Image analysis and data visualization

A human-computer affair

Valedictory Speech delivered in slightly adapted form at the University of Groningen on Friday October 15th, 2021 by prof. dr. Jos B.T.M. Roerdink
Dear attendees, in this room or connected via the livestream:

**Before we start**

You have all received an invitation in Dutch and/or English. So far I have left it open which language I would use during this valedictory lecture. Now it is true that since many years English has been the standard language at this university, both in research, education, and increasingly also at many other activities, such as meetings, opening of the academic year, etc.

One of the goals of this speech is actually to answer a question my family has asked me many times: ‘what exactly are you doing at the university?’ And this is simply more easily done in the language I grew up with. Also, two of my grandchildren (10 and 11 years of age) are in the room. One of them has asked me whether it would not be too boring. I will do my best. On the other hand I want of course to give a clear impression of the content of my speech to those who are less well versed in Dutch.

For this reason I have made the following choice: I will speak in Dutch and use English on the slides. The written version of this speech will become available in both Dutch and English, so you can read it later in the language of your choice if you like.

I will not seize this opportunity to present a purely scientific talk or give a last lecture. Apart from attention for the content I will also give a sketch of my scientific career. That I would end up in the field of image analysis and data visualization was initially not obvious at all. Therefore I will start by briefly looking back at my education and first steps on the path of scientific research.

**How it all started**

After obtaining bachelor degrees in biology and physics I graduated in theoretical physics at the Catholic University Nijmegen (now Radboud University) in 1979. My master’s project was a collaborative project of the Department of Physics (Statistical Physics) and the Department of Biophysics (part of the Medical Faculty). So I came into contact with interdisciplinary research quite early.

Then I went to the Institute for Theoretical Physics in Utrecht where I did a mathematically oriented PhD project in the area of random processes in physics and chemistry with prof. Nico van Kampen.

I continued working on random walks during a postdoctoral stay at the Department of Chemistry of the University of California San Diego with prof. Kurt Shuler.

In 1985 I returned with my wife Hedwig and our oldest son Erik to the Netherlands where I was appointed as scientific collaborator at the Centre for Mathematics and
Computer Science (CWI) in Amsterdam at the Department of Applied Mathematics. This was the time when I switched topic to image reconstruction and analysis. This brings me to the main topics of today, that is, image processing and visualization. But before I elaborate on this I will first give an example of the fascination that images can evoke.

![Figure 1: The earth rising above the horizon of the moon. Image taken from Apollo 8 on Dec. 24, 1968](https://en.wikipedia.org/wiki/Earthrise)

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**A picture is worth a thousand words**

At least, this is what popular wisdom wants. Now it is certainly true that certain images can make an overwhelming impression that is difficult to put into words.

As an example we can take the image in Figure 1 known as *Earth rise*. The picture was taken by astronaut William Anders on December 24th, 1968, from Apollo 8, when he was encircling the moon and saw the earth rising. It has been described as ‘the most influential ecological photograph ever taken’ (Galen Rowell).

This image is very powerful and in a way speaks for itself. But what exactly do we mean when we say that this picture is worth a thousand words? Which words exactly? Isn’t it rather that there is something in this image that cannot be expressed into words at all?

But of course this is not where we stop in science. There we demand more information about how this image was created, so that we can extract useful insights from it. For example, we would like to know where the original picture can be found, which camera
has been used, what the settings were, what the position and velocity of the spaceship were, and which postprocessing has been applied. For example, it is known that the image in Figure 1 was cropped and rotated clockwise by 95 degrees with respect to the original photo.

What strikes me in this image is that no humans or animals are visible. This illustrates an important principle: what is (can be made) visible depends on the scale at which you (want to/can) look. Furthermore, we see here a change of viewpoint. We now look at the earth (ourselves) from a location far away.

Such a change of viewpoint is also very useful in daily life!

**Digital Image Processing**

Let me now introduce the topic of image processing with a simple example. First of all, it is important to realize that we work with digital images. I will explain this using Figure 2.

