Image Processing and Computer Vision

Dr. Pascal Peter

Faculty of Mathematics and Computer Science
Saarland University, Saarbrücken

peter@mia.uni-saarland.de
www.mia.uni-saarland.de/peter

Summer Term 2023
http://www.mia.uni-saarland.de/Teaching/ipcv23.shtml

Welcome to this class!
Please do not hesitate to pose questions (in English or German).

M I A
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43

Lecture 1:
Introduction

Contents

© 2020 – 2023 Joachim Weickert, Pascal Peter

Motivation

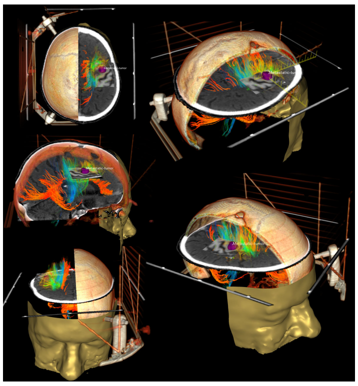
Images and Applications

- in our everyday lives: increasing amount of devices that create images and videos
- Numerous applications require to analyse, improve, or modify those images.

autonomous driving/robotics

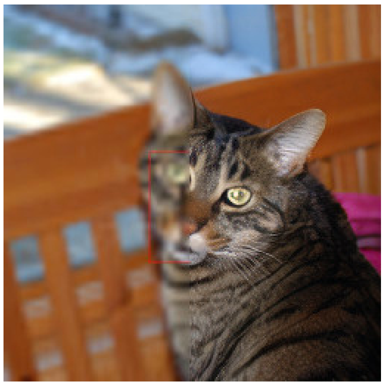
ESA/RAL Space/ESO

medical imaging



A. Jakab, University of Debrecen

image enhancement



Rombach et al. 2021

Synthetic Images

- also: fully synthetic images
- current trend: AI for image-to-text
- examples generated with stable diffusion (Rombach et al. 2021, DreamStudio)
- prompts below the images

a researcher with glasses, short beard, sitting in front of a screen, creating an image with stable diffusion, highly detailed, soft lighting

a student traveling through a perilous landscape made of exam papers, style: fantasy art

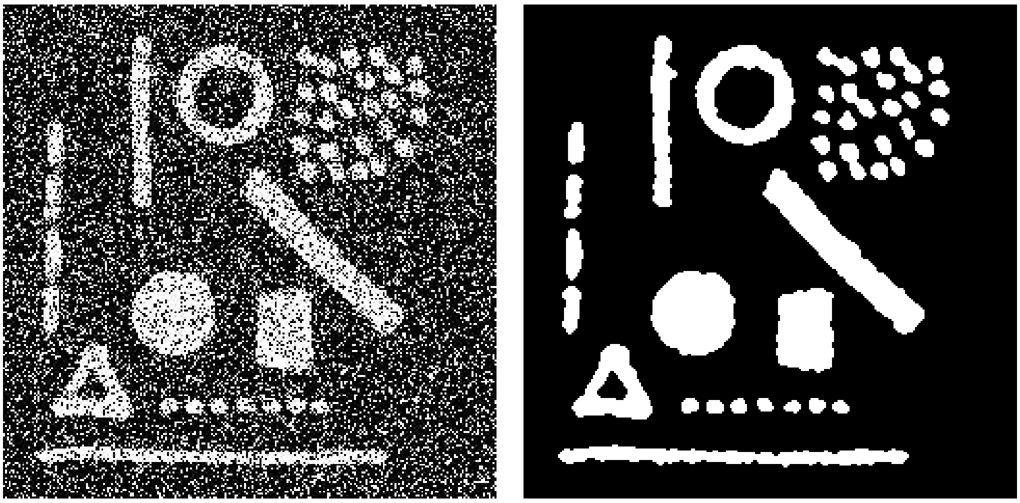
a cat studying computer science, style: pixel art

M I A
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43

Important Areas within Visual Computing

Image Processing (Bildverarbeitung)

- transforms a digital image to another digital image that allows a better interpretation by humans or computers



Example of an image processing application. **Left:** Noisy image. **Right:** Filtered. Author: J. Weickert.

