BO1 History of Mathematics
Lecture XV
Geometry and number theory

MT 2022 Week 8

Summary

- Euclid's *Elements* revisited
- The parallel postulate
- Non-Euclidean geometry
- Number theory down the centuries

Euclid's *Elements*

Euclid's Elements, in 13 books, compiled c. 250 BC.

Books I–V:	definitions, postulates, plane geometry of lines and circles
Book VI:	similarity, proportion
Books VII–IX:	number theory
Book X:	commensurability, irrational numbers, surds
Books XI–XIII:	solid geometry ending with the classification of the regular polyhedra

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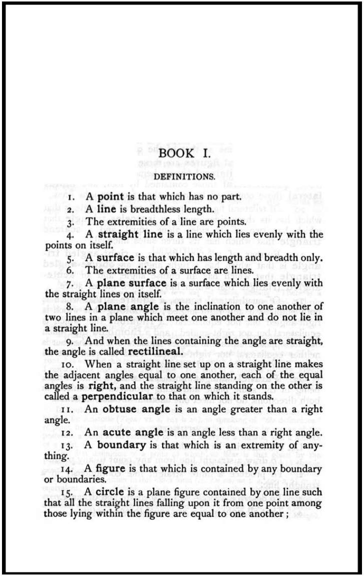
Euclid in English



BOOK I.

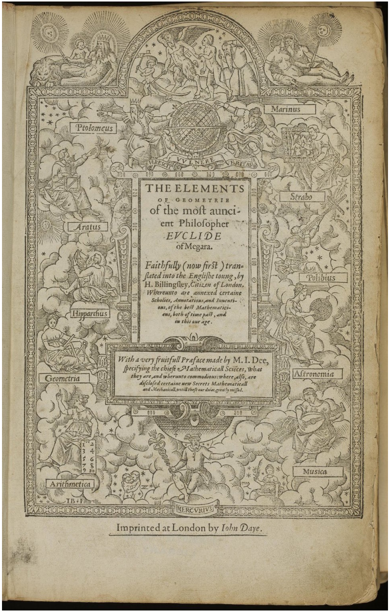
DEFINITIONS.

1. A **point** is that which has no part.
2. A **line** is breadthless length.
3. The extremities of a line are points.
4. A **straight line** is a line which lies evenly with the points on itself.
5. A **surface** is that which has length and breadth only.
6. The extremities of a surface are lines.
7. A **plane surface** is a surface which lies evenly with the straight lines on itself.
8. A **plane angle** is the inclination to one another of two lines in a plane which meet one another and do not lie in a straight line.
9. And when the lines containing the angle are straight, the angle is called **rectilineal.**
10. When a straight line set up on a straight line makes the adjacent angles equal to one another, each of the equal angles is **right,** and the straight line standing on the other is called a **perpendicular** to that on which it stands.
11. An **obtuse angle** is an angle greater than a right angle.
12. An **acute angle** is an angle less than a right angle.
13. A **boundary** is that which is an extremity of anything.
14. A **figure** is that which is contained by any boundary or boundaries.
15. A **circle** is a plane figure contained by one line such that all the straight lines falling upon it from one point among those lying within the figure are equal to one another;

Canonical English edition by Sir Thomas L. Heath, 1908

See also the Reading Euclid Project

Billingsley's Euclid, 1570


THE ELEMENTS OF GEOMETRIE of the moſt aunci-ent Philoſopher EVCLIDE of Megara.

Faithfully (now firſt) tranſlated into the Engliſhe toung, by H. Billingſley, Citizen of London. Whereunto are annexed certaine Scholies, Annotations, and Inuentions, of the beſt Mathematicians, both of time paſt, and in this our age.

With a very fruitfull Præface made by M. I. Dee, ſpecifying the chiefe Mathematicall Sciēces, what they are, and wherunto commodious: where, alſo, are diſcloſed certaine new Secrets Mathematicall and Mechanicall, untill theſe our daies, greatly miſſed.

Imprinted at London by Iohn Daye.

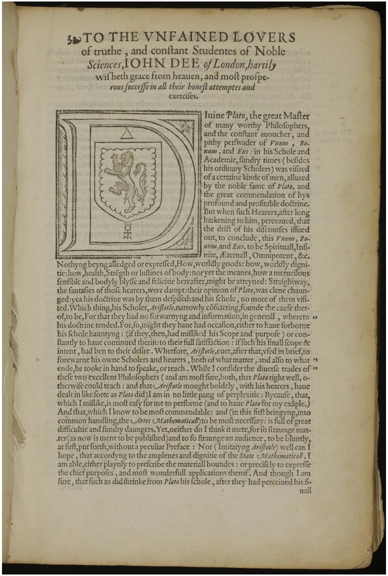
The Elements of Geometrie:

"Faithfully (now first) translated into the Englishe toung" by H. Billingsley, London, 1570

Available online

Preface by John Dee

Dee's Preface



TO THE VNFAINED LOVERS of truthe, and conſtant Studentes of Noble *Sciences*, IOHN DEE *of London, hartily* wiſheth grace from heauen, and moſt proſpe- *rous ſucceſſe in all their honeſt attemptes and* exerciſes.

Diuine *Plato*, the great Maſter of many worthy Philoſophers, and the conſtant auoucher, and pithy perſwader of *Vnum*, *Bonum*, and *Ens*: in his Schole and Academie, ſundry times (beſides his ordinary Scholers) was viſited of a certaine kinde of men, allured by the noble fame of *Plato*, and the great commendation of hys profound and profitable doctrine. But when ſuch Hearers, after long harkening to him, perceaued, that the drift of his diſcourſes iſſued out, to conclude, this *Vnum*, *Bonum*, and *Ens*, to be Spirituall, Infinite, Æternall, Omnipotent, &c. Nothyng beyng alledged or expreſſed, How, worldly goods: how, worldly dignitie: how, health, Strẽgth or luſtines of body: nor yet the meanes, how a merueilous ſenſible and bodyly blyſſe and felicitie hereafter, might be atteyned: Straightway, the fantaſies of thoſe hearers, were dampt: their opinion of *Plato*, was clene chaunged: yea his doctrine was by them deſpiſed: and his ſchole, no more of them viſited. Which thing, his Scholer, *Ariſtotle*, narrowly cõſidering, founde the cauſe therof, to be, For that they had no forwarnyng and information, in generall, whereto ” his doctrine tended. For, ſo, might they haue had occaſion, either to haue forborne his ſchole hauntyng: (if they, then, had miſliked his Scope and purpoſe) or conſtantly to haue continued therin: to their full ſatiſfaction: if ſuch his finall ſcope & intent, had ben to their deſire. Wherfore, *Ariſtotle*, euer, after that, vſed in brief, to forewarne his owne Scholers and hearers, both of what matter, and alſo to what ” ende, he tooke in hand to ſpeake, or teach. While I conſider the diuerſe trades of ” theſe two excellent Philoſophers (and am moſt ſure, both, that *Plato* right well, otherwiſe could teach: and that *Ariſtotle* mought boldely, with his hearers, haue dealt in like ſorte as *Plato* did) I am in no little pang of perplexitie: Bycauſe, that, which I miſlike, is moſt eaſy for me to performe (and to haue *Plato* for my exãple.) And that, which I know to be moſt commendable: and (in this firſt bringyng, into common handling, the *Artes Mathematicall*) to be moſt neceſſary: is full of great difficultie and ſundry daungers. Yet, neither do I think it mete, for ſo ſtraunge matter (as now is ment to be publiſhed) and to ſo ſtraunge an audience, to be bluntly, at firſt, put forth, without a peculiar Preface: Nor (Imitatyng *Ariſtotle*) well can I hope, that accordyng to the amplenes and dignitie of the *State Mathematicall*, I am able, either playnly to preſcribe the materiall boundes: or preciſely to expreſſe the chief purpoſes, and moſt wonderfull applications therof. And though I am ſure, that ſuch as did ſhrinke from *Plato* his ſchole, after they had perceiued his fi-

