ACSE-2

Part 2
Continuum mechanics and vector/tensor calculus

Lecture 5

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Lecture Materials

- Lecture slides
- Problem sets
- Solutions (after workshop)

All available on GitHub

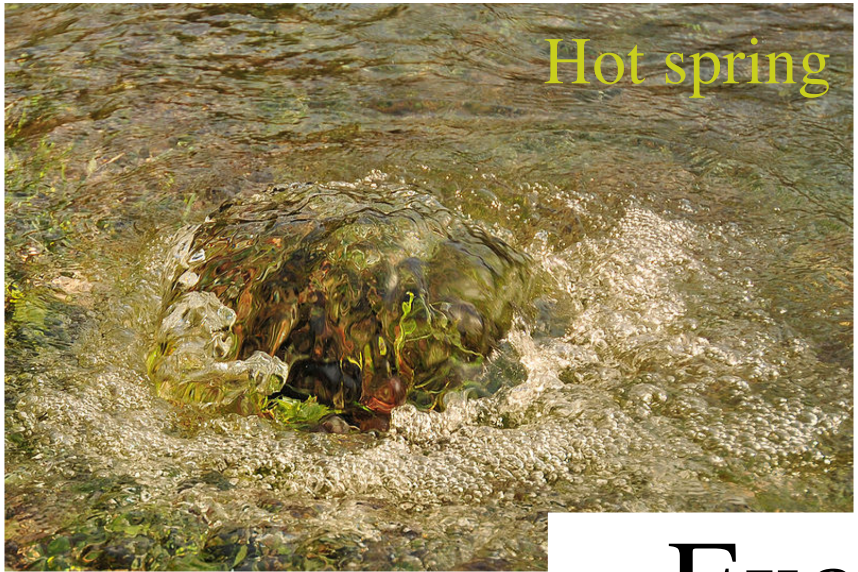
Outline of course

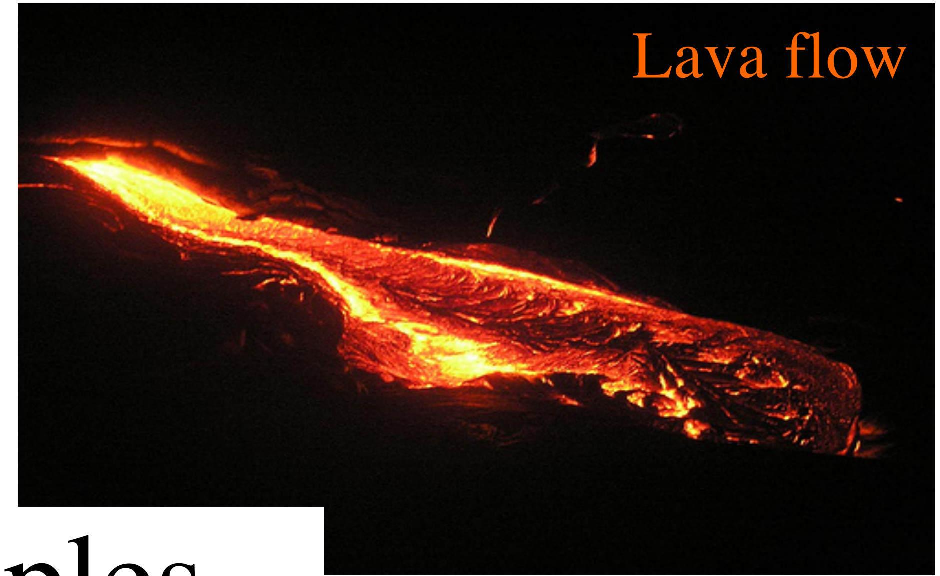
- **1.** Mathematical essentials – *Matthew Piggott*
- **2.** Linear Algebra I – *Matthew Piggott*
- **3.** Linear Algebra II, ODEs– *Matthew Piggott*
- **4.** Verifying models– *Matthew Piggott*
- **5.** Vector and Tensor Calculus - *Saskia Goes*
- **6.** Stress principles - *Saskia Goes*
- **7.** Kinematics and strain - *Saskia Goes*
- **8.** Rheology and conservation equations - *Saskia Goes*
- **9.** Dimensional analysis - *Stephen Neethling*
- **10.** Potential flow - *Stephen Neethling*
- **11.** Fluid flow I - *Stephen Neethling*
- **12.** Fluid flow & turbulence – *Stephen Neethling*