M I A
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43

Computer Vision, Image Understanding (Rechnersehen, Bildverstehen)

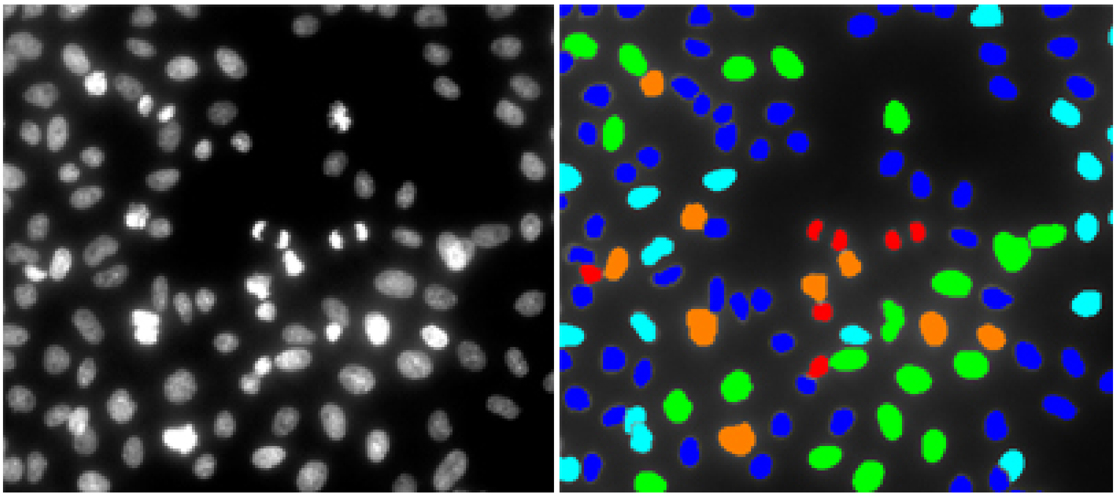
- extraction of information about the 3-D world from 2-D images

Example of a computer vision application. **Left:** Stereo image pair. **Right:** 3-D reconstruction. Authors: L. Alvarez, R. Deriche, J. Sánchez, J. Weickert.

Important Areas within Visual Computing (3)

Pattern Recognition (Mustererkennung)

- labelling of image structures to certain classes



Example of a pattern recognition application. **Left:** Cells. **Right:** Classification into different cell cycle phases. Source: MetaMorph Analysis, `http://www.moleculardevices.com/`.

Important Areas within Visual Computing (4)

M I A
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43

Computer Graphics (Computergrafik)

- synthesis of a digital image that is supposed to look like an image of a 3-D scene

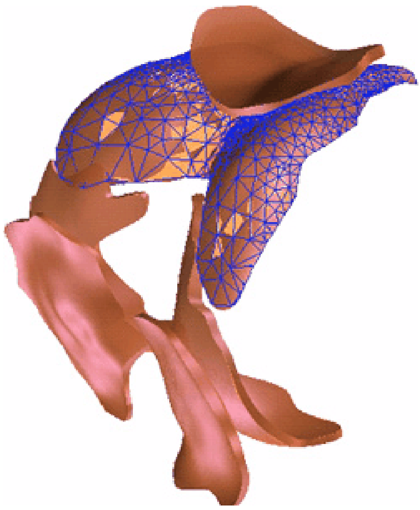
Example of a computer graphics application: Realistically looking simulation of a forest using ray tracing. Author: P. Slusallek.

Important Areas within Visual Computing (5)

M I A
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43

Geometric Modelling (Geometrische Modellierung)

- mathematical representation of curves and surfaces
- allows to synthesise 2-D and 3-D objects on a computer



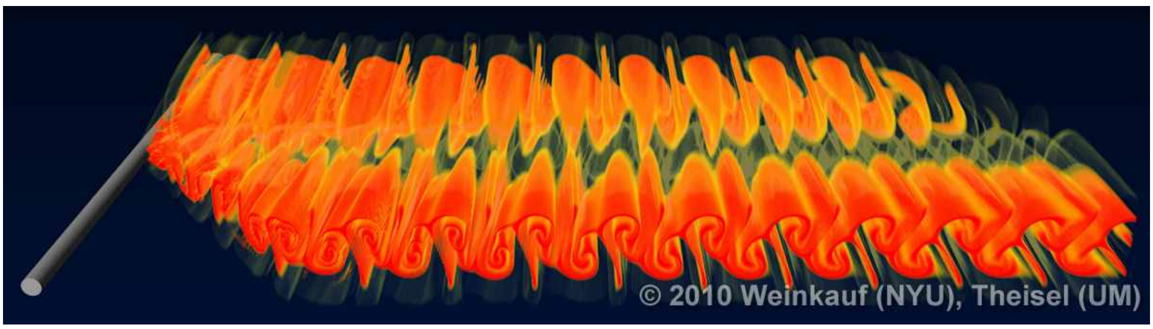
Example of a geometric modelling application: A surface model of a tissue in a human knee using a triangulation. Source: `http://www.scorec.rpi.edu/research_biomechanical.html`.

