

Technische Mechanik

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LTD read <https://engineeringstatics.org>

Kinematics - How a model is currently at motion without concern for the causes (forces)

Statics - Which conditions (forces & moments) are needed to keep a system at rest

Dynamics - Which conditions are needed to create movement in a system in a certain way

Vector Identities:

$$\vec{a} \times \vec{b} = \|\vec{a}\| \|\vec{b}\| \sin(\theta) \vec{n} = \text{Area of parallelogram spanned by } \vec{a} \text{ and } \vec{b}$$

$$\vec{a} \times (b + c) = \vec{a} \times \vec{b} + \vec{a} \times \vec{c}$$

$$a \cdot (b \times c) = b \cdot (c \times a) = c \cdot (a \times b) \text{ (Pacman Identity)}$$

Trig Identities:

$$\cos\left(\frac{\pi}{2} - \theta\right) = \sin(\theta)$$

$$\sin\left(\frac{\pi}{2} - \theta\right) = \cos(\theta)$$

$$\sin(-\theta) = -\sin(\theta)$$

$$\cos(-\theta) = \cos(\theta)$$

$$\tan(-\theta) = -\tan(\theta)$$

Calculus Rules:

$$\frac{dy}{dx} = \frac{dy}{du} \frac{du}{dx}$$

$$\frac{d(uv)}{dx} = u \frac{dv}{dx} + v \frac{du}{dx}$$

Notation:

κ - Set of all points in a body

Time derivative - $\dot{x} = \frac{dy}{dt}$

Coordinate Systems

Orthogonal base vectors:

$$\text{Cartesian: } e_x \times e_y = e_z$$

$$\text{Cylindrical: } e_\rho \times e_\varphi = e_z$$

Position Vectors:

$$\text{Cartesian: } \mathbf{r} = xe_x + ye_y + ze_z$$

$$\text{Cylindrical: } \mathbf{r} = \rho e_\rho + ze_z$$

There is no separate e_φ component in a cylindrical position vector, as it's already accounted for by the changing e_ρ unit vector. The following relations are useful for calculations in the cylindrical coordinate system:

$$\text{Wegen des Einheitskreises: } e_\rho = \cos(\varphi)e_x + \sin(\varphi)e_y$$

$$\text{Intuitiv: } e_\varphi = \frac{d(e_\rho)}{d\varphi} = -\sin(\varphi)e_x + \cos(\varphi)e_y$$

$$\frac{d(e_\varphi)}{d\varphi} = -\cos(\varphi)e_x - \sin(\varphi)e_y = -e_\rho \text{ (Centripetal acceleration!)}$$

$$\frac{d(e_\rho)}{d\varphi} = e_\varphi$$

The time derivatives can be found by deriving the cartesian formulae with respect to time and doing some substitution:

$$\frac{d(e_\varphi)}{dt} = -\dot{\varphi}e_\rho$$

$$\frac{d(e_\rho)}{dt} = \dot{\varphi}e_\varphi$$

Thus the velocity formula in the cylindrical co-ordinate system:

$$\begin{aligned}\vec{v} &= \frac{d(\vec{r})}{dt} \\ &= \dot{\rho}e_\rho + \rho\dot{\varphi}e_\varphi + \dot{z}e_z\end{aligned}$$

Rigid bodies

A body in which deformation is negligible. There are no ideal rigid bodies in real life.

Let P, Q be points in a rigid body

$$\forall P, Q \in \mathbb{R}^3, |\mathbf{r}_Q - \mathbf{r}_P| = \text{Constant}$$

Satz der Projizierten Geschwindigkeiten

The velocities of any two points in a rigid body projected on the vector between them is always the same. This means the body is never getting shorter or longer between two points (deforming).

This is useful for determining the velocities of points on rigid bodies with relation to each other.

$$\vec{v}_Q \cdot e = \vec{v}_P \cdot e$$

$$\text{wo } e = \frac{r_Q - r_P}{|r_Q - r_P|}$$

$\vec{v}_A \cdot e = v'_A$ = Velocity of A projected onto a unit vector within a rigid body.

Translation - for all points P , \vec{v}_P is equal

Movement across a plane

- All velocities are parallel to a certain plane
- All points along a normal to the plane have the same velocity
- It is either a translation or a rotation at any point in time

Rotation

If at least two points in a rigid body do not have the same velocity, it is currently rotating. The momentary, static center of rotation is the intersection of lines perpendicular to the velocities of two points. All points rotate around the center with the **same angular velocity** ω .

