

Chapter III a

Equilibrium 2D



Lecture Overview

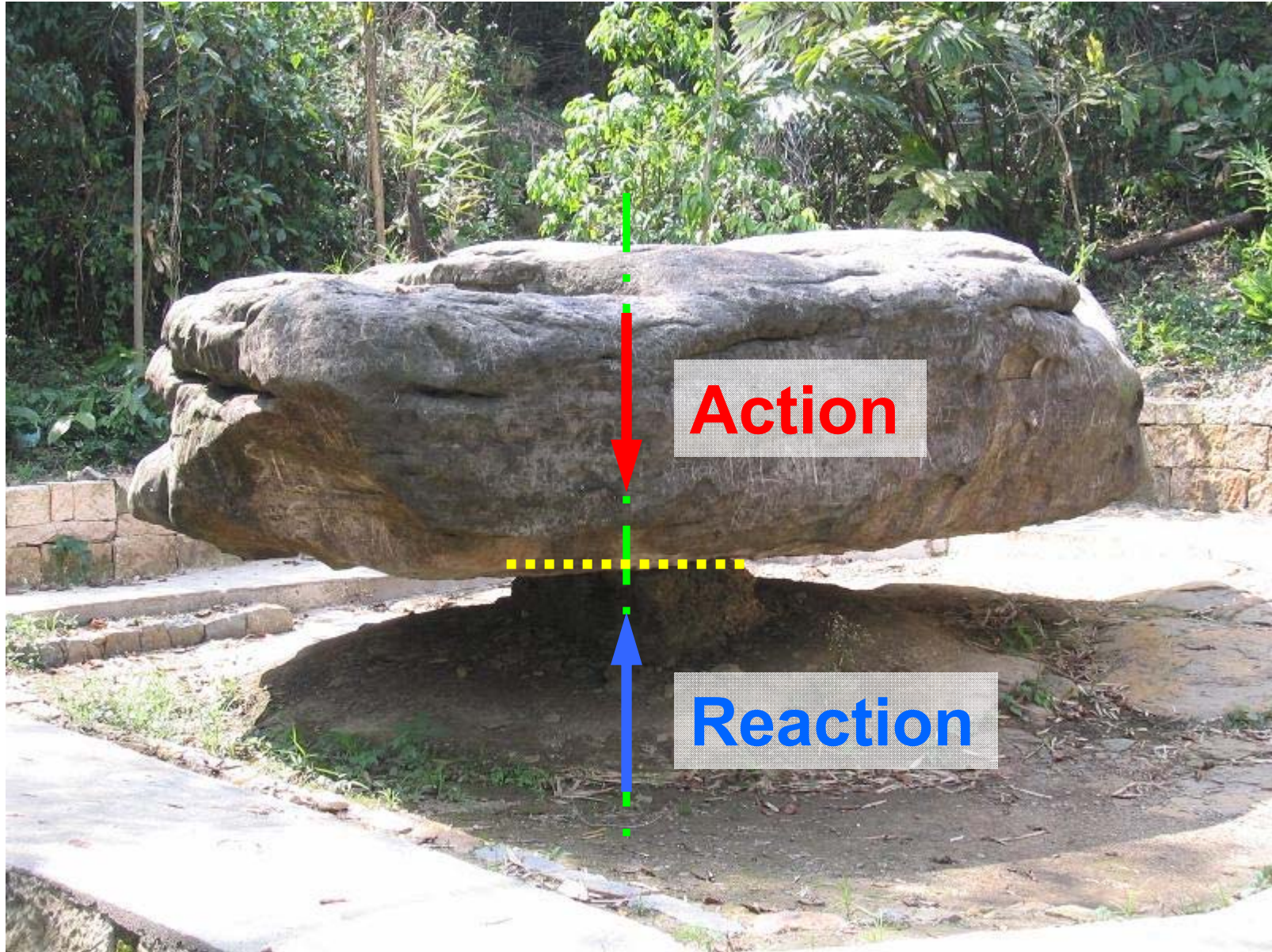
- Body at rest
- equilibrium conditions
- free body diagram
- statical determinacy

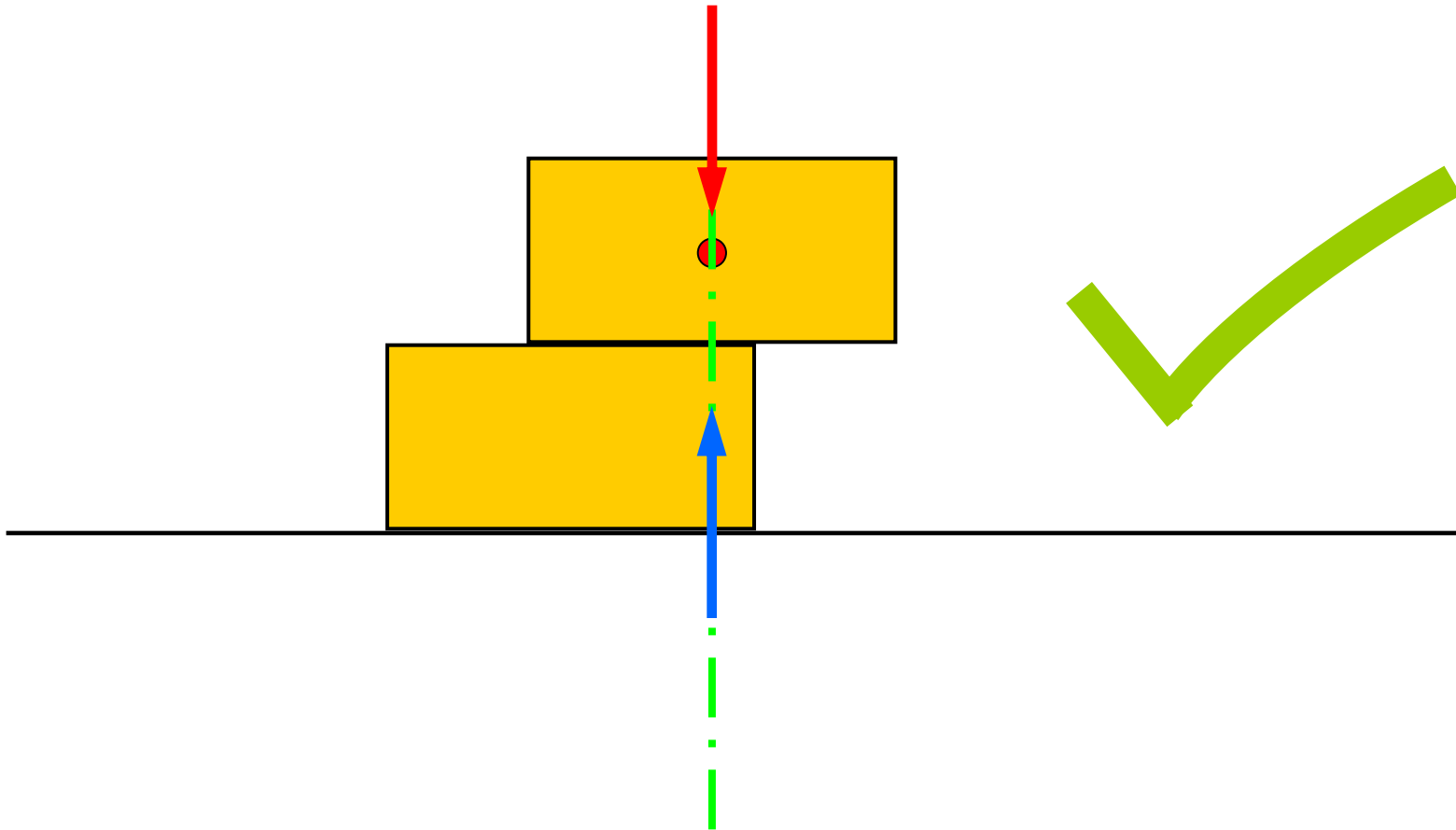


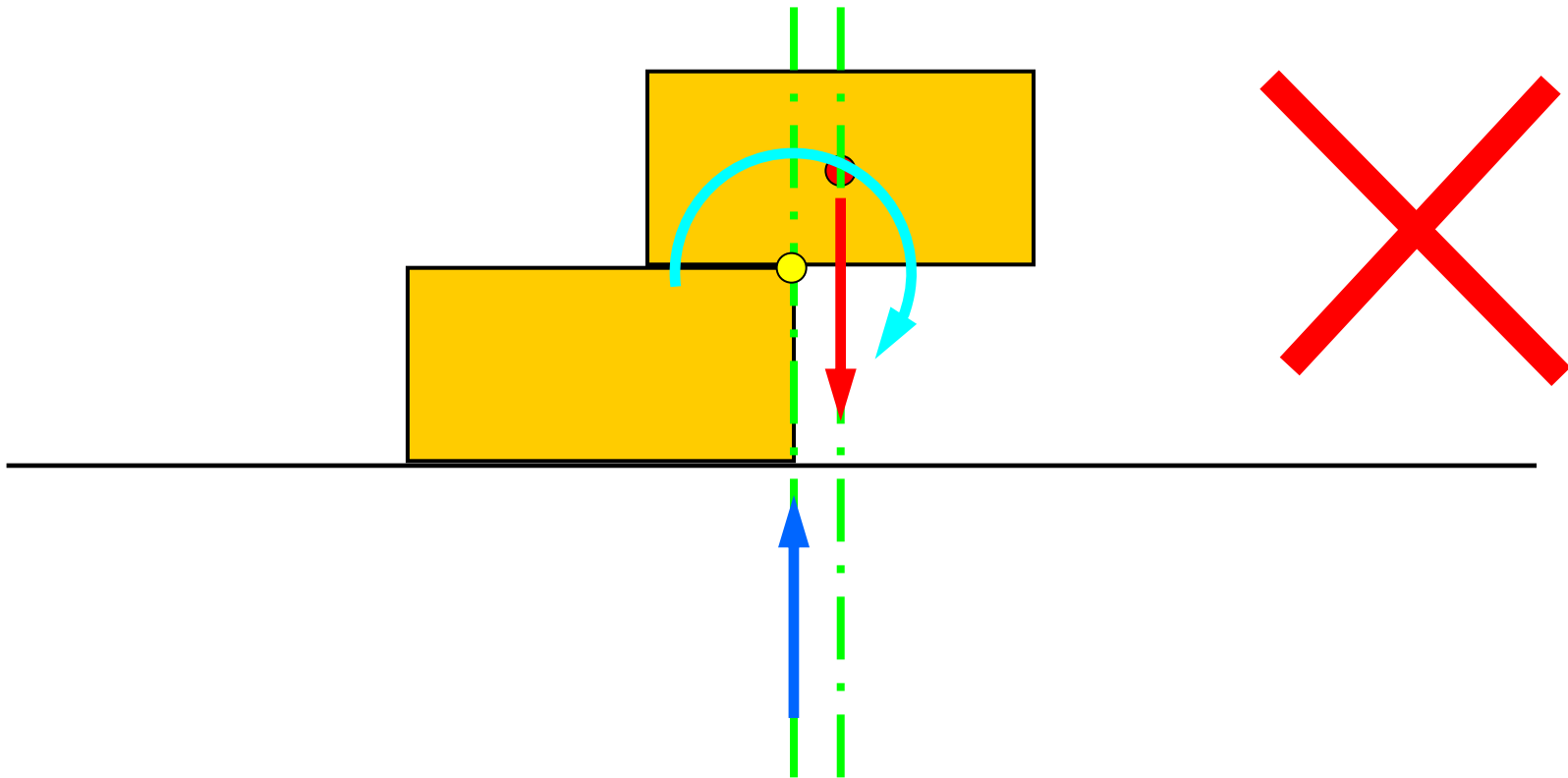
Equilibrium: Body at Rest

no linear displacement or rotation

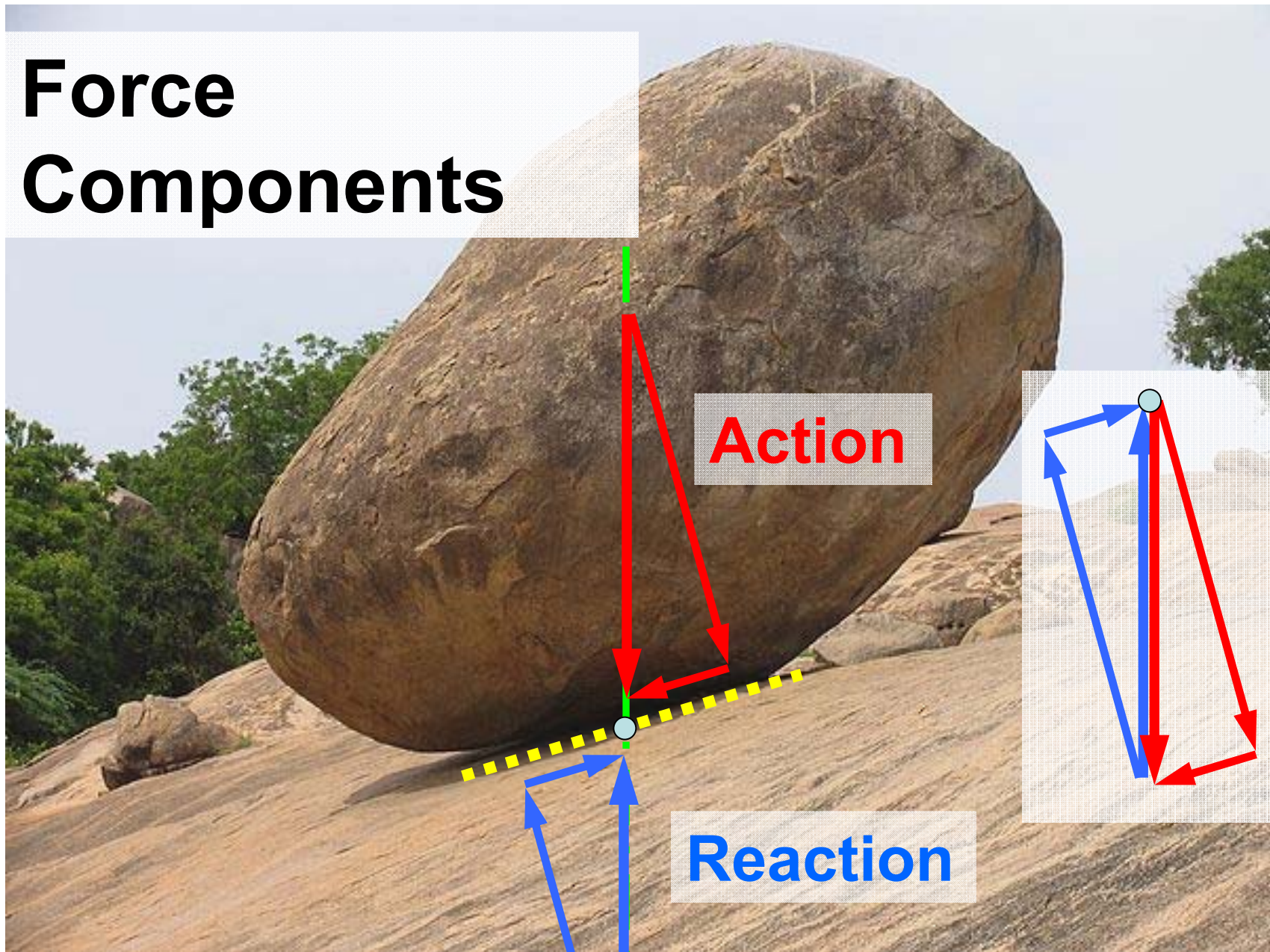








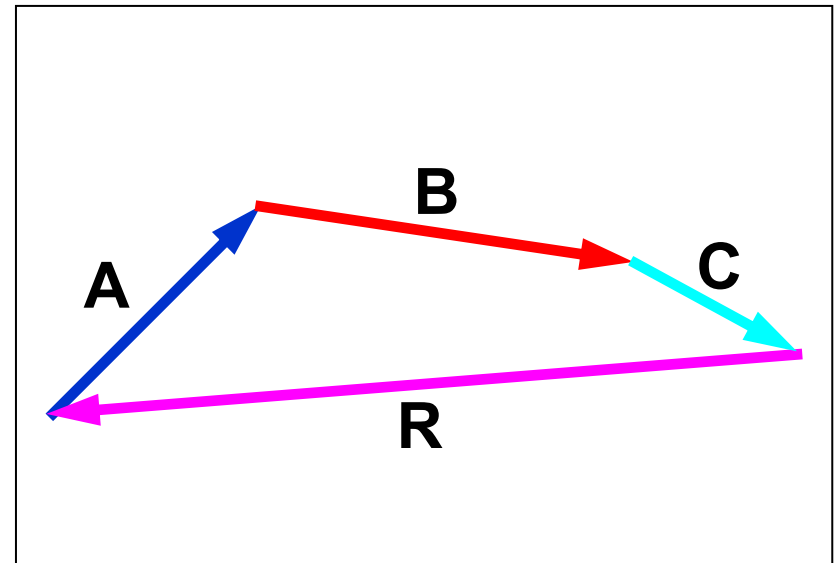
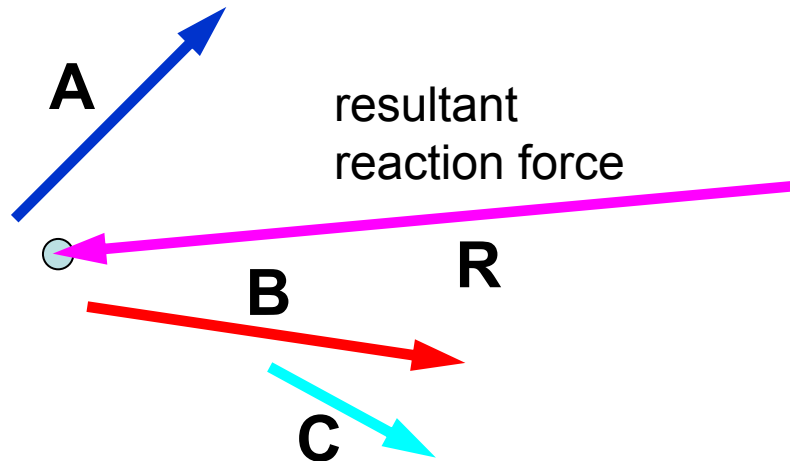
Force Components

