Faculty of Automotive and Construction Machinery Engineering
WARSAW UNIVERSITY OF TECHNOLOGY

Theory of Machines and Automatic Control

Winter 2019/2020

Lecturer: Sebastian Korczak, PhD, Eng.

Theory of Machines and Automatic Control

full-time study, winter semester, 2019/2020

Field of studies: Electric and Hybrid Vehicle Engineering
Mechatronics of Vehicles and Construction Machinery

form of studies: 30 hrs lecture, 15 hrs project class

ECTS: 4

course leader: Sebastian Korczak, PhD Eng.

Lecture: Tuesdays at 8:15 (room 2.19)

Course website: http://myinventions.pl/students/

Theory of Machines and Automatic Control
COURSE REGULATIONS

Course form and content

Recommendations, restrictions, attendance

Partial verification of learning outcomes

Project class regulations

Project topics

Providing information on grades awarded

Final verification of learning outcomes (exam)

Final course grade

Materials and devices approved

Rules on retaking

Project class schedule

Theory of Machines and Automatic Control
COURSE REGULATIONS

Presence at the lecture – not obligatory

Presence at the project class – obligatory

Recommended preliminaries:

Algebra,

Analysis,

differential equations,

theoretical mechanics I & II.

Theory of Machines and Automatic Control
COURSE REGULATIONS

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- **Partial verification of learning outcomes**
- **Project class regulations**
- **Project topics**
- **Providing information on grades awarded**
- Final verification of learning outcomes (exam)
- Final course grade
- Materials and devices approved
- Rules on retaking
- Project class schedule

Lecture – no partial verification during semester.

Project class – partial verification of learning outcomes with three individual projects.

Details – to present on first project class.

Last day of final project class grading – last day of a semester.

Theory of Machines and Automatic Control
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Project class schedule

There will be a written exam on skills and knowledge during examination session.

Passed project class with positive mark is obligatory for exam attendance.

Students with positive marks from the exam and the project class will obtain positive final course grade calculated as a mean value of project and exam mark. Final mark rounding depends on previous marks from exam.

Theory of Machines and Automatic Control
COURSE REGULATIONS

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Project class schedule

During the project class all materials are allowed.

You can not use any written materials and electronic devices during the exam (mobile phones, smart watches, calculators). Table of Laplce transform if needed will be displayed on the screen or table.

Theory of Machines and Automatic Control
COURSE REGULATIONS

Positive project class marks from previous academic year could be accepted during present course. Student have to send a proposal to course leader with an information about a mark to transfer.

Assessment method

Exam: written examination on skills and knowledge after completing and successful attestation of project classes.

2 terms in the winter examination session (01.02 – 14.02)

1 term in the autumn examination session (2.09 – 15.09)

Final_mark = 0.5 * project_mark + 0.5 * exam_mark

Negativ mark: 2,0
Positiv marks: 3,0; 3,5; 4,0; 4,5; 5,0

Theory of Machines and Automatic Control

Projects:

Wednesdays at 8:15 (1st EHVE group in room 3.14)

Wednesdays at 10:15 (2nd EHVE group in room 3.11)

Fridays at 8:15 (MTR group in room 0.3)

1st meeting on 23rd October

Contact:

Sebastian Korczak, PhD Eng.

room: 2.8b

e-mail: sebastian.korczak@pw.edu.pl

consultations: Tuesdays at 11:00-12:00 and Fridays at 13:00-14:00

website with presentations: http://myinventions.pl/students/

Lecture contents – overview (30 hrs)

1.Mechanisms – mobility, velocities and accelerations, dynamics.

2. Machine dynamics – equation of machine motion, flywheel.

3. Laplace transform & transfer functions.

4. Basic automatic control elements and their characteristics.

5. Block diagram algebra.

6. Controllers.

7. Stability.

Project class contents – overview (15 hrs)

1. Kinematic analysis of a given mechanism.
2. Dynamic analysis of a given machine – inertia end forces reduction, solution of a machine equation of motion and flywheel calculation.
3. Project of a control system for a simple mechanical system with stability analysis.

Lecture contents – details

1. Classification of kinematic pairs. Structural formula. Overconstraints. Four-bar chain. Examples.
2. Planar mechanisms and their classification. Methods of determining velocities and accelerations in planar mechanisms.
3. Velocity and acceleration schemes in mechanisms, incl. Coriolis acceleration. Four-bar linkage. Grashof's conditions.
4. Analytical methods for determining velocities and accelerations in plane mechanisms.
5. Cam mechanisms. Methods for determining velocities and accelerations.
6. Synthesis of cam mechanisms. Kinematics of Cardan mechanism.

Lecture contents – details cont.

7. Dynamics of plane mechanisms. Method of reduced mass. Inertia forces.
8. Analytic-graphical method for determining forces in plane mechanisms.
9. Machine dynamics. Reduction of masses and forces. Machine equation of motion. Non□uniformity of machine motion. Flywheel.

Lecture contents – details cont.

10. Basic notions of automatic control. Principles of operational calculus.
11. Types of system inputs. Input time- and frequency characteristics.
12. Characteristics of basic automatic control elements in the time- and frequency domains. Inertialess elements. Inertial elements of the 1-st and 2-nd order. Integral, derivative and time delay elements.
13. Block diagram algebra.
14. Types of controllers. Proportional-plus-itegral-plus-differential controller. Stability of linear automatic control systems.
15. Hurwitz and Nyquist criteria of stability. Module and phase stocks. System correction.
16. State space representation.

<u>Literature</u>:

R. S. Khurmi, J. K. Gupta, *Theory of Machines*, chapters 5-10.

Jacqueline Wilkie, Michael Johnson, Reza Katebi, *Control engineering - An introductory course.*

Jan Willem Polderman, Jan C. Willems, *Introduction to the Mathematical Theory of Systems and Control, chapters 7-8.*

T. Kołacin, *Podstawy teorii maszyn i automatyki*, Oficyna Wydawnicza Politechniki Warszawskiej, Warszawa, 2005.

http://myinventions.pl/students/ *password:* ***********

Objectives

After completion of the course student should have acquired:

- basic knowledge of planar mechanisms, machine dynamics and control theory,
- ability to describe kinematic and dynamic properties of planar mechanisms and simple machines,
- ability to prepare time and frequency characteristics of simple elements and control systems,
- ability to use stability criteria.

Intended teaching effects

Student who has completed this course:

Has the basic knowledge on application of laws and principles of Mechanics to describe motion of mechanisms and machines and analyze the dynamics of their elements and whole systems including stability in case of automatic control.

Knows the basic methods being applied to solve simple problems of machine and mechanism motions. Has the knowledge concerning description of elements and systems of automatic control.

Is able to analyze motion of mechanisms and machines and draw conclusions from the analysis or experiments made.

Is skilled to apply analytical and graphical methods to determine kinematic and dynamic parameters of mechanisms and machines, incl. automatic control systems and their elements.

Is able to identify mechanisms, machines and automatic control systems on the basis of their dynamic characteristics.

Contact:

Sebastian Korczak, PhD Eng.

room: 2.8b

e-mail: sebastian.korczak@pw.edu.pl

consultations: Tuesdays at 11:00-12:00 and Fridays at 13:00-14:00

website with presentations: http://myinventions.pl/lectures/

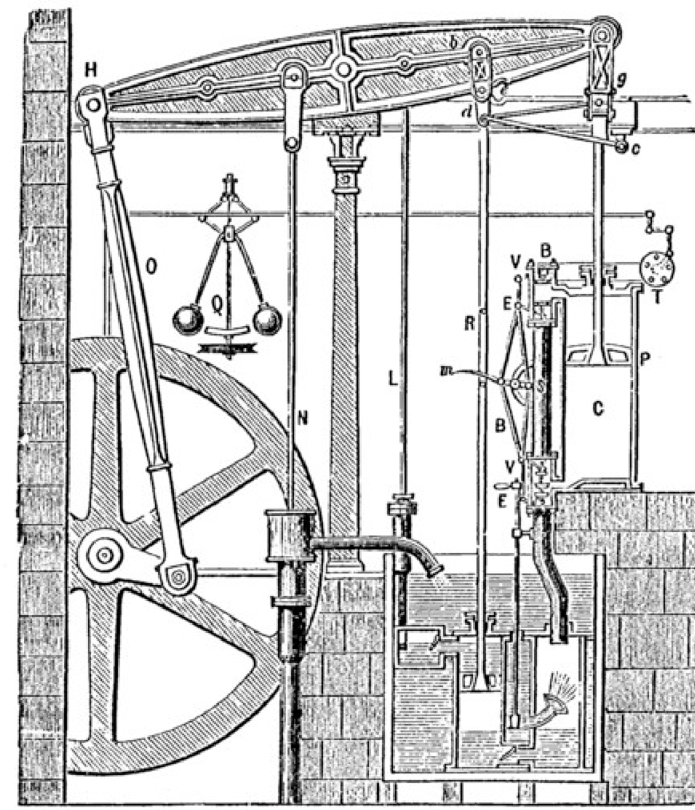
Lecture 1

kinematic pairs, mechanisms, mobility

Machines & mechanisms

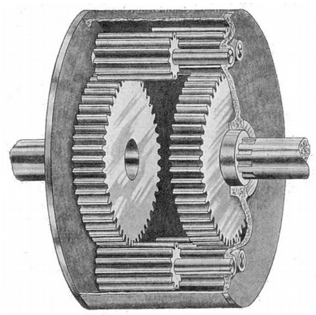
Machine – a tool containing one or more parts that uses energy to perform an intended action. Machines are assembled from components.

Mechanism – assembly of components (kinematic chain) that control movement. It transform input forces/movement into desired output forces/movement.



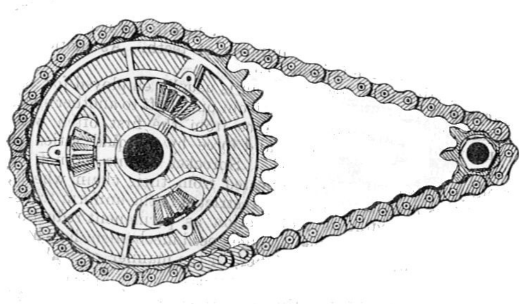
source: wikipedia.org, The Boulton & Watt Steam Engine, 1784

Components of machines



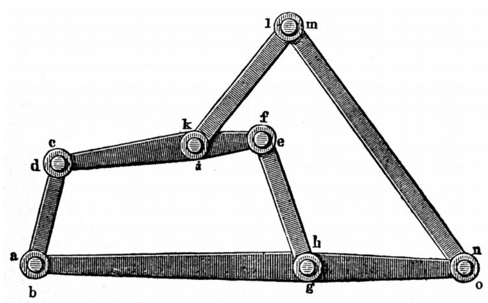
gear train

belt drive

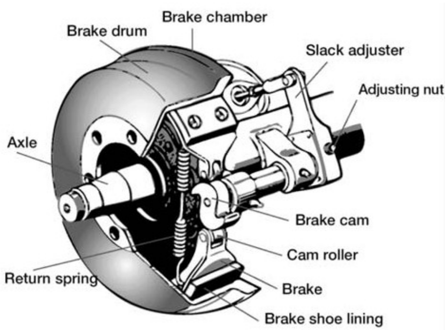


chain drive

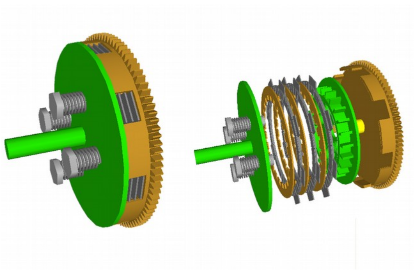
cam



linkage



brake

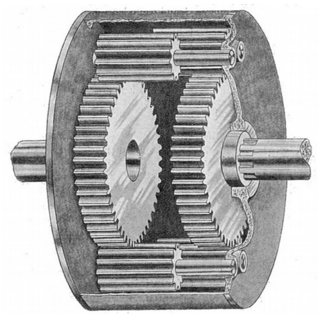


clutch

fastener

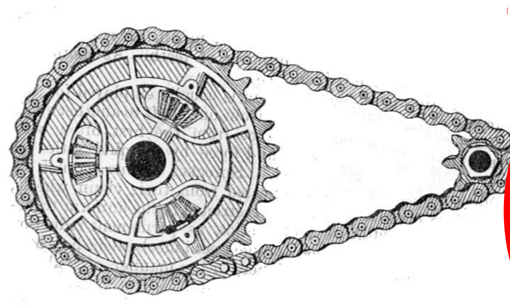
graphics source: https://en.wikipedia.org

Components of machines



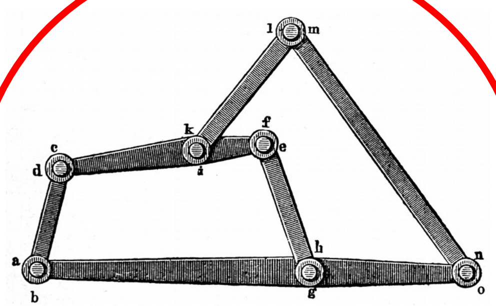
gear train

belt drive



chain drive

cam



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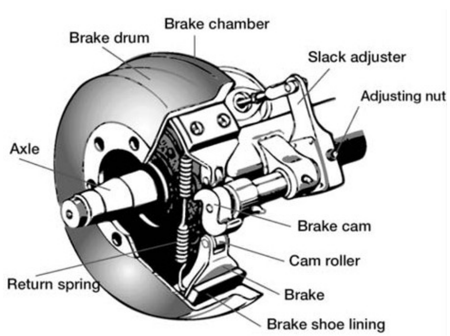
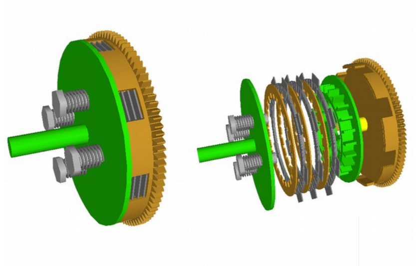


brake



clutch

fastener

graphics source: https://en.wikipedia.org

Members of mechanisms

member = part = element = segment = link

Members of mechanisms

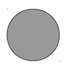
member = part = element = segment = link

Rigid members – described by material points (*Theoretical Mechanics I, 2nd semester lecture*) or rigid bodies (*Theoretical Mechanics II, 3rd semester lecture).*

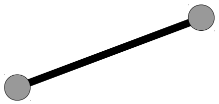
Deformable members – springs, ropes, belts, air etc.

Degrees of freedom

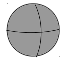
material point (2D)



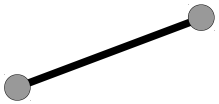
rigid body (2D)



material point (3D)

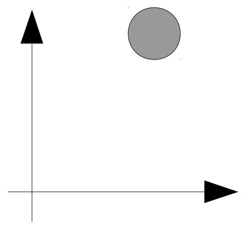


rigid body (3D)



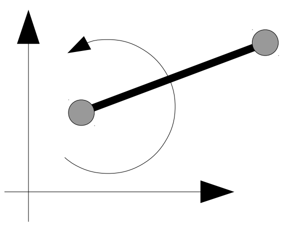
Degrees of freedom

material point (2D)



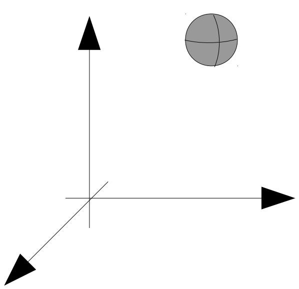
2 DoF

rigid body (2D)



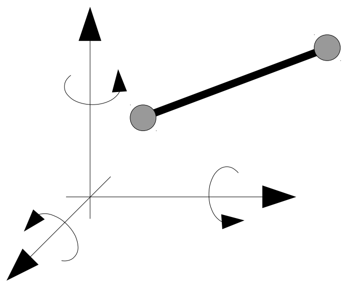
3 DoF

material point (3D)



3 DoF

rigid body (3D)



6 DoF

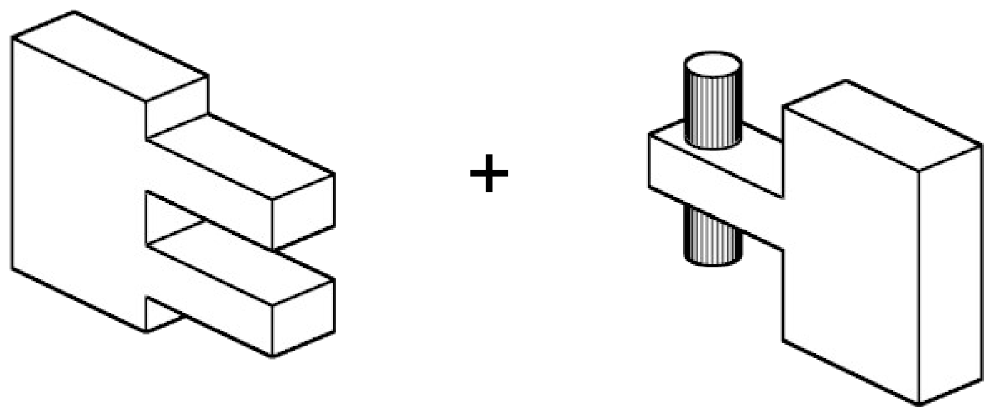
Kinematic pairs & chains

A kinematic pair is a movable coupling of two rigid members that imposes restraints on the relative motion of the members by the conditions of linkage.

