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ARVR

- Goals
- learn to build good VR experience
- Understand how VR works
- learn to criticize VR
- learn fundamentals to shape future of VR.

VR = Comfortable + Adaquate for any task

* Definition of VR
inducing targeted behavior in an organism by using artifical sensory simulation while the organism has little or no awareness of the interence.

- immersion - feeling
- presence - tricking the brain that you are somewhere else
- ~~open loop & closed loop~~
- Tele presense / Tele operations
- Augmented Reality

* What does VR include
- watching a movie?
- Video Conferencing?
- listening music?
- Talking on phone?

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Diff AR VR.

- VR provides completely immersive experience where user feels like a part of another world	AR overlays the computer generated 3D content in real world
- Completely gets in new world & detached from real world	- Users have ability to interact with Augmented technology & the real world
- user needs VR devices like head sets & immersive sound & motion controllers	- AR can be experienced by S.phone, Tablet or AR devices
- fully enclosed reality	- AR is partially enclosed reality

immersion - experience closer to reality using immersive graphical content & sound.
- involvement in something deeply

Birds eye view - is an immersive & engaging way to explore environments from different perspective

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* Birds eye view
- Pick a sensor on your body or a sense organ on your (human body)
  - eye, ear, fingertips, tounge,

What is a sensor -
its a transducer (form of)
it converts energy from one form to another
- So sensor is a measure which converts whatever physical energy it is measuring from the physical world into signals or something.
- if its a digital circuit then it will convert it into digital signal.
if its brain than signals converted into neuron pulses.
- So signal that goes into the system so its a transducer

* Each sensor moves through a space & these changes are controlled by the brain ~~are~~ & the nervous system together

Q)

→ What are the degrees or freedom (DOF) does a sensor have.
- the no of independent parameters that define the state of the system
Each sensor has a configuration space

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its very important thing to take into account the our bodies are changing the configurations of our sensor all the time without telling us, ~~we or with cou~~

Examples - left ear

Position part - 3 DOF
- we can go ~~left~~ back & forth
forward backward
up & down

- we can also rotate our ear to different directions
→ So total 3 DOF - Rotation

few animals can bend their ears we dont have it but our eyes do.

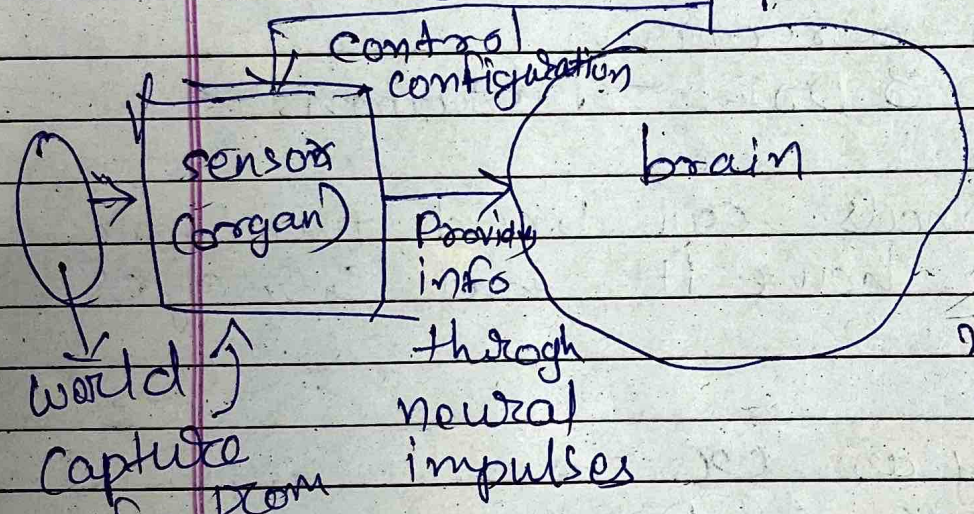
lets say an ex.
Right eye - 6 DOFs corresponds to head movement.
if you move your head around then view of eye will be diff
I can hold my head fix & then
- a. can start rotating my left eye around
So on the Rotation of eye - 2 DOFs

if your younger than 28 then your eye has an ability to refocus.
- so if you bring things closely to your eye muscles are changing your lens so that you can look at things very closely.
so it refocuses - 1 DOF
- So total 9 DOFs.

if your are developing in virtual reality or testing something in it DOF is very imp

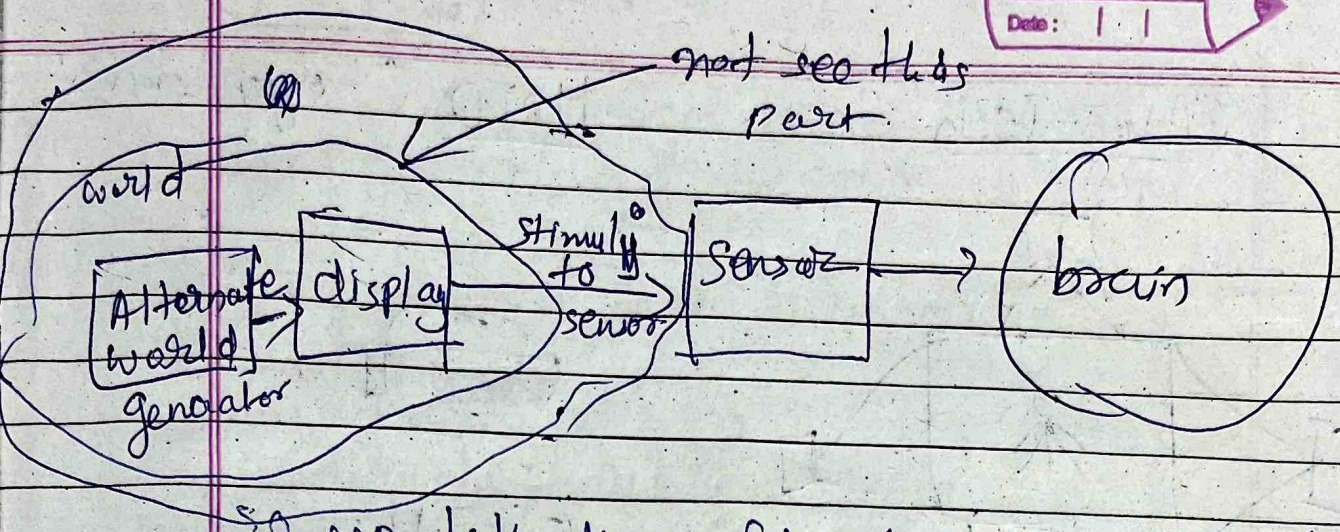
- Abstract view

an abstract view refers to a representation or visualization that doesnt necessarily show reality but conveys ideas & concepts expressions through non realistic means



