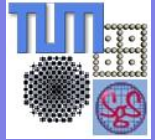


# 1. Interpreting the Results: Visualization 1



*Interpreting the ...*

*Methods of Image ...*

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*Aspects of Computer ...*

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*Simulation Data ...*

*Visualizing Simulation ...*

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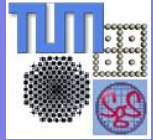
*Component Hierarchy ...*

*Animation*

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# 1. Interpreting the Results: Visualization 1

- visual/graphical/optical representation of large sets of data:



*Interpreting the ...*

*Methods of Image ...*

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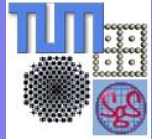
*Component Hierarchy ...*

*Animation*

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# 1. Interpreting the Results: Visualization 1

- visual/graphical/optical representation of large sets of data:
- data from experiments or measurements: satellite images, tomography in medicine, microscopy,...



*Interpreting the ...*

*Methods of Image ...*

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*Simulation Data ...*

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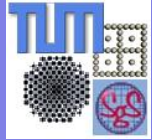
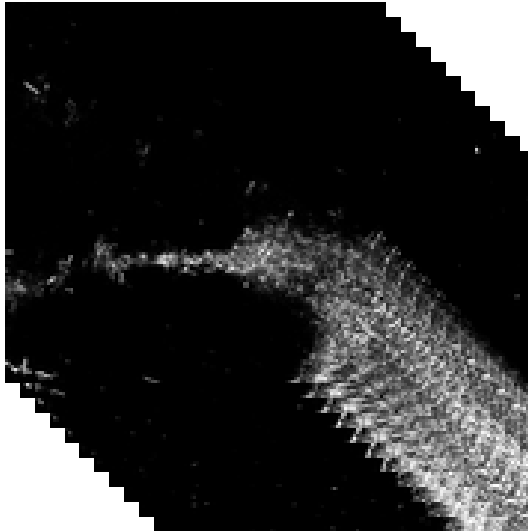
*Component Hierarchy ...*

*Animation*

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# 1. Interpreting the Results: Visualization 1

- visual/graphical/optical representation of large sets of data:
- data from experiments or measurements: satellite images, tomography in medicine, microscopy,...



Interpreting the ...

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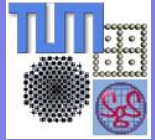
Visualizing Simulation ...

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- data from simulations:



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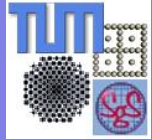
*Visualizing Simulation ...*

*Visualizing Simulation ...*

*Component Hierarchy ...*

*Animation*

- data from simulations:
  - with resolution of space (and time): fluid mechanics, structural mechanics, quantum physics,...



*Interpreting the ...*

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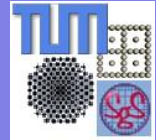
*Visualizing Simulation ...*

*Component Hierarchy ...*

*Animation*

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- data from simulations:
  - with resolution of space (and time): fluid mechanics, structural mechanics, quantum physics,...
  - without spatial resolution: vehicle dynamics, optimal control,...



*Interpreting the ...*

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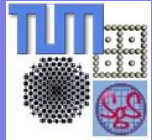
- data from simulations:
  - with resolution of space (and time): fluid mechanics, structural mechanics, quantum physics,...
  - without spatial resolution: vehicle dynamics, optimal control,...

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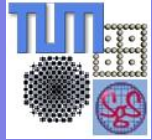
Visualizing Simulation ...

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## 2. Interpreting the Results: Visualization 2

- Visualization is often the only chance to tackle a fast interpretation.



*Interpreting the ...*

*Methods of Image ...*

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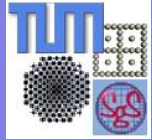
*Component Hierarchy ...*

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## 2. Interpreting the Results: Visualization 2

- Visualization is often the only chance to tackle a fast interpretation.
- Methods stem from
  - image processing,



*Interpreting the ...*

*Methods of Image ...*

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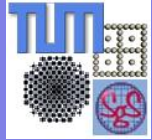
*Visualizing Simulation ...*

*Component Hierarchy ...*

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## 2. Interpreting the Results: Visualization 2

- Visualization is often the only chance to tackle a fast interpretation.
- Methods stem from
  - image processing,
  - computer graphics,



*Interpreting the ...*

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*Simulation Data ...*

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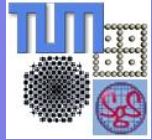
*Component Hierarchy ...*

*Animation*

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## 2. Interpreting the Results: Visualization 2

- Visualization is often the only chance to tackle a fast interpretation.
- Methods stem from
  - image processing,
  - computer graphics,
  - virtual and augmented reality,
  - ...



