# ROTATIONS

I Main Topics
- A Uses of rotation in geology (and engineering) I
- B Concepts behind rotation
- C Rotations using a stereonet
- D Comments on rotations using stereonets and matrices
- E Uses of rotation in geology (and engineering) II

II Uses of rotation in geology (and engineering) I
- A Return tilted bedding to horizontal to examine:
  1. pre-tilting orientation of sedimentary structures (e.g. ripples)
  2. pre-tilting orientation of beds below angular unconformities
  3. pre-tilting orientation of paleomagnetic orientations
- B To determine the orientations of features from drill cores
- C <u>Need to consider whether object is rotated and coordinate axes are fixed or whether the object is fixed and coordinate axes are rotated. This affects the sign(s) and sequence of the angle(s) of rotation.</u>

III Concepts behind rotation
- A <u>Any</u> orthogonal coordinate system with axes $x_1$,$x_2$,$x_3$ can be rotated to coincide with another orthogonal coordinate system $x_1'$, $x_2'$, $x_3'$ by using the direction cosines relating the axes of the two systems.

| Dir. cosines | $x_1$ axis | $x_2$ axis | $x_3$ axis |
|---|---|---|---|
| $x_1'$ axis | $a_{11'} = a_{1'1}$ | $a_{12'} = a_{2'1}$ | $a_{13'} = a_{3'1}$ |
| $x_2'$ axis | $a_{21'} = a_{1'2}$ | $a_{22'} = a_{2'2}$ | $a_{23'} = a_{3'2}$ |
| $x_3'$ axis | $a_{31'} = a_{1'3}$ | $a_{32'} = a_{2'3}$ | $a_{33'} = a_{3'3}$ |

$$\begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} a_{11'} & a_{12'} & a_{13'} \\ a_{21'} & a_{22'} & a_{23'} \\ a_{31'} & a_{32'} & a_{33'} \end{bmatrix} \begin{bmatrix} x_1' \\ x_2' \\ x_3' \end{bmatrix} \quad \text{and} \quad \begin{bmatrix} x_1' \\ x_2' \\ x_3' \end{bmatrix} = \begin{bmatrix} a_{1'1} & a_{1'2} & a_{1'3} \\ a_{2'1} & a_{2'2} & a_{2'3} \\ a_{3'1} & a_{3'2} & a_{3'3} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}$$

**<u>Right-hand rule:</u> If the right thumb is along a rotation axis, then fingers of the right hand curl in positive $\theta$ direction**

B <u>Any</u> orthogonal coordinate system with axes $x_1,x_2,x_3$ can always be rotated to coincide with another orthogonal coordinate system by the following **<u>three</u>** steps:

**1** <u>Rotate the xyz system about the $x_1$ axis by angle $\omega_1$</u>,
so $x_1,x_2,x_3$ -> $x_1',x_2',x_3'$ (Note that $x_1=x_1'$)

$$\begin{bmatrix} x_1' \\ x_2' \\ x_3' \end{bmatrix} = \begin{bmatrix} a_{1'1} & a_{1'2} & a_{1'3} \\ a_{2'1} & a_{2'2} & a_{2'3} \\ a_{3'1} & a_{3'2} & a_{3'3} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\omega_1 & \sin\omega_1 \\ 0 & -\sin\omega_1 & \cos\omega_1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}$$

**2** Rotate the $x_1',x_2',x_3'$ system about the $x_2'$ axis by angle $\omega_2$,
so $x_1',x_2',x_3'$ -> $x_1'',x_2'',x_3''$ (Note that $x_2'=x_2''$)

$$\begin{bmatrix} x_1'' \\ x_2'' \\ x_3'' \end{bmatrix} = \begin{bmatrix} a_{1''1'} & a_{1''2'} & a_{1''3'} \\ a_{2''1'} & a_{2''2'} & a_{2''3'} \\ a_{3''1'} & a_{3''2'} & a_{3''3'} \end{bmatrix} \begin{bmatrix} x_1' \\ x_2' \\ x_3' \end{bmatrix} = \begin{bmatrix} \cos\omega_2 & 0 & -\sin\omega_2 \\ 0 & 1 & 0 \\ \sin\omega_2 & 0 & \cos\omega_2 \end{bmatrix} \begin{bmatrix} x_1' \\ x_2' \\ x_3' \end{bmatrix}$$

