Modelling and
Numerical Methods

Lecture 3
Kinematics of Continua
& Conservation Equations

Outline Lecture 3

Part 1: Kinematics

- Material vs. spatial descriptions
- Time derivatives

chapter3.ipynb

- Displacement
- Infinitesimal Strain Tensor

Part 2: Conservation Equations

- Conservation of Mass

chapter4.ipynb

- Conservation of Momentum

Learning Objectives
Kinematics

- Be able to use material and spatial descriptions of variables and their time derivatives.

- Be able to compute infinitesimal strain (strain rate) tensor given a displacement (velocity) field.

- Know meaning of the different components of the infinitesimal strain (rate) tensor

- Be able to find principal strain(rate)s and strain (rate) invariants and know what they represent

- Understand difference between infinitesimal and finite strain

Displacement

Can result in

(a) Rigid body motion

(b) Deformation of the body
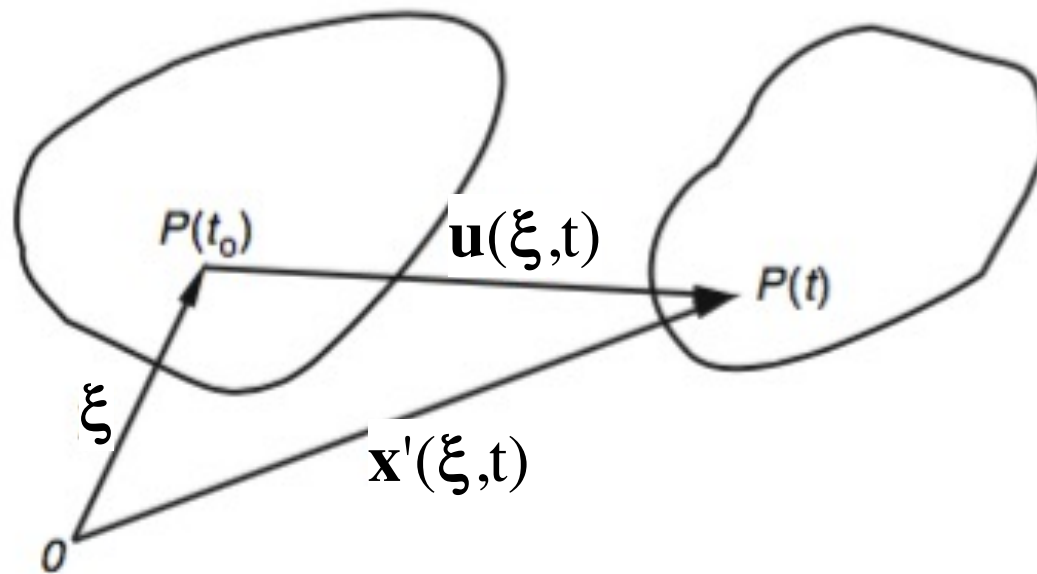
Rigid body motion

- Translation: $\mathbf{x'}=\boldsymbol{\xi}+\mathbf{c}(t)$, with $\mathbf{c}(0)=\mathbf{0}$

  $\Rightarrow \quad \mathbf{u}=\mathbf{x'}-\boldsymbol{\xi}$, each point same $\mathbf{u}(t)=\mathbf{c}(t)$

- Rotation: $\mathbf{x'}-\mathbf{b}=\mathbf{R}(t)(\boldsymbol{\xi}-\mathbf{b})$, where $\mathbf{R}(t)$ is rotation tensor, with $\mathbf{R}(0)=\mathbf{I}$, $\mathbf{b}$ is the point of rotation. $\mathbf{R}(t)$ is an orthogonal transformation (preserves lengths and angles, $\mathbf{R}^{\mathrm{T}}\mathbf{R}=\mathbf{I}$, $\det(\mathbf{R})=1$)
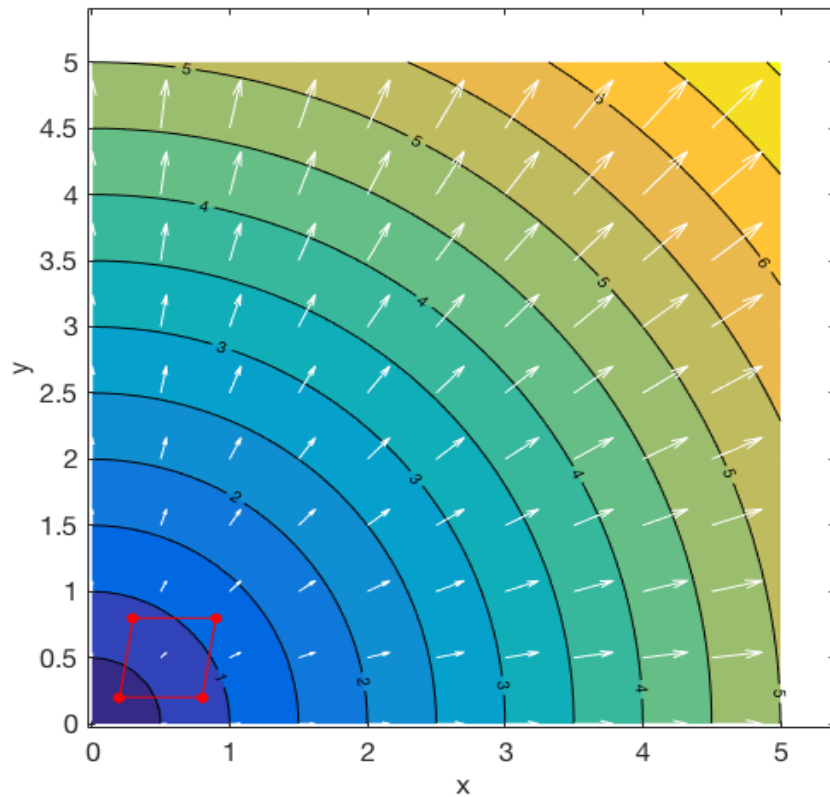
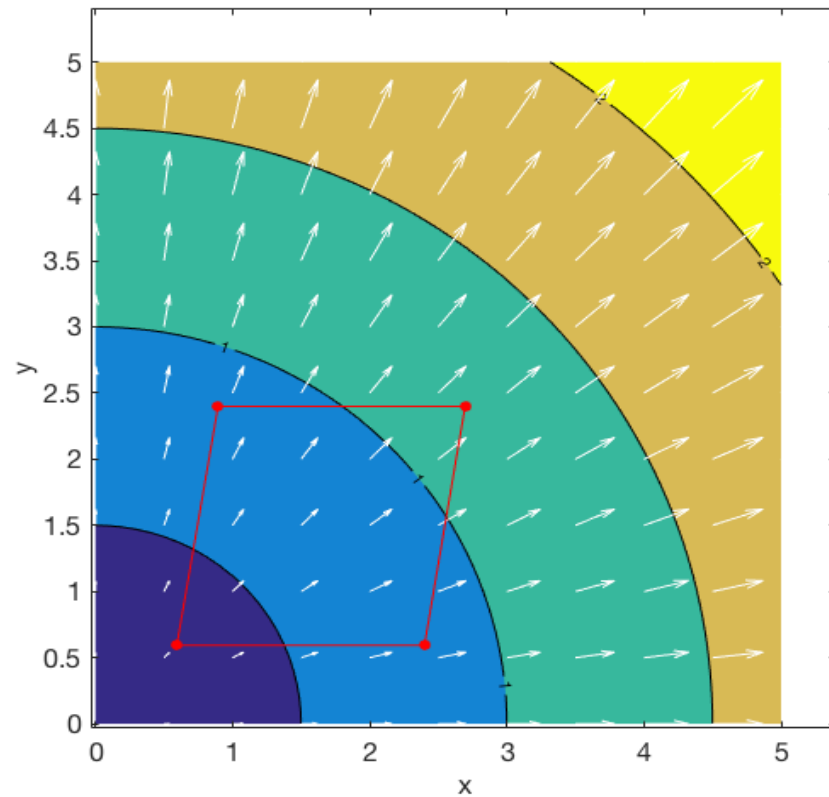If $\mathbf{u}$ depends on $\mathbf{x}$ and t, then internal deformation

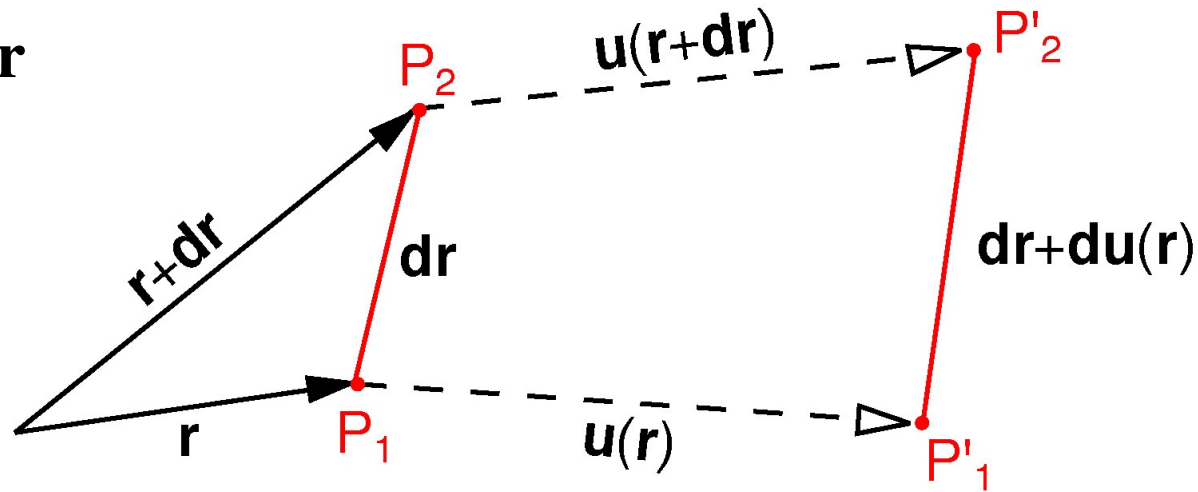*Example:*

$$v_i = \frac{kx_i}{1+kt}$$

Displacement

t=0

t=2

translation &
deformation

Deformation tensor

For small **dr**

P_1 at **r** -> P'_1 at **r+u(r)** , P_2 at **r+dr** -> P'_2 at **r+dr+u(r+dr)**.