*Interpreting the ...*

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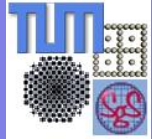
*Component Hierarchy ...*

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### 3. Methods of Image Processing 1

- image: array of 2D/3D discrete greyscale/colour data



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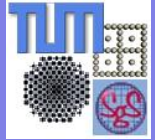
*Visualizing Simulation ...*

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*Animation*

### 3. Methods of Image Processing 1

- image: array of 2D/3D discrete greyscale/colour data
- **geometric processing:**
  - changes of shapes



*Interpreting the ...*

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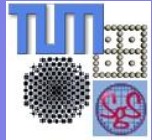
*Visualizing Simulation ...*

*Component Hierarchy ...*

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### 3. Methods of Image Processing 1

- image: array of 2D/3D discrete greyscale/colour data
- **geometric processing:**
  - changes of shapes
  - depend on pixels' position, not on their values



*Interpreting the ...*

*Methods of Image ...*

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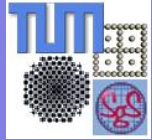
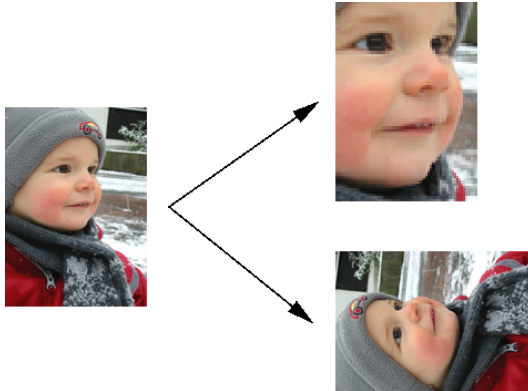
*Visualizing Simulation ...*

*Component Hierarchy ...*

*Animation*

### 3. Methods of Image Processing 1

- image: array of 2D/3D discrete greyscale/colour data
- **geometric processing:**
  - changes of shapes
  - depend on pixels' position, not on their values
  - examples: zooming, rotation,...



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Methods of Image ...

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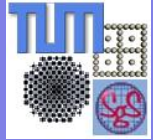
Visualizing Simulation ...

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## 4. Methods of Image Processing 2

- image: array of 2D/3D discrete greyscale/colour data
- **point-to-point processing:**



*Interpreting the ...*

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*Simulation Data ...*

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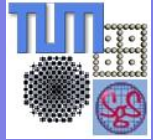
*Component Hierarchy ...*

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## 4. Methods of Image Processing 2

- image: array of 2D/3D discrete greyscale/colour data
- **point-to-point processing:**
  - local changes of pixel values



*Interpreting the ...*

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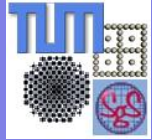
*Component Hierarchy ...*

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## 4. Methods of Image Processing 2

- image: array of 2D/3D discrete greyscale/colour data
- **point-to-point processing:**
  - local changes of pixel values
  - depend on current values, but neither on geometry nor on neighbours' values



*Interpreting the ...*

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*Simulation Data ...*

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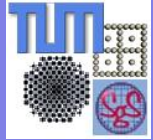
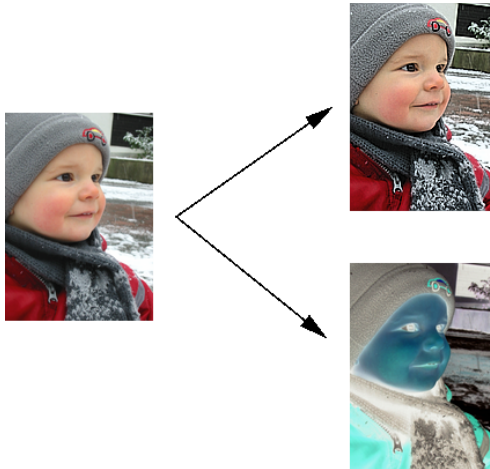
*Visualizing Simulation ...*

*Component Hierarchy ...*

*Animation*

## 4. Methods of Image Processing 2

- image: array of 2D/3D discrete greyscale/colour data
- **point-to-point processing:**
  - local changes of pixel values
  - depend on current values, but neither on geometry nor on neighbours' values
  - examples: addition of constants, contrast stretching, false colours, exponential transformations



Interpreting the ...

