Warsaw University of Technology
The Faculty of Automotive
and Construction Machinery Engineering
Institute of Machine Design Fundamentals
Department of Mechanics
http://www.ipbm.simr.pw.edu.pl/

Theory of Machines and Automatic Control

Winter 2017/2018

Lecturer: Sebastian Korczak, PhD Eng.

Lecture 4

Analytical method. Cam mechanisms.

Methods of velocities and accelerations determination

Graphical methods

- velocity projection method,
- instantaneous center of rotation method,
- instantaneous center of acceleration method,
- method of rotated velocities,
- velocity decomposition method,
- acceleration decomposition method,
- velocity scheme (diagram) method,
- accelerations scheme (diagram) method.

Analytical method

Limitations of analytical method

Only for closed kinematic chains (both simple and complex).

Procedure of analytical determination of velocities and accelerations in planar mechanisms.

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4. Define "directed angles" for all vectors defined in the same manner. Assume that this angles are created by the positive x axis counter-clockwise rotation.

5. Fore each of polygon write down sum of vectors, e.g.:

$$\sum_{i=1}^{i=n} \vec{l}_i = 0$$

Procedure of analytical determination of velocities and accelerations in planar mechanisms.

6a. Write down projections of each polygon onto coordinate system's axes:

$$\text{x:} \quad \sum_{i=1}^{i=n} l_i \cos\varphi_i = 0 \qquad \text{y:} \quad \sum_{i=1}^{i=n} l_i \sin\varphi_i = 0$$

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(we do not need to analyze signs because of „directed angles” setup procedure)

6b. Define which vectors' lengths and angles are given and/or constant (related to geometry), and which are variable in time and unknown.

(for a proper defined system number of unknown variables is equal to the number of equations)

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6b. Define which vectors' lengths and angles are given and/or constant (related to geometry), and which are variable in time and unknown.

(for a proper defined system number of unknown variables is equal to the number of equations)

7. Solve the equations. The resulting functions describes motion of the mechanism.

Procedure of analytical determination of velocities and accelerations in planar mechanisms.

8. Differentiate functions achieved in p.7 to obtain velocities. Differentiate once again to obtain accelerations.

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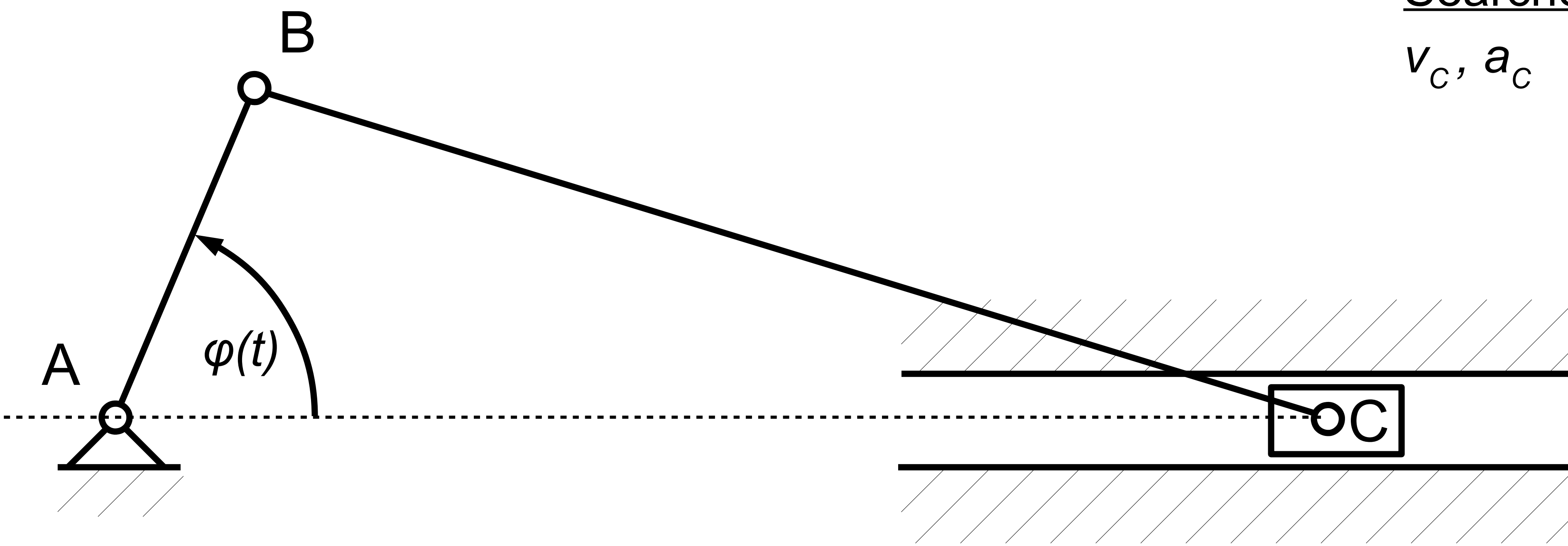
9. If desired informations was not obtained in p.8, differentiate equations from p.6. Sometimes rotation of the coordinate system is useful here.

Analytical method – example:
crank-slider mechanism

Given:
|AB| = r
|BC| = l
$\varphi(t)$
Searched:
v_C, a_C



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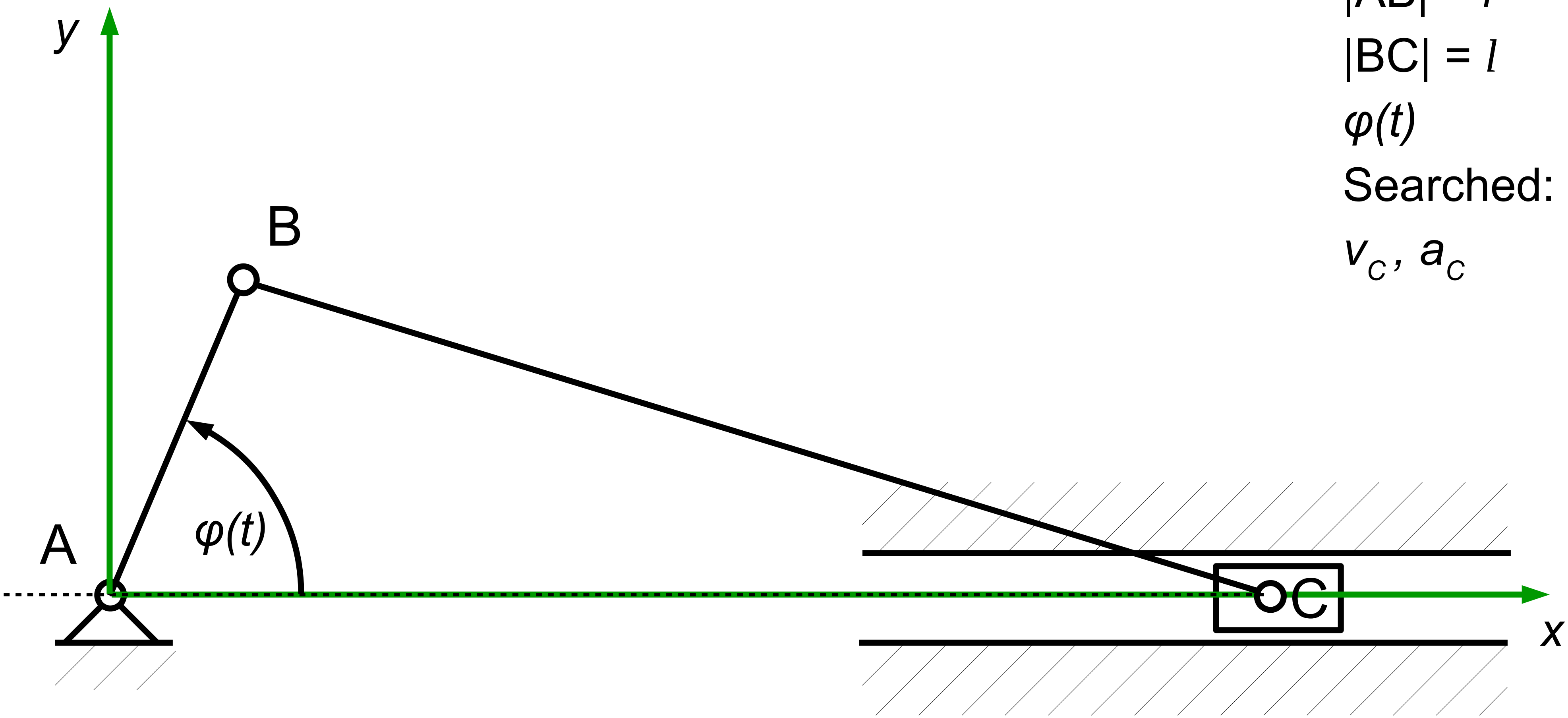

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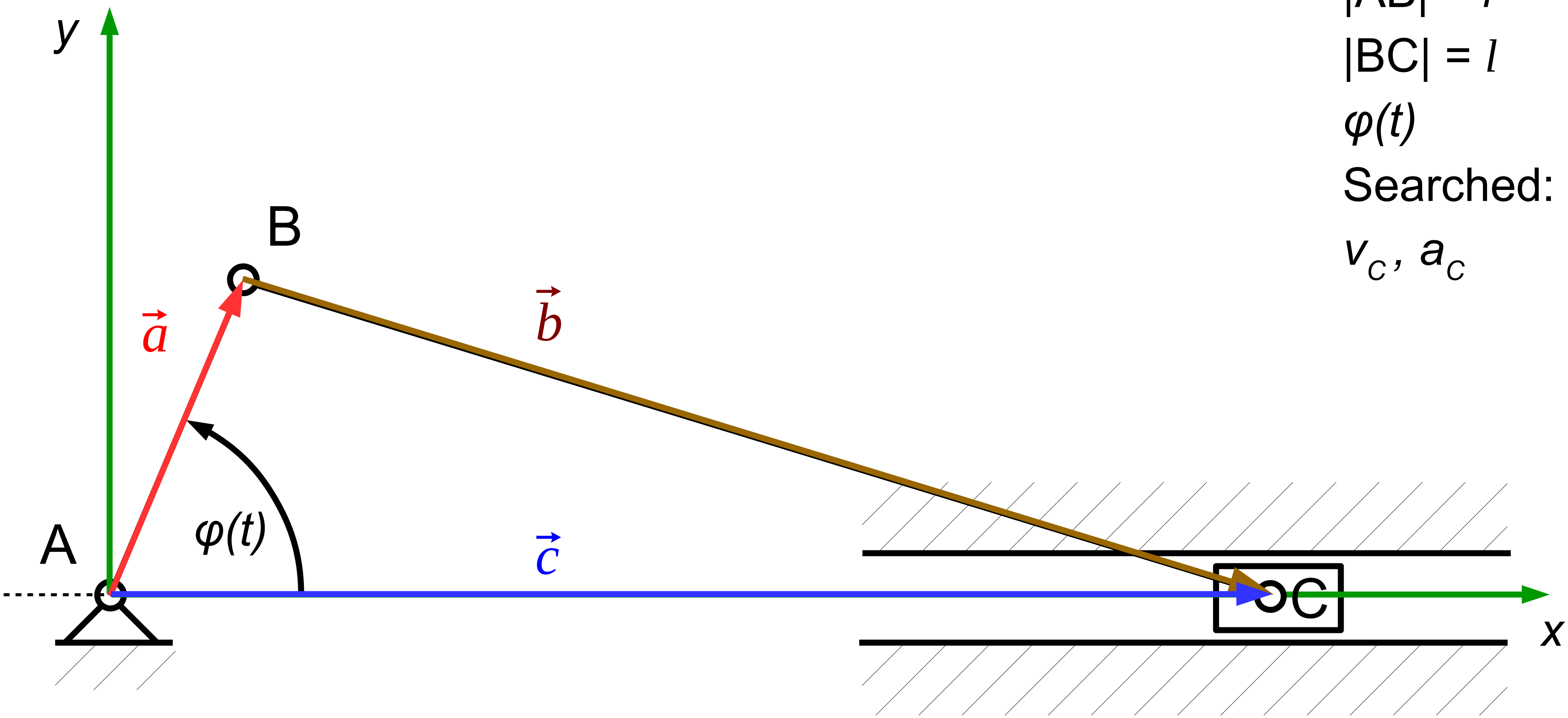

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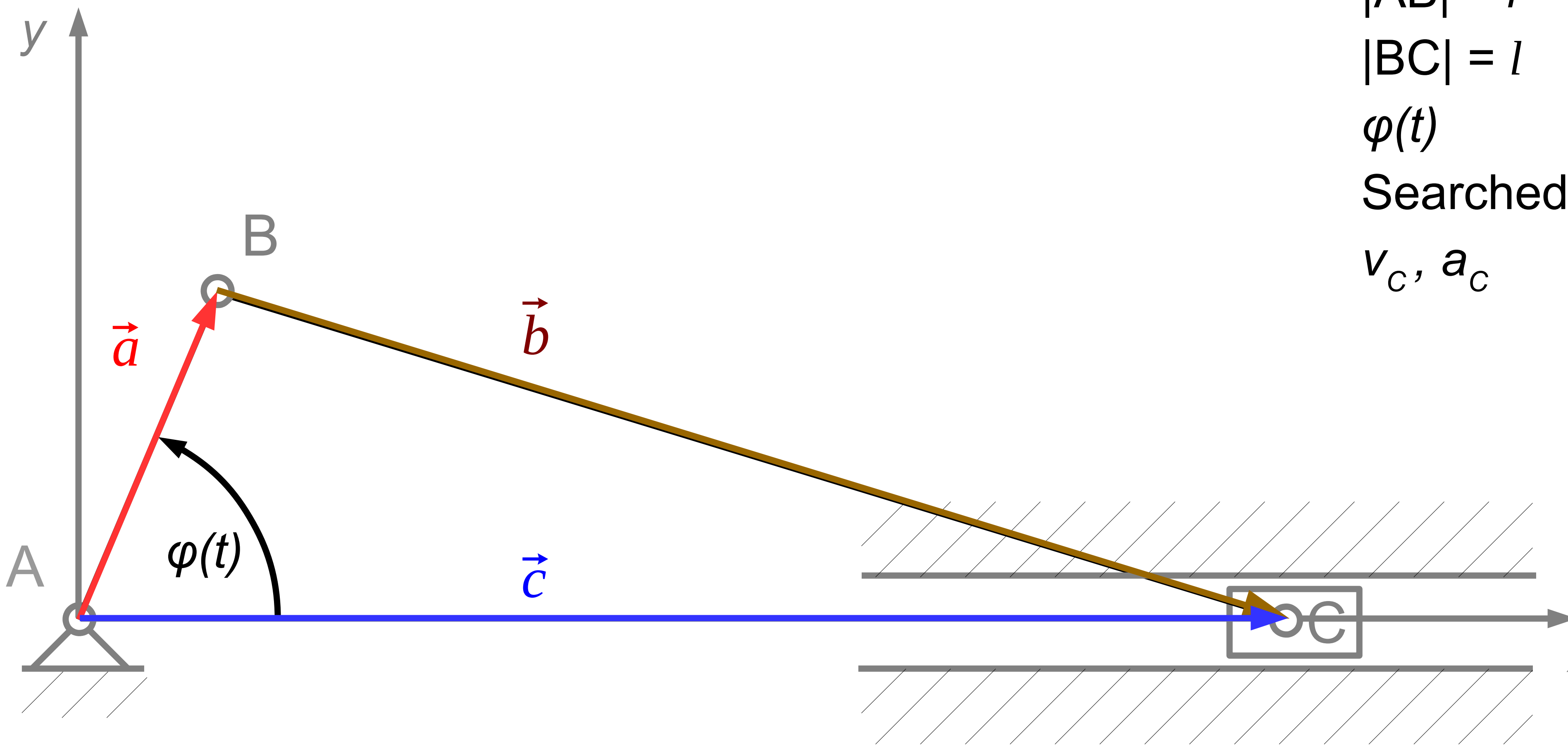