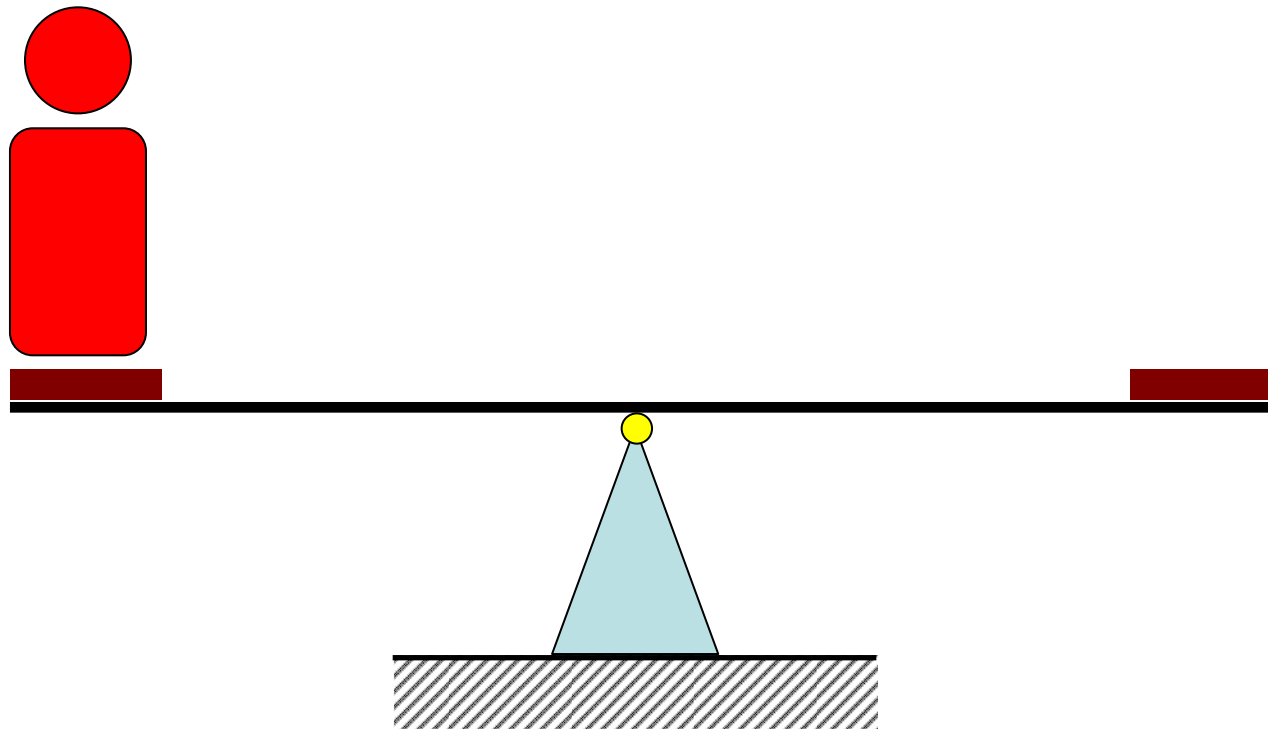


Vector Addition – graphical method

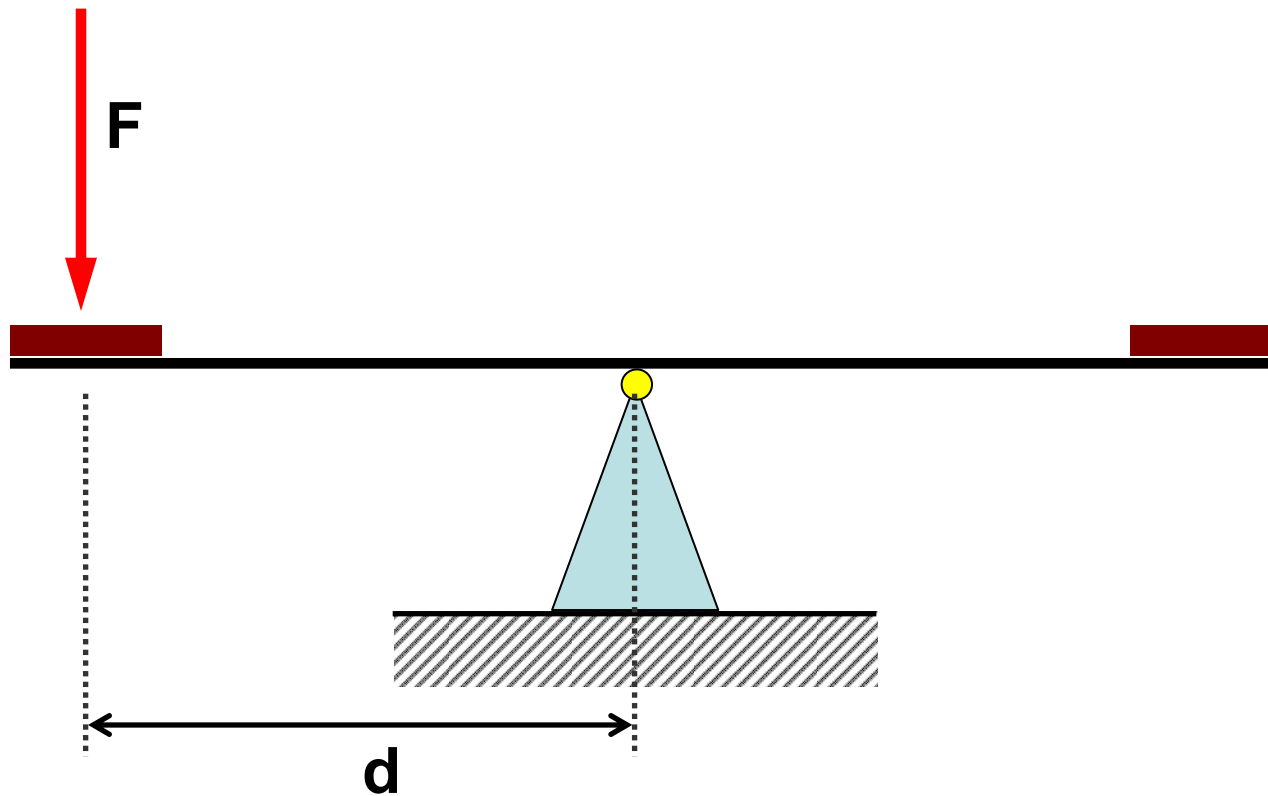
**e.g.: equilibrium at particle:
addition of all vectors = 0**

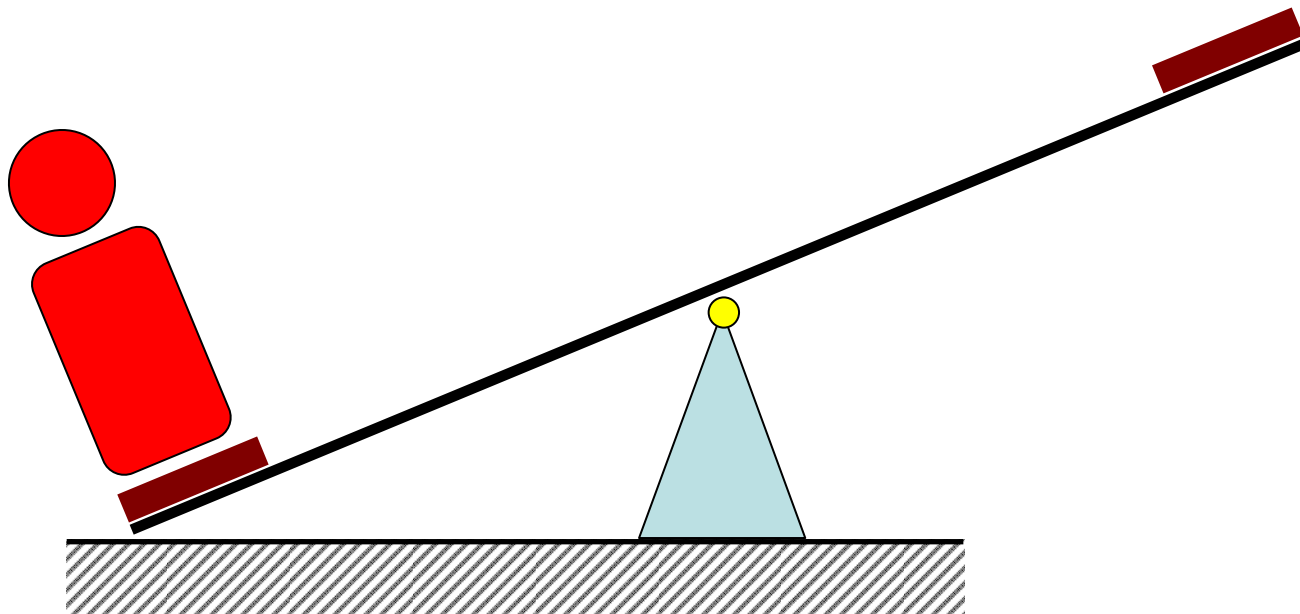
situation at
particle:



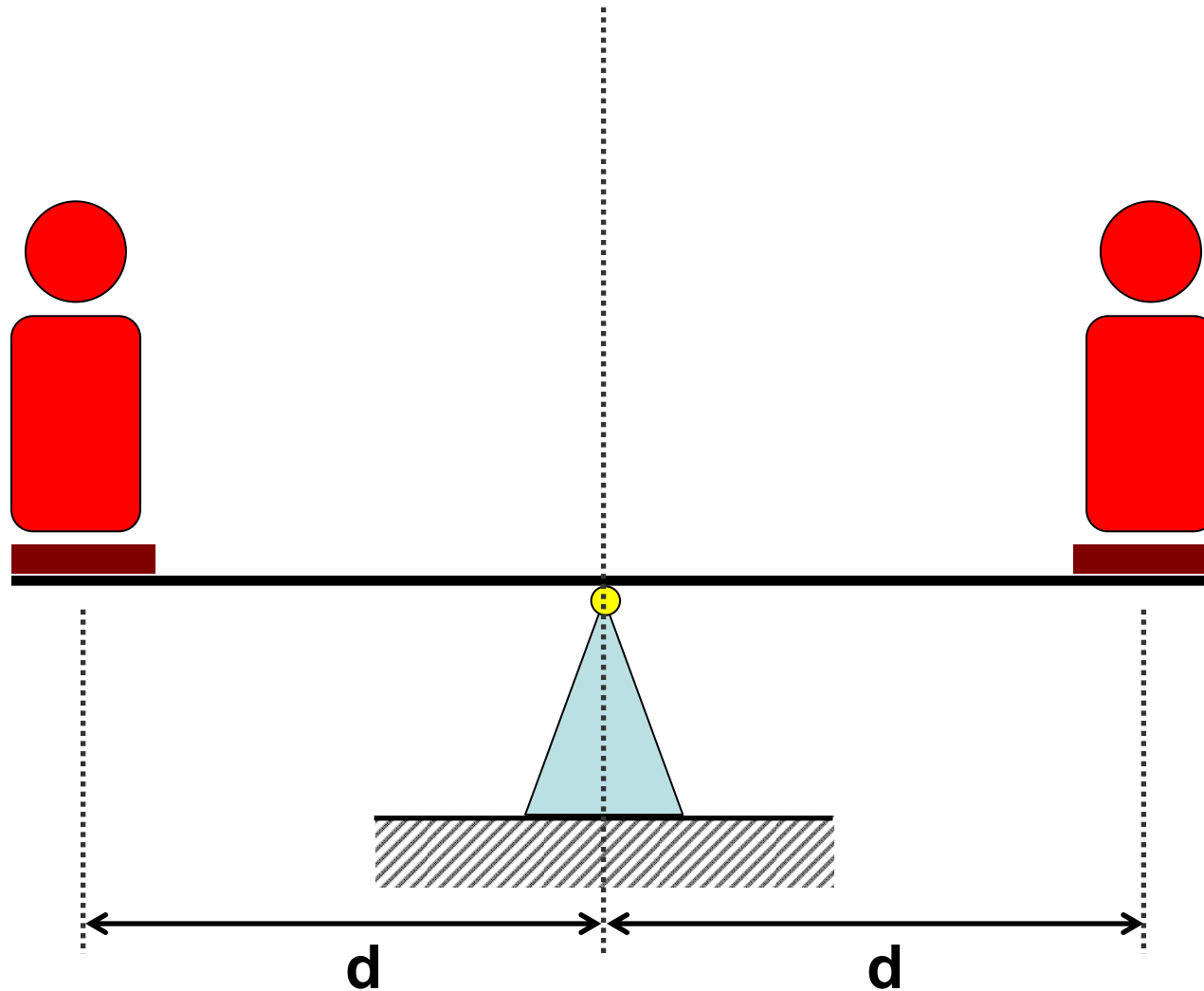


$$M = F \cdot d$$





Equilibrium!



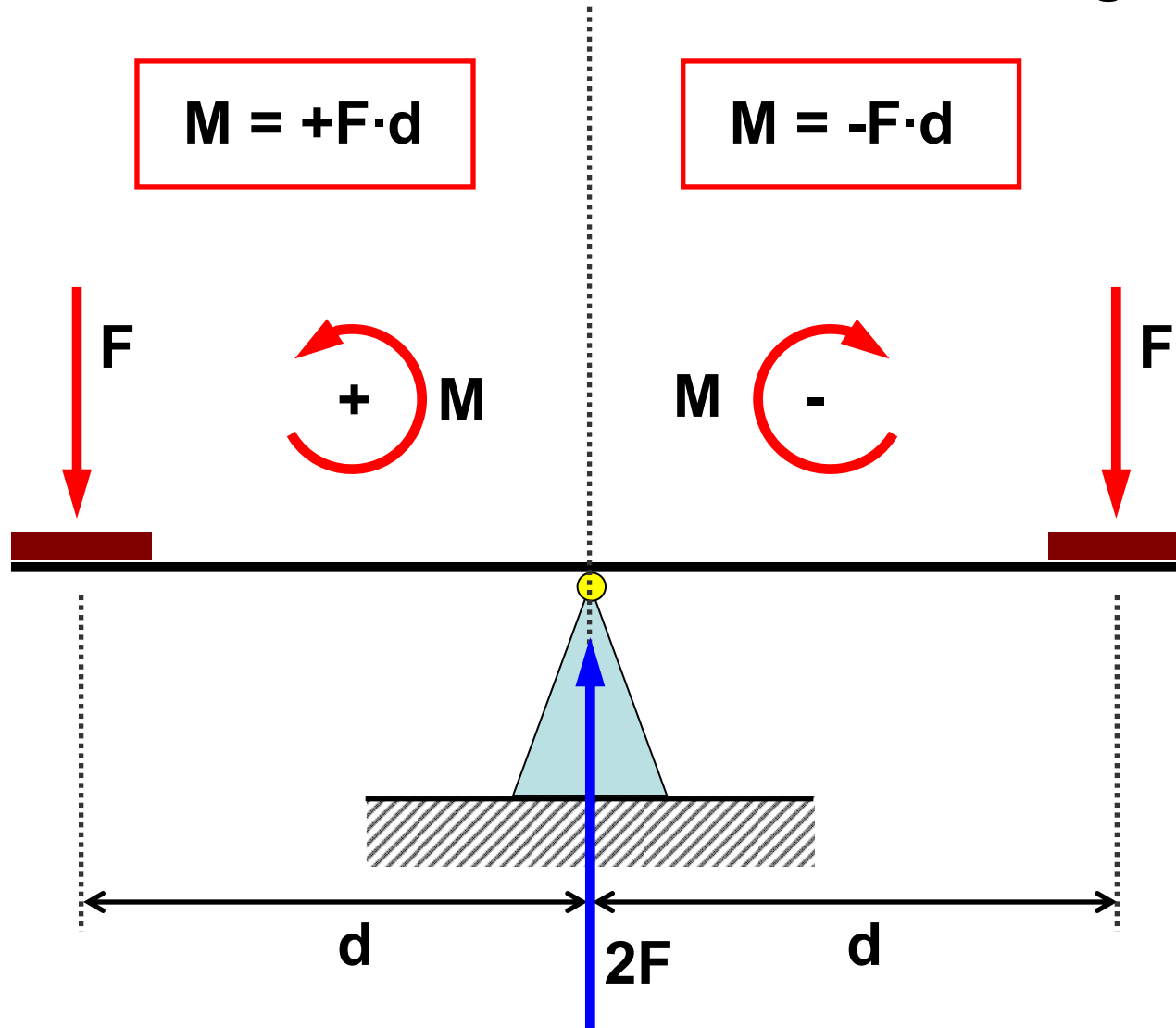
left side

Equilibrium!

right side

$$M = +F \cdot d$$

$$M = -F \cdot d$$



equilibrium conditions

$$R = \sum F = 0$$

$$\sum F_x = 0$$

$$\sum F_y = 0$$

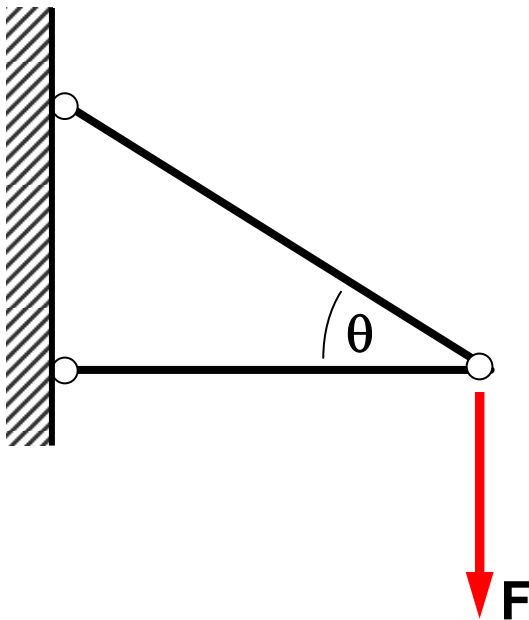
$$M = \sum M = 0$$

$$\sum M = 0$$



example 3.1 (equilibrium at particle)

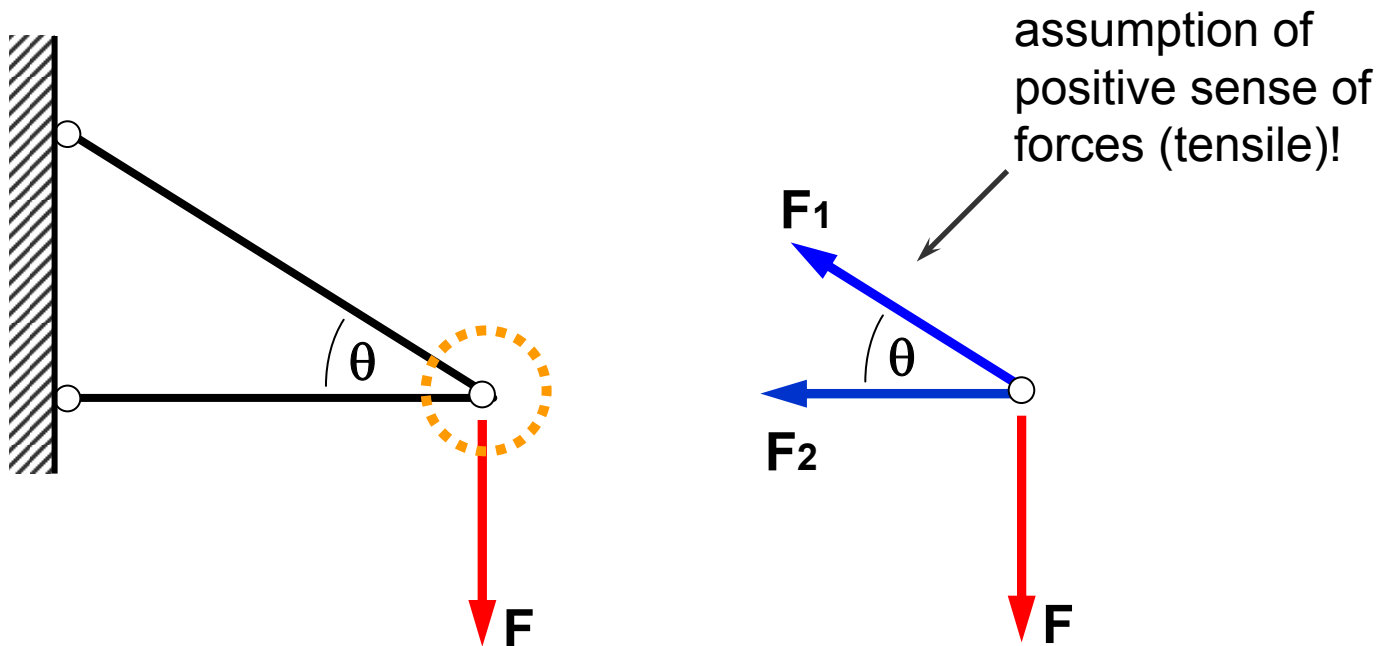
The support for a shop sign consists of two two-force-members that are attached to a wall. Determine the forces acting in the members if $F = 3 \text{ kN}$ and $\theta = 30^\circ$.



example 3.1 (equilibrium at particle)

The support for a shop sign consists of two two-force-members that are attached to a wall. Determine the forces acting in the members if $F = 3 \text{ kN}$ and $\theta = 30^\circ$.

Step 1: Isolation of Particle

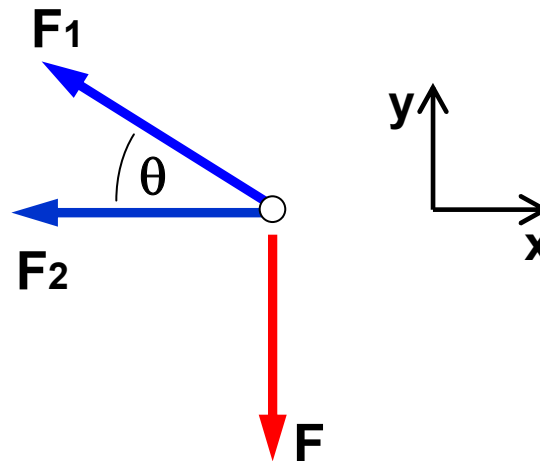
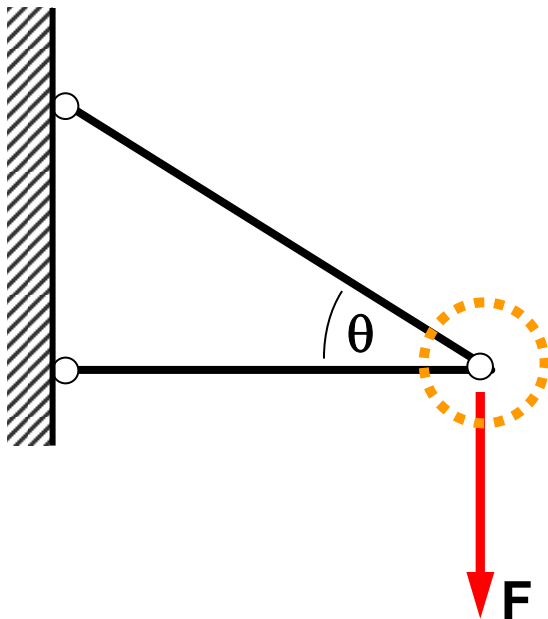


example 3.1 (equilibrium at particle)

The support for a shop sign consists of two two-force-members that are attached to a wall. Determine the forces acting in the members if $F = 3 \text{ kN}$ and $\theta = 30^\circ$.

