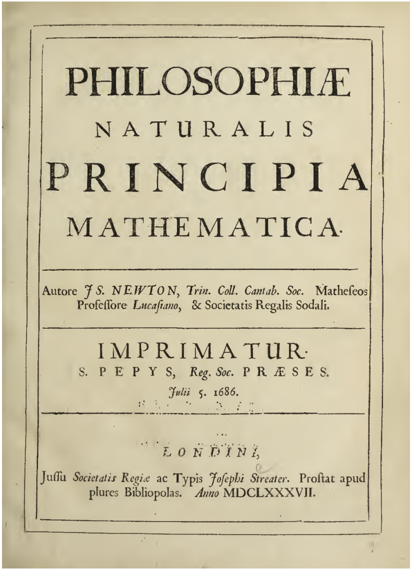
BO1 History of Mathematics
Lecture IV
Newton's *Principia*
Part 3: The *Principia*

MT 2021 Week 2

Isaac Newton: *The mathematical principles of natural philosophy* (London, 1687)



PHILOSOPHIÆ

NATURALIS

PRINCIPIA

MATHEMATICA.

Autore *J. S.* NEWTON, *Trin. Coll. Cantab. Soc.* Mathefeos Profeffore *Lucafiano*, & Societatis Regalis Sodali.

IMPRIMATUR.

S. PEPYS, *Reg. Soc.* PRÆSES.

Julii 5. 1686.

LONDINI,

Juffu *Societatis Regiæ* ac Typis *Jofephi Streater*. Proftat apud plures Bibliopolas. *Anno* MDCLXXXVII.

Contents of the *Principia*

- Eight definitions — of matter, motion, innate force, impressed force, acceleration, ...

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- Book III: The system of the world

The laws of motion

AXIOMATA SIVE LEGES MOTUS

Lex. I.

Corpus omne perſeverare in ſtatu ſuo quieſcendi vel movendi uniformiter in directum, niſi quatenus a viribus impreſſis cogitur ſtatum illum mutare.

Projectilia perſeverant in motibus ſuis niſi quatenus a reſiſtentia aeris retardantur & vi gravitatis impelluntur deorſum. Trochus, cujus partes cohærendo perpetuo retrahunt ſeſe a motibus rectilineis, non ceſſat rotari niſi quatenus ab aere retardatur. Majora autem Planetarum & Cometarum corpora motus ſuos & progreſſivos & circulares in ſpatiis minus reſiſtentibus factos conſervant diutius.

Lex. II.

Mutationem motus proportionalem eſſe vi motrici impreſſæ, & fieri ſecundum lineam rectam qua vis illa imprimitur.

Si vis aliqua motum quemvis generet, dupla duplum, tripla triplum generabit, ſive ſimul & ſemel, ſive gradatim & ſucceſſive impreſſa fuerit. Et hic motus quoniam in eandem ſemper plagam cum vi generatrice determinatur, ſi corpus antea movebatur, motui ejus vel conſpiranti additur, vel contrario ſubducitur, vel oblique oblique adjicitur, & cum eo ſecundum utriuſq; determinationem componitur.

Lex. III.

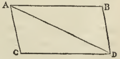
Lex. III.

Actioni contrariam ſemper & æqualem eſſe reactionem: ſive corporum duorum actiones in ſe mutuo ſemper eſſe æquales & in partes contrarias dirigi.

Quicquid premit vel trahit alterum, tantundem ab eo premitur vel trahitur. Siquis lapidem digito premit, premitur & hujus digitus a lapide. Si equus lapidem funi allegatum trahit, retrahetur etiam & equus æqualiter in lapidem: nam funis utrinq; diſtentus eodem relaxandi ſe conatu urgebit Equum verſus lapidem, ac lapidem verſus equum, tantumq; impediet progreſſum unius quantum promovet progreſſum alterius. Si corpus aliquod in corpus aliud impingens, motum ejus vi ſua quomodocunq; mutaverit, idem quoque viciſſim in motu proprio eandem mutationem in partem contrariam vi alterius (ob æqualitatem preſſionis mutuæ) ſubibit. His actionibus æquales fiunt mutationes non velocitatum ſed motuum, (ſcilicet in corporibus non aliunde impeditis:) Mutationes enim velocitatum, in contrarias itidem partes factæ, quia motus æqualiter mutantur, ſunt corporibus reciproce proportionales.