**3** Rotate the $x_1'',x_2'',x_3''$ system about the $x_3''$ axis by angle $\omega_3$,
so $x_1'',x_2'',x_3''$ -> $x_1''',x_2''',x_3'''$ (Note that $x_3''=x_3'''$)

$$\begin{bmatrix} x_1''' \\ x_2''' \\ x_3''' \end{bmatrix} = \begin{bmatrix} a_{1'''1''} & a_{1'''2''} & a_{1'''3''} \\ a_{2'''1''} & a_{2'''2''} & a_{2'''3''} \\ a_{3'''1''} & a_{3'''2''} & a_{3'''3''} \end{bmatrix} \begin{bmatrix} x_1'' \\ x_2'' \\ x_3'' \end{bmatrix} = \begin{bmatrix} \cos\omega_3 & \sin\omega_3 & 0 \\ -\sin\omega_3 & \cos\omega_3 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_1'' \\ x_2'' \\ x_3'' \end{bmatrix}$$

Note that the rotation matrices can be obtained by permutation:
$x_1$ -> $x_2$, $x_2$ -> $x_3$, and $x_3$ -> $x_1$.

The direction cosines relating the x''' and x systems are:

| Dir. cosines | $x_1$ axis | $x_2$ axis | $x_3$ axis |
|---|---|---|---|
| $x_1'''$ axis | $a_{1'''1} = a_{11}'''$ | $a_{1'''2'''} = a_{2'''1}$ | $a_{1'''3} = a_{31}'''$ |
| $x_2'''$ axis | $a_{2'''1} = a_{12}'''$ | $a_{2'''2} = a_{22}'''$ | $a_{2'''3} = a_{32}'''$ |
| $x_3'''$ axis | $a_{3'''1} = a_{13}'''$ | $a_{3'''2} = a_{23}'''$ | $a_{3'''3} = a_{33}'''$ |

C <u>Any</u> orthogonal coordinate system with axes $x_1, x_2, x_3$ can always be rotated to coincide with another orthogonal coordinate system by one rotation about a specially chosen axis (Euler's theorem). This single rotation can be found by successively applying the three rotations listed above:

$$\begin{bmatrix} x_1''' \\ x_2''' \\ x_3''' \end{bmatrix} = \begin{bmatrix} a_{1'''1''} & a_{1'''2''} & a_{1'''3''} \\ a_{2'''1''} & a_{2'''2''} & a_{2'''3''} \\ a_{3'''1''} & a_{3'''2''} & a_{3'''3''} \end{bmatrix} \left( \begin{bmatrix} a_{1''1'} & a_{1''2'} & a_{1''3'} \\ a_{2''1'} & a_{2''2'} & a_{2''3'} \\ a_{3''1'} & a_{3''2'} & a_{3''3'} \end{bmatrix} \left( \begin{bmatrix} a_{1'1} & a_{1'2} & a_{1'3} \\ a_{2'1} & a_{2'2} & a_{2'3} \\ a_{3'1} & a_{3'2} & a_{3'3} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} \right) \right)$$

$$\begin{bmatrix} x_1''' \\ x_2''' \\ x_3''' \end{bmatrix} = \begin{bmatrix} a_{1'''1} & a_{1'''2} & a_{1'''3} \\ a_{2'''1} & a_{2'''2} & a_{2'''3} \\ a_{3'''1} & a_{3'''2} & a_{3'''3} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}$$

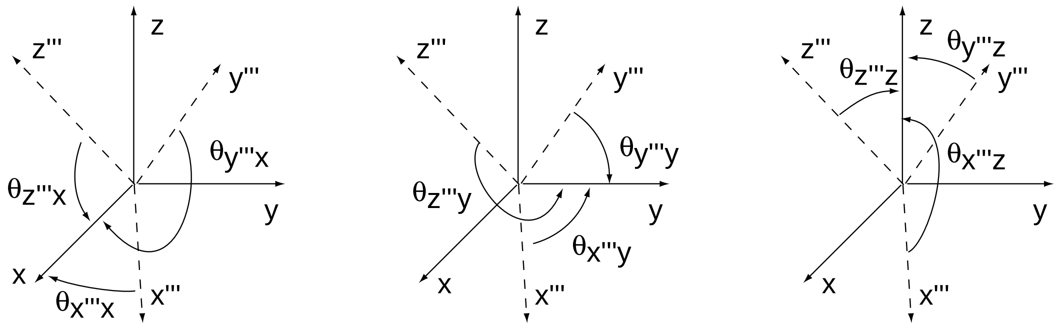
| Dir. cosines | $x_1$ axis | $x_2$ axis | $x_3$ axis |
|---|---|---|---|
| $x_1'''$ axis | $+\cos\omega_3 \cos\omega_2$ | $+\sin\omega_3 \cos\omega_2$ | $-\sin\omega_2$ |
| $x_2'''$ axis | $-\sin\omega_3 \cos\omega_1$<br>$+\cos\omega_3 \sin\omega_2 \sin\omega_1$ | $+\cos\omega_3 \cos\omega_1$<br>$+\sin\omega_3 \sin\omega_2 \sin\omega_1$ | $+\cos\omega_2 \sin\omega_1$ |
| $x_3'''$ axis | $+\sin\omega_3 \sin\omega_1$<br>$+\cos\omega_3 \sin\omega_2 \cos\omega_1$ | $-\cos\omega_3 \sin\omega_1$<br>$+\sin\omega_3 \sin\omega_2 \cos\omega_1$ | $+\cos\omega_2 \cos\omega_1$ |

