Process Analytical Technology in the food industry

Food drying as a case study

University of Teramo - 19 March 2024

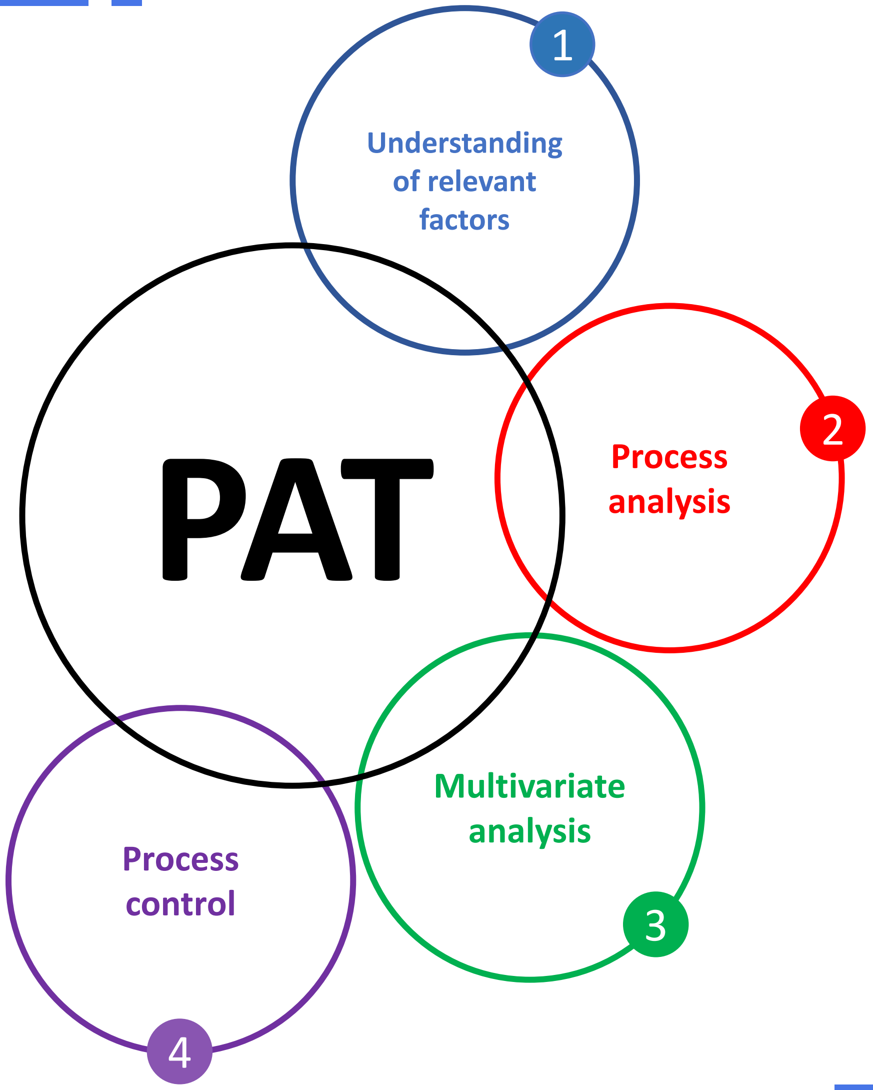
Prof. Roberto Moscetti

Department for Innovation in Biological, Agro-food and Forest systems (DIBAF)

University of Tuscia, Viterbo, Italy

rmoscetti@unitus.it

The Process Analytical Technologies (PATs)



U.S. FOOD & DRUG ADMINISTRATION

Introduced by FDA for pharmaceutical industry

PAT enhances understanding and control of the manufacturing process

Process Analytical Technology (PAT) in food industry

is 'a silent revolution in industrial quality control in food processing'

Source: Berg et al. 2013

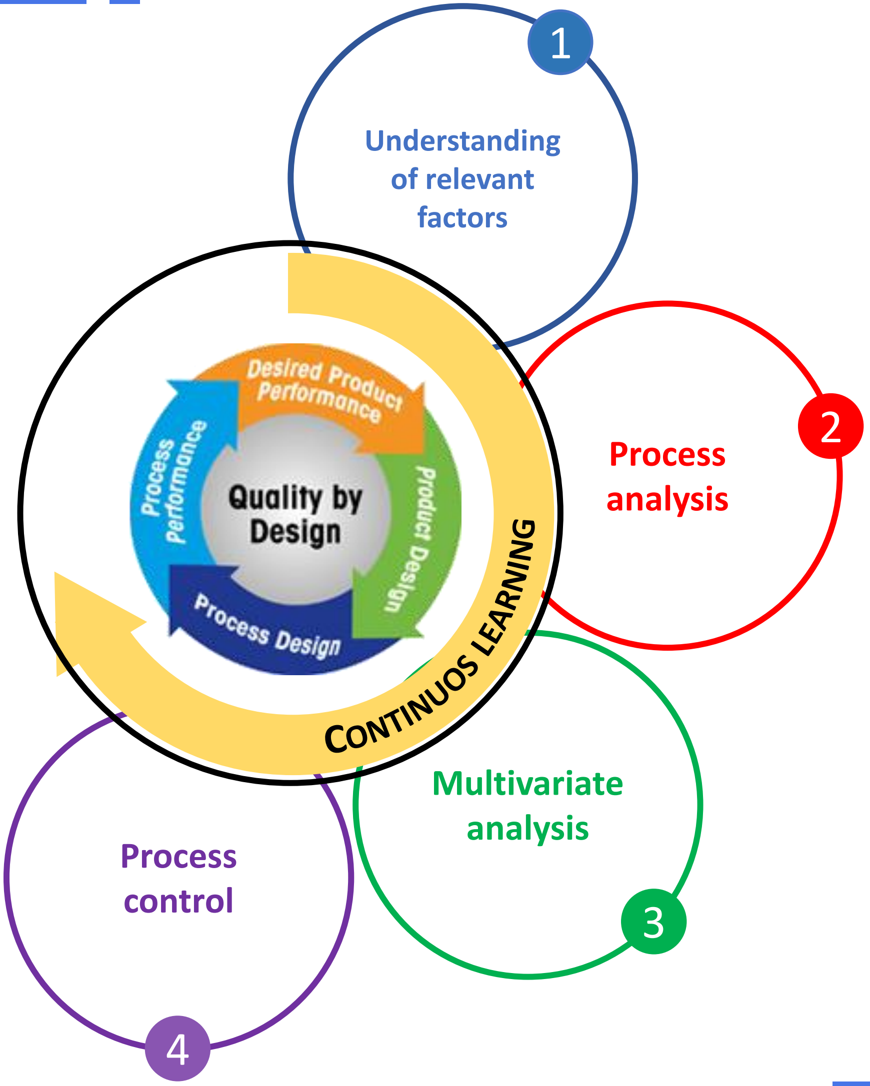
From a feedback approach to a model-predictive approach

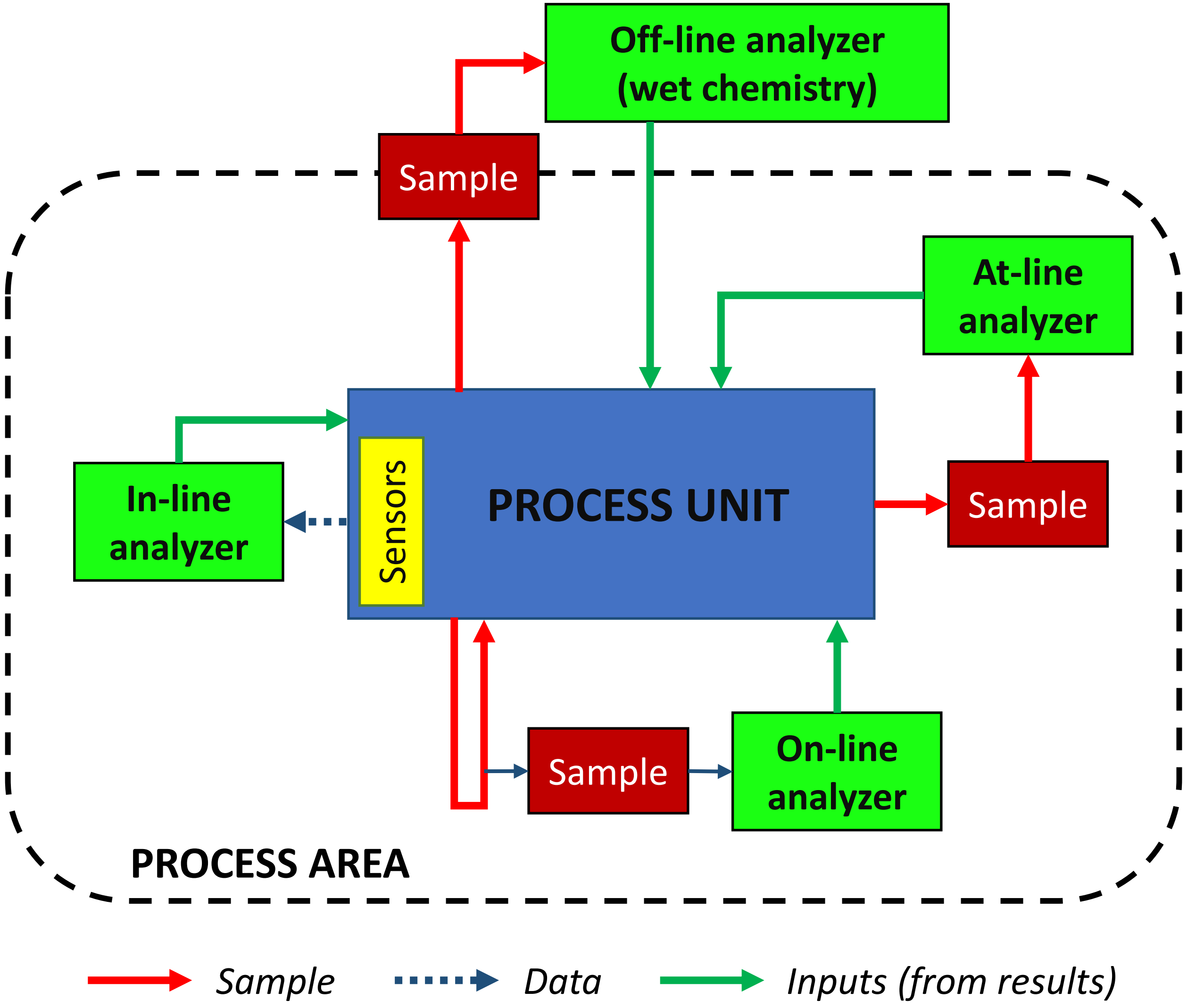
through timely measurements (i.e. during processing) of critical quality and performance attributes of raw and in-process materials and processes

The use of modeling and control strategies can help in ensuring

- *Food safety*
- *Food quality*
- *Authenticity*
- *Low production costs*
- *High energy efficiency*

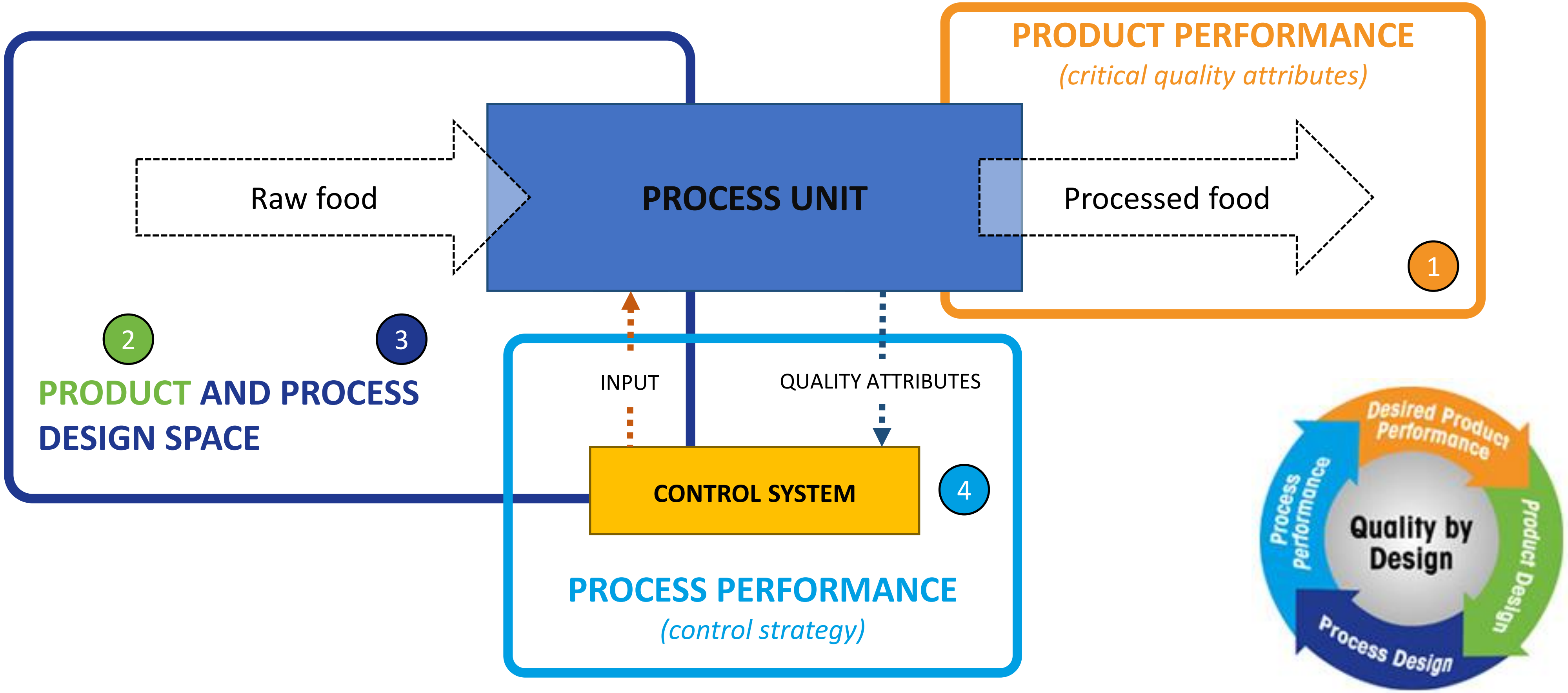
The Process Analytical Technologies (PATs)





The Quality-by-Design (QbD) approch

*PAT enables a deep understanding and a **continuous learning** about food materials and process dynamics, paving the way for innovations through a quality by design (QbD) approach*



Industry 4.0 and 5.0

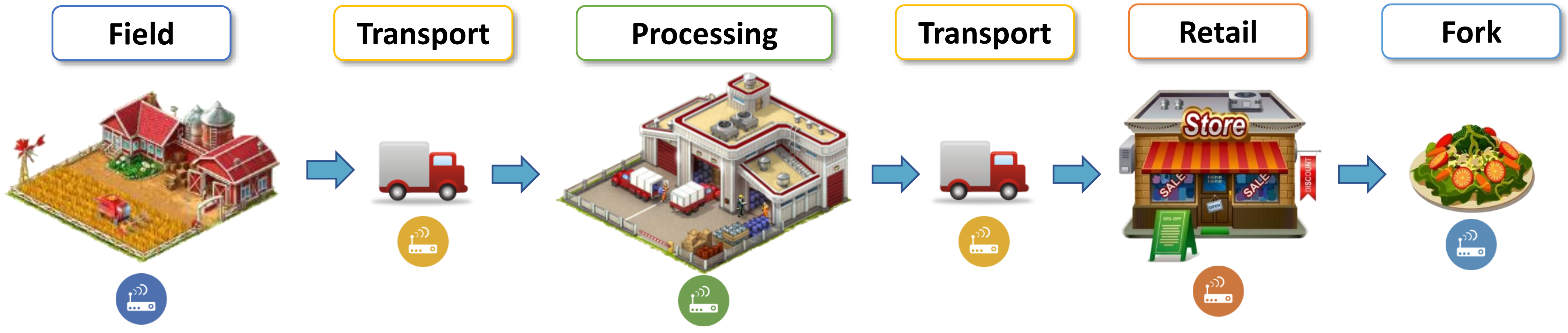
Internet of Things

'[…] describes the network of physical objects—a.k.a. "things"—that are embedded with sensors, software, and other technologies for the purpose of connecting and exchanging data with other devices and systems over the Internet.'

source: wikipedia.com

Classic	Social	Sematic
WEB 1.0	**WEB 2.0**	**WEB 3.0**
Reading	*Reading* *Writing*	*Reading* *Writing* *Comprension*

Industry 4.0 and 5.0



Food **Safety**

Prediction of **maintenance**

Use of **artificial intelligence**

Increasing **efficiency** and reducing **costs**

Collecting valuable **data** for future use

Remote management

Increasing **productivity**

Scalability of adopted solutions

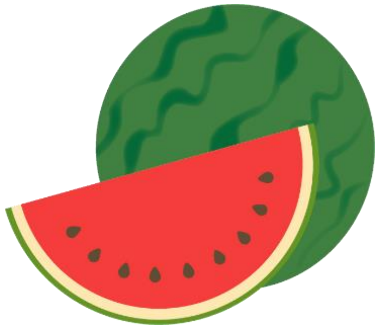
Increased **quality**

Food drying – a case study

Food drying is an industrial process to reduce the water content in fruits and vegetables, spices and herbs, meat, fish, liquid foods and cheese to 2-5% in order to significantly increase shelf life. Fruit and vegetables have a very high initial moisture content, between 85 and 95 %.

