

## Using Conservation Laws

Ahmed Saad Sabit

April 16, 2021

# Introduction to Momentum

Momentum defines some mechanical characteristics.

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

For a constant mass body, if we take derivative,

$$\frac{dp}{dt} = m \frac{dv}{dt} = F$$

So, rate of change of momentum is force.

## Example of momentum

Assume two blocks of same mass.

You need to push the blocks.

One block will have a speed of  $10 \frac{m}{s}$ , (say) and another shall have  $100 \frac{m}{s}$ , which one has greater momentum?

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- $(m_1 + m_2)\vec{v}_{COM} = m_1\vec{v}_1 + m_2\vec{v}_2$ .

## Momentum if there is no external force

Suppose in a system there are masses, but there is no external source of *Force*. Then by definition,

$$\frac{dp}{dt} = m \frac{dv}{dt} = F$$

Now,  $F = 0$ , thus,

$$\frac{dp}{dt} = 0$$

that is  $p$  is a constant. As you know,

$$\frac{d}{dt} C = 0$$

Where if  $C$  is a constant that doesn't vary with time. Now, if our system starts from *rest*, then there is no momentum either, that means,  $p$  is 0 for initial rest.

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If it happens that system starts from rest, then total momentum is zero. We will use these to solve problems later.

# The real force Equation

## Idea

The real definition of Force is

$$\vec{F} = \frac{d\vec{p}}{dt}$$

And believe me this is much more useful than  $\vec{F} = m\vec{a}$  sometimes

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- If there is no external force, change of  $\vec{p}$  momentum is zero, which means, the value of **momentum is constant**.
- The better formulation for  $\vec{F}$ orce is,

$$\vec{F} = \frac{d\vec{p}}{dt}$$

- Momentum is a type of Conserved quantity in many problems. We can use this at your

## A small problem to show how $\vec{p} = m\vec{v}$ is used

### Problem.

Suppose there is a ball (name first ball) that is moving in the  $x$  axis in  $v$  speed. And suppose another ball (name second ball) comes and hit the ball at  $u$  speed, but a bit on the side, not center.

So the two balls move away in opposite directions and the angle the two trajectory make is  $\alpha$  *symmetrically*

We know that the first ball moves away with velocity  $\vec{v}'$  and we perfectly know about it.

But we don't know anything about the second ball velocity after collision. Find it.

Before Collision

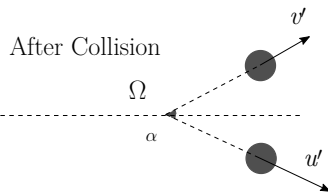
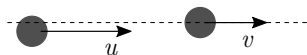


Figure:

## Task for problem 4

We don't know the second ball speed, call it  $u'$ , we have to find it.

## Clear what a vector conserved looks like

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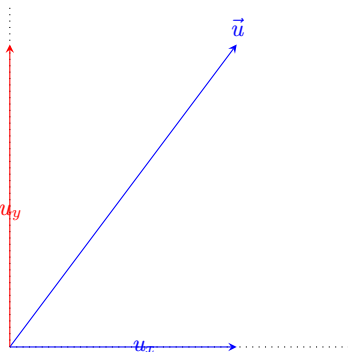
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Obviously if you have  $\vec{u}$ , then  $u_x$  means,

$$u_x = u \cos \theta$$

$$u_y = u \sin \theta$$

Depending on the system. Momentum will be conserved in the  $x$  axis and  $y$  axis separately.



## Problem 4

Momentum is going to be conserved in this case, because there is no external source that is causing force into the balls.

Momentum along  $x$  axis is going to be conserved,

$$P_x = mu + mv = m(u + v)$$



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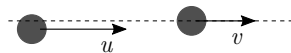
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**This is before collision**

Before Collision



After Collision

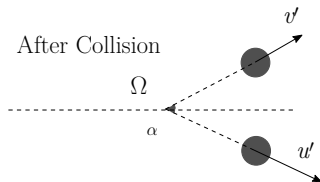


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Momentum of the ball's after collision,

$$P'_x = mv' \cos 30^\circ + mu' \cos 30^\circ$$

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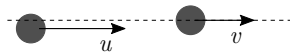
Note that we have to find  $u'$ .