![Figure 2: Left: Object projected on a raster. Right: Raster image as result of sampling and quantization.](Picture © R. C. Gonzalez and R. E. Woods, Digital Image Processing 3/E, Pearson Prentice Hall, 2008.)

In the left image of this figure we see an real object with smooth contours. To store this image in a computer we imagine that we project it on a raster (matrix) consisting of horizontal and vertical rows of small squares that we call pixels. This process is known as ‘sampling’. Furthermore, each pixel gets a certain greytone (greyvalue) or color that closely matches the greytone or color of the real object which has been projected on the corresponding pixel.

The greytones are chosen from a finite set of values. This process is called ‘quantization’. The image we have obtained in this way is called a raster image or digital image. The result is shown in the right image of Figure 2. Now the contours have become ragged, but this effect is no longer visible when the raster consists of a sufficiently large number of pixels.
There exists another important image representation, that is, as *vector images*, but it would take us too far to discuss this variant here.

In digital image processing we can use computers to apply various operations on the images for achieving a desired effect. Examples of such operations are: enhancement, compression, segmentation, reconstruction, description, recognition, interpretation and transmission.

![Image](https://via.placeholder.com/150)

**Figure 3:** (a): Original; (b): Noisy version of (a); (c): image (b) after application of a uniform filter; (d): image (b) after application of a median filter.

**Example**

Let us now look at a simple example in the area of image enhancement. Imagine that you are walking on the Broerplein in Groningen where you take a picture of the Academy Building while it is hailing. The result could look like Figure 3, top right image. In fact, I processed the original picture of the Academy Building (the top-left image) with the computer by first converting it to a greyvalue image and then adding so-called salt-and-pepper noise to it. As a result many black pixels have appeared in light areas of the image and white pixels in dark areas.

There exist several ways to process (filter) the image so that noise is suppressed. In the bottom-left image we see the effect of a filter where the greytone of each pixel has been replaced by the average of the greyvalues of pixels in the neighbourhood of this pixel. In the bottom-right image a so-called median filter has been applied, where the greytone of each pixel has been replaced by the median (middle element) of the greytones (ordered by increasing values) of pixels in the neighbourhood of this pixel.

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The effect of these two filters is quite different. In the bottom-left image the noise pixels have been aggregated into somewhat larger areas. Also, the contours of the building have become fuzzy. In the bottom-right image many of the noise pixels have disappeared, but the contours have remained sharp.

To clarify, the upper-left image in Figure 3 has been processed by computer by adding to the original color image of the Academy Building a colored bow with the symbol $4\times\infty$ (pronounced as ‘for infinity’). This on the occasion of the 400th anniversary of the University of Groningen in 2014.

**The key question**

This brings us to the key question: Which result is better?

I have posed this question for many years to students who attended my course Image Processing. It always gave rise to interesting discussions. Although many of you probably (just like the students) would prefer the result obtained via the median filter, the question remains: what exactly do we mean by better? Of course, in science we are not satisfied with purely subjective statements (‘that is just what I think’, or, ‘that is obvious’). And in some cases, the judgment can vary greatly from person to person.

For this reason we invent in science objective ways to assess the quality of an image via quality measures. In our example we can do this by comparing the filtered image pixel by pixel with the original image, via computing the difference of the corresponding values and adding the differences (in practice, their absolute value or square) of all pixel pairs. The filtered image that has the smallest total difference with the original image we then call ‘the best’. The advantage of this kind of simple objective measures is also that they can be calculated fast by a computer.

This is an elegant solution that is applied widely in my research field. Nevertheless, a number of questions arise. First, how do we choose a quality measure in a concrete case? Because there exists not just a single measure, but a large number of them have been developed. Then how do we choose the ‘best’ one? If we do not want to make a choice we can also combine several measures. But then again the question arises whether this combined measure is ‘the best’.

Second, does the chosen quality measure agree with how people intuitively judge the quality of an image? A solution that is widely used is to have the result assessed by a number of experts and put their subjective rating next to the objective measures. But this does beg the question how these experts should be chosen and what to do if they differ in their judgment.