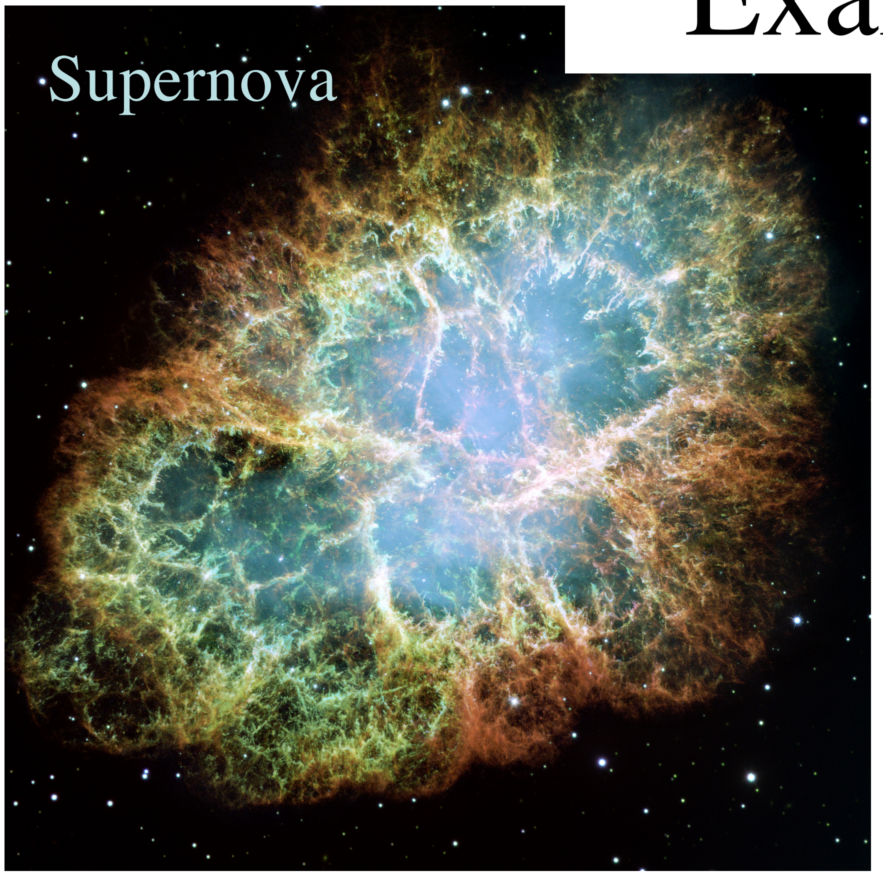
Continuum Mechanics

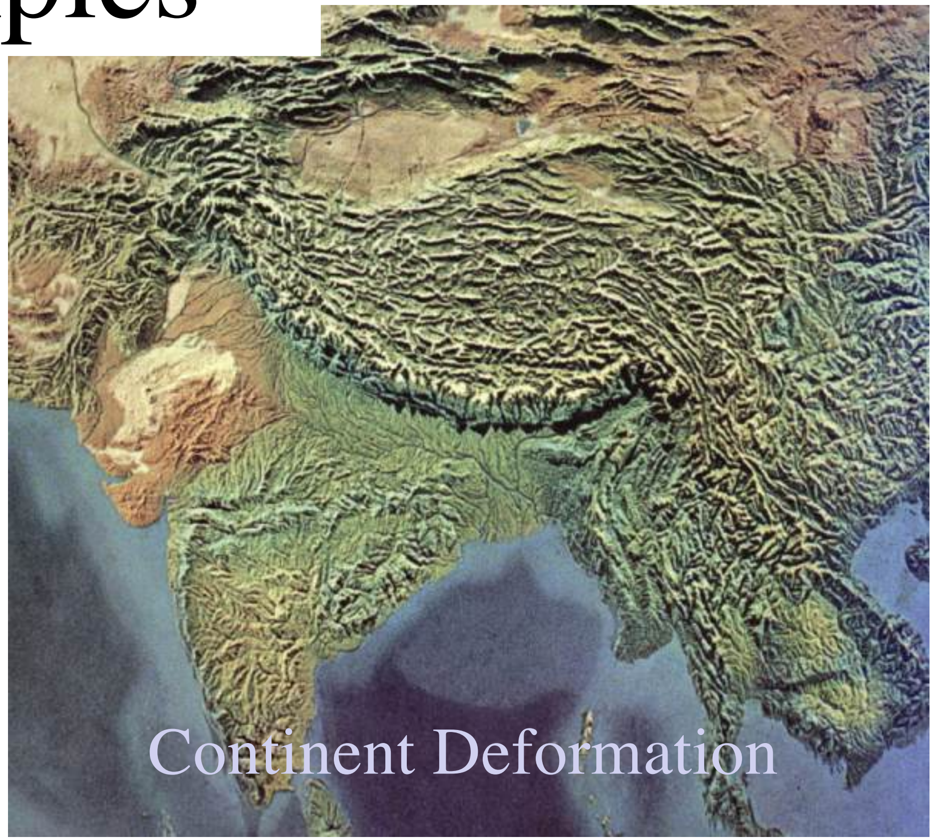
- *Macroscopic description* of the collective behavior of atoms/molecules in the limit where scale >> scale of the individual components
- Treat a material, be it solid, liquid, gas, as hypothetical continuum where all quantities vary continuously so that spatial derivatives exist
- In such a treatment, we can consider infinitesimally small volumes of the material and define point quantities, like mass, velocity, stress
- Such a description has been found to be applicable in a wide range of problems in engineering and physical sciences