→ what can i put into physical world to try to fool the brain

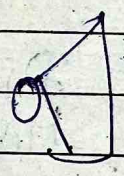
→ so its still there a world when you put a V.R device



so we take the information from the alternate w.g & it is rendered to display that provides the sesory simulation

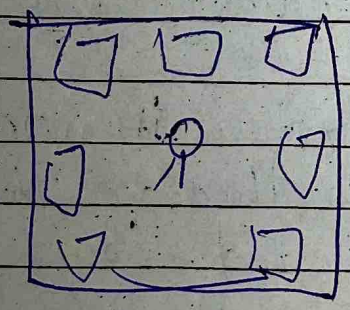
- So by the time the brain imagines that there is an alternate world.
- we can take n sensors on the basis of immersion
- Vision is the most powerful sensors that audio immersion

2) Displays & Rendering
Audio & hearing
So here display is speaker

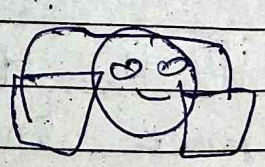


Rendering - produces appropriate signal to convert air pressure waves

- Compare 2 audio system



Dolby sytm



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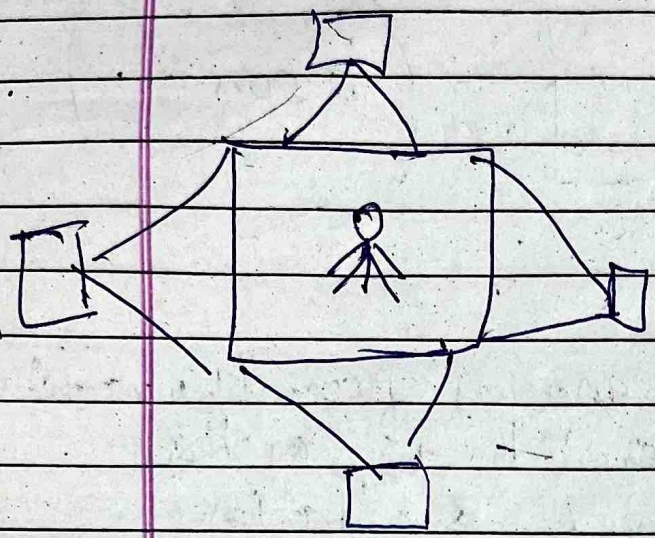
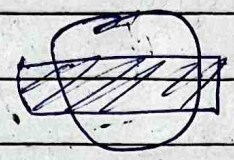
CAVE Tech



Projection systems
- so we can change the viewpoint when we move the head around, on screens

HMD ("eyephones")



Everything moves according to the head as it moves
- In vision sense you are gone see much more detail how every thing moves as you move your head.

→ Distance of Display from sense
HMD - if you wear it the display is very close so need to put on some lenses to focus as the eyes do have enough optical powers to focus on something very close.
- lenses can help to overcome it

if the display is far then it needs more power, so if its in theatre that it should be big and loud but in HMD, it can be small.

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- The closer you get the harder it get engineering wise.

* Bird eye view - hardware.
* Displays
visuals which are screens (CRT, LCD, OLED)
→ Virtual ~~Reality~~ Retina display
→ Take a tiny projector which project images directly onto your retina ~~but~~
→ Light field displays - rather than presenting thing on 2D, try to capture entire field of light within 3D region so its helpful when you rotate your head you can take real time information on ~~account~~ small motions Virtual reality
→ Projectors

* Audio / speakers / earphones
- Feel the Bone conduction technique

* Touch - Haptic devices
Ex (vibration as a kind of feedback for ex - motion getting blocke by some force like a robot.
↳ Example of kinesthesia.

* Smell / Taste - Vestibular simulation

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* CPU / GPU
Input devices
- Game controller
- keyboard
- Data gloves

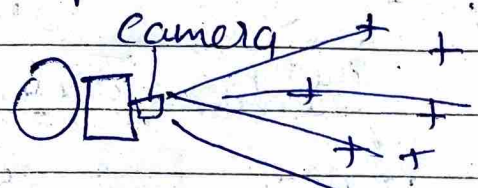
How do you write a software in virtual reality? How do you find a keyboard & mouse.

Tracking - what do we use for tracking
HMD - if you move your head you need to get the visual info correctly
- so the more the device get closer to the organ the more kind of tracking you need
- if we are in cave, can see my whole body around but if i am wearing HMD, not able to see my body
So here i can track my body
- we can attach sesors to body or wear some sensor designed suits

Tracking hardware
* Inertial measure unit - IMU
- designed for navigation; useful in aircraft & space craft
- used for orientation or rotation
- measure 3D angular velocity, 3D linear acceleration
- so angular velocity called a gyroscope ~~and is~~
- smart phones have IMUs
- device confused about gravity

- another is magnetometer
  - measures magnetic fields (3D) also used to provide orientation information
- Cameras - 2 ways to track

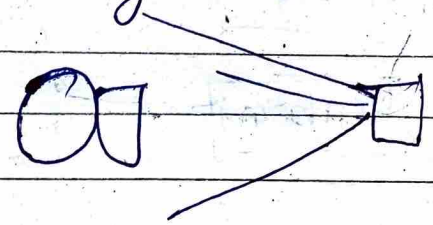
Inside out
Top down view



so camera see these markers, on the base of how these markers are appear to camera which is fixed to head you can figure out where you are