Important Areas within Visual Computing (6)

M I A
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43

Scientific Visualisation (Wissenschaftliche Visualisierung)

- useful visual representation of data from real experiments or computer simulations

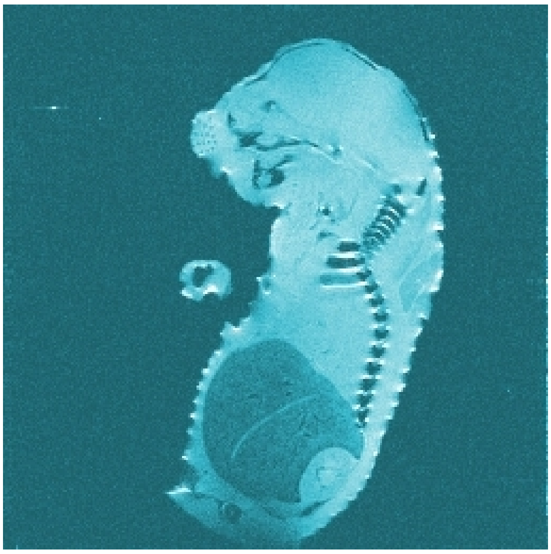


Example of a scientific visualisation application: Three-dimensional flow visualisation. Authors: T. Weinkauf, H. Theisel.

Important Areas within Visual Computing (7)

Image Acquisition, Imaging (Bildgebende Verfahren)

- deals with all aspects of image creation



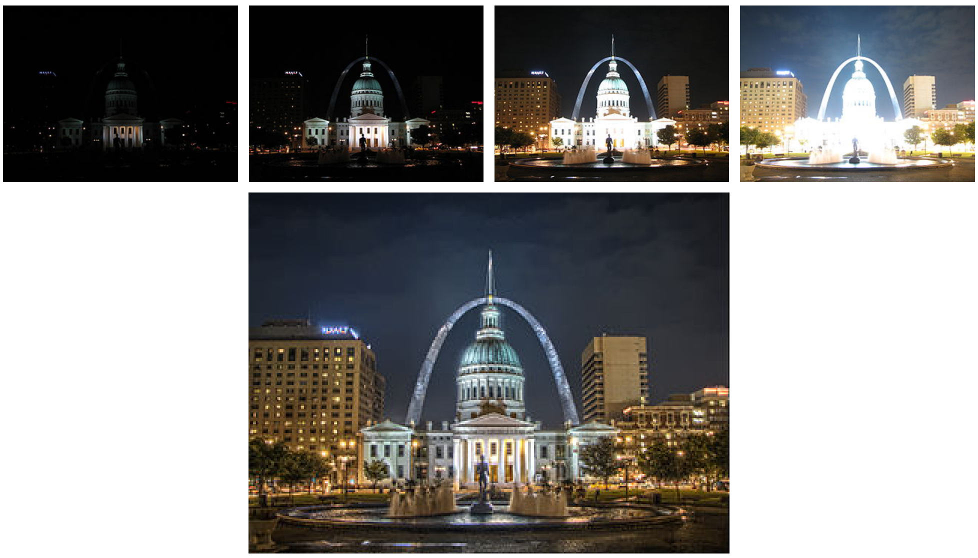
Example of an imaging application: Magnetic resonance image of a mouse embryo. Author: F. Volke.

M I A
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43

Important Areas within Visual Computing (8)

Computational Photography

- combines image capture, processing and manipulation



Example of a computational photography application: **Top row:** Four differently exposed images. **Bottom row:** Fusion to a single image with local tone mapping. Source: `en.wikipedia.org/wiki/High_dynamic_range_imaging`.

Important Areas within Visual Computing (9)

Collective Terms

- **Image Analysis (Bildanalyse):**
  includes image processing, computer vision, pattern recognition
- **Image Synthesis (Bildsynthese):**
  includes computer graphics, geometric modelling, scientific visualisation
- **Visual Computing, Image Sciences (Bildwissenschaften):**
  comprises image acquistion and the analysis and synthesis of digital images

We focus on image analysis, in particular on image processing and computer vision.

There is a growing confluence between the individual areas:

- Human motion capture and embedding into virtual scenes combines image analysis and image synthesis.
- Computational photography combines image acquisition, image analysis, and image synthesis.

Outline

Lecture 1: Introduction

Contents

1. Motivation and Important Areas within Visual Computing
2. **Organisational Issues**
3. Introductory Examples
4. Forthcoming Topics

M I A
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43

Organisatorial Issues

Why is this Class Important?

- introduction to mathematically well-founded, model-based areas of image processing and computer vision
- important in numerous applications, e.g. medical imaging, computer-aided quality control, driver assistance systems, robotics, bioinformatics, computer graphics, multimedia, and artificial intelligence
- beautiful application area for almost all branches of mathematics
- qualifies for starting a bachelor thesis in our group;
  for a master thesis, one also has to attend
  Differential Equations in Image Processing and Computer Vision

M I A
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43

How Can I Make Use of These Classes?