Let the axis of rotation be called axis **N** and the direction cosines relating the N axis to <u>**either**</u> the $x_1$, $x_2$, $x_3$ system <u>**or**</u> the $x_1'''$, $x_2'''$, $x_3'''$ system be $a_{xN}$, $a_{yN}$, and $a_{zN}$, respectively. If the angle of rotation about **N** is $\omega$, then the nine direction cosines in the rotation matrix above can be expressed as:

| Dir. cosines | $x_1$ axis | $x_2$ axis | $x_3$ axis |
|---|---|---|---|
| $x_1'''$ axis | $a_{xN}\, a_{xN}\, (1-\cos\omega)$<br>$+ \cos\omega$ | $a_{xN}\, a_{yN}\, (1-\cos\omega)$<br>$+ \eta_3 \sin\omega$ | $a_{xN}\, a_{zN}\, (1-\cos\omega)$<br>$- a_{yN} \sin\omega$ |
| $x_2'''$ axis | $a_{yN}\, a_{xN}\, (1-\cos\omega)$<br>$- a_{zN} \sin\omega$ | $a_{yN}\, a_{yN}\, (1-\cos\omega)$<br>$+ \cos\omega$ | $a_{yN}\, a_{zN}\, (1-\cos\omega)$<br>$+ a_{xN} \sin\omega$ |
| $x_3'''$ axis | $a_{zN}\, a_{xN}\, (1-\cos\omega)$<br>$+ a_{yN} \sin\omega$ | $a_{zN}\, a_{yN}\, (1-\cos\omega)$<br>$- a_{xN} \sin\omega$ | $a_{zN}\, a_{zN}\, (1-\cos\omega)$<br>$+ \cos\omega$ |

# Methods of Rotation

## 1 All the angles between the x,y,z axes and x''',y''',z''' axes are known

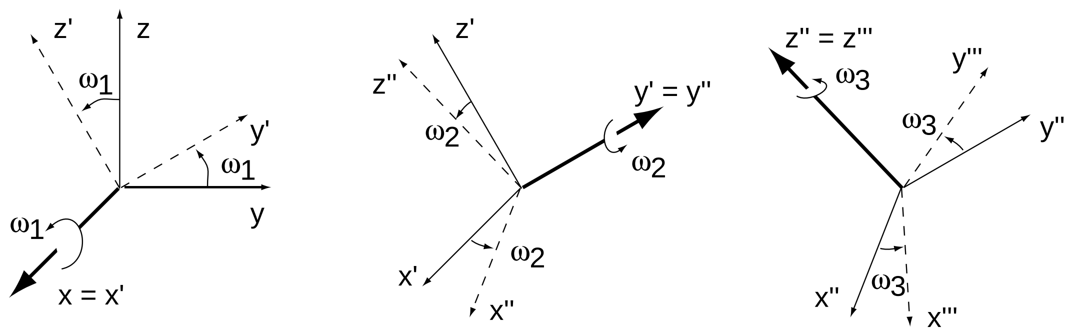



$a_{x'''x} = \cos \theta_{x'''x}$ $a_{x'''y} = \cos \theta_{x'''y}$ $a_{x'''z} = \cos \theta_{x'''z}$

$a_{y'''x} = \cos \theta_{y'''x}$ $a_{y'''y} = \cos \theta_{y'''y}$ $a_{y'''z} = \cos \theta_{y'''z}$