Dehydration methods

- Heat transfer techniques
- Smoking
- Freeze-drying
- Osmosis



Watermelon

93%

Water

Salad
Berries
Tomatoes

Ravanelli
Cauliflower
Zucchini

90%

Water

Pumpkin

85%

Water

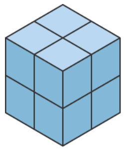
Food drying – the advantages

Reducing moisture content in food matrices decreases storage and transportation costs

FRESH PRODUCT

VS

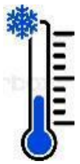
DRIED PRODUCT

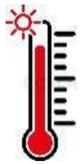
Large size/volume 

 Smaller size/volume

High weight 

 Less weight

Must be stored at low temperature 

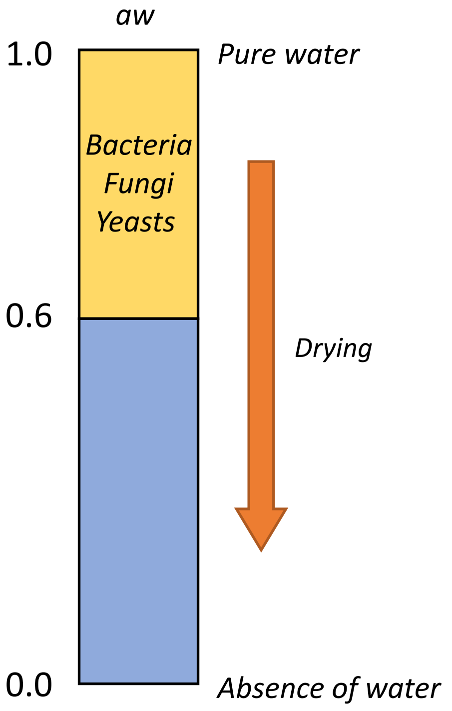
 Can be stored at room temperature

Food drying – the advantages

In addition, dehydration is used to reduce the water activity (a_w) of a food in order to:

(1) ensure product safety during storage and transport

(2) prevent loss of quality in the product itself



Prof. Roberto Moscetti, PhD
Lecture: University of Teramo 19-03-24

The three main steps of drying

PRE-TREATMENT | DRYING | POST-DRYING

Prof. Roberto Moscetti, PhD
Lecture: University of Teramo 19-03-24

Food drying – phase 1

1

The type pre-treatment depends on:

- *The drying technology and the kinetics of process*
- *The physical structure of the raw product*
- *The quality of the final product*

SOLID

ANTIOXIDANT
PRE-DRYING
BLANCHING
FREEZING
…

LIQUID

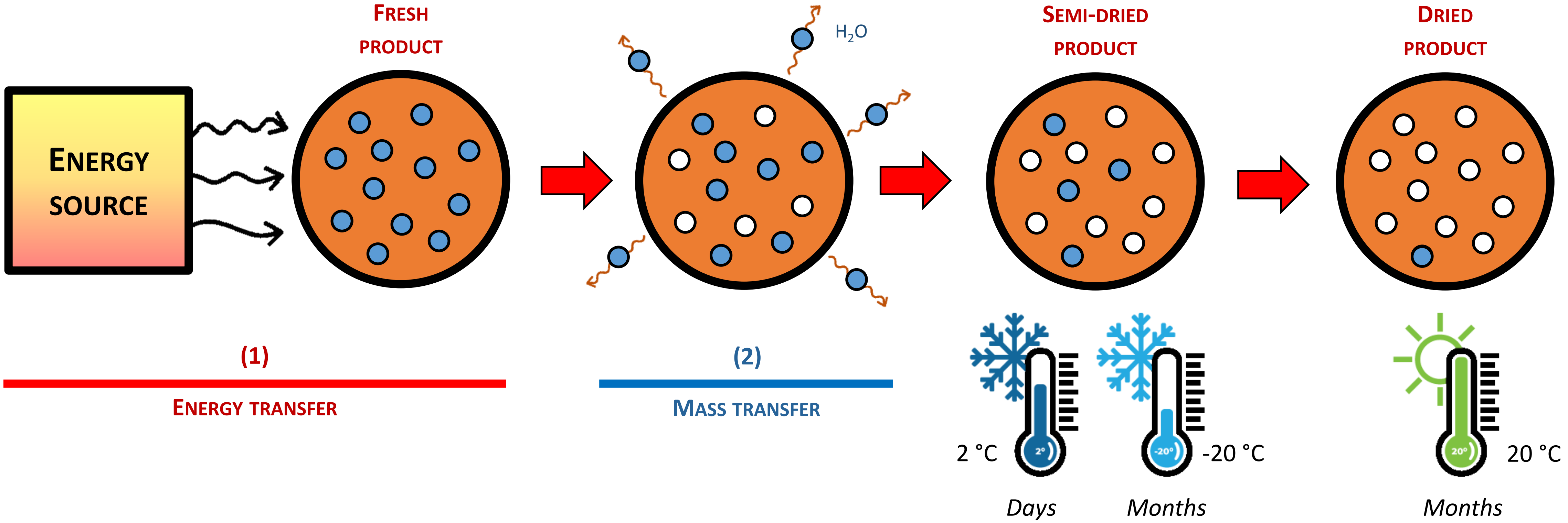
CONCENTRATION
VACUUM
ENZYMATIC TREATMENT
FOAMING
…

Food drying – phase 2

Drying is characterized by two processes occurring simultaneously:

(1) *Heat transfer from energy source to product*

(2) *Mass transfer in the form of water vapor*



Food drying – phase 3

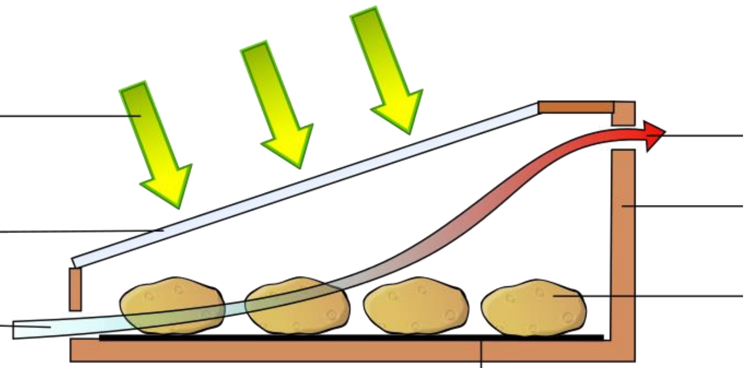
3

THE DRIED PRODUCT IS NOT THERMODYNAMICALLY STABLE

- Both pre-treatment and drying process affect the shelf-life of dried product
- The post-drying practices should minimise undesirable changes in the dried product
- The product is more stable when in a glassy state
- Contact with oxygen should be avoided or minimised
- The post-drying phase is also intended to increase the final value of the dried product

Food drying – most common drying technologies

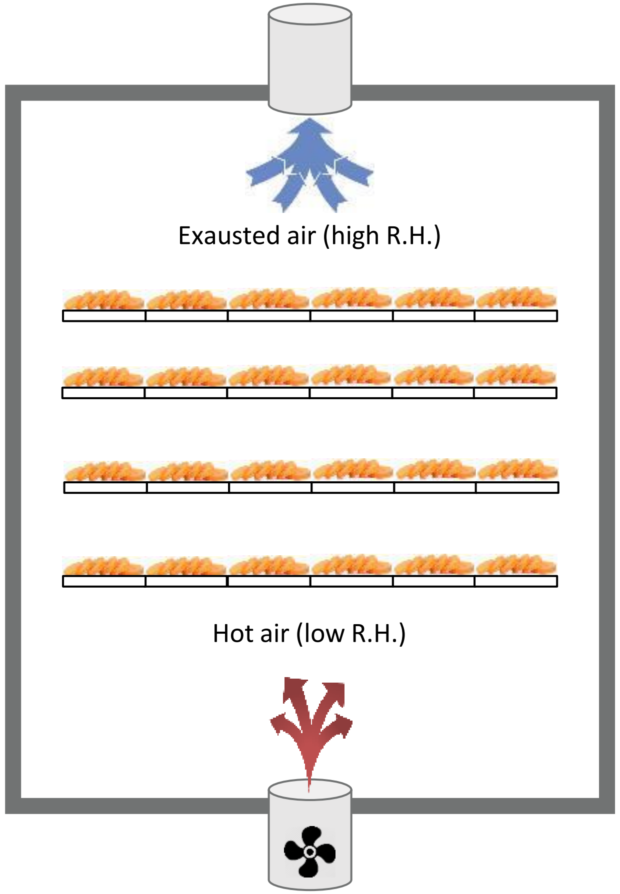
The oldest drying thecnology is solar drying.



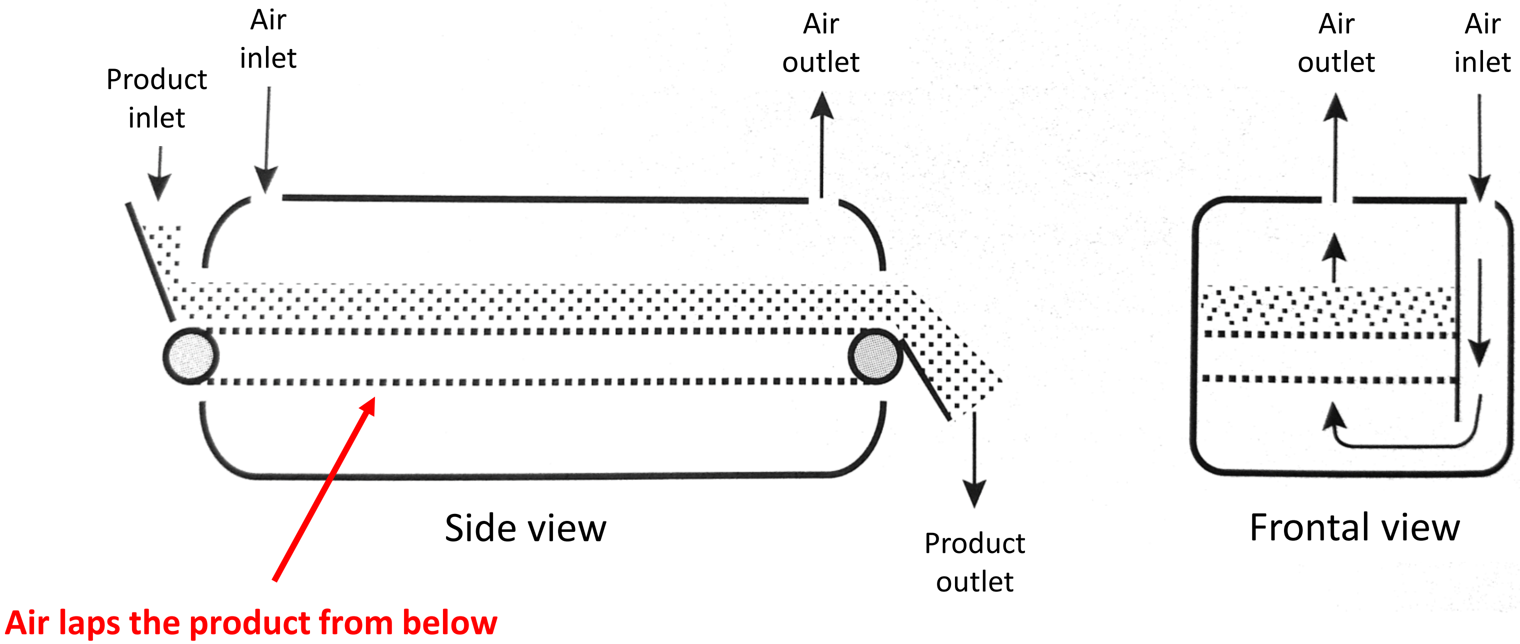
Example of sun-drying of tomato

Food drying – most common drying technologies

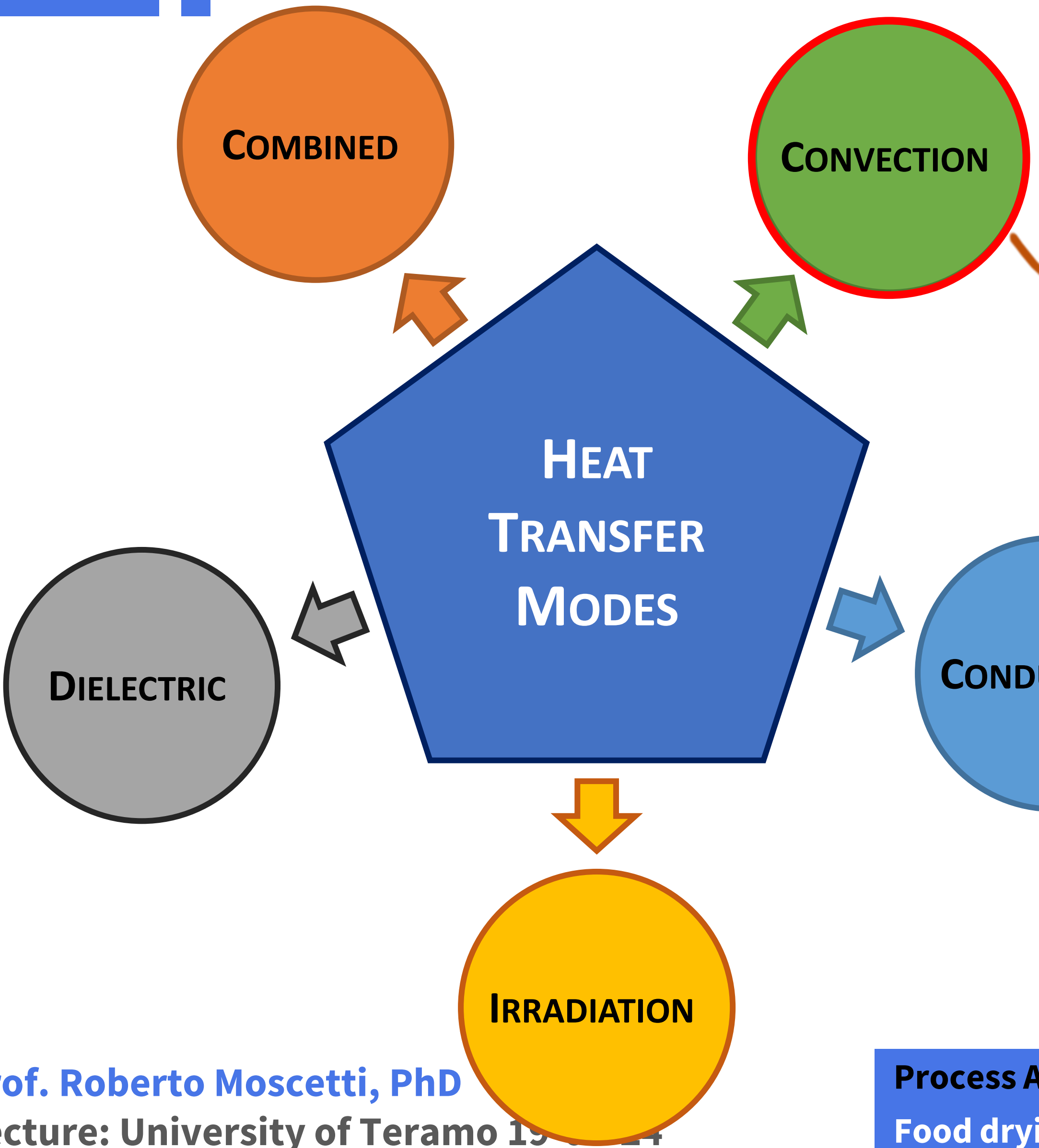
The hot-air drying is very popular for dehydrating fruit and vegetables. It is very versatile and lends itself to other uses. They can operate discontinuously (labour-intensive) or continuously.