→ camera inside the headset looking outward

Outside in
head looking straight down



features are on the headset itself

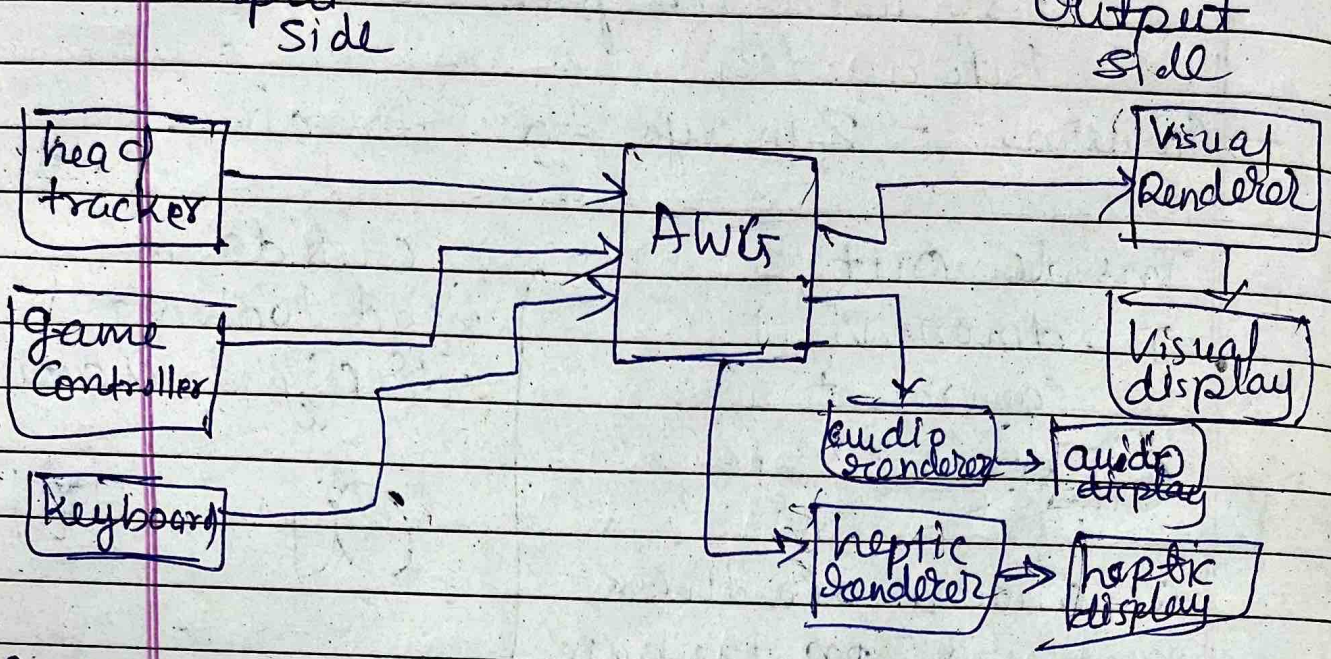
→ camera outside looking inward

- RGBD sensors - gives color & distance info - In depth
- question is what you want to track
  - your eye, head, body, entire room of people

~~AWG – the job of alternate world generator is to maintain a lot of physics of that world a lot of geometry so that you can~~

Birds eye view Software

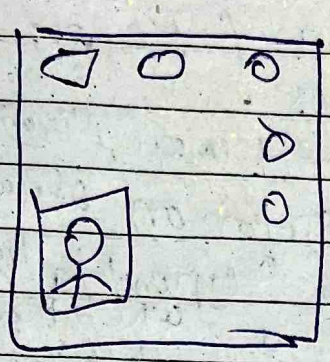
We get inputs from tracking devices



AWG needs this information to make some kind of updates to the renderers.

Automatic world generator – it maintains ficious or remote or recorded whatever kind of world it is. It has to maintain a lot of geometry, physics of that world in a way so that you can output to this renderers which then output to the displays. which then output to your sense organs to fool your brain

- another way to look at it
  imagine we are super imposing so there is an alternate world & real world. so somehow there is an alternate world that is being generated by AWG



So there is a stuff like furniture in this alternate world. So story is being maintaind that you are placed into this world.

So you have your own kind of region where you are able to move around. So your head has been transformed into this world & embedded into this alternate world.

So if you move your head and there is a obstale arond you, you will get smacked, ~~So there is a collision detection~~ then you get a heptic feedback so it could smack you on the head right

So you need collision detection that will tell you know you can't go that way or

* Self motion

Kinds of self motion

1) User moves & motion is matched in alternate world.

moving into physical world

or game controller

2) Through an interface, user locomotes its virtual self.

↓ not moving into physical world
- just grabbing on to a controller and can move your virtual body

1- Comfortable - can travel long distance

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Birds eye view - Esensetion & Perception
- Classification of senses
→ What sense Called - Human Vision
→ stimulus - energy Reaction on
→ Receptor - organ Acell respond to which transfor signal to sensor
→ sensory structure - eyes
→ Engineering equivalent - Camera

electro magnetic photo receptor

organ or tissue light, heat

stimulus - electromagnetic energy or photons - a visible spectrum. because thats what our eyes respond to. on eyes we have photo receptors which are like input pixels. same like for output pixels So photo receptors are the parts where you sense.

→ So for cameras very similar to the way our eyes are designed except all the extra movements & things that our eyes do is very complex & interesting

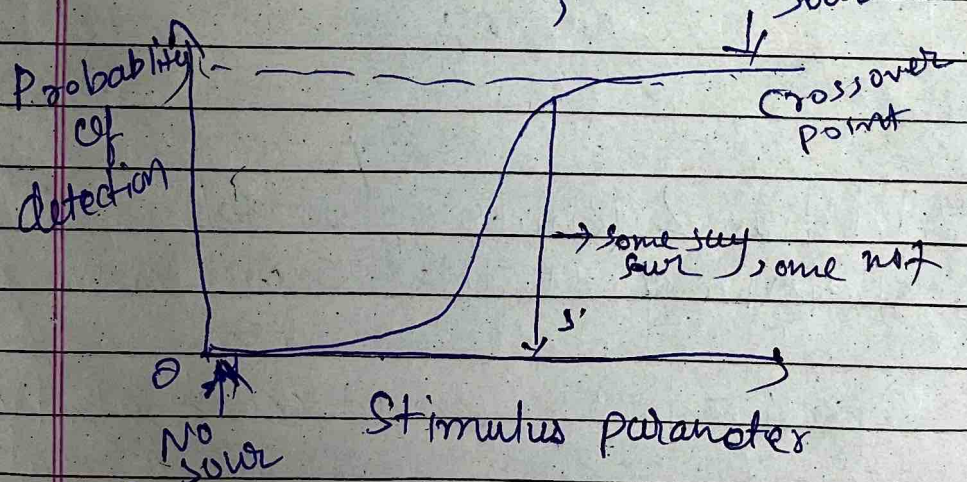
→ seses → vision ✓
→ Hearing ✓
→ Touch
→ Balance - vertibular organ
→ Taste / smell -