Examples

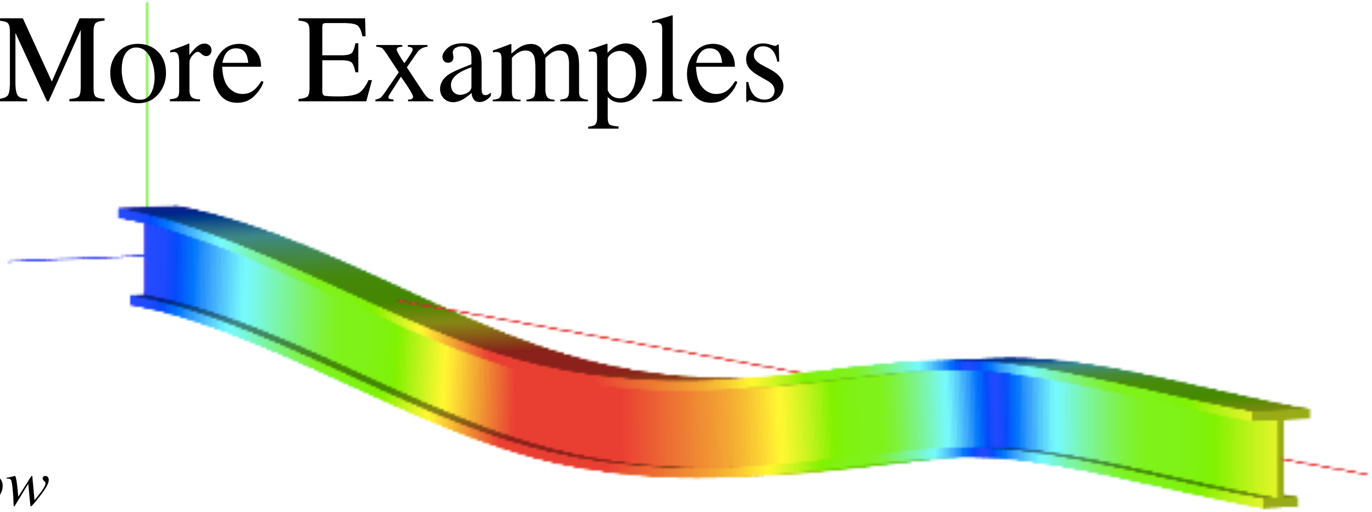






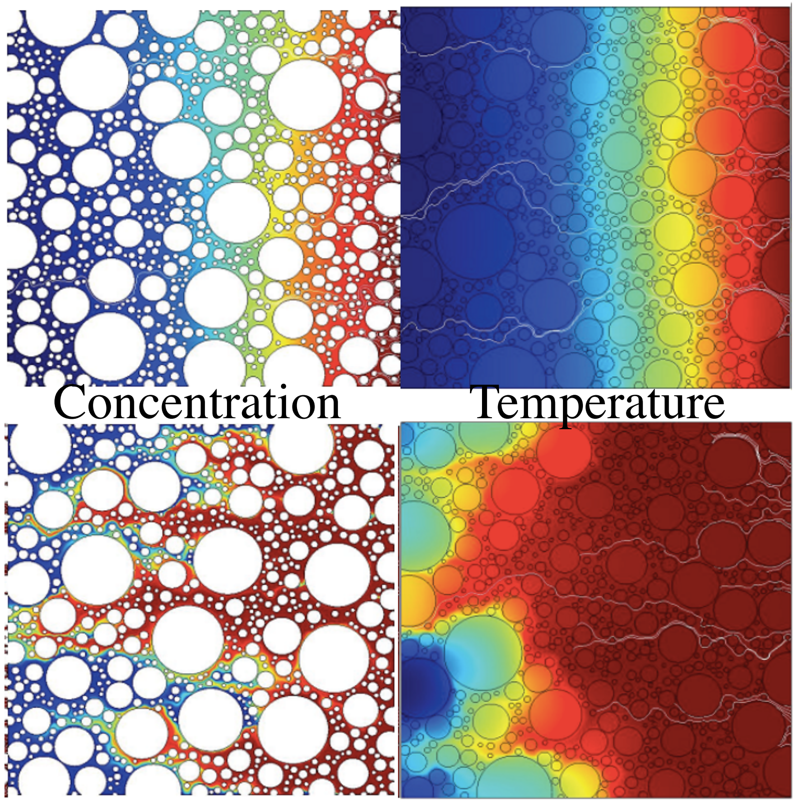


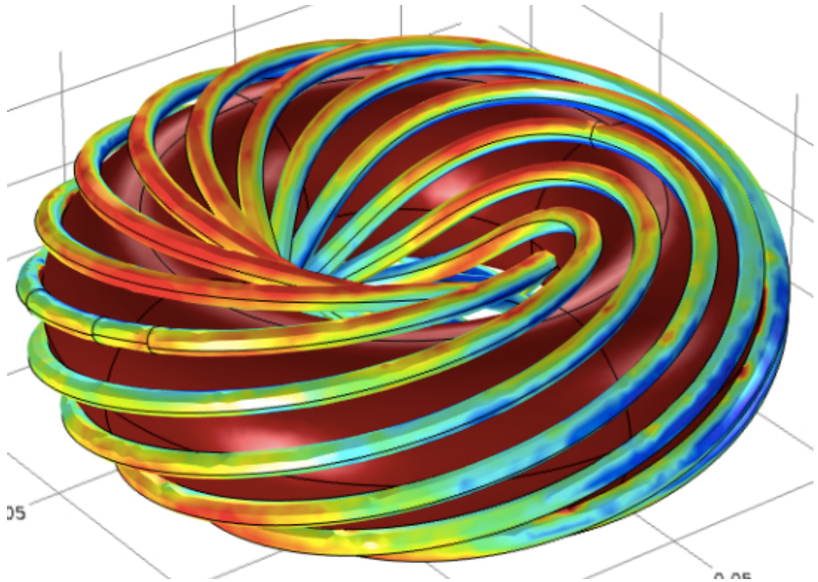
More Examples



Beam bending

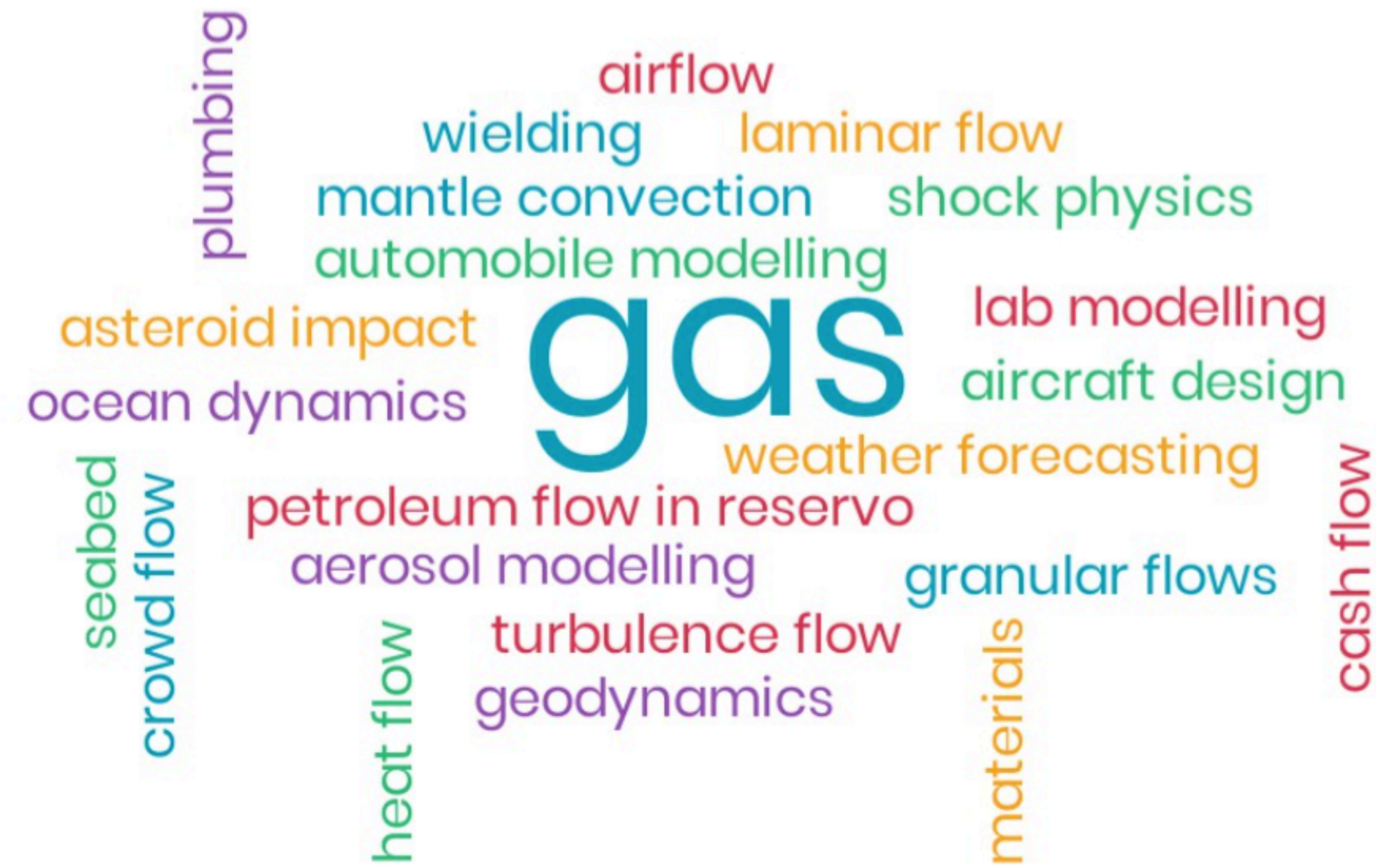
Porous flow





Electromagnetism

Other Examples?



No required text

Possible textbooks for additional background

- Introduction to Continuum Mechanics, W.M. Lai, D. Rubin, E. Krempl, 4^{th} edition, Elsevier – available in electronic form through IC library

- An Introduction to Continuum Mechanics, J.N. Reddy, 2^{nd} edition, Cambridge University Press, 2013

- Khan Academy – online lectures on Maths, Physics

The books use similar notation as this course and cover many of the topics in ACSE-2. However, do note different reading may be suggested for other parts of the course

Continuum Mechanics Equations

General:

1.<u>Kinematics</u> – describing deformation and velocity without considering forces

2.<u>Dynamics</u> – equations that describe force balance, conservation of linear and angular momentum

3.<u>Thermodynamics</u> – relations temperature, heat flux, stress, entropy

Material-specific

4.<u>Constitutive equations</u> – relations describing how material properties vary as a function of T,P, stress,…. Such material properties govern dynamics (e.g., density), response to stress (viscosity, elastic parameters), heat transport (thermal conductivity, diffusivity)

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$\Rightarrow$ *Yields a set of Partial Differential Equations that can be solved for displacement, velocity, temperature,…*

Partial Differential Equations

- **Ordinary Differential Equations** – describe how variables depend on a single independent parameter (e.g., time or distance).

For example:

$$m\frac{d^2x}{dt^2} = F$$

Newton's second law

- **Partial Differential Equations** – describe how variables depend on several independent parameters (e.g., time, x,y,z coordinates)

For example:

$$\frac{\partial T}{\partial t} = \kappa \frac{\partial^2 T}{\partial x^2}$$

Thermal diffusion equation

∂ - partial derivative

Today
Vectors and Tensors

- Revision vectors
  - Addition, linear independence
  - Orthonormal Cartesian bases, transformation
  - Multiplication
  - Derivatives, del, div, curl
- Revision/introduction tensors
  - Tensors, rank, stress tensor
  - Index notation, summation convention
  - Addition, multiplication
  - Special tensors, δ_{ij} and ε_{ijk}
  - Tensor calculus: gradient, divergence, curl, ..

Learning Objectives

- Be able to perform vector/tensor operations (addition, multiplication) on Cartesian orthonormal bases
- Be able to do basic vector/tensor calculus (time and space derivatives, divergence, curl of a vector field) on these bases.
- Perform transformation of a vector from one to another Cartesian basis.
- Understand differences/commonalities tensor and vector
- Use index notation and Einstein convention
- Be able to use the special tensors δ_{ij} and ε_{ijk}

Key characteristics of a vector?

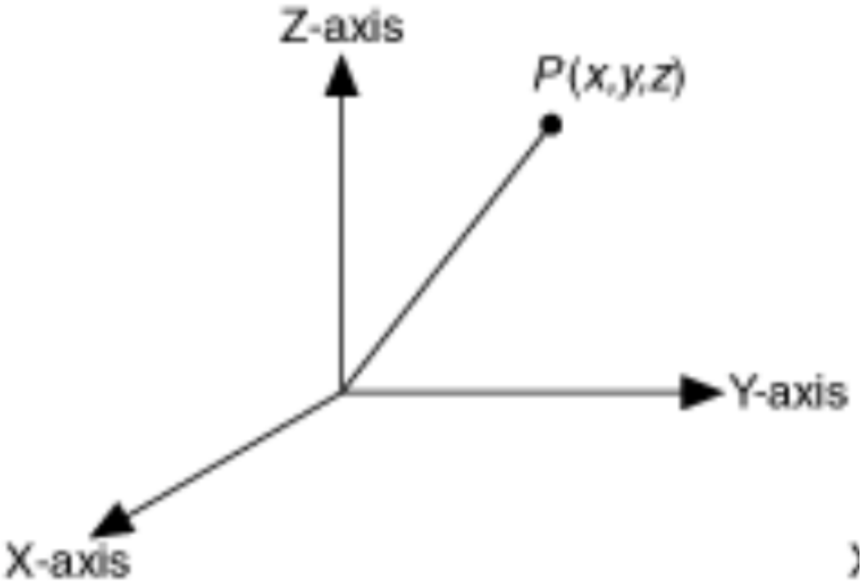
1. Anything that is not a scalar
2. Has three components
3. Has magnitude and direction
4. Depends on coordinate frame
5. Velocity and rotation are two examples
6. Multiplication of two vectors gives another vector

