must have," since he is considering only real positive roots.

^[185] That is as the number denoting the degree of the equation.

^[186] "Tout ensemble,"—not quite the modern idea.

^[187] "Racines fausses," a term formerly used for "negative roots." Fibonacci, for example, does not admit negative quantities as roots of an equation. *Scritti de Leonardo Pisano*, published by Boncompagni, Rome, 1857. Cardan recognizes them, but calls them "æstimationes falsæ" or "fictæ," and attaches no special significance to them. See Cardan, *Ars Magna*, Nurnberg, 1545, p. 2. Stifel called them "Numeri absurdi," as also in Rudolff's *Coss*, 1545.

^[188] "Le défaut." If $x = -5$, -5 is the "defect" of 5, that is, the remainder when 5 is subtracted from zero.

^[189] That is, three positive roots, 2, 3, and 4, and one negative root, -5 .

^[190] "Somme," the left member when the right member is zero; that is, what we represent by $f(x)$ in the equation $f(x) = 0$.

^[191] That is, by performing the division.

^[192] "Si la somme d'un équation."

minus some other quantity, then this latter quantity is not a root of the equation. Thus the^[100] above equation $x^4 - 4x^3 - 19x^2 + 106x - 120 = 0$ is divisible by $x-2$, $x-3$, $x-4$ and $x+5$,^[101] but is not divisible by x plus or minus any other quantity. Therefore the equation can have only the four roots, 2, 3, 4, and 5.^[102] We can determine also the number of true and false roots that any equation can have, as follows:^[103]

An equation can have as many true roots as it contains changes of sign, from $+$ to $-$ or from $-$ to $+$; and as many false roots as the number of times two $+$ signs or two $-$ signs are found in succession.

Thus, in the last equation, since $+x^4$ is followed by $-4x^3$, giving a change of sign from $+$ to $-$, and $-19x^2$ is followed by $+106x$ and $+106x$ by -120 , giving two more changes, we know there are three true roots; and since $-4x^3$ is followed by $-19x^2$ there is one false root.

It is also easy to transform an equation so that all the roots that were false shall become true roots, and all those that were true shall become false. This is done by changing the signs of the second, fourth,

^[100] First member of the equation. Descartes always speaks of dividing the equation.

^[101] Incorrectly given as $x-5$ in some editions.

^[102] Where 5 would now be written -5 . Descartes neither states nor explicitly assumes the fundamental theorem of algebra, namely, that every equation has at least one root.

^[103] This is the well known "Descartes's Rule of Signs." It was known however, before his time, for Harriot had given it in his *Artis analyticae praxis*, London, 1631. Cantor says Descartes may have learned it from Cardan's writings, but was the first to state it as a general rule. See Cantor, Vol. II(1) pp. 496 and 725.

*Descartes rule of
signs*

de la quan-
té, cela ref-
r d'aucune
Cōment
on peut
examiner
si quelque
quantité
donnée
est la va-
leur d'une
racine.
r -- 3, & par
ou -- aucu-
neut auoir

*16 - 32 - 19 - 104 - 120
+ - 32 - 19 - 104 - 120
16 - 32 - 19 - 104 - 120
16 - 32 - 19 - 104 - 120*

auoir de Combien
fausses il peut y
ue Equa- auoir de
at auoir autant qu'il y a, que vrayes
ouuent de fois estre changés ; & racines en
ils'y trouue de fois deux signes +, chaque
qui s'entresuiuent. Comme en la der- Equatiō.
après + x⁴ il y a -- 4 x³, qui est vn chan-
ne + en --, & après -- 19 x il y a + 106 x,
16 x il y a -- 120 qui sont encore deux autres
us, on connoist qu'il y a trois vrayes racines, &
autie, a cause que les deux signes --, de 4 x³, & 19 xx,
entresuiuent.

De plus il est aysé de faire en vne mesme Equation, Cōment
que toutes les racines qui estoient fausses deuient on fait
vrayes, & par mesme moyen que toutes celles qui estoient que les
vrayes deuient fausses : a sçauoir en changeant tous fausses
les signes + ou -- qui sont en la seconde, en la racines
quatriesme, en la sixiesme, ou autres places qui se d'une E-
designent par les nombres pairs, sans changer ceux quation
de la premiere, de la troisieme, de la cinquiesme deuient
& semblables qui se designent par les nombres vrayes, &
fausses.
Aaa 3 impairs.

impairs. Comme si au lieu de

$$+x^4 - 4x^3 - 19xx + 106x - 120 \propto 0$$

on escrit

$$+x^4 + 4x^3 - 19xx - 106x - 120 \propto 0$$

on a vne Equation en laquelle il n'y a qu'une vraie racine, qui est 5, & trois fausses qui sont 2, 3, & 4.

Cóment
on peut
augmen-
ter ou di-
minuer
les racines
d'une E-
quation,
sans les
connoi-
stre.

Que si sans connoistre la valeur des racines d'une Equation, on la veut augmenter, ou diminuer de quelque quantité connue, il ne faut qu'au lieu du terme inconnu en supposer vn autre, qui soit plus ou moins grand de cete me sine quantité, & le substituer par tout en la place du premier.

Comme si on veut augmenter de 3 la racine de cete Equation

$$x^4 + 4x^3 - 19xx - 106x - 120 \propto 0$$

il faut prendre y au lieu d' x , & penser que cete quantité y est plus grande qu' x de 3, en sorte que $y - 3$ est esgal a x , & au lieu d' xx , il faut mettre le quarré d' $y - 3$ qui est $yy - 6y + 9$ & au lieu d' x^3 il faut mettre son cube qui est $y^3 - 9yy + 27y - 27$, & enfin au lieu d' x^4 il faut mettre son quarré de quarré qui est $y^4 - 12y^3 + 54yy - 108y + 81$. Et ainsi descriuant la somme precedente en substituant par tout y au lieu d' x on a

$$\begin{aligned} y^4 - 12y^3 + 54yy - 108y + 81 \\ + 4y^3 - 36yy + 108y - 108 \\ - 19yy + 114y - 171 \\ - 106y + 318 \\ - 120 \end{aligned}$$

$$y^4 - 8y^3 - 1yy + 8y^2 \propto 0$$

oubien

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sixth, and all even terms, leaving unchanged the signs of the first, third, fifth, and other odd terms. Thus, if instead of

$$+x^4-4x^3-19x^2+106x-120=0$$

we write

$$+x^4+4x^3-19x^2-106x-120=0$$

we get an equation having one true root, 5, and three false roots, 2, 3, and 4.^[197]

If the roots of an equation are unknown and it be desired to increase or diminish each of these roots by some known number, we must substitute for the unknown quantity throughout the equation, another quantity greater or less by the given number. Thus, if it be desired to increase by 3 the value of each root of the equation

$$x^4+4x^3-19x^2-106x-120=0$$

put y in the place of x , and let y exceed x by 3, so that $y-3=x$. Then for x^2 put the square of $y-3$, or y^2-6y+9 ; for x^3 put its cube, $y^3-9y^2+27y-27$; and for x^4 put its fourth power,^[198] or

$$y^4-12y^3+54y^2-108y+81.$$

Substituting these values in the above equation, and combining, we have

$$\begin{array}{r} y^4 - 12y^3 + 54y^2 - 108y + 81 \\ + 4y^3 - 36y^2 + 108y - 108 \\ - 19y^2 + 114y - 171 \\ - 106y + 318 \\ - 120 \\ \hline y^4 - 8y^3 - y^2 + 8y = 0, \end{array} \quad [199]$$

or
$$y^3-8y^2-y+8=0,$$

[197] In absolute value.

[198] "Son quarré de quarré," that is, its fourth power.

[199] Descartes wrote this $y^4-8y^3-y^2+8y * \infty 0$, indicating by a star the absence of a term in a complete polynomial.

whose true root is now 8 instead of 5, since it has been increased by 3. If, on the other hand, it is desired to diminish by 3 the roots of the same equation, we must put $y+3 = x$ and $y^2+6y+9 = x^2$, and so on. so that instead of $x^4 + 4x^3 - 19x^2 - 106x - 120 = 0$, we have

$$\begin{array}{r}
 y^4 + 12y^3 + 54y^2 + 108y + 81 \\
 + 4y^3 + 36y^2 + 108y + 108 \\
 - 19y^2 - 114y - 171 \\
 - 106y - 318 \\
 - 120 \\
 \hline
 y^4 + 16y^3 + 71y^2 - 4y - 420 = 0.
 \end{array}$$

It should be observed that increasing the true roots of an equation diminishes^[800] the false roots by the same amount; and on the contrary diminishing the true roots increases the false roots; while diminishing either a true or a false root by a quantity equal to it makes the root zero; and diminishing it by a quantity greater than the root renders a true root false or a false root true.^[801] Thus by increasing the true root 5 by 3, we diminish each of the false roots, so that the root previously 4 is now only 1, the root previously 3 is zero, and the root previously 2 is now a true root, equal to 1, since $-2+3 = +1$. This explains why the equation $y^3-8y^2-y+8 = 0$ has only three roots.

^[800] In absolute value.

^[801] For example, the false root 5 diminished by 7 means $-(5-7) = +2$.

ou bien $y^3 - 8yy - 1y + 8 = 0$.

où la vraie racine qui estoit 5 est maintenant 8, a cause du nombre trois qui luy est aiousté.

Que si on veut au contraire diminuer de trois la racine de cete mesme Equation, il faut faire $y + 3 = x$ & $yy + 6y + 9 = xx$. & ainsi des autres de façon qu'au lieu de

$$x^4 + 4x^3 - 19xx - 106x - 120 = 0$$

on met

$$\begin{aligned} y^4 + 12y^3 + 54yy + 108y + 81 \\ + 4y^3 + 36yy + 108y + 108 \\ - 19yy - 114y - 171 \\ - 106y - 318 \\ - 120 \end{aligned}$$

$$y^4 + 16y^3 + 71yy - 4y - 420 = 0.$$

Et il est a remarquer qu'en augmentant les vrayes racines d'une Equation, on diminue les fausses de la mesme quantité; ou au contraire en diminuant les vrayes, on augmente les fausses. Et que si on diminue soit les vnes soit les autres, d'une quantité qui leur soit esgale, elles deviennent nulles, & que si c'est d'une quantité qui les surpasse, de vrayes elles deviennent fausses, ou de fausses vrayes. Comme icy en augmentant de 3 la vraie racine qui estoit 5, on a diminué de 3 chascune des fausses, en sorte que celle qui estoit 4 n'est plus qu'1, & celle qui estoit 3 est nulle, & celle qui estoit 2 est devenue vraie & est 1, a cause que $-2 + 3$ fait $+1$. c'est pourquoy en cete Equation $y^3 - 8yy - 1y + 8 = 0$ il ny a plus que 3 racines, entre lesquelles il y en a deux qui sont vrayes,

1. &

1, & 8, & vne fausse qui est aussi 1. & en cete autre

$$y^4 + 16y^3 + 71yy - 4y - 420 \propto 0$$

il n'y en a qu'une vraye qui est 2, a cause que $+5 - 3$ fait $+2$, & trois fausses qui sont 5, 6, & 7.

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d'une E-
quation.

Or par cete façon de changer la valeur des racines sans les connoistre, on peut faire deux choses, qui auront cy après quelque usage: la premiere est qu'on peut toujours oster le second terme de l'Equation qu'on examine, a sçauoir en diminuant les vrayes racines, de la quantité connue de ce second terme diuisée par le nombre des dimensions du premier, si l'un de ces deux termes estant marqué du signe $+$, l'autre est marqué du signe $-$; ou bien en l'augmentant de la mesme quantité, s'ils ont tous deux le signe $+$, ou tous deux le signe $-$. Comme pour oster le second terme de la derniere Equatiō qui est

$$y^4 + 16y^3 + 71yy - 4y - 420 \propto 0$$

ayant diuisé 16 par 4, a cause des 4 dimensions du terme y^4 , il vient derechef 4, c'est pourquoy ie fais $x = 4 \propto y$, & i'escris

$$\begin{aligned} x^4 - 16x^3 + 96xx - 256x + 256 \\ + 16x^3 - 192xx + 768x - 1024 \\ + 71xx - 568x + 1136 \\ - 4x + 16 \\ - 420 \end{aligned}$$

$$x^4 - 25xx - 60x - 36 \propto 0.$$

ou la vraye racine qui estoit 2, est 6, a cause qu'elle est augmentée de 4; & les fausses qui estoient 5, 6, & 7, ne sont plus que 1, 2, & 3, a cause qu'elles sont diminuées chacune de 4.

Tout

two of them, 1 and 8, being true roots, and the third, also 1, being false ; while the other equation $y^4-16y^3+71y^2-4y-420=0$ has only one true root, 2, since $+5-3=+2$, and three false roots, 5, 6, and 7.

Now this method of transforming the roots of an equation without determining their values yields two results which will prove useful: First, we can always remove the second term of an equation by diminishing its true roots by the known quantity of the second term divided by the number of dimensions of the first term, if these two terms have opposite signs; or, if they have like signs, by increasing the roots by the same quantity.^[202] Thus, to remove the second term of the equation $y^4+16y^3+71y^2-4y-420=0$ I divide 16 by 4 (the exponent of y in y^4), the quotient being 4. I then make $z-4=y$ and write

$$\begin{array}{r}
 z^4 - 16z^3 + 96z^2 - 256z + 256 \\
 + 16z^3 - 192z^2 + 768z - 1024 \\
 + 71z^2 - 568z + 1136 \\
 - 4z + 16 \\
 - 420 \\
 \hline
 z^4 - 25z^2 - 60z - 36 = 0.
 \end{array}$$

The true root of this equation which was 2 is now 6, since it has been increased by 4, and the false roots, 5, 6, and 7, are only 1, 2, and 3,

^[202] That is, by diminishing the roots by a quantity equal to the coefficient of the second term divided by the exponent of the highest power of x , with the opposite sign.

since each has been diminished by 4. Similarly, to remove the second terms of $x^4 - 2ax^3 + (2a^2 - c^2)x^2 - 2a^3x + a^4 = 0$; since $2a \div 4 = \frac{1}{2}a$ we must put $z + \frac{1}{2}a = x$ and write

$$\begin{array}{r}
 z^4 + 2az^3 + \frac{3}{2}a^2z^2 + \frac{1}{2}a^3z + \frac{1}{16}a^4 \\
 - 2az^3 - 3a^2z^2 - \frac{3}{2}a^3z - \frac{1}{4}a^4 \\
 + 2a^2z^2 + 2a^3z + \frac{1}{2}a^4 \\
 - c^2z^2 - ac^2z - \frac{1}{4}a^2c^2 \\
 - 2a^3z - a^4 \\
 + a^4 \\
 \hline
 z^4 + \left(\frac{1}{2}a^2 - c^2\right)z^2 - (a^3 + ac^2)z + \frac{5}{16}a^4 - \frac{1}{4}a^2c^2 = 0.
 \end{array}$$

Having found the value of z , that of x is found by adding $\frac{1}{2}a$. Second, by increasing the roots by a quantity greater than any of the false roots^[208] we make all the roots true. When this is done, there will be no two consecutive + or - terms; and further, the known quantity of the third term will be greater than the square of half that of the second term. This can be done even when the false roots are unknown, since approximate values can always be obtained for them and the roots can then be increased by a quantity as large as or larger than is required. Thus, given,

^[208] In absolute value.

Tout de mesme si on veut oster le second terme de

$$x^4 - 2ax^3 + \frac{1}{2}a^2x^2 - 2a^3x + a^4 = 0,$$

pourceque diuisant $2a$ par 4 il vient $\frac{1}{2}a$; il faut faire

$x + \frac{1}{2}a = 0$ & escrire

$$\begin{array}{r} x^4 + 2ax^3 + \frac{1}{2}a^2x^2 + \frac{1}{2}a^3x + \frac{1}{16}a^4 \\ - 2ax^3 \quad - 3a^2x^2 - \frac{3}{2}a^3x \quad - \frac{1}{4}a^4 \\ + 2a^2x^2 + 2a^3 \quad + \frac{1}{2}a^4 \\ \quad \quad \quad - a^3 \quad - \frac{1}{4}a^4 \\ \quad \quad \quad - 2a^3 \quad - a^4 \\ \quad \quad \quad + a^4 \end{array}$$

$$\begin{array}{r} x^4 \quad + \frac{1}{2}a^2x^2 - a^3 \quad x + \frac{5}{16}a^4 = 0 \\ - a^3 \quad - a^4 \quad - \frac{1}{4}a^4 \end{array}$$

& si on trouue après la valeur de x , en luy adioustant $\frac{1}{2}a$ on aura celle de x .