Simplified structure of a drying chamber



Food drying



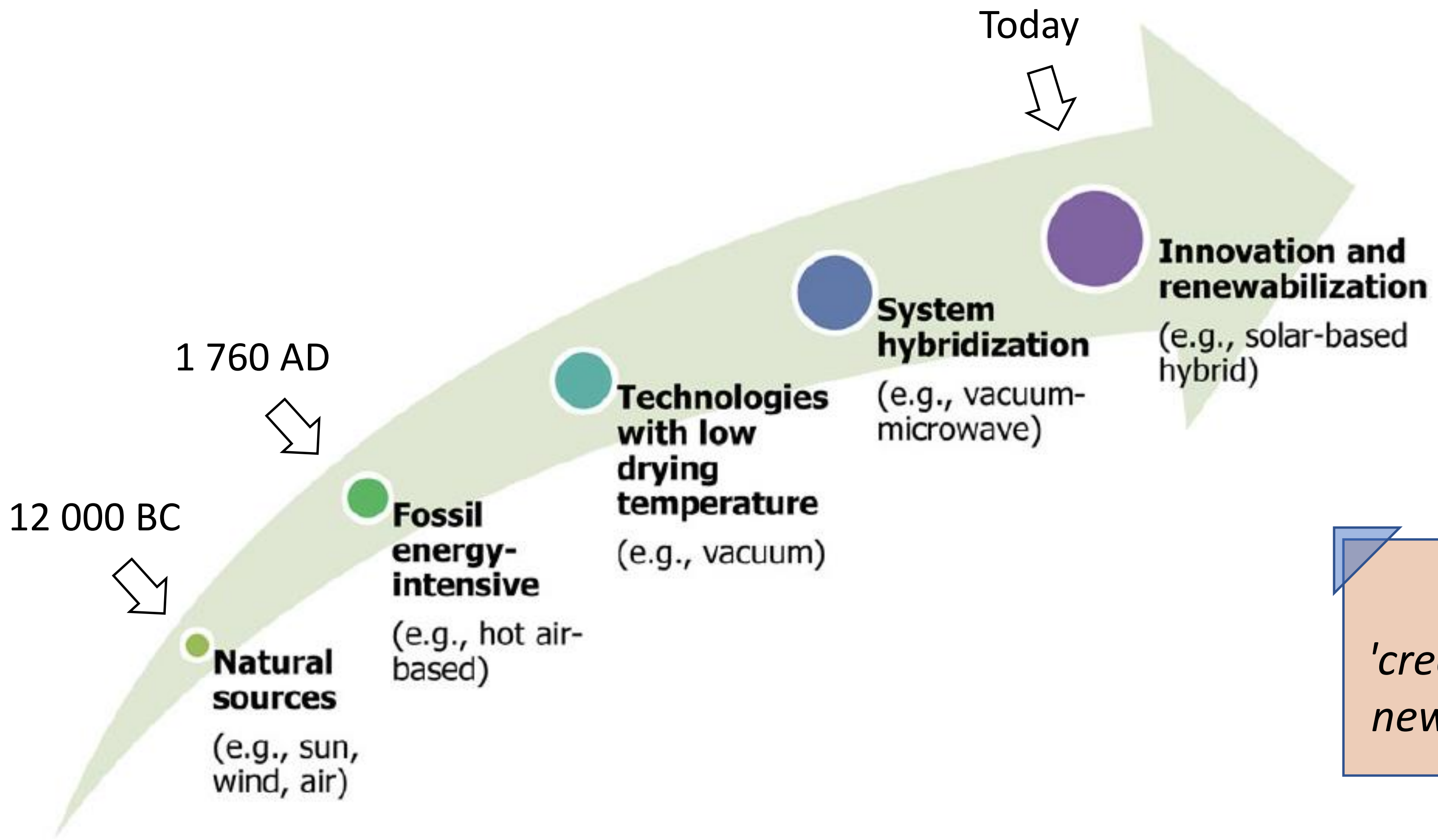
TYPES OF ENERGY SOURCES

FOSSIL | NUCLEAR | BIOMASS | RECOVERED | RENEWABLE

» *To date, more than 85 % of driers are conventional and use hot air as a medium for moisture removal*

» *Responsible for up to 20 % of the process energy consumption*
» *They have an energy efficiency of about 30 %*
» *Account for 90 % of production costs*
» *Up to 45 % of the energy input is lost as heat output, resulting in low efficiency, high greenhouse gas emissions and high operating costs*

Food drying – the evolution of



R&I

Research & Innovation

- INNOVATE MEANS -

'create value from the application of new solutions to concrete problems'

Figure - source: Acar et al. 2020, Drying Technology

Food drying – sustainability of Organic product

Improving the sustainability of a drying process

- **Better efficiency**, *get the same output with less power consumption*
- **Better use of resources**, *use of renewable energy sources and reduced environmental impact*
- **Better cost-effectiveness**, *reduce investment costs and operating costs*
- **Better respect for the environment**, *reduce the emission of greenhouse gases and environmental pollutants in general*
- **Improved energy security**, *employing reliable, affordable, renewable, and secure energy sources*
- **Better management**, *reduce temperature and dehydration time to obtain a high quality product with the lowest possible energy consumption*

Source: Acar et al. 2020, Drying Technology

Improving the sustainability of a drying process

1) There is a need to develop smart or intelligent dryers for the next two decades

2) It is necessary to make drying a sustainable process implementing the latest advances in allied technologies and scientific sectors, such as:
   - *computer technology*
   - *microcontroller and sensor technology*
   - *on-line, in-line, at-line detection technology*
   - *mathematical modeling of dryers*
   - *machine learning (e.g., deep learning)*
   - *low power wide area network*
   - *big data management and cloud computing*

3) Researchers are turning to the application of smart technology from the laboratory-scale research to the industrial production

4) Industry has become more quality conscious and thus is prone to invest on quality control in drying technology

Improving the sustainability of a drying process

1) Control systems for drying environment
   - *pressure*
   - *temperature*
   - *air velocity*
   - *humidity*

2) Biomimetic systems
   - *odor-sensing system (electronic nose)*
   - *taste-sensing system (electronic tongue)*

3) Computer vision technology

4) Microwave/dielectric spectroscopy

5) Visible and/or Near Infrared spectroscopy
   - *single point*
   - *multi/hyperspectral imaging*

6) Magnetic resonance imaging

7) Ultrasound techniques

- Influence on the quality of the product
- Information about the progress of drying

- Smell and taste
- Size, shape and colour
- Chemical, physical and physicochemical characteristics
- Information about the progress of drying

Prof. Roberto Moscetti, PhD

A SMART dryer prototype

CMOS camera

- » 2/3 inch Sony CMOS Pregius sensor
- » 2448×2048 (5 MP), fino a 38 fps
- » Global shutter
- » Trigger e I/O inputs

Load cell

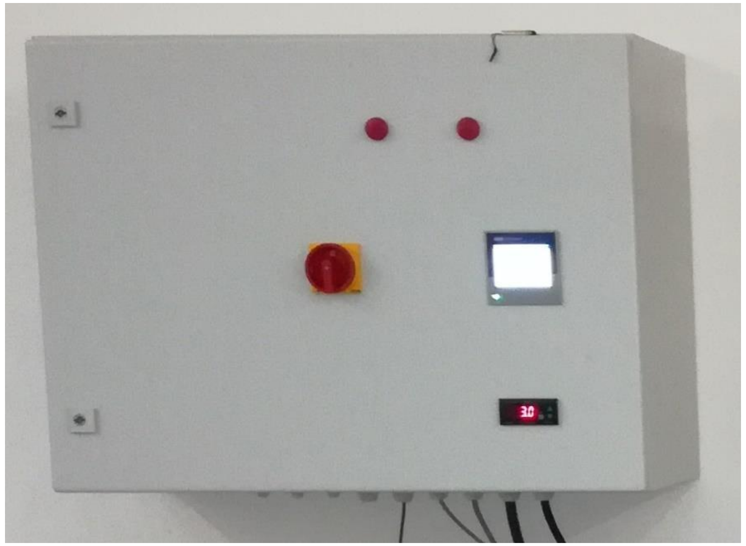
- » Max weight 5 kg
- » Precision 0.01 g
- » Max T 70 °C

Lights

Glass

Shelf

JUMO Dicon touch - controller

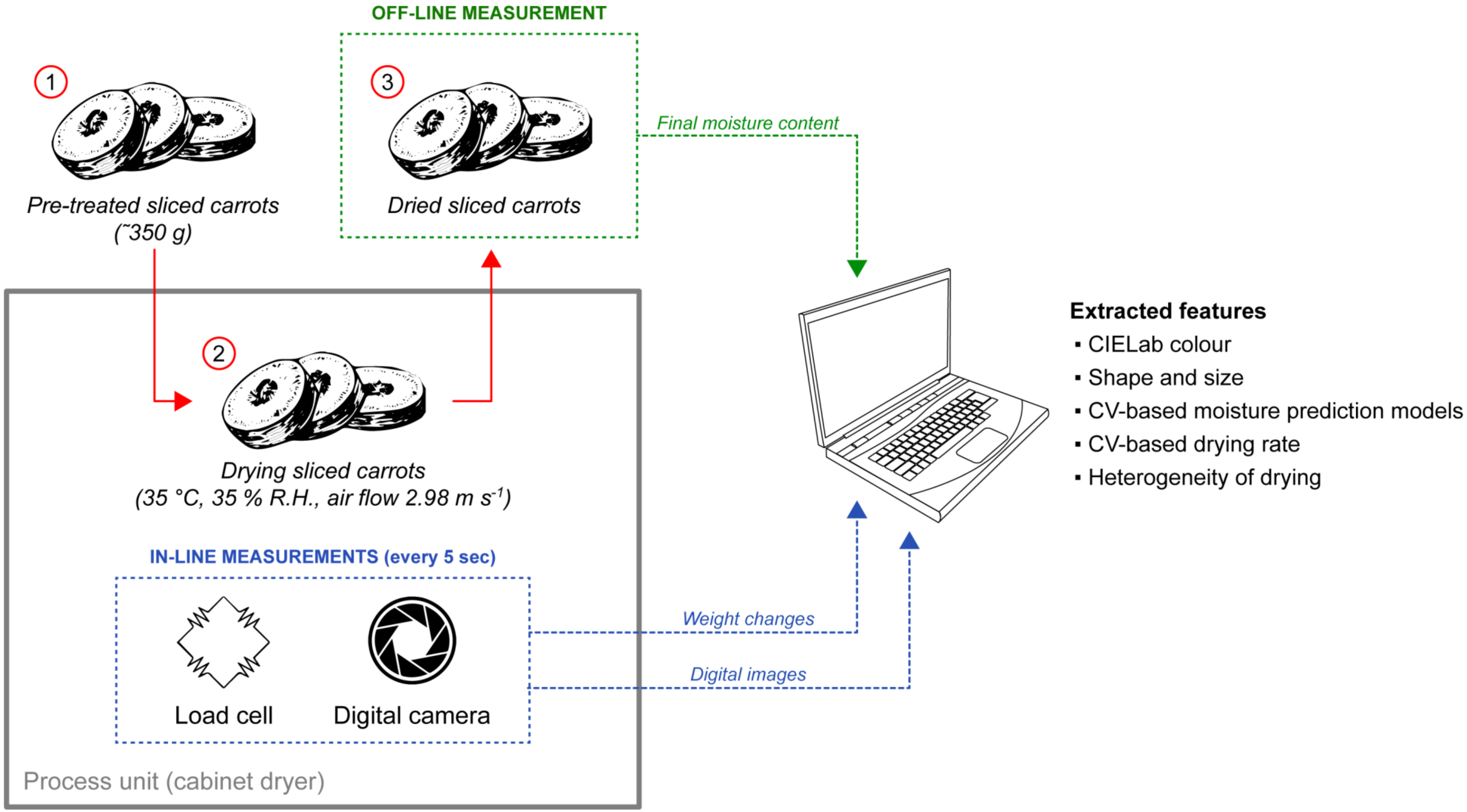


Drying parameters:

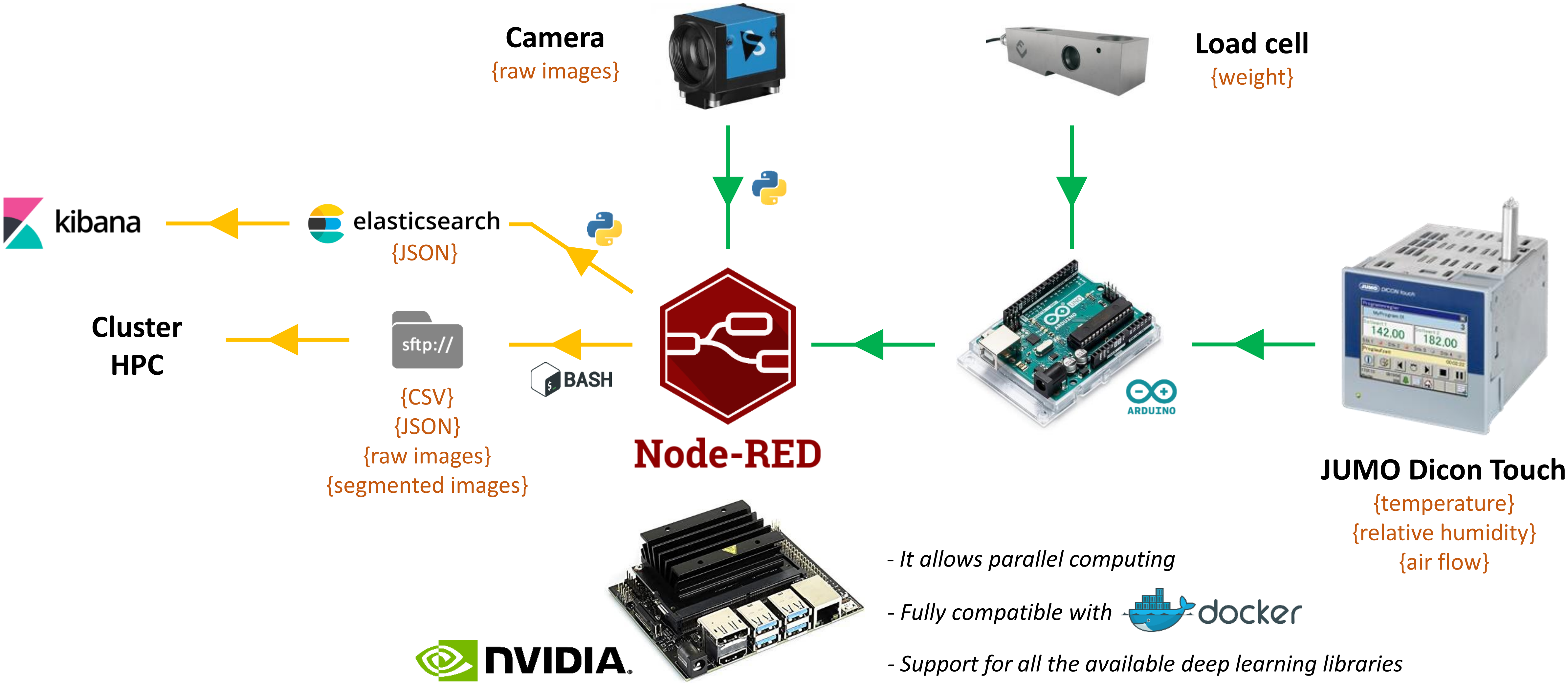
- » Relative Humiduty (R.H.)
- » Temperature
- » Air flow

JUMO

A SMART dryer prototype



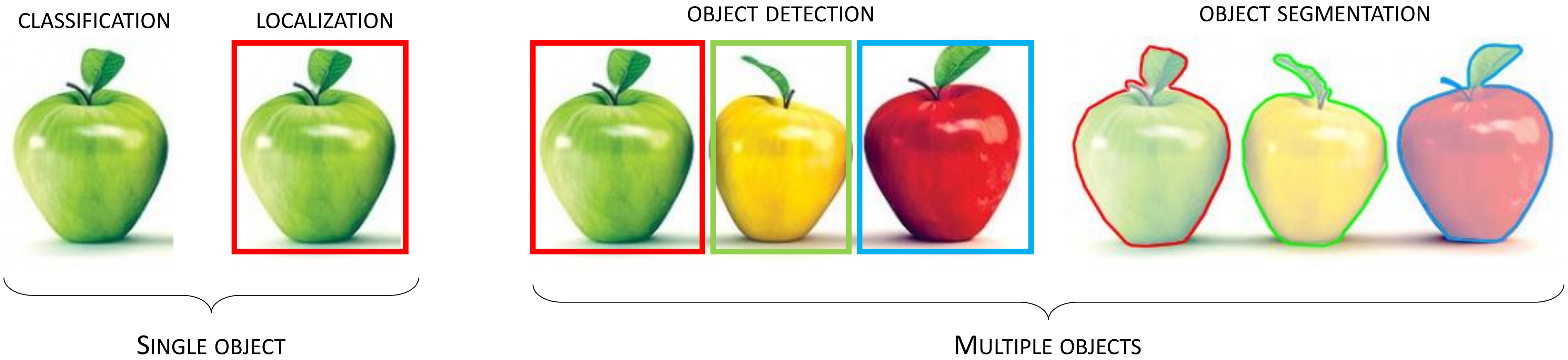
A SMART dryer prototype



What about computer vision (CV)?

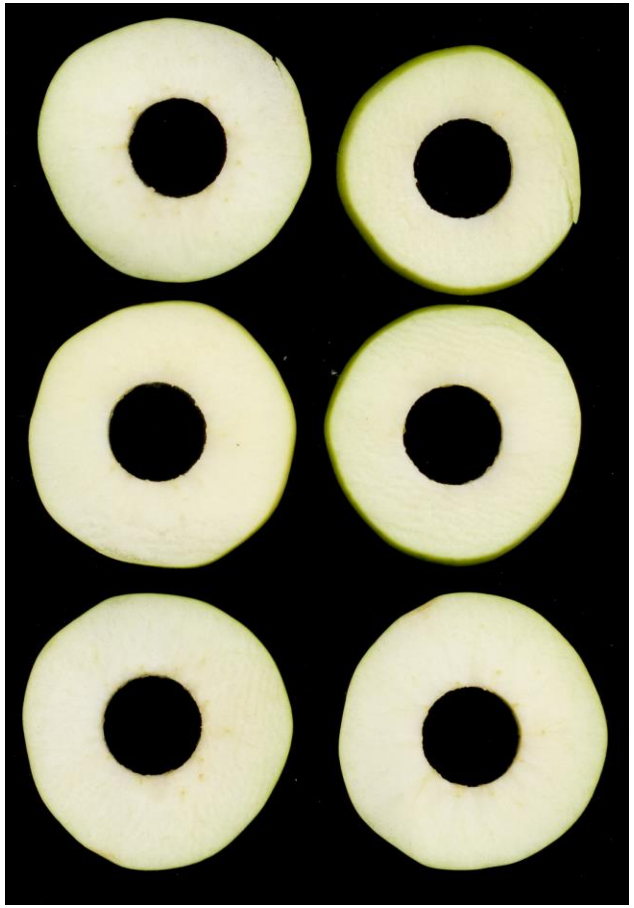
Computer Vision deals with allowing computers to understand digital images or videos with the aim of performing tasks better than human, such as:

1) *Colour measurement*
2) *Shape and size measurement*
3) *Object recognition*
4) *and so on…*

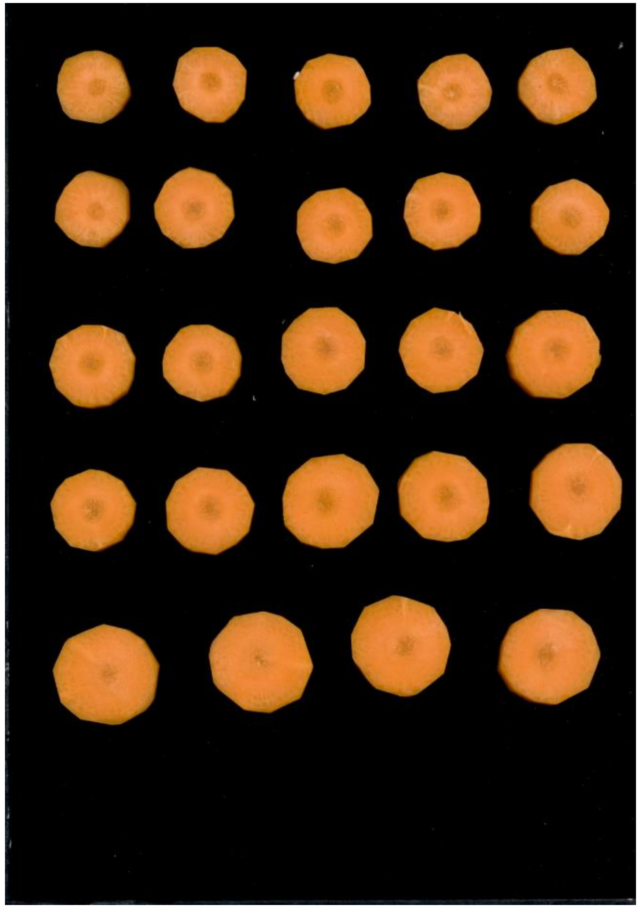


The image recognition problem

Recognize a product and set the proper process parameters (temperature, air flow and relative humidity)



Apple slices

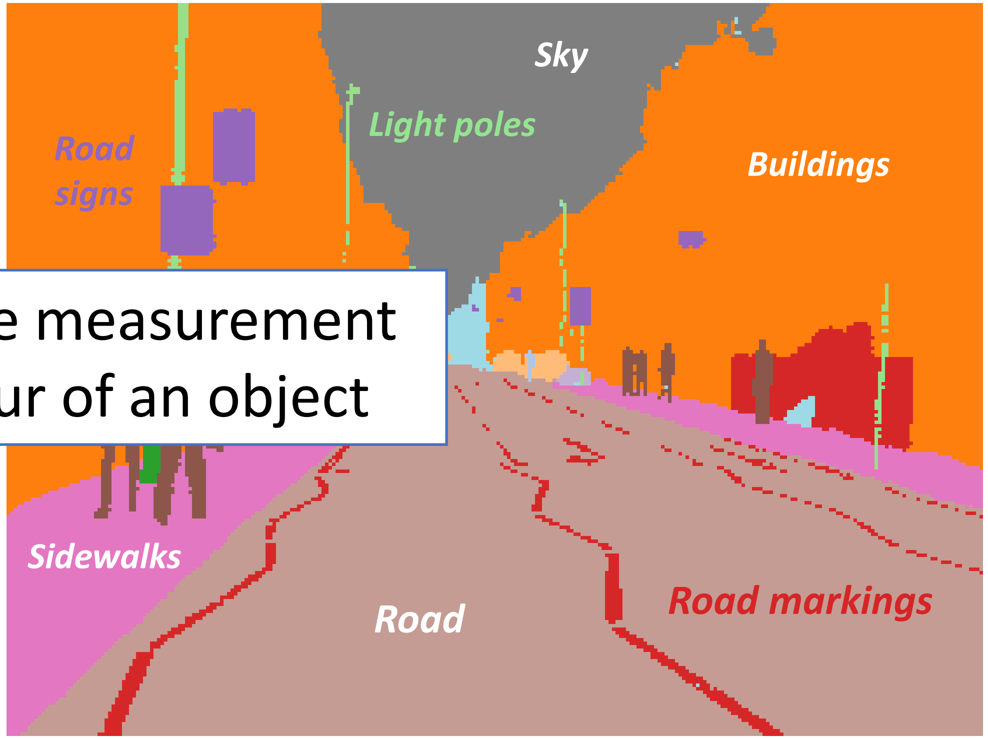


Carrot slices

Cucumber slices

The image segmentation problem

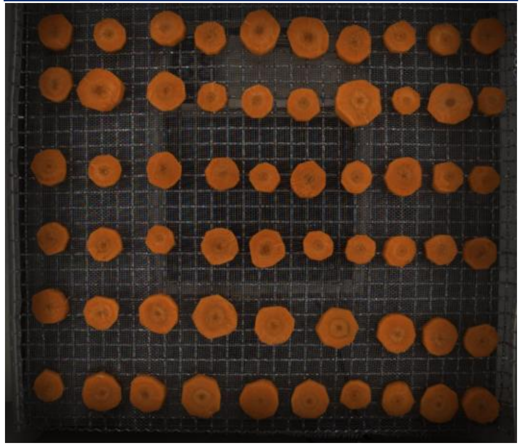
- ***Classical segmentation*** consists in splitting an image into several coherent parts, without any attempt to understand what these parts represent
- ***Semantic segmentation*** attempts to partition the image into semantically meaningful parts, and to classify each part into one of the pre-determined classes



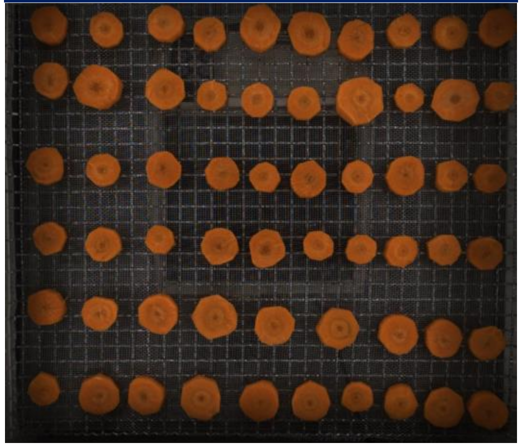
Segmentation allows the measurement of shape, size and colour of an object

The SMART monitoring and control system

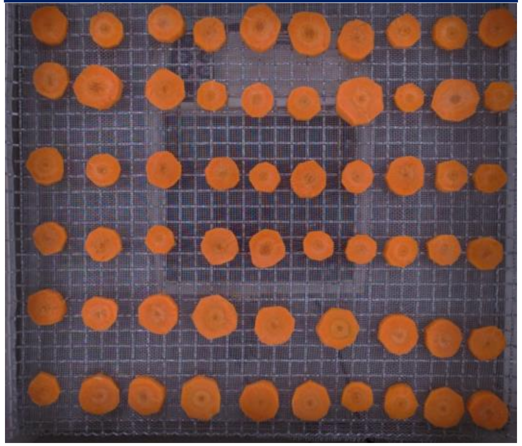
I RAW image (RGB)



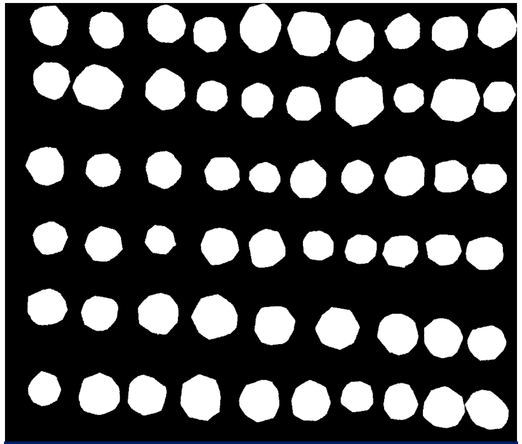
II Image calibration



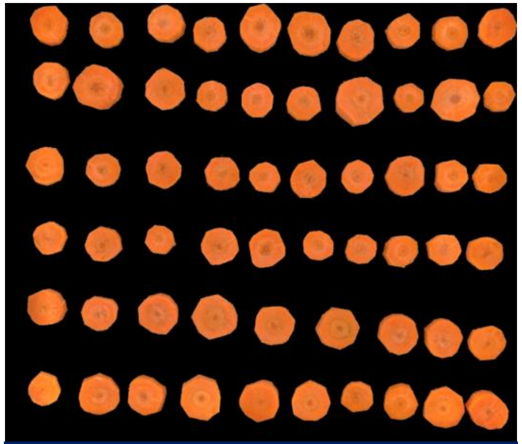
III Colour correction



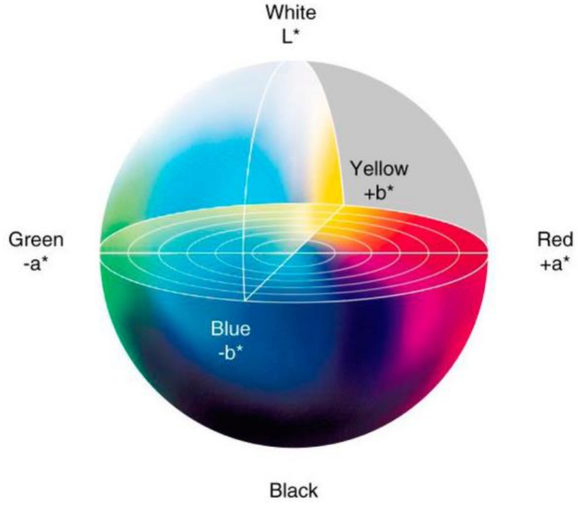
IV Flat-field correction



V Mask development



VI Image segmentation



Colour

Product size

MATLAB jupyter

Prof. Roberto Moscetti, PhD

The SMART monitoring and control system

MODEL	TYPE OF MODEL	FORMULA
Linear	**Classic**	$y = mx + q$
	Segmented	$x > BP,\ y = m_I x + q_I$ $x \leq BP,\ y = m_{II} x + q_{II}$
Thin layer	**Newton (Lewis)**	$y = \exp(-kt)$
	Page	$y = \exp(-(kt^n))$
	Handerson & Pabis	$y = a \exp(-kt^n)$
	Logarithmic	$y = a \exp(-kt)+c$