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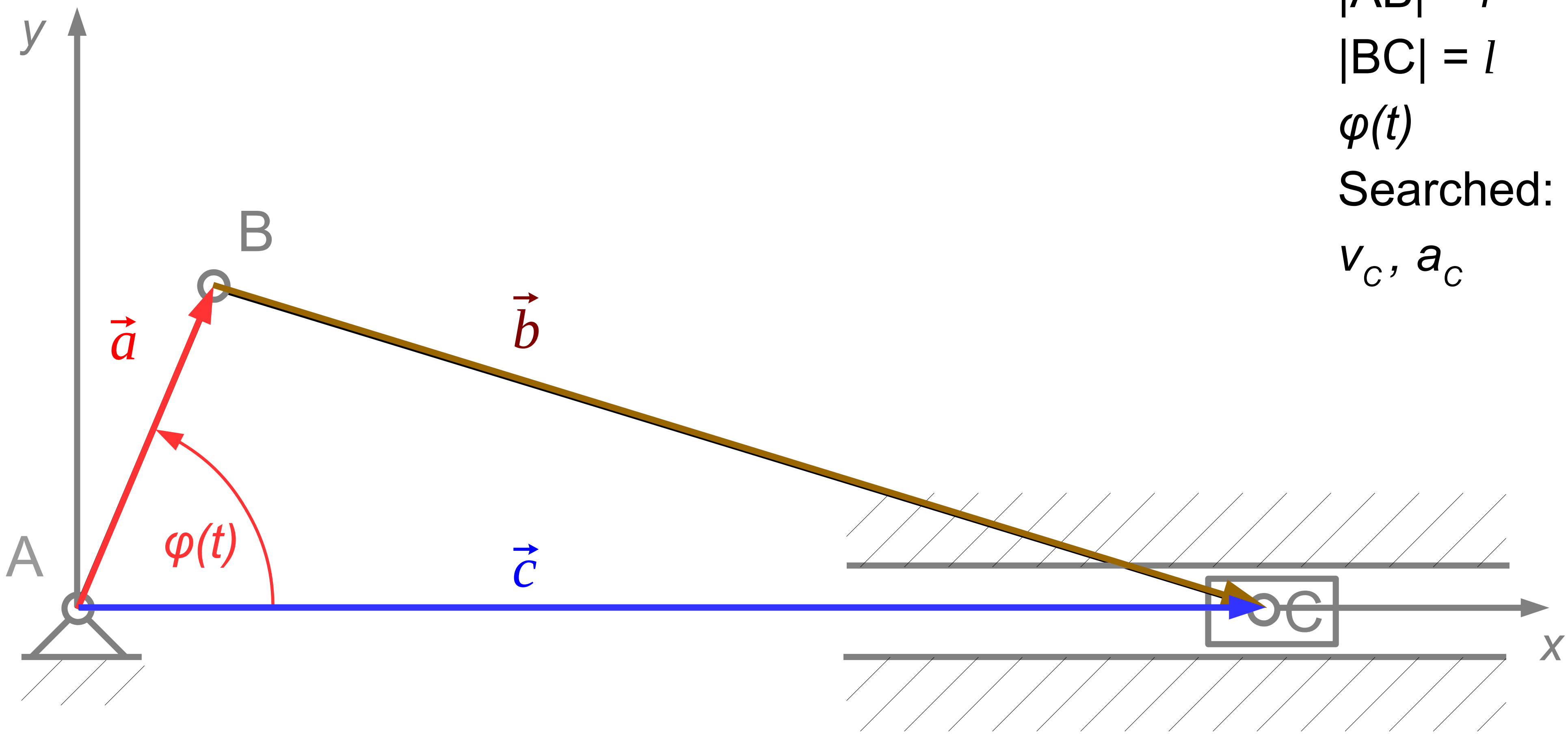

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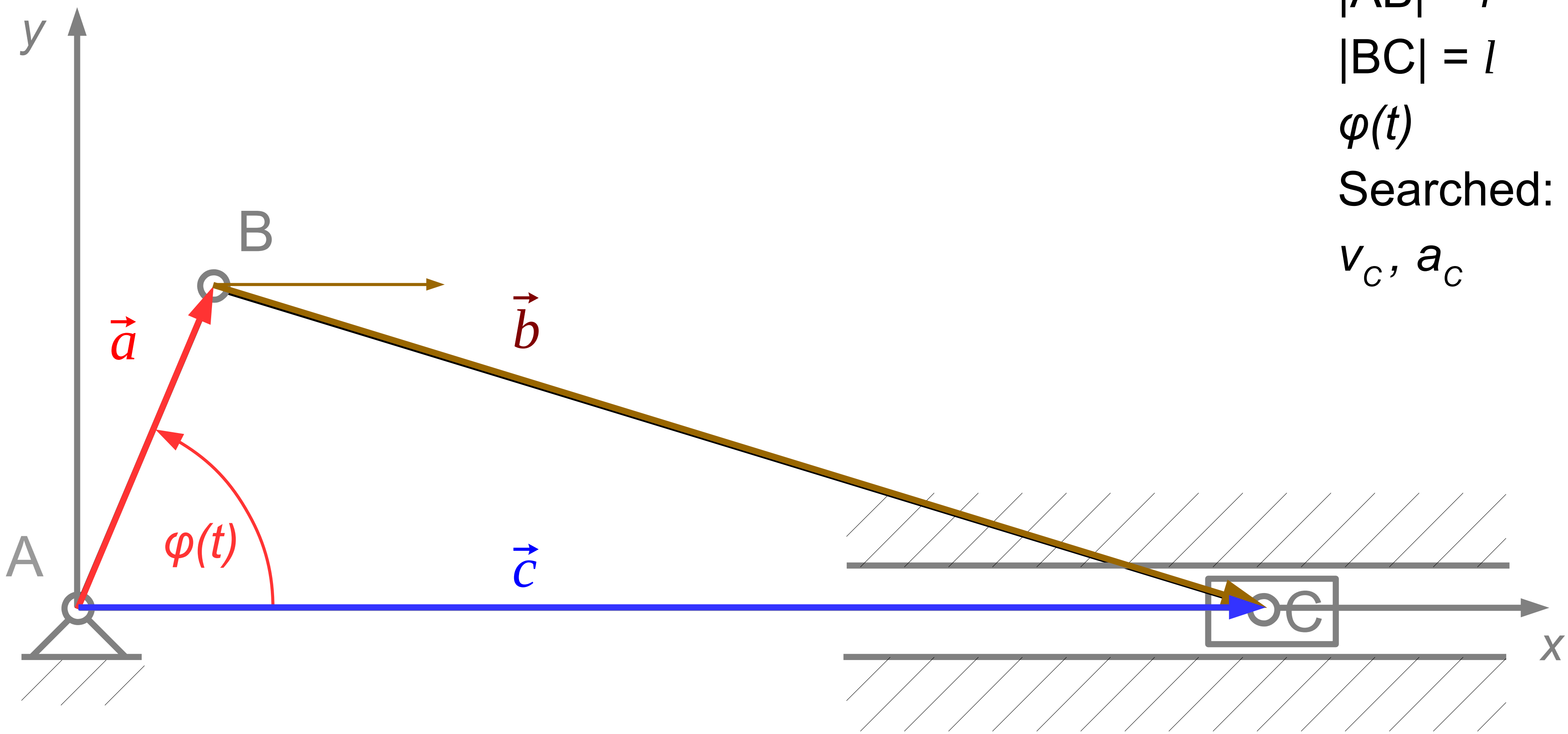

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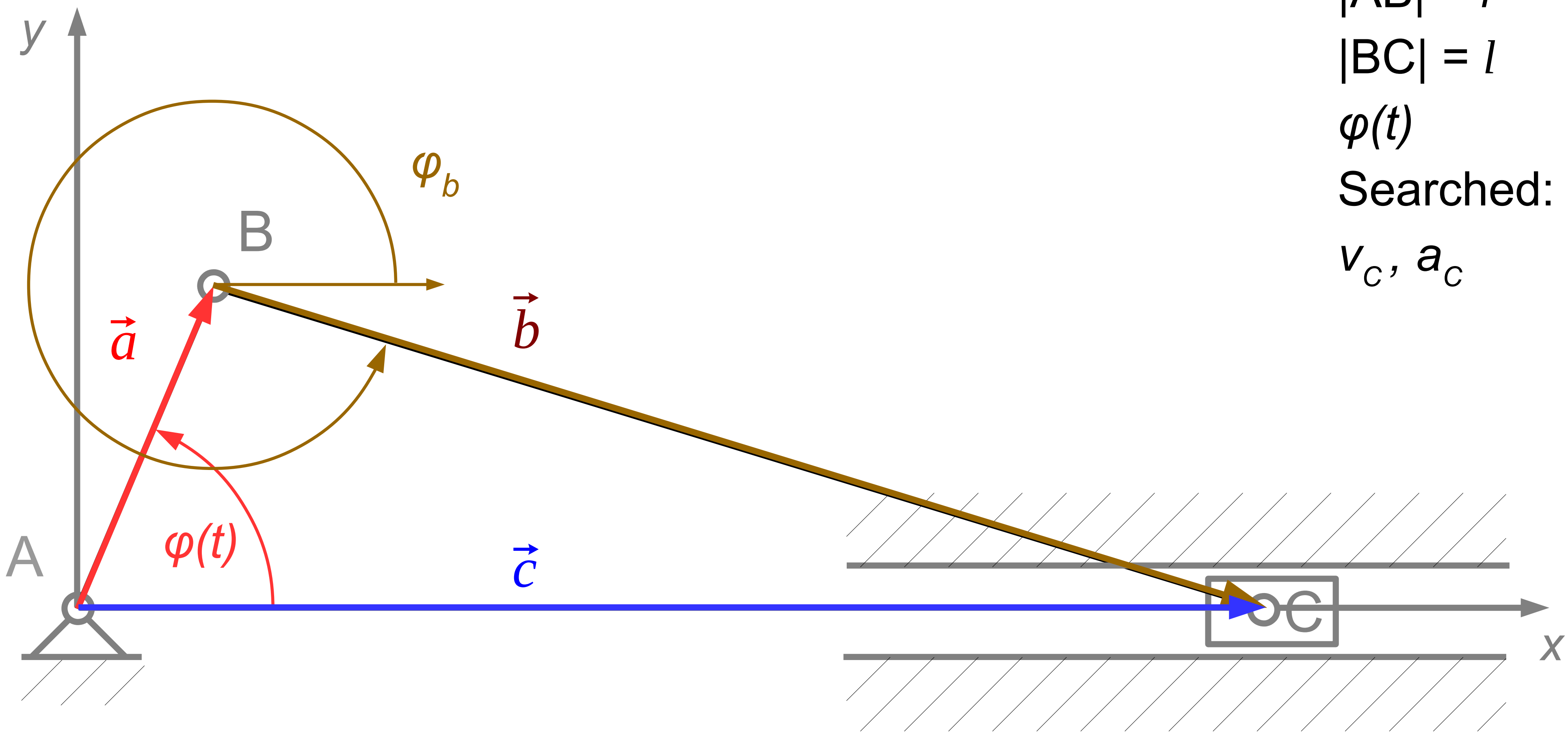

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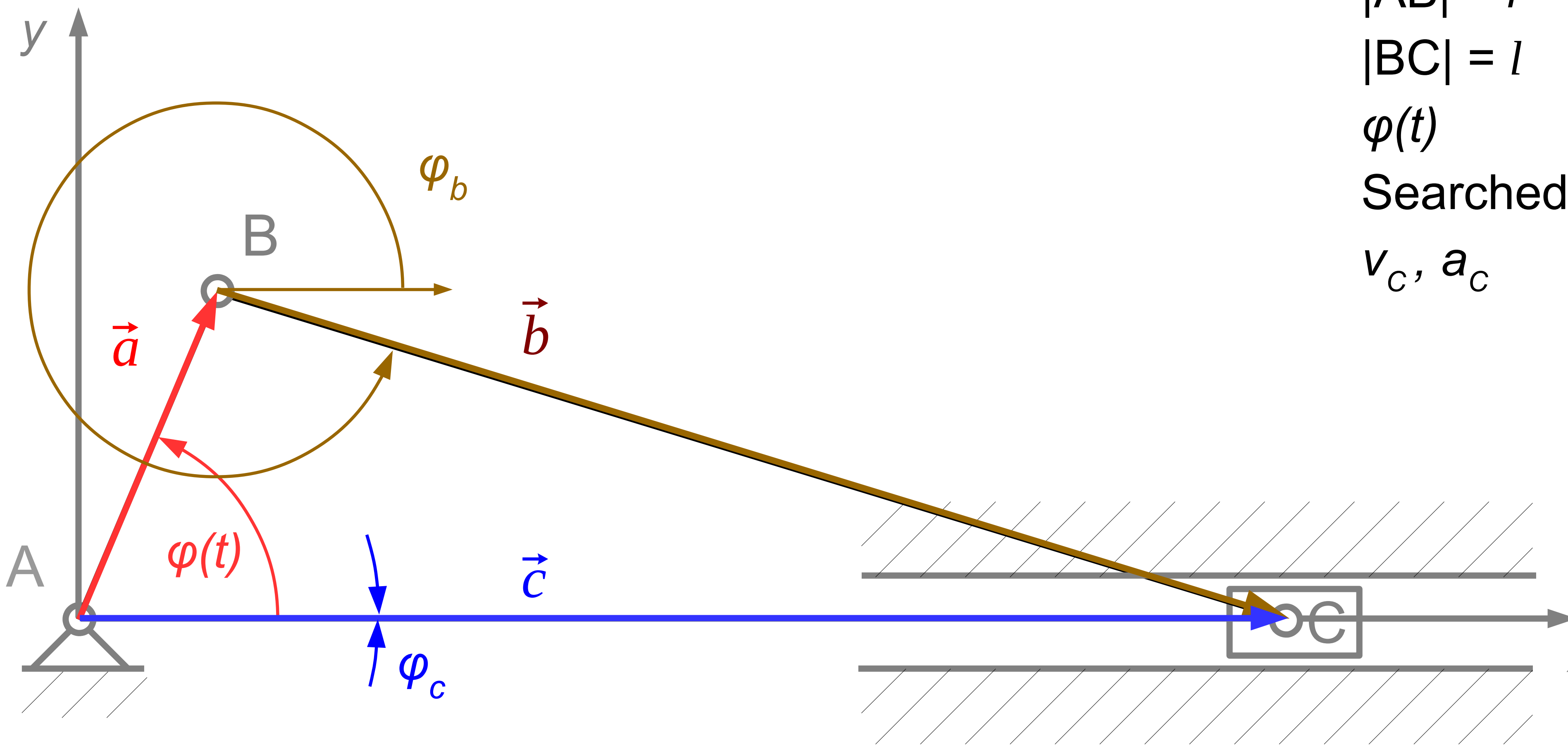

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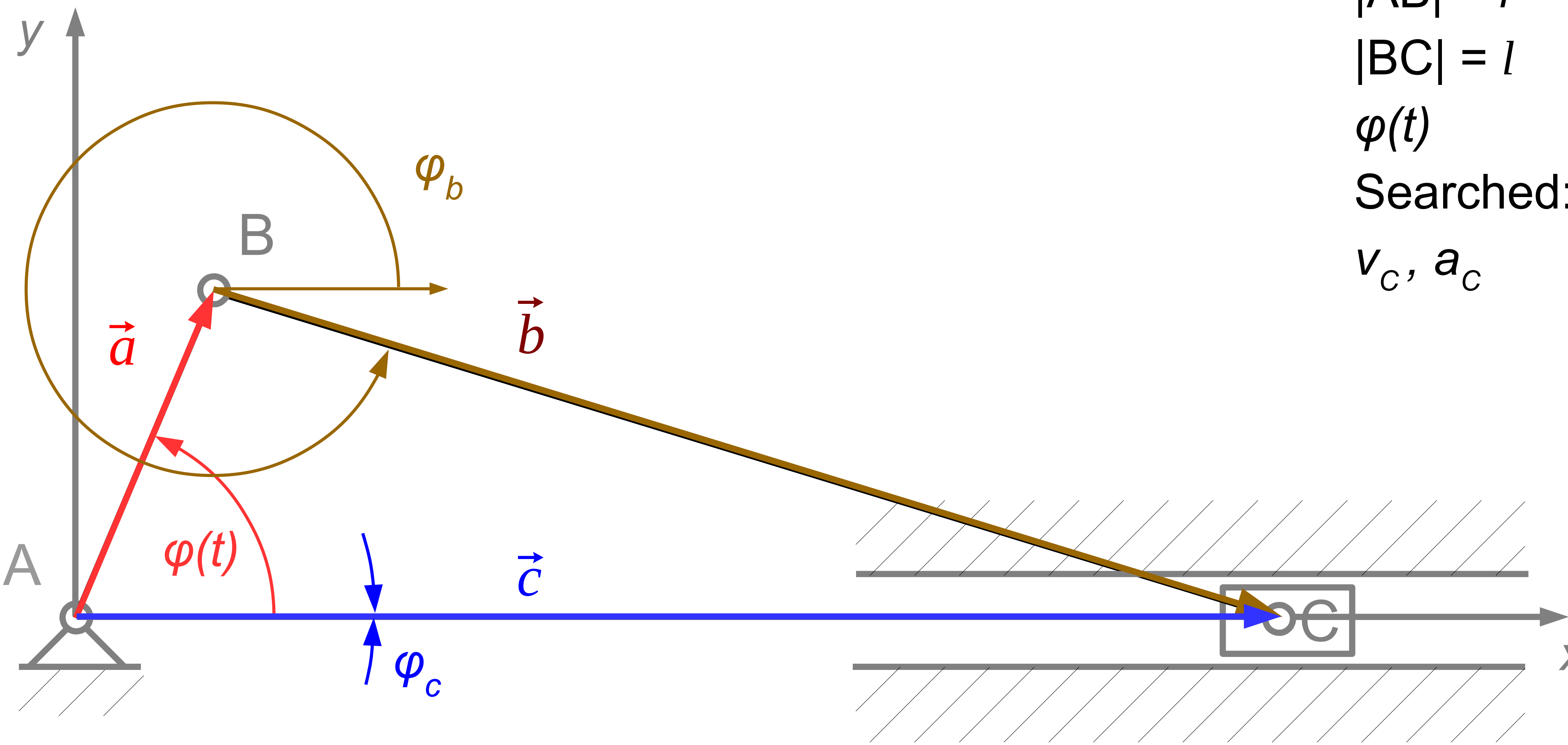

Given:

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φ(t)