The situation is reminiscent of a waterbed. One can press anywhere to make things more objective. But inevitably somewhere else the subjective aspects pop up.
One way out of these dilemmas is to look at the goal for which the images are used. For example, which image helps to perform a task in the most correct way? Which image helps to make the fastest decision in a given situation? A combination of computer-controlled quality measures and human judgments often produces the most effective results in practice.

**Visual presentation**

The way we display image information has an important influence on the visual experience. For example, let’s look at the left picture in Figure 4.

![Figure 4: 'Photo' of the shadow of a black hole.](https://iopscience.iop.org/article/10.3847/2041-8213/ab0ec7)

Left: in greytone. Middle: in color. Right: in greytone, but after application of contrast enhancement.

Many of you may find this greyscale image rather uninteresting. Yet not so long ago it featured prominently in the news, that is, in the color version (the middle picture in Figure 4). You may recognize it now. Anyway, I am sure that the astronomers among you are fascinated by this image, which was created in 2019 by an international team of astronomers and published in the Astrophysical Journal Letters, Volume 875, No. 1 (195 authors!).

It is in fact the closest possible approximation of a ‘photo’ of (the shadow of) a black hole: an image of the diffracted light around the black hole in galaxy M87. A black hole is an object in space where gravity is so strong that nothing can escape from it, not even light. I put the word ‘photo’ between quotes because it wasn’t created by someone pressing a button at any given moment. On the contrary, it has been reconstructed from the observations made by a large number of telescopes spread over several countries on April 11, 2017, where an image filter also has been applied to the data.
As a nice touch, I have applied a digital filter on the greyscale version that improves the contrast (for the experts: through histogram equalization). The result in the image on the right now shows a lot more detail.

We can draw a number of conclusions from this example. Firstly, the way of presentation has an effect on the experience. Secondly, the impression an image makes is highly dependent on the context and the background knowledge of the viewer. And finally, digital image processing allows us to extract more information from the image.

I now return to the timeline.

**Image processing at CWI**

Fairly soon after my appointment in 1985 at the Center for Mathematics and Computer Science (CWI) a new project Analysis and Reconstruction of Images was started. This seemed very interesting to me and at that moment I shifted my research to this area. In this project I have intensively collaborated with Henk Heijmans. It was an exciting time when we explored a field that was new for both of us. Also, we set up a number of lecture series. We got to know the (close-knit) image processing community in the Netherlands, first via colleagues from the University of Amsterdam who were located in the same area as the CWI, next by a tour that we took along various universities. This resulted in many fruitful contacts and helped us to find our own way.

Personally, I was initially mainly involved in a sub-project on dynamic tomographic reconstruction of the human heart by means of Magnetic Resonance Imaging (MRI), in collaboration with Philips Medical Systems and the Department of Mathematics of the Free University Amsterdam. In addition, I became acquainted with mathematical morphology, which primarily focuses on the shape of image objects and works with non-linear image transformations within the mathematical framework of complete lattices. This is not the place to delve into the theory.

Mathematical morphology was Henk’s specialization. His book *Morphological Image Operators* from 1994 is still a standard work, as appears for example from last year’s reissue.¹

In 1998 we organized the biennial *International Symposium for Mathematical Morphology and Applications in Image and Signal Processing* at the Institute for the Tropics in Amsterdam. But now I am getting ahead of things. For at that time I had already taken the next step in my career: to the University of Groningen.

The next step: Groningen

After a brief intermezzo at the DLO-Institute for Soil Research in Haren, I was appointed as associate professor at the Department of Computer Science of the University of Groningen in 1992.

This was followed by an appointment as full professor and chair of Scientific Visualization and Computer Graphics in 2003. At the same time I had a second appointment at the Neuroimaging Center of the University Medical Center Groningen.

In education I taught courses in the bachelor and master programs of Computing Science. Regularly, these courses were attended by students from other programs, in particular Biomedical Engineering and Artificial Intelligence, but sometime also Astronomy, Physics, Chemistry or Biology.