dr'= P'_2-P'_1 = **dr** + [**u(r+dr)** - **u(r)**] = **dr+du(r)** = **dr+ dr** $\cdot$ **∇u(r)**

deformation of P_2-P_1 described by: $du_i = dx_j \dfrac{\partial u_i}{\partial x_j}$

du = **dr** $\cdot$ **∇u** = ∇^T**u** $\cdot$ **dr**

$$du_i = dx_j \frac{\partial u_i}{\partial x_j} \quad : \quad \begin{pmatrix} du_1 \\ du_2 \\ du_3 \end{pmatrix} = \begin{pmatrix} dx_1 & dx_2 & dx_3 \end{pmatrix} \begin{bmatrix} \dfrac{\partial u_1}{\partial x_1} & \dfrac{\partial u_2}{\partial x_1} & \dfrac{\partial u_3}{\partial x_1} \\[2mm] \dfrac{\partial u_1}{\partial x_2} & \dfrac{\partial u_2}{\partial x_2} & \dfrac{\partial u_3}{\partial x_2} \\[2mm] \dfrac{\partial u_1}{\partial x_3} & \dfrac{\partial u_2}{\partial x_3} & \dfrac{\partial u_3}{\partial x_3} \end{bmatrix}$$

$$\frac{\partial u_i}{\partial x_j} = \underbrace{\frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)}_{\varepsilon_{ij}} + \underbrace{\frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} - \frac{\partial u_j}{\partial x_i} \right)}_{\omega_{ij}}$$

$$\nabla \mathbf{u} = \frac{1}{2}\left(\nabla \mathbf{u} + \nabla \mathbf{u}^T \right) + \frac{1}{2}\left(\nabla \mathbf{u} - \nabla \mathbf{u}^T \right)$$

Total deformation is:
- rigid body translation - $\mathbf{u(r)}$
- rigid body rotation - $\boldsymbol{\omega} \cdot \mathbf{dr}$
- internal deformation, strain - $\boldsymbol{\varepsilon} \cdot \mathbf{dr}$ - result of stresses

Infinitesimal strain and rotation tensors

$$\varepsilon = \begin{bmatrix} \dfrac{\partial u_1}{\partial x_1} & \dfrac{1}{2}\left(\dfrac{\partial u_2}{\partial x_1} + \dfrac{\partial u_1}{\partial x_2}\right) & \dfrac{1}{2}\left(\dfrac{\partial u_3}{\partial x_1} + \dfrac{\partial u_1}{\partial x_3}\right) \\[3ex] \dfrac{1}{2}\left(\dfrac{\partial u_1}{\partial x_2} + \dfrac{\partial u_2}{\partial x_1}\right) & \dfrac{\partial u_2}{\partial x_2} & \dfrac{1}{2}\left(\dfrac{\partial u_3}{\partial x_2} + \dfrac{\partial u_2}{\partial x_3}\right) \\[3ex] \dfrac{1}{2}\left(\dfrac{\partial u_1}{\partial x_3} + \dfrac{\partial u_3}{\partial x_1}\right) & \dfrac{1}{2}\left(\dfrac{\partial u_2}{\partial x_3} + \dfrac{\partial u_3}{\partial x_2}\right) & \dfrac{\partial u_3}{\partial x_3} \end{bmatrix}$$

$$\omega = \begin{bmatrix} 0 & \dfrac{1}{2}\left(\dfrac{\partial u_2}{\partial x_1} - \dfrac{\partial u_1}{\partial x_2}\right) & \dfrac{1}{2}\left(\dfrac{\partial u_3}{\partial x_1} - \dfrac{\partial u_1}{\partial x_3}\right) \\[3ex] \dfrac{1}{2}\left(\dfrac{\partial u_1}{\partial x_2} - \dfrac{\partial u_2}{\partial x_1}\right) & 0 & \dfrac{1}{2}\left(\dfrac{\partial u_3}{\partial x_2} - \dfrac{\partial u_2}{\partial x_3}\right) \\[3ex] \dfrac{1}{2}\left(\dfrac{\partial u_1}{\partial x_3} - \dfrac{\partial u_3}{\partial x_1}\right) & \dfrac{1}{2}\left(\dfrac{\partial u_2}{\partial x_3} - \dfrac{\partial u_3}{\partial x_2}\right) & 0 \end{bmatrix}$$
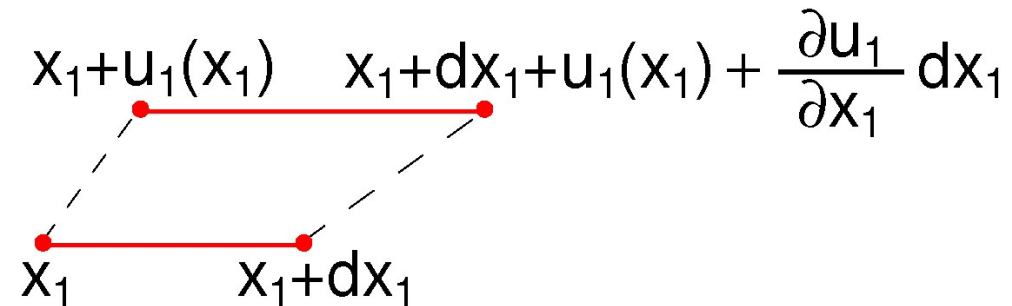
diagonal infinitesimal strain tensor elements

For a line segment
$\mathbf{dr} = (dx_1, 0, 0)$
deforming
in displacement
field $\mathbf{u}=(u_1, 0, 0)$:

$$x_1+u_1(x_1) \qquad x_1+dx_1+u_1(x_1) + \frac{\partial u_1}{\partial x_1} \, dx_1$$
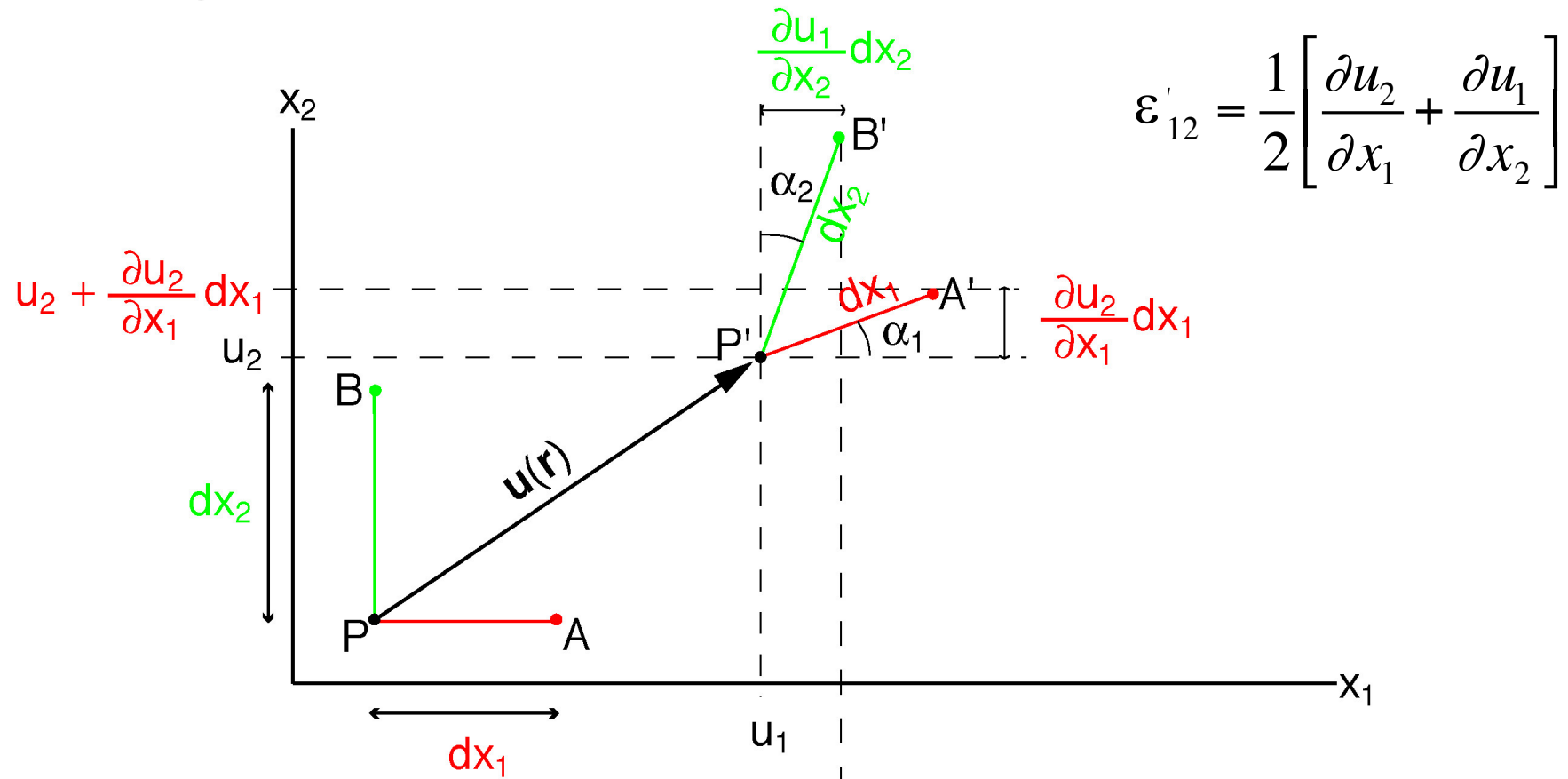
$$x_1 \qquad\qquad x_1+dx_1$$

the new length $dx'_1 \approx dx_1 + (\partial u_1/\partial x_1)dx_1 = dx_1 + \varepsilon_{11}dx_1$

$\Rightarrow \varepsilon_{11}=[dx'_1 - dx_1]/dx_1 = $ the relative change in length of a line element, originally in x_1 direction.