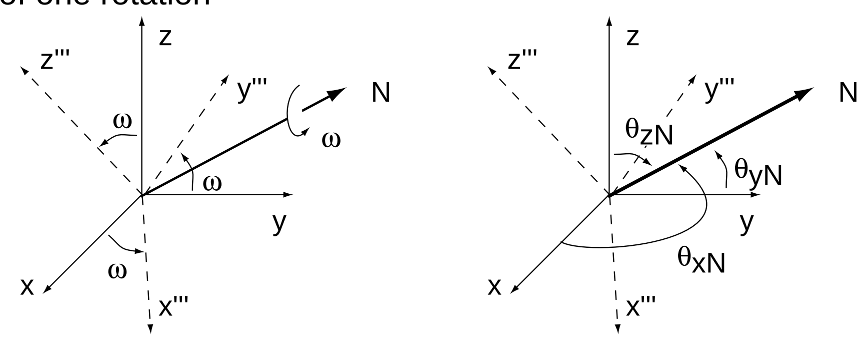
$a_{z'''x} = \cos \theta_{z'''x}$ $a_{z'''y} = \cos \theta_{z'''y}$ $a_{z'''z} = \cos \theta_{z'''z}$

## 2 Method of three rotations




A: Rotate about x-axis B: Rotate about y'-axis C: Rotate about z''-axis

## 3 Method of one rotation




This shows the angle of rotation about the rotation axis

This shows the orientation of the rotation axis relative to the three coordinate axes

$a_{xN} = \cos \theta_{xN}$ $a_{yN} = \cos \theta_{yN}$ $a_{zN} = \cos \theta_{zN}$

IV Rotations using a stereonet

- A Best uses
  - 1 Rotation axis is vertical (but this case is trivial)
  - 2 Rotation axis is horizontal (e.g., to restore tilted beds)
- B **Construction technique**
  - 1 Find orientation of rotation axis
  - 2 Find angle of rotation and rotate **pole** to plane (or a linear feature) along a **small circle** perpendicular to the rotation axis.
    - a For a horizontal rotation axis the small circle is vertical
    - b For a vertical rotation axis the small circle is horizontal
  - 3 **WARNING**: DON'T rotate a plane by rotating its dip direction vector; this doesn't work

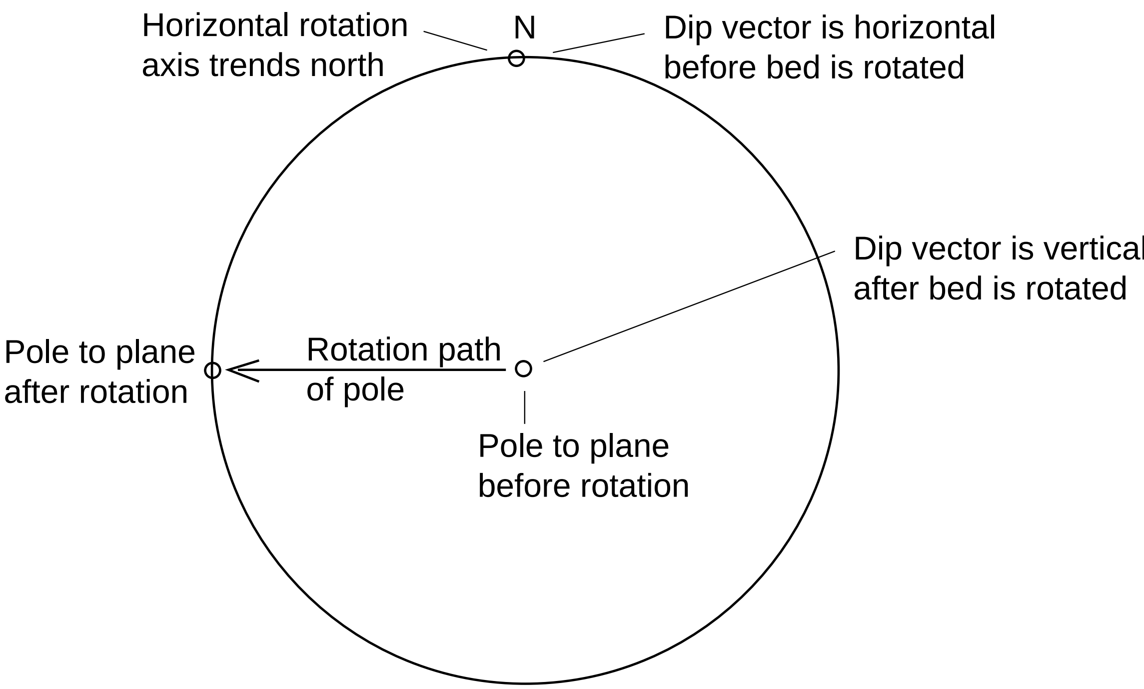
V Comments on rotations using stereonets and matrices

| | Advantages | Disadvantages |
|---|---|---|
| Stereonets | Good for visualization<br>Can bring into field | Relatively slow<br>Need good stereonets, paper |
| Matrices | Speed and flexibility<br>Good for multiple rotations | Computer really required to cut down on errors |

# Rotations of planes using poles;
# Problem with attempted rotation of planes using dip vectors

Consider a horizontal plane. We will consider it to strike to the north and dip to the east at 0°; these directions are consistent with a right-hand rule.
The pole to the plane trends west (270°) and plunges 90°.
The dip vector trends east (90°) and plunges 0°.