Research in Groningen: a bird’s eye view

It is impossible in this short time frame to go into all the details of the research in which I have been involved since my appointment in Groningen. That is why I limit myself here to a general overview.

This research falls into two categories: on the one hand, projects where the development of new methods is central, and on the other hand applied projects in collaboration with other scientific disciplines.

It is important to emphasize that my research on image processing and visualization falls primarily within the discipline of Computer Science. This is a technical discipline in which algorithm design and software development are central. Mathematics plays an important role in this.

On the other hand, we need to duly take into account what research on human perception and cognition teaches us. The interaction between humans and computers also plays an essential role. Therefore, the developed methods must be tested for their usability. This is often done through user studies, in which the method is tested in a realistic situation. Finally, it is important that we take into account the mutual interaction between several people.

This means that we also need knowledge about perception, psychology, and perhaps even sociology. Since we do not have all this knowledge in-house within Computer Science, much of this research is carried out in teams of researchers, who all make their own contribution. Working with researchers from so many different disciplines has been very enriching for me.

On the other hand, I have also always enjoyed research that I could do on my own. Mono- and multidisciplinary research: both are necessary and stimulating!
**Project gallery**

Figure 5 shows a collage of images from a selection of research projects I have been involved in. Many of them concern research by PhD students and postdocs. Some are about fundamental research, others concern applications in collaborative projects with medical science, molecular genetics, astronomy, and movement research.

\[
f(x, y, z) = \sum_{k, l, m} c_{j, k, l, m}^0 \phi_{j, k, l, m}(x, y, z) + \sum_{j=1 \text{ even}, k, l, m} \sum_{d_{j, k, l, m}} d_{j, k, l, m}^j \phi_{j, k, l, m}(x, y, z).
\]
Visual environments

Significant development has taken place in the field of visual environments. In addition to the flat screen, computerized virtual environments have emerged in which we can view a three-dimensional presentation.

![Visual environments](image)

The RUG has three such virtual environments, namely the cube (better known as Cave), a theater, and a Dome (the DOT Live Planetarium); see Figure 6. In a Cave, one is in a way completely surrounded by the visualized data (immersion), and can navigate through it. The theater is suitable for groups of up to 30 people, and can be used for education and demonstration purposes. The Dome is a large theater where the images are projected onto a spherical surface and can be viewed in three dimensions.

The disadvantage of these large environments is that people must physically travel there. By now, numerous mobile environments have been developed. Think of systems that one carries on the head. Some of these provide objects in the real world with perceptual information generated by computer (Augmented Reality).

But it is even easier to use a tablet or mobile phone. In many situations, collaboration between several people is more important than immersion. Many visualizations are
nowadays available in a standard Internet browser, which does not require any special software to be installed. An additional advantage is that these systems are much cheaper. This brings this visualization technology within reach of a much larger group of users. I was able to observe this in practice when I visited Uganda as part of an exchange project between the University of Groningen and two universities over there. Expensive equipment such as medical scanners is rare. However, internet is available everywhere, even in the most remote places of the country. Data can then be collected via mobile telephones, forwarded to a central computer, and finally one can view the visualizations that have been calculated by this computer and returned to the mobile phone.

**Visual Analytics**

The visualization of astronomical data has turned out to be a rich field for collaborative research. This concerns extremely large datasets, obtained by measurements through all kinds of telescope.

![Figure 7: Research on astronomical datasets via interactive touch displays.](image)

Automated computer tools have been developed for the analysis and visualization of structures, patterns, and outliers in galaxy datasets, with a large number of attributes for each object (the so-called high-dimensional parameter spaces). The goal is to scale up these methods to huge amounts of data (terabytes, petabytes). To this end, efficient computer algorithms are required. On the other hand, it must be possible for the researcher to be part of the analysis through interactive visualizations, using perceptual and analytical capabilities, and human creativity.