Considering a point with vector \vec{r}_P from the center of rotation, rotating with angular velocity $\omega = \frac{d\Theta}{dt}$. Its velocity vector can be determined as:

$$\vec{v}_P = (\omega e_z) \times \vec{r}_P$$

The unit vector e_z is simply needed so the resulting direction is anticlockwise (for a positive ω) and perpendicular to \vec{r}_P .

Polbahn - The path traced by the series of momentary centers of rotation of a rigid body.

Movement in space

In 3D space, simultaneous translation & rotation is possible due to the extra dimension.

Rotation Axis - The body rotates around an entire axis instead of a single point. The velocity of all points on this axis are the same and equal to the object's overall translational velocity. $\vec{\omega}$ is defined as the unit vector in the direction of the axis times the angular velocity: $\vec{\omega} := \omega \vec{e}_r$

LTD: Parametric equation of points along the rotational axis

Starrkörperformel

The following extremely useful relationship can be used to link the unique angular velocity vector to the velocity of any two points in a rotating body:¹

$$\vec{v}_P = \vec{v}_B + \vec{\omega} \times \vec{r}_{BP}$$

This essentially shows that every point in a rigid body rotates around every other point in the body with the same angular velocity.

The following properties of movement in space are constant and called "Invariants":

1. $I_1 = \vec{\omega} \forall P \in \kappa$ - The angular velocity is the same regardless of the reference point
2. $I_2 = \vec{\omega} \cdot \vec{v}_P \forall P \in \kappa$ - The component of the velocity of a point in the direction of the rotation axis is the same for all points in the body. This is the translation velocity of the body.

Therefore the momentary movement of any point in the body can be described with just two values called the **Kinemate**: $\{\vec{v}_B, \vec{\omega}\}$

¹Derivation available in the 5th Powerpoint of Dr. P Tiso

LTD: Test these in a simulation :)

Schraubung - The combination of a rotation with a translation in the direction of the rotation axis

Types of momentary movement in space:

1. Translation: $\vec{\omega} = 0$
2. Rotation: $\vec{\omega} \neq 0 \wedge I_2 = 0$
3. Schraubung: $I_2 \neq 0$

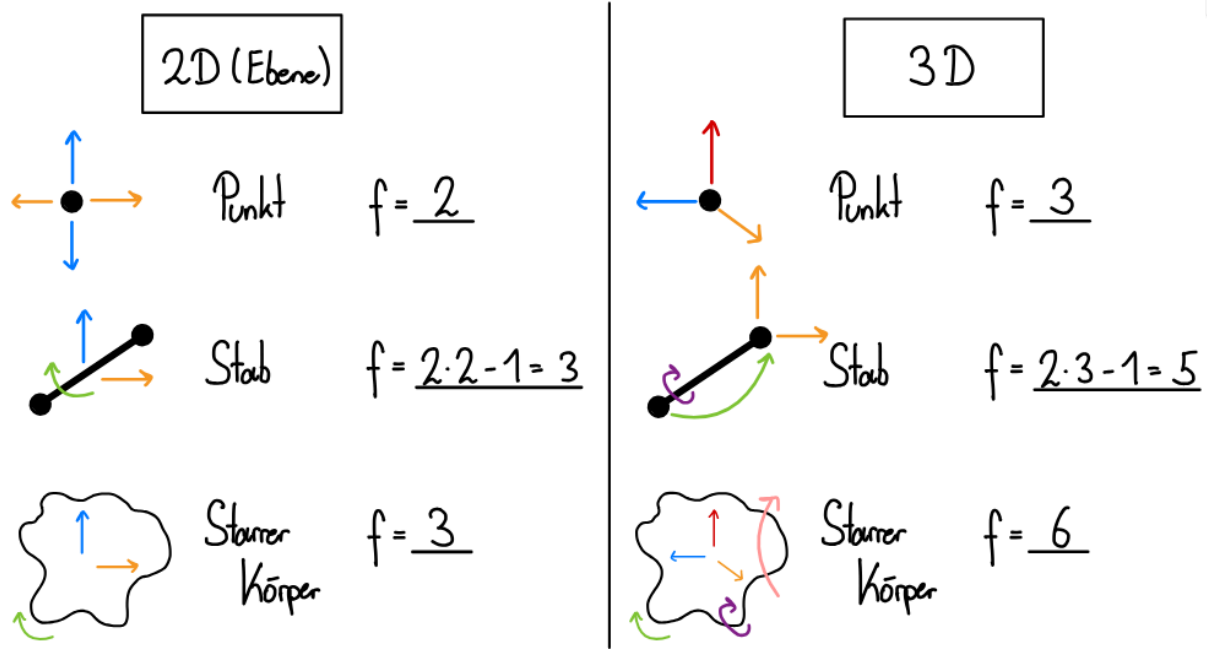
LTD: Understand Rechteck Beispiel in script

