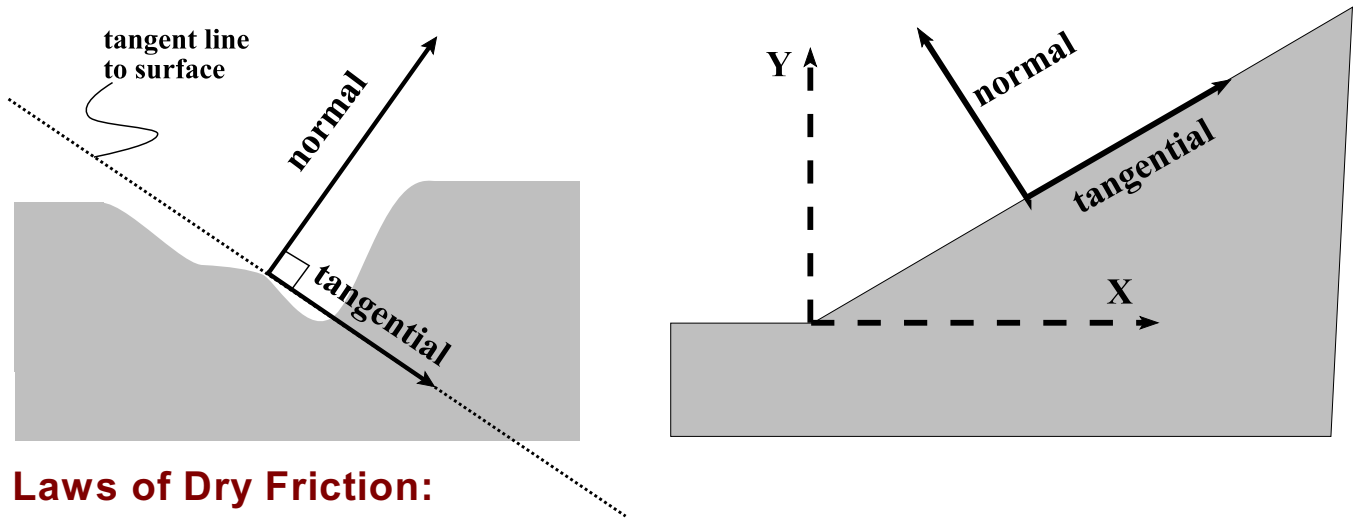


# Friction

## Normal and Tangential Axes:

- **normal axis** is perpendicular to surface
- **tangential axis** is parallel to surface



## Laws of Dry Friction:

**Static:** maximum static friction =  $F_{static} = \text{static } F_{normal}$   
**Kinetic:** maximum kinetic friction =  $F_{kinetic} = \text{kinetic } F_{normal}$

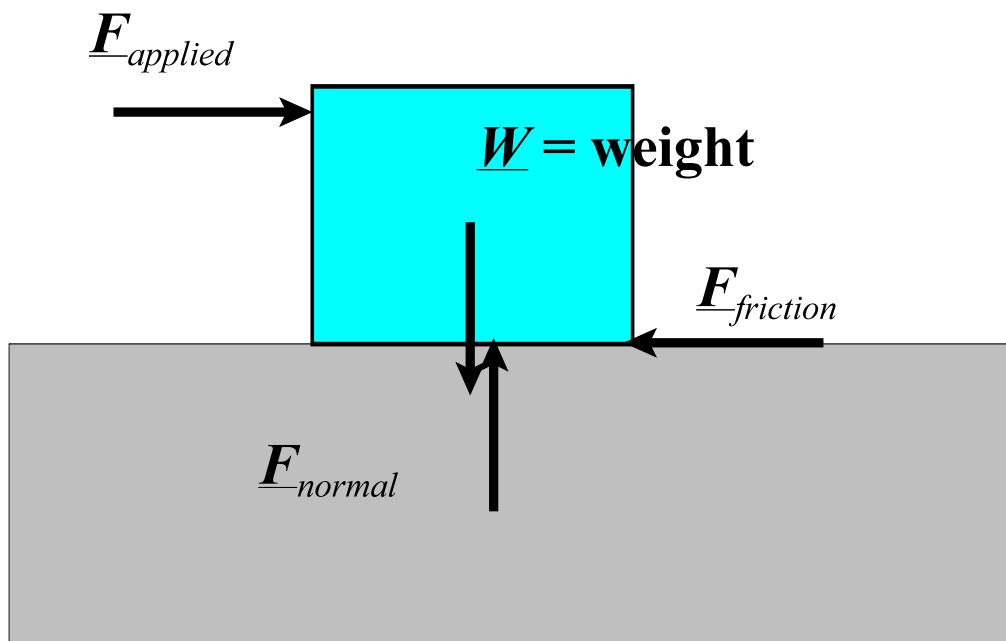
## Coefficients of Static Dry Friction

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Metal on metal	0.15 – 0.60
Metal on wood	0.20 – 0.60
Metal on stone	0.30 – 0.70
Wood on wood/leather	0.25 – 0.50
Stone on stone	0.40 – 0.70
Earth on earth	0.20 – 1.00
Rubber on concrete	0.60 – 0.90
Nylon on nylon	0.15 – 0.25
Bone on bone (cartilage)	0.10 – 0.20
Steel on Teflon	0.04 – 0.05
Metal on ice	0.02 – 0.05

