Lecture 7
Wed. 9.12.2018

Kepler Geometry of IHO (Isotropic Harmonic Oscillator) Elliptical Orbits

(Ch. 9 and Ch. 11 of Unit 1)

Constructing 2D IHO orbital phasor "clock" dynamics in uniform-body

Constructing 2D IHO orbits using Kepler anomaly plots
- *Mean-anomaly and eccentric-anomaly geometry*
- *Calculus and vector geometry of IHO orbits*
- *A confusing introduction to Coriolis-centrifugal force geometry* *(Derived better in Ch. 12)*

Some Kepler's "laws" for all central (isotropic) force F(r) fields
- *Angular momentum invariance of IHO: $F(r)=-k\cdot r$ with $U(r)=k\cdot r^2/2$* *(Derived here)*
- *Angular momentum invariance of Coulomb: $F(r)=-GMm/r^2$ with $U(r)=-GMm\cdot/r$* *(Derived in Unit 5)*
- *Total energy E=KE+PE invariance of IHO: $F(r)=-k\cdot r$* *(Derived here)*
- *Total energy E=KE+PE invariance of Coulomb: $F(r)=-GMm/r^2$* *(Derived in Unit 5)*

Introduction to dual matrix operator contact geometry (based on IHO orbits)
- *Quadratic form ellipse $\mathbf{r}\bullet Q\bullet\mathbf{r}=1$ vs.inverse form ellipse $\mathbf{p}\bullet Q^{-1}\bullet\mathbf{p}=1$*
  - *Duality norm relations ($\mathbf{r}\bullet\mathbf{p}=1$)*
  - *Q-Ellipse tangents $\mathbf{r}'$ normal to dual Q^{-1}-ellipse position $\mathbf{p}$ ($\mathbf{r}'\bullet\mathbf{p}=0=\mathbf{r}\bullet\mathbf{p}'$)*
- *Operator geometric sequences and eigenvectors*
- *Alternative scaling of matrix operator geometry*
  - *Vector calculus of tensor operation*

Q:Where is this headed? A: Lagrangian-Hamiltonian duality

Link ⇒ BoxIt simulation of IHO orbits
Link → IHO orbital time rates of change
Link → IHO Exegesis Plot

A running collection of links to course-relevant sites and articles

2018 CMwBang! site

Class YouTube Channel

You-Tube site displays related videos world-wide

AIP publications

AJP article on superball dynamics

AAPT summer reading

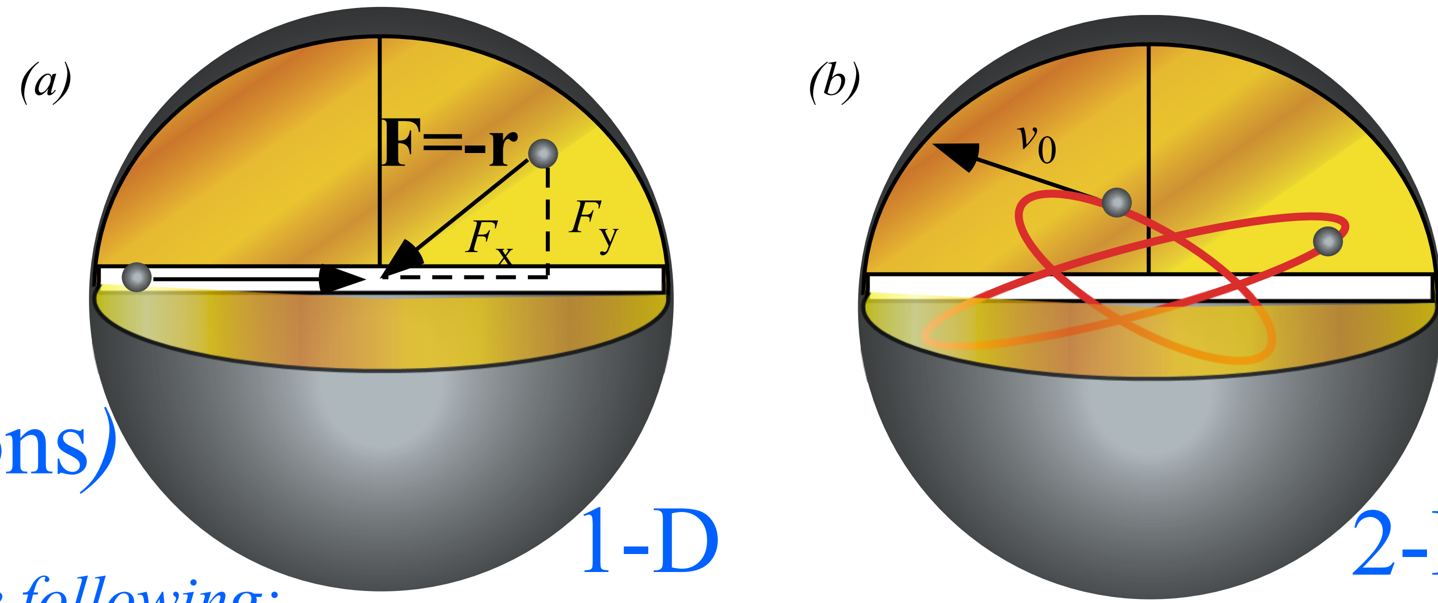
These *are* hot off the presses. Out in MISC for quick reference.
https://modphys.hosted.uark.edu//ETC/MISC/Sorting_ultracold_atoms_in_a_three-dimensional_optical_lattice_in_a_realization_of_Maxwell%e2%80%99s_demon_-_Kumar-n-2018.pdf
https://modphys.hosted.uark.edu//ETC/MISC/Synthetic_three-dimensional_atomic_structures_assembled_atom_by_atom_-_Barredo-n-2018.pdf

Older ones:
https://modphys.hosted.uark.edu//ETC/MISC/Wave–particle_duality_of_C60_molecules_-_arndt-ltn-1999.pdf
https://modphys.hosted.uark.edu//ETC/MISC/Optical_Vortex_Knots_–_One_Photon__At_A_Time_-_Tempone-Wiltshire-Sr-2018.pdf

→ *Introducing 2D IHO orbits and phasor geometry*

Phasor "clock" geometry

Isotropic Harmonic Oscillator phase dynamics in uniform-body



Unit 1
Fig. 9.10

(Paths are *always* 2-D ellipses if viewed right!)

I.H.O. Force law

$F = -x$ (1-Dimension)

$\mathbf{F} = -\mathbf{r}$ (2 or 3-Dimensions)

Each dimension x, y, or z obeys the following:

$$Total\ E = KE + PE = \frac{1}{2}mv^2 + U(x) = \frac{1}{2}mv^2 + \frac{1}{2}kx^2 = const.$$

Isotropic Harmonic Oscillator phase dynamics in uniform-body

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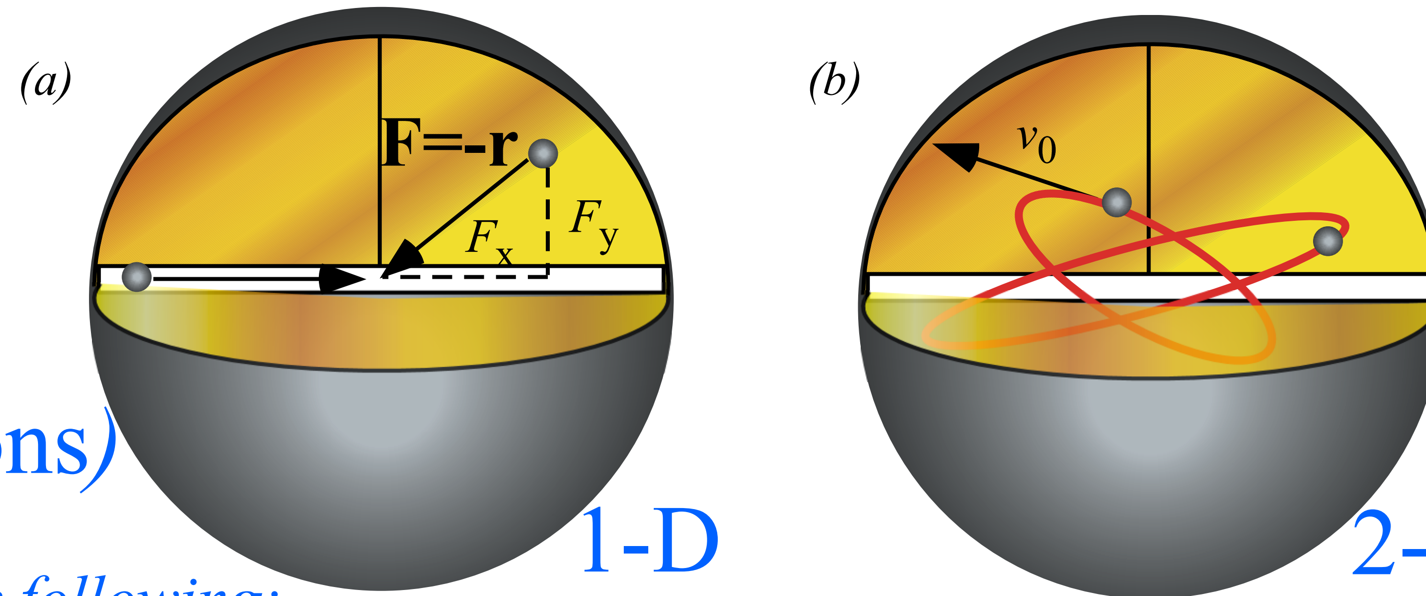

1-D

2-D or 3-D

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Isotropic Harmonic Oscillator phase dynamics in uniform-body

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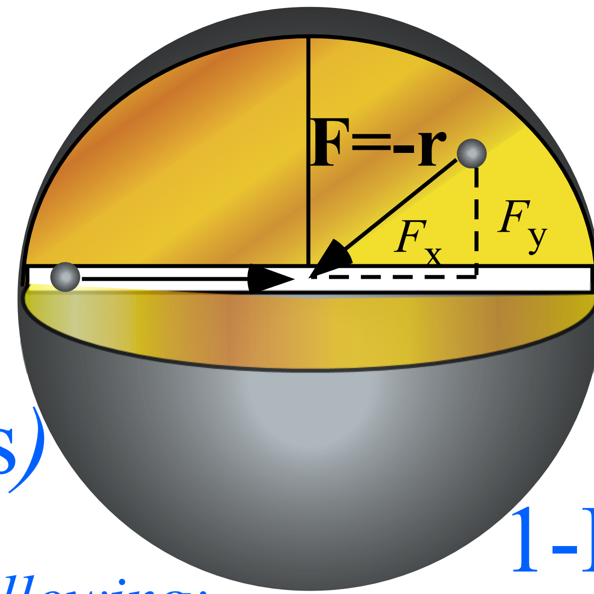

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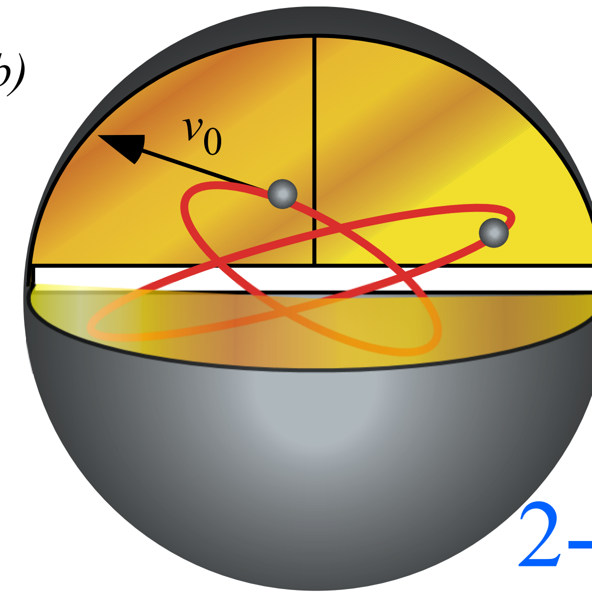

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$$1 = \frac{mv^2}{2E} + \frac{kx^2}{2E} = (\cos\theta)^2 + (\sin\theta)^2$$

Another example of the old "scale-a-circle" trick...

velocity: *position:*

$$Let: \ \mathbf{(1)}\ v = \sqrt{2E/m}\cos\theta, \quad and: \ \mathbf{(2)}\ x = \sqrt{2E/k}\sin\theta$$

Isotropic Harmonic Oscillator phase dynamics in uniform-body

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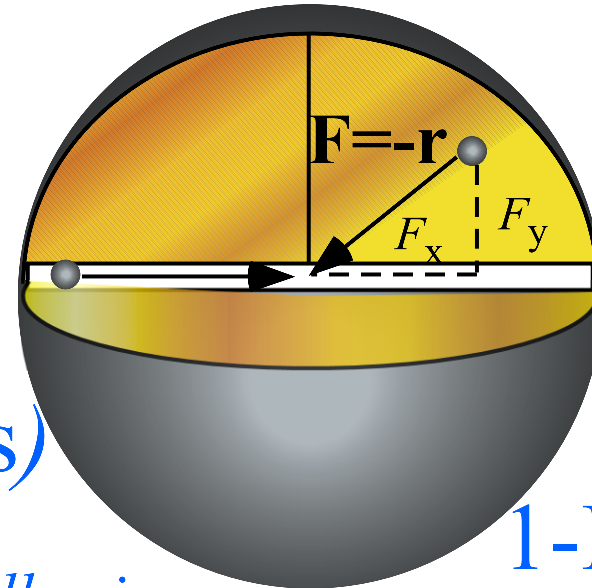
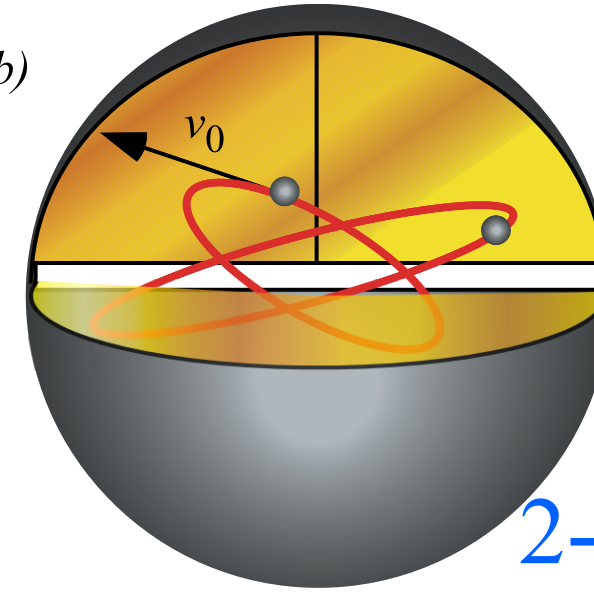


1-D

(b)



Unit 1
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Isotropic Harmonic Oscillator phase dynamics in uniform-body

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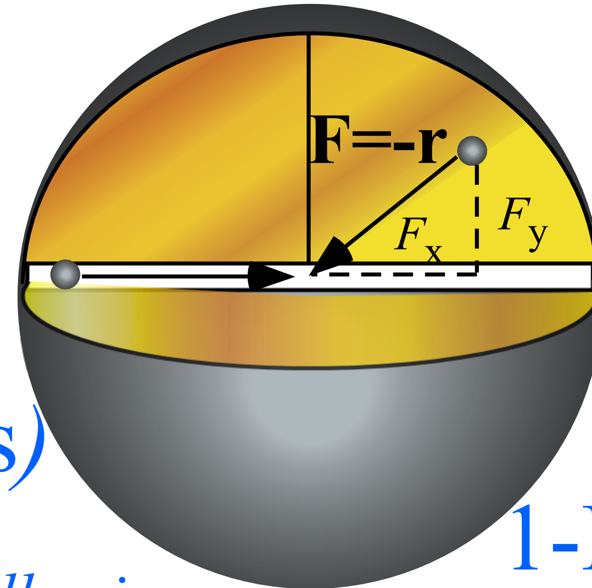

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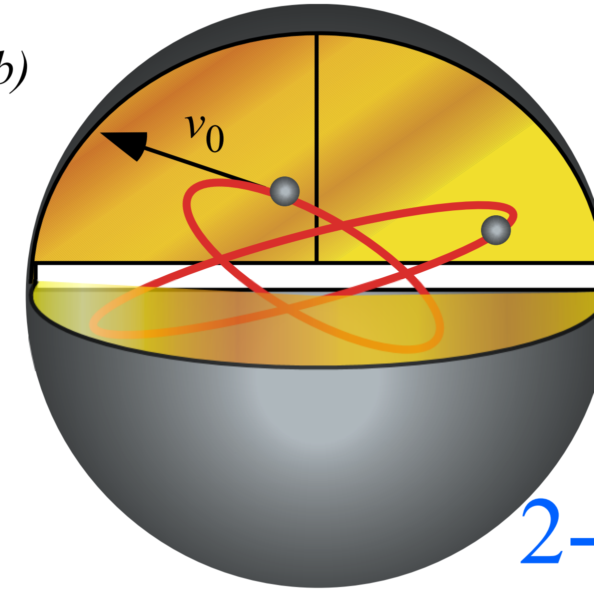

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velocity: Let : **(1)** $v = \sqrt{2E/m}\cos\theta$, and : *position:* **(2)** $x = \sqrt{2E/k}\sin\theta$

angular velocity: def. **(3)** $\omega = \frac{d\theta}{dt}$

$$\sqrt{\frac{2E}{m}}\cos\theta = v = \frac{dx}{dt}$$

by **(1)**

Isotropic Harmonic Oscillator phase dynamics in uniform-body

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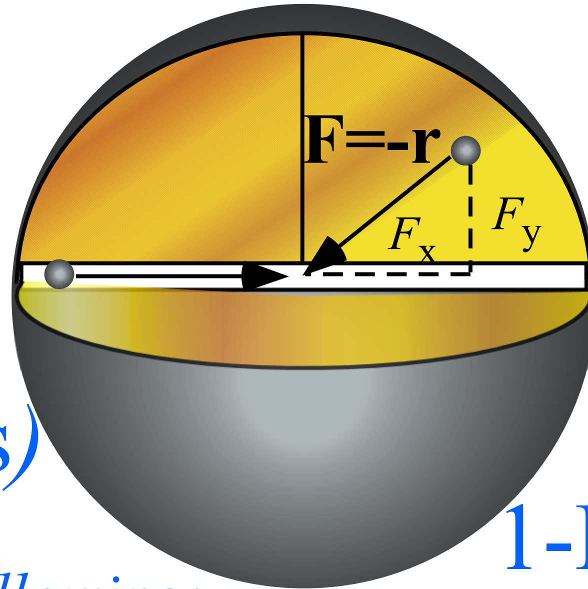

1-D

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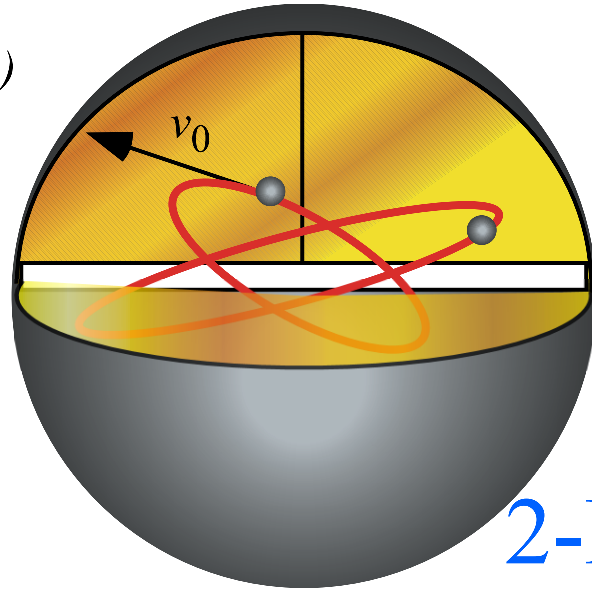

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Another example of the old "scale-a-circle" trick...

Let : (1) $v = \sqrt{2E/m}\cos\theta$ (*velocity:*), and : (2) $x = \sqrt{2E/k}\sin\theta$ (*position:*)

angular velocity: *def.* (3) $\omega = \frac{d\theta}{dt}$

$$\sqrt{\frac{2E}{m}}\cos\theta = v = \frac{dx}{dt} = \frac{d\theta}{dt}\frac{dx}{d\theta}$$

by (1) ... *simple calculus*

Isotropic Harmonic Oscillator phase dynamics in uniform-body

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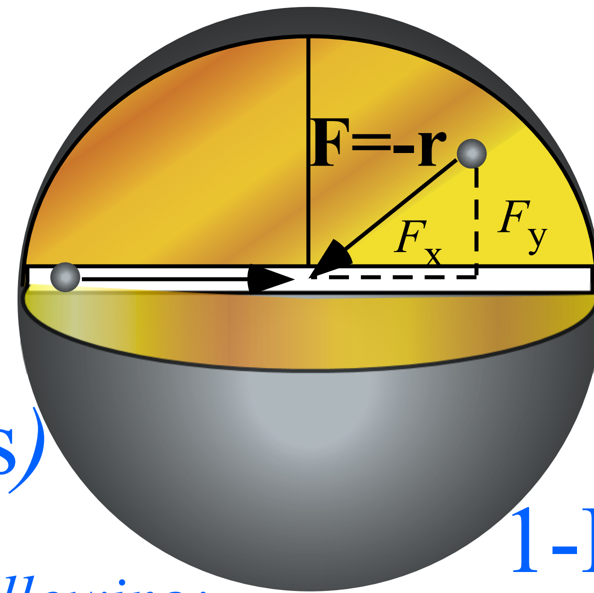

1-D

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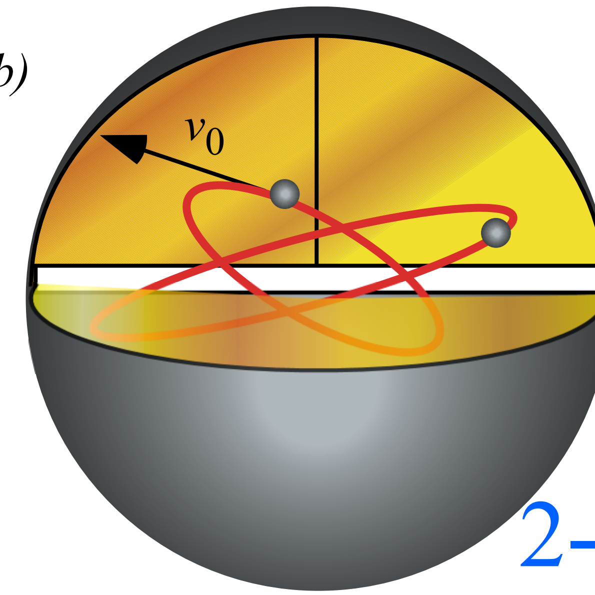

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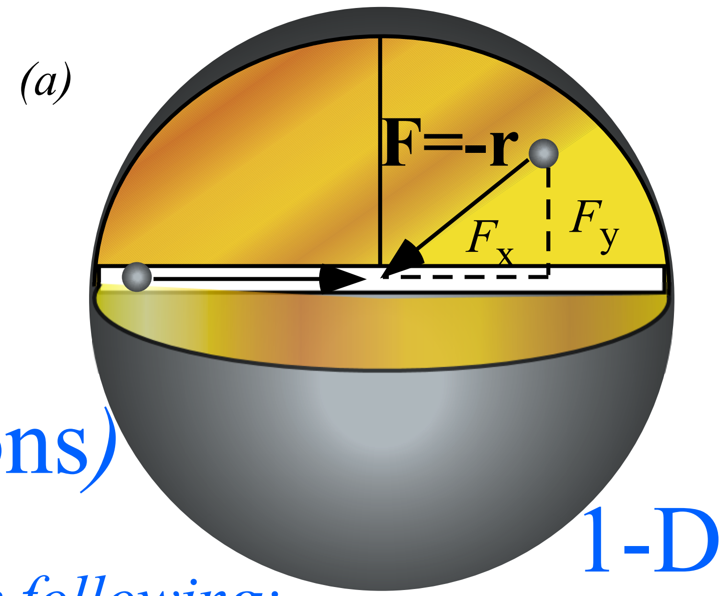
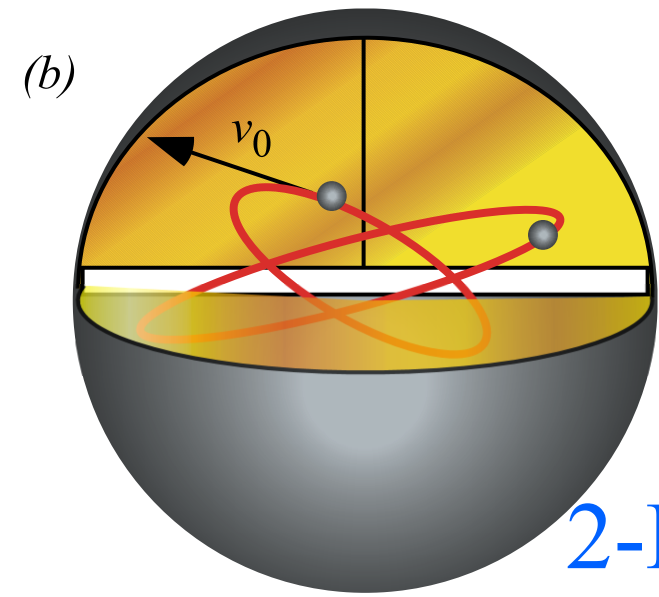
by **(1)** *by def.* **(3)**

Isotropic Harmonic Oscillator phase dynamics in uniform-body





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Unit 1
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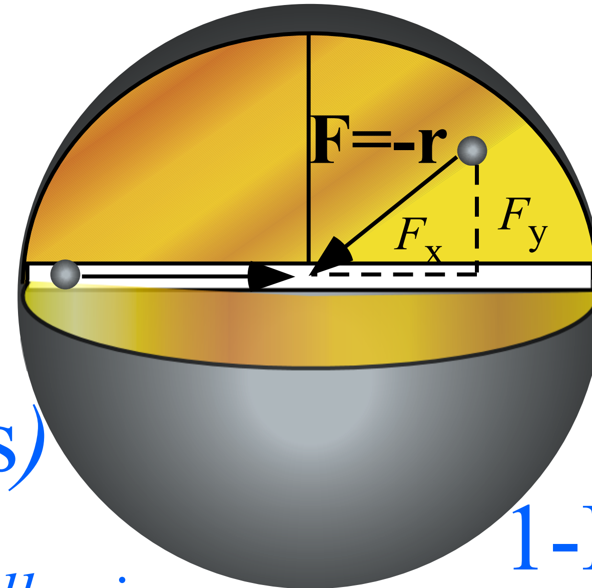
by (1) *by def.* (3) *by* (2)

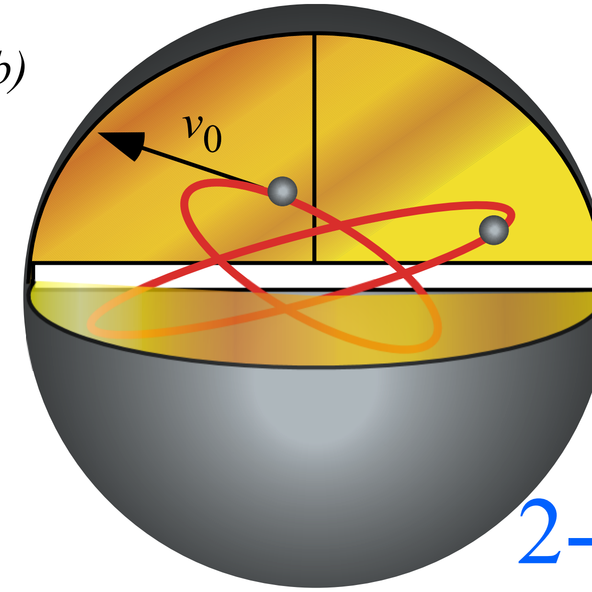
Isotropic Harmonic Oscillator phase dynamics in uniform-body

(a)



1-D

(b)



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by def. **(3)**

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Isotropic Harmonic Oscillator phase dynamics in uniform-body

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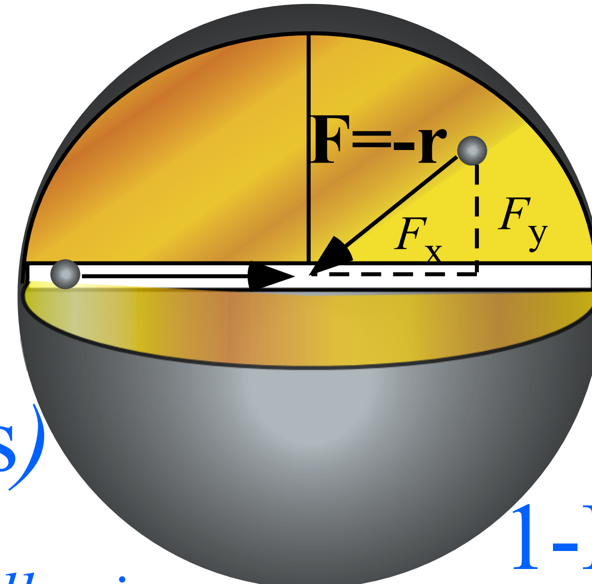

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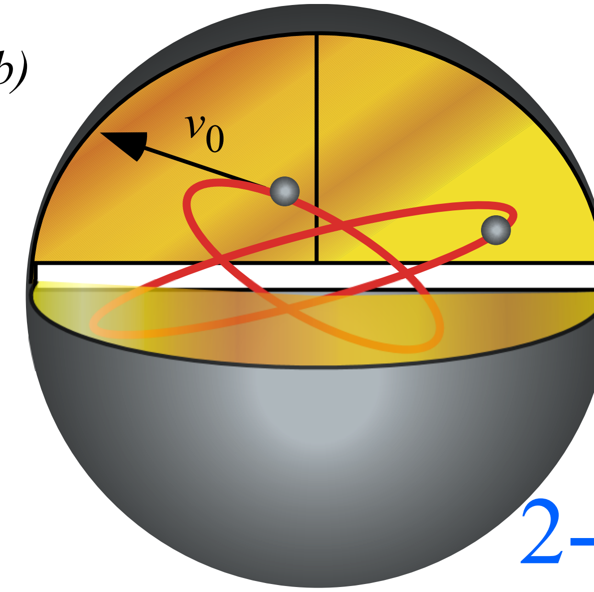

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by **(1)** — *by def.* **(3)** — *by* **(2)**

by def. **(3)**

$$\omega = \frac{d\theta}{dt} = \frac{\sqrt{\frac{2E}{m}}\cos\theta}{\sqrt{\frac{2E}{k}}\cos\theta}$$

divide **(1)** — *by* **(2)** *derivative*

Isotropic Harmonic Oscillator phase dynamics in uniform-body

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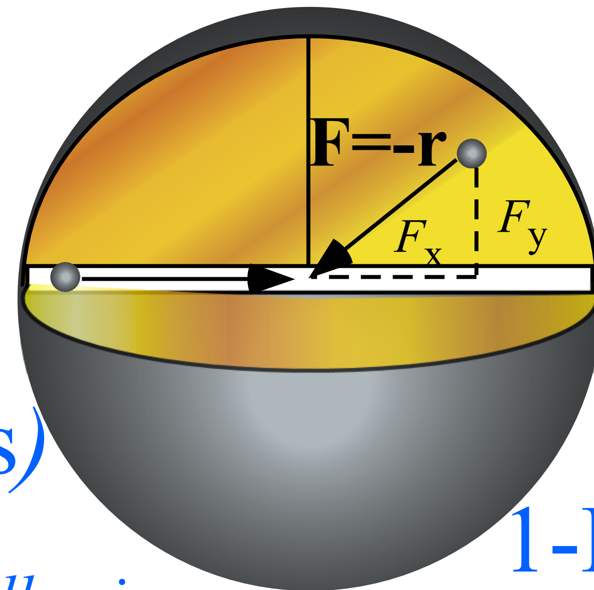

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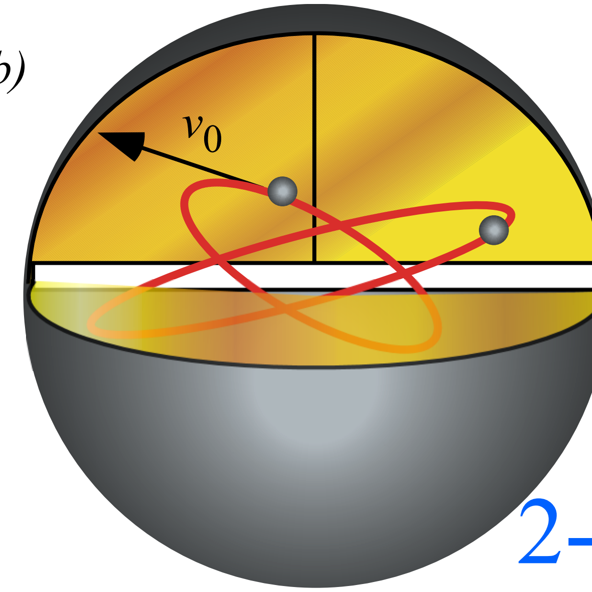

Unit 1
Fig. 9.10

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by **(1)** *by def.* **(3)** *by* **(2)**

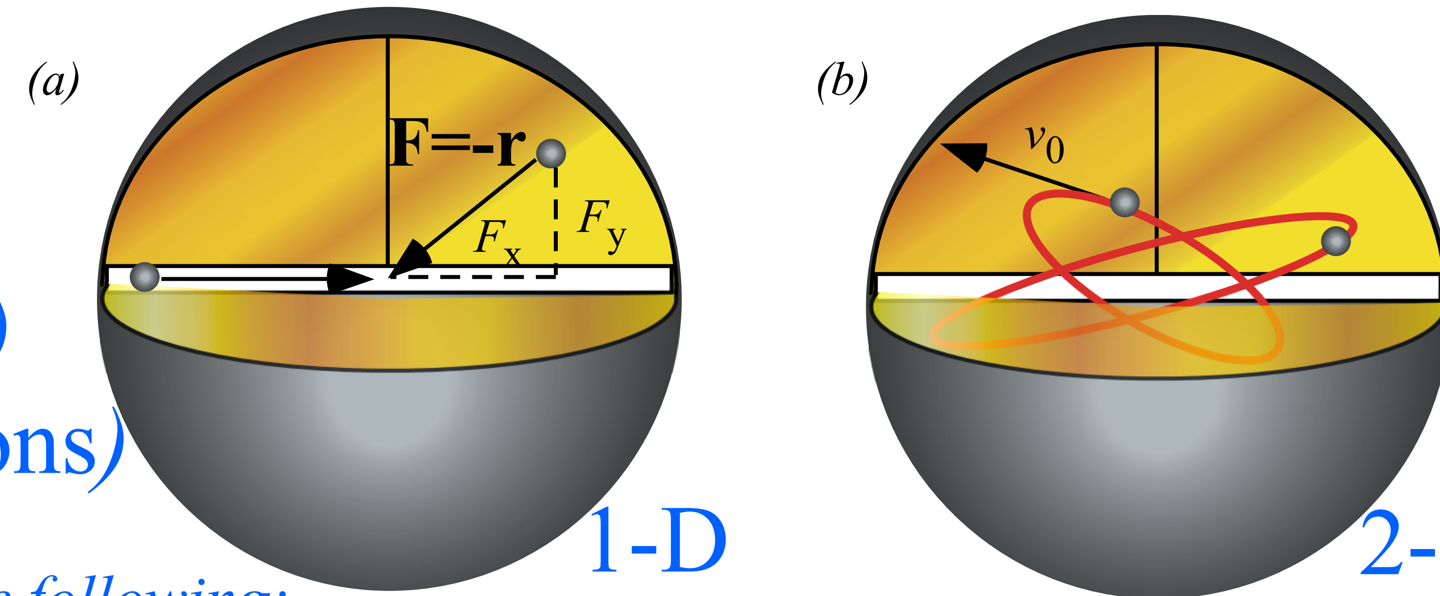
by def. **(3)**

$$\omega = \frac{d\theta}{dt} = \frac{\sqrt{\frac{2E}{m}}\cos\theta}{\sqrt{\frac{2E}{k}}\cos\theta} = \sqrt{\frac{k}{m}}$$

divide **(1)**

by **(2)** *derivative*

Isotropic Harmonic Oscillator phase dynamics in uniform-body



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2-D or 3-D

(Paths are *always* 2-D ellipses if viewed right!)