Corol. I.

Corpus viribus conjunctis diagonalem parallelogrammi eodem tempore deſcribere, quo latera ſeparatis.



Si corpus dato tempore, vi ſola *M*, ferretur ab *A* ad *B*, & vi ſola *N*, ab *A* ad *C*, compleatur parallelogrammum *ABDC*, & vi utraq; feretur id eodem tempore ab *A* ad *D*. Nam quoniam vis *N* agit ſecundum lineam *AC* ipſi *BD* parallelam, hæc vis nihil mutabit velocitatem accedendi ad lineam illam *BD* a vi altera genitam. Accedet igitur corpus eodem tempore ad lineam *BD* ſive vis *N* imprimatur, ſive non, atq; adeo in fine illius temporis reperietur alicubi in linea

illa

Book I: Motion of bodies

Book I, Section I: On the method of first and last ratios

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Lemma I: Quantities, and ratios of quantities, which [...] approach nearer to each other than by any given difference, become ultimately equal.

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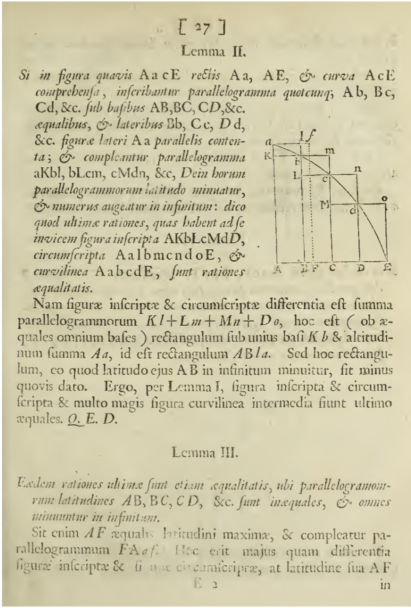
Lemma I: Quantities, and ratios of quantities, which [...] approach nearer to each other than by any given difference, become ultimately equal.

For suppose they are ultimately unequal, and their ultimate difference is D. Then they cannot approach nearer to equality than by that difference.

Book I, Lemma II



Lemma II.

Si in figura quavis AacE *rectis* Aa, AE, *& curva* AcE *comprehenſa, inſcribantur parallelogramma quotcunq;* Ab, Bc, Cd, &c. *ſub baſibus* AB, BC, CD, &c. *æqualibus, & lateribus* Bb, Cc, Dd, &c. *figuræ lateri* Aa *parallelis contenta; & compleantur parallelogramma* aKbl, bLcm, cMdn, &c. *Dein horum parallelogrammorum latitudo minuatur, & numerus augeatur in infinitum: dico quod ultimæ rationes, quas habent ad ſe invicem figura inſcripta* AKbLcMdD, *circumſcripta* AalbmcndoE, *& curvilinea* AabcdE, *ſunt rationes æqualitatis.*

Nam figuræ inſcriptæ & circumſcriptæ differentia eſt ſumma parallelogrammorum $Kl+Lm+Mn+Do$, hoc eſt (ob æquales omnium baſes) rectangulum ſub unius baſi *Kb* & altitudinum ſumma *Aa*, id eſt rectangulum *ABla*. Sed hoc rectangulum, eo quod latitudo ejus AB in infinitum minuitur, fit minus quovis dato. Ergo, per Lemma I, figura inſcripta & circumſcripta & multo magis figura curvilinea intermedia fiunt ultimo æquales. *Q. E. D.*

Lemma III.