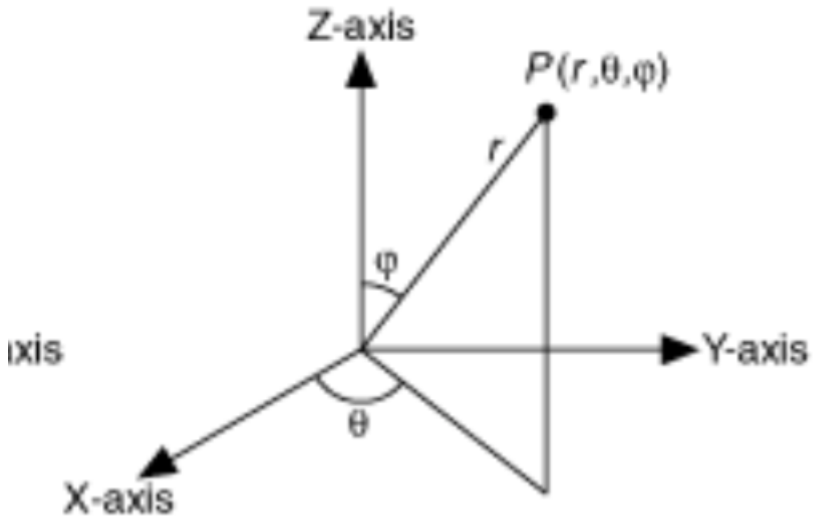
Choose all that are correct

Intro Vectors, Tensors

Continuum mechanics equations require vectors and tensors. E.g., velocity is a vector, with magnitude and direction in 3-D, and so are forces like gravity.

The components of a vector depend on the coordinate system chosen to represent them in. However, the actual size and orientation of the vector is not dependent on the choice of coordinate system





Notation

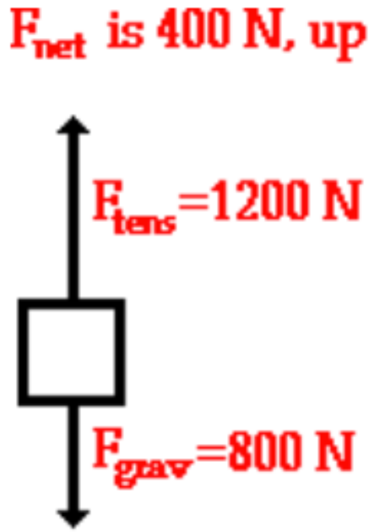
- Vectors as **v** or $\vec{v}$ or $\overline{v}$
- Length of vectors v or $|\mathbf{v}|$
- Vector in Cartesian components v_x, v_y, v_z
- Index notation v_i, $i=x,y,z$ or $i=1,2,3$
- Unit vector along direction of **v**: $\hat{\mathbf{e}}_v = \dfrac{\mathbf{v}}{|\mathbf{v}|}$

$$\mathbf{v} = \hat{\mathbf{e}}_v |\mathbf{v}|$$

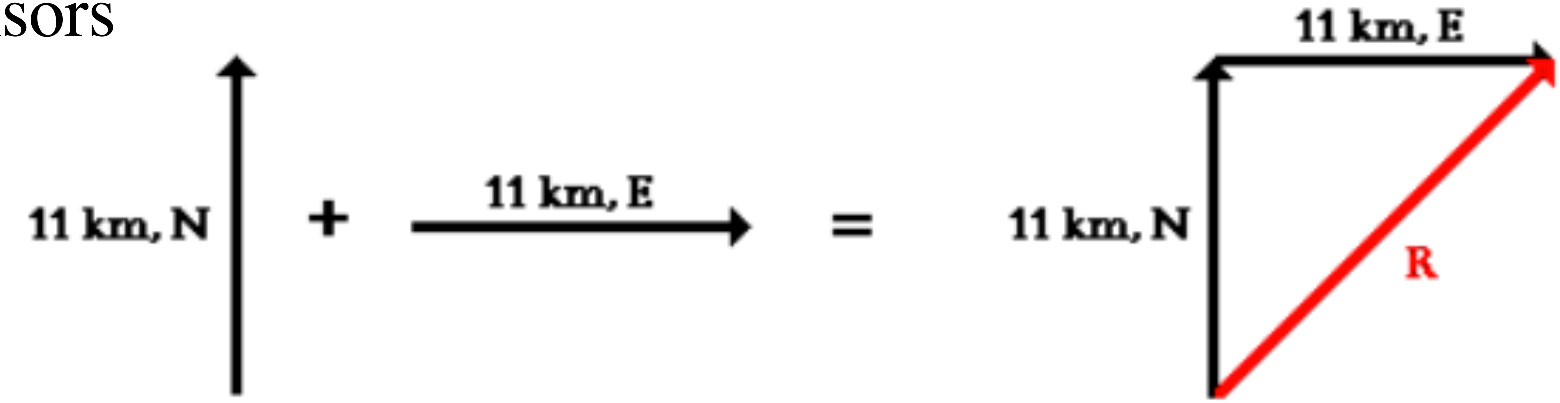
Vectors

Vectors satisfy certain rules of addition and scalar multiplication,

- $\mathbf{a}+\mathbf{b}=\mathbf{b}+\mathbf{a}$ (commutative)
- $(\mathbf{a}+\mathbf{b})+\mathbf{c}=\mathbf{a}+(\mathbf{b}+\mathbf{c})$ (associative)
- $\alpha(\mathbf{a}+\mathbf{b}) = \alpha\mathbf{a}+\alpha\mathbf{b}$ (distributive)
- $\mathbf{a}+\mathbf{0}=\mathbf{a}$ (zero vector)
- $1\cdot\mathbf{a}=\mathbf{a}\cdot 1$; $0\cdot\mathbf{a}=\mathbf{0}$