Each dimension x, y, or z obeys the following:

$$Total\ E = KE + PE = \frac{1}{2}mv^2 + U(x) = \frac{1}{2}mv^2 + \frac{1}{2}kx^2 = const.$$

Equations for x-motion [x(t) and v_x=v(t)] are given first. They apply as well to dimensions [y(t) and v_y=v(t)] and [z(t) and v_z=v(t)] in the ideal isotropic case.

$$1 = \frac{mv^2}{2E} + \frac{kx^2}{2E} = \left(\frac{v}{\sqrt{2E/m}}\right)^2 + \left(\frac{x}{\sqrt{2E/k}}\right)^2$$

$$1 = \frac{mv^2}{2E} + \frac{kx^2}{2E} = (\cos\theta)^2 + (\sin\theta)^2$$

Another example of the old "scale-a-circle" trick...

angular velocity: def. (3) $\omega = \frac{d\theta}{dt}$

$$Let:\ (1)\ v = \sqrt{2E/m}\cos\theta, \quad and:\ (2)\ x = \sqrt{2E/k}\sin\theta$$

$$\sqrt{\frac{2E}{m}}\cos\theta = v = \frac{dx}{dt} = \frac{d\theta}{dt}\frac{dx}{d\theta} = \omega\frac{dx}{d\theta} = \omega\sqrt{\frac{2E}{k}}\cos\theta$$

by (1) — by def. (3) — by (2)

by def. (3)

$$\omega = \frac{d\theta}{dt} = \sqrt{\frac{k}{m}}$$

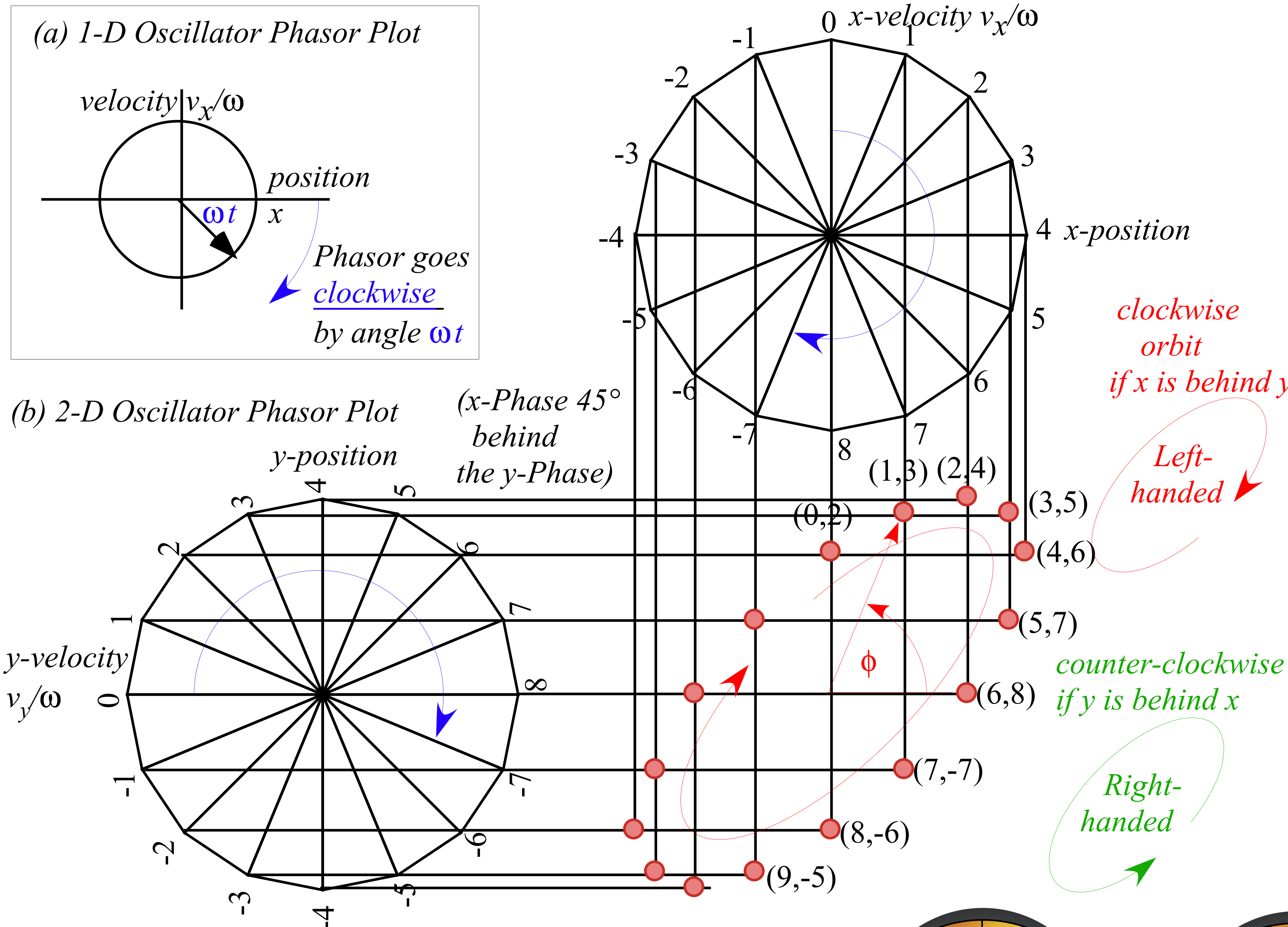
by integration given constant ω:

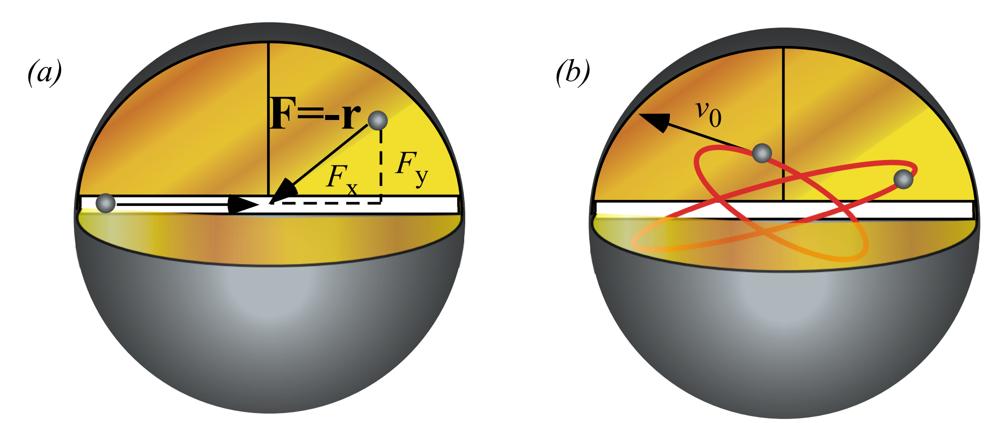
$$\theta = \int \omega \cdot dt = \omega \cdot t + \alpha$$

→ *Review of IHO orbital phasor "clock" dynamics in uniform-body with two "movie" examples*

Review of IHO orbital phase dynamics in uniform-body

Unit 1
Fig. 9.10



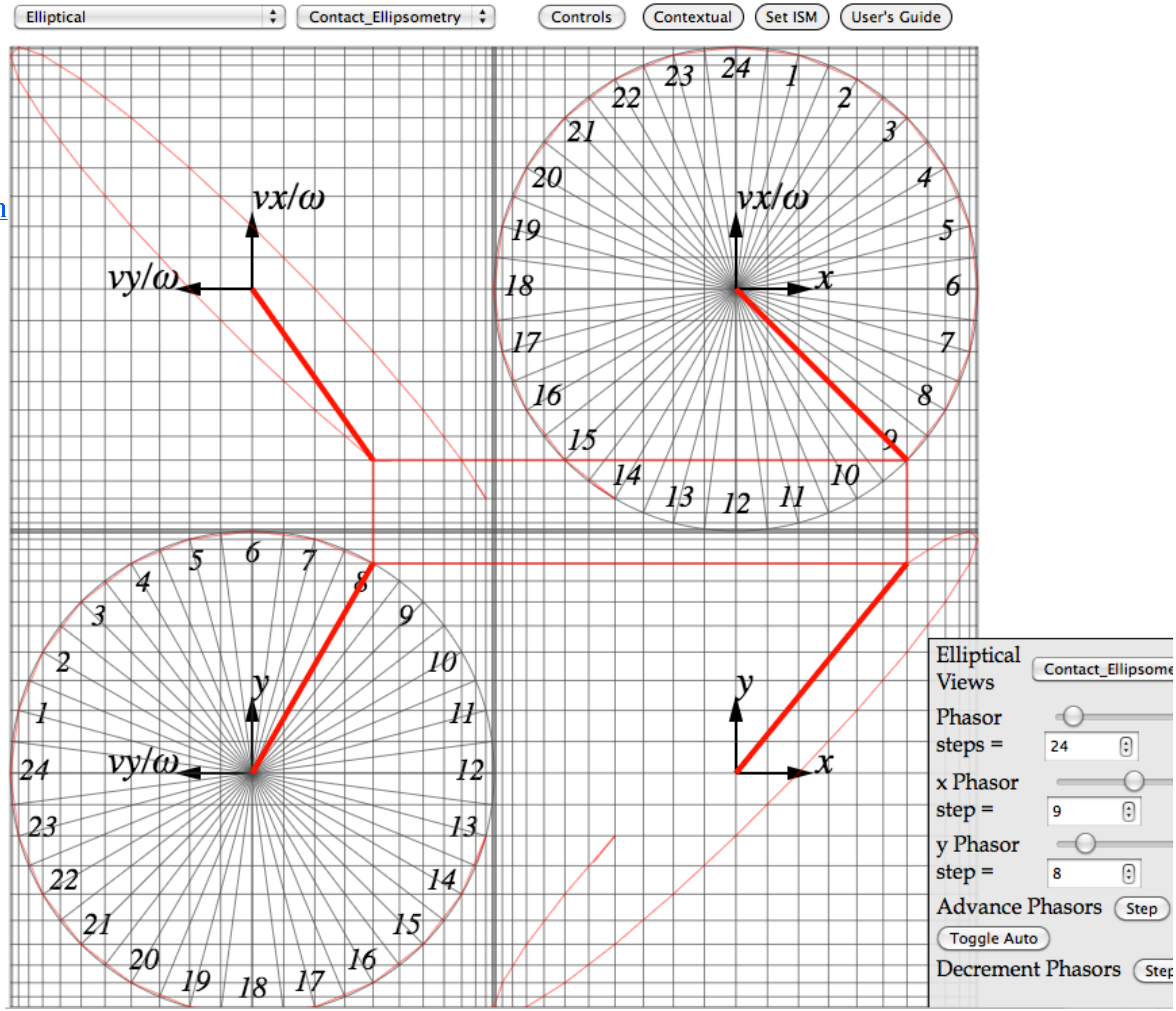


[RelaWavity web simulation - Contact ellipsometry]()

[*Introduction to Phasors at our Pirelli Relativity Site*]()

[BoxIt web simulation - *With y-Phasor is on other side of xy plot*]()

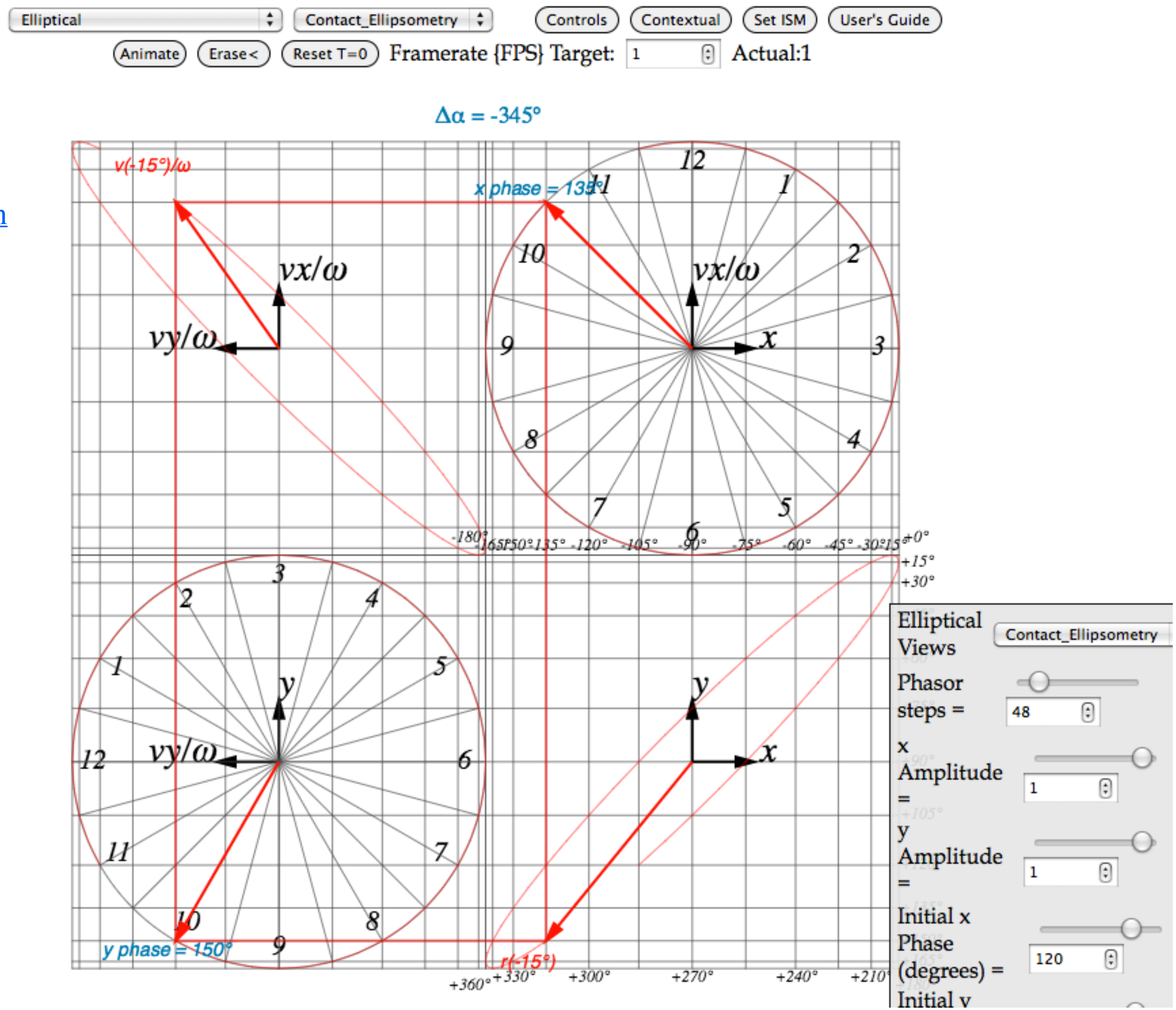
[RelaWavity Web Simulation Ellipsometry]



Geometry of Kepler anomalies for vectors [**r**(*ϕ*), **v**(*ϕ*)] *in coordinate (x,y) space rendered by animation web-apps BoxIt and RelaWavity described below after p.70.*

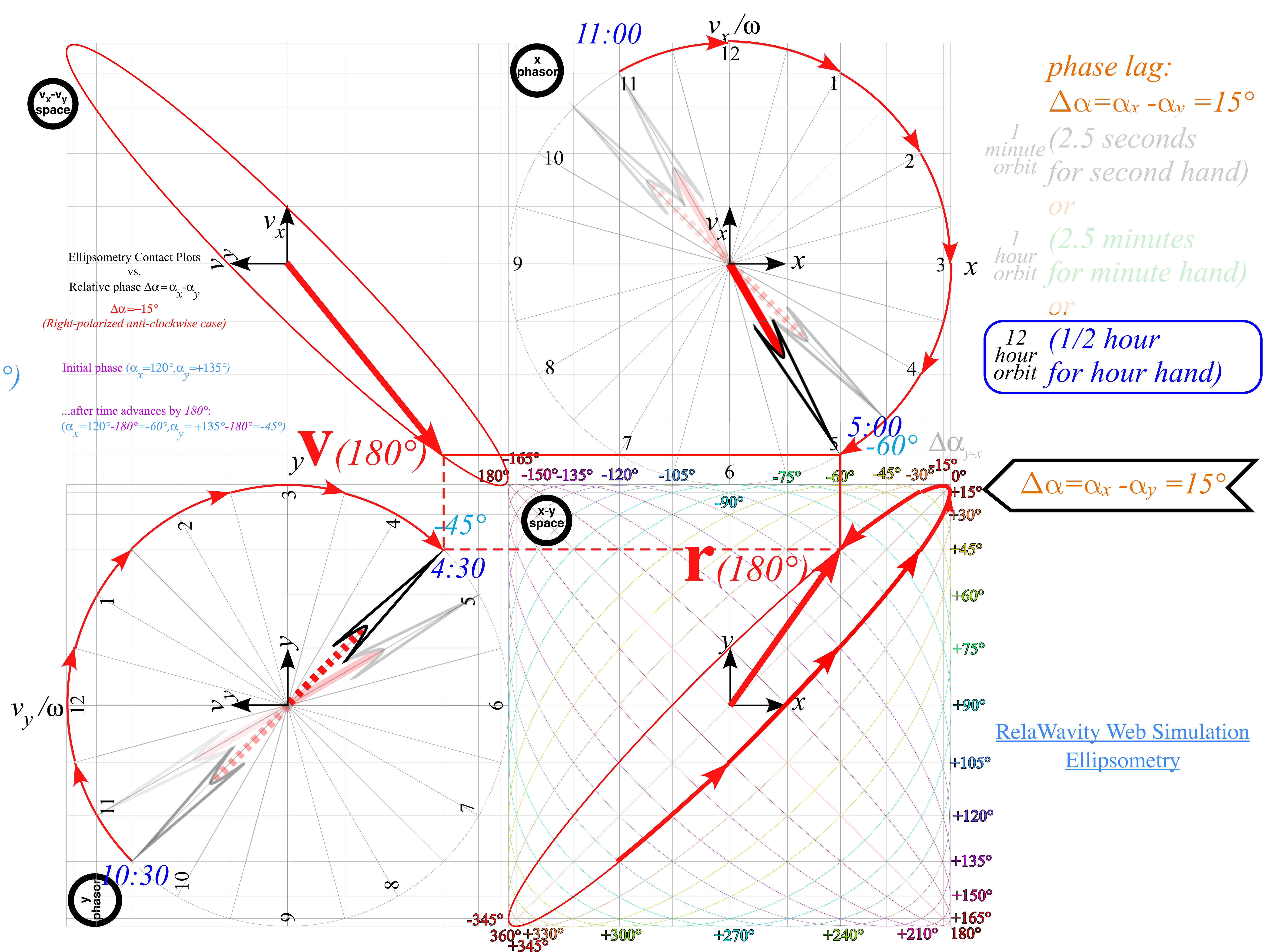
[RelaWavity web simulation - Contact ellipsometry] *(User Mouse Input allowed for setting phasor values)*

RelaWavity Web Simulation
Ellipsometry



Geometry of Kepler anomalies for vectors [**r**(ϕ), **v**(ϕ)] *in coordinate (x,y) space rendered by animation web-apps BoxIt and RelaWavity described below after p.7 and p.17.*

RelaWavity web simulation - Contact ellipsometry *(User Mouse Input allowed for setting phasor values)*

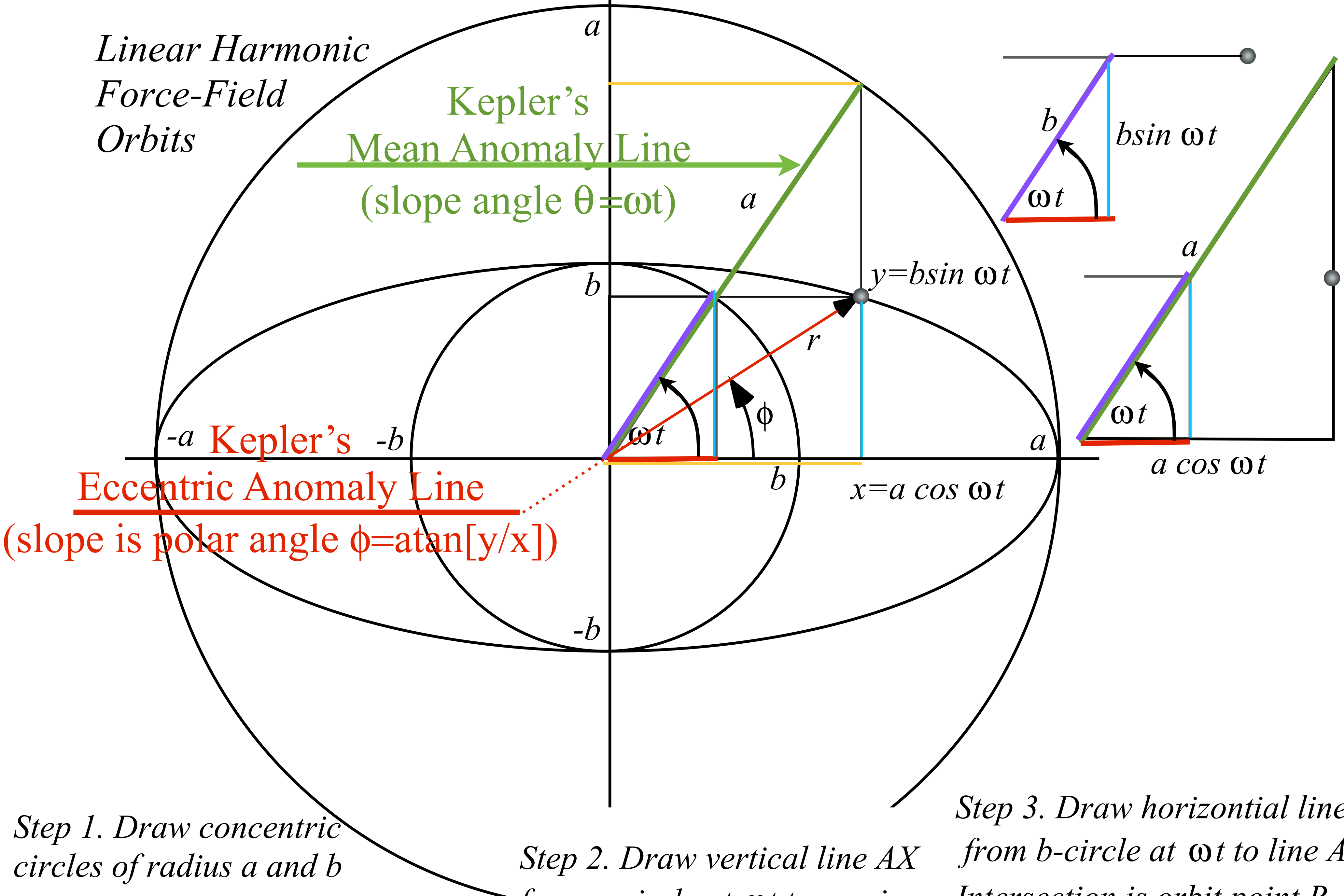

Ellipsometry Contact Plots
vs.
Relative phase Δα=αx-αy
Δα=–15°
(Right-polarized anti-clockwise case)
Initial phase (αx=120°,αy=+135°)
...after time advances by 180°:
(αx=120°-180°=-60°,αy = +135°-180°=-45°)
vx-vy space
x phasor
y phasor
x-y space
11:00
5:00
4:30
10:30
vx/ω
vy/ω
V(180°)
r(180°)
-60°
-45°
Δαy-x
phase lag:
Δα=αx -αy =15°
1 minute orbit (2.5 seconds for second hand)
or
1 hour orbit (2.5 minutes for minute hand)
or
12 hour orbit (1/2 hour for hour hand)
Δα=αx -αy =15°
RelaWavity Web Simulation
Ellipsometry

Constructing 2D IHO orbits using Kepler anomaly plots

→ *Mean-anomaly and eccentric-anomaly geometry*

Calculus and vector geometry of IHO orbits

A confusing introduction to Coriolis-centrifugal force geometry *(Derived better in Ch. 12)*

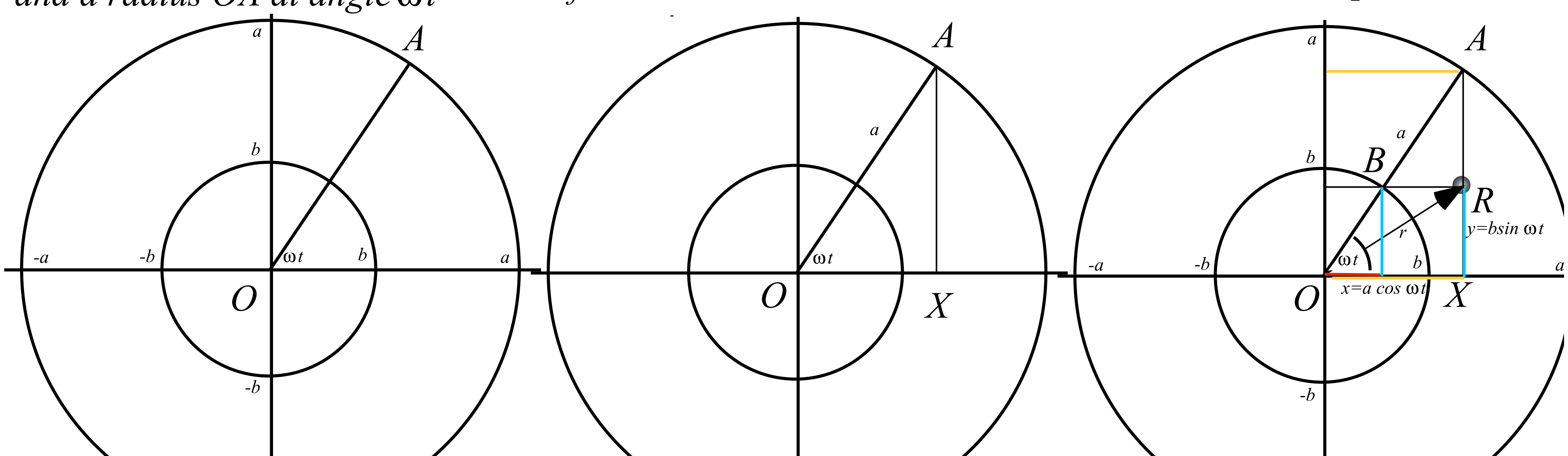


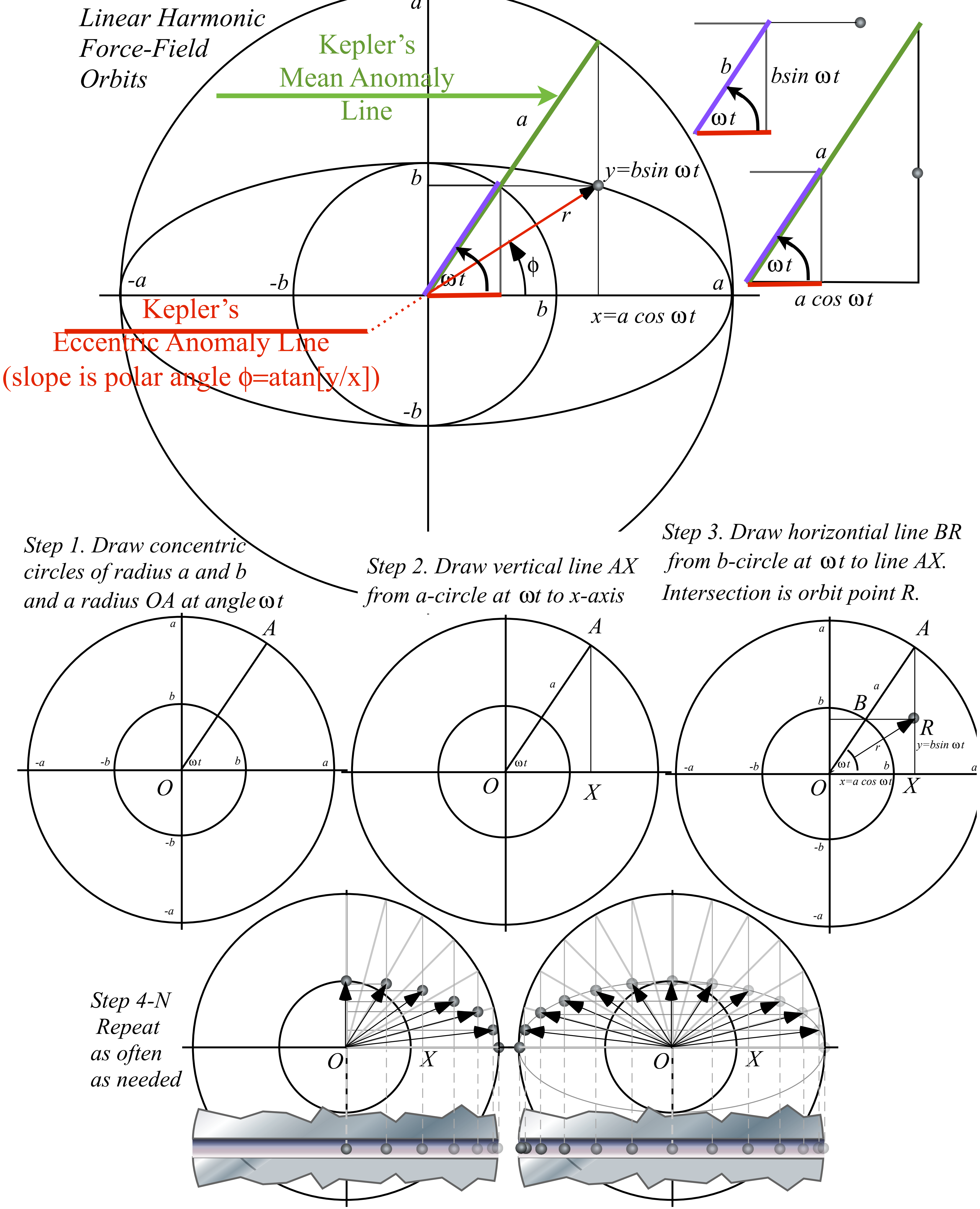
Unit 1
Fig. 11.1
(top 2/3's)

Step 1. Draw concentric circles of radius a and b and a radius OA at angle ωt

Step 2. Draw vertical line AX from a-circle at ωt to x-axis

Step 3. Draw horizontial line BR from b-circle at ωt to line AX. Intersection is orbit point R.





Unit 1
Fig. 11.1

Constructing 2D IHO orbits using Kepler anomaly plots

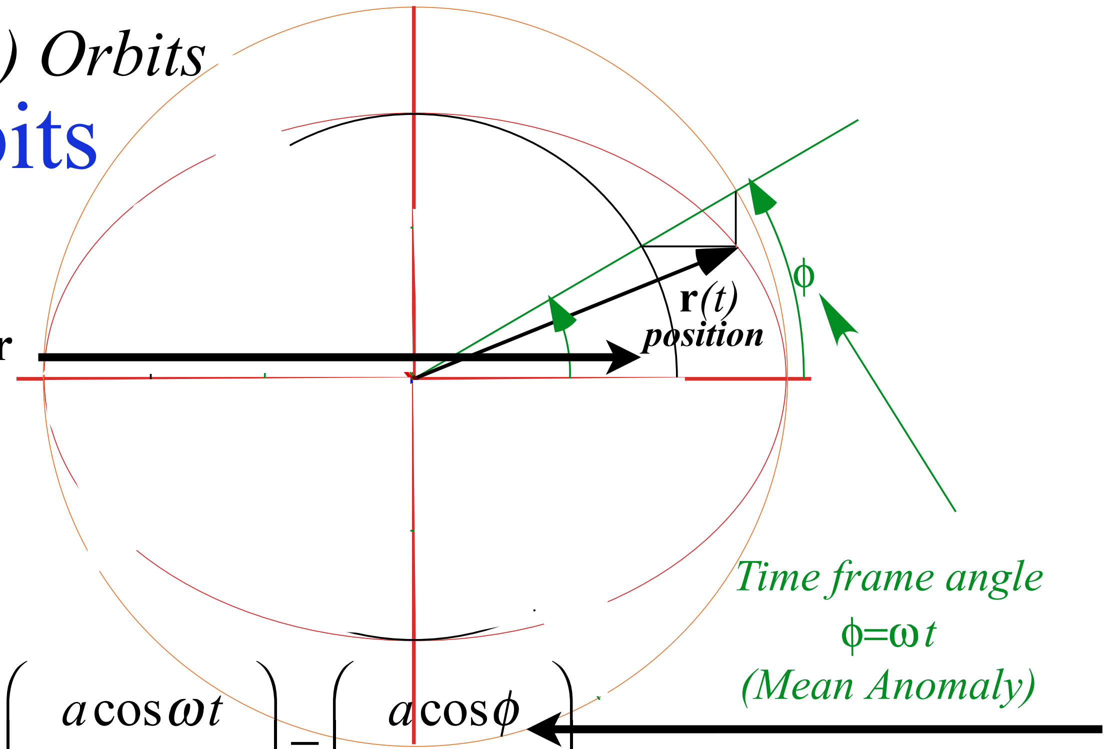
Mean-anomaly and eccentric-anomaly geometry

→ *Calculus and vector geometry of IHO orbits*

A confusing introduction to Coriolis-centrifugal force geometry *(Derived better in Ch. 12)*

Calculus of IHO orbits

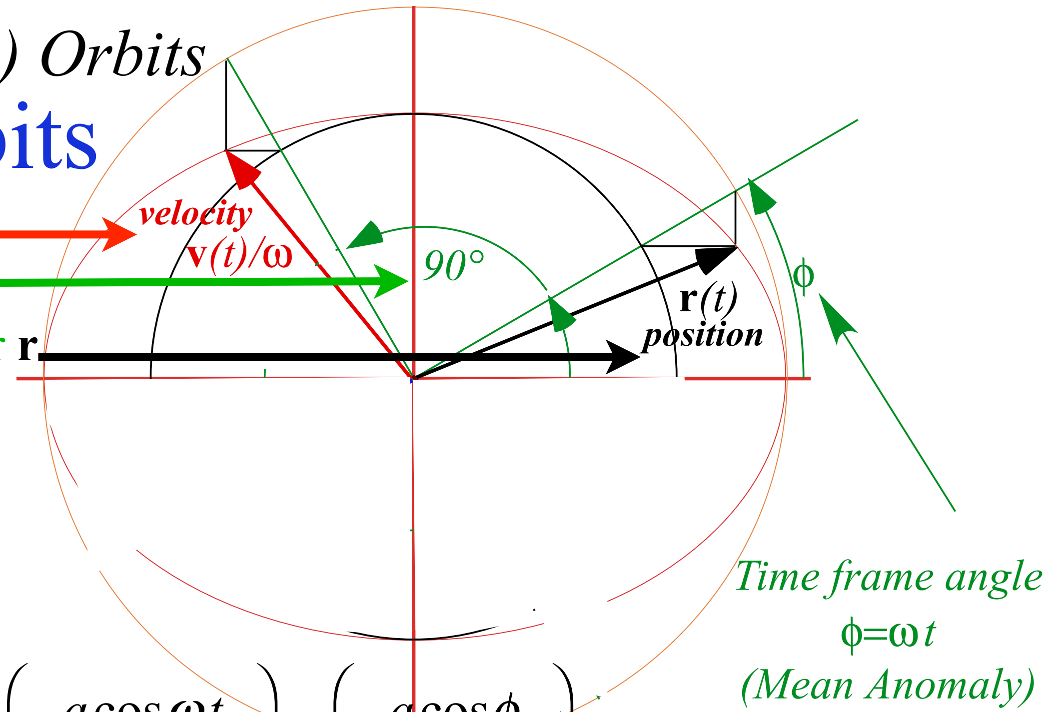
mean-anomaly ϕ of position vector $\mathbf{r}$



$$radius\ vector: \mathbf{r} = \begin{pmatrix} r_x \\ r_y \end{pmatrix} = \begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} a\cos\omega t \\ b\sin\omega t \end{pmatrix} = \begin{pmatrix} a\cos\phi \\ b\sin\phi \end{pmatrix}$$

Unit 1
Fig. 11.5

Calculus of IHO orbits



To make velocity vector **v**
just rotate by π/2 or 90°
the mean-anomaly φ of position vector **r**

$$radius\ vector: \mathbf{r} = \begin{pmatrix} r_x \\ r_y \end{pmatrix} = \begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} a\cos\omega t \\ b\sin\omega t \end{pmatrix} = \begin{pmatrix} a\cos\phi \\ b\sin\phi \end{pmatrix}$$

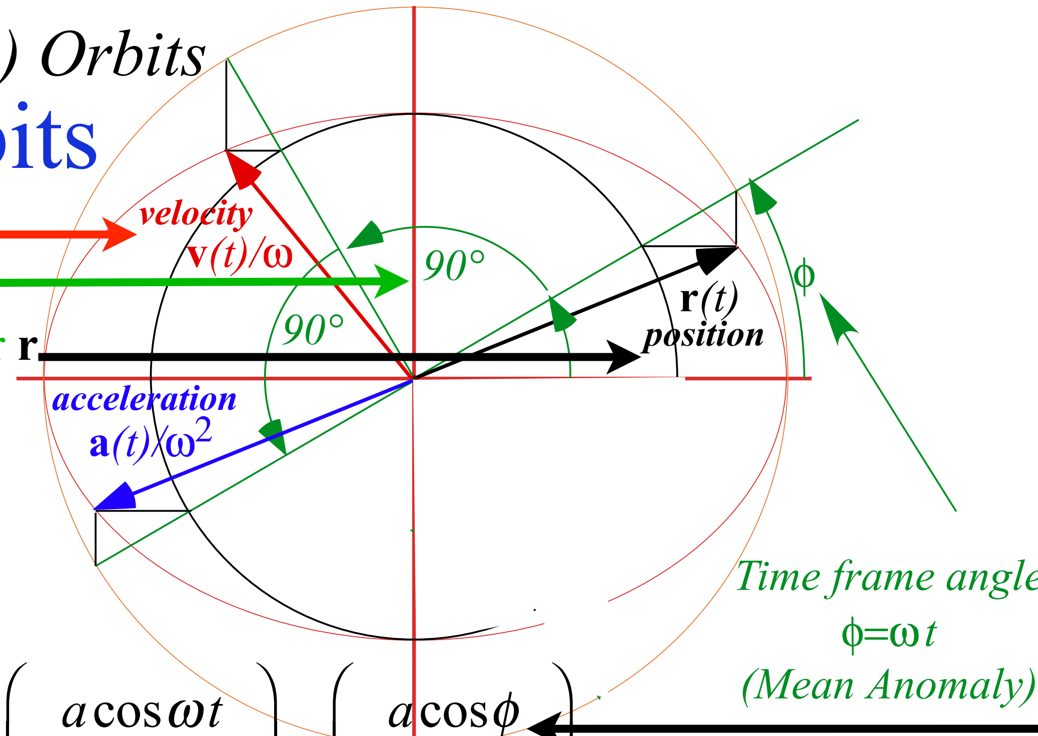
mean-anomaly φ of position vector **r**
rotated by π/2 or 90° is *m.a.* of vector **v**

$$velocity\ vector: \mathbf{v} = \begin{pmatrix} v_x \\ v_y \end{pmatrix} = \begin{pmatrix} -a\omega\sin\omega t \\ b\omega\cos\omega t \end{pmatrix} = \frac{d\mathbf{r}}{dt} = \dot{\mathbf{r}} = \begin{pmatrix} a\cos\left(\phi + \frac{\pi}{2}\right) \\ b\sin\left(\phi + \frac{\pi}{2}\right) \end{pmatrix} (for\ \omega = 1)$$

Unit 1
Fig. 11.5

Calculus of IHO orbits

To make velocity vector **v** just rotate by π/2 or 90° the mean-anomaly φ of position vector **r**