Step 2: equilibrium conditions

$$\begin{aligned}\sum F_x &= 0 \\ \sum F_y &= 0 \\ \sum M &= 0\end{aligned}$$



example 3.1 (equilibrium at particle)

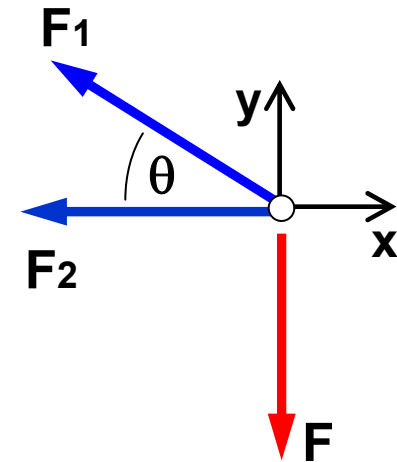
The support for a shop sign consists of two two-force-members that are attached to a wall. Determine the forces acting in the members if $F = 3 \text{ kN}$ and $\theta = 30^\circ$.

Step 2: equilibrium conditions

$$\sum F_x = 0 \quad (1) \quad : -F_2 - F_1 \cos\theta = 0$$

$$\sum F_y = 0$$

$$\sum M = 0$$



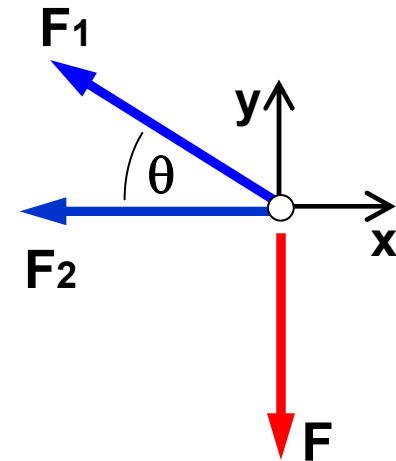
example 3.1 (equilibrium at particle)

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Step 2: equilibrium conditions

$$\sum F_x = 0 \quad (1) \quad : -F_2 - F_1 \cos\theta = 0$$

$$\sum F_y = 0 \quad (2) \quad : F_1 \sin\theta - F = 0 \rightarrow F_1 = F/\sin\theta$$
$$F_1 = 6.0 \text{ kN}$$



example 3.1 (equilibrium at particle)

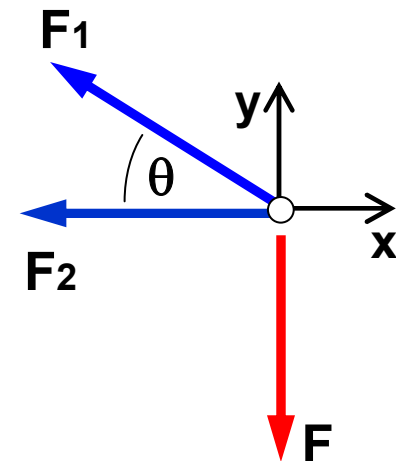
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$$(2) \text{ in } (1) : F_2 = -F_1 \cos\theta = -5.2 \text{ kN}$$



example 3.1 (equilibrium at particle)

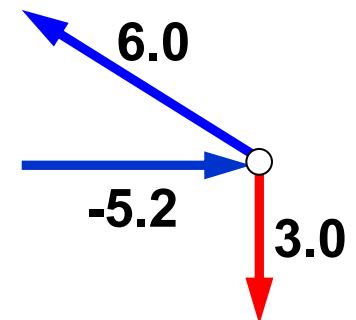
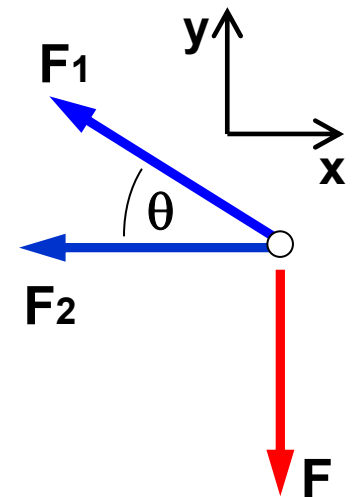
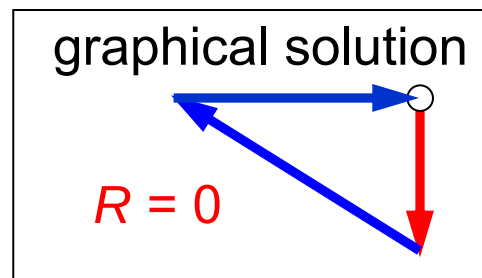
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Free body diagram

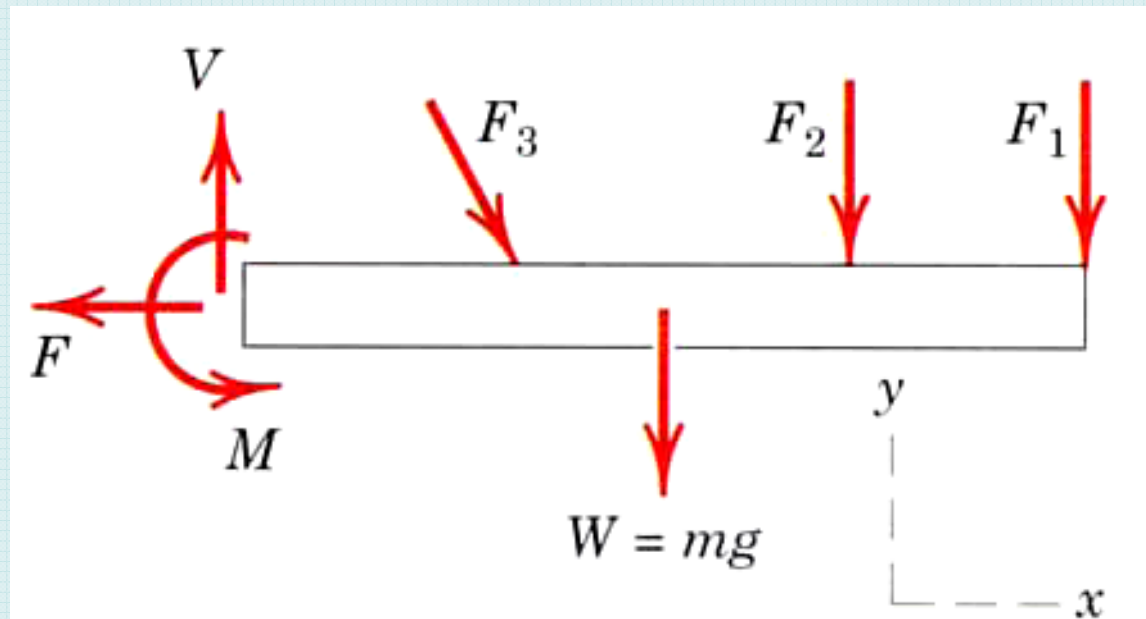


fig by J.L. Meriam, L.G. Kraige, Engineering Mechanics I



Free body diagram

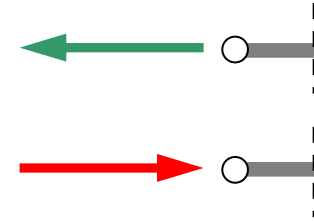
- **define the particular body and its system**
(boundary conditions, support)
- **isolate the body**
- **draw all possible external forces acting on it**
(action forces: known actions, weight, load concentrated / distributed
reaction forces: contact with other bodies / support)
- **choose coordinate system**



Free body diagram

- sign convention: assign arbitrarily the sense of force

e.g. tension: away from body
 compression: towards body



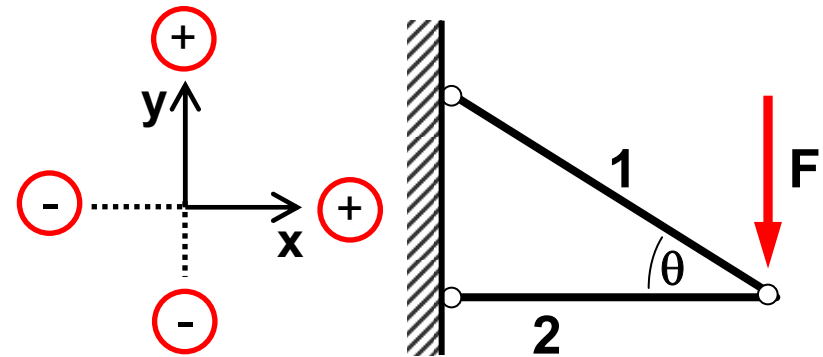
- solution: always follow the initial sense of the forces.
 apply the algebraic sign due to the sense of the force and the directions of the coord. system (right hand rule).

positive result: initial sense was correct
negative result: force acts in opposite sense

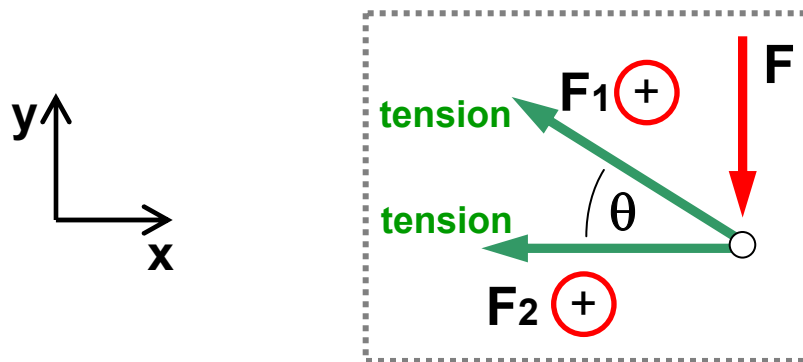


example on sign convention

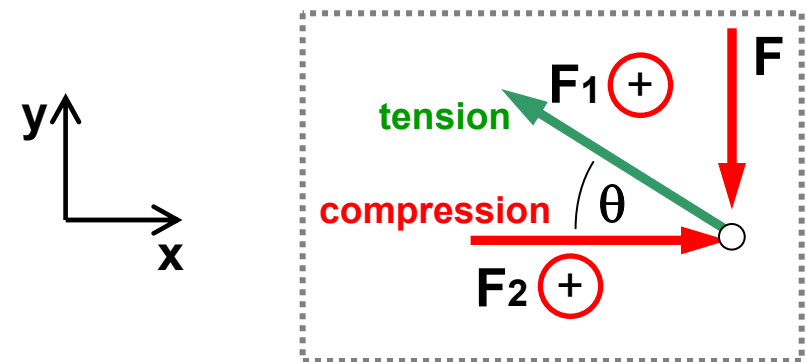
$F = 3 \text{ kN}$ and $\theta = 30^\circ$



Assumption: tensile forces in both members

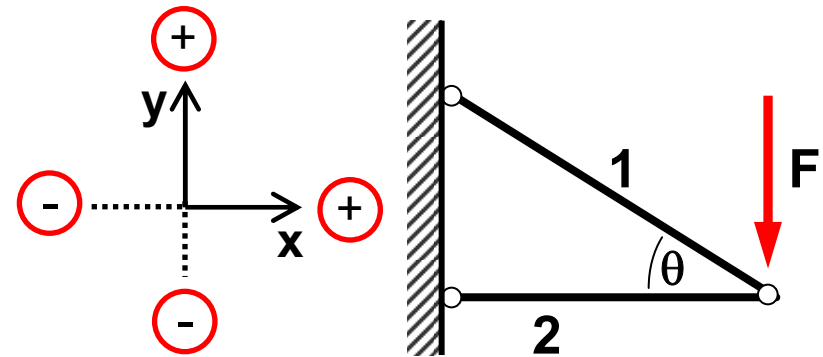


Sense of forces assigned due to estimation

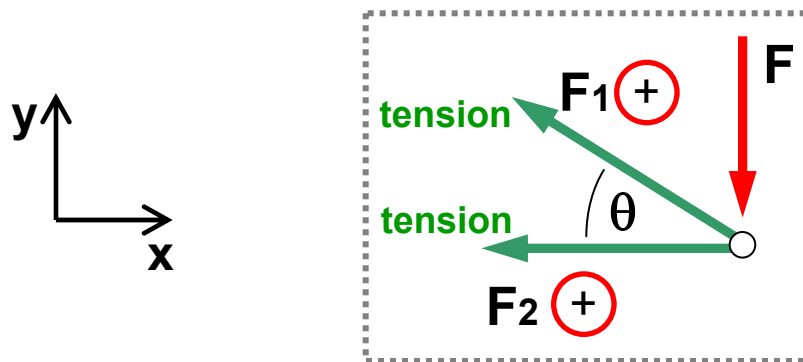


example on sign convention

$$F = 3 \text{ kN and } \theta = 30^\circ$$



Assumption: tensile forces in both members



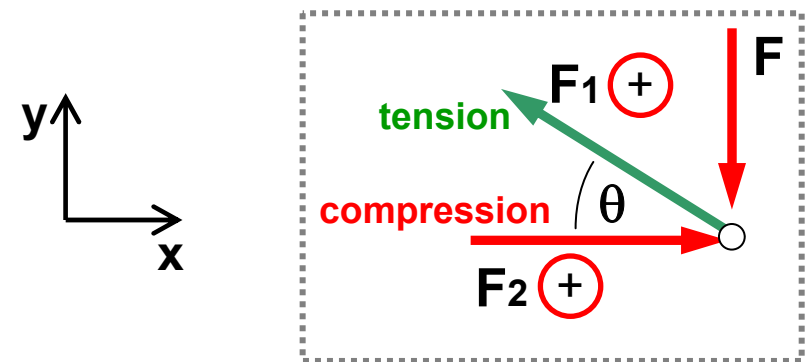
$$(1) \sum F_x = 0 : -F_2 - F_1 \cos \theta = 0$$

$$(2) \sum F_y = 0 : F_1 \sin \theta - F = 0 \quad \begin{matrix} F_1 = F / \sin \theta \\ F_1 = 6.0 \text{ kN} \end{matrix}$$

$$(1) \text{ in } (2) : F_2 = -F_1 \cos \theta = -5.2 \text{ kN}$$

Sense of F_2 opposite to its assignment.

Sense of forces assigned due to estimation



$$(1) \sum F_x = 0 : +F_2 - F_1 \cos \theta = 0$$

$$(2) \sum F_y = 0 : F_1 \sin \theta - F = 0 \quad \begin{matrix} F_1 = F / \sin \theta \\ F_1 = 6.0 \text{ kN} \end{matrix}$$

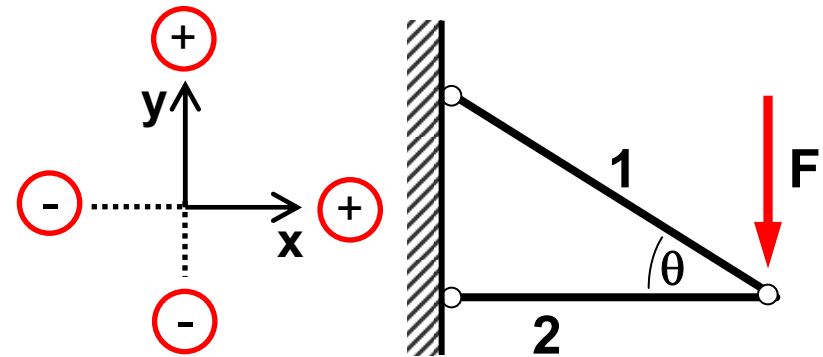
$$(1) \text{ in } (2) : F_2 = +F_1 \cos \theta = +5.2 \text{ kN}$$

Initial sense of both forces correct.

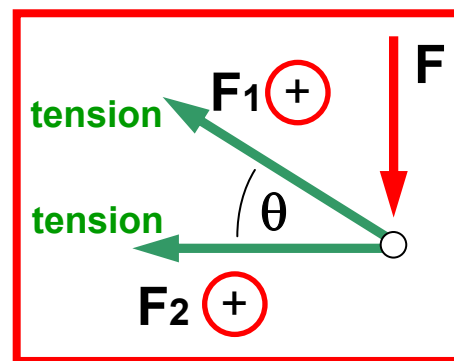


example on sign convention

$$F = 3 \text{ kN and } \theta = 30^\circ$$



Assumption: tensile forces in both members



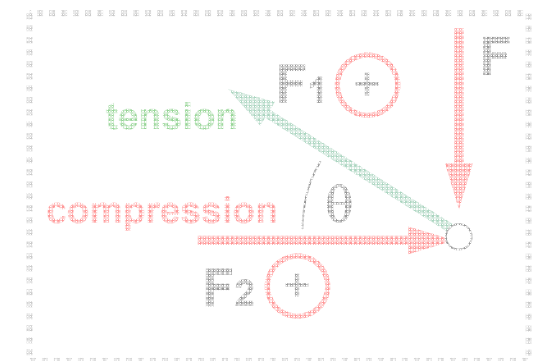
Convenient approach:

- a positive result always indicates a **tensile** force
- a negative result always indicates a **compressive** force

(+)

(-)

Sense of forces assigned due to estimation



$$(1) \sum F_x = 0 : +F_2 - F_1 \cos \theta = 0$$

$$(2) \sum F_y = 0 : F_1 \sin \theta - F = 0 \quad F_1 = F / \sin \theta$$

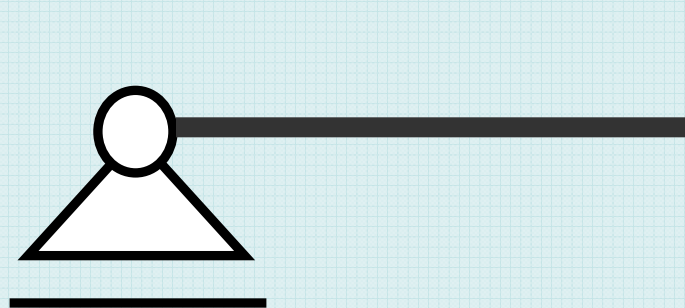
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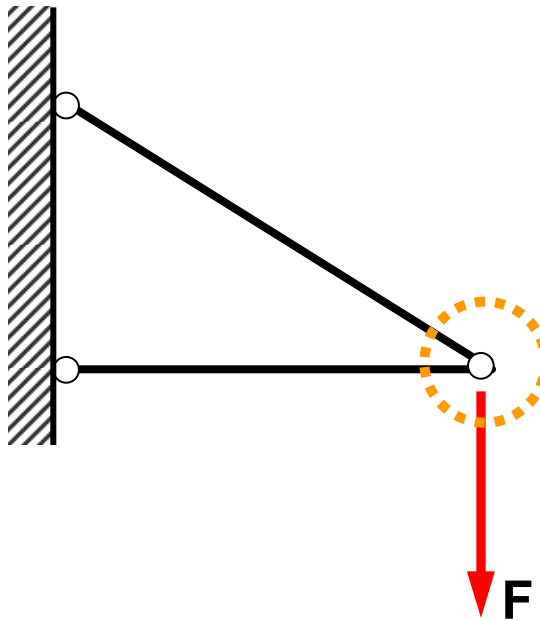
Initial sense of both forces correct.