Suppose we wish to rotate the plane by +90° about a horizontal axis that trends north. We can visualize that after the rotation the plane will still strike to the north but will dip 90°. How do the pole to the plane and the dip vector rotate?




Equal area projection

**The pole will rotate about the rotation axis** and yield a result consistent with the final orienation of the the rotated plane. **The original dip vector will not rotate about the rotation axis**, so there is no rotation path to link the pre-rotation dip vector for the plane to the post-rotation dip vector for the plane.

**Bottom line: do rotations with poles, not dip vectors**

VI Uses of rotation in geology (and engineering) II

A **General comments** about stereonets vs. rotation matrices

1 **With stereonets, an object is usually considered to be rotated and the coordinate axes are held fixed.**

2 **The rotation matrices, an object is usually considered to be held fixed and the coordinate axes are rotated.**

B To return tilted bedding to horizontal choose a rotation axis that coincides with the direction of strike. The angle of rotation is the **negative** of the dip of the bedding (right-hand rule!) if the bedding is to be rotated back to horizontal and **positive** if the axes are to be rotated to the plane of the tilted bedding. Only one rotation is typically used; seldom are beds then rotated about a vertical axis.

C Orientations of features from drill cores

1 Orientations measured relative to core are called apparent

2 To determine the in-situ (true) orientations of features from the apparent orientations, two rotations are needed

a Rotate the core (or the coordinate axes) about a vertical axis. The rotation angle involves the trend of the core.

b Rotate the core (or the coordinate axes) about a horizontal axis perpendicular to the trend of the core . The rotation angle is the involves the plunge of the core .

c The rotations are given by

$$\begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} \cos(-\theta) & \sin(-\theta) & 0 \\ -\sin(-\theta) & \cos(-\theta) & 0 \\ 0 & 0 & 1 \end{bmatrix} \left( \begin{bmatrix} \cos(-[90-\phi]) & 0 & -\sin(-[90-\phi]) \\ 0 & 1 & 0 \\ \sin(-[90-\phi]) & 0 & \cos(-[90-\phi]) \end{bmatrix} \begin{bmatrix} x_1' \\ x_2' \\ x_3' \end{bmatrix} \right)$$

or

$$\begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} \cos(-\theta)\cos(-[90-\phi]) & \sin(-\theta) & -\cos(-\theta)\sin(-[90-\phi]) \\ -\sin(-\theta)\cos(-[90-\phi]) & \cos(-\theta) & \sin(-\theta)\sin(-[90-\phi]) \\ \sin(-[90-\phi]) & 0 & \cos(-[90-\phi]) \end{bmatrix} \begin{bmatrix} x_1' \\ x_2' \\ x_3' \end{bmatrix}$$

or

$$\begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} \cos\theta\sin\phi & -\sin\theta & \cos\theta\cos\phi \\ \sin\theta\sin\phi & \cos\theta & \sin\theta\cos\phi \\ -\cos\phi & 0 & \sin\phi \end{bmatrix} \begin{bmatrix} x_1' \\ x_2' \\ x_3' \end{bmatrix}$$

3 In the approach described in the figure below the primed axes are rotated to coincide with the unprimed axes. An alternative to rotate the unprimed axes to coincide with the primed axes. This can be accomplished by the following two steps:

a Rotate the unprimed axes about the vertical $x_3$ axis by angle $\theta$. The $x_2$ axis becomes the $x_2^a$ axis.

b Rotate the unprimed axes about the $x_2^a$ axis by angle $(90°-\phi)$.

c The rotations are given by

$$\begin{bmatrix} x_1' \\ x_2' \\ x_3' \end{bmatrix} = \begin{bmatrix} \cos(90°-\phi) & 0 & -\sin(90°-\phi) \\ 0 & 1 & 0 \\ \sin(90°-\phi) & 0 & \cos(90°-\phi) \end{bmatrix} \left( \begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} \right)$$