BP, *break point;* ***m*** *slope;* ***q*** *intercept;* ***k*** *drying constant;* ***a***, ***c*** *and* ***n*** *empirical adimensional constants*

One-way ANOVA on model coefficients

To evaluate whether a model was applicable to both treatments

Performance metrics

- Mean BIAS Error (**MBE**)
- Root Mean Squared Error (**RMSE**)
- Reduced Chi-squared (**reduced χ^2**)
- Adjusted coeff. of determination (**R^2**)

The SMART monitoring and control system

MODEL	TYPE OF MODEL	FORMULA
Linear	**Classic**	$y = mx + q$
	Segmented	$x > BP,\ y = m_I x + q_I$ $x \leq BP,\ y = m_{II} x + q_{II}$
Thin layer	**Newton (Lewis)**	$y = \exp(-kt)$
	Page	$y = \exp(-(kt^n))$
	Handerson & Pabis	$y = a\ \exp(-kt^n)$
	Logarithmic	$y = a\ \exp(-kt)+c$

__BP__, break point; __m__ slope; __q__ intercept; __k__ drying constant; __a__, __c__ and __n__ empirical adimensional constants

product size

One-way ANOVA on model coefficients

To evaluate whether a model was applicable to both treatments

Performance metrics

- Mean BIAS Error (**MBE**)
- Root Mean Squared Error (**RMSE**)
- Reduced Chi-squared (**reduced χ^2**)
- Adjusted coeff. of determination (**R^2**)

The SMART monitoring and control system

Model	Type of model	Formula
Linear	Classic	$y = mx + q$
	Segmented	$x > BP,\ y = m_I x + q_I$ $x \leq BP,\ y = m_{II} x + q_{II}$
Thin layer	Newton (Lewis)	$y = \exp(-kt)$
	Page	$y = \exp(-(kt^n))$
	Handerson & Pabis	$y = a \exp(-kt^n)$
	Logarithmic	$y = a \exp(-kt)+c$

***BP**, break point; **m** slope; **q** intercept; **k** drying constant; **a**, **c** and **n** empirical adimensional constants*

product size

time

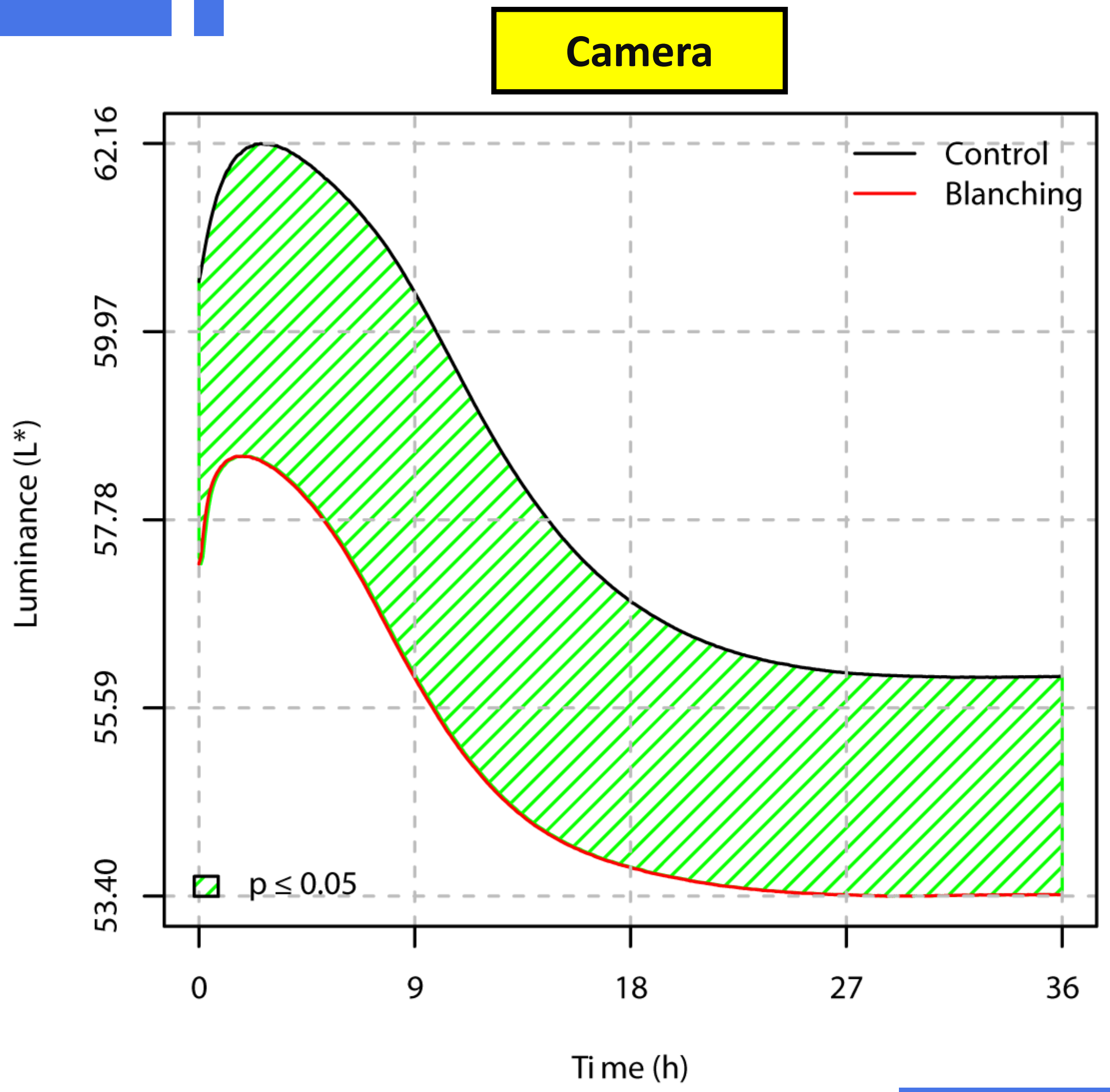
One-way ANOVA on model coefficients

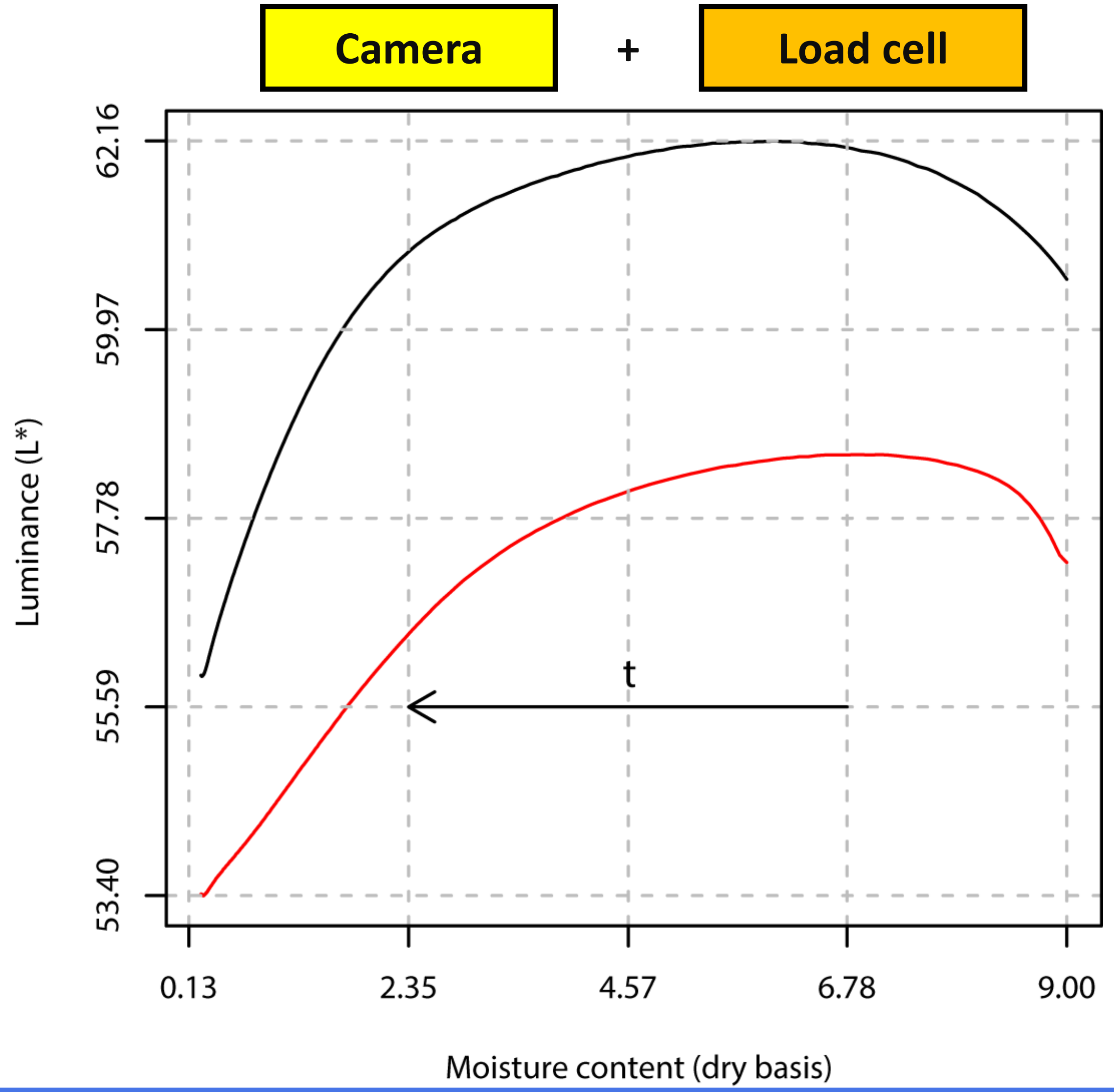
To evaluate whether a model was applicable to both treatments

Performance metrics

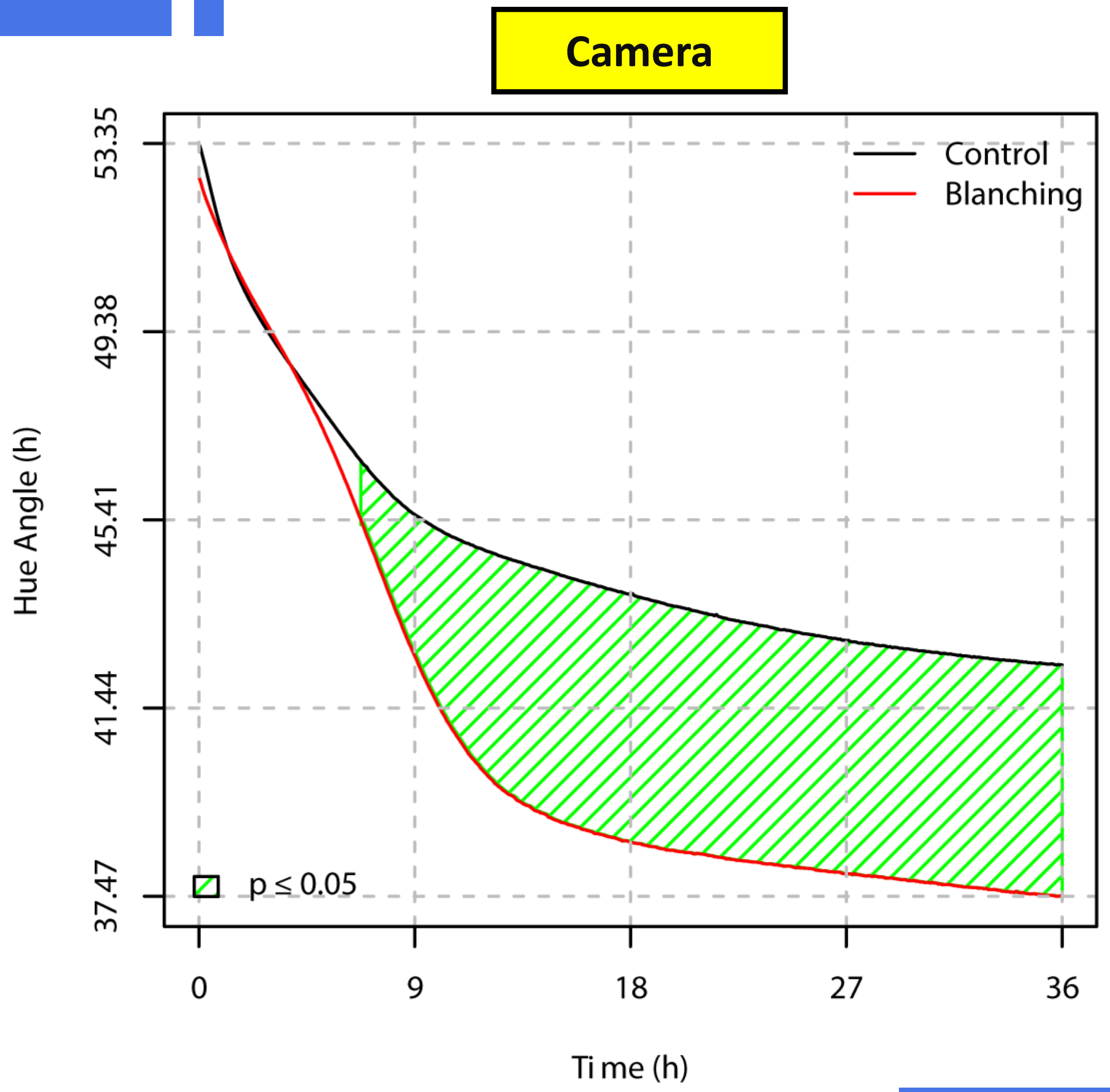
- Mean BIAS Error (**MBE**)
- Root Mean Squared Error (**RMSE**)
- Reduced Chi-squared (**reduced χ^2**)
- Adjusted coeff. of determination (**R^2**)