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## Forces of Friction:

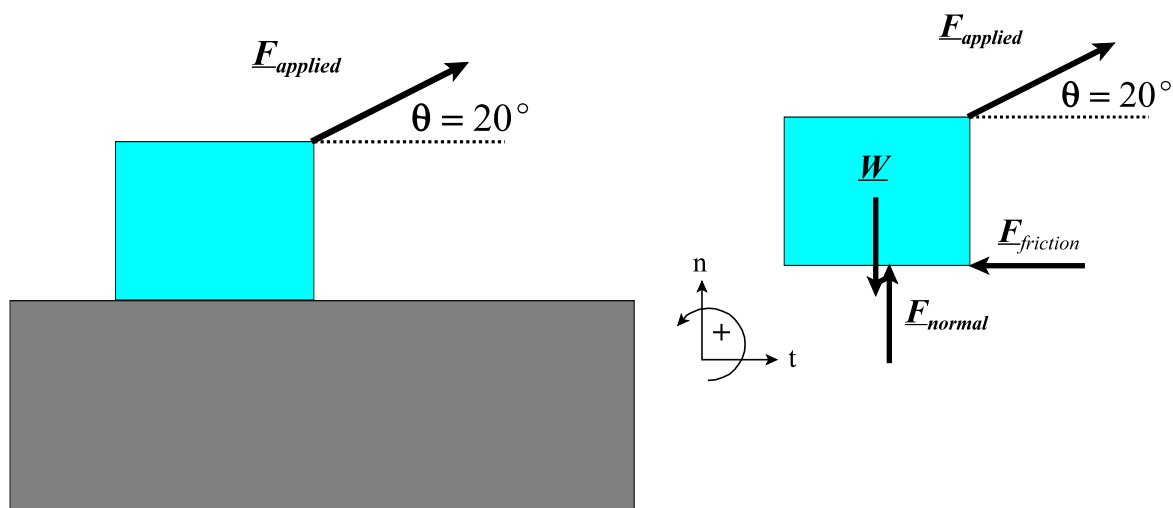


### Example:

If  $F_{applied} = 25.0 \text{ N}$ ,  $F_{static} = 100 \text{ N}$ ,  $W = 30.0 \text{ N}$ , compute  $F_{friction}$ .

Space diagram

Free-body diagram



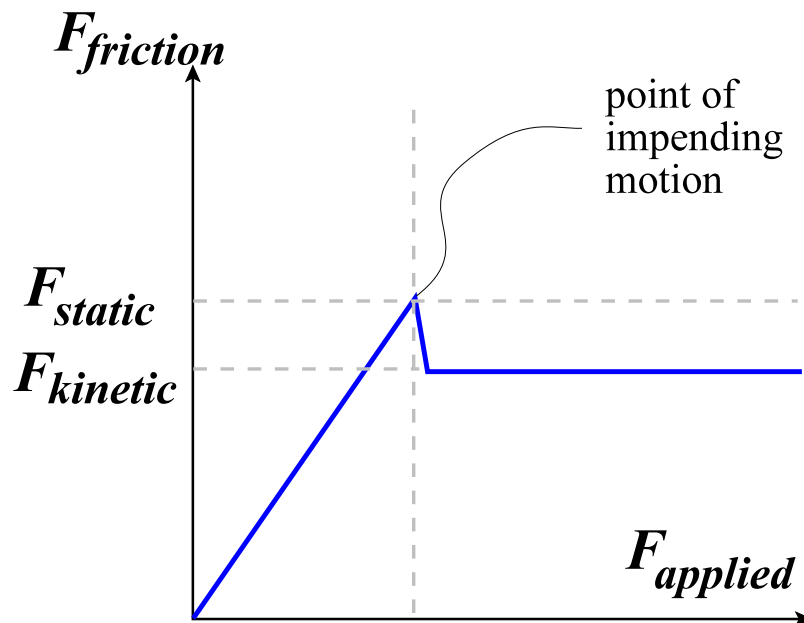
$$F_t = 0: F_{friction} + F_{applied} \cos 20^\circ = 0$$

therefore  $F_{friction} = -25.0 \cos 20^\circ = -23.5 \text{ N}$

(note answer must be  $> 100$  newtons, i.e., maximum static friction)