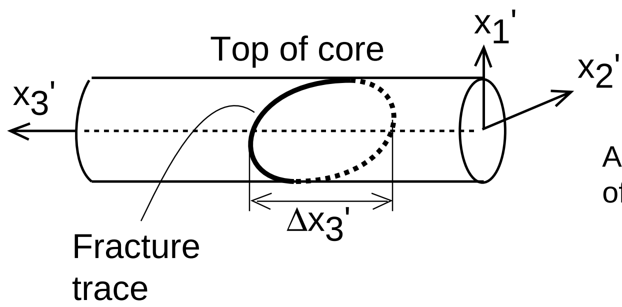
or

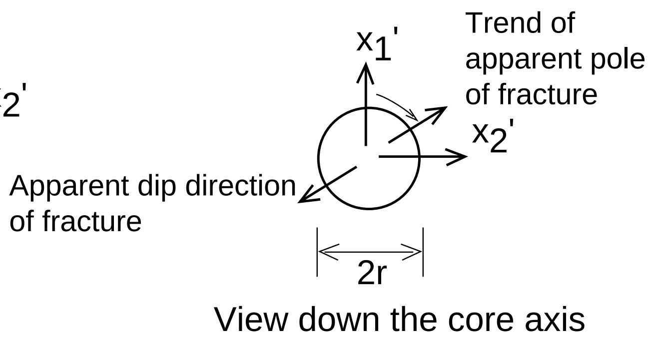
$$\begin{bmatrix} x_1' \\ x_2' \\ x_3' \end{bmatrix} = \begin{bmatrix} \sin\phi\cos\theta & \sin\phi\sin\theta & -\cos\phi \\ -\sin\theta & \cos\theta & 0 \\ \cos\phi\cos\theta & \cos\phi\sin\theta & \sin\phi \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}$$

**d From (2c), if [x] = [a][x'], then, from (3c), [x'] = $[a]^T$[x]**

# Conversion of apparent orientation scheme of Goodman to in-situ orientations (I)

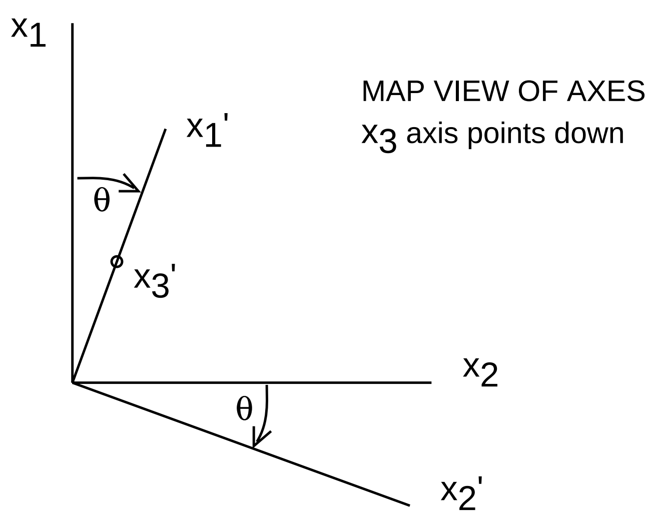
Let the coordinate system for the apparent orientations be the $x_1'$,$x_2'$,$x_3'$ system, where $x_3'$ points down the core axis and $x_1'$ points towards a line scribed on the top surface of the core. In this reference frame the apparent dip direction of a fracture = $\alpha$ and the apparent dip angle of the fracture = $\beta$.



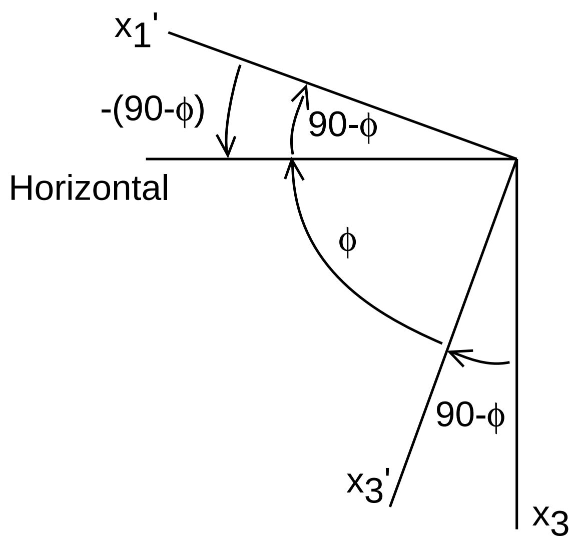

**In practice, this means the "apparent orientations" are measured with the core held vertically and its top line facing north.**
If the radius of the core is r, and the limits of the fracture trace in the $x_3'$ direction is $\Delta x_3$, then $\beta = \tan^{-1} ( \Delta x_3' /2r)$

Suppose the in-situ geographic coordinate system is chosen to be $x_1$ = north, $x_2$ = east, and $x_3$ = down. The vertical plane containing the borehole contains the $x_1'$ and $x_3'$ axes, and the $x_2'$ axis is horizontal. The trend and plunge of the $x_3'$ axis coincide with the trend ($\theta$) and plunge ($\phi$) of the borehole.