Connections and Supports



Hinge Connection – free rotation





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Free body diagram

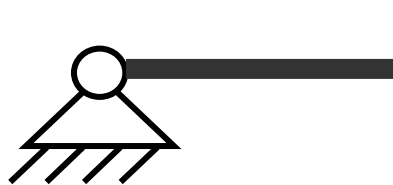
Types of Supports

roller



1 support reaction

pin



2 support reactions

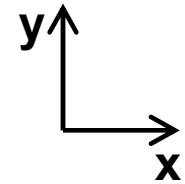
fixed



3 support reactions



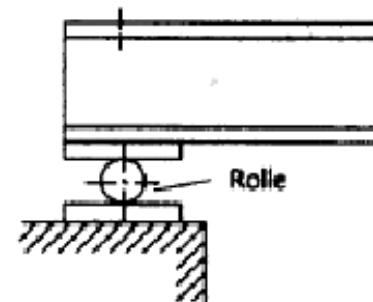
Roller Support – 1 Reaction Force F_y



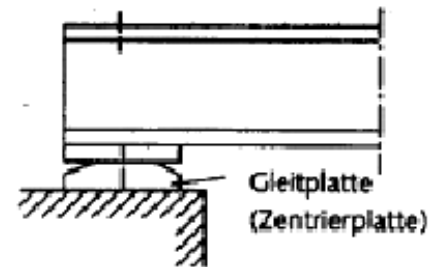
symbol



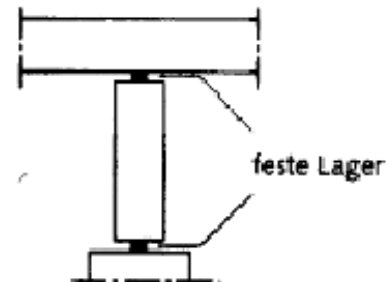
Konstruktive Ausbildung



Rollenlager

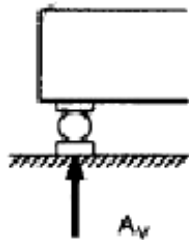


Gleitplattenlager

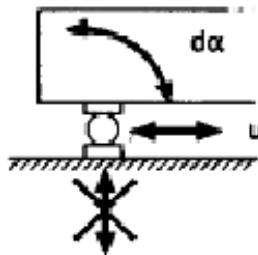


Pendelstütze

1 possible reaction forces



2 degrees of freedom





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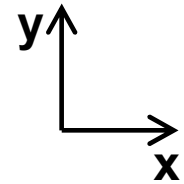


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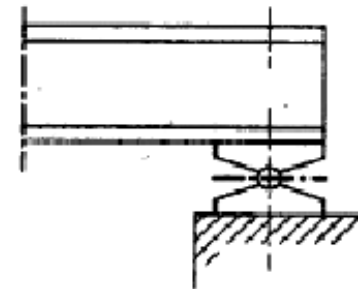
Pin Connection – 2 Reaction Forces F_x , F_y



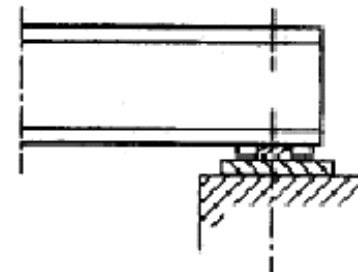
symbol



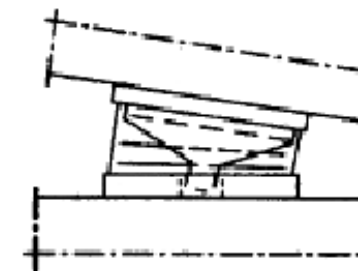
Konstruktive Ausbildung



Auflager mit
Zentrierwalze

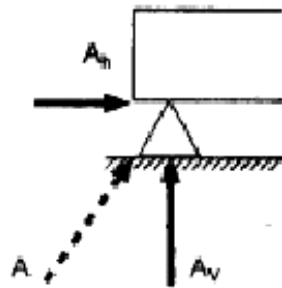


Auflager mit
Zentrierleiste

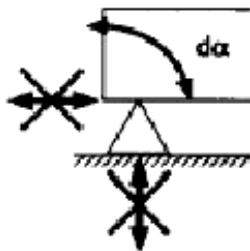


Elastomerlager mit
Zentrierbolzen

2 possible reaction forces



1 degree of freedom





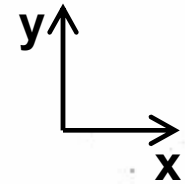
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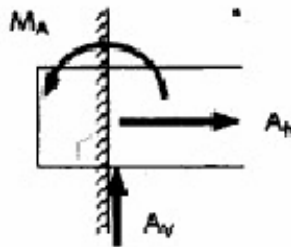
Fixed Support – 3 Reactions F_x , F_y , M



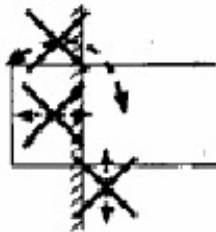
symbol



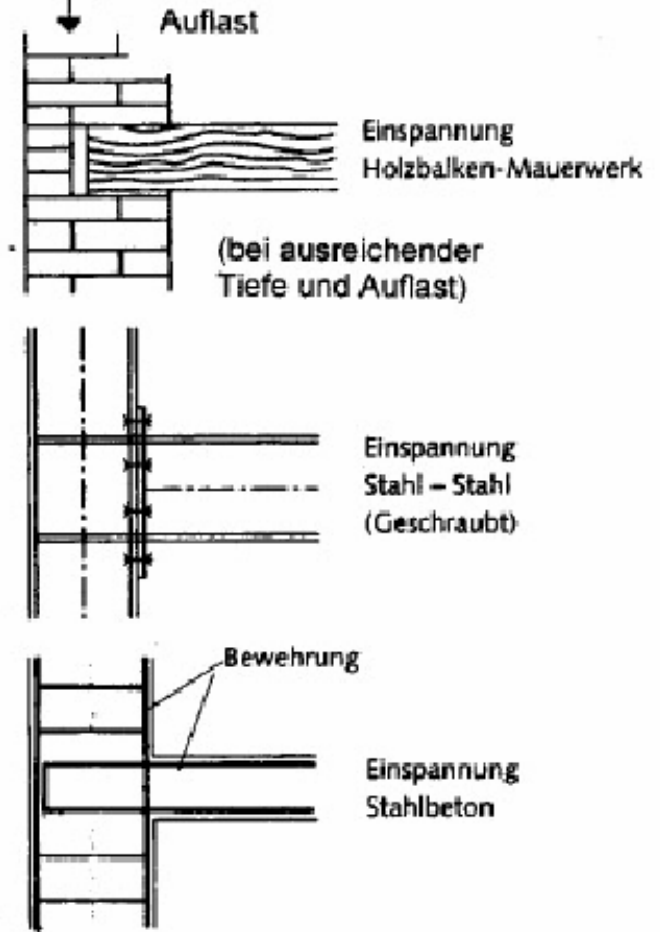
3 possible reaction forces



0 degrees of freedom

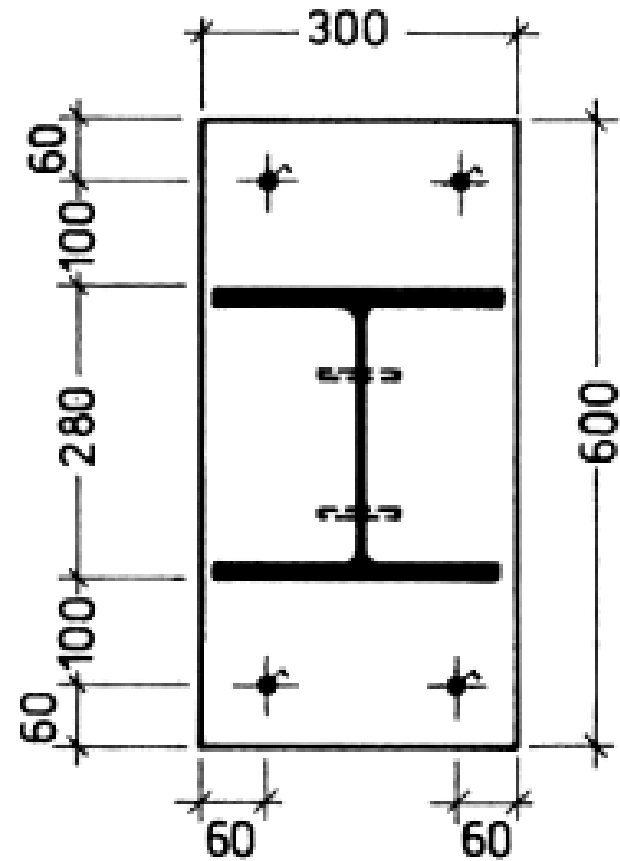
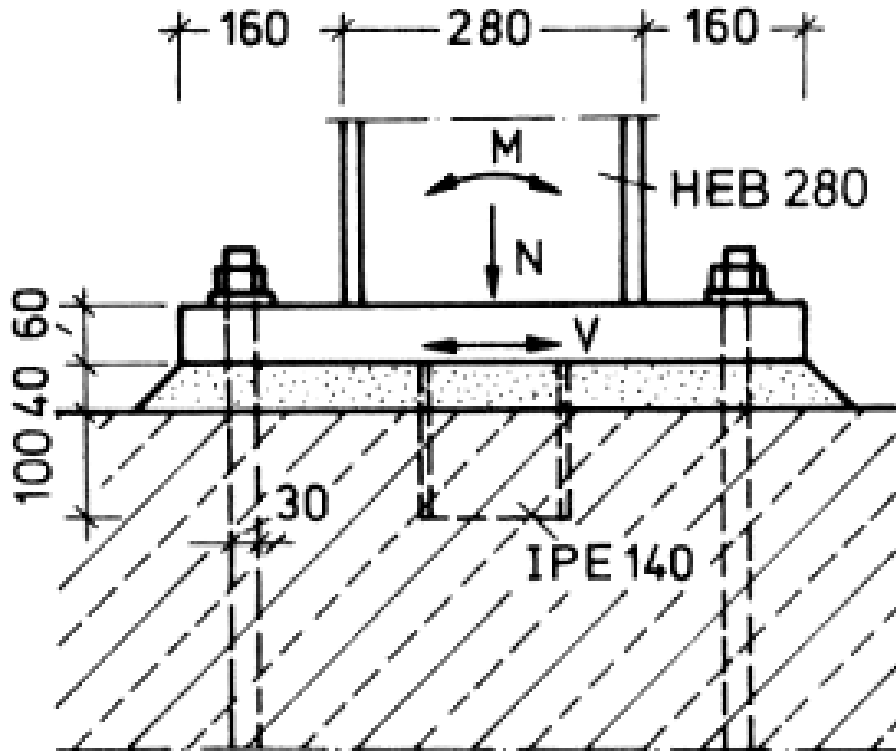


Konstruktive Ausbildung





Fixed Foot Support of Steel Column





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Free body diagram – Boundary Conditions

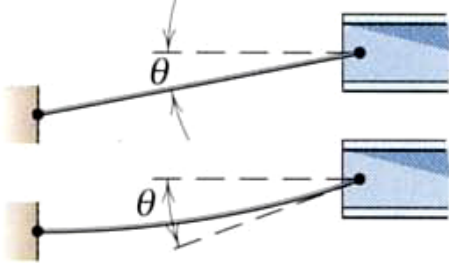
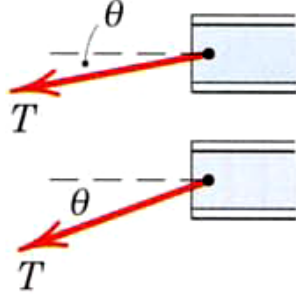
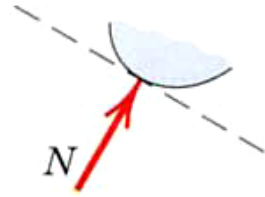
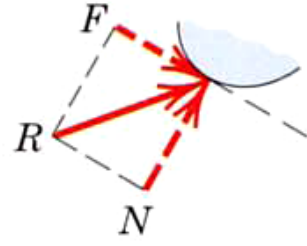
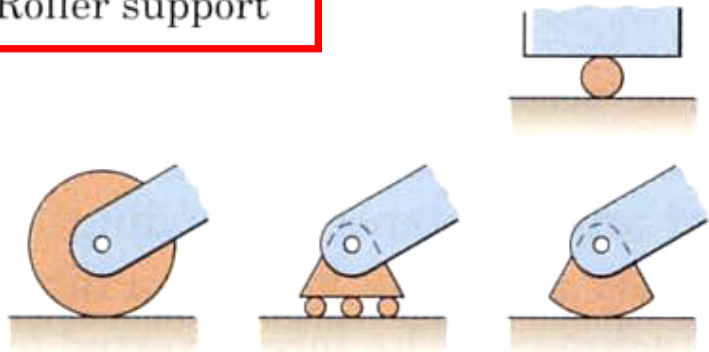
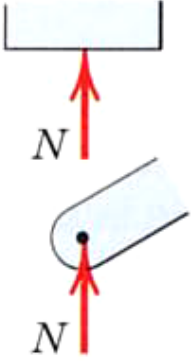
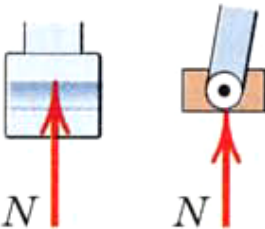
Type of Contact and Force Origin	Action on Body to Be Isolated
1. Flexible cable, belt, chain, or rope Weight of cable negligible Weight of cable not negligible 	 Force exerted by a flexible cable is always a tension away from the body in the direction of the cable.
2. Smooth surfaces 	 Contact force is compressive and is normal to the surface.
3. Rough surfaces 	 Rough surfaces are capable of supporting a tangential component F (frictional force) as well as a normal component N of the resultant contact force R.

fig by J.L. Meriam, L.G. Kraige, Engineering Mechanics I



Free body diagram – Boundary Conditions

4. Roller support 	 Roller, rocker, or ball support transmits a compressive force normal to the supporting surface.
5. Freely sliding guide 	 Collar or slider free to move along smooth guides; can support force normal to guide only.

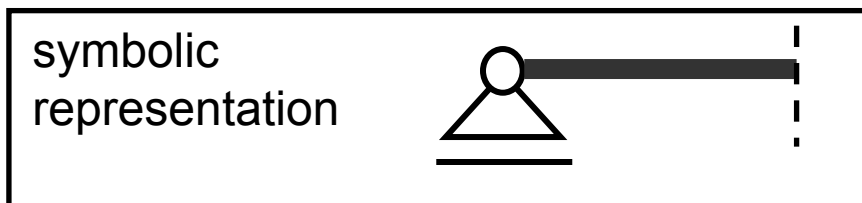


fig by J.L. Meriam, L.G. Kraige, Engineering Mechanics I



Free body diagram – Boundary Conditions

Type of Contact and Force Origin	Action on Body to Be Isolated
6. Pin connection symbolic representation	Pin free to turn A freely hinged pin connection is capable of supporting a force in any direction in the plane normal to the axis; usually shown as two components R_x and R_y.
7. Built-in or fixed support symbolic representation	A built-in or fixed support is capable of supporting an axial force F, a transverse force V (shear force), and a couple M (bending moment) to prevent rotation.

fig by J.L. Meriam, L.G. Kraige, Engineering Mechanics I



Free body diagram – Boundary Conditions

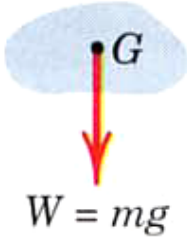
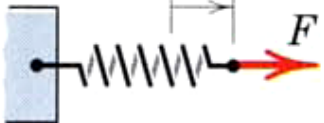
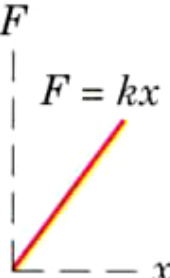
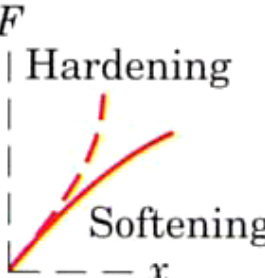
8. Gravitational attraction 	The resultant of gravitational attraction on all elements of a body of mass m is the weight $W = mg$ and acts toward the center of the earth through the center mass G. 
9. Spring action  Linear  $F = kx$ Nonlinear  Hardening Softening	Spring force is tensile if spring is stretched and compressive if compressed. For a linearly elastic spring the stiffness k is the force required to deform the spring a unit distance. 

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examples of free body diagrams



examples of free body diagrams

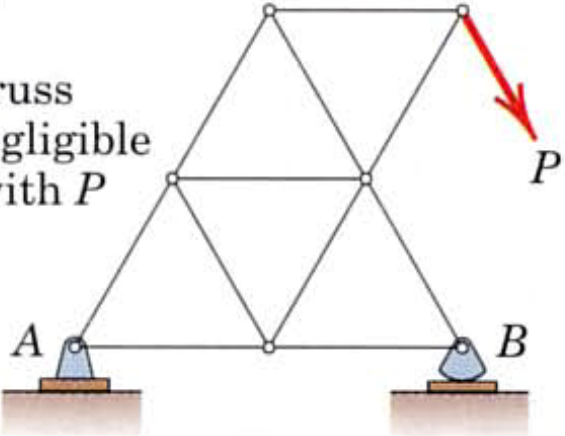
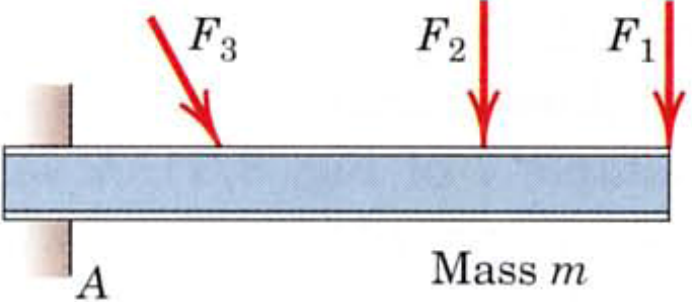
Mechanical System	Free-Body Diagram of Isolated Body
1. Plane truss Weight of truss assumed negligible compared with P 	
2. Cantilever beam 	

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examples of free body diagrams