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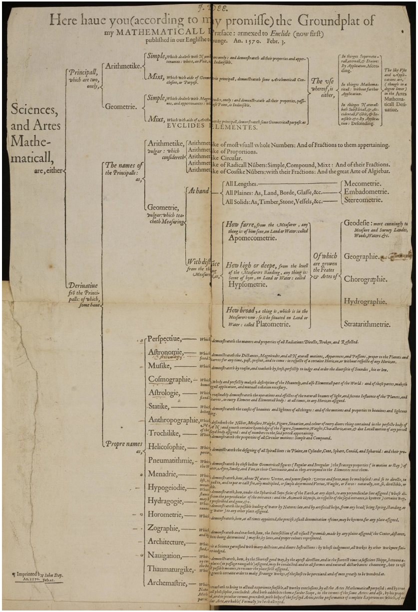
Dee's 'Groundplat'



See: Jennifer M. Rampling, 'The Elizabethan mathematics of everything: John Dee's 'Mathematicall praeface' to Euclid's *Elements*', *BSHM Bulletin: Journal of the British Society for the History of Mathematics* **26**(3) (2011) 135–146

Billingsley's Preface, pp. 1, 3

There is (gentle Reader) nothing (the word of God onely ſet apart) which ſo much beautifieth and adorneth the ſoule and minde of mã, as doth the knowledge of good artes and ſciences: as the knowledge of naturall and morall Philoſophie. The one ſetteth before our eyes, the creatures of God, both in the heauens aboue, and in the earth beneath: in which as in a glaſſe, we beholde the exceding maieſtie and wiſedome of God, in adorning and beautifying them as we ſee: in geuing vnto them ſuch wonderfull and manifolde proprieties, and naturall workinges, and that ſo diuerſly and in ſuch varietie: farther in maintaining and conſeruing them continually, whereby to praiſe and adore him, as by S. Paule we are taught. The other teacheth vs rules and preceptes of vertue, how, in common life amongeſt men, we ought to walke vprightly: what dueties pertaine to our ſelues, what pertaine to the gouernment or good order both of an houſholde, and alſo of a citie or common wealth. The reading likewiſe of hiſtories, conduceth not a litle, to the adorning of the ſoule & minde of man, a ſtudie of all men cõmended: by it are ſeene and knowen the artes and doinges of infinite wiſe men gone before vs. In hiſtories are contained infinite examples of heroicall vertues to be of vs followed, and horrible examples of vices to be of vs eſchewed. Many other artes alſo there are which beautifie the minde of man: but of all other none do more garniſhe & beautifie it, then thoſe artes which are called Mathematicall. Unto the knowledge of which no man can attaine, without the perfecte knowledge and inſtruction of the principles, groundes, and Elementes of Geometrie. But per-

...

well perceaue. The fruite and gaine which I require for theſe my paines and trauaile, ſhall be nothing els, but onely that thou gentle reader, will gratefully accept the ſame: and that thou mayeſt thereby receaue ſome profite: and moreouer to excite and ſtirre vp others learned, to do the like, & to take paines in that behalfe. By meanes wherof, our Engliſhe tounge ſhall no leſſe be enriched with good Authors, then are other ſtraunge tounges: as the Dutch, French, Italian, and Spaniſhe: in which are red all good authors in a maner, found amongeſt the Grekes or Latines. Which is the chiefeſt cauſe, that amongeſt thẽ do floriſhe ſo many cunning and ſkilfull men, in the inuentions of ſtraunge and wonderfull thinges, as in theſe our daies we ſee there do. Which fruite and gaine if I attaine vnto, it ſhall encourage me hereafter, in ſuch like ſort to tranſlate, and ſet abroad ſome other good authors, both pertaining to religion (as partly I haue already done) and alſo pertaining to the Mathematicall Artes. Thus gentle reader farewell.

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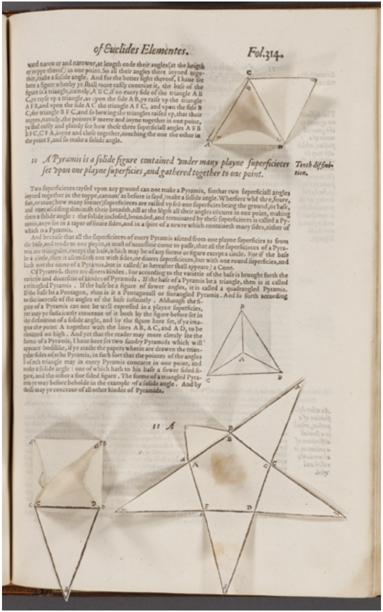
Pop-up Euclid



of Euclides Elementes. *Fol.314.*

ward narower and narower, at length ende their angles (at the heigth or toppe thereof) in one point. So all their angles there ioyned together, make a solide angle. And for the better sight thereof, I haue set here a figure wherby ye shall more easily conceiue it, the base of the figure is a triangle, namely, A B C, if on euery side of the triangle A B C, ye rayse vp a triangle, as vpon the side A B, ye raise vp the triangle A F B, and vpon the side A C the triangle A F C, and vpon the side B C, the triangle B F C, and so bowing the triangles raised vp, that their toppes, namely, the pointes F meete and ioyne together in one point, ye shal easily and plainly see how these three superficiall angles A F B, B F C, C F A, ioyne and close together, touching the one the other in the point F, and so make a solide angle.

10 *A Pyramis is a solide figure contained vnder many playne superficieces set vpon one playne superficies, and gathered together to one point.* *Tenth diffinition.*

Two superficieces raysed vpon any ground can not make a Pyramis, forthat two superficiall angles ioyned together in the toppe, cannot (as before is sayd) make a solide angle. Wherfore whē thre, foure, fiue, or moe (how many soeuer) superficieces are raised vp frō one superficies being the ground, or base, and euer ascēding diminish their breadth, till at the lēgth all their angles cōcurre in one point, making there a solide angle: the solide inclosed, bounded, and terminated by these superficieces is called a Pyramis, as ye see in a taper of foure sides, and in a spire of a towre which containeth many sides, either of which is a Pyramis.

And because that all the superficieces of euery Pyramis ascend from one playne superficies as from the base, and tende to one poynt, it must of necessitie come to passe, that all the superficieces of a Pyramis are triangular, except the base, which may be of any forme or figure except a circle. For if the base be a circle, then it ascendeth not with sides, or diuers superficieces, but with one round superficies, and hath not the name of a Pyramis, but is called (as hereafter shall appeare) a Cone.

Of Pyramids there are diuers kindes. For according to the varietie of the base is brought forth the varietie and diuersitie of kindes of Pyramids. If the base of a Pyramis be a triangle, then is it called a triangled Pyramis. If the base be a figure of fower angles, it is called a quadrangled Pyramis. If the base be a Pentagon, then is it a Pentagonall or fiuangled Pyramis. And so forth according to the increase of the angles of the base infinitely. Although the figure of a Pyramis can not be well expressed in a playne superficies, yet may ye sufficiently conceaue of it both by the figure before set in the definition of a solide angle, and by the figure here set, if ye imagine the point A together with the lines A B, A C, and A D, to be eleuated on high. And yet that the reader may more clerely see the forme of a Pyramis, I haue here set two sundry Pyramids which will appeare bodilike, if ye erecte the papers wherin are drawen the triangular sides of eche Pyramis, in such sort that the pointes of the angles F of ech triangle may in euery Pyramis concurre in one point, and make a solide angle: one of which hath to his base a fower sided figure, and the other a fiue sided figure. The forme of a triangled Pyramis ye may before beholde in the example of a solide angle. And by these may ye conceaue of all other kindes of Pyramids.

11 A

Book I: definitions

¶ The firſt booke of Eu-clides Elementes.

The argument of the firſt Booke.

IN THIS FIRST BOOKE is intreated of the moſt ſimple, eaſie, and firſt matters and groundes of Geometry, as, namely, of Lynes, Angles, Triangles, Parallels, Squares, and Parallelogrammes. Firſt of theyr definitions, ſhewyng what they are. After that it teacheth how to draw Parallel lynes, and how to forme diuerſly figures of three ſides, & foure ſides, according to the varietie of their ſides, and Angles : & cōpareth them all with Triangles, & alſo together the one with the other. In it alſo is taught how a figure of any forme may be chaunged into a Figure of an other forme. And for that it entreateth of theſe moſt common and generall thynges, thys booke is more vniuerſall then is the ſeconde, third, or any other, and therefore iuſtly occupieth the firſt place in order : as that without which, the other bookes of *Euclide* which follow, and alſo the workes of others which haue written in Geometry, cannot be perceaued nor vnderſtanded. And foraſmuch as all the demonſtrations and proofes of all the propoſitions in this whole booke, depende of theſe groundes and principles following, which by reaſon of their playnnes neede no greate declaration, yet to remoue all (be it neuer ſo litle) obſcuritie, there are here ſet certayne ſhorte and manifeſt expoſitions of them.