A kinematic chain is an assembly of kinematic pairs.

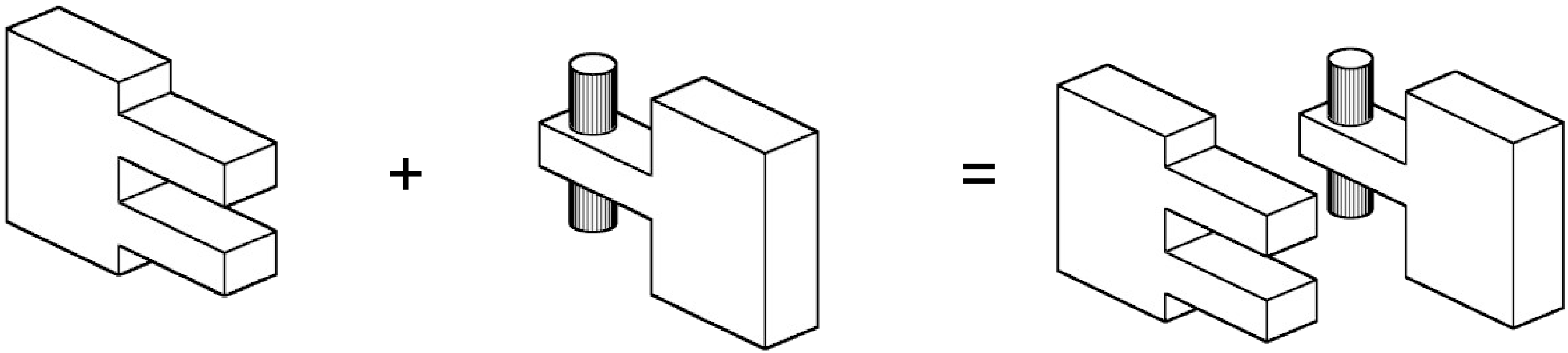
A base is a fixed (motionless) member of mechanism.

Kinematic pairs (3D)



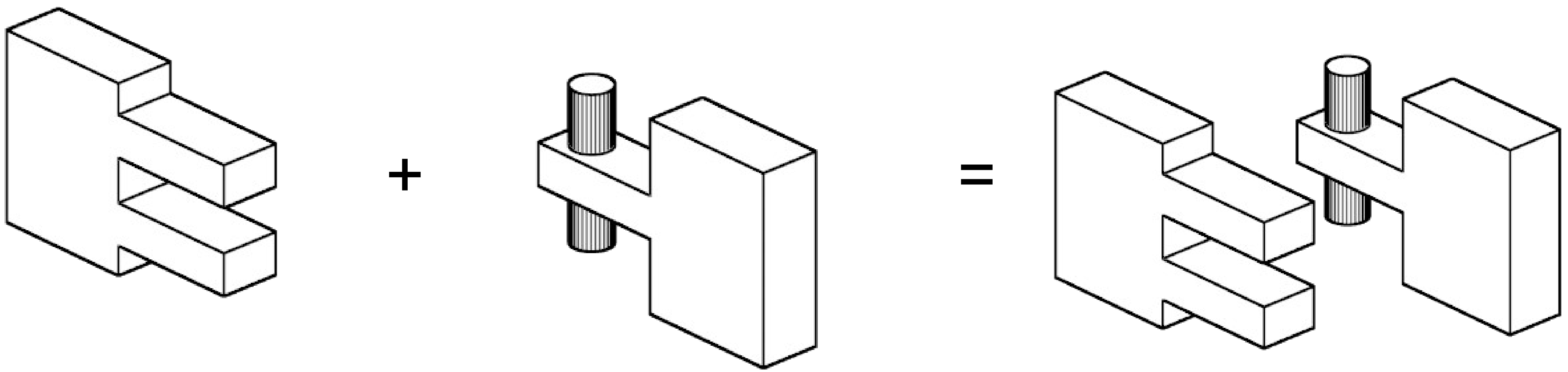
Kinematic pairs (3D)

not connected



Kinematic pairs (3D)

not connected



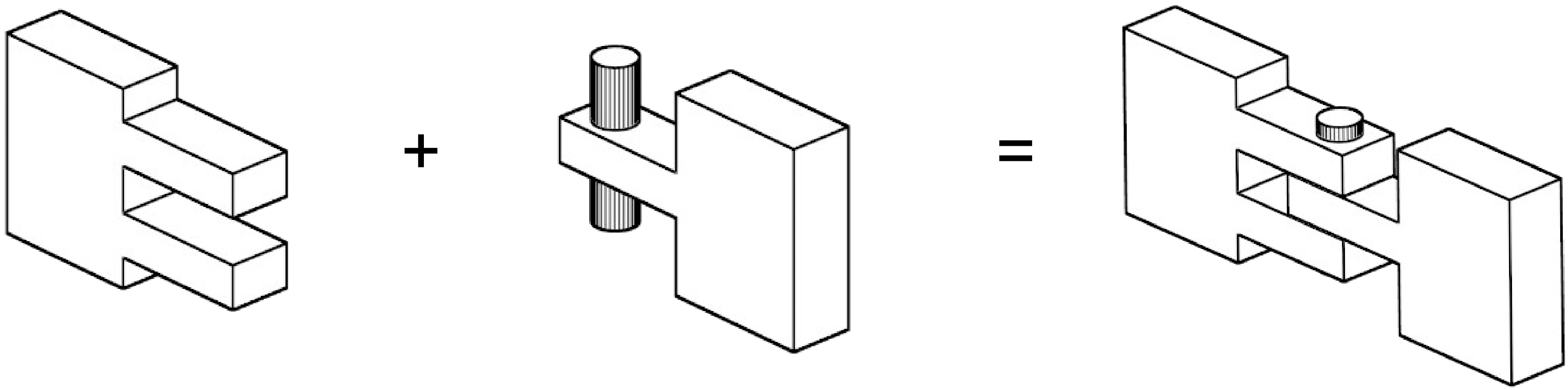
6 DoF

6 DoF

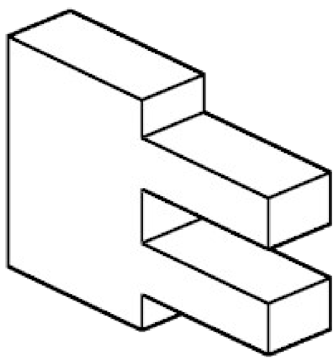
total: 12 DoF

relative motion: 6DoF

Kinematic pairs (3D)

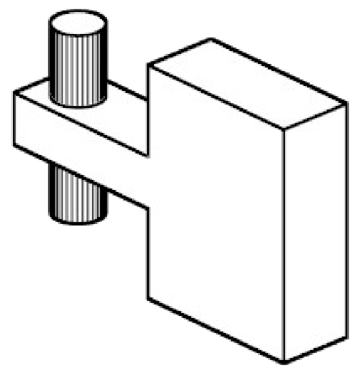


Kinematic pairs (3D)



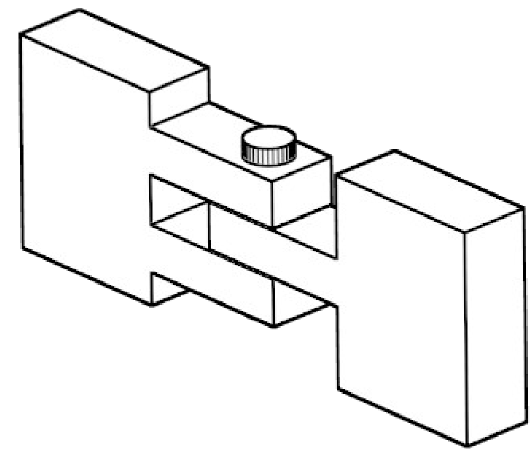
6 DoF

+



6 DoF

=



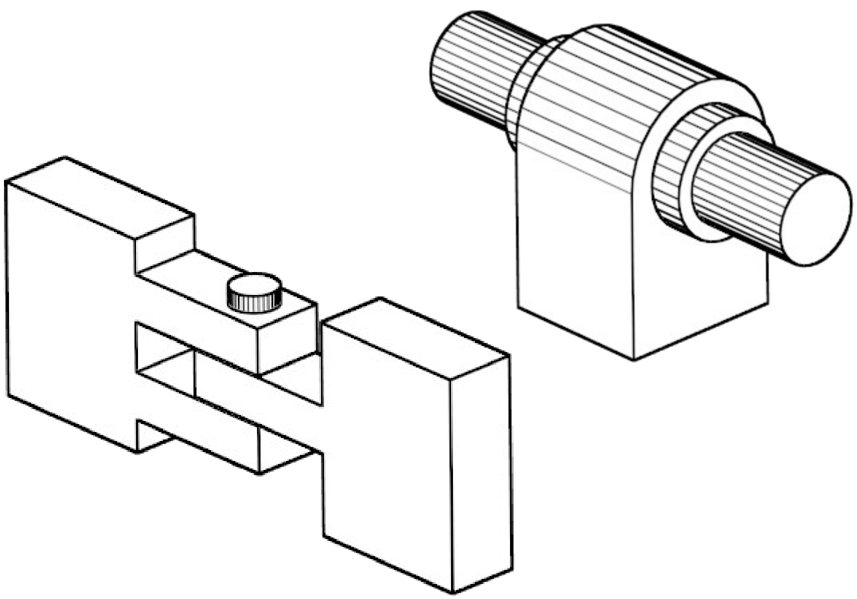
relative motion: 1DoF

total: 7DoF

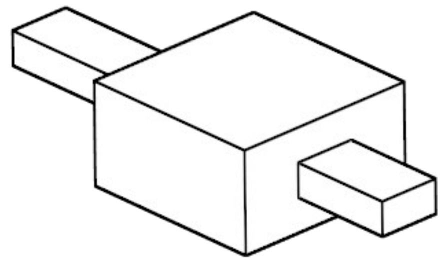
Kinematic pairs (3D)

Class V = 6 - 1

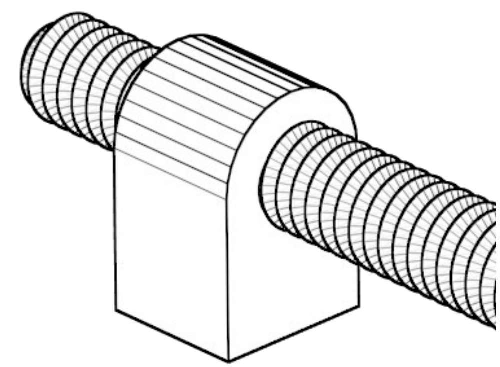
rotary



translatory



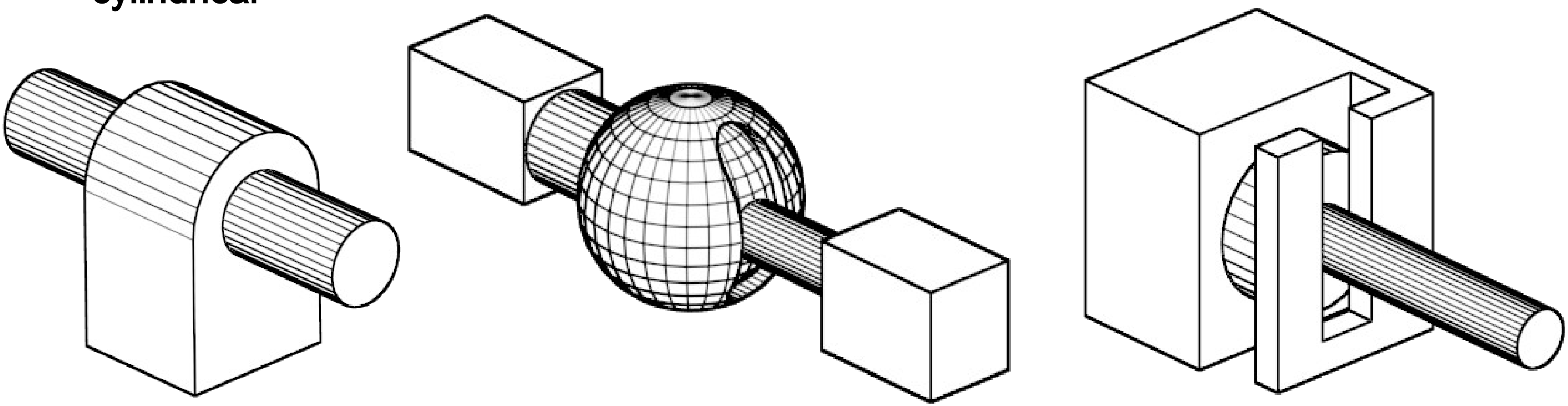
screw-type



Kinematic pairs (3D)

Class IV = 6 - 2

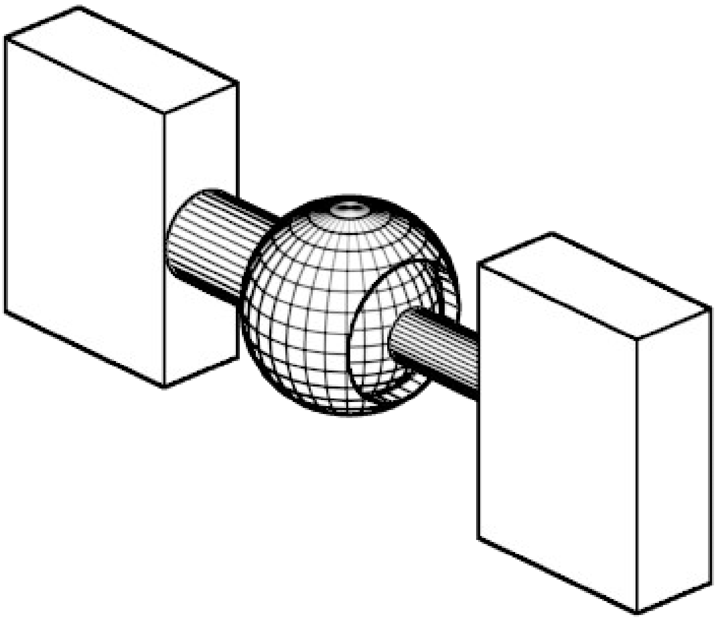
cylindrical

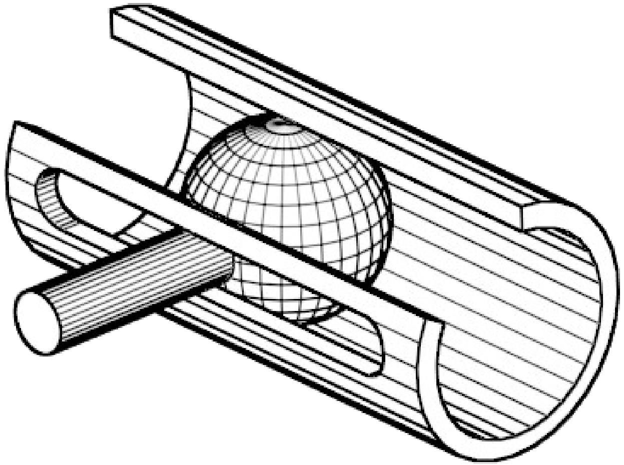


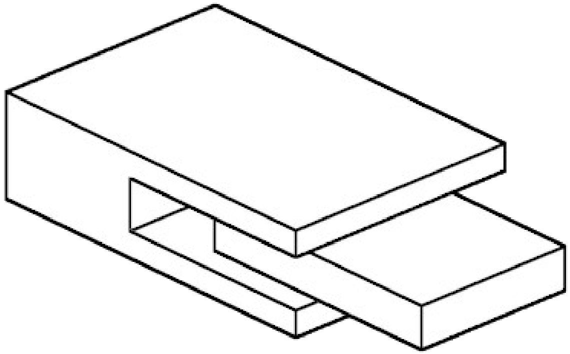
Kinematic pairs (3D)