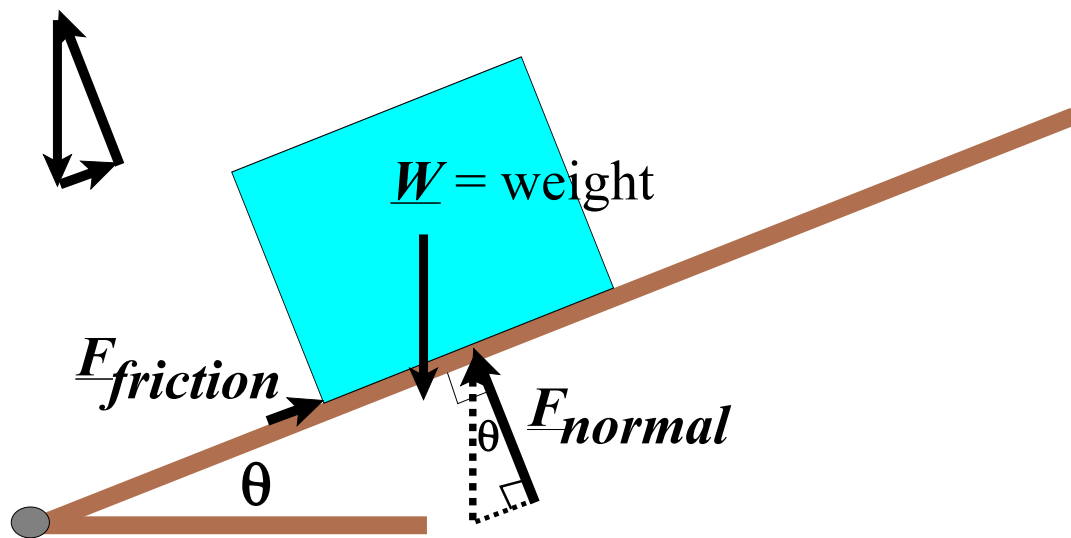
## Relationship between Applied Force and Friction

- as applied force increases friction increases until a maximum is reached and slipping occurs
- maximum is called  $F_{static}$
- after body starts to move frictional force drops to a new level called  $F_{kinetic}$
- any further increase in the applied force is resisted by  $F_{kinetic}$
- figure below is called the “standard model of friction”



## Empirical Method for Calculating Coefficient of Static Friction

- cover a load and incline with two surfaces to be tested
- place load on an incline that can be raised at one end
- make sure incline and load are flat and clean
- increase incline until load just starts to slip
- measure angle of incline,
- repeat and obtain average angle
- coefficient of static friction =  $\mu_{static} = \tan \theta$
- proof follows

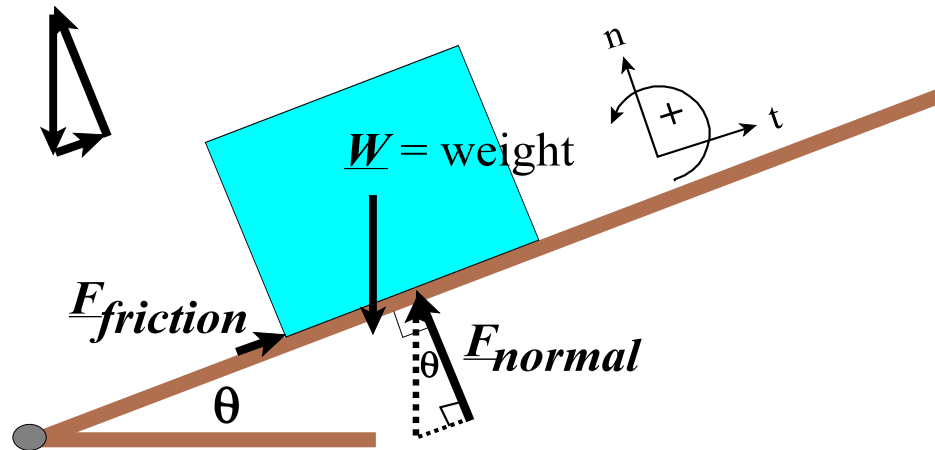


At instant of impending motion:  $\mu_{static} = \tan \theta$

- coefficient of kinetic friction is more difficult to obtain
- tan of angle that keeps load moving at constant velocity

## Angles of Friction

- angle of an incline at the point of **impending motion**
- tangent (tan) of this angle is the same as the coefficient of static friction