Unit 1
Fig. 11.5

$$\textit{radius vector}: \mathbf{r} = \begin{pmatrix} r_x \\ r_y \end{pmatrix} = \begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} a\cos\omega t \\ b\sin\omega t \end{pmatrix} = \begin{pmatrix} a\cos\phi \\ b\sin\phi \end{pmatrix}$$

mean-anomaly φ of position vector **r** rotated by π/2 or 90° is *m.a.* of vector **v**

$$\textit{velocity vector}: \mathbf{v} = \begin{pmatrix} v_x \\ v_y \end{pmatrix} = \begin{pmatrix} -a\omega\sin\omega t \\ b\omega\cos\omega t \end{pmatrix} = \frac{d\mathbf{r}}{dt} = \dot{\mathbf{r}} = \begin{pmatrix} a\cos\left(\phi + \frac{\pi}{2}\right) \\ b\sin\left(\phi + \frac{\pi}{2}\right) \end{pmatrix} (\textit{for } \omega = 1)$$

m.a. φ+π/2 of vector **v** rotated by another π/2 is *m.a.* of vector **a**

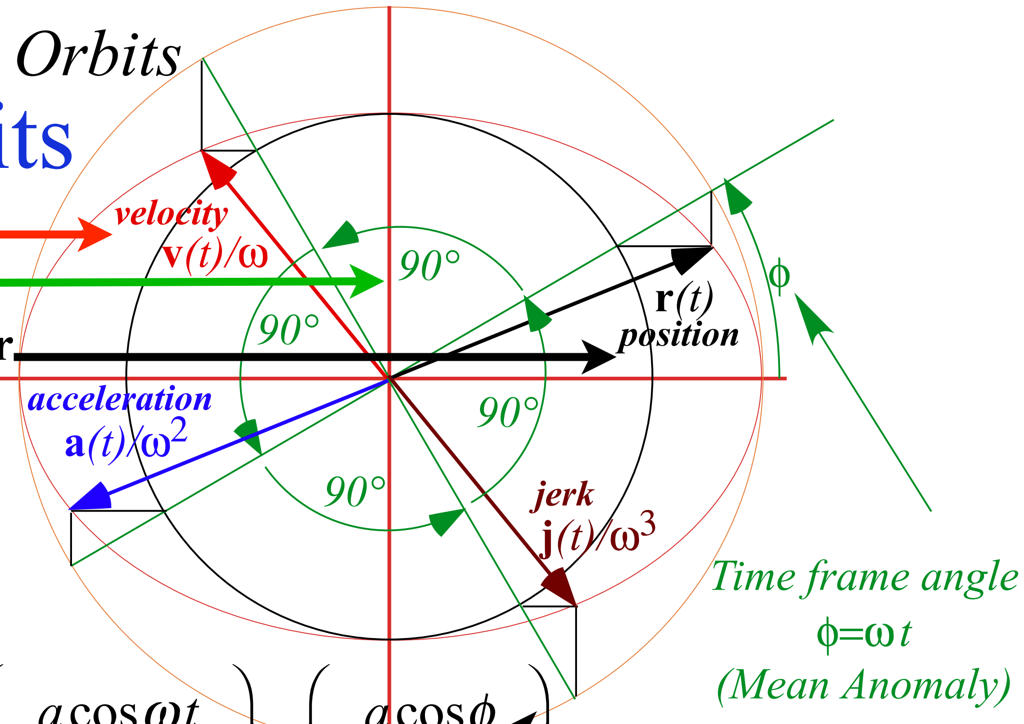
$$\textit{acceleration or force vector}: \frac{\mathbf{F}}{m} = \mathbf{a} = \begin{pmatrix} a_x \\ a_y \end{pmatrix} = \begin{pmatrix} -a\omega^2\cos\omega t \\ -b\omega^2\sin\omega t \end{pmatrix} = \frac{d\mathbf{v}}{dt} = \dot{\mathbf{v}} = \ddot{\mathbf{r}} = \frac{d^2\mathbf{r}}{dt^2} = \begin{pmatrix} a\cos\left(\phi + \frac{2\pi}{2}\right) \\ b\sin\left(\phi + \frac{2\pi}{2}\right) \end{pmatrix}$$

or change of velocity

Calculus of IHO orbits

(a) Orbits

To make velocity vector **v**
just rotate by π/2 or 90°
the mean-anomaly ϕ of position vector **r**



Unit 1
Fig. 11.5

$$\textit{radius vector}: \mathbf{r} = \begin{pmatrix} r_x \\ r_y \end{pmatrix} = \begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} a\cos\omega t \\ b\sin\omega t \end{pmatrix} = \begin{pmatrix} a\cos\phi \\ b\sin\phi \end{pmatrix}$$

mean-anomaly ϕ of position vector **r** rotated by π/2 or 90° is *m.a.* of vector **v**

$$\textit{velocity vector}: \mathbf{v} = \begin{pmatrix} v_x \\ v_y \end{pmatrix} = \begin{pmatrix} -a\omega\sin\omega t \\ b\omega\cos\omega t \end{pmatrix} = \frac{d\mathbf{r}}{dt} = \dot{\mathbf{r}} = \begin{pmatrix} a\cos\left(\phi + \frac{\pi}{2}\right) \\ b\sin\left(\phi + \frac{\pi}{2}\right) \end{pmatrix} (\textit{for } \omega = 1)$$

m.a. ϕ+π/2 of vector **v** rotated by another π/2 is *m.a.* of vector **a**

$$\textit{acceleration or force vector}: \frac{\mathbf{F}}{m} = \mathbf{a} = \begin{pmatrix} a_x \\ a_y \end{pmatrix} = \begin{pmatrix} -a\omega^2\cos\omega t \\ -b\omega^2\sin\omega t \end{pmatrix} = \frac{d\mathbf{v}}{dt} = \dot{\mathbf{v}} = \ddot{\mathbf{r}} = \frac{d^2\mathbf{r}}{dt^2} = \begin{pmatrix} a\cos\left(\phi + \frac{2\pi}{2}\right) \\ b\sin\left(\phi + \frac{2\pi}{2}\right) \end{pmatrix}$$

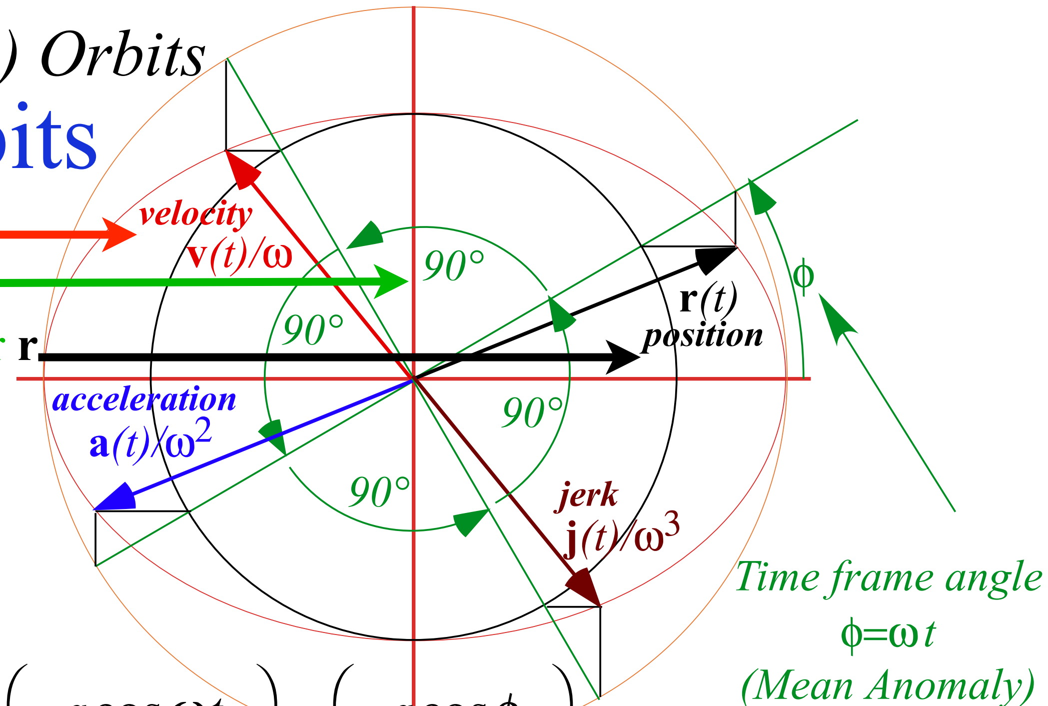
or change of velocity

$$\textit{jerk or change of acceleration}: \mathbf{j} = \begin{pmatrix} j_x \\ j_y \end{pmatrix} = \begin{pmatrix} +a\omega^3\sin\omega t \\ -b\omega^3\cos\omega t \end{pmatrix} = \frac{d\mathbf{a}}{dt} = \dot{\mathbf{a}} = \ddot{\mathbf{v}} = \dddot{\mathbf{r}} = \frac{d^3\mathbf{r}}{dt^3} = \begin{pmatrix} a\cos\left(\phi + \frac{3\pi}{2}\right) \\ b\sin\left(\phi + \frac{3\pi}{2}\right) \end{pmatrix}$$

...and so forth...

Calculus of IHO orbits

(a) Orbits



To make velocity vector **v**
just rotate by π/2 or 90°
the mean-anomaly φ of position vector **r**

Unit 1
Fig. 11.5

$$\textit{radius vector}: \mathbf{r} = \begin{pmatrix} r_x \\ r_y \end{pmatrix} = \begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} a\cos\omega t \\ b\sin\omega t \end{pmatrix} = \begin{pmatrix} a\cos\phi \\ b\sin\phi \end{pmatrix}$$

mean-anomaly φ of position vector **r**
rotated by π/2 or 90° is *m.a.* of vector **v**

$$\textit{velocity vector}: \mathbf{v} = \begin{pmatrix} v_x \\ v_y \end{pmatrix} = \begin{pmatrix} -a\omega\sin\omega t \\ b\omega\cos\omega t \end{pmatrix} = \frac{d\mathbf{r}}{dt} = \dot{\mathbf{r}} = \begin{pmatrix} a\cos\left(\phi + \frac{\pi}{2}\right) \\ b\sin\left(\phi + \frac{\pi}{2}\right) \end{pmatrix} (\textit{for } \omega = 1)$$

m.a. φ+π/2 of vector **v** rotated by
another π/2 is *m.a.* of vector **a**

$$\textit{acceleration or force vector}: \frac{\mathbf{F}}{m} = \mathbf{a} = \begin{pmatrix} a_x \\ a_y \end{pmatrix} = \begin{pmatrix} -a\omega^2\cos\omega t \\ -b\omega^2\sin\omega t \end{pmatrix} = \frac{d\mathbf{v}}{dt} = \dot{\mathbf{v}} = \ddot{\mathbf{r}} = \frac{d^2\mathbf{r}}{dt^2} = \begin{pmatrix} a\cos\left(\phi + \frac{2\pi}{2}\right) \\ b\sin\left(\phi + \frac{2\pi}{2}\right) \end{pmatrix}$$

or change of velocity

$$\textit{jerk or change of acceleration}: \mathbf{j} = \begin{pmatrix} j_x \\ j_y \end{pmatrix} = \begin{pmatrix} +a\omega^3\sin\omega t \\ -b\omega^3\cos\omega t \end{pmatrix} = \frac{d\mathbf{a}}{dt} = \dot{\mathbf{a}} = \ddot{\mathbf{v}} = \dddot{\mathbf{r}} = \frac{d^3\mathbf{r}}{dt^3} = \begin{pmatrix} a\cos\left(\phi + \frac{3\pi}{2}\right) \\ b\sin\left(\phi + \frac{3\pi}{2}\right) \end{pmatrix}$$

...and so forth...

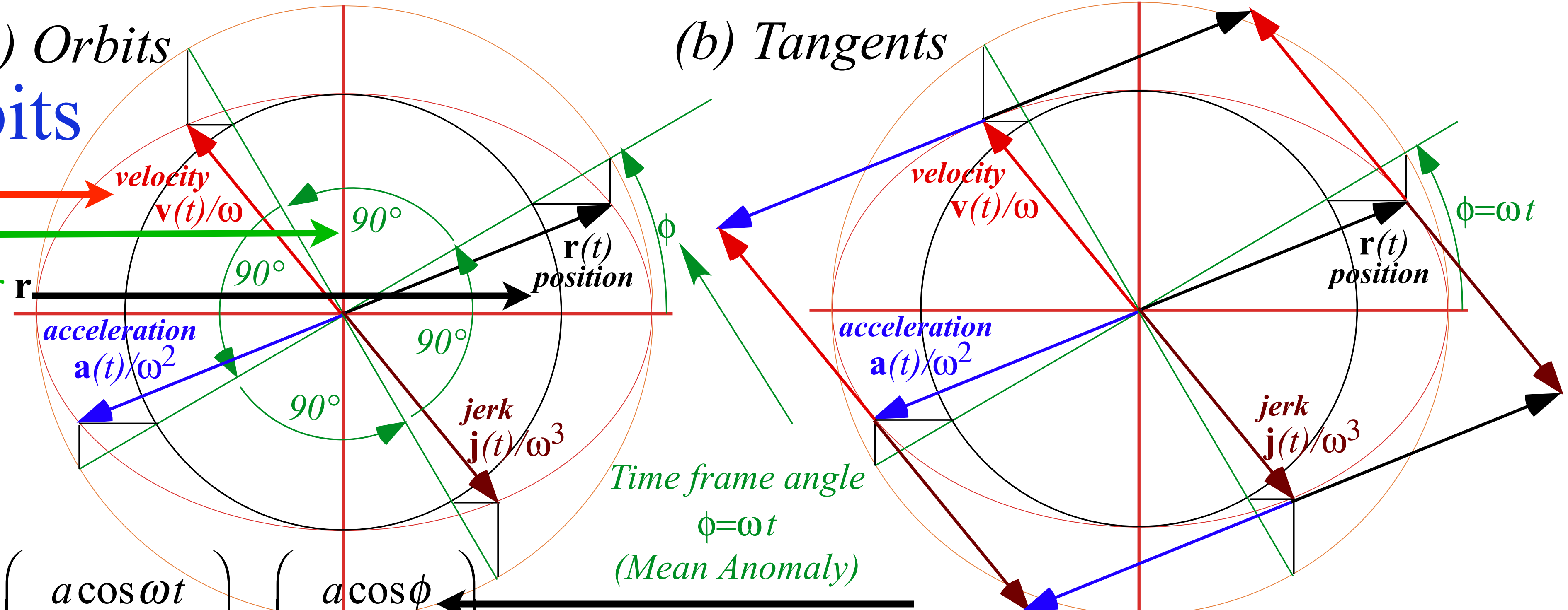
$$\textit{inauguration or change of jerk}: \mathbf{i} = \begin{pmatrix} i_x \\ i_y \end{pmatrix} = \begin{pmatrix} +a\omega^4\cos\omega t \\ +b\omega^4\sin\omega t \end{pmatrix} = \frac{d\mathbf{j}}{dt} = \dot{\mathbf{j}} = \ddot{\mathbf{a}} = \dddot{\mathbf{v}} = \ddddot{\mathbf{r}} = \frac{d^4\mathbf{r}}{dt^4} = \begin{pmatrix} a\cos\left(\phi + \frac{4\pi}{2}\right) \\ b\sin\left(\phi + \frac{4\pi}{2}\right) \end{pmatrix}$$

...and so on...
...But, now it repeats after 4 *t*-derivatives

Calculus of IHO orbits

To make velocity vector **v** just rotate by π/2 or 90° the mean-anomaly φ of position vector **r**

Link ⇒ BoxIt simulation of IHO orbits



$$radius\ vector: \mathbf{r} = \begin{pmatrix} r_x \\ r_y \end{pmatrix} = \begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} a\cos\omega t \\ b\sin\omega t \end{pmatrix} = \begin{pmatrix} a\cos\phi \\ b\sin\phi \end{pmatrix}$$

mean-anomaly φ of position vector **r** rotated by π/2 or 90° is *m.a.* of vector **v**

Unit 1
Fig. 11.5

Link → IHO Exegesis Plot

Link → IHO orbital time rates of change

$$velocity\ vector: \mathbf{v} = \begin{pmatrix} v_x \\ v_y \end{pmatrix} = \begin{pmatrix} -a\omega\sin\omega t \\ b\omega\cos\omega t \end{pmatrix} = \frac{d\mathbf{r}}{dt} = \dot{\mathbf{r}} = \begin{pmatrix} a\cos\left(\phi + \frac{\pi}{2}\right) \\ b\sin\left(\phi + \frac{\pi}{2}\right) \end{pmatrix} (for\ \omega = 1)$$

m.a. φ+π/2 of vector **v** rotated by another π/2 is *m.a.* of vector **a**

$$acceleration\ or\ force\ vector: \frac{\mathbf{F}}{m} = \mathbf{a} = \begin{pmatrix} a_x \\ a_y \end{pmatrix} = \begin{pmatrix} -a\omega^2\cos\omega t \\ -b\omega^2\sin\omega t \end{pmatrix} = \frac{d\mathbf{v}}{dt} = \dot{\mathbf{v}} = \ddot{\mathbf{r}} = \frac{d^2\mathbf{r}}{dt^2} = \begin{pmatrix} a\cos\left(\phi + \frac{2\pi}{2}\right) \\ b\sin\left(\phi + \frac{2\pi}{2}\right) \end{pmatrix}$$

$$or\ change\ of\ velocity$$

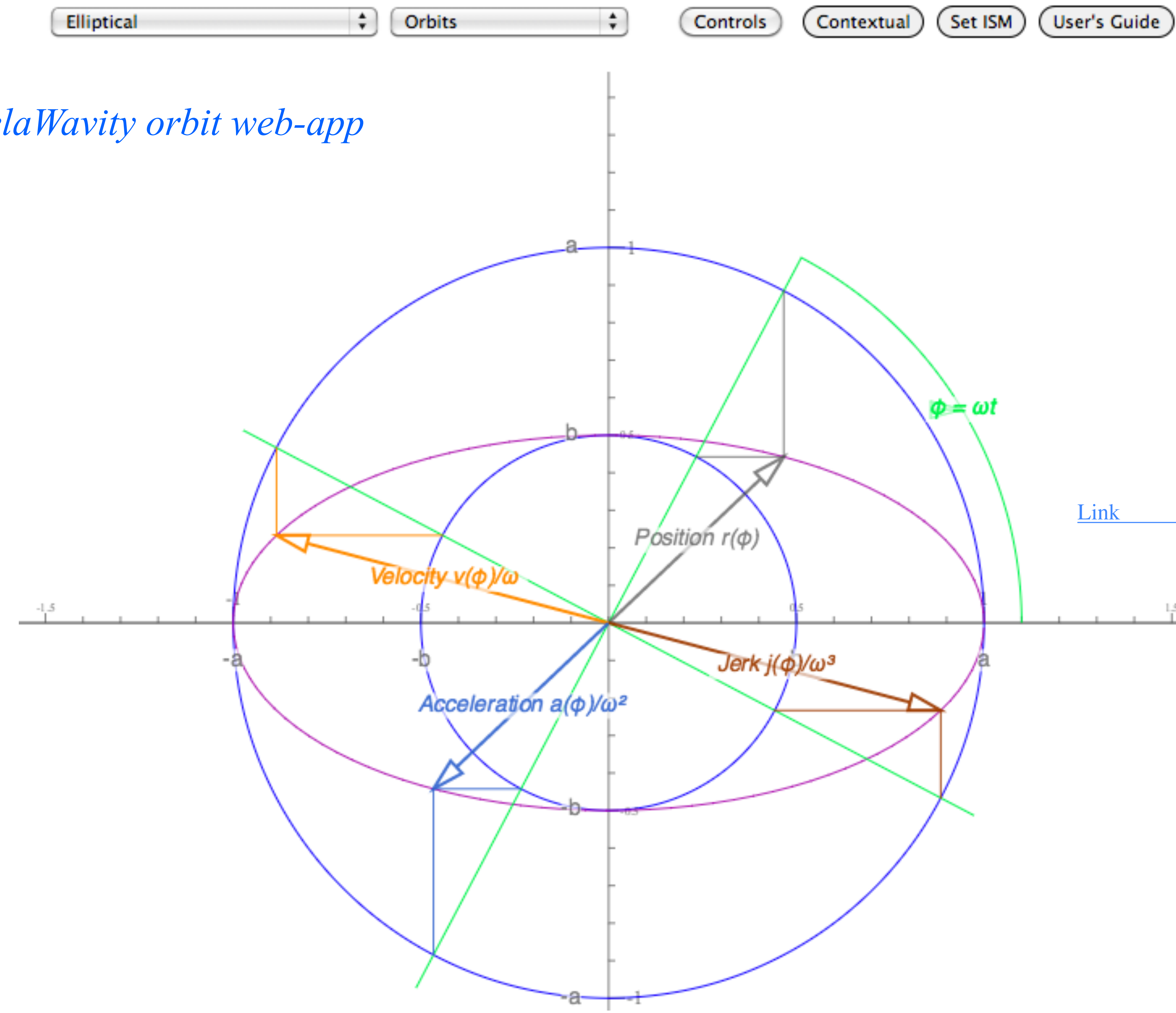
$$jerk\ or\ change\ of\ acceleration: \mathbf{j} = \begin{pmatrix} j_x \\ j_y \end{pmatrix} = \begin{pmatrix} +a\omega^3\sin\omega t \\ -b\omega^3\cos\omega t \end{pmatrix} = \frac{d\mathbf{a}}{dt} = \dot{\mathbf{a}} = \ddot{\mathbf{v}} = \dddot{\mathbf{r}} = \frac{d^3\mathbf{r}}{dt^3} = \begin{pmatrix} a\cos\left(\phi + \frac{3\pi}{2}\right) \\ b\sin\left(\phi + \frac{3\pi}{2}\right) \end{pmatrix}$$

...and so forth...

$$inauguration\ or\ change\ of\ jerk: \mathbf{i} = \begin{pmatrix} i_x \\ i_y \end{pmatrix} = \begin{pmatrix} +a\omega^4\cos\omega t \\ +b\omega^4\sin\omega t \end{pmatrix} = \frac{d\mathbf{j}}{dt} = \dot{\mathbf{j}} = \ddot{\mathbf{a}} = \dddot{\mathbf{v}} = \ddddot{\mathbf{r}} = \frac{d^4\mathbf{r}}{dt^4} = \begin{pmatrix} a\cos\left(\phi + \frac{4\pi}{2}\right) \\ b\sin\left(\phi + \frac{4\pi}{2}\right) \end{pmatrix}$$

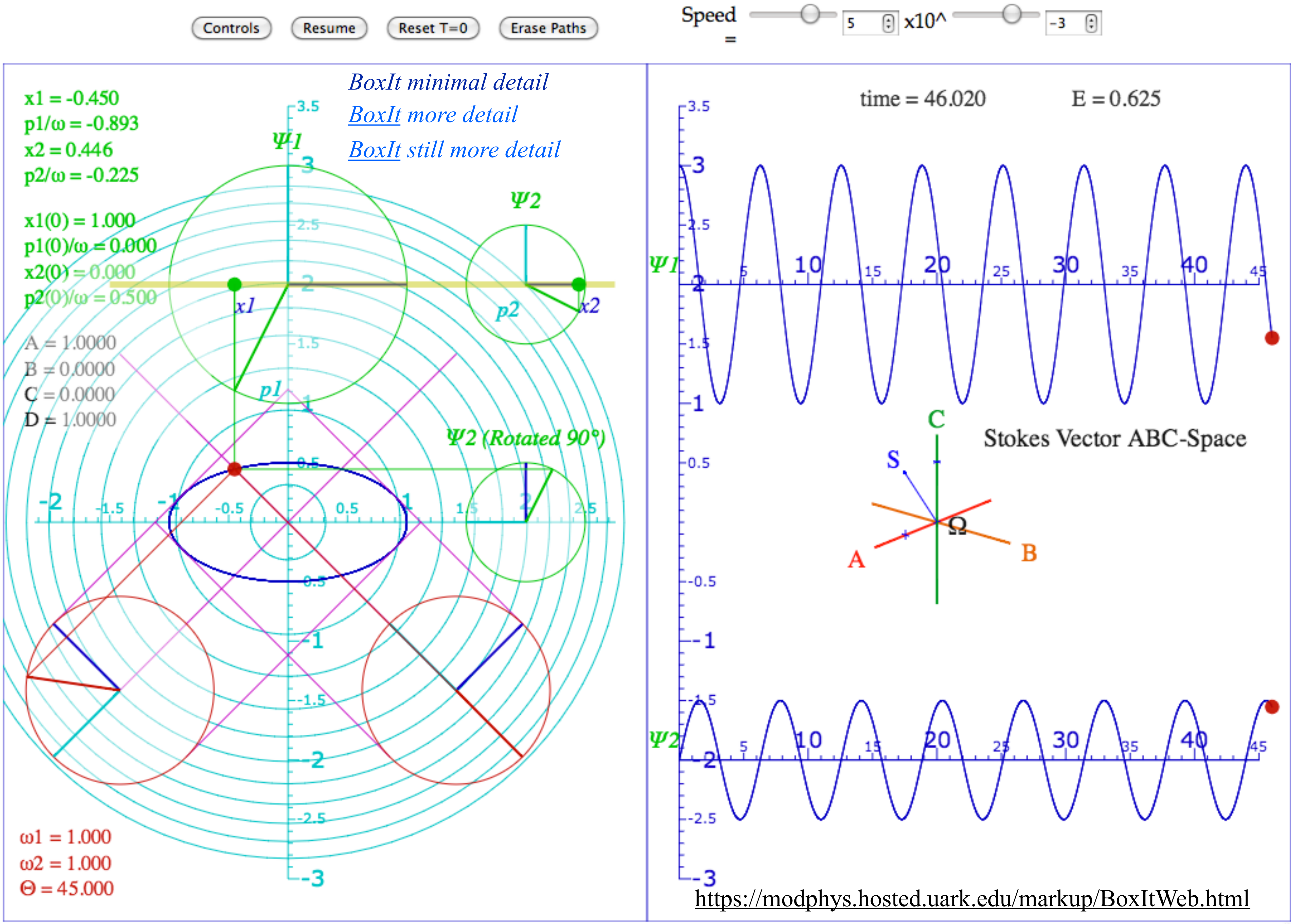
...and so on...
...But, now it repeats after 4 *t*-derivatives

RelaWavity orbit web-app



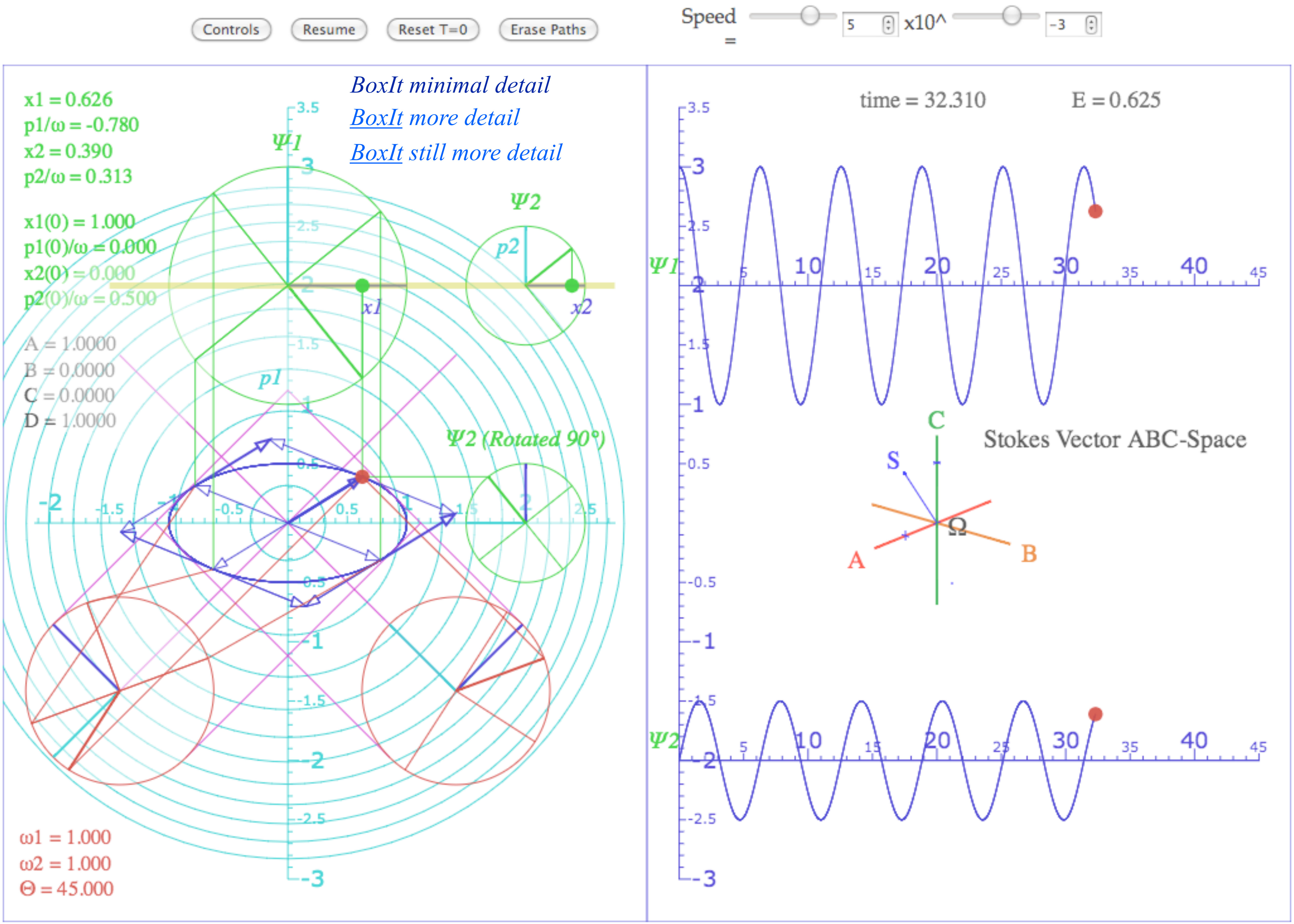
Link

Geometry of Kepler anomalies for vectors [$\mathbf{r}(\phi)$, $\mathbf{v}(\phi)$, $\mathbf{a}(\phi)$, $\mathbf{j}(\phi)$,] *in coordinate (x,y) space rendered by animation web-apps BoxIt and RelaWavity.*



*Geometry of Kepler anomalies for vectors [**r**(ϕ)] in coordinate (x,y) space and 2-particle (x_1,x_2) space rendered by animation web-apps BoxIt.*

BoxIt Web Stokes Simulation



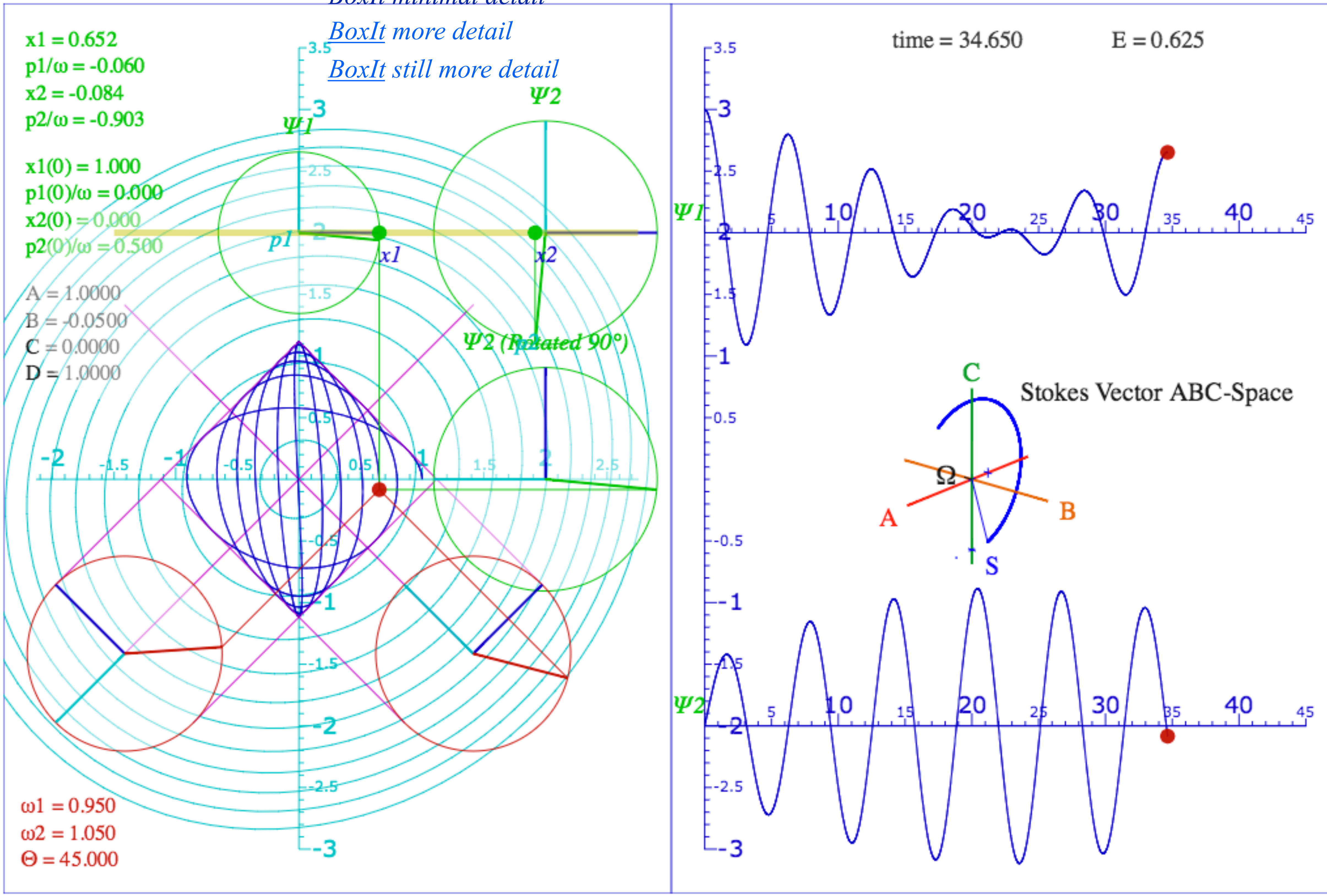
Geometry of Kepler anomalies for vectors [**r**(ϕ), **v**(ϕ), **a**(ϕ), **j**(ϕ),] *in coordinate* (x,y) *space and 2-particle* (x_1,x_2) *space rendered by animation web-apps BoxIt.*

BoxIt Web Simulation - *w/Derivatives*

BoxIt minimal detail

BoxIt more detail

BoxIt still more detail



Geometry of vectors [**r**(ϕ), **p**(ϕ)] *and quantum spin S-space and 2-particle* (x_1,x_2) *space rendered by animation web-apps BoxIt.*

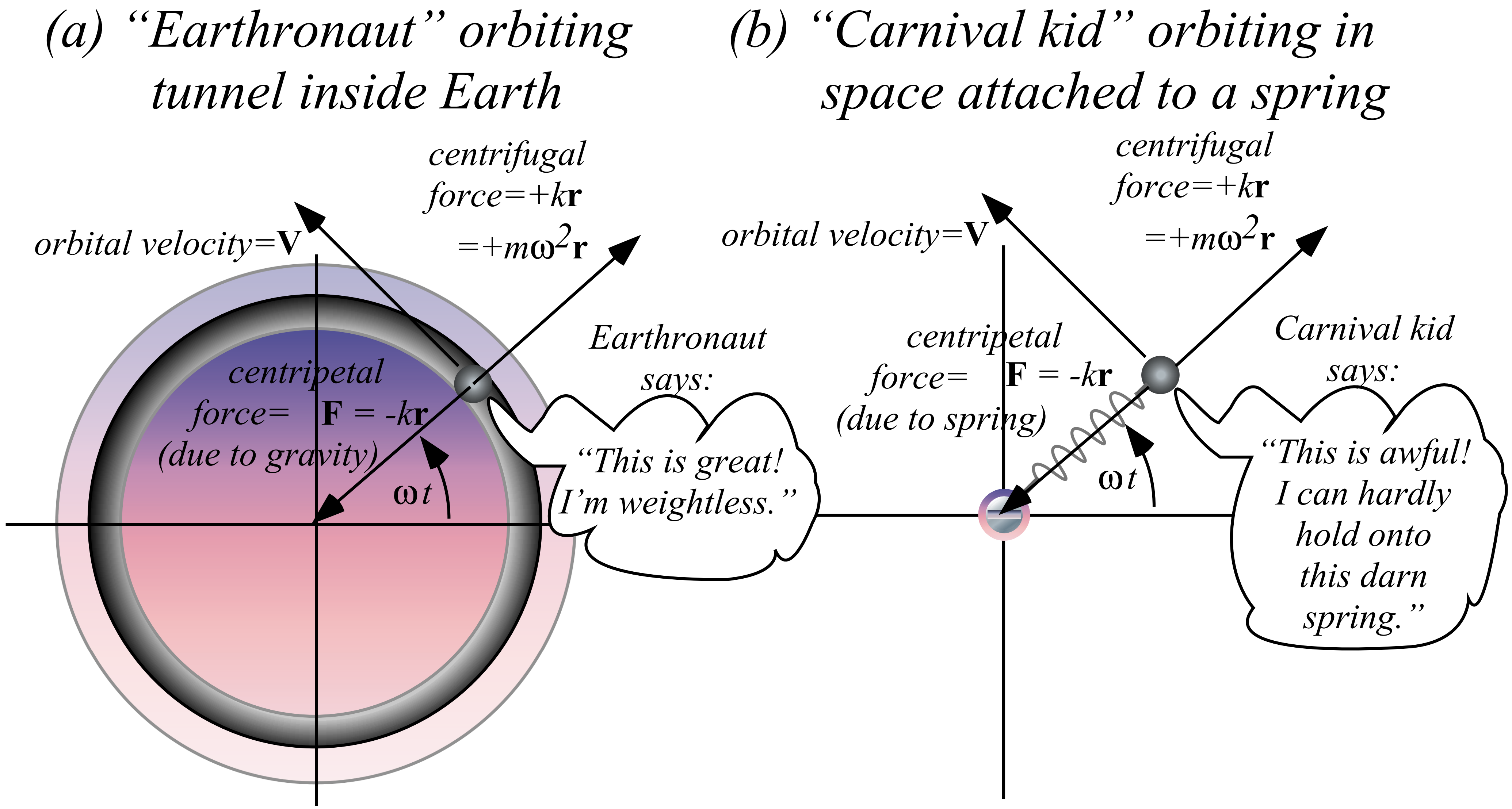
BoxIt Web Simulation - *B-Type Motion*

Constructing 2D IHO orbits using Kepler anomaly plots

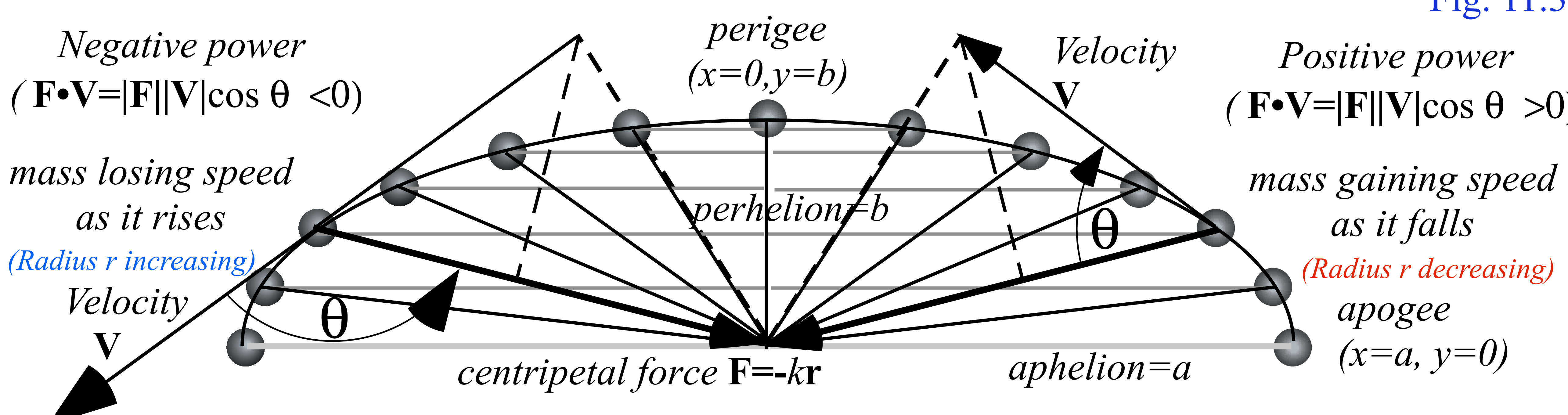
Mean-anomaly and eccentric-anomaly geometry