Class III = 6 - 3

spherical

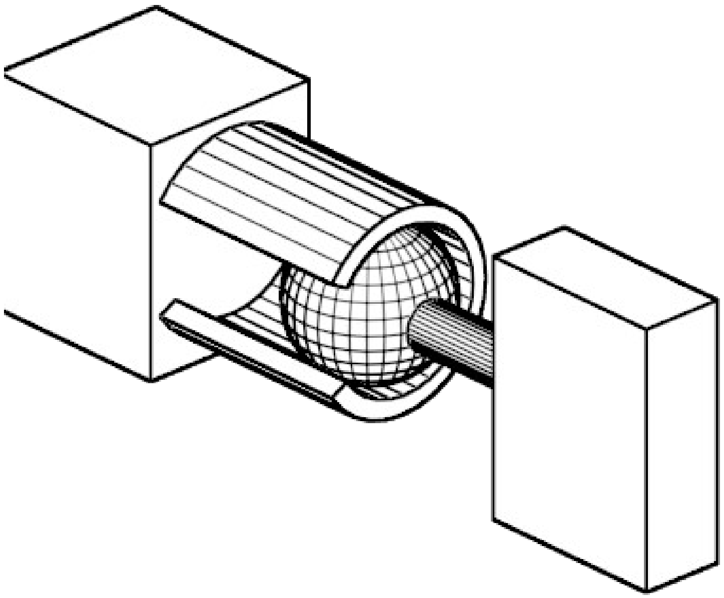


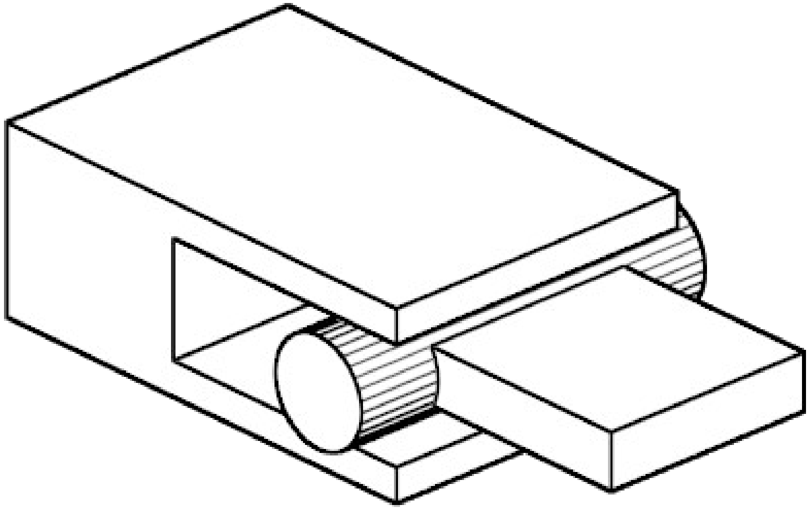




Kinematic pairs (3D)

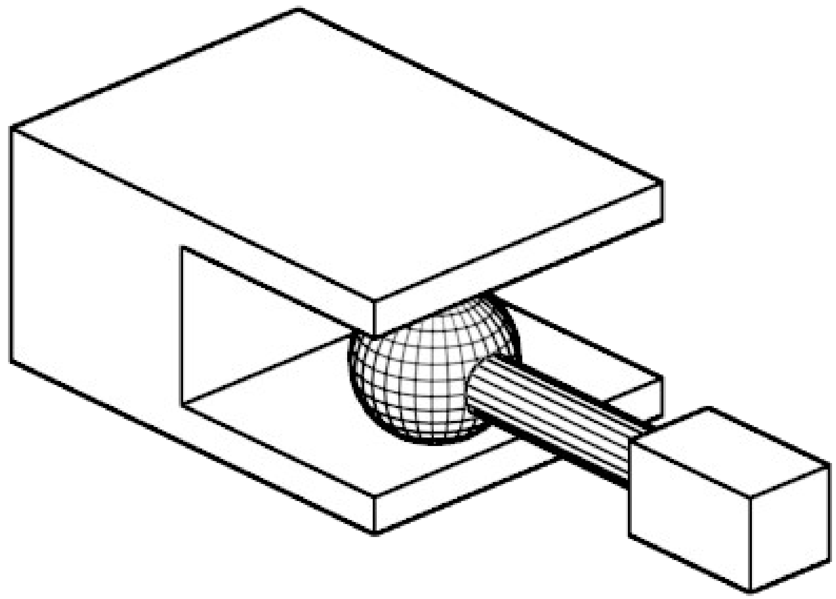
Class II = 6 - 4





Kinematic pairs (3D)

Class I = 6 – 5



Kinematic pairs (2D)

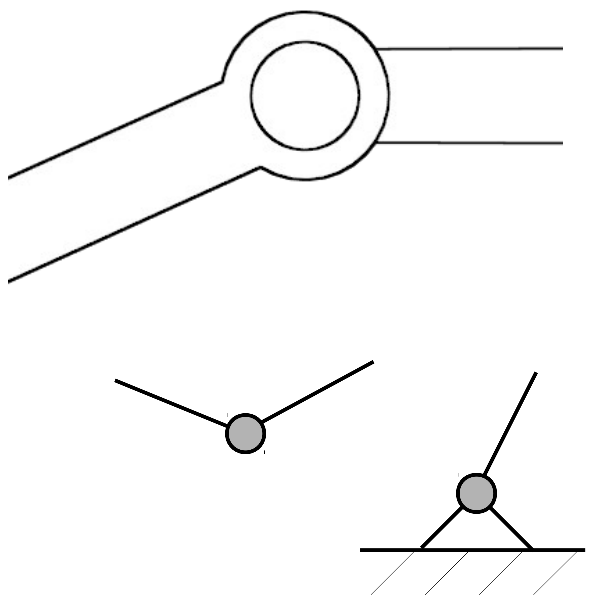
Class I, class II → not possible in 2D

Class III → free body in 2D

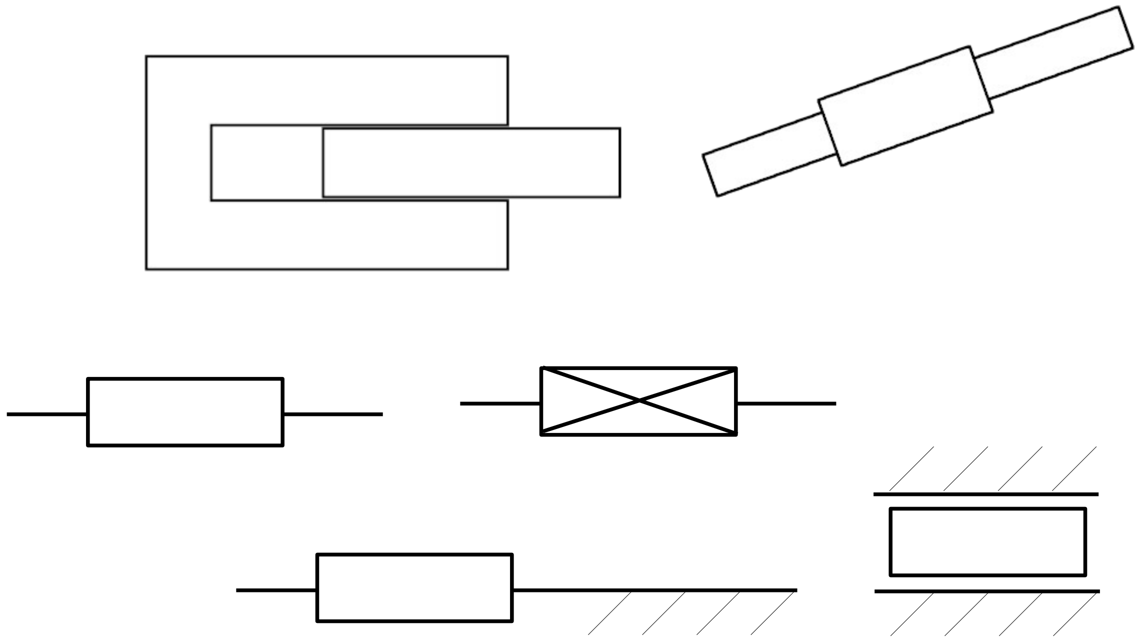
Kinematic pairs (2D)

Class V = 6 - 1

rotary

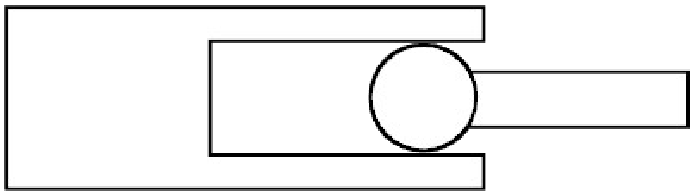


translatory

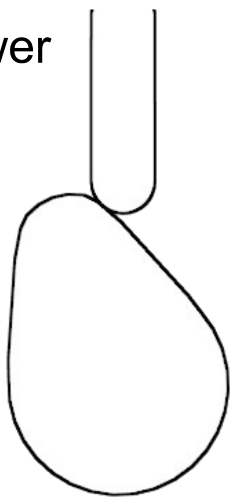


Kinematic pairs (2D)

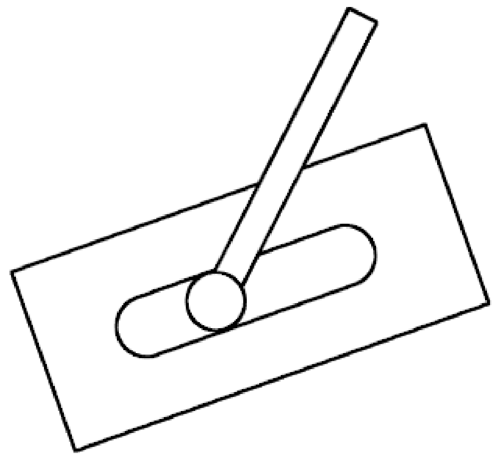
Class IV = 6 - 2

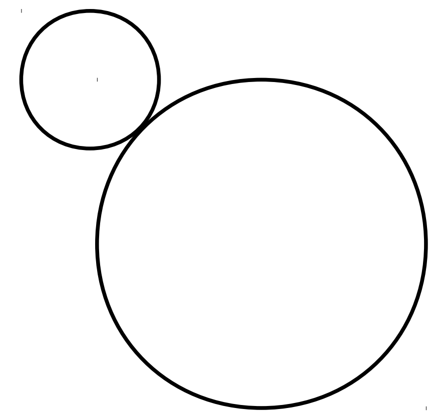


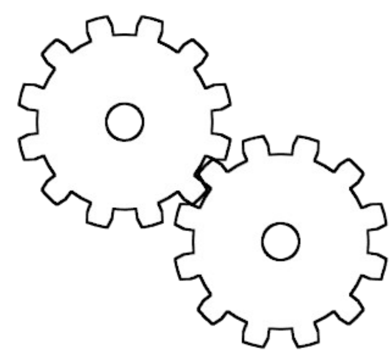
cam follower
(tapper)



cam joint







Kinematic pairs

lower kinematic pair – surface contact

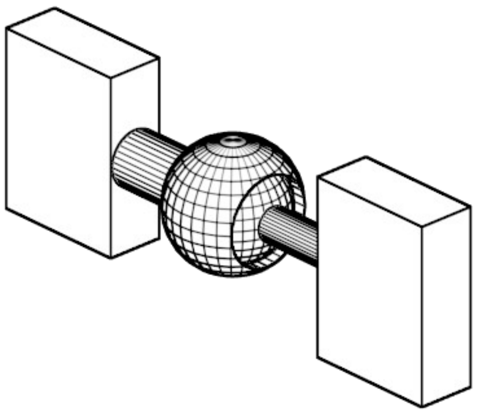
higher kinematic pair – line or point contact

Kinematic pairs

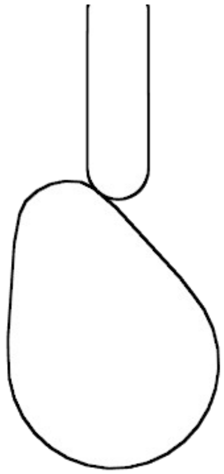
<u>**closed pair (self-closed pair)**</u> – contact because of shape

<u>**open pair (force-closed pair)**</u> – force required for constant contact

Kinematic pairs



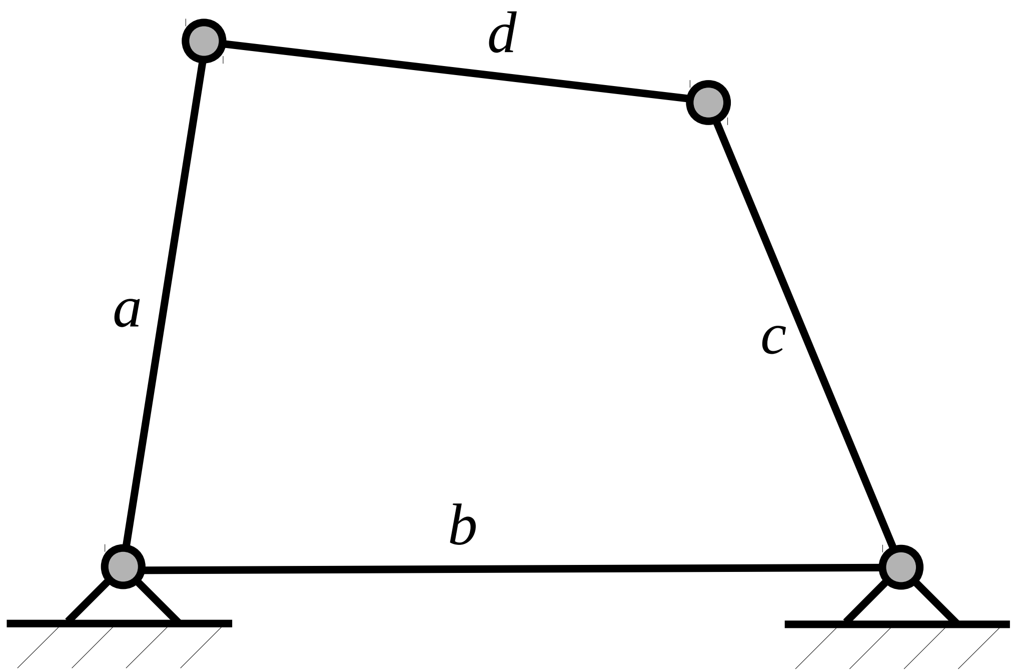
closed pair – contact because of shape



open pair – force required for constant contact

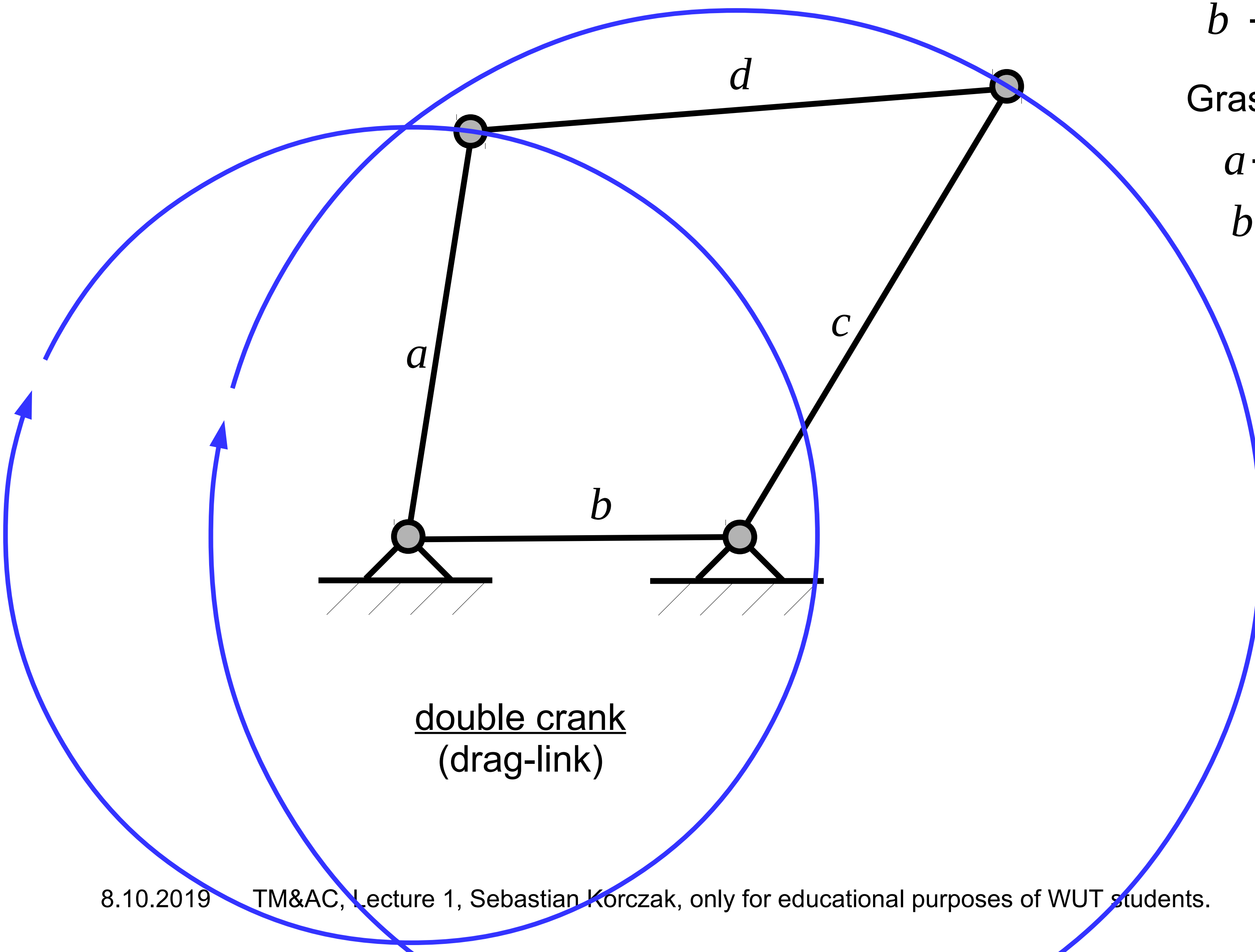
Kinematic chain - examples

Four-bar chain



Kinematic chain - examples

Four-bar chain



b - the shortest

Grashof conditions:

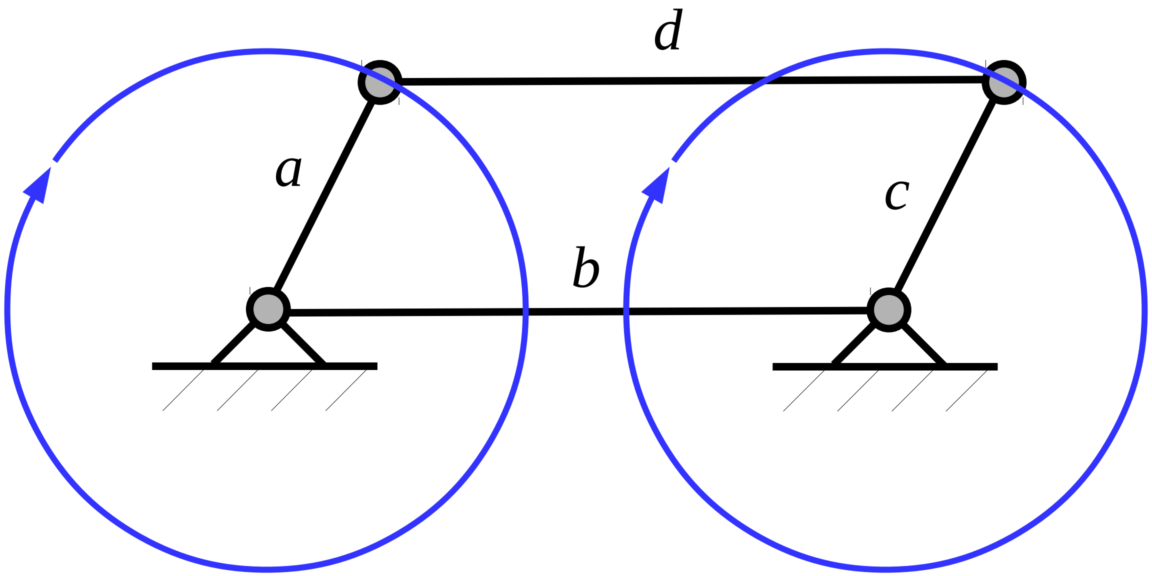
$$a+b \leqslant c+d$$

$$b+c \leqslant a+d$$

double crank
(drag-link)

Kinematic chain - examples

Four-bar chain

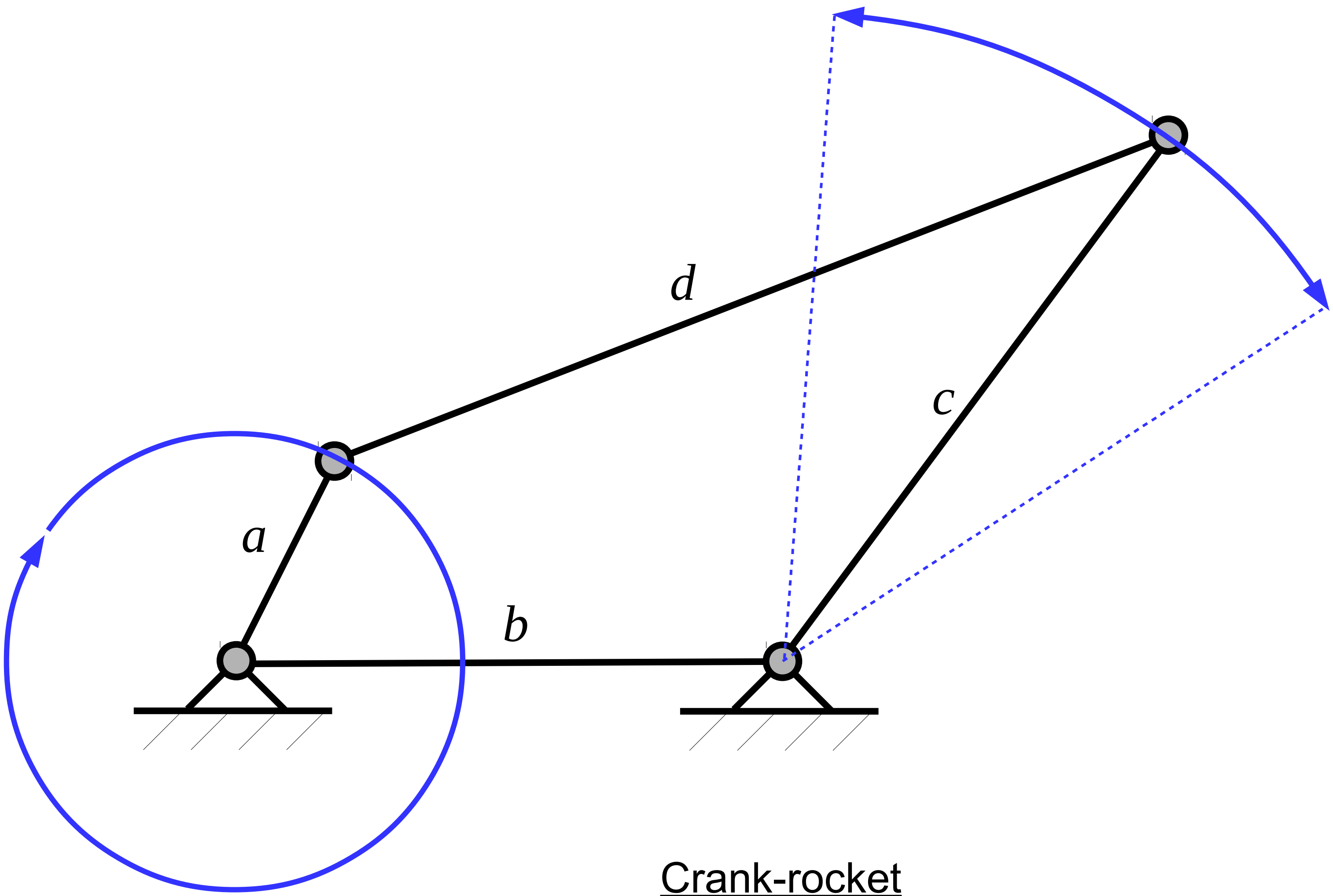


$$a+b=c+d$$
$$a=c$$

<u>Parallelogram linkage</u>
(double crank mechanism)

Kinematic chain - examples

Four-bar chain



Crank-rocket

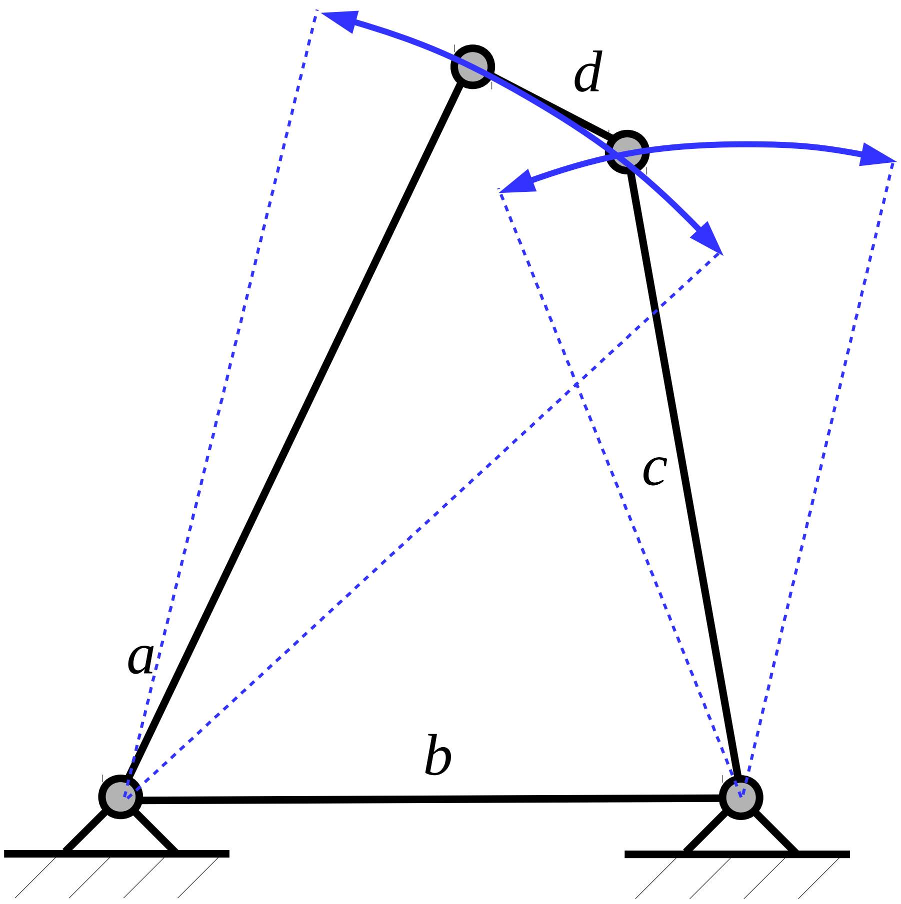
Grashof condition:

$$a+d<b+c$$

a - the shortest

Kinematic chain - examples

Four-bar chain



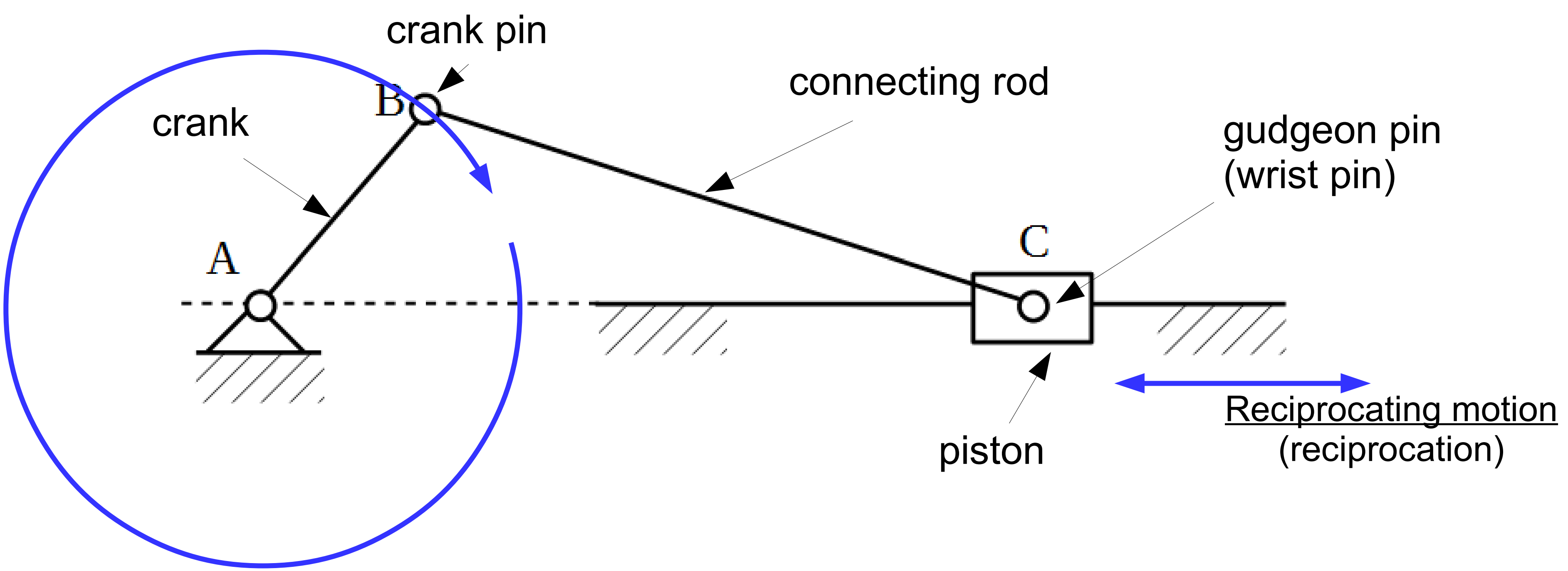
$$a+d>b+c$$

d - the shortest

Double-rocket

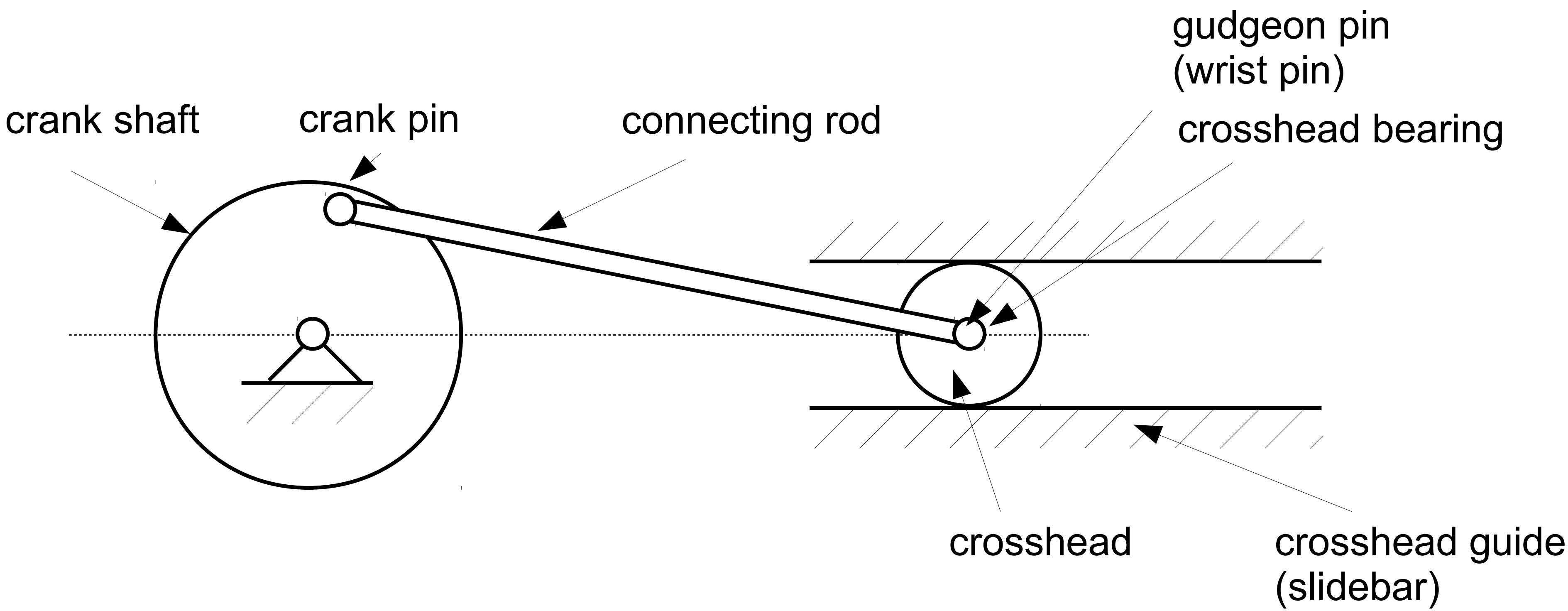
Kinematic chain - examples

Crank-slider mechanism



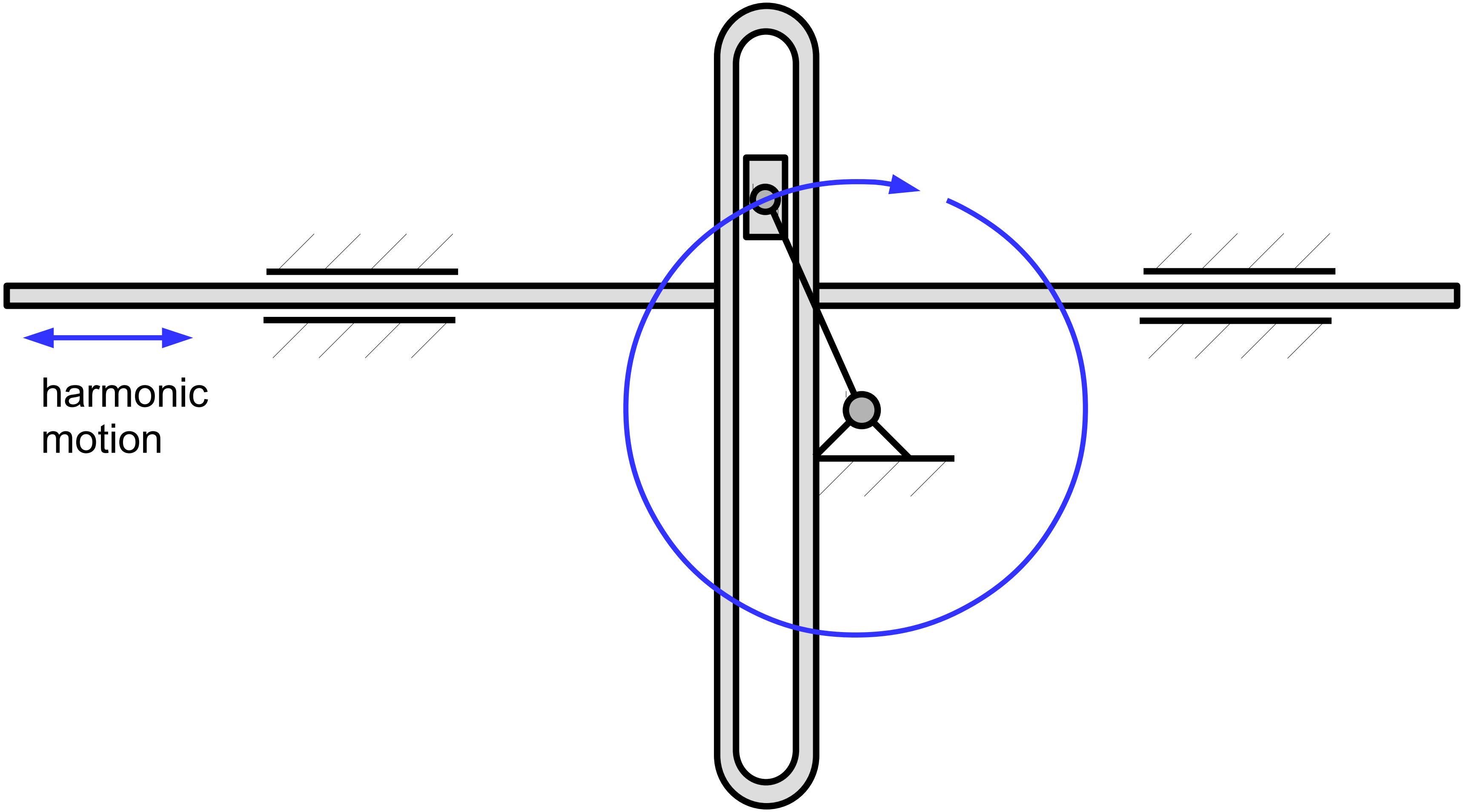
Kinematic chain - examples

Crank-slider mechanism

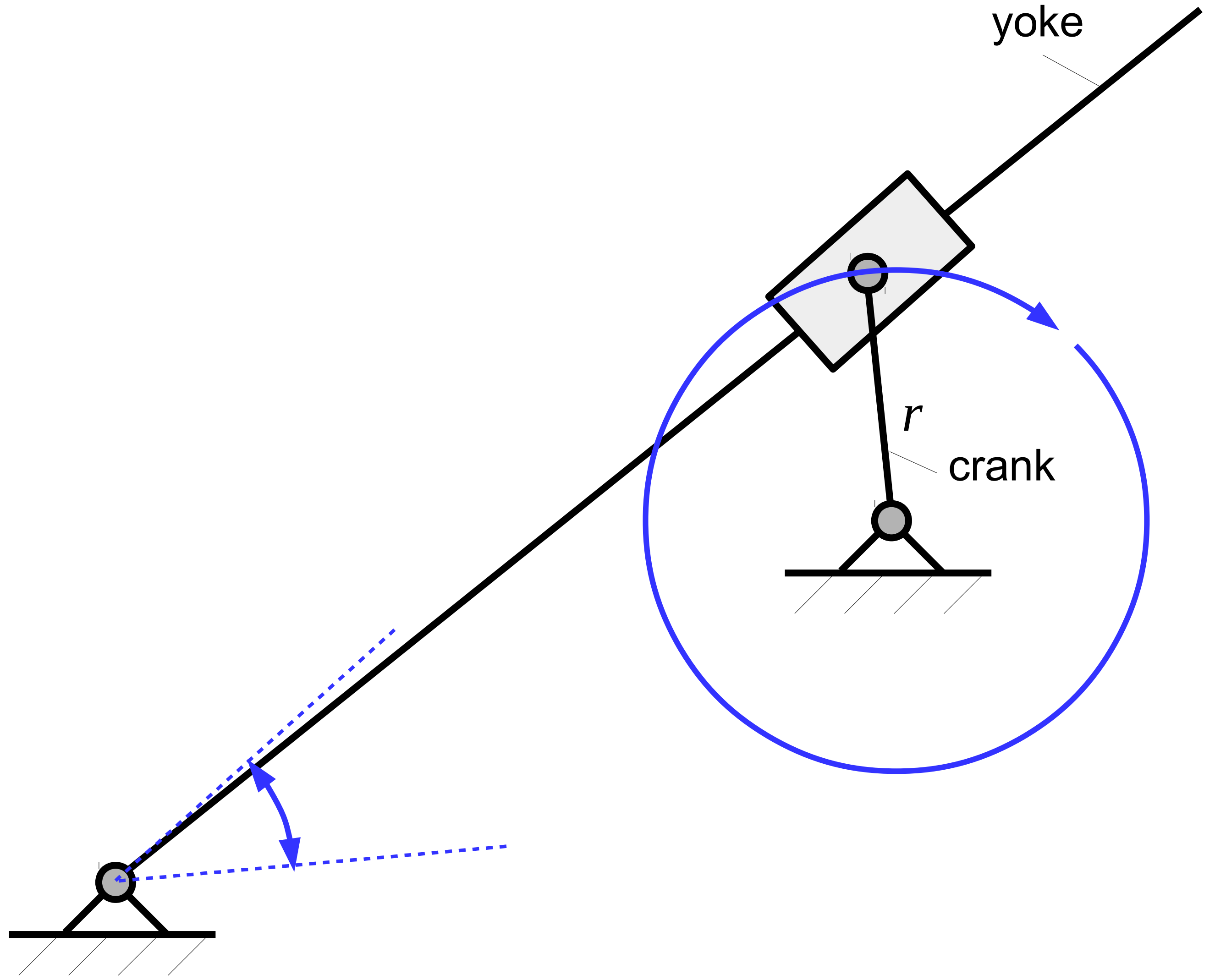


Kinematic chain - examples

Scotch yoke mechanism

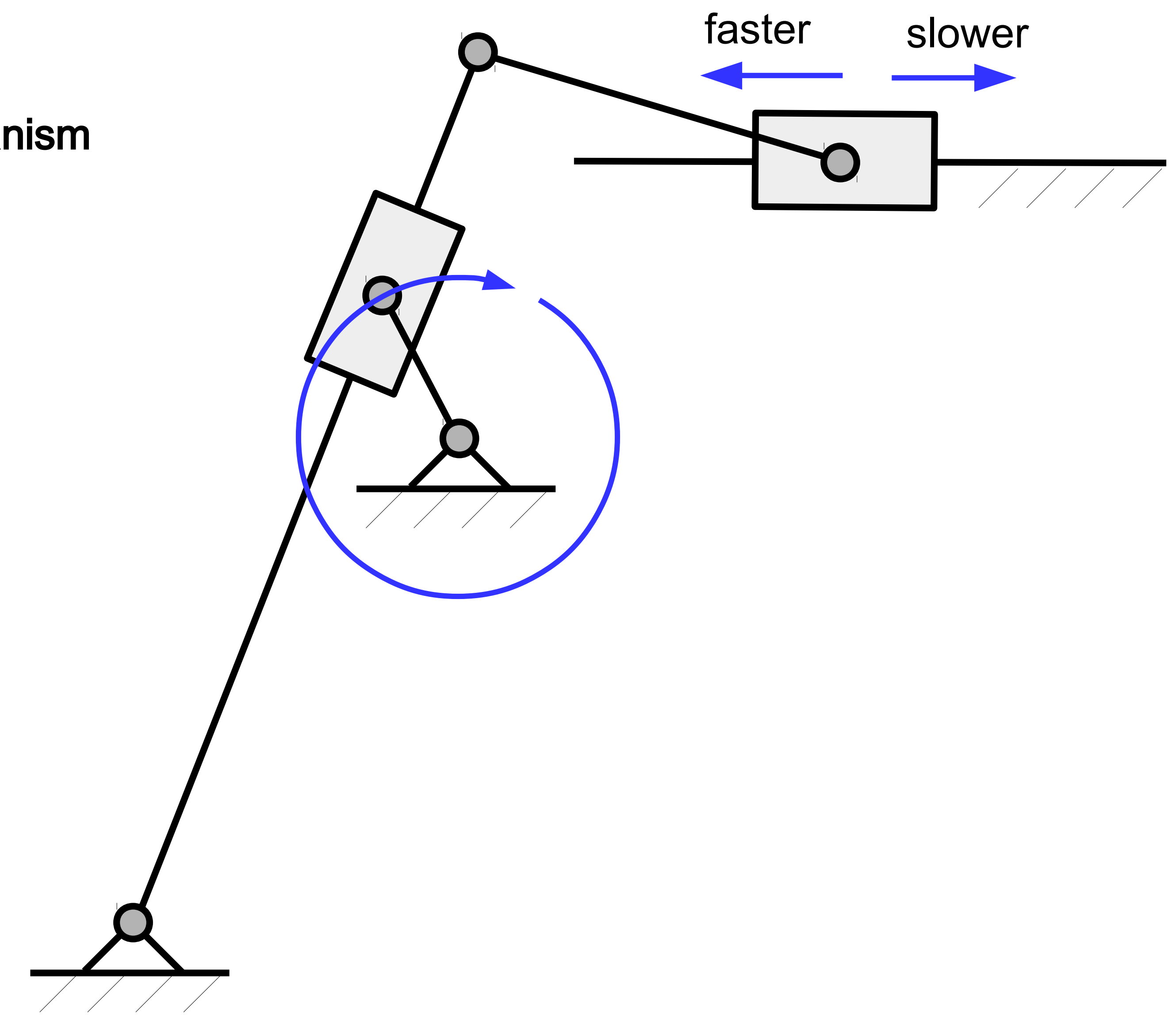


Kinematic chain - examples



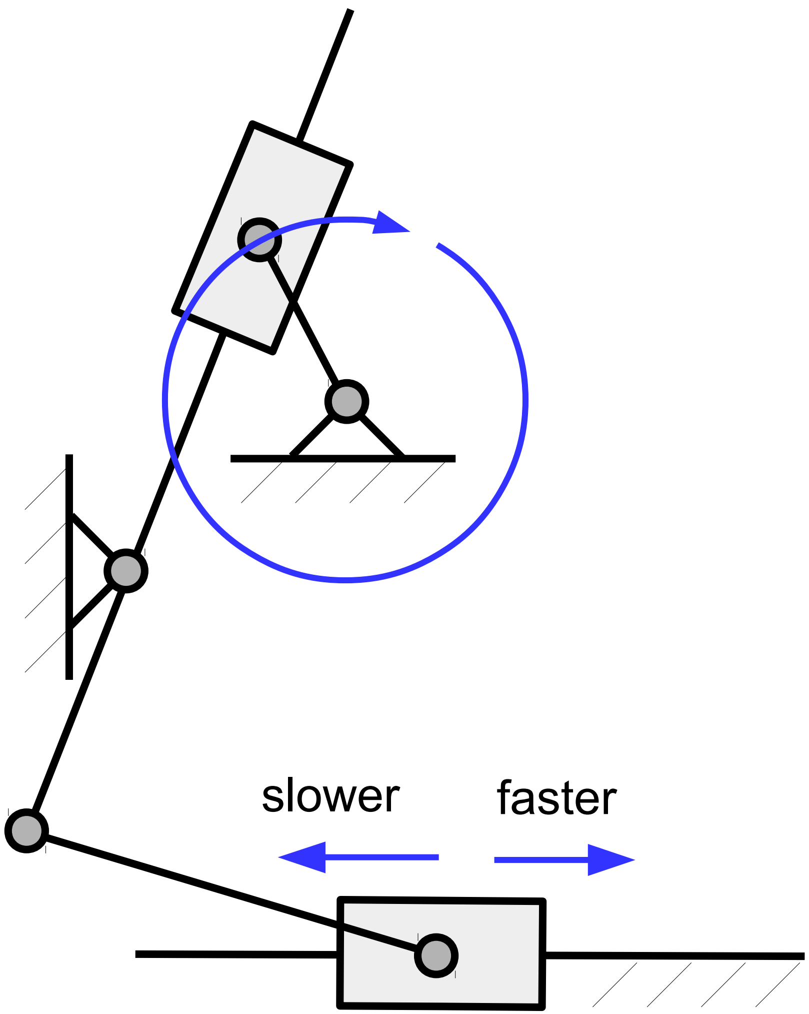
Kinematic chain - examples

Slotted lever mechanism



Kinematic chain - examples

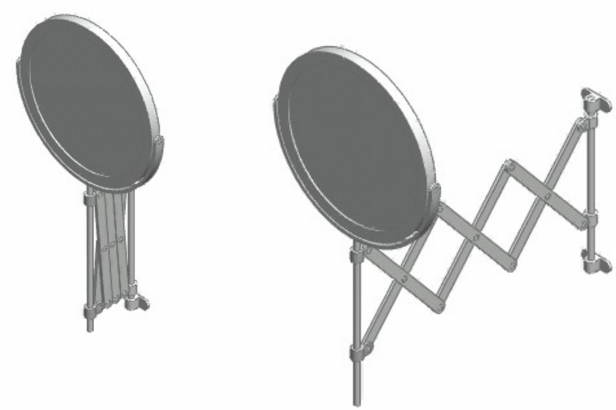
Whitworth Quick Return mechanism

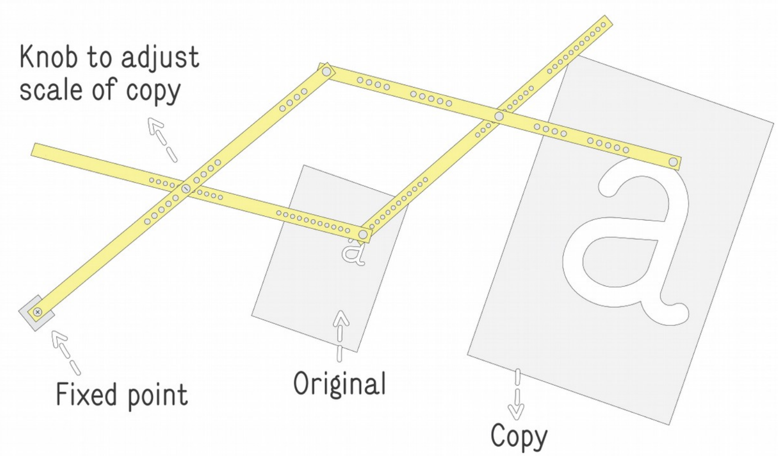