Eædem rationes ultimæ ſunt etiam æqualitatis, ubi parallelogrammorum latitudines AB, BC, CD, *&c. ſunt inæquales, & omnes minuuntur in infinitum.*

Sit enim *AF* æqualis latitudini maximæ, & compleatur parallelogrammum *FAaf*. Hoc erit majus quam differentia figuræ inſcriptæ & ſi [illegible] circumſcriptæ, at latitudine ſua AF

Lemma II: Ultimate equality of inscribed figure, circumscribed figure, and curved area

Motion under centripetal forces

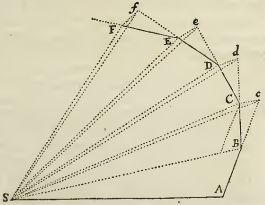
SECT. II.

De Inventione Virium Centripetarum.

Prop. I. Theorema. I.

Areas quas corpora in gyros acta radiis ad immobile centrum virium ductis deſcribunt, & in planis immobilibus conſiſtere, & eſſe temporibus proportionales.

Dividatur tempus in partes æquales, & prima temporis parte deſcribat corpus vi inſita rectam *AB*. Idem ſecunda temporis parte, ſi nil impediret, recta pergeret ad *c*, (per Leg. I) deſcribens lineam *Bc* æqualem ipſi *A*B, adeo ut radiis *AS*, B*S*, *cS* ad centrum actis, confectæ forent æquales areæ *A* *S*B, B*Sc*. Verum ubi corpus venit ad B, agat vis centripeta impulſu unico ſed magno, faciatq; corpus a recta B*c* deflectere & pergere in recta B*C*. Ipſi B*S* parallela agatur *cC* occurrens B*C* in



C, & completa ſecunda temporis parte, corpus (per Legum Corol. 1) reperietur in *C*, in eodem plano cum triangulo A*SB*. Junge *SC*, & triangulum *SBC*, ob parallelas *SB*, *Cc*, æquale erit triangulo *SBc*, atq; adeo etiam triangulo *SAB*. Simili argumento ſi

vis

Book I, Section II: Motion under centripetal forces.

Motion under centripetal forces

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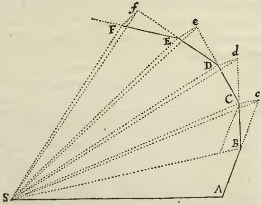
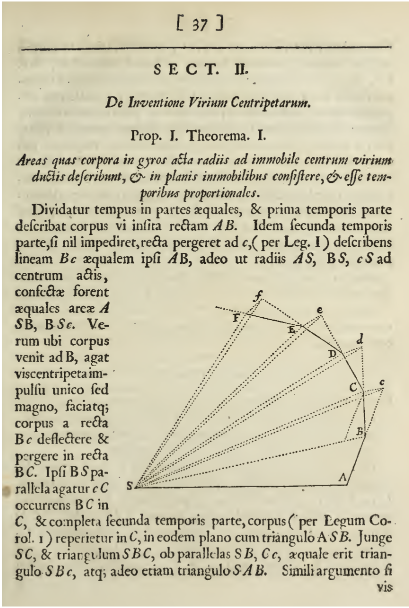


Book I, Section II: Motion under centripetal forces.

Proposition I: Bodies constrained by a central force to orbit a fixed point move in a plane and sweep out equal areas in equal times.

Motion under centripetal forces



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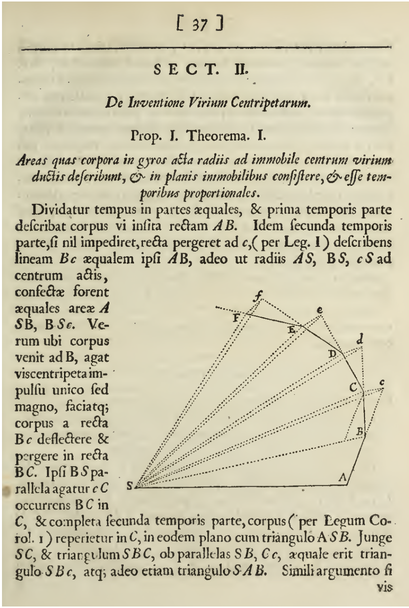
Book I, Section II: Motion under centripetal forces.