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Aspects of Computer ...

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Simulation Data ...

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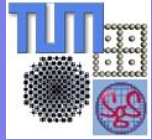
Visualizing Simulation ...

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## 5. Methods of Image Processing 3

- image: array of 2D/3D discrete greyscale/colour data
- **local-to-point processing:**
  - local changes of pixels' values due to environment



*Interpreting the ...*

*Methods of Image ...*

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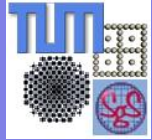
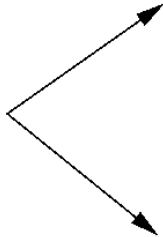
*Visualizing Simulation ...*

*Component Hierarchy ...*

*Animation*

## 5. Methods of Image Processing 3

- image: array of 2D/3D discrete greyscale/colour data
- **local-to-point processing:**
  - local changes of pixels' values due to environment
  - examples: local weighted averaging (convolution, smoothing), local rank operators (median, sorting), segmentation (thresholds, filtering), edge detection, feature extraction, . . .



*Interpreting the . . .*

*Methods of Image . . .*

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*Aspects of Computer . . .*

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*Simulation Data . . .*

*Visualizing Simulation . . .*

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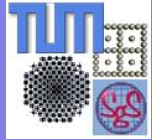
*Visualizing Simulation . . .*

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*Animation*

## 6. Methods of Image Processing 4

- image: array of 2D/3D discrete greyscale/colour data
- **ensemble processing:**
  - comparison of different images of the same scene



*Interpreting the ...*

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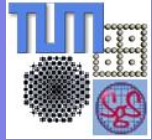
*Component Hierarchy ...*

*Animation*

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## 6. Methods of Image Processing 4

- image: array of 2D/3D discrete greyscale/colour data
- **ensemble processing:**
  - comparison of different images of the same scene
  - examples: detection of motion (military), difference images (medicine, monitoring agricultural activities or vegetation)



*Interpreting the ...*

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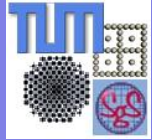
*Component Hierarchy ...*

*Animation*

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## 6. Methods of Image Processing 4

- image: array of 2D/3D discrete greyscale/colour data
- **ensemble processing:**
  - comparison of different images of the same scene
  - examples: detection of motion (military), difference images (medicine, monitoring agricultural activities or vegetation)
- **domain processing:**
  - complicated modifications of pixel values due to both local and global information



*Interpreting the ...*

*Methods of Image ...*

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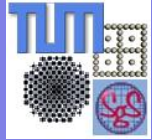
*Visualizing Simulation ...*

*Component Hierarchy ...*

*Animation*

## 6. Methods of Image Processing 4

- image: array of 2D/3D discrete greyscale/colour data
- **ensemble processing:**
  - comparison of different images of the same scene
  - examples: detection of motion (military), difference images (medicine, monitoring agricultural activities or vegetation)
- **domain processing:**
  - complicated modifications of pixel values due to both local and global information
  - examples: Fourier or cosine transform (JPEG), wavelet transform, tomography (CT, NMR,...)



*Interpreting the ...*

*Methods of Image...*

*Methods of Image...*

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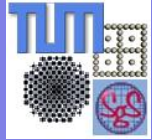
*Visualizing Simulation...*

*Visualizing Simulation...*

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## 7. Aspects of Computer Graphics 1



*Interpreting the ...*

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*Aspects of Computer ...*

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*Simulation Data ...*

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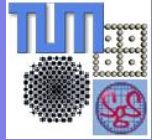
*Component Hierarchy ...*

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## 7. Aspects of Computer Graphics 1

- visualization is based on methods from graphics:
  - crash simulation: representation of cars and the whole scene, perspective view, . . .