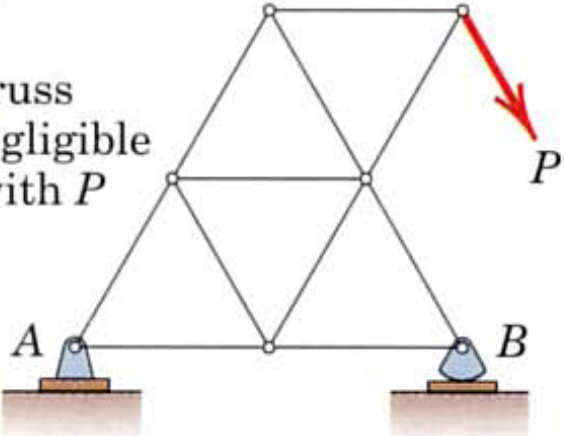
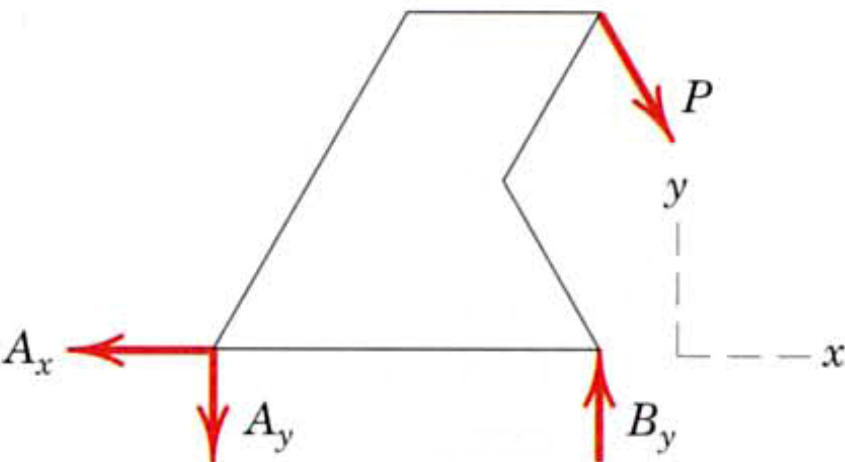
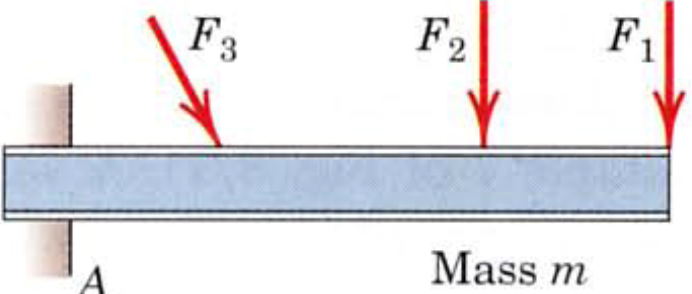
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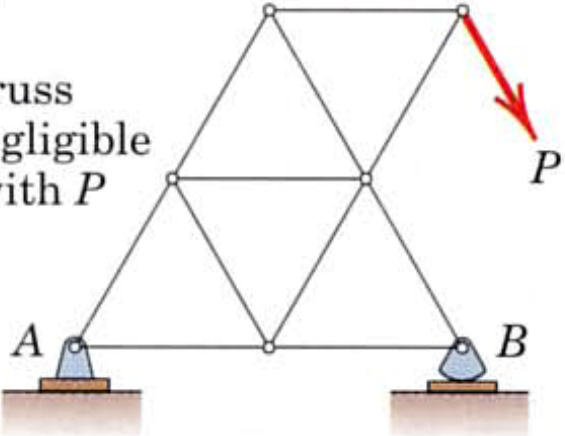
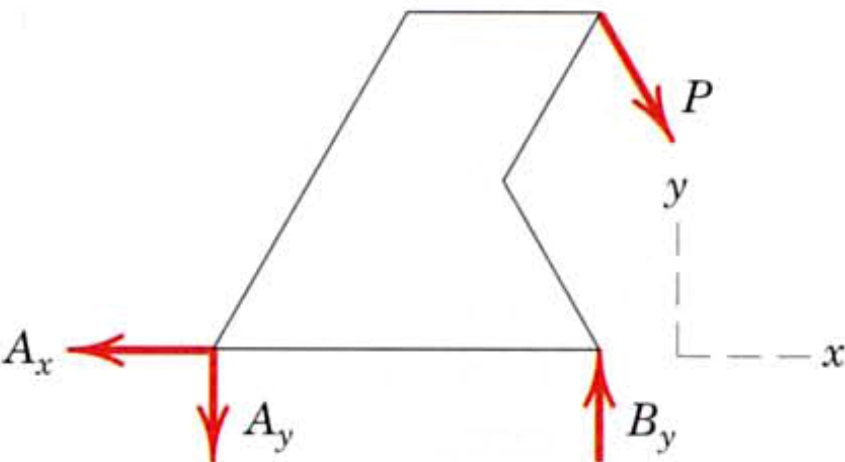
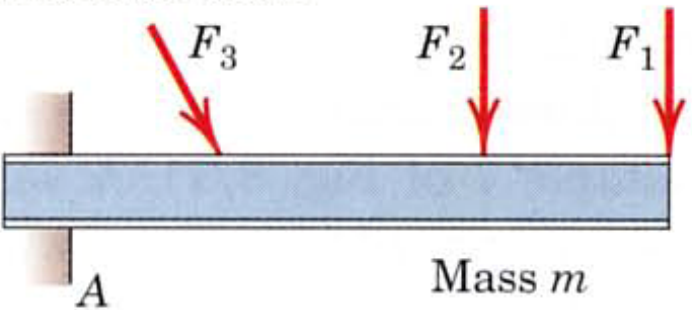
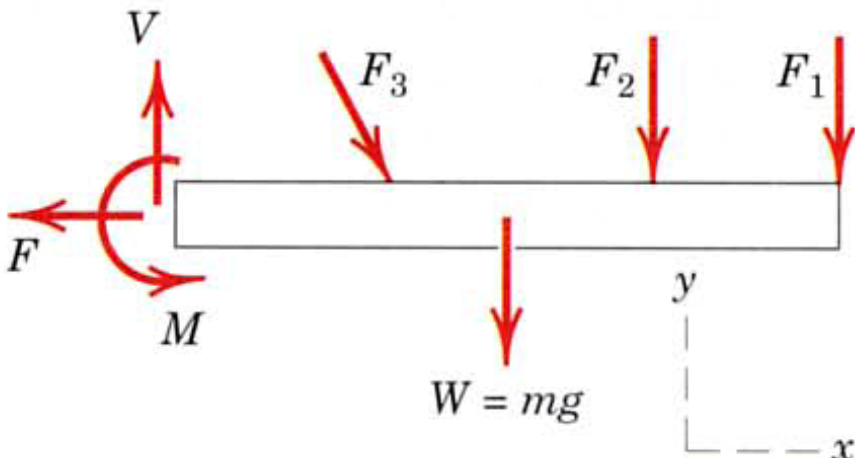
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examples of free body diagrams

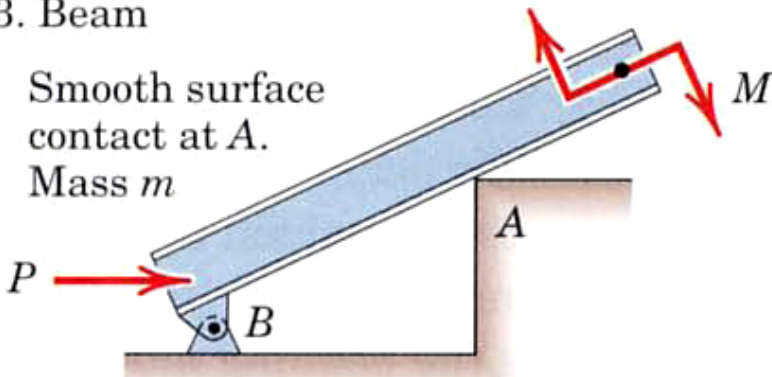
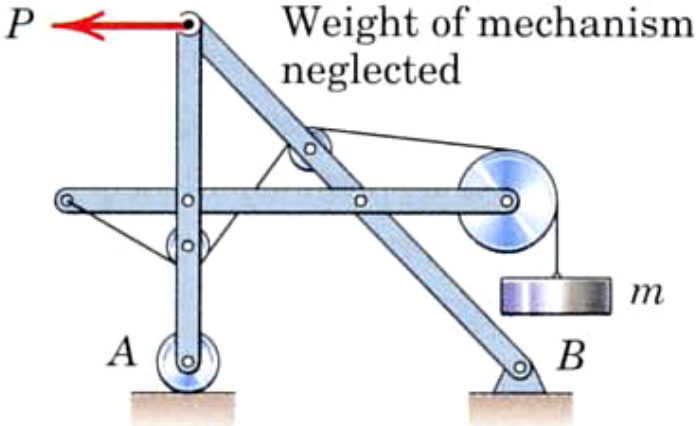
Mechanical System	Free-Body Diagram of Isolated Body
3. Beam Smooth surface contact at A. Mass m 	
4. Rigid system of interconnected bodies analyzed as a single unit Weight of mechanism neglected 	

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examples of free body diagrams

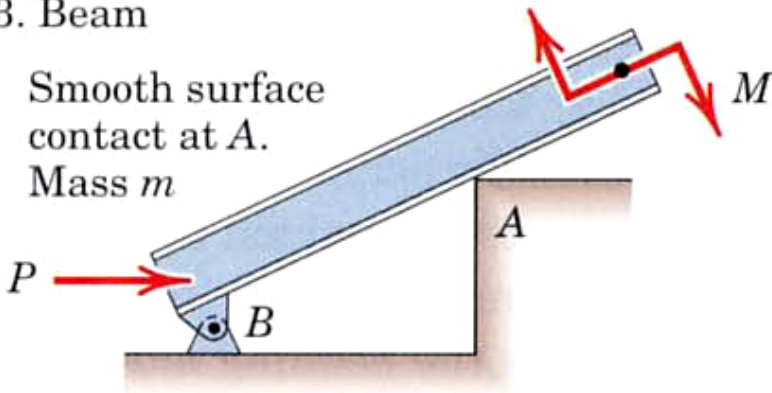
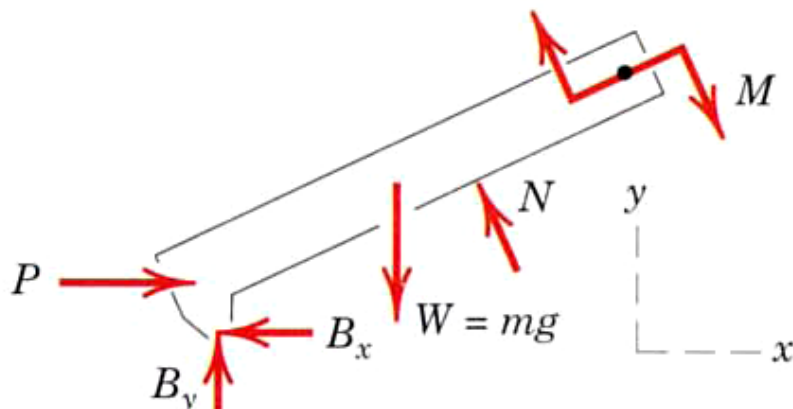
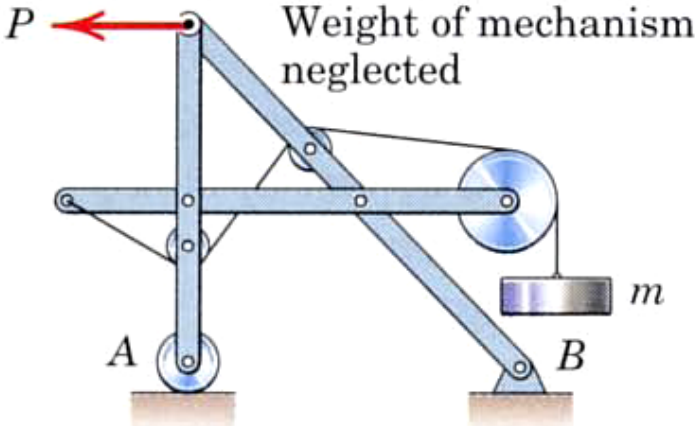
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examples of free body diagrams

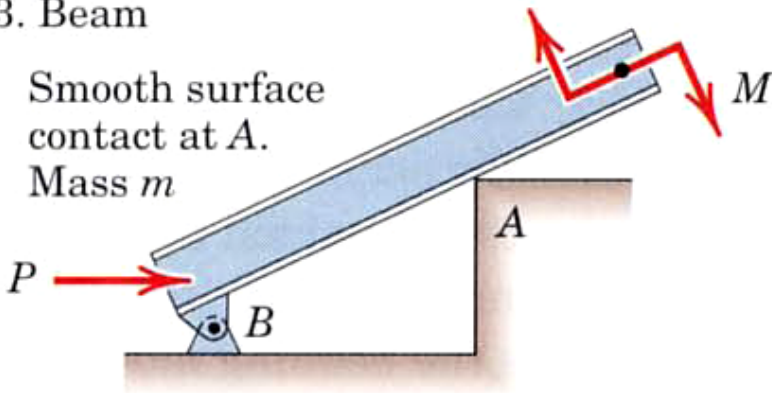
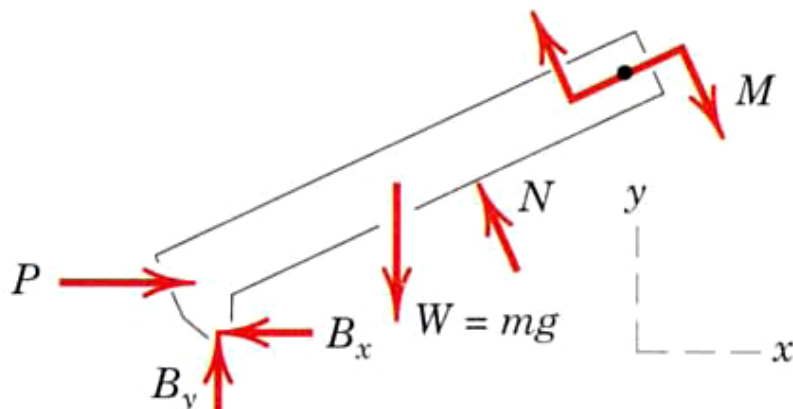
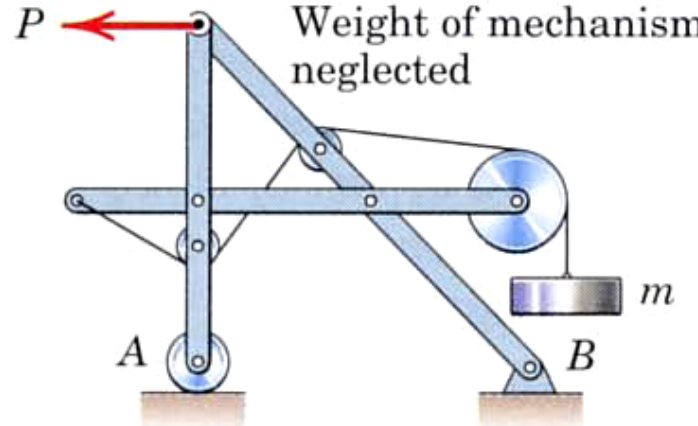
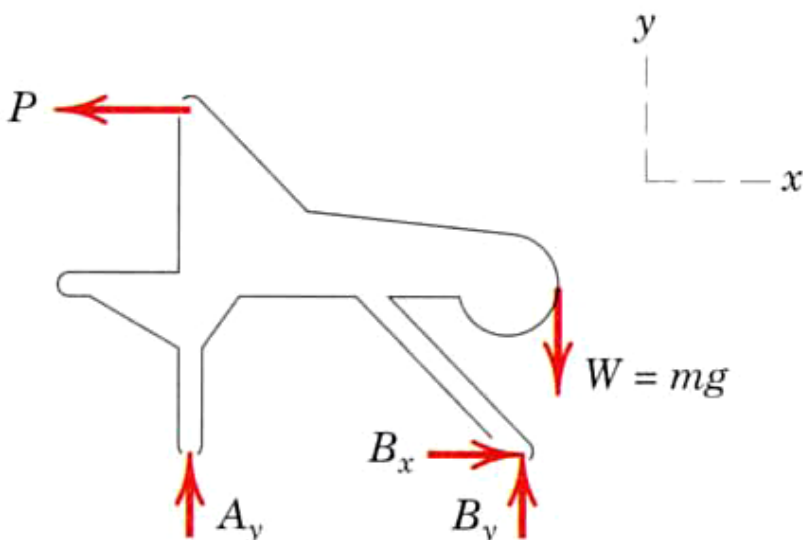
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examples of free body diagrams

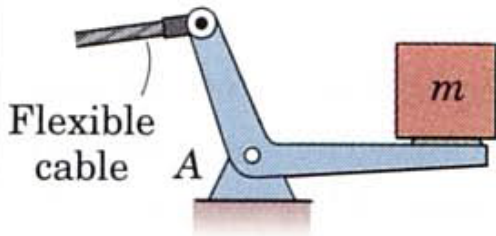
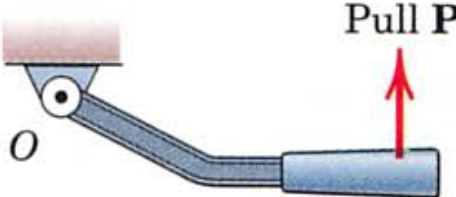
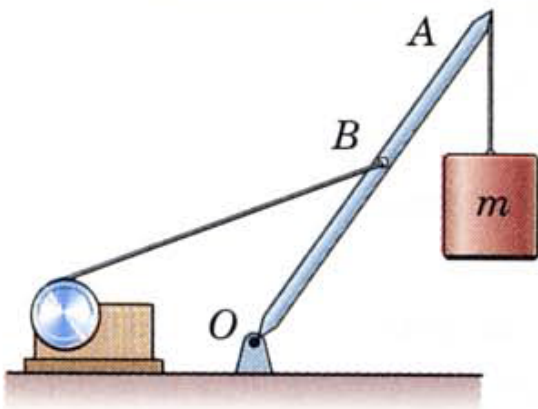
	Body	<i>FBD</i>
1. Bell crank supporting mass m with pin support at A .		
2. Control lever applying torque to shaft at O .		
3. Boom OA , of negligible mass compared with mass m . Boom hinged at O and supported by hoisting cable at B .		

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examples of free body diagrams

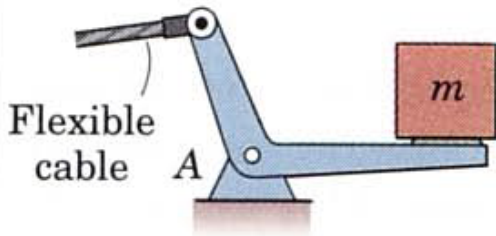
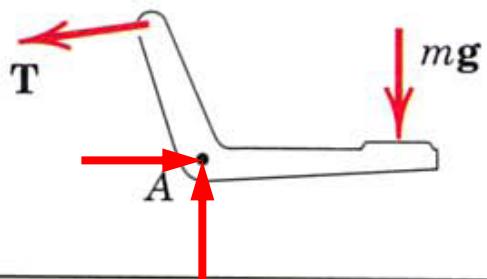
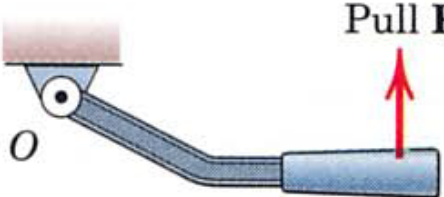
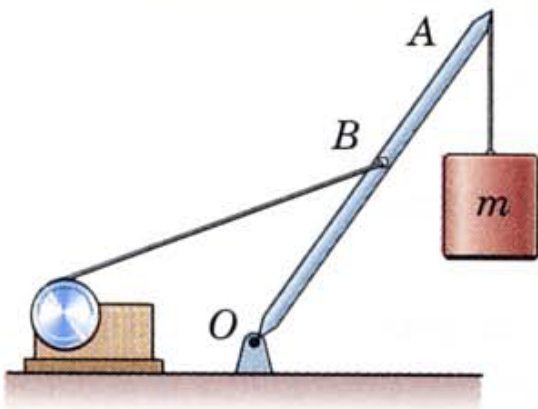
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examples of free body diagrams

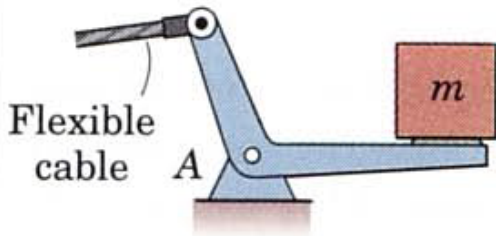
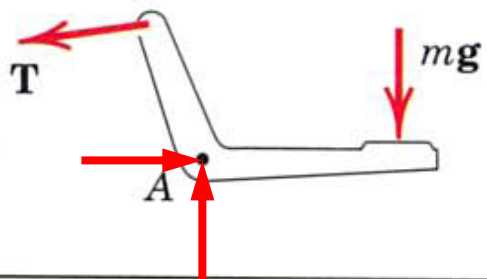
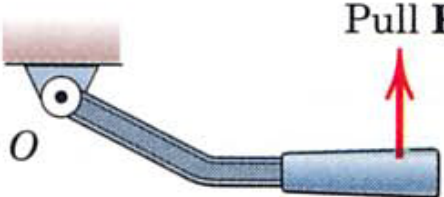
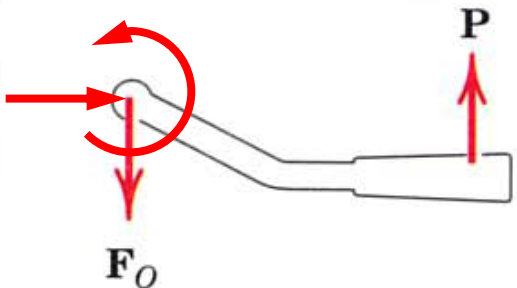
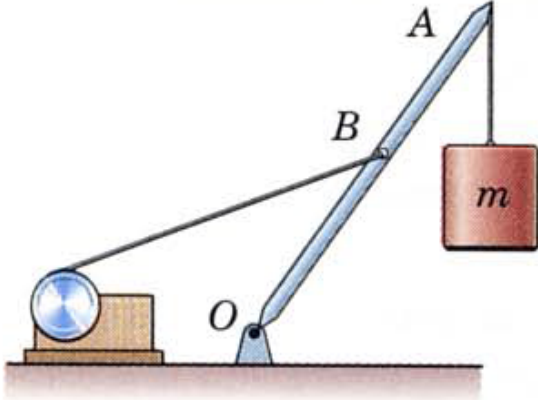
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examples of free body diagrams

