Today 15.3, 15.4

$\boxed{L22}$

Today 15.3, 15.4

L22

instantaneous
center of rotation

Today 15.3, $\underbrace{15.4}$ $\boxed{L22}$

Rigid

body acceleration

Today 15.3, 15.4

Monday 16.1

$\boxed{L22}$

Kinetics of rigid bodies

For every point on the rigid body (in plane motion that is rotating) $V_p = \omega r_{p/c}$

For every point on the rigid body (in plane motion that is rotating) $v_P = \omega r_{P/C}$

Here ω is fixed $\Rightarrow v_P$ scales with distance $r_{P/C}$

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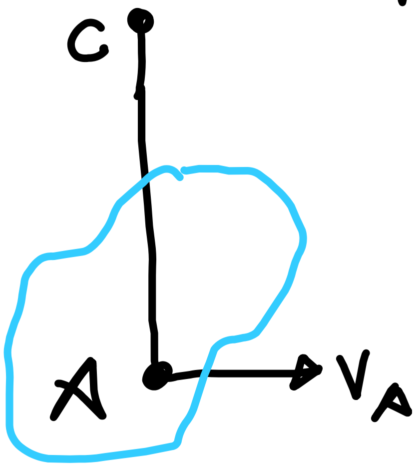

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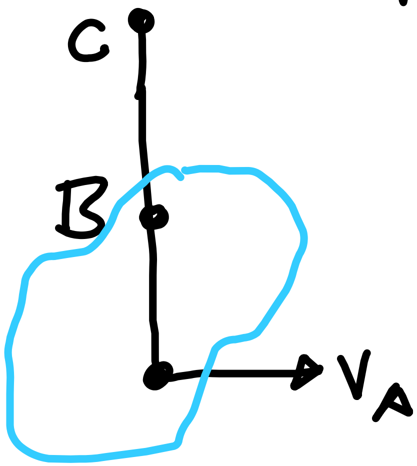

If point B is $\frac{1}{2}$ distance from C as is A

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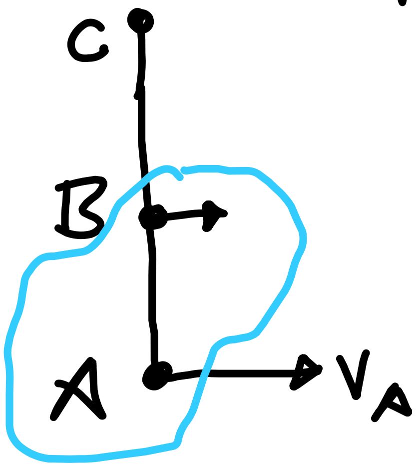

If point B is $\frac{1}{2}$ distance from C as is A, then V_B is $\frac{1}{2} V_A$.

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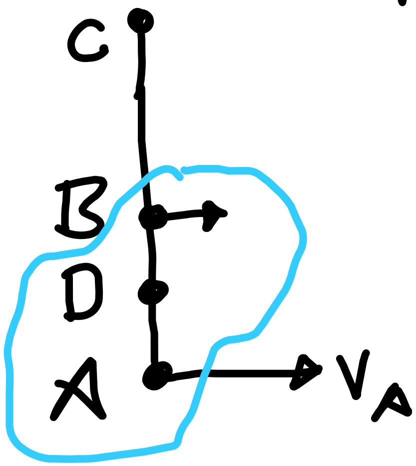

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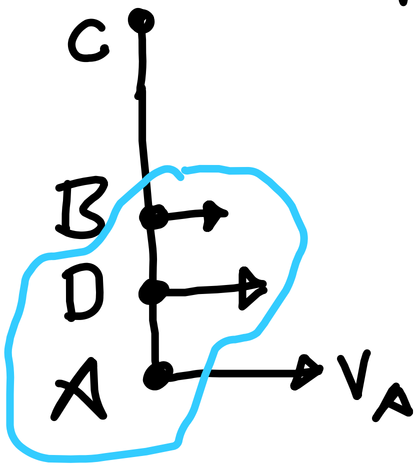

If point B is $\frac{1}{2}$ distance from C as is A, then V_B is $\frac{1}{2} V_A$.

If point D is $3/4$ distance from C as A is, then

$V_D = (3/4) V_A$

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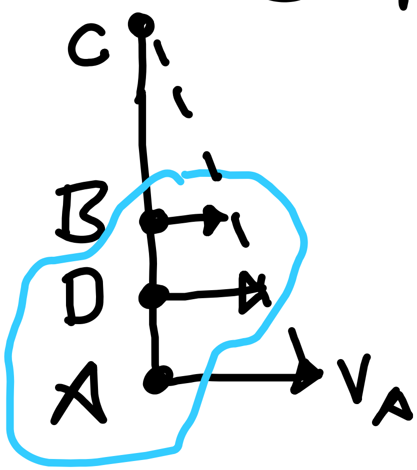

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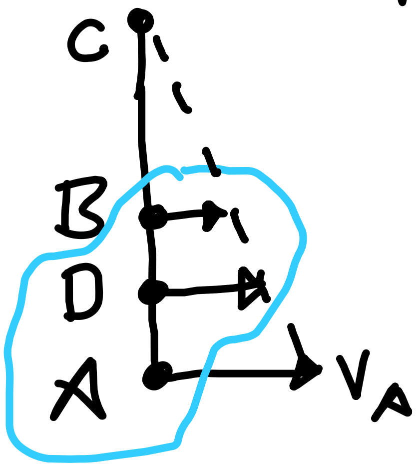

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This form similar triangles

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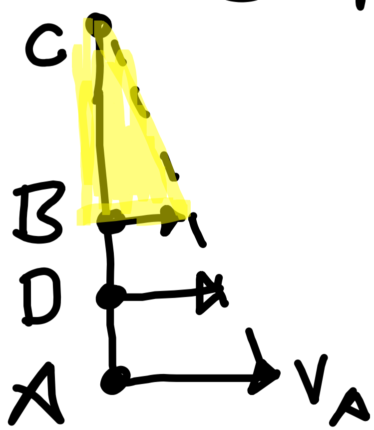

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This form similar triangles $\Rightarrow$

$$\frac{V_B}{r_{B/C}} = \frac{V_D}{r_{D/C}} = \frac{V_A}{r_{A/C}}$$

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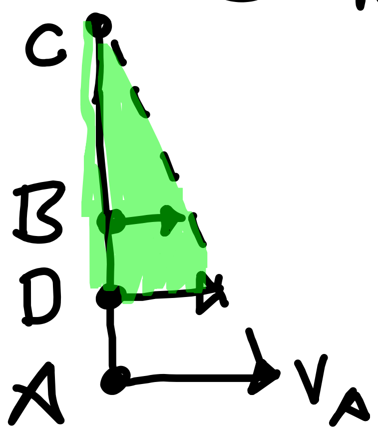

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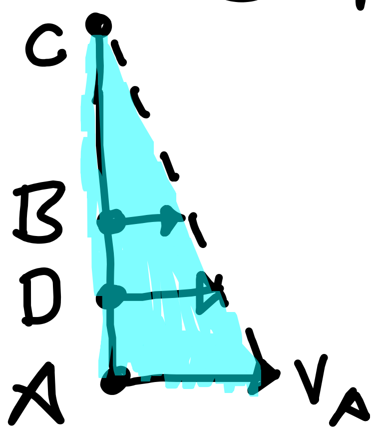

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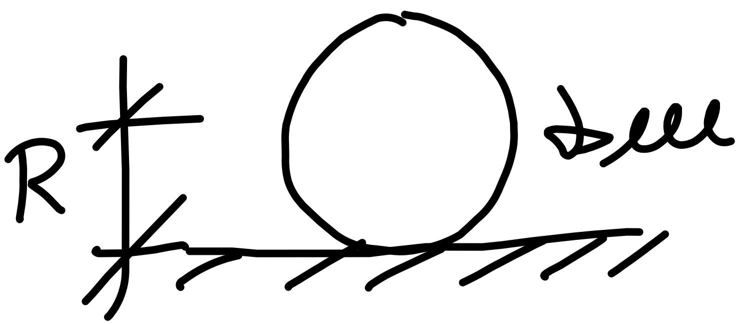
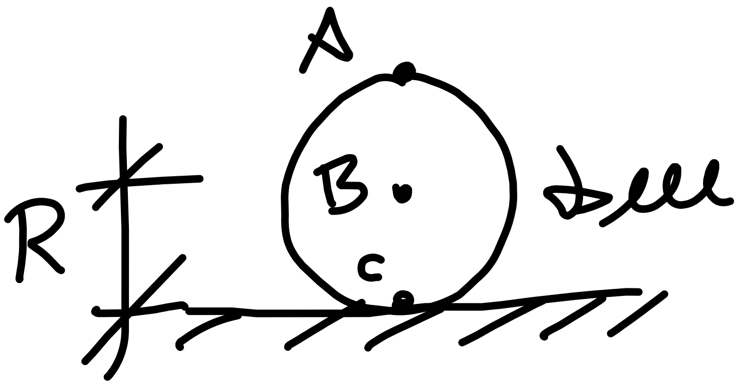
Wheel rolling w/no slipping



Wheel rolling w/no slipping

We know that

$V_A = 2V_B$ & $V_C = 0$.