*Interpreting the . . .*

*Methods of Image . . .*

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*Aspects of Computer . . .*

*Aspects of Computer . . .*

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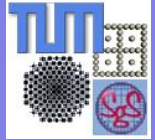
*Component Hierarchy . . .*

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## 7. Aspects of Computer Graphics 1

- visualization is based on methods from graphics:
  - crash simulation: representation of cars and the whole scene, perspective view, . . .
  - illumination for increasing realism



*Interpreting the . . .*

*Methods of Image . . .*

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*Aspects of Computer . . .*

*Aspects of Computer . . .*

*Simulation Data . . .*

*Visualizing Simulation . . .*

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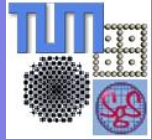
*Visualizing Simulation . . .*

*Component Hierarchy . . .*

*Animation*

## 7. Aspects of Computer Graphics 1

- visualization is based on methods from graphics:
  - crash simulation: representation of cars and the whole scene, perspective view, . . .
  - illumination for increasing realism
  - visualizing weather forecast (virtual flights): clouds, fog, . . .



*Interpreting the . . .*

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*Component Hierarchy . . .*

*Animation*

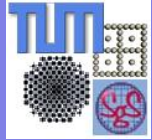
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## 7. Aspects of Computer Graphics 1

- visualization is based on methods from graphics:
  - crash simulation: representation of cars and the whole scene, perspective view,...
  - illumination for increasing realism
  - visualizing weather forecast (virtual flights): clouds, fog,...
  - virtual reality and augmented reality techniques



(movie)



*Interpreting the ...*

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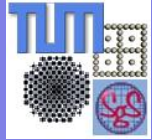
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## 8. Aspects of Computer Graphics 2

- geometric modelling:
  - representing 3D objects



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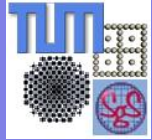
*Component Hierarchy ...*

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## 8. Aspects of Computer Graphics 2

- geometric modelling:
  - representing 3D objects
- graphical representation / rendering:
  - perspective
  - illumination
  - shading



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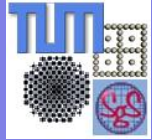
*Component Hierarchy ...*

*Animation*

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## 8. Aspects of Computer Graphics 2

- geometric modelling:
  - representing 3D objects
- graphical representation / rendering:
  - perspective
  - illumination
  - shading
- stereoscopy (cf. VR)



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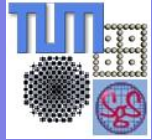
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## 9. Simulation Data Resolved in Time & Space

- given: result (data set) of some numerical simulation

$$f : \mathbb{R}^d \supset \Omega \rightarrow \mathbb{R}^m, m \in \mathbb{N}$$

f: scalar or vector valued



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## 9. Simulation Data Resolved in Time & Space

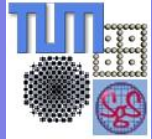
- given: result (data set) of some numerical simulation

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- examples:

–  $\vec{u}(x, y, (z))$  two-/three-dimensional velocities,



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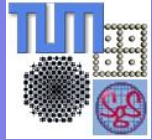
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- $p(x, y, (z))$  pressure,



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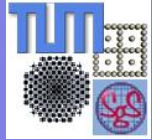
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- examples:

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- $p(x, y, (z))$  pressure,
- $c(x, y, (z))$  solute concentration in a fluid,



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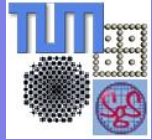
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- $\vec{u}(x, y, (z))$  two-/three-dimensional velocities,
- $p(x, y, (z))$  pressure,
- $c(x, y, (z))$  solute concentration in a fluid,

- visualization clear for 2D,  
but 3D?



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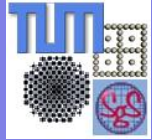
Visualizing Simulation ...

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## 10. Visualizing Simulation Data 1

- different techniques for the visualization of 3D data:



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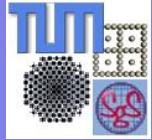
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## 10. Visualizing Simulation Data 1

- different techniques for the visualization of 3D data:
  - lower-dimensional subdomains:



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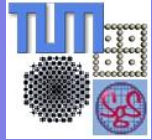
*Visualizing Simulation ...*

*Component Hierarchy ...*

*Animation*

## 10. Visualizing Simulation Data 1

- different techniques for the visualization of 3D data:
  - lower-dimensional subdomains:
    - \* **(ortho-) slices:**
      - the respective quantity is considered on some plane only (aligned with coordinate directions or not)



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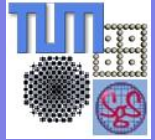
Visualizing Simulation...