La seconde chose, qui aura cy après quelque vsage, est, qu'on peut tousiours en augmentant la valeur des vraies racines, d'une quantité qui soit plus grande que n'est celle d'aucune des fausses, faire qu'elles deuiennent toutes vraies, en sorte qu'il n'y ait point deux signes $+$, ou deux signes $-$ qui s'entresuiuent, & outre cela que la quantité conuë du troisieme terme soit plus grande, que le quarré de la moitié de celle du second. Car encore que cela se face, lorsque ces fausses racines sont inconnuës, il est aysé neanmoins de iuger a peu près de leur grandeur, & de prendre vne quantité, qui les surpasse d'autant, ou de plus, qu'il n'est requis a cet effect. Comme si on a

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x^6

$$x^6 + nx^5 - 6n^2x^4 + 36n^3x^3 - 216n^4x^2 + 1296n^5x - 7776n^6 = 0,$$

make $y - 6n = x$ and we have,

$$\begin{array}{r} y^6 - 36n \{ y^5 + 540n^2 \} y^4 - 4320n^3 \{ y^3 + 19440n^4 \} y^2 - 46656n^5 \{ y + 46656n^6 \\ + \quad n \} \quad - 30n^2 \} \quad + 360n^3 \{ \quad - 2160n^4 \} \quad + 6480n^5 \{ \quad - 7776n^6 \\ \quad \quad - 6n^2 \} \quad + 144n^3 \{ \quad - 1296n^4 \} \quad + 5184n^5 \{ \quad - 7776n^6 \\ \quad \quad \quad + 36n^3 \} \quad - 648n^4 \{ \quad + 3888n^5 \} \quad - 7776n^6 \\ \quad \quad \quad \quad - 216n^4 \} \quad + 2592n^5 \{ \quad - 7776n^6 \\ \quad \quad \quad \quad \quad + 1296n^5 \} \quad - 7776n^6 \\ \hline y^6 - 35ny^5 + 504n^2y^4 - 3780n^3y^3 + 15120n^4y^2 - 27216n^5y = 0. \end{array}$$

Now it is evident that $504n^2$, the known quantity^[304] of the third term, is larger than $\left(\frac{35}{2}n\right)^2$; that is, than the square of half that of the second term; and there is no case for which the true roots need be increased by a quantity larger in proportion to those given than for this one.

If it is undesirable to have the last term zero, as in this case, the roots must be increased just a little more, yet not too little, for the purpose. Similarly if it is desired to raise the degree of an equation, and also to have all its terms present, as if instead of $x^5 - b = 0$, we wish an equation of the sixth degree with no term zero, first, for $x^5 - b = 0$ write $x^6 - bx = 0$, and letting $y - a = x$ we have

$$y^6 - 6ay^5 + 15a^2y^4 - 20a^3y^3 + 15a^4y^2 - (6a^5 + b)y + a^6 + ab = 0.$$

It is evident that, however small the quantity a , every term of this equation must be present.

[304] I. e., the coefficient.

We can also multiply or divide all the roots of an equation by a given quantity, without first determining their values. To do this, suppose the unknown quantity when multiplied or divided by the given number to be equal to a second unknown quantity. Then multiply or divide the known quantity of the second term by the given quantity, that in the third term by the square of the given quantity, that in the fourth term by its cube, and so on, to the end.

This device is useful in changing fractional terms of an equation to whole numbers, and often^[206] in rationalizing the terms. Thus, given $x^3 - \sqrt{3}x^2 + \frac{26}{27}x - \frac{8}{27\sqrt{3}} = 0$, let there be required another equation in which all the terms are expressed in rational numbers. Let $y = \sqrt{3}$ and multiply the second term by $\sqrt{3}$, the third by 3, and the last by $3\sqrt{3}$. The resulting equation is $y^3 - 3y^2 + \frac{26}{9}y - \frac{8}{9} = 0$. Next let it be required to replace this equation by another in which the known quantities are expressed only by whole numbers. Let $z = 3y$. Multiplying 3 by 3, $\frac{26}{9}$ by 9, and $\frac{8}{9}$ by 27, we have

$$z^3 - 9z^2 + 26z - 24 = 0.$$

The roots of this equation are 2, 3, and 4; and hence the roots of the

^[206] But not always. Compare the case mentioned on page 175.

supposée toutes les places de l'Equation ne laissent pas d'estre remplies.

De plus on peut, sans connoître la valeur des vraies racines d'une Equation, les multiplier, ou diuifer toutes, par telle quantité connue qu'on veut. Ce qui se fait en supposant que la quantité inconnue étant multipliée, ou diuisée, par celle qui doit multiplier, ou diuifer les racines, est esgale à quelque autre. Puis multipliant, ou diuisant la quantité connue du second terme, par cette mesme qui doit multiplier, ou diuifer les racines; & par son quarré, celle du troisieme; & par son cube, celle du quatrieme; & ainsi iusques au dernier. Ce qui peut seruir pour reduire à des nombres entiers & rationaux, les fractions, ou souuent aussi les nombres sours, qui se trouuent dans les termes des Equations. Comme si on a

$$x^3 - \sqrt{3} x^2 + \frac{26}{27} x - \frac{8}{27\sqrt{3}} = 0,$$

& qu'on veuille en auoir une autre en sa place, dont tous les termes s'expriment par des nombres rationaux; il faut supposer $y = x\sqrt{3}$, & multiplier par $\sqrt{3}$ la quantité connue du second terme, qui est aussi $\sqrt{3}$, & par son quarré qui est 3 celle du troisieme qui est $\frac{26}{27}$, & par son cube qui est 3 $\sqrt{3}$ celle du dernier, qui est $\frac{8}{27\sqrt{3}}$, ce qui fait

$$y^3 - 3yy + \frac{26}{9}y - \frac{8}{9} = 0$$

Puis si on en veut auoir encore une autre en la place de celle cy, dont les quantités connues ne s'expriment que par des nombres entiers; il faut supposer $z = 3y$, & multipliant 3 par 3, $\frac{26}{9}$ par 9, & $\frac{8}{9}$ par 27 on trouue

$z^3 - 9zz + 26z - 24 = 0$, où les racines étant 2, 3, & 4, on connoît de là que celles de l'autre d'aparauant

B b b 2

estioient

estoyent $\frac{2}{3}$, 1, & $\frac{4}{3}$, & que celles de la première estoyent $\frac{2}{9}\sqrt{3}$, $\frac{1}{3}\sqrt{3}$, & $\frac{4}{9}\sqrt{3}$.

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de l'un
des ter-
mes d'une
Equation
esgale a
celle autre
qu'on
veut.

Cete operation peut aussy seruir pour rendre la quantité connue de quelqu'un des termes de l'Equatiõ esgale a quelque autre donnée, comme si ayant

$$x^3 + \dots - b b x + c^3 \propto a$$

On veut auoir en la place vne autre Equation, en laquelle la quantité connue, du terme qui occupe là troisieme place, a sçauoir celle qui est icy $b b$, soit $3 a a$, il faut suppo-

fer $y \propto x \sqrt{\frac{3 a a}{b b}}$; puis escrire $y^3 + \dots - 3 a a y + \frac{3 a^3 c^3}{b^3} \sqrt{3} \propto a$.

Que les
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les ou
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Au reste tant les vrayes racines que les fausses ne sont pas tousiours reelles; mais quelquefois seulement imaginaires; c'est a dire qu'on peut bien tousiours en imaginer autant que iay dit en chasque Equation, mais qu'il n'y a quelquefois aucune quantité, qui corresponde a celles qu'on imagine. comme encore qu'on en puisse imaginer trois en celle cy, $x^3 - 6 x x + 13 x - 10 \propto 0$, il n'y en a toutefois qu'une réelle, qui est 2, & pour les deux autres, quoy qu'on les augmente, ou diminue, ou multiplie en la façon que ie viens d'expliquer, on ne sçauoit les rendre autres qu'imaginaires.

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Or quand pour trouuer la construction de quelque problème, on vient a vne Equation, en laquelle la quantité inconnüe a trois dimensions; premierement si les quantités connües, qui y sont, contiennent quelques nombres rompus, il les faut reduire a d'autres entiers, par la multiplication tantost expliquée; Et s'ils en contiennent de sours, il faut aussy les reduire a d'autres rationaux, autant qu'il sera possible, tant par cete mesme multiplication,

preceding equation are $\frac{2}{3}$, 1 and $\frac{4}{3}$, and those of the first equation are

$$\frac{2}{9}\sqrt{3}, \frac{1}{3}\sqrt{3}, \text{ and } \frac{4}{9}\sqrt{3}.$$

This method can also be used to make the known quantity of any term equal to a given quantity. Thus, given the equation

$$x^3 - b^2x + c^3 = 0,$$

let it be required to write an equation in which the coefficient of the third term.^[206] namely b^2 , shall be replaced by $3a^2$. Let

$$y = x\sqrt{\frac{3a^2}{b^2}}$$

and we have

$$y^3 - 3a^2y + \frac{3a^3c^3}{b^3}\sqrt{3} = 0.$$

Neither the true nor the false roots are always real; sometimes they are imaginary;^[207] that is, while we can always conceive of as many roots for each equation as I have already assigned,^[208] yet there is not always a definite quantity corresponding to each root so conceived of. Thus, while we may conceive of the equation $x^3 - 6x^2 + 13x - 10 = 0$ as having three roots, yet there is only one real root, 2, while the other two, however we may increase, diminish, or multiply them in accordance with the rules just laid down, remain always imaginary.

When the construction of a problem involves the solution of an equation in which the unknown quantity has three dimensions,^[209] the following steps must be taken:

First, if the equation contains some fractional coefficients,^[210] change them to whole numbers by the method explained above;^[211] if it con-

^[206] Descartes wrote this equation $x^3 - b^2x + c^3 = 0$, the star showing, as explained on page 163, that a term is missing. Hence, he speaks of $-b^2x$ as the third term.

^[207] "Mais quelquefois seulement imaginaires." This is a rather interesting classification, signifying that we may have positive and negative roots that are imaginary. The use of the word "imaginary" in this sense begins here.

^[208] This seems to indicate that Descartes realized the fact that an equation of the n th degree has exactly n roots. Cf. Cantor, Vol. II(1), p. 724.

^[209] That is, a cubic equation.

^[210] "Nombres rompues," the "numeri fracti" of the medieval Latin writers and "numeri rotti" of the Italians. The expression "broken numbers" was often used by early English writers.

^[211] That is, transform the equation into one having integral coefficients.

tains surds, change them as far as possible into rational numbers, either by multiplication or by one of several other methods easy enough to find. Second, by examining in order all the factors of the last term, determine whether the left member of the equation is divisible^[212] by a binomial consisting of the unknown quantity plus or minus any one of these factors. If it is, the problem is plane, that is, it can be constructed by means of the ruler and compasses; for either the known quantity of the binomial is the required root^[213] or else, having divided the left member of the equation by the binomial, the quotient is of the second degree, and from this quotient the root can be found as explained in the first book.^[214]

Given, for example, $y^6 - 8y^4 - 124y^2 - 64 = 0$.^[215] The last term, 64, is divisible by 1, 2, 4, 8, 16, 32, and 64; therefore we must find whether the left member is divisible by $y^2 - 1$, $y^2 + 1$, $y^2 - 2$, $y^2 + 2$, $y^2 - 4$, and so on. We shall find that it is divisible by $y^2 - 16$ as follows:

$$\begin{array}{r}
 + y^6 - 8y^4 - 124y^2 - 64 = 0 \\
 - y^6 - 8y^4 - 4y^2 \\
 \hline
 0 - 16y^4 - 128y^2 - 64 \\
 - 16y^4 - 16y^2 \\
 \hline
 + y^4 + 8y^2 + 4 = 0
 \end{array}$$

Beginning with the last term, I divide -64 by -16 which gives $+4$; write this in the quotient; multiply $+4$ by $+y^2$ which gives $+4y^2$ and

^[212] "Qui divise toute la somme."

^[213] That is, the root that satisfies the conditions of the problem.

^[214] See page 13.

^[215] Descartes considers this equation as a function of y^2 .

tiplication, que par diuers autres moyens, qui sont affés faciles a trouuer. Puis examinant par ordre toutes les quantités, qui peuuent diuifer sans fraction le dernier terme, il faut voir, si quelqu'une d'elles, iointe avec la quantité inconnue par le signe + ou --, peut composer vn binome, qui diuise toute la somme; & si cela est le Probleme est plan, c'est a dire il peut estre construit avec la reigle & de compas; Car ou bien la quantité connue de ce binome est la racine cherchée; ou bien l'Equation estant diuisée par luy, se reduist a deux dimensions, en sorte qu'on en peut trouuer après la racine, par ce qui a esté dit au premier liure.

Par exemple si on a

$$y^6 - 8y^4 - 124y^2 - 64 = 0.$$

le dernier terme, qui est 64, peut estre diuisé sans fraction par 1, 2, 4, 8, 16, 32, & 64; C'est pourquoy il faut examiner par ordre si cete Equation ne peut point estre diuisée par quelqu'un des binomes, $yy - 1$ ou $yy + 1$, $yy - 2$ ou $yy + 2$, $yy - 4$ &c. & on trouue qu'elle peut l'estre par $yy - 16$, en cete sorte.

$$\begin{array}{r}
 + y^6 - 8y^4 - 124yy - 64 = 0 \\
 - 1 y^6 - 8y^4 - 4yy \quad \quad \quad - 16 \\
 \hline
 0 \quad - 16y^4 - 128yy \\
 \quad \quad \quad 16 \quad \quad \quad 16 \\
 \hline
 + y^4 + 8yy + 4 = 0.
 \end{array}$$

Je commence par le dernier terme, & diuise -- 64 par -- 16, ce qui fait + 4, que j'escriis dans le quotient, puis ie multiplie + 4 par + yy, ce qui fait + 4yy; c'est pourquoy j'escriis -- 4yy en la somme, qu'il faut diuifer. car il y

B b b 3

La facon de diuiser vne Equation par vn binome qui contient la racine.

faut toujours escrire le signe $+$ ou $-$ tout contraire a celui que produist la multiplication. & ioignant $- 124yy$ avec $- 4yy$, iay $- 128yy$, que ie diuise derechef par $- 16$, & iay $+ 8yy$, pour mettre dans le quotient & en le multipliant par yy , iay $- 8y^4$, pour ioindre avec le terme qu'il faut diuiser, qui est aussy $- 8y^4$, & ces deux ensemble font $- 16y^4$, que ie diuise par $- 16$, ce qui fait $+ 1y^4$ pour le quotient, & $- 1y^4$ pour ioindre avec $+ 1y^4$, ce qui fait 0 , & monstre que la diuision est acheuée. Mais s'il estoit resté quelque quantité, ou bien qu'on n'eust pû diuiser sans fraction quelqu'un des termes precedens, on eust par la reconnu, quelle ne pouuoit estre faire.