- 4 hours classroom lectures, 2 hours tutorials (9 ECTS points)
- can be used in numerous bachelor or master programs, e.g.:

Study Program	Usage
Visual Computing (VC)	VC core area / subarea image analysis
Computer Science (CS)	core class (Stammvorlesung) or mathematics class if minor is mathematics
Mathematics	mathematics core class or CS class if minor is CS
Mathematics & CS	core class in mathematics or CS
DSAI	DSAI core class (bachelor and master)
Embedded Systems	master core class
Media Informatics	master core class
Bioinformatics	master core class
Physics	non-physical free elective master class

Organisatorial Issues (3)

Which Prerequisits are Required?

- **undergraduate mathematics (e.g. Mathematik für Informatiker I–III)**
  examples of suitable textbooks:
  - E. Kreyszig: *Advanced Engineering Mathematics*. Wiley, Chichester, 2010.
  - M. Wolff, P. Hauck und W. Küchlin: *Mathematik für Informatik und Bioinformatik*. Springer, Berlin, 2004.
- **elementary C knowledge (for the programming assignments)**
  can be learned e.g. in
  - R. Kirsch, U. Schmitt: *Programmieren in C – Eine mathematikorientierte Einführung*. Springer, Berlin, 2013.
  - *C Programming*
    `https://www.learn-c.org/`
- **reasonable working knowledge of English**

Organisatorial Issues (4)

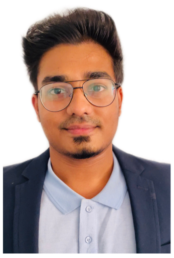
Tutorials

- combined theoretical and programming assignments
- coordinated by Michael Ertel (Teams and `ertel@mia.uni-saarland.de`)

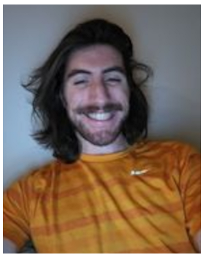
Head Tutor

Michael Ertel

Tutors



Aseer Ahmad Ansari



Cameron Braunstein

Soumava Paul

Chengjiangrong Peng

Aheli Saha

- Tutorials are designed for group work in groups of three students.
- In order to form a group, write a message or mail to Michael Ertel.

M I A
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43

Organisatorial Issues (5)

Tutorials

- **Register for the tutorials in Teams until April 20.**
  This is mandatory for course participation.
- multiple options for in person and online tutorials:
  - Group T1: Tue, 12:15 – 14:00
  - Group T2: Tue, 14:15 – 16:00
  - Group T3: Tue, 16:15 – 18:00
  - Group W1: Wed, 10:15 – 12:00
  - Group W2: Wed, 12:15 – 14:00
  - Group W3: Wed, 14:15 – 16:00
  - Group W4: Wed, 16:15 – 18:00
- Optional Guided Programming Helpdesk: Tue, 18:15 – 20:00
  contact Michael Ertel (`ertel@mia.uni-saarland.de`) for online appointments

M I A 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43

Organisatorial Issues (6)

Homework

- Each week: theory or programming assignments worth 24 points in total.
- Submit assignments by posting your solutions in your private channel in teams.
- Both handwritten (scanned) and digitally typeset solutions in pdf format are fine for theory submissions, as long as they are readable.

Classroom Work

- There are additional assignments each week intended for group work.
- You get 12 points for participation with either of these 3 options:

  Option 1: Attend in-person tutorials.

  Option 2: Cooperate online in your private channels and report to your tutor.

  Option 3: Submit solution attempts (not graded, do not have to be complete).

M I A 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43

Organisatorial Issues (7)

Written Exams

- Self-test problems (Probeklausur) with sample solutions will be available.
- admission: 312/468 tutorial points (13 tutorials)
- Two written exams (physical presences at UdS required):
  Tuesday, July 25, 2023, 2 pm, Building E2.2, Günter Hotz Lecture Theatre.
  Monday, October 9, 2023, 2 pm, Building E2.2, Günter Hotz Lecture Theatre
- **You need to register for the exams on LSF.**
- Two exams count as two attempts.
  If you participate in both, the better grade counts.
- Both exams will be closed book exams.
  You are allowed and obliged to bring three things to your desk only:
  – your student ID card (Studierendenausweis)
  – a ball-pen that has no function other than writing
  – one double-sided, hand-written A4 cheat sheet
  (will be collected after the exam and returned at the inspection meeting)
- You must not take anything with you that contains information about the exam.