Kinematic chain - examples

Four-bar chain examples

Pantograph



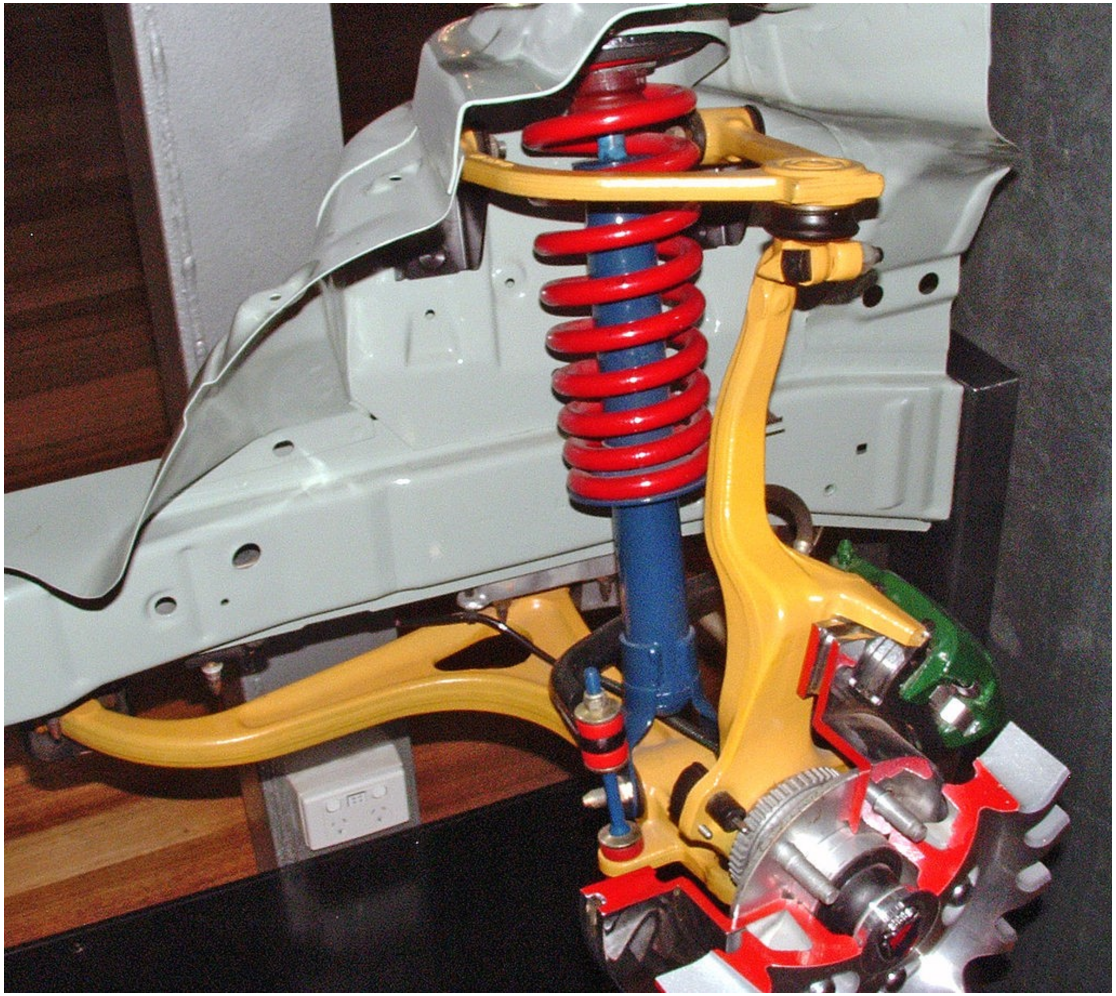


source: http://en.wikipedia.org/wiki/Pantograph

Kinematic chain - examples

Four-bar chain examples

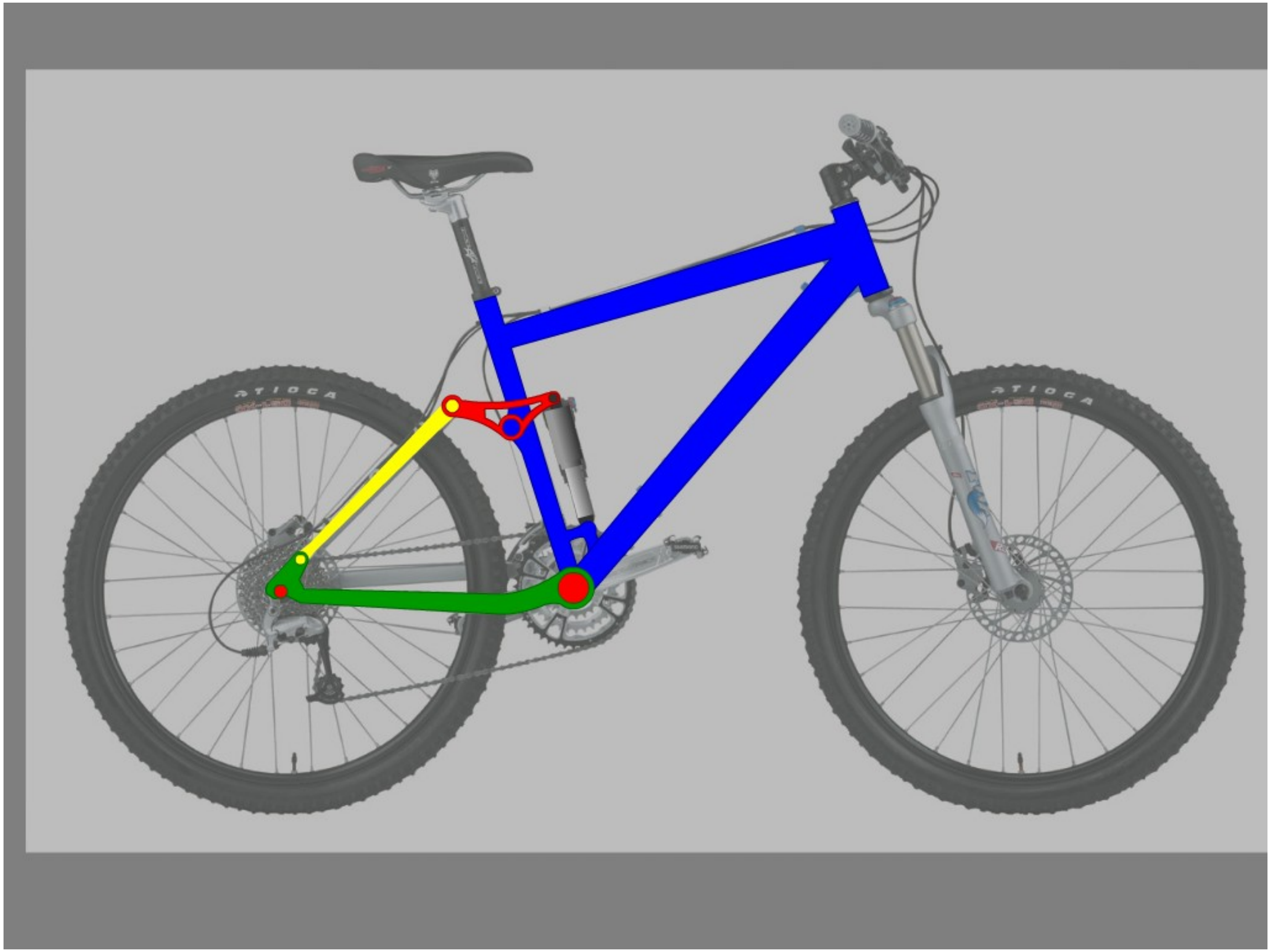
Double wishbone suspension



source: http://en.wikipedia.org/wiki/Double_wishbone_suspension

Kinematic chain - examples

Four-bar chain examples

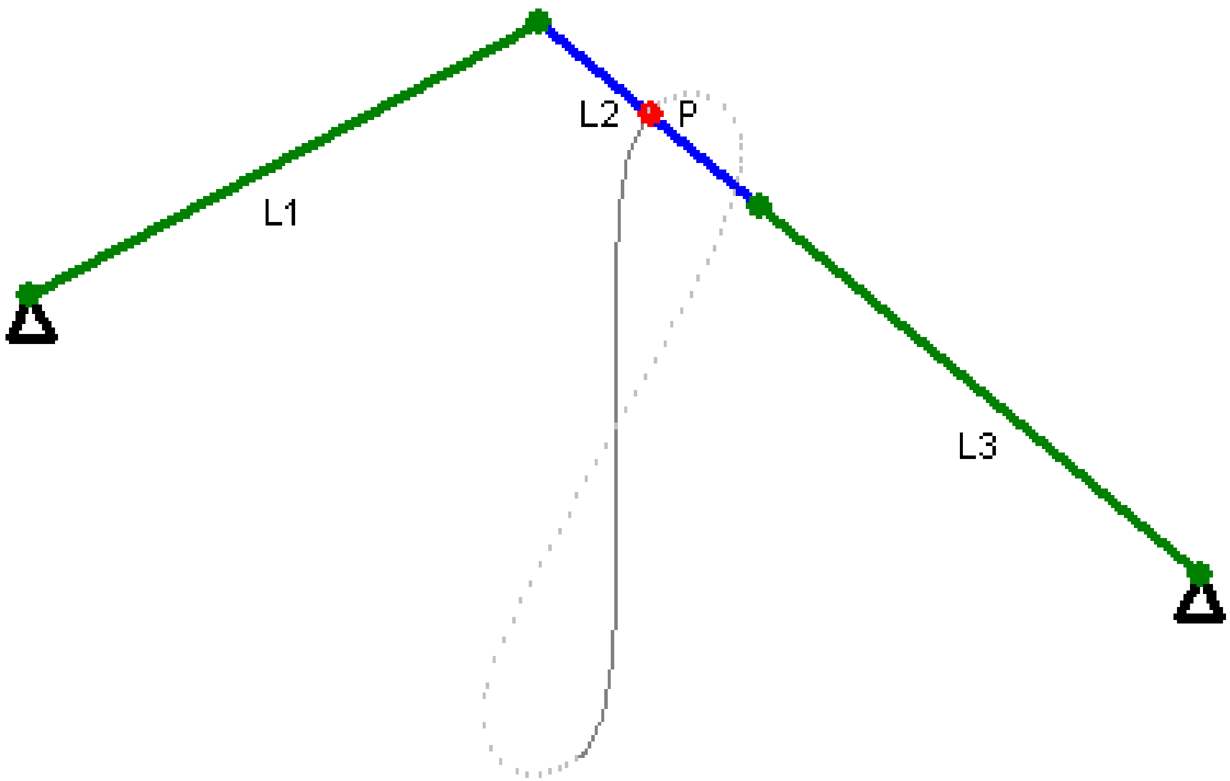


http://en.wikipedia.org/wiki/Bicycle_suspension

Kinematic chain - examples

Four-bar chain examples

Watt's linkage (parallel linkage)

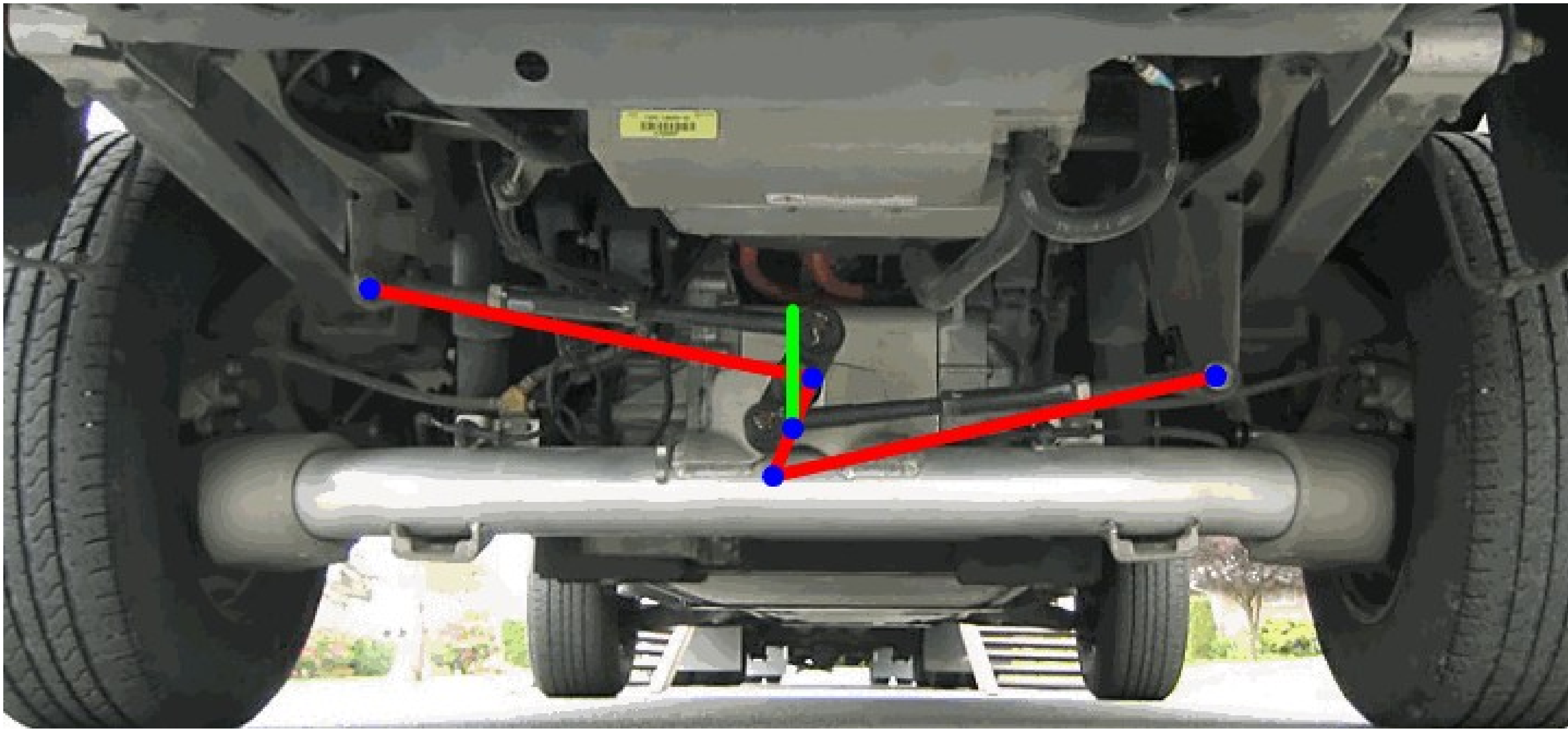


http://en.wikipedia.org/wiki/Watt%27s_linkage

Kinematic chain - examples

Four-bar chain examples

Watt's linkage (parallel linkage)

