From the electric pulse to image quality

the analysis chain of an imaging detector

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Section 1

Imaging detectors

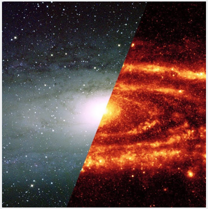
Incoming radiation $\longrightarrow$ electric pulse

Imaging detector: any instrument that converts incoming radiation into an image.

Radiation type	Radio	Microwave	Infrared	Visible	Ultraviolet	X-ray	Gamma ray
Wavelenght (m)	10^{3}	10^{-2}	10^{-5}	0.5×10^{-6}	10^{-8}	10^{-10}	10^{-12}

Why are they so important? They extend the capabilities of our eyes!

Who doesn't want to be Superman?

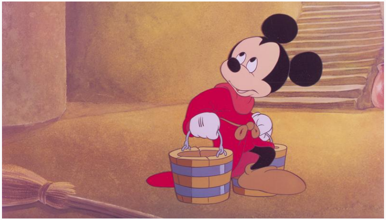


Imaging detector: any instrument that converts incoming radiation into an image.

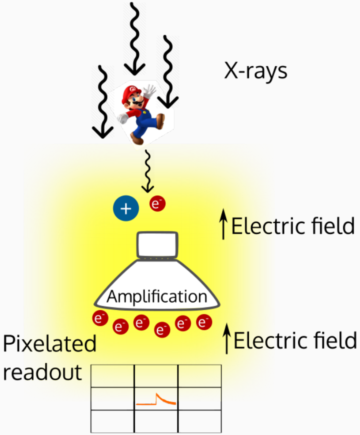
How?

Magic?

Physics and hard work



Let's take the example of **X-ray gaseous imaging detectors**.

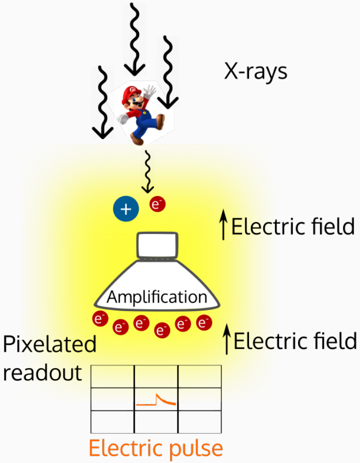


Working principle

1. X-rays are attenuated by the object we want to image;
2. The (noble) gas converts the photons into electrons and ions;
3. We apply an electric field that guides the electrons to an amplification stage;
4. Another electric field guides the final electrons to a pixelated readout.
5. Each electron that arrives generates an electronic pulse.

The number of pulses in each pixel is what codifies the final image.

But physics doesn't work without the engineers.



So many variables to optimize:

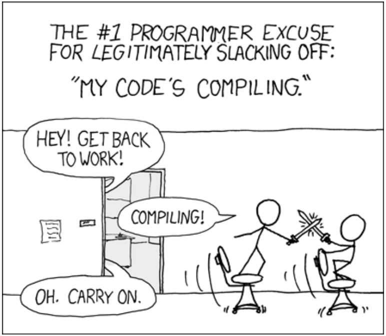
- How strong are the electric fields?
- Which gas to use?
- What are the distances between the detector regions?
- Which amplification mechanism to use?

The ultimate goals:

- Maximum charge gain.
- Minimum noise.
- Uniform response.
- The sharpest image.

Images get better with longer exposure times.

5 min. 10 min 30 min. 1 hour



- **Imaging detectors** convert incoming radiation into an image;
- There are **many types** of imaging detectors, with **different working principles**;
- **X-ray imaging gaseous detectors** convert X-rays into a flow of electrons that produces an electric pulse. **The object is codified by the number of electric pulses produced in each readout pixel**.
- Any imaging detector has **many variables** that we can optimize to get **the best performance possible**.

Section 2

The electronic chain

Electric pulse $\longrightarrow$ data file

This is what happens in each readout pixel.