At instant of impending motion:  $\mu_{static} = \tan \theta$

### Proof:

$$\sum F_n = 0: F_{normal} - W \cos \theta = 0$$

$$F_{normal} = W \cos \theta$$

$$\sum F_t = 0: F_{static} - W \sin \theta = 0$$

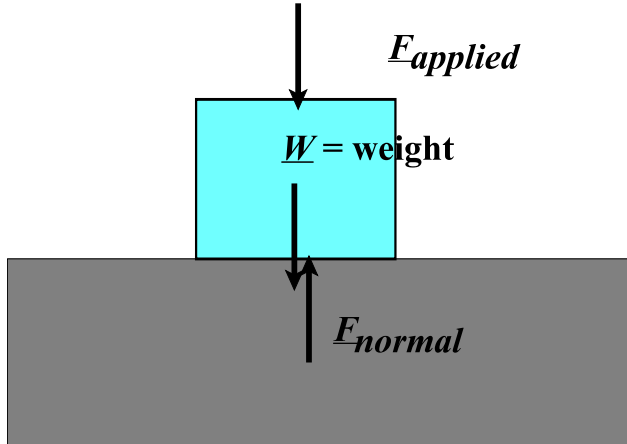
$$F_{static} = W \sin \theta$$

$$\mu_{static} = \frac{F_{static}}{F_{normal}} = \frac{W \sin \theta}{W \cos \theta} = \tan \theta$$

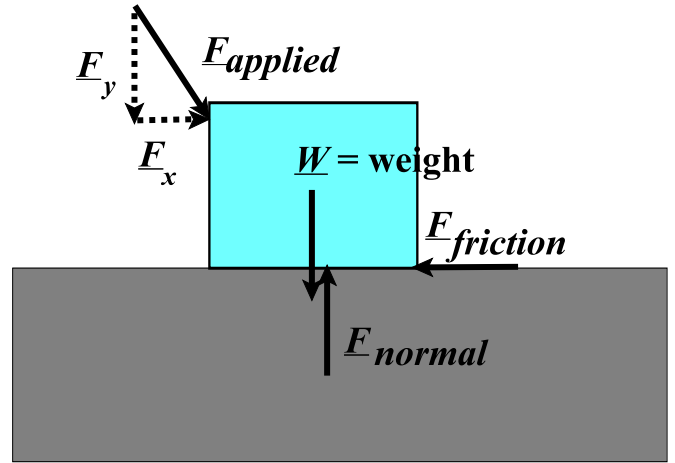
- To compute the **coefficient of kinetic friction**, lower the incline slowly until the mass just stops—this is the angle of kinetic friction.
- The tan of this angle is the coefficient of kinetic friction.

# Frictional States

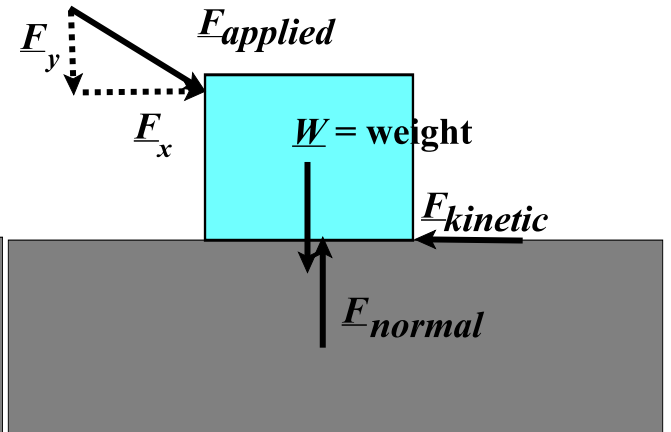
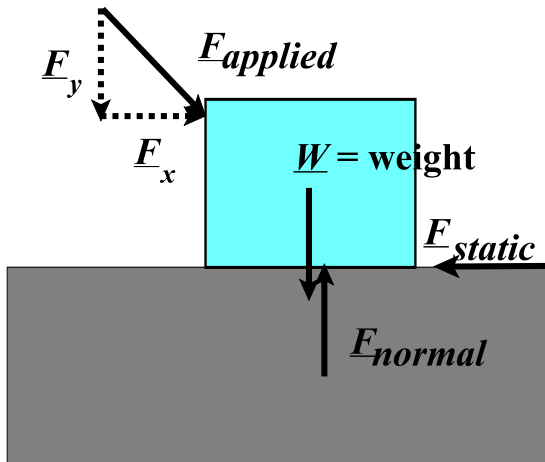
(a) no friction



(b) no motion ( $F_x < F_{static}$ )



(c) motion impending ( $F_x = F_{static}$ ) (d) motion ( $F_x > F_{static}$ )



## Measuring Friction using Force Platforms

- line load and force platform with surfaces to be tested
- pull load across clean level force platform
- record maximum horizontal force ( $F_x$ ) at point load starts to move
- $\mu_{static} = \text{horizontal force} / \text{vertical force} = F_x / F_y$
- record horizontal force when load is moving
- $\mu_{kinetic} = \text{horizontal force} / \text{vertical force} = F_x / F_y$