Calculus and vector geometry of IHO orbits

→ *A confusing introduction to Coriolis-centrifugal force geometry* *(Derived better in Ch. 12)*

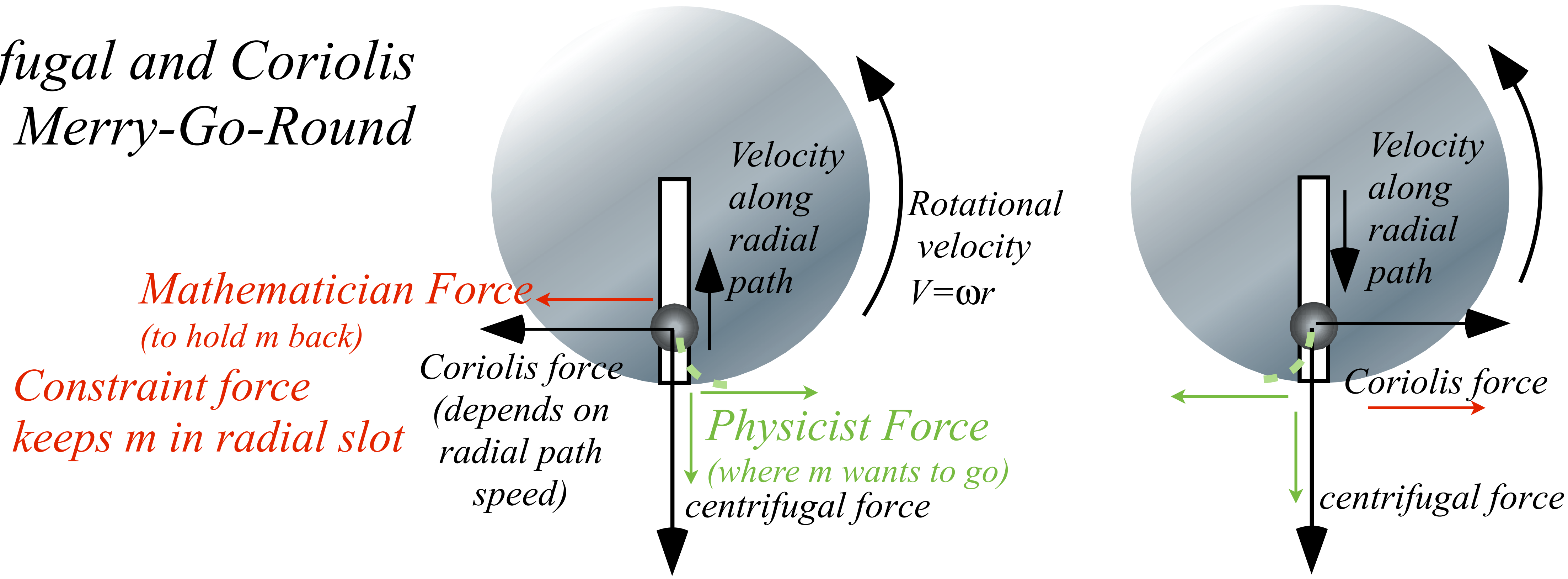


Unit 1
Fig. 11.2

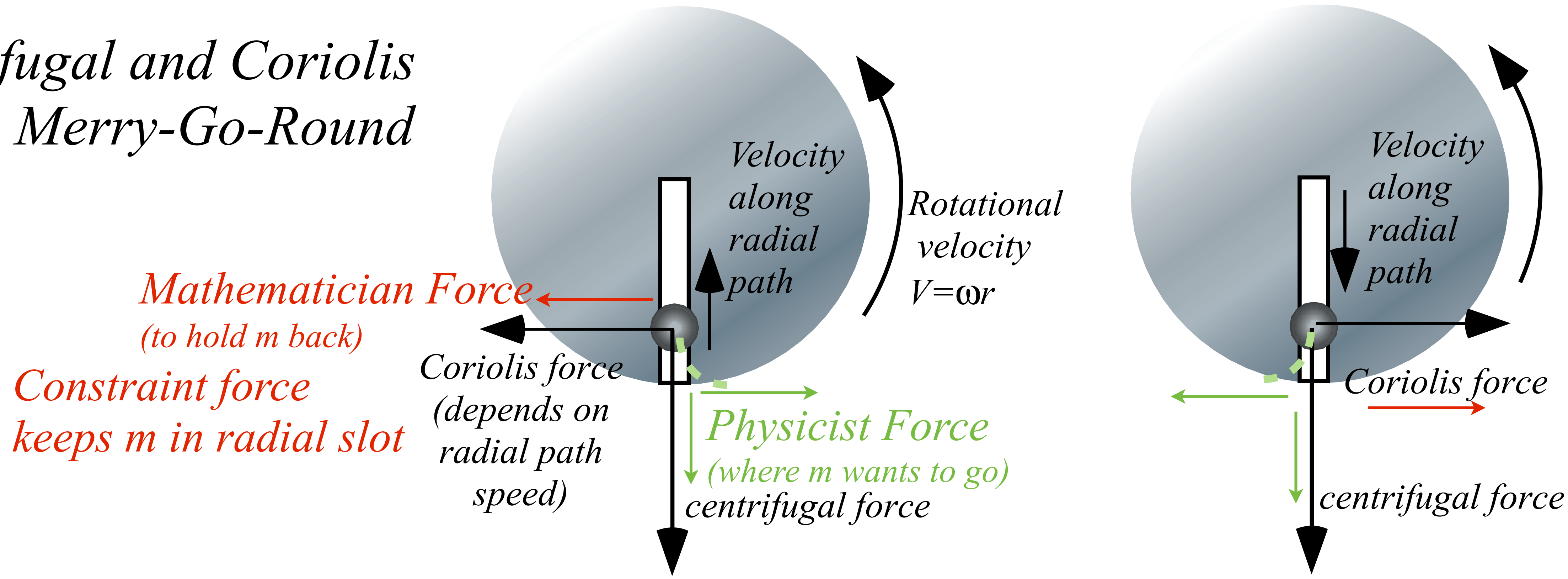


Unit 1
Fig. 11.3

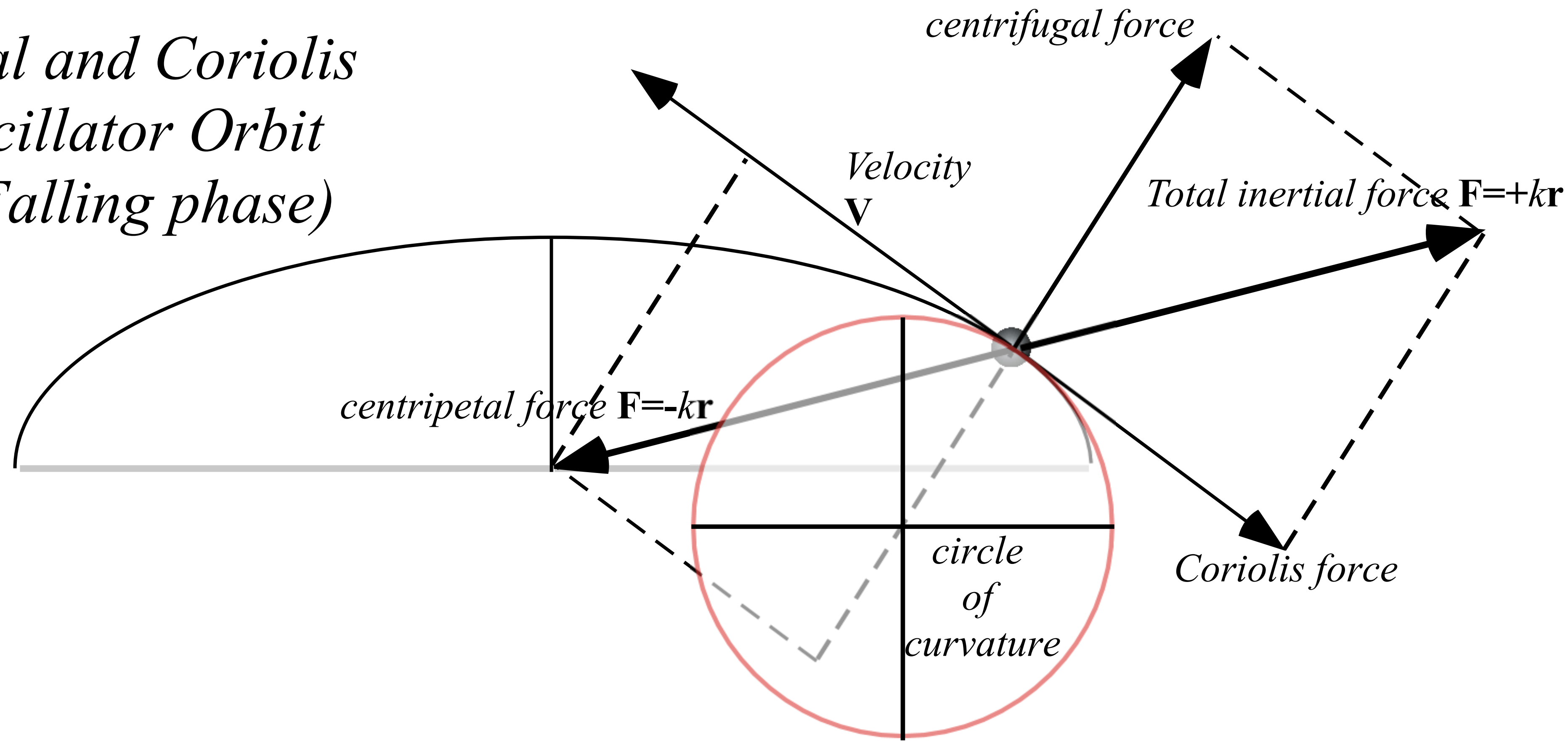
(a) Centrifugal and Coriolis Forces on Merry-Go-Round

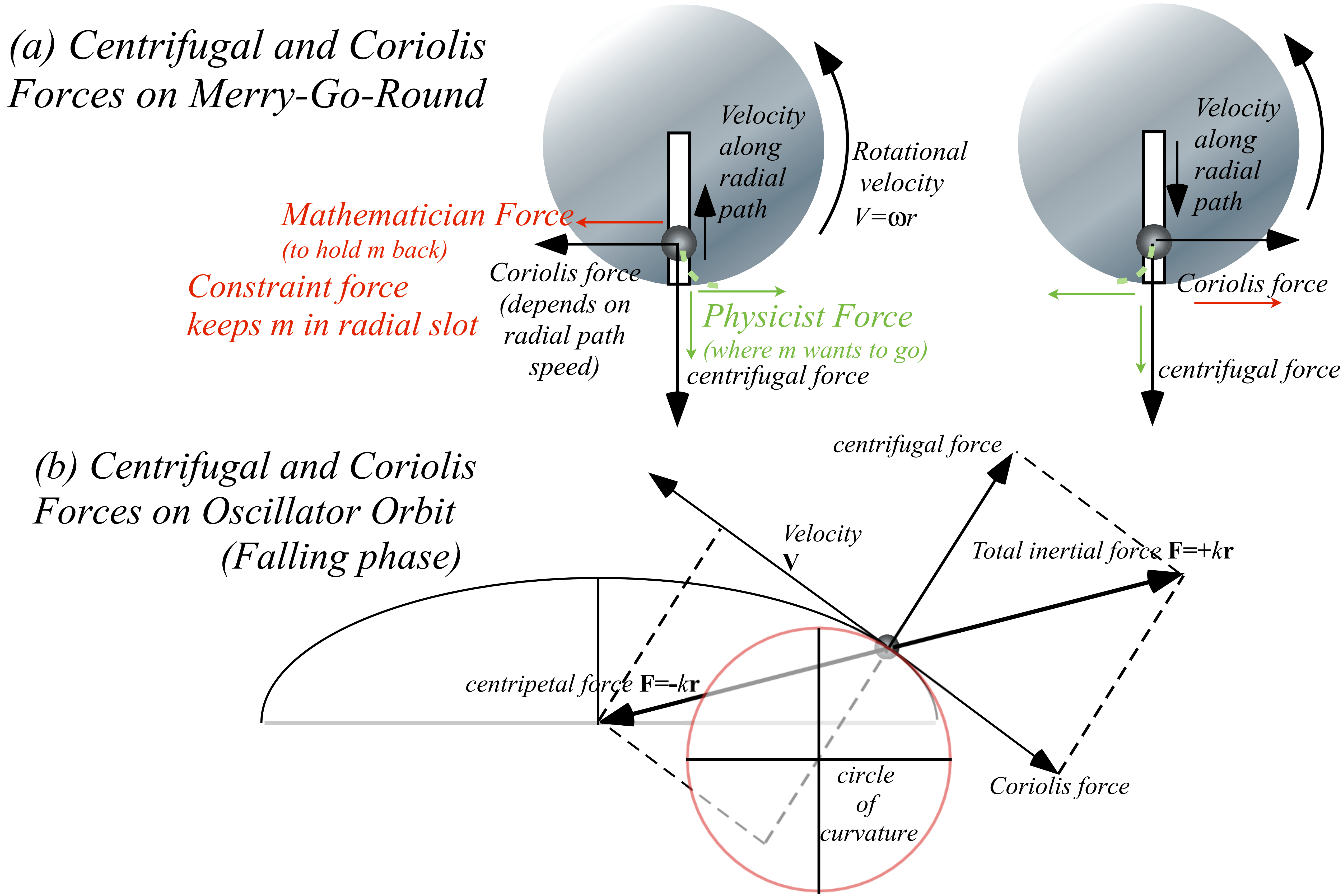


(a) Centrifugal and Coriolis Forces on Merry-Go-Round



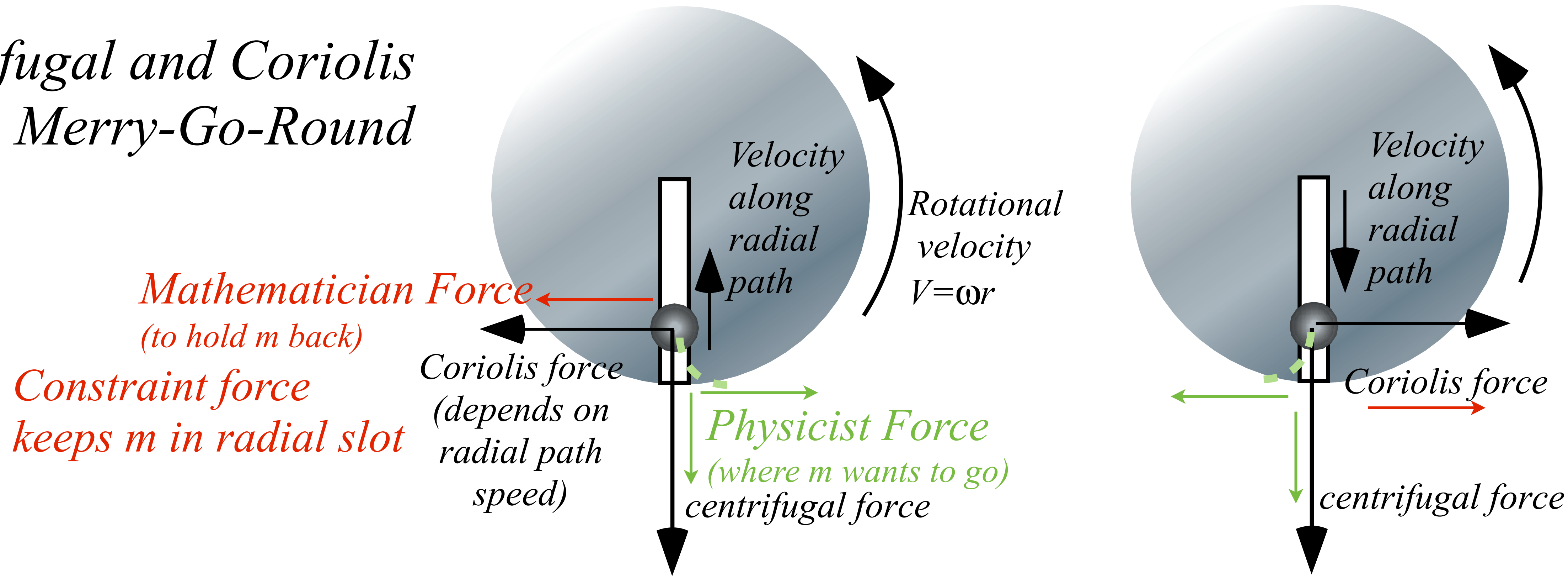
(b) Centrifugal and Coriolis Forces on Oscillator Orbit (Falling phase)



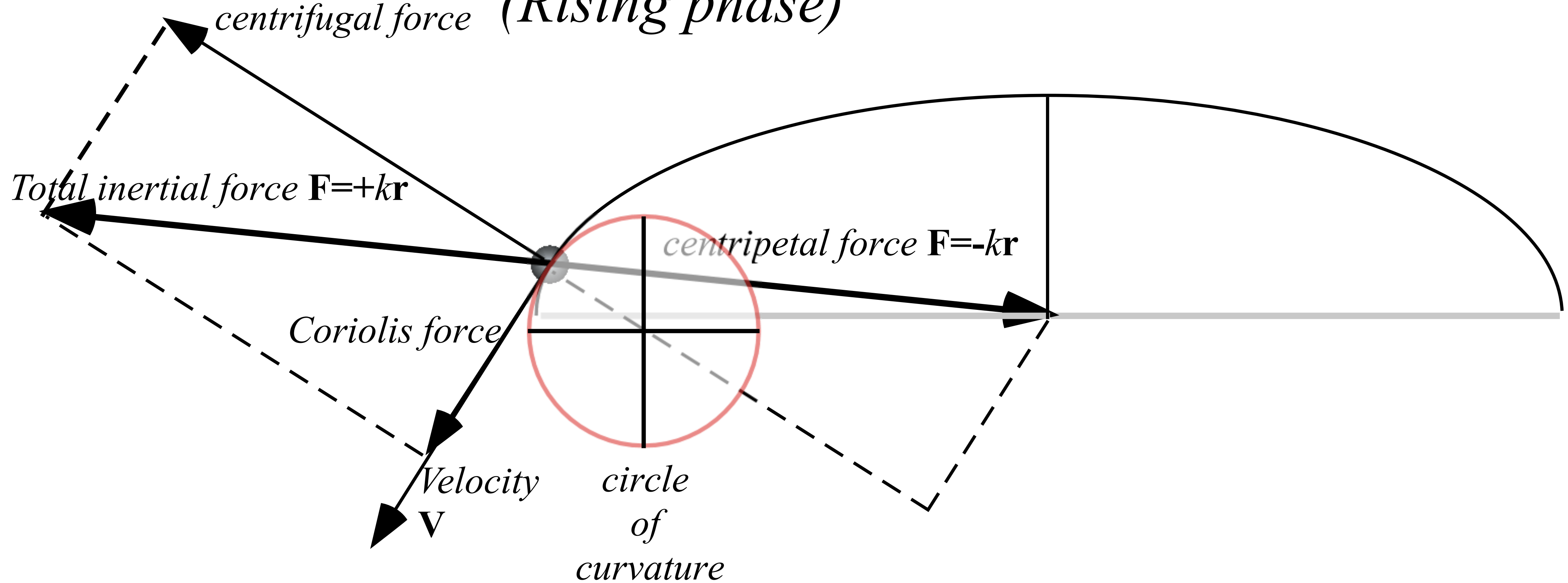


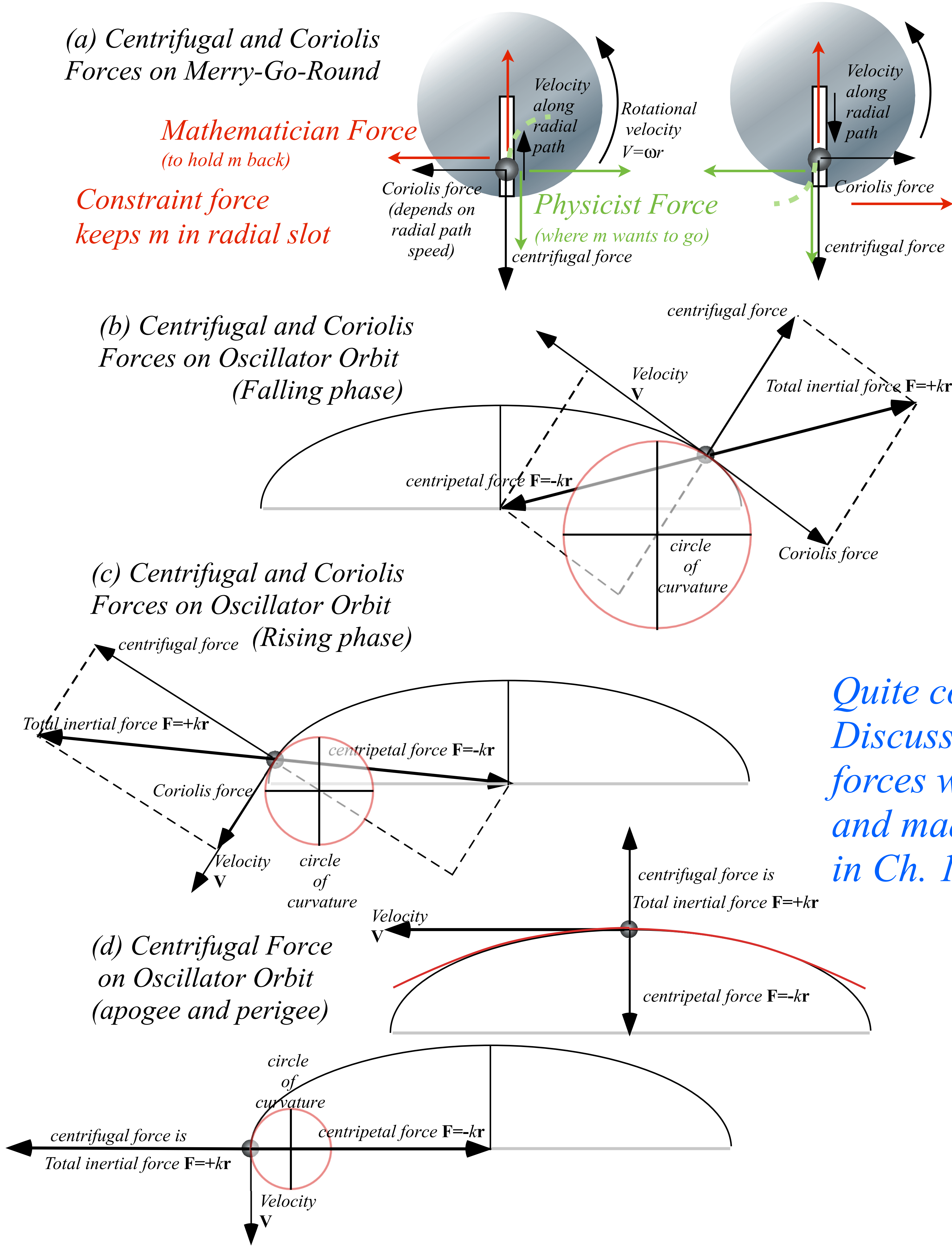
(a) Centrifugal and Coriolis
Forces on Merry-Go-Round
Velocity along radial path
Rotational velocity V=ωr
Mathematician Force
(to hold m back)
Constraint force keeps m in radial slot
Coriolis force (depends on radial path speed)
Physicist Force
(where m wants to go)
centrifugal force
Velocity along radial path
Coriolis force
centrifugal force
(b) Centrifugal and Coriolis
Forces on Oscillator Orbit
(Falling phase)
centrifugal force
Velocity V
Total inertial force F=+kr
centripetal force F=-kr
circle of curvature
Coriolis force

(a) Centrifugal and Coriolis Forces on Merry-Go-Round



(c) Centrifugal and Coriolis Forces on Oscillator Orbit (Rising phase)





Unit 1
Fig. 11.4
a-d

Quite confusing?
Discussion of Coriolis forces will be done more elegantly and made more physically intuitive in Ch. 12 of Unit1 and in Unit 6.

Some Kepler's "laws" for <u>all</u> central (isotropic) force F(r) fields

- *Angular momentum invariance of* IHO: $F(r)=-k\cdot r$ with $U(r)=k\cdot r^2/2$ *(Derived here)*
- *Angular momentum invariance of* Coulomb: $F(r)=-GMm/r^2$ with $U(r)=-GMm\cdot/r$ *(Derived in Unit 5)*
- *Total energy E=KE+PE invariance of* IHO: $F(r)=-k\cdot r$ *(Derived here)*
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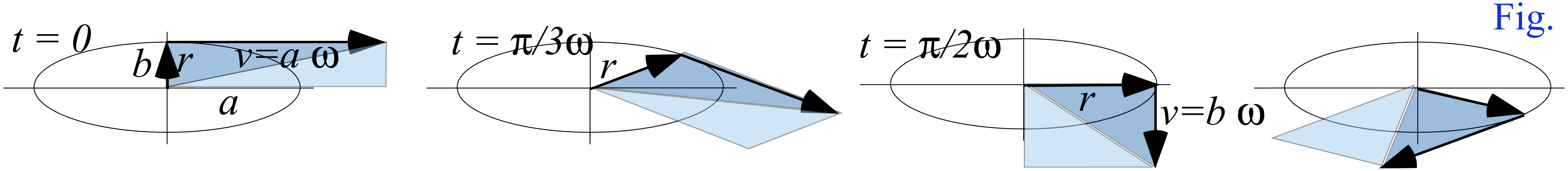
Some Kepler's "laws" for central (isotropic) force F(r)

...and certainly apply to the IHO: F(r)=-k·r with U(r)=k·r²/2 (Recall from Lecture 6: $k = Gm\frac{4\pi}{3}\rho_\oplus$)

Unit 1 Fig. 11.8



1. Area of triangle $\measuredangle_{\mathbf{r}}^{\mathbf{v}} = \mathbf{r}\times\mathbf{v}/2$ is constant

$$\mathbf{r}\times\mathbf{v} = r_x v_y - r_y v_x = a\cos\omega t\cdot(b\omega\cos\omega t) - b\sin\omega t\cdot(-a\omega\sin\omega t) = ab\cdot\omega\left(\cos^2\omega t + \sin^2\omega t\right)$$

✓ *for IHO*

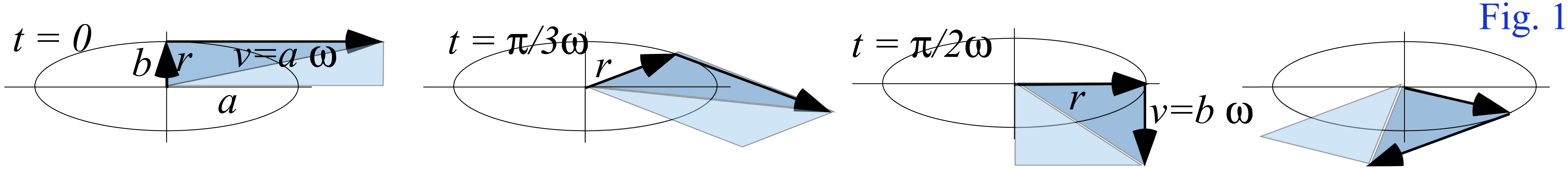
$$\begin{pmatrix} r_x \\ r_y \end{pmatrix} = \begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} a\cos\omega t \\ b\sin\omega t \end{pmatrix} \qquad \begin{pmatrix} v_x \\ v_y \end{pmatrix} = \begin{pmatrix} -a\omega\sin\omega t \\ b\omega\cos\omega t \end{pmatrix}$$

Some Kepler's "laws" that apply to any central (isotropic) force F(r)

...and certainly apply to the IHO: $F(r)=-k\cdot r$ with $U(r)=k\cdot r^2/2$

(Recall from Lecture 6: $k = Gm\frac{4\pi}{3}\rho_{\oplus}$)

Unit 1
Fig. 11.8



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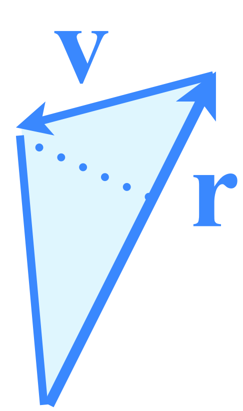
✓ *for IHO*

2. *Angular momentum* $\mathbf{L} = m\,\mathbf{r}\times\mathbf{v}$ is conserved

$$L = m\,|\mathbf{r}\times\mathbf{v}| = m\left(r_x v_y - r_y v_x\right) = m\cdot ab\cdot\omega$$

✓ *for IHO*

$$|\mathbf{r}\times\mathbf{v}| = r\cdot v\cdot \sin\measuredangle_r^v$$



Some Kepler's "laws" that apply to any central (isotropic) force F(r)

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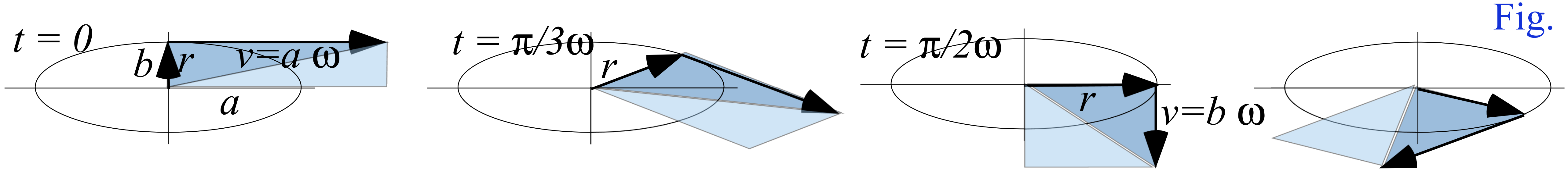
Unit 1
Fig. 11.8



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✓ *for IHO*

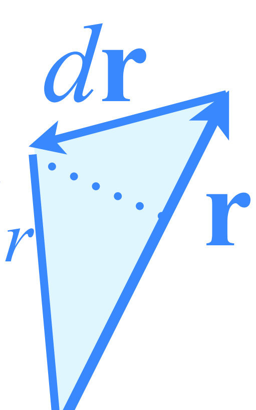
3. Equal area is swept by radius vector in each equal time interval T

$$A_T = \int_0^T \frac{\mathbf{r}\times d\mathbf{r}}{2} = \int_0^T \frac{\mathbf{r}\times\frac{d\mathbf{r}}{dt}}{2}dt = \int_0^T \frac{\mathbf{r}\times\mathbf{v}}{2}dt = \frac{L}{2m}\int_0^T dt = \frac{L}{2m}T$$

by 2.

✓ *for IHO*

$|\mathbf{r}\times d\mathbf{r}| = r\cdot dr\cdot \sin\measuredangle_r^{dr}$



Some Kepler's "laws" that apply to any central (isotropic) force F(r)

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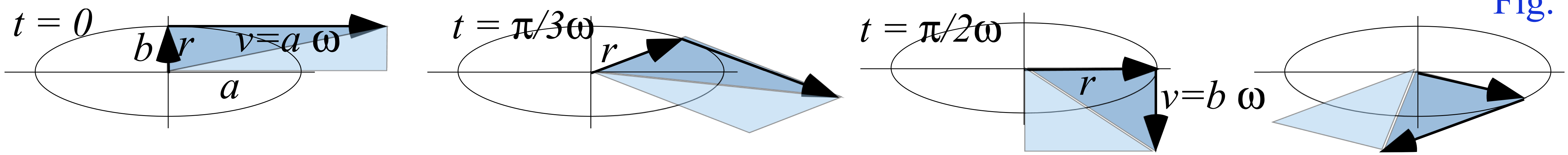
Unit 1
Fig. 11.8



1. Area of triangle $\measuredangle^{\mathbf{v}}_{\mathbf{r}} = \mathbf{r}\times\mathbf{v}/2$ is constant

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✓ *for IHO*

2. *Angular momentum* $L = m\,\mathbf{r}\times\mathbf{v}$ is conserved

$$L = m\,\mathbf{r}\times\mathbf{v} = m(r_x v_y - r_y v_x) = m\cdot ab\cdot\omega = m\cdot ab\cdot\frac{2\pi}{\tau}$$

✓ *for IHO*

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In one period: $\tau = \frac{1}{\upsilon} = \frac{2\pi}{\omega} = \frac{2mA_\tau}{L}$ the area is: $A_\tau = \frac{L\tau}{2m}$ $(= ab\cdot\pi$ for ellipse orbit)

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...and certainly apply to the IHO: $F(r)=-k\cdot r$ with $U(r)=k\cdot r^2/2$

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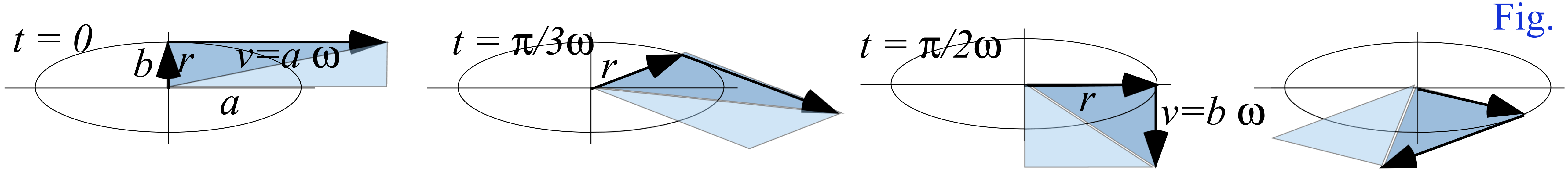
Unit 1
Fig. 11.8



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(Recall from Lecture 6: $\omega = \sqrt{k/m} = \sqrt{G\rho_\oplus 4\pi/3}$)

(G IHO formulas from Lect. 6 p.70-79)

Some Kepler's "laws" for <u>all</u> central (isotropic) force F(r) fields

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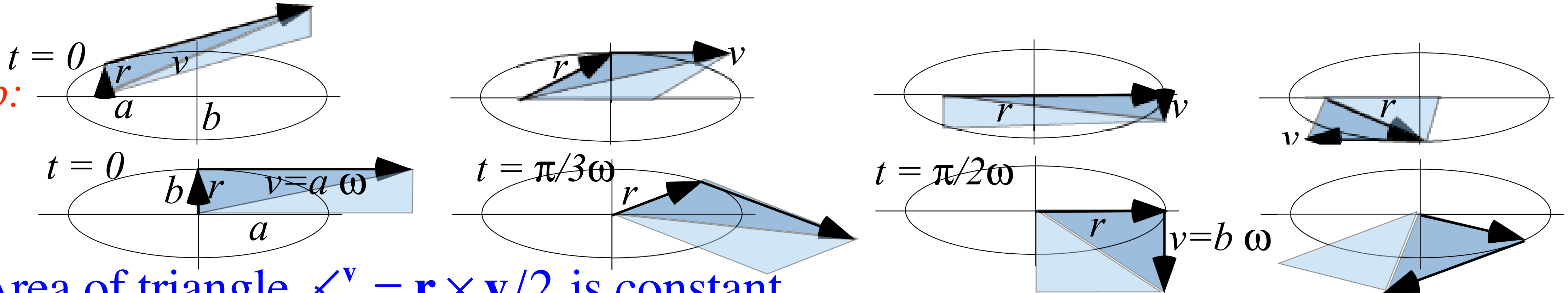
Some Kepler's "laws" that apply to any central (isotropic) force F(r)

Apply to IHO: $F(r)=-k\cdot r$ with $U(r)=k\cdot r^2/2$ and Coulomb: $F(r)=-GMm/r^2$ with $U(r)=-GMm\cdot/r$



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✓ *for IHO*

(Derived in Unit 5) ✓ *for Coul.*

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Some Kepler's "laws" that apply to any central (isotropic) force F(r)

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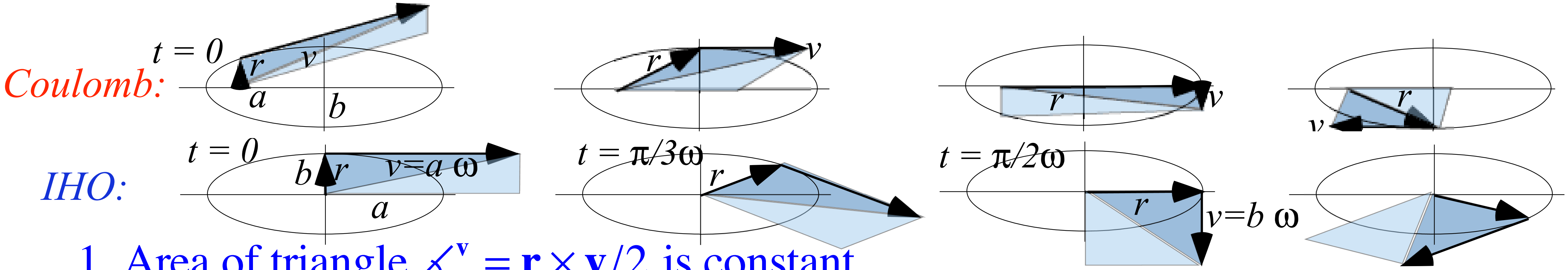

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(... in Unit 5) ✓ *for Coul.*

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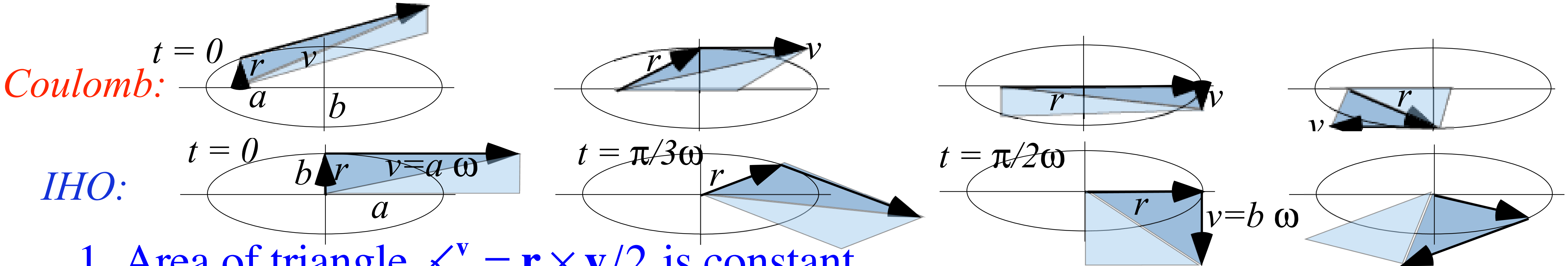
Apply to IHO: $F(r)=-k\cdot r$ with $U(r)=k\cdot r^2/2$ and Coulomb: $F(r)=-GMm/r^2$ with $U(r)=-GMm\cdot/r$



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(... in Unit 5)

✓ for IHO

✓ for Coul.