Degrees of freedom




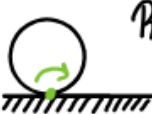
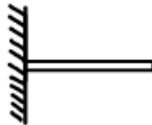

The dimensions needed (using an arbitrary basis for this specific system) to clearly determine the state of a system. This could for example be the location of a slider and the angle at which a rod is attached to it (much more concise than for example the cartesian coordinates of the slider and the other end of the rod).

Considering a system with several bodies. For a sum of degrees of freedom of n , and b restricted degrees of freedom due to connections, the resulting degrees of freedom of the whole system is:

$$f = n - b$$



IMPORTANT: The joint at a roller / pivot must be accounted for too, in case it has more than 1 rod connected! (using the n-Gelenk formula)

b von	2D	b von	2D
 Auflager (beidseitig)	1	 Gelenk (2 SKs verbunden)	2
 Gelenk (Festlager)	2	 Rollen ohne gleiten	2
 Einspannung	3	 Gelenk (n SK verbunden)	$(n-1) \cdot 2$

Forces

Force - An influence that can cause an object's velocity to change. It is a vector quantity applied at an attack point. The line through the attack point in the direction of the force is called the line of action.

In reality, there are 4 fundamental forces (electromagnetic, gravitational, weak and strong nuclear) but in many practical applications we consider integral values such as contact forces and friction.

Inner vs outer forces

Every inner force in a system exists in a pair with its corresponding reaction force. Forces whose reaction we don't care about are so-called *external forces*.

$$\sum \text{Inner Forces} = 0$$

Force groups

The set of forces acting on a body is known as the force group.

Two force groups are statically equivalent when:

$$\mathcal{P}_{\text{tot}}(G_1) = \mathcal{P}_{\text{tot}}(G_2)$$

Static equivalence in a rigid body

Due to the total power of a rigid body formula (see power), static equivalence in a rigid body requires:

$$R_1 = R_2$$

$$(M_B)_1 = (M_B)_2$$

Where B is the same point on the body these force groups are acting on.

Furthermore, two forces are equivalent if they have the same magnitude and line of action.

Forces with lines of action going through the same point have only a resultant force - no moment:



$$M_P = 0, R \neq 0$$

Moments

A moment is a concept for describing the capacity of a force to rotate an object around an arbitrary center of rotation with units Nm .

The moment of a force around the center of rotation O in vector form is:

$$M_O = \vec{r}_{OP} \times \vec{F}$$

The resulting moment lies along the axis of rotation and describes the angular direction of the rotation caused by the moment.

Alternatively, it can be expressed as a scalar with the perpendicular distance from the line of action of F to O: d :

$$M_O = dF$$

Transformation of moments

The moment of a force can be transformed with respect to a different point using the following formula:

$$M_A = M_B + r_{AB} \times R$$

Torque

A torque (also known as couple) is a pair of antiparallel moments with equal magnitude F with respect to the same point. Considering the perpendicular distance between their lines of action d , these result in:

$$\begin{aligned} R &= 0 \\ M_P &= dF \end{aligned}$$

Where P is the midpoint between their lines of attack.

Whenever the resultant force is 0, the moment around all points in the body is the same.

Dynamic

The dynamic of a force group with respect to a point O describes the entire set of forces on the body:

$$\{R, M_O\}$$

Where R is the resultant force and M_O is the resultant moment around O: $\sum \vec{r}_{OP_i} \times \vec{F}_i$

The following invariants apply to the dynamic:

- $I_1 = R \forall P \in \kappa$
- $I_1 = R \cdot M_O \forall P \in \kappa$ - the component of the resultant in the direction of the moment with respect to the same point is the same for all points

Power

The rate of transfer of energy.