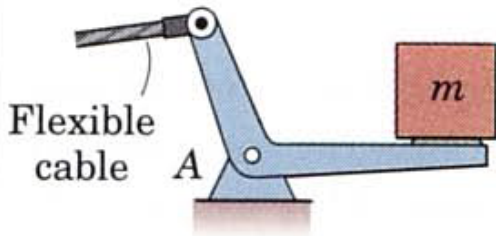
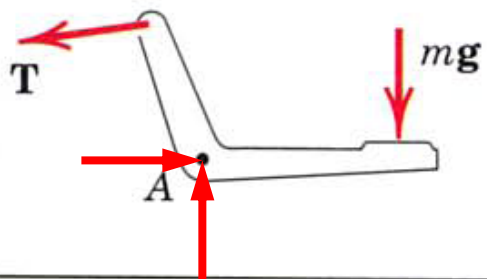
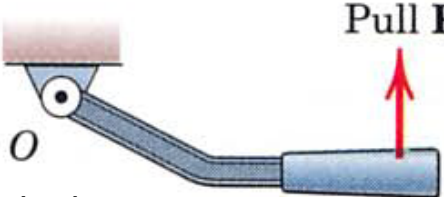
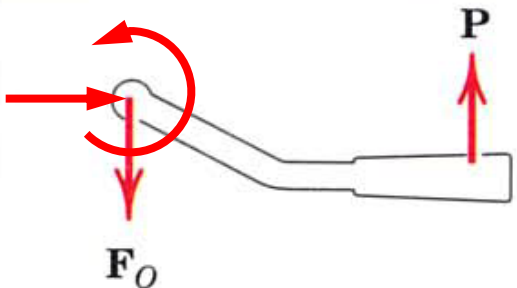
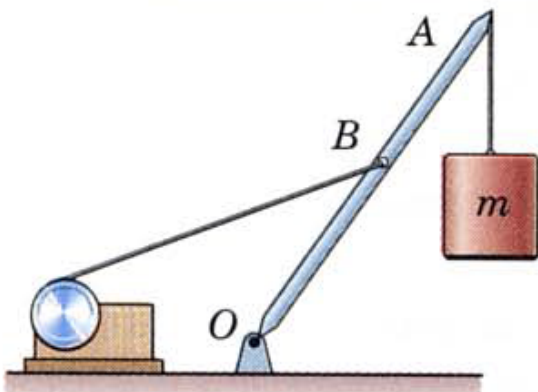
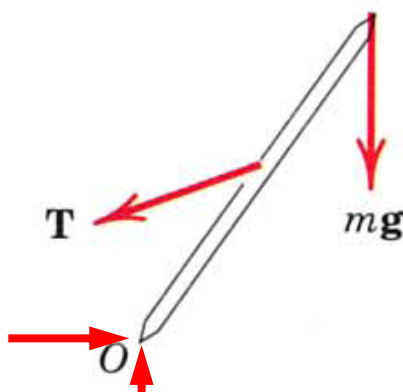
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examples of free body diagrams

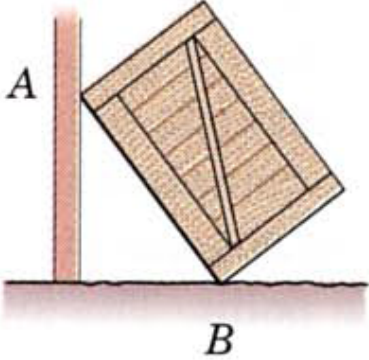
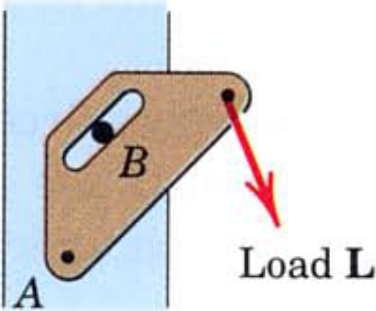
4. Uniform crate of mass m leaning against smooth vertical wall and supported on a rough horizontal surface.	 The diagram shows a rectangular crate with diagonal hatching, representing its internal structure. It is leaning against a smooth vertical wall on the left, with the point of contact labeled 'A'. The bottom of the crate rests on a rough horizontal surface, with the point of contact labeled 'B'. The wall is represented by a vertical line, and the surface by a horizontal line with a slightly irregular texture at the contact point B.	
5. Loaded bracket supported by pin connection at A and fixed pin in smooth slot at B.	 The diagram shows a bracket with a curved shape. It is supported by a pin connection at point A, which is located at the bottom left. At point B, there is a fixed pin in a smooth slot, which is represented by a vertical line. A red arrow labeled 'Load L' points downwards from the right side of the bracket, indicating the direction of the applied force.	

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examples of free body diagrams

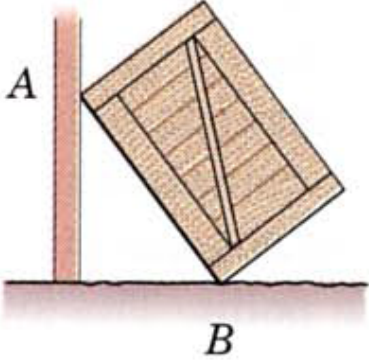
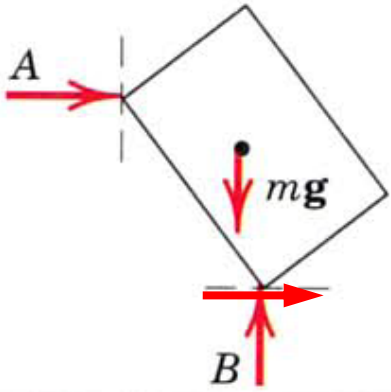
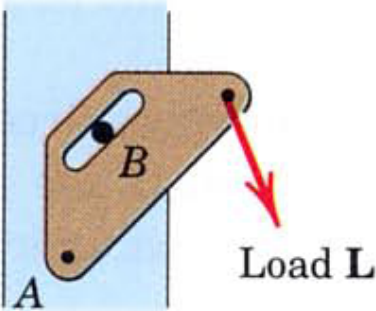
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examples of free body diagrams

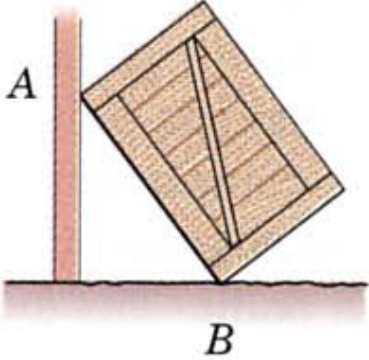
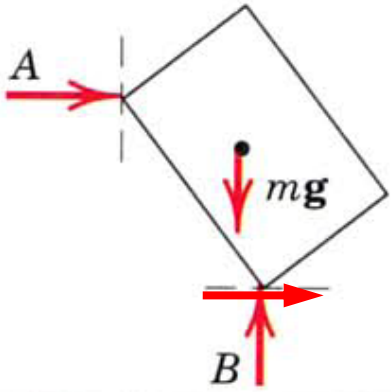
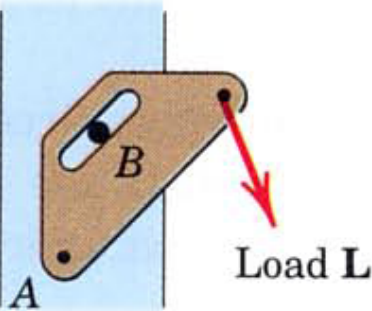
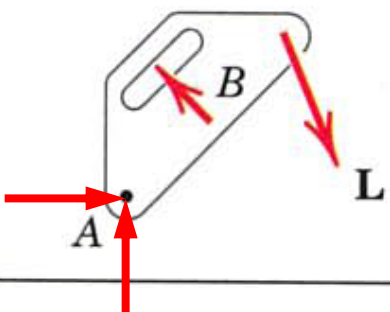
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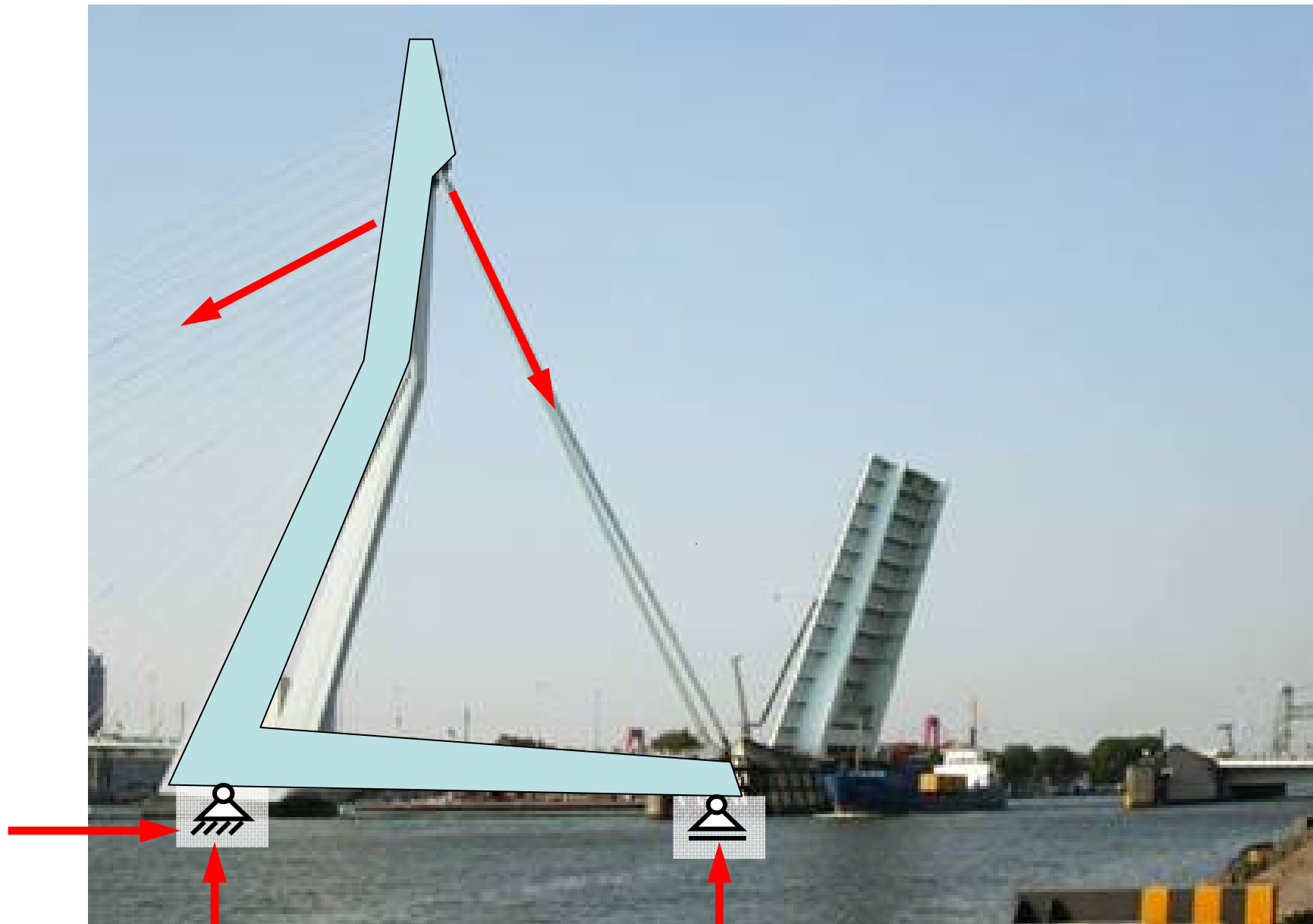




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General equilibrium conditions

$$R = \sum F = 0$$

$$\sum F_x = 0$$

$$\sum F_y = 0$$

$$M = \sum M = 0$$

$$\sum M = 0$$

**three equations for three unknown variables
(forces) for statically determinate systems!**



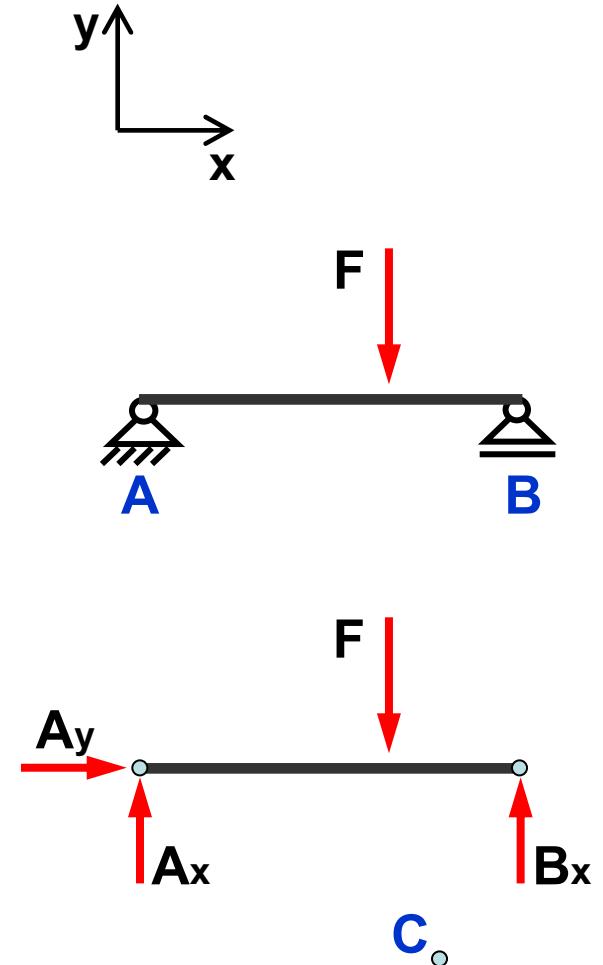
Alternative equilibrium conditions

$$\sum F_x = 0 \quad \sum F_y = 0 \quad \sum M_A = 0$$

$$\sum F_x = 0 \quad \sum M_A = 0 \quad \sum M_B = 0$$

$$\sum F_y = 0 \quad \sum M_A = 0 \quad \sum M_B = 0$$

$$\sum M_A = 0 \quad \sum M_B = 0 \quad \sum M_C = 0$$



examples



example 3.2

Determine the tension T in the supporting cable and the reaction force on pin A for the jib crane. Beam AB is a standard I-beam with a weight of 93.2 N per meter of length.

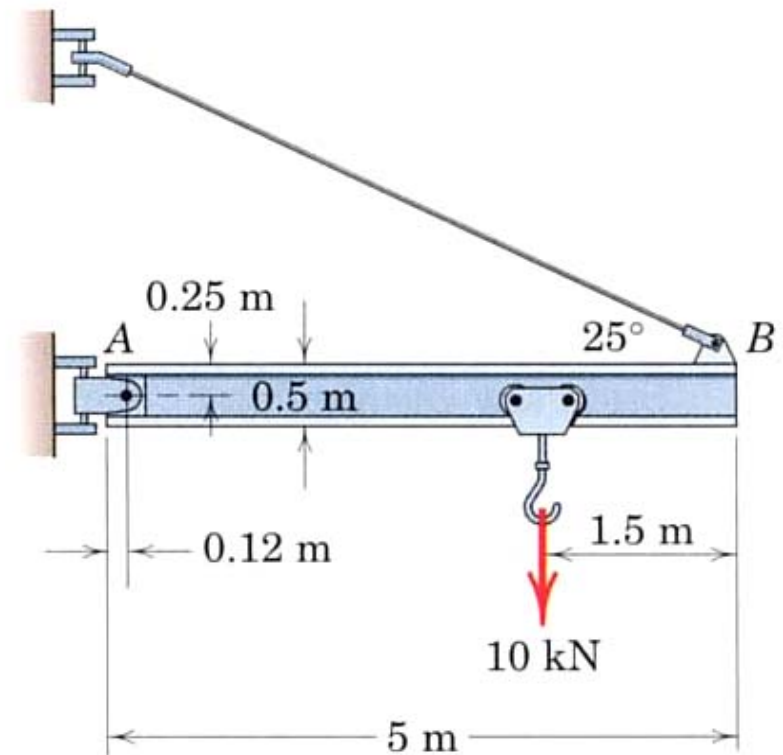


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example 3.2

Determine the tension T in the supporting cable and the reaction force on pin A for the jib crane. Beam AB is a standard I-beam with a weight of 93.2 N per meter of length.

Weight of Beam: $93.2 \text{ N} \cdot 5 \text{ m} = 4.66 \text{ kN}$

Free Body diagram:

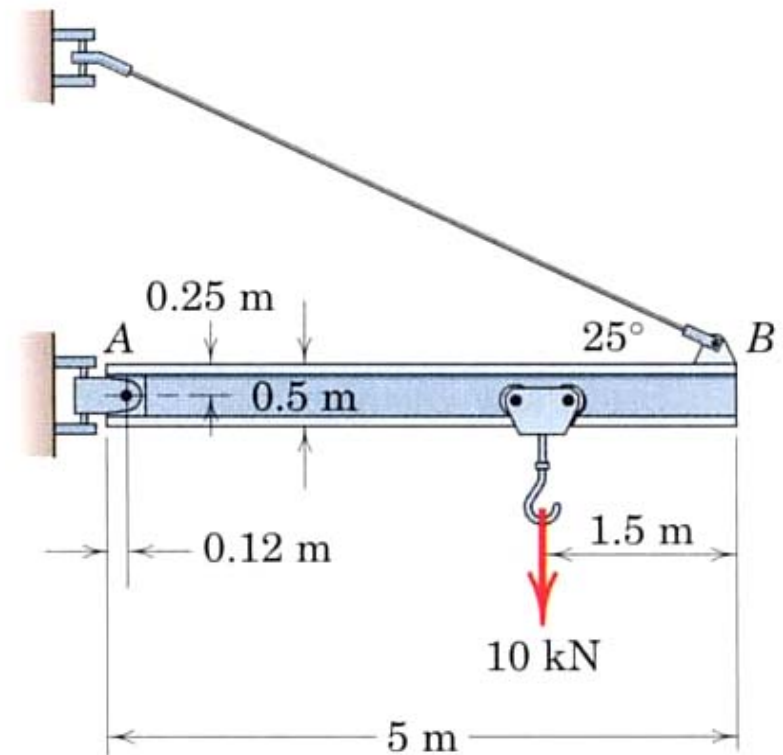


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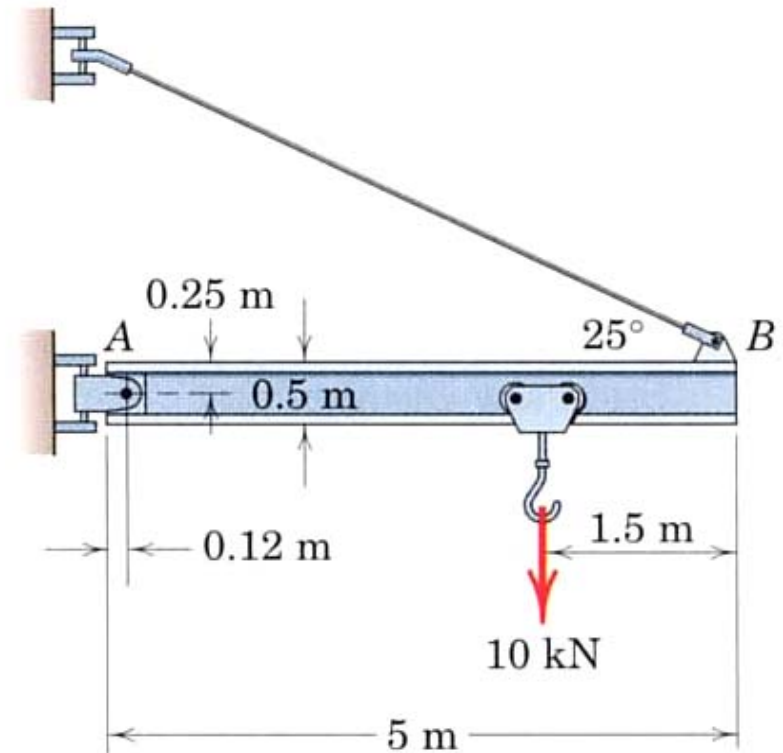
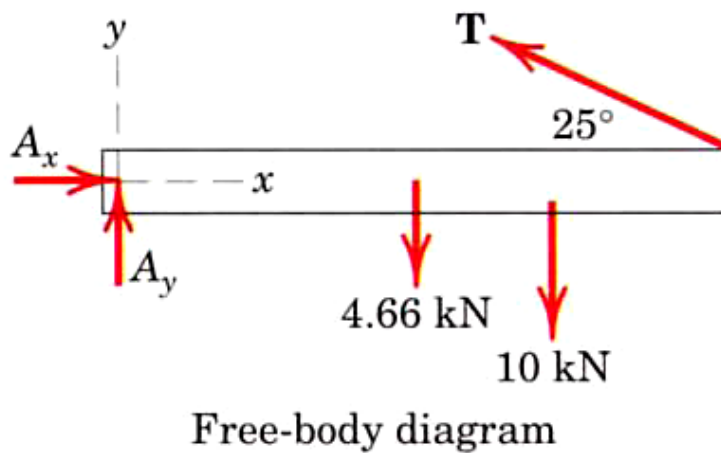