Tout de mesme si on a $y^6 \pm 2ccy^4 \pm c^4yy \pm 2a^4cc \propto 0$.

le dernier terme se peut diuiser sans fraction par a , aa , $aa + cc$, $a^4 + acc$, & semblables. Mais il n'y en a que deux qu'on ait besoin de considerer, a sçauoir aa & $aa + cc$; car les autres donnant plus ou moins de dimensions dans le quotient, qu'il n'y en a en la quantité connue du penultiesme terme, empescheroient que la diuision ne s'y pût faire. Et notés, que ie ne conte icy les dimensions d' y^6 , que pour trois, a cause qu'il ny a point d' y^5 , ny d' y^3 , ny d' y en toute la somme. Or en examinant le binôme $yy - aa \pm cc \propto 0$, on trouue que la diuision se peut faire par luy en cete sorte.

$$\begin{array}{r}
 + y^6 \pm 2ccy^4 \pm c^4yy \pm 2a^4cc \propto 0, \\
 \hline
 \frac{- y^6 \pm 2ccy^4 \pm c^4yy \pm 2a^4cc}{0} \\
 \hline
 + y^4 \pm 2ccy^2 \pm c^4 \propto 0.
 \end{array}$$

Ce-

write in the dividend (for the opposite sign from that obtained by the multiplication must always be used). Adding $-124y^2$ and $-4y^2$ I have $-128y^2$. Dividing this by -16 I have $+8y^2$ in the quotient, and multiplying by y^2 I have $-8y^4$ to be added to the corresponding term, $-8y^4$, in the dividend. This gives $-16y^4$ which divided by -16 yields $+y^4$ in the quotient and $-y^6$ to be added to $+y^6$ which gives zero, and shows that the division is finished.

If, however, there is a remainder, or if any modified term is not exactly divisible by 16, then it is clear that the binomial is not a divisor.^[206]

Similarly, given

$$\left. \begin{array}{r} y^6 + a^2 \{ y^4 - a^4 \} y^2 - a^6 \\ - 2c^2 \{ \quad \quad \} + c^4 \{ \quad \quad \} - 2a^4 c^2 \\ \quad \quad \quad \quad \quad \quad \quad - a^2 c^4 \end{array} \right\} = 0,$$

the last term is divisible by a , a^2 , a^2+c^2 , a^3+ac^2 , and so on, but only two of these need be considered, namely a^2 and a^2+c^2 . The others give a term in the quotient of lower or higher degree than the known quantity of the next to the last term, and thus render the division impossible.^[207] Note that I am here considering y^6 as of the third degree, since there are no terms in y^5 , y^3 , or y . Trying the binomial

$$y^2 - a^2 - c^2 = 0$$

we find that the division can be performed as follows:

$$\begin{array}{r} + y^6 + a^2 \{ y^4 - a^4 \} y^2 - a^6 \\ - y^6 - 2c^2 \{ \quad \quad \} + c^4 \{ \quad \quad \} - 2a^4 c^2 \\ \hline 0 - 2a^2 \{ y^4 - a^4 \} y^2 - a^2 c^4 \\ + \quad \quad \quad \quad \quad \quad \quad - a^2 c^2 \\ \hline - a^2 - c^2 \quad - a^2 - c^2 \quad - a^2 - c^2 \\ \hline + y^4 \quad + 2a^2 \{ y^2 + a^4 \} \\ \quad \quad \quad \quad \quad \quad \quad - c^2 \{ \quad \quad \} + a^2 c^2 \end{array} \left. \begin{array}{l} \\ \\ \\ \end{array} \right\} = 0,$$

^[206] This is evidently a modified form of our modern "synthetic division," the basis of our "Remainder Theorem," and of Horner's Method of solving numerical equations, a method known to the Chinese in the thirteenth century. See Cantor, Vol. II(1), pp. 279 and 287. See also Smith and Mikami, *History of Japanese Mathematics*, Chicago, 1914; Smith, I, 273.

^[207] This is not a general rule.

This shows that a^2+c^2 is the required root, which can easily be proved by multiplication.

But when no binomial divisor of the proposed equation can be found, it is certain that the problem depending upon it is solid,^[215] and it is then as great a mistake to try to construct it by using only circles and straight lines as it is to use the conic sections to construct a problem requiring only circles; for any evidence of ignorance may be termed a mistake.

Again, given an equation in which the unknown quantity has four dimensions.^[216] After removing any surds or fractions, see if a binomial having one term a factor of the last term of the expression will divide the left member. If such a binomial can be found, either the known quantity of the binomial is the required root, or,^[217] after the division is performed, the resulting equation, which is of only three dimensions, must be treated in the same way. If no such binomial can be found, we must increase or diminish the roots so as to remove the second term, in the way already explained, and then reduce it to another of the third degree, in the following manner: Instead of

$$x^4 \pm px^2 \pm qx \pm r = 0$$

write

$$y^6 \pm 2py^4 + (p^2 \pm 4r)y^2 - q^2 = 0.^[218]$$

^[215] That is, that it involves a conic or some higher curve.

^[216] A biquadratic equation.

^[217] "Either, or," as in the original. It is like saying that the root of $x^2-a^2=0$ is either $x=a$ or $x=-a$.

^[218] Descartes wrote substantially "Instead of

$$+ x^4 \pm .pxx.qx.r \approx 0$$

write

$$+ y^6 .2py^4 + (pp.4r)yy - qq \approx 0."$$

The symbolism is characteristic of Descartes.

Ce qui montre que la racine cherchée est $aa + cc$.
Et la preuve en est aysée a faire par la multiplication.

Mais lorsqu'on ne trouve aucun binôme, qui puisse ainsi diviser toute la somme de l'Equation proposée, il est certain que le Problème qui en depend est solide. Et ce n'est pas vne moindre faute après cela, de tascher a le construire sans y employer que des cercles & des lignes droites, que ce seroit d'employer des sections coniques a construire ceux auxquels on n'a besoin que de cercles. car enfin tout ce qui tesmoigne quelque ignorance s'appelle faute.

Que si on a vne Equation dont la quantité inconnüe ait quatre dimensions, il faut en même façon, après en avoir osté les nombres sours, & rompus, s'il y en a, voir si on pourra trouver quelque binôme, qui divise toute la somme, en le composant de l'une des quantités, qui divisent sans fraction le dernier terme. Et si on en trouve vn, ou bien la quantité connue de ce binôme est la racine cherchée; on du moins après cete division, il ne reste en l'Equation, que trois dimensions, en suite dequoy il faut derechef l'examiner en la même sorte. Mais lorsqu'il ne se trouve point de tel binôme, il faut en augmentant, ou diminuant la valeur de la racine, oster le second terme de la somme, en la façon tantost expliquée. Et après la reduire a vne autre, qui ne contienne que trois dimensions. Ce qui se fait en cete sorte.

Au lieu de $+x^4 . pxx . qx . r \propto 0$,

il faut escrire $+y^4 . 2py^2 . \frac{p^2}{r}yy - qq \propto 0$.

Et pour les signes $+$ ou $-$ que iay omis, s'il y a
en

Quels
problèmes
sont
solides,
lorsque
l'Equa-
tion est
cubique.

La redu-
ction des
Equa-
tions qui
ont qua-
tre di-
mensions,
lorsque le
problème
est
plan. Et
quels sont
ceux qui
sont soli-
des.

eu $+p$ en la precedente Equation, il faut mettre en cel-
 lecy $+2p$, ou s'il y a eu $-p$, il faut mettre $--2p$. & au
 contraire s'il y a eu $+r$, il faut mettre $--4r$, ou s'il y a eu
 $--r$, il faut mettre $+4r$. & soit qu'il y ait eu $+q$, ou
 $--q$, il faut toujours mettre $--qq$, & $+pp$. au moins si
 on suppose que x^4 , & y^6 sont marqués du signes $+$,
 car ce seroit tout le contraire si on y supposoit le si-
 gne $--$.

Par exemple si on a $+x^4^*--4xx--8x+35x^0$
 il faut escrire en son lieu $y^6--8y^4--124yy--64x^0$. car
 la quantité que iay, nommée p estant $--4$, il faut mettre
 $--8y^4$ pour $2py^4$. & celle, que iay nommée r estant 35 ,
 il faut mettre $\frac{16}{140}yy$, c'est a dire $--124yy$, au lieu de
 $\frac{16}{4r}yy$. & enfin q estant 8 , il faut mettre $--64$, pour $--qq$.
 Toutdemefme au lieu de $+x^4^*--17xx--20x--6x^0$.
 il faut escrire $+y^6--34y^4+313yy--400x^0$.
 Car 14 est double de 17 , & 313 en est le quarré ioint au
 quadruple de 6 , & 400 est le quarré de 20 .

Tout de mesme aussi au lieu de

$$+x^4^*+\frac{1}{2}aa--a^4+\frac{5}{30}a^4x^0,$$

Il faut escrire

$$y^6+\frac{1}{2}aa y^4+\frac{1}{30}a^4 yy--\frac{1}{30}a^4ccx^0.$$

Car p est $+\frac{1}{2}aa--cc$, & pp , est $\frac{1}{4}a^4--aacc+c^4$, & $4r$
 est $--\frac{5}{4}a^4+aacc$, & enfin $--qq$ est $--a^6--2a^4cc--aac^4$.

Après que l'Equation est ainsi reduite a trois dimen-
 sions, il faut chercher la valeur d' yy par la methode desia
 expliquée; Et si celle ne peut estre trouuée, on n'a point
 besoin

For the ambiguous^[288] sign put $+2p$ in the second expression if $+p$ occurs in the first; but if $-p$ occurs in the first, write $-2p$ in the second; and on the contrary, put $-4r$ if $+r$, and $+4r$ if $-r$ occurs; but whether the first expression contains $+q$ or $-q$ we always write $-q^2$ and $+p^2$ in the second, provided that x^4 and y^6 have the sign $+$; otherwise, we write $+q^2$ and $-p^2$. For example, given

$$x^4 - 4x^2 - 8x + 35 = 0$$

replace it by

$$y^6 - 8y^4 - 124y^2 - 64 = 0.$$

For since $p = -4$, we replace $2py^4$ by $-8y^4$; and since $r = 35$, we replace $(p^2 - 4r)y^2$ by $(16 - 140)y^2$ or $-124y^2$; and since $q = 8$, we replace $-q^2$ by -64 .

Similarly, instead of

$$x^4 - 17x^2 - 20x - 6 = 0$$

we must write

$$y^6 - 34y^4 + 313y^2 - 400 = 0,$$

for 34 is twice 17, and 313 is the square of 17 increased by four times 6, and 400 is the square of 20.

In the same way, instead of

$$+z^4 + \left(\frac{1}{2}a^2 - c^2\right)z^2 - (a^3 + ac^2)z - \frac{5}{16}a^4 - \frac{1}{4}a^2c^2 = 0,$$

we must write

$$y^6 + (a^2 - 2c^2)y^4 + (c^4 - a^4)y^2 - a^6 - 2a^4c^2 - a^2c^4 = 0;$$

for

$$p = \frac{1}{2}a^2 - c^2, p^2 = \frac{1}{4}a^4 - a^2c^2 + c^4, 4r = -\frac{5}{4}a^4 + a^2c^2.$$

And, finally,

$$-q^2 = -a^6 - 2a^4c^2 - a^2c^4.$$

When the equation has been reduced to three dimensions, the value of y^2 is found by the method already explained. If this cannot be

^[288] Descartes wrote "pour les signes $+$ ou $-$ que j'ai omis."

done it is useless to pursue the question further, for it follows inevitably that the problem is solid. If, however, the value of y^2 can be found, we can by means of it separate the preceding equation into two others, each of the second degree, whose roots will be the same as those of the original equation. Instead of $+x^4 \pm px^2 \pm qx \pm r = 0$, write the two equations

$$+x^2 - yx + \frac{1}{2}y^2 \pm \frac{1}{2}p \pm \frac{q}{2y} = 0$$

and

$$+x^2 + yx + \frac{1}{2}y^2 \pm \frac{1}{2}p \pm \frac{q}{2y} = 0.$$

For the ambiguous signs write $+\frac{1}{2}p$ in each new equation, when p has a positive sign, and $-\frac{1}{2}p$ when p has a negative sign, but write $+\frac{q}{2y}$ when we have $-yx$, and $-\frac{q}{2y}$ when we have $+yx$, provided q has a positive sign, and the opposite when q has a negative sign. It is then easy to determine all the roots of the proposed equation, and consequently to construct the problem of which it contains the solution, by the exclusive use of circles and straight lines. For example, writing $y^6 - 34y^4 + 313y^2 - 400 = 0$ instead of $x^4 - 17x^2 - 20x - 6 = 0$ we find that $y^2 = 16$; then, instead of the original equation

$$+x^4 - 17x^2 - 20x - 6 = 0$$

write the two equations $+x^2 - 4x - 3 = 0$ and $+x^2 + 4x + 2 = 0$.

For, $y = 4$, $\frac{1}{2}y^2 = 8$, $p = 17$, $q = 20$, and therefore

$$+\frac{1}{2}y^2 - \frac{1}{2}p - \frac{q}{2y} = -3$$

and

$$+\frac{1}{2}y^2 - \frac{1}{2}p + \frac{q}{2y} = +2.$$

besoin de passer outre; car il fuit de là infalliblement, que le problème est solide. Mais si on la trouve, on peut diuifer par son moyen la précédente Equation en deux autres, en chascune desquelles la quantité inconnue n'aura que deux dimensions, & dont les racines feront les mêmes que les siennes. A sçauoir, au lieu de

$+x^4 \cdot pxx \cdot qx \cdot r \propto 0$,
il faut escrire ces deux autres

$$+xx -- yx + \frac{1}{2}yy \cdot \frac{1}{2}p \cdot \frac{q}{2y} \propto 0, \&$$

$$+xx + yx + \frac{1}{2}yy \cdot \frac{1}{2}p \cdot \frac{q}{2y} \propto 0.$$

Et pour les signes $+$ & $--$ que iay omis, s'il y a $+p$ en l'Equation précédente, il faut mettre $+\frac{1}{2}p$ en chascune de celles cy; & $-\frac{1}{2}p$, s'il y a en l'autre $--p$. Mais il faut mettre $+\frac{q}{2y}$, en celle où il y a $--yx$; & $-\frac{q}{2y}$, en celle où il y a $+yx$, lorsqu'il y a $+q$ en la première. Et au contraire s'il y a $--q$, il faut mettre $-\frac{q}{2y}$, en celle où il y a $--yx$; & $+\frac{q}{2y}$, en celle où il y a $+yx$. En suite dequoy il est aysé de connoître toutes les racines de l'Equation proposée, & par conséquent de construire le problème, dont elle contient la solution, sans y employer que des cercles, & des lignes droites.

Par exemple a cause que faisant

$y^6 -- 34y^4 + 313yy - 400 \propto 0$, pour
 $x^4 -- 17xx -- 20x -- 6 \propto 0$, on trouue que yy est 16, on doit au lieu de cete Equation

$+x^4 -- 17xx -- 20x -- 6 \propto 0$, escrire ces deux
C c c autres

autres $+xx - 4x - 3 = 0$. Et $+xx + 4x + 2 = 0$.
 car y est 4, $\frac{1}{2}yy$ est 8, p est 17, & q est 20, de façon que
 $+\frac{1}{2}yy - \frac{1}{2}p - \frac{q}{2y}$ fait -3 , & $+\frac{1}{2}yy - \frac{1}{2}p + \frac{q}{2y}$ fait $+2$. Et
 tirant les racines de ces deux Equations, on trouve toutes
 les mesmes, que si on les tiroit de celle où est x^4 , a
 sçavoir on en trouve vne vraie, qui est $\sqrt{7+2}$, & trois
 fausses, qui sont $\sqrt{7-2}$, $2 + \sqrt{2}$, & $2 - \sqrt{2}$.
 Ainsi ayant $x^4 - 4xx - 8x + 3 = 0$, pour ce que la racine
 de $y^6 - 8y^4 - 124yy + 64 = 0$, est derechef 16, il faut
 écrire

$$xx - 4x + 5 = 0, \text{ \& } xx + 4x + 7 = 0.$$

Car icy $+\frac{1}{2}yy - \frac{1}{2}p - \frac{q}{2y}$ fait 5, & $+\frac{1}{2}yy - \frac{1}{2}p + \frac{q}{2y}$
 fait 7. Et pour ce qu'on ne trouve aucune racine, ny
 vraie, ny fausse, en ces deux dernières Equations, on
 connoist de là que les quatre de l'Equation dont elles
 procedent sont imaginaires; & que le Probleme, pour
 lequel on l'a trouvée, est plan de sa nature; mais qu'il
 ne sçauroit en aucune façon estre construit, a cause que
 les quantités données ne peuvent se joindre.