Due to the work done by a force $\int_c \vec{F} d\vec{s}$, the power exerted by a force at a point in time can be expressed as:

$$\mathcal{P} = \vec{F} \cdot \vec{v}$$

- *Accelerating force* ($\frac{\pi}{2} < \alpha \leq \pi$) - A force with a positive component in the direction of the velocity is contributing kinetic energy to the object and increasing the power
- *Braking Force* ($0 < \alpha < \frac{\pi}{2}$) - Reduces the kinetic energy of the object
- A force perpendicular to the velocity of an object does not contribute to its power until the object begins moving with a component in the direction of the perpendicular force.

Total power of a rigid body

The total power of a force group is the sum of powers for each force acting on the body:

$$\mathcal{P}_{\text{tot}} = \sum_{i=1}^n \vec{F}_i \cdot \vec{v}_i$$

When the kinematic $\{v_B, \omega\}$ and dynamic $\{R, M_B\}$ with respect to a point B are known, we can calculate the total momentary power thanks to the rigid body formula and the “pacman” identity:

$$\mathcal{P}_{\text{tot}} = R \cdot v_B + M_B \cdot \omega$$

Parallel Forces

When all forces acting on a body point in the same direction (negative direction also allowed), they can be written as:

$$\vec{F}_i = F_i \vec{e}$$

Where \vec{e} is the unit vector of their common direction.

The dynamic with reference to a point O is:

$$R = \sum \vec{F}_i = \vec{e} \sum F_i$$
$$M = \sum \vec{r}_i \times \vec{F}_i = \left(\sum \vec{r}_i F_i \right) \times \vec{e}$$

Where \vec{r}_i is the vector from O to \vec{F}_i 's point of attack.

The sum $\sum \vec{r}_i F_i$ is called the dipole moment (sometimes written as N) of a set of parallel forces. It is independent of the point O and, as long as it's consistent for each force included, and describes the distribution of a parallel force group. This can be intuitively understood by choosing O as the midpoint along a line of forces with equal magnitude - the x-components would cancel each other out, and the cross product of the two parallel vectors (dipole moment and \vec{e}) is 0.

Center of Forces

This is the “midpoint” on which a pivot can be placed so that no resultant moment arises due to a force group (for example the body's weight distribution or the forces of an electric field). It is unique to a dipole moment and the direction of \vec{e} is irrelevant.

The position vector of the center of forces from the point O can be calculated using a dipole moment with **the same point O** as its origin:

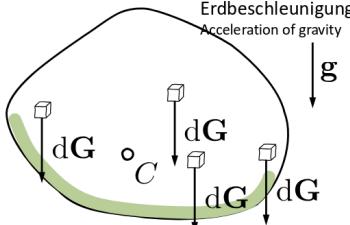
$$\mathbf{r}_{OC} = \frac{\sum \vec{r}_i F_i}{\sum F_i}$$

For a dipole moment with the specific direction of the forces \vec{e} , an entire line can serve as a center of forces:

$$\vec{r}_{OC}(\lambda) = \vec{r}_{OC} + \lambda \vec{e}$$

Center of Mass

This is the average location of all the weight of an object. It can be calculated using a volume integral over the density of the body:



Erdbeschleunigung
Acceleration of gravity

g

Infinitesimale Schwerkraft: $d\mathbf{G} = \mathbf{g}dm$
Infinitesimal weight force:

Schwerkraft: $\mathbf{G} = m\mathbf{g}$
Weight force:

$$\mathbf{r}_{OC} = \frac{\sum F_i \mathbf{r}_i}{\sum F_i} \rightarrow \mathbf{r}_{OC} = \frac{\iiint \mathbf{g} \mathbf{r} dm}{\iiint \mathbf{g} dm} = \frac{g \iiint \mathbf{r} dm}{g \iiint dm} = \frac{g}{mg} \iiint \mathbf{r} dm = \frac{1}{m} \iiint \mathbf{r} dm$$