Searched:

v_C, a_C

$|\vec{a}| = r$ $\qquad \varphi(t)$

$|\vec{b}| = l$ $\qquad \varphi_b(t)$

$|\vec{c}| = c(t)$ $\qquad \varphi_c = 0$

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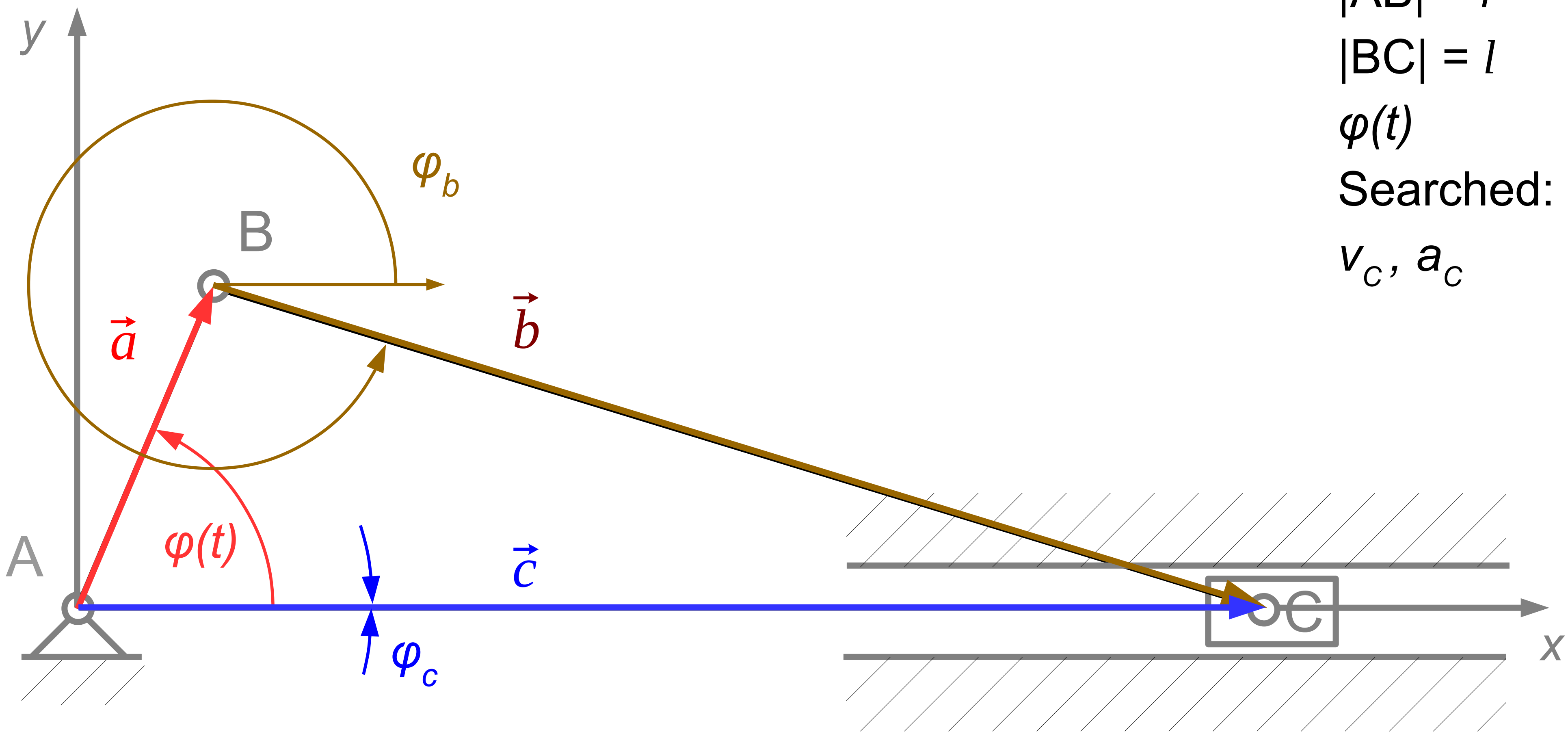

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φ(t)

Searched:

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$|\vec{a}| = r$ $\quad \varphi(t)$

$|\vec{b}| = l$ $\quad \varphi_b(t)$ $\quad \vec{a} + \vec{b} = \vec{c}$

$|\vec{c}| = c(t)$ $\quad \varphi_c = 0$

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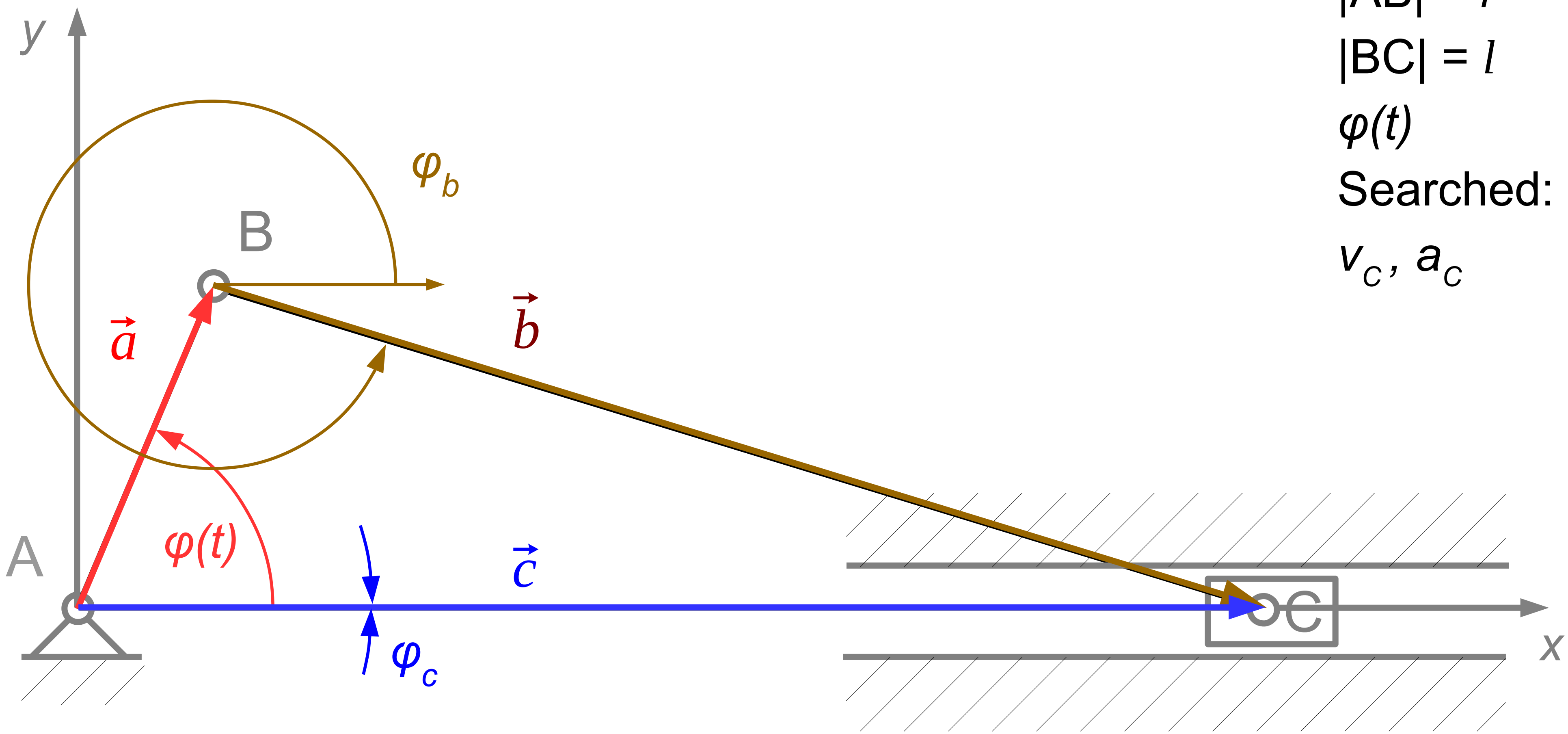

$$|\vec{a}|=r \qquad \varphi(t)$$

$$|\vec{b}|=l \qquad \varphi_b(t)$$

$$|\vec{c}|=c(t) \qquad \varphi_c=0$$

$$\vec{a}+\vec{b}=\vec{c}$$

$$\text{x:}\ r\cos\varphi(t)+l\cos\varphi_b(t)=c(t)\cos 0$$

$$\text{y:}\ r\sin\varphi(t)+l\sin\varphi_b(t)=c(t)\sin 0$$

Analytical method – example:
crank-slider mechanism

$$r\cos\varphi(t)+l\cos\varphi_b(t)=c(t)\cos 0$$
$$r\sin\varphi(t)+l\sin\varphi_b(t)=c(t)\sin 0$$

2 unknowns

Analytical method – example:
crank-slider mechanism

$$r\cos\varphi(t) + l\cos\varphi_b(t) = c(t)\cos 0$$
$$r\sin\varphi(t) + l\sin\varphi_b(t) = c(t)\sin 0$$

2 unknowns

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$$\sin\varphi_b(t)=-\frac{r}{l}\sin\varphi(t)=-\lambda\sin\varphi(t)$$

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$$\cos\varphi_b(t)=\pm\sqrt{1-\sin^2\varphi_b(t)}$$

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Analytical method – example:
crank-slider mechanism

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$$c(t)=r\cos\varphi(t)\pm l\sqrt{1-\lambda^2\sin^2\varphi(t)}$$

$$\text{for }\ \varphi(t)=0$$
$$c(t)=r+l$$

Analytical method – example:
crank-slider mechanism

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for $\varphi(t)=0$

$$c(t)=r+l$$

$$\boxed{c(t)=r\cos\varphi(t)+l\sqrt{1-\lambda^2\sin^2\varphi(t)}}$$

Analytical method – example:
crank-slider mechanism

slider movement

$$c(t) = r\cos\varphi(t) + l\sqrt{1-\lambda^2\sin^2\varphi(t)}$$

$$v_C(t) = \frac{dc(t)}{dt} = -r\,\dot{\varphi}(t)\sin\varphi(t) - \frac{-2l\lambda^2\dot{\varphi}(t)\sin\varphi(t)\cos\varphi(t)}{2\sqrt{1-\lambda^2\sin^2\varphi(t)}}$$

$$a_C(t) = \frac{dv_C(t)}{dt} = \ldots$$

Analytical method – example:
crank-slider mechanism

calculations with wxmaxima

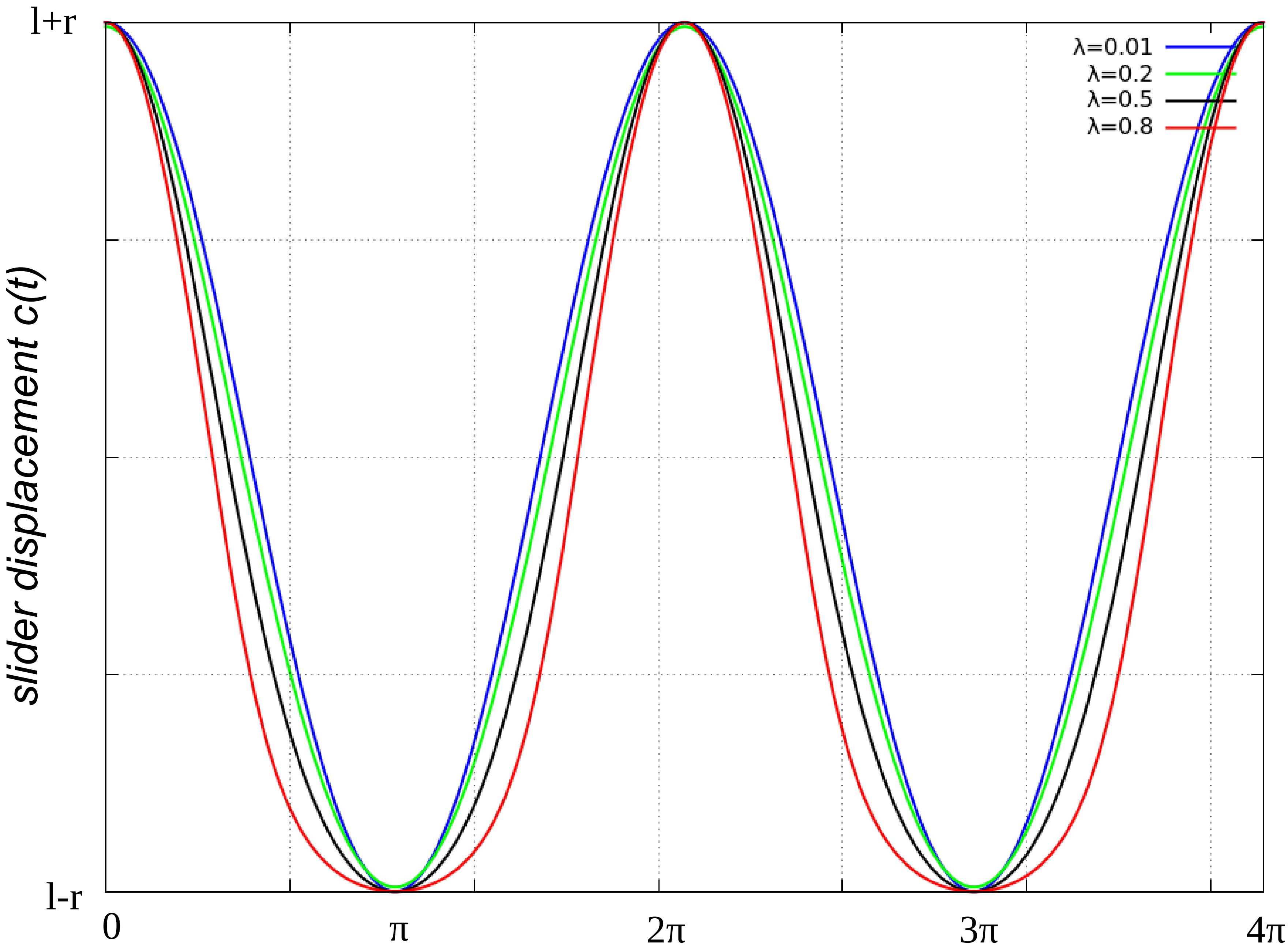
```
(%i14)  c: r*cos(%phi(t))+l*sqrt(1-%lambda^2*(sin(%phi(t)))^2);
        v: diff(c,t,1);
        a: diff(v,t,1);
```

(c) $$l\sqrt{1-\lambda^2\sin(\varphi(t))^2}+r\cos(\varphi(t))$$

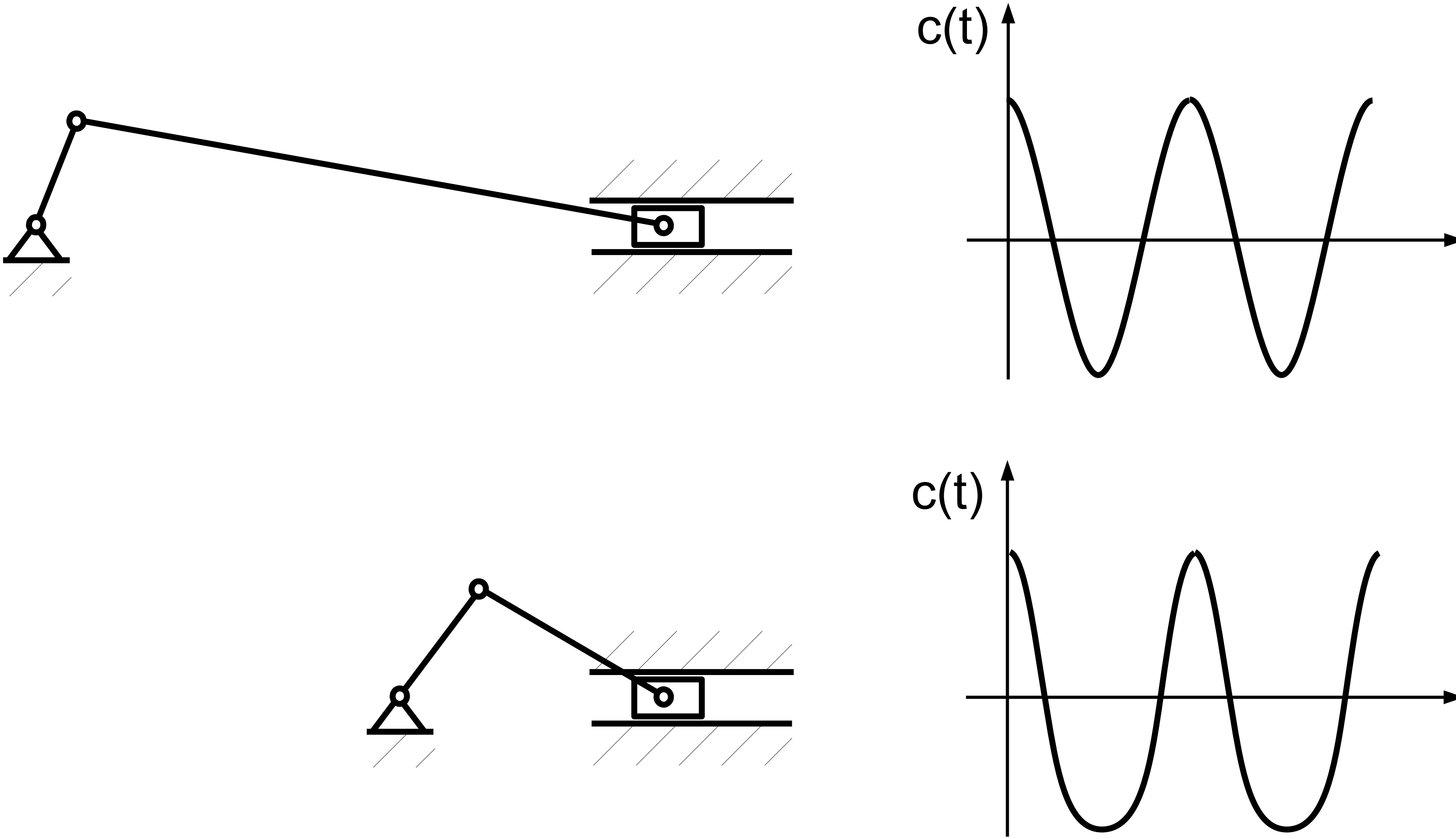
(v) $$-\frac{\lambda^2 l\cos(\varphi(t))\sin(\varphi(t))\left(\frac{d}{d\,t}\varphi(t)\right)}{\sqrt{1-\lambda^2\sin(\varphi(t))^2}}-r\sin(\varphi(t))\left(\frac{d}{d\,t}\varphi(t)\right)$$