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## 10. Visualizing Simulation Data 1

- different techniques for the visualization of 3D data:
  - lower-dimensional subdomains:
    - \* **(ortho-) slices:**
      - the respective quantity is considered on some plane only (aligned with coordinate directions or not)
    - \* **isosurfaces:**
      - surface on which the scalar  $f$  or one component of its components takes some prescribed value  $t$ :  
$$I(c) = \{(x, y, z) \in \Omega : f(x, y, z) = c\}$$



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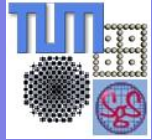
Visualizing Simulation ...

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  - lower-dimensional subdomains:
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    - \* **isosurfaces:**
      - surface on which the scalar  $f$  or one component of its components takes some prescribed value  $t$ :
$$I(c) = \{(x, y, z) \in \Omega : f(x, y, z) = c\}$$
      - interactive creation or modification (change of  $c$ , change in time) require efficient algorithms (marching cubes, e.g.)



Interpreting the ...

Methods of Image ...

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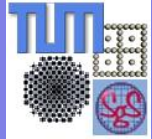
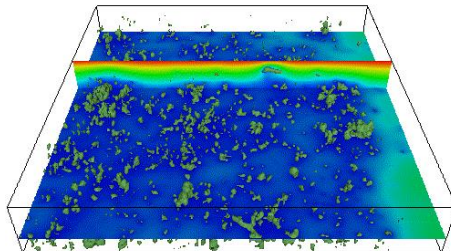
Visualizing Simulation ...

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Interpreting the ...

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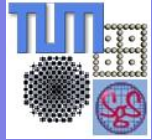
Component Hierarchy ...

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## 11. Visualizing Simulation Data 2

- visualization of 3D data (continued):
  - lower-dimensional subdomains (continued):
    - \* **streamlines**:
      - for the visualization of vector fields ( $m > 1$ );



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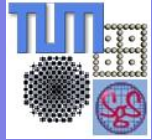
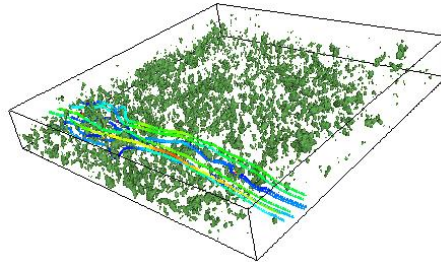
Visualizing Simulation ...

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## 11. Visualizing Simulation Data 2

- visualization of 3D data (continued):
  - lower-dimensional subdomains (continued):
    - \* **streamlines**:
      - for the visualization of vector fields ( $m > 1$ );
      - curves with tangent always parallel to local vectors of the given vector field (velocities in CFD, e.g.)



Interpreting the ...

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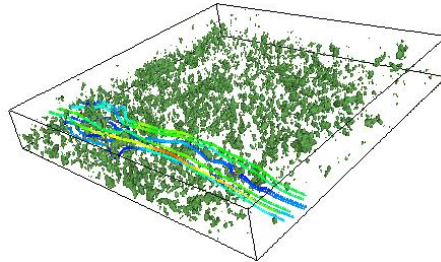
Visualizing Simulation ...

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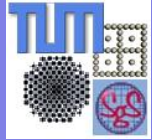
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## 11. Visualizing Simulation Data 2

- visualization of 3D data (continued):
  - lower-dimensional subdomains (continued):
    - \* **streamlines:**
      - for the visualization of vector fields ( $m > 1$ );
      - curves with tangent always parallel to local vectors of the given vector field (velocities in CFD, e.g.)



- \* **particle tracing:**
  - for the visualization of time-dependent vector fields;



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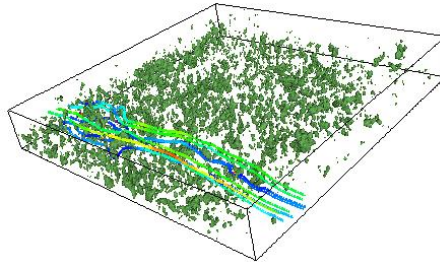
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## 11. Visualizing Simulation Data 2

- visualization of 3D data (continued):
  - lower-dimensional subdomains (continued):

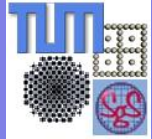
- \* **streamlines:**

- for the visualization of vector fields ( $m > 1$ );
- curves with tangent always parallel to local vectors of the given vector field (velocities in CFD, e.g.)