$$\mathbf{r}_{OC} = \frac{1}{m} \iiint \mathbf{r} dm$$

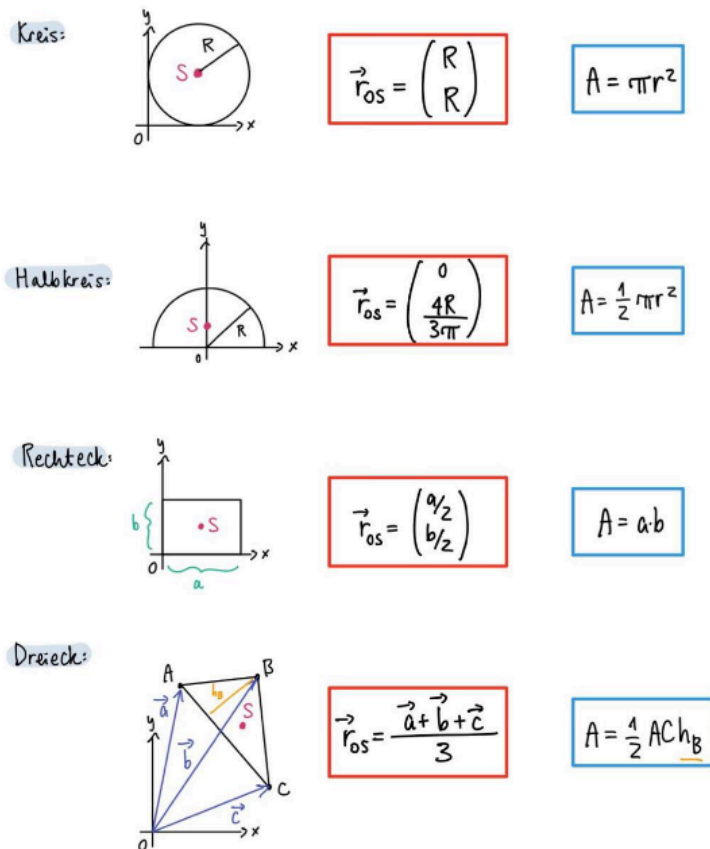
$$x_{OC} = \frac{1}{m} \iiint x dm$$

$$y_{OC} = \frac{1}{m} \iiint y dm$$

$$z_{OC} = \frac{1}{m} \iiint z dm$$

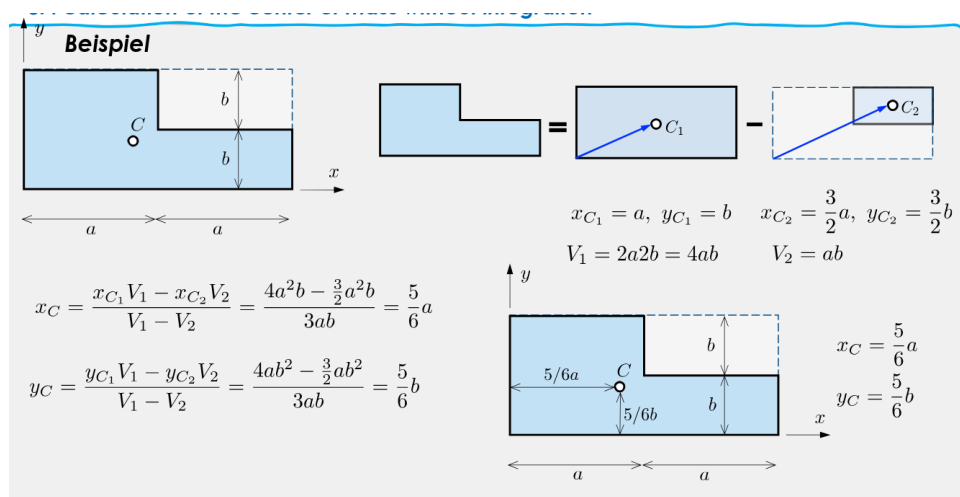
ETH zürich

Where dm is effectively the density at the point of each differential.



Integration is a linear transformation - a center of mass can be calculated as the sum of separate integrals (which of course can also be negative):

$$\vec{r}_{OC} = \frac{\sum \iiint \vec{r} dm}{\sum m_i}$$



LTD: General formula

$$\vec{r}_C = \frac{\sum m_i \vec{r}_{Ci}}{\sum m_i}$$

Rest

A system is at rest when all of its velocities are 0.