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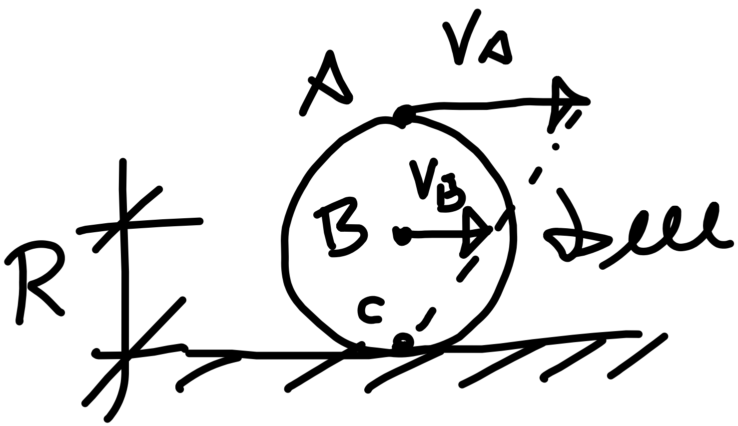

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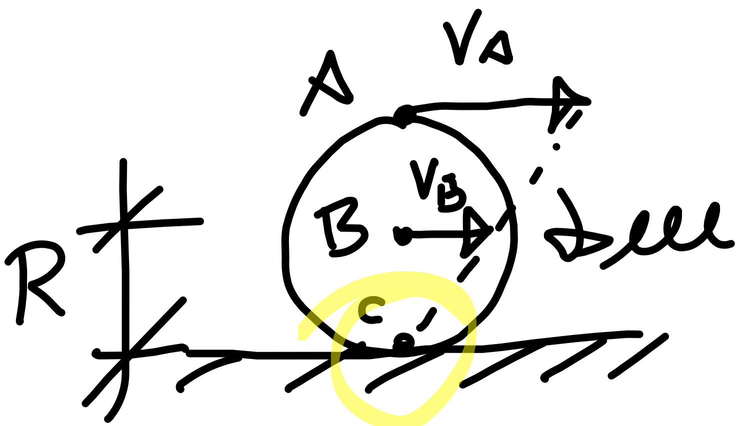

we know that

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In fact, we now know that point c is the instantaneous center of rotation

Relative motion for two points:

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$$\vec{r}_{A/B} \equiv \vec{r}_A - \vec{r}_B$$

ASU

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Acceleration

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$\vec{a} = \frac{d\vec{v}}{dt}$

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$\vec{a} = \frac{d\vec{v}}{dt} \Rightarrow$

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So $\vec{v}_{A/B} = \vec{\omega} \times \vec{r}_{A/B}$

Acceleration

$\vec{a} = \frac{d\vec{v}}{dt} \Rightarrow$

$\vec{a}_A = \vec{a}_{A/B} + \vec{a}_B$, where

$$\vec{a}_{A/B} = \vec{\alpha} \times \vec{r}_{A/B} + \vec{\omega} \times [\vec{\omega} \times \vec{r}_{A/B}]$$

ASU

In the past we used $\vec{a} = a_n \hat{e}_n + a_t \hat{e}_t$ for circular motion

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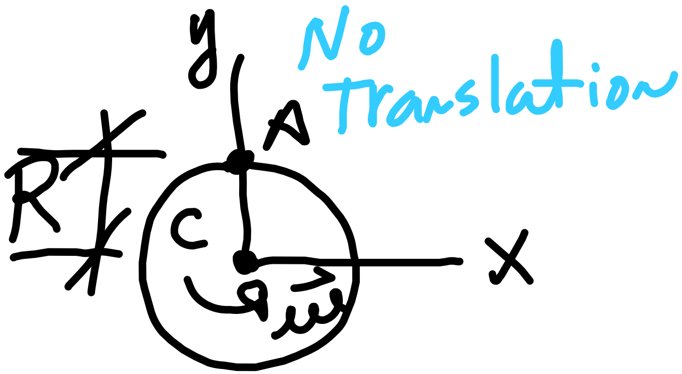

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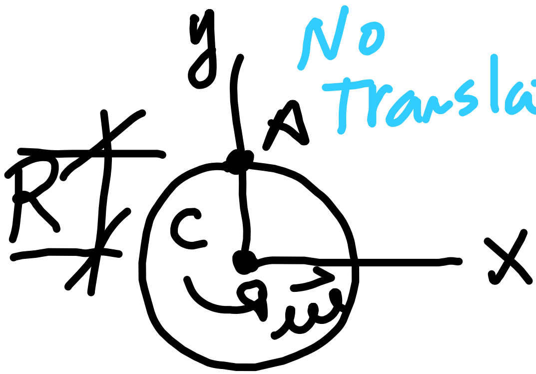
No Translation

$\vec{\omega} = \omega \hat{z}$



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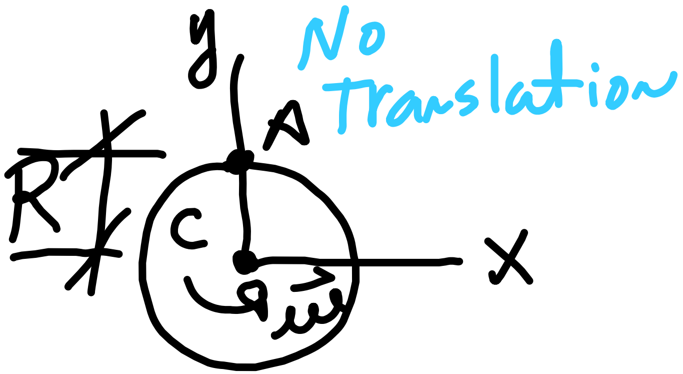
$\vec{\omega} = \omega \hat{z}$, with $\omega = \text{const.}$



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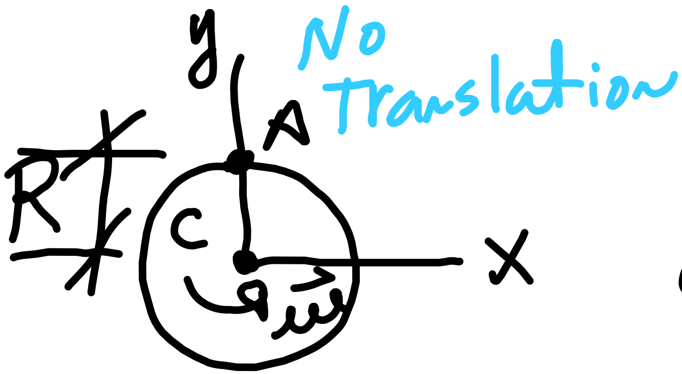

$\vec{\omega} = \omega \hat{z}$, with $\omega = const.$

$\vec{a}_A = a_n \hat{e}_n + a_t \hat{e}_t$, where

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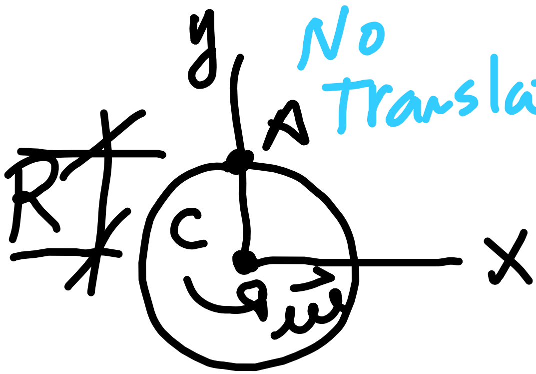

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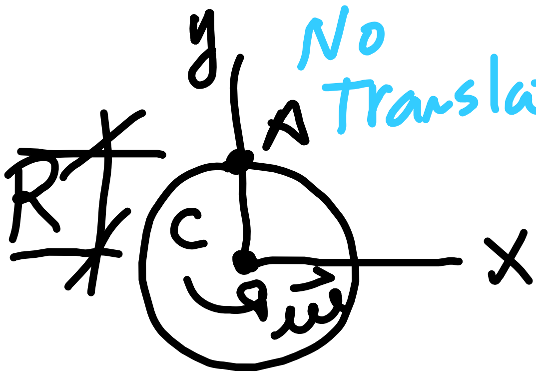

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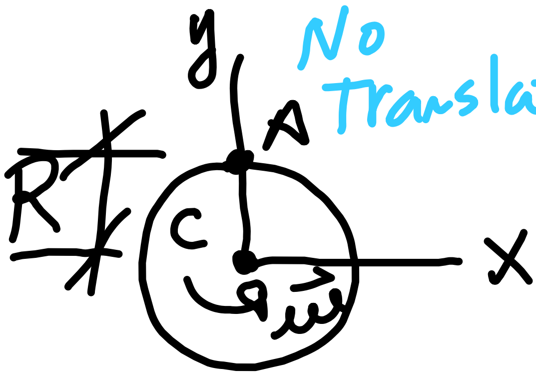

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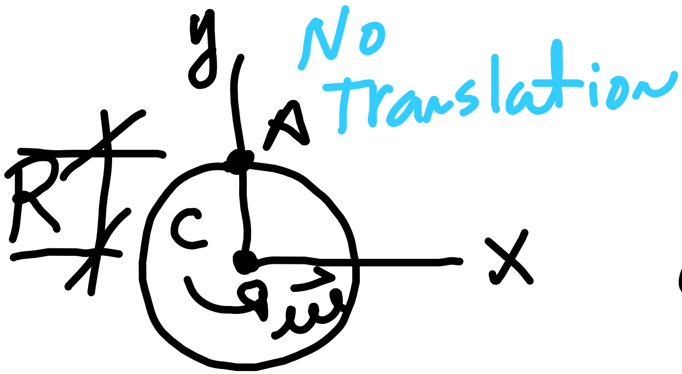

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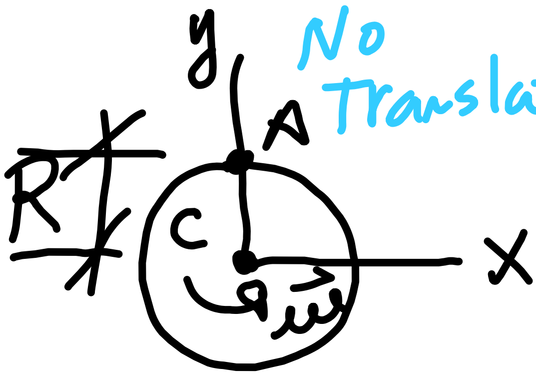

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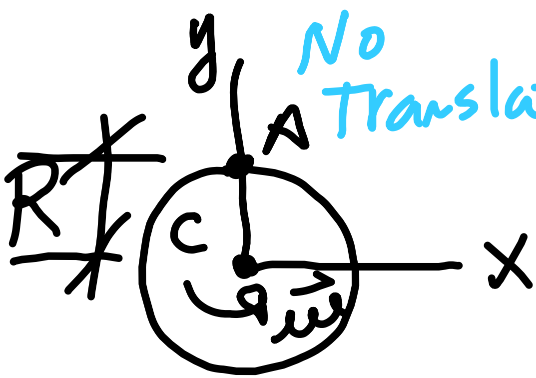

$\vec{\omega} = \omega\hat{z}$, with $\omega = \text{const.}$

$\vec{a}_A = a_N\hat{e}_N + a_t\hat{e}_t$, where

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$\hat{e}_N$ points from A to C and $\hat{e}_t$ is tangential to the path that A takes. For uniform circular motion $V_A = R\omega$ & $\frac{dV_A}{dt} = 0$ so