Vision + Balance

1) Vection - if you are in train example you are doing same in virtual Reality you are convincing your brain that you are moving but your vestibular organ knows that you are not so thats vection

2) Vestibulo ocular Reflex
- Spec example
- Chalk example
- brain learn to Compensate thant your brain learn to adapt but your might have headache after 20 mins

3) Psychophysics
- scientific studies about Connecting physical stimuli → perceptual phenomena
ex - Odor, taste sour

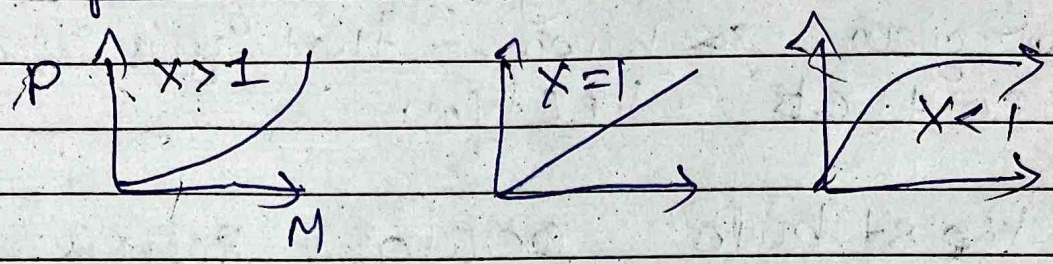


for ex - changing acidity in some chemical taste experiment so it give sour taste.

Stevens power law (1961)
M = magnitude of stimulus
P = perceived magnitude
so mapping like

$P = CM^x$ C = constant

so plot looks like



sound experiment
You adapt in VR as time passes
Adaptation

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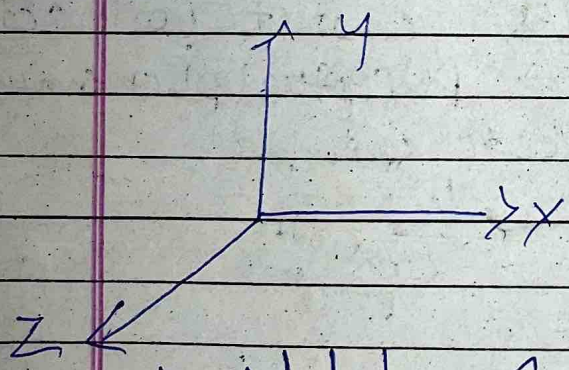
* Geomatric modeling of Alternate world generator
let W be a 3D world
$W \subseteq R^3$ — R is coordinates 3 dimensions



so in 3D, Each point in world has coordinates $(x, y, z) \in W$

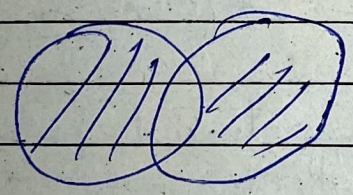
World has 2 kinds of models
fixed 1) stationary Models - never moves
buildings, trees,
Described in world coordinate frame
match coordinates from real world to the axis
2) Movable Models
have space of possible transformations

- many moving thing
  Charaters, avtars, animals
- usually composed of rigid bodies each of which defined in its own body frame
- so we will not use the real world frame but each body have body parts connected and make a rigid body

* Two modeling choices
1) Solid representation - 3D primitives
2) Boundary represention - 2D primitives
   ↳ GU

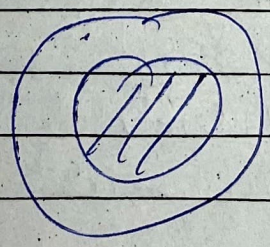
Obstacles & collision detection
Ex fogy, table, book

so with regard to these 2 choices
2 bodies

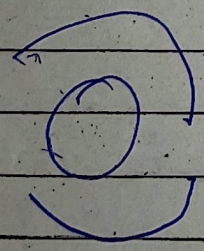


- They are in collision because they intersect

This is 2D - so check boundarie intersection



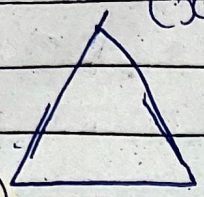
← No boundary intersection



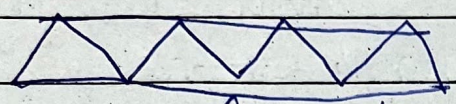
- model coherency

Lets use triangle primitives

$(x, y, z) \leftarrow$ vertices



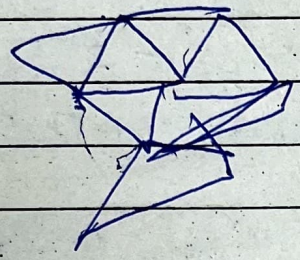
(x_2, y_2, z_2) (x_3, y_3, z_3)



- Save space

strip

mesh



- surface of Boundary representation

Why are we performing transformation

1) Movable models
2) perception of stationarity

So if I move my head you all will move perfectly that counter rotate if i design a VR system like cave and also it is fixed but if i wear stimulus on my head so you have to compensate for the transformation so your brain dont confuse.

→ Need to counter rotate the mounted stimulus (inverse transform) requires tracking needs sensors

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Transforming Rigid bodies

- Transform each vertex of each triangle

3 Caiese

1) Easy : Translation ------

DOFs

2D	3D
2	3

2) Harder : Rotation ------

DOF

2D	3D
1	3

3) Hardest : Rotation + Translation

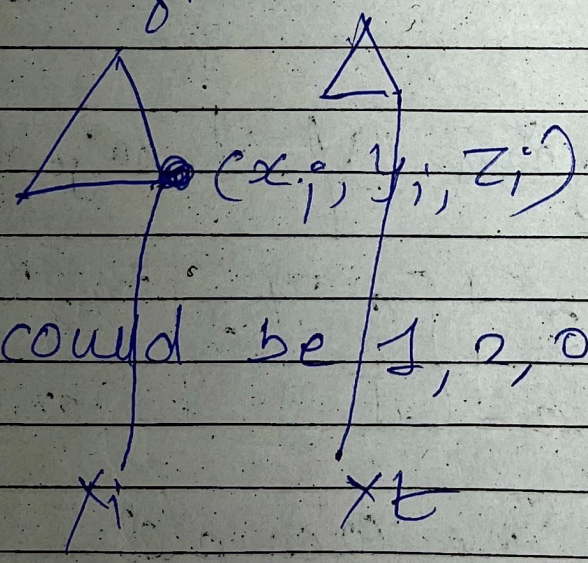
DoF

2D	3D
3	6

* Translation (Easy case)

shift the triangle by (x_t, y_t, z_t)

we shift the coordinates



(x_i, y_i, z_i)