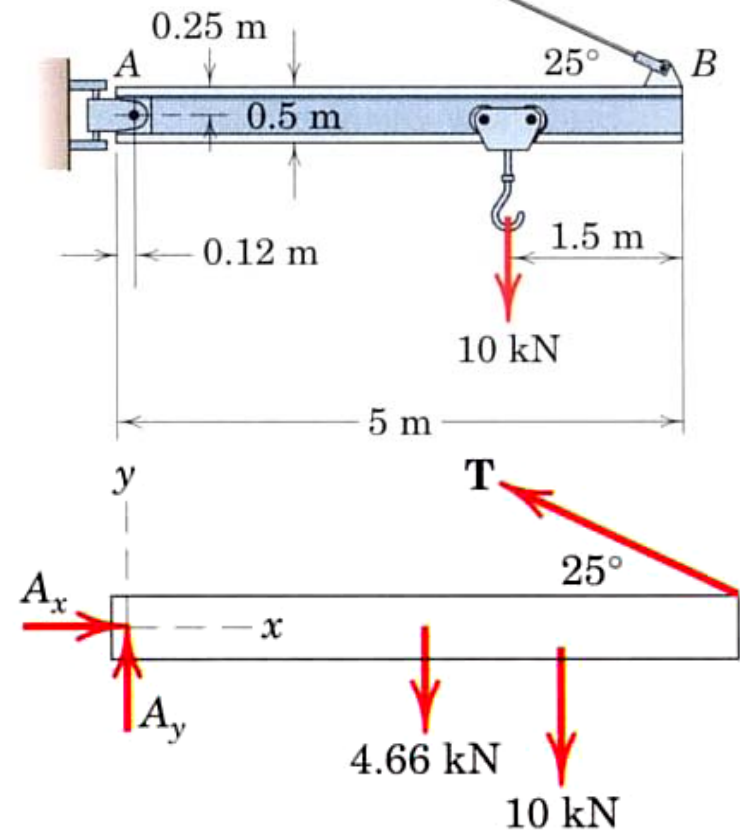
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example 3.2

Determine the tension T in the supporting cable and the reaction force on pin A for the jib crane. Beam AB is a standard I-beam with a weight of 93.2 N per meter of length.

$$\begin{aligned} \sum M_A = 0 : & -4.66(2.5-0.12) - 10(3.5-0.12) \\ & + T \cos 25^\circ 0.25 + T \sin 25^\circ (5-0.12) = 0 \\ \rightarrow & \quad T = 19.61 \text{ kN} \end{aligned}$$



Free-body diagram

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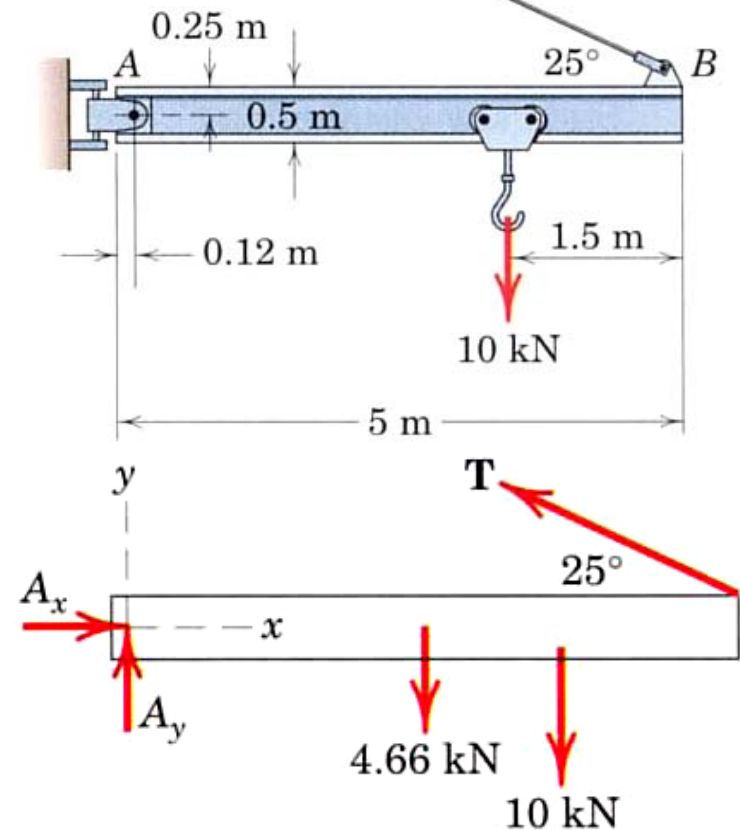


example 3.2

Determine the tension T in the supporting cable and the reaction force on pin A for the jib crane. Beam AB is a standard I-beam with a weight of 93.2 N per meter of length.

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$$\begin{aligned} \sum F_x = 0 : & A_x - T \cos 25^\circ = 0 \\ \rightarrow & \quad A_x = 17.77 \text{ kN} \end{aligned}$$



Free-body diagram

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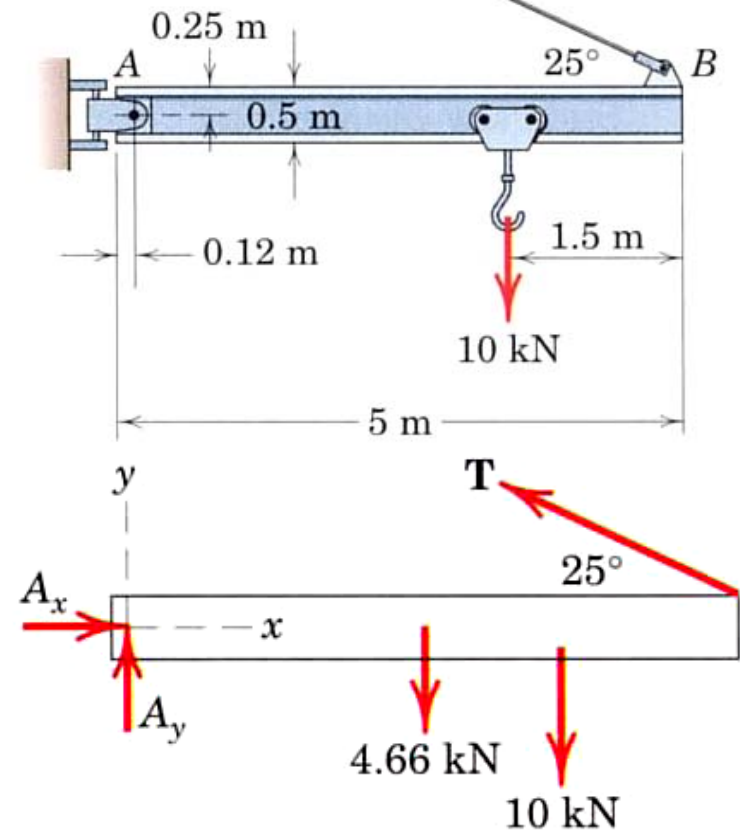
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Free-body diagram

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example 3.2

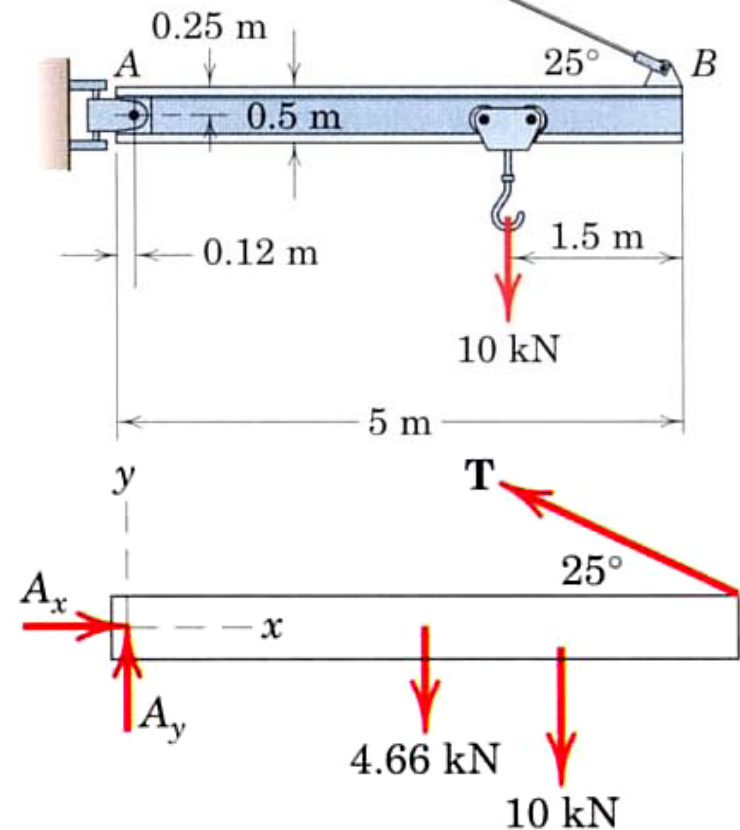
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$$A = \sqrt{A_x^2 + A_y^2} = 18.88 \text{ kN}$$



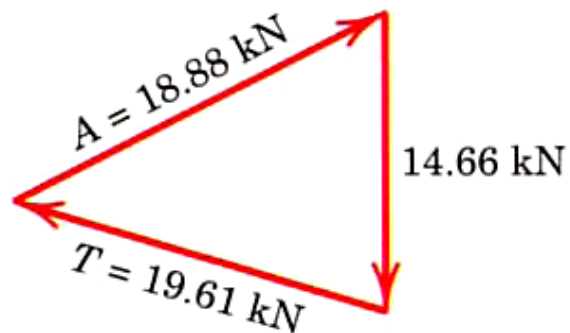
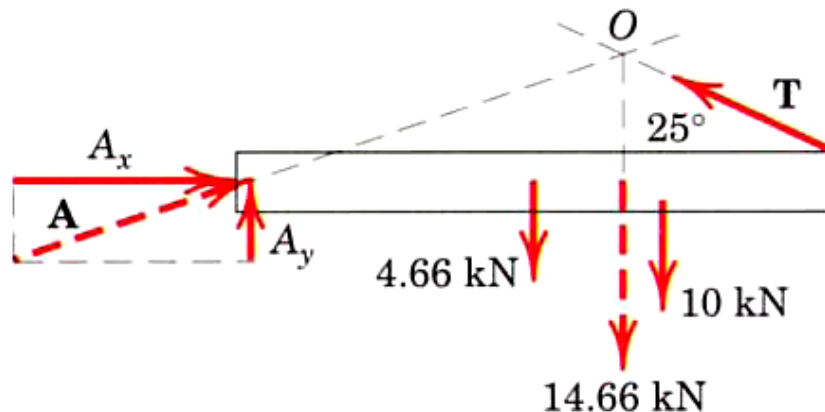
Free-body diagram

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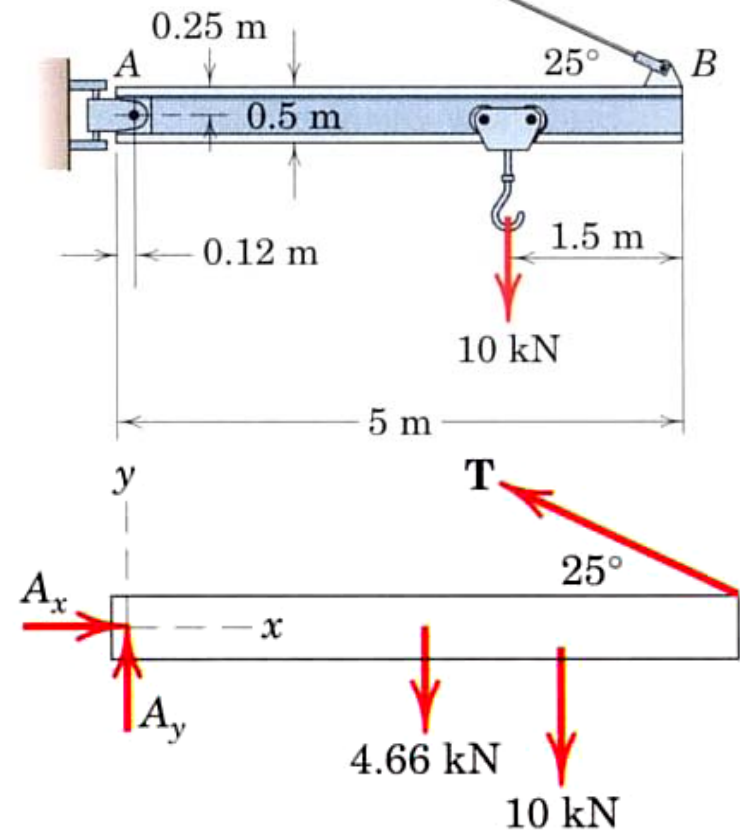


example 3.2

Determine the tension T in the supporting cable and the reaction force on pin A for the jib crane. Beam AB is a standard I-beam with a weight of 93.2 N per meter of length.



Graphical solution



Free-body diagram

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example 3.3

Determine tension P in the cable required to elevate end B of the beam (weight 100 N) and reaction A_y .

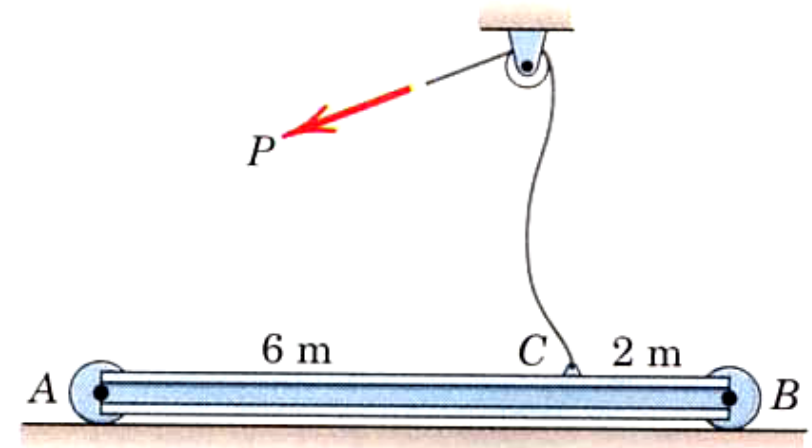


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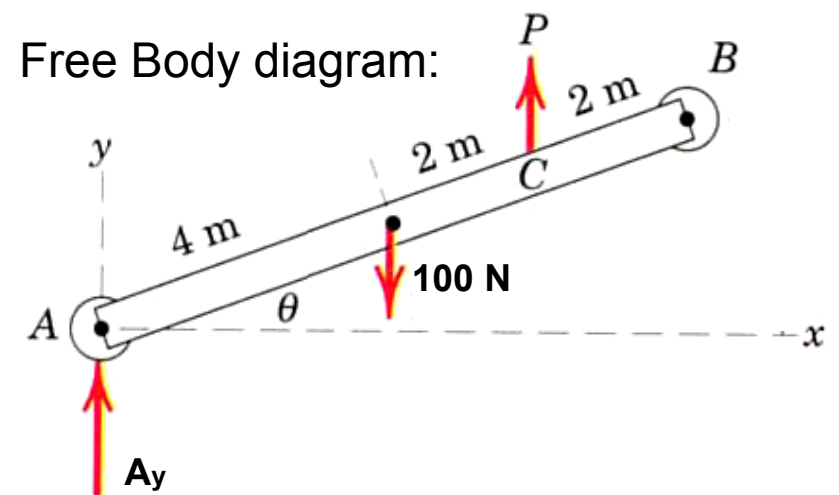
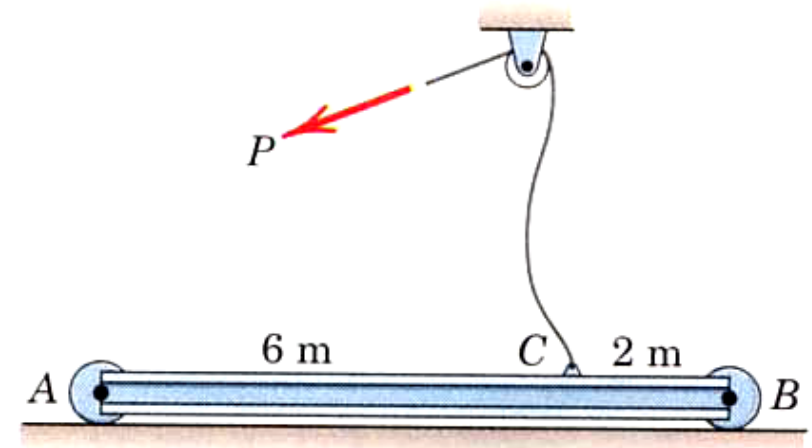


fig by J.L. Meriam, L.G. Kraige, Engineering Mechanics I



example 3.3

Determine tension P in the cable required to elevate end B of the beam (weight 100 N) and reaction A_y .