Momentum of the ball's along  $y$  axis after the collision,

$$P'_y = mv' \sin 30^\circ - mu' \sin 30^\circ$$

This above equation is solely caused because of the opposite direction of the  $u'$  along  $y$  axis relative to  $v'$ .

Before Collision



After Collision

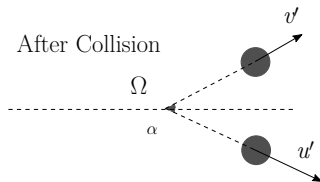


Figure:

## Problem 4 equation solving

From the conservation of momentum, we know that the,

### Idea

Momentum before and after collision is the same if no external force acts on the system

, hence,

$$P_x = P'_x$$

$$P_y = P'_y$$

This tell's us,

$$m(v + u) = m \cos 30^\circ (v' + u')$$

$$0 = m \sin 30^\circ (v' - u')$$

Because this problem had some nice symmtry and  $m_1 = m_2$  for the two balls, the solution is simple, we directly get,

$$v' = u'$$

We can also solve for  $v'$  in terms of  $v, u$ . But information has already been given in the problem.

# Energy and Work

Energy is like a currency, it increases if fed, decreases if used.  
If you apply *Work* to a system, then it's *Energy* will increase.

$$W = \Delta E$$

Where work is equal to the change in system energy.

**For Example:** if you put Work on a block resting on a frictionless surface, it's Energy will increase.

**What energy?** It can be Kinetic energy, for which the Speed of the block increase.

**Otherwise** it can be Thermal energy for which the temperature Increase.

# Define Work

Let me be clear from the first minute.

Let us have a **system** that has no energy at first,

$$E = 0$$

Now, if you feed in  $W$  amount of work, it will be,

$$W = \Delta E$$

This increase of Energy is exactly equal to work. (Remember this).

Now,

$$W = \Delta E = E_{final} - E_{initial} = E_{final} - 0 = E_{final}$$

Because the system had **No Energy**, thus,

$$W = E_{final}$$

## Idea

So remember this, if a system starts from 0 energy, then the final energy is exactly equal to the work done

# Mathematical Definition of Work

Work is defined to be, exactly,

$$W = \int_a^b \vec{F} \cdot d\vec{l}$$

But I hope you don't need to use it now, stick with this simple definition, for a constant force,

$$W = Fx \cos \theta$$

You will use integral form if  $F$  is not constant in magnitude or it's direction changes.



## Work is giving force of $F$ for $x$ distance

We are pushing a block with  $F$  force along the  $x$  axis for a distance  $d$ , then the work done, assumed  $F$  stays constant,

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$$W = Fd = (ma) d$$

Now this can be solved a little more, as we know (from kinematics),

$$v^2 = 2ad$$

Hence,

$$W = md \frac{v^2}{2d} = \frac{1}{2}mv^2$$

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So work done is  $v$ , which starts from 0 to  $v$ . End because we started from  $E = 0$ , this is also that,  $E_f = \frac{1}{2} mv^2$  Don't know  $v^2 = 2ad$ ? No problem, we have better formula.

# Integrals look Cute for Kinetic Energy

We just know for  $E_i = 0$  so,

$$E_f = W = \int F \cdot dx$$

We can solve this,

$$E_f = \int ma \cdot dx$$

$$E_f = \int m \frac{dv}{dt} dx = \int m dv \frac{dx}{dt} = \int mv \, dv$$

This is easy,

$$E_f = \int mv \, dv = \frac{1}{2}mv^2 + C$$

For  $E_i = 0$ ,  $v = 0$ , so,  $C = 0$ , thus,

$$E_f = \frac{1}{2}mv^2$$

This is kinetic Energy.