$\downarrow$

$(x_i + x_t, y_i + y_t, z_i + z_t)$

i could be 1, 2, or 3

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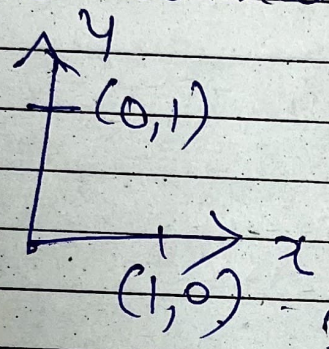
2D linear Transformations

2x2 matrix - Real valued Entries

$$\begin{bmatrix} x' \\ y' \end{bmatrix} = \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix}$$

$(x, y) \rightarrow (x', y')$

2D Coordinate systems



when we perform transformation

x axis Coordinates

$$\begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} \begin{bmatrix} 1 \\ 0 \end{bmatrix} = \begin{bmatrix} m_{11} \\ m_{21} \end{bmatrix}$$

lets perform y ~~transform~~

$$\begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} \begin{bmatrix} 0 \\ 1 \end{bmatrix} = \begin{bmatrix} m_{12} \\ m_{22} \end{bmatrix}$$

lets take some examples

$$\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$ ⇐ This identity matrix
⇐ There is no change
⇐ no effect

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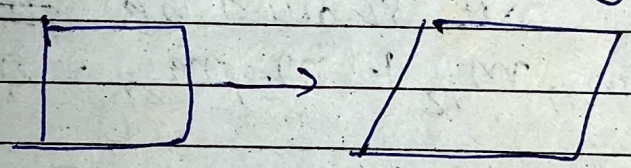
$$\begin{bmatrix} 2 & 0 \\ 0 & 2 \end{bmatrix}$$ ← scale.
Streches
the aspect ratio

$$\begin{bmatrix} -1 & 0 \\ 0 & 1 \end{bmatrix}$$ ← mirror image.

$$\begin{bmatrix} -1 & 0 \\ 0 & -1 \end{bmatrix}$$ ← This will Rotate the object to apposite side (↻ 180°)

$$\begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix}$$ ← x is increasing as y increases
← x is replaced by x+y



X - shear

$$\begin{bmatrix} 1 & 0 \\ 1 & 1 \end{bmatrix}$$

Y-Shear

~~So to apply transfor.~~

How many DOF is 2×2 matrix
= 4

for rotations
what we dont allowed to have.
1) No streching of axis
2) No shearing

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4 DOFs = $\begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix}$

so columns have lenght constraints

1) Columns have lenght one

$m_{11}^2 + m_{21}^2 = 1 \rightarrow \left[(\ ) \ (\ ) \right] \rightarrow m_{12}^2 + m_{22}^2 = 1$

So we lost 2 DOFs, we have only 2 DOF

2) No shearing
- so axis should be perpendicular.
  it should be ~~right~~ θ

$m_{11} m_{12} + m_{21} m_{22} = 0$

so here lost 1 DOF

so we have enoright DOF which 1 for 2D transformation.

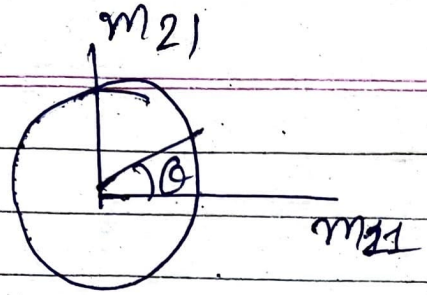
3) No mirror images
so no orientation change

$\det\left(\begin{bmatrix} \cdot & \cdot \\ \cdot & \cdot \end{bmatrix}\right) = 1$ (not -1)

what matrices remain?
So lets give parameters to the matrix

$m_{11} = \cos\theta$

$m_{21} = \sin\theta$



$$\begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix}$$

So this thing were for 2D rotation

3D Rotations

$$\begin{bmatrix} \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \end{bmatrix} = 9 \text{ DOF}$$

lets give names to the columns vectors

$V_1 \quad V_2 \quad V_3$

1) Constraint 1

$\|V_1\| = \|V_2\| = \|V_3\| = 1$

square and add $= 1$

so here we loss 3 DOFs

2) avoid shearing

dot products, so here we choose pairs

$V_1 \cdot V_2 = 0 \quad V_2 \cdot V_3 = 0 \quad V_1 \cdot V_3 = 0$

so here we lost 3 more DOF

3) no mirror images

$\det\left(\begin{bmatrix} \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \end{bmatrix}\right) = 1$

here he got 3DOF in 3D rotations

3. Canonical stations
- Yaw, Pitch & Roll

seperatly they are good combined is mess

1) Yaw - left & Right head
2) Pitch → yes (up down) no
3) Roll ⇒ may be

Yaw
Rotation matrix

$$R(\alpha) = \begin{bmatrix} \cos\alpha & 0 & \sin\alpha \\ 0 & 1 & 0 \\ -\sin\alpha & 0 & \cos\alpha \end{bmatrix}$$

centre part is like identity matrix
So y axis not changing only X, Z

Pitch

$$R(\beta) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\beta & -\sin\beta \\ 0 & \sin\beta & \cos\beta \end{bmatrix}$$