Proposition I: Bodies constrained by a central force to orbit a fixed point move in a plane and sweep out equal areas in equal times.

(Kepler's second law)

Motion under centripetal forces



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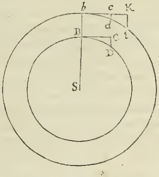
NB. independent of the 'law of force' involved.

Book I, Section II: Circular motion

Prop. IV. Theor. IV.

Corporum quæ diverſos circulos æquabili motu deſcribunt, vires centripetas ad centra eorundem circulorum tendere, & eſſe inter ſe ut arcuum ſimul deſcriptorum quadrata applicata ad circulorum radios.

Corpora *B*, *b* in circumferentiis circulorum *BD*, *bd* gyrantia, ſimul deſcribant arcus *BD*, *bd*. Quoniam ſola vi inſita deſcriberent tangentes *BC*, *bc* his arcubus æquales, manifeſtum eſt quod vires centripetæ ſunt quæ perpetuo retrahunt corpora de tangentibus ad circumferentias circulorum, atq; adeo hæ ſunt ad invicem in ratione prima ſpatiorum naſcentium *CD*, *cd*: tendunt vero ad centra circulorum per Theor. II, propterea quod areæ radiis deſcriptæ ponuntur temporibus proportionales. Fiat figura *tkb* figuræ *DCB* ſimilis, & per Lemma V, lineola *CD* erit ad lineolam *kt* ut arcus B*D* ad arcum *bt*: nec non, per Lemma XI, lineola naſcens *tk* ad lineolam naſcentem *dc* ut *bt quad.* ad *bd quad.* & ex æquo lineola naſcens *DC* ad lineolam naſcentem *dc* ut B*D* × *bt* ad *bd quad.* ſeu quod perinde eſt, ut $\frac{BD \times bt}{Sb}$ ad $\frac{bd\ quad.}{Sb}$, adeoq; (ob æquales rationes $\frac{bt}{Sb}$ & $\frac{BD}{SB}$) ut $\frac{BD\ quad.}{SB}$ ad $\frac{bd\ quad.}{Sb}$. *Q. E. D.*

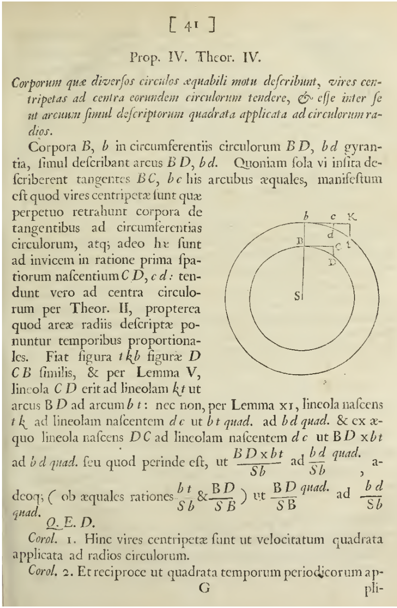


Corol. 1. Hinc vires centripetæ ſunt ut velocitatum quadrata applicata ad radios circulorum.

Corol. 2. Et reciproce ut quadrata temporum periodicorum appli-

Book I, Sect. II, Prop. IV: Motion under centripetal forces: motion in a circle.

Book I, Section II: Circular motion



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Corol. 1. Hinc vires centripetæ ſunt ut velocitatum quadrata applicata ad radios circulorum.

Corol. 2. Et reciproce ut quadrata temporum periodicorum ap-

G pli-

Book I, Sect. II, Prop. IV: Motion under centripetal forces: motion in a circle.

Corollary 1: For motion in a circle centripetal force is proportional to $\frac{v^2}{r}$.