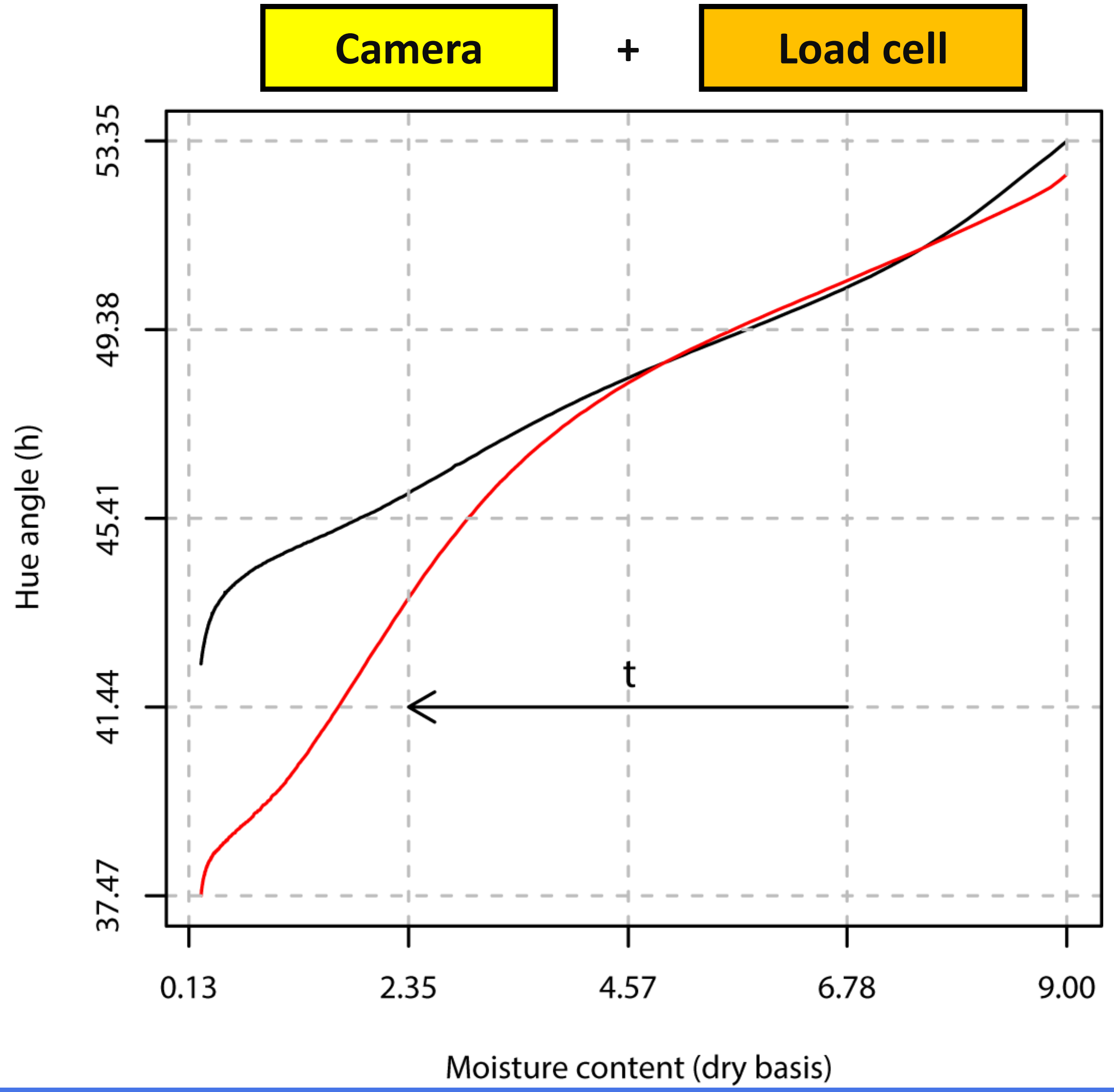
Results – in-line data processing



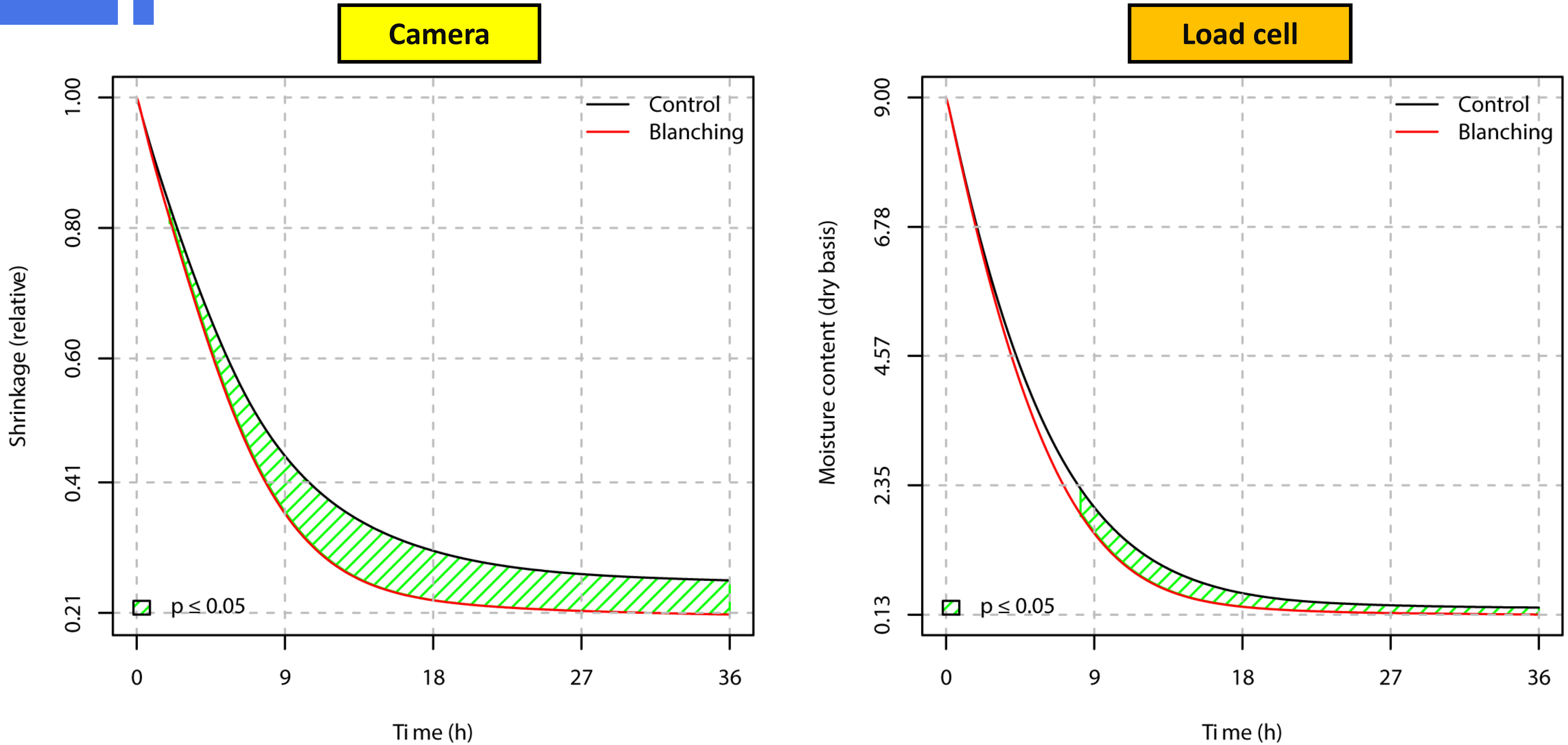


Results – in-line data processing



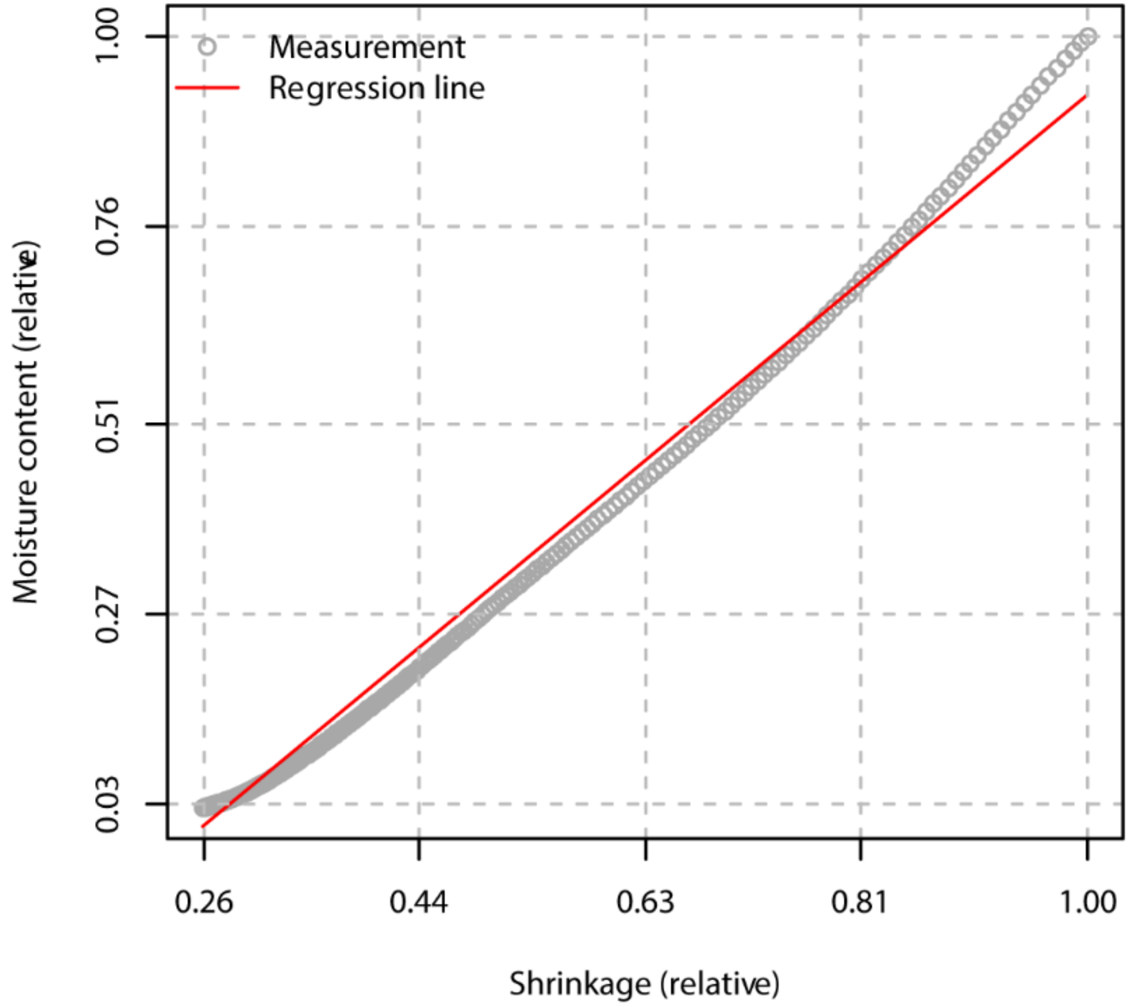


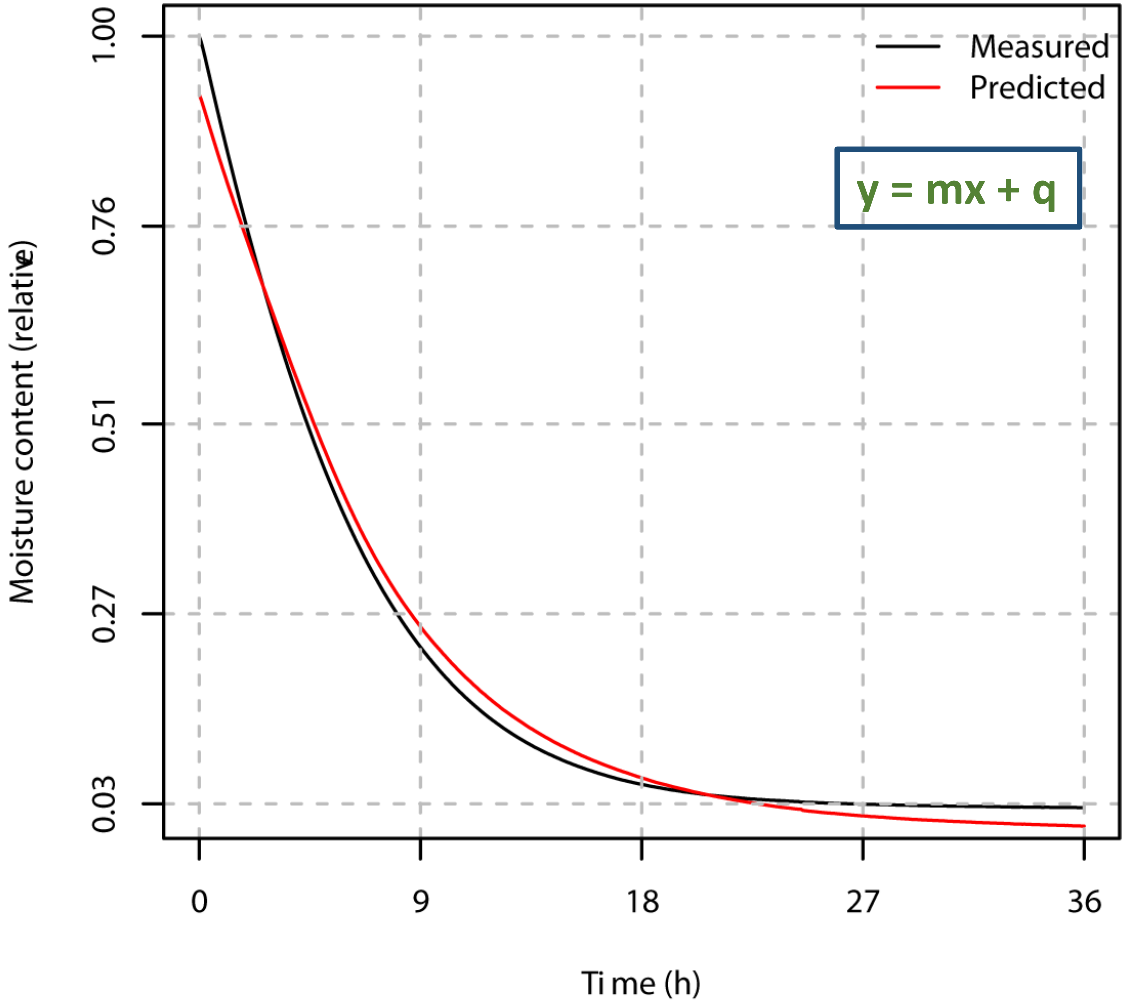
Results – in-line data processing



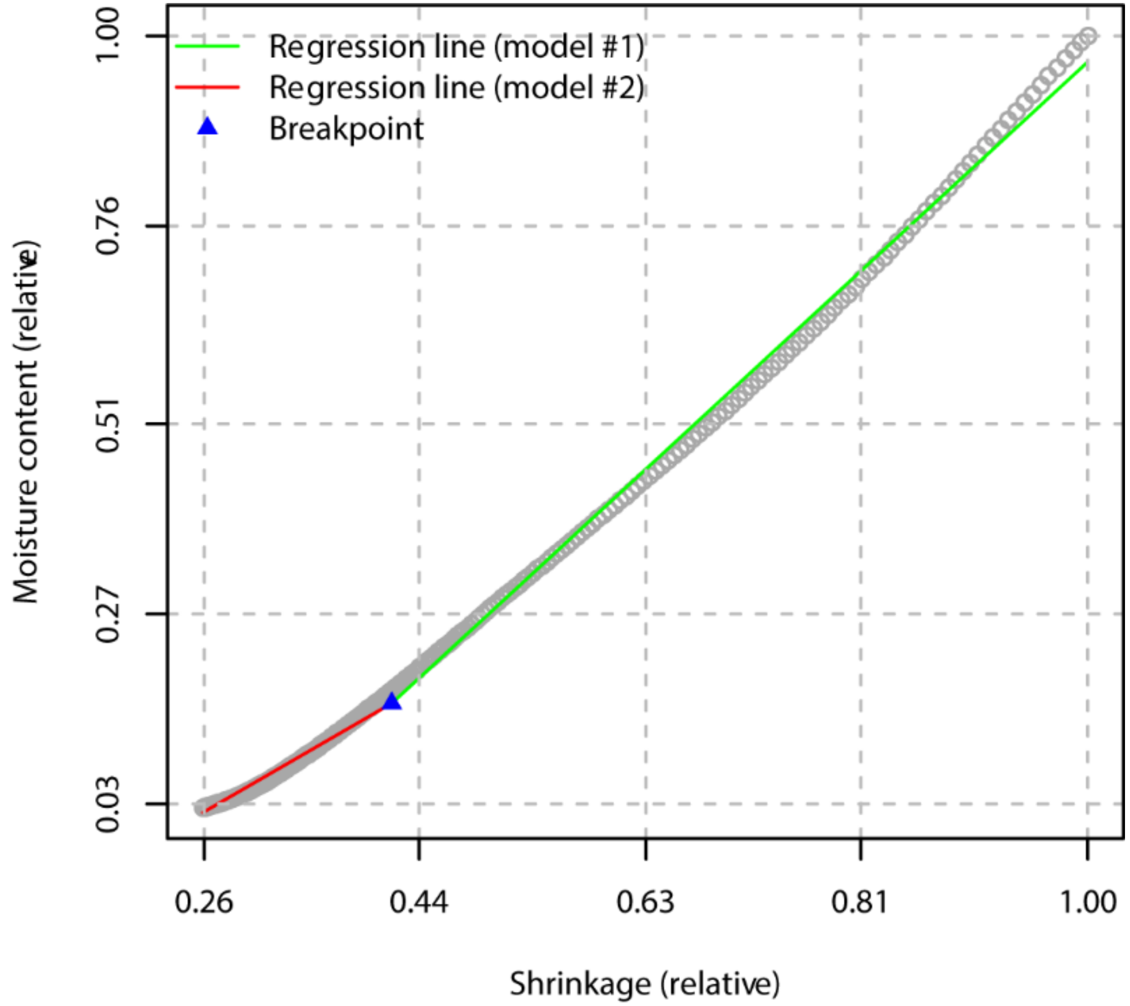