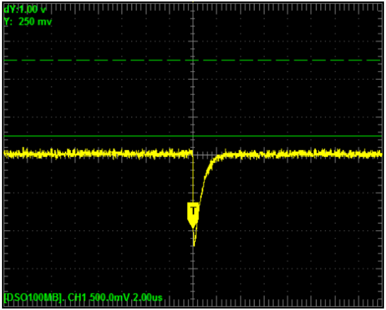


Figure: Detector pulse measured with an oscilloscope.

What can we know from the pulse?

- **Time:** the pulse begins when a cloud of electrons arrives;
- **Radiation energy:** proportional to the area of the pulse.
- **Position:** the pixel of the readout that was triggered.

Engineering challenges

The electronics should determine the time and the radiation energy from this profile as accurately as possible.

The electronic chain: the preamplifier

The preamplifier shapes the detector pulse into a **step function voltage pulse**.
It also **amplifies the signal** to decrease the noise effects.

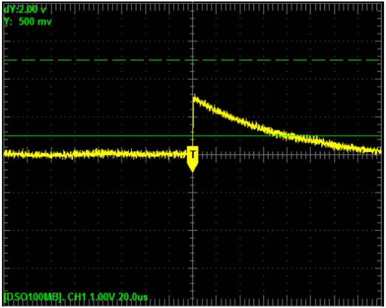


Figure: Preamplifier pulse measured with an oscilloscope.

The perfect preamplifier pulse

- Short rise time;
- Long decay time, but not too long.

Why? Pile-up

Measurement:

- **Time:** start of pulse.
- **Radiation energy:** proportional to the amplitude of the pulse.

It's easier to calculate the amplitude of the pulse,
but it's still not an accurate and reproducible measure.
The pulse needs a better shape.

The shaping amplifier shapes the detector pulse into a **quasi-Gaussian**.
It also **amplifies** and **filters high and low frequency noise**.

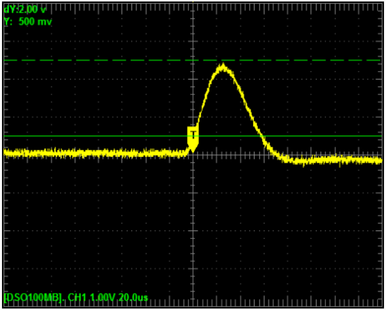


Figure: Shaping amplifier pulse measured with an oscilloscope.

How can we quantify the pulse?

The electronics can evaluate the Gaussian profile and get:

- **Time:** prior threshold definition;
- **Radiation energy:** from the amplitude (proportional to energy).
- **Position:** the pixel of the readout that was triggered.

Now we have accurate values of **time** and **energy**.
These values are digitized (**ADC**) and saved into a file.

The electronic chain: the computer file

Each channel creates a **different file** in the computer with information on the **energy** and **time** of each event.

Each electronic channel corresponds to a detector pixel.

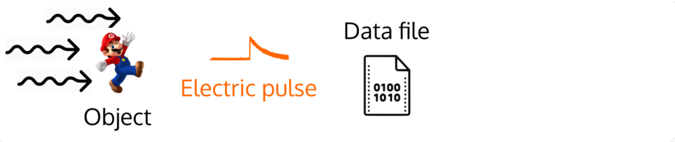
Channel 0	Channel 1	...	Channel n
(Energy, Time)	(Energy, Time)		(Energy, Time)

We need to conjugate all the information in a single file, with **energy** values for each **x**, **y** position.

x	*y*	Energy	(Time)
23245	27044	4622	0000
42360	27505	3511	0010
25944	41019	5242	0013
36118	32834	4325	0018
...	...	...	...

The electronic chain: key messages

- The output of the detector is an electric pulse with its **area proportional to the radiation energy**;
- A **preamplifier** converts the output pulse into a **step function voltage pulse**, with **amplitude proportional to the radiation energy**;
- The **shaping amplifier** converts the preamplifier pulse into a **quasi-Gaussian**, allowing a reproducible measurement of energy and time;
- For each pixel, the time and energy values of the pulses are **digitized and saved into a file**;
- Every step of the electronic chain introduces an **amplification** and **filters the electronic noise**.