Book I, Section II: Circular motion

[41]

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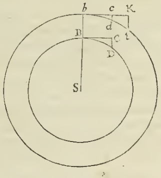
Corpora B, b in circumferentiis circulorum BD, bd gyrantia, ſimul deſcribant arcus BD, bd. Quoniam ſola vi inſita deſcriberent tangentes BC, bc his arcubus æquales, manifeſtum eſt quod vires centripetæ ſunt quæ perpetuo retrahunt corpora de tangentibus ad circumferentias circulorum, atq; adeo hæ ſunt ad invicem in ratione prima ſpatiorum naſcentium CD, cd: tendunt vero ad centra circulorum per Theor. II, propterea quod areæ radiis deſcriptæ ponuntur temporibus proportionales. Fiat figura tkb figuræ DCB ſimilis, & per Lemma V, lineola CD erit ad lineolam kt ut arcus BD ad arcum bt: nec non, per Lemma XI, lineola naſcens tk ad lineolam naſcentem dc ut bt quad. ad bd quad. & ex æquo lineola naſcens DC ad lineolam naſcentem dc ut BD x bt ad bd quad. ſeu quod perinde eſt, ut $\frac{BD \times bt}{Sb}$ ad $\frac{bd\ quad.}{Sb}$, adeoq; (ob æquales rationes $\frac{bt}{Sb}$ & $\frac{BD}{SB}$) ut $\frac{BD\ quad.}{SB}$ ad $\frac{bd\ quad.}{Sb}$. *Q. E. D.*



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Corol. 2. Et reciproce ut quadrata temporum periodicorum ap-

G pli-

Book I, Sect. II, Prop. IV: Motion under centripetal forces: motion in a circle.

Corollary 1: For motion in a circle centripetal force is proportional to $\frac{v^2}{r}$.

Corollary 6: For motion in a circle Kepler's third law implies an inverse square law of force.

Book I, Section III: orbits that are conic sections

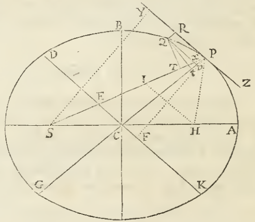
SECT. III.

De motu Corporum in Conicis Sectionibus excentricis.

Prop. XI. Prob. VI.

Revolvatur corpus in Ellipſi: Requiritur lex vis centripetæ tendentis ad umbilicum Ellipſeos.

Eſto Ellipſeos ſuperioris umbilicus S. Agatur *SP* ſecans Ellipſeos tum diametrum *DK* in *E*, tum ordinatim applicatam *Qv* in *x*, & compleatur parallelogrammum *Qx*P*R*. Patet *E*P æqualem eſſe ſemiaxi majori *AC*, eo quod acta ab altero Ellipſeos umbilico H linea *HI* ipſi *EC* parallela, (ob æquales *CS*, *CH*) æquentur *ES*, *EI*, adeo ut *EP* ſemiſumma ſit ipſarum PS, P*I*, id eſt (ob parallelas *HI*, P*R* & angulos æquales *I*P*R*, *H*P*Z*) ipſorum PS, P*H*, quæ conjunctim axem totum 2*AC* adæquant. Ad SP demittatur perpendicularis *QT*, & Ellipſeos latere recto principali (ſeu $\frac{2BC\ quad.}{AC}$) dicto *L*, erit *L*x*QR* ad *L*xP*v* ut *QR* ad P*v*; id eſt ut *PE* (ſeu *AC*) ad *PC*: & *L*xP*v* ad *GvP* ut *L* ad *Gv*;



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Proposition XI: Motion under centripetal forces: Kepler's First Law (orbit is an ellipse with sun at focus) implies an inverse square law of force.