If we pull something against the ground, the gravity pulls it down. We have to lift up with slightly more force than gravity pointing up to lift it,

$$W = \int mg \cdot dh = mgh$$

This stores potential energy of gravity in the mass. After lifting  $h$  height, and letting go that mass  $m$  will turn to  $\frac{1}{2}mv^2$  as it falls.

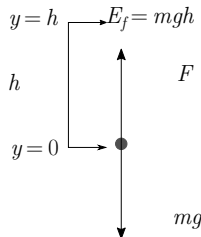


Figure:

# Standard Pendulum

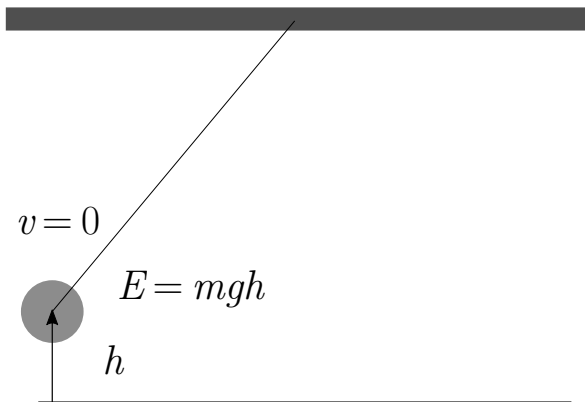


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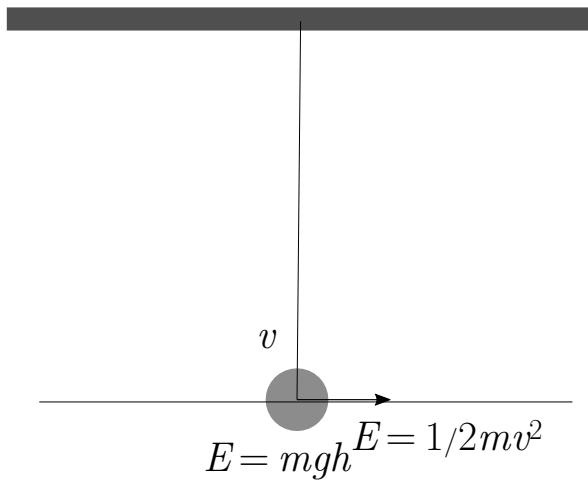


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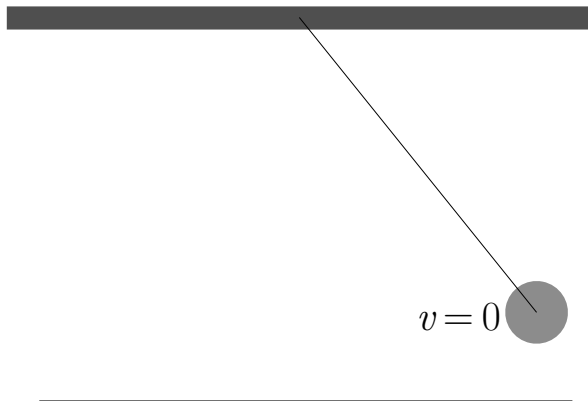


Figure:

## Problem 5: Using Energy and Pendulum

### Problem.

String  $l$  length hangs a rod at the end of length  $l$ . The two ceiling and ground has distance  $H$ . There is no friction so,  $\mu = 0$  for all case. Now, if the rod starts to move and slide, find the *maximum speed* of the rods center of mass. Mass of rod is  $m$ .

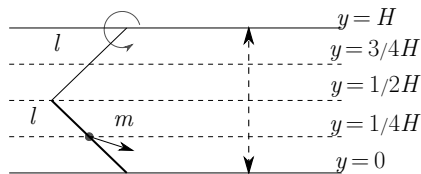


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## Problem 5: We need the speed at lowest possible point

We need the lowest position height first.