- Instantaneous rest - $\vec{v}_p = 0 \forall p \in \kappa \mid t = t_0$
- State of rest - $\vec{v}_p = 0 \forall p \in \kappa, \forall t$

Fundamental Theorem of Statics

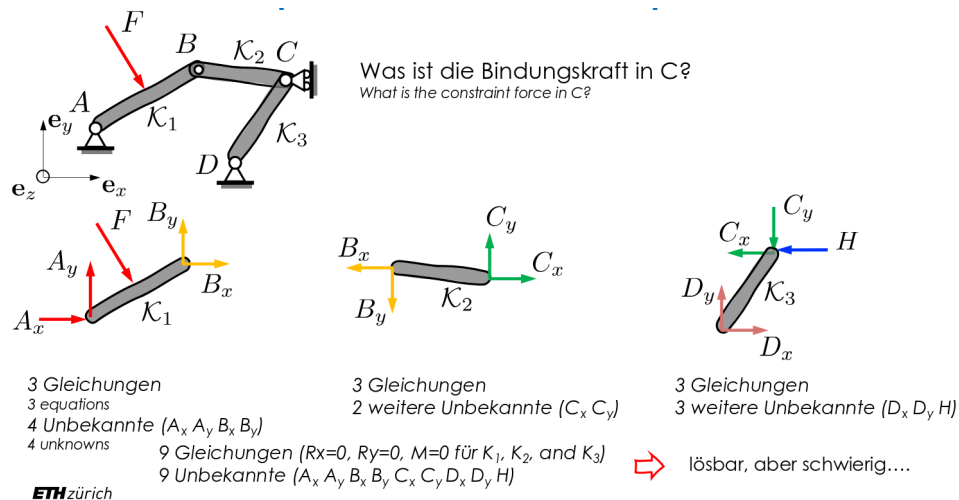
This also means that the resultant force and resultant moment around any point (the moment is always the same if $R = 0$ due to the transformation of moments relationship - consider a torque couple for intuition) is 0:

$$\vec{R} = 0$$

$$\vec{M} = 0$$

Constraints exert equal and opposite forces to prevent an object moving through them.

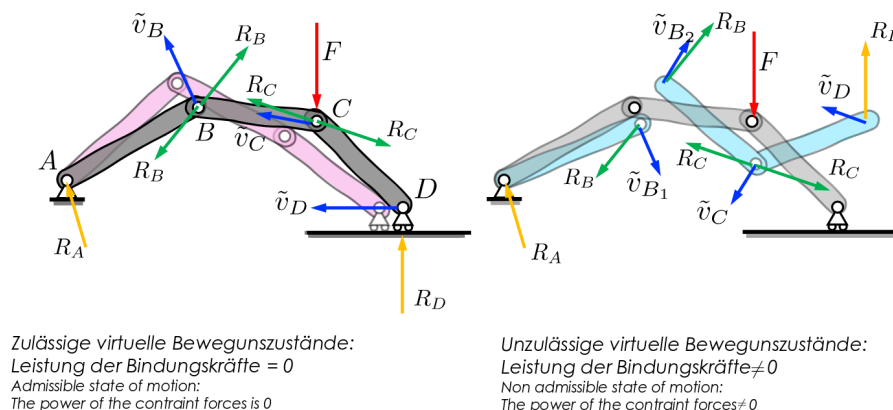
Forces in a system at rest with multipled bodies can be solved by including forces at constraints:



These systems of equations are linear can be solved through Gaussian elimination.

Virtual Motion

A system can be modelled as in virtual motion when virtual velocities are modelled at each point, such that the total power of constraint forces is 0:



- For example, velocity at the slider is perpendicular to its constraint force, and equal and opposite constraint forces at joints cancel each other's accelerating and braking power out.
- There can be no virtual velocity at a pivot, as it exerts constraint forces in both the x and y component - they are orthogonal and the power of this force would never be 0.

- There can however exist a rotational velocity around a pivot.
- TODO: When can constraints be removed? Clarify this after learning the Euler-Lagrange formalism

These subsequent virtual velocities, denoted as \tilde{v} can be found using techniques in the kinematics of rigid bodies.

Theorem of Virtual Power

A system is at rest when the virtual total power is 0 for every virtual state of motion:

$$\mathcal{P}_{\text{tot}} = \sum_{i=1}^n \vec{F}_i \cdot \tilde{v}_i = 0$$

This is useful to calculate a few external / constraint forces, by strategically allowing virtual motion which involves that force. Other forces with an equal and opposite reaction can be ignored as the resultant at that point is 0.

If many forces in a system are needed, then a full analysis using the theorem of statics is more appropriate.