Tout de mesme ayant

$$x^4 + \frac{1}{2}aa \} xx - a \} x + \frac{5}{16}a^4 \\ - cc \} xx - a \} x - \frac{1}{4}aacc = 0,$$

pour ce qu'on trouve $aa + cc$ pour yy , il faut écrire

$$xx - \sqrt{aa + cc} x + \frac{3}{4}aa - \frac{1}{2}a\sqrt{aa + cc} = 0, \text{ \& } \\ xx + \sqrt{aa + cc} x + \frac{3}{4}aa + \frac{1}{2}a\sqrt{aa + cc} = 0.$$

Car y est $\sqrt{aa + cc}$, & $+\frac{1}{2}yy + \frac{1}{2}p$ est $\frac{3}{4}aa$, & $\frac{q}{2y}$
 est $\frac{1}{2}a\sqrt{aa + cc}$. D'où on connoist que la valeur de x
 est.

Obtaining the roots of these two equations, we get the same results as if we had obtained the roots of the equation containing x^4 , namely, one true root, $\sqrt{7} + 2$, and three false ones, $\sqrt{7} - 2$, $2 + \sqrt{2}$, and $2 - \sqrt{2}$. Again, given $x^4 - 4x^2 - 8x + 35 = 0$, we have $y^6 - 8y^4 - 124y^2 - 64 = 0$, and since the root of the latter equation is 16, we must write $x^2 - 4x + 5 = 0$ and $x^2 + 4x + 7 = 0$. For in this case,

$$+ \frac{1}{2} y^2 - \frac{1}{2} p - \frac{q}{2y} = 5$$

and

$$+ \frac{1}{2} y^2 - \frac{1}{2} p + \frac{q}{2y} = 7.$$

Now these two equations have no roots either true or false,^[288] whence we know that the four roots of the original equation are imaginary; and that the problem whose solution depends upon this equation is plane, but that its construction is impossible, because the given quantities cannot be united.^[289]

Similarly, given

$$z^4 + \left(\frac{1}{2} a^2 - c^2 \right) z^2 - (a^3 + ac^2) z + \frac{5}{16} a^4 - \frac{1}{4} a^2 c^2 = 0,$$

since we have found $y^2 = a^2 + c^2$, we must write

$$z^2 - \sqrt{a^2 + c^2} z + \frac{3}{4} a^2 - \frac{1}{2} a \sqrt{a^2 + c^2} = 0,$$

and

$$z^2 + \sqrt{a^2 + c^2} z + \frac{3}{4} a^2 + \frac{1}{2} a \sqrt{a^2 + c^2} = 0.$$

^[288] That is, all its roots are imaginary.

^[289] That is, the given quantities cannot be taken together in the same problem.

For $y = \sqrt{a^2 + c^2}$ and $+\frac{1}{2}y^2 + \frac{1}{2}p = \frac{3}{4}a^2$, and $\frac{q}{2y} = \frac{1}{2}a\sqrt{a^2 + c^2}$, then we have

$$z = \frac{1}{2}\sqrt{a^2 + c^2} + \sqrt{-\frac{1}{2}a^2 + \frac{1}{4}c^2 + \frac{1}{2}a\sqrt{a^2 + c^2}}$$

or

$$z = \frac{1}{2}\sqrt{a^2 + c^2} - \sqrt{-\frac{1}{2}a^2 + \frac{1}{4}c^2 + \frac{1}{2}a\sqrt{a^2 + c^2}}.$$

Now we already have $z + \frac{1}{2}a = x$, and therefore x , the quantity in the search for which we have performed all these operations, is

$$+\frac{1}{2}a + \sqrt{\frac{1}{4}a^2 + \frac{1}{4}c^2} - \sqrt{\frac{1}{4}c^2 - \frac{1}{2}a^2 + \frac{1}{2}a\sqrt{a^2 + c^2}}.$$

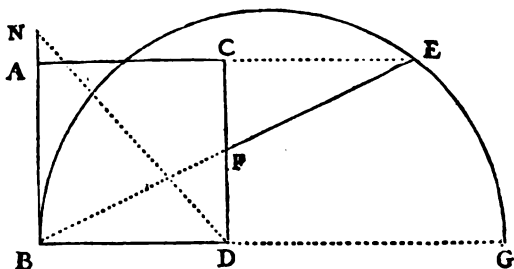
To emphasize the value of this rule, I shall apply it to a problem. Given the square AD and the line BN, to prolong the side AC to E, so that EF, laid off from E on EB, shall be equal to NB.

Pappus showed that if BD is produced to G, so that DG = DN, and a circle is described on BG as diameter, the required point E will be the intersection of the straight line AC (produced) with the circumference of this circle.^[288]

Those not familiar with this construction would not be likely to discover it, and if they applied the method suggested here they would never think of taking DG for the unknown quantity rather than CF or FD, since either of these would much more easily lead to an equa-

^[288] Pappus Lib. VII, Prop. 72, Vol. II, p. 783. The following is in substance the proof given by Pappus. He first gives an elaborate proof of the following lemma: Given a square ABCD, and E a point in AC produced, EG perpendicular to BE at E, meeting BD produced in G, and F the point of intersection of BE and CD. Then $CD^2 + FE^2 = \overline{DG}^2$. Then he proceeds as follows: By the construction given in the problem, $\overline{DN}^2 = \overline{BD}^2 + \overline{BN}^2$. By the lemma, $\overline{DG}^2 = \overline{CD}^2 + \overline{FE}^2$. By construction, BD = CD and DG = DN. Therefore, FE = BN.

est $\frac{1}{2} \sqrt{aa + cc} + \sqrt{-\frac{1}{2}aa + \frac{1}{4}cc + \frac{1}{2}a \sqrt{aa + cc}}$
 ou bien $\frac{1}{2} \sqrt{aa + cc} - \sqrt{-\frac{1}{2}aa + \frac{1}{4}cc + \frac{1}{2}a \sqrt{aa + cc}}$.
 Et pourceque nous auions fait cy dessus $x + \frac{1}{2}a \propto x$,
 nous apprenons que la quantité x , pour la connoissance
 de laquelle nous auons fait toutes ces operations, est
 $-\frac{1}{2}a + \sqrt{\frac{1}{4}aa + \frac{1}{4}cc} - \sqrt{\frac{1}{4}cc - \frac{1}{2}aa + \frac{1}{2}a \sqrt{aa + cc}}$.



Mais afin qu'on puisse mieux connoître l'utilité de
cette règle il faut que ie l'applique a quelq; Probleme.

Exemple
de l'usage
de ces re-
ductions

Si le quarré A D, & la ligne B N estant donnés, il faut prolonger le costé A C iusques a E, en sorte qu'E F, tirée d'E vers B, soit esgale a N B. On apprend de Pappus, qu'ayant premierement prolongé B D iusques à G, en sorte que D G soit esgale à D N, & ayant descrit vn cercle dont le diametre soit B G, si on prolonge la ligne droite A C, elle rencontrera la circonference de ce cercle au point E, qu'on demandoit. Mais pour ceux qui ne scauroient point cete cōstruction elle seroit assés difficile à rencōtrer, & en la cherchāt par la methode icy proposée, ils ne s'auiseroiēt iamais de prēdre D G pour la quantité inconnuē, mais plutost C F, ou F D, a cause que ce

Ccc 2

font

font elles qui conduisent le plus aysément a l'Equatiō: & lors ils en trouueroiēt vne qui ne seroit pas facile a demesler, sans la reigle que ie viens d'expliquer. Car posant a pour BD ou CD , & c pour EF , & x pour DF , on a $CF \propto a - x$, & cōme CF ou $a - x$, est à $F E$ ou c , ainsi $F D$ ou x , est a BF , qui par consequent est $\frac{cx}{a-x}$. Puis a cause du triangle rectangle $BD F$, dont les costés sont l'un x & l'autre a , leurs quarrés, qui sont $xx + aa$, sont esgaux a celui de la baze, qui est $\frac{c^2 xx}{xx - 2ax + aa}$, de façon que multipliant le tout par $xx - 2ax + aa$, on trouue que l'Equation est $x^4 - 2ax^3 + 2aaxx - 2a^3x + a^4 \propto ccxx$, ou bien $x^4 - 2ax^3 + \frac{2aa}{cc}xx - 2a^3x + a^4 \propto 0$. Et on connoist par les reigles precedentes, que sa racine, qui est la longueur de la ligne DF , est $\frac{1}{2}a + \sqrt{\frac{1}{4}aa + \frac{1}{4}cc}$.
 $-- \sqrt{\frac{1}{4}cc - \frac{1}{2}aa + \frac{1}{2}a\sqrt{aa + cc}}$.

Que si on posoit BF , ou CE , ou BE pour la quantité inconnüe, on viendroit derechef a vne Equation, en laquelle il y auroit 4 dimensions, mais qui seroit plus aysée a demesler, & on y viendroit assés aysément; au lieu que si c'estoit DG qu'on supposast, on viendroit beaucoup plus difficilement a l'Equation, mais aussy elle seroit tres simple. Ce que ie mets icy pour vous auertir, que lorsque le Probleme proposé n'est point solide, si en le cherchant par vn chemin on vient a vne Equation fort composée, on peut ordinairement venir a vne plus simple, en le cherchant par vn autre.

Ie pourrois encore aionster diuerses reigles pour demesler les Equations, qui vont au Cube, ou au Quarre de

tion. They would thus get an equation which could not easily be solved without the rule which I have just explained.

For, putting a for BD or CD , c for EF and x for DF , we have $CF = a - x$, and, since CF is to FE as FD is to BF , we have

$$a - x : c = x : BF,$$

whence $BF = \frac{cx}{a-x}$. Now, in the right triangle BDF whose sides are x and a , $x^2 + a^2$, the sum of their squares, is equal to the square of the hypotenuse, which is $\frac{c^2 x^2}{x^2 - 2ax + a^2}$. Multiplying both sides by

$$x^2 - 2ax + a^2$$

we get the equation,

$$x^4 - 2ax^3 + 2a^2x^2 - 2a^3x + a^4 = c^2x^2,$$

or

$$x^4 - 2ax^3 + (2a^2 - c^2)x^2 - 2a^3x + a^4 = 0,$$

and by the preceding rule we know that its root, which is the length of the line DF , is

$$\frac{1}{2}a + \sqrt{\frac{1}{4}a^2 + \frac{1}{4}c^2} - \sqrt{\frac{1}{4}c^2 - \frac{1}{2}a^2 + \frac{1}{2}a\sqrt{a^2 + c^2}}.$$

If, on the other hand, we consider BF , CE , or BE as the unknown quantity, we obtain an equation of the fourth degree, but much easier to solve, and quite simply obtained.^[200]

Again, if DG were used, the equation would be much more difficult to obtain, but its solution would be very simple. I state this simply to warn you that, when the proposed problem is not solid, if one method of attack yields a very complicated equation a much simpler one can usually be found by some other method.

^[200] Taking BF as the unknown quantity, the resulting equation is

$$x^4 + 2cx^3 + (c^2 - 2a^2)x^2 - 2a^2cx - a^2c^2 = 0.$$

Rabuel, p. 487.

I might add several different rules for the solution of cubic and biquadratic equations but they would be superfluous, since the construction of any plane problem can be found by means of those already given.

I could also add rules for equations of the fifth, sixth, and higher degrees, but I prefer to consider them all together and to state the following general rule:

First, try to put the given equation into the form of an equation of the same degree obtained by multiplying together two others, each of a lower degree. If, after all possible ways of doing this have been tried, none has been successful, then it is certain that the given equation cannot be reduced to a simpler one; and, consequently, if it is of the third or fourth degree, the problem depending upon it is solid; if of the fifth or sixth, the problem is one degree more complex, and so on. I have also omitted here the demonstration of most of my statements, because they seem to me so easy that if you take the trouble to examine them systematically the demonstrations will present themselves to you and it will be of much more value to you to learn them in that way than by reading them.

de quarré, mais elles feroient superflus; car lorsque les Problemes sont plans, on en peut tousiours trouver la construction par celles cy.

Je pourrois aussy en adiouster d'autres pour les Equations qui montent iusques au surfolide, ou au Quarré de cube, ou au delà, mais i'ayme mieux les comprendre toutes en vne, & dire en general, que lorsqu'on atasché de les reduire a mesme forme, que celles d'autant de dimensions, qui viennent de la multiplication de deux autres qui en ont moins, & qu'ayant dénombré tous les moyens, par lesquels cete multiplication est possible, la chose n'a pû succeder par aucun, on doit s'assurer qu'elles ne scauroient estre reduites a de plus simples. En sorte que si la quantité inconnuë a 3 ou 4 dimensions, le Probleme pour lequel on la cherche est solide; & si elle en a 5, on 6, il est d'un degré plus composé; & ainsi des autres.

Regle generale pour reduire les Equations qui passent le quarré de quarré.

Au reste i'ay omis icy les demonstrations de la plus part de ce que i'ay dit a cause qu'elles m'ont semblé si faciles, que pourvû que vous preniés la peine d'examiner methodiquement si i'ay failly, elles se presenteront a vous d'elles mesme: & il sera plus utile de les apprendre en cete façon, qu'en les lisant.

Or quand on est assuré, que le Probleme proposé est solide, soit que l'Equation par laquelle on le cherche monte au quarré de quarré, soit qu'elle ne monte que iusques au cube, on peut tousiours en trouver la racine par l'une des trois sections coniques, laquelle que ce soit ou mesme par quelque partie del'une d'elles, tant petite qu'elle puisse estre, en ne se servant au reste que de lignes droites, & de cercles. Mais ie me contenteray icy de

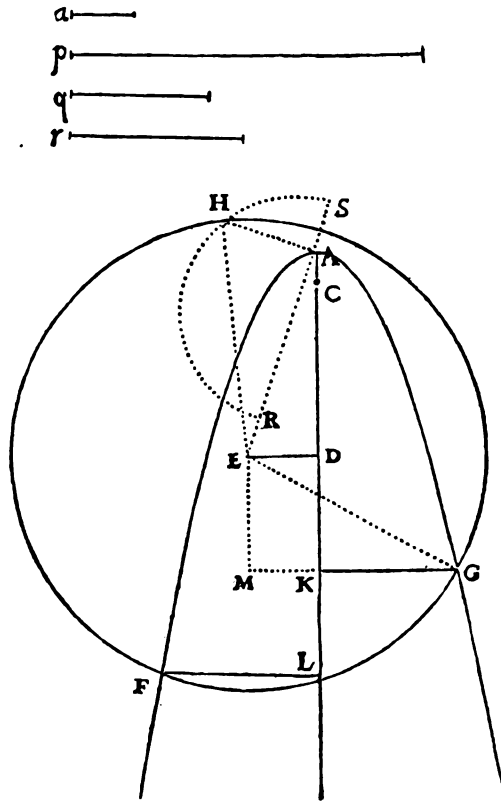
Facon generale pour construire tous les problemes solides, reduits a une Equation de trois ou quatre dimensions.

Ccc 3

donner

donner vne reigle generale pour les trouuer toutes par le moyend'une Parabole, a cause qu'elle est en quelque fa-
çon la plus simple.

Premierement il faut ofter le second terme de l'Equa-
tion proposée, s'il n'est desia nul, & ainsi la reduire à tel-
le forme, $x^3 \propto^*$. $a p x$. $a a q$, si la quantité inconnue n'a
que trois dimensions; ou bien à telle, $x^4 \propto^*$. $a p x x$. $a a q x$.
 $a^3 r$, si elle en a quatre; ou bien en prenant a pour l'unité,
à telle, $x^3 \propto^*$. $p x$. q , & à telle
 $x^4 \propto^*$. $p x x$. $q x$. r .



Après

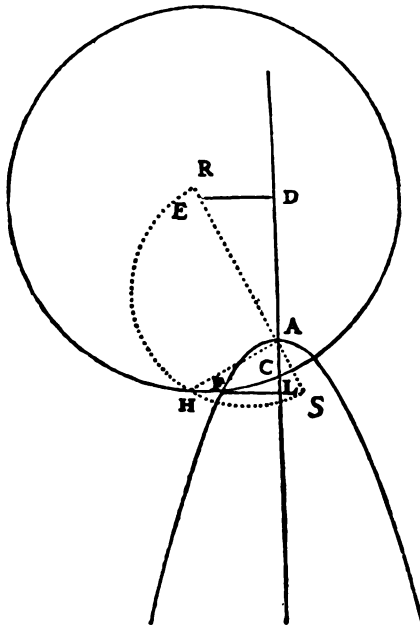
THIRD BOOK

Now, when it is clear that the proposed problem is solid, whether the equation upon which its solution depends is of the fourth degree or only of the third, its roots can always be found by any one of the three conic sections, or even by some part of one of them, however small, together with only circles and straight lines. I shall content myself with giving here a general rule for finding them all by means of a parabola, since that is in some respects the simplest of these curves.