Organisatorial Issues (8)

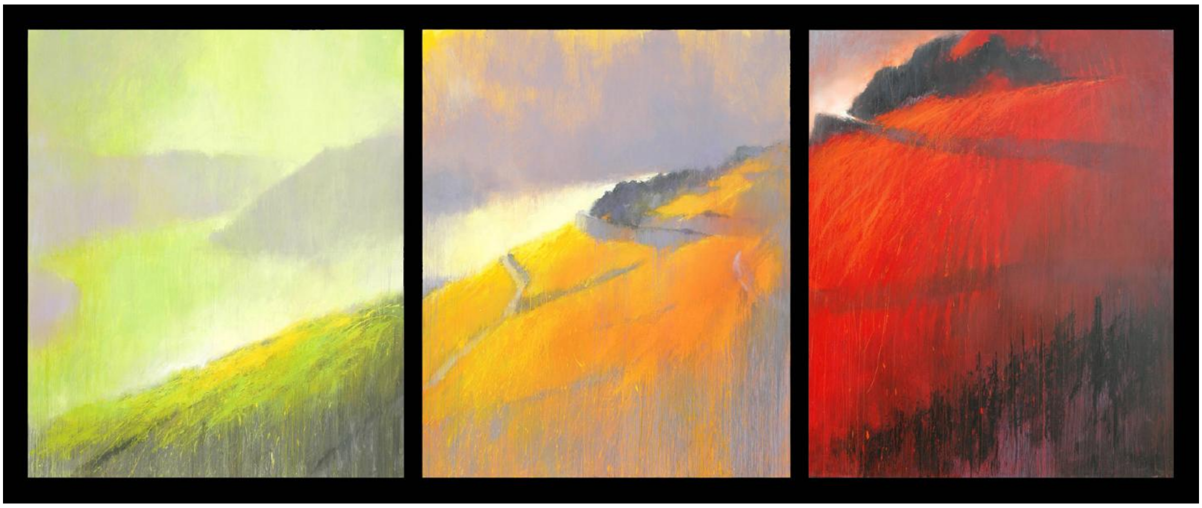
Questions and Problems

- Please feel free to ask me during the lectures, in the break,
  or in the office hour
  (Tue, 12:30–13:30, send message or mail for an appointment).
- Also your tutor and Michael Ertel will be happy to help.
  - Michael Ertel's office hour is on Tuesday, 15:00–16:00.
  - Tutor office hours will be provided on the IPCV webpage.

M I A
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43

Planned Contents (1)

Planned Contents



Foundations and Transformations | Image Processing | Computer Vision and Image Understanding

The IPCV class resembles a tryptichon, consisting of three parts of roughly equal size. Image source: `https://commons.wikimedia.org/wiki/File:Welterbe-Wein-Triptychon.jpg`.

M I A
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43

Planned Contents (2)

Part I: Foundations and Transformations

1. **Foundations**
   - 1.1 Definitions, Image Types, Discretisation
   - 1.2 Degradations in Digital Images
   - 1.3 Colour Perception and Colour Spaces
2. **Image Transformations**
   - 2.1 Continuous Fourier Transform
   - 2.2 Discrete Fourier Transform
   - 2.3 Discrete Cosine Transform
   - 2.4 Image Pyramids
   - 2.5 Wavelet Transform
3. **Image Compression**
4. **Image Interpolation**

M I A
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43

Planned Contents (3)

MIA
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43

Part II: Image Processing

5. **Point Operations**
6. **Linear Filters**
   - 6.1 System Theory
   - 6.2 Derivative Approximations
   - 6.3 Edge and Corner Detection
7. **Nonlinear Filters**
   - 7.1 Morphology and Median Filters
   - 7.2 Wavelet Shrinkage
   - 7.3 Bilateral Filters
   - 7.4 NL Means
   - 7.5 Nonlinear Diffusion Filtering
8. **Global Filters**
   - 8.1 Discrete Variational Methods
   - 8.2 Continuous Variational Methods
   - 8.3 Deconvolution Methods
9. **Texture Analysis**

Planned Contents (4)

MIA
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43

Part III: Computer Vision and Image Understanding

10. **Image Sequence Analysis**
    - 10.1 Local Methods
    - 10.2 Variational Methods
11. **3-D Reconstruction**
    - 11.1 Camera Geometry
    - 11.2 Stereo Reconstruction
    - 11.3 Shape-from-Shading
12. **Object Recognition**
    - 12.1 Segmentation
    - 12.2 Hough Transform
    - 12.3 Invariants
    - 12.4 Eigenspace Methods
    - 12.5 Neural Networks and Deep Learning

References

We do **not** rely on a single textbook:
Our didactic concept differs from all of them.
However, here are some of the more useful books:

Textbooks on Image Processing

- J. Bigun: *Vision with Direction.* Springer, Berlin, 2010.
  One of most systematic books on image processing, with a clear focus on matrix representations.
- R. C. Gonzalez, R. E. Woods: *Digital Image Processing*. Global Edition, Pearson Prentice Hall, Upper Saddle River, 2017.
  A classical book on image processing. Comprehensive and fairly well readable.
- H. Süße, E. Rodner: *Bildverarbeitung und Objekterkennung.* Springer, Wiesbaden, 2014.
  German book on selected aspects of image processing, computer vision, and machine learning.