The relative change in volume $(V'-V)/V$ of a cube $V=dx_1dx_2dx_3$

$$dV/V \approx \varepsilon_{11}+\varepsilon_{22}+\varepsilon_{33} = \varepsilon_{ii} = tr(\boldsymbol{\varepsilon}) = \nabla\cdot\mathbf{u}.$$

off-diagonal infinitesimal strain tensor elements

$$\varepsilon'_{12} = \frac{1}{2}\left[\frac{\partial u_2}{\partial x_1} + \frac{\partial u_1}{\partial x_2}\right]$$

$$\alpha_1 \approx \sin\alpha_1 = \frac{(\partial u_2 / \partial x_1)dx_1}{dx_1} = \frac{\partial u_2}{\partial x_1}$$

$$\alpha_2 \approx \frac{(\partial u_1 / \partial x_2)dx_2}{dx_2} = \frac{\partial u_1}{\partial x_2}$$

$$\varepsilon_{12} = \varepsilon_{21} = (\alpha_1 + \alpha_2)/2$$

$2\varepsilon_{12}$ is the change in angle of an originally 90° angle between dx_1 and dx_2

infinitesimal rotation tensor elements
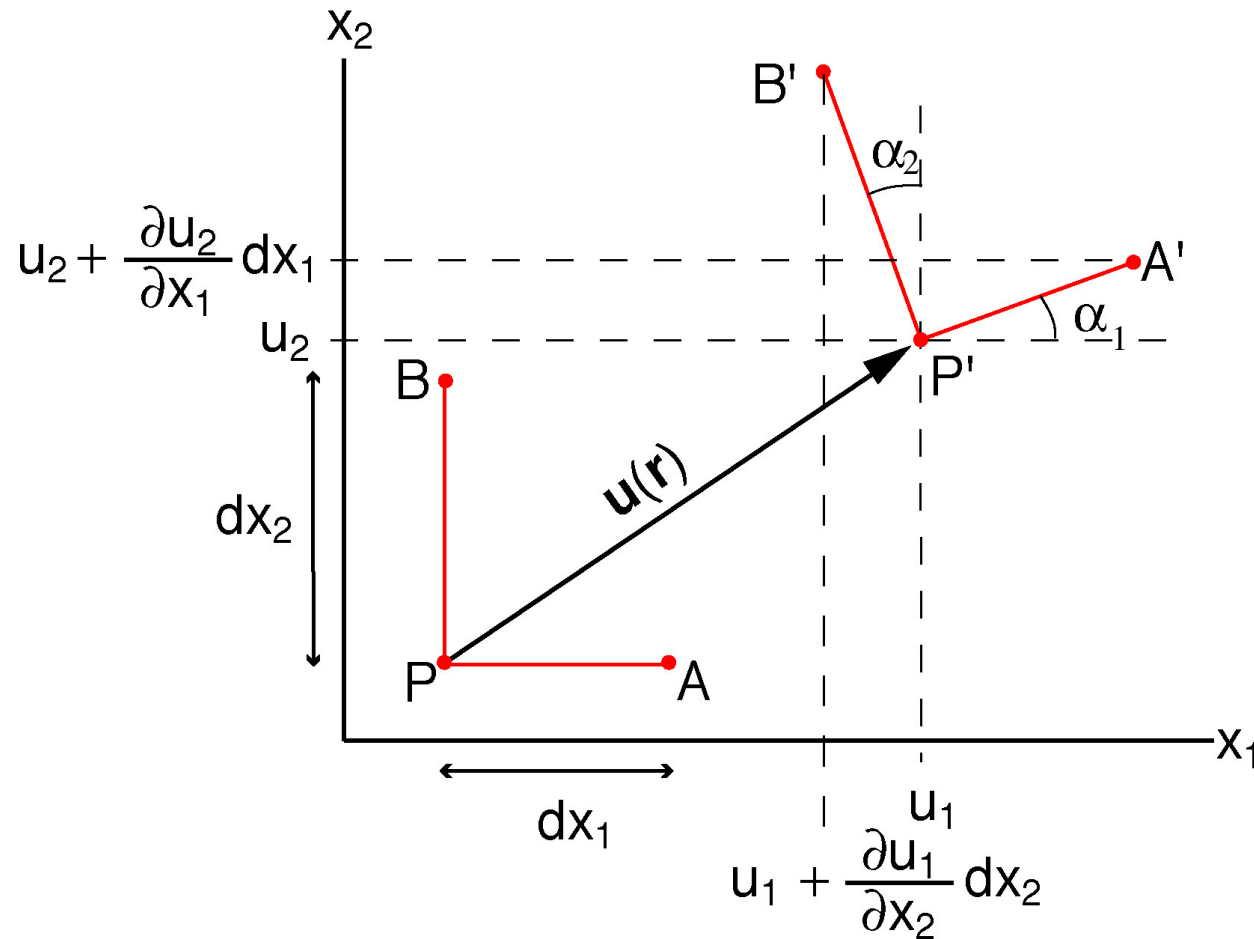
$$\omega_{12} = -\omega_{21} = [(\partial u_2 / \partial x_1) - (\partial u_1 / \partial x_2)]/2 = (\alpha_1 - \alpha_2)/2$$

ω_{12} is common rigid rotation angle of vectors in the dx_1 - dx_2 plane (around x_3)

Extra: **Rotation tensor and rotation vector**

For any antisymmetric tensor $\mathbf{W}$, a corresponding *dual* or *axial vector* $\mathbf{w}$ can be found so that

$$\mathbf{W} \cdot \mathbf{a} = \mathbf{w} \times \mathbf{a}$$

Vector $\mathbf{w}$ relates to the components of $\mathbf{W}$ as:

$$\mathbf{w} = -W_{23}\hat{\mathbf{e}}_1 + W_{13}\hat{\mathbf{e}}_2 - W_{12}\hat{\mathbf{e}}_3$$

For the rotation tensor, an equivalent rotation vector exists:

$$\boldsymbol{\omega} \cdot \mathbf{dx} = r_\omega \times \mathbf{dx} \qquad \text{where:} \qquad r_\omega = \frac{1}{2}\nabla \times \mathbf{u}$$

Note that $\boldsymbol{\omega}$ only describes the overall rigid body rotation, not the total rotation of each individual segment $\mathbf{dx}$, which is also influenced by $\boldsymbol{\varepsilon}$

Example displacement – infinitesimal strain
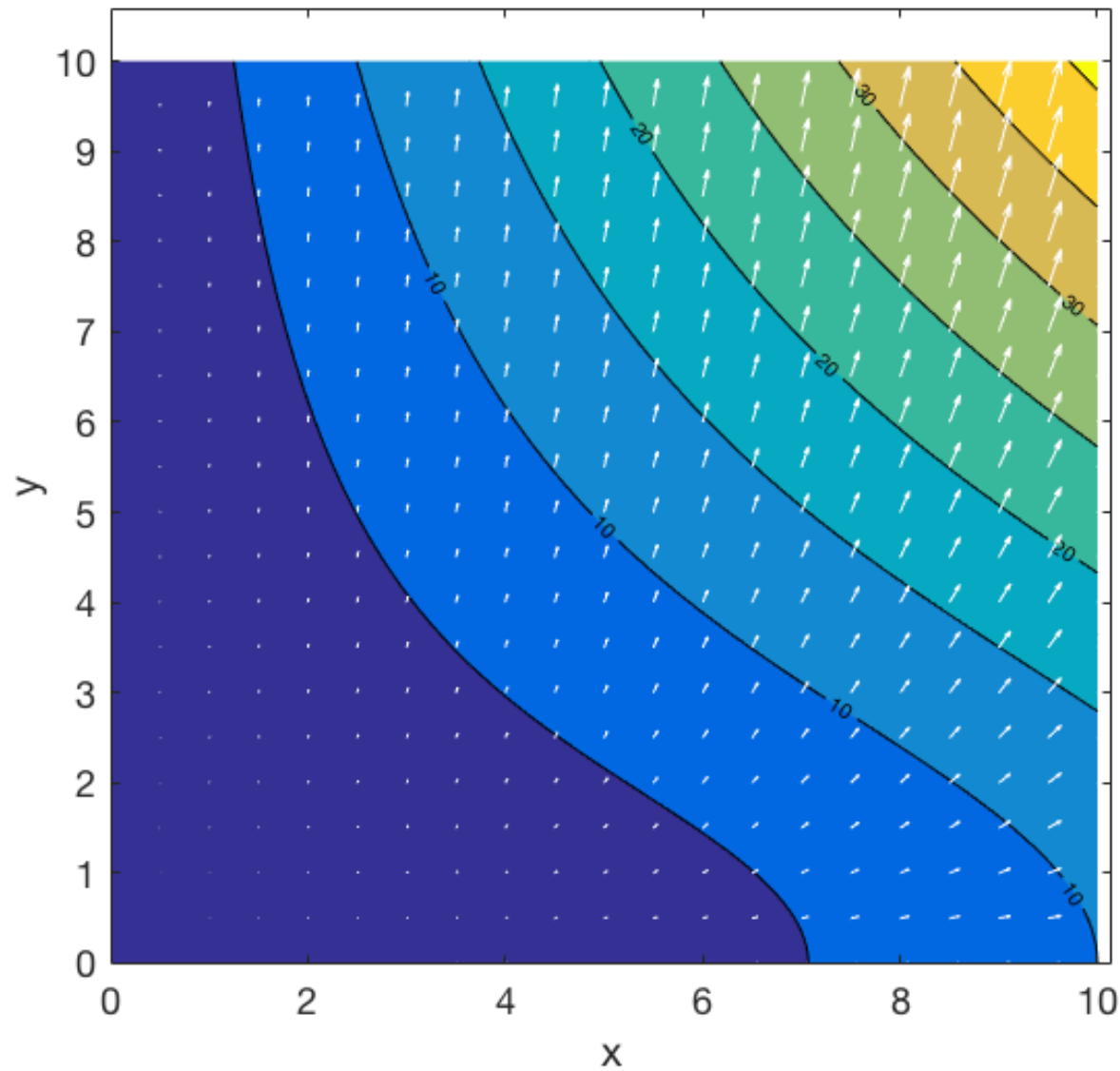
displacement

$$u_x = 0.1x^2$$

$$u_y = 0.4xy$$

Please take a break

And then look at the "Class Exercise"
on Displacement and Strain fields and
Exercise 8