$a_N = R\omega^2$

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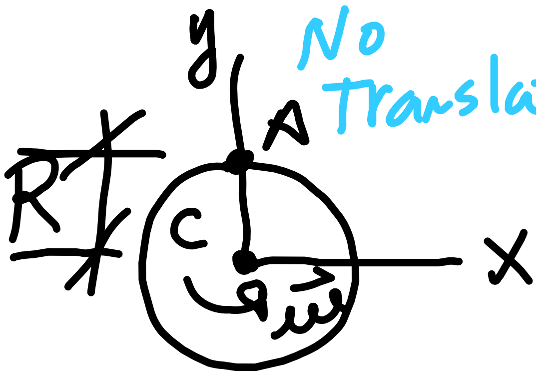

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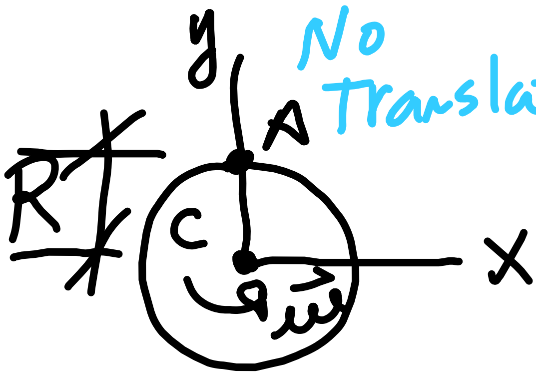

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$\hat{e}_n$ points from A to C and $\hat{e}_t$ is tangential to the path that A takes. For uniform circular motion $V_A = R\omega$ & $\frac{dV_A}{dt} = 0$ so

$a_n = R\omega^2$ & $a_t = 0$ & $\hat{e}_n = -\hat{y}$

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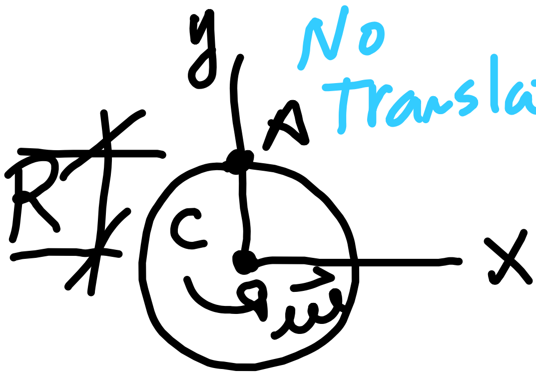

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$a_n = R\omega^2$ & $a_t = 0$ & $\hat{e}_n = -\hat{y}$ $\Rightarrow$

$\vec{a}_{A/C} = \vec{a}_A$

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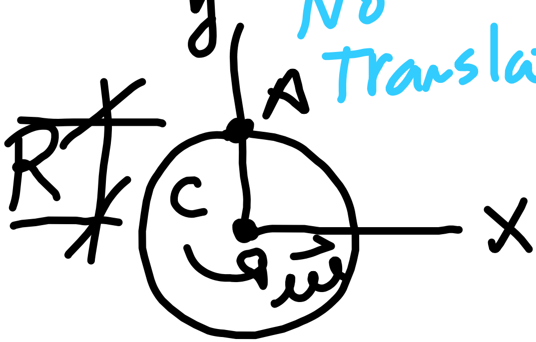

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$\hat{e}_N$ points from A to C and $\hat{e}_t$ is tangential to the path that A takes. For uniform circular motion $V_A = R\omega$ & $\frac{dV_A}{dt} = 0$ so

$a_N = R\omega^2$ & $a_t = 0$ & $\hat{e}_N = -\hat{y}$ $\Rightarrow$

$$\vec{a}_{A/C} = \vec{a}_A = R\omega^2(-\hat{y})$$

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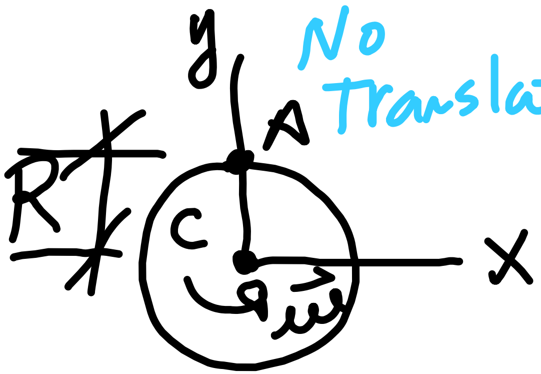

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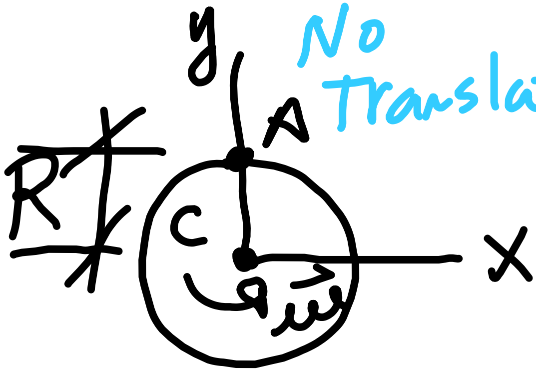
$\hat{e}_n$ points from A to C and $\hat{e}_t$ is tangential to the path that A takes. For uniform circular motion $V_A = R\omega$ & $\frac{dV_A}{dt} = 0$ so

$a_n = R\omega^2$ & $a_t = 0$ & $\hat{e}_n = -\hat{y}$ $\Rightarrow$

$\vec{a}_{A/C} = \vec{a}_A = R\omega^2(-\hat{y})$ If $\vec{\omega} \neq \text{const.}$

In the past we used $\vec{a} = a_n\hat{e}_n + a_t\hat{e}_t$ for circular motion How does this relate to our new expression?



No Translation

$\vec{\omega} = \omega\hat{z}$, with ω = const.

$\vec{a}_N = a_N\hat{e}_N + a_t\hat{e}_t$, where

$$a_N = \frac{V_A^2}{R} \quad \& \quad a_t = \frac{dV_A}{dt}$$

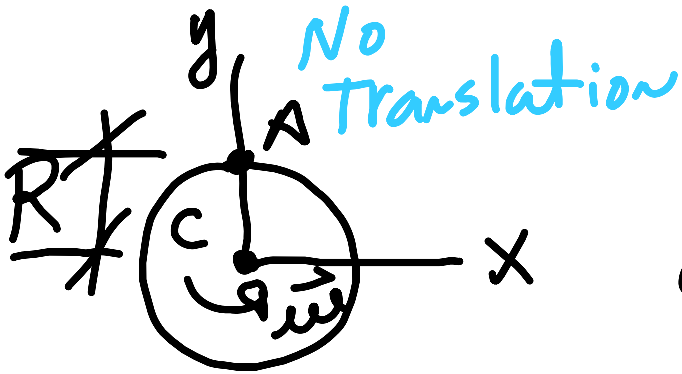
$\hat{e}_N$ points from A to C and $\hat{e}_t$ is tangential to the path that A takes. For uniform circular motion $V_A = R\omega$ & $\frac{dV_A}{dt} = 0$ so

$a_N = R\omega^2$ & $a_t = 0$ & $\hat{e}_N = -\hat{y}$ ⇒

$\vec{a}_{A/C} = \vec{a}_A = R\omega^2(-\hat{y})$ If $\vec{\omega} \neq$ const. we get

$$\frac{dV_A}{dt} = R\frac{d\omega}{dt}$$

In the past we used $\vec{a} = a_n \hat{e}_n + a_t \hat{e}_t$ for circular motion. How does this relate to our new expression?



$\vec{\omega} = \omega \hat{z}$, with $\omega = \text{const.}$

$\vec{a}_A = a_n \hat{e}_n + a_t \hat{e}_t$, where

$$a_n = \frac{V_A^2}{R} \quad \& \quad a_t = \frac{dV_A}{dt}$$

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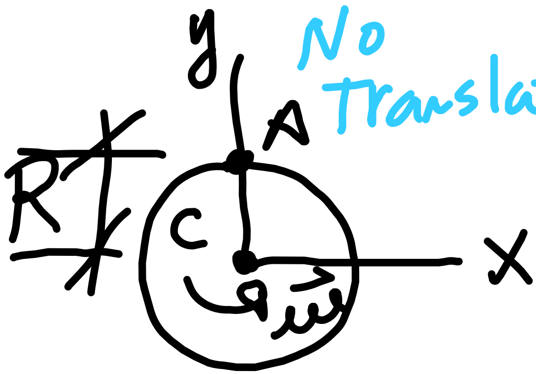
$a_n = R\omega^2$ & $a_t = 0$ & $\hat{e}_n = -\hat{y}$ $\Rightarrow$

$\vec{a}_{A/C} = \vec{a}_A = R\omega^2(-\hat{y})$. If $\vec{\omega} \neq \text{const.}$ we get

$$\frac{dV_A}{dt} = R\frac{d\omega}{dt} = R\alpha$$

In the past we used $\vec{a} = a_n\hat{e}_n + a_t\hat{e}_t$ for circular motion. How does this relate to our new expression?