3. Equal area is swept by radius vector in each equal time interval T

In one period:

$$\tau = \frac{1}{\upsilon} = \frac{2\pi}{\omega} = \frac{2mA_\tau}{L} = \frac{2m\cdot ab\cdot\pi}{L} = \begin{cases} \dfrac{2m\cdot ab\cdot\pi}{m\cdot ab\cdot\sqrt{G\rho_\oplus 4\pi/3}} \\[2ex] \dfrac{2m\cdot ab\cdot\pi}{m\cdot a^{-1/2} b\sqrt{GM_\oplus}} \end{cases}$$

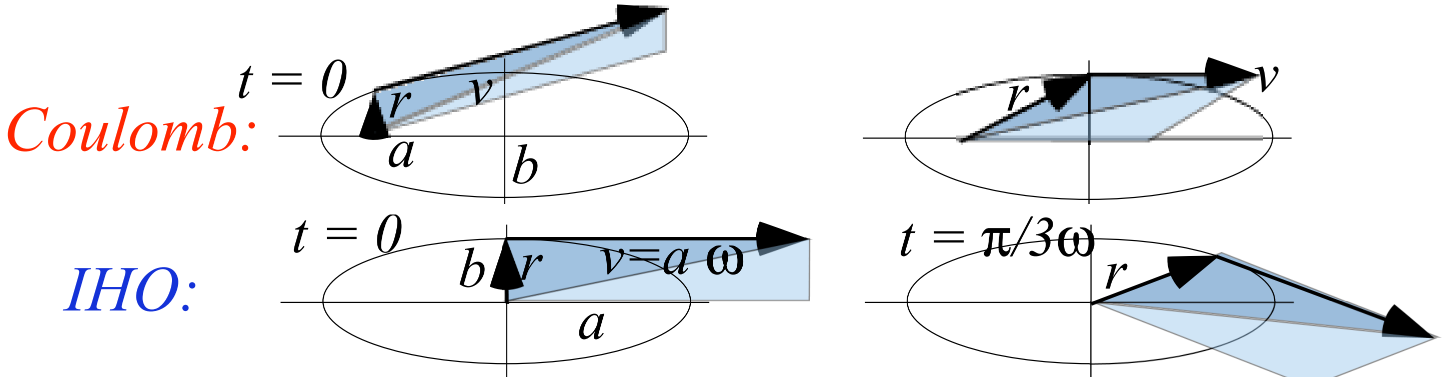
Applies to any central F(r)

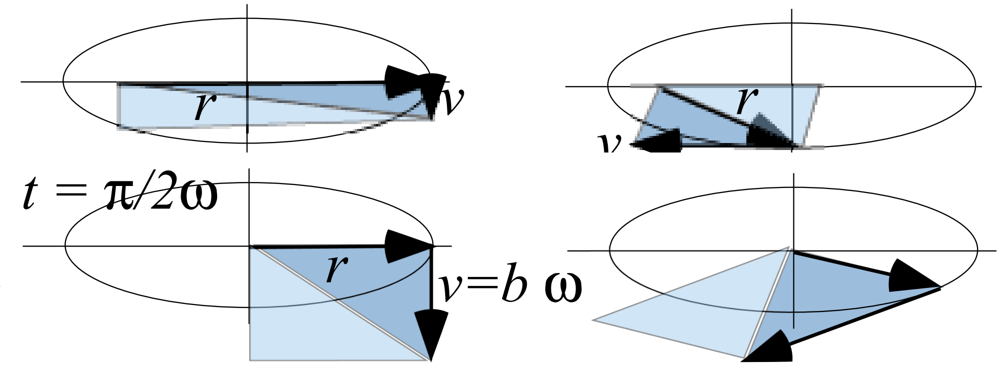
Applies to IHO and Coulomb

(G IHO formulas from Lect. 6 p.70-79)

Some Kepler's "laws" that apply to any central (isotropic) force F(r)

Apply to IHO: $F(r)=-k\cdot r$ with $U(r)=k\cdot r^2/2$ and Coulomb: $F(r)=-GMm/r^2$ with $U(r)=-GMm\cdot/r$





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✓ *for IHO*

(Derived in Unit 5) ✓ *for Coul.*

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(... in Unit 5) ✓ *for Coul.*

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In one period:

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Applies to any central F(r)

Applies to IHO and Coulomb

(not a function of *a* or *b*)

that is ω_{IHO}

that is ω_{Coul}

(not a function of *b*)

Some Kepler's "laws" for <u>all</u> central (isotropic) force F(r) fields

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Kepler laws involve ∡-momentum conservation in isotropic force F(r)

Now consider orbital energy conservation of the IHO: F(r)=-k·r with U(r)=k·r²/2

Total energy=$KE+PE$ is constant

$$KE+PE=\frac{1}{2}\mathbf{v}\bullet\mathbf{M}\bullet\mathbf{v}+\frac{1}{2}\mathbf{r}\bullet\mathbf{K}\bullet\mathbf{r}$$

$$=\frac{1}{2}\begin{pmatrix} v_x & v_y \end{pmatrix}\bullet\begin{pmatrix} m & 0 \\ 0 & m \end{pmatrix}\bullet\begin{pmatrix} v_x \\ v_y \end{pmatrix}+\begin{pmatrix} r_x & r_y \end{pmatrix}\bullet\begin{pmatrix} k & 0 \\ 0 & k \end{pmatrix}\bullet\begin{pmatrix} r_x \\ r_y \end{pmatrix}$$

$$=\frac{1}{2}mv_x^2+\frac{1}{2}mv_y^2+\frac{1}{2}kr_x^2+\frac{1}{2}kr_y^2$$

$$=\frac{1}{2}m(-a\omega\sin\omega t)^2+\frac{1}{2}m(b\omega\cos\omega t)^2+\frac{1}{2}k(a\cos\omega t)^2+\frac{1}{2}k(b\sin\omega t)^2$$

$$\begin{pmatrix} v_x \\ v_y \end{pmatrix}=\begin{pmatrix} -a\omega\sin\omega t \\ b\omega\cos\omega t \end{pmatrix}$$

$$\begin{pmatrix} r_x \\ r_y \end{pmatrix}=\begin{pmatrix} x \\ y \end{pmatrix}=\begin{pmatrix} a\cos\omega t \\ b\sin\omega t \end{pmatrix}$$

Kepler laws involve ∡-momentum conservation in isotropic force F(r)

Now consider orbital energy conservation of the IHO: F(r)=-k·r with U(r)=k·r²/2

Total *IHO* energy=$KE + PE$ is constant

$$KE + PE = \frac{1}{2}\mathbf{v} \bullet \mathbf{M} \bullet \mathbf{v} + \frac{1}{2}\mathbf{r} \bullet \mathbf{K} \bullet \mathbf{r}$$

$$= \frac{1}{2}\begin{pmatrix} v_x & v_y \end{pmatrix} \bullet \begin{pmatrix} m & 0 \\ 0 & m \end{pmatrix} \bullet \begin{pmatrix} v_x \\ v_y \end{pmatrix} + \begin{pmatrix} r_x & r_y \end{pmatrix} \bullet \begin{pmatrix} k & 0 \\ 0 & k \end{pmatrix} \bullet \begin{pmatrix} r_x \\ r_y \end{pmatrix}$$

$$= \frac{1}{2}mv_x^2 + \frac{1}{2}mv_y^2 + \frac{1}{2}kr_x^2 + \frac{1}{2}kr_y^2$$

$$= \frac{1}{2}m(-a\omega\sin\omega t)^2 + \frac{1}{2}m(b\omega\cos\omega t)^2 + \frac{1}{2}k(a\cos\omega t)^2 + \frac{1}{2}k(b\sin\omega t)^2$$

$$= \frac{1}{2}ma^2\omega^2(\sin^2\omega t) + \frac{1}{2}mb^2\omega^2(\cos^2\omega t)^2 + \frac{1}{2}ka^2(\cos^2\omega t) + \frac{1}{2}kb^2(\sin^2\omega t)$$

$$= \frac{1}{2}m\omega^2(a^2 + b^2)$$

$Given: k = m\omega^2$

Kepler laws involve ∡-momentum conservation in isotropic force F(r)

Now consider orbital energy conservation of the IHO: $F(r)=-k\cdot r$ with $U(r)=k\cdot r^2/2$

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$$=\frac{1}{2}m\omega^2(a^2+b^2)$$

$Given: k=m\omega^2$

$$E=KE+PE=\frac{1}{2}m\omega^2(a^2+b^2)=\frac{1}{2}k(a^2+b^2)$$

since: $\omega=\sqrt{\frac{k}{m}}=\sqrt{G\rho_\oplus 4\pi/3}$ or: $m\omega^2=k$

(G IHO formulas from Lect. 6 p.70-79)

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$$KE+PE=\frac{1}{2}\mathbf{v}\bullet\mathbf{M}\bullet\mathbf{v}+\frac{1}{2}\mathbf{r}\bullet\mathbf{K}\bullet\mathbf{r}$$

$$=\frac{1}{2}\begin{pmatrix} v_x & v_y\end{pmatrix}\bullet\begin{pmatrix} m & 0\\ 0 & m\end{pmatrix}\bullet\begin{pmatrix} v_x\\ v_y\end{pmatrix}+\begin{pmatrix} r_x & r_y\end{pmatrix}\bullet\begin{pmatrix} k & 0\\ 0 & k\end{pmatrix}\bullet\begin{pmatrix} r_x\\ r_y\end{pmatrix}$$

$$=\frac{1}{2}mv_x^2+\frac{1}{2}mv_y^2+\frac{1}{2}kr_x^2+\frac{1}{2}kr_y^2$$

$$=\frac{1}{2}m(-a\omega\sin\omega t)^2+\frac{1}{2}m(b\omega\cos\omega t)^2+\frac{1}{2}k(a\cos\omega t)^2+\frac{1}{2}k(b\sin\omega t)^2$$

$$=\frac{1}{2}ma^2\omega^2(\sin^2\omega t)+\frac{1}{2}mb^2\omega^2(\cos^2\omega t)^2+\frac{1}{2}ka^2(\cos^2\omega t)+\frac{1}{2}kb^2(\sin^2\omega t)$$

$$=\frac{1}{2}m\omega^2(a^2+b^2)$$

$Given: k=m\omega^2$

$E=KE+PE=\frac{1}{2}m\omega^2(a^2+b^2)=\frac{1}{2}k(a^2+b^2)$ since: $\omega=\sqrt{\frac{k}{m}}=\sqrt{G\rho_\oplus 4\pi/3}$ or: $m\omega^2=k$

We'll see that the Coul. orbits are simpler: (*like the period*...not a function of b)

(G IHO formulas from Lect. 6 p.70-79)

Kepler laws involve ∡-momentum conservation in isotropic force F(r)

Now consider orbital energy conservation of the IHO: F(r)=-k·r with U(r)=k·r²/2

Total *IHO* energy=$KE+PE$ is constant

$$KE+PE=\frac{1}{2}\mathbf{v}\bullet\mathbf{M}\bullet\mathbf{v}+\frac{1}{2}\mathbf{r}\bullet\mathbf{K}\bullet\mathbf{r}$$

$$=\frac{1}{2}\begin{pmatrix} v_x & v_y \end{pmatrix}\bullet\begin{pmatrix} m & 0 \\ 0 & m \end{pmatrix}\bullet\begin{pmatrix} v_x \\ v_y \end{pmatrix}+\begin{pmatrix} r_x & r_y \end{pmatrix}\bullet\begin{pmatrix} k & 0 \\ 0 & k \end{pmatrix}\bullet\begin{pmatrix} r_x \\ r_y \end{pmatrix}$$

$$=\frac{1}{2}mv_x^2+\frac{1}{2}mv_y^2+\frac{1}{2}kr_x^2+\frac{1}{2}kr_y^2$$

$$=\frac{1}{2}m(-a\omega\sin\omega t)^2+\frac{1}{2}m(b\omega\cos\omega t)^2+\frac{1}{2}k(a\cos\omega t)^2+\frac{1}{2}k(b\sin\omega t)^2$$

$$=\frac{1}{2}ma^2\omega^2(\sin^2\omega t)+\frac{1}{2}mb^2\omega^2(\cos^2\omega t)^2+\frac{1}{2}ka^2(\cos^2\omega t)+\frac{1}{2}kb^2(\sin^2\omega t)$$

$$=\frac{1}{2}m\omega^2(a^2+b^2)\qquad Given: k=m\omega^2$$

$$E=KE+PE=\frac{1}{2}m\omega^2(a^2+b^2)=\frac{1}{2}k(a^2+b^2)\quad \text{since: } \omega=\sqrt{\frac{k}{m}}=\sqrt{G\rho_\oplus 4\pi/3}\quad \text{or: } m\omega^2=k$$

We'll see that the Coul. orbits are simpler: (*like the period*...not a function of *b*)

$$E=KE+PE=\frac{1}{2}mv_x^2+\frac{1}{2}mv_y^2-\frac{k}{r}=\frac{1}{2}mv_x^2+\frac{1}{2}mv_y^2-\frac{GM_\oplus m}{r}=-\frac{GM_\oplus m}{a}$$

Introduction to dual matrix operator contact geometry (based on IHO orbits)

Quadratic form ellipse $\mathbf{r}\bullet Q\bullet\mathbf{r}=1$ *vs.inverse form ellipse* $\mathbf{p}\bullet Q^{-1}\bullet\mathbf{p}=1$

Duality norm relations ($\mathbf{r}\bullet\mathbf{p}=1$*)*

Q-Ellipse tangents $\mathbf{r}'$ *normal to dual* Q^{-1}*-ellipse position* $\mathbf{p}$ *(* $\mathbf{r}'\bullet\mathbf{p}=0=\mathbf{r}\bullet\mathbf{p}'$*)*

Operator geometric sequences and eigenvectors

Alternative scaling of matrix operator geometry

Vector calculus of tensor operation

Quadratic forms and tangent contact geometry of their ellipses

A matrix Q that generates an ellipse by **r**•*Q*•**r**=*1 is called* positive-definite (*if* **r**•*Q*•**r** *always >0*)

$$\overbrace{\begin{pmatrix} x & y \end{pmatrix} \bullet \begin{pmatrix} \frac{1}{a^2} & 0 \\ 0 & \frac{1}{b^2} \end{pmatrix} \bullet \begin{pmatrix} x \\ y \end{pmatrix}}^{\mathbf{r}\bullet\mathbf{Q}\bullet\mathbf{r}\;=1} = 1 = \overbrace{\begin{pmatrix} x & y \end{pmatrix}}^{\mathbf{r}} \bullet \overbrace{\begin{pmatrix} \frac{x}{a^2} \\ \frac{y}{b^2} \end{pmatrix}}^{\mathbf{Q}\bullet\mathbf{r}} = \frac{x^2}{a^2} + \frac{y^2}{b^2}$$

A inverse matrix Q^{-1} *generates an ellipse by* **p**•Q^{-1}•**p**=*1 called* inverse *or* dual *ellipse:*

$$\overbrace{\begin{pmatrix} p_x & p_y \end{pmatrix} \bullet \begin{pmatrix} a^2 & 0 \\ 0 & b^2 \end{pmatrix} \bullet \begin{pmatrix} p_x \\ p_y \end{pmatrix}}^{\mathbf{p}\bullet\mathbf{Q}^{-1}\bullet\mathbf{p}\;=1} = 1 = \overbrace{\begin{pmatrix} p_x & p_y \end{pmatrix}}^{\mathbf{p}} \bullet \overbrace{\begin{pmatrix} a^2 p_x \\ b^2 p_y \end{pmatrix}}^{\mathbf{Q}^{-1}\bullet\mathbf{p}} = a^2 p_x^2 + b^2 p_y^2$$

Quadratic forms and tangent contact geometry of their ellipses

A matrix Q that generates an ellipse by **r**•*Q*•**r**=*1 is called* positive-definite (*if* **r**•*Q*•**r** *always >0*)

$$\overbrace{\begin{pmatrix} x & y \end{pmatrix} \bullet \begin{pmatrix} \frac{1}{a^2} & 0 \\ 0 & \frac{1}{b^2} \end{pmatrix} \bullet \begin{pmatrix} x \\ y \end{pmatrix}}^{\mathbf{r}\bullet\mathbf{Q}\bullet\mathbf{r}\,=1} = 1 = \overbrace{\begin{pmatrix} x & y \end{pmatrix}}^{\mathbf{r}} \bullet \overbrace{\begin{pmatrix} \frac{x}{a^2} \\ \frac{y}{b^2} \end{pmatrix}}^{\mathbf{Q}\bullet\mathbf{r}=\mathbf{p}} = \frac{x^2}{a^2} + \frac{y^2}{b^2}$$

Defined mapping between ellipses

A inverse matrix Q^{-1} *generates an ellipse by* **p**•Q^{-1}•**p**=*1 called* inverse *or* dual *ellipse:*

$$\overbrace{\begin{pmatrix} p_x & p_y \end{pmatrix} \bullet \begin{pmatrix} a^2 & 0 \\ 0 & b^2 \end{pmatrix} \bullet \begin{pmatrix} p_x \\ p_y \end{pmatrix}}^{\mathbf{p}\bullet\mathbf{Q}^{-1}\bullet\mathbf{p}\,=1} = 1 = \overbrace{\begin{pmatrix} p_x & p_y \end{pmatrix}}^{\mathbf{p}} \bullet \overbrace{\begin{pmatrix} a^2 p_x \\ b^2 p_y \end{pmatrix}}^{\mathbf{Q}^{-1}\bullet\mathbf{p}=\mathbf{r}} = a^2 p_x^2 + b^2 p_y^2$$

Introduction to dual matrix operator contact geometry (based on IHO orbits)

→ *Quadratic form ellipse* $\mathbf{r}\bullet Q\bullet\mathbf{r}=1$ *vs.inverse form ellipse* $\mathbf{p}\bullet Q^{-1}\bullet\mathbf{p}=1$

Duality norm relations ($\mathbf{r}\bullet\mathbf{p}=1$)

Q-Ellipse tangents $\mathbf{r}'$ *normal to dual* Q^{-1}*-ellipse position* $\mathbf{p}$ ($\mathbf{r}'\bullet\mathbf{p}=0=\mathbf{r}\bullet\mathbf{p}'$)

Operator geometric sequences and eigenvectors

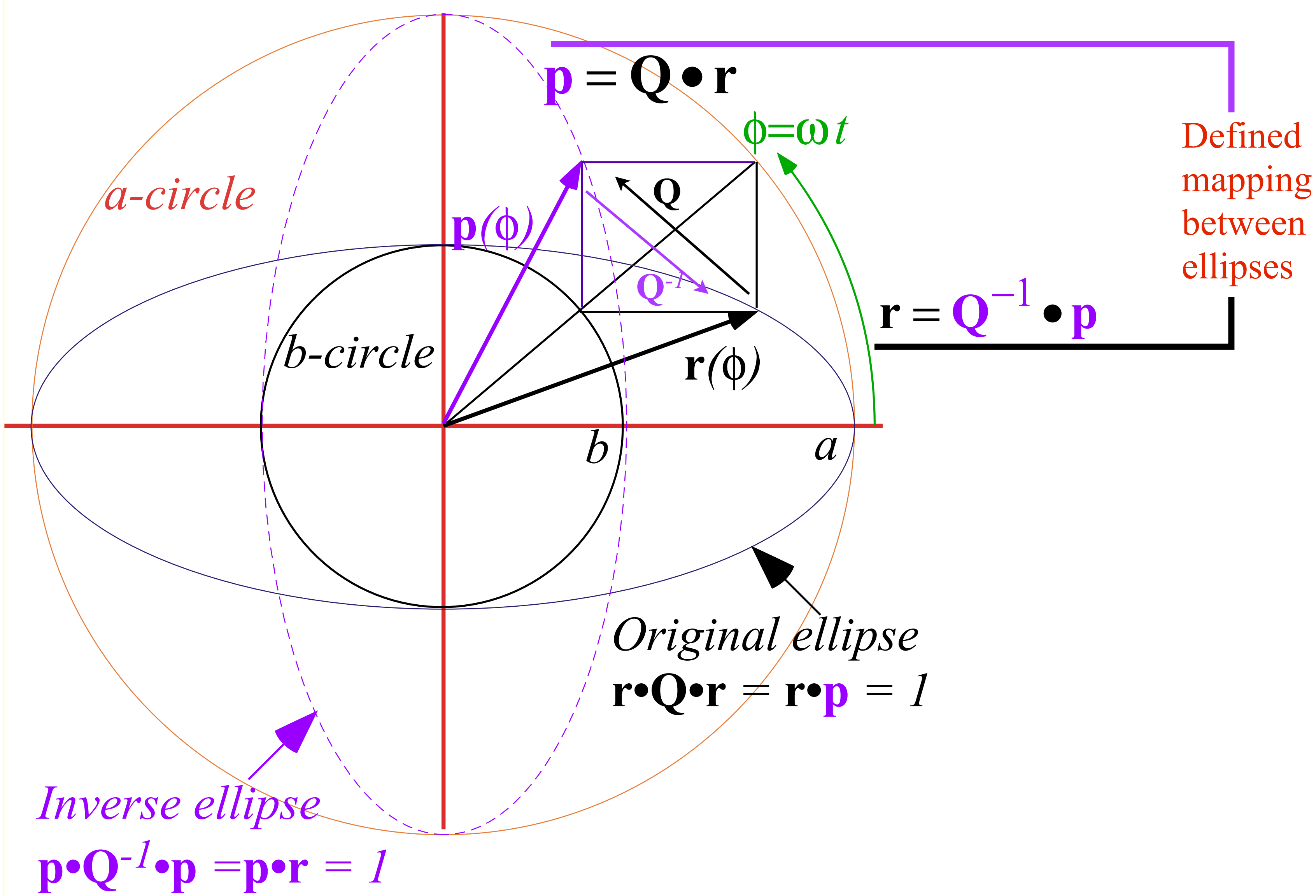
Alternative scaling of matrix operator geometry

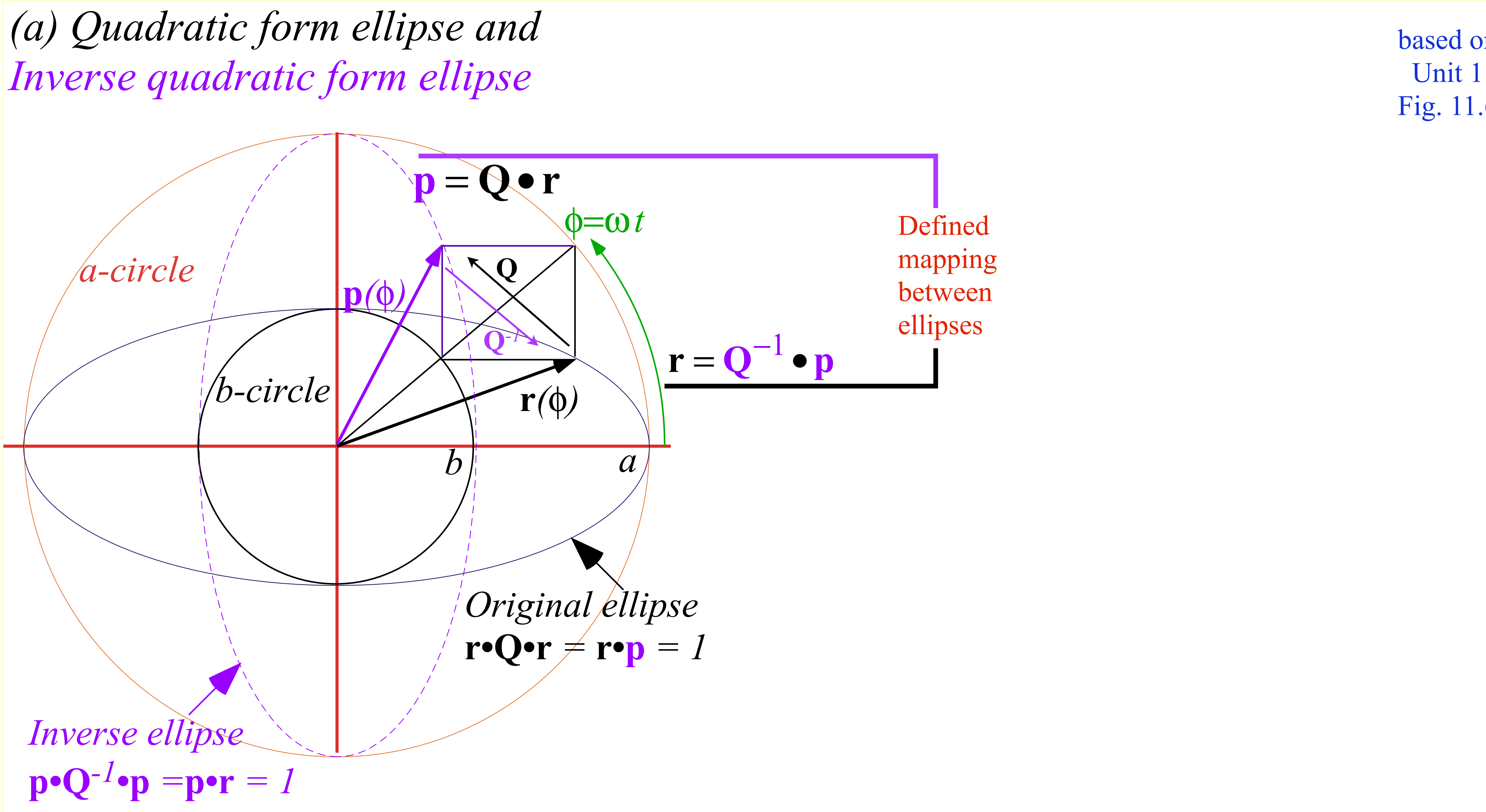
Vector calculus of tensor operation

(a) Quadratic form ellipse and

Inverse quadratic form ellipse

based on
Unit 1
Fig. 11.6





Here plot of **p**-ellipse is re-scaled by scalefactor $S=a \cdot b$

p-ellipse x-radius=$1/a$ plotted at: $S(1/a)=b$ (=1 for a=2, b=1)

p-ellipse y-radius=$1/b$ plotted at: $S(1/b)=a$ (=2 for a=2, b=1)

Introduction to dual matrix operator geometry (based on IHO orbits)

Quadratic form ellipse $\mathbf{r}\bullet Q\bullet\mathbf{r}=1$ *vs.inverse form ellipse* $\mathbf{p}\bullet Q^{-1}\bullet\mathbf{p}=1$

→ *Duality norm relations (* $\mathbf{r}\bullet\mathbf{p}=1$*)*

Q-Ellipse tangents $\mathbf{r}'$ *normal to dual* Q^{-1}*-ellipse position* $\mathbf{p}$ *(* $\mathbf{r}'\bullet\mathbf{p}=0=\mathbf{r}\bullet\mathbf{p}'$*)*

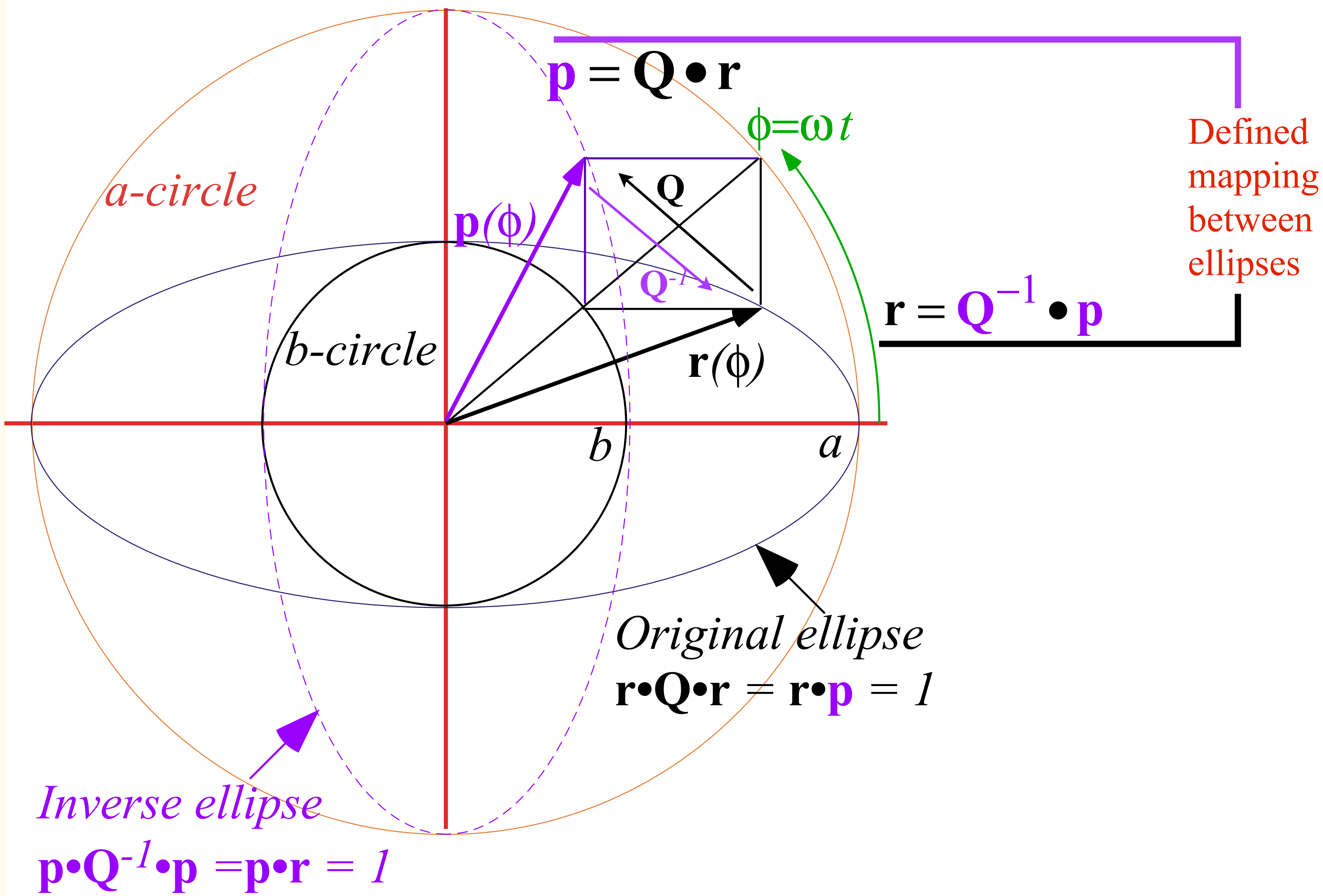
Operator geometric sequences and eigenvectors

Alternative scaling of matrix operator geometry

Vector calculus of tensor operation

(a) Quadratic form ellipse and
Inverse quadratic form ellipse

based on
Unit 1
Fig. 11.6



Quadratic form $\mathbf{r}\bullet\mathbf{Q}\bullet\mathbf{r}=1$ *has mutual duality relations with inverse form* $\mathbf{p}\bullet\mathbf{Q}^{-1}\bullet\mathbf{p}=1=\mathbf{p}\bullet\mathbf{r}$

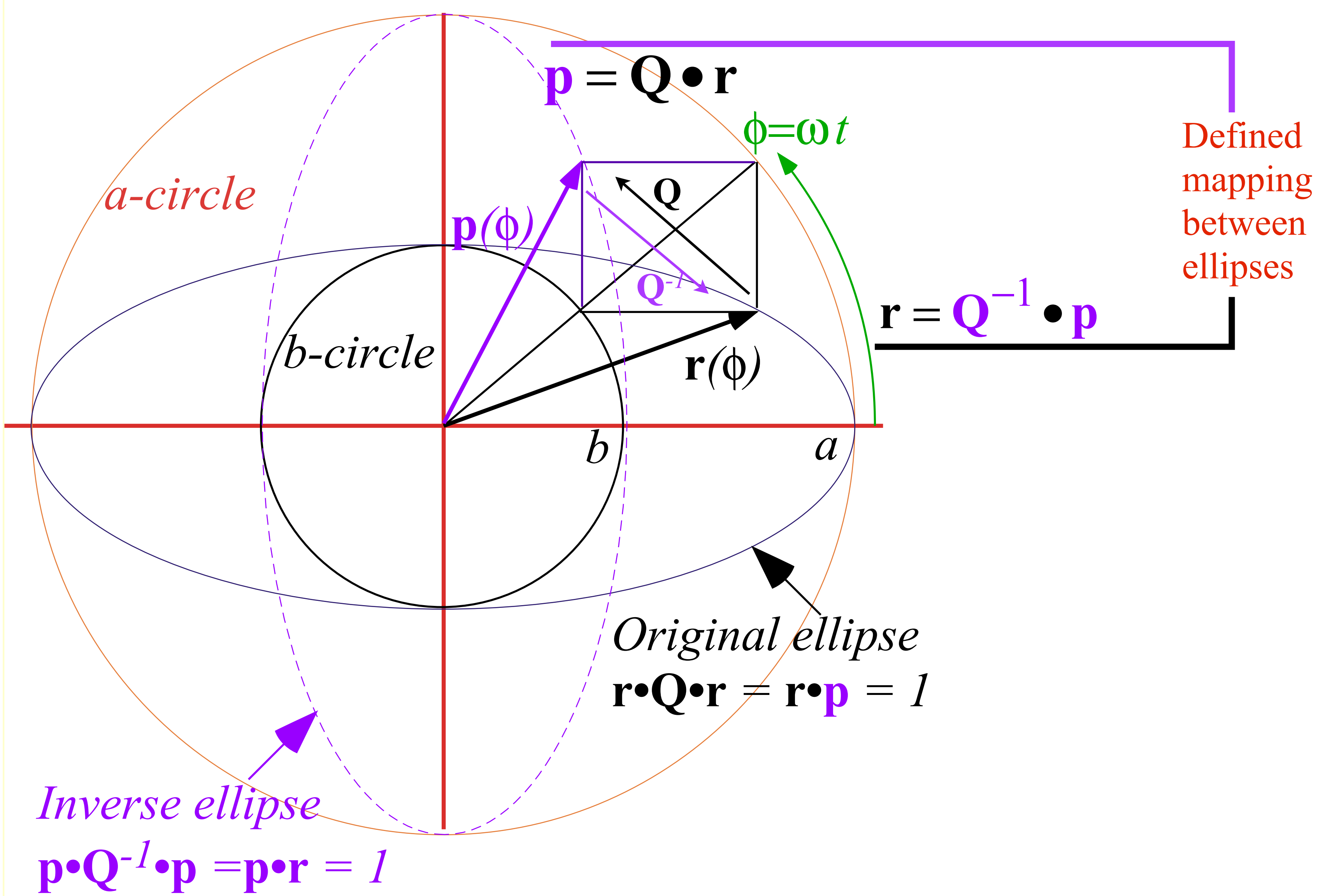
Here plot of **p**-ellipse is re-scaled by scalefactor $S=a\cdot b$

p-ellipse x-radius=$1/a$ plotted at: $S(1/a)=b$ (=1 for a=2, b=1)

p-ellipse y-radius=$1/b$ plotted at: $S(1/b)=a$ (=2 for a=2, b=1)

(a) Quadratic form ellipse and *Inverse quadratic form ellipse*

based on
Unit 1
Fig. 11.6



Quadratic form **r•Q•r** $=1$ *has mutual duality relations with inverse form* **p•Q**$^{-1}$**•p** $=1=$ **p•r**

$$\mathbf{p}=\mathbf{Q}\bullet\mathbf{r}=\overbrace{\begin{pmatrix}1/a^2 & 0\\ 0 & 1/b^2\end{pmatrix}}^{\mathbf{Q}}\bullet\overbrace{\begin{pmatrix}x\\ y\end{pmatrix}}^{\mathbf{r}}=\overbrace{\begin{pmatrix}x/a^2\\ y/b^2\end{pmatrix}}^{\mathbf{p}}=\begin{pmatrix}(1/a)\cos\phi\\ (1/b)\sin\phi\end{pmatrix}$$

where: $x=r_x=a\cos\phi=a\cos\omega t$, $y=r_y=b\sin\phi\ =b\sin\omega t$ so: $\boxed{\mathbf{p}\bullet\mathbf{r}=1}$