- \* **particle tracing:**

- for the visualization of time-dependent vector fields;
- introduce a virtual particle somewhere and follow its path through the domain according to the vector field



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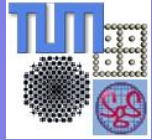
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## 12. Visualizing Simulation Data 3

- visualization of 3D data (continued):
  - lower-dimensional subdomains (continued):
    - \* **streaklines**:
      - for time-dependent vector fields, too;



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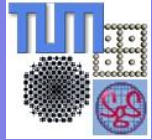
*Visualizing Simulation ...*

*Component Hierarchy ...*

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## 12. Visualizing Simulation Data 3

- visualization of 3D data (continued):
  - lower-dimensional subdomains (continued):
    - \* **streaklines:**
      - for time-dependent vector fields, too;
      - introduce a sequence of virtual particles somewhere and catch their positions at some point of time



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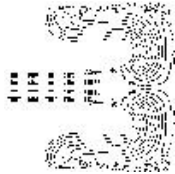
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## 12. Visualizing Simulation Data 3

- visualization of 3D data (continued):
  - lower-dimensional subdomains (continued):

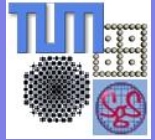
- \* **streaklines:**

- for time-dependent vector fields, too;
- introduce a sequence of virtual particles somewhere and catch their positions at some point of time



(movie)

- \* In the stationary case, all three methods lead to the same lines!



Interpreting the ...

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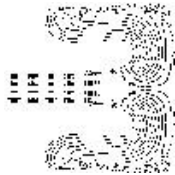
Animation

## 12. Visualizing Simulation Data 3

- visualization of 3D data (continued):
  - lower-dimensional subdomains (continued):

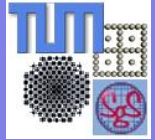
- \* **streaklines:**

- for time-dependent vector fields, too;
- introduce a sequence of virtual particles somewhere and catch their positions at some point of time



(movie)

- \* In the stationary case, all three methods lead to the same lines!
- \* furthermore: **streakbands**, **streaktubes** (allow to visualize additional quantities as well as rotation, e.g.)



Interpreting the ...

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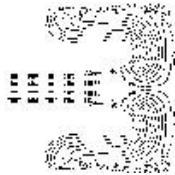
Animation

## 12. Visualizing Simulation Data 3

- visualization of 3D data (continued):
  - lower-dimensional subdomains (continued):

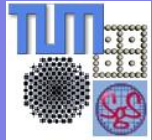
- \* **streaklines:**

- for time-dependent vector fields, too;
- introduce a sequence of virtual particles somewhere and catch their positions at some point of time



(movie)

- \* In the stationary case, all three methods lead to the same lines!
- \* furthermore: **streakbands**, **streaktubes** (allow to visualize additional quantities as well as rotation, e.g.)
- \* widespread: combinations of the above methods



Interpreting the ...

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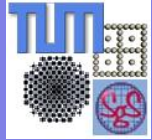
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## 13. Visualizing Simulation Data 4

- visualization of 3D data (continued):



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*Methods of Image ...*

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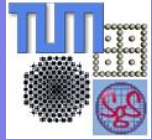
***Component Hierarchy ...***

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## 13. Visualizing Simulation Data 4

- visualization of 3D data (continued):
  - colours: use hue or intensity for expressing a scalar quantity



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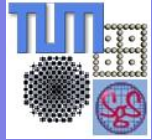
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## 13. Visualizing Simulation Data 4

- visualization of 3D data (continued):
  - colours: use hue or intensity for expressing a scalar quantity
    - \* use intuition: red/blue for temperature



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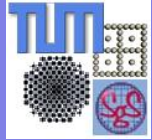
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## 13. Visualizing Simulation Data 4

- visualization of 3D data (continued):
  - colours: use hue or intensity for expressing a scalar quantity
    - \* use intuition: red/blue for temperature
    - \* also possible: different colours for different quantities (temperature and concentration, e.g.; limit: about 5)



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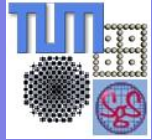
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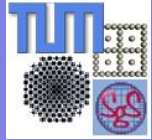
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  - use of graphical primitives:
    - \* arrows, balls,...
    - \* parameters: colour, size, distance (for speed)