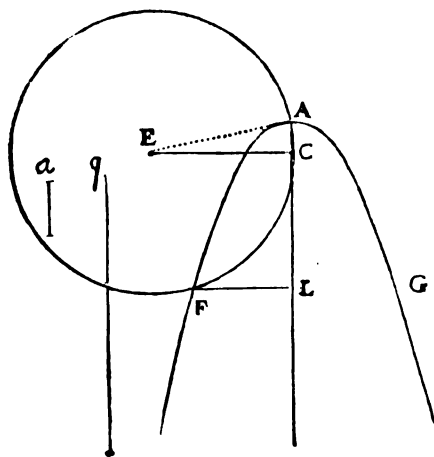
First, remove the second term of the proposed equation. if this is not already zero, thus reducing it to the form $z^3 = \pm apz \pm a^2q$, if the given equation is of the third degree, or $z^4 = \pm apz^2 \pm a^2qz \pm a^3r$, if it is of the fourth degree. By choosing a as the unit, the former may be written

$z^3 = \pm pz \pm q$ and the latter $z^3 = \pm pz^2 \pm qz \pm r$. Suppose that the parabola FAG (pages 194-198) is already described; let ACDKL be its axis, a , or 1 which equals $2AC$, its latus rectum (C being within the parabola), and A its vertex. Lay off CD equal to $\frac{1}{2}p$ so that the points D and A lie on the same side of C if the equation contains $+p$ and on opposite sides if it contains $-p$. Then at the point D (or, if $p=0$, at C), erect DE perpendicular to CD, so that DE is equal to $\frac{1}{2}q$, and about E as center with AE as radius describe the circle FG, if the given equation is a cubic, that is, if r is zero.

Après cela supposant que la Parabole FAG est desia descrite, & que son aissieu est $ACDKL$, & que son costé droit est a , ou 1 , dont A C est la moitié, & enfin que le point C est au dedans de cete Parabole, & que A en est le sommet; Il faut faire $CD \propto \frac{1}{2}p$, & la prendre du mesme costé, qu'est le point A au regard du point C , s'il y a $+p$ en l'Equation; mais s'il y a $-p$ il faut la prendre de l'autre costé. Et du point D , ou bien, si la quantité

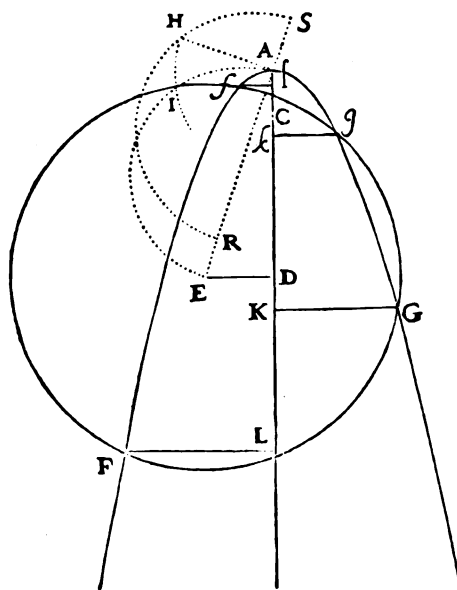


p estoit nulle, du point C il faut eleuer vne ligne a angles droits insques a E , en sorte qu'elle soit esgale $a\frac{1}{2}q$. Et enfin du centre E il faut descire le cercle FG , dont
le



le demidiambre soit
 AE , si l'Equation
 n'est que cubique, en
 sorte que la quanti-
 té r soit nulle. Mais
 quand il y a $+r$ il
 faut dans cete ligne
 AE prolongée, pren-
 dre d'un costé AR
 esgale à r , & de l'autre
 AS esgale au costé
 droit de la Parabole
 qui est r , & ayant de-

scrit vn cercle dont le diametre soit RS , il faut faire AH



perpẽdiculaire sur
 AE , laquelle AH
 rencontre ce cer-
 cle RHS au point
 H , qui est celuy par
 où l'autre cercle
 FHG doit passer.
 Et quand il y a $-r$
 il faut après auoir
 ainsi trouué la ligne
 AH , inscrire AI ,
 qui luy soit esgale,
 dans vn autre cer-
 cle, dont AE soit
 le diametre, & lors
 c'est par le point I ,
 que

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If the equation contains $+r$, on one side of AE produced, lay off AR equal to r , and on the other side lay off AS equal to the latus rectum of the parabola, that is, to 1, and describe a circle on RS as diameter. Then if AH is drawn perpendicular to AE it will meet the circle RHS in the point H, through which the other circle FHG must pass.

If the equation contains $-r$, construct a circle upon AE as diameter and in it inscribe AI, a line equal to AH;^[227] then the first circle must pass through the point I.

^[227] That is, draw a chord equal to AH.

Now the circle FG can cut or touch the parabola in 1, 2, 3, or 4 points; and if perpendiculars are drawn from these points upon the axis they will represent all the roots of the equation, both true and false. If the quantity q is positive the true roots will be those perpendiculars, such as FL, on the same side of the parabola, as E,^[228] the center of the circle; while the others, as GK, will be the false roots. On the other hand, if q is negative, the true roots will be those on the opposite side, and the false or negative roots^[229] will be those on the same side as E, the center of the circle. If the circle neither cuts nor touches the parabola at any point, it is an indication that the equation has neither a true nor a false root, but that all the roots are imaginary.^[230]

This rule is evidently as general and complete as could possibly be desired. Its demonstration is also very easy. If the line GK thus constructed be represented by z , then AK is z^2 , since by the nature of the parabola, GK is the mean proportional between AK and the latus rectum, which is 1. Then if AC or $\frac{1}{2}$, and CD or $\frac{1}{2}p$, be subtracted from AK, the remainder is DK or EM, which is equal to $z^2 - \frac{1}{2}p - \frac{1}{2}$ of which the square is

$$z^4 - pz^2 - z^2 + \frac{1}{4}p^2 + \frac{1}{2}p + \frac{1}{4}.$$

And since $DE = KM = \frac{1}{2}q$, the whole line $GM = z + \frac{1}{2}q$, and the square of GM equals $z^2 + qz + \frac{1}{4}q^2$. Adding these two squares we have

$$z^4 - pz^2 + qz + \frac{1}{4}q^2 + \frac{1}{4}p^2 + \frac{1}{2}p + \frac{1}{4}$$

[228] That is, on the same side of the axis of the parabola.

[229] "Les fausses ou moindres que rien." This is the first time Descartes has directly used this synonym.

[230] It may be noted that Descartes considers the cubic as a quartic having zero as one of its roots. Therefore, the circle always cuts the parabola at the vertex. It must then cut it in another point, since the cubic must have one real root. It may or may not cut it in two other points. It may cut it in two coincident points at the vertex, in which case the equation reduces to a quadratic.

que doit passer FIG le premier cercle cherché. Or ce cercle FG peut couper, ou toucher la Parabole en 1, ou 2, ou 3, ou 4 points, desquels tirant des perpendiculaires sur laissieu, on a toutes les racines de l'Equation tant vrayes, que fausses. A sçavoir si la quantité q est marquée du signe +, les vrayes racines seront celles de ces perpendiculaires, qui se trouveront du mesme costé de la parabole, que E le centre du cercle, comme FL; & les autres, comme GK, seront fausses: Mais au contraire si cete quantité q est marquée du signe -- les vrayes seront celles de l'autre costé; & les fausses, ou moindres que rien seront du costé où est E le centre du cercle. Et enfin si ce cercle ne coupe, ny ne touche la Parabole en aucun point, cela tesmoigne qu'il n'y a aucune racine ny vraie ny fausse en l'Equation, & qu'elles sont toutes imaginaires. En sorte que cete reigle est la plus generale, & la plus accomplie qu'il soit possible de souhaiter.

Et la demonstration en est fort aysée. Car si la ligne GK, trouuée par cete construction, se nomme x , AK sera xx , a cause de la Parabole, en laquelle GK doit estre moyene proportionelle, entre AK, & le costé droit qui est 1. puis si de AK i'oste AC, qui est $\frac{1}{2}$, & CD qui est $\frac{1}{2}p$, il reste DK, ou EM, qui est $xx - \frac{1}{2}p - \frac{1}{2}$, dont le quarré est

$xx^2 - pxx - xx + \frac{1}{4}pp + \frac{1}{2}p + \frac{1}{4}$. & a cause que DE, ou KM est $\frac{1}{2}q$, la toute GM est $x + \frac{1}{2}q$, dont le quarré est $xx + qx + \frac{1}{4}qq$, & assemblant ces deux quarrés, on a

$$xx^2 - pxx + qx + \frac{1}{4}qq + \frac{1}{4}pp + \frac{1}{2}p + \frac{1}{4}$$

D d d

pour

THIRD BOOK

for the square of GE, since GE is the hypotenuse of the right triangle EMG.

But GE is the radius of the circle FG and can therefore be expressed in another way. For since $ED = \frac{1}{2} g$, and $AD = \frac{1}{2} p + \frac{1}{2}$, and ADE is a right angle, we have

$$EA = \sqrt{\frac{1}{4} g^2 + \frac{1}{4} p^2 + \frac{1}{2} p + \frac{1}{4}}.$$

Then, since HA is the mean proportional between AS or 1 and AR or r , $HA = \sqrt{r}$; and since EAH is a right angle, the square of HE or of EG is

$$\frac{1}{4} g^2 + \frac{1}{4} p^2 + \frac{1}{2} p + \frac{1}{4} + r,$$

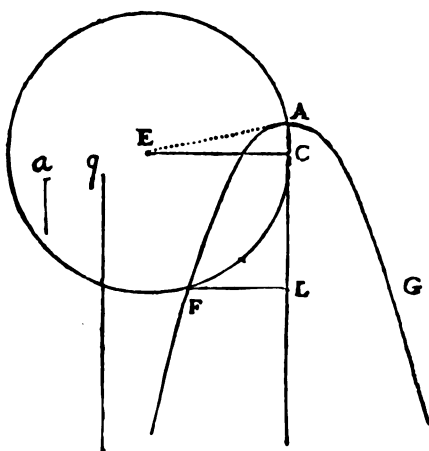
and we can form an equation from this expression and the one already

obtained. This equation will be of the form $z^4 = pz^2 - qz + r$, and therefore the line GK, or z , is the root of this equation, which was to be proved. If you will apply this method in all the other cases, with the proper changes of sign, you will be convinced of its usefulness, without my writing anything further about it.

Let us apply it to the problem of finding two mean proportionals between the lines a and q . It is evident that if we represent one of the mean proportionals by z , then $a : z = z : \frac{z^2}{a} = \frac{z^2}{a} : \frac{z^3}{a^2}$. Thus we have an equation between q and $\frac{z^3}{a^2}$, namely, $z^3 = a^2 q$.

Describe the parabola FAG with its axis along AC, and with AC equal to $\frac{1}{2} a$, that is, to half the latus rectum. Then erect CE equal to $\frac{1}{2} q$ and perpendicular to AC at C, and describe the circle AF

entre cete somme & la precedente. cequi est le mesme que $x^2 \propto p x x - q x + r$. & par consequent la ligne trouuee GK qui a esté nommée x est la racine de cete Equation. ainsi qu'il falloit demonstrier. Et si vous appliquez ce mesme calcul a tous les autres cas de cete reigle, en changeant les signes $+$ & $-$ selon l'occasion, vous y trouuerés vostre conte en mesme sorte, sans qu'il soit besoin que ie m'y areste.



Si on veut donc suiuant cete reigle trouuer deux moyennes proportionnelles entre les lignes a & q ; chascun sçait que posant x pour l'vne, comme a est à x , ainsi

x à $\frac{x^2}{a}$, & $\frac{x^2}{a}$ à $\frac{x^3}{aa}$; de façon qu'il y a Equation entre q & $\frac{x^3}{aa}$, c'est a dire, $x^3 \propto a a q$. Et la Parabole FAG estant

L'invention de deux moyennes proportionnelles.

Ddd 2

about E as center, passing through A. Then FL and LA are the required mean proportionals.^[301]

Again, let it be required to divide the angle NOP, or rather, the circular arc NQTP, into three equal parts. Let NO = 1 be the radius of the circle, NP = q be the chord subtending the given arc, and NQ = z be the chord subtending one-third of that arc; then the equation is $z^3 = 3z - q$. For, drawing NQ, OQ and OT, and drawing QS parallel to TO, it is obvious that NO is to NQ as NQ is to QR as QR is to RS. Since NO = 1 and NQ = z , then QR = z^2 and RS = z^3 ; and since NP or q lacks only RS or z^3 of being three times NQ or z , we have $q = 3z - z^3$ or $z^3 = 3z - q$.^[302]

Describe the parabola FAG so that CA, one-half its latus rectum, shall be equal to $\frac{1}{2}$; take CD = $\frac{3}{2}$ and the perpendicular DE = $\frac{1}{2}q$; then describe the circle FAG about E as center, passing through A. This circle cuts the parabola in three points, F, g , and G, besides the vertex, A. This shows that the given equation has three roots, namely, the two true roots, GK and gk , and one false root, FL.^[303] The smaller

^[303] This may be shown as follows: Draw FM $\perp$ to EC; let FL = z . From the nature of the parabola, $\overline{FL}^2 = a \cdot AL$; $AL = \frac{z^2}{a}$; $\overline{EC}^2 + \overline{CA}^2 = \overline{EA}^2$; $\overline{EM}^2 + \overline{FM}^2 = \overline{EF}^2$; $\overline{EA}^2 = \frac{q^2}{4} + \frac{a^2}{4}$; $\overline{EM}^2 = (EC - FL)^2 = \left(\frac{1}{2}q - z\right)^2$; $\overline{FM}^2 = \overline{CL}^2 = (AL - AC)^2 = \left(\frac{z^2}{a} - \frac{a}{2}\right)^2$; $\overline{EF}^2 = \frac{q^2}{4} - qz + z^2 + \frac{z^4}{a^2} - z^2 + \frac{a^2}{4}$. But EF = EA.

$$\therefore \frac{q^2}{4} + \frac{a^2}{4} = \frac{q^2}{4} - qz + z^2 + \frac{z^4}{a^2} - z^2 + \frac{a^2}{4},$$

whence $z^3 = a^2q$.

^[302] $\angle NOQ$ is measured by arc NQ;
 $\angle QNS$ is measured by $\frac{1}{2}$ arc QP or arc NQ;
 $\angle SQR = \angle QOT$ is measured by arc QT or NQ;
 $\therefore \angle OQN = \angle NQR = \angle QSR$.
 $\therefore NO : NQ = NQ : QR = QR : RS$.
 $QR = z^2$; $RS = z^3$. Let OT cut NP at M.
 $NP = 2NR + MR = 2NQ + MR$
 $= 2NQ + MS - RS$
 $= 2NQ + QT - RS$
 $= 3NQ - RS$.

Or $q = 3z - z^3$.

Rabuel, p. 534.

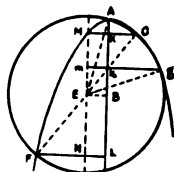
^[300] G and g being on the opposite side of the axis from E, and F being on the same side.

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of the two roots, gk , must be taken as the length of the required line NQ , for the other root, GK , is equal to NV , the chord subtended by one-third the arc VNP ,^[284] which, together with the arc NQP constitutes the circle; and the false root, FL , is equal to the sum of QN and NV , as may easily be shown.^[228]

It is unnecessary for me to give other examples here, for all problems that are only solid can be reduced to such forms as not to require this rule for their construction except when they involve the finding of two mean proportionals or the trisection of an angle. This will be obvious if it is noted that the most difficult of these problems can be

[234] For proof, see Rabuel, page 535.