 $\sum M_A = 0 : P \cos\theta (4+2) - 100 \cos\theta 4 = 0$

$\rightarrow P 6 - 100 4 = 0$

$\rightarrow P = 66.67 \text{ N}$

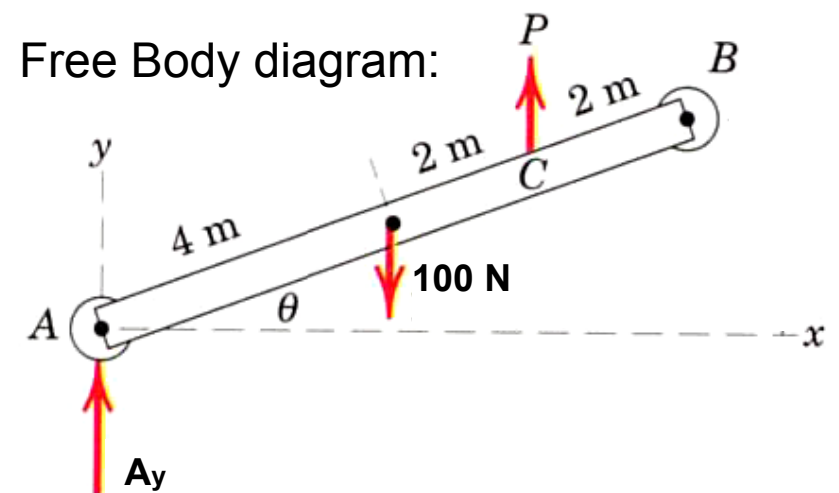
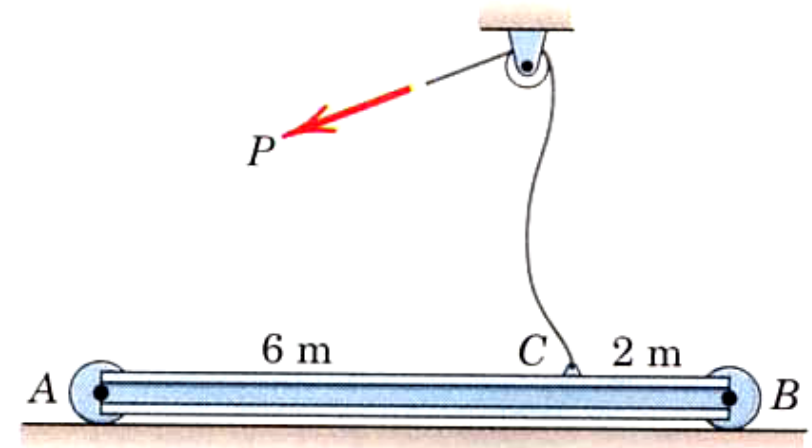


fig by J.L. Meriam, L.G. Kraige, Engineering Mechanics I



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$$\rightarrow P = 66.67 \text{ N}$$

$$\sum F_y = 0 : A_y + P - 100 = 0$$

$$\rightarrow A_y = 33.33 \text{ N}$$

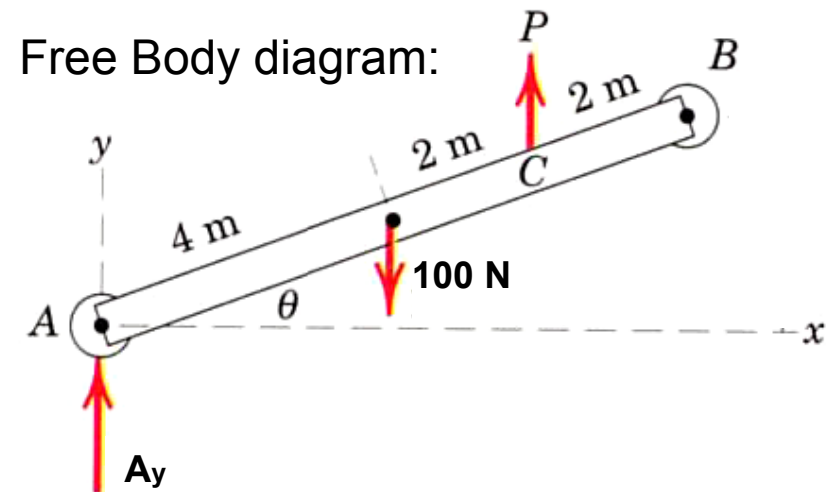
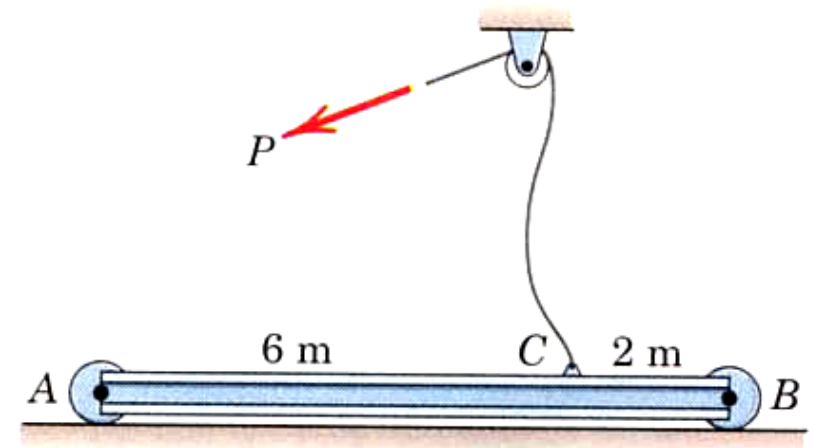


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example 3.4

The student pulls on the rope so that the spring dynamometer B registers 76 N. The scale A reads 268 N.

What is the weight of the student?

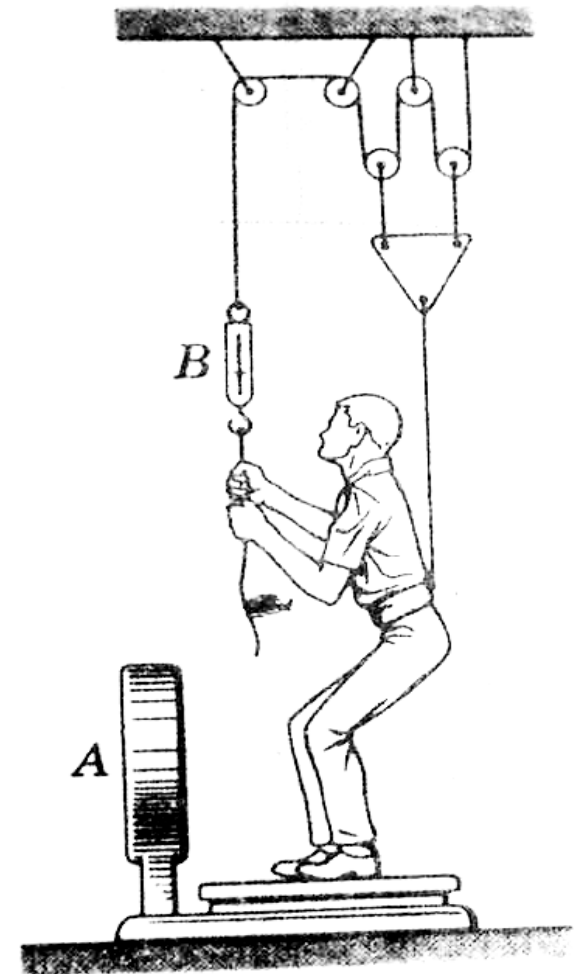


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Civil Engineering

example 3.4

The student pulls on the rope so that the spring dynamometer B registers 76 N. The scale A reads 268 N.

What is the weight of the student?

isolating the student's body:

$$\sum F_y = 0 : \quad 268 \text{ N} + 76 \text{ N} + F = \text{Weight}$$

two unknown forces left ...

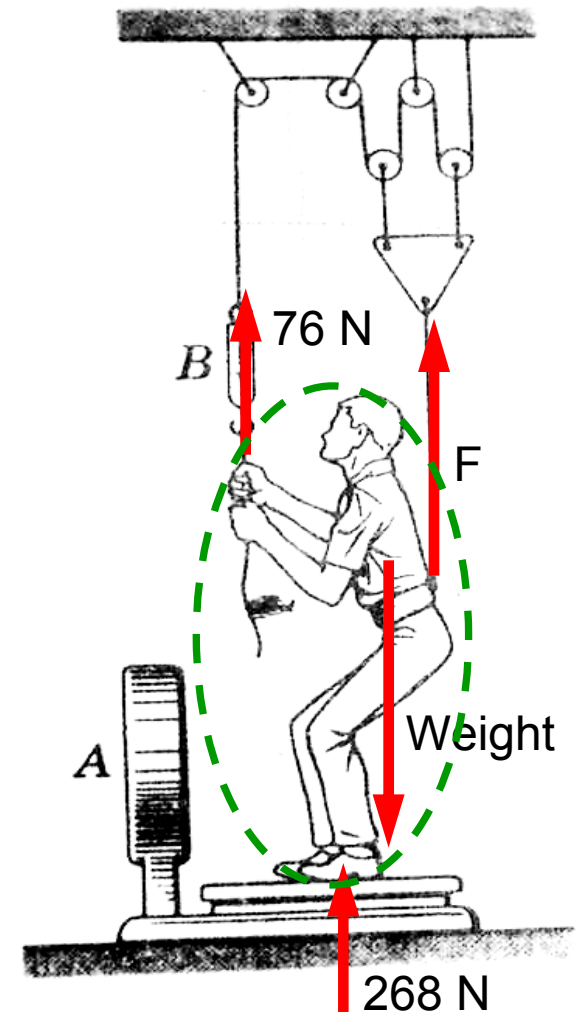
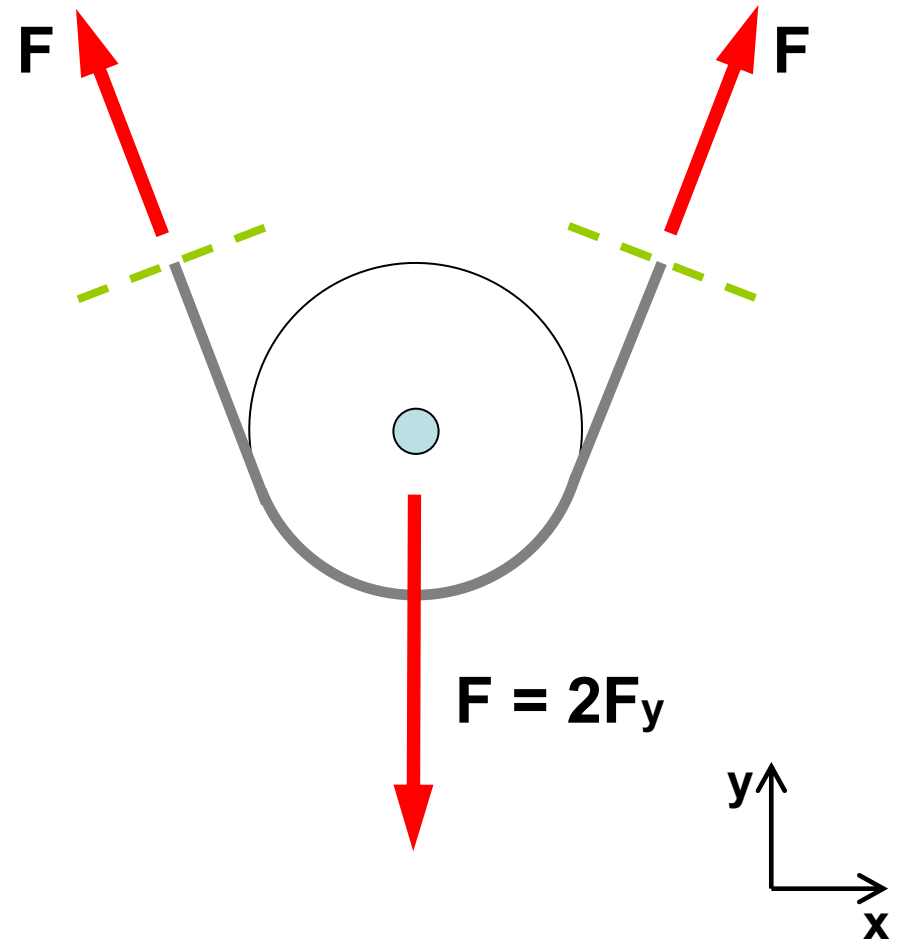
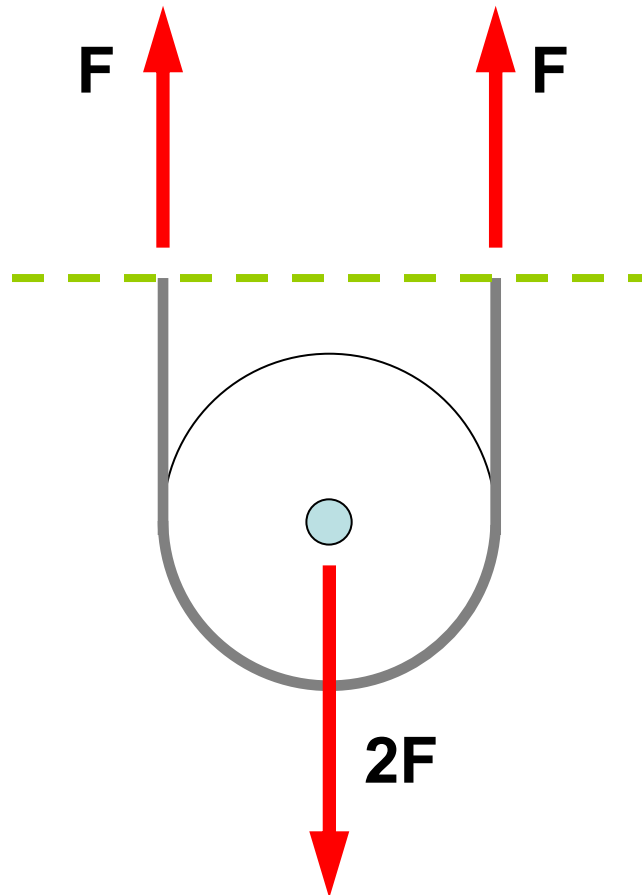


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example 3.4

equilibrium at roller:



example 3.4

The student pulls on the rope so that the spring dynamometer B registers 76 N. The scale A reads 268 N.

What is the weight of the student?

isolating the lower part of the diagram by a cut through the cables and applying the rules of the rollers ...

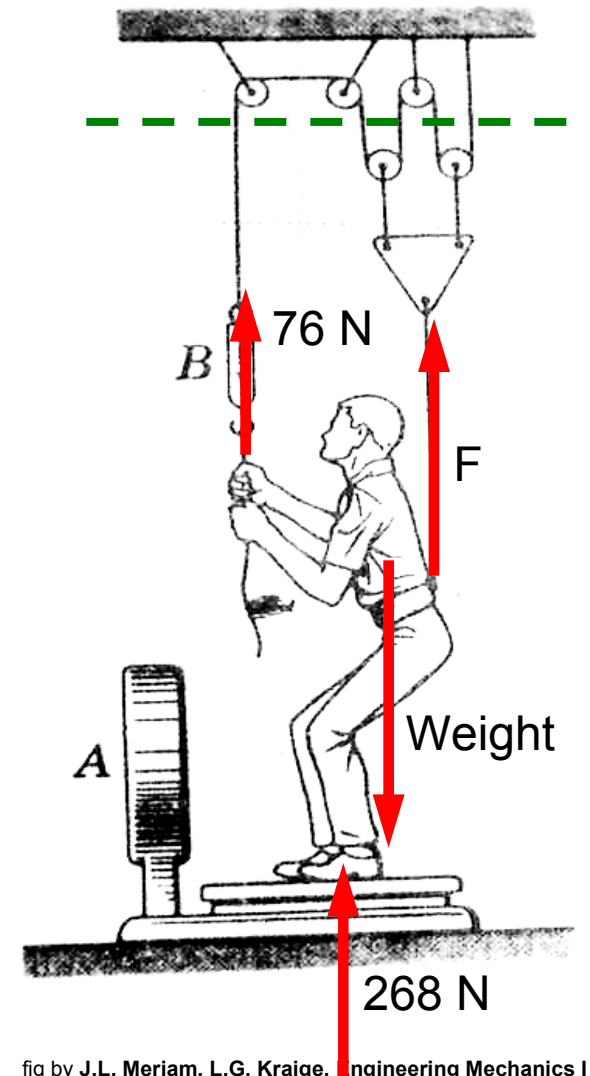


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example 3.4

The student pulls on the rope so that the spring dynamometer B registers 76 N. The scale A reads 268 N.

What is the weight of the student?

$$\begin{aligned}\sum F_y = 0 : \quad & 268 \text{ N} + 5 \cdot 76 \text{ N} = \text{Weight} \\ \text{Weight} = & 648 \text{ N} \quad (= 66.1 \text{ kg})\end{aligned}$$

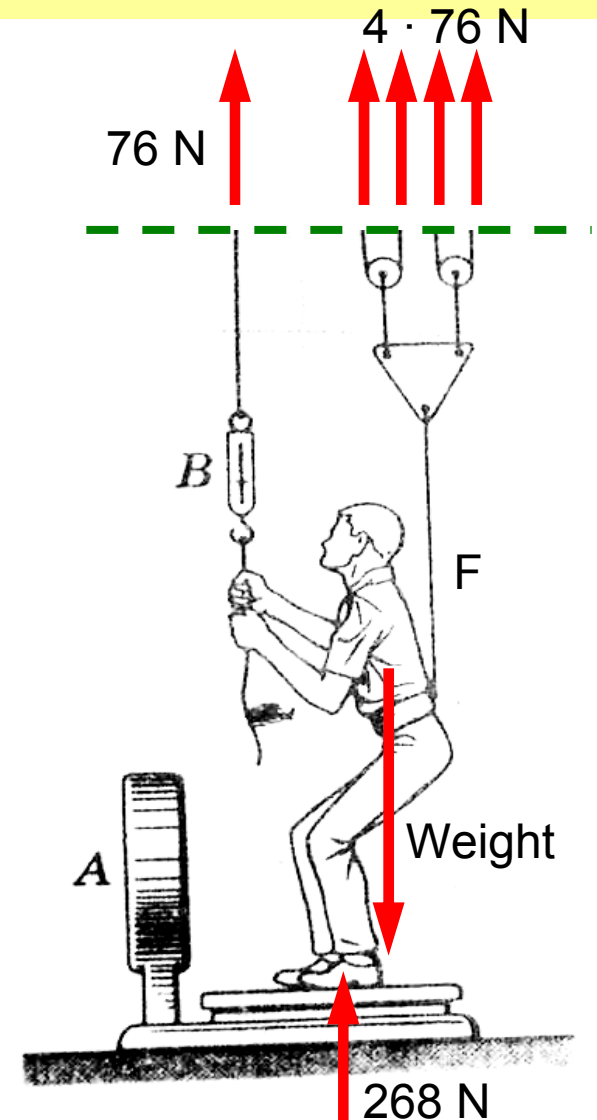


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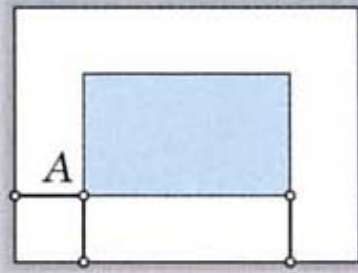


Constraints and Statical Determinacy

$$\sum F_x = 0$$

$$\sum F_y = 0$$

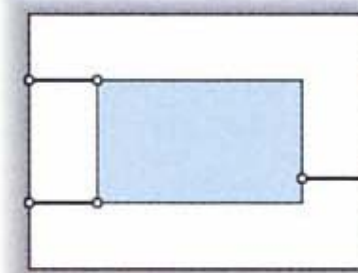
$$\sum M = 0$$



(a) Complete fixity
Adequate constraints

$$\sum F_x = 0$$

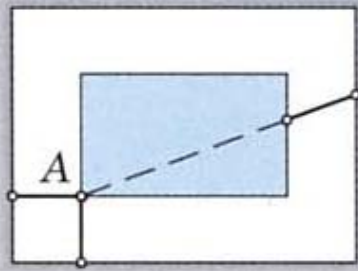
$$\sum M = 0$$



(c) Incomplete fixity
Partial constraints

$$\sum F_x = 0$$

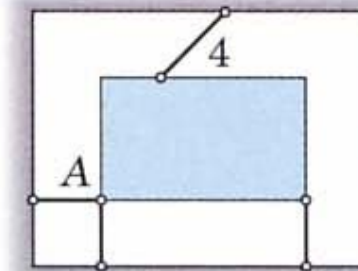
$$\sum F_y = 0$$



(b) Incomplete fixity
Partial constraints

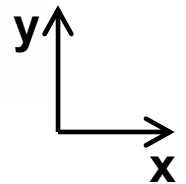
**Statically
indeterminate**

**3 equations
4 unknowns**



(d) **Excessive fixity**
Redundant constraint

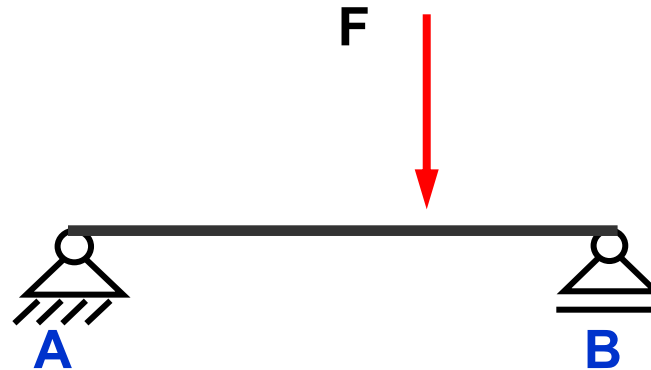
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example

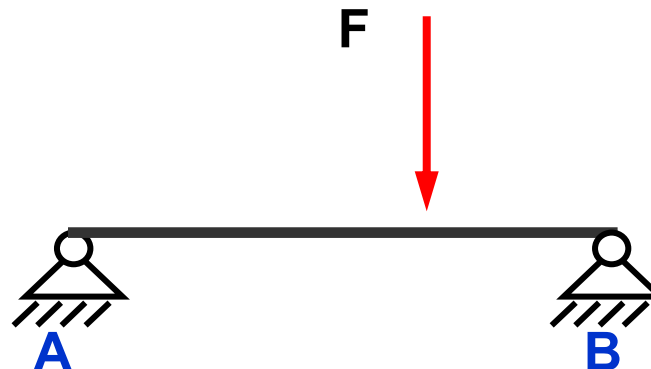
Statically Determinate System

- 3 unknown forces
- 3 equations



Statically Indeterminate System

- 4 unknown forces
- 3 equations
- possible internal constraint force





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