(a) $$-\frac{\lambda^2 l\cos(\varphi(t))\sin(\varphi(t))\left(\frac{d^2}{d\,t^2}\varphi(t)\right)}{\sqrt{1-\lambda^2\sin(\varphi(t))^2}}-r\sin(\varphi(t))\left(\frac{d^2}{d\,t^2}\varphi(t)\right)+\frac{\lambda^2 l\sin(\varphi(t))^2\left(\frac{d}{d\,t}\varphi(t)\right)^2}{\sqrt{1-\lambda^2\sin(\varphi(t))^2}}$$
$$\frac{\lambda^2 l\cos(\varphi(t))^2\left(\frac{d}{d\,t}\varphi(t)\right)^2}{\sqrt{1-\lambda^2\sin(\varphi(t))^2}}-\frac{\lambda^4 l\cos(\varphi(t))^2\sin(\varphi(t))^2\left(\frac{d}{d\,t}\varphi(t)\right)^2}{\left(1-\lambda^2\sin(\varphi(t))^2\right)^{3/2}}-r\cos(\varphi(t))\left(\frac{d}{d\,t}\varphi(t)\right)^2$$

Analytical method – example:
crank-slider mechanism



Analytical method – example:
crank-slider mechanism



Analytical method – example:
crank-slider mechanism

connecting rod motion

$$\varphi_b(t) = -\arcsin(\lambda \sin\varphi(t))$$

$$\omega_b(t) = \frac{d\varphi_b(t)}{dt} = \frac{-\lambda\dot{\varphi}(t)\cos\varphi(t)}{\sqrt{1-\lambda^2\sin^2\varphi(t)}}$$

$$\varepsilon_b(t) = \frac{d\omega_b(t)}{dt} = -\frac{\lambda\cos(\varphi(t))\left(\frac{d^2}{dt^2}\varphi(t)\right)}{\sqrt{1-\lambda^2\sin(\varphi(t))^2}} + \frac{\lambda\sin(\varphi(t))\left(\frac{d}{dt}\varphi(t)\right)^2}{\sqrt{1-\lambda^2\sin(\varphi(t))^2}} - \frac{\lambda^3\cos(\varphi(t))^2\sin(\varphi(t))\left(\frac{d}{dt}\varphi(t)\right)^2}{\left(1-\lambda^2\sin(\varphi(t))^2\right)^{3/2}}$$

Analytical method – example:
slider-yoke

<u>Given</u>:

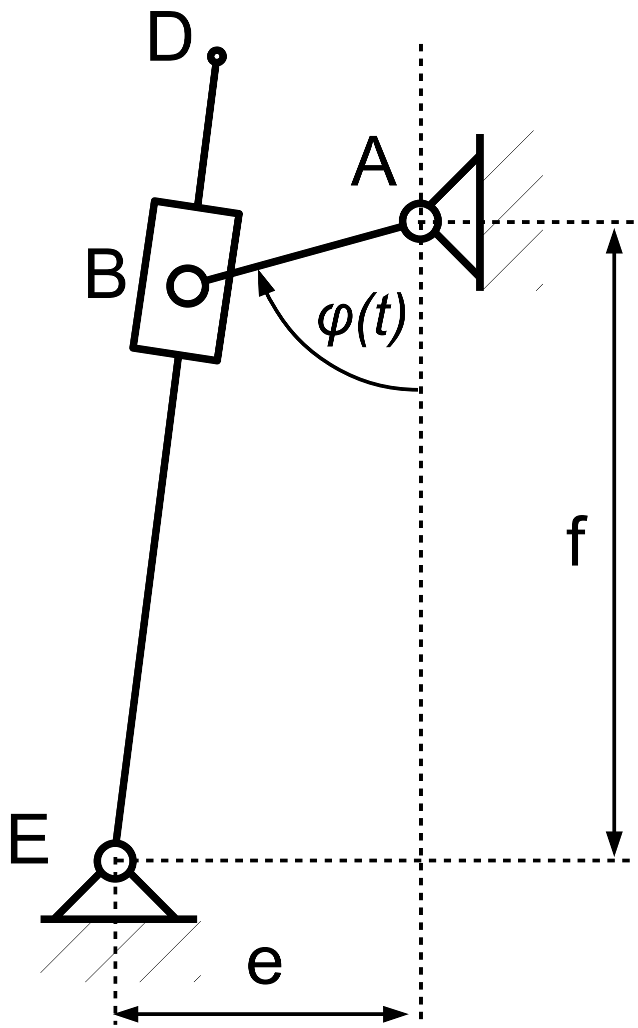
|AB| = *r*

e, f, *φ(t)*

<u>Searched</u>:

angular velocity ω_2 and acceleration ε_2

of ED element



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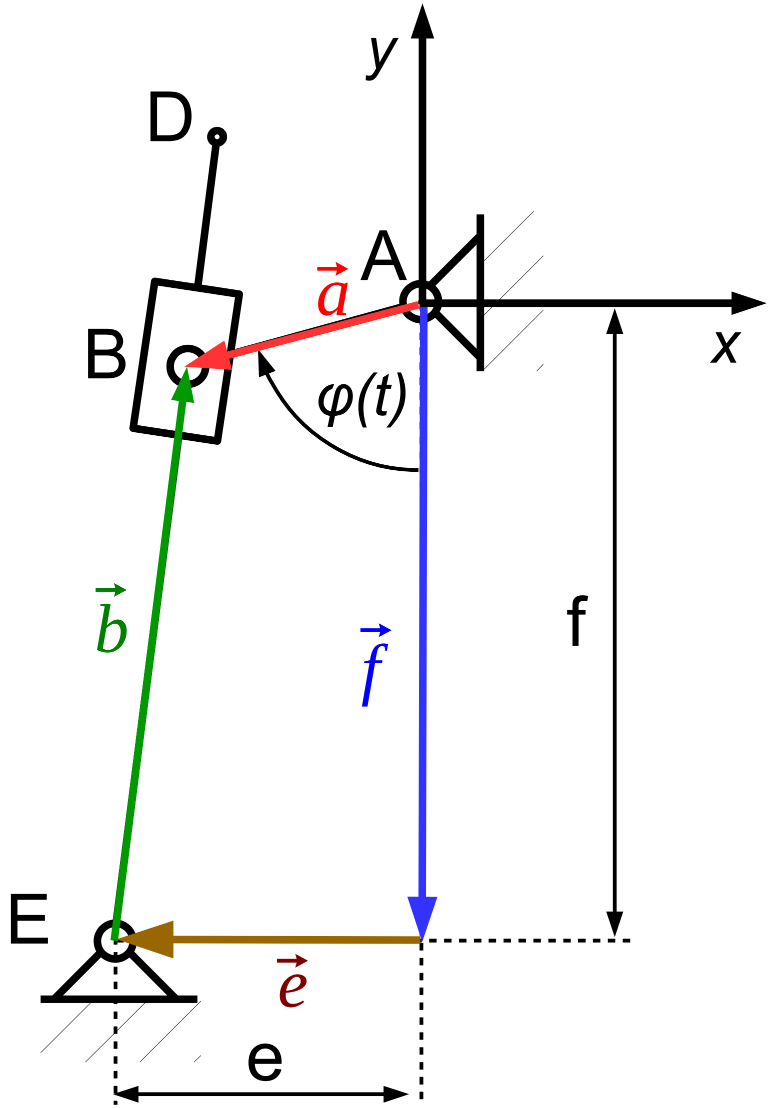

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slider-yoke

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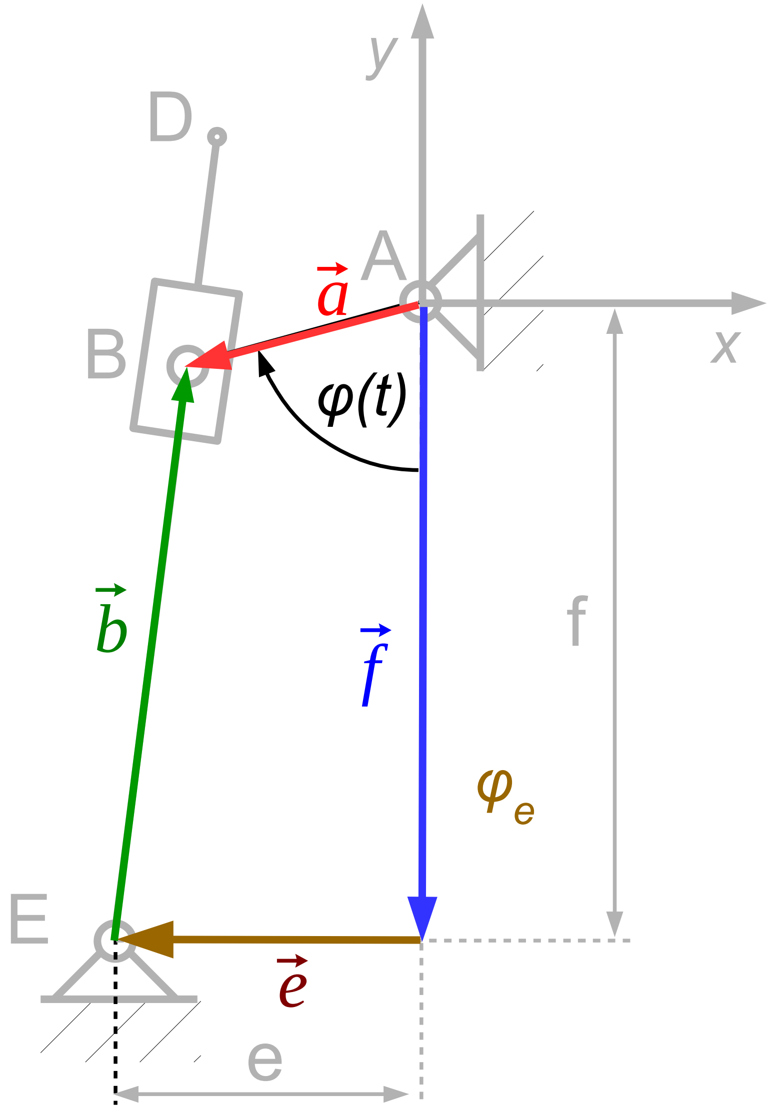

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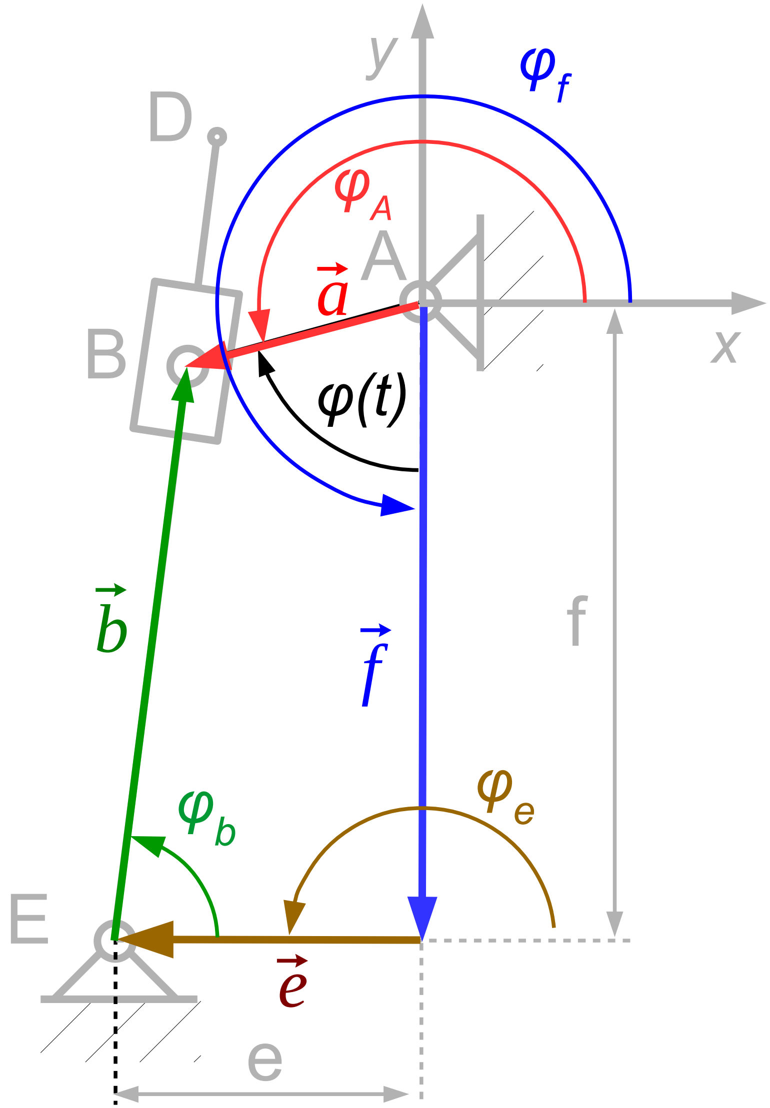

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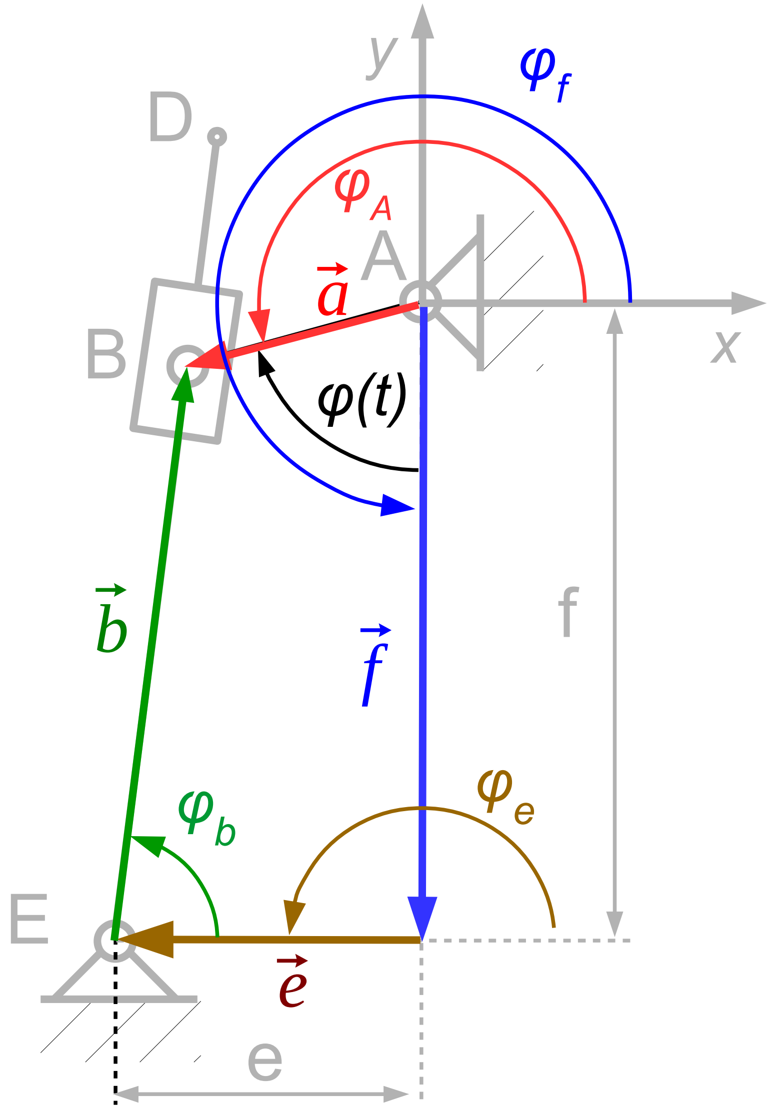