This combination of analytical reasoning with automated data analysis techniques, facilitated by visual interactive interfaces, has grown into a field of its own, called **Visual Analytics**. We also speak about the **human in the loop**.

Figure 7 shows an example of an application on a touch display, which was developed within a long-term cooperation with the Kapteyn Astronomical Institute in Groningen.
Visualization and responsible data science

One can consciously or unconsciously design visualizations that misrepresent reality. In the course *Big Data in a Digital Society* I have contributed a guest lecture on *Visualization and responsible data science* for a number of years. One can position this within the broader pursuit of *Responsible Artificial Intelligence/Computer Science* (Responsible AI/CS). The field of visualization can play an important role in raising awareness about misleading visualizations. In this it also has a social responsibility.

The visualization community has been paying close attention for many years to the occurrence of what is called visual misinformation (or simply ‘Visualization Lies – VisLies’).

**FIGURE 8:** Vislies ([https://www.vislies.org/2021](https://www.vislies.org/2021)).

The more common phenomenon is that conclusions are drawn too soon, more or less thoughtlessly. What we need in science is rather ‘slow’ thinking. The book *Thinking, Fast and Slow* by Daniel Kahneman from 2013 is highly recommended in this respect.

**A 3D visualization is not a photo**

An example of a misleading visualization can be seen in Figure 9. This image was posted by the photographer Anthony Hearsey on Facebook on January 5, 2020. It ‘went viral’ after it was shared on Twitter, suggesting that it was a photo by NASA taken from space.

In fact, it was a 3D visualization, where data collected by a NASA satellite during the period December 5, 2019 until January 5, 2020 were merged and projected on an elevation map of Australia, with the addition of a glow effect.

The impression the picture gives is that of a glowing piece of charcoal which is already charring in some places but under which the fire is still burning brightly.

The creator said the following about it: ‘The idea was to attempt to visualize data in a more interesting way’. Later he made an effort to correct the wrong impression.

This example shows that even with the best of intentions, people can introduce undesirable effects in a visualization that go unnoticed. Some mistakes are almost ineradicable.

See the annual ‘Vislies’ web pages ([https://www.vislies.org](https://www.vislies.org)).
Developments in teaching

I would like to briefly touch on the developments in education since my arrival in Groningen in 1992. This was before the introduction of the ‘Modernization of the University Administrative Organization Act’ (MUB) in 1997. I remember very low student numbers in Computer science in Groningen and very long meetings.

At the time, the Computer Science study lasted four years. That changed in 2002 into five years with the establishment of the bachelor-master structure. In 2003 the flexible bachelor was added (the major-minor structure), next from 2013 on the internationalization of the bachelor education, the international classroom, e-learning, learning communities and the language and culture policy. And recently the educational organization in the entire Faculty of Science and Engineering changed again.

You will understand that all these changes did not come naturally. I have been involved in many of them to a greater or lesser degree, for example via the curriculum committee Computer Science. Much has been accomplished. Still I often could not help feeling that the workplace had to deal with too many changes in a short period of time, where sufficient room for a proper evaluation was not always available. Incidentally, many of these changes came about under pressure from government policies.
**Developments in research organization**

Much has happened in the field of research since I was appointed at the University of Groningen in 1992 and started working in a department where Mathematics and Computer Science formed two sections with a daily board each. People were mostly busy with internal affairs and the word ‘competition’ was hardly mentioned.

That changed in 1998 with the establishment of the (Research) Institute for Mathematics and Computer Science (IWI), after a critical external research evaluation in 1996. In the document entitled *Esprit de Corps* recommendations were made for improvements, such as attention to a good balance between common and own interests, and more openness, both internally and towards the scientific outside world. In 2010 the institute’s name changed to *Johann Bernoulli Institute of Mathematics and Computer Science* (JBI).

We have seen the rise of *Big Data* and the scientific answer to it, *Data Science*. The Faculty of Science and Engineering participates fully in this through the Center for Data Science and Systems Complexity established in 2015 (DSSC).