Book I, Section III: orbits that are conic sections

[50]

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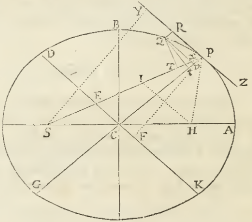


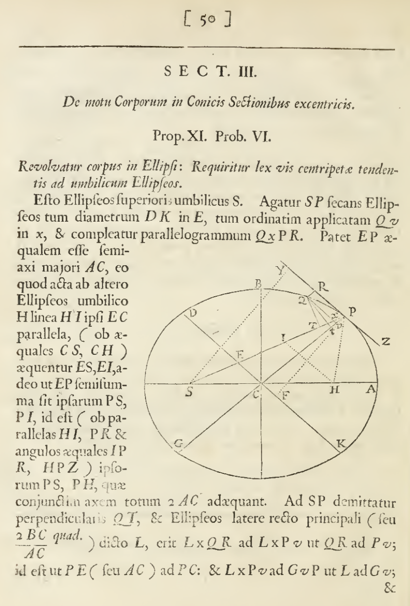
conjunctim axem totum 2*AC* adæquant. Ad SP demittatur perpendicularis *QT*, & Ellipseos latere recto principali (seu $\frac{2BC \text{ quad.}}{AC}$) dicto *L*, erit *L*x*QR* ad *L*xP*v* ut *QR* ad P*v*; id est ut *PE* (seu *AC*) ad *PC*: & *L*xP*v* ad *Gv*P ut *L* ad *Gv*;

&

Proposition XI: Motion under centripetal forces: Kepler's First Law (orbit is an ellipse with sun at focus) implies an inverse square law of force.

Proposition XII: Motion under centripetal forces: hyperbolic orbit implies an inverse square law of force.

Book I, Section III: orbits that are conic sections



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SECT. III.

De motu Corporum in Conicis Sectionibus excentricis.

Prop. XI. Prob. VI.

Revolvatur corpus in Ellipſi: Requiritur lex vis centripetæ tendentis ad umbilicum Ellipſeos.

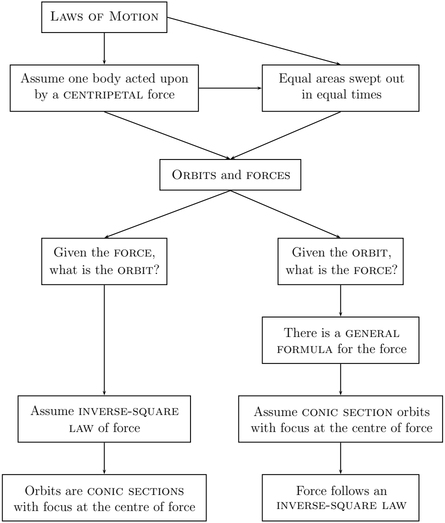
Eſto Ellipſeos ſuperioris umbilicus S. Agatur *SP* ſecans Ellipſeos tum diametrum *DK* in *E*, tum ordinatim applicatam *Qv* in *x*, & compleatur parallelogrammum *Qx*P*R*. Patet *E*P æqualem eſſe ſemiaxi majori *AC*, eo quod acta ab altero Ellipſeos umbilico H linea *HI* ipſi *EC* parallela, (ob æquales *CS*, *CH*) æquentur *ES*, *EI*, adeo ut *EP* ſemiſumma ſit ipſarum PS, P*I*, id eſt (ob parallelas *HI*, P*R* & angulos æquales *I*P*R*, *H*P*Z*) ipſorum PS, P*H*, quæ conjunctim axem totum 2*AC* adæquant. Ad SP demittatur perpendicularis *QT*, & Ellipſeos latere recto principali (ſeu $\frac{2BC\ quad.}{AC}$) dicto *L*, erit *L*x*QR* ad *L*xP*v* ut *QR* ad P*v*; id eſt ut *PE* (ſeu *AC*) ad *PC*: & *L*xP*v* ad *Gv*P ut *L* ad *Gv*; &

Proposition XI: Motion under centripetal forces: Kepler's First Law (orbit is an ellipse with sun at focus) implies an inverse square law of force.

Proposition XII: Motion under centripetal forces: hyperbolic orbit implies an inverse square law of force.

Proposition XIII: Motion under centripetal forces: parabolic orbit implies an inverse square law of force.