X is identity matrix
Y, Z change

Roll

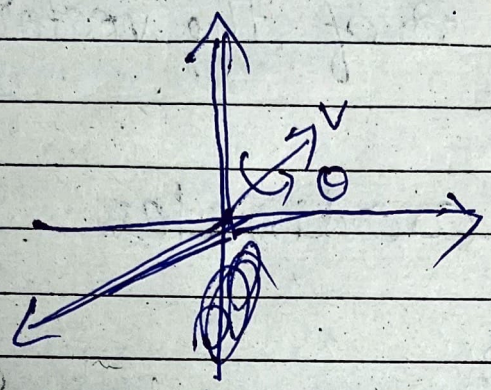
$$R(\gamma) = \begin{bmatrix} \cos\gamma & -\sin\gamma & 0 \\ \sin\gamma & \cos\gamma & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Z part is identity

we can apply them sequentialy and change the physical Rotation

Euler's Rotation theorem

All 3D rotations have an axis angle Representation



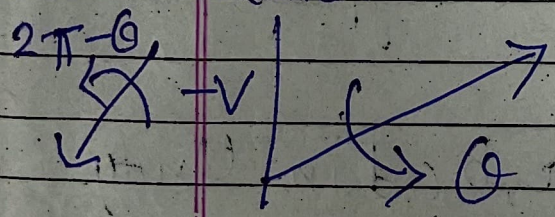
important for oriententation Representation

→ find some ~~axe~~ axis through the origin and some amount of rotation

→ ~~Some amt of axis~~ angle about the axis or counterclockwise rotation θ is describes the rotation of body

→ access through the origin

Vector



Some amount of θ

norm of vect $||V|| = 1$

There is an ambiguity

There is a double representation problem.

$(v, \theta) \cdot (v', \theta') = ?$
make an algebra
* parameter → lenght doesnt matter
$(\theta v_1, \theta v_2, \theta v_3)$
Assume $\|v\| = 1$
Closer the rotation the smaller the vector
direction of the vector corresponds to the axis
called
Exponential coordinates

* quaternions
Unit quaternions as a better reprentation of 3D rotation

4D vector
$q = (a, b, c, d) \in R^4$

quaternion is called a vector part (imaginary part) & scaler part

$a^2 + b^2 + c^2 + d^3 = 1$ DOF = 1

↓
shap? → hypersphere

set of all unit q is a hypersphere
(maths called S^3)

How do we used a, b, c, d in Unity
3D & in dimensions
here we use diff rep

$(x, y, z, w) = (b, c, d, a)$
we can represent it like
$a + bi + cj + dk$
complex numbers

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How to encode a 3D rotation using (a, b, c, d) parameters

$V = (v_1, v_2, v_3)$, θ

Representation — 4D vector

$(V, \theta) \longleftrightarrow (\underset{a}{\cos\theta/2}, \underset{b}{v_1 \sin\theta/2}, \underset{c}{v_2 \sin\theta/2}, \underset{d}{v_3 \sin\theta/2})$

squaring & adding gives = 1

angle θ and axis V

Useful Examples

1) $(1, 0, 0, 0) \rightarrow$ what this quaternion does

$\theta = 0$ $\quad b, c, d = 0$

$\cos\theta/2 = 1$

So this is identity rotation

no axis - didnt rotate

2) $(0, 1, 0, 0) \rightarrow$ 180° Rotation about axis

Pitch by π $\rightarrow$ rotation about x-axis

3) $(0, 0, 1, 0) \rightarrow$ Yaw by π - Rotation abt y axis

4) $(0, 0, 0, 1) \rightarrow$ Raw by π

5) $(\frac{1}{\sqrt{2}}, \frac{1}{\sqrt{2}}, 0, 0) \rightarrow$ x axis

$\rightarrow$ 90° Rotation

$\rightarrow$ Pitch by $\pi/2$

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6) $\left(\frac{1}{\sqrt{2}}, 0, \frac{1}{\sqrt{2}}, 0\right)$ yaw by $\pi/2$

7) $\left(\frac{1}{\sqrt{2}}, 0, 0, \frac{1}{\sqrt{2}}\right)$ roll by $\frac{\pi}{2}$

* Inverses of multiple Representation

$(a, b, c, d) \xleftrightarrow{\text{equivalent}} (-a, -b, -c, -d)$

same Rotation

Related to some 3D Rotation

$\left(\cos\theta/2,\ V_1 \sin\theta/2,\ V_2 \sin\theta/2,\ V_3 \sin\theta/2\right)$

a b c d

better - Same object

V & twist it in opposite direction or flip it around so it will negate b, c, d & if i negate the a but not b, c, d.

So if we travel in 3D sphere & if we go in opposite point on earth so the it will be equivalent.

$2\pi - \theta$

Inverses

$(a, -b, -c, -d)$ this will undo the rotation

if you use rotation matrix then transpose

$(a, -b, -c, -d) \xleftrightarrow{\text{equal}} (-a, b, c, d)$

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multiplication of quartnions

$q = (a, b, c, d)$ let $p = (b, c, d)$ - treat as 3D vector

$q_1 \times q_2 = q_3$

Scaler part, dot Prod, X Prod

$$q_1 \cdot q_2 = (\underbrace{a_1 a_2}_{a_1} - \underbrace{P_1 \cdot P_2}_{C_3}, \underbrace{P_1 \times P_2}_{D_3} + \underbrace{a_1 P_2}_{C_3} + \underbrace{a_2 P_1}_{D_3})$$

R_1 & R_2 Rotation matrices

$R_1 \cdot R_2 = R_3$
$q_1 \cdot q_2 = q_3$

Results Same

Rotation to quaternion and convert the quartnion you will get the same results.

4.1 ~~mult~~ Converting & multiplying rotations

Conversions → R rotation matrix

Unit quaternions q ⟷ Yaw, Pitch, Raw
$R(\alpha)\, R(\beta)\, R(\gamma)$

Axis angle (V, θ) axis-angle Representation

All these will be helpful when we will doing head tracking

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if we have Rotation matrix or quaternions
$R_1 R_2$ $q_1 \cdot q_2$
so which applied first?