$\vec{\omega} = \omega\hat{z}$, with $\omega = \text{const.}$

$\vec{a}_N = a_N\hat{e}_N + a_t\hat{e}_t$, where

$$a_N = \frac{V_A^2}{R} \;\&\; a_t = \frac{dV_A}{dt}$$

$\hat{e}_N$ points from A to C and $\hat{e}_t$ is tangential to the path that A takes. For uniform circular motion $V_A = R\omega$ & $\frac{dV_A}{dt} = 0$ so $a_N = R\omega^2$ & $a_t = 0$ & $\hat{e}_N = -\hat{y}$ $\Rightarrow$

$\vec{a}_{A/C} = \vec{a}_A = R\omega^2(-\hat{y})$ If $\underline{\underline{\vec{\omega} \neq \text{const.}}}$ we get

$\frac{dV_A}{dt} = R\frac{d\omega}{dt} = R\alpha$ and $\hat{e}_t = -\hat{x}$

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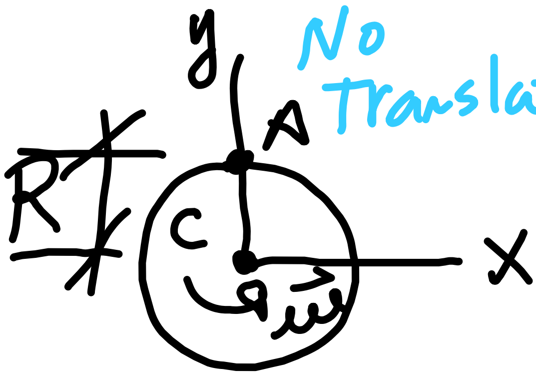


No Translation

$\vec{\omega} = \omega\hat{z}$, with $\omega = \text{const.}$

$\vec{a}_N = a_n\hat{e}_n + a_t\hat{e}_t$, where

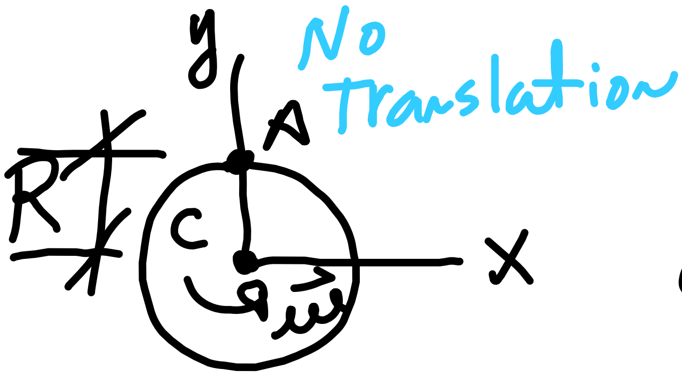
$$a_n = \frac{v_A^2}{R} \quad \& \quad a_t = \frac{dv_A}{dt}$$

$\hat{e}_n$ points from A to C and $\hat{e}_t$ is tangential to the path that A takes. For uniform circular motion $v_A = R\omega$ & $\frac{dv_A}{dt} = 0$ so $a_n = R\omega^2$ & $a_t = 0$ & $\hat{e}_n = -\hat{y}$ $\Rightarrow$

$\vec{a}_{A/C} = \vec{a}_A = R\omega^2(-\hat{y})$ If $\underline{\underline{\vec{\omega} \neq \text{const.}}}$ we get

$\frac{dv_A}{dt} = R\frac{d\omega}{dt} = R\alpha$ and $\hat{e}_t = -\hat{x}$ $\Rightarrow$ $\vec{a}_{A/C} = \alpha R(-\hat{x}) +$

In the past we used $\vec{a} = a_n\hat{e}_n + a_t\hat{e}_t$ for circular motion How does this relate to our new expression?



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$\vec{a}_{A/C} = \vec{a}_A = R\omega^2(-\hat{y})$ If $\underline{\underline{\vec{\omega} \neq \text{const.}}}$ we get

$\frac{dV_A}{dt} = R\frac{d\omega}{dt} = R\alpha$ and $\hat{e}_t = -\hat{x}$ ⇒ $\vec{a}_{A/C} = \alpha R(-\hat{x}) + R\omega^2(-\hat{y})$

Our expression $\underline{\vec{a}_{A/C} = \alpha R(-\hat{x}) + R\omega^2(-\hat{y})}$

Our expression $\vec{a}_{A/C} = \alpha R(-\hat{x}) + R\omega^2(-\hat{y})$ has to match what we would get using
$\vec{a}_{A/C} = \vec{\alpha} \times \vec{r}_{A/C} + \vec{\omega} \times [\vec{\omega} \times \vec{r}_{A/C}]$

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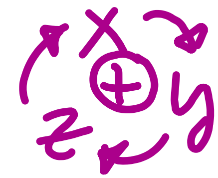

$$\vec{a}_{A/C} = \alpha R\,\hat{z}\times\hat{y} + \omega^2 R\,\hat{z}\times[\hat{z}\times\hat{y}]$$

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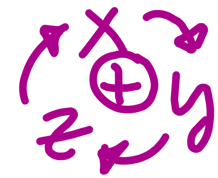

$$\vec{a}_{A/C} = \alpha R\,\hat{z} \times \hat{y} + \omega^2 R\,\hat{z} \times [\hat{z} \times \hat{y}]$$

But $\hat{z} \times \hat{y} = -\hat{x}$

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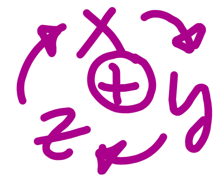

$$\vec{a}_{A/C} = \alpha R\, \hat{z} \times \hat{y} + \omega^2 R\, \hat{z} \times [\hat{z} \times \hat{y}]$$

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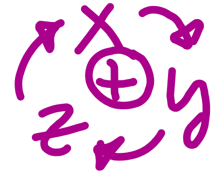

$$\vec{a}_{A/C} = \alpha R\, \hat{z} \times \hat{y} + \omega^2 R\, \hat{z} \times [\hat{z} \times \hat{y}]$$

But $\hat{z} \times \hat{y} = -\hat{x}$ & $\hat{z} \times (-\hat{x}) = -\hat{y}$ so

$$\vec{a}_{A/C} = \alpha R(-\hat{x}) + \omega^2 R\, \hat{z} \times (-\hat{x})$$

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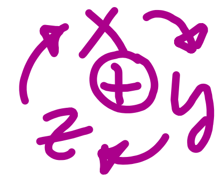

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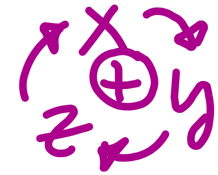


$$\vec{a}_{A/C} = \alpha R\,\hat{z}\times\hat{y} + \omega^2 R\,\hat{z}\times[\hat{z}\times\hat{y}]$$

But $\hat{z}\times\hat{y} = -\hat{x}$ & $\hat{z}\times(-\hat{x}) = -\hat{y}$ so

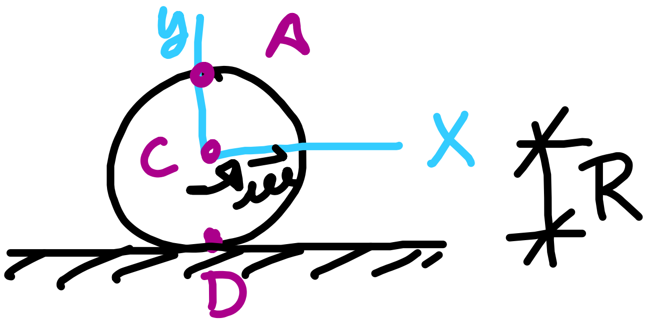
$$\vec{a}_{A/C} = \alpha R(-\hat{x}) + \omega^2 R\,\hat{z}\times(-\hat{x}) \Rightarrow$$

$$\vec{a}_{A/C} = \alpha R(-\hat{x}) + \omega^2 R(-\hat{y})$$

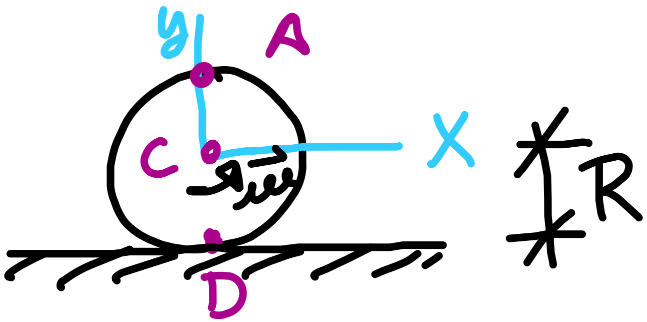
matches previous expression

Example: Wheel rolling w/no slip

Example: Wheel rolling w/no slip

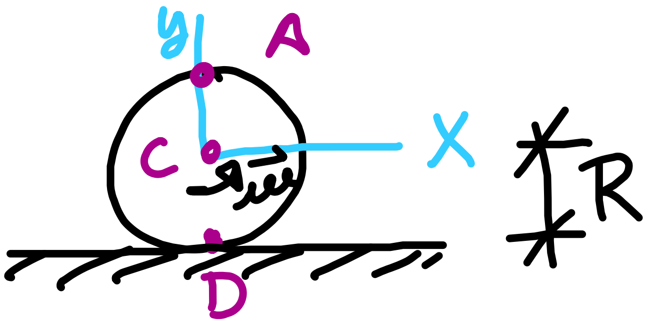


Example: Wheel rolling w/no slip



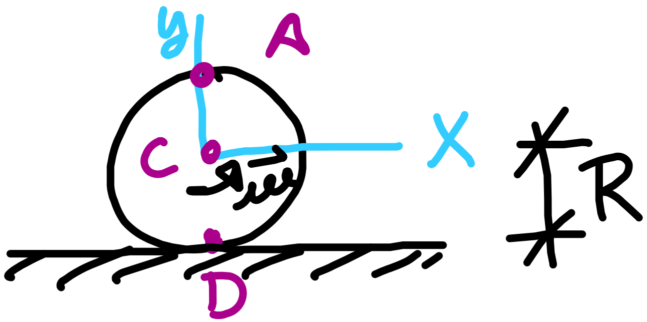
$$\vec{a}_A = \vec{a}_{A/C} + \vec{a}_C$$