Definitions.

Definition of a poynt.

1. *A ſigne or point is that, which hath no part.*

The better to vnderſtand what maner of thing a ſigne or point is, ye muſt note that the nature and propertie of quantitie (wherof Geometry entreateth) is to be deuided, ſo that whatſoeuer may be deuided into ſundry partes, is called quantitie. But a point, although it pertayne to quantitie, and hath his beyng in quantitie, yet is it no quantitie, for that it cannot be deuided. Becauſe (as the definition ſaith) it hath no partes into which it ſhould be deuided. So that a pointe is the leaſt thing that by minde and vnderſtanding can be imagined and conceyued : then which, there can be nothing leſſe, as the point *A* in the margent.

A.

Definition of a poynt after Pithagoras.

A ſigne or point is of *Pithagoras* Scholers after this manner defined: *A poynt is an vnitie which hath poſition.* Nūbers are conceaued in mynde without any forme & figure, and therfore without matter wheron to receaue figure, & conſequently without place and poſition. Wherfore vnitie beyng a part of number, hath no poſition, or determinate place. Wherby it is manifeſt, that number is more ſimple and pure then is magnitude, and alſo immateriall: and ſo vnity which is the beginning of number, is leſſe materiall then a ſigne or poynt, which is the beginnyng of magnitude. For a poynt is materiall, and requireth poſition and place, and therby differeth from vnitie.

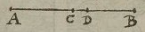
Definition of a line.

2. *A line is length without breadth.*

There pertaine to quantitie three dimenſions, length, bredth, & thicknes, or depth: and by theſe thre are all quātities meaſured & made known. There are alſo, according

B.j. to

to theſe three dimenſions, three kyndes of continuall quantities : a lyne, a ſuperficies, or plaine, and a body. The firſt kynde, namely, a line is here defined in theſe wordes, *A lyne is length without breadth.* A point, for that it is no quantitie nor hath any partes into which it may be deuided, but remaineth indiuiſible, hath not, nor can haue any of theſe three dimenſions. It neither hath length, breadth, nor thickenes. But to a line, which is the firſt kynde of quantitie, is attributed the firſt dimenſion, namely, length, and onely that, for it hath neither breadth nor thicknes, but is conceaued to be drawne in length onely, and by it, it may be deuided into partes as many as ye liſt, equall, or vnequall. But as touching breadth it remaineth indiuiſible. As the lyne A B, which is onely drawen in length, may be deuided in the pointe C equally, or in the point D vnequally, and ſo into as many partes as ye liſt. There are alſo of diuers other geuen other definitions of a lyne : as theſe which follow.



An other definition of a line.

A lyne is the mouyng of a poynte, as the motion or draught of a pinne or a penne to your ſence maketh a lyne.

An other.

Agayne, *A lyne is a magnitude hauing one onely ſpace or dimenſion,* namely, *length wantyng breadth and thicknes.*

The endes of a line.

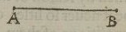
3 *The endes or limites of a lyne, are pointes.*

For a line hath his beginning from a point, and likewiſe endeth in a point: ſo that by this alſo it is manifeſt, that pointes, for their ſimplicitie and lacke of compoſition, are neither quantitie, nor partes of quantitie, but only the termes and endes of quantitie. As the pointes *A*, *B*, are onely the endes of the line *A B*, and no partes thereof. And herein differeth a poynte in quantitie, from vnitie in number: for that although vnitie be the beginning of nombers, and no number (as a point is the beginning of quantitie, and no quantitie) yet is vnitie a part of number. For number is nothyng els but a collection of vnities, and therfore may be deuided into them, as into his partes. But a point is no part of quantitie, or of a lyne: neither is a lyne compoſed of pointes, as number is of vnities. For things indiuiſible being neuer ſo many added together, can neuer make a thing diuiſible, as an inſtant in time, is neither tyme, nor part of tyme, but only the beginning and end of time, and coupleth & ioyneth partes of tyme together.

Difference of a point frō vnity.

Vnitie is a part of number.

A poynt is no part of quantitie.



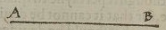
Definition of a right line.

4 *A right lyne is that which lieth equally betwene his pointes.*

As the whole line *A B* lyeth ſtraight and equally betwene the poyntes *A B* without any going vp or comming downe on eyther ſide.

Definition of a right line after Campanus.

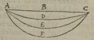
Campanus and certain others, define a right line thus:



A right line is the ſhorteſt extenſion or draught, that is or may be from one poynt to an other. *Archimedes* defineth it thus.

Definitiō therof after Archimedes.

A right line is the ſhorteſt of all lines, which haue one and the ſelf ſame limites or endes: which is in maner al one with the definitiō of *Campanus*. As of all theſe lines *A B C*, *A D C*, *A E C*, *A F C*, which are all drawen from the point *A*, to the poynte *B*, as *Campanus* ſpeaketh, or which haue the ſelf ſame limites or endes, as *Archimedes* ſpeaketh, the lyne *A B C*, beyng a right line, is the ſhorteſt.



Definitiō therof after Plato.

Plato defineth a right line after this maner: *A right line is that whoſe middle part ſhadoweth the extremes.* As if you put any thyng in the middle of a right lyne, you ſhall not ſee from the one ende to the other, which thyng happeneth not in a crooked lyne. The Ecclipſe of the Sunne (ſay Aſtronomers) then happeneth, when the Sunne, the Moone, & our eye are in one right line. For the Moone then being in the midſt betwene vs and the Sunne, cauſeth it to be darkened. Diuers other define a right line diuerſly, as followeth.

An other definition.

A right lyne is that which ſtandeth firme betwene his extremes.

Another.

Agayne, *A right line is that which with an other line of lyke forme cannot make a figure.*

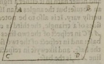
Agayne,

Book I: postulates

Definition of a diamondlike figure.

33 *Rhombaides (or a diamond like) is a figure, whoſe oppoſite ſides are equall, and whoſe oppoſite angles are alſo equall, but it hath neither equall ſides, nor right angles.*

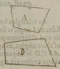
As in the figure ABCD, all the foure ſides are not equall, but the two ſides AB and CD, being oppoſite the one to the other, alſo the other two ſides AC and BD, being alſo oppoſite, are equall the one to the other. Likewiſe the angles are not right angles, but the angles CAB, and CDB, are obtuſe angles, and oppoſite and equall the one to the other. Likewyſe the angles ABD, and ACD, are acute angles, and oppoſite, and alſo equall the one to the other.



Trapezia or tables.

34 *All other figures of foure ſides beſides theſe, are called trapezia, or tables.*

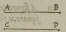
Such are all figures, in which is obſerued no equallitie of ſides nor angles: as the figures A and B, in the margēt, which haue neither equall ſides, nor equal angles, but are deſcribed at all aduenture without obſeruation of order, and therefore they are called irregular figures.



Definition of Parallel lines.

35 *Parallel or equidiſtant right lines are ſuch, which being in one and the ſelfe ſame ſuperficies, and produced infinitely on both ſydes, do neuer in any part concurre.*

As are the lines AB, and CD, in the example.

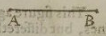


Peticions or requeſtes.

1 *From any point to any point, to draw a right line.*

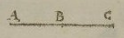
What Peticions are.

After the definitions, which are the firſt kind of principles, now follow petitions, which are the ſecond kynd of principles: which are certain general ſentences, ſo plain, & ſo perſpicuous, that they are perceiued to be true as ſoone as they are vttered, & no man that hath but common ſence, can, nor will deny them. Of which, the firſt is that, which is here ſet. As from the point A, to the point B, who wil deny, but eaſily graunt that a right line may be drawn? For two points howſoeuer they be ſet, are imagined to be in one and the ſelfe ſame plaine ſuperficies, wherfore from the one to the other there is ſome ſhorteſt draught, whiche is a right line. Likewiſe any two right lines howſoeuer they be ſet, are imagined to be in one ſuperficies, and therefore from any one line to any one line, may be drawen a ſuperficies.