Book I, Sections II and III summarised



(Adapted from Colin Pask, *Magnificent Principia*, Prometheus Books, 2013, p. 218)

Book I, later sections

More mechanics of motion:

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- converses: an inverse square law of force implies that orbits are conic sections;

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All treated geometrically

Books II and III

Book II: Motion of bodies in resisting media:

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Book III: The system of the world:

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Book II: Motion of bodies in resisting media:

Conclusion: "… it is manifest that the planets are not carried round in corporeal vortices …" (Scholium to Proposition LIII)

Book III: The system of the world:

- Reconciliation of observation and theory
- Shape of the earth (correct?)
- Motion of the moon (wrong)
- Prediction of tides
- Comets

Influence of the *Principia*

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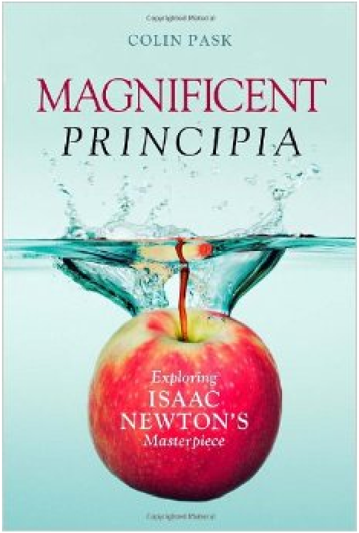
Predictions could be verified by observation and experiment — verified (after some controversy) in the case of the shape of the earth, contradicted in the case of the motion of the moon.

For more on the *Principia*...



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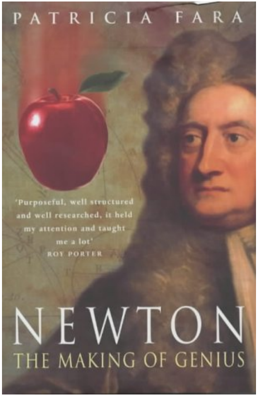
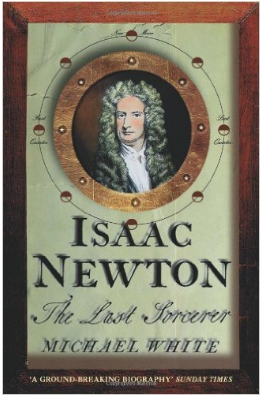
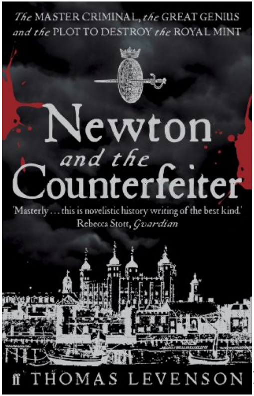
Three (very different) books among many...







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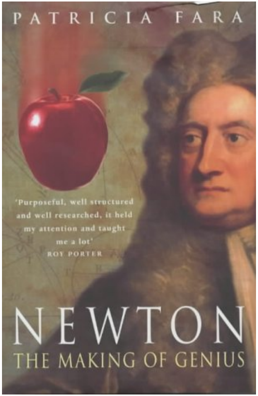

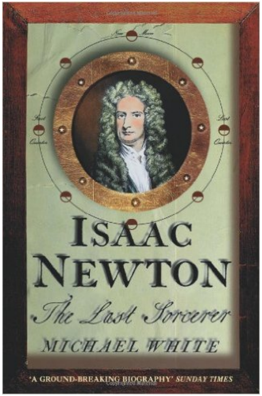

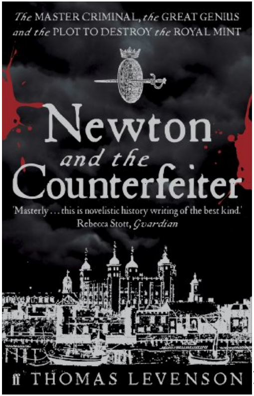

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And a lecture given at Gresham College:
www.gresham.ac.uk/lectures-and-events/isaac-newtons-world

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