M I A
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43

Textbooks on Computer Vision

- R. Klette: *Concise Computer Vision*. Springer, London, 2014.
  Covers also some more recent methods, but not everything.
- R. Szeliski: *Computer Vision: Algorithms and Applications.* Springer, New York, Second Edition, 2022.
  `http://szeliski.org/Book/drafts/SzeliskiBook_20100903_draft.pdf`
  Covers many things, but not very detailed.
- E. Trucco, A. Verri: *Introductory Techniques for 3-D Computer Vision*. Prentice-Hall, Upper Saddle River, 1998.
  Good selection of some important aspects, but not up to date in others.
- B. K. P. Horn: *Robot Vision.* MIT Press, Cambridge, MA, 1986.
  Very old, but stood the test of time. Excellent w.r.t. continuous modelling.

These and other textbooks can be found in the course reading (Semesterapparat) of our Computer Science and Mathematics Library (Building E2.3).

M I A
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43

Useful Internet Resources

- **CV Online**
  `https://homepages.inf.ed.ac.uk/rbf/CVonline/`
  Online compendium on numerous image processing and computer vision topics. Often very useful.

- **Annotated Computer Vision Bibliography**
  `www.visionbib.com/bibliography/contents.html`
  helpful when searching for specific references for a certain topic

- **Google Scholar**
  `https://scholar.google.com`
  provides links to highly cited articles of all scientific areas

Lecture 1:
Foundations I: Image Types and Discretisation

Contents

M I A
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43

Sampling and Quantisation

Continuous Greyscale Image (Kontinuierliches Grauwertbild)

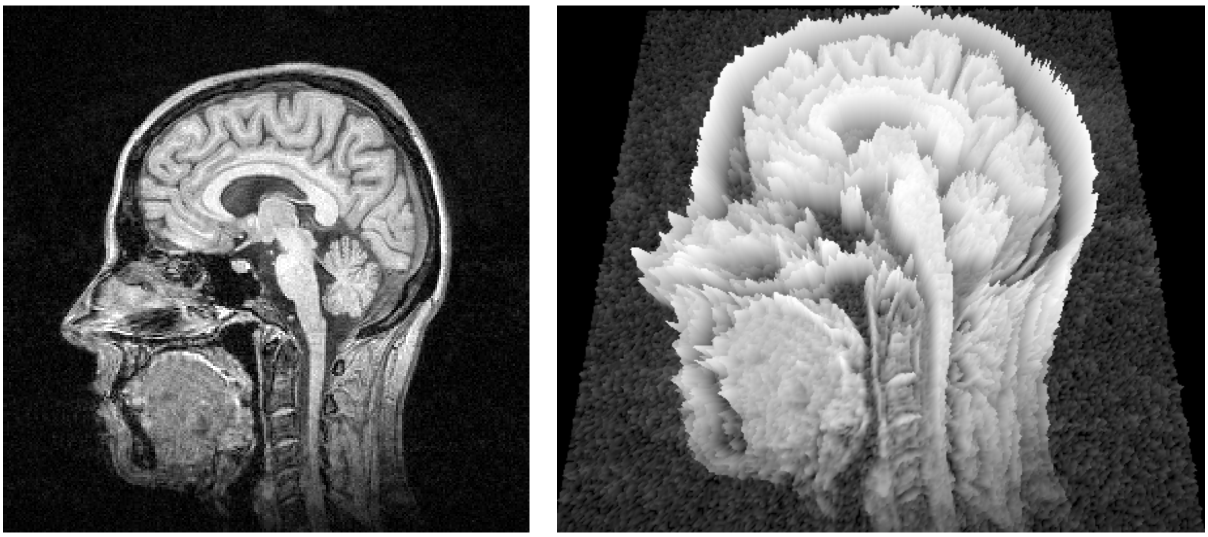
- mapping f from a rectangular domain (Definitionsbereich) $\Omega = (0, a_1) \times (0, a_2)$ to a co-domain (Wertebereich) $\mathbb{R}$:

$$f : \mathbb{R}^2 \supset \Omega \rightarrow \mathbb{R}$$

- domain Ω is called *image domain* or *image plane*
- co-domain $\mathbb{R}$ specifies *grey value*
- Low grey values are dark and high grey values bright.

M I A

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43



Left: Magnetic resonance (MR) image of a human head. **Right:** Representation as a function $f(x, y)$ over a rectangular image domain Ω. Authors: J. Weickert, C. Schnörr.