2 *To produce a right line finite, ſtraight forth continually.*

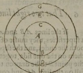
As to draw in length continually the right line AB, who will not graunt? For there is no magnitude ſo great, but that there may be a greter, nor any ſo litle, but that there may be a leſſe. And a line



a line is a draught from one point to an other, therfore from the point B, which is the ende of the line AB, may be drawn a line to ſome other point, as to the point C, and from that to an other, and ſo infinitely.

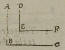
3 *Vpon any centre and at any diſtance, to deſcribe a circle.*

A playne ſuperficies may in compaſſe be extended infinitely: as from any pointe to any pointe may be drawen a right line, by reaſon wherof it commeth to paſſe that a circle may be deſcribed vpon any centre and at any ſpace or diſtance. As vpon the centre A, and vpon the ſpace AB, ye may deſcribe the circle BC, & vpon the ſame centre, vpon the diſtance AD, ye may deſcribe the circle DE, or vppon the ſame centre A, according to the diſtaunce AF, ye may deſcribe the circle FG, and ſo infinitely extendyng your ſpace.



4 *All right angles are equall the one to the other.*

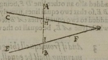
This peticion is moſt plaine, and offreth it ſelfe euen to the ſence. For as much as a right angle is cauſed of one right lyne falling perpendicularly vppon an other, and no one line can fall more perpendicularly vpō a line then an other: therfore no one right angle can be greater thē an other: neither do the length or ſhortenes of the lines alter the greatnes of the angle. For in the example, the right angle ABC, though it be made of much longer lines then the right angle DEF, whoſe lines are much ſhorter, yet is that angle no greater then the other. For if ye ſet the point E iuſt vpon the point B, then ſhal the line ED, euenly and iuſtly fall vpon the line AB, and the line EF, ſhall alſo fall equally vpon the line BC, and ſo ſhal the angle DEF, be equall to the angle ABC, for that the lines which cauſe them, are of like inclination.



It may euidently alſo be ſene at the centre of a circle. For if ye draw in a circle two diameters, the one cutting the other in the centre by right angles, ye ſhall deuide the circle into fowre equall partes, of which eche contayneth one right angle, ſo are all the foure right angles about the centre of the circle equall.

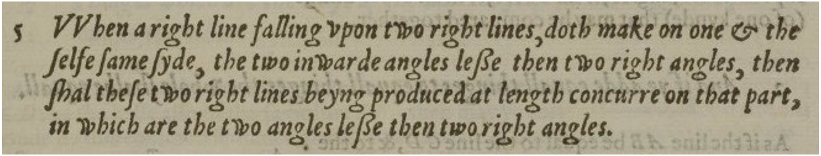
5 *VVhen a right line falling vpon two right lines, doth make on one & the ſelfe ſame ſyde, the two inwarde angles leſſe then two right angles, then ſhal theſe two right lines beyng produced at length concurre on that part, in which are the two angles leſſe then two right angles.*

As if the right line AB, fall vpon two right lines, namely, CD and EF, ſo that it make the two inward angles on the one ſide, as the angles DHI & FIH, leſſe then two right angles (as in the example they do) the ſaid two lines CD, and EF, being drawen forth in lēgth on that part, wheron the two angles being leſſe thē two right angles conſiſt, ſhal at lēgth concurre and meete together: as in the point D, as it is eaſie to ſee. For the partes of the lines towardes DF, are more enclined the one to

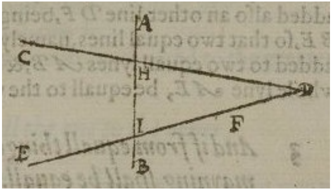


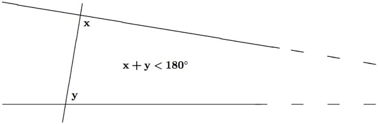
the

Postulate 5



5 VVhen a right line falling vpon two right lines, doth make on one & the ſelfe ſame ſyde, the two inwarde angles leſſe then two right angles, then ſhal theſe two right lines beyng produced at length concurre on that part, in which are the two angles leſſe then two right angles.





Equivalent formulation (Proclus, 5th century; John Playfair, 1795): given a straight line L and a point P not on L there is one and only one straight line through P that is parallel to L.

Classical disquiet about the fifth postulate

Original to Euclid? Less 'self-evident' than the other postulates?

Euclid used it (e.g., in the proof of Proposition 29 of Book I), so the property is necessary — but does it in fact follow from the other postulates?

Proclus in commentary on Euclid, 5th century (after citing Ptolemy's attempted proof of the parallel postulate, and discussing the nature of truth, with reference to Aristotle and Plato):

> *It is then clear from this that we must seek a proof of the present theorem, and that it is alien to the special character of postulates.*

Attempted (unsuccessfully) to prove the fifth postulate on the basis of the others

See Heath, pp. 202–220

Mediaeval disquiet about the fifth postulate

In the Islamic world:

Ibn al-Haytham (Alhazen) (965–1039) attempted (unsuccessfully) to prove the parallel postulate by contradiction

Omar Khayyám (1050–1123) attempted to prove the fifth postulate on the basis of the following alternative:

> *two convergent straight lines intersect and it is impossible for two convergent straight lines to diverge in the direction in which they converge*

Described the situations that may occur if the postulate is omitted

Nasir al-Din al-Tusi (1201–1274) criticised Khayyám's attempted proof, offered his own

Al-Tusi's thoughts found their way into Europe via the writings (1298) of his son Sadr al-Tusi

Early modern disquiet about the fifth postulate

After reading al-Tusi, John Wallis showed that the parallel postulate is equivalent to the following:

> *on a given finite straight line it is always possible to construct a triangle similar to a given triangle*

He lectured on this in Oxford in 1663

Attempts to prove the fifth postulate on the basis of Euclid's other axioms had resulted only in equivalent forms — so can we have a consistent geometry in which it the parallel postulate fails?

Early hints of non-Euclidean geometry

Giovanni Girolamo Saccheri (1667–1733): sought to establish the validity of Euclidean geometry — negated the parallel postulate in search of a contradiction; two cases:

- internal angles of a triangle add up to less than two right angles — contradicts Euclid's second postulate
- internal angles of a triangle add up to more than two right angles — leads to non-intuitive ideas

Similar results derived by Johann Heinrich Lambert (1728–1777) in his *Theorie der Parallellinien* (1766)

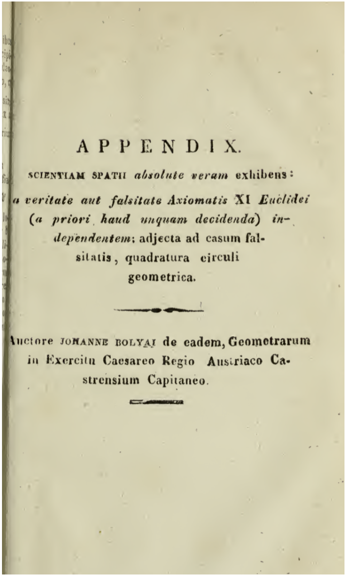
Non-Euclidean geometries

Consistent non-Euclidean geometry probably first constructed (tentatively) by Gauss, c. 1817–1830, but remained unpublished

Problem pursued independently (without success) by Gauss' friend Farkas Bolyai (1775–1856)

Pursued (against paternal advice) and solved by János Bolyai (1802–1860): "I have created a new and different world out of nothing" (1823)

Bolyai's geometry


APPENDIX.

SCIENTIAM SPATII *absolute veram* exhibens:
a veritate aut falsitate Axiomatis XI *Euclidei* (*a priori haud unquam decidenda*) *independentem*; adjecta ad casum falsitatis, quadratura circuli geometrica.

Auctore JOHANNE BOLYAI de eadem, Geometrarum in Exercitu Caesareo Regio Austriaco Castrensium Capitaneo.

Published as appendix 'The science absolute of space: independent of the truth or falsity of Euclid's axiom XI (which can never be decided a priori)' to father's textbook *Tentamen iuventutem studiosam in elementa matheosos introducendi* (1832)

English translation by George Bruce Halstead (1896)

Meanwhile in Russia...

Non-Euclidean geometry developed independently by Nikolai Ivanovich Lobachevskii [Николай Иванович Лобачевский] (1792–1856) using the negation of Playfair's axiom

Lobachevskii's works


Geometrische Untersuchungen

zur

Theorie der Parallellinien

von

Nicolaus Lobatschewsky,

Kaiserl. russ. wirkl. Staatsrathe und ord. Prof. der Mathematik
bei der Universität Kasan.