Framework

The constraints in a framework can be calculated by removing one of the rods, whose compression (or tension, this becomes apparent if a negative value is calculated) is acting as a constraint force.

LTD: Force cut

Power of Torque

It is useful to solve statics problems with pulleys using the virtual power of a torque (the cable around a pulley has the same tension throughout):

$$\mathcal{P} = \vec{\omega} \cdot \vec{M}$$

As usual in a torque, the origin of the moment is irrelevant.

LTD: Do not assume all tensions are equal in pulleys exam!

Static Determinacy

Statically Determinate - A system where the constraint forces can be determined through the statics conditions when an external dynamic (effect of a force) is applied (for example the weight of a rod etc). The linear system of constraints (reaction forces + moments) has a single solution.

This essentially means that the system of equations doesn't have full rank and has infinite / no solutions when a resultant force + moment needs to be found to counteract a new external force.

Each degree of a freedom in the system delivers one independent constraint, this can be used to easily check if the system is statically determinate:

- $f = 0$ - Statically determinate; an equilibrium is always possible
- $f < 0$ - Statically underdetermined; not enough conditions to determine unique, suitable constraints. The constraint forces can take on infinite values (described by the free variables) to maintain rest as an external dynamic is introduced.
- $f > 0$ - The system is statically overdetermined. A solution is only possible for very specific loads.

LTD: Double check above intuition, might be erroneous

Stability

Contact area - the smallest convex area that encloses all of a bodies contact points with the floor.



Stability problems can be solved using the **average** reaction force and its corresponding moment as the individual molecular forces and contact points are obviously unknown. However, the mechanically accurate resultant and moment would look like:

$$N_R = \iint d\vec{N}$$

$$N_M = \iint \vec{r} \times d\vec{N}$$

Stability - A system is stable if the average normal force and its corresponding moment acts within the contact area.

Another way to think of this is if the “average” weight (from the center of mass in simple systems) acts within the contact area (before the tipping point of a block for instance), as the normal reacts at that point too.

We can then formulate constraints under which stability remains satisfied which are useful when choosing the dimensions of an object.

Alternatively individual contact forces can be analysed, for example each leg of a table, however this is often more cumbersome.

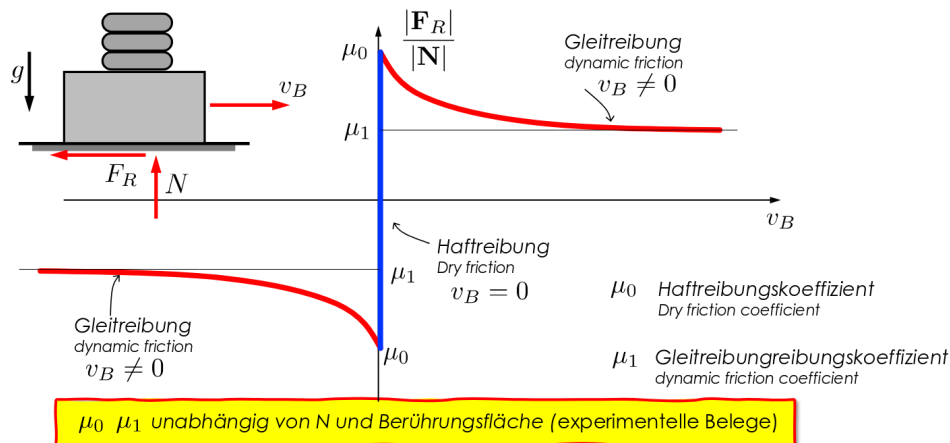
Friction

Friction is the phenomenon of irregularities in the surfaces of materials resisting their relative motion. It is completely a braking force, acting in the opposite direction of the velocity and converting energy away from the system into heat. Friction is responsible for 20% of our energy expenditure!

However it is more often than not a useful force, which is for example needed to exert lift in airplane wings and to keep vehicles from crashing as they take a turn.

Dry Friction

Of course, calculating the exact frictional force of each irregularity in a surface is not a good idea. Experiments show that the force needed to accelerate and then maintain an object on a frictional surface at a certain velocity (ie it becomes equal to the current friction) is initially higher than after it is in motion, where it becomes linearly proportional to the current normal force (and therefore the weight of the object).



In practice we can ignore the changing constant of proportionality and simply define two constants:

- μ_0 - Dry static friction (Haftreibung):

$$|F| \leq \mu_0 |N|$$

The force is \leq because it would only be at full effect if the object is on the verge of sliding.