Prof. Roberto Moscetti, PhD

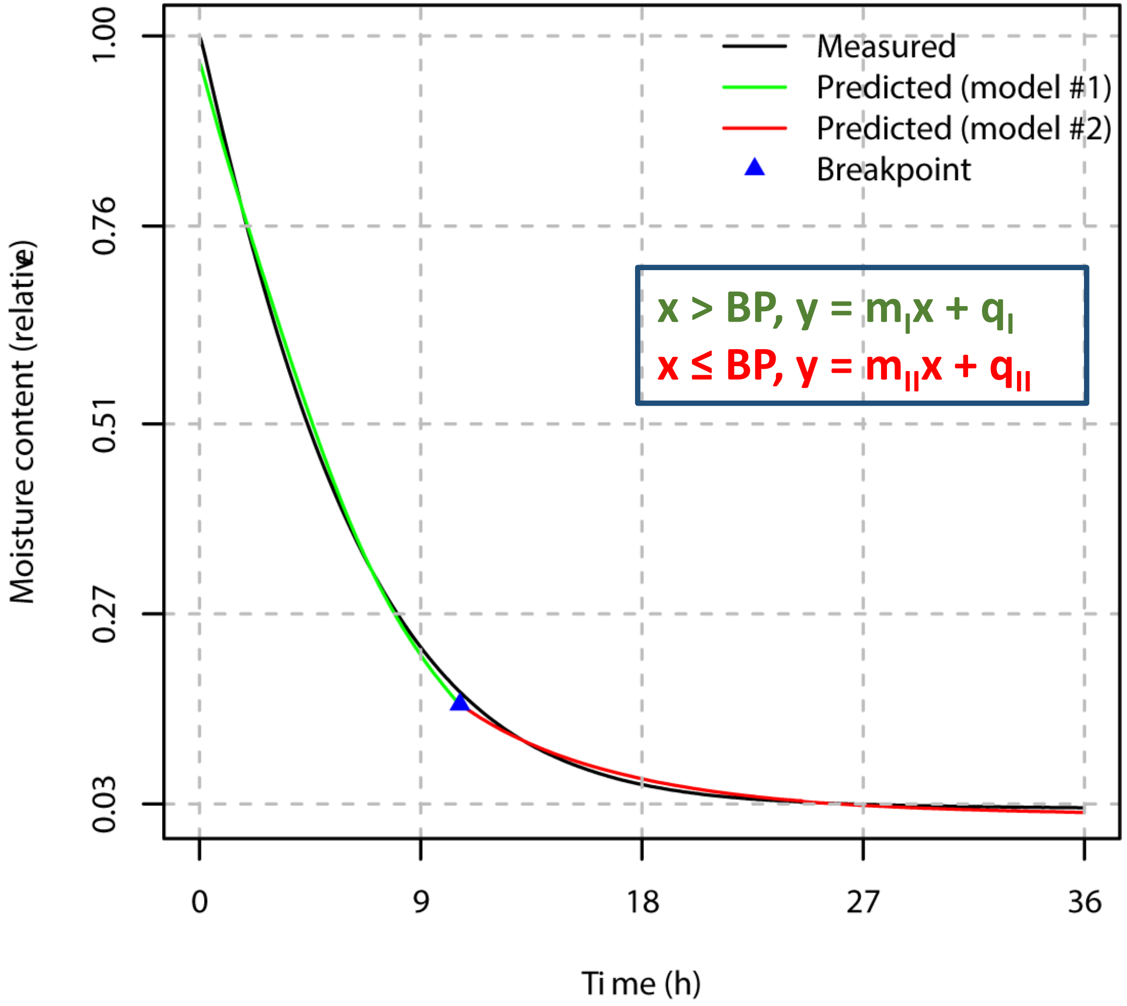
Results – model development (linear)



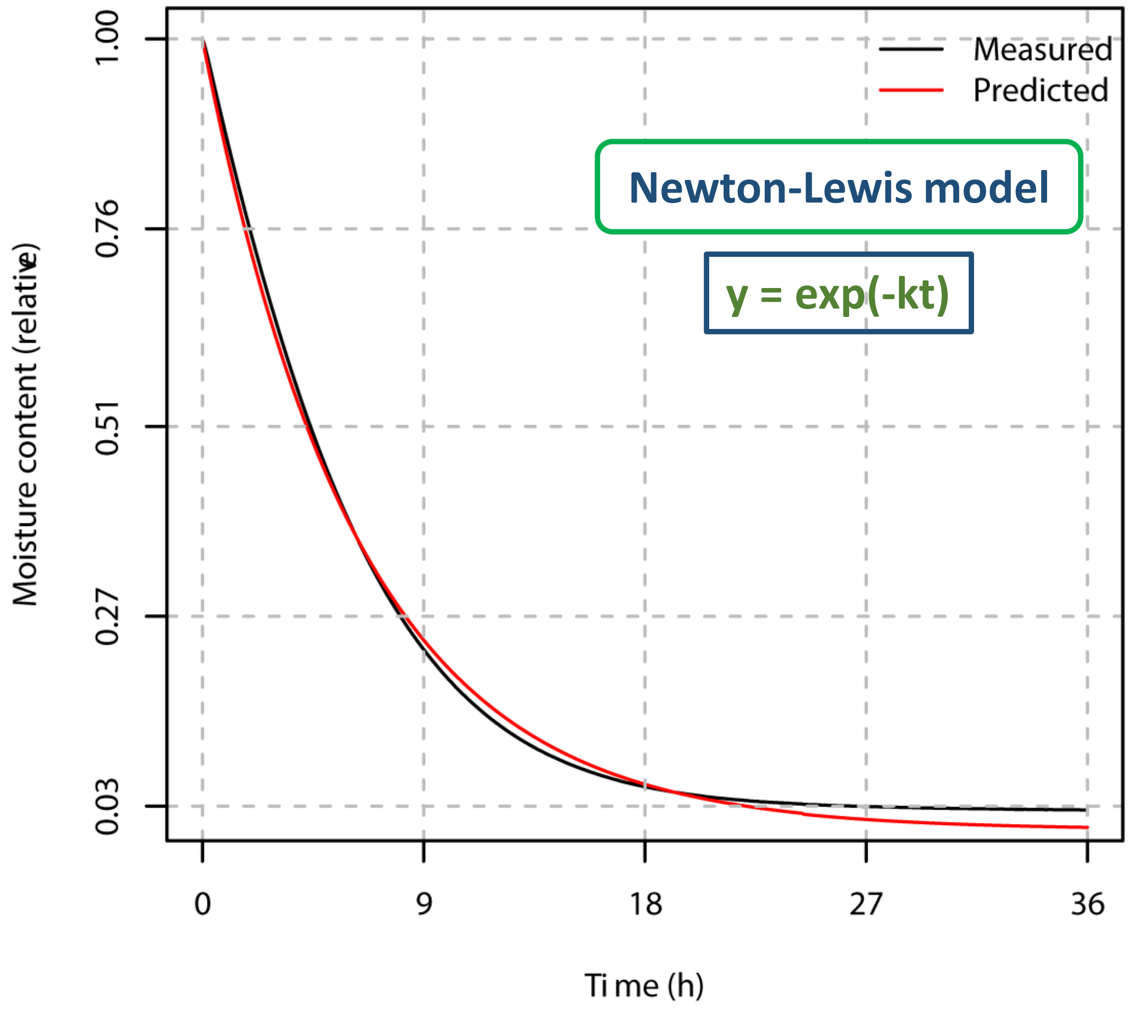


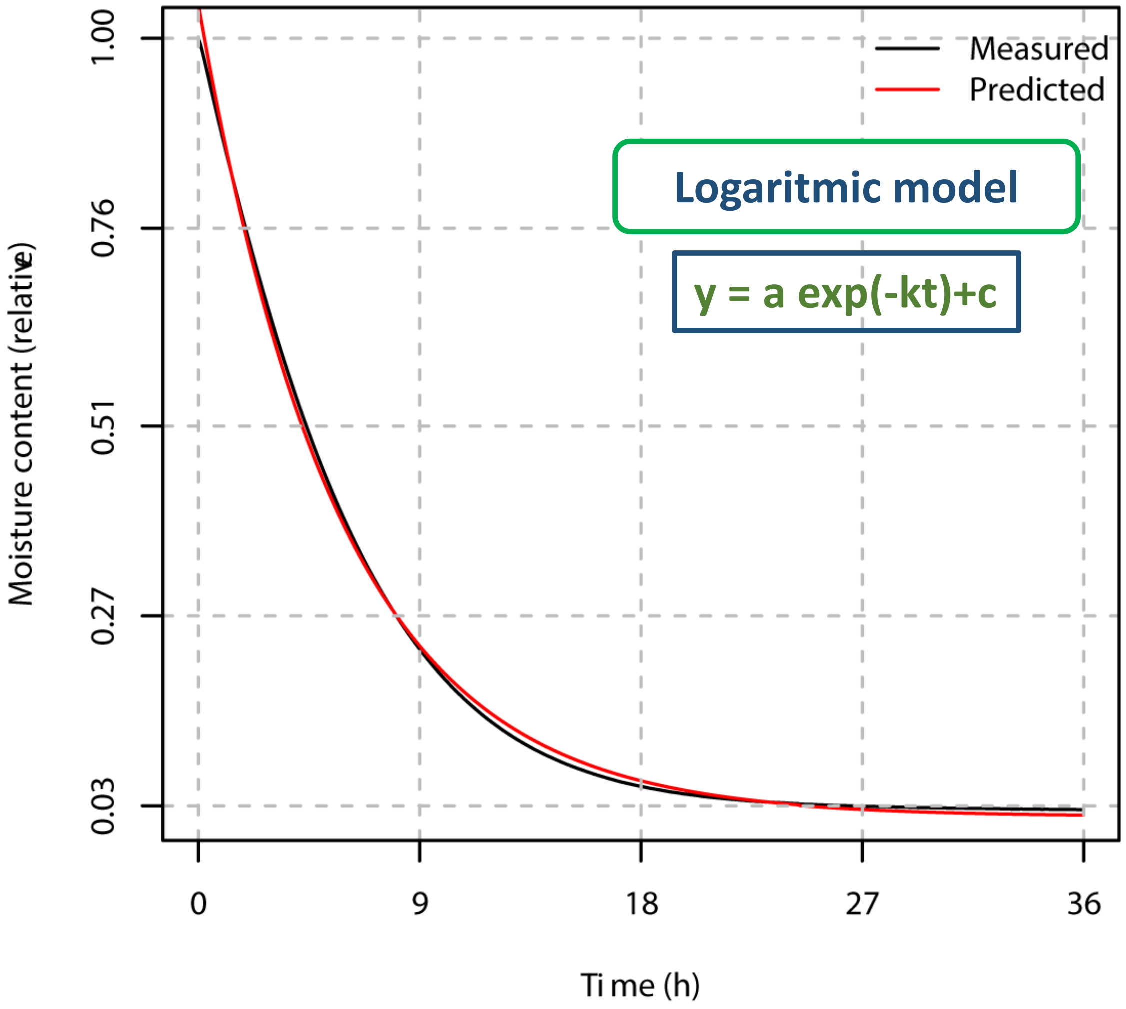
Results – model development (segmented)



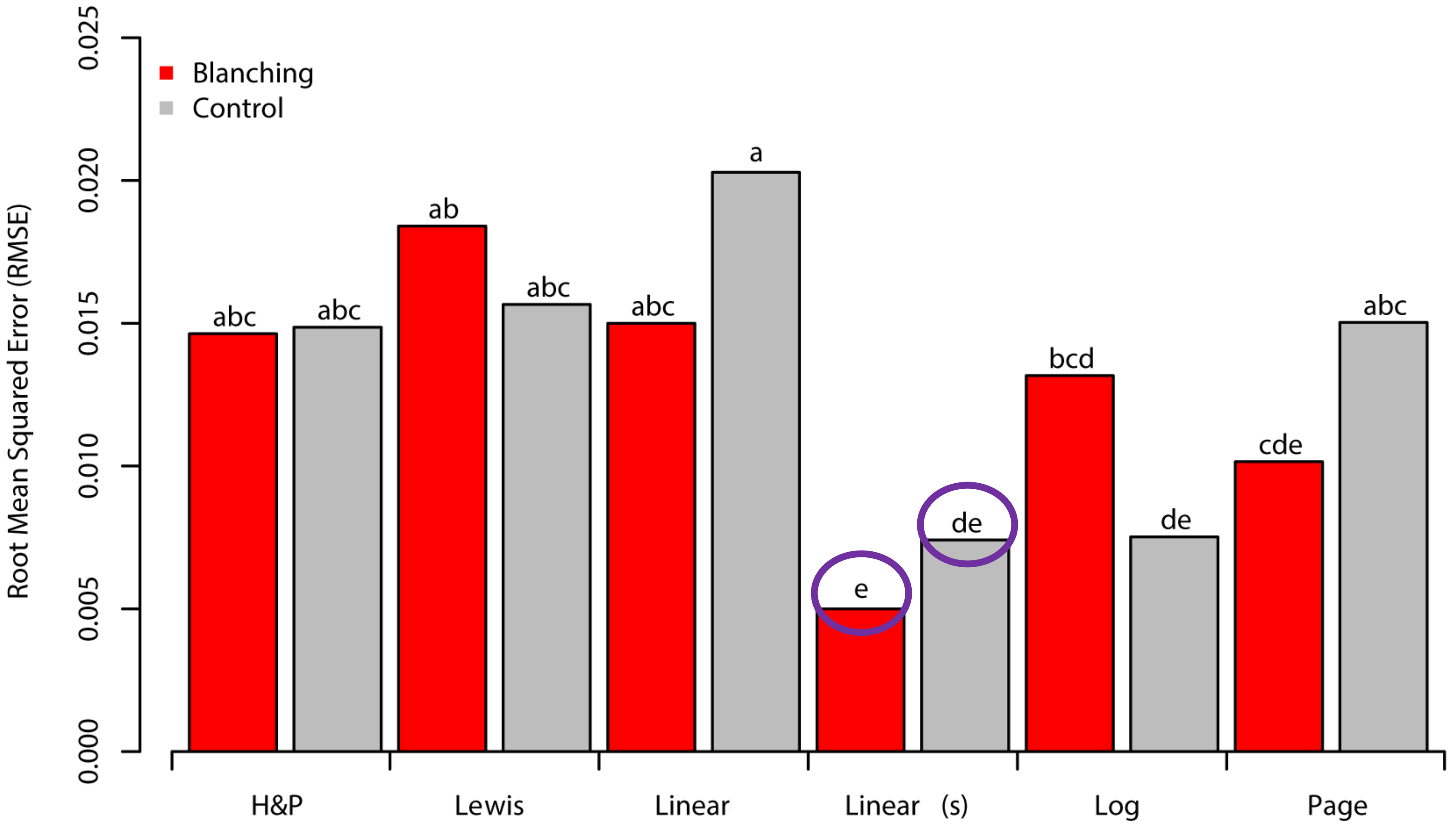


Results – model development (thin-layer)