Berlin. 1840.

In der G. Fincke'schen Buchhandlung

Complicated story of dissemination...

Geometriya [Геометрия] written in 1823 but not published until 1909

Ideas presented in Kazan in 1826, published there 1829 — but rejected by St Petersburg Academy

Other works in Russian, French and German, including *Geometrische Untersuchungen zur Theorie der Parallellinien* (1840), *Pangéométrie* (1855)

(See Tom Lehrer for an unfair characterisation of Lobachevskii: https://youtu.be/IL4vWJbwmqM)

Acceptance and impact of non-Euclidean geometries

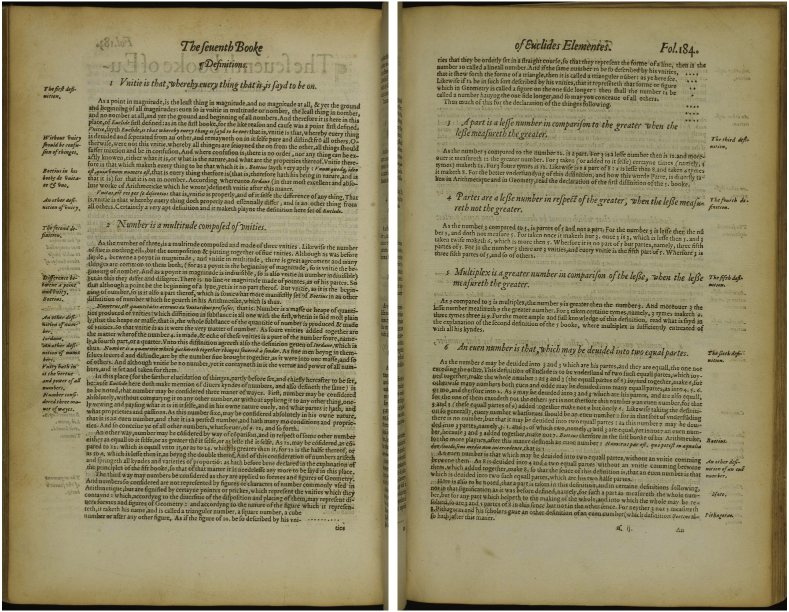
Slow to gain acceptance due to

- obscurity of publications
- lack of intuitive understanding

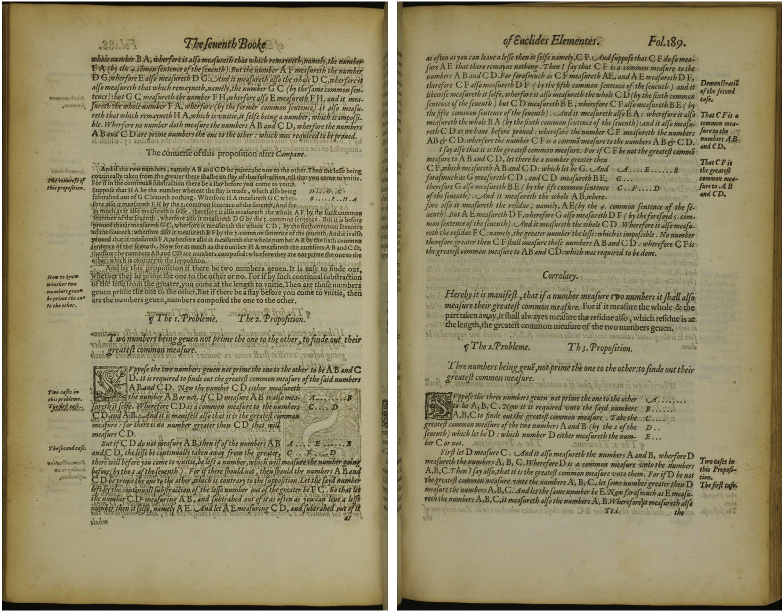
But non-Euclidean geometries

- overturned old ideas of mathematical certainty
- introduced new ideas about space
- helped drive the late 19th-century move towards axiomatisation

Euclid on numbers (positive integers)



The Euclidean algorithm (Proposition VII.2)



The ſeuenth Booke

whole number B A, *wherfore it alſo meaſureth that which remayneth, namely, the number* F A *(by the 4. cōmon ſentence of the ſeuenth). But the number* A F *meaſureth the number* D G, *wherfore* E *alſo meaſureth* D G. *And it meaſureth alſo the whole* D C, *wherfore it alſo meaſureth that which remayneth, namely, the number* G C *(by the ſame common ſentence): but* G C *meaſureth the number* F H, *wherfore alſo* E *meaſureth* F H, *and it meaſureth the whole number* F A, *wherfore (by the former common ſentence) it alſo meaſureth that which remayneth* H A, *which is vnitie, it ſelfe being a number, which is impoſſible. Wherfore no number doth meaſure the numbers* A B *and* C D, *wherfore the numbers* A B *and* C D *are prime numbers the one to the other: which was required to be proued.*

The conuerſe of this propoſition after *Campane.*

The conuerſe of this propoſition.

And if the two numbers, namely A B and C D be prime the one to the other. Then the leſſe being continually taken from the greater there ſhalbe no ſtay of that ſuſtraction, till that you come to vnitie. For if in the continuall ſubſtraction there be a ſtay before you come to vnitie. Suppoſe that H A be the number whereat the ſtay is made, which alſo being ſubtrahed out of G C leaueth nothing. Wherfore H A meaſureth G C wherfore alſo it meaſureth F H by the 5. common ſentence of the ſeuenth. And for as much as it alſo meaſureth it ſelfe, therefore it alſo meaſureth the whole A F by the ſixth common ſentence of the ſeuenth, wherfore alſo it meaſureth D G by the 5. common ſentence. But it is before proued that it meaſureth G C, wherfore it meaſureth the whole C D, by the ſixth common ſentence of the ſeuenth: wherfore alſo it meaſureth B F by the 5. common ſentence of the ſeuenth. And it is alſo proued that it meaſureth F A, wherfore alſo it meaſureth the whole number A B by the ſixth common ſentence of the ſeuenth. Now for as much as the number H A meaſureth the numbers A B and C D, therfore the numbers AB and CD are numbers compoſed: wherfore they are not prime the one to the other: which is contrary to the ſuppoſition.

D . . . G . . C
B . . . . . F . . H . A

How to know whether two numbers geuen be prime the one to the other.

And by this propoſition if there be two numbers geuen. It is eaſy to finde out, whether they be prime the one to the other or no. For if by ſuch continual ſubſtraction of the leſſe from the greater, you come at the length to vnitie. Then are thoſe numbers geuen prime the one to the other. But if there be a ſtay before you come to vnitie, then are the numbers geuen, numbers compoſed the one to the other.

¶ The 1. Probleme. The 2. Propoſition.

Two numbers being geuen not prime the one to the other, to finde out their greateſt common meaſure.

Two caſes in this probleme. The firſt caſe.

Suppoſe the two numbers geuen not prime the one to the other to be A B *and* C D. *It is required to finde out the greateſt common meaſure of the ſaid numbers* A B *and* C D. *Now the number* C D *either meaſureth the number* A B *or not. If* C D *meaſure* A B *it alſo meaſureth it ſelfe. Wherefore* C D *is a common meaſure to the numbers* C D *and* A B. *And it is manifest alſo that it is the greateſt common meaſure: for there is no number greater then* C D *that will meaſure* C D.

A . . . . B
C . . . . D

The ſecond caſe.