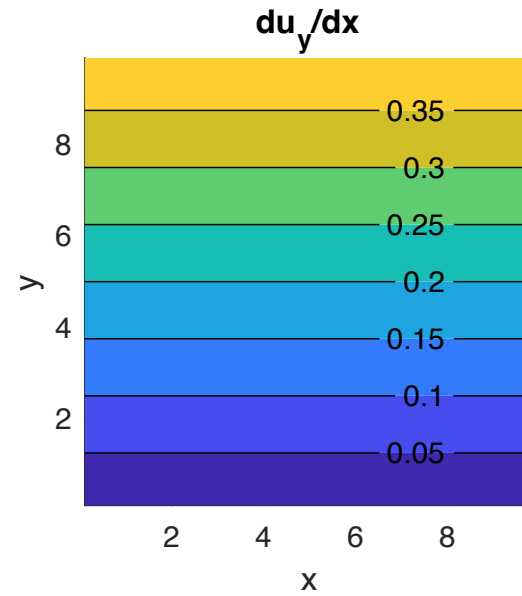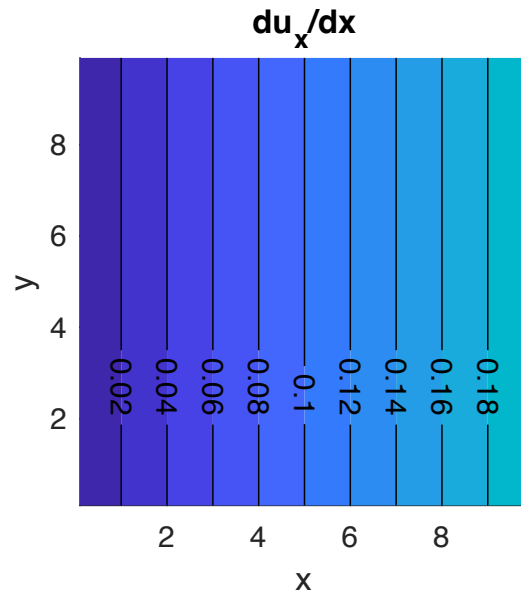# Example displacement – infinitesimal strain
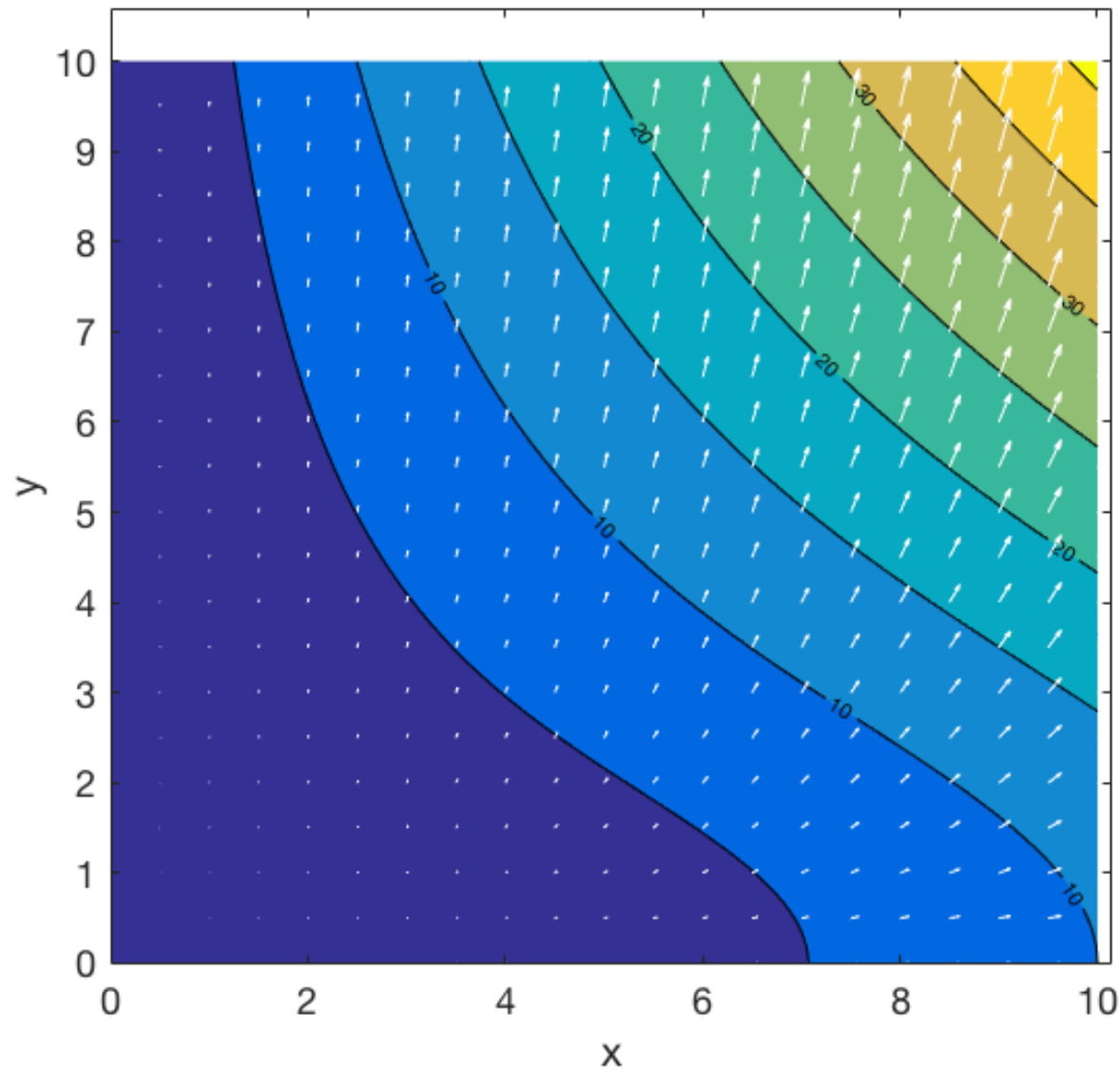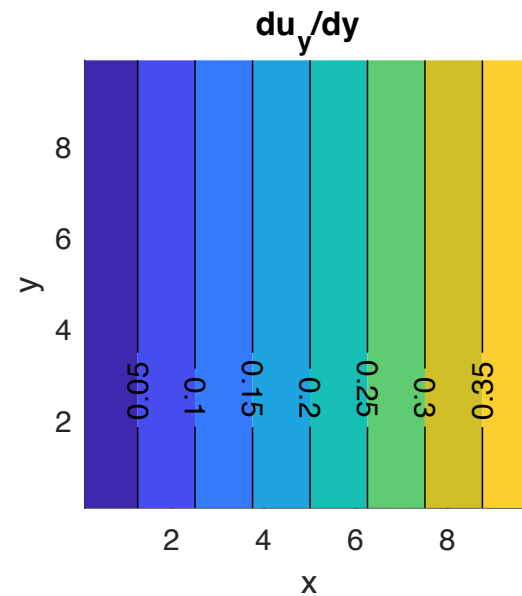

displacement

$$u_x = 0.1x^2$$

$$u_y = 0.4xy$$

Example displacement gradient

$u_x = 0.1x^2$

$u_y = 0.4xy$

$\dfrac{\partial u_x}{\partial x} = 0.2x$

$\dfrac{\partial u_y}{\partial x} = 0.4y$

$\dfrac{\partial u_x}{\partial y} = 0$
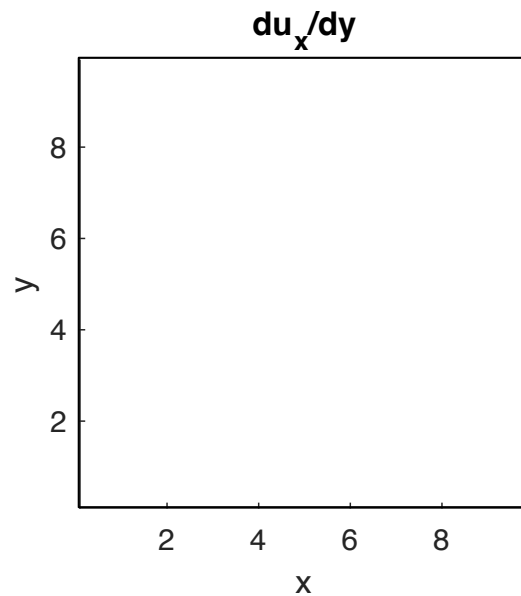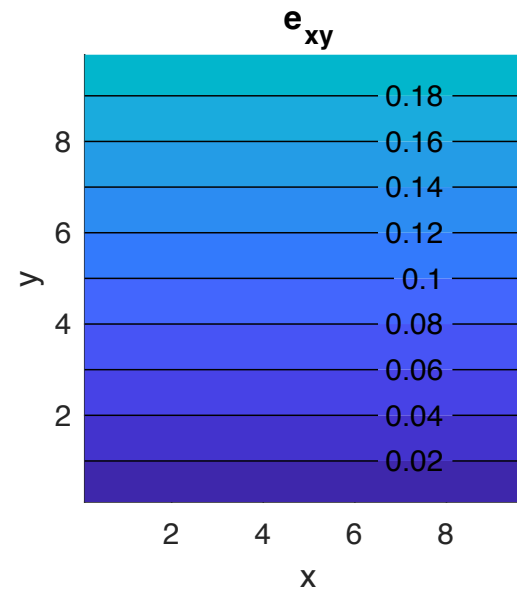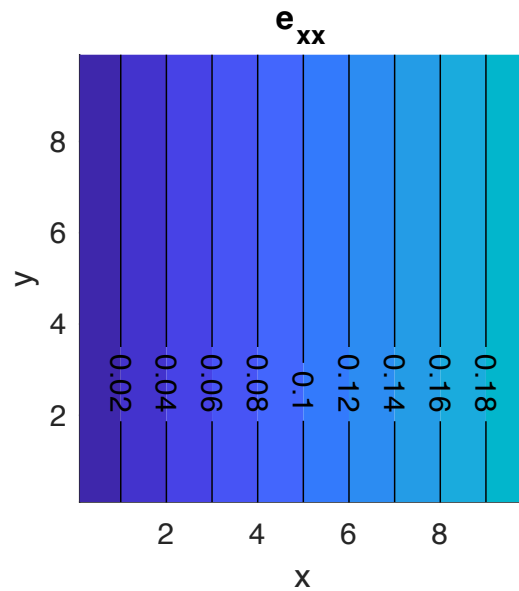
$\dfrac{\partial u_y}{\partial y} = 0.4x$
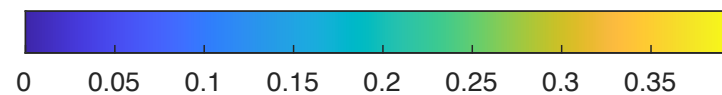
Example infinitesimal strain

$$u_x = 0.1x^2$$

$$u_y = 0.4xy$$

$$\frac{\partial u_x}{\partial x} = 0.2x$$

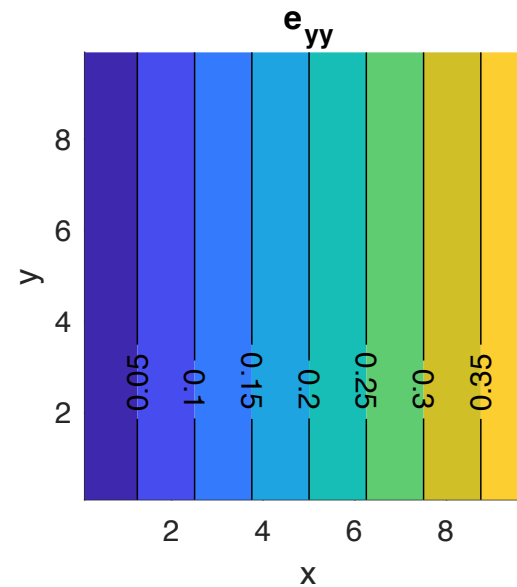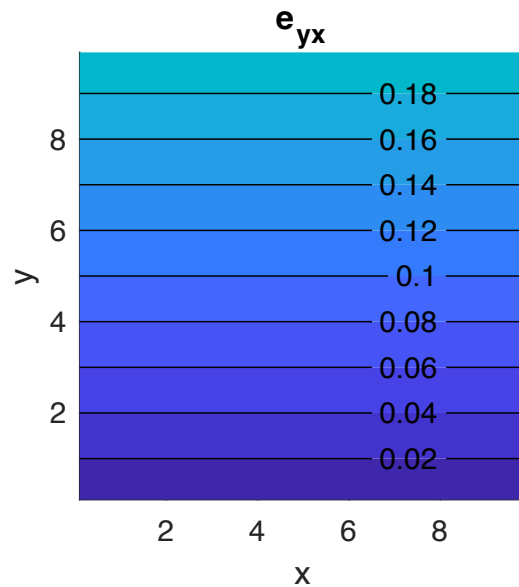$$\varepsilon_{xx} = \frac{\partial u_x}{\partial x}$$