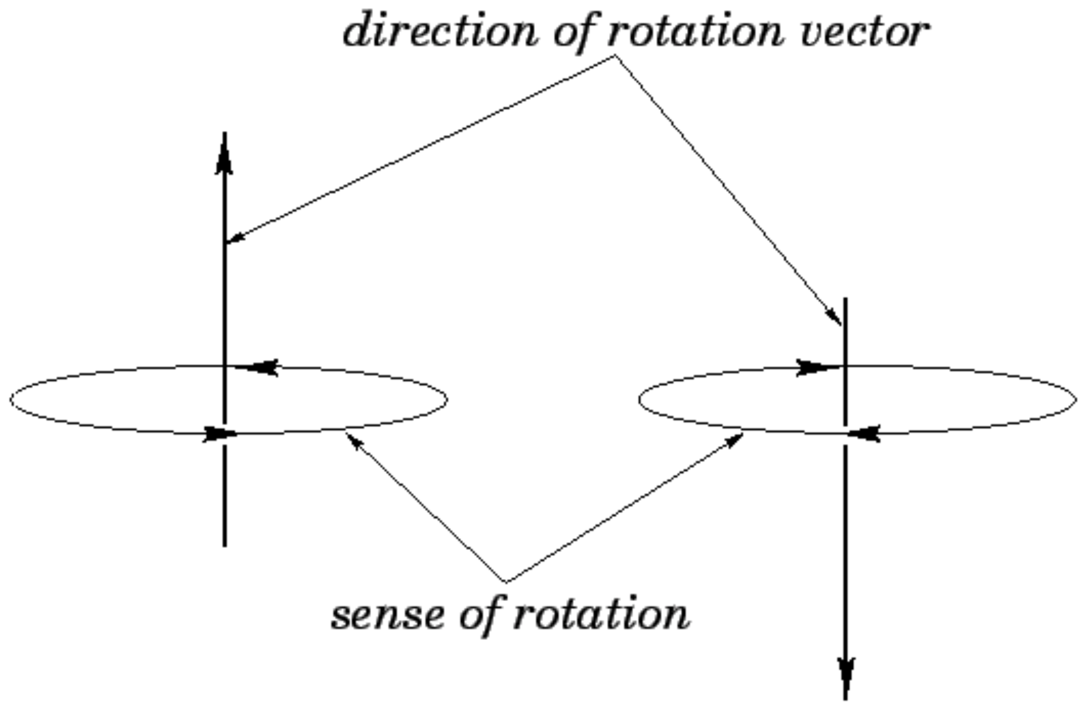


We will see that similar rules apply to tensors



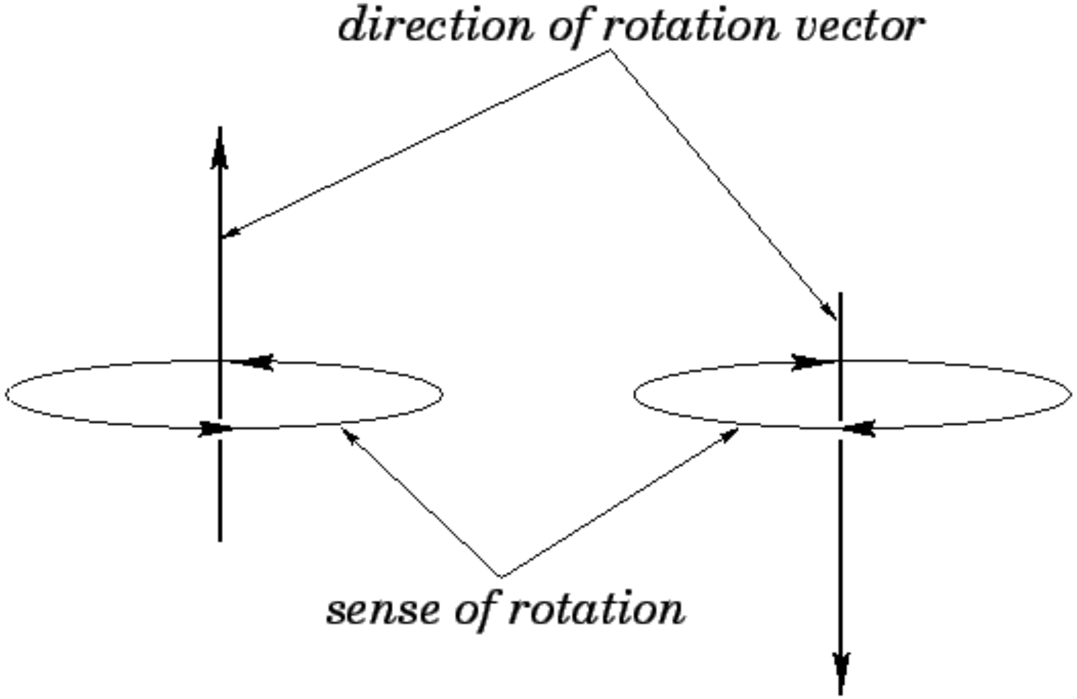
e.g. see http://mathworld.wolfram.com/Vector.html

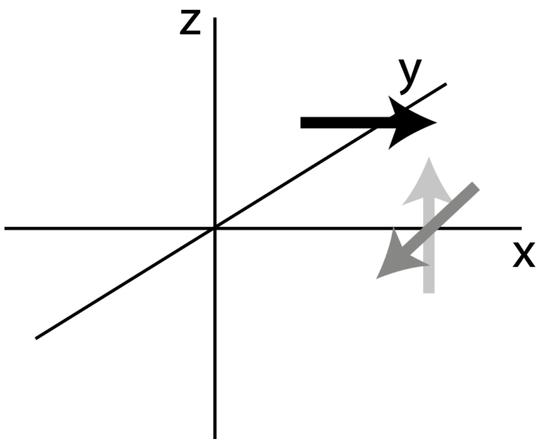
Finite Rotation "Vector"



Right-hand rule

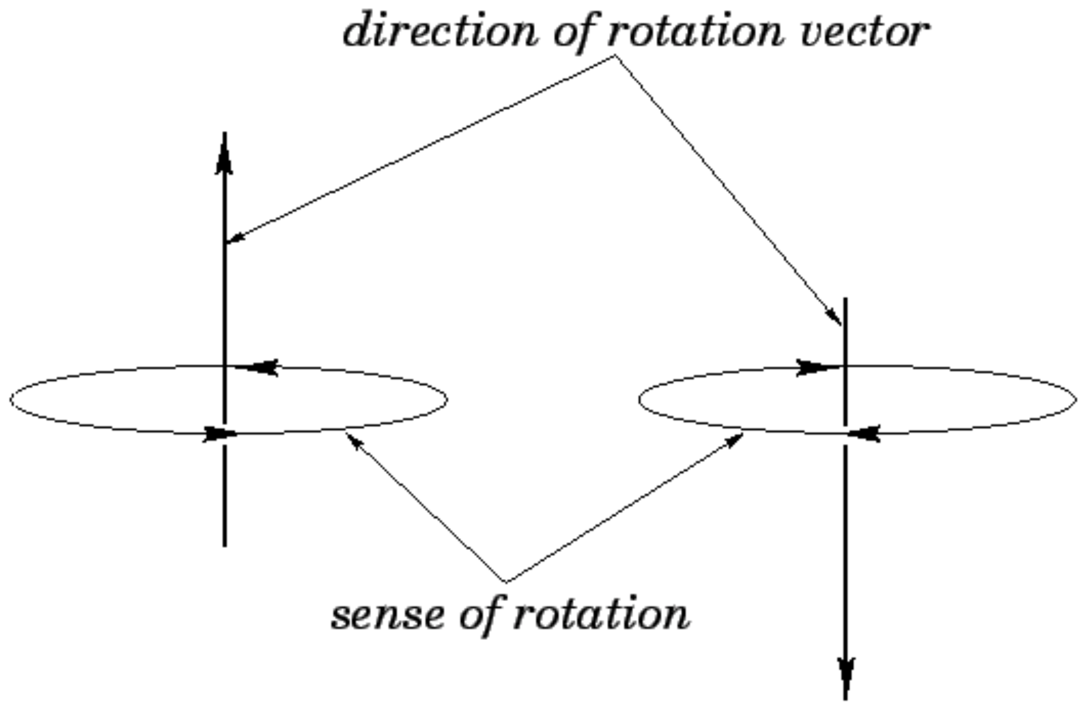
Finite Rotation "Vector"

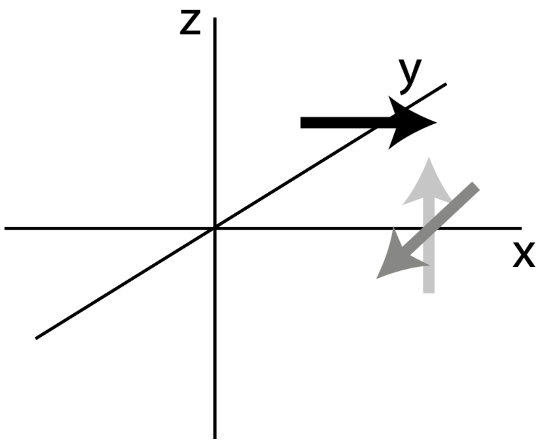




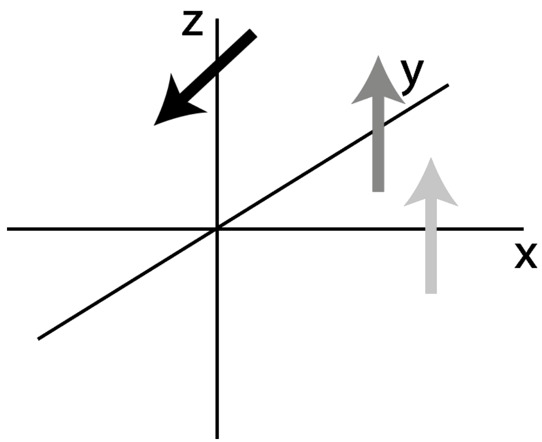
rotate 90˚ around **x** +
90˚ around **z**

Finite Rotation "Vector"





rotate 90° around **x** + 90° around **z**



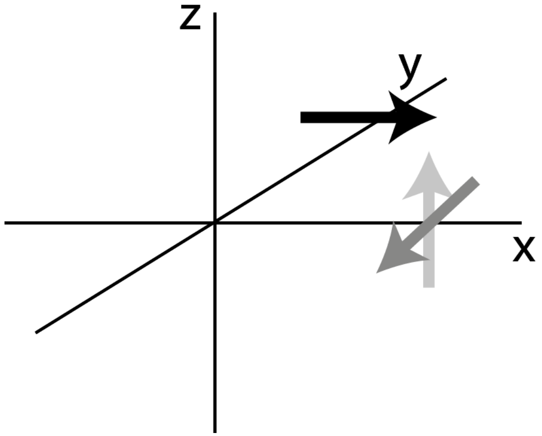
rotate 90° around **z** + 90° around **x**

Finite Rotation "Vector"

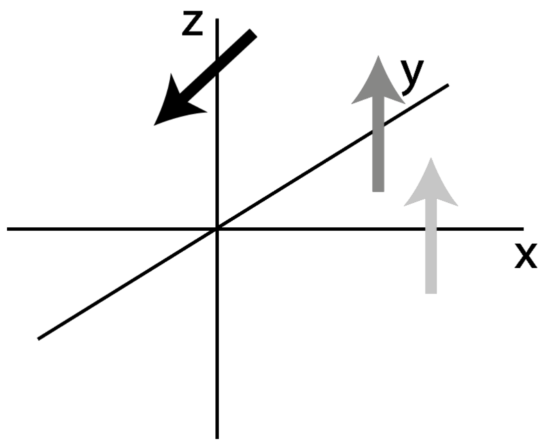
If **a** and **b** are two general vectors, then **a+b=b+a**

However, addition of two finite rotations is not commutative.