- At lowest, there we can see the rod is within  $H - l$  region.
- The *COM* is at the center of it, so, height of COM is,

$$h = \frac{H - l}{2}$$

- The potential Energy at that lowest point is,

$$E_p = mg \frac{H - l}{2}$$

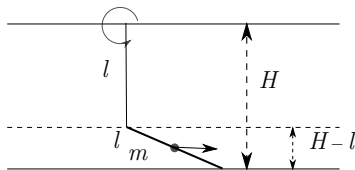


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- Where this change go? It goes to increase kinetic energy.

$$\Delta E_k = \frac{1}{2}mv^2 - 0 = mg\left(l - \frac{H}{2}\right)$$

Solve this for  $v$  and we have,

$$v = \sqrt{g\left(l - \frac{H}{2}\right)}$$

## Some extra on Potential Energy

Remember this,

*Potential Energy will appear if and only if there is a Force Field.*

And always keep this in mind that **Potential Energy is relative to position.**

What do I mean with this?

- In gravity, if you pull something from the ground up, then some energy is used to pull it up. Where is that energy now? It is stored as Potential Energy.

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- In electric field, to move a charge you need to put energy, that is stored as Potential energy in cases.

If there is a force  $\vec{F}_e$  from a field, then you have to put  $-\vec{F}_e$  to move something against it. This force that you give requires you to spend energy. That spent energy is the work.

$$\int -\vec{F} \cdot d\vec{x} = W$$

If this  $F$  force is used against a sort of field, then this  $W$  work can be stored as potential energy. So,

$$E_p = - \int \vec{F} \cdot d\vec{x}$$



# Chain rule

$$\frac{df}{dx} = \frac{dt}{dx} \frac{df}{dt}$$

if  $f = f(t)$  and you need to solve for  $\frac{df(t)}{dx}$ .

# The Easy Analytical Mechanics Method

## Idea

Total Energy in a system can be,

$$E = \frac{1}{2} \mathcal{M} v^2 + E_p$$

$E_p$  is the Potential depending on the system, gravity or anything else. Let us take a differential,

$$\frac{d}{dt} E = \frac{1}{2} \mathcal{M} \frac{d}{dt} v^2 + \frac{d}{dt} E_p$$

Now,

$$\frac{d}{dt} v^2 = \frac{dv}{dt} \frac{dv^2}{dv} = 2av$$

Now, if our potential energy is written with dependency on  $x$  coordinate, then,

$$\frac{d}{dt} E_p(x) = \frac{dx}{dt} \frac{dE_p}{dx} = v \frac{dE_p}{dx}$$

Hence, this equation solves to,

$$0 = \mathcal{M}av + v \frac{dE_p}{dx} \rightarrow \boxed{a = -\frac{\frac{dE_p}{dx}}{\mathcal{M}} = -\frac{E'_p(x)}{\mathcal{M}}}$$

# Description of the Method

## Idea

For a position variable  $x$  in this case,

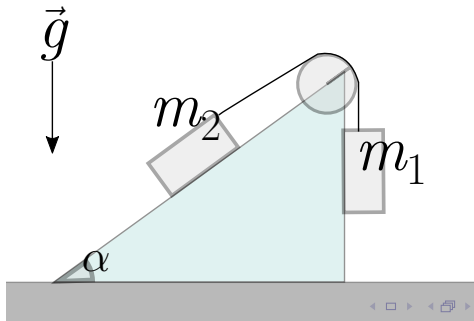
$$a = -\frac{E'_p(x)}{\mathcal{M}}$$

Here,  $\mathcal{M}$  is the part of kinetic energy if it can be written in the form  $\frac{1}{2}\mathcal{M}v^2$ .  $a$  is the acceleration.  $E'_p(x) = \frac{dE_p(x)}{dx}$  derivative. We can find acceleration using Energy equation. Remember there can only be one variable, this case  $x$ .

## Problem 1: LOL Again

### Problem.

There is a system made of an incline with two masses attached with string as shown. One is  $m_1$  another is  $m_2$ , gravity works  $\vec{g}$ . Find the acceleration of both bodies  $m_1$  and  $m_2$ .