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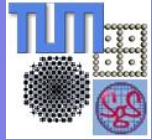
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    - \* parameters: colour, size, distance (for speed)
  - use of textures:
    - \* for indicating material or other characteristics (type of soil)



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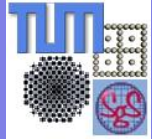
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  - use of graphical primitives:
    - \* arrows, balls,...
    - \* parameters: colour, size, distance (for speed)
  - use of textures:
    - \* for indicating material or other characteristics (type of soil)
  - use of legends and annotations:
    - \* very important: which scenario, which quantities, which scale



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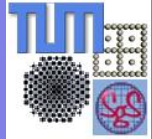
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  - use of graphical primitives:
    - \* arrows, balls,...
    - \* parameters: colour, size, distance (for speed)
  - use of textures:
    - \* for indicating material or other characteristics (type of soil)
  - use of legends and annotations:
    - \* very important: which scenario, which quantities, which scale
    - \* images without legends may be pretty, but not useful



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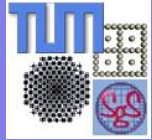
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## 14. Component Hierarchy of AVS/Express

- examples of commercial visualization tools:



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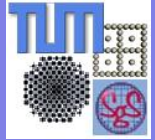
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## 14. Component Hierarchy of AVS/Express

- examples of commercial visualization tools:
  - AVS/Express
  - Explorer



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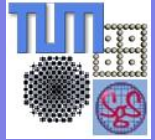
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## 14. Component Hierarchy of AVS/Express

- examples of commercial visualization tools:
  - AVS/Express
  - Explorer
- internal representation of data (hopefully able to profit from data structures used for the computations):



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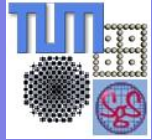
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## 14. Component Hierarchy of AVS/Express

- examples of commercial visualization tools:
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- internal representation of data (hopefully able to profit from data structures used for the computations):
- example AVS:
  - component hierarchy (tree structure)



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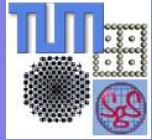
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- example AVS:
  - component hierarchy (tree structure)
  - **field**: highest component, whole information



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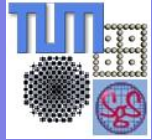
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- example AVS:
  - component hierarchy (tree structure)
  - **field**: highest component, whole information
  - **mesh**: geometric description
    - \* **grid**: position of grid points



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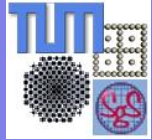
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    - \* **cells**: neighbourhood relations, connectivity (edges, faces, elements,...)



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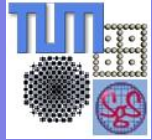
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    - \* **grid**: position of grid points
    - \* **cells**: neighbourhood relations, connectivity (edges, faces, elements,...)
  - **data**: data of the grid (values of f), node data and cell data



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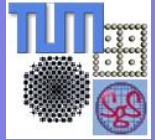
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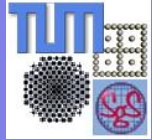
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## 15. Animation

- tremendous increase in data:



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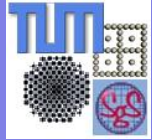
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## 15. Animation

- tremendous increase in data:
  - one image: some 4 MB, e.g.  $(1024 \times 1280, 4 \text{ B per point})$



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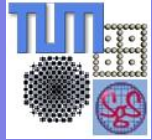
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## 15. Animation

- tremendous increase in data:
  - one image: some 4 MB, e.g. (1024×1280, 4 B per point)
  - video: some 25–30 images per second!



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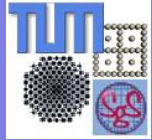
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  - compression necessary (mpg,...)



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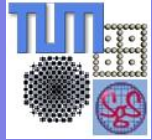
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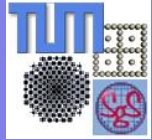
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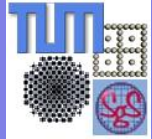
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- pay attention:
  - smooth transitions (w.r.t. movement, colour,...)
  - choice of scale:
    - \* stationary state: too restricted colour-scale at the beginning may suggest convergence even if there are still (small) oscillations
    - \* increasing differences: now, whole-spectrum colour-state at the beginning may prevent the actual values from being represented



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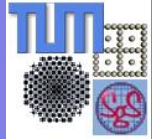
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  - if interpolation / inbetweening / frame techniques necessary: don't neglect (or even hide) disturbing details!



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