Suppose we have some point
$P = (x, y, z)$
$P' = R_1 P$ $P'' = R_2 P'$

now i combine both matrices
$P'' = R_1 R_2 P$ or $P'' = R_2 R_1 P$

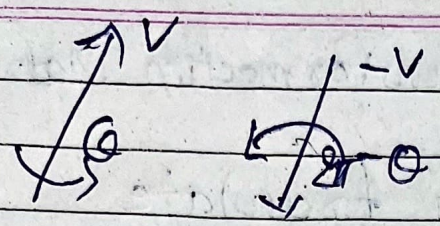
here matrices works backward

$P'' = R_2 (R_1 P)$ if you add parenthesis you can see first $(R_1 P)$ applied then R_2

now for if you take inverses
$(R_1 R_2 R_3)^{-1} = R_3^{-1} R_2^{-1} R_1^{-1}$

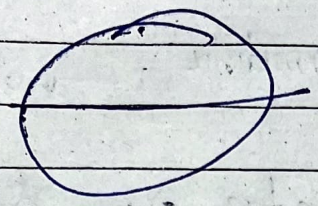
here we have to reverse the order of Rotation matrix same for quaternions

Suppose we say we want to transform (x, y, z) to another ~~location~~ Rotate it
extend it by 1 dimen $P = (x, y, z, 1)$
$P' = q \cdot P \cdot q^{-1}$
q is the rotation that we like to apply on (x, y, z)



→ quaternions

2 different ~~rotation~~ unit quaternions for every rotation



Ex Rotate (x, y, z) to some point

$$R_1 \begin{bmatrix} x \\ y \\ z \end{bmatrix}$$

now if again want to Rotate it

$$R_2 \left(R_1 \begin{bmatrix} x \\ y \\ z \end{bmatrix} \right)$$

So we can say $(R_2 R_1) \begin{bmatrix} x \\ y \\ z \end{bmatrix}$

R_1 is applied first then R_2
so we go Right to left

Now if you make an inverse

$$(R_1 R_2 R_3)^{-1} = R_3^{-1} R_2^{-1} R_1^{-1}$$

now apply inverse

So we get $R_3^{-1} R_2^{-1} R_1^{-1} R_1 R_2 R_3$

So we get Identity matrix

Homogeneous transformation Matrices

→ Rotate followed by translate

$$\begin{bmatrix} x' \\ y' \\ z' \end{bmatrix} = \begin{bmatrix} \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} + \begin{bmatrix} x_t \\ y_t \\ z_t \end{bmatrix}$$

↓ transformed Point

R ↓ Rotation matrix

translation

Homogeneous linear translation

$y = Ax + B$

- so here we can generate any position of a rigid body

→ DOF = 6 $\quad 3(x, y, z) \triangleleft R(\ldots)$

so we make a 4 X 4 matrix that is algebrically equivalent

here i will extend matrix by 1 $(x, y, z, 1)$

$$\begin{bmatrix} x' \\ y' \\ z' \\ 1 \end{bmatrix} = \begin{bmatrix} \boxed{R_{matrix}^{3\times3}} & \begin{matrix} x_t \\ y_t \\ z_t \end{matrix} \\ 0 \; 0 \; 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}$$

perform multiplication

What is T^{-1}

$$T^{-1} = \begin{bmatrix} \boxed{R^T} & \begin{matrix} -x_t \\ -y_t \\ -z_t \end{matrix} \\ 0 \; 0 \; 0 & 1 \end{bmatrix}$$

first inverse translate then inverse rotate

Inverse

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$$T^{-1} = \begin{bmatrix} R^T & \begin{matrix} 0 \\ 0 \\ 0 \end{matrix} \\ 0\ 0\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & -x_t \\ 0 & 1 & 0 & -y_t \\ 0 & 0 & 1 & -z_t \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

T is Rotation then translation

T^{-1} inverse translation then inverse Rotation

SUMS

1) Compute product AB

$$A = \begin{bmatrix} 1 & 3 & 2 \\ 2 & 5 & 1 \end{bmatrix} \qquad B = \begin{bmatrix} 4 & 1 \\ 3 & 2 \\ 6 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} 1\times4+3\times3+6\times2 & 1\times1+3\times2+2\times1 \\ 2\times4+5\times3+1\times6 & 2\times1+5\times2+1\times1 \end{bmatrix}$$

$$= \begin{bmatrix} 4+9+12 & 1+6+2 \\ 8+15+6 & 2+10+1 \end{bmatrix}$$

$$= \begin{bmatrix} 25 & 9 \\ 29 & 13 \end{bmatrix}$$

2) A & B matrices find $A^T * B^T$

$$A = \begin{bmatrix} 3 & 4 & 2 \\ 3 & 1 & 1 \\ 1 & 3 & 4 \end{bmatrix} \qquad B = \begin{bmatrix} 3 & 3 & 2 \\ -1 & -6 & 1 \\ 2 & 6 & 4 \end{bmatrix}$$

$$= \begin{bmatrix} 3 & 3 & 1 \\ 4 & 1 & 3 \\ 2 & 1 & 4 \end{bmatrix} \times \begin{bmatrix} 3 & -1 & 2 \\ 3 & -6 & 6 \\ 2 & 1 & 4 \end{bmatrix}$$

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$$= \begin{bmatrix} 20 & -20 & 28 \\ 21 & -7 & 26 \\ 17 & -4 & 26 \end{bmatrix}$$

3) Compute $(2A)^T - (3B)^T$

$$A = \begin{bmatrix} 3 & 4 & 2 \\ 3 & 1 & 1 \\ 1 & 3 & 4 \end{bmatrix} \qquad B = \begin{bmatrix} 3 & 3 & 2 \\ -1 & -6 & 1 \\ 2 & 6 & 4 \end{bmatrix}$$

$$2A = \begin{bmatrix} 6 & 8 & 4 \\ 6 & 2 & 2 \\ 2 & 6 & 8 \end{bmatrix} \qquad 3B = \begin{bmatrix} 9 & 9 & 6 \\ -3 & -18 & 3 \\ 6 & 18 & 12 \end{bmatrix}$$

$$(2A)^T = \begin{bmatrix} 6 & 6 & 2 \\ 8 & 2 & 6 \\ 4 & 2 & 8 \end{bmatrix} \qquad (3B)^T = \begin{bmatrix} 9 & -3 & 6 \\ 9 & -18 & 18 \\ 6 & 3 & 12 \end{bmatrix}$$

$$= (2A)^T - (3B)^T$$

$$= \begin{bmatrix} -3 & 9 & -4 \\ -1 & 20 & -12 \\ -2 & -1 & -4 \end{bmatrix}$$

4)