^[285] Let $AB = b$; $EB = MR = mk = NL = c$; $AK = t$; $Ak = s$; $AL = r$; $KG = y$; $kg = z$, $FL = v$. Then $GM = y + c$, $gm = z + c$, $FN = v - c$, $GK^2 = a \cdot AK$, $at = y^2$, $t = \frac{y^2}{a}$, $\overline{gk^2} = a \cdot Ak$, $as = z^2$, $s = \frac{z^2}{a}$, $\overline{FL^2} = a \cdot AL$, $ar = v^2$, $r = \frac{v^2}{a}$.

$$ME = AB - AK = b - \frac{y^2}{a}$$

$$mE = b - \frac{z^2}{a}$$

$$EN = \frac{v^2}{a} - b$$

$$\overline{EG}^2 = \overline{EM}^2 + \overline{MG}^2$$

$$\overline{EA}^2 = \overline{AB}^2 + BE^2$$

$$\overline{EG}^2 = b^2 - \frac{2by^2}{a} + \frac{y^4}{a^2} + y^2 + 2cy + c^2$$

$$2ab = \frac{y^3 + 2a^2c + a^2y}{y}$$

$$2ab = \left| \frac{x^3 + 2a^2c + a^2x}{2} \right|$$

$$\frac{y^3 + 2a^2c + a^2y}{y} = \frac{x^3 + 2a^2c + a^2x}{x}$$

$$2a^2c = x^2y + xy^2$$

Similarly,

$$2a^2c = v^2y - vy^2$$

$$x^2y + xy^2 = v^2y - vy^2$$

$$v^2 - g^2 = v\gamma + g\gamma$$

$$v - z = y$$

$$v = y + z$$

$$FL = KG + kg$$

Rabuel, p. 540.

que NO estant 1 , & NQ estant x , QR est xx , & RS est x' : Et a cause qu'il s'en faut seulement RS , ou x' , que la ligne NP , qui est q , ne soit triple de NQ , qui est x , ou à $q \propto 3x - x'$ ou bien,

$$x' \propto^* 3x - q.$$

Puis la Parabole FAG estant descrite, & CA la moitié de son costé droit principal estant $\frac{1}{2}$, si on prend $CD \propto \frac{1}{2}$, & la perpendiculaire $DE \propto \frac{1}{2}q$, & que du centre E , par A , on descrie le cercle FAG , il coupe cete Parabole aux trois points F , g , & G , sans conter le point A qui en est le sommet. Ce qui monstre qu'il y a trois racines en cete Equation, à sçavoir les deux GK , & gk , qui sont vrayes; & la troisieme qui est fausse, à sçavoir FL . Et de ces deux vrayes c'est gk la plus petite qu'il faut prendre pour la ligne NQ qui estoit cherchée. Car l'autre GK , est esgale à NV , la subtendue de la troisieme partie de l'arc NVP , qui avec l'autre arc NQP acheue le cercle. Et la fausse FL est esgale a ces deux ensemble QN & NV , ainsi qu'il est aisé a voir par le calcul.

Il seroit superflus que ie m'arestasse a donner icy d'autres exemples; car tous les Problemes qui ne sont que solides se peuvent reduire a tel point, qu'on n'a aucun besoin de cete reigle pour les construire, sinon entant qu'elle sert a trouver deux moyennes proportionelles, ou bien a diuiser vn angle en trois parties esgalés. Ainsi que vous connoistres en considerant, que leurs difficultés peuvent tousiours estre comprises en des Equations, qui ne montent que iusque au quarré de quarré, ou au cube : Et que toutes celles qui montent au quarré de quarré, se reduisent au quarré, par le moyen de quelques autres, qui ne

Que tous les problemes solides se peuvent reduire a ces deux constructions.

D d d 3 montent

montent que infques au cube: Et enfin qu'on peut oster le fecond terme de celles cy. En forte qu'il n'y en a point qui ne fe puiſſe reduire a quelq; vne de ces trois formes.

$$x^3 \infty^* - p x + q.$$

$$x^3 \infty^* + p x + q.$$

$$x^3 \infty^* + p x - q.$$

Or ſi on a $x^3 \infty^* - p x + q$, la reigle dont Cardan attribue l'inuention a vn nommé Scipio Ferreus, nous apprend que la racine eſt,

$$\sqrt[3]{C. + \frac{1}{2}q + \sqrt{\frac{1}{4}qq + \frac{1}{27}p^3}} - \sqrt[3]{C. - \frac{1}{2}q + \sqrt{\frac{1}{4}qq + \frac{1}{27}p^3}}$$

Comme auſſy lorſqu'on a $x^3 \infty^* + p x + q$, & que le quarré de la moitié du dernier terme eſt plus grand que le cube du tiers de la quantité connue du penultieſme, vne pareille reigle nous apprend que la racine eſt,

$$\sqrt[3]{C. + \frac{1}{2}q + \sqrt{\frac{1}{4}qq - \frac{1}{27}p^3}} + \sqrt[3]{C. + \frac{1}{2}q - \sqrt{\frac{1}{4}qq - \frac{1}{27}p^3}}$$

D'où il paroît qu'on peut conſtruire tous les Problemes, dont les difficultés ſe reduiſent a l'une de ces deux formes, ſans auoir beſoin des ſections coniques pour autre choſe, que pour tirer les racines cubiques de quelques quantité, données, c'eſt a dire, pour trouuer deux moyennes proportionelles entre ces quantités & l'vnité.

Puis ſi on a $x^3 \infty^* + p x + q$, & que le quarré de la moitié du dernier terme ne ſoit point plus grand que le cube du tiers de la quantité connue du penultieſme, en ſuppoſant le cercle N Q P V, dont le demidiametre NO ſoit $\sqrt[3]{\frac{1}{3}p}$, c'eſt a dire la moyenne proportionelle entre le tiers de la quantité donnée p & l'vnité, & ſuppoſant auſſy la ligne N P inſcrite dans ce cercle qui ſoit $\frac{3q}{p}$, c'eſt

expressed by equations of the third or fourth degree; that all equations of the fourth degree can be reduced to quadratic equations by means of other equations not exceeding the third degree; and finally, that the second terms of these equations can be removed; so that every such equation can be reduced to one of the following forms:

$$x^3 = -pz + q \qquad x^3 = +pz + q \qquad x^3 = +pz - q$$

Now, if we have $x^3 = -pz + q$, the rule, attributed by Cardan^[206] to one Scipio Ferreus, gives us the root

$$\sqrt[3]{\frac{1}{2}q + \sqrt{\frac{1}{4}q^2 + \frac{1}{27}p^3}} - \sqrt[3]{-\frac{1}{2}q + \sqrt{\frac{1}{4}q^2 + \frac{1}{27}p^3}}. \quad [207]$$

Similarly, when we have $x^3 = +pz + q$ where the square of half the last term is greater than the cube of one-third the coefficient of the next to the last term, the corresponding rule gives us the root

$$\sqrt[3]{\frac{1}{2}q + \sqrt{\frac{1}{4}q^2 - \frac{1}{27}p^3}} + \sqrt[3]{\frac{1}{2}q - \sqrt{\frac{1}{4}q^2 - \frac{1}{27}p^3}}.$$

It is now clear that all problems of which the equations can be reduced to either of these two forms can be constructed without the use of the conic sections except to extract the cube roots of certain known quantities, which process is equivalent to finding two mean proportionals between such a quantity and unity. Again, if we have $x^3 = +pz + q$, where the square of half the last term is not greater than the cube of one-third the coefficient of the next to the last term,

describe the circle NQPV with radius NO equal to $\sqrt{\frac{1}{3}p}$, that is to the mean proportional between unity and one-third the known quantity p . Then take $NP = \frac{3q}{p}$, that is, such that NP is to q , the other known

[206] Cardan; Liber X, Cap. XI, fol. 29: "Scipio Ferreus Bononiensis iam annis ab hinc triginta ferme capitulum hoc inuenit, tradidit uero Anthonio Mariæ Florido Veneto, qui cū in certamen cū Nicolao Tartalea Brixellense aliquando uenisset, occasionem dedit, ut Nocolaus inuenerit & ipse, qui cum nobis rogantibus tradidisset, suppressa demonstratione, freti hoc auxilio, demonstrationem quæliuimus, eamque in modos, quod difficillimum fuit, redactam sic subjecimus."

See also Cantor, Vol. II (1), p. 444; Smith, Vol. II, p. 462.

[207] Descartes wrote this:

$$\sqrt{C. + \frac{1}{2}q + \sqrt{\frac{1}{4}qq + \frac{1}{27}p^3}} + \sqrt{C. \frac{1}{2}q + \sqrt{\frac{1}{4}qq + \frac{1}{27}p^3}}.$$

quantity, as 1 is to $\frac{1}{3}p$, and inscribe NP in the circle. Divide each of the two arcs NQP and NVP into three equal parts, and the required root is the sum of NQ, the chord subtending one-third the first arc, and NV, the chord subtending one-third of the second arc.^[288]

Finally, suppose that we have $x^3 = px - q$. Construct the circle NQPV whose radius NO is equal to $\sqrt{\frac{1}{3}p}$, and let NP, equal to $\frac{3q}{p}$, be inscribed in this circle; then NQ, the chord of one-third the arc NQP, will be the first of the required roots, and NV, the chord of one-third the other arc, will be the second.

An exception must be made in the case in which the square of half the last term is greater than the cube of one-third the coefficient of the next to the last term;^[289] for then the line NP cannot be inscribed in the circle, since it is longer than the diameter. In this case, the two

^[288] It may be noted that the equation $x^3 = 3x - q$ may be obtained from the equation $x^3 = 3x + q$ by transforming the latter into an equation whose roots have the opposite signs. Then the true roots of $x^3 = 3x - q$ are the false roots of $x^3 = 3x + q$ and vice-versa. Therefore FL = NQ + NP is now the true root.

^[289] The so-called irreducible case.

cines de cete Equation ne seroient qu'imaginaires , & qu'il ny en auroit de reelles que la fausse , qui suiuant la reigle de Cardan seroit,

$$\sqrt[3]{C. \frac{1}{4}q} + \sqrt[3]{\frac{1}{4}qq - \frac{1}{27}p^3} + \sqrt[3]{C. \frac{1}{2}q - \sqrt[3]{\frac{1}{4}qq - \frac{1}{27}p^3}}.$$

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Au reste il est a remarquer que cete façon d'exprimer la valeur des racines par le rapport qu'elles ont aux costés de certains cubes dont il n'y a que le contenu qu'on connoisse, n'est en rien plus intelligible, ny plus simple, que de les exprimer par le rapport qu'elles ont aux subtendus de certains arcs, ou portions de cercles , dont le triple est donné. En sorte que toutes celles des Equations cubiques qui ne peuuent estre exprimées par les reigles de Cardan, le peuuent estre autant ou plus clairement par la façon icy proposée.

Car si par exemple , on pense connoistre la racine de cete Equation, $x^3 \propto * - q x + p$. a cause qu'on sçait qu'elle est composée de deux lignes. dont l'une est le costé d'un cube, duquel le contenu est $\frac{1}{2} q$, adiousté au costé d'un quarré , duquel derechef le contenu est $\frac{1}{4} qq - \frac{1}{27} p^3$; Et l'autre est le costé d'un autre cube, dont le contenu est la difference , qui est entre $\frac{1}{2} q$, & le costé de ce quarré dont le contenu est $\frac{1}{4} qq - \frac{1}{27} p^3$, qui est tout ce qu'on en apprend par la reigle de Cardan. Il ny a point de doute qu'on ne connoisse autant ou plus distinctement la racine de celle cy, $x^3 \propto * + q - p$, en la considerant inscrite dans un cercle, dont le demidiametre est $\sqrt[3]{\frac{1}{3}p}$, & sçachant qu'elle y est la subtendue d'un arc dont le triple a pour sa subtendue $\frac{3q}{p}$. Mesme ces ter-

mes

roots that were true are merely imaginary, and the only real root is the one previously false, which according to Cardan's rule is

$$\sqrt[3]{\frac{1}{2}q + \sqrt{\frac{1}{4}q^2 - \frac{1}{27}p^3}} + \sqrt[3]{\frac{1}{2}q - \sqrt{\frac{1}{4}q^2 - \frac{1}{27}p^3}}.$$

Furthermore it should be remarked that this method of expressing the roots by means of the relations which they bear to the sides of certain cubes whose contents only are known^[240] is in no respect clearer or simpler than the method of expressing them by means of the relations which they bear to the chords of certain arcs (or portions of circles), when arcs three times as long are known. And the roots of the cubic equations which cannot be solved by Cardan's method can be expressed as clearly as any others, or more clearly than the others, by the method given here.

For example, grant that we may consider a root of the equation $x^3 = -qx + p$ known, because we know that it is the sum of two lines of which one is the side of a cube whose volume is $\frac{1}{2}q$ increased by the side of a square whose area is $\frac{1}{4}q^2 - \frac{1}{27}p^3$, and the other is the side of another cube whose volume is the difference between $\frac{1}{2}q$ and the side of a square whose area is $\frac{1}{4}q^2 - \frac{1}{27}p^3$. This is as much knowledge of the roots as is furnished by Cardan's method. There is no doubt that the value of the root of the equation $x^3 = +qx - p$ is quite as well known and as clearly conceived when it is considered as the length of a chord inscribed in a circle of radius $\sqrt{\frac{1}{3}p}$ and subtending an arc that is one-third the arc subtended by a chord of length $\frac{3q}{p}$.

^[240] Descartes here makes use of the geometrical conception of finding the cube root of a given quantity.

Indeed, these terms are much less complicated than the others, and they might be made even more concise by the use of some particular symbol to express such chords,^[941] just as the symbol $\sqrt[3]{}$ ^[942] is used to represent the side of a cube.

By methods similar to those already explained, we can express the roots of any biquadratic equation, and there seems to me nothing further to be desired in the matter; for by their very nature these roots cannot be expressed in simpler terms, nor can they be determined by any construction that is at the same time easier and more general.

It is true that I have not yet stated my grounds for daring to declare a thing possible or impossible, but if it is remembered that in the method I use all problems which present themselves to geometers reduce to a single type, namely, to the question of finding the values of the roots of an equation, it will be clear that a list can be made of all the ways of finding the roots, and that it will then be easy to prove our method the simplest and most general. Solid problems in particular cannot, as I have already said, be constructed without the use of a curve more complex than the circle. This follows at once from the fact that they all reduce to two constructions, namely, to one in which two mean pro-

^[941] This is another indication of the tendency of Descartes's age toward symbolism. This suggestion was never adopted.

^[942] In Descartes's notation, $\sqrt[3]{}$ C.

Et on peut auffy en fuite de cecy exprimer les racines de toutes les Equations qui montent iufques au quarré de quarré, par les reigles cy deffus expliquées. En forte que ie ne fçache rien de plus a defirer en cete matiere. Car enfin la nature de ces racines ne permet pas qu'on les exprime en termes plus fimples, ny qu'on les determine par aucune conftitution qui foit enfemble plus generale & plus facile.

Il est vray que ie n'ay pas encore dit sur quelles raisons ie me fonde, pour oser ainsi assurer, si vne chose est possible, ou ne l'est pas. Mais si on prend garde comment, par la methode dont ieme sers, tout ce qui tombe sous la consideration des Geometres, se reduist a vn mesme genre de Problemes, qui est de chercher la valeur des racines de quelque Equation; on iugera bien qu'il n'est pas malaysé de faire vn dénombrement de toutes les voyes par lesquelles on les peut trouuer, qui soit suffisant pour demonstrier qu'on a choisi la plus generale, & la plus simple. Et particulièrement pour ce qui est des Problemes solides, que iay dit ne pouuoir estre construits, sans qu'on y employe quelque ligne plus composée que la circulaire, c'est chose qu'on peut assez trouuer, de ce qu'ils se reduisent tous a deux constructions; en l'vne desquelles il faut auoir tout ensemble les deux points, qui determinent deux moyenes proportionnelles entre deux

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lignes données; & en l'autre les deux points, qui diuisent en trois parties esgales vn arc donné: Car d'autant que la courbure du cercle ne depend, que d'un simple rapport de toutes ses parties, au point qui en est le centre; on ne peut aussy s'en seruir qu'a determiner vn seul point entre deux extremes, comme a trouuer vne moyenne proportionnelle entre deux lignes droites données, ou diuiser en deux vn arc donné: Au lieu que la courbure des sections coniques, dependant tousiours de deux diuerses choses, peut aussy seruir a determiner deux points differens.