## Problem 1: Using Energy Technic

So, suppose the blocks move from their initial position. The  $m_2$  moves along the ramp and the  $m_1$  block comes down with  $x$  distance. This will cause the  $m_2$  to raise up in height too.

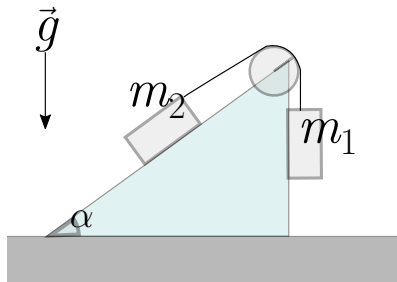


Figure:

## The Position Variable $x$ .

Now, for  $x$  shift along height for  $m_1$ , the  $m_2$  will gain some height along the ramp. So,

## Problem 1: Find the Energy exchange

If  $m_1$  comes down by  $x$ , then there is some potential energy by  $m_1$  lost.  
This potential energy will,

- Increase Kinetic energy of both  $m_1$  and  $m_2$ .

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The equation,

Energy lost by one = Energy gained by other parts

$$m_1 g x = \frac{1}{2} (m_1 + m_2) v^2 + m g \sin \alpha x$$

## Problem 1: Taking the Derivative

We will take derivative respect to time,

$$\frac{d}{dt}(m_1 g x) = \frac{d}{dt} \left( \frac{1}{2} (m_1 + m_2) v^2 + m g \sin \alpha x \right)$$

This is,

$$m_1 g v = (m_1 + m_2) v a + m_2 g \sin \alpha v$$

Factor off  $v$  and solve for acceleration  $a$ , that gives,

$$a = \frac{g(m_1 - m_2 \sin \alpha)}{m_1 + m_2}$$

Weirdly this result is correct.

## Problem 1: With friction

This equation will work assuming  $m_1$  gets down.

Energy lost = Energy gained by other parts of same system

So, this equation is now,

$$m_1 g x = \frac{1}{2} (m_1 + m_2) v^2 + m_2 g \cos \alpha x + m_2 g \sin x$$

$$\frac{d}{dt}(m_1 g x) = \frac{d}{dt} \left( \frac{1}{2} (m_1 + m_2) v^2 + m_2 g \mu \cos \alpha x + m_2 g \sin x \right)$$

This solves similiary,

$$a = \frac{g(m_1 - m_2 \sin \alpha - m_2 \mu \cos \alpha)}{m_1 + m_2}$$

This can be done the same with  $m_1$  towing up.

# The most powerful method of Mechanics

## Idea

This idea of Using Analytical Mechanics (taking derivative of Energy keeping a variable) is the most useful technique in case of complex mechanical systems)

## But why this Energy Technique Works?

Sneak peek to the inside of the thing.

So, the basic reason for this is that, you know, that for force case, we can solve it just using force balances and using  $F = ma$ . But in case of energy, you know that,  $\int F \cdot dx = W$ .

In case of Energy, we are considering the integral of forces respect to  $x$ . And when we differentiate the energy, we are left with force again.

Why will you use Energy Technique of doing when you already have  $\vec{F} = m\vec{a}$ ?

- Energy method is much more straightforward in almost  $\frac{1}{2}$  of the cases than  $\vec{F}$  force balance.

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# Why will you use Energy Technique of doing when you already have $\vec{F} = m\vec{a}$ ?

- Energy method is much more straightforward in almost  $\frac{1}{2}$  of the cases than  $\vec{F}$  force balance.
- All you need to do is correctly find the energy and just differentiate it without any further thinking.
- In case of  $\vec{F}$  force method, you need to do intense geometry, some times, and need to solve a system of equations. You don't need to do this in Energy technique.

- Analytical Mechanics

# Further Reference to Energy Method

- Analytical Mechanics
- Lagrangian
  - Euler Lagrangian equation.

## Problem 2: Again, but using Ninja technique

Find stable position.