But if C D *do not meaſure* A B, *then if of the numbers* A B *and* C D, *the leſſe be continually taken away from the greater, there will before you come to vnitie, be left a number, which will meaſure the number going before (by the 1. of the ſeuenth). For if there ſhould not, then ſhould the numbers* A B *and* C D *be prime the one to the other, which is contrary to the ſuppoſition. Let the ſayd number left by the continuall ſubſtraction of the leſſe number out of the greater be* F C. *So that let the number* C D *meaſuring* A B, *and ſubtrahed out of it as often as you can leue a leſſe number then it ſelfe, namely* A E. *And let* A E *meaſuring* C D, *and ſubtrahed out of it*

A . . . . E . . . . . . B
C . . F . . . . D

of Euclides Elementes. Fol. 189.

as often as you can leaue a leſſe then it ſelfe namely, C F. *And ſuppoſe that* C F *do ſo meaſure* A E *that there remayne nothing. Then I ſay that* C F *is a common meaſure to the numbers* A B *and* C D. *For foraſmuch as* C F *meaſureth* AE, *and* A E *meaſureth* D F, *therefore* C F *alſo meaſureth* D F *(by the fifth common ſentence of the ſeuenth) and it likewiſe meaſureth it ſelfe, wherfore it alſo meaſureth the whole* C D *(by the ſixth common ſentence of the ſeuenth) but* C D *meaſureth* B E, *wherefore* C F *alſo meaſureth* B E *(by the fifte common ſentence of the ſeuenth). And it meaſureth alſo* E A: *wherefore it alſo meaſureth the whole* B A *(by the ſixth common ſentence of the ſeuenth): and it alſo meaſureth* C D *as we haue before proued: wherefore the number* C F *meaſureth the numbers* AB *&* C D: *wherfore the number* C F *is a cōmō meaſure to the numbers* A B *&* C D.

Demonſtratiō of the ſecond caſe.

That C F is a common meaſure to the numbers A B and C D.

I ſay alſo that it is the greateſt common meaſure. For if C F *be not the greateſt cōmō meaſure to* A B *and* C D, *let there be a number greater then* C F, *which meaſureth* A B *and* C D: *which let be* G. *And foraſmuch as* G *meaſureth* C D, *and* C D *meaſureth* B E, *therefore* G *alſo meaſureth* B E *(by the fift common ſentence of the ſeuenth). And it meaſureth the whole* A B, *wherefore alſo it meaſureth the reſidue, namely,* A E *(by the 4. common ſentence of the ſeuenth). But* A E *meaſureth* D F, *wherefore* G *alſo meaſureth* D F *(by the foreſayd 5. common ſentence of the ſeuenth). And it meaſureth the whole* C D. *Wherefore it alſo meaſureth the reſidue* F C: *namely, the greater number the leſſe: which is impoſſible. No number therefore greater then* C F *ſhall meaſure thoſe numbers* A B *and* C D: *wherefore* C F *is the greateſt common meaſure to* AB *and* CD: *which was required to be done.*

A . . . . E . . . . . . B
G . . .
C . . F . . . . D

That C F is the greateſt common meaſure to A B and C D.

Corrolary.

Hereby it is manifeſt, that if a number meaſure two numbers it ſhall alſo meaſure their greateſt common meaſure. For if it meaſure the whole & the part taken away, it ſhall alwayes meaſure the reſidue alſo, which reſidue is at the length, the greateſt common meaſure of the two numbers geuen.

¶ The 2. Probleme. Th 3. Propoſition.

Thre numbers being geuē, not prime the one to the other: to finde out their greateſt common meaſure.

Suppoſe the three numbers geuen not prime the one to the other to be A, B, C. *Now it is required vnto the ſayd numbers* A, B, C *to finde out the greateſt common meaſure. Take the greateſt common meaſure of the two numbers* A *and* B *(by the 2 of the ſeuenth) which let be* D: *which number* D *either meaſureth the number* C *or not.*

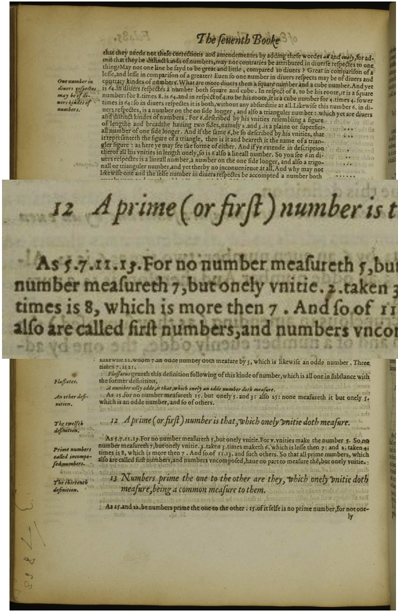
A . . . .
B . . . . . .
C . . . .
D . .
E . . .

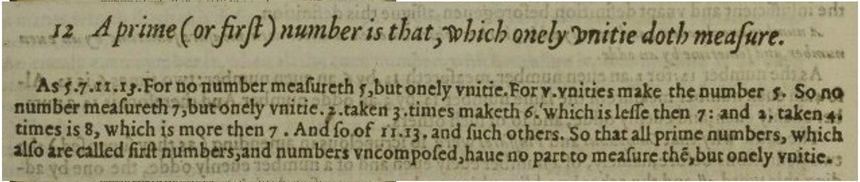
Two caſes in this Propoſition. The firſt caſe.

Firſt let D *meaſure* C. *And it alſo meaſureth the numbers* A *and* B, *wherfore* D *meaſureth the numbers* A, B, C. *Wherefore* D *is a common meaſure vnto the numbers* A, B, C. *Then I ſay alſo, that it is the greateſt common meaſure vnto them. For if* D *be not the greateſt common meaſure vnto the numbers* A, B, C, *let ſome number greater then* D *meaſure the numbers* A, B, C. *And let the ſame number be* E. *Now foraſmuch as* E *meaſureth the numbers* A, B, C, *it meaſureth alſo the numbers* A, B. *Wherefore it meaſureth alſo the*

Tt.i.

Euclid on prime numbers

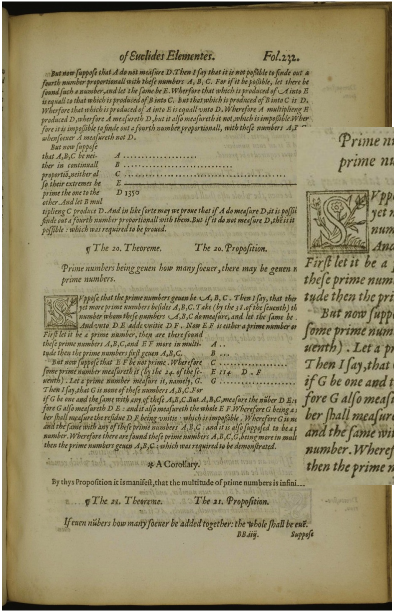




12 *A prime (or first) number is that, which onely vnitie doth measure.*

As 5.7.11.13. For no number measureth 5, but onely vnitie. For v. vnities make the number 5. So no number measureth 7, but onely vnitie. 2. taken 3. times maketh 6. which is lesse then 7: and 2. taken 4. times is 8, which is more then 7. And so of 11.13. and such others. So that all prime numbers, which also are called first numbers, and numbers vncomposed, haue no part to measure thẽ, but onely vnitie.

Euclid on prime numbers (Proposition IX.20)



But now suppose that A do not measure D. Then I say that it is not possible to finde out a fourth number proportionall with these numbers A, B, C. For if it be possible, let there be found such a number, and let the same be E. Wherfore that which is produced of A into E is equall to that which is produced of B into C. But that which is produced of B into C is D. Wherfore that which is produced of A into E is equall vnto D. Wherefore A multiplieng E produced D, wherfore A measureth D, but it also measureth it not, which is impossible. Wherfore it is impossible to finde out a fourth number proportionall, with these numbers A, B, C whensoeuer A measureth not D.

But now suppose that A, B, C be neither in continuall proportiõ, neither also their extremes be prime the one to the other. And let B multiplieng C produce D. And in like sorte may we proue that if A do measure D, it is possib[le to] finde out a fourth number proportionall with them. But if it do not measure D, thẽ is it [im]possible : which was required to be proued.

A ....
B ....
C ....
E ——————————————
D 1350

¶ The 20. Theoreme. The 20. Proposition.

Prime numbers being geuen how many soeuer, there may be geuen more prime numbers.

Suppose that the prime numbers geuen be A, B, C. Then I say, that there are yet more prime numbers besides A,B,C. Take (by the 38. of the seuenth) the least number whom these numbers A,B,C do measure, and let the same be D E. And vnto D E adde vnitie D F. Now E F is either a prime number or not. First let it be a prime number, then are there found these prime numbers A,B,C, and E F more in multitude then the prime numbers first geuen A,B,C.