$$\frac{\partial u_y}{\partial x} = 0.4y$$

$$\varepsilon_{xy} = \frac{1}{2}\left[\frac{\partial u_y}{\partial x} + \frac{\partial u_x}{\partial y}\right]$$
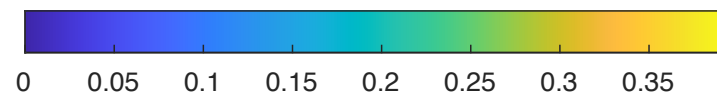
$$\frac{\partial u_x}{\partial y} = 0$$

$$\varepsilon_{yx} = \varepsilon_{xy}$$

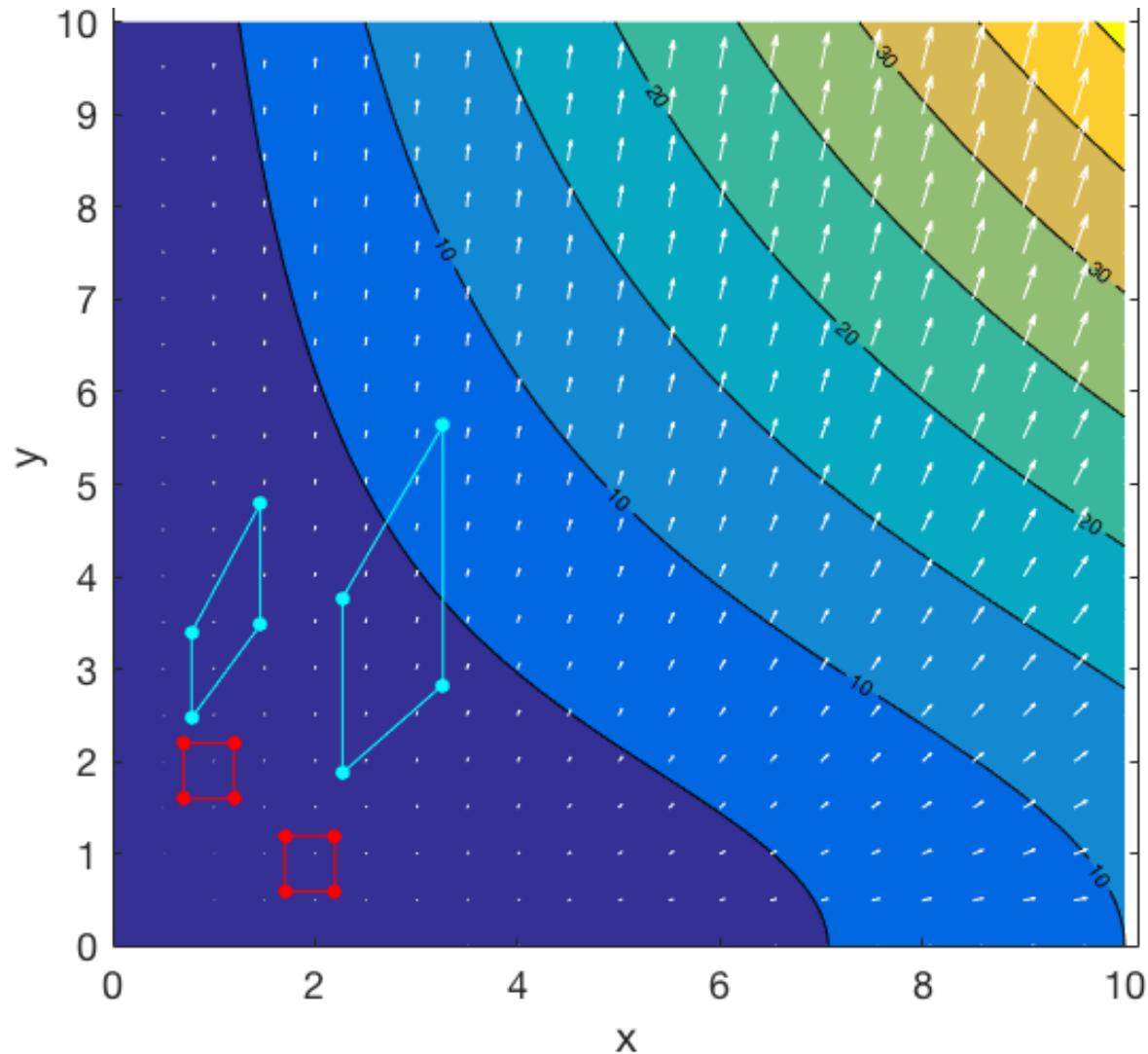$$\frac{\partial u_y}{\partial y} = 0.4x$$

$$\varepsilon_{yy} = \frac{\partial u_y}{\partial y}$$

Deformation after finite strain

original shape (red)

shape at later time (teal)
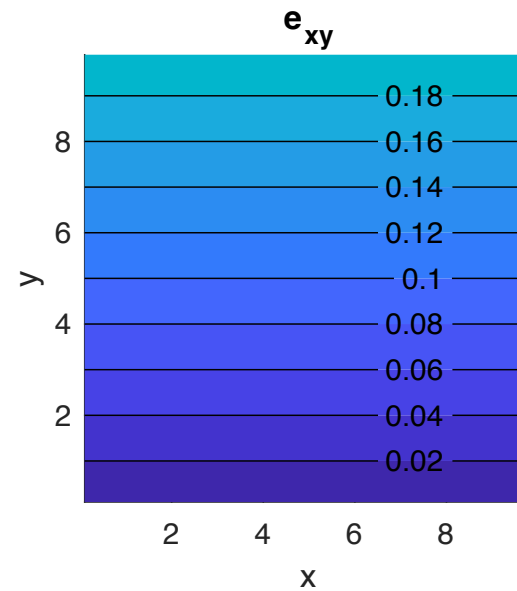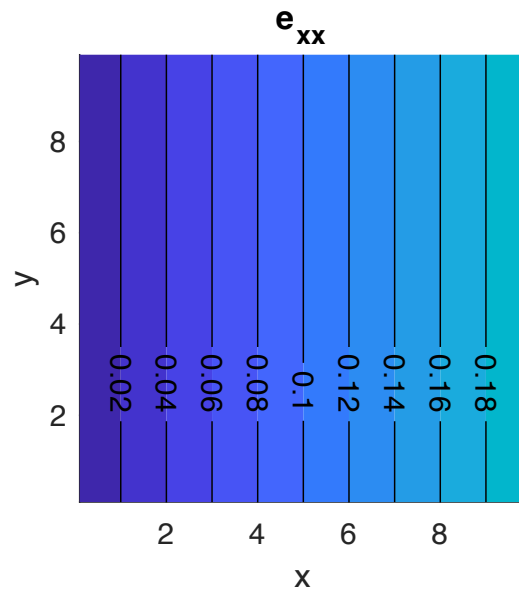
displacement

$$u_x = 0.1x^2$$

$$u_y = 0.4xy$$

Example infinitesimal strain

$u_x = 0.1x^2$

$u_y = 0.4xy$

$\dfrac{\partial u_x}{\partial x} = 0.2x$

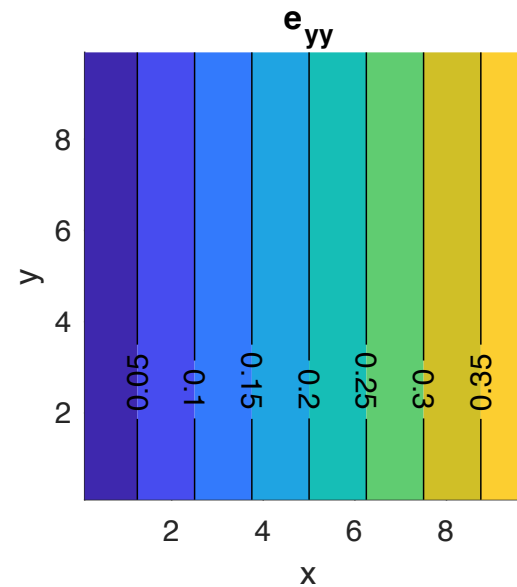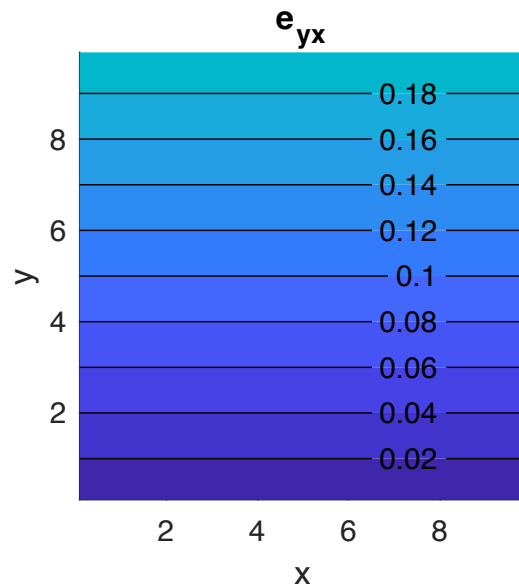$\varepsilon_{xx} = \dfrac{\partial u_x}{\partial x}$

$\dfrac{\partial u_y}{\partial x} = 0.4y$

$\varepsilon_{xy} = $

$\dfrac{1}{2}\left[\dfrac{\partial u_y}{\partial x} + \dfrac{\partial u_x}{\partial y} \right]$
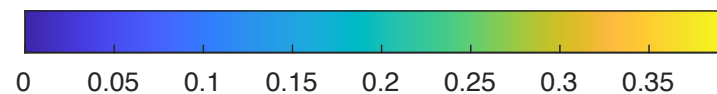
$\dfrac{\partial u_x}{\partial y} = 0$

$\varepsilon_{yx} = \varepsilon_{xy}$

$\dfrac{\partial u_y}{\partial y} = 0.4x$

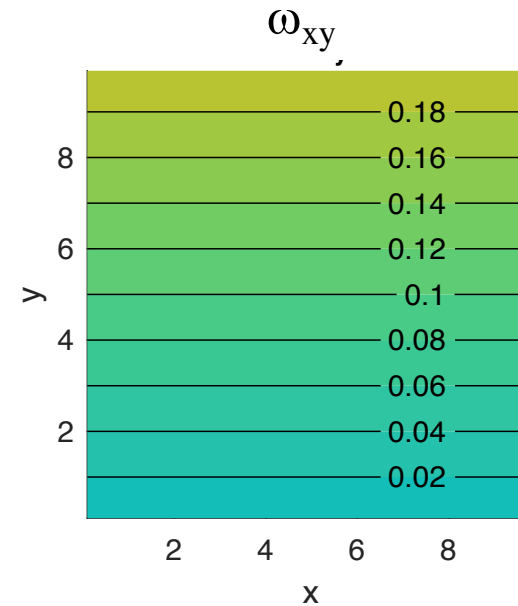$\varepsilon_{yy} = \dfrac{\partial u_y}{\partial y}$