Example: Wheel rolling w/no slip



$\vec{a}_A = \vec{a}_{A/C} + \vec{a}_c$ **If** $\vec{v}_c = const.$

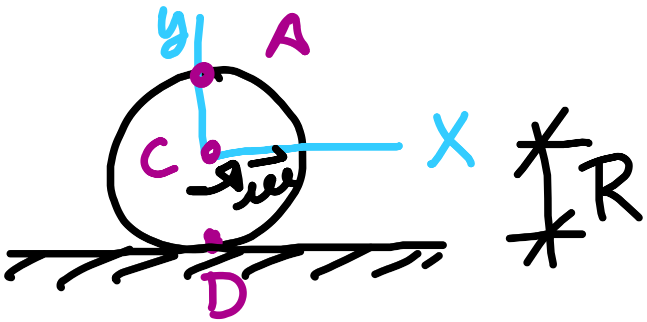
Example: Wheel rolling w/no slip



$\vec{a}_A = \vec{a}_{A/C} + \vec{a}_C$ <u>If</u> $\vec{v}_C = \text{const.}$

then $\vec{a}_C = 0$

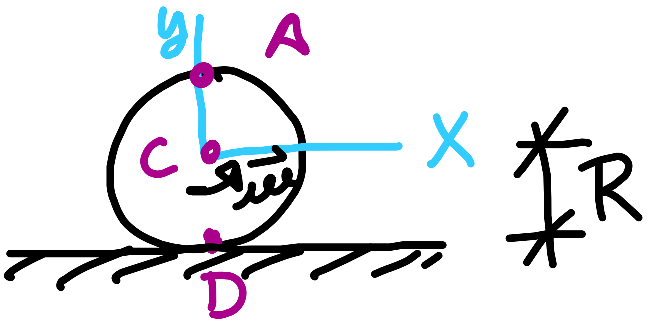
Example: Wheel rolling w/no slip



$\vec{a}_A = \vec{a}_{A/C} + \vec{a}_C$ <u>If</u> $\vec{v}_C = \text{const.}$

then $\vec{a}_C = 0$ & $\vec{\alpha} = 0$

Example: Wheel rolling w/no slip

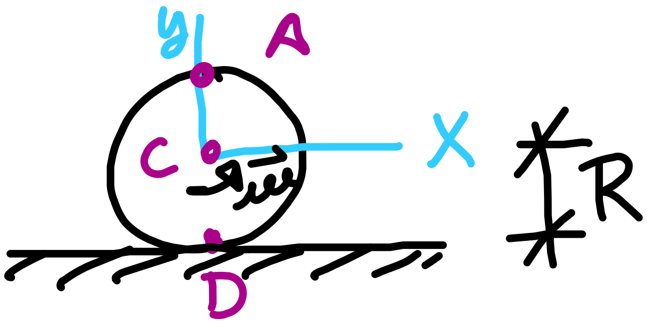


$\vec{a}_A = \vec{a}_{A/C} + \vec{a}_c$ <u>If</u> $\vec{v}_c = \text{const.}$

then $\vec{a}_c = 0$ & $\vec{\alpha} = 0$

& $v_c = R\omega$

Example: Wheel rolling w/no slip

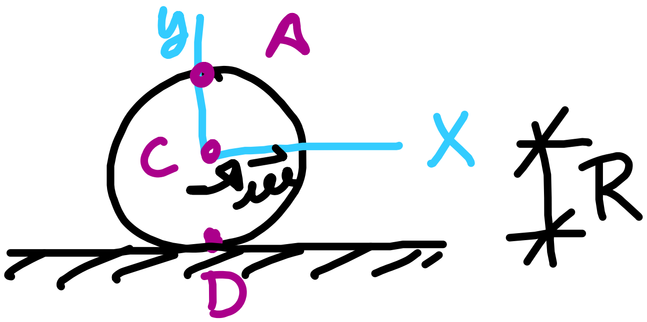


$\vec{a}_A = \vec{a}_{A/C} + \vec{a}_C$ If $\vec{v}_C = \text{const.}$

then $\vec{a}_C = 0$ & $\vec{\alpha} = 0$

& $v_C = R\omega$ If $v_C \neq \text{const.}$

Example: Wheel rolling w/no slip



$\vec{a}_A = \vec{a}_{A/C} + \vec{a}_C$ $\underline{\underline{\text{If}}}$ $\vec{v}_C = \text{const.}$

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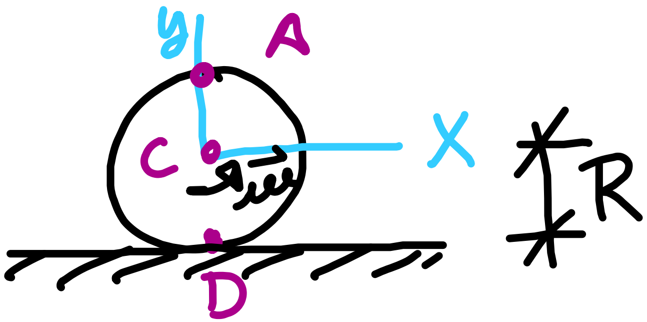
& $v_C = R\omega$ $\underline{\underline{\text{If}}}$ $v_C \neq \text{const.}$

then $\vec{\alpha} \neq 0$

Example: Wheel rolling w/no slip



$\vec{a}_A = \vec{a}_{A/C} + \vec{a}_c$

If $\vec{v}_c = \text{const.}$

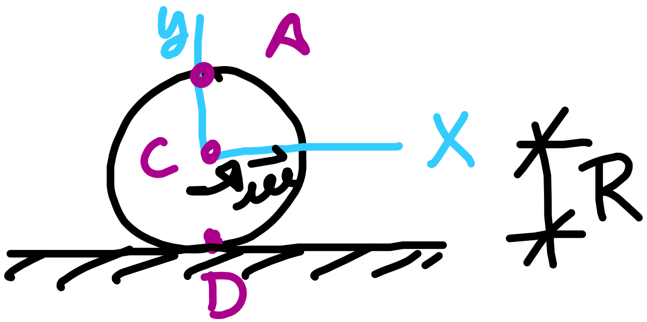
then $\vec{a}_c = 0$ & $\vec{\alpha} = 0$

& $v_c = R\omega$

If $v_c \neq \text{const.}$

then $\vec{\alpha} \neq 0$ & $a_c \neq 0$

Example: Wheel rolling w/no slip

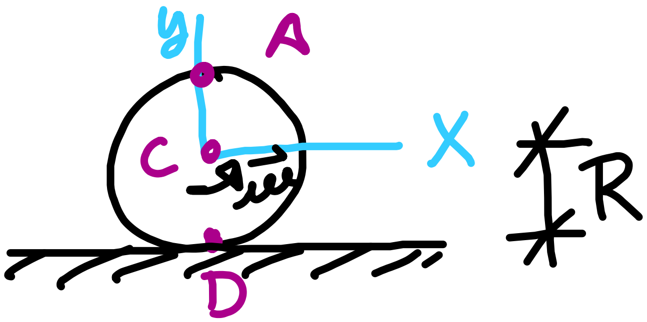


$\vec{a}_A = \vec{a}_{A/C} + \vec{a}_c$

If $\vec{v}_c = \text{const.}$ then $\vec{a}_c = 0$ & $\vec{\alpha} = 0$ & $v_c = R\omega$

If $v_c \neq \text{const.}$ then $\vec{\alpha} \neq 0$ & $a_c \neq 0 \Rightarrow \vec{a}_A = \alpha R(-\hat{x}) + \omega^2 R(-\hat{y}) + \vec{a}_c$

Example: Wheel rolling w/no slip



$\vec{a}_A = \vec{a}_{A/C} + \vec{a}_c$ **If** $\vec{v}_c = \text{const.}$

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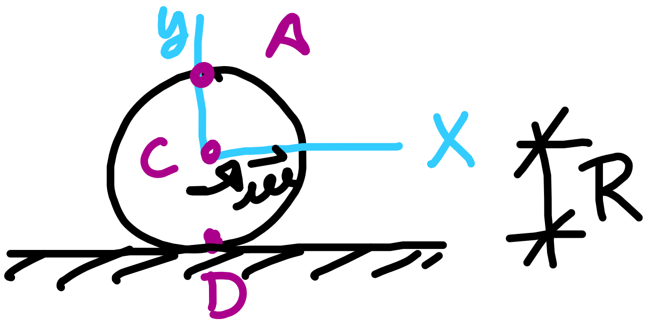
& $v_c = R\omega$ **If** $v_c \neq \text{const.}$

then $\vec{\alpha} \neq 0$ & $a_c \neq 0 \Rightarrow \vec{a}_A = \alpha R(-\hat{x}) + \omega^2 R(-\hat{y}) + \vec{a}_c$

Example: Flywheel on shaft rolling on rail

Example: Wheel rolling w/no slip



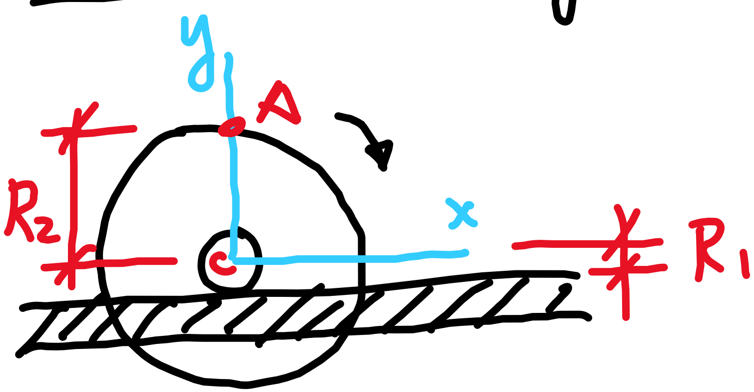
$\vec{a}_A = \vec{a}_{A/C} + \vec{a}_C$ <u>If</u> $\vec{v}_C = \text{const.}$

then $\vec{a}_C = 0$ & $\vec{\alpha} = 0$

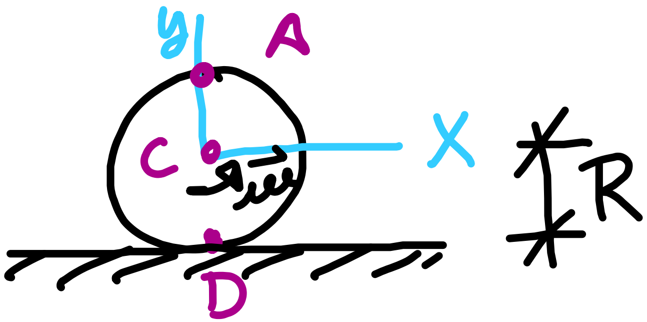
& $v_C = R\omega$ <u>If</u> $v_C \neq \text{const.}$

then $\vec{\alpha} \neq 0$ & $a_C \neq 0 \Rightarrow \vec{a}_A = \alpha R(-\hat{x}) + \omega^2 R(-\hat{y}) + \vec{a}_C$

Example: Flywheel on shaft rolling on rail



Example: Wheel rolling w/no slip



$\vec{a}_A = \vec{a}_{A/C} + \vec{a}_C$ **If** $\vec{v}_C = \text{const.}$

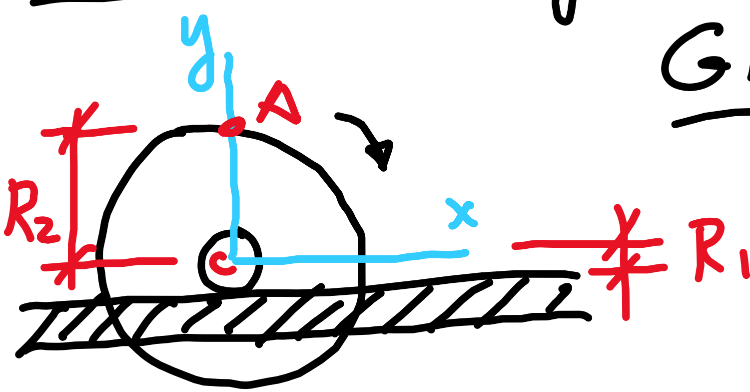
then $\vec{a}_C = 0$ & $\vec{\alpha} = 0$