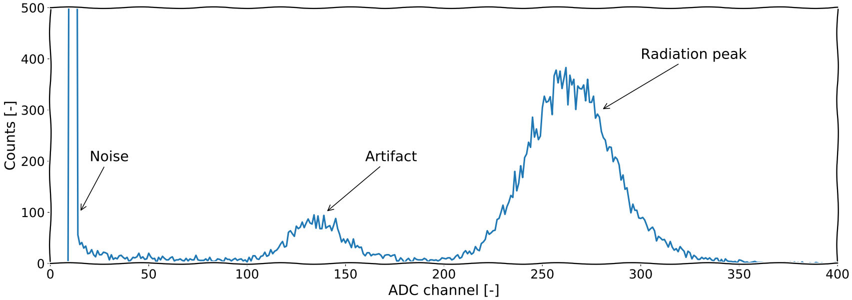


Let's take a break: detectors without position discrimination

What distinguishes non-imaging detectors? There is only one channel!

What information can we get from a single channel?

What is the response of a single pixel in an imaging detector?



The ADC channel of the radiation peak is proportional to the **radiation energy** and the **charge gain**. We can also calculate the **energy resolution** of the detector.

Section 3

Event selection and image reconstruction

Data file $\longrightarrow$ image

Are all the events recorded in the files valid?

Sometimes we have surprising information that give unexpected errors.

Empty rows

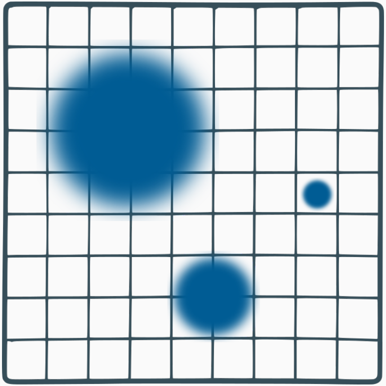
Energy	Time
23245	4622
42360	
NaN	41019
...	...

Out-of-range data

Energy	Time
23245	27044
42360	-3511
0	41012
...	...

Some of these problems can be solved easily.

Sometimes, only one readout channel (pixel) is triggered, which does not make much (physical) sense.



- **Electron clouds are spread** over a certain area;
- This **triggers neighbor cells** simultaneously.
- In a certain time interval, we look for **clusters of triggered cells**.
- Individual triggered cells are probably **noise** or other **electronic artifacts**.

Normally, we **discard** signals that are only recorded in a **single channel**.

The data file looks like this:

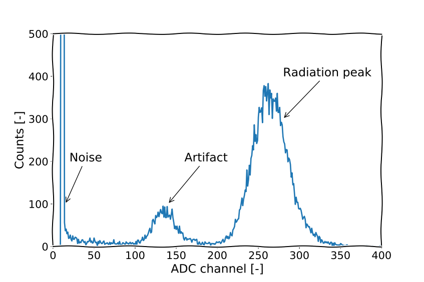
x	y	Energy
23245	27044	4622
42360	27505	3511
25944	41019	5242
36118	32834	4325

Can you guess the units?

cm? mm? µm?
J? keV?

We only know that these values are proportional to their real measurement.

The solution: **Calibrate!**



Physics tells us that:

- A ^{55}Fe source has 5.89 keV;
- This artifact has 2.93 keV.

With **extrapolation**:
Energy [ADC unit] $\longrightarrow$ Energy [Physical unit].

The reconstructed image is simply a **2D histogram** of the data points.

But what should be the weights?

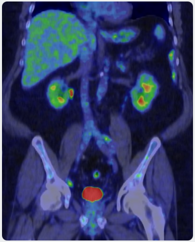
Count wise

All events contribute the same, regardless of their energy value.

Good for object recognition.

Energy wise

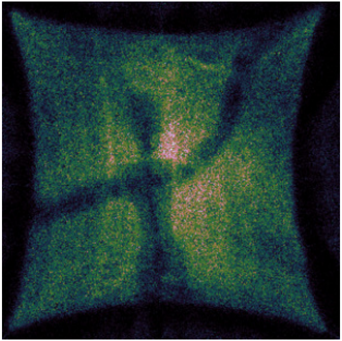
More energetic events are favored in the final image.