At the beginning of 2018, the Center for Cognitive Systems and Materials Groningen (CogniGron) was established, which focuses on the development of materials and systems that can ‘learn’, with a much lower energy consumption than that of today’s computers, inspired by knowledge about how the human brain works.

The disciplines Mathematics, Computer Science, and Artificial Intelligence play an important role in the centers DSSC and CogniGron.

Since June 1, 2018, the Johann Bernoulli Institute of Mathematics and Computer Science and the ALICE institute for Artificial Intelligence and Cognitive Engineering are a joint institute, the *Bernoulli Institute*. The institute has strongly grown recently, in the first place through investments by the faculty and the university in DSSC and CogniGron, and secondly through additional stimulus funds from the national government, the ‘sector plans’. The combination of Mathematics, Computer Science, and Artificial Intelligence in a single institute is (as far as I know) unique in the Netherlands and offers many opportunities.

I have been involved in these developments on the management level since 2009, first as chairman of the board of the Johann Bernoulli Institute, then as director of this institute, and finally as director of the new Bernoulli Institute (until mid 2020).

Of course, not everything went smoothly during this long period. I have regularly been asked whether all this administrative work is actually ‘nice’. That never seemed the right word to me. Good governance within the university is a necessity, which I also have regarded as my own responsibility.
Wrapping up

Dear attendees, I have tried today to sketch a picture of my adventures in the science of image processing and visualization. Of course I could not give much detail on the methods from Mathematics and Computer Science that play a role in this. But on a day like this a bird’s eye view is the most appropriate.

Looking back it is my strong conviction that the interplay of humans and computers is the way forward to discover in a responsible way new insights from the tremendous amounts of data that reach us, often in teams of researchers who all make their specific contribution. I consider myself lucky to have met so much fascinating science and, just as important, so many engaged scientists.

Words of thanks

Finally, I would like to say a few words of thanks. I mention in particular:

- my promotor, the late Nico van Kampen, professor of Physics in Utrecht, whom I remember for his acumen and passion for precise formulations. This greatly helped me to develop my own critical sense.
- all PhD students and postdocs, for their essential contribution to the scientific research. It was (and is) a great privilege to have worked (work) with all of you.
- the students who attended my lectures or did their master’s project with me, for asking difficult questions and for their contribution to the research.
- the staff members of my research group, for their great efforts in research and teaching, and in translating the results of our scientific work to society. Initially, these were Gert Vegter and Henk Bekker, later followed by Alex Telea and Tobias Isenberg, then by Jiri Kosinka, and finally Renata Raidou and Steffen Frey. Some have since retired or moved elsewhere, but their contribution to the group’s development was essential.
- the colleagues of IWI/JBI/BI with whom I spent a large part of my working life. We shared in successes and disappointments, happy occasions and sad events, times at which the survival of the institute was at stake and times at which we got over it. We saw a continuous stream of changes on all levels: research, teaching, and organization. I am grateful to all those involved for their (critical) contribution to the creation of the Bernoulli Institute. A special word of thanks to all members of the secretariat; without your support the institute could not function.
- colleagues from a large number of joint projects and initiatives, within the institute, the Faculty of Science and Engineering, the Center for Information Technol-
ogy, the University Medical Center Groningen, the Centre for Mathematics and Computer Science in Amsterdam, and (inter)nationally. Time does not permit to mention everyone by name. Therefore, thanks to all of you!

- colleagues from the Dutch image processing and visualization community, for the many contacts and advice.

- everyone with whom I have collaborated at the management level, within the institute, the faculty, the university, or on the (inter)national level.

- the colleagues from the Netherlands Organisation for Scientific Research (NWO), for their dedicated and constructive contribution to the many committees I have been part of.

- Alex Telea, Alle Meije Wink, and Jack van Wijk, for their contribution to the workshop of today; and Ineke Schelhaas, Jan van Hoogen and Jiri Kosinka, for organizing this farewell event.

- Finally, I thank my wife Hedwig. I would not be standing here today if it wasn’t for you.

Dixi.