Finite rotation is pseudo-vector
Infinitesimal rotation is vector



rotate 90° around **x** + 90° around **z**



rotate 90° around **z** + 90° around **x**

Linear independence

Vectors v_1 through v_n are linearly dependent if coefficients c_i can be found such that:

$$c_1v_1+c_2v_2+c_3v_3+\ldots c_nv_n=0$$

1. if two vectors are linearly dependent, they are?
2. if three vectors are linearly dependent, they are?
3. four or more vectors are always linearly dependent

Important for defining bases, independent solutions to a problem

Try yourself

- *What steps would be required to determine in a code whether two given 2-D vectors **a** and **b** are linearly independent or not? Write them out.*

Linear independence two vectors

$\mathbf{a}=(a_1,a_2)$, $\mathbf{b}=(b_1,b_2)$

- $c_1a_1+c_2b_1=0$
- $c_1a_2+c_2b_2=0$

$\Rightarrow c_1=-c_2b_1/a_1$

$\Rightarrow -c_2a_2b_1/a_1+c_2b_2=0$

$\Rightarrow c_2(b_2-a_2b_1/a_1)=0$

$\Rightarrow a_1b_2-a_2b_1=0$

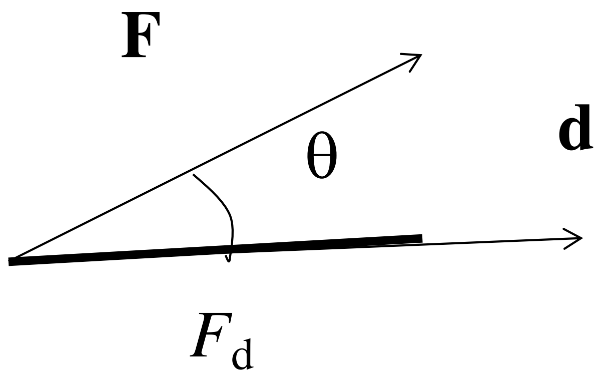
if true, linearly dependent

Products of vectors

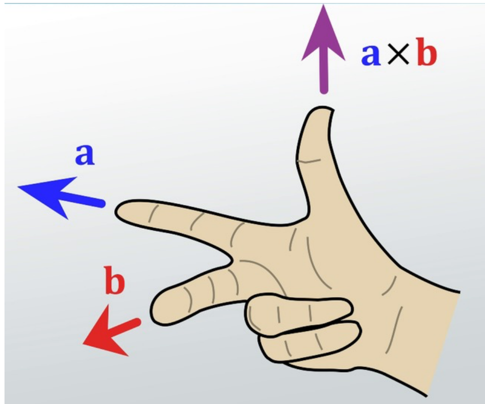
Inner product, dot product, scalar product

Geometric definition

- $\mathbf{F} \cdot \mathbf{d} = |\mathbf{F}||\mathbf{d}|\cos\theta$
  - scalar,
  - projection of **F** on **d** times |**d**|,
  - = 0 if **F** and **d** perpendicular,
  - **F**·**d** = **d**·**F**



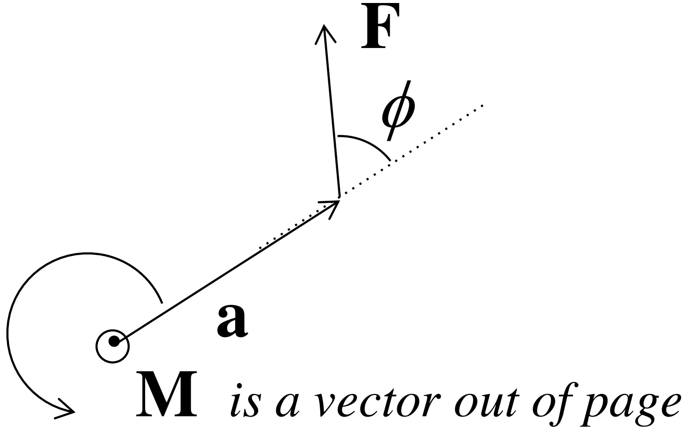
- If **F** is force, **d** is displacement, then **F**·**d** is the work done by the force **F** for displacement **d**
- **a**·**a**= length(**a**)^2= $|\mathbf{a}|^2$



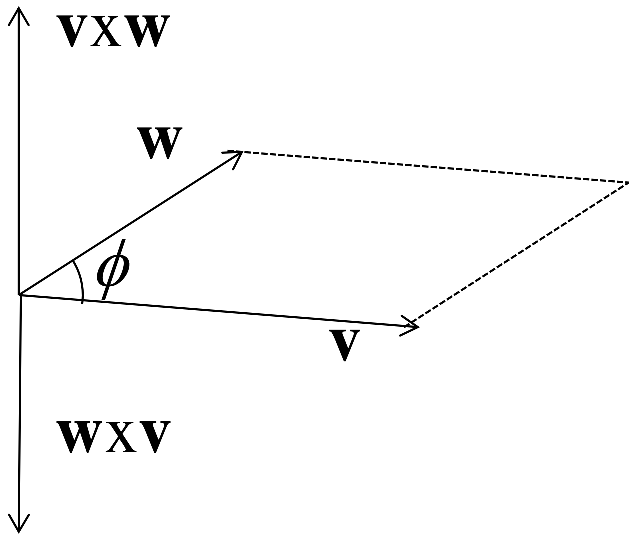
Products of vectors
Cross product, vector product, outer product
Geometric definition

- Example moment:

$$\mathbf{M} = \mathbf{a} \times \mathbf{F} = aF\sin\phi\,\hat{\mathbf{e}}_M$$



- Properties **vxw**
  - vector
  - magnitude = area of parallellogram spanned by **v**, **w**
  - direction is that of plane normal (right-hand rule)
  - =0 if **v** and **w** are parallel
  - **vxw** =-**wxv**



Products of vectors

Algebraic, in rectangular Cartesian coordinates:

in 2D

$$\mathbf{v} \cdot \mathbf{w} = v_1 w_1 + v_2 w_2 \qquad \mathbf{v} \times \mathbf{w} = v_1 w_2 - v_2 w_1$$

in 3D

$$\mathbf{v} \cdot \mathbf{w} = v_1 w_1 + v_2 w_2 + v_3 w_3$$

$$\mathbf{v} \times \mathbf{w} = \begin{pmatrix} v_2 w_3 - v_3 w_2 \\ v_3 w_1 - v_1 w_3 \\ v_1 w_2 - v_2 w_1 \end{pmatrix}$$