Good to find radioactive materials.

The choice varies from application to application.

In real life detector response is not uniform — it varies with position.



Some examples are:

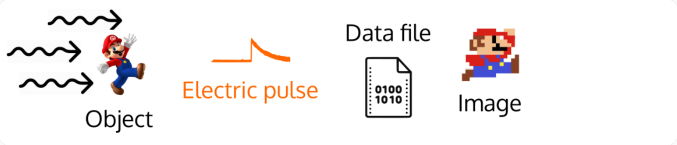
- Charge gain
- Energy resolution
- Background
- Distortion

Why?

- Detector geometry
- Electronics

We need to **map the response** of these parameters along the detector's area and then correct every acquired image with a **correction matrix**.

- **Not all information in the data files are real events**: we have to filter them;
- We usually analyze **triggered neighbor cells** to evaluate a true event;
- Quantities in the data file have to be **calibrated** to have physical meaning;
- The reconstructed image is a **2D histogram** of the true events and can be weighted by **energy** value or by **counts**, depending on the final application.
- After reconstruction, the necessary **correction matrices** should be applied.



Section 4

Image quality assessment

Image $\longrightarrow$ quality parameters

How can we measure image quality?

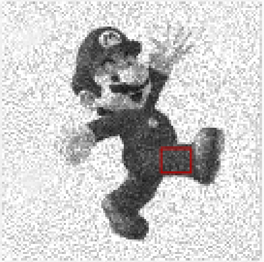
How much noise?

How many details?

Image quality assessment: Signal-to-noise ratio (SNR)

Noise is a consequence of:

- Statistical fluctuations
- Electronic fluctuations



Measuring SNR

1. Select a **uniform region** of the image.
2. Determine:
   - μ: average pixel value;
   - σ: standard deviation.
3. Calculate

$$SNR = 20 \times \log_{10}\left(\frac{\mu}{\sigma}\right) \quad [\text{dB}]$$

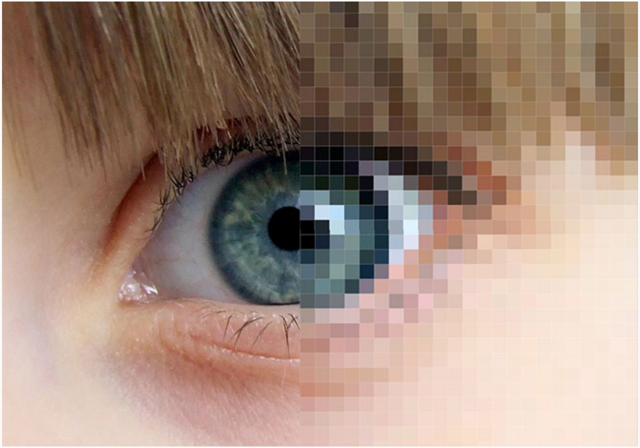
Evaluating SNR

The Rose Criterion:

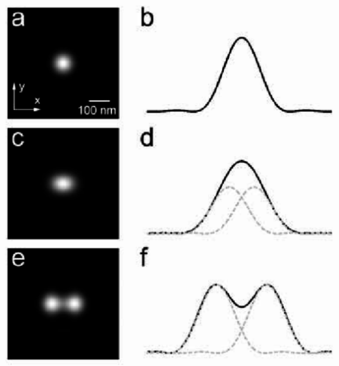
The amount of noise in an image is appropriate if $SNR \geq 13.98$ dB

What is the most important thing for an imaging detector to do?

High level of position discrimination — **Resolution!**



Position resolution: the minimum required distance between two objects for them to be distinguished by the imaging system.



Is limited by

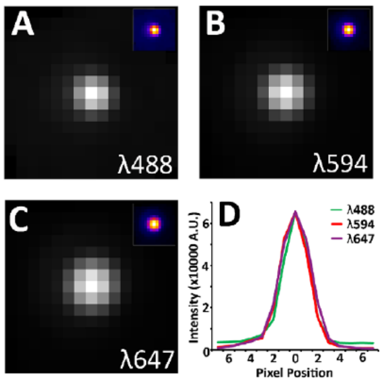
Readout pixelization;

Physical processes:

- Type of gas;
- Radiation energy;
- Amplification process:
- ...