But now suppose that E F be not prime. Wherefore some prime number measureth it (by the 24. of the seuenth). Let a prime number measure it, namely, G. Then I say, that G is none of these numbers A,B,C. For if G be one and the same with any of these A,B,C. But A,B,C, measure the nũber D E: wherfore G also measureth D E : and it also measureth the whole E F. Wherefore G being a number shall measure the residue D F being vnitie : which is impossible. Wherefore G is not one and the same with any of these prime numbers A,B,C : and it is also supposed to be a prime number. Wherefore there are found these prime numbers A,B,C,G, being more in multitude then the prime numbers geuen A,B,C : which was required to be demonstrated.

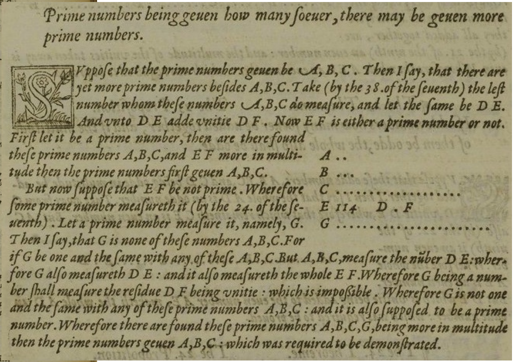
A ..
B ...
C ....
E 114 D . F
G ....

✻ A Corollary.

By thys Proposition it is manifest, that the multitude of prime numbers is infinite.

¶ The 21. Theoreme. The 21. Proposition.

If euen nũbers how many soeuer be added together: the whole shall be euẽ.



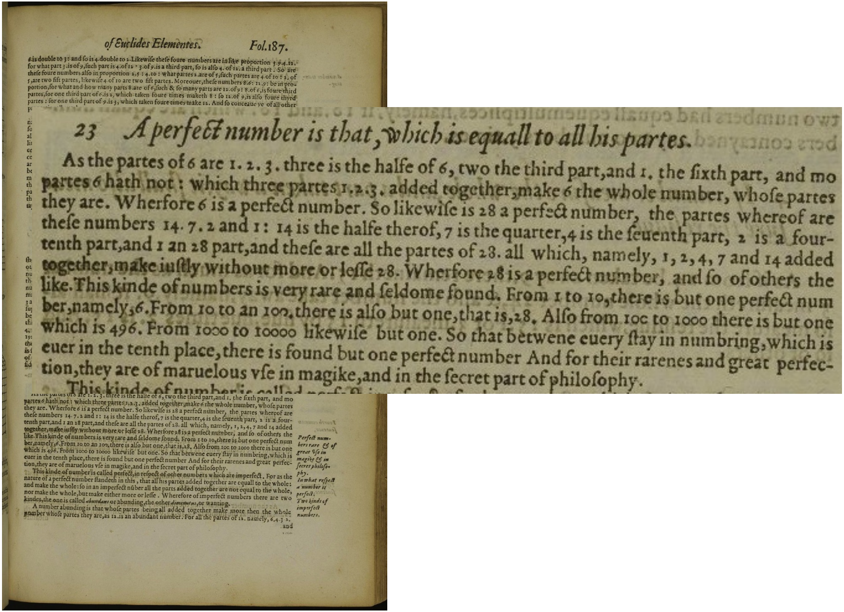
Prime numbers being geuen how many soeuer, there may be geuen more prime numbers.

Suppose that the prime numbers geuen be A, B, C. Then I say, that there are yet more prime numbers besides A,B,C. Take (by the 38. of the seuenth) the least number whom these numbers A,B,C do measure, and let the same be D E. And vnto D E adde vnitie D F. Now E F is either a prime number or not. First let it be a prime number, then are there found these prime numbers A,B,C, and E F more in multitude then the prime numbers first geuen A,B,C.

But now suppose that E F be not prime. Wherefore some prime number measureth it (by the 24. of the seuenth). Let a prime number measure it, namely, G. Then I say, that G is none of these numbers A,B,C. For if G be one and the same with any of these A,B,C. But A,B,C, measure the nũber D E: wherfore G also measureth D E : and it also measureth the whole E F. Wherefore G being a number shall measure the residue D F being vnitie : which is impossible. Wherefore G is not one and the same with any of these prime numbers A,B,C : and it is also supposed to be a prime number. Wherefore there are found these prime numbers A,B,C,G, being more in multitude then the prime numbers geuen A,B,C : which was required to be demonstrated.

A ..
B ...
C ....
E 114 D . F
G ....

Euclid on perfect numbers



of Euclides Elementes. Fol.187.

23 *A perfect number is that, which is equall to all his partes.*

As the partes of 6 are 1. 2. 3. three is the halfe of 6, two the third part, and 1. the sixth part, and mo partes 6 hath not: which three partes 1.2.3. added together, make 6 the whole number, whose partes they are. Wherfore 6 is a perfect number. So likewise is 28 a perfect number, the partes whereof are these numbers 14. 7. 2 and 1: 14 is the halfe therof, 7 is the quarter, 4 is the seuenth part, 2 is a fourtenth part, and 1 an 28 part, and these are all the partes of 28. all which, namely, 1, 2, 4, 7 and 14 added together, make iustly without more or lesse 28. Wherfore 28 is a perfect number, and so of others the like. This kinde of numbers is very rare and seldome found. From 1 to 10, there is but one perfect number, namely, 6. From 10 to an 100, there is also but one, that is, 28. Also from 100 to 1000 there is but one which is 496. From 1000 to 10000 likewise but one. So that betwene euery stay in numbring, which is euer in the tenth place, there is found but one perfect number And for their rarenes and great perfection, they are of maruelous vse in magike, and in the secret part of philosophy.

This kinde of number is called perfect, in respect of other numbers which are imperfect. For as the nature of a perfect number standeth in this, that all his partes added together are equall to the whole: and make the whole: so in an imperfect nũber all the parts added together are not equal to the whole, nor make the whole, but make either more or lesse. Wherefore of imperfect numbers there are two kindes, the one is called *abundans* or abunding, the other *diminutus*, or wanting.

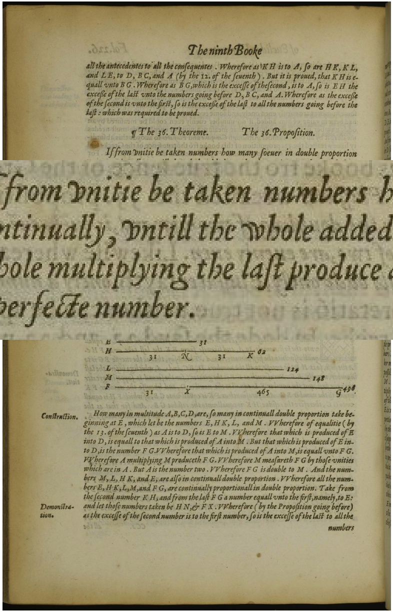
A number abunding is that whose partes being all added together make more then the whole number whose partes they are, as 12. is an abundant number. For all the partes of 12. namely, 6. 4. 3. 2. and

Perfect numbers rare & of great vse in magike & in secret philosophy.

In what respect a number is perfect.

Two kinds of imperfect numbers.

Euclid on perfect numbers (Proposition IX.36)



The ninth Booke

all the antecedentes to all the consequentes. Wherefore as K H is to A, so are H K, K L, and L E, to D, B C, and A (by the 12. of the seuenth). But it is proued, that K H is equall vnto B G. Wherefore as B G, which is the excesse of the second, is to A, so is E H the excesse of the last vnto the numbers going before D, B C, and A. Wherefore as the excesse of the second is vnto the first, so is the excesse of the last to all the numbers going before the last: which was required to be proued.

¶ The 36. Theoreme. The 36. Proposition.

If from vnitie be taken numbers how many soeuer in double proportion continually, vntill the whole added together be a prime number, and if the whole multiplying the last produce any number, that which is produced is a perfecte number.

Construction. How many in multitude A, B, C, D, are, so many in continuall double proportion take beginning at E, which let be the numbers E, H K, L, and M. VVherefore of equalitie (by the 13. of the seuenth) as A is to D, so is E to M. VVherefore that which is produced of E into D, is equall to that which is produced of A into M. But that which is produced of E into D, is the number F G. VVherefore that which is produced of A into M, is equall vnto F G. VVherefore A multiplying M produceth F G. VVherefore M measureth F G by those vnities which are in A. But A is the number two. VVherefore F G is double to M. And the numbers M, L, H K, and E, are also in continuall double proportion. VVherefore all the numbers E, H K, L, M, and F G, are continually proportionall in double proportion. Take from the second number K H, and from the last F G a number equall vnto the first, namely, to E: and let those numbers taken be H N, & F X. VVherefore (by the Proposition going before) as the excesse of the second number is to the first number, so is the excesse of the last to all the numbers

Demonstration.