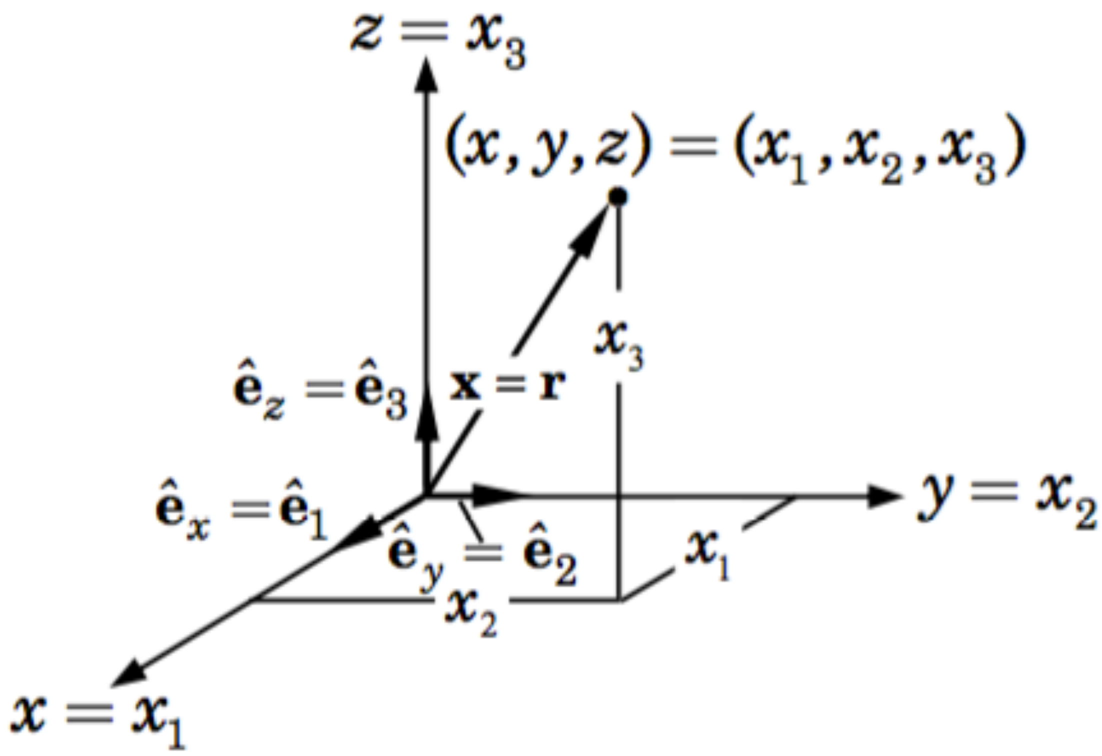
Rectangular Cartesian Coordinate System

Orthonormal basis –
Basis vectors are:
orthogonal

$\hat{\mathbf{e}}_i \cdot \hat{\mathbf{e}}_j = 0$ if i≠j

and unit length

$\hat{\mathbf{e}}_i \cdot \hat{\mathbf{e}}_i = |\hat{\mathbf{e}}_i|^2 = 1$



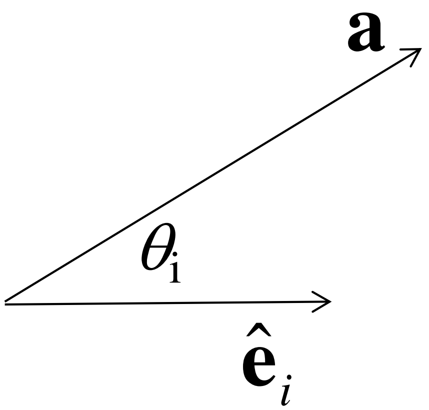
Cartesian – basis vectors with constant length and direction

In following, we will assume Cartesian orthonormal bases

Other orthonormal bases, e.g. polar or spherical, not discussed here

	Cartesian Coordinates	Cylindrical Coordinates	Spherical Coordinates
Coordinate variables	x, y, z	r, ϕ, z	R, θ, ϕ
Vector representation $\mathbf{A} =$	$\hat{\mathbf{x}}A_x + \hat{\mathbf{y}}A_y + \hat{\mathbf{z}}A_z$	$\hat{\mathbf{r}}A_r + \hat{\boldsymbol{\phi}}A_\phi + \hat{\mathbf{z}}A_z$	$\hat{\mathbf{R}}A_R + \hat{\boldsymbol{\theta}}A_\theta + \hat{\boldsymbol{\phi}}A_\phi$
Magnitude of A $\quad \lvert\mathbf{A}\rvert =$	$\sqrt[+]{A_x^2 + A_y^2 + A_z^2}$	$\sqrt[+]{A_r^2 + A_\phi^2 + A_z^2}$	$\sqrt[+]{A_R^2 + A_\theta^2 + A_\phi^2}$
Position vector $\quad \overrightarrow{OP_1} =$	$\hat{\mathbf{x}}x_1 + \hat{\mathbf{y}}y_1 + \hat{\mathbf{z}}z_1$, for $P(x_1, y_1, z_1)$	$\hat{\mathbf{r}}r_1 + \hat{\mathbf{z}}z_1$, for $P(r_1, \phi_1, z_1)$	$\hat{\mathbf{R}}R_1$, for $P(R_1, \theta_1, \phi_1)$
Base vectors properties	$\hat{\mathbf{x}}\cdot\hat{\mathbf{x}} = \hat{\mathbf{y}}\cdot\hat{\mathbf{y}} = \hat{\mathbf{z}}\cdot\hat{\mathbf{z}} = 1$ $\hat{\mathbf{x}}\cdot\hat{\mathbf{y}} = \hat{\mathbf{y}}\cdot\hat{\mathbf{z}} = \hat{\mathbf{z}}\cdot\hat{\mathbf{x}} = 0$ $\hat{\mathbf{x}}\times\hat{\mathbf{y}} = \hat{\mathbf{z}}$ $\hat{\mathbf{y}}\times\hat{\mathbf{z}} = \hat{\mathbf{x}}$ $\hat{\mathbf{z}}\times\hat{\mathbf{x}} = \hat{\mathbf{y}}$	$\hat{\mathbf{r}}\cdot\hat{\mathbf{r}} = \hat{\boldsymbol{\phi}}\cdot\hat{\boldsymbol{\phi}} = \hat{\mathbf{z}}\cdot\hat{\mathbf{z}} = 1$ $\hat{\mathbf{r}}\cdot\hat{\boldsymbol{\phi}} = \hat{\boldsymbol{\phi}}\cdot\hat{\mathbf{z}} = \hat{\mathbf{z}}\cdot\hat{\mathbf{r}} = 0$ $\hat{\mathbf{r}}\times\hat{\boldsymbol{\phi}} = \hat{\mathbf{z}}$ $\hat{\boldsymbol{\phi}}\times\hat{\mathbf{z}} = \hat{\mathbf{r}}$ $\hat{\mathbf{z}}\times\hat{\mathbf{r}} = \hat{\boldsymbol{\phi}}$	$\hat{\mathbf{R}}\cdot\hat{\mathbf{R}} = \hat{\boldsymbol{\theta}}\cdot\hat{\boldsymbol{\theta}} = \hat{\boldsymbol{\phi}}\cdot\hat{\boldsymbol{\phi}} = 1$ $\hat{\mathbf{R}}\cdot\hat{\boldsymbol{\theta}} = \hat{\boldsymbol{\theta}}\cdot\hat{\boldsymbol{\phi}} = \hat{\boldsymbol{\phi}}\cdot\hat{\mathbf{R}} = 0$ $\hat{\mathbf{R}}\times\hat{\boldsymbol{\theta}} = \hat{\boldsymbol{\phi}}$ $\hat{\boldsymbol{\theta}}\times\hat{\boldsymbol{\phi}} = \hat{\mathbf{R}}$ $\hat{\boldsymbol{\phi}}\times\hat{\mathbf{R}} = \hat{\boldsymbol{\theta}}$
Dot product $\quad \mathbf{A}\cdot\mathbf{B} =$	$A_xB_x + A_yB_y + A_zB_z$	$A_rB_r + A_\phi B_\phi + A_zB_z$	$A_RB_R + A_\theta B_\theta + A_\phi B_\phi$
Cross product $\quad \mathbf{A}\times\mathbf{B} =$	$\begin{vmatrix} \hat{\mathbf{x}} & \hat{\mathbf{y}} & \hat{\mathbf{z}} \\ A_x & A_y & A_z \\ B_x & B_y & B_z \end{vmatrix}$	$\begin{vmatrix} \hat{\mathbf{r}} & \hat{\boldsymbol{\phi}} & \hat{\mathbf{z}} \\ A_r & A_\phi & A_z \\ B_r & B_\phi & B_z \end{vmatrix}$	$\begin{vmatrix} \hat{\mathbf{R}} & \hat{\boldsymbol{\theta}} & \hat{\boldsymbol{\phi}} \\ A_R & A_\theta & A_\phi \\ B_R & B_\theta & B_\phi \end{vmatrix}$
Differential length $\quad d\mathbf{l} =$	$\hat{\mathbf{x}}\,dx + \hat{\mathbf{y}}\,dy + \hat{\mathbf{z}}\,dz$	$\hat{\mathbf{r}}\,dr + \hat{\boldsymbol{\phi}}r\,d\phi + \hat{\mathbf{z}}\,dz$	$\hat{\mathbf{R}}\,dR + \hat{\boldsymbol{\theta}}R\,d\theta + \hat{\boldsymbol{\phi}}R\sin\theta\,d\phi$
Differential surface areas	$d\mathbf{s}_x = \hat{\mathbf{x}}\,dy\,dz$ $d\mathbf{s}_y = \hat{\mathbf{y}}\,dx\,dz$ $d\mathbf{s}_z = \hat{\mathbf{z}}\,dx\,dy$	$d\mathbf{s}_r = \hat{\mathbf{r}}r\,d\phi\,dz$ $d\mathbf{s}_\phi = \hat{\boldsymbol{\phi}}\,dr\,dz$ $d\mathbf{s}_z = \hat{\mathbf{z}}r\,dr\,d\phi$	$d\mathbf{s}_R = \hat{\mathbf{R}}R^2\sin\theta\,d\theta\,d\phi$ $d\mathbf{s}_\theta = \hat{\boldsymbol{\theta}}R\sin\theta\,dR\,d\phi$ $d\mathbf{s}_\phi = \hat{\boldsymbol{\phi}}R\,dR\,d\theta$
Differential volume $\quad dV =$	$dx\,dy\,dz$	$r\,dr\,d\phi\,dz$	$R^2\sin\theta\,dR\,d\theta\,d\phi$