& $v_C = R\omega$ **If** $v_C \neq \text{const.}$

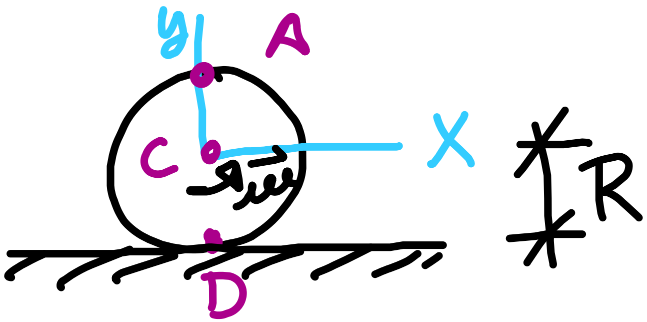
then $\vec{\alpha} \neq 0$ & $a_C \neq 0 \Rightarrow \vec{a}_A = \alpha R(-\hat{x}) + \omega^2 R(-\hat{y}) + \vec{a}_C$

Example: Flywheel on shaft rolling on rail

Given v_C, a_C, R_1 & R_2



Example: Wheel rolling w/no slip



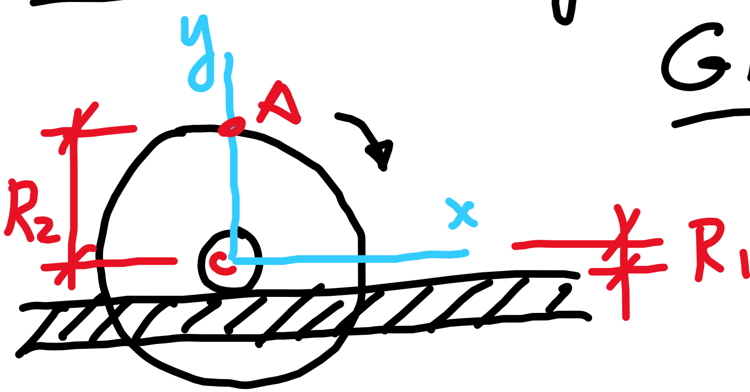
$\vec{a}_A = \vec{a}_{A/C} + \vec{a}_C$ **If** $\vec{v}_C = \text{const.}$

then $\vec{a}_C = 0$ & $\vec{\alpha} = 0$

& $v_C = R\omega$ **If** $v_C \neq \text{const.}$

then $\vec{\alpha} \neq 0$ & $a_C \neq 0 \Rightarrow \vec{a}_A = \alpha R(-\hat{x}) + \omega^2 R(-\hat{y}) + \vec{a}_C$

Example: Flywheel on shaft rolling on rail



Given v_C, a_C, R_1 & R_2 Find $\vec{a}_A$:

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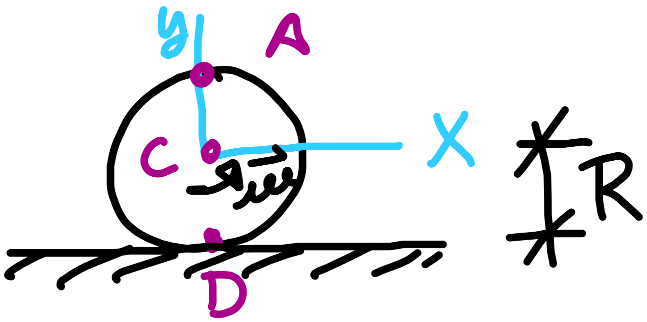

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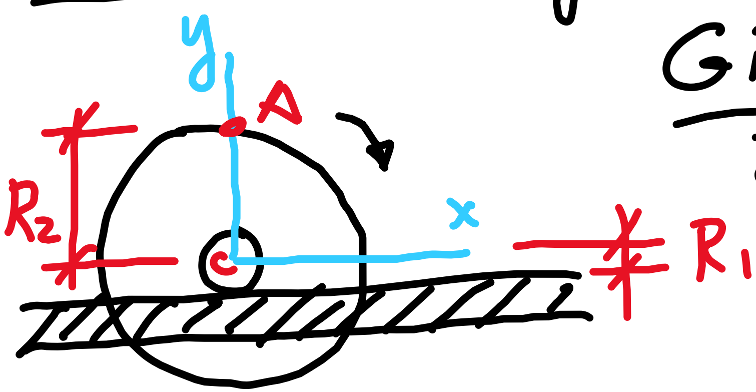
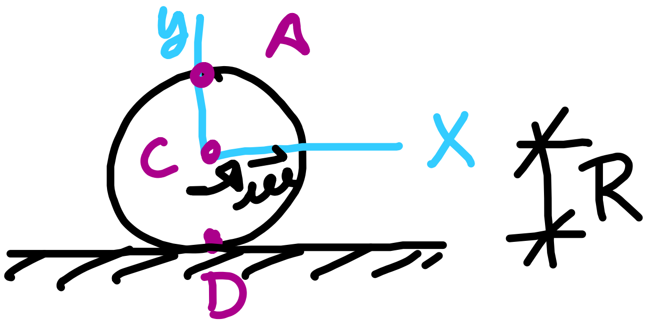


Given v_C, a_C, R_1 & R_2 Find $\vec{a}_A$:

$$\vec{a}_{A/C} = \vec{\alpha} \times \vec{r}_{A/C} + \vec{\omega} \times [\vec{\omega} \times \vec{r}_{A/C}]$$

Need to obtain $\vec{\alpha}, \vec{r}_{A/C}$ & $\vec{\omega}$ from v_C, a_C, R_1 & R_2

Example: Wheel rolling w/no slip



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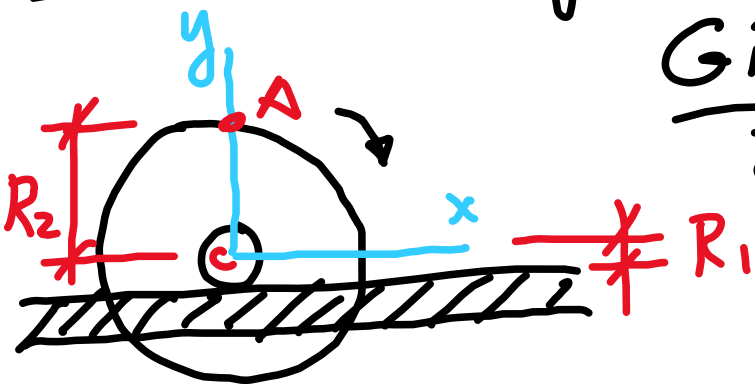

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$\vec{v}_C = \omega R_1 \hat{x}$

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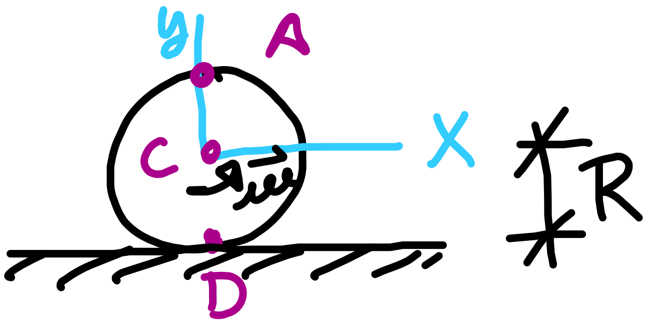

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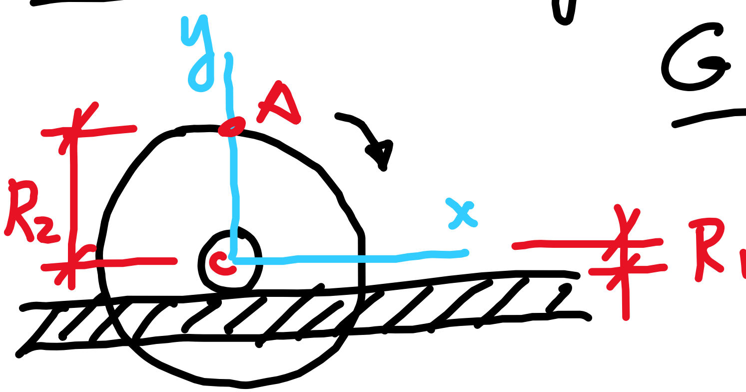

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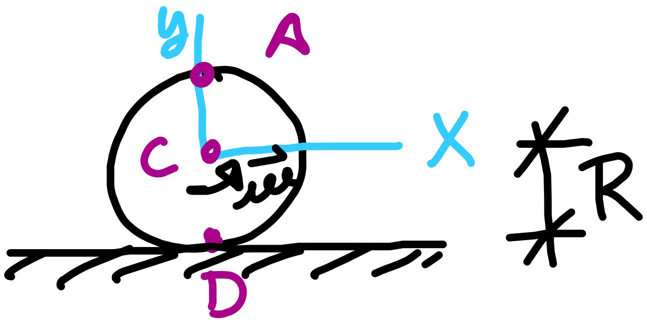

$\vec{a}_A = \vec{a}_{A/C} + \vec{a}_C$ **If** $\vec{v}_C = \text{const.}$

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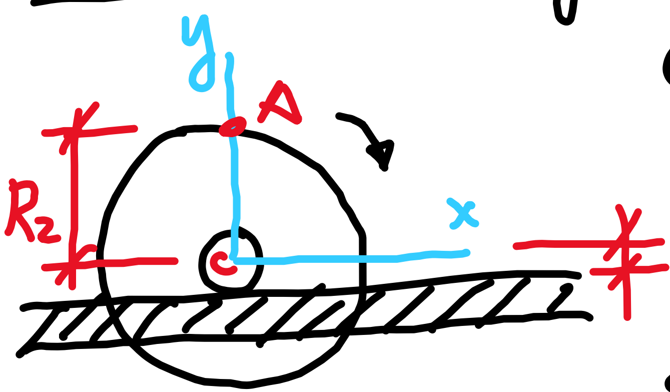