Sampling and Quantisation (3)

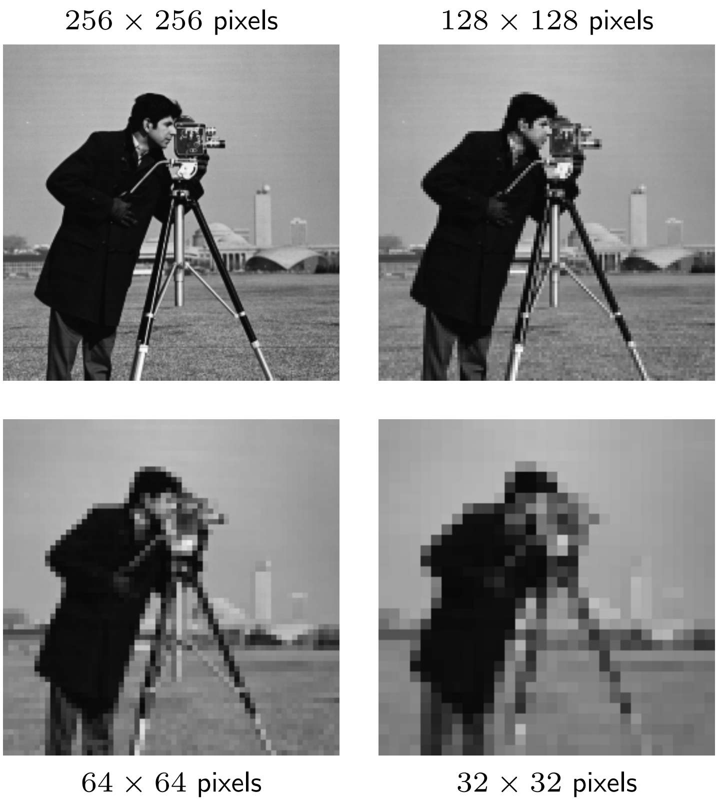
Sampling (Abtastung)

- discretisation of the *domain* Ω
- Image data are only given on a rectangular point grid within the image domain Ω.
- creates a digital image

$$\{f_{i,j} \mid i = 1, ..., N;\ j = 1, ..., M\}$$

- The grid point / cell (i, j) is called *pixel* (picture element).
- 2-D images often have equal pixel distances in both directions.
- Lazy image processing people often normalise these grid sizes to 1.
  This can be dangerous and is **not** recommended!
- If the sampling is too coarse, the image quality degrades severely.

Sampling and Quantisation (4)



Digital test image with different sampling rates. Author: J. Weickert.

M I A
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43

Sampling and Quantisation (5)

Quantisation (Quantisierung)

- discretisation of the *co-domain*
- saves disk space
- Often a grey value is encoded with a single byte.
  Then the discrete co-domain is given by $\{0, 1, ..., 255\}$.
- Binary images have the co-domain $\{0, 1\}$.
- Humans can distinguish only about 40 greyscales.
  They are even very good in recognising the content of binary images.

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43

Sampling and Quantisation (6)

256 greyscales

32 greyscales

8 greyscales

2 greyscales

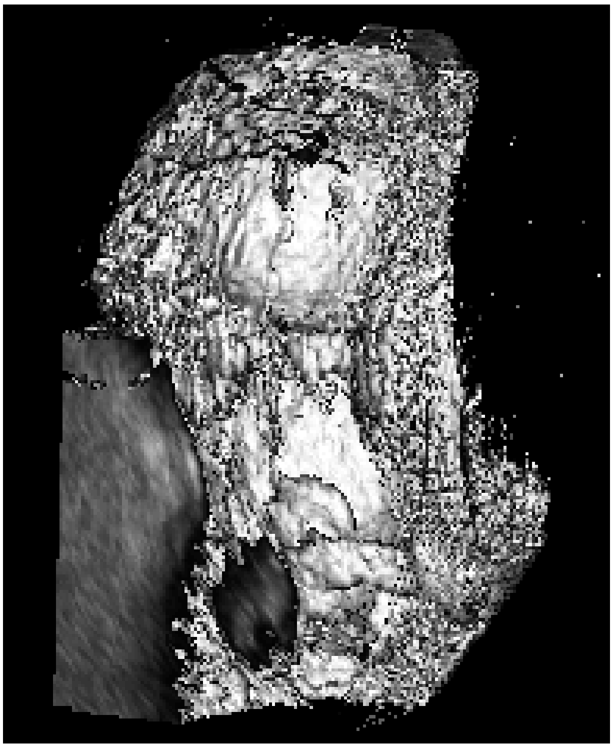
Digital test image (256×256 pixels) with different quantisation rates. Author: J. Weickert.

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43

Types of Images

m-dimensional Images

- have their domain in $\mathbb{R}^m$
- $m = 1$: signals
- $m = 2$: (two-dimensional) images
- $m = 3$: three-dimensional images
  - important in medical imaging, e.g.
    computerised tomography (CT, Computertomographie),
    magnetic resonance imaging (MRI, Kernspintomographie).
  - Image points/cells in 3-D are called *voxels* (volume elements).
  - Voxel dimensions usually differ in different directions!