Example infinitesimal rotation

$$u_x = 0.1x^2$$

$$u_y = 0.4xy$$

ω_{xx}

ω_{xy}

ω_{yx}

ω_{yy}

$$\omega_{xx} = 0$$
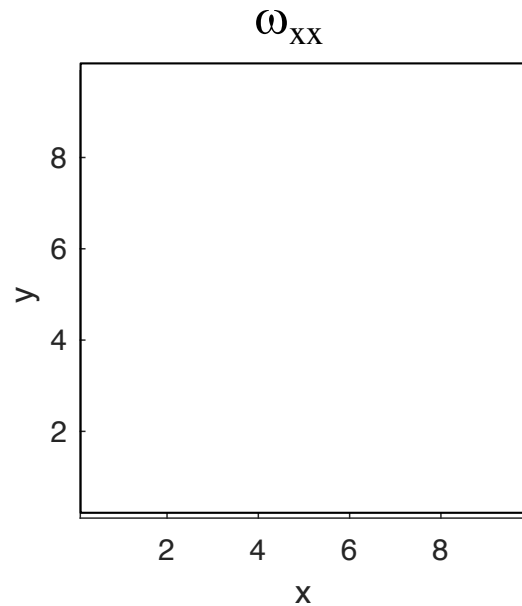
$$\omega_{xy} = \varepsilon_{xy}$$

$$\omega_{yx} = -\varepsilon_{yx}$$
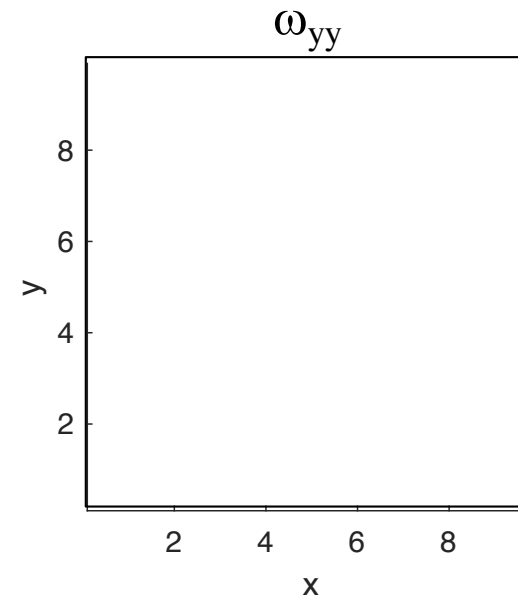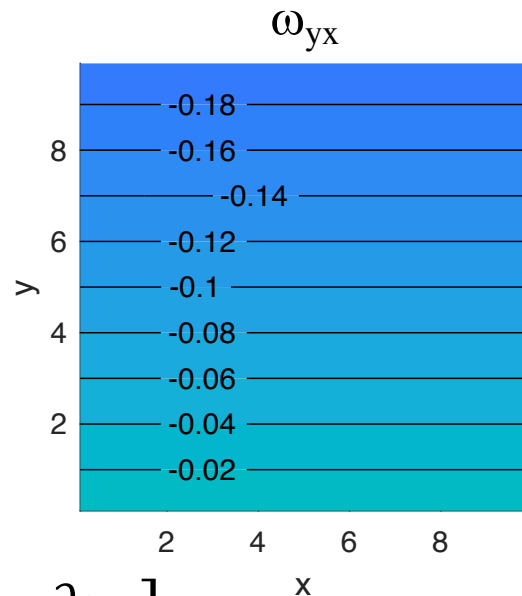
$$\omega_{yy} = 0$$

$$\varepsilon_{xy} = \frac{1}{2}\left[\frac{\partial u_y}{\partial x} + \frac{\partial u_x}{\partial y}\right]$$
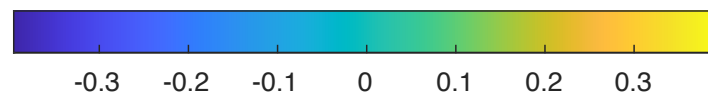
$$\omega_{xy} = \frac{1}{2}\left[\frac{\partial u_y}{\partial x} - \frac{\partial u_x}{\partial y}\right]$$

Example displacement – infinitesimal strain

div(**u**)

curl(**u**)
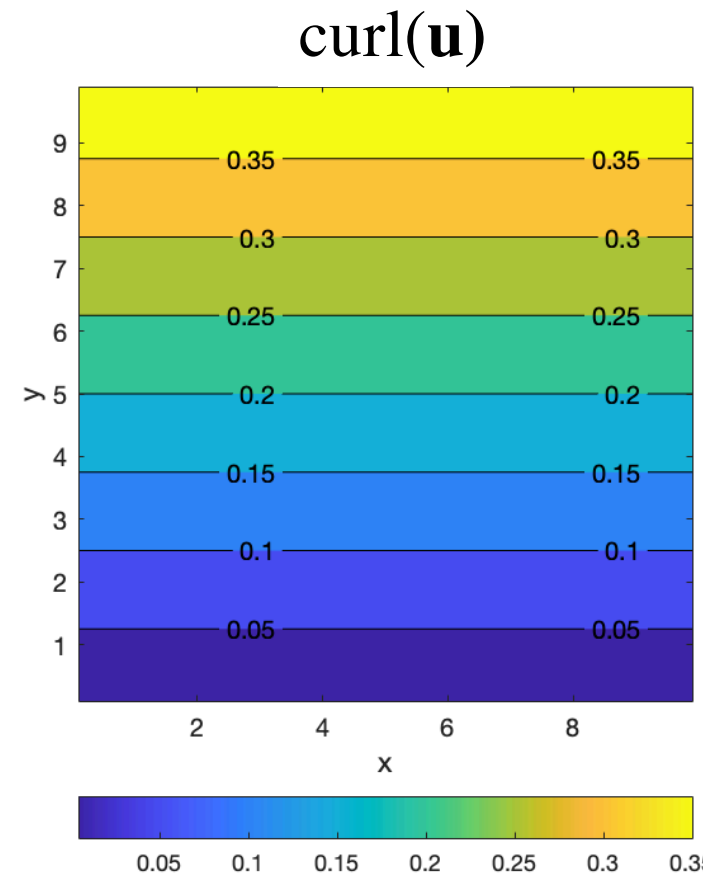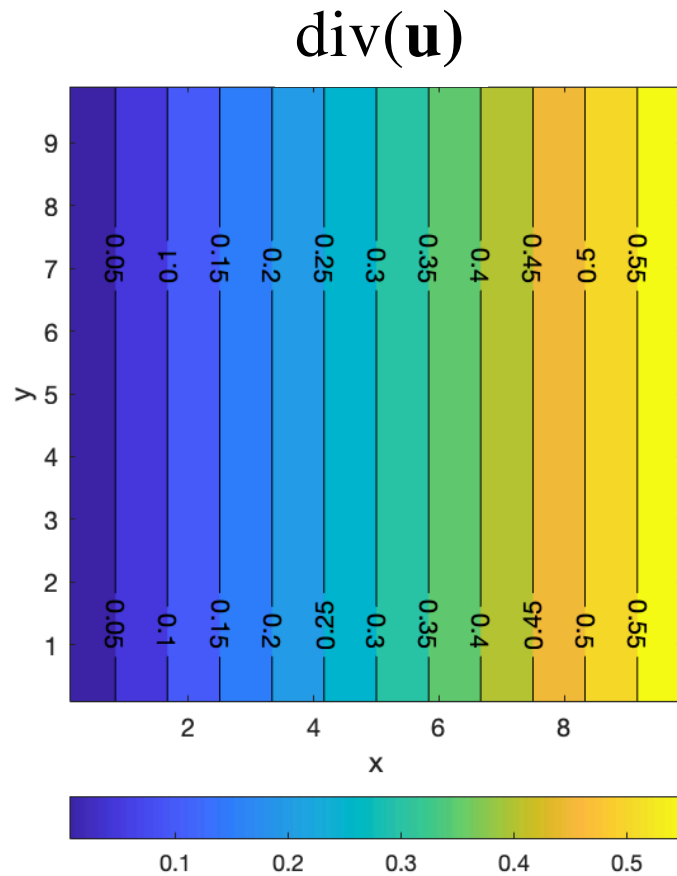
$$\nabla \cdot \mathbf{u} = \frac{\partial u_x}{\partial x} + \frac{\partial u_y}{\partial y}$$

$$\nabla \times \mathbf{u} = \left(\frac{\partial u_y}{\partial x} - \frac{\partial u_x}{\partial y} \right) \hat{\mathbf{e}}_z$$

infinitesimal strain tensor properties

transform to arbitrary *coordinate frame*:

$\varepsilon_{nn} = \varepsilon_{11}\cos^2\phi + \varepsilon_{21}\sin\phi\cos\phi + \varepsilon_{12}\sin\phi\cos\phi + \varepsilon_{22}\sin^2\phi$

$\varepsilon_{ns} = \varepsilon_{11}\sin\phi\cos\phi + \varepsilon_{21}\sin^2\phi - \varepsilon_{12}\cos^2\phi - \varepsilon_{22}\sin\phi\cos\phi$

$\varepsilon_1, \varepsilon_2, \varepsilon_3$ - *principal strains* : minimum, maximum and intermediate fractional length changes

isotropic, *deviatoric* strain: $\varepsilon_{ij} = (\theta/3)\delta_{ij} + \varepsilon'_{ij}$

- $\text{tr}(\boldsymbol{\varepsilon}) = \theta$ = sum of normal strains = volume change
- ε'_{ij} is deviatoric strain, change in shape; no change in volume
- $\text{tr}(\boldsymbol{\varepsilon}') = 0$, does not imply $\varepsilon'_{ij} = 0$ for $i = j$
- $\varepsilon_{ij} = 0$ for $i \neq j$ does not ensure no shape change