# Conversion of apparent orientation scheme of Goodman to in-situ orientations (II)

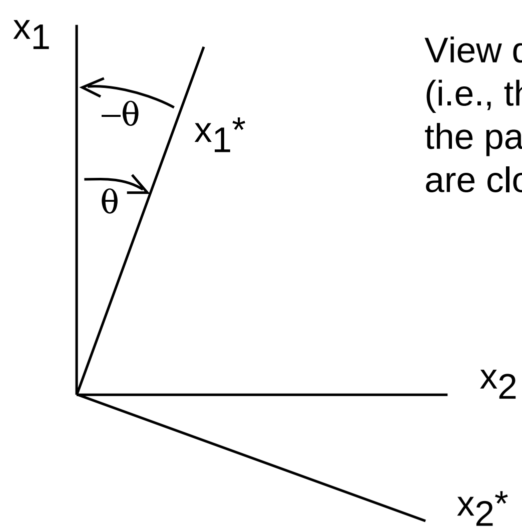
**Rotation 1**
Rotating the primed axes about the horizontal $x_2'$ axis by the angle **-**(90°-ϕ) will bring the $x_3'$ and $x_3$ axes into coincidence.




View down along the $x_2'$ axis (i.e., the $x_2'$ axis points into the page). Positive angles are clockwise.

The $x_3'$ axis becomes the $x_3^*$ axis.

**Rotation 2**
Rotating the starred axes about the vertical $x_3^*$ axis by the angle (-θ) will bring all the axes into coincidence.




View down along the $x_3^*$ axis (i.e., the $x_3^*$ axis points into the page). Positive angles are clockwise.

Lab 7

Exercise 1: Apparent dip problem **(28 points total)**

1a) An apparent dip of 62° to the northwest is measured for a bedding plane in a vertical cross section that strikes N40°W (call this apparent dip vector 1). An apparent dip of 34° to the southwest is measured for a bedding plane in a vertical cross section that strikes S20° W (call this apparent dip vector 2). What is the strike of the bedding plane and the true dip of the bedding plane? Solve this problem requires you to find the common plane that contains two intersecting lines. Solve the problem using an equal-angle spherical projection **(7 points total; 2 points for plotting each line, 1 pt for graphically identifying the common plane, and 2 pts for getting the strike and dip of the common plane)**

| Strike | Dip |
|---|---|
| | |

1b) Solve the problem using cross products using Matlab. Include a copy of your Matlab printout. **(21 points total, 1 point per box)**

| | Trend | Plunge | α | β | γ |
|---|---|---|---|---|---|
| Vector **v1** | | | | | |
| Vector **v2** | | | | | |

| | Vx | Vy | Vz | \|**V**\| |
|---|---|---|---|---|
| **N=v2xv1** | | | | |

| | α | β | γ | Pole Trend | Pole Plunge | Plane strike | Plane dip |
|---|---|---|---|---|---|---|---|
| **n=N/\|N\|** | | | | | | | |

<u>Exercise 2: Rotation problem 2</u> **(15 points total)**

2 ) An outcrop displays a regular set of current ripple marks. The axes of the ripple marks pitch 32° north in the bedding plane, and the bedding plane strikes 325° and dips 20°NE. Determine the direction of the original paleocurrents responsible for the ripple marks by restoring the beds back to horizontal (assume the current flowed perpendicular to the axes of the ripples. Before you answer that question, first determine the orientation of the rotation axis **N** and the angle of rotation θ. Neatly label your stereonets to show how the relevant features rotate (i.e., the ripple axis and the pole to bedding). **(1 pt/box here, 5 subjective points for clarity of stereonet work)**

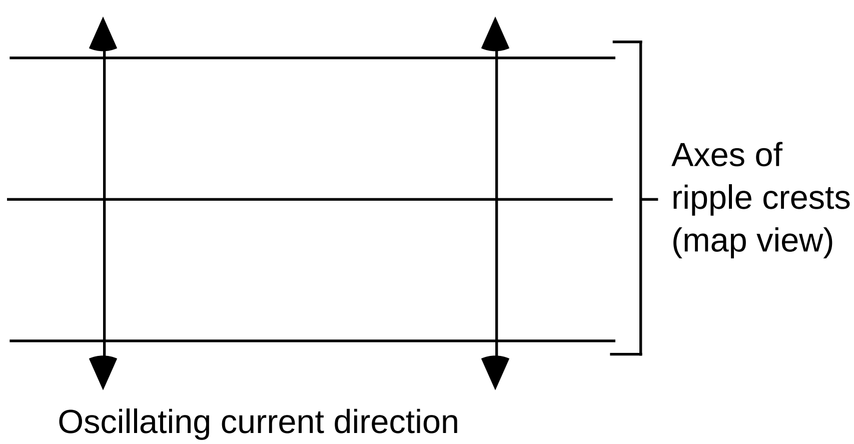
| Trend of rotation axis θ | Plunge of rotation axis ϕ | Rotation angle ω |
|---|---|---|
| | | |