Given v_C, a_C, R_1 & R_2 Find $\vec{a}_A$:

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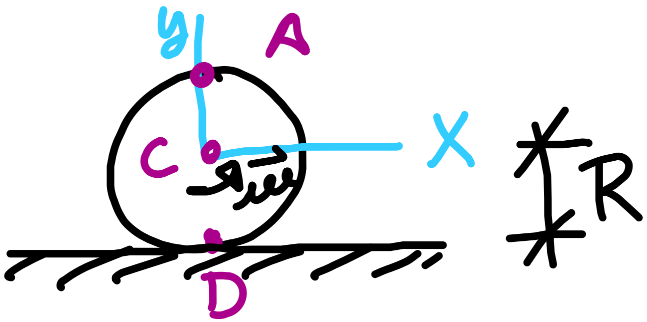

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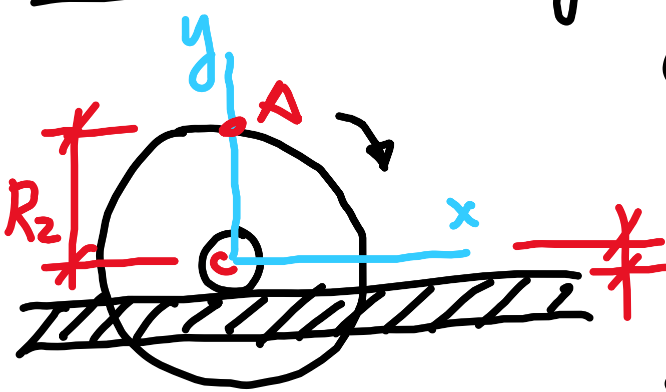

<u>Given v_C, a_C, R_1 & R_2</u> <u>Find $\vec{a}_A$</u>:

$\vec{a}_{A/C} = \vec{\alpha} \times \vec{r}_{A/C} + \vec{\omega} \times [\vec{\omega} \times \vec{r}_{A/C}]$

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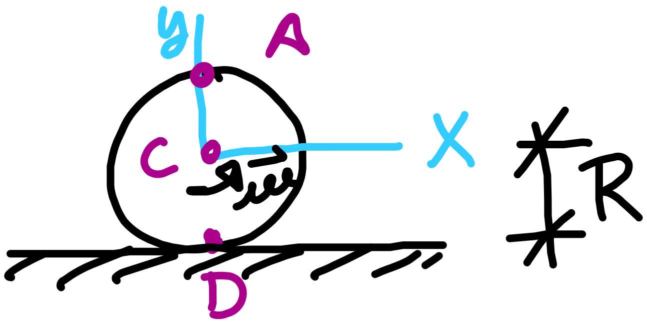

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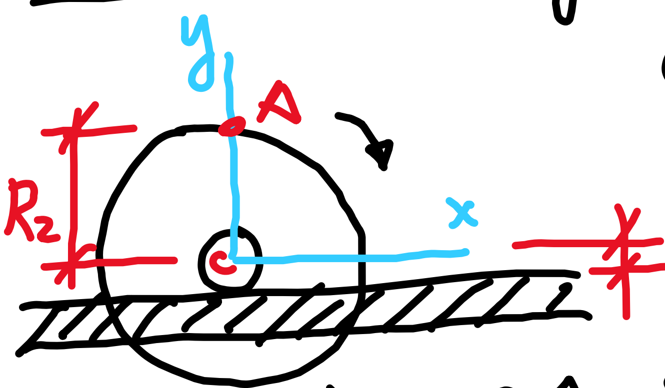

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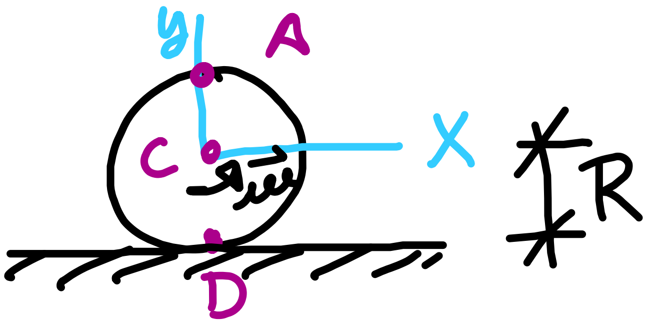
& $\vec{a}_C = \alpha R_1 \hat{x}$ so $\vec{\alpha} = (a_C/R)(-\hat{z})$

Also $\vec{r}_{A/C} = R_1 \hat{y}$

Example: Wheel rolling w/no slip



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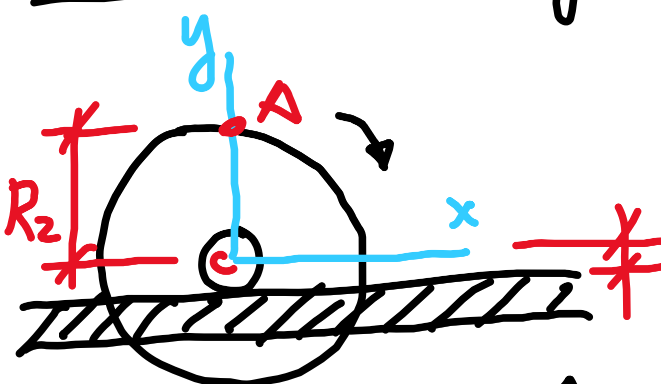

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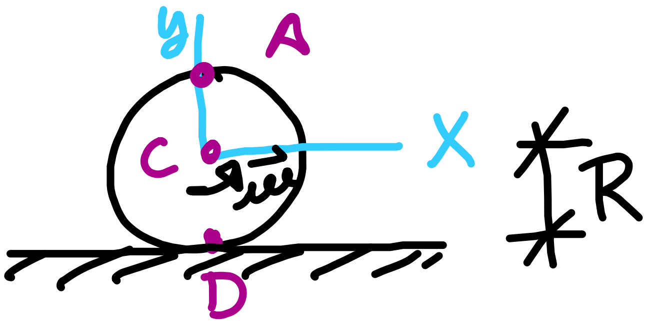
Example: Wheel rolling w/no slip



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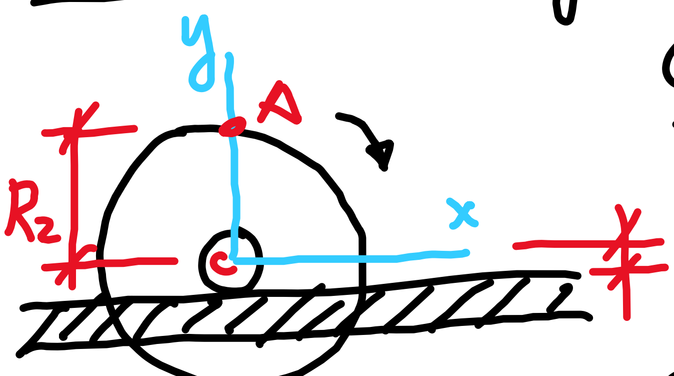

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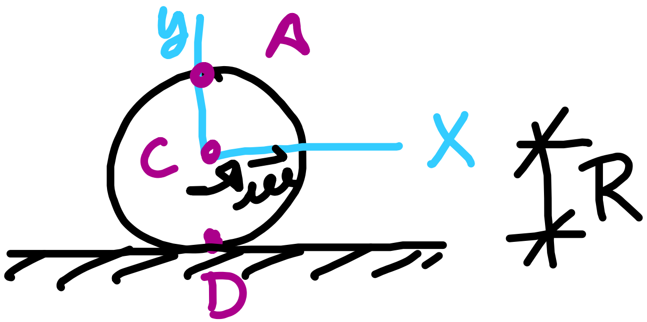
Also $\vec{r}_{A/C} = R_1 \hat{y}$ so $\vec{a}_A = \vec{a}_{A/C} + \vec{a}_C = \frac{a_C}{R_1} R_2 (-\hat{z}) \times \hat{y} +$

$\frac{V_C^2}{R_1^2} R_2 \hat{z} \times [\hat{z} \times \hat{y}] + \vec{a}_C$

Example: Wheel rolling w/no slip



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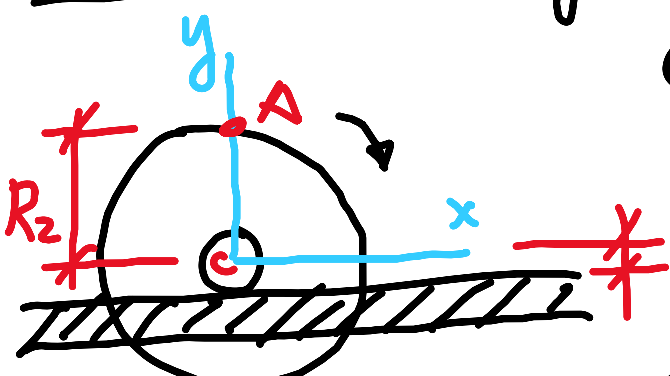
Example: Flywheel on shaft rolling on rail



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Also $\vec{r}_{A/C} = R_1 \hat{y}$ so $\vec{a}_A = \vec{a}_{A/C} + \vec{a}_C = \frac{a_C}{R_1} R_2 (-\hat{z}) \times \hat{y} +$

$$\frac{v_C^2}{R_1^2} R_2 \hat{z} \times [\hat{z} \times \hat{y}] + \vec{a}_C = \left(\frac{a_C R_2}{R_1}\right)\hat{x} + a_C \hat{x} + \left(\frac{v_C^2}{R_1^2}\right)(R_2)(-\hat{y})$$

<u>Note</u>: In this case $\vec{a}_c = a_c \hat{x}$

Note: In this case $\vec{a}_c = a_c \hat{x}$ If rail was tilted some angle θ with respect to horizontal

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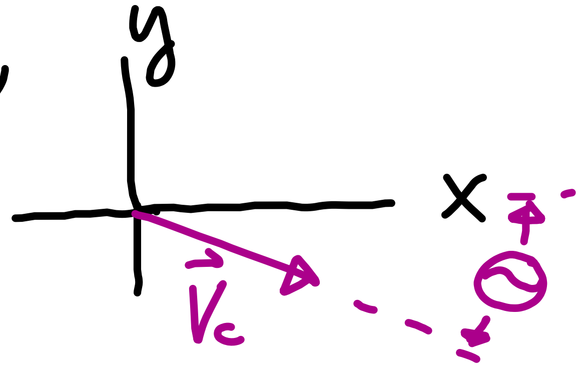
Then