$|\vec{a}| = r$

$\varphi_a(t) = 270^o - \varphi(t)$

$|\vec{b}| = b(t)$

$\varphi_b(t)$

$|\vec{e}| = e$

$\varphi_e = 180^o$

$|\vec{f}| = f$

$\varphi_f = 270^o$

Analytical method – example:
slider-yoke

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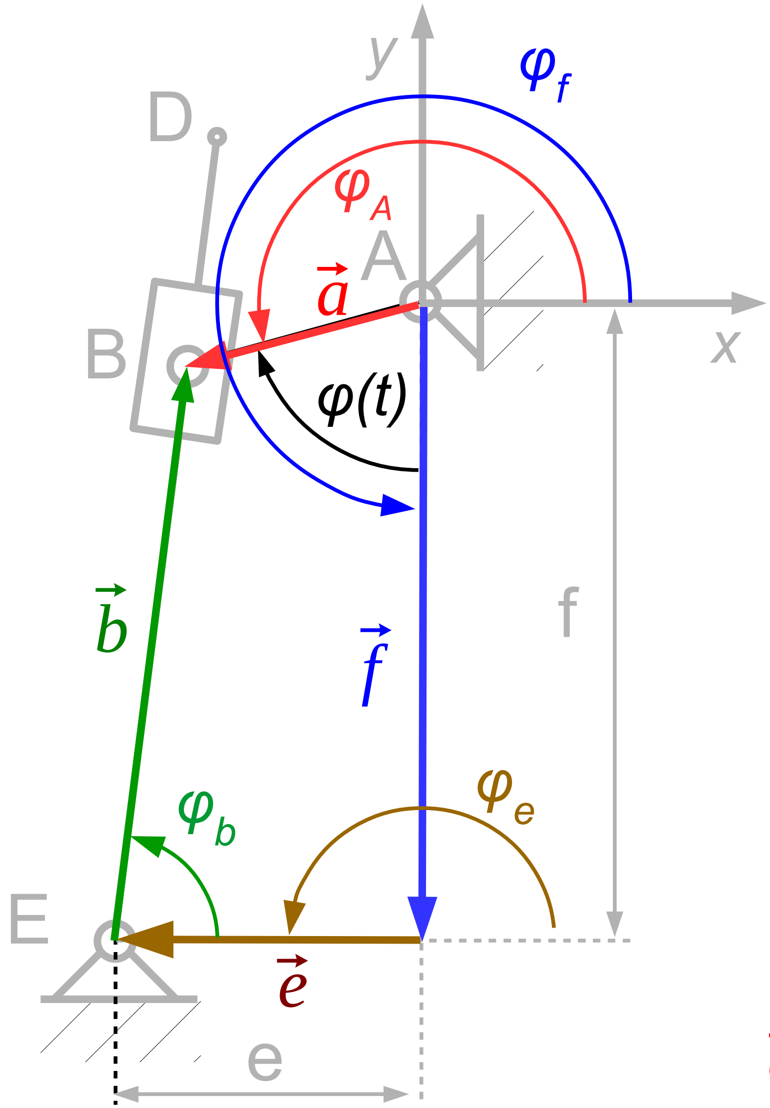

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$|\vec{f}| = f$

$\varphi_f = 270^o$

$$\vec{a} = \vec{b} + \vec{e} + \vec{f}$$

Analytical method – example:
slider-yoke

Given:

|AB| = *r*

e, f, *φ(t)*

Searched:

angular velocity ω_2 and acceleration ε_2

of ED element

$$|\vec{a}| = r$$
$$\varphi_a(t) = 270^o - \varphi(t)$$
$$|\vec{b}| = b(t)$$
$$\varphi_b(t)$$

$$|\vec{e}| = e$$
$$\varphi_e = 180^o$$
$$|\vec{f}| = f$$
$$\varphi_f = 270^o$$

$$\vec{a} = \vec{b} + \vec{e} + \vec{f}$$

$$\text{x: } r\cos\left(270^o - \varphi(t)\right) = b(t)\cos\varphi_b(t) + e\cos 180^o + f\cos 270^o$$
$$\text{y: } r\sin\left(270^o - \varphi(t)\right) = b(t)\sin\varphi_b(t) + e\sin 180^o + f\sin 270^o$$

Analytical method – example:
slider-yoke

Given:

|AB| = *r*

e, f, *φ(t)*

Searched:

angular velocity ω_2 and acceleration ε_2

of ED element

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$$\varphi_a(t) = 270^o - \varphi(t)$$
$$|\vec{b}| = b(t)$$
$$\varphi_b(t)$$

$$|\vec{e}| = e$$
$$\varphi_e = 180^o$$
$$|\vec{f}| = f$$
$$\varphi_f = 270^o$$

$$\vec{a} = \vec{b} + \vec{e} + \vec{f}$$

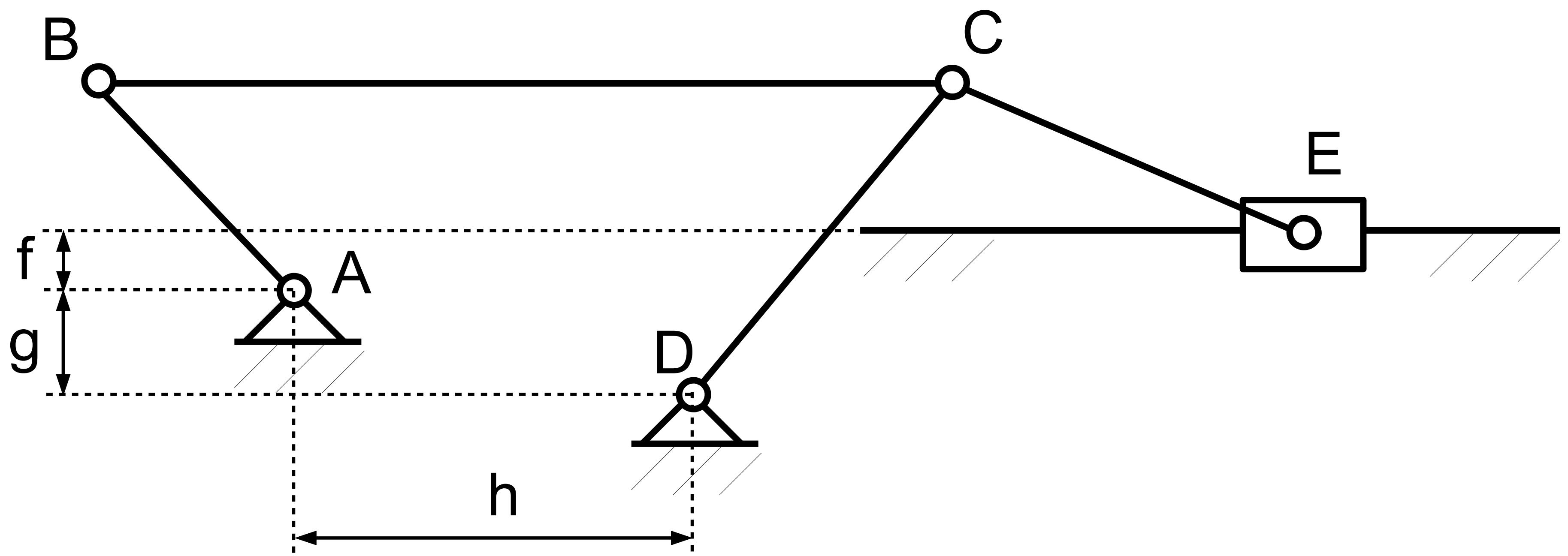
$$\text{x: } r\cos(270^o - \varphi(t)) = b(t)\cos\varphi_b(t) + e\cos 180^o + f\cos 270^o$$
$$\text{y: } r\sin(270^o - \varphi(t)) = b(t)\sin\varphi_b(t) + e\sin 180^o + f\sin 270^o$$

$$\text{x: } -r\sin\varphi(t) = b(t)\cos\varphi_b(t) - e$$
$$\text{y: } -r\cos\varphi(t) = b(t)\sin\varphi_b(t) - f$$

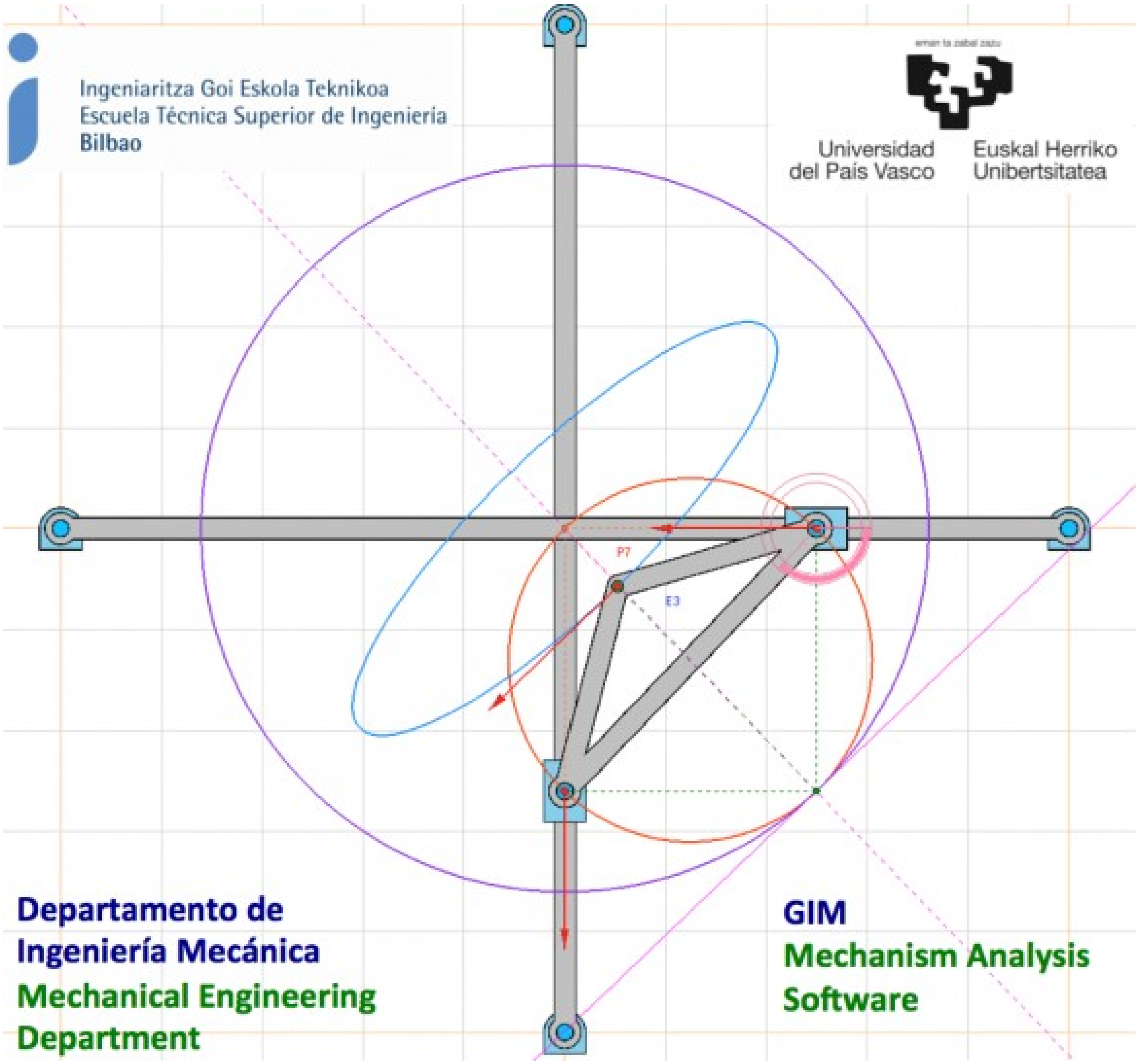
Analytical method – example:
slider-yoke

$$b(t)\cos\varphi_b(t) = -r\sin\varphi(t) + e$$
$$b(t)\sin\varphi_b(t) = -r\cos\varphi(t) + f$$

Analytical method – example



Software

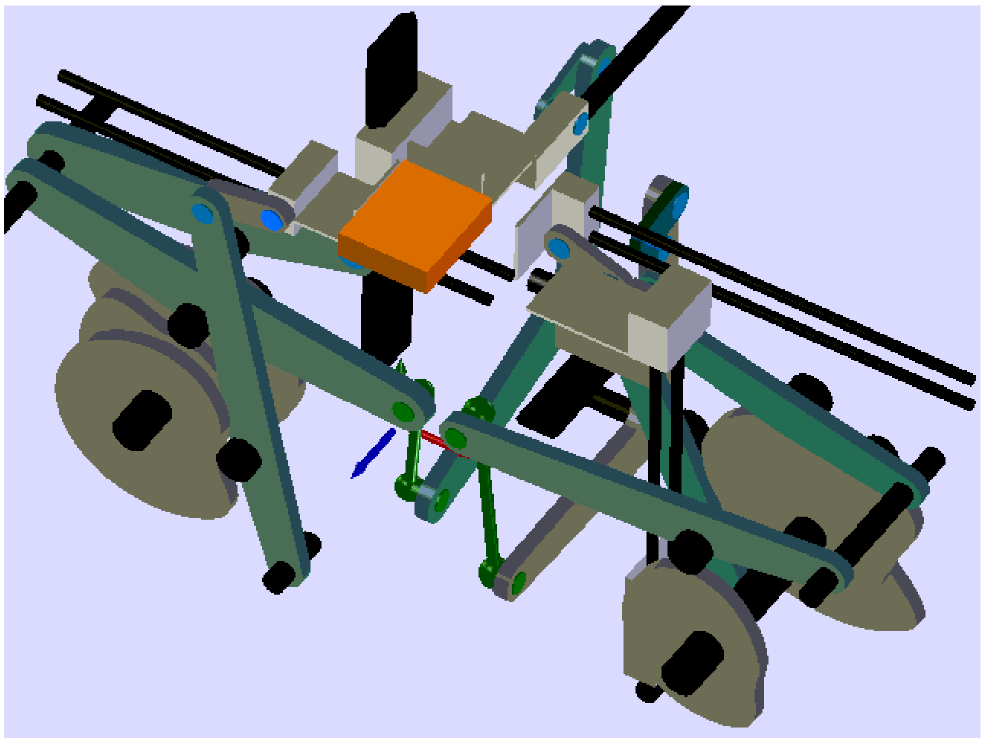


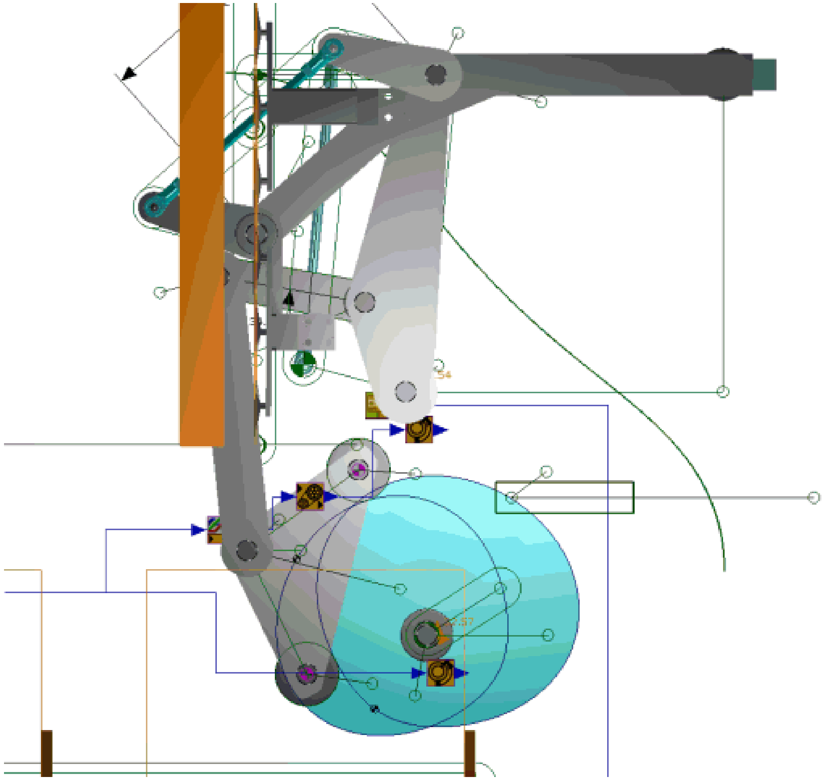
http://www.ehu.eus/compmech/software/

Cam-follower mechanisms

Cam-follower

Inspirations



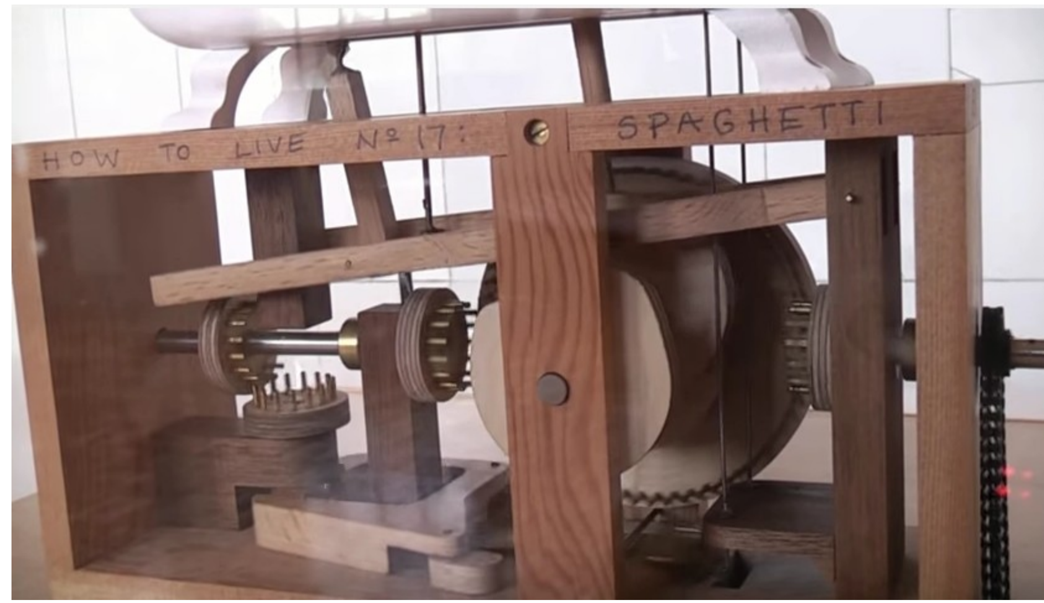


source: psmotion.com

Cam-follower

<u>art inspiration</u>

The "Draughtsman-Writer" automaton by Henri Maillardet
https://en.wikipedia.org/wiki/File:Maillardet
%27s_automaton_at_the_Franklin_Institute.webm



Mechanics Alive! Cabaret Mechanical
Theatre Automata Exhibition
https://www.youtube.com/watch?v=kv1CpJi60xQ

Cam-follower

Cam-follower mechanism – mechanism build of a cam and a follower (tappet) connected as a IV class kinematic pair.