In modern terms: if $2^n - 1$ is prime, then $2^{n-1}(2^n - 1)$ is perfect

Number theory after Euclid

Very little for many centuries...

Recall that Diophantus' *Arithmetica* (13 books, c. AD 250) featured number problems; for example [from Lecture IX]:

> Problem I.27: *Find two numbers such that their sum and product are given numbers*

The *Arithmetica* also features problems and ideas that we would now classify as number-theoretic; for example:

> Problem III.19: *To find four numbers such that the square of their sum plus or minus any one singly gives a square*

> Problem V.9: *To divide unity into two parts such that, if a given number is added to either part, the result will be a square*

Restrictions on the permitted form of solutions to problems eventually gave rise to the notion of Diophantine equations

Number theory outside Europe

Sūnzǐ Suànjīng 孙子算经 (*The Mathematical Classic of Master Sun*) (3rd–5th century BC) contains a statement, but no proof, of the Chinese Remainder Theorem for the solution of simultaneous congruences

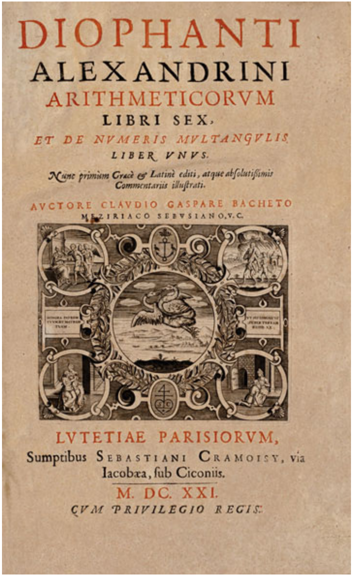
An algorithm for the solution was provided by Aryabhata in 6th-century India

In 7th-century India, Brahmagupta studied Diophantine equations (including Pell's equation — see later, and also: Toke Knudsen and Keith Jones, 'The Pell Equation in India', 2017)

These works were unknown in Europe until the 19th century

See: Eva Caianiello, 'Indeterminate linear problems from Asia to Europe', *Lettera Matematica* 6 (2018), 233–243

17th-century number theory



Bachet's Latin edition of Diophantus' *Arithmetica* (1621)

Pierre de Fermat owned a 1637 edition, which he studied and annotated

Fermat on number theory

Fermat's Little Theorem: if a is any integer and p is prime then p divides $a^p - a$

Studies of 'Pell's Equation' $x^2 - Dy^2 = 1$

Conjectures on perfect numbers [more in a moment]

Studies of diophantine problems leading to 'Fermat's Last Theorem' [more in a moment]

Published nothing — had to be exhorted to write his ideas down

(See *Mathematics emerging*, §§6.1–6.3)

The ‘Last Theorem’

Arithmetica Problem II.8 concerns the splitting of a given square number into two other squares

Fermat’s marginal note:

> *It is impossible to separate a cube into two cubes, or a fourth power into two fourth powers, or in general, any power higher than the second, into two like powers. I have discovered a truly marvelous proof of this, which this margin is too narrow to contain.*

(See: Simon Singh, *Fermat’s Last Theorem*, Fourth Estate, 1998)

Perfect numbers

Euclid's Theorem: if $2^n - 1$ is prime then $2^{n-1}(2^n - 1)$ is perfect

Fermat to Mersenne (1640): if $2^n - 1$ is prime then n must be prime

Mersenne (1644): if $p \leq 257$ and $2^p - 1$ is prime then p is one of 2, 3, 5, 7, 13, 17, 67 (a misprint for 61 perhaps?), 127, 257. Not quite right: $2^{89} - 1$, $2^{107} - 1$ are prime and $2^{257} - 1$ is composite.

Euler: proof that all even perfect numbers are of Euclid's form (proved 1749, but published posthumously)

(See *Mathematics emerging*, §6.1.2)

NB. 51 Mersenne primes are currently known, the largest being $2^{82,589,933} - 1$ (found in June 2019)

17th-century attitudes to number theory

Fermat failed to spark an interest in number theory in his contemporaries

Pascal to Fermat (1655):

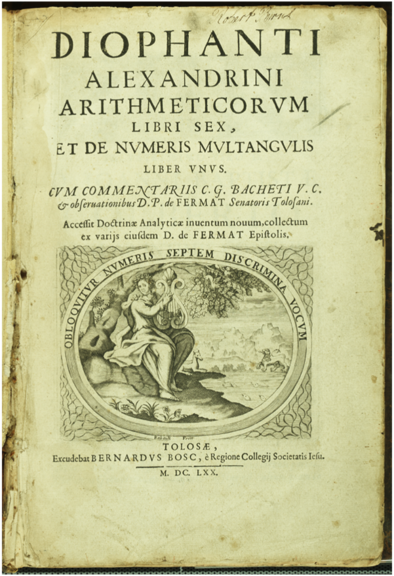
> *... seek elsewhere those who can follow you in your numerical discoveries ... I confess to you that this goes far beyond me ...*

Number-theoretic investigations were widely regarded as trivial and uninteresting

Huygens to Wallis:

> *There is no lack of better topics for us to spend our time on ...*

The ‘rebirth’ of number theory



1670 edition of Bachet, published by Samuel Fermat, including his father’s notes

The ‘Last Theorem’ was not the only result for which Fermat failed to provide a proof

Number theory was ‘reborn’ from the attempts of Euler (and later Lagrange and Legendre) to fill the gaps left by Fermat

Euler on number theory

Euler (1747):

Nor is the author disturbed by the authority of the greatest mathematicians when they sometimes pronounce that number theory is altogether useless and does not deserve investigation. In the first place, knowledge is always good in itself, even when it seems to be far removed from common use. Secondly, all the aspects of the truth which are accessible to our mind are so closely related to one another that we dare not reject any of them as being altogether useless. ...

Consequently, the present author considers that he has by no means wasted his time and effort in attempting to prove various theorems concerning integers and their divisors. ... Moreover, there is little doubt that the method used here by the author will turn out to be of no small value in other investigations of greater import.

19th-century number theory

Gauss's *Disquisitiones arithmeticae* (1801) became a key text for many years to come: modular arithmetic, quadratic forms, cyclotomy, ...

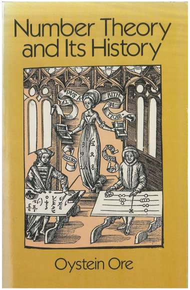
Number-theoretic problems (especially attempts to prove Fermat's Last Theorem) led to the development of ideal theory, and the linking of number theory and abstract algebra in algebraic number theory

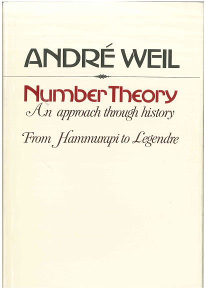
By the end of the 19th century, a new branch, analytic number theory, had also emerged (e.g., Riemann hypothesis, Prime Number Theory $\pi(x) \sim \frac{x}{\log x}, \ldots$)

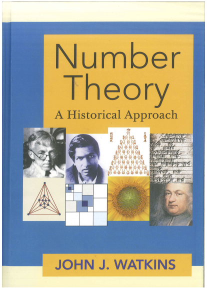
Sophie Germain (1776–1831)

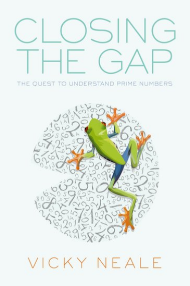
- Largely self-taught in mathematics by reading the works of Newton, Euler, and others
- Corresponded with Lagrange, Legendre, Gauss
- Pioneer of elasticity theory, but also solved some cases of Fermat's Last Theorem
- See: Jenny Boucard, 'Arithmetic and memorial practices by and around Sophie Germain in the 19th century', in *Against all odds: Women's ways to mathematical research since 1800* (ed. Eva Kaufholz-Soldat & Nicola M. R. Ostwald), Springer, 2020, pp. 185–230

The history of number theory









Leonard Eugene Dickson, *History of the theory of numbers*, 3 vols., Carnegie Institution of Washington, 1919–1923: I, II, III