Mais pour cete mesme raison il est impossible, qu'aucun des Probleſmes qui sont d'un degré plus composés que les solides, & qui presuppōsent l'inuention de quatre moyennes proportionnelles, ou la diuision d'un angle en cinq parties esgales, puissent estre construits par aucune des sections coniques. C'est pourquoy ie croyray faire en cecy tout le mieux qui se puisse, si ie donne vne reigle generale pour les construire, en y employant la ligne courbe qui se décrit par l'intersección d'une Parabole & d'une ligne droite en la façon cy dessus expliquée. car i'ose asſurer qu'il ny en a point de plus simple en la nature, qui puisse seruir a ce mesme effect; & vous aués vû comme elle suit immediatement les sections coniques, en cete question tant cherchée par les anciens, dont la solution enseigne par ordre toutes les lignes courbes, qui doivent estre receuës en Geometrie.

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Vous ſçaués desia comment, lorsqu'on cherche les quantités qui sont requises pour la construction de ces Probleſmes, on les peut tousiours reduire a quelque Equation, qui ne monte que iusques au quarré de cube, ou
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portionals are to be found between two given lines, and one in which two points are to be found which divide a given arc into three equal parts. Inasmuch as the curvature of a circle depends only upon a simple relation between the center and all points on the circumference, the circle can only be used to determine a single point between two extremes, as, for example, to find one mean proportional between two given lines or to bisect a given arc; while, on the other hand, since the curvature of the conic sections always depends upon two different things,^[243] it can be used to determine two different points.

For a similar reason, it is impossible that any problem of degree more complex than the solid, involving the finding of four mean proportionals or the division of an angle into five equal parts, can be constructed by the use of one of the conic sections.

I therefore believe that I shall have accomplished all that is possible when I have given a general rule for constructing problems by means of the curve described by the intersection of a parabola and a straight line, as previously explained;^[244] for I am convinced that there is nothing of a simpler nature that will serve this purpose. You have seen, too, that this curve directly follows the conic sections in that question to which the ancients devoted so much attention, and whose solution presents in order all the curves that should be received into geometry.

^[243] As, for example, the distance of any point from the two foci. Descartes does not say "all points on the circumference," but "toutes ses parties."

^[244] See page 84.

When quantities required for the construction of these problems are to be found, you already know how an equation can always be formed that is of no higher degree than the fifth or sixth. You also know how by increasing the roots of this equation we can make them all true, and at the same time have the coefficient of the third term greater than the square of half that of the second term. Also, if it is not higher than the fifth degree it can always be changed into an equation of the sixth degree in which every term is present.

Now to overcome all these difficulties by means of a single rule, I shall consider all these directions applied and the equation thereby reduced to the form:

$$y^6 - py^5 + qy^4 - ry^3 + sy^2 - ty + u = 0$$

in which q is greater than the square of $\frac{1}{2} p$.

au surfolide. Puis vous sçavez aussi comment, en augmentant la valeur des racines de cete Equation, on peut toujours faire qu'elles deviennent toutes vraies, & avec cela que la quantité connue du troisieme terme soit plus grande que le quarré de la moitié de celle du second: Et enfin comment, si elle ne monte que jusques au surfolide, on la peut hausser jusques au quarré de cube, & faire que la place d'aucun de ses termes ne manque d'estre remplie. Or afin que toutes les difficultés, dont il est icy question, puissent estre résolues par vne mesme règle, ie desire qu'on face toutes ces choses, & par ce moyen qu'on les reduise toujours a vne Equation de telle forme,

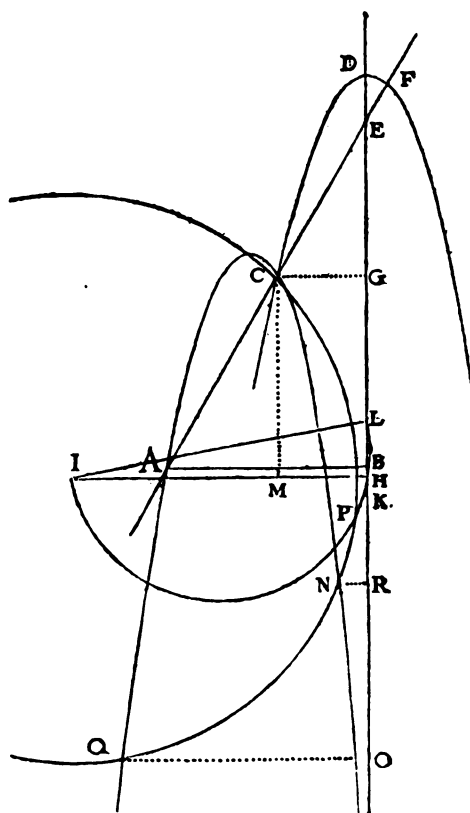
$$y^6 - py^5 + qy^4 - ry^3 + sy^2 - ty + v = 0,$$

& en laquelle la quantité nommée q soit plus grande que le quarré de la moitié de celle qui est nommée p .

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E c c 2

Puis



Puis ayant fait a ligne B K indefiniment longue des deux costés; & du point B ayant tiré la perpendiculaire A B, dont la longueur soit $\frac{1}{2}p$; il faut dans vn plan separé decrire vne Parabole, comme C D F dont le costé droit principal soit

$$\sqrt{\frac{v}{v} + q - \frac{1}{4}pp},$$

que ie nommeray n pour abreger. Après cela il faut poser le plan dans

lequel est cete Parabole sur celui ou sont les lignes A B & B K, en forte que son aissieu D E se rencontre iustement au dessus de la ligne droite B K: Et ayant pris la partie de cet aissieu, qui est entre les points E & D, esgale à $\frac{2Vv}{pn}$, il faut appliquer sur ce point E vne longue reigle, en telle façon qu'estant aussy appliquée sur le point A du plan de dessous, elle demeure tousiours iointe a ces deux poins, pendant qu'on haussera ou baissera la Parabole

Produce BK indefinitely in both directions, and at B draw AB perpendicular to BK and equal to $\frac{1}{2}p$. In a separate plane^[246] describe the parabola CDF whose principal parameter is

$$\sqrt{\frac{t}{\sqrt{u}} + q - \frac{1}{4}p^2}$$

which we shall represent by n .

Now place the plane containing the parabola on that containing the lines AB and BK, in such a way that the axis DE of the parabola falls along the line BK. Take a point E such that $DE = \frac{2\sqrt{u}}{pn}$ and place a ruler so as to connect this point E and the point A of the lower plane. Hold the ruler so that it always connects these points, and slide the parabola up or down, keeping its axis always along BK. Then the

^[246] This does not mean in a fixed plane intersecting the first, but, for example, on another piece of paper.

point C, the intersection of the parabola and the ruler, will describe the curve ACN, which is to be used in the construction of the proposed problem.

Having thus described the curve, take a point L in the line BK on the concave side of the parabola, and such that $BL = DE = \frac{2\sqrt{u}}{pn}$; then lay off on BK, toward B, LH equal to $\frac{t}{2n\sqrt{u}}$, and from H draw HI perpendicular to LH and on the same side as the curve ACN. Take HI equal to

$$\frac{r}{2n^2} + \frac{\sqrt{u}}{n^2} + \frac{pt}{4n^2\sqrt{u}}$$

which we may, for the sake of brevity, set equal to $\frac{m}{n^2}$. Join L and I, and describe the circle LPI on LI as diameter; then inscribe in this circle the line LP equal to $\sqrt{\frac{s+p\sqrt{u}}{n^2}}$. Finally, describe the circle PCN about I as center and passing through P. This circle will cut or touch the curve ACN in as many points as the equation has roots; and hence the perpendiculars CG, NR, QO, and so on, dropped from these points upon BK, will be the required roots. This rule never fails nor does it admit of any exceptions.

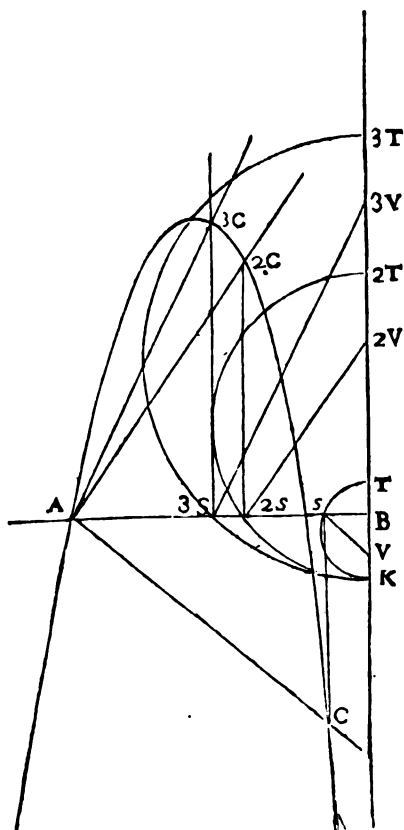
For if the quantity s were so large in proportion to the others, p , q , r , t , u , that the line LP was greater than the diameter of the circle

bole tout le long de la ligne BK, sur laquelle son aissieu
 est appliqué au moyen de quoy l'interfection de cete Pa-
 rabole, & de cete reigle, qui se fera au point C, descrira
 la ligne courbe ACN, qui est celle dont nous avons be-
 soin de nous servir pour la construction du Probleſme
 proposé. Car après qu'elle est ainsi descrite, si on prend
 le point L en la ligne BK, du costé vers lequel est tourné
 le sommet de la Parabole, & qu'on face BL esgale à D
 E, c'est à dire à $\frac{2Vv}{pn}$: Puis du point L, vers B, qu'on
 prene en la mesme ligne BK, la ligne LH, esgale à
 $\frac{t}{2nVv}$; & que du point H ainsi trouué, on tire à angles
 droits, du costé qu'est la courbe ACN, la ligne HI,
 dont la longueur soit $\frac{r}{2nn} + \frac{Vv}{nn} + \frac{pt}{4nnVv}$, qui pour abreger
 sera nommée $\frac{m}{nn}$: Et après, ayant ioint les points L & I,
 qu'on descriue le cercle LPI, dont IL soit le diametre;
 & qu'on inscriue en ce cercle la ligne LP dont la lon-
 gueur soit $\sqrt{\frac{2ptVv}{nn}}$: Puis enfin du centre I, par le point P
 ainsi trouué, qu'on descriue le cercle PCN. Ce cercle
 coupera ou touchera la ligne courbe ACN, en autant
 de points qu'il y aura de racines en l'Equation : En sorte
 que les perpendiculaires tirées de ces points sur la ligne
 BK, comme CG, NR, QO, & semblables, seront les
 racines cherchées. Sans qu'il y ait aucune exception ny
 aucun deffaut en cete reigle. Car si la quantité s estoit
 si grande, à proportion des autres p, q, r, t , & v , que la li-
 gne LP se trouuaſt plus grande que le diametre du cer-

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cle

cle I L, en sorte qu'elle n'y pust estre inscrite, il ny auroit aucune racine en l'Equation proposée qui ne fust imaginaire: Non plus que si le cercle I P estoit si petit, qu'il ne coupast la courbe A C N en aucun point. Et il la peut couper en six differens , ainsi qu'il peut y auoir six diuerses racines en l'Equation. Mais lorsqu'il la coupe en moins , cela tesmoigne qu'il y a queloues vnes de ces racines qui sont esgales entre elles , ou bien qui ne sont qu'imaginaires.



Que

THIRD BOOK

LI,^[246] so that LP could not be inscribed in it, every root of the proposed equation would be imaginary ; and the same would be true if the circle IP^[247] were so small that it did not cut the curve ACN at any point. The circle IP will in general cut the curve ACN in six different points, so that the equation can have six distinct roots.^[248] But if it cuts it in fewer points, this indicates that some of the roots are equal or else imaginary.

^[246] That is, the circle IPL, of which the diameter is t , page 222.

^[247] That is, the circle PCN.

^[248] The points determining these roots must be points of intersection of the circle with the main branch of the curve obtained, that is, of the branch ACN.

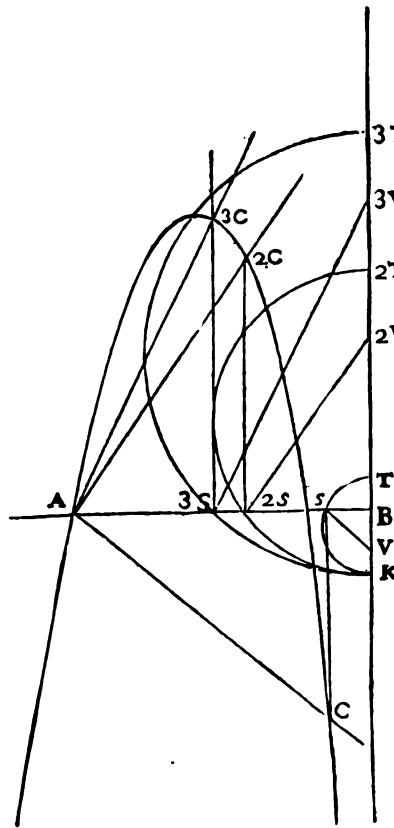
GEOMETRY

If, however, this method of tracing the curve ACN by the translation of a parabola seems to you awkward, there are many other ways of describing it. We might take AB and BL as before (page 226), and BK equal to the latus rectum of the parabola, and describe the semi-circle KST with its center in BK and cutting AB in some point S. Then from the point T where it ends, take TV toward K equal to BL and join S and V. Draw AC through A parallel to SV, and draw SC through S parallel to BK; then C, the intersection of AC and SC will be one point of the required curve. In this way we can find as many points of the curve as may be desired.

Que si la façon de tracer la ligne ACN par le mouvement d'une Parabole vous semble incommode, il est aisé de trouver plusieurs autres moyens pour la décrire. Comme si ayant les mesmes quantités que devant pour AB & BL , & la mesme pour BK , qu'on auroit posée pour le costé droit principal de la Parabole, on décrit le demi-cercle KST dont le centre soit pris a discretion dans la ligne BK , en sorte qu'il coupe quelq; part la ligne AB , comme au point S , & que du point T , où il finist, on prene vers K la ligne TV , esgale à BL ; puis ayant tiré la ligne SV , qu'on en tire vne autre, qui luy soit parallele, par le point A , comme AC ; & qu'on en tire aussy vne autre par S , qui soit parallele a BK , comme SC ; le point C , où ces deux paralleles se rencontrent, sera l'un de ceux de la ligne courbe cherchée. Et on en peut trouver, en mesme sorte, autant d'autres qu'on en desire.

Or

Or la demonstration de tout cecy est affés facile. car appliquant la règle A E avec la Parabole E D sur le point C; comme il est certain qu'elles peuvent y estre appliquées ensemble, puisque ce point C est en la courbe A C N, qui est descrite par leur intersection; si C G se nomme y , G D sera $\frac{yy}{n}$, à cause que le costé droit, qui est n , est à C G, comme C G à G D. & ostant D E., qui est $\frac{2 \cdot Vv}{pn}$, de G D, on à $\frac{yy}{n} - \frac{2 \cdot Vv}{pn}$, pour G E. Puis à cause que



A B est a B E, comme C G est a G E; A B estant $\frac{1}{2} p$, B E est $\frac{py}{2n} - \frac{Vv}{ny}$.