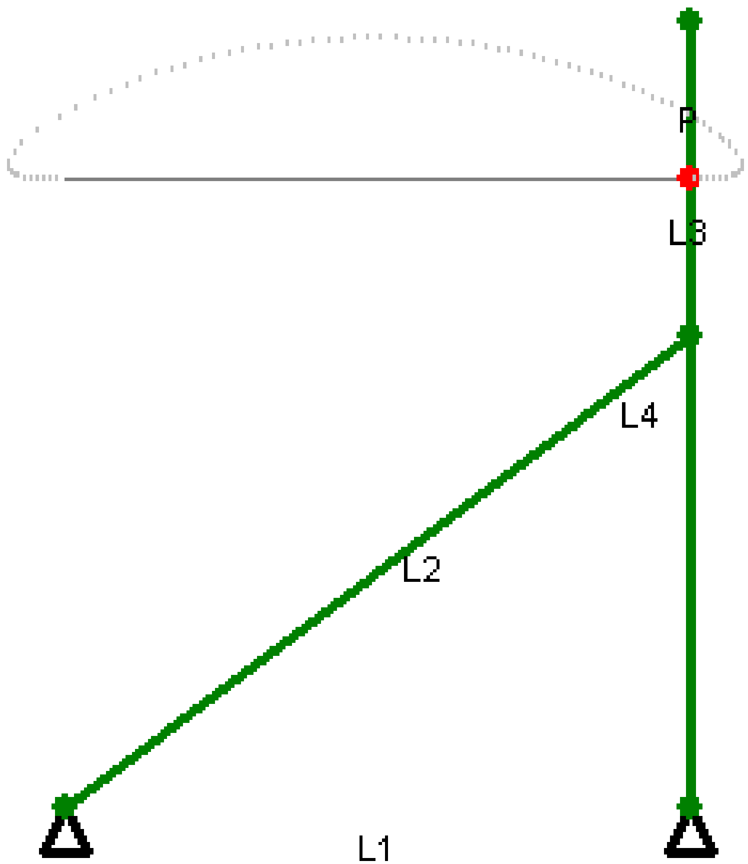


http://en.wikipedia.org/wiki/Watt%27s_linkage

Kinematic chain - examples

Four-bar chain examples

Chebyshev

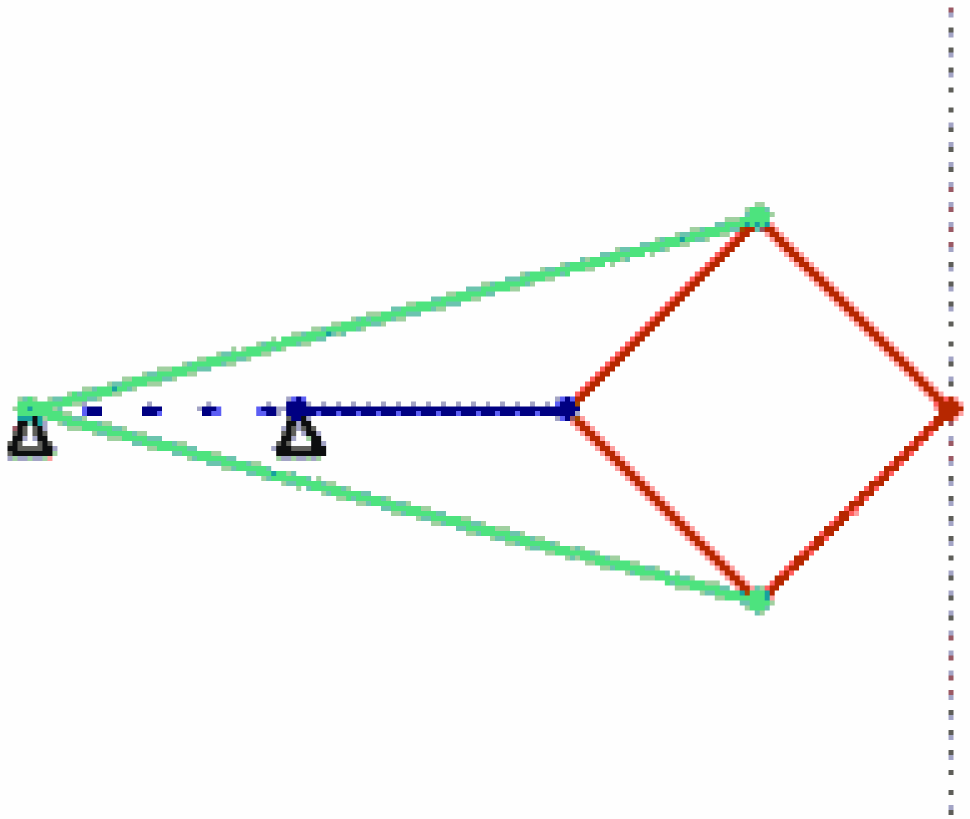


http://en.wikipedia.org/wiki/Chebyshev_linkage

Kinematic chain - examples

Four-bar chain examples

Peaucellier–Lipkin linkage

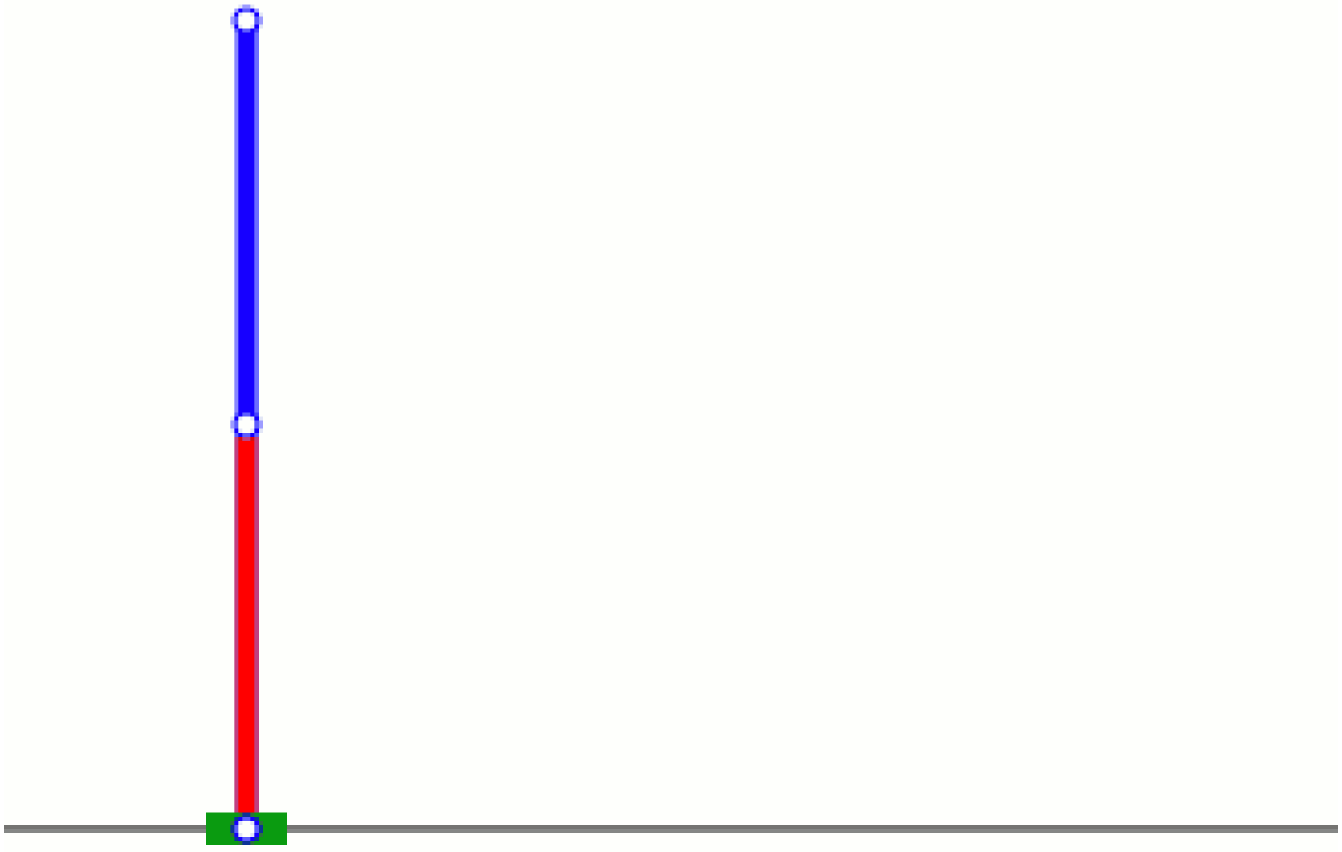


http://en.wikipedia.org/wiki/Peaucellier%E2%80%93Lipkin_linkage

Kinematic chain - examples

Four-bar chain examples

Scott-Russell linkage

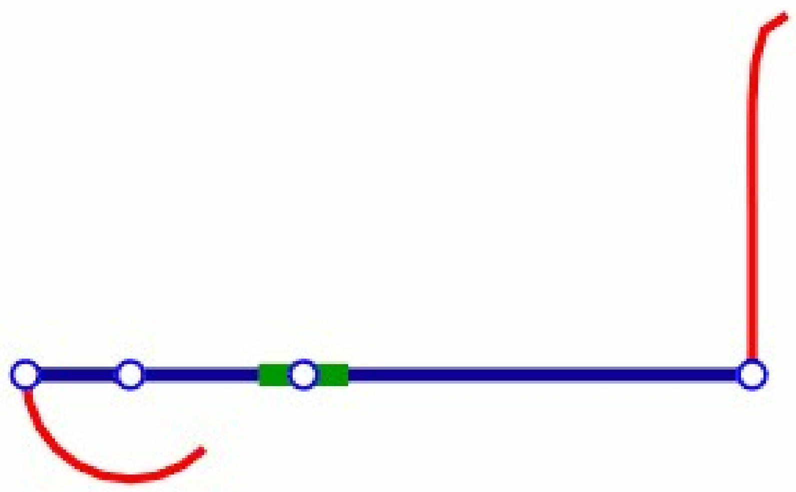


http://en.wikipedia.org/wiki/Scott_Russell_linkage

Kinematic chain - examples

Four-bar chain examples

Hoeckens linkage

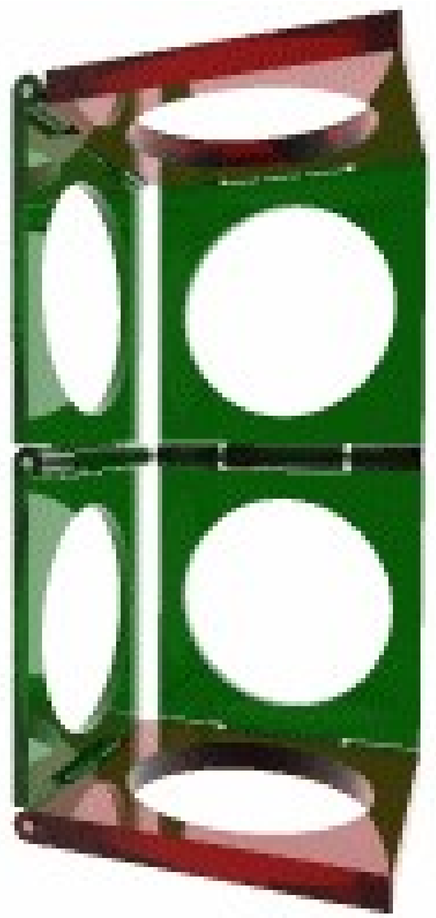


http://en.wikipedia.org/wiki/Hoeckens_linkage

Kinematic chain - examples

Four-bar chain examples

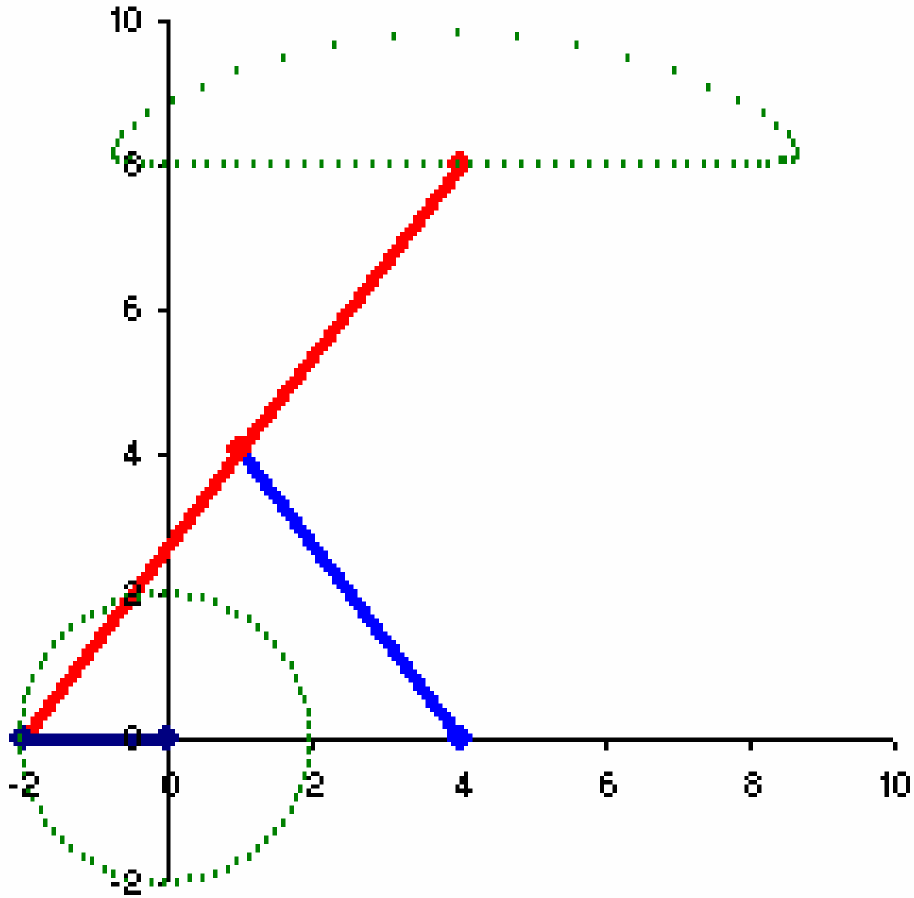
Sarrus linkage linkage



http://en.wikipedia.org/wiki/Sarrus_linkage

Kinematic chain - examples

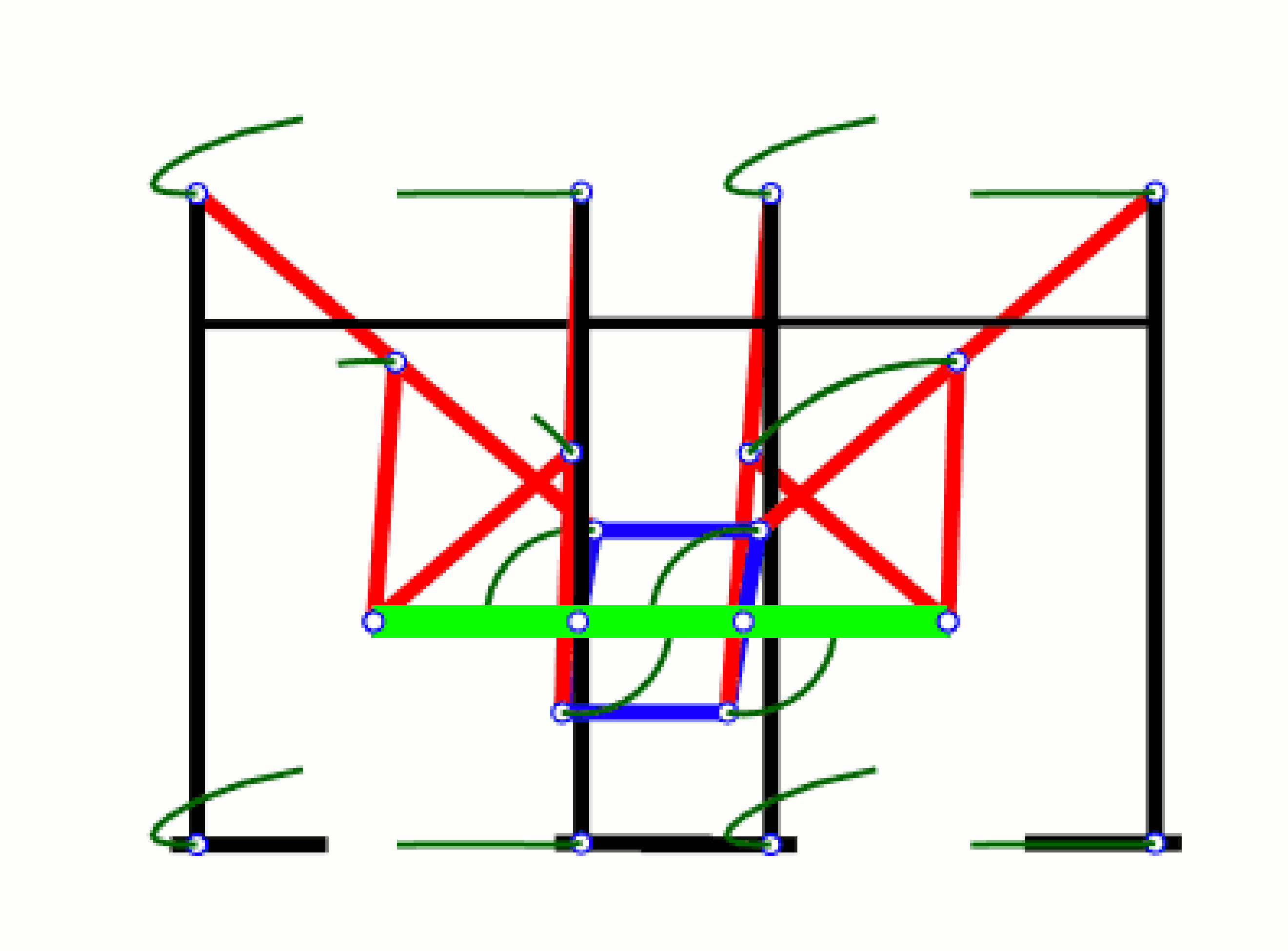
Chebyshev's Lambda Mechanism



https://en.wikipedia.org/wiki/Chebyshev%27s_Lambda_Mechanism

Kinematic chain - examples

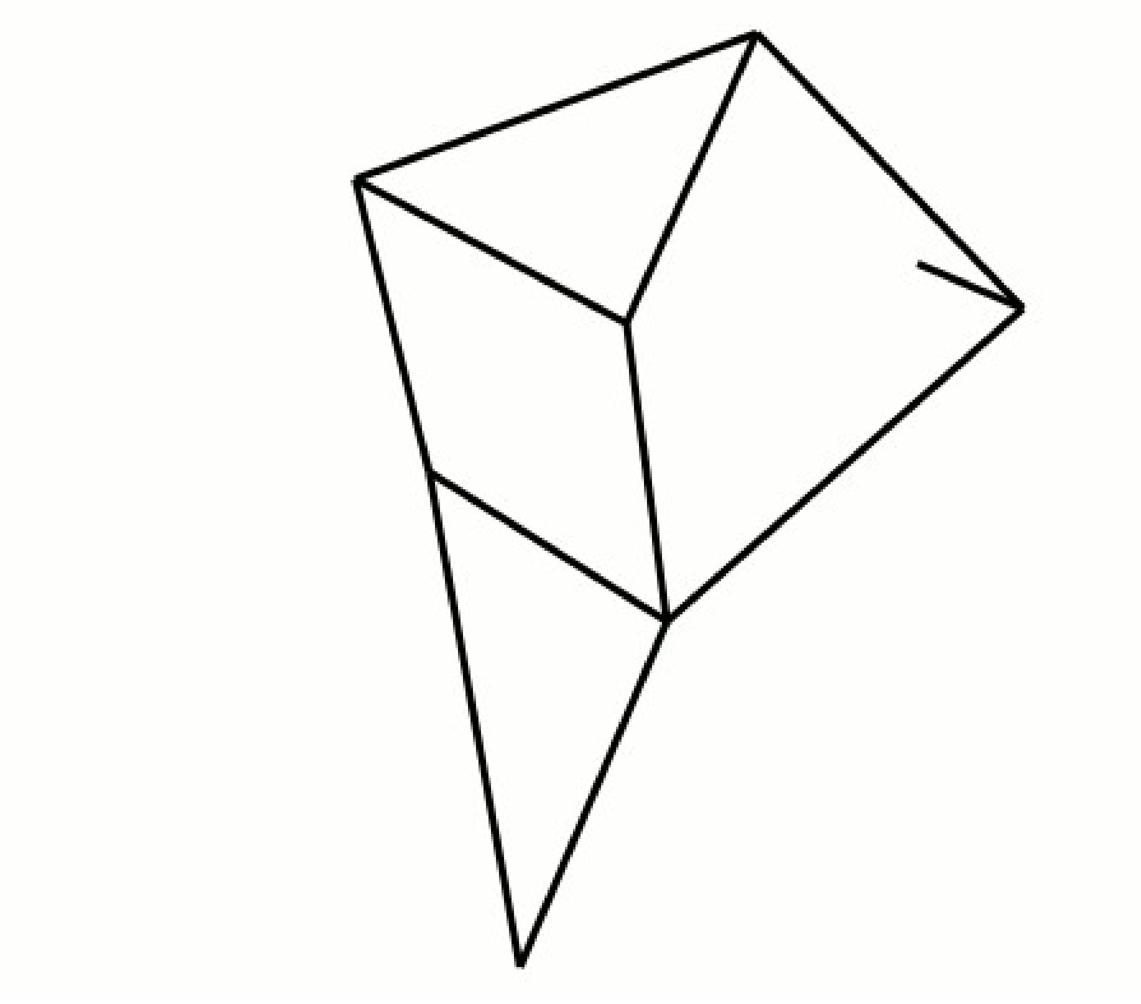
Chebyshev's Lambda Mechanism



https://en.wikipedia.org/wiki/Chebyshev%27s_Lambda_Mechanism

Kinematic chain - examples