Cam is rotating (sometimes is translating)

follower is reciprocating (sometimes is swinging/oscillating)

advantages

- simple to construction,
- simple to create,
- any dimensions,
- simple to create advanced motions.

disadvantages

- small strength with hight loads,
- no adaptation possible.

Cam-follower

Classification

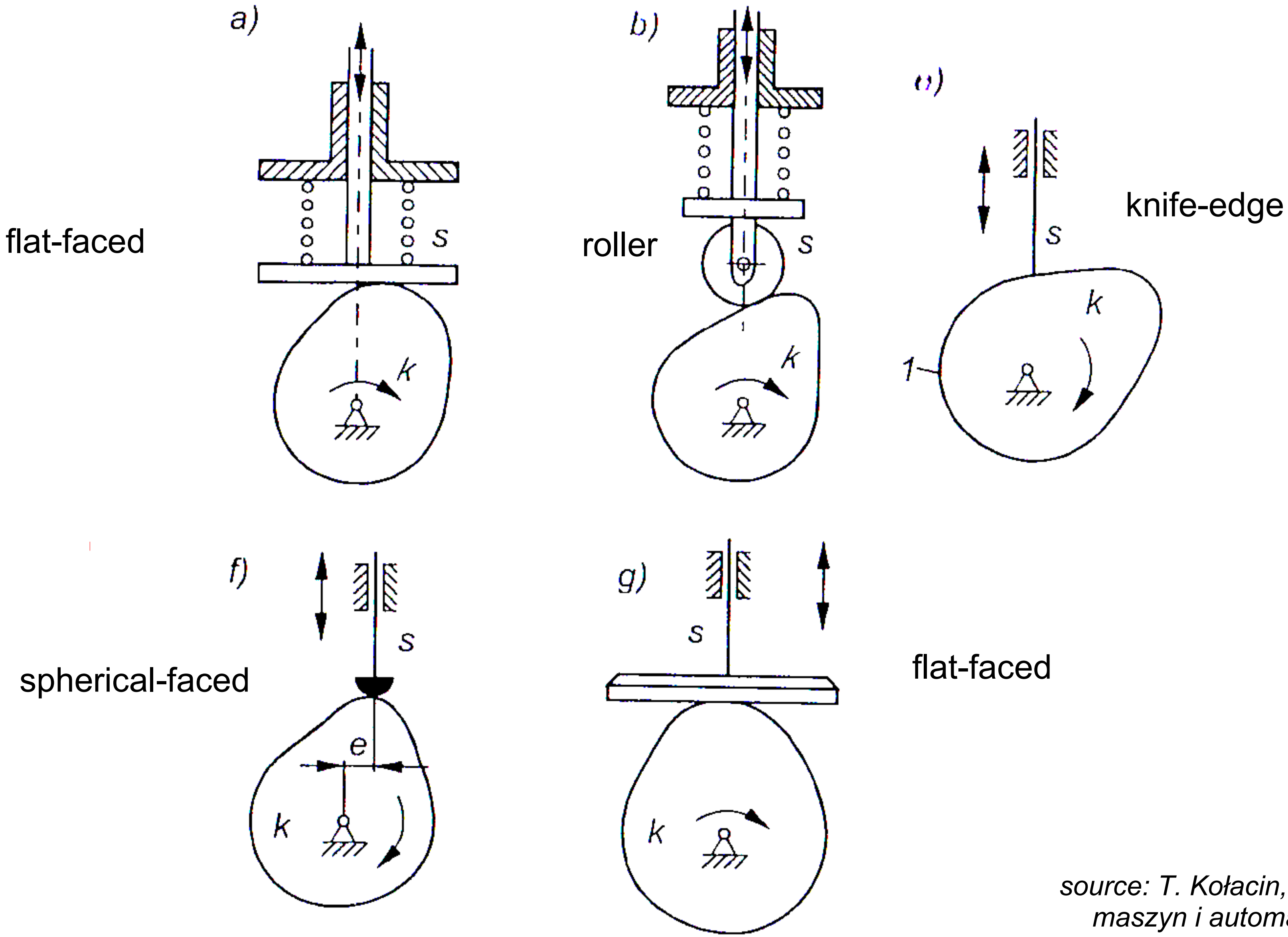
flat / spatial

with in-line (central) follower / with offset (eccentric) follower

closed with geometry / closed with force

Cam-follower

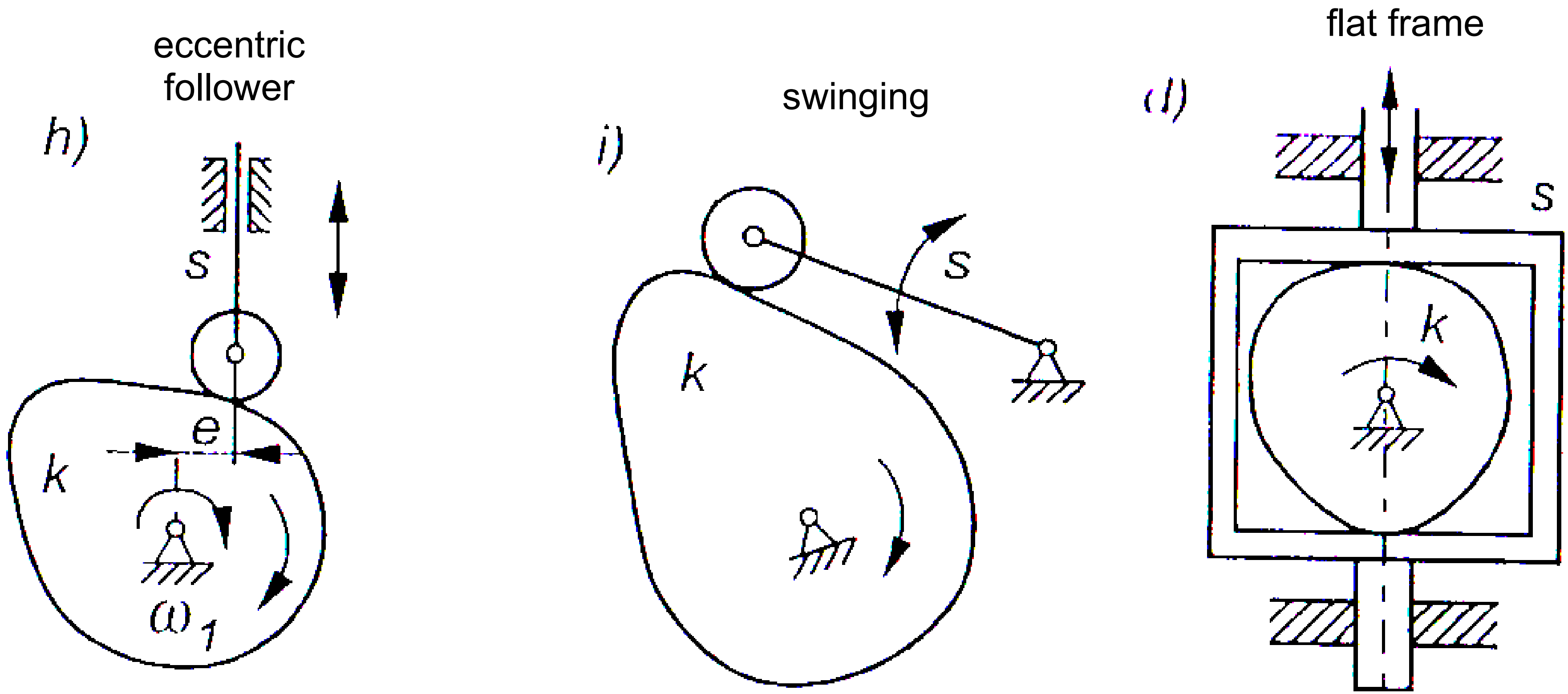
Followers



source: T. Kołacin, „Podstawy teorii maszyn i automatyki”, OW PW

Cam-follower

Followers

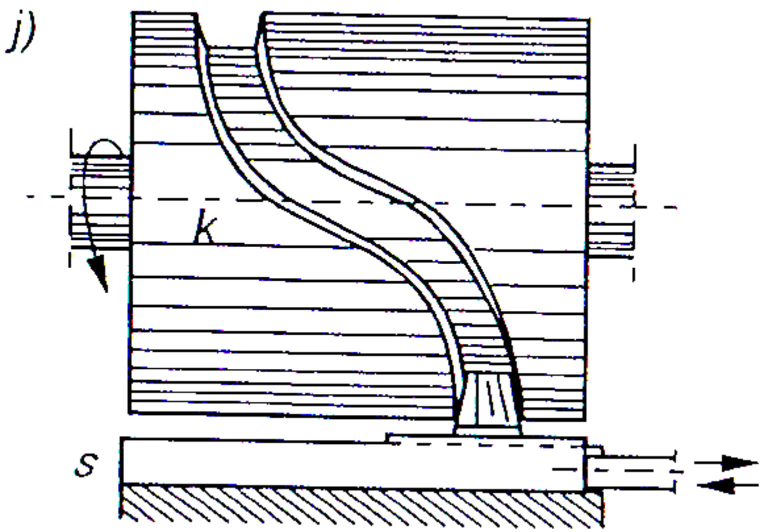


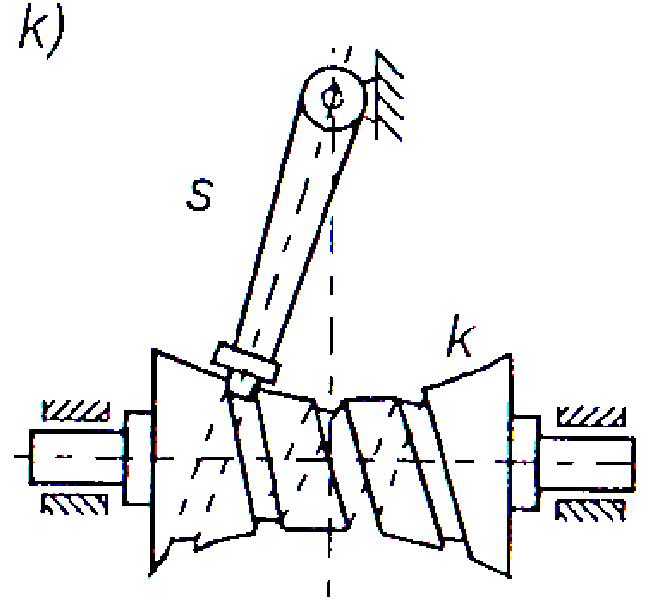
source: T. Kołacin, „Podstawy teorii maszyn i automatyki”, OW PW

Cam-follower

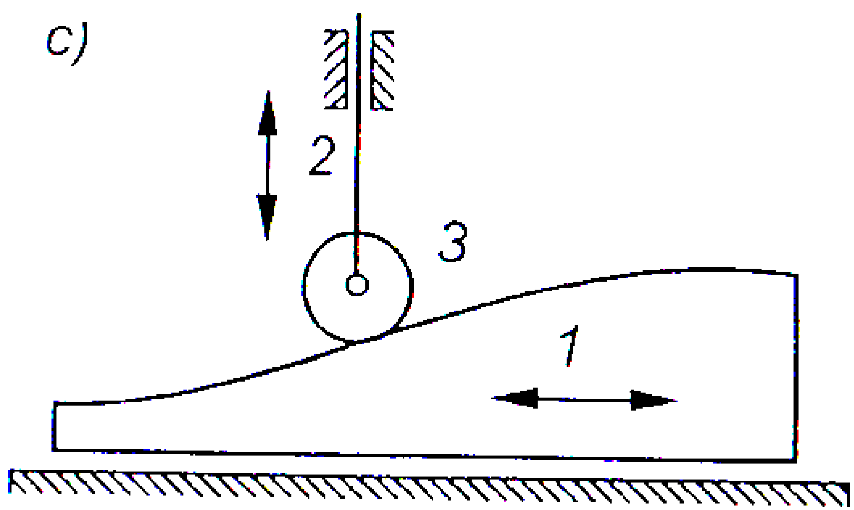
examples

cylindrical cam





globoidal



translating cam

source: T. Kołacin, „Podstawy teorii maszyn i automatyki", OW PW

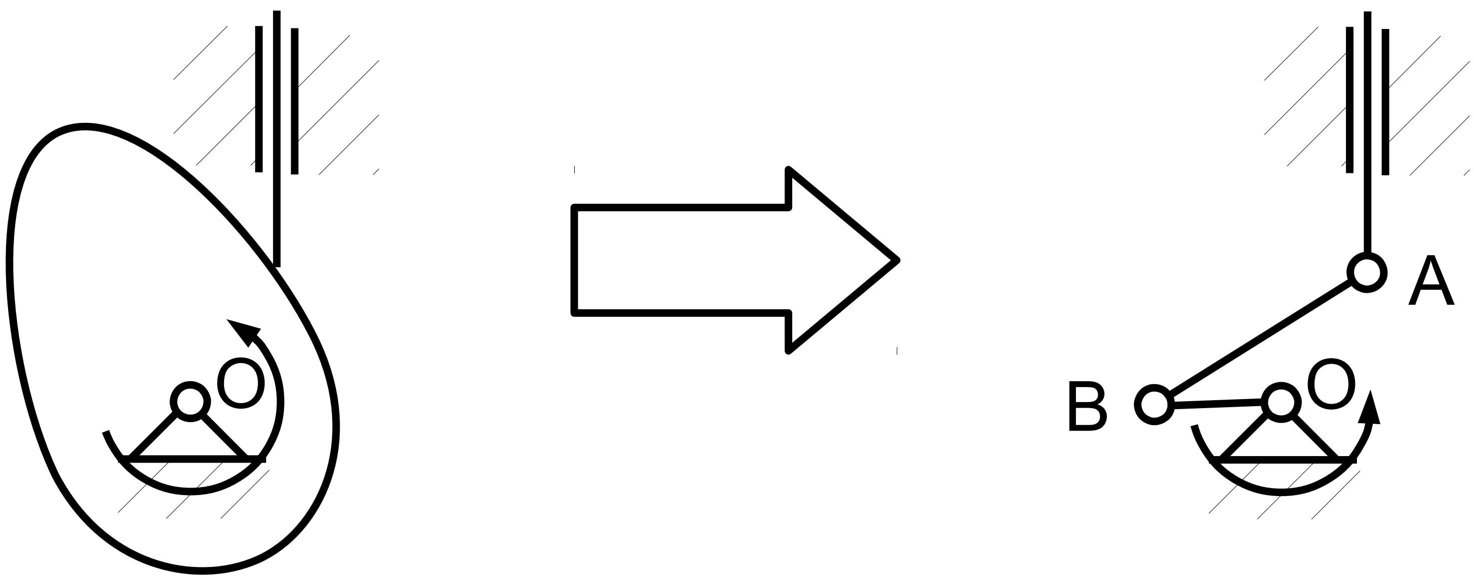
Analysis and synthesis of cam-follower mechanism

Analysis – calculation of displacement, velocity and acceleration functions for a follower motion with respect to a cam's rotations angle for arbitrary given geometry.

Synthesis – calculation of a cam geometry needed to obtain given displacement/velocity/acceleration functions. Limitations must be included, i.e. some maximum values, geometry limitations and jerk values (third derivative).

Analysis of a cam-follower mechanism

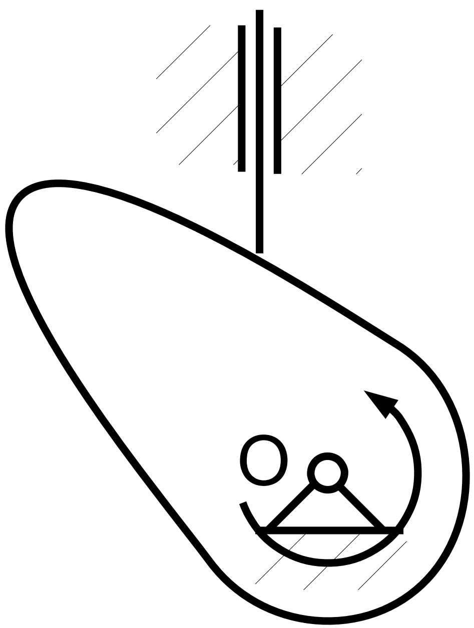
Graphical method with IV. class kinematic pair substitution with V. class kinematic pairs.