Rendering of a 3-D ultrasound image of a human fetus in its 10th week. Authors: J. Weickert, K. Zuiderveld, B.M. ter Haar Romeny, W. Niessen.

Types of Images (3)

Vector-Valued Images

- have their co-domain in $\mathbb{R}^n$, containing n channels
- **Example 1: Colour Images**
  - three channels: R (red), G (green), B (blue)
  - Humans can distinguish two million colours!
- **Example 2: Satellite Images**
  - Different channels represent different frequency bands.
  - Multispectral images use only a few channels.
    Hyperspectral images involve hundreds or thousands of channels.

Types of Images (4)

Colour image as example for a vector-valued image. **Top left:** Original image. **Top right:** Red channel. **Bottom left:** Green channel. **Bottom right:** Blue channel. Author: J. Weickert.

M I A
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43

Types of Images (5)

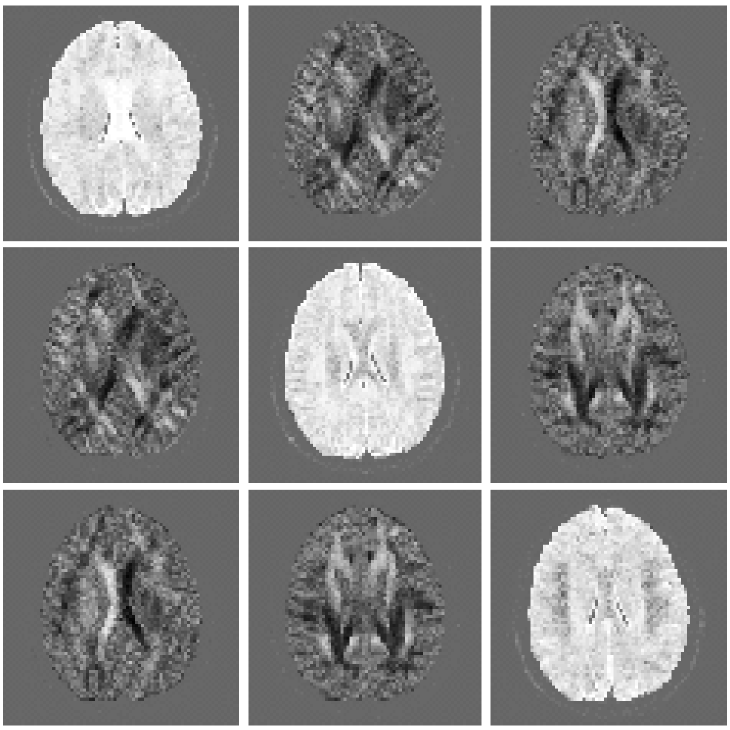
M I A 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43

Matrix-Valued Images

- have their co-domain in $\mathbb{R}^{n\times n}$
- **Example: Diffusion Tensor Magnetic Resonance Imaging (DT-MRI)**
  - measures in each voxel in 3-D the diffusion properties of water molecules
  - described by a symmetric positive definite 3×3 matrix
- may create additional constraints, e.g.:
  A reasonable filter should not destroy phyiscally relevant properties,
  such as positive definiteness of the matrix field.

Types of Images (6)

M I A 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43



Images of the nine coefficients of a DT-MRI data set of a human brain. Since the diffusion matrix is a symmetric 3×3 matrix, only 6 out of 9 images differ. Authors: D. Weinstein, G. Kindlmann, E. Lundberg.

Types of Images (7)

Image Sequences (Bildfolgen)

- One can consider image squences for any of the above mentioned types of images.
- The time variable increases the dimensionality of the domain from m to $m+1$.
- **Example: 3-D Echo Cardiography (Echokardiographie)**
  - creates a sequence of 3-D scalar-valued ultrasound images (can be regarded as 4-D image)

Relevant Images in This Class

- We mainly focus on 2-D scalar-valued (i.e. greyscale) images, and their image sequences.
- This keeps the description as simple as possible.
- Many of our methods can be generalised to other types of images. Often this is not very challenging.

M I A
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43

Types of Images (8)

Form left to right and from top to bottom: Four subsequent frames of an image sequence (the famous Hamburg taxi scene, 256×190 pixels). Can you recognise what has moved in which direction? Source: `i21www.ira.uka.de/image_sequences/`

M I A
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43

Summary

- Digital images are discretised in two ways:
  in the domain (sampling) and the co-domain (quantisation).
- generalisation of the domain:
  m-dimensional images, image sequences
- generalisation of the co-domain:
  vector-valued images, matrix-valued images