Considering for example a box on a ramp, when the angle of the ramp is 0, no friction is acting on it yet. $|F| = \mu_0 |N|$ when the so called **critical angle** of the ramp is reached. This also helps us define a range for an external, tangential force within which the object remains at rest.

- μ_1 - Dry kinetic friction (Gleitreibung):

$$|F| = \mu_1 |N|$$

This is called Coulomb's Frictional Law. As a vector:

$$\vec{F} = -\mu_1 |N| \frac{\vec{v}}{|\vec{v}|}$$

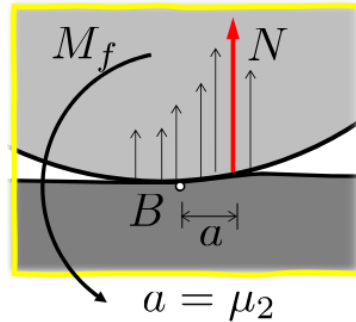
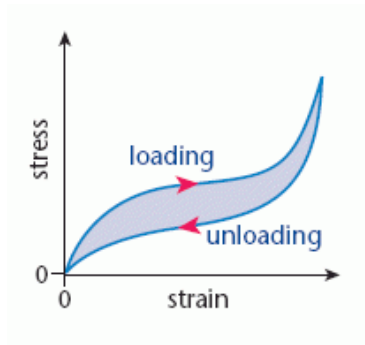
Here are some typical coefficient values:

Materialkombination	Haftreibungskoeffizient μ_0	Gleitreibungskoeffizient μ_1
Stahl / Stahl	0.1 bis 0.5	0.1 bis 0.4
Stahl / Eis	0.02 bis 0.03	0.014 bis 0.015
Stahl / Teflon	0.04	0.04
Aluminium / Aluminium	1	1
Leder / Metall	0.4 bis 0.6	0.2 bis 0.3
Holz / Metall	0.5 bis 0.65	0.2 bis 0.5
Autoreifen / Strasse (trocken)	0.7 bis 0.9	0.5 bis 0.8
Ski / Schnee	0.1 bis 0.3	0.04 bis 0.2

They depend on both materials as seen above.

Frictional Moment

The front of a tire slightly compresses as it rolls, which is especially evident in elastic materials like rubber. Due to their hysteresis curve, less elastic potential energy is released as they decompress by exerting a normal force.



This lost energy can be modelled as a braking moment in the opposite direction to the current angular velocity, which is proportional to the net normal force:

$$|M_r| \leq \mu_2 |N|$$

$$M_r = -\mu_2 |N| \frac{\omega}{|\omega|}$$

Dynamics

Acceleration Formulae

Acceleration is the rate of change of velocity, can be found by taking the derivative of velocity:

$$\vec{a} = \dot{\vec{v}} = \frac{d(\dot{x}e_x + \dot{y}e_y + \dot{z}e_z)}{dt} = \ddot{x}e_x + \ddot{y}e_y + \ddot{z}e_z$$

In cylindrical coordinates:

$$v = \dot{\rho}e_\rho + \rho\dot{\phi}e_\phi + \dot{z}e_z$$

$$a = (\ddot{\rho} - \rho\dot{\phi}^2)e_\rho + (2\dot{\rho}\dot{\phi} + \rho\ddot{\phi})e_\phi + \ddot{z}e_z$$

This can of course be integrated to determine the velocity and position functions. IMPORTANT: Do not forget to account for the initial velocity / position! Integration only returns the total velocity gained / lost or the displacement.

Momentum

Momentum is a conserved quantity (within a system, provided the total external force is 0) of how much force is needed to change the velocity of an object with units kg ms^{-1} :

$$\vec{p} = m\vec{v}$$

Newton's Second Law of motion states: "The resultant force acting on a point mass is the rate of change of the momentum of the object."

$$F = \frac{d\vec{P}}{dt} = m\vec{a}$$

Circular Motion

Projectile Motion

Key formulas from A levels The maximum distance is achieved when the initial velocity is 45° to the ground.

Harmonic Oscillators

Approximate solution for non-linear differential equation using Taylor series \rightarrow small angle approximation
Key polar coordinate dynamics functions in terms of angular velocity

TODO:

- Coefficient of restitution
- Add useful conversions to formula sheet (km/h - m/s etc.)