Stress components

Reminder
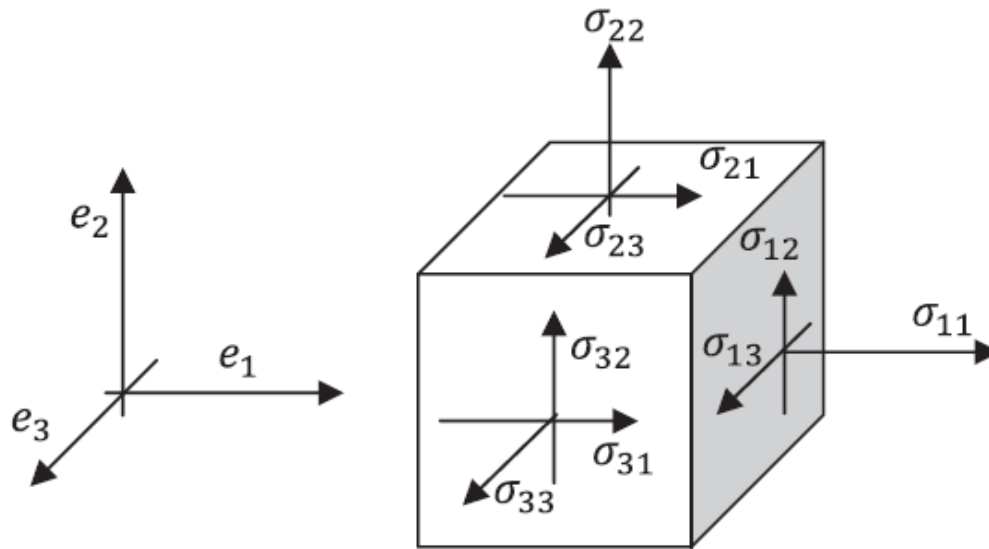
traction on a plane $\quad \mathbf{t} = \begin{bmatrix} \sigma_{11} & \sigma_{21} & \sigma_{31} \\ \sigma_{12} & \sigma_{22} & \sigma_{32} \\ \sigma_{13} & \sigma_{23} & \sigma_{33} \end{bmatrix} \cdot \hat{\mathbf{n}}$

what is $\quad \hat{\mathbf{e}}_1 \cdot \mathbf{t} = \hat{\mathbf{e}}_1 \cdot \mathbf{\sigma}^T \cdot \hat{\mathbf{n}}$?

t_1 on plane with normal $\hat{\mathbf{n}}$

what is $\hat{\mathbf{e}}_1 \cdot \mathbf{\sigma}^T \cdot \hat{\mathbf{e}}_1$? $\quad \sigma_{11}$ $\qquad$ what is $\hat{\mathbf{e}}_1 \cdot \mathbf{\sigma}^T \cdot \hat{\mathbf{e}}_2$? $\quad \sigma_{21}$

Strain components

$$\boldsymbol{\varepsilon} = \begin{bmatrix} \varepsilon_{11} & \varepsilon_{12} & \varepsilon_{13} \\ \varepsilon_{21} & \varepsilon_{22} & \varepsilon_{23} \\ \varepsilon_{31} & \varepsilon_{32} & \varepsilon_{33} \end{bmatrix}$$

$$\hat{\mathbf{e}}_1 \cdot \boldsymbol{\varepsilon} \cdot \hat{\mathbf{e}}_1 = \varepsilon_{11}$$

$$\hat{\mathbf{e}}_1 \cdot \boldsymbol{\varepsilon} \cdot \hat{\mathbf{e}}_2 = \varepsilon_{12}$$

$\boldsymbol{\varepsilon} \cdot \hat{\mathbf{p}} = \mathbf{dp}'$ the change in unit vector $\hat{\mathbf{p}}$ after deformation by $\boldsymbol{\varepsilon}$

$\hat{\mathbf{p}} \cdot \boldsymbol{\varepsilon} \cdot \hat{\mathbf{p}} =$ elongation by $\boldsymbol{\varepsilon}$ of unit vector $\hat{\mathbf{p}}$ in direction $\hat{\mathbf{p}}$

$= \hat{\mathbf{p}} \cdot \mathbf{dp}' = |\mathbf{dp}'| \cos \alpha$ *Where α is angle between $\mathbf{dp}'$ and $\hat{p}$*

Strain Rate Tensor

In similar way as strain tensor, a tensor that describes the rate of change of deformation can be defined from **velocity gradient**:

$$\frac{D}{Dt}\mathbf{dr} = \nabla\mathbf{v}$$

$$\nabla\mathbf{v} = \begin{bmatrix} \dfrac{\partial v_1}{\partial x_1} & \dfrac{\partial v_2}{\partial x_1} & \dfrac{\partial v_3}{\partial x_1} \\[2ex] \dfrac{\partial v_1}{\partial x_2} & \dfrac{\partial v_2}{\partial x_2} & \dfrac{\partial v_3}{\partial x_2} \\[2ex] \dfrac{\partial v_1}{\partial x_3} & \dfrac{\partial v_2}{\partial x_3} & \dfrac{\partial v_3}{\partial x_3} \end{bmatrix}$$
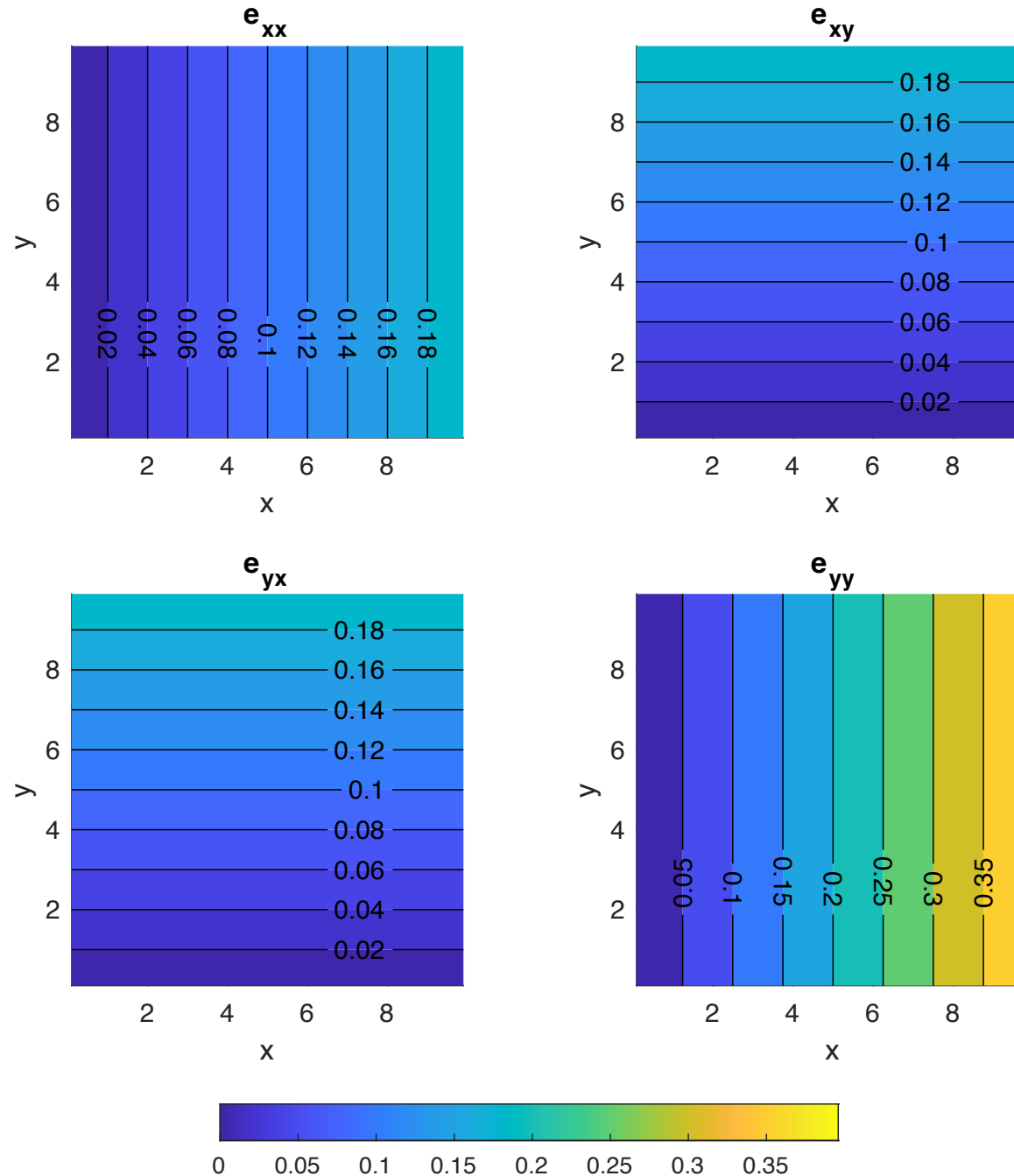
$$\nabla\mathbf{v} = \frac{1}{2}\left(\nabla\mathbf{v} + \nabla\mathbf{v}^T\right) + \frac{1}{2}\left(\nabla\mathbf{v} - \nabla\mathbf{v}^T\right)$$

$$\nabla\mathbf{v} = \mathbf{D} + \mathbf{W}$$

Velocity gradient tensor is the sum of **strain rate** and **vorticity** tensors
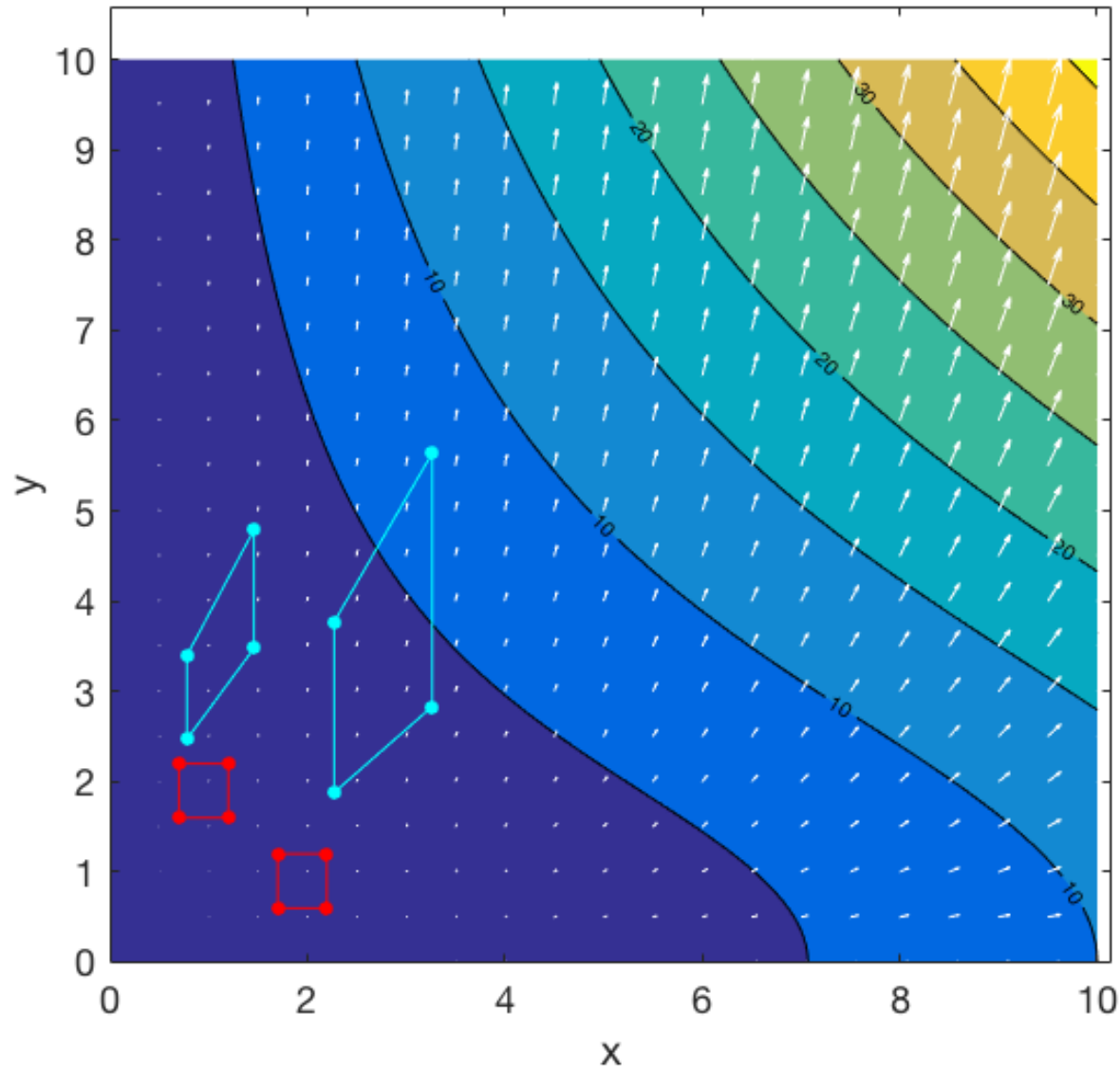
Infinitesimal strain