A bunch of well-defined points becomes a well-known picture.

Point-spread function (PSF): is the response of the imaging system to an input point source.



Measurement

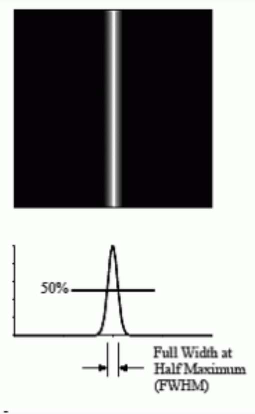
Usually the PSF can be modeled as a **2D Gaussian function**. The position resolution is equal to the **Full-Width at Half Maximum** in each direction.

$$FWHM = 2\sqrt{2\ln 2}\sigma$$

Problem

Point-sources are not experimentally feasible.

Line-spread function (LSF): is the response of the imaging system to a line stimuli.



Measurement

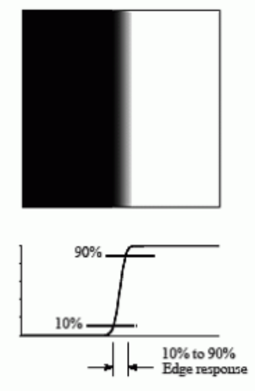
The LSF can be modeled as a **1D Gaussian** function. Again, the position resolution is equal to the FWHM.

$$\mathrm{LSF}(x) = \int_{-\infty}^{+\infty} \mathrm{PSF}(x, y)\, dy$$

Problem

The line should have an infinitesimal width.

Edge-spread function (ESF): is the response of the imaging system to a sharp edge.



Measurement

The ESF can be modeled as a Gauss error function:

$$\mathrm{erf}(z) = \frac{2}{\sqrt{\pi}} \int_0^z e^{-t^2}\, dt$$

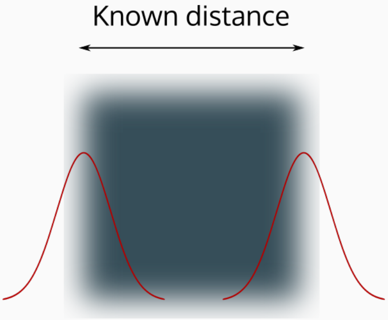
$$\mathrm{ESF}(x) = \int_{-\infty}^{x'} \mathrm{LSF}(x)\, dx$$

The algorithm — **Edge-gradient method**

1. Image a sharp edge;
2. Get the ESF
3. Derive to get the LSF and fit to a Gaussian function.

The *x* and *y* values of the image are still in pixels/ADC channels.

We need to translate them into physical units (cm, mm, ...) — **Position Calibration**.

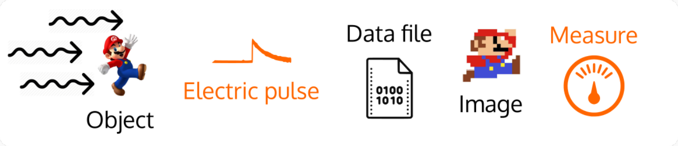


All we need is to image a known distance and get the distance between the two LSFs.

Pixels $\longrightarrow$ Physical units.

Image quality assessment: key messages

- To quantify the quality of an imaging detector, we have many parameters at hand, like **SNR** and **position resolution**.
- **SNR** is limited by **statistical** and **electronic** fluctuations in the system and should be above 13.98 dB.
- **Position resolution** is limited by **pixelization** and the **physical processes**. It is calculated by the **edge-gradient method**.
- **Position calibration** can be achieved by imaging a known distance.