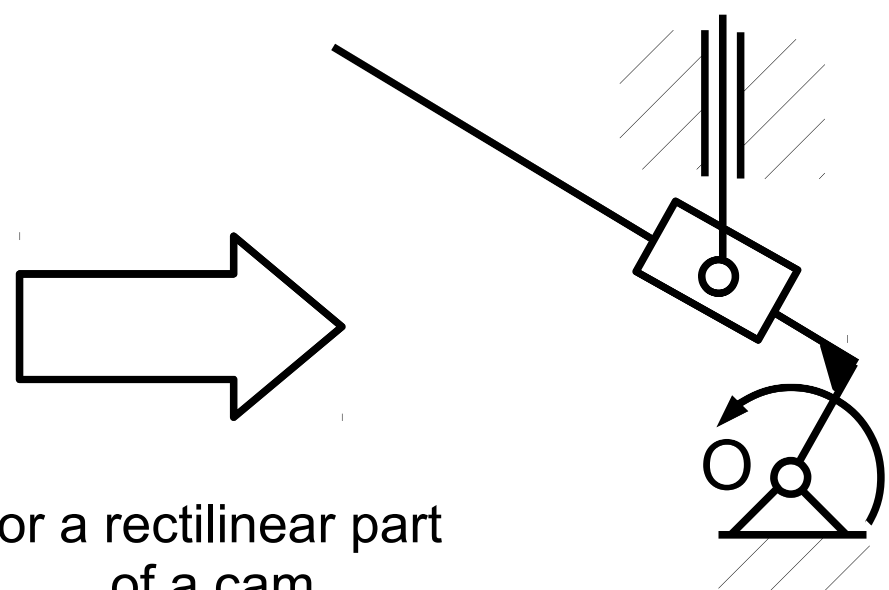
AB – radius of curvature in the contact point

Analysis of a cam-follower mechanism

<u>Graphical method with IV. class kinematic pair substitution with V. class kinematic pairs.</u>

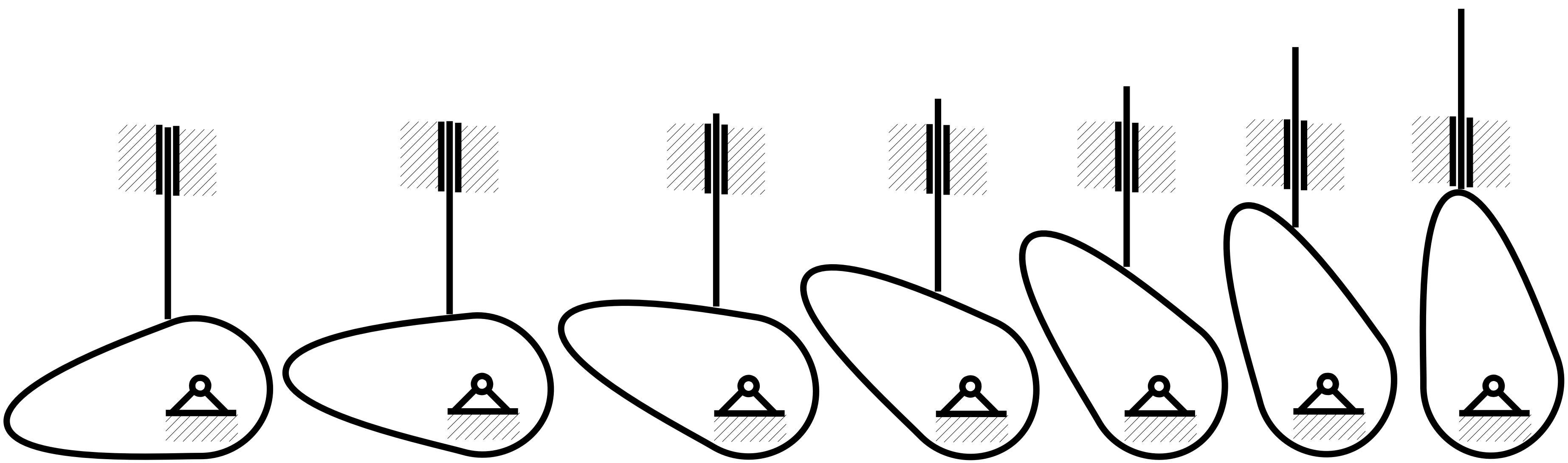


for a rectilinear part
of a cam



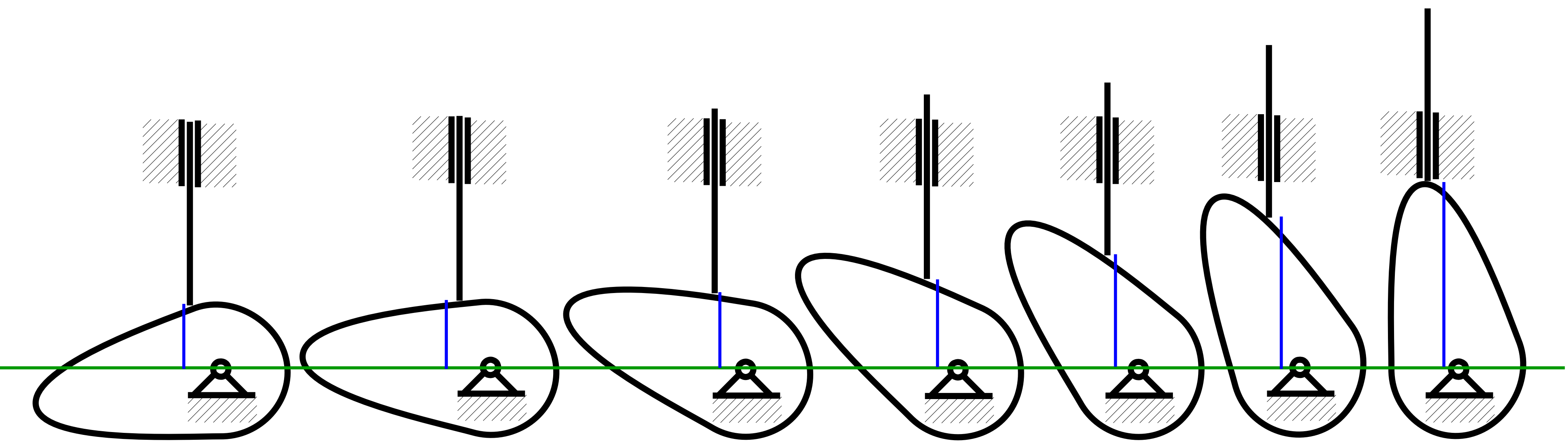
Analysis of a cam-follower mechanism

Graphical determination of a follower movement



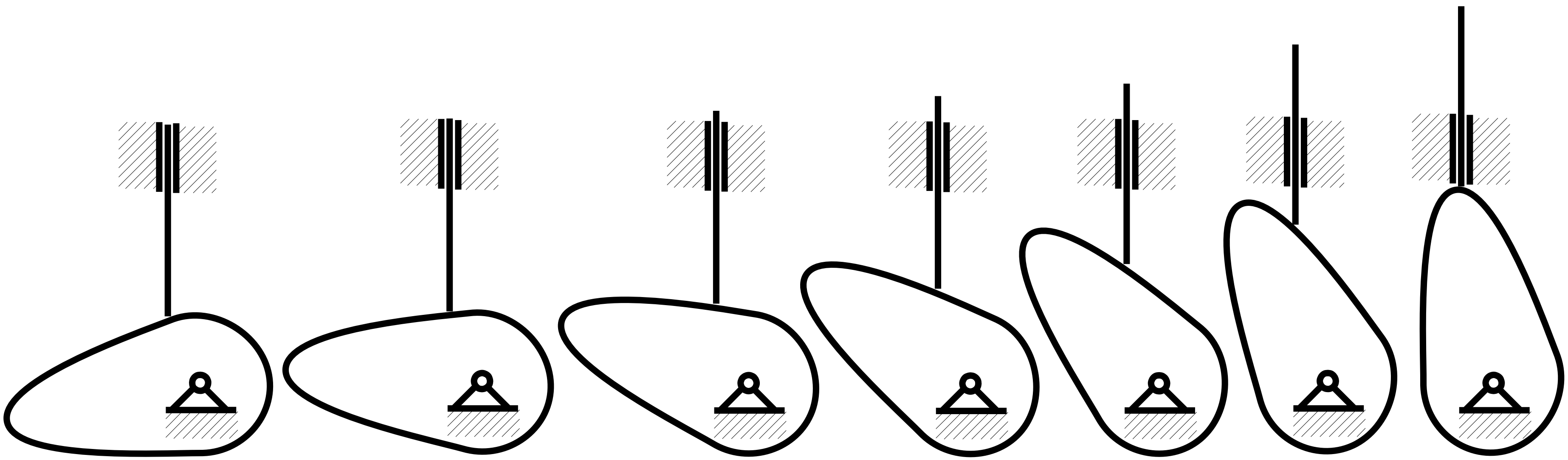
Analysis of a cam-follower mechanism

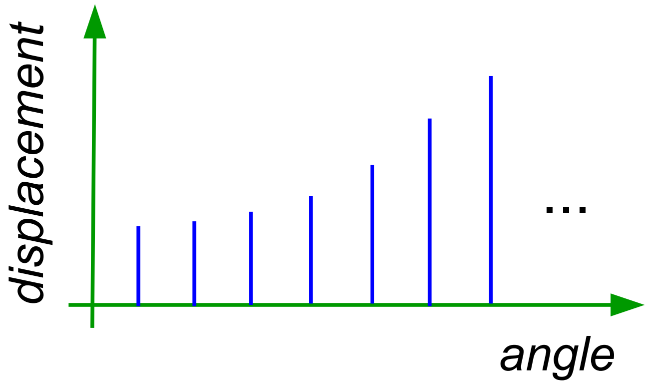
<u>Graphical determination of a follower movement</u>



Analysis of a cam-follower mechanism

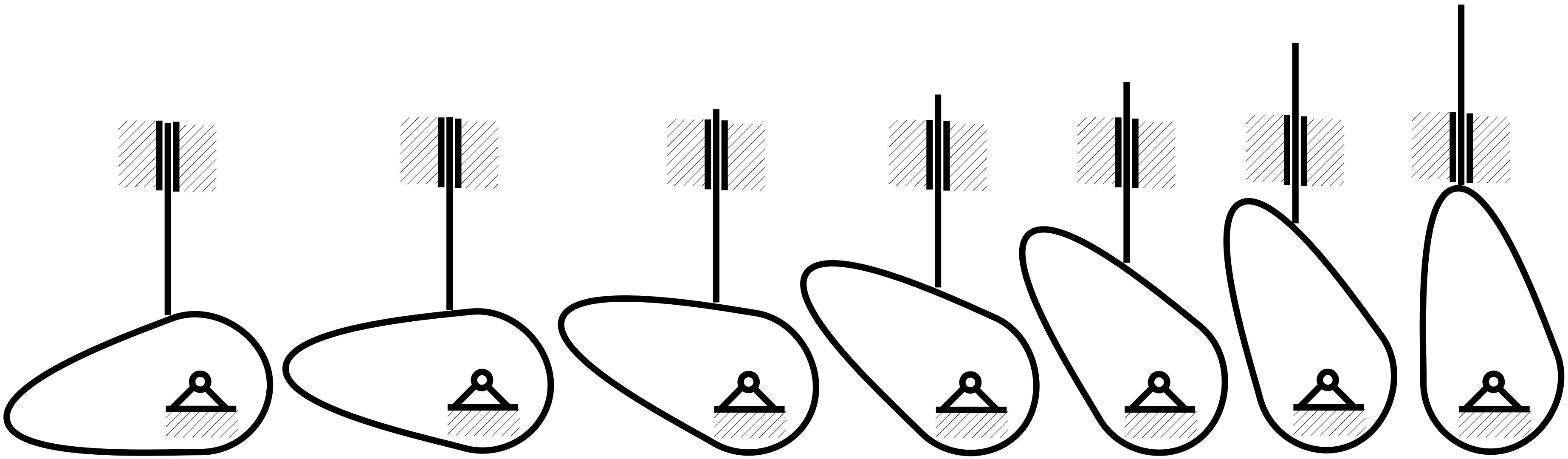
Graphical determination of a follower movement

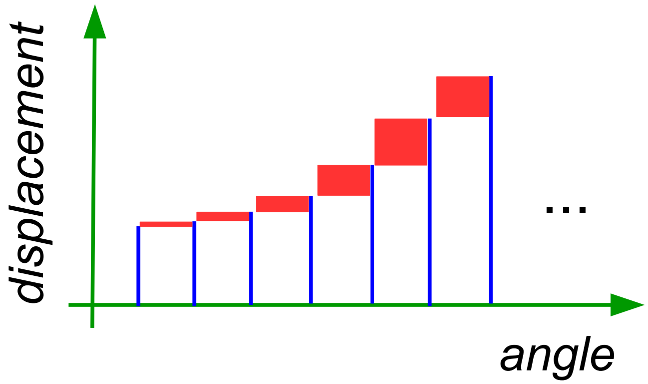




Analysis of a cam-follower mechanism

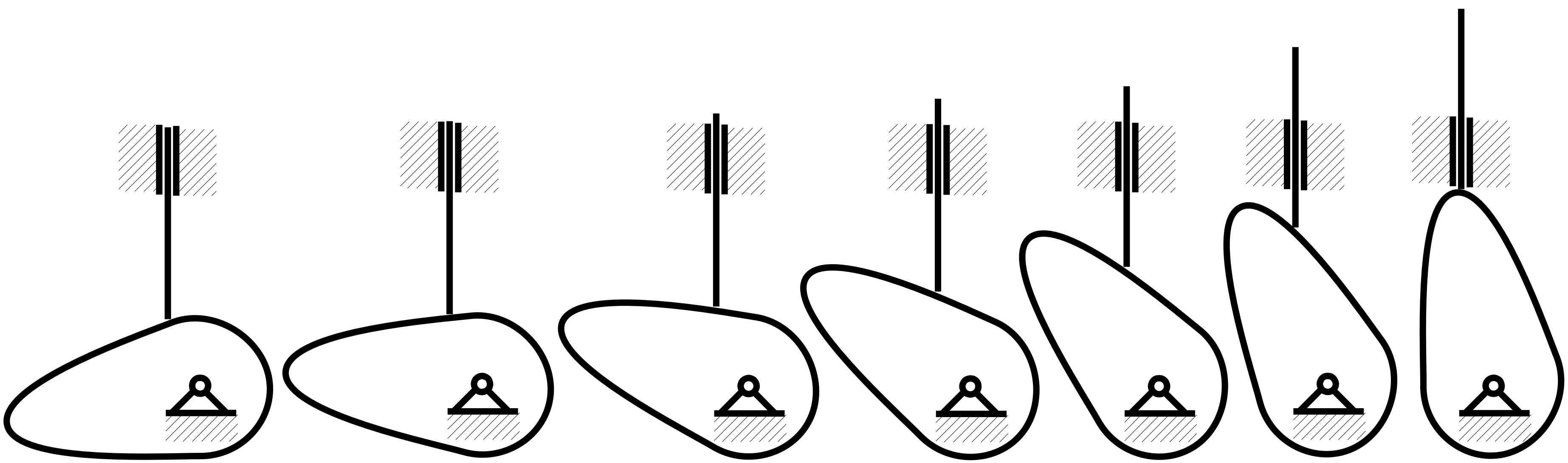
Graphical determination of a follower movement