Here plot of **p**-ellipse is re-scaled by scalefactor $S=a\cdot b$

p-ellipse x-radius=$1/a$ plotted at: $S(1/a)=b$ (=1 for a=2, b=1)

p-ellipse y-radius=$1/b$ plotted at: $S(1/b)=a$ (=2 for a=2, b=1)

Link ⇒ BoxIt simulation of IHO orbits
Link → IHO orbital time rates of change
Link → IHO Exegesis Plot

Introduction to dual matrix operator geometry (based on IHO orbits)

Quadratic form ellipse $\mathbf{r}\bullet Q\bullet\mathbf{r}=1$ *vs.inverse form ellipse* $\mathbf{p}\bullet Q^{-1}\bullet\mathbf{p}=1$

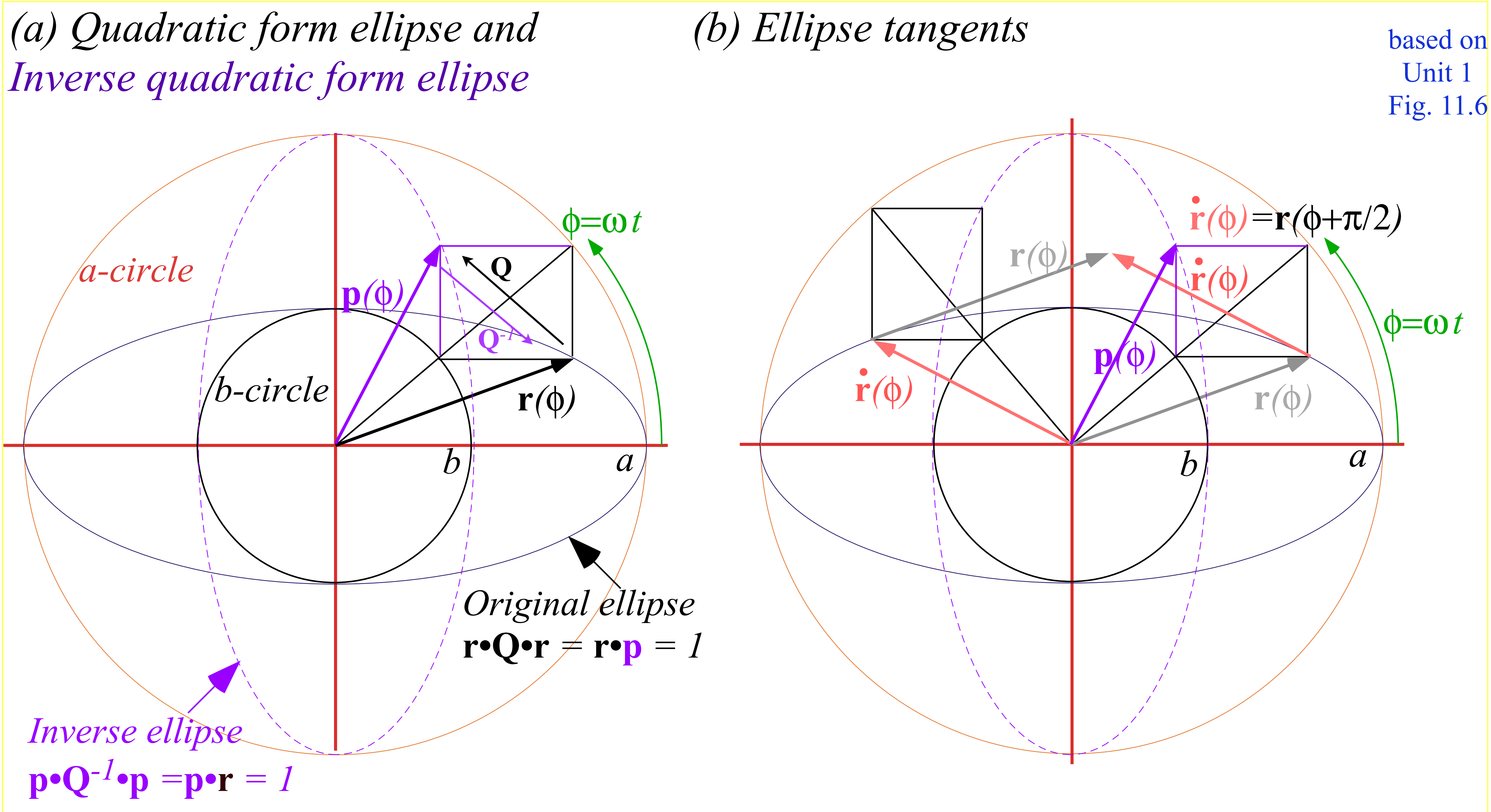
Duality norm relations $(\mathbf{r}\bullet\mathbf{p}=1)$

→ *Q-Ellipse tangents* $\mathbf{r}'$ *normal to dual* Q^{-1}*-ellipse position* $\mathbf{p}$ $(\mathbf{r}'\bullet\mathbf{p}=0=\mathbf{r}\bullet\mathbf{p}')$

Operator geometric sequences and eigenvectors

Alternative scaling of matrix operator geometry

Vector calculus of tensor operation



Quadratic form **r•Q•r** *=1 has mutual duality relations with inverse form* **p•Q**$^{-1}$**•p** *=1=* **p•r**

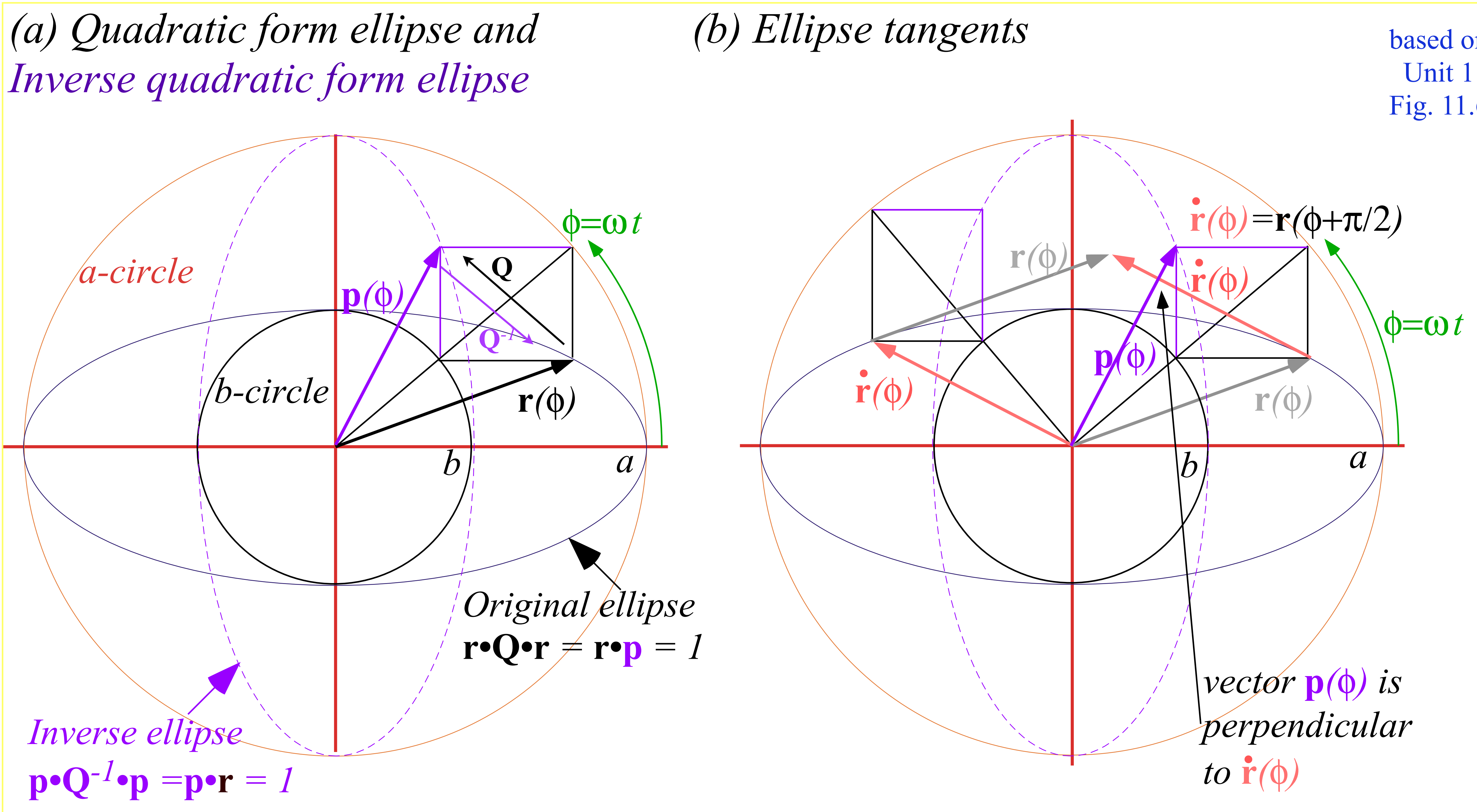
$$\mathbf{p}=\mathbf{Q}\cdot\mathbf{r}=\begin{pmatrix}1/a^2 & 0\\ 0 & 1/b^2\end{pmatrix}\bullet\begin{pmatrix}x\\ y\end{pmatrix}=\begin{pmatrix}x/a^2\\ y/b^2\end{pmatrix}=\begin{pmatrix}(1/a)\cos\phi\\ (1/b)\sin\phi\end{pmatrix}$$

where: $x=r_x=a\cos\phi=a\cos\omega t$, $y=r_y=b\sin\phi=b\sin\omega t$ so: $\mathbf{p}\cdot\mathbf{r}=1$

Here plot of **p**-ellipse is re-scaled by scalefactor $S=a\cdot b$

p-ellipse x-radius=$1/a$ plotted at: $S(1/a)=b$ (=1 for a=2, b=1)

p-ellipse y-radius=$1/b$ plotted at: $S(1/b)=a$ (=2 for a=2, b=1)



Quadratic form $\mathbf{r}\bullet\mathbf{Q}\bullet\mathbf{r} = 1$ *has mutual duality relations with inverse form* $\mathbf{p}\bullet\mathbf{Q}^{-1}\bullet\mathbf{p} = 1 = \mathbf{p}\bullet\mathbf{r}$

$$\mathbf{p} = \mathbf{Q}\bullet\mathbf{r} = \begin{pmatrix} 1/a^2 & 0 \\ 0 & 1/b^2 \end{pmatrix}\bullet\begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} x/a^2 \\ y/b^2 \end{pmatrix} = \begin{pmatrix} (1/a)\cos\phi \\ (1/b)\sin\phi \end{pmatrix}$$

where: $x = r_x = a\cos\phi = a\cos\omega t$, $y = r_y = b\sin\phi = b\sin\omega t$

so: $\boxed{\mathbf{p}\bullet\mathbf{r} = 1}$

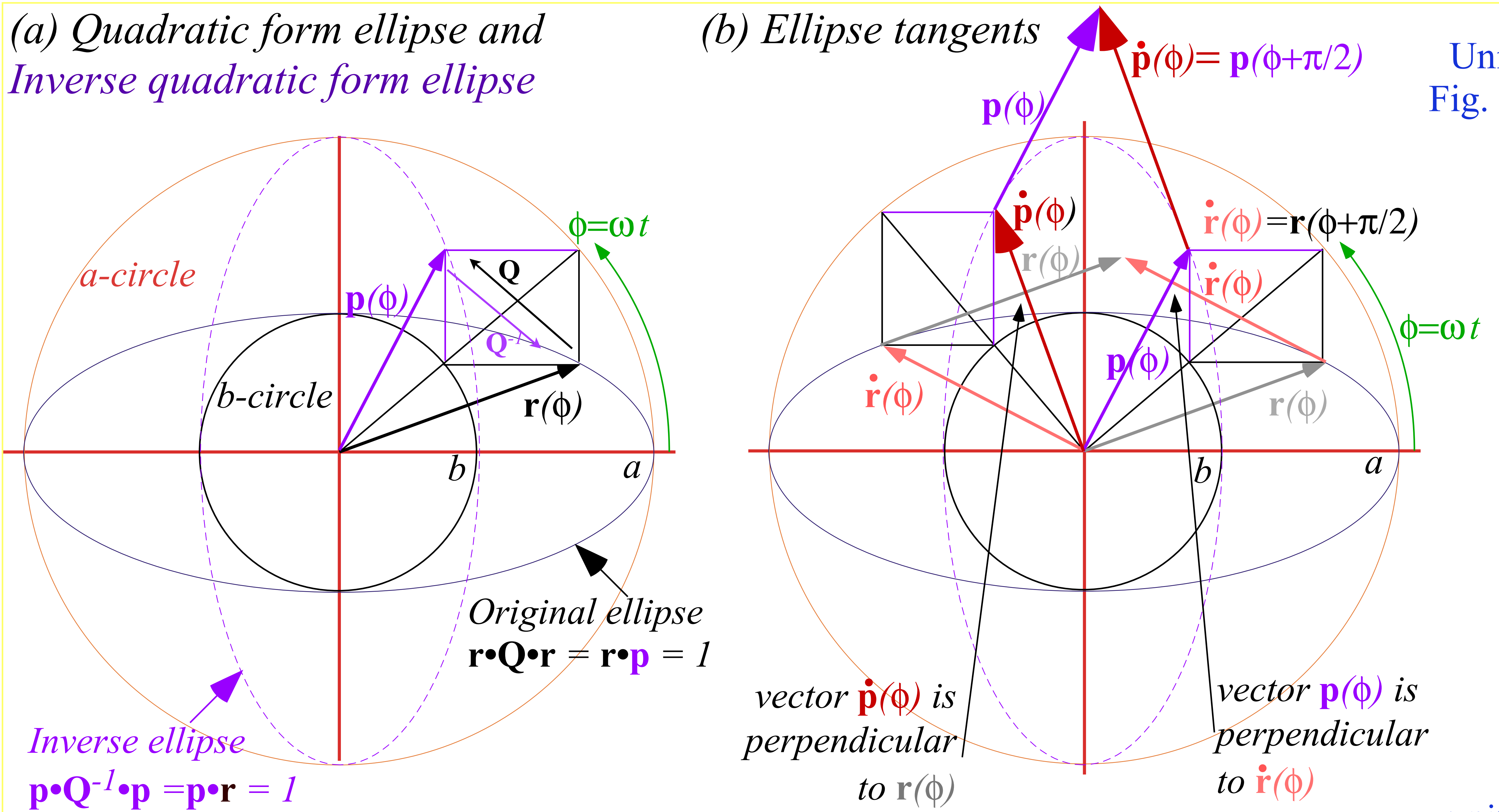
$\mathbf{p}$ *is perpendicular to velocity* $\mathbf{v}=\dot{\mathbf{r}}$ *, a mutual orthogonality*

$$\boxed{\dot{\mathbf{r}}\bullet\mathbf{p} = 0} = \begin{pmatrix} \dot{r}_x & \dot{r}_y \end{pmatrix}\bullet\begin{pmatrix} p_x \\ p_y \end{pmatrix} = \begin{pmatrix} -a\sin\phi & b\cos\phi \end{pmatrix}\bullet\begin{pmatrix} (1/a)\cos\phi \\ (1/b)\sin\phi \end{pmatrix}$$

where: $\dot{r}_x = -a\sin\phi$, $\dot{r}_y = b\cos\phi$

and: $p_x = (1/a)\cos\phi$, $p_y = (1/b)\sin\phi$

Unit 1
Fig. 11.6



Quadratic form **r•Q•r** *=1 has mutual duality relations with inverse form* **p•Q**$^{-1}$**•p** *=1*   *unit mutual projection*

$$\mathbf{p}=\mathbf{Q}\bullet\mathbf{r}=\begin{pmatrix}1/a^2 & 0\\ 0 & 1/b^2\end{pmatrix}\bullet\begin{pmatrix}x\\ y\end{pmatrix}=\begin{pmatrix}x/a^2\\ y/b^2\end{pmatrix}=\begin{pmatrix}(1/a)\cos\phi\\ (1/b)\sin\phi\end{pmatrix}$$

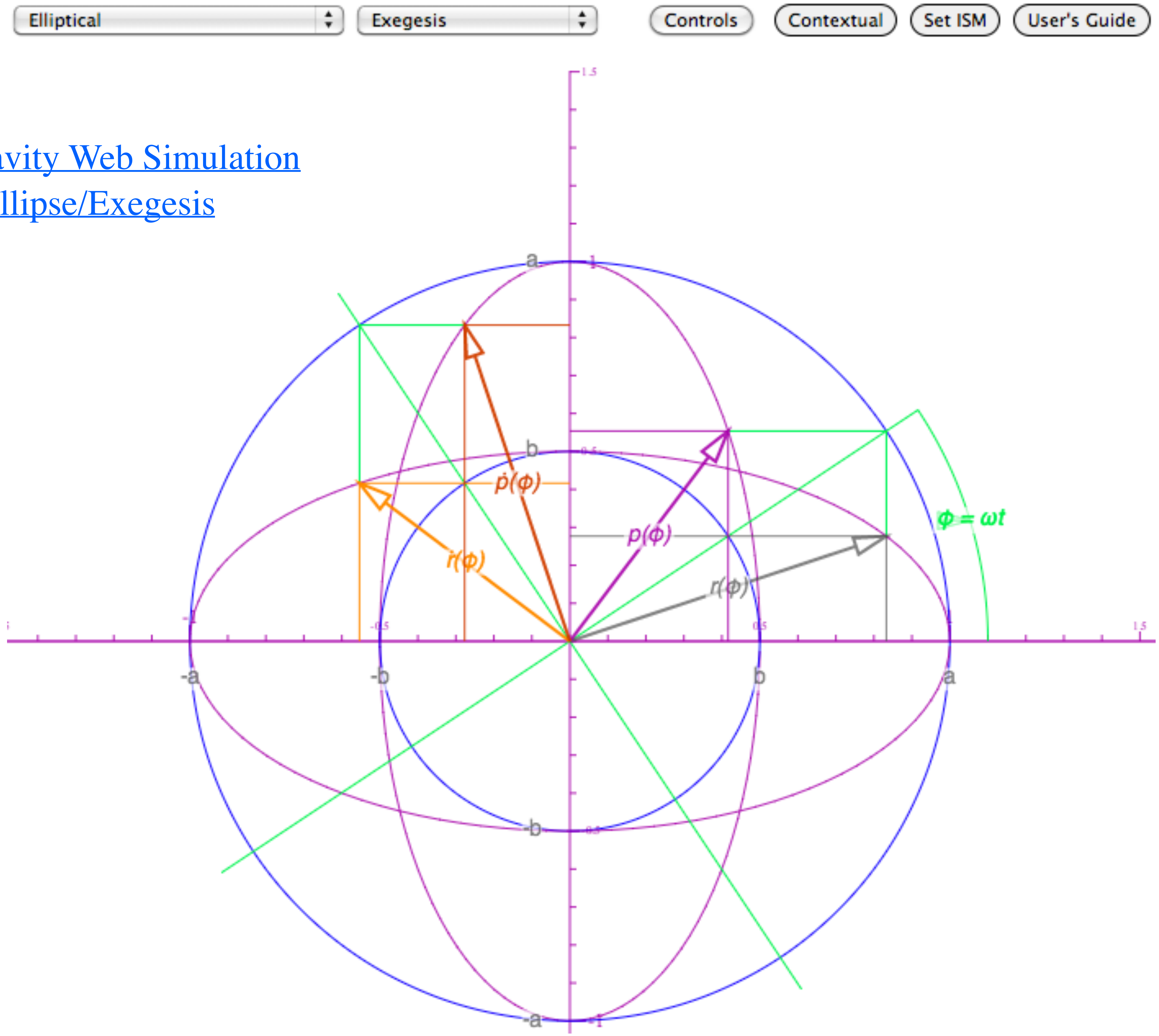
where: $x=r_x=a\cos\phi=a\cos\omega t$, $y=r_y=b\sin\phi\ \ =b\sin\omega t$ so: $\boxed{\mathbf{p}\bullet\mathbf{r}=1}$

p *is perpendicular to velocity* **v**=**ṙ** *, a mutual orthogonality. So is* **r** *perpendicular to* **ṗ**: $\boxed{\dot{\mathbf{p}}\bullet\mathbf{r}=0}$

$$\boxed{\dot{\mathbf{r}}\bullet\mathbf{p}=0}=\begin{pmatrix}\dot{r}_x & \dot{r}_y\end{pmatrix}\bullet\begin{pmatrix}p_x\\ p_y\end{pmatrix}=\begin{pmatrix}-a\sin\phi & b\cos\phi\end{pmatrix}\bullet\begin{pmatrix}(1/a)\cos\phi\\ (1/b)\sin\phi\end{pmatrix}$$

where: $\dot{r}_x=-a\sin\phi$, $\dot{r}_y=b\cos\phi$ and: $p_x=(1/a)\cos\phi$, $p_y=(1/b)\sin\phi$

RelaWavity Web Simulation
Ellipse/Exegesis



Geometry of dual ellipse Kepler anomalies for vectors [$\mathbf{r}(\phi)$, $\mathbf{p}(\phi)$] and $^{d}/_{dt}$[$\mathbf{r}(\phi)$, $\mathbf{p}(\phi)$,] *in coordinate (x,y) space rendered by animation web-app in RelaWavity and described in Lect. 12-advanced.*

Introduction to dual matrix operator geometry (based on IHO orbits)

Quadratic form ellipse $\mathbf{r}\bullet Q\bullet\mathbf{r}=1$ *vs.inverse form ellipse* $\mathbf{p}\bullet Q^{-1}\bullet\mathbf{p}=1$

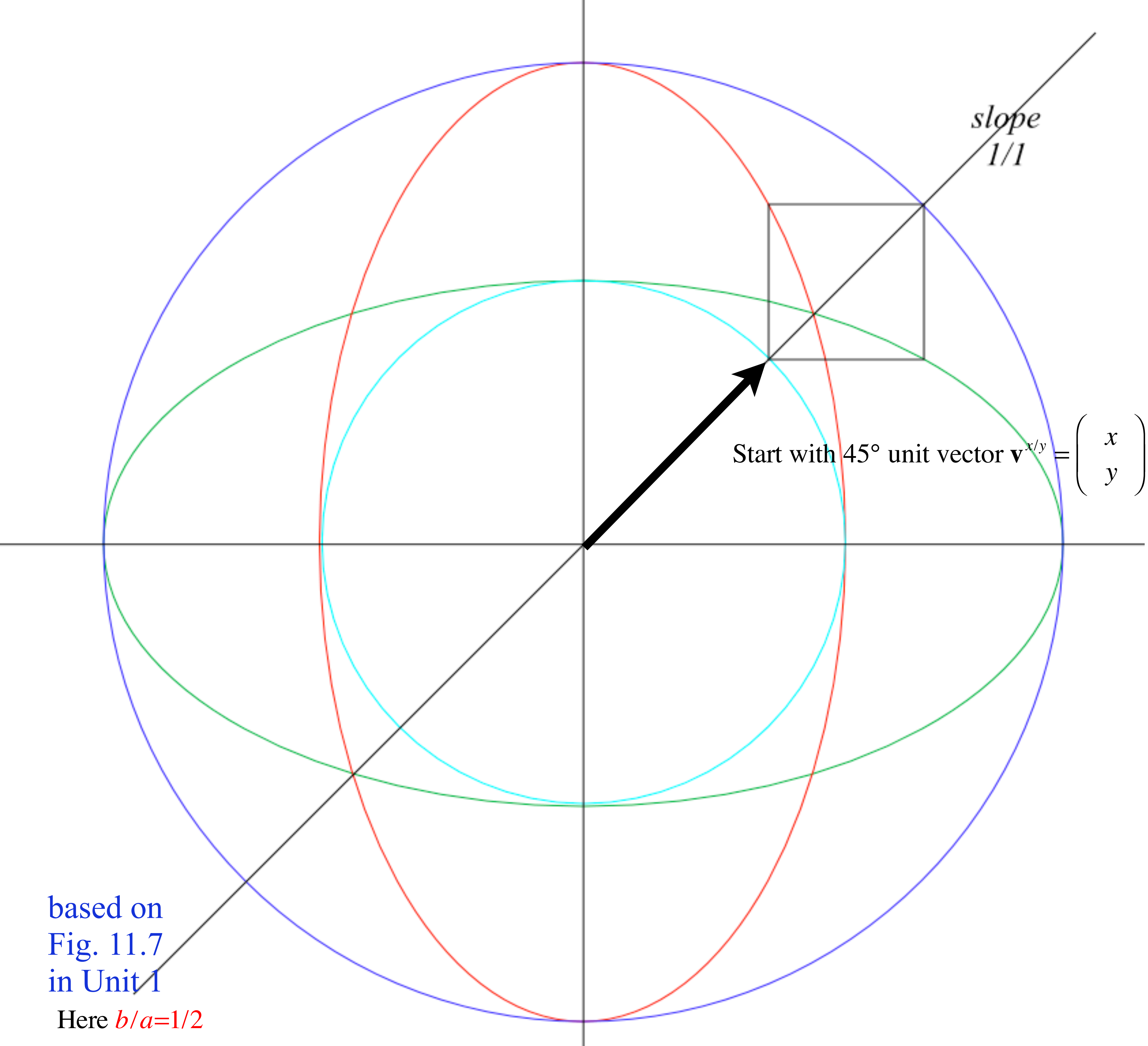
Duality norm relations ($\mathbf{r}\bullet\mathbf{p}=1$)

Q-Ellipse tangents $\mathbf{r}'$ *normal to dual* Q^{-1}*-ellipse position* $\mathbf{p}$ ($\mathbf{r}'\bullet\mathbf{p}=0=\mathbf{r}\bullet\mathbf{p}'$)

→ *Operator geometric sequences and eigenvectors*

Alternative scaling of matrix operator geometry

Vector calculus of tensor operation



Start with 45° unit vector $\mathbf{v}^{x/y} = \begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} 1/\sqrt{2} \\ 1/\sqrt{2} \end{pmatrix}$.

based on
Fig. 11.7
in Unit 1

Here b/a=1/2

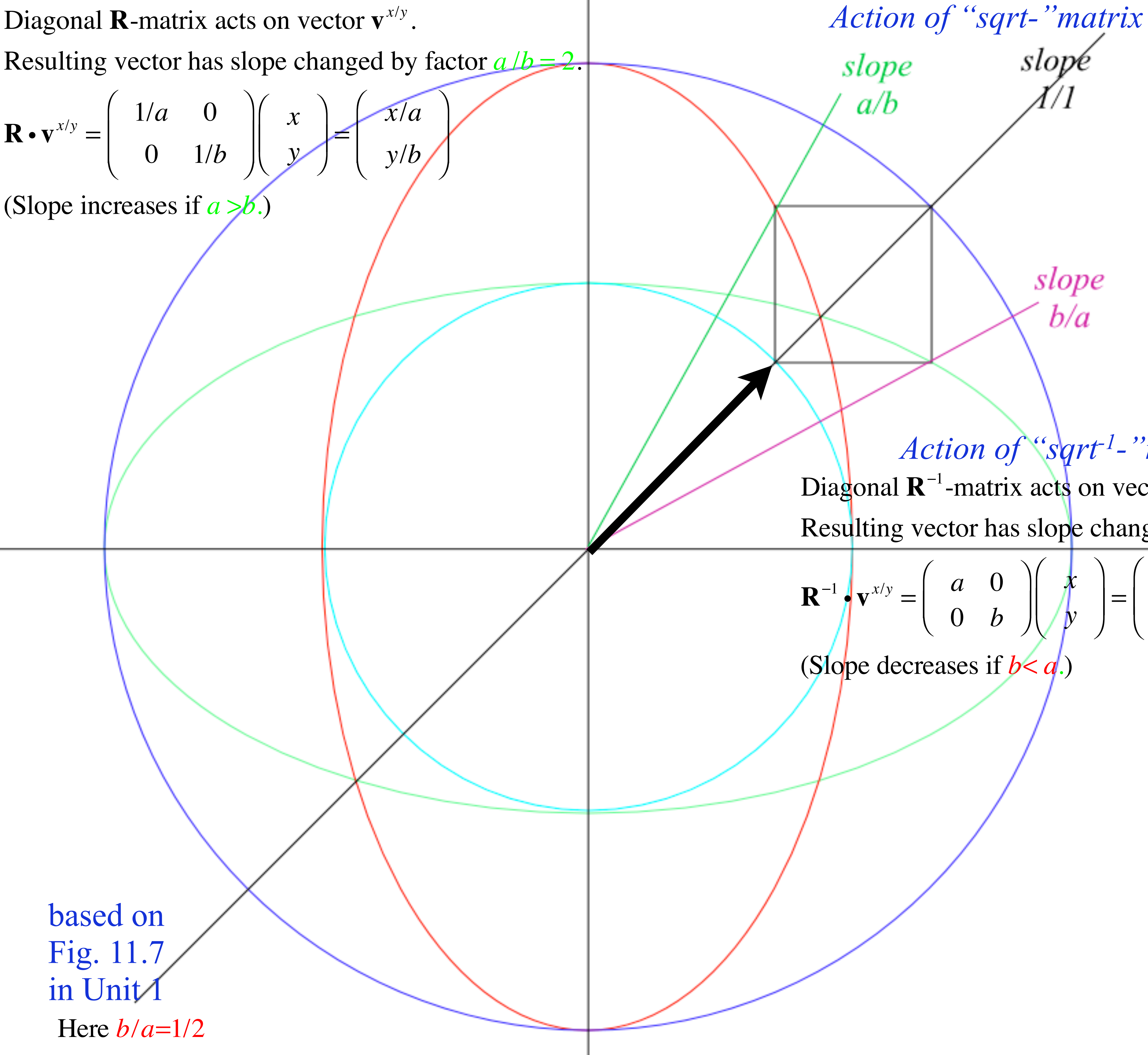
Diagonal **R**-matrix acts on vector $\mathbf{v}^{x/y}$.

Resulting vector has slope changed by factor $a/b = 2$.

$$\mathbf{R}\bullet\mathbf{v}^{x/y} = \begin{pmatrix} 1/a & 0 \\ 0 & 1/b \end{pmatrix}\begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} x/a \\ y/b \end{pmatrix}$$

(Slope increases if $a > b$.)

Action of "sqrt-"matrix $R=\sqrt{Q}$



Action of "sqrt^{-1}-"matrix $R^{-1} = \sqrt{Q}^{-1}$

Diagonal $\mathbf{R}^{-1}$-matrix acts on vector $\mathbf{v}^{x/y}$.

Resulting vector has slope changed by factor b/a.

$$\mathbf{R}^{-1}\bullet\mathbf{v}^{x/y} = \begin{pmatrix} a & 0 \\ 0 & b \end{pmatrix}\begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} x\cdot a \\ y\cdot b \end{pmatrix}$$

(Slope decreases if $b < a$.)

based on
Fig. 11.7
in Unit 1

Here $b/a=1/2$

Diagonal **R**-matrix acts on vector $\mathbf{v}^{x/y}$.

Resulting vector has slope changed by factor $a/b=2$.

$$\mathbf{R}\bullet\mathbf{v}^{x/y}=\begin{pmatrix}1/a & 0\\ 0 & 1/b\end{pmatrix}\begin{pmatrix}x\\ y\end{pmatrix}=\begin{pmatrix}x/a\\ y/b\end{pmatrix}$$

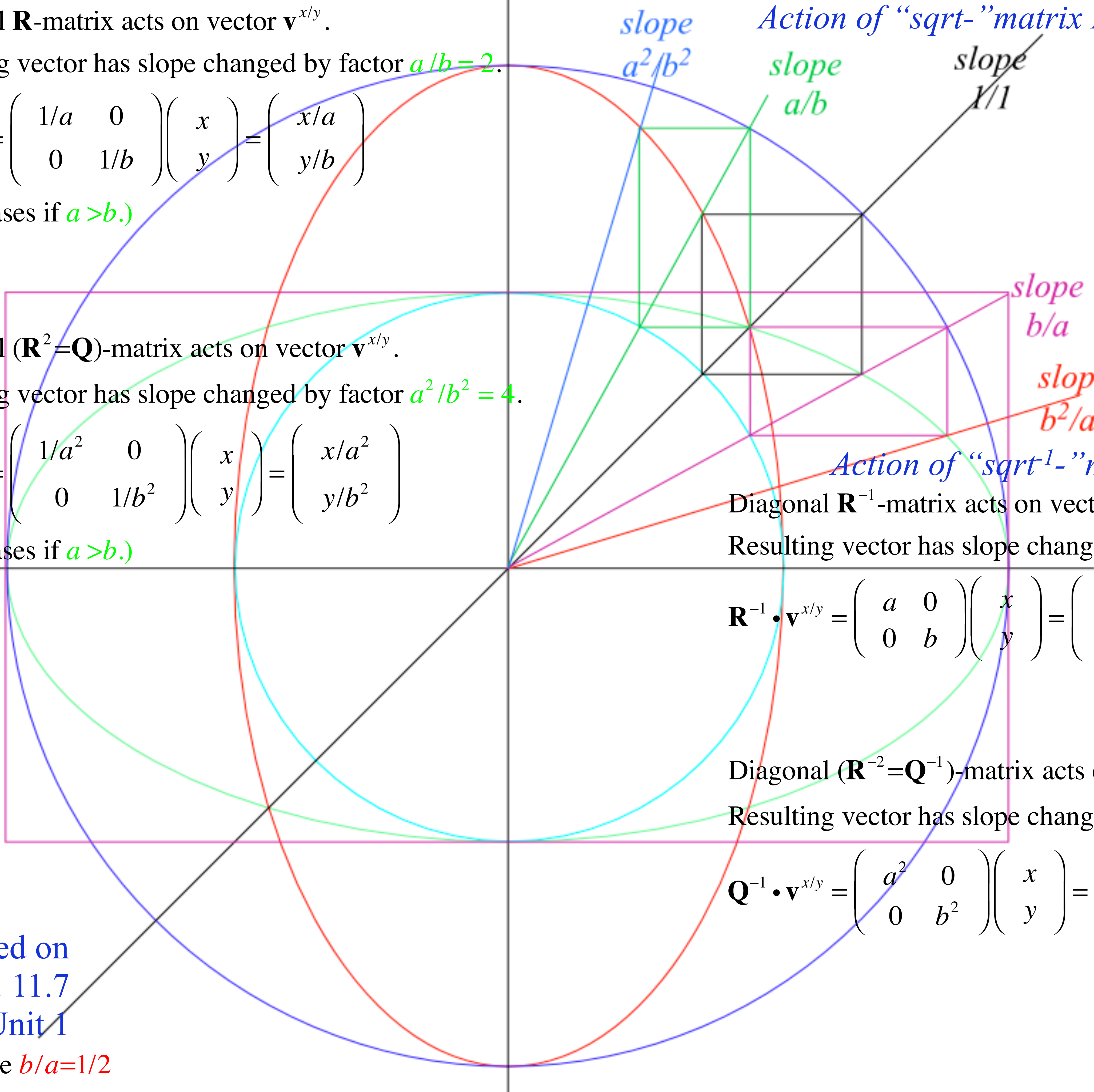
(It increases if $a>b$.)

Diagonal ($\mathbf{R}^2=\mathbf{Q}$)-matrix acts on vector $\mathbf{v}^{x/y}$.

Resulting vector has slope changed by factor $a^2/b^2=4$.

$$\mathbf{Q}\bullet\mathbf{v}^{x/y}=\begin{pmatrix}1/a^2 & 0\\ 0 & 1/b^2\end{pmatrix}\begin{pmatrix}x\\ y\end{pmatrix}=\begin{pmatrix}x/a^2\\ y/b^2\end{pmatrix}$$

(It increases if $a>b$.)



Diagonal $\mathbf{R}^{-1}$-matrix acts on vector $\mathbf{v}^{x/y}$.

Resulting vector has slope changed by factor $b/a=1/2$.

$$\mathbf{R}^{-1}\bullet\mathbf{v}^{x/y}=\begin{pmatrix}a & 0\\ 0 & b\end{pmatrix}\begin{pmatrix}x\\ y\end{pmatrix}=\begin{pmatrix}x\cdot a\\ y\cdot b\end{pmatrix}$$

Diagonal ($\mathbf{R}^{-2}=\mathbf{Q}^{-1}$)-matrix acts on vector $\mathbf{v}^{x/y}$.

Resulting vector has slope changed by factor $b^2/a^2=1/4$.

$$\mathbf{Q}^{-1}\bullet\mathbf{v}^{x/y}=\begin{pmatrix}a^2 & 0\\ 0 & b^2\end{pmatrix}\begin{pmatrix}x\\ y\end{pmatrix}=\begin{pmatrix}x\cdot a^2\\ y\cdot b^2\end{pmatrix}$$

based on
Fig. 11.7
in Unit 1

Here $b/a=1/2$

Diagonal **R**-matrix acts on vector $\mathbf{v}^{x/y}$.