Et tout de mesme en supposant que le point C de la courbe à esté trouué par l'intersection des lignes droites, S C parallele à B K, & A C parallele a S V. S B qui est esgale à C G, est y : & B K estant esgale au costé droit de la Parabole, que iay nommé n , B T est $\frac{yy}{n}$, car comme K B est a B S, ainsi B S est a B T. Et T V estant

THIRD BOOK

The demonstration of all this is very simple. Place the ruler AE and the parabola FD so that both pass through the point C. This can always be done, since C lies on the curve ACN which is described by the intersection of the parabola and the ruler. If we let $CG = y$, GD will equal $\frac{y^2}{n}$, since the latus rectum n is to CG as CG is to GD. Then $DE = \frac{2\sqrt{u}}{pn}$, and subtracting DE from GD we have $GE = \frac{y^2}{n} - \frac{2\sqrt{u}}{pn}$. Since AB is to BE as CG is to GE, and AB is equal to $\frac{1}{2}p$, therefore $BE = \frac{py}{2n} - \frac{\sqrt{u}}{ny}$. Now let C be a point on the curve generated by the intersection of the line SC, which is parallel to BK, and AC, which is parallel to SV. Let $SB = CG = y$, and $BK = n$, the latus rectum of the parabola. Then $BT = \frac{y^2}{n}$, for KB is to BS as BS is

to BT, and since $TV = BL = \frac{2\sqrt{u}}{pn}$ we have $BV = \frac{y^2}{n} - \frac{2\sqrt{u}}{pn}$. Also SB is to BV as AB is to BE, whence $BE = \frac{py}{2n} - \frac{\sqrt{u}}{ny}$ as before. It is evident, therefore, that one and the same curve is described by these two methods.

Furthermore, $BL = DE$, and therefore $DL = BE$; also $LH = \frac{t}{2n\sqrt{u}}$

and
$$DL = \frac{py}{2n} - \frac{\sqrt{u}}{ny}$$

therefore
$$DH = LH + DL = \frac{py}{2n} - \frac{\sqrt{u}}{ny} + \frac{t}{2n\sqrt{u}}.$$

Also, since $GD = \frac{y^2}{n}$,

$$GH = DH - GD = \frac{py}{2n} - \frac{\sqrt{u}}{ny} + \frac{t}{2n\sqrt{u}} - \frac{y^2}{n}$$

which may be written

$$GH = \frac{-y^3 + \frac{1}{2}py^2 + \frac{ty}{2\sqrt{u}} - \sqrt{u}}{ny}$$

and the square of GH is equal to

$$\frac{y^6 - py^5 + \left(\frac{1}{4}p^2 - \frac{t}{\sqrt{u}}\right)y^4 + \left(2\sqrt{u} + \frac{pt}{2\sqrt{u}}\right)y^3 + \left(\frac{t^2}{4u} - p\sqrt{u}\right)y^2 - ty + u}{n^2y^2}$$

Whatever point of the curve is taken as C, whether toward N or toward Q, it will always be possible to express the square of the segment of BH between the point H and the foot of the perpendicular from C to BH in these same terms connected by these same signs.

estant la mesme que BL, c'est à dire $\frac{2Vv}{pn}$, BV est $\frac{yy}{n} - \frac{2Vv}{pn}$: & comme SB est à BV, ainsi AB est à BE, qui est par consequent $\frac{py}{2n} - \frac{Vv}{ny}$ comme devant, d'où on voit que c'est vne mesme ligne courbe qui se descrit en ces deux façons.

Après cela, pourceque BL & DE sont esgales, DL & BE le sont aussi: de façon qu'adioustant LH, qui est $\frac{t}{2nVv}$, à DL, qui est $\frac{py}{2n} - \frac{Vv}{ny}$, on a la toute DH, qui est $\frac{py}{2n} - \frac{Vv}{ny} + \frac{t}{2nVv}$; & en ostant GD, qui est $\frac{yy}{n}$ on a GH, qui est $\frac{py}{2n} - \frac{Vv}{ny} + \frac{t}{2nVv} - \frac{yy}{n}$. Ceque j'escriis par ordre en cete sorte $GH \propto -y^3 + \frac{1}{2}pyy + \frac{t}{2Vv} - \sqrt{v}$.

Et le quarré de GH est,

$$\frac{y^6 - py^4 - \frac{t}{Vv}y^4 + 2\sqrt{v}y^3 + \frac{pt}{2Vv}y^2 - \frac{p^2}{4v}y^2 - tyy - ty + v}{nn yy}$$

Et en quelque autre endroit de cete ligne courbe qu'on veuille imaginer le point C, comme vers N, ou vers Q, on trouuera tousiours que le quarré de là ligne droite, qui est entre le point H & celui où tombe la perpendiculaire du point C sur BH, peut estre exprimé en ces mesmes termes, & avec les mesmes signes + & --.

De plus IH estant $\frac{m}{nn}$, & LH estant $\frac{t}{2nVv}$, IL est $\sqrt{\frac{mm}{n^4} + \frac{tt}{2nVv}}$, à cause de l'angle droit IHL, & LP estant

Fff

$\sqrt{v}$

THIRD BOOK

Again, $IH = \frac{m}{n^2}$, $LH = \frac{l}{2n\sqrt{u}}$, whence

$$IL = \sqrt{\frac{m^2}{n^4} + \frac{l^2}{4n^2u}},$$

since the angle IHL is a right angle; and since

$$LP = \sqrt{\frac{s^2}{n^2} + \frac{p\sqrt{u}}{n^2}}$$

and the angle IPL is a right angle,

$$IC = IP = \sqrt{\frac{m^2}{n^4} + \frac{l^2}{4n^2u} - \frac{s}{n^2} - \frac{p\sqrt{u}}{n^2}}.$$

Now draw CM perpendicular to IH, and

$$IM = HI - HM = HI - CG = \frac{m}{n^2} - y;$$

whence the square of IM is $\frac{m^2}{n^4} - \frac{2my}{n^2} + y^2$.

GEOMETRY

Taking this from the square of IC there remains the square of CM, or

$$\frac{t^2}{4n^2u} - \frac{s}{n^2} - \frac{p\sqrt{u}}{n^2} + \frac{2my}{n^2} - y^2,$$

and this is equal to the square of GH, previously found. This may be written

$$\frac{-n^2y^4 + 2my^3 - p\sqrt{u}y^2 - sy^2 + \frac{t^2}{4u}y^2}{n^2y^2}.$$

Now, putting

$$\frac{t}{\sqrt{u}}y^4 + qy^4 - \frac{1}{4}p^2y^4$$

for n^2y^4 , and

$$ry^3 + 2\sqrt{u}y^3 + \frac{pt}{2\sqrt{u}}y^3$$

for $2my^3$, and multiplying both members by n^2y^2 , we have

$$y^6 - py^5 + \left(\frac{1}{4}p^2 - \frac{t}{\sqrt{u}}\right)y^4 + \left(2\sqrt{u} + \frac{pt}{2\sqrt{u}}\right)y^3 + \left(\frac{t^2}{4u} - p\sqrt{u}\right)y^2 - ty + u$$

equals

$$\left(\frac{1}{4}p^2 - q - \frac{t}{\sqrt{u}}\right)y^4 + \left(r + 2\sqrt{u} + \frac{pt}{2\sqrt{u}}\right)y^3 + \left(\frac{t^2}{4u} - s - p\sqrt{u}\right)y^2,$$

or

$$y^6 - py^5 + qy^4 - ry^3 + sy^2 - ty + u = 0,$$

whence it appears that the lines CG, NR, QO, etc., are the roots of this equation.

If then it be desired to find four mean proportionals between the lines a and b , if we let x be the first, the equation is $x^5 - a^4b = 0$ or $x^6 - a^4bx = 0$. Let $y - a = x$, and we get

$$y^6 - 6ay^5 + 15a^2y^4 - 20a^3y^3 + 15a^4y^2 - (6a^5 + a^4b)y + a^6 + a^5b = 0.$$

Therefore, we must take $AB = 3a$, and BK , the latus rectum of the

de IC, il reste $\frac{ss}{4nnv} - \frac{s}{nn} - \frac{pVv}{nn} + \frac{2my}{nn} - yy$.

pour le quarré de CM, qui est esgal au quarré de GH de-
fia trouué. Oubien en faisant que cete somme soit diui-
sée comme l'autre par $nn yy$, on a

$$\frac{-nny^4 + 2my^3 - pVvyy - syy + \frac{ss}{4v}yy}{nn yy} \text{ Puis}$$

remettant $\frac{s}{v}y^4 + qy^4 - \frac{1}{4}pp y^4$, pour nny^4 ; &
 $ry^3 + 2Vv y^3 + \frac{ps}{2Vv}y^3$, pour $2my^3$: & multipliant
l'une & l'autre somme par $nn yy$, on a

$$y^6 - py^5 - \frac{s}{v}y^4 + 2Vv y^4 - pVv y^3 - ty + v$$

$$+ \frac{1}{4}pp y^4 + \frac{ps}{2Vv} y^3 + \frac{ss}{4v} yy$$

esgal à

$$- \frac{s}{v}y^4 + r y^4 + 2Vv y^3 - pVv y^3 - s yy$$

$$- \frac{q}{4}pp y^4 + \frac{ps}{2Vv} y^3 + \frac{ss}{4v} yy$$

C'est a dire qu'on a,

$$y^6 - py^5 + qy^4 - ry^3 + syy - ty + v = 0.$$

D'où il paroist que les lignes C G, N R, Q O, & sembla-
bles sont les racines de cete Equation, qui est ce qu'il fal-
loit demonstrier.

Ainsi donc si on veut trouuer quatre moyennes pro-
portionnelles entre les lignes a & b , ayant posé x pour la
premiere, l'Equation est $x^6 - a^4b = 0$ ou bien
 $x^6 - a^4b = 0$. Et faisant $y = a \propto x$ il vient

$$y^6 - 6ay^5 + 15a^2y^4 - 20a^3y^3 + 15a^4y^2 - 6a^5y + a^6 = 0.$$

C'est pourquoy il faut prendre a pour la ligne AB, &

$$\sqrt[6]{\frac{6a^5 + 15a^4b}{15a^4b + 6a^5}} + 6aa \text{ pour BK, ou le costé droit de la Pa-}$$

Fff 2

rabole

rabole que iay nommé n . & $\frac{2}{3} \sqrt[3]{aa + ab}$ pour D E ou B L. Et après auoir descrit la ligne courbe A C N sur la mesure de ces trois, il faut faire L H, $\propto \frac{6a^3 + aab}{2n\sqrt{aa + ab}}$.
 & H I $\propto \frac{10a^3}{nn} + \frac{aa}{nn} \sqrt{aa + ab} + \frac{18a^4 + 3a^3b}{nn\sqrt{aa + ab}}$ & L P $\propto \sqrt[3]{\frac{15a^4 + 6a^3\sqrt{aa + ab}}{nn}}$ Car le cercle qui ayant son centre

au point I passera par le point P ainsi trouue, coupera la courbe aux deux points C & N; desquels ayant tiré les perpendiculaires N R & C G, si la moindre, N R, est ostée de la plus grande, C G, le reste sera, x , la premiere des quatre moyennes proportionnelles cherchées.

Il est aysé en mesme façon de diuiser vn angle en cinq parties esgales, & d'inscrire vne figure d'unze ou treze costés esgaux dans vn cercle, & de trouuer vne infinité d'autres exemples de cete reigle.

Toutefois il est a remarquer, qu'en plusieurs de ces exemples, il peut arriuer que le cercle coupe si obliquement la parabole du second genre; que le point de leur intersection soit difficile a reconnoistre: & ainsi que cete construction ne soit pas commode pour la pratique. A quoy il seroit aysé de remedier en composant d'autres regles, à l'imitation de celle cy, comme on en peut composer de mille sortes.

Mais mon dessein n'est pas de faire vn gros liure, & ie tasche plutost de comprendre beaucoup en peu de mots: comme on iugera peutestre que iay fait, si on considere, qu'ayant reduit à vne mesme construction tous les

parabola must be

$$\sqrt{\frac{6a^3+a^2b}{\sqrt{a^2+ab}}} + 6a^2$$

which I shall call n , and DE or BL will be

$$\frac{2a}{3n} \sqrt{a^2+ab}.$$

Then having described the curve ACN, we must have

$$LH = \frac{6a^3+a^2b}{2n \sqrt{a^2+ab}}$$

and

$$HI = \frac{10a^3}{n^2} + \frac{a^2}{n^2} \sqrt{a^2+ab} + \frac{18a^4+3a^3b}{2n^2 \sqrt{a^2+ab}},$$

and

$$LP = \frac{a}{n} \sqrt{15a^2+6a \sqrt{a^2+ab}}.$$

For the circle about I as center will pass through the point P thus found, and cut the curve in the two points C and N. If we draw the perpendiculars NR and CG, and subtract NR, the smaller, from CG, the greater, the remainder will be x , the first of the four required mean proportionals.^[249]

This method applies as well to the division of an angle into five equal parts, the inscription of a regular polygon of eleven or thirteen sides in a circle, and an infinity of other problems. It should be remarked, however, that in many of these problems it may happen that the circle cuts the parabola of the second class so obliquely^[250] that it is hard to determine the exact point of intersection. In such cases this construction is not of practical value.^[251] The difficulty could easily be overcome by forming other rules analogous to these, which might be done in a thousand different ways.

^[249] The two roots of the above equation in y are NR and CG. But we know that a is one of the roots of this equation, and therefore NR, the shorter length, must be a , and CG must be y . Then $x = y - a = CG - NR$, the first of the required mean proportionals. Rabuel, p. 580.

^[250] That is, makes so small an angle with it.

^[251] This is especially noticeable when there are six real positive roots.

GEOMETRY

But it is not my purpose to write a large book. I am trying rather to include much in a few words, as will perhaps be inferred from what I have done, if it is considered that, while reducing to a single construction all the problems of one class, I have at the same time given a method of transforming them into an infinity of others, and thus of solving each in an infinite number of ways; that, furthermore, having constructed all plane problems by the cutting of a circle by a straight line, and all solid problems by the cutting of a circle by a parabola; and, finally, all that are but one degree more complex by cutting a circle by a curve but one degree higher than the parabola, it is only necessary to follow the same general method to construct all problems, more and more complex, ad infinitum; for in the case of a mathematical progression, whenever the first two or three terms are given, it is easy to find the rest.

I hope that posterity will judge me kindly, not only as to the things which I have explained, but also as to those which I have intentionally omitted so as to leave to others the pleasure of discovery.

[THE END]

les Problemes d'un mesme genre, iay tout ensemble donné la façon de les reduire à vne infinité d'autres diverses; & ainsi de refoudre chascun deux en vne infinité de façons. Puis outre cela qu'ayant construit tous ceux qui sont plans, en coupant d'un cercle vne ligne droite; & tous ceux qui sont solides, en coupant aussi d'un cercle vne Parabole; & enfin tous ceux qui sont d'un degré plus composés, en coupant tout de mesme d'un cercle vne ligne qui n'est que d'un degré plus composée que la Parabole; il ne faut que suivre la mesme voye pour construire tous ceux qui sont plus composés à l'infini. Car en matiere de progressions Mathématiques, lorsqu'on a les deux ou trois premiers termes, il n'est pas malaysé de trouver les autres. Et j'espere que nos neveux me sçauront gré, non seulement des choses que iay icy expliquées; mais aussi de celles que iay omises volontairement, afin de leur laisser le plaisir de les inventer.

F I N.

PAr grace & priuilege du Roy tres chrestien il est permis a l'Autheur du liure intitulé *Discours de la Methode &c. plus la Dioptrique, les Meteores, & la Geometrie &c.* de le faire imprimer en telle part que bon luy semblera dedans & dehors le royaume de France, & ce pendant le terme de dix annees consequitiues, a conter du iour qu'il sera paracheuë d'imprimer, sans qu'aucun autre que le libraire qu'il aura choisi le puisse imprimer, ou faire imprimer, en tout ny en partie, sous quelque pretexte ou deguisement que ce puisse estre; ny en vendre ou debiter d'autre impression que de celle qui aura esté faite par sa permission, a peine de mil liures d'amande, confiscation de tous les exemplaires &c. Ainsi qu'il est plus amplement déclaré dans les lettres donnees a Paris le 4 iour de May 1637. signees par le Roy en son conseil *Ceberet* & scellees du grand sceau de cire iaune sur simple queuë.

L'Autheur a permis a Ian Maire marchand libraire a Leyde, d'imprimer le dit liure & de iouir du dit priuilege pour le tems & aux conditions entre eux accordees.

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The printing is completed the eighth day of June, 1637.

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