static Prob y d
663 Avg - 13454
504 " - 17591

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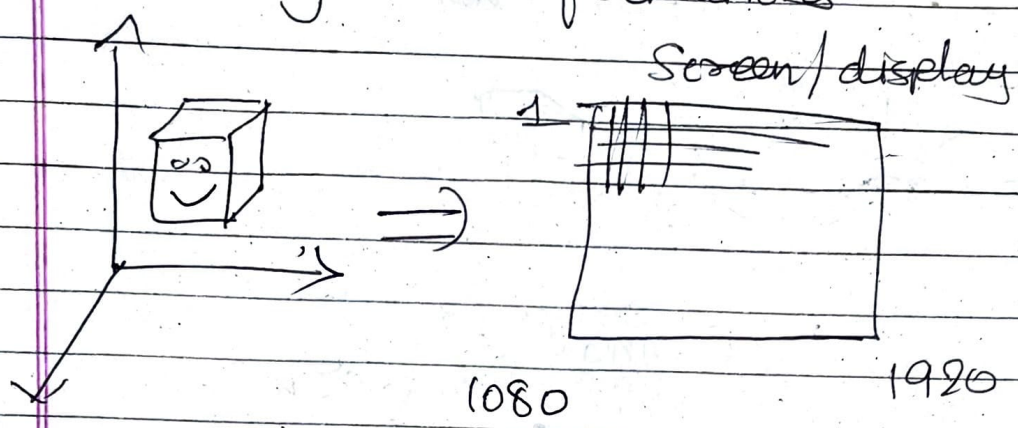
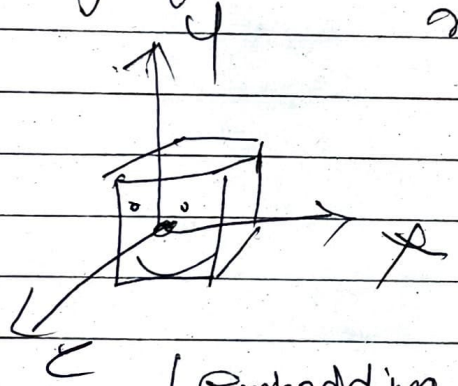
Viewing Transformations



Where the object displayed on the screen.

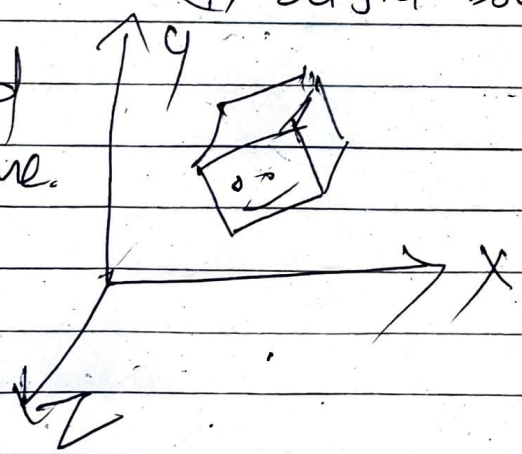
Geometric Transfo
The chain of Transformations
+ body frame: a way of expressing our movable model



we perform transformation to move the body into world frame

Embedding rigid bodies

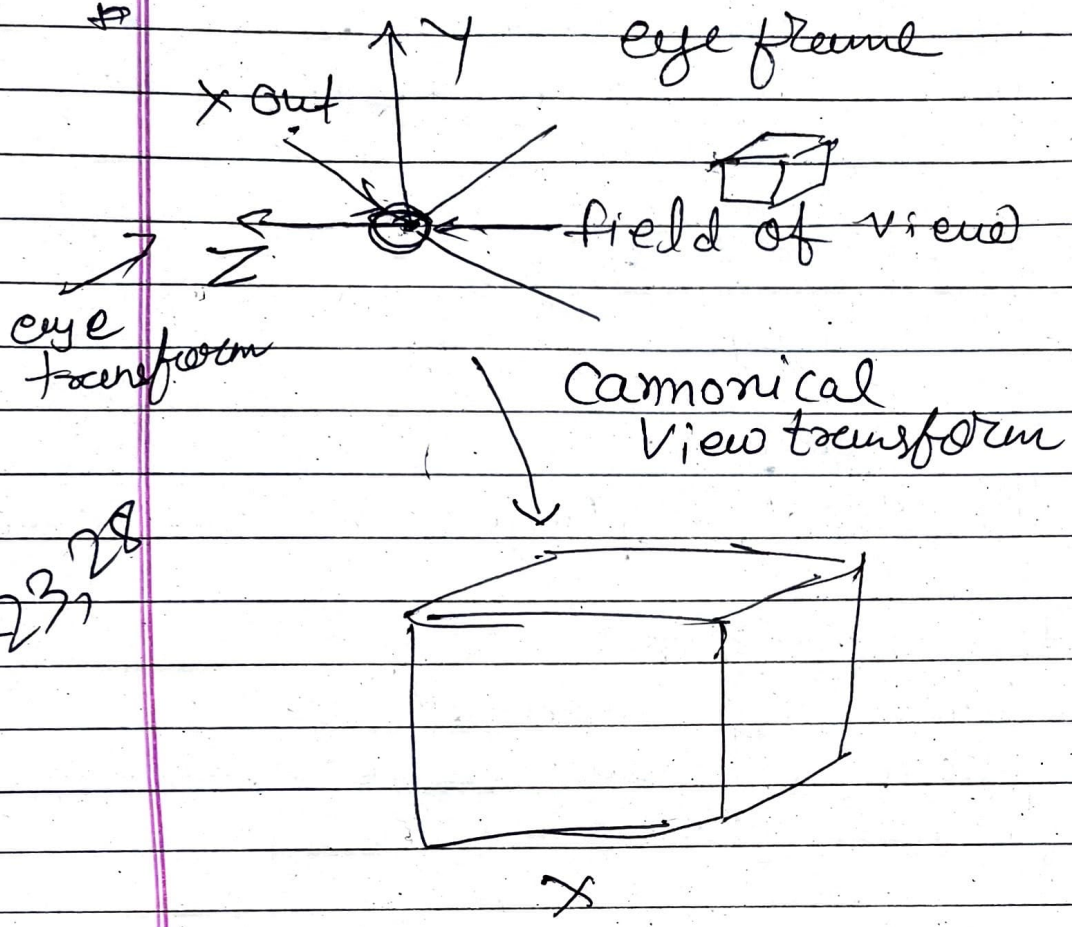
World frame.



Stationary model

different name - body frame (local)
(object)

world frame (Global)



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