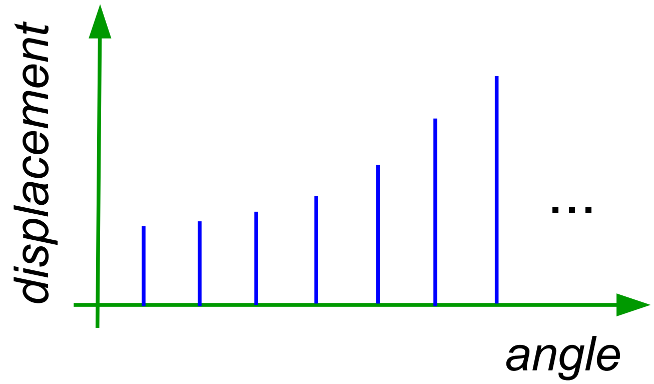


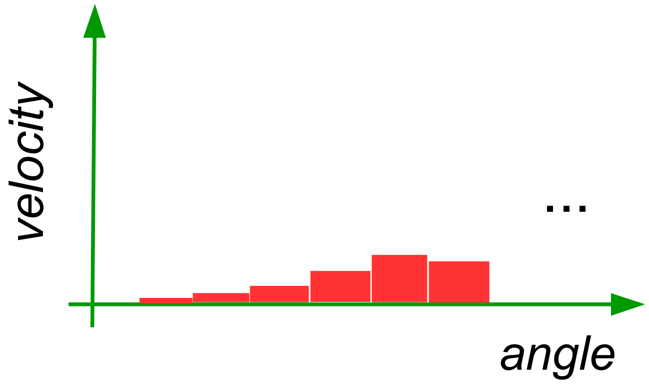


Analysis of a cam-follower mechanism

Graphical determination of a follower movement

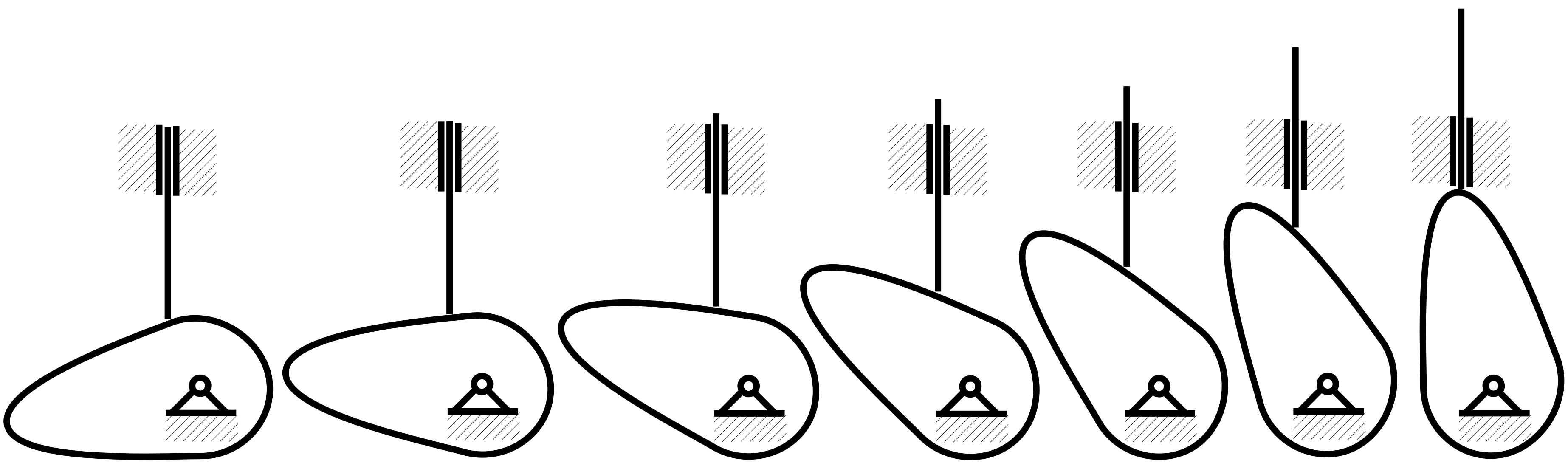


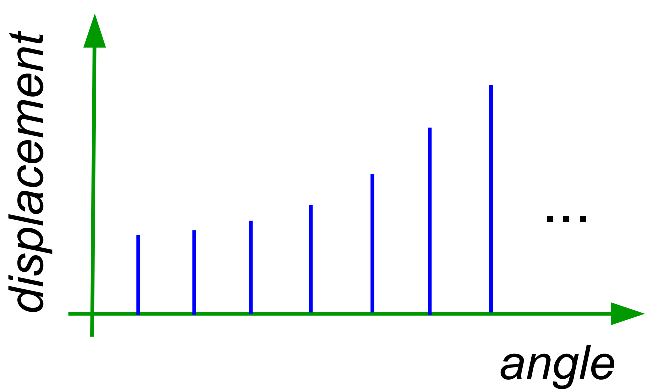


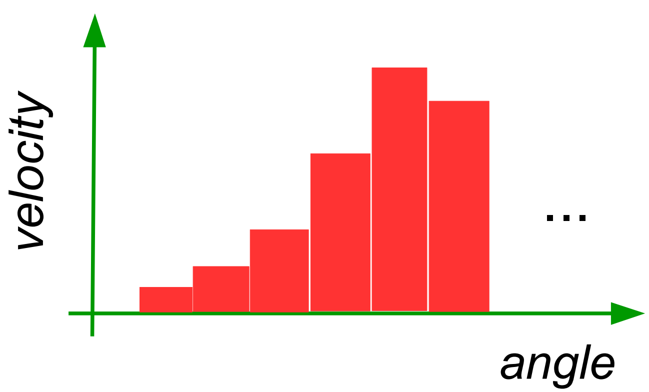


Analysis of a cam-follower mechanism

Graphical determination of a follower movement

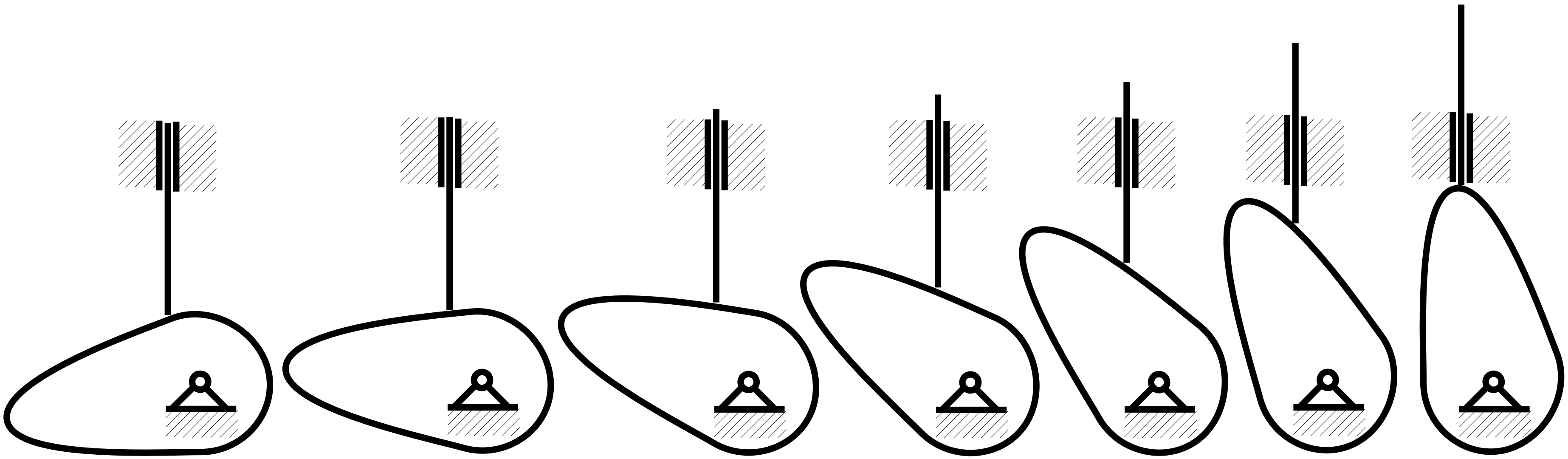


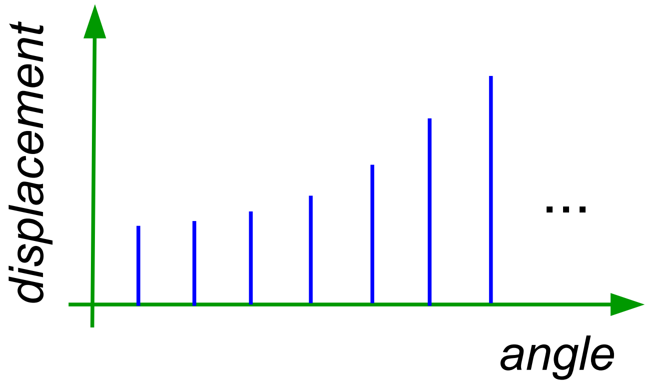


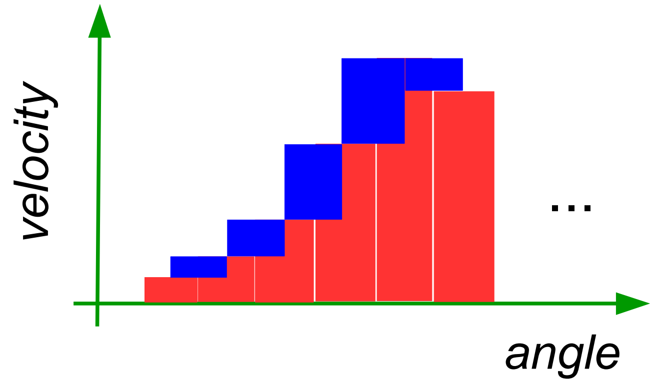


Analysis of a cam-follower mechanism

Graphical determination of a follower movement

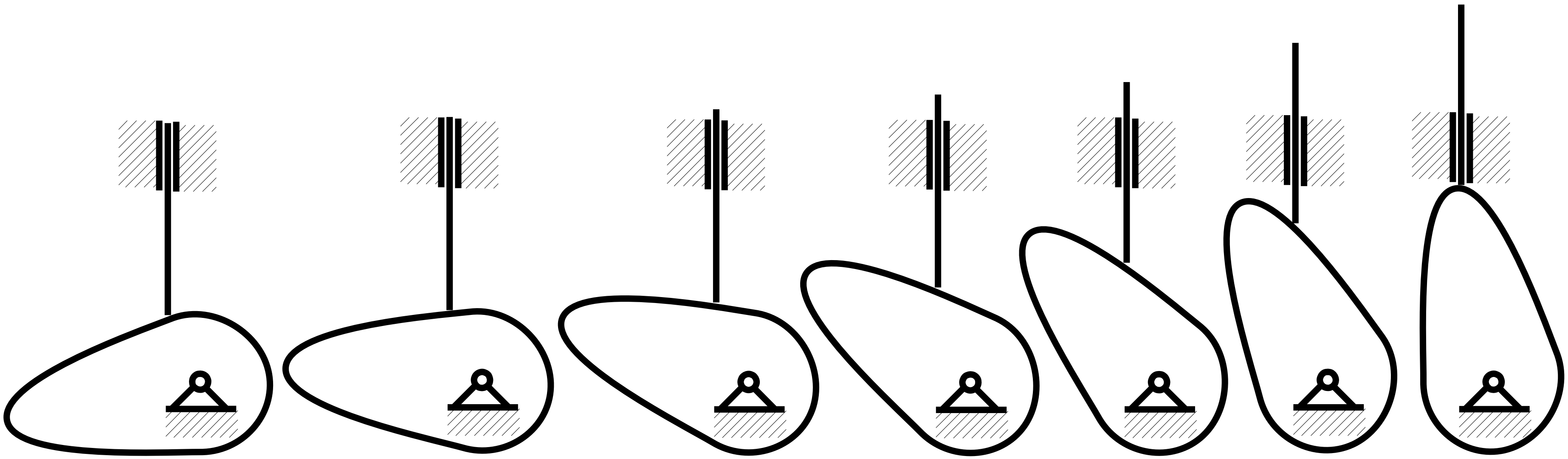


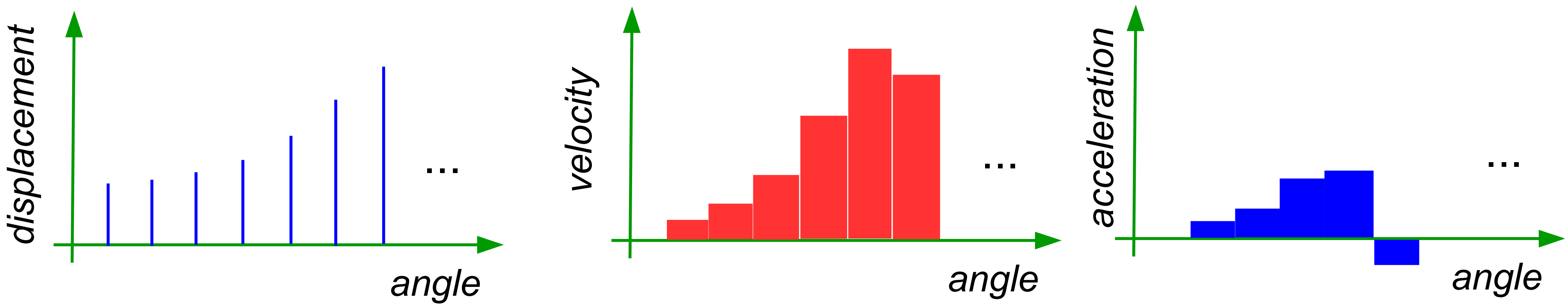




Analysis of a cam-follower mechanism

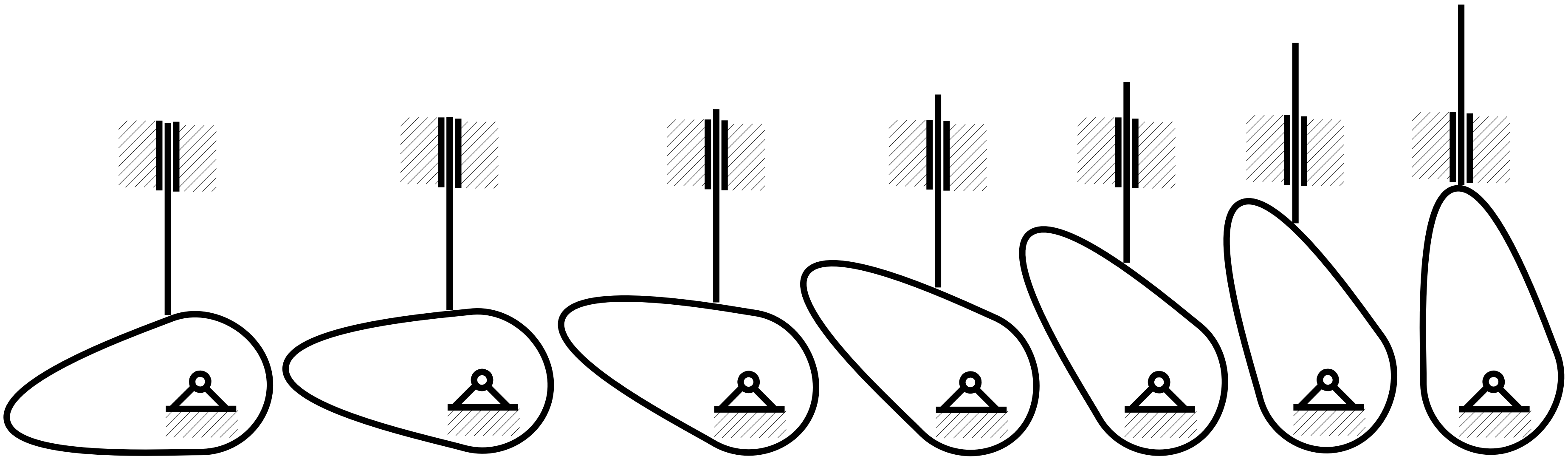
Graphical determination of a follower movement

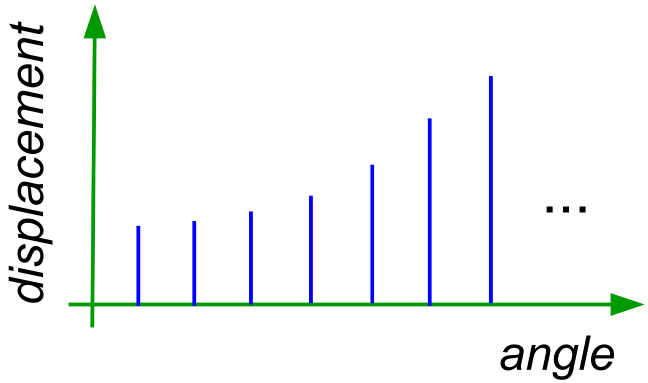


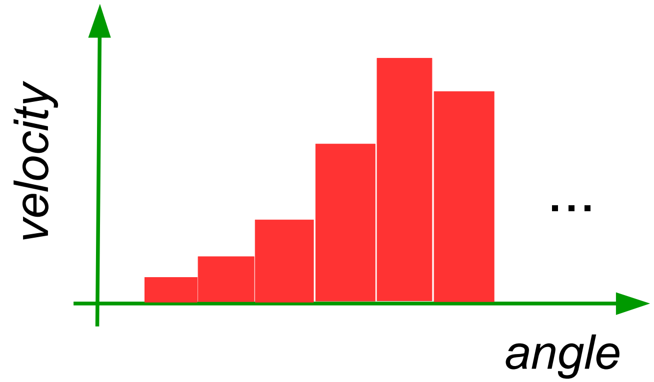


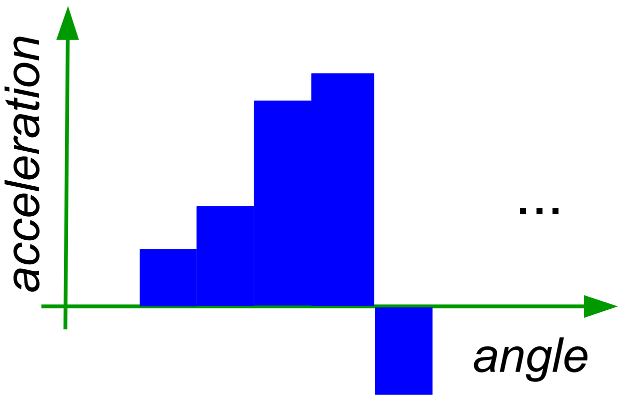
Analysis of a cam-follower mechanism

Graphical determination of a follower movement









Analysis of a cam-follower mechanism

Analytical method - example