Over small increments, can assume constant displacement gradient encountered

Deformation after finite strain

original shape

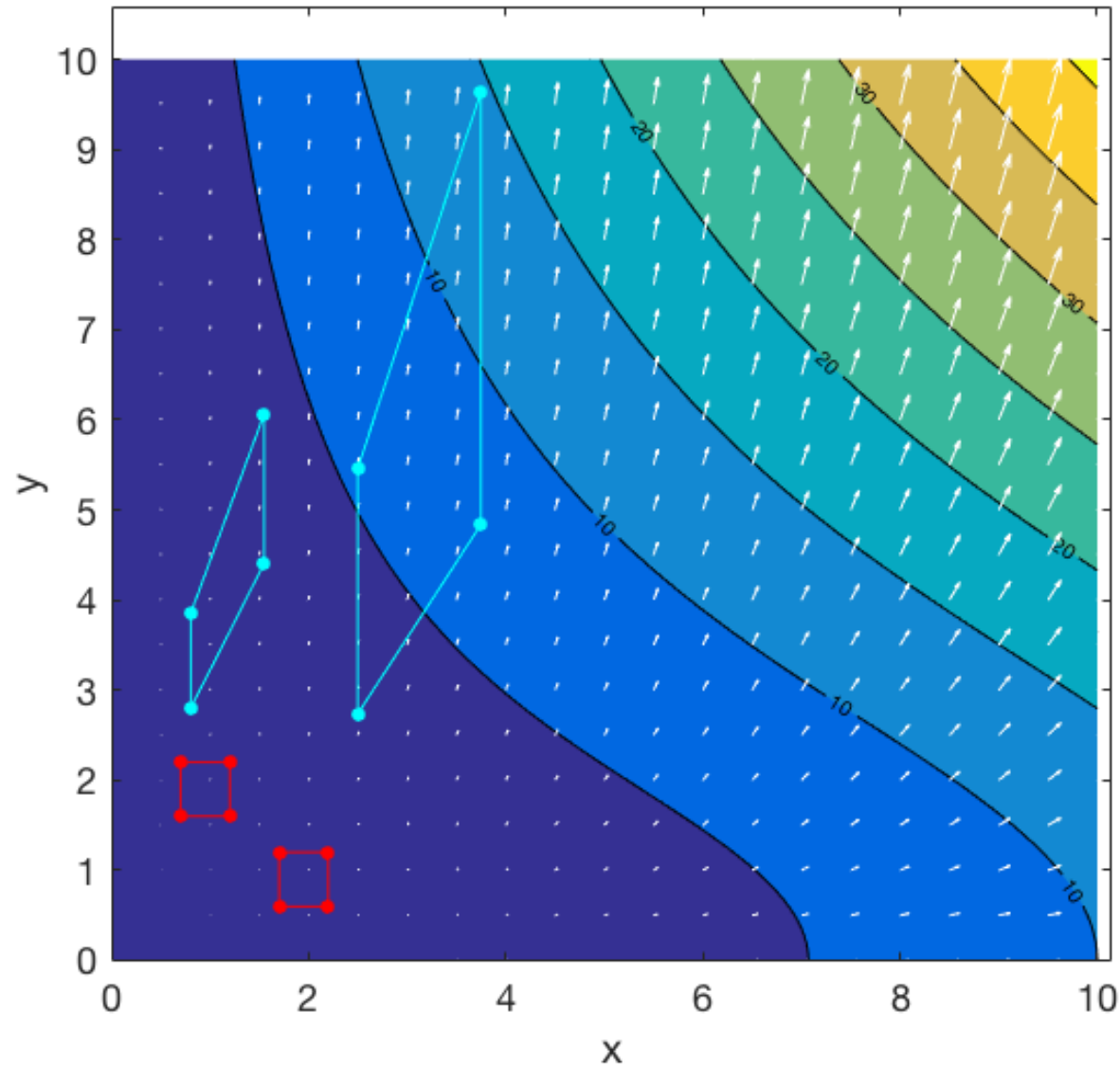**shape at later time**

displacement

$$u_x = 0.1x^2$$

$$u_y = 0.4xy$$

Deformation after finite strain

original shape

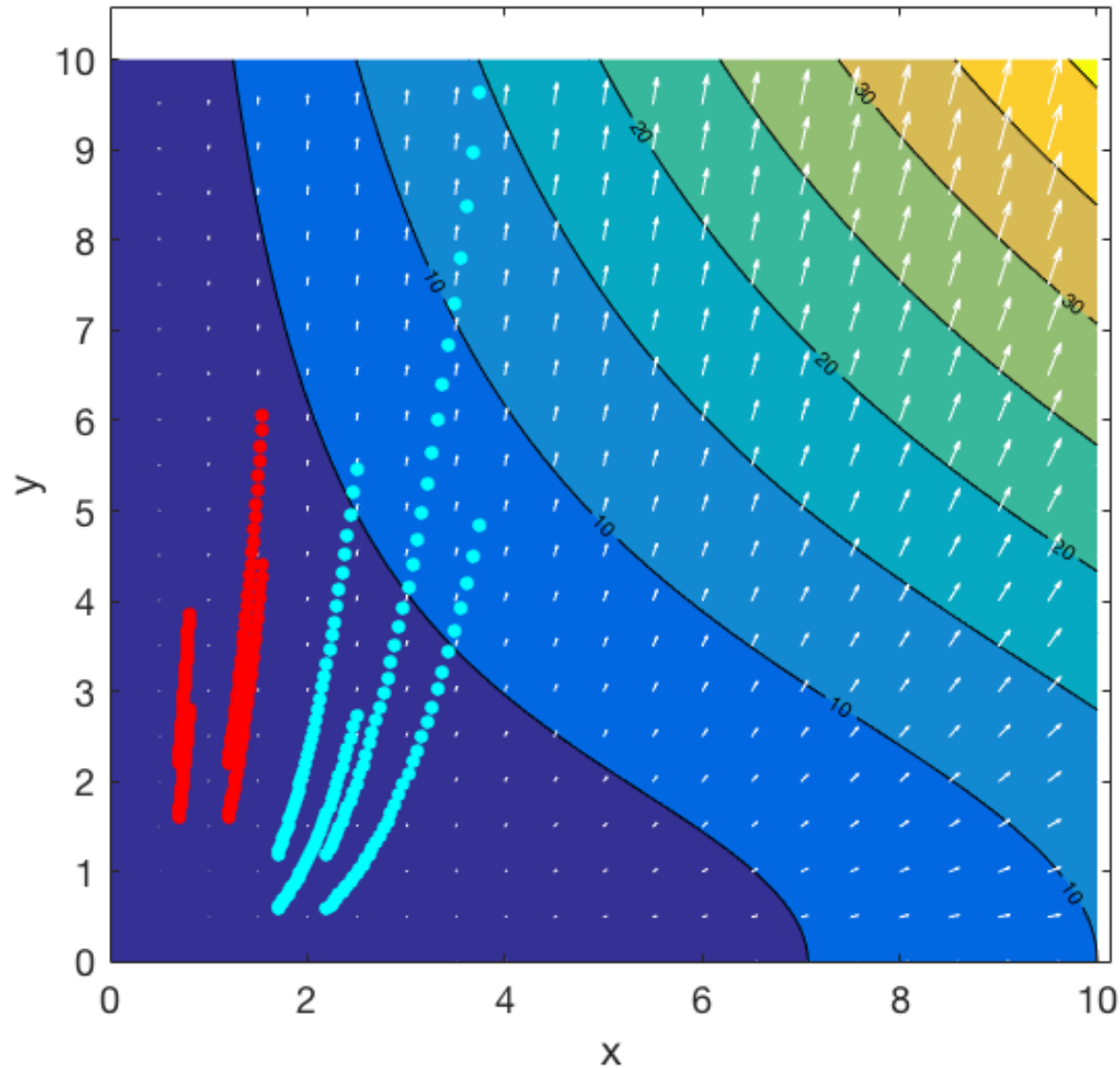**shape at even later time**

displacement

$$u_x = 0.1x^2$$

$$u_y = 0.4xy$$

Deformation after finite strain

points
shape 1
points
shape 2

displacement

$$u_x = 0.1x^2$$

$$u_y = 0.4xy$$

Learning Objectives

- Be able to use material and spatial descriptions of variables and their time derivatives.

- Be able to compute infinitesimal strain (strain rate) tensor given a displacement (velocity) field.

- Know meaning of the different components of the infinitesimal strain (rate) tensor

- Be able to find principal strain(rate)s and strain (rate) invariants and know what they represent

- Understand difference between infinitesimal and finite strain

Outline Lecture 3

- Material vs. spatial descriptions
- Time derivatives
- Displacement
- Infinitesimal Deformation

Further reading on the topics in the lecture can be done in for example: Lai, Rubin, Kremple (2010): Ch. 3-1 through 3-15 and we covered some of the basics discussed in 3-20 to 3-26

Try yourself

Complete any of the remaining exercises in
chapter3.ipynb:

Exercise 1, 2, 5, 7, 9a

- Additional practise: **Exercise 3, 6, 8**
- Advanced practise: **Exercise 4, 9b, 10**