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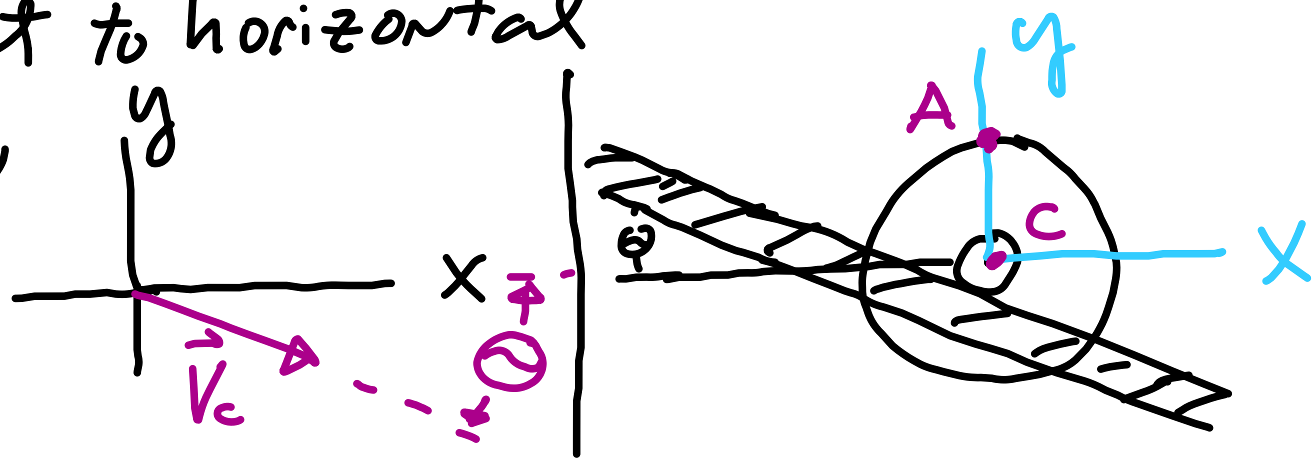

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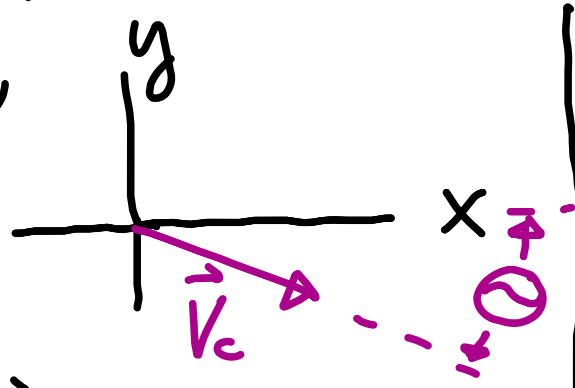
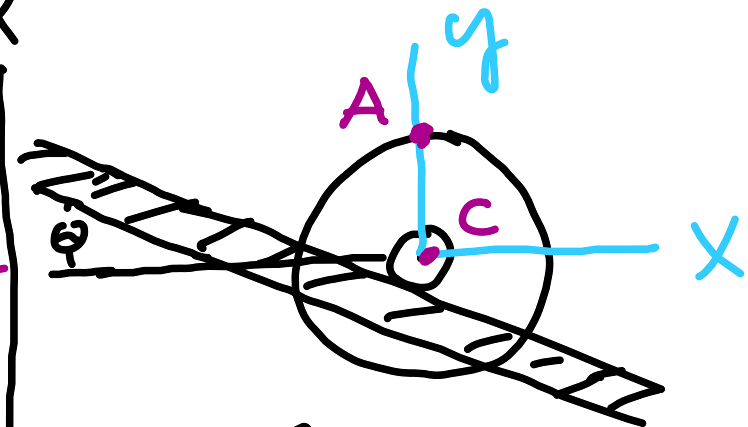
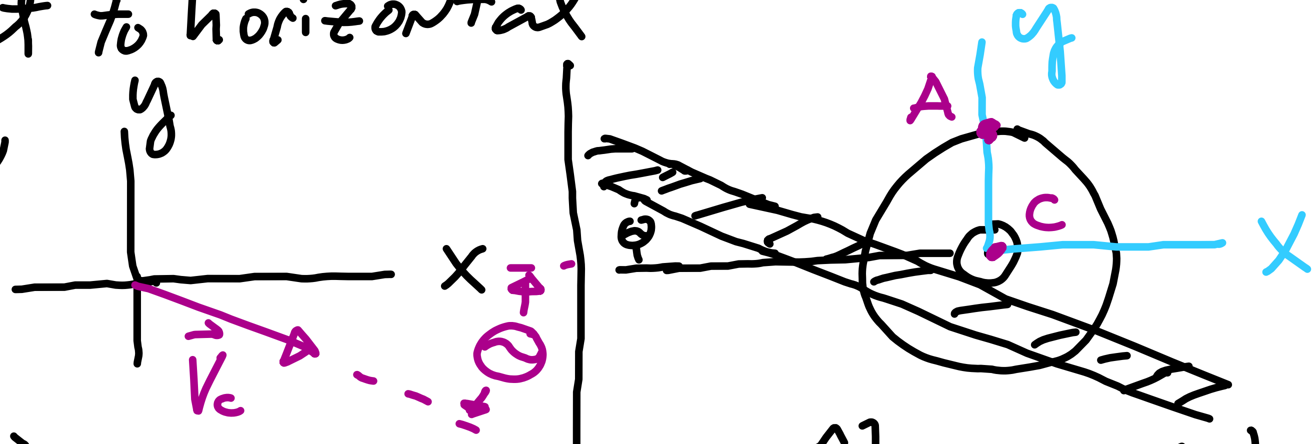




& $\vec{V}_c = V_c[\cos\theta\hat{x} - \sin\theta\hat{y}]$

Note: In this case $\vec{a}_c = a_c \hat{x}$ If rail was tilted some angle θ with respect to horizontal

Then



& $\vec{V}_c = V_c[\cos\theta\,\hat{x} - \sin\theta\,\hat{y}]$ Just have to be consistent with the sign convention

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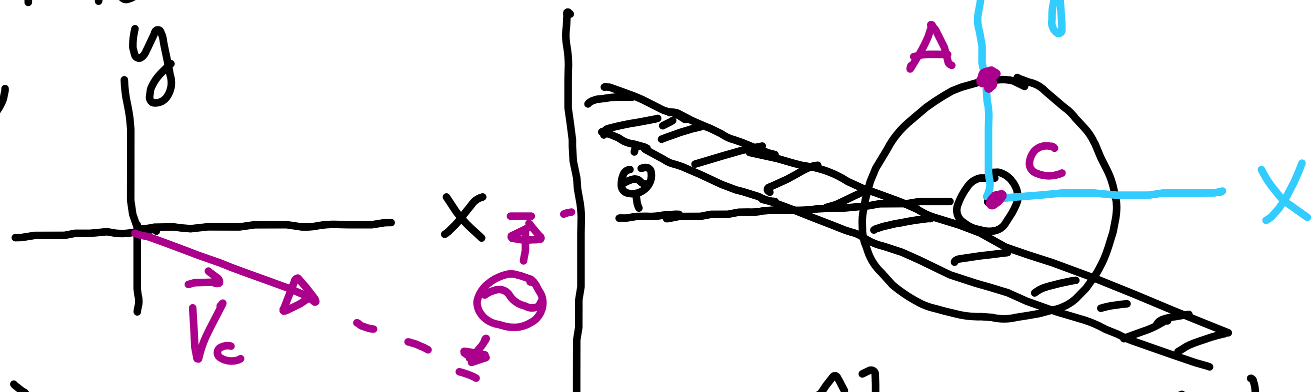

& $\vec{V}_c = V_c[\cos\theta\,\hat{x} - \sin\theta\,\hat{y}]$ Just have to be consistent with the sign convention

Also [Keeping $\theta > 0$] $\vec{a}_c = a_c\cos\theta\,\hat{x} - a_c\sin\theta\,\hat{y}$

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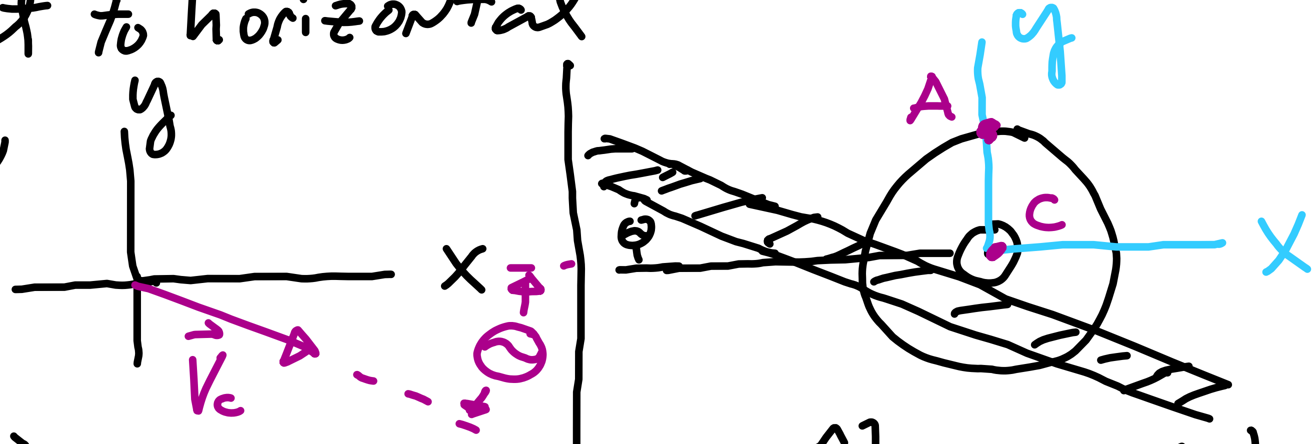
Then



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Also [Keeping $\theta > 0$] $\vec{a}_c = a_c\cos\theta\hat{x} - a_c\sin\theta\hat{y}$

Now

$$\vec{a}_A = \left\{\left[\frac{a_c R_2}{R_1}\right]\hat{x} + a_c\cos\theta\hat{x}\right\} + \left\{\left[\frac{V_c^2}{R_1^2}R_2\right](-\hat{y}) + a_c\sin\theta\hat{y}\right\}$$