Resulting vector has slope changed by factor $a/b=2$.

$$\mathbf{R}\bullet\mathbf{v}^{x/y}=\begin{pmatrix}1/a & 0\\ 0 & 1/b\end{pmatrix}\begin{pmatrix}x\\ y\end{pmatrix}=\begin{pmatrix}x/a\\ y/b\end{pmatrix}$$

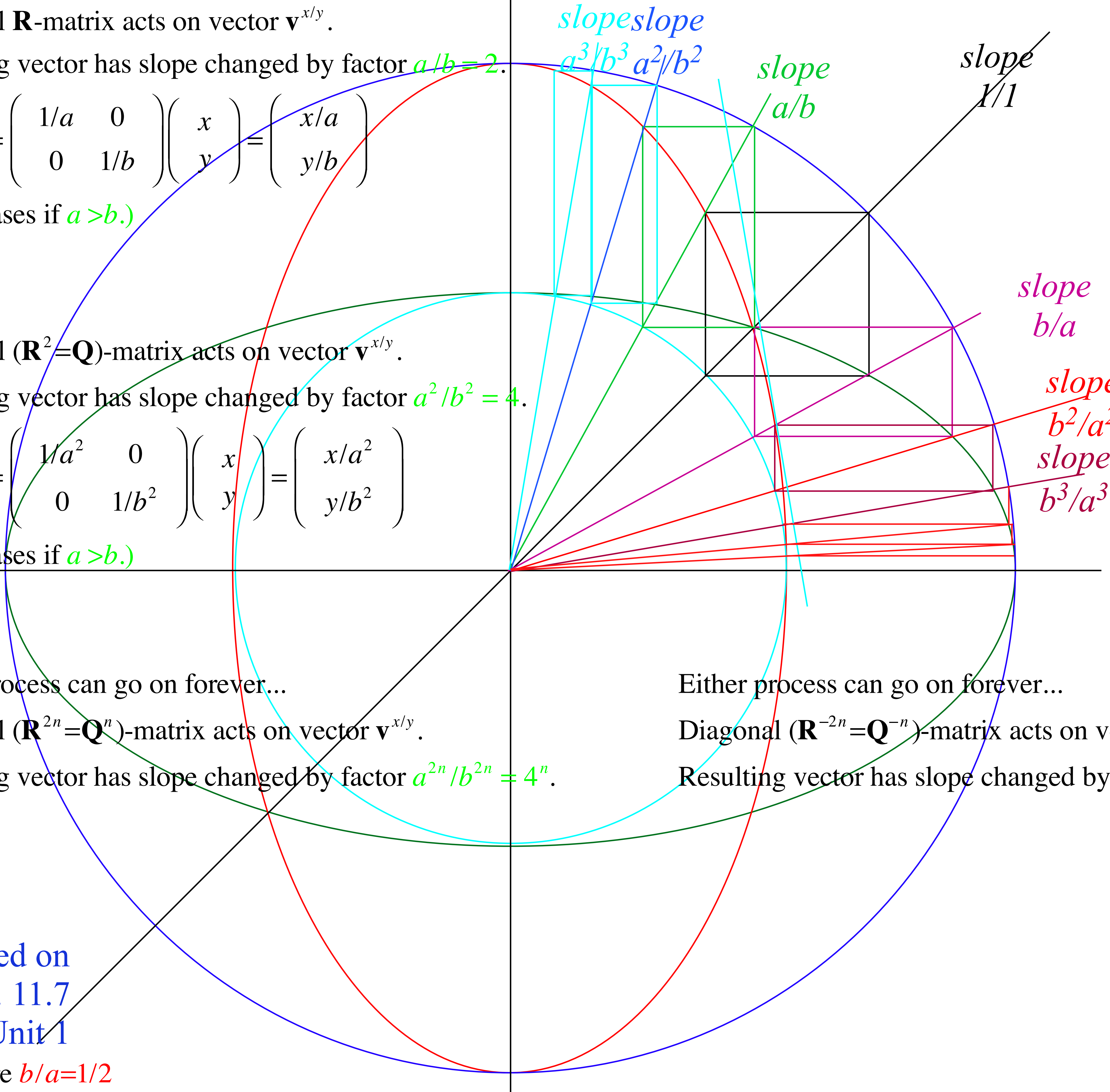
(It increases if $a>b$.)

Diagonal ($\mathbf{R}^2$=**Q**)-matrix acts on vector $\mathbf{v}^{x/y}$.

Resulting vector has slope changed by factor $a^2/b^2=4$.

$$\mathbf{Q}\bullet\mathbf{v}^{x/y}=\begin{pmatrix}1/a^2 & 0\\ 0 & 1/b^2\end{pmatrix}\begin{pmatrix}x\\ y\end{pmatrix}=\begin{pmatrix}x/a^2\\ y/b^2\end{pmatrix}$$

(It increases if $a>b$.)



Either process can go on forever...

Diagonal ($\mathbf{R}^{2n}$=$\mathbf{Q}^n$)-matrix acts on vector $\mathbf{v}^{x/y}$.

Resulting vector has slope changed by factor $a^{2n}/b^{2n}=4^n$.

Either process can go on forever...

Diagonal ($\mathbf{R}^{-2n}$=$\mathbf{Q}^{-n}$)-matrix acts on vector $\mathbf{v}^{x/y}$.

Resulting vector has slope changed by factor $b^{2n}/a^{2n}=4^{-n}$.

based on
Fig. 11.7
in Unit 1

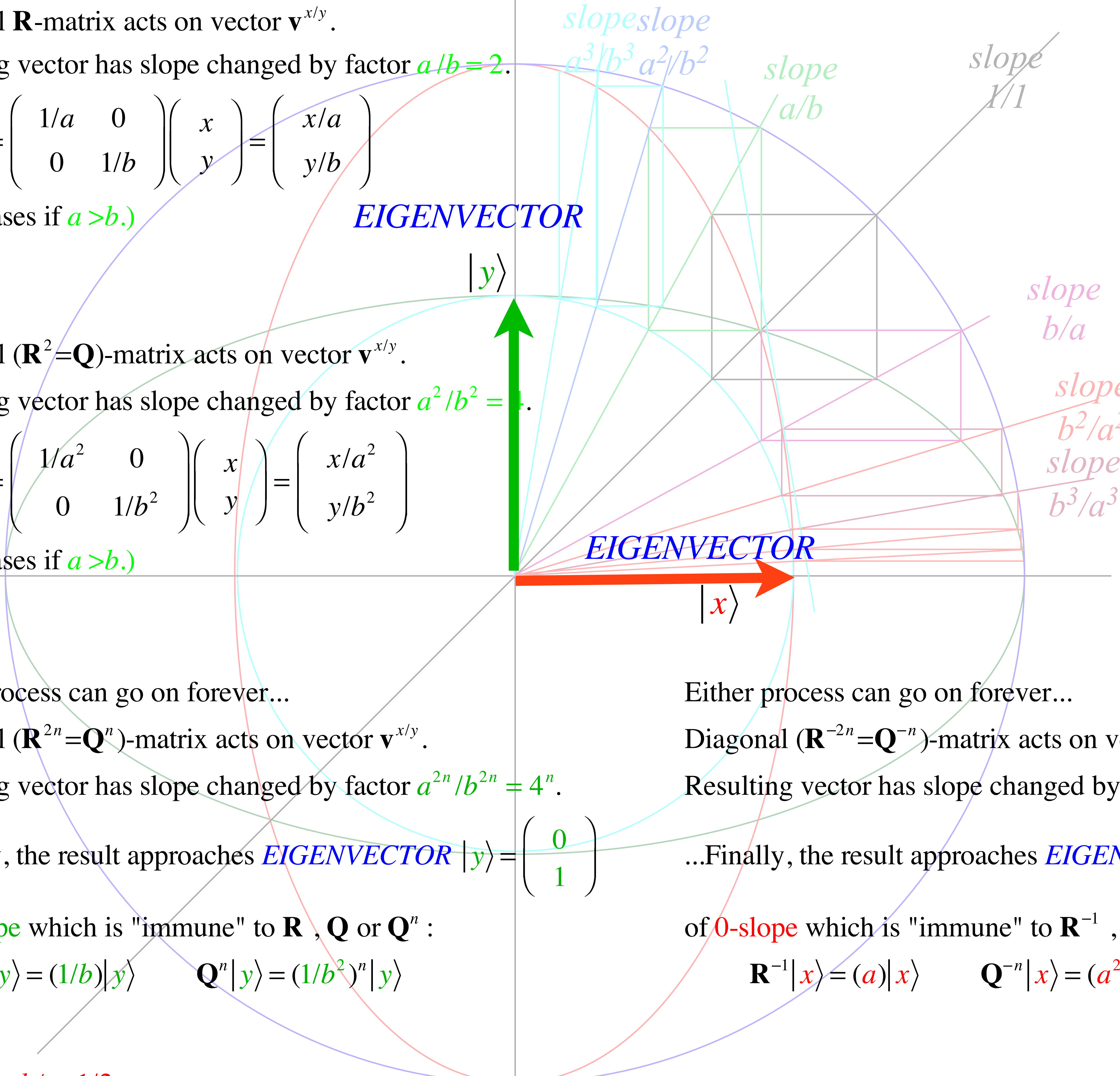
Here b/a=1/2

Diagonal **R**-matrix acts on vector $\mathbf{v}^{x/y}$.

Resulting vector has slope changed by factor $a/b = 2$.

$$\mathbf{R}\bullet\mathbf{v}^{x/y} = \begin{pmatrix} 1/a & 0 \\ 0 & 1/b \end{pmatrix}\begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} x/a \\ y/b \end{pmatrix}$$

(It increases if $a > b$.)



Diagonal ($\mathbf{R}^2 = \mathbf{Q}$)-matrix acts on vector $\mathbf{v}^{x/y}$.

Resulting vector has slope changed by factor $a^2/b^2 = 4$.

$$\mathbf{Q}\bullet\mathbf{v}^{x/y} = \begin{pmatrix} 1/a^2 & 0 \\ 0 & 1/b^2 \end{pmatrix}\begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} x/a^2 \\ y/b^2 \end{pmatrix}$$

(It increases if $a > b$.)

Either process can go on forever...

Diagonal ($\mathbf{R}^{2n} = \mathbf{Q}^n$)-matrix acts on vector $\mathbf{v}^{x/y}$.

Resulting vector has slope changed by factor $a^{2n}/b^{2n} = 4^n$.

...Finally, the result approaches *EIGENVECTOR* $|y\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$

of ∞-slope which is "immune" to **R** , **Q** or $\mathbf{Q}^n$:

$$\mathbf{R}|y\rangle = (1/b)|y\rangle \qquad \mathbf{Q}^n|y\rangle = (1/b^2)^n|y\rangle$$

Either process can go on forever...

Diagonal ($\mathbf{R}^{-2n} = \mathbf{Q}^{-n}$)-matrix acts on vector $\mathbf{v}^{x/y}$.

Resulting vector has slope changed by factor $b^{2n}/a^{2n} = 4^{-n}$.

...Finally, the result approaches *EIGENVECTOR* $|x\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$

of 0-slope which is "immune" to $\mathbf{R}^{-1}$, $\mathbf{Q}^{-1}$ or $\mathbf{Q}^{-n}$:

$$\mathbf{R}^{-1}|x\rangle = (a)|x\rangle \qquad \mathbf{Q}^{-n}|x\rangle = (a^2)^n|x\rangle$$

Here $b/a = 1/2$

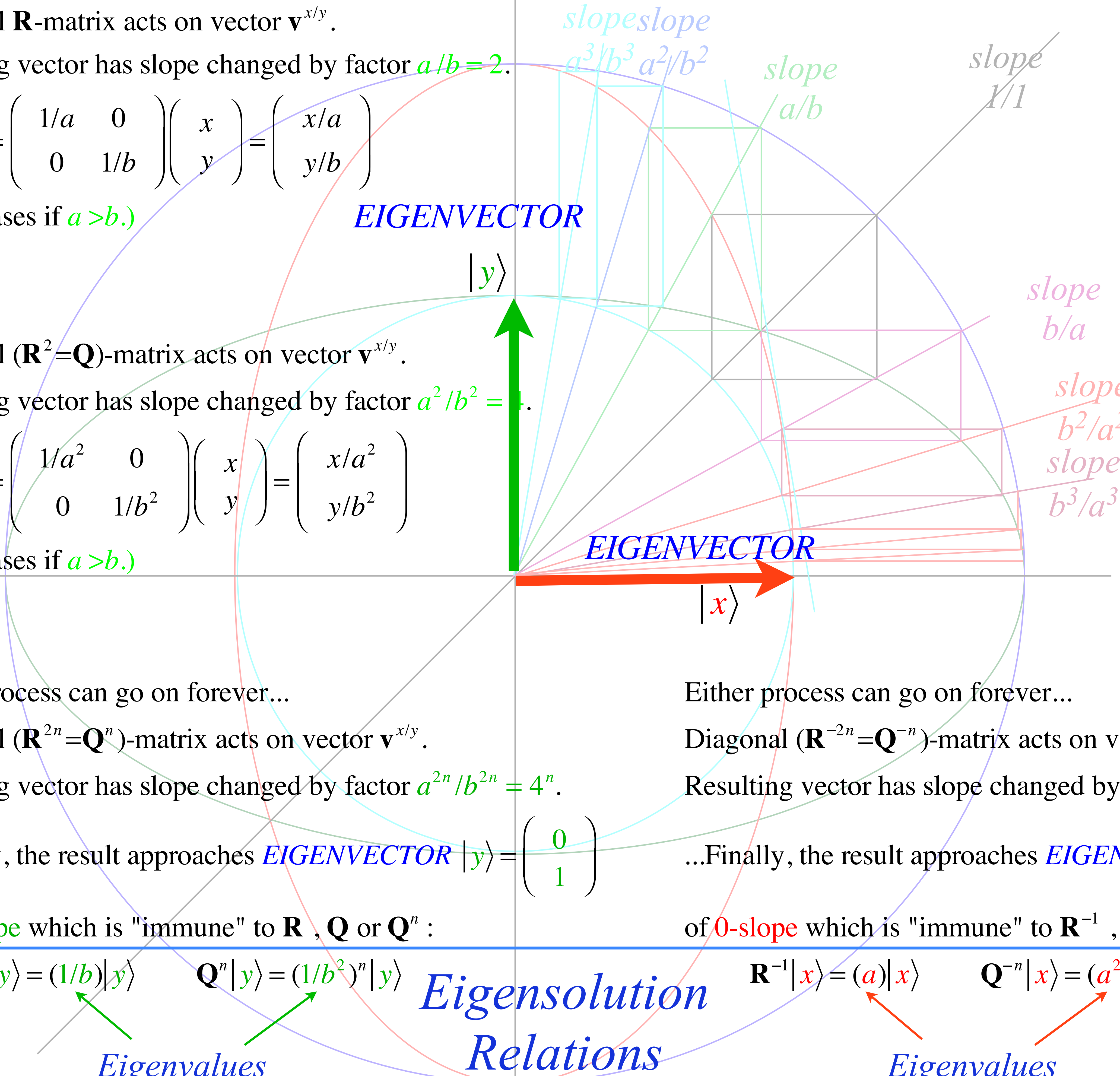
Diagonal **R**-matrix acts on vector $\mathbf{v}^{x/y}$.

Resulting vector has slope changed by factor $a/b = 2$.

$$\mathbf{R}\bullet\mathbf{v}^{x/y} = \begin{pmatrix} 1/a & 0 \\ 0 & 1/b \end{pmatrix}\begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} x/a \\ y/b \end{pmatrix}$$

(It increases if $a > b$.)

Here $b/a = 1/2$



Diagonal ($\mathbf{R}^2 = \mathbf{Q}$)-matrix acts on vector $\mathbf{v}^{x/y}$.

Resulting vector has slope changed by factor $a^2/b^2 = 4$.

$$\mathbf{Q}\bullet\mathbf{v}^{x/y} = \begin{pmatrix} 1/a^2 & 0 \\ 0 & 1/b^2 \end{pmatrix}\begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} x/a^2 \\ y/b^2 \end{pmatrix}$$

(It increases if $a > b$.)

Either process can go on forever...

Diagonal ($\mathbf{R}^{2n} = \mathbf{Q}^n$)-matrix acts on vector $\mathbf{v}^{x/y}$.

Resulting vector has slope changed by factor $a^{2n}/b^{2n} = 4^n$.

...Finally, the result approaches *EIGENVECTOR* $|y\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$

of ∞-slope which is "immune" to **R** , **Q** or $\mathbf{Q}^n$:

Either process can go on forever...

Diagonal ($\mathbf{R}^{-2n} = \mathbf{Q}^{-n}$)-matrix acts on vector $\mathbf{v}^{x/y}$.

Resulting vector has slope changed by factor $b^{2n}/a^{2n} = 4^{-n}$.

...Finally, the result approaches *EIGENVECTOR* $|x\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$

of 0-slope which is "immune" to $\mathbf{R}^{-1}$, $\mathbf{Q}^{-1}$ or $\mathbf{Q}^{-n}$:

$\mathbf{R}|y\rangle = (1/b)|y\rangle$ $\qquad$ $\mathbf{Q}^n|y\rangle = (1/b^2)^n|y\rangle$

Eigenvalues

Eigensolution Relations

$\mathbf{R}^{-1}|x\rangle = (a)|x\rangle$ $\qquad$ $\mathbf{Q}^{-n}|x\rangle = (a^2)^n|x\rangle$

Eigenvalues

Introduction to dual matrix operator geometry (based on IHO orbits)

Quadratic form ellipse $\mathbf{r}\bullet Q\bullet\mathbf{r}=1$ *vs.inverse form ellipse* $\mathbf{p}\bullet Q^{-1}\bullet\mathbf{p}=1$

Duality norm relations ($\mathbf{r}\bullet\mathbf{p}=1$)

Q-Ellipse tangents $\mathbf{r}'$ *normal to dual* Q^{-1}*-ellipse position* $\mathbf{p}$ ($\mathbf{r}'\bullet\mathbf{p}=0=\mathbf{r}\bullet\mathbf{p}'$)

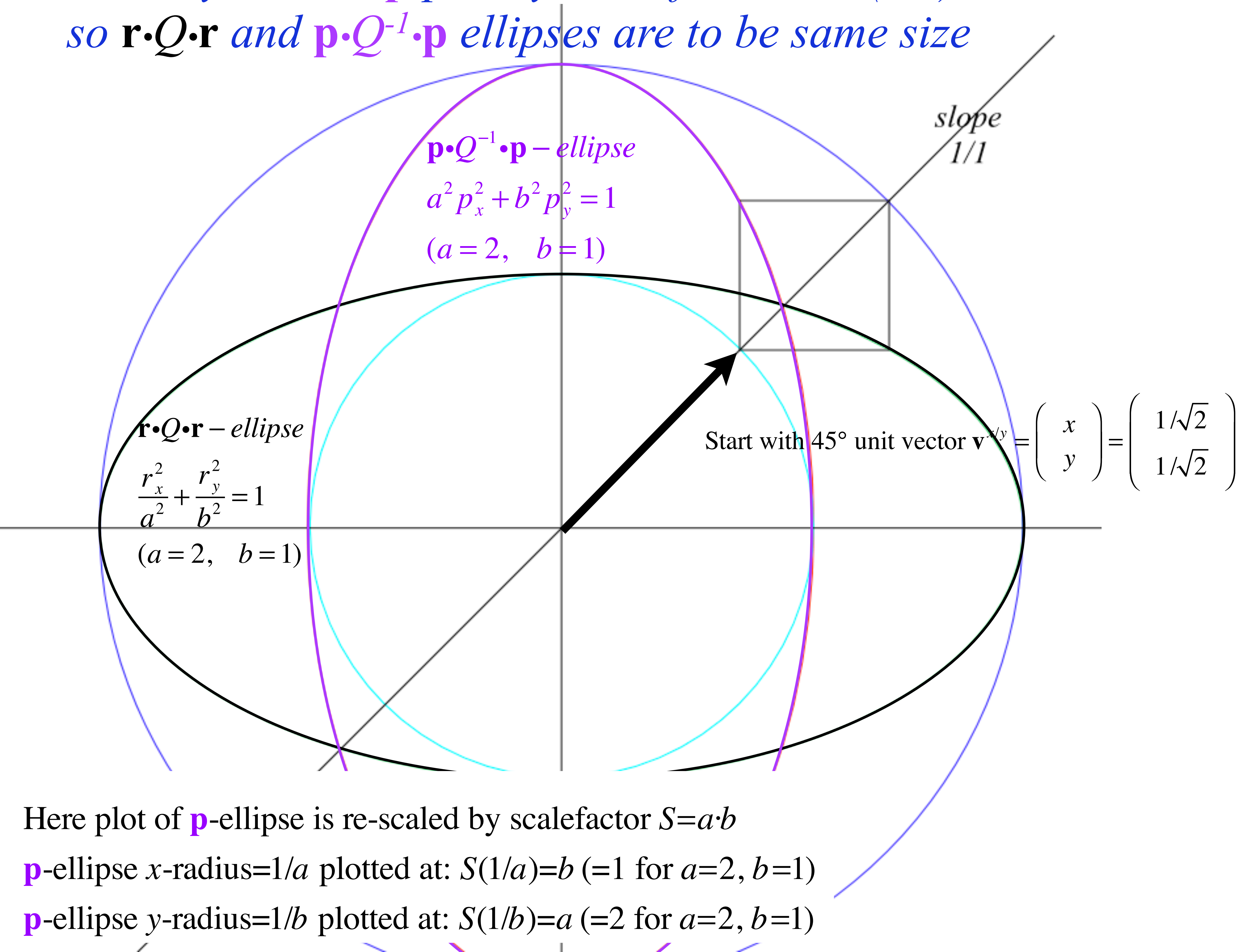
Operator geometric sequences and eigenvectors

→ *Alternative scaling of matrix operator geometry*

Vector calculus of tensor operation

You may rescale **p**-*plot by scale factor* $S=(a \cdot b)$
so $\mathbf{r} \cdot Q \cdot \mathbf{r}$ *and* $\mathbf{p} \cdot Q^{-1} \cdot \mathbf{p}$ *ellipses are to be same size*

Here $b/a=1/2$



Here plot of **p**-ellipse is re-scaled by scalefactor $S=a \cdot b$

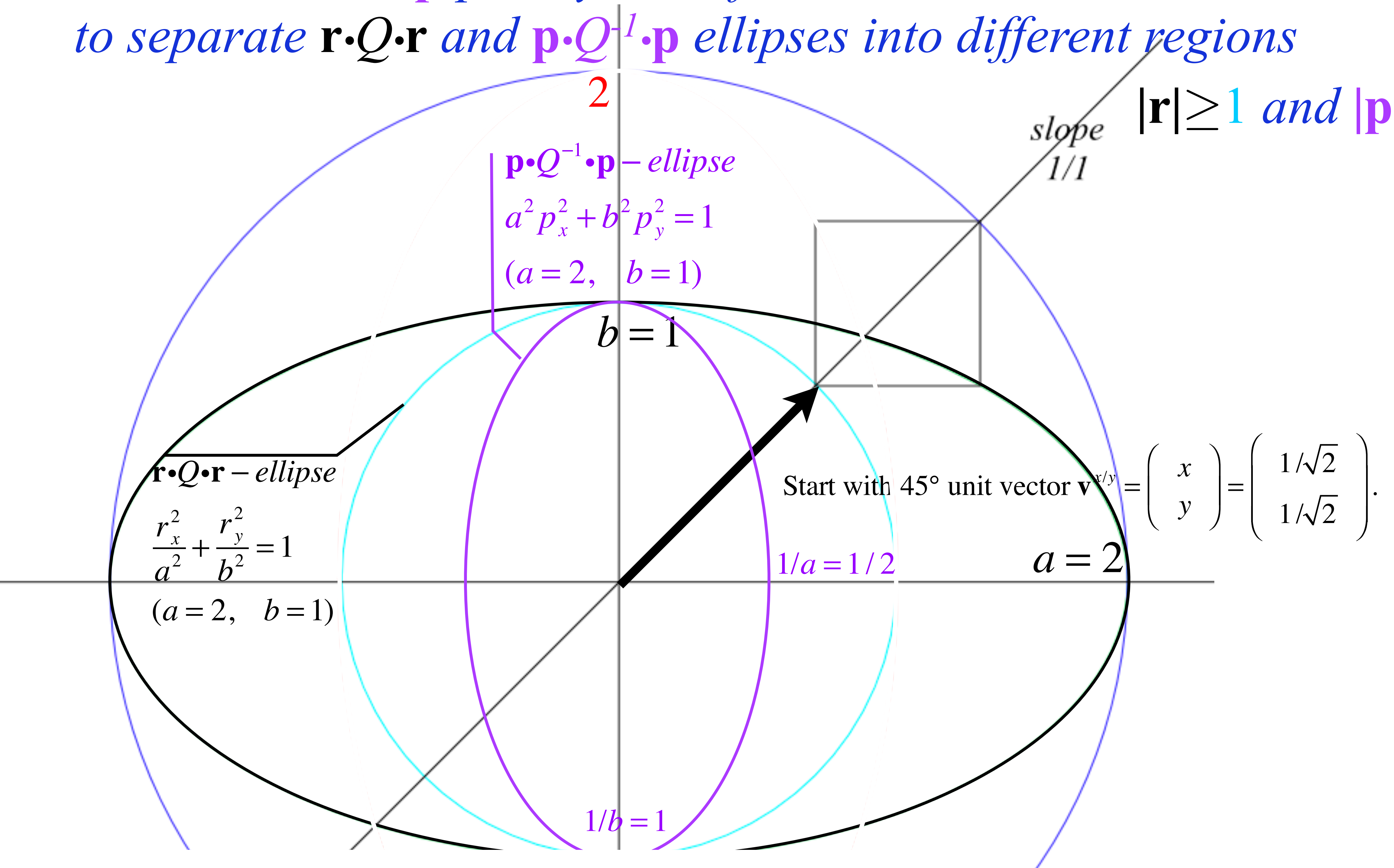
p-ellipse x-radius=$1/a$ plotted at: $S(1/a)=b$ (=1 for a=2, b=1)

p-ellipse y-radius=$1/b$ plotted at: $S(1/b)=a$ (=2 for a=2, b=1)

..or else rescale **p***-plot by scale factor S=b*

to separate **r**·*Q*·**r** *and* **p**·Q^{-1}·**p** *ellipses into different regions*

Here $b/a=1/2$



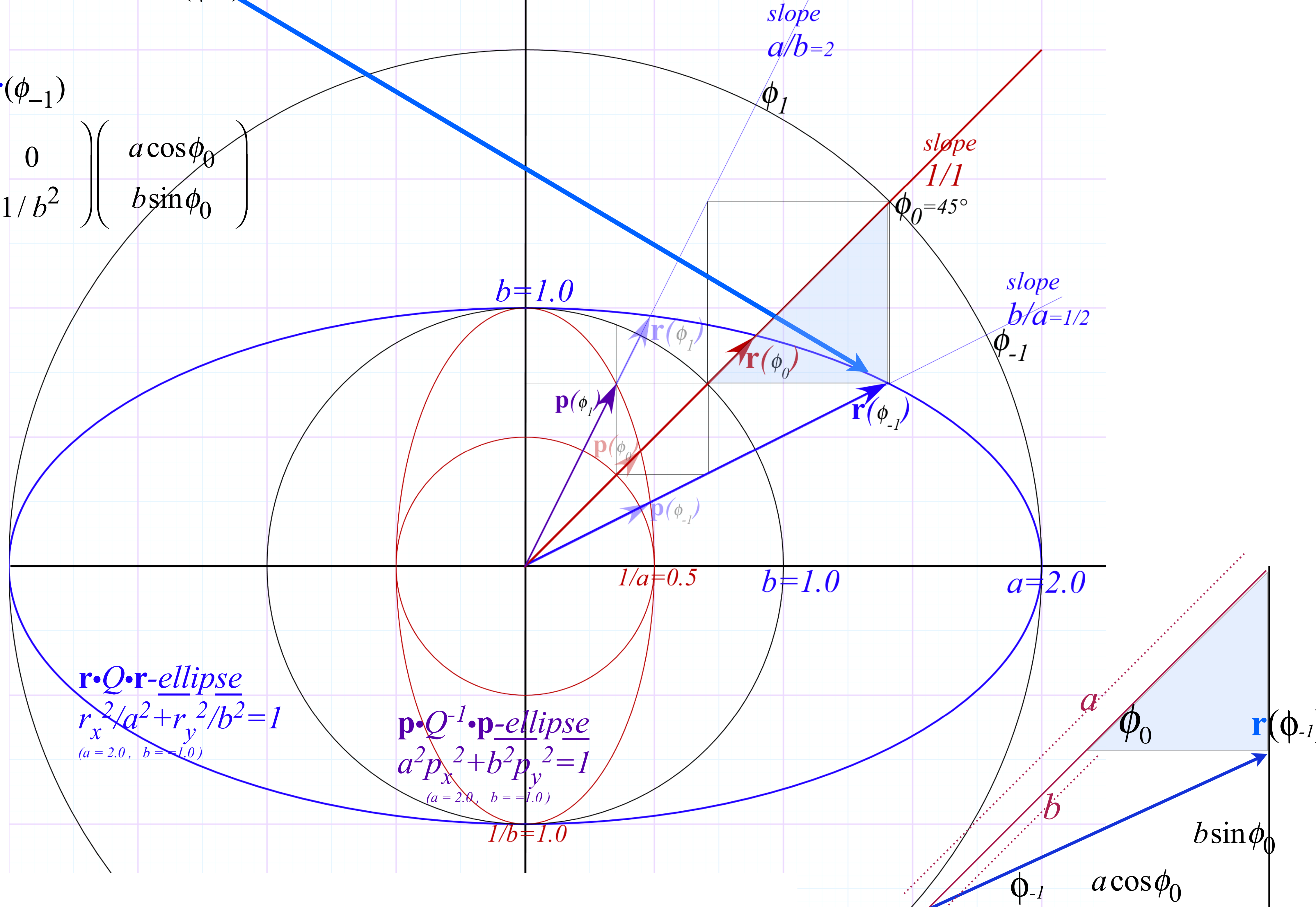
Here plot of **p**-ellipse is re-scaled by scalefactor $S=b$

p-ellipse x-radius$=1/a$ plotted at: $S(1/a)=b/a$ ($=1/2$ for $a=2$, $b=1$)

p-ellipse y-radius$=1/b$ plotted at: $S(1/b)=1$

Action of matrix Q that generates an **r**-*ellipse* (**r**•*Q*• **r** =*1*)
on a single **r**-*vector* **r**(ϕ-1)...

$$\mathbf{p}(\phi_1) = \mathbf{Q} \bullet \mathbf{r}(\phi_{-1})$$
$$= \begin{pmatrix} 1/a^2 & 0 \\ 0 & 1/b^2 \end{pmatrix} \begin{pmatrix} a\cos\phi_0 \\ b\sin\phi_0 \end{pmatrix}$$



Variation of
Fig. 11.7
in Unit 1

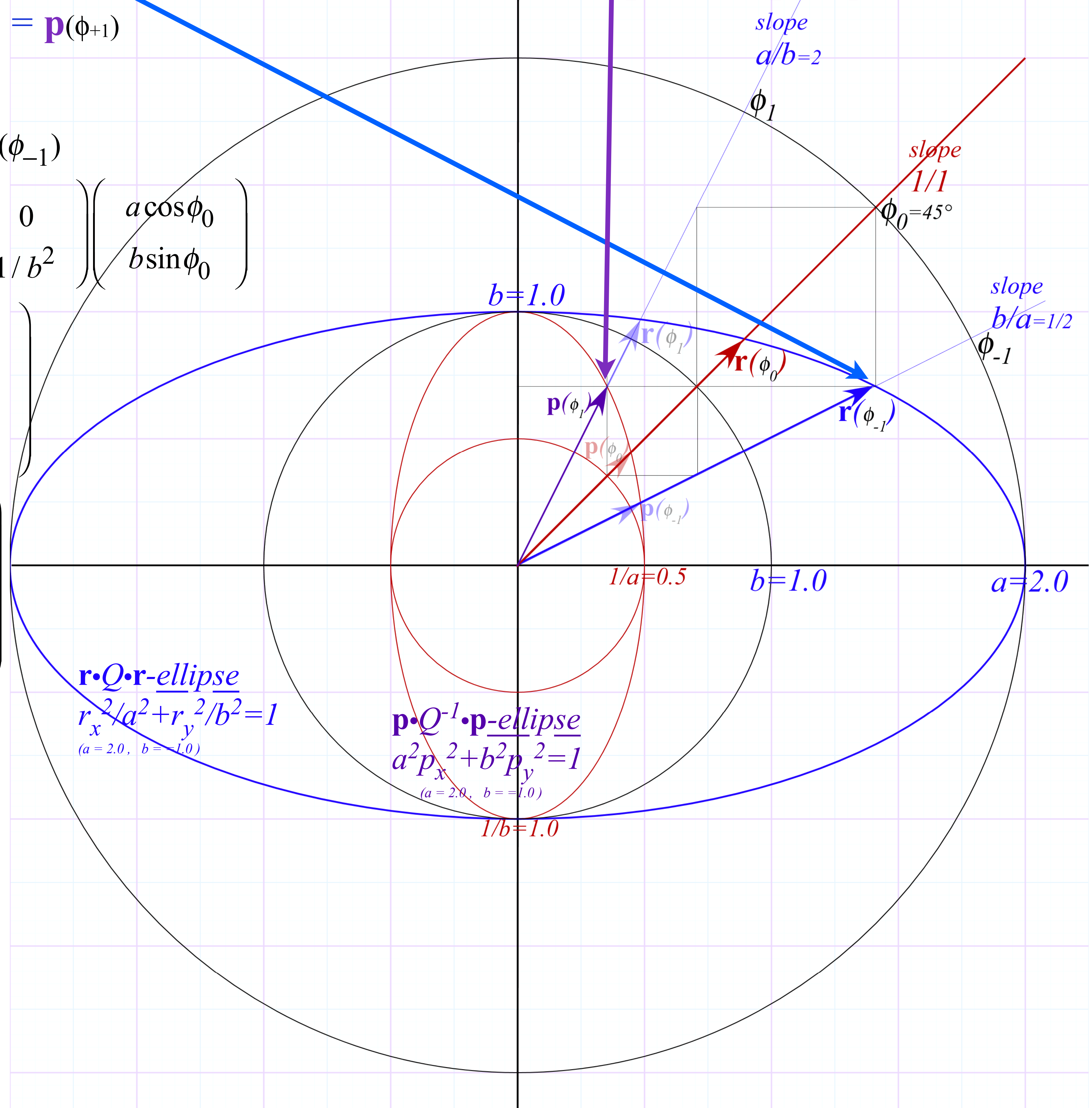
Here plot of **p**-ellipse is re-scaled by scalefactor $S=b$

p-ellipse x-radius=$1/a$ plotted at: $S(1/a)=b/a$ (=1/2 for a=2, b=1)

p-ellipse y-radius=$1/b$ plotted at: $S(1/b)=1$

Action of matrix Q that generates an **r***-ellipse (***r***•Q•***r** *=1)*
on a single **r***-vector* **r**(ϕ_{-1})*... is to rotate it to a new vector* **p** *on the* **p***-ellipse (***p***•Q^{-1}•* **p** *=1),*
that is, $Q\bullet\mathbf{r}(\phi_{-1}) = \mathbf{p}(\phi_{+1})$

$$\mathbf{p}(\phi_1) = \mathbf{Q}\bullet\mathbf{r}(\phi_{-1})$$
$$= \begin{pmatrix} 1/a^2 & 0 \\ 0 & 1/b^2 \end{pmatrix}\begin{pmatrix} a\cos\phi_0 \\ b\sin\phi_0 \end{pmatrix}$$
$$= \begin{pmatrix} \frac{1}{a}\cos\phi_0 \\ \frac{1}{b}\sin\phi_0 \end{pmatrix}$$
$$= \begin{pmatrix} \frac{1}{2}\frac{1}{\sqrt{2}} \\ \frac{1}{1}\frac{1}{\sqrt{2}} \end{pmatrix}$$



Variation of
Fig. 11.7
in Unit 1

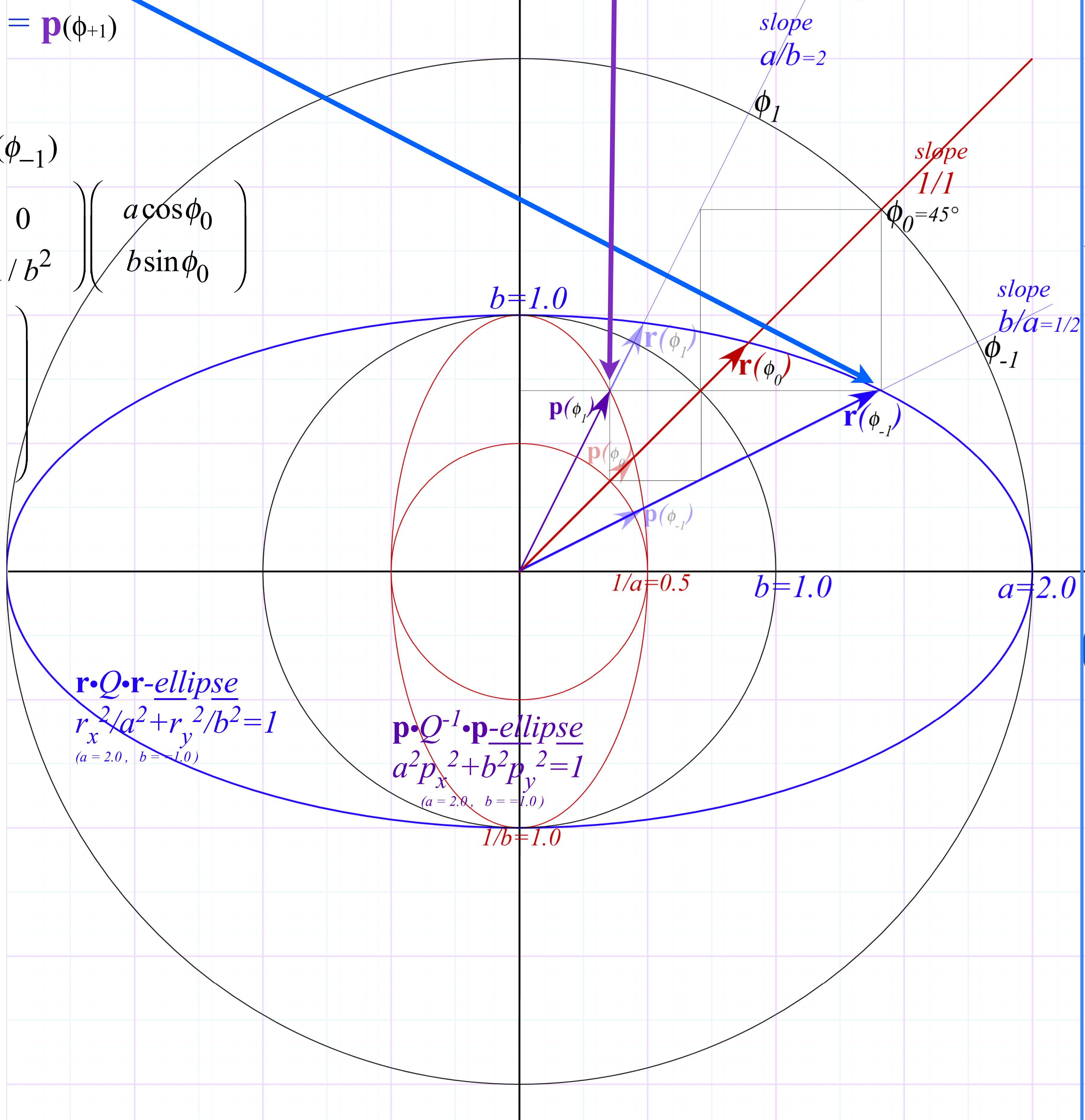
Action of matrix Q that generates an $\mathbf{r}$*-ellipse* $(\mathbf{r}\bullet Q\bullet\mathbf{r} = 1)$
on a single $\mathbf{r}$*-vector* $\mathbf{r}(\phi_{-1})$*... is to rotate it to a new vector* $\mathbf{p}$ *on the* $\mathbf{p}$*-ellipse* $(\mathbf{p}\bullet Q^{-1}\bullet\mathbf{p} = 1)$,
that is, $Q\bullet\mathbf{r}(\phi_{-1}) = \mathbf{p}(\phi_{+1})$

$$\mathbf{p}(\phi_1) = \mathbf{Q}\bullet\mathbf{r}(\phi_{-1})$$

$$= \begin{pmatrix} 1/a^2 & 0 \\ 0 & 1/b^2 \end{pmatrix}\begin{pmatrix} a\cos\phi_0 \\ b\sin\phi_0 \end{pmatrix}$$

$$= \begin{pmatrix} \frac{1}{a}\cos\phi_0 \\ \frac{1}{b}\sin\phi_0 \end{pmatrix}$$