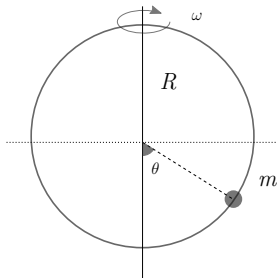


Figure:

We are going to write the total energy, and it's constant, and that's the trick

$$E = \frac{1}{2}mv_{rot}^2 + \frac{1}{2}mv_{\text{along circle}}^2 - mgR \cos \theta$$

Please note, we are going to consider the horizontal line containing circle center to be  $V = 0$ , to it's relative we will measure the potential energy. So, below it potential energy is negative, so we take negative.

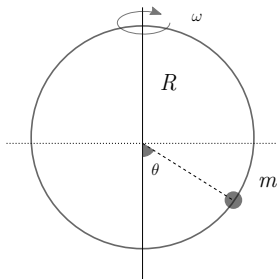


Figure:

## Problem 2: Solution

Here, look that  $\theta$  can change. And  $\frac{d}{dt}\theta = \Omega$

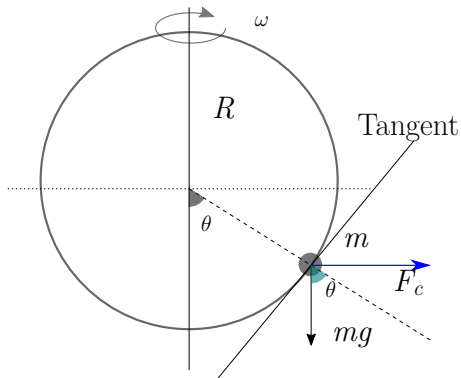


Figure:

## Problem 2

Total energy using only 1 variable,

$$E = \frac{1}{2}m(R\sin\theta\omega)^2 + \frac{1}{2}m(R\Omega)^2 - mgR\cos\theta$$

Now in previous Idea I talked about this form,

$$E = \frac{1}{2}\mathcal{M}v^2 + V(x)$$

Where  $V$  is not always potential too. It can be anything that depends on  $x$  (not  $\frac{d}{dt}x$ ). So, to write in this special form, note, we have,

$$E = \frac{1}{2}mR^2\Omega^2 + \left( \frac{1}{2}mR^2\omega^2\sin^2\theta - mgR\cos\theta \right)$$

Now, we can show,

$$\frac{d^2}{dt^2}\theta = \frac{-V'(\theta)}{\mathcal{M}}$$

Derivative of  $V(x)$  is needed.

## Problem 2

Here, our  $V(\theta)$  is,

$$V(\theta) = \frac{1}{2}mR^2\omega^2 \sin^2 \theta - mgR \cos \theta$$

Derivative,

$$V'(\theta) = \frac{dV(\theta)}{d\theta} = mR^2\omega^2 \sin \theta \cos \theta + mgR \sin \theta$$



## Problem 2

The kinetic energy was to be shown in  $\frac{1}{2}\mathcal{M}v^2$ , it is,

$$\mathcal{M} = mR^2$$

We need this form.

Now, we were told,

$$\frac{d^2\theta}{dt^2} = -\frac{V'(\theta)}{\mathcal{M}}$$

So,

$$\frac{d^2\theta}{dt^2} = -\frac{mR^2\omega^2 \sin\theta \cos\theta + mgR \cos\theta}{mR^2}$$

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So,

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$$\frac{d^2\theta}{dt^2} = -\omega^2 \sin\theta \cos\theta - \frac{g}{R} \cos\theta$$

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$$\frac{d^2\theta}{dt^2} = -\omega^2 \sin\theta \cos\theta - \frac{g}{R} \cos\theta$$

When there is no force  $F = 0$ , then  $a = 0$ , acceleration is obviously zero. So, for stability,  $\frac{d^2\theta}{dt^2} = 0$ , although we have to be careful making this assumption.

$$\omega^2 \sin\theta \cos\theta = \frac{g}{R} \cos\theta$$

$$\boxed{\cos\theta = \frac{g}{\omega^2 R}}$$