| Existing ripple axis trend | Existing ripple axis plunge |
|---|---|
| | |

| Restored ripple axis trend | Restored ripple axis plunge |
|---|---|
| | |

| Original trend of current | Original plunge of current |
|---|---|
| | |

| Rake of restored ripple axis |
|---|
| |



Exercise 3: Rotation problem 1 **(40 points total)**

3a The beds below an angular unconformity (the "b beds) strike S30°E and dip 40° to the west. The sequence above the unconformity (the "a beds") is tilted, with a strike of N20°E and a dip of 30°E. What was the attitude of the "b beds" before the younger beds were tilted? In other words, if the "a beds" are restored to horizontal, what is the restored orientation of the "b beds"? Before you answer that question, first determine the orientation of the rotation axis **N** and the angle of rotation θ. Neatly label your stereonets to show how the relevant features rotate (i.e., the pole(s) to the "a beds" and the pole(s) to the "b beds"). **(14 points total; 1 pt/box here, 5 subjective points for stereonet work)**

| Trend θ of rotation axis **N** | Plunge ϕ of rotation axis **N** | Rotation angle ω |
|---|---|---|
| | | |

| Existing trend of pole **b** to "b beds" | Existing plunge of pole **b** to "b beds" |
|---|---|
| | |

| Restored trend of pole **b'** to "b beds" | Restored plunge of pole **b'** to "b beds" | Restored strike of "b beds" | Restored dip of "b beds" |
|---|---|---|---|
| | | | |

3b) Solve the problem using a rotation matrix and Matlab. Include a copy of your Matlab printout. Know what your reference frame is! **(26 points total, 1 point per box)**

| | Trend | Plunge | α | β | γ |
|---|---|---|---|---|---|
| Vector **N** | | | | | |
| Pole **b** | | | | | |

Rotation matrix

| | | |
|---|---|---|
| | | |
| | | |
| | | |

| Restored Pole α | Restored Pole β | Restored Pole γ | Restored Pole Trend | Restored Pole Plunge | Plane strike | Plane dip |
|---|---|---|---|---|---|---|
| | | | | | | |

Exercise 4: Borehole problem **(45 points total)**

4a The apparent dip of a fracture in a core is 10° and the apparent direction of dip (measured from the top line of the core; see figure on borehole rotations) is 180°. The core comes from a borehole with a trend of 60° and a plunge of 40°. Find the in-situ (in-place) orientation of the fracture. Plot the pole to the fracture and the orientation of the core at each step through this problem. Neatly label your stereonet to show how the core axis and the pole to bedding rotate. **(19 points total; 1 pt/box; 5 subjective points for stereonet)**

| Trend of rotation axis1 | Plunge of rotation axis1 | Rotation angle $\omega 1$ | Trend of rotation axis2 | Plunge of rotation axis2 | Rotation angle $\omega 2$ |
|---|---|---|---|---|---|
| | | | | | |

| Apparent trend of fracture pole | Apparent plunge of fracture pole |
|---|---|
| | |

| Pole trend after first rotation | Pole plunge after first rotation | Pole trend after second rotation | Pole plunge after second rotation |
|---|---|---|---|
| | | | |

| In-situ strike of fracture | In-situ dip of fracture |
|---|---|
| | |

4b) Solve the problem using a rotation matrix and Matlab. Include a copy of your Matlab printout. Know what your reference frame is! **(26 points total, 1 point per box)**

| | Trend | Plunge | $\alpha$ | $\beta$ | $\gamma$ |
|---|---|---|---|---|---|
| Vector **N** | | | | | |
| Apparent pole **n** | | | | | |

Rotation matrix

| | | |
|---|---|---|
| | | |
| | | |
| | | |

Restored orientations

| Restored Pole $\alpha$ | Restored Pole $\beta$ | Restored Pole $\gamma$ | Restored Pole Trend | Restored Pole Plunge | Plane strike | Plane dip |
|---|---|---|---|---|---|---|
| | | | | | | |

# Equal-Angle Net
# (Wulff Net)

N