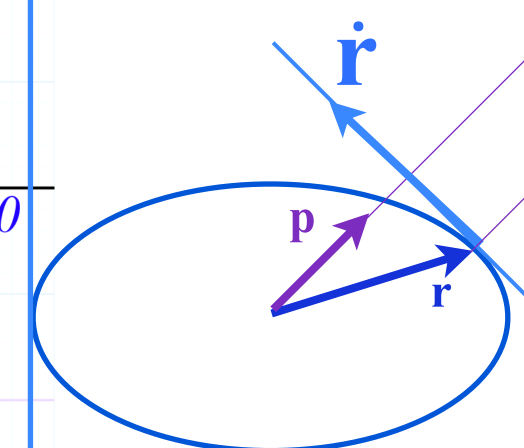
$$= \begin{pmatrix} \frac{1}{2}\frac{1}{\sqrt{2}} \\ \frac{1}{1}\frac{1}{\sqrt{2}} \end{pmatrix}$$



Variation of
Fig. 11.7
in Unit 1

Key points of matrix geometry:

Matrix Q maps any vector $\mathbf{r}$ *to a new vector* $\mathbf{p}$ *normal to the tangent* $\dot{\mathbf{r}}$ *to its* $\mathbf{r}\bullet Q\bullet\mathbf{r}$*-ellipse.*



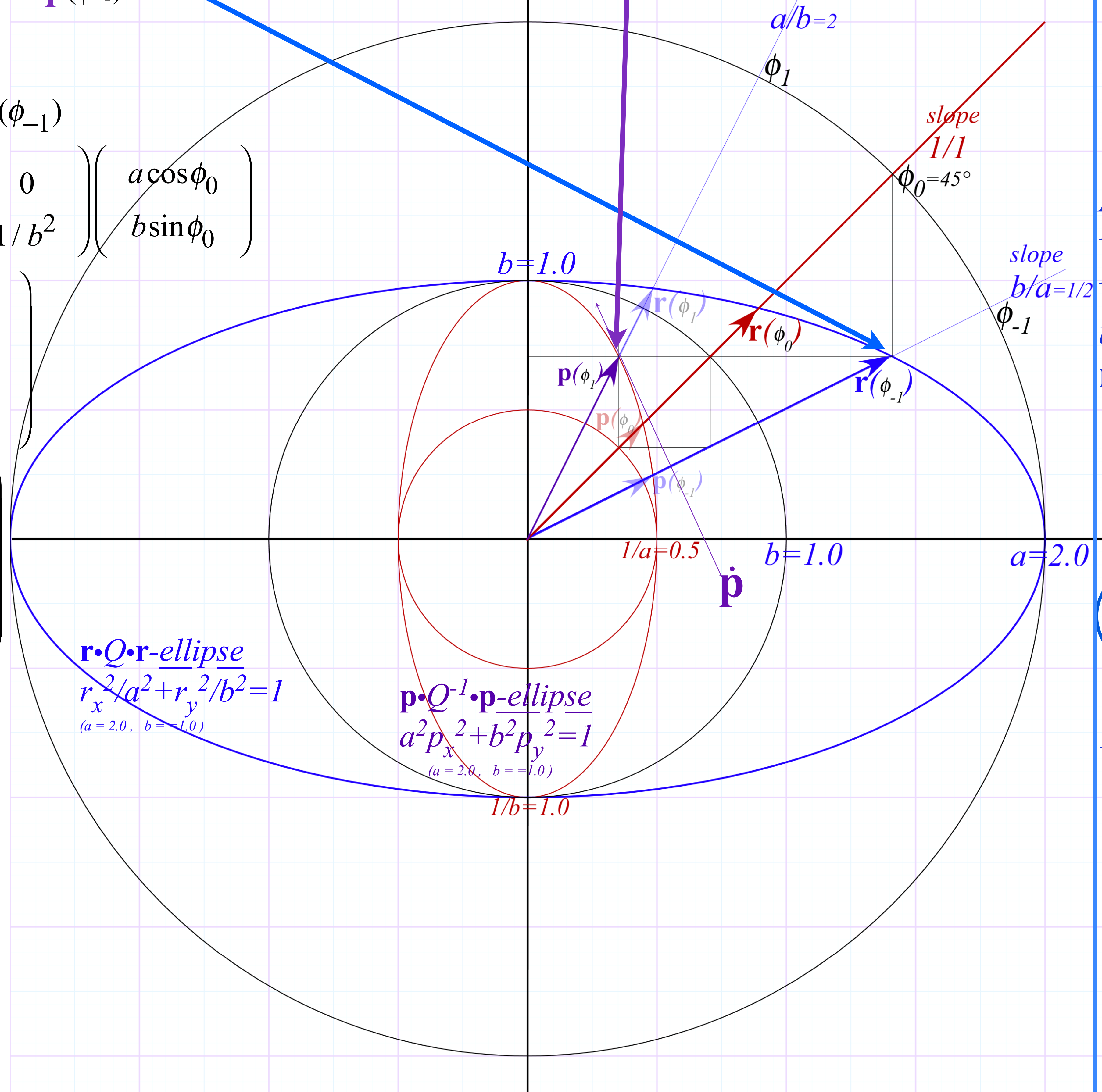
Action of matrix Q that generates an **r**-*ellipse* (**r**•*Q*•**r** =*1*)
on a single **r**-*vector* **r**(ϕ_{-1})... *is to rotate it to a new vector* **p** *on the* **p**-*ellipse* (**p**•Q^{-1}• **p** =*1*),
that is, Q•**r**(ϕ_{-1}) = **p**(ϕ_{+1})

$$\mathbf{p}(\phi_1) = \mathbf{Q}\bullet\mathbf{r}(\phi_{-1})$$

$$= \begin{pmatrix} 1/a^2 & 0 \\ 0 & 1/b^2 \end{pmatrix}\begin{pmatrix} a\cos\phi_0 \\ b\sin\phi_0 \end{pmatrix}$$

$$= \begin{pmatrix} \frac{1}{a}\cos\phi_0 \\ \frac{1}{b}\sin\phi_0 \end{pmatrix}$$

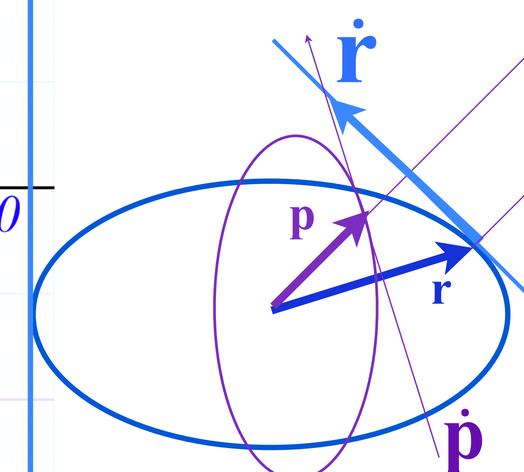
$$= \begin{pmatrix} \frac{1}{2}\frac{1}{\sqrt{2}} \\ \frac{1}{1}\frac{1}{\sqrt{2}} \end{pmatrix}$$



Variation of
Fig. 11.7
in Unit 1

Key points of matrix geometry:

Matrix Q maps any vector **r** *to a new vector* **p** *normal to the tangent* **ṙ** *to its* **r**•*Q*•**r**-*ellipse.*



Matrix Q^{-1} *maps* **p** *back to* **r** *that is normal to the tangent* **ṗ** *to its* **p**• Q^{-1}• **p**-*ellipse.*

Introduction to dual matrix operator geometry (based on IHO orbits)

Quadratic form ellipse $\mathbf{r}\bullet Q\bullet\mathbf{r}=1$ *vs.inverse form ellipse* $\mathbf{p}\bullet Q^{-1}\bullet\mathbf{p}=1$

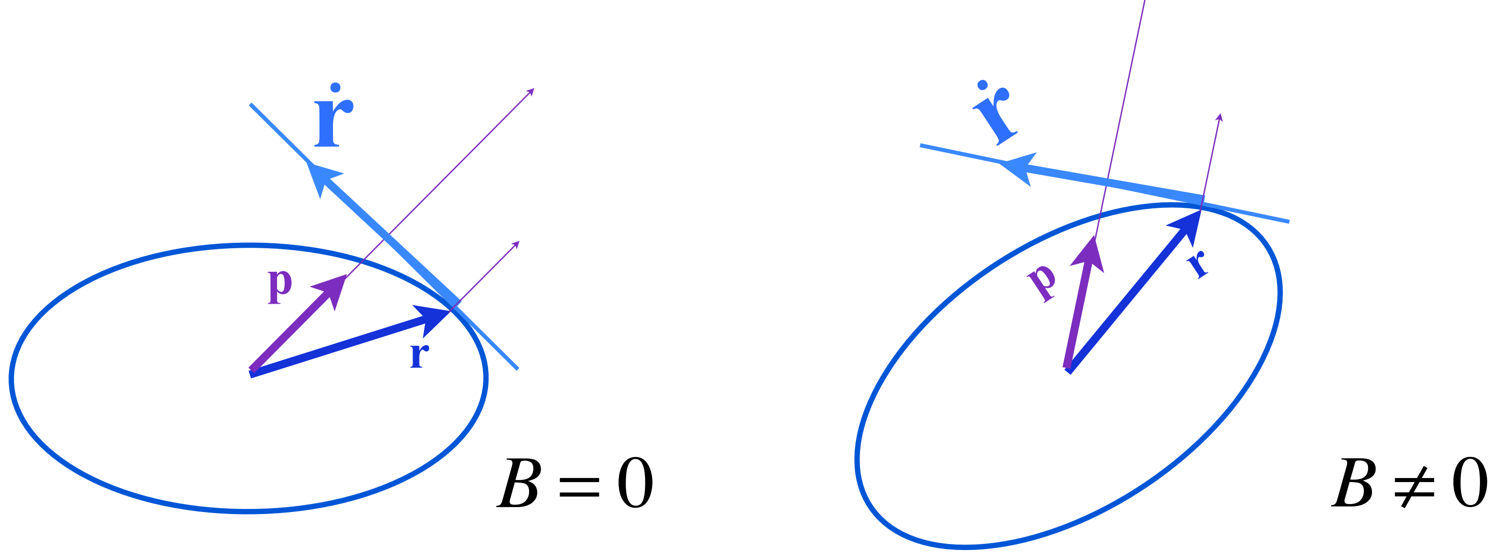
Duality norm relations $(\mathbf{r}\bullet\mathbf{p}=1)$

Q-Ellipse tangents $\mathbf{r}'$ *normal to dual* Q^{-1}*-ellipse position* $\mathbf{p}$ $(\mathbf{r}'\bullet\mathbf{p}=0=\mathbf{r}\bullet\mathbf{p}')$

Operator geometric sequences and eigenvectors

Alternative scaling of matrix operator geometry

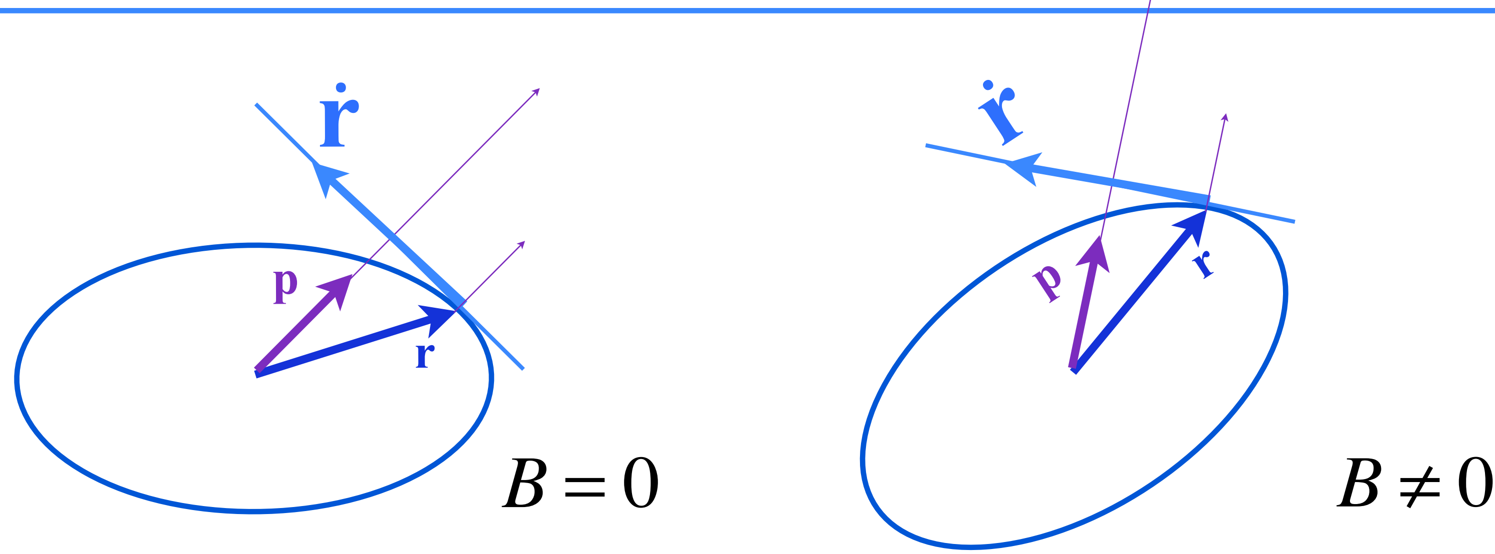
→ *Vector calculus of tensor operation*



Derive matrix "normal-to-ellipse"geometry by vector calculus:

Let matrix $Q = \begin{pmatrix} A & B \\ B & D \end{pmatrix}$

define the ellipse $1=\mathbf{r}\bullet Q\bullet\mathbf{r} = \begin{pmatrix} x & y \end{pmatrix}\bullet\begin{pmatrix} A & B \\ B & D \end{pmatrix}\bullet\begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} x & y \end{pmatrix}\bullet\begin{pmatrix} A\cdot x + B\cdot y \\ B\cdot x + D\cdot y \end{pmatrix} = A\cdot x^2 + 2B\cdot xy + D\cdot y^2 = 1$



Derive matrix "normal-to-ellipse"geometry by vector calculus:

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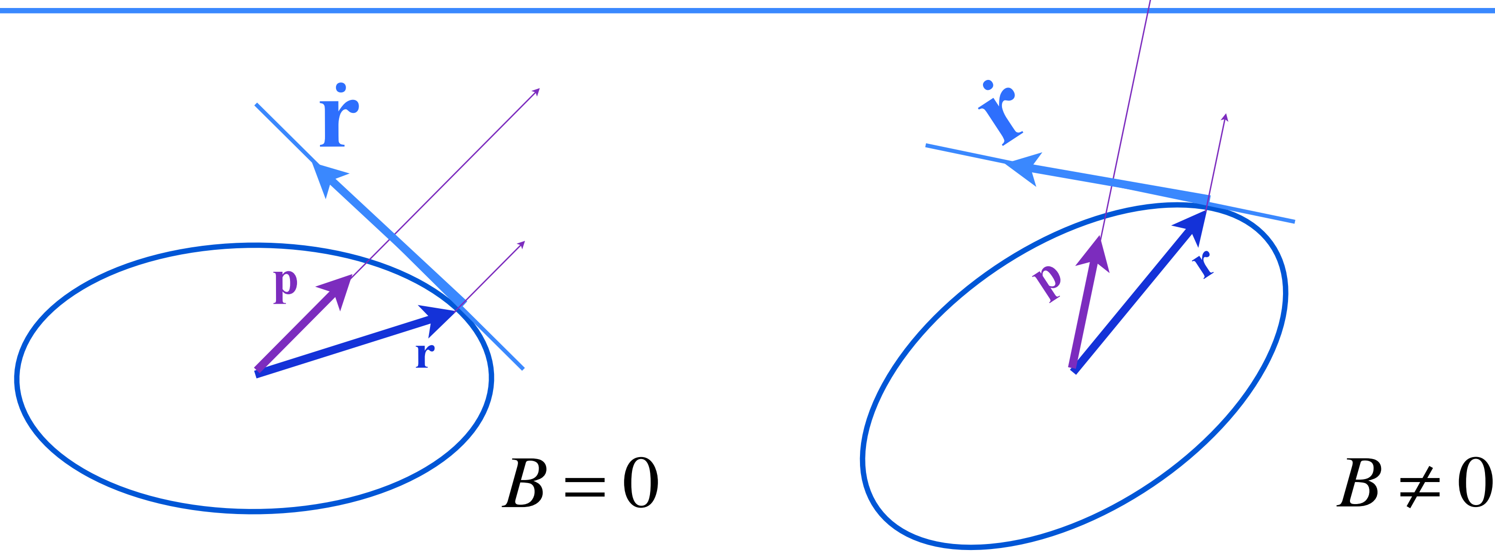
Compare operation by Q on vector **r** *with* *vector derivative or gradient of* $\mathbf{r}\bullet Q\bullet\mathbf{r}$

$$\begin{pmatrix} A & B \\ B & D \end{pmatrix}\bullet\begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} A\cdot x + B\cdot y \\ B\cdot x + D\cdot y \end{pmatrix}$$

$$\frac{\partial}{\partial \mathbf{r}}(\mathbf{r}\bullet Q\bullet\mathbf{r}) = \nabla(\mathbf{r}\bullet Q\bullet\mathbf{r})$$

$$\begin{pmatrix} \frac{\partial}{\partial x} \\ \frac{\partial}{\partial y} \end{pmatrix}\left(A\cdot x^2 + 2B\cdot xy + D\cdot y^2\right) = \begin{pmatrix} 2A\cdot x + 2B\cdot y \\ 2B\cdot x + 2D\cdot y \end{pmatrix}$$



Derive matrix "normal-to-ellipse" geometry by vector calculus:

Let matrix $Q = \begin{pmatrix} A & B \\ B & D \end{pmatrix}$

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Compare operation by Q on vector $\mathbf{r}$ *with vector derivative or gradient of* $\mathbf{r}\bullet Q\bullet\mathbf{r}$

$$\frac{\partial}{\partial\mathbf{r}}(\mathbf{r}\bullet Q\bullet\mathbf{r}) = \nabla(\mathbf{r}\bullet Q\bullet\mathbf{r})$$

$$\begin{pmatrix} A & B \\ B & D \end{pmatrix}\bullet\begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} A\cdot x + B\cdot y \\ B\cdot x + D\cdot y \end{pmatrix}$$

$$\begin{pmatrix} \dfrac{\partial}{\partial x} \\ \dfrac{\partial}{\partial y} \end{pmatrix}\left(A\cdot x^2 + 2B\cdot xy + D\cdot y^2\right) = \begin{pmatrix} 2A\cdot x + 2B\cdot y \\ 2B\cdot x + 2D\cdot y \end{pmatrix}$$

Very simple result:

$$\frac{\partial}{\partial\mathbf{r}}\left(\frac{\mathbf{r}\bullet Q\bullet\mathbf{r}}{2}\right) = \nabla\left(\frac{\mathbf{r}\bullet Q\bullet\mathbf{r}}{2}\right) = Q\bullet\mathbf{r}$$

Introduction to dual matrix operator geometry (based on IHO orbits)

Quadratic form ellipse $\mathbf{r}\bullet Q\bullet\mathbf{r}=1$ *vs.inverse form ellipse* $\mathbf{p}\bullet Q^{-1}\bullet\mathbf{p}=1$

Duality norm relations ($\mathbf{r}\bullet\mathbf{p}=1$)

Q-Ellipse tangents $\mathbf{r}'$ *normal to dual* Q^{-1}*-ellipse position* $\mathbf{p}$ ($\mathbf{r}'\bullet\mathbf{p}=0=\mathbf{r}\bullet\mathbf{p}'$)

(Still more) Operator geometric sequences and eigenvectors

Alternative scaling of matrix operator geometry

Vector calculus of tensor operation

Action of "sqrt-"matrix $R=\sqrt{Q}$ *(R generates another ellipse* $\mathbf{r}\bullet R\bullet\mathbf{r}=1$ *not shown)*

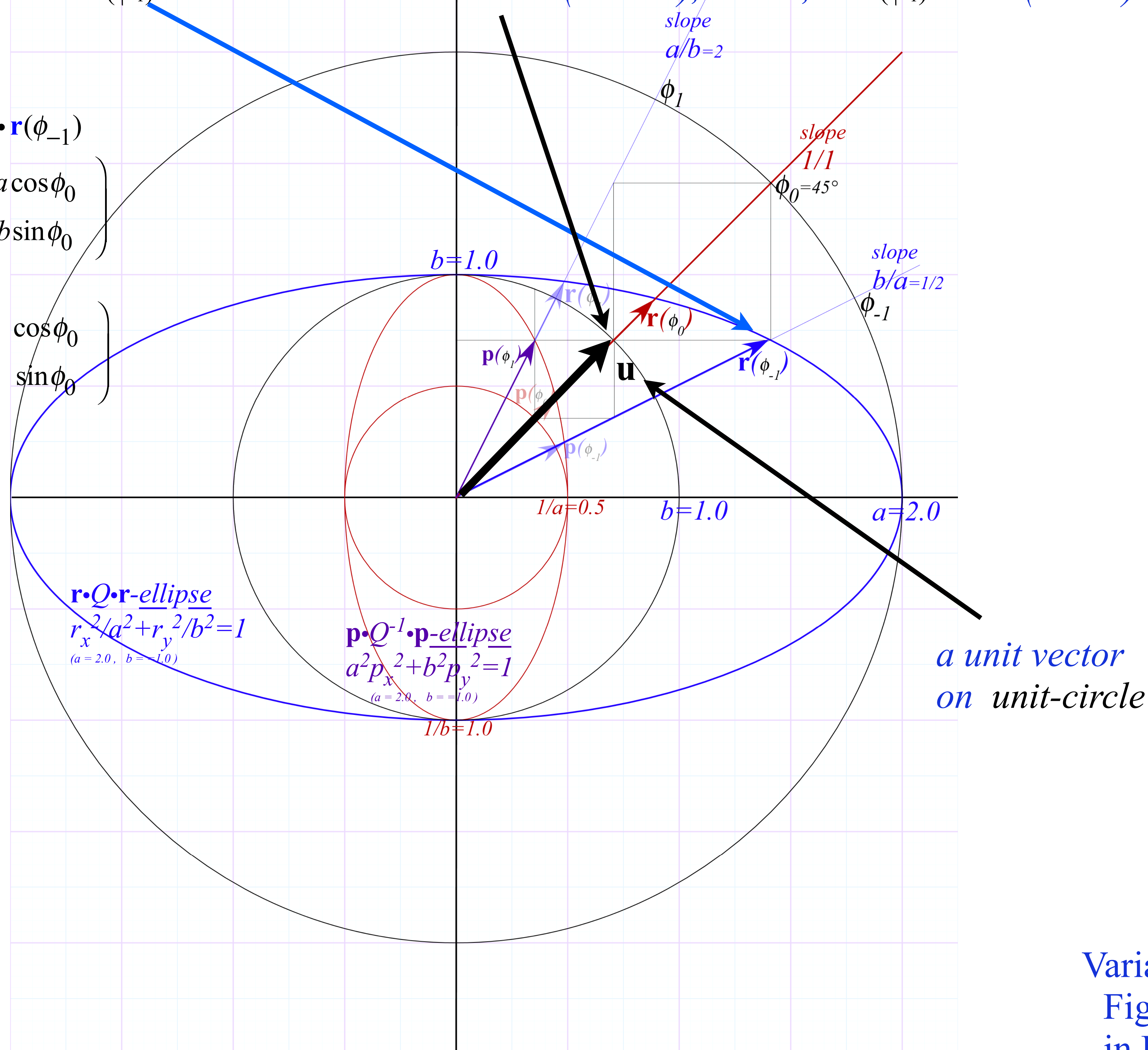
on a single **r**-*vector* $\mathbf{r}(\phi_{-1})$... *is to rotate it to* **u**-*circle* ($\mathbf{u}\bullet\mathbf{u}=1$), *that is,* $R\bullet\mathbf{r}(\phi_{-1})=\mathbf{u}=(const.)\mathbf{r}(\phi_0)$

$$\mathbf{u}=\sqrt{\mathbf{Q}}\bullet\mathbf{r}(\phi_{-1})=\mathbf{R}\bullet\mathbf{r}(\phi_{-1})$$

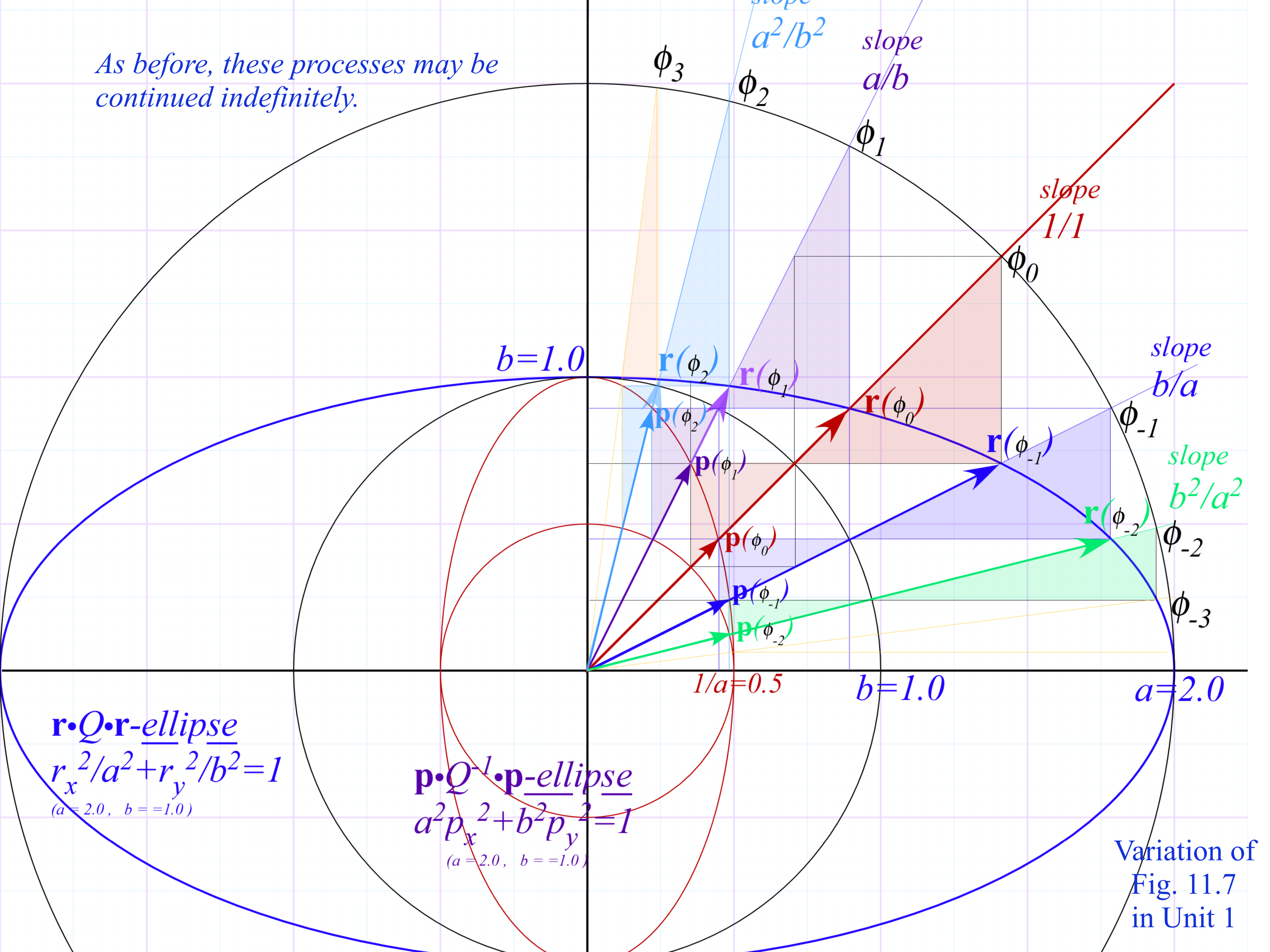
$$=\begin{pmatrix}1/a & 0\\ 0 & 1/b\end{pmatrix}\begin{pmatrix}a\cos\phi_0\\ b\sin\phi_0\end{pmatrix}$$

$$=\begin{pmatrix}\frac{1}{a}a\cos\phi_0\\ \frac{1}{b}b\sin\phi_0\end{pmatrix}=\begin{pmatrix}\cos\phi_0\\ \sin\phi_0\end{pmatrix}$$

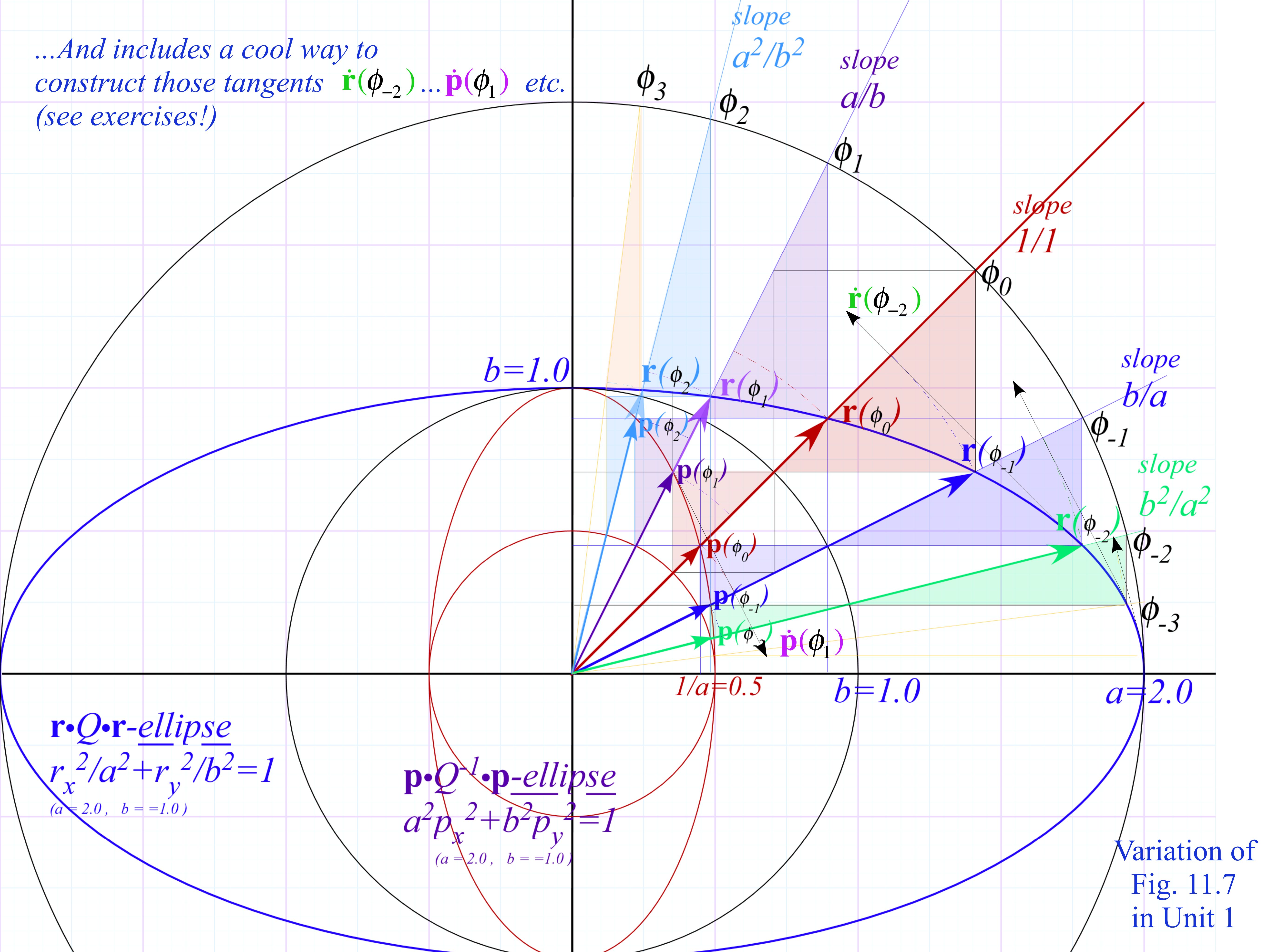
$$=\begin{pmatrix}\frac{1}{\sqrt{2}}\\ \frac{1}{\sqrt{2}}\end{pmatrix}$$



Variation of
Fig. 11.7
in Unit 1



Variation of Fig. 11.7 in Unit 1



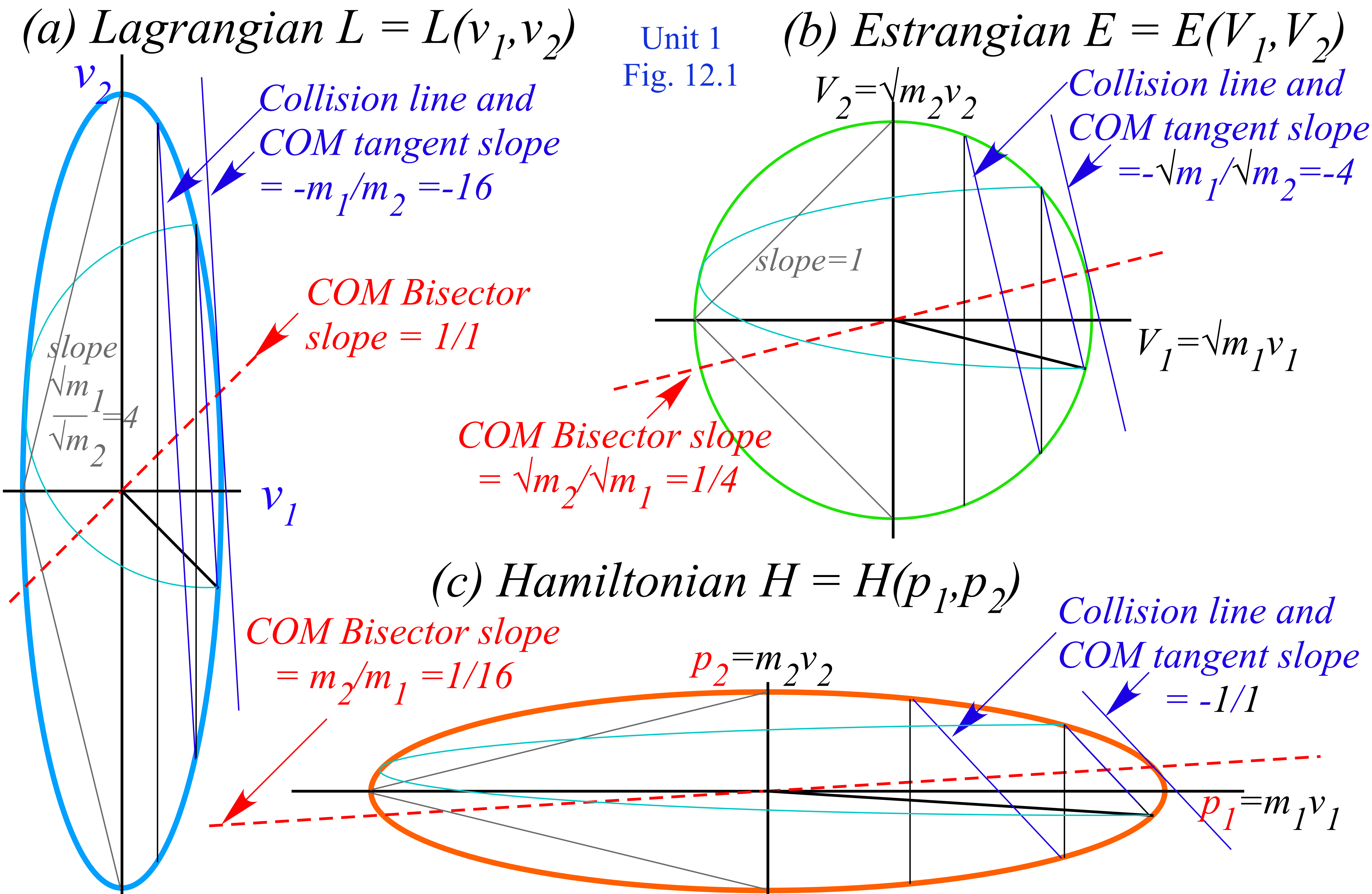
Variation of Fig. 11.7 in Unit 1

Q:Where is this headed? *A: Lagrangian-Hamiltonian duality*

Preview of Lecture 8

The R and Q matrix transformations are like the mechanics rescaling matrices $\sqrt{\mathbf{M}}$ *and* $\mathbf{M}$:

Like $Q=R^2$: $\mathbf{M}=\begin{pmatrix} m_1 & 0 \\ 0 & m_2 \end{pmatrix}=\mathbf{R}^2$ *Like* $\sqrt{Q}=R$: $\sqrt{\mathbf{M}}=\begin{pmatrix} \sqrt{m_1} & 0 \\ 0 & \sqrt{m_2} \end{pmatrix}=\mathbf{R}$ *Like* $Q^{-1}=R^{-2}$: $\mathbf{M}^{-1}=\begin{pmatrix} 1/m_1 & 0 \\ 0 & 1/m_2 \end{pmatrix}=\mathbf{R}^{-2}$



Unit 1
Fig. 12.2