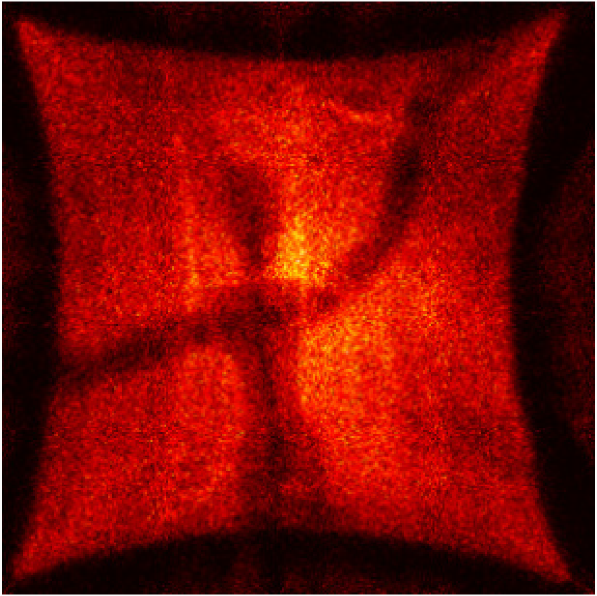


Section 5

Live Quiz

Go to **live.voxvote.com**
Enter the pin **64256**.

X-ray imaging Can you recognize these objects?



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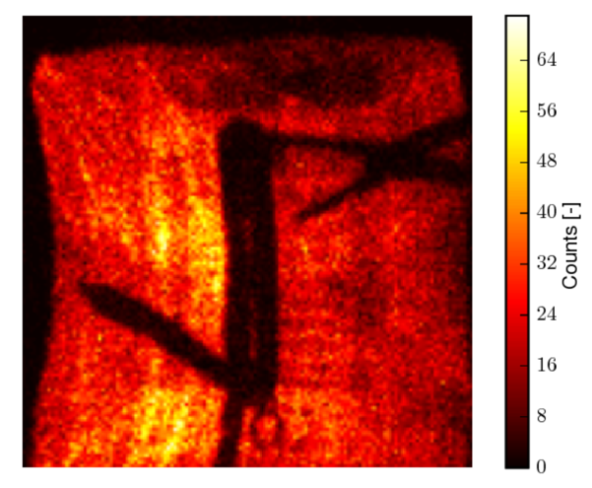

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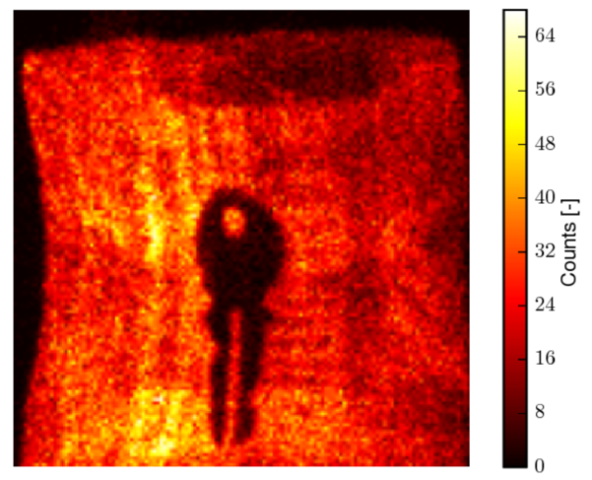

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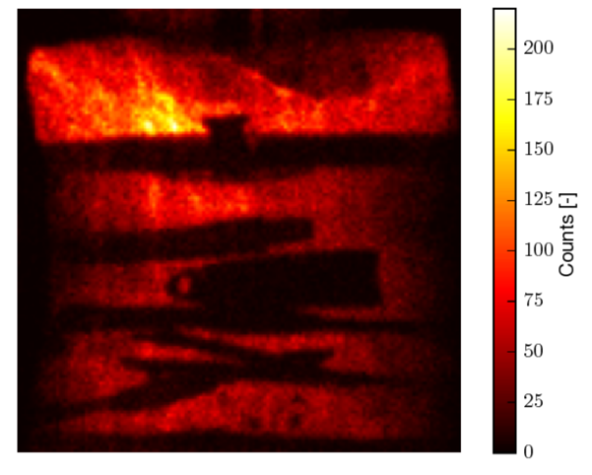

X-ray imaging Can you recognize these objects?