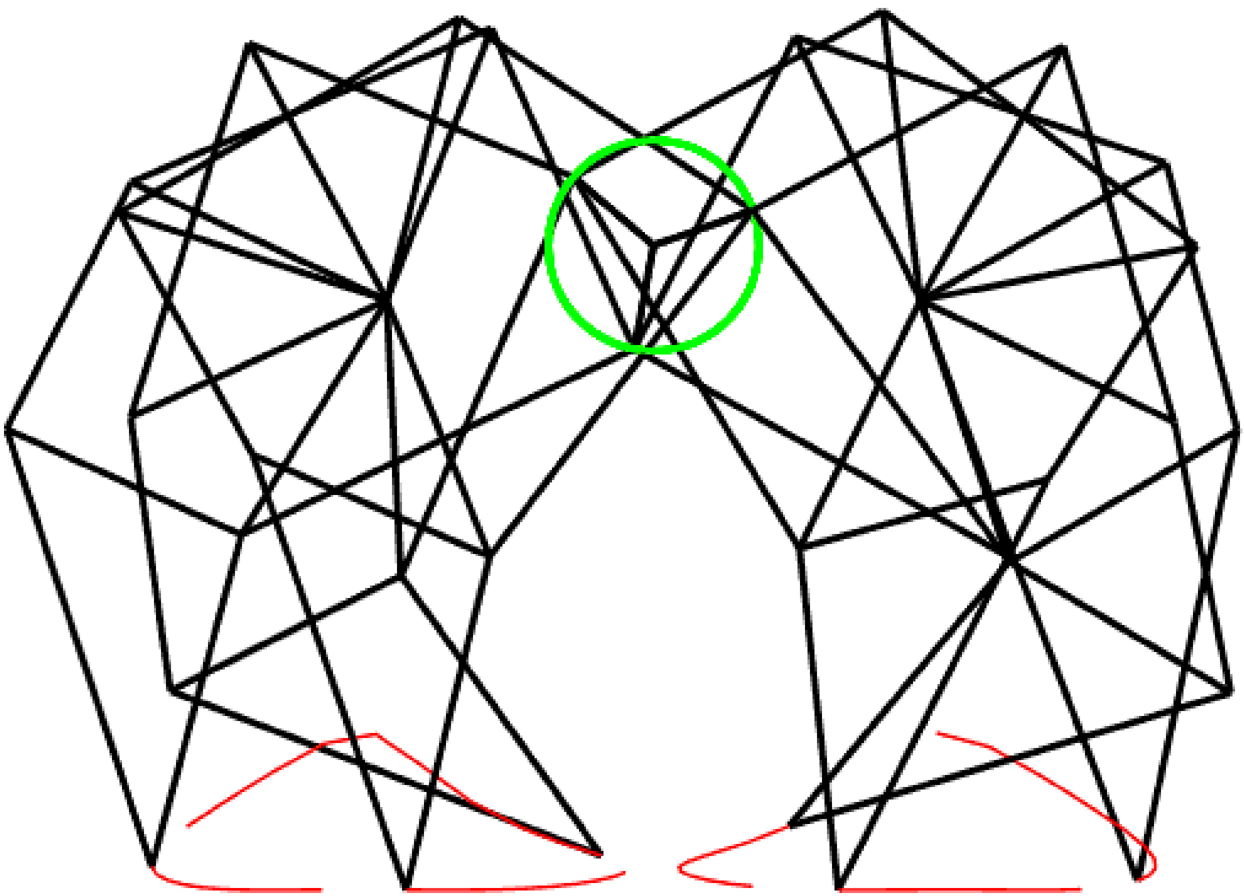
Jansen's linkage



http://en.wikipedia.org/wiki/Jansen%27s_linkage

Kinematic chain - examples

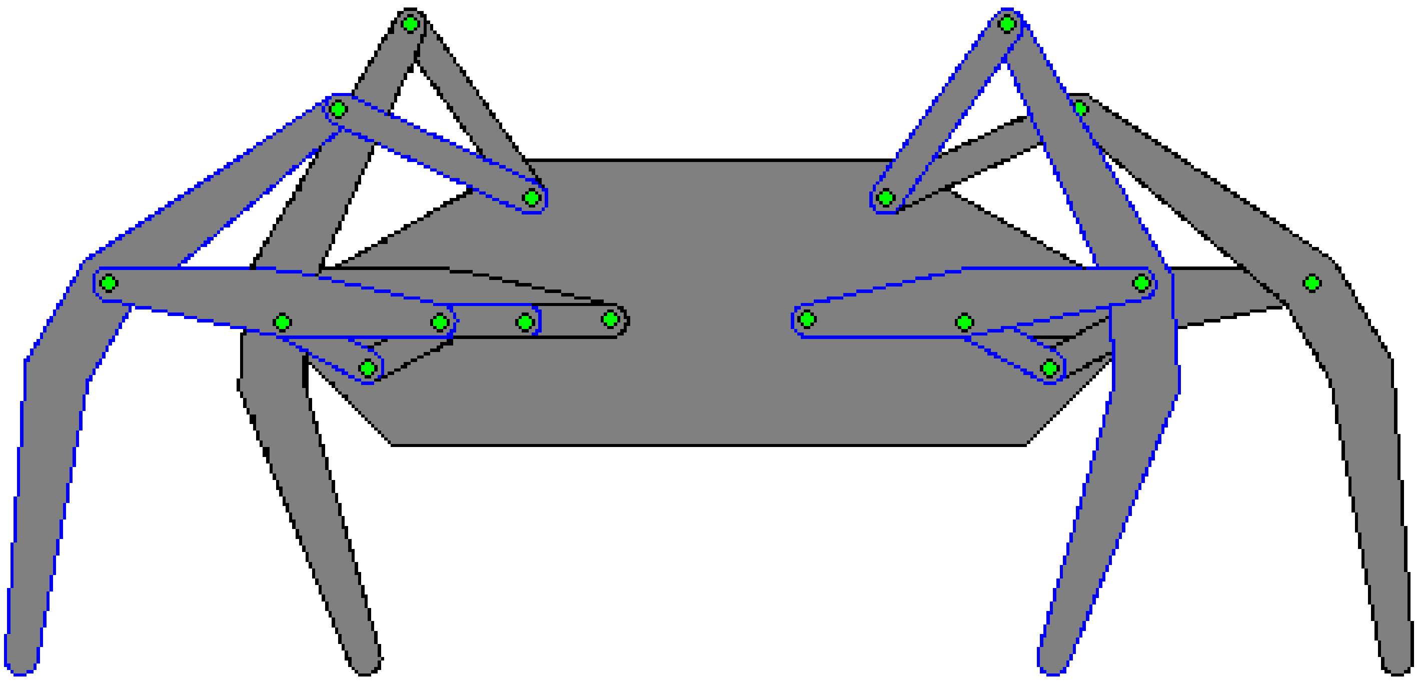
Jansen's linkage



http://en.wikipedia.org/wiki/Jansen%27s_linkage

Kinematic chain - examples

Klann linkage



http://en.wikipedia.org/wiki/Klann_linkage

Kinematic chain mobility

kinematic chain mobility – total number of degrees of freedom with respect to base

kinematic chain mobility – structural formula

(the Chebychev–Grübler–Kutzbach criterion)

$$(3\,D\ chain)\ \ F=6\,N-p_1-2\,p_2-3\,p_3-4\,p_4-5\,p_5$$

$$(2\,D\ chain)\ \ F=3\,N-p_4-2\,p_5$$

$$N-number\,of\ moving\ members$$

$$p_i-number\,of\ i-type\ classes$$

Kinematic chain mobility

<u>kinematic chain mobility – structural formula</u>

(the Chebychev–Grübler–Kutzbach criterion)

$$(3\,D\ chain)\quad F=6N-p_1-2p_2-3p_3-4p_4-5p_5$$

$$(2\,D\ chain)\quad F=3N-p_4-2p_5$$

$$N-number\,of\ moving\ bodies$$

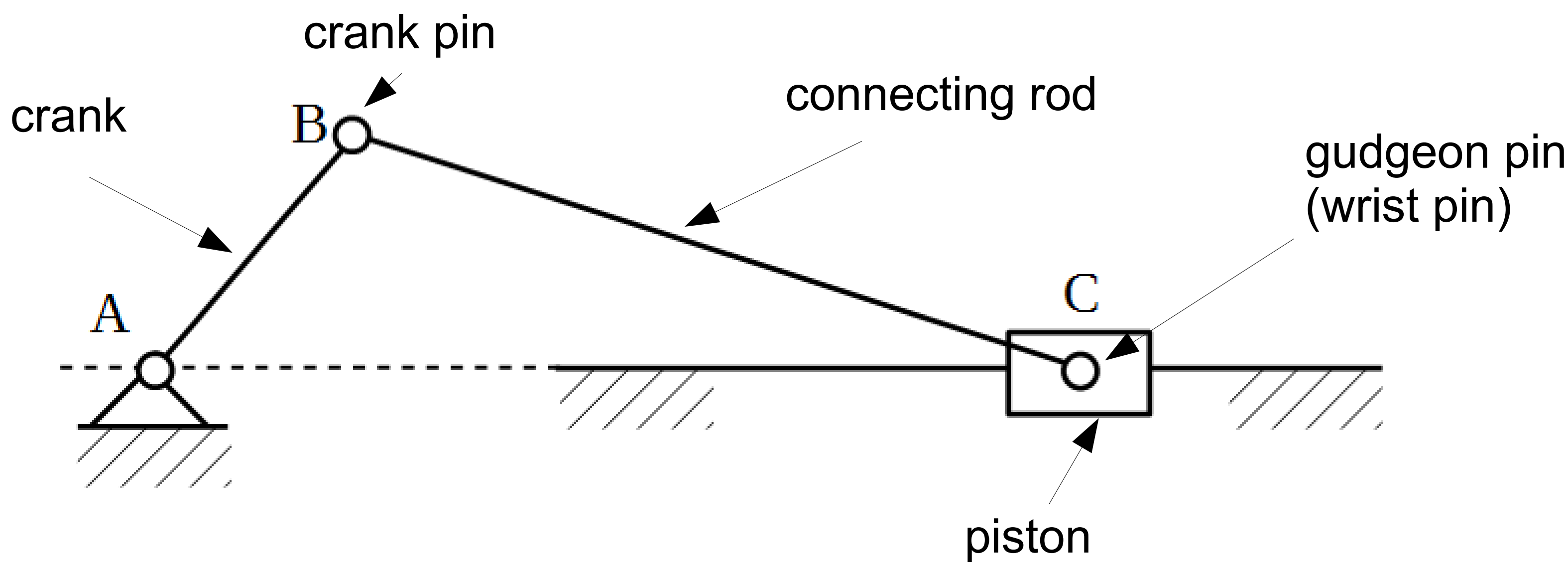
$$p_i-number\ of\ i-type\ classes$$

F >= 1 – movable

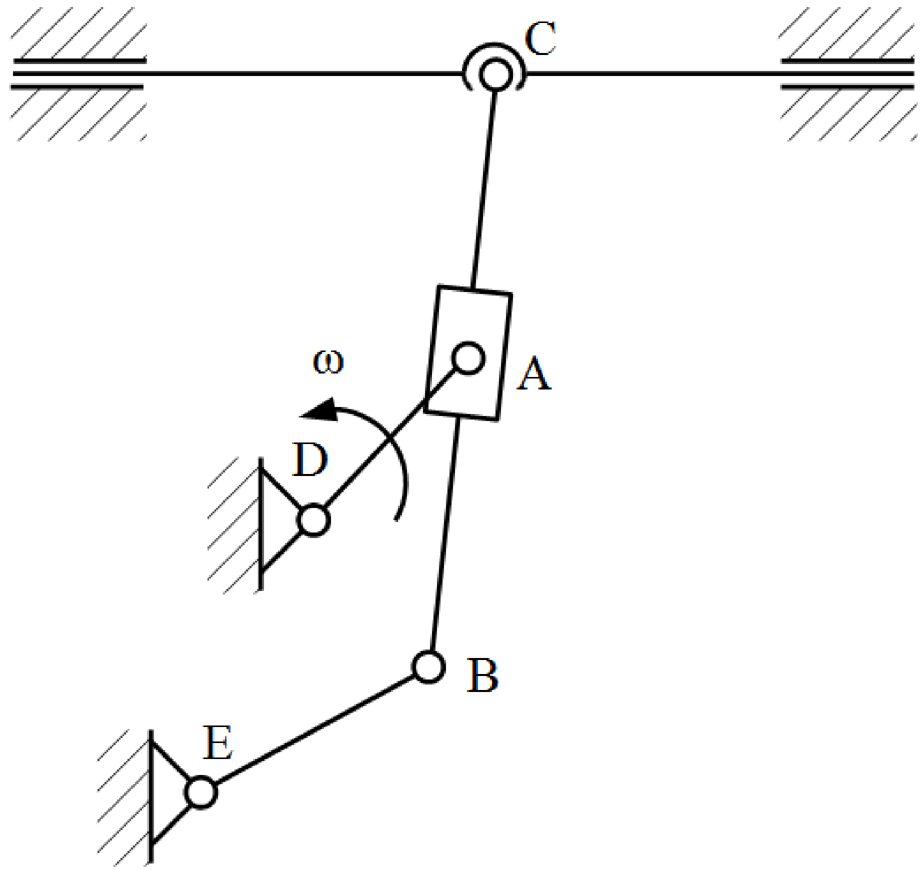
F < 1 – locked or overconstrained

Kinematic chain - examples

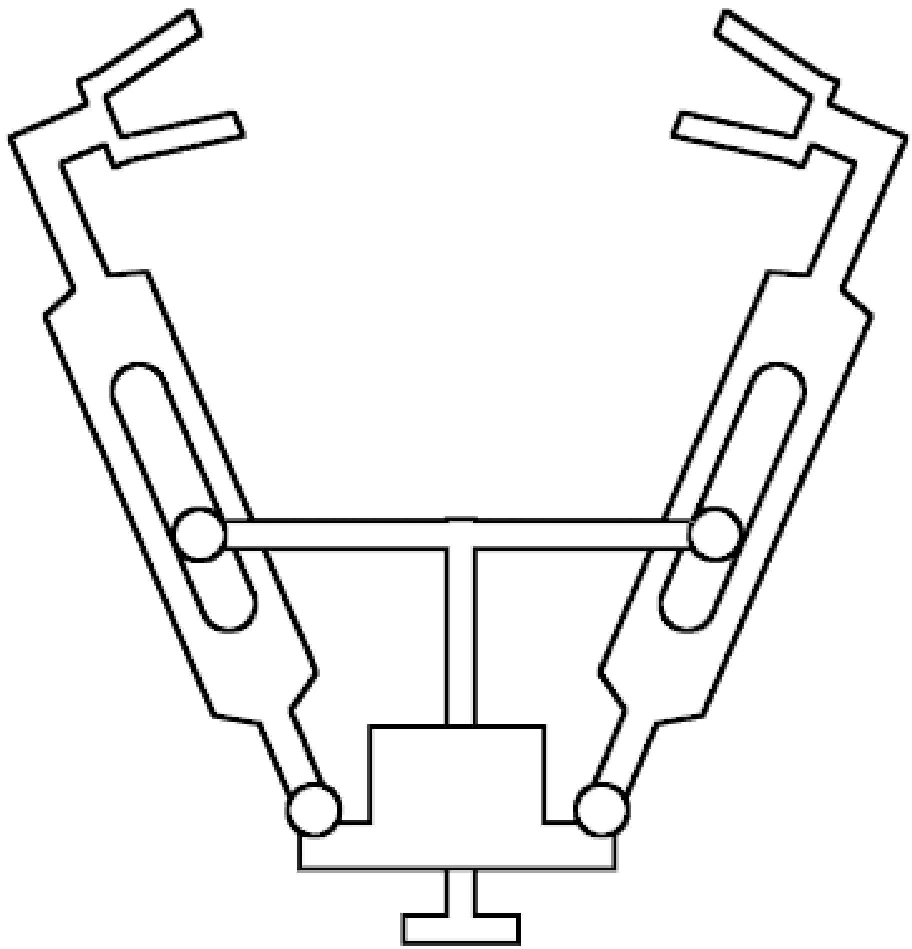
Crank-slider mechanism



Kinematic chain - examples



Kinematic chain - examples



Kinematic chain - examples