Equivalence Cartesian geometric and algebraic dot product



$$\mathbf{a} = \sum_i a_i \hat{\mathbf{e}}_i \qquad \mathbf{b} = \sum_i b_i \hat{\mathbf{e}}_i$$

$$\mathbf{a} \cdot \hat{\mathbf{e}}_i = |\mathbf{a}||\hat{\mathbf{e}}_i|\cos\vartheta_i = |\mathbf{a}|\cos\vartheta_i = a_i$$

$$\mathbf{a} \cdot \mathbf{b} = \mathbf{a} \cdot \sum_i b_i \hat{\mathbf{e}}_i = \sum_i b_i (\mathbf{a} \cdot \hat{\mathbf{e}}_i) = \sum_i b_i a_i = \sum_i a_i b_i$$

Products of vectors

Algebraic, in rectangular Cartesian coordinates:

in 2D

$$\mathbf{v} \cdot \mathbf{w} = v_1 w_1 + v_2 w_2 \qquad \mathbf{v} \times \mathbf{w} = v_1 w_2 - v_2 w_1$$

in 3D

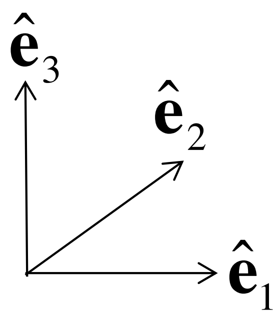
$$\mathbf{v} \cdot \mathbf{w} = v_1 w_1 + v_2 w_2 + v_3 w_3$$

$$\mathbf{v} \times \mathbf{w} = \begin{pmatrix} v_2 w_3 - v_3 w_2 \\ v_3 w_1 - v_1 w_3 \\ v_1 w_2 - v_2 w_1 \end{pmatrix}$$

Cartesian algebraic cross product

$$\hat{\mathbf{e}}_i \times \hat{\mathbf{e}}_i = 0 \qquad \begin{aligned} \hat{\mathbf{e}}_1 \times \hat{\mathbf{e}}_2 &= \hat{\mathbf{e}}_3 & \hat{\mathbf{e}}_2 \times \hat{\mathbf{e}}_1 &= -\hat{\mathbf{e}}_3 \\ \hat{\mathbf{e}}_2 \times \hat{\mathbf{e}}_3 &= \hat{\mathbf{e}}_1 & \hat{\mathbf{e}}_3 \times \hat{\mathbf{e}}_2 &= -\hat{\mathbf{e}}_1 \\ \hat{\mathbf{e}}_3 \times \hat{\mathbf{e}}_1 &= \hat{\mathbf{e}}_2 & \hat{\mathbf{e}}_1 \times \hat{\mathbf{e}}_3 &= -\hat{\mathbf{e}}_2 \end{aligned}$$

$$\begin{aligned} \mathbf{a} \times \mathbf{b} &= (a_1\hat{\mathbf{e}}_1 + a_2\hat{\mathbf{e}}_2) \times (b_1\hat{\mathbf{e}}_1 + b_2\hat{\mathbf{e}}_2) \\ &= a_1 b_1(\hat{\mathbf{e}}_1 \times \hat{\mathbf{e}}_1) + a_1 b_2(\hat{\mathbf{e}}_1 \times \hat{\mathbf{e}}_2) \\ &\quad + a_2 b_1(\hat{\mathbf{e}}_2 \times \hat{\mathbf{e}}_1) + a_2 b_2(\hat{\mathbf{e}}_2 \times \hat{\mathbf{e}}_2) \\ &= (a_1 b_2 - a_2 b_1)\hat{\mathbf{e}}_3 \end{aligned}$$



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in 3D

$$\mathbf{v}\cdot\mathbf{w} = v_1 w_1 + v_2 w_2 + v_3 w_3$$

$$\mathbf{v}\times\mathbf{w} = \begin{pmatrix} v_2 w_3 - v_3 w_2 \\ v_3 w_1 - v_1 w_3 \\ v_1 w_2 - v_2 w_1 \end{pmatrix}$$

Triple products

- **a**(**b**·**c**) – vector times scalar
- <u>scalar triple product</u> **a**·(**b**x**c**)

  a·(**b**x**c**)= (**a**x**b**)·**c** – *show this*

  = **c**·(**a**x**b**)=**b**·(**c**x**a**) (with cyclical permutation) – *show*

  = -**a**·(**c**x**b**)=-**c**·(**b**x**a**)=-**b**·(**a**x**c**) (with order changed) – *show*

  = 0 if coplanar
- **a**x(**b**x**c**) – lies in plane formed by **b**x**c** and is normal to **a**

  ≠(**a**x**b**)x**c**

  = (**a**·**c**)**b**-(**a**·**b**)**c** *Problem 5-3*

Try now

- *How would you find components of a 3D vector* ***a*** *normal and parallel to 3D vector* ***b****?*

Try later

- *You could program this up and test with special cases*

- *How would you find components of a 3D vector* ***a*** *normal and parallel to 3D vector* ***b****?*

parallel component: $$(\mathbf{a}\cdot\frac{\mathbf{b}}{|\mathbf{b}|})\hat{\mathbf{e}}_b = (\mathbf{a}\cdot\hat{\mathbf{e}}_b)\hat{\mathbf{e}}_b = |\mathbf{a}|\cos\theta\hat{\mathbf{e}}_b$$

perpendicular component: $$\mathbf{a}-(\mathbf{a}\cdot\hat{\mathbf{e}}_b)\hat{\mathbf{e}}_b$$

$$= (\hat{\mathbf{e}}_b\cdot\hat{\mathbf{e}}_b)\mathbf{a}-(\mathbf{a}\cdot\hat{\mathbf{e}}_b)\hat{\mathbf{e}}_b = \hat{\mathbf{e}}_b\times(\mathbf{a}\times\hat{\mathbf{e}}_b)$$
$$= |\mathbf{a}|\sin\theta\left[\hat{\mathbf{e}}_b\times(\hat{\mathbf{e}}_a\times\hat{\mathbf{e}}_b)\right]$$

Covered so far

- Revision of main characteristics of a vector
- Linear independence of vectors
- Vector products: dot product, cross product
- Definition Cartesian orthonormal basis

Please take a break

- And try the questions in the lecture slides before moving on to the second part of Lecture 5
- The exercises for this lecture are best done once you have also watched part 2 and part 3 of Lecture 5