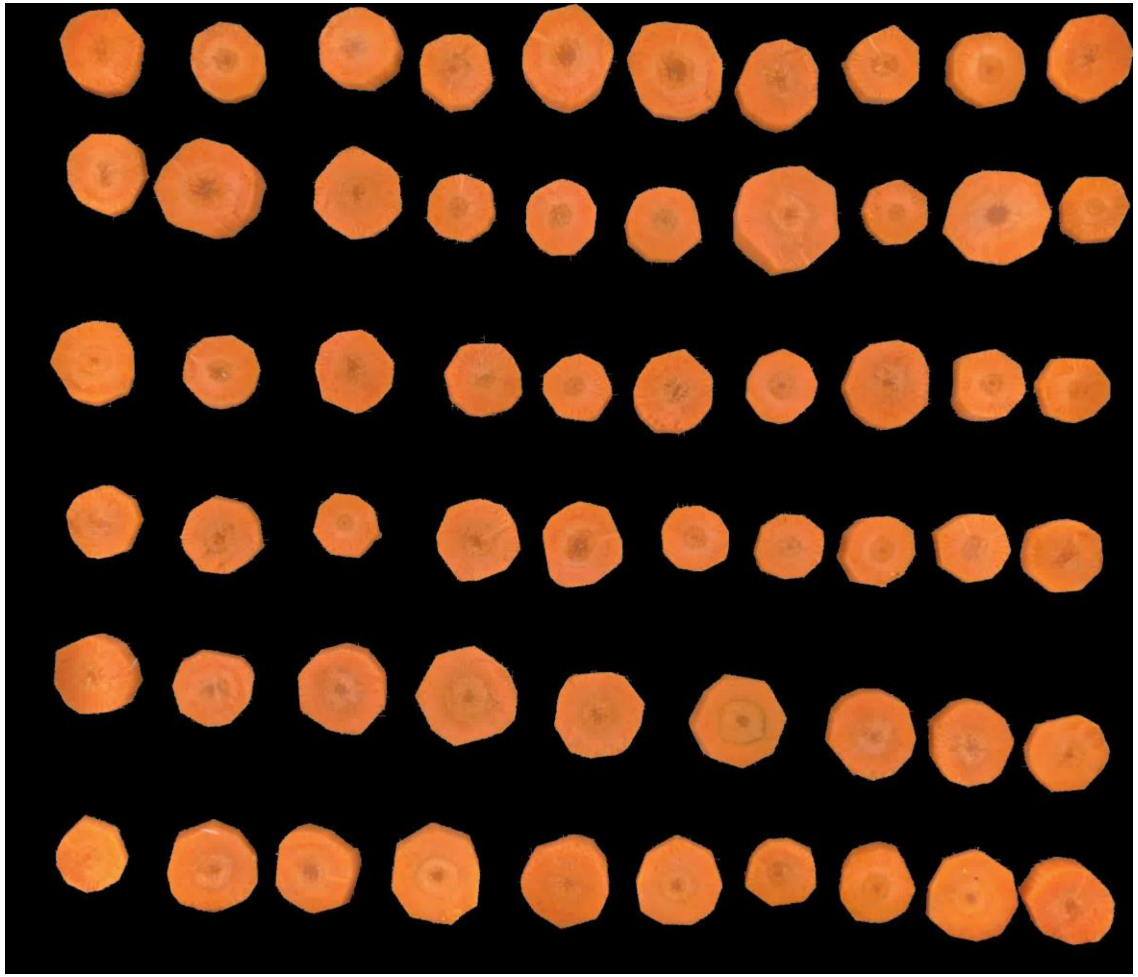
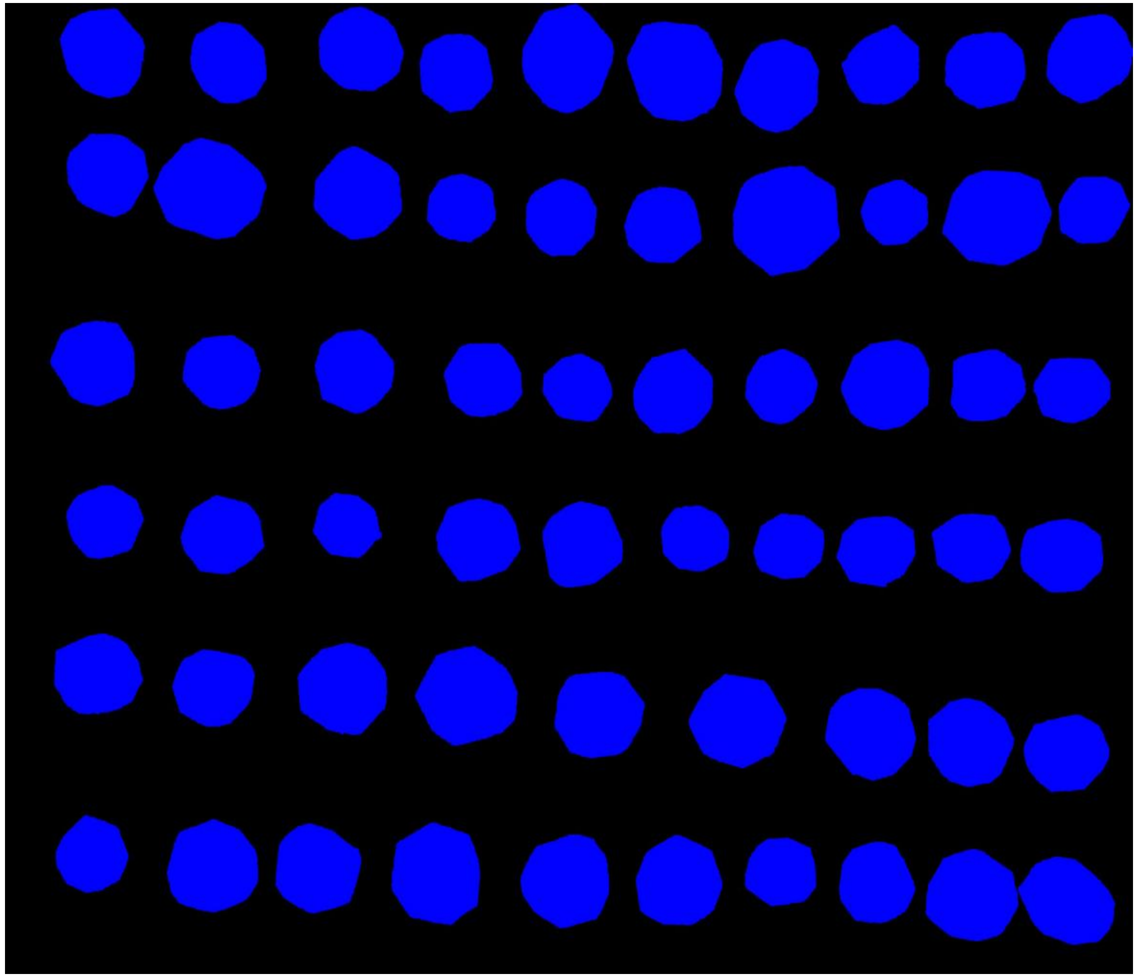




Results – model performances



Heterogeneity of the drying process

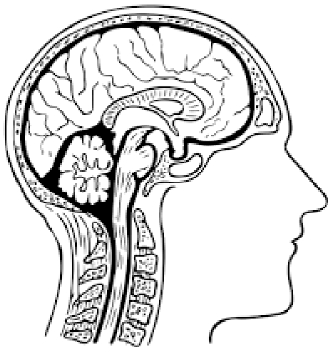



Further development

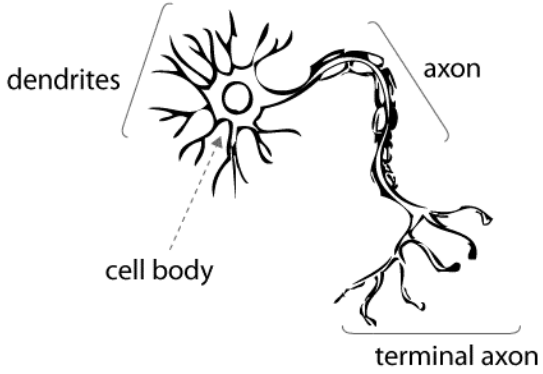
The Deep Learning

What is an Artificial Neural Network?

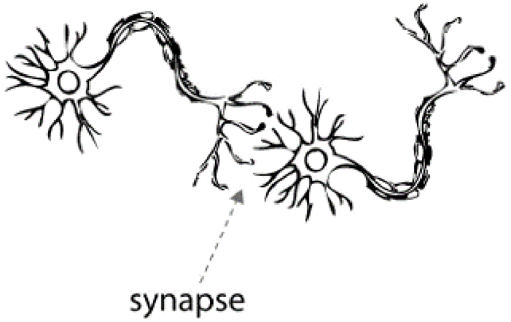
Biological Intelligence



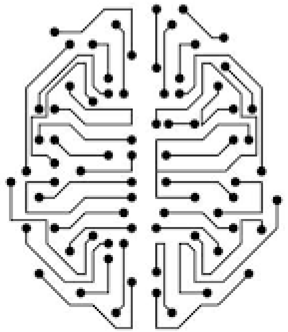
Biological neuron



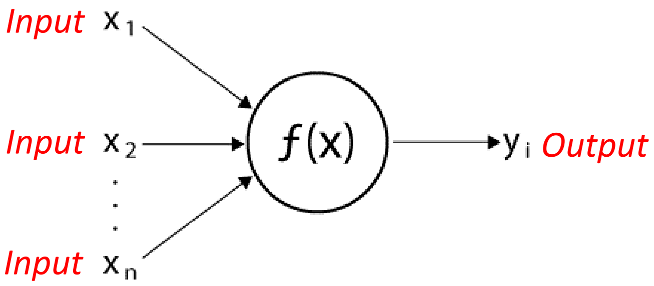
Biological synapse



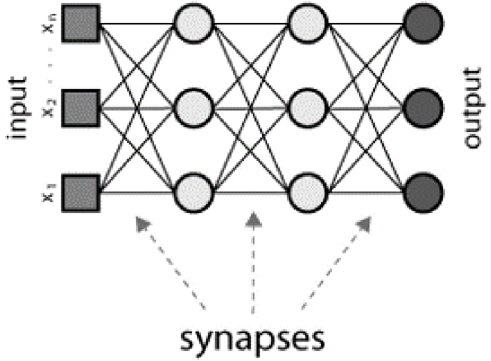
Artificial Intelligence



Artificial neuron



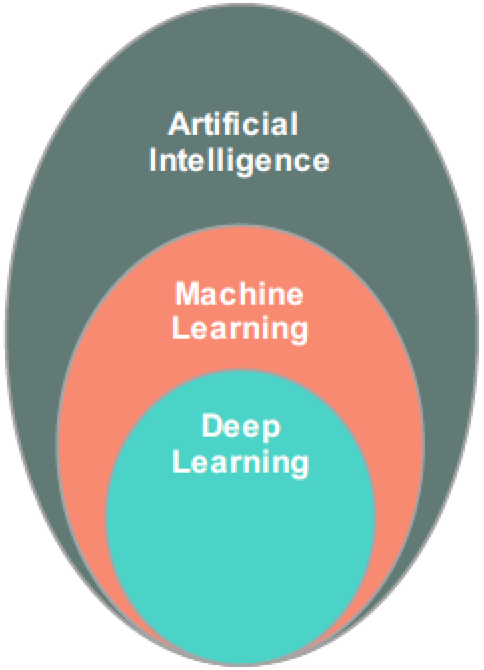
Artificial synapse

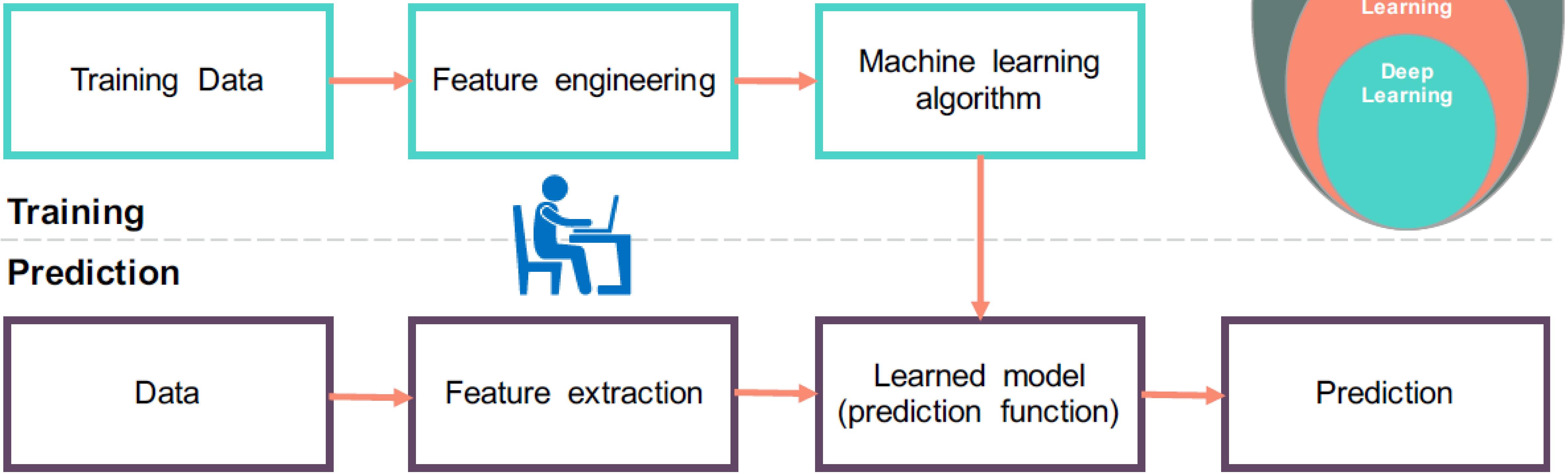


Prof. Roberto Moscetti, PhD
Lecture: University of Teramo 19-03-24

Artificial Intelligence – Machine learning

Machine learning requires feature engineering: *the use of domain knowledge of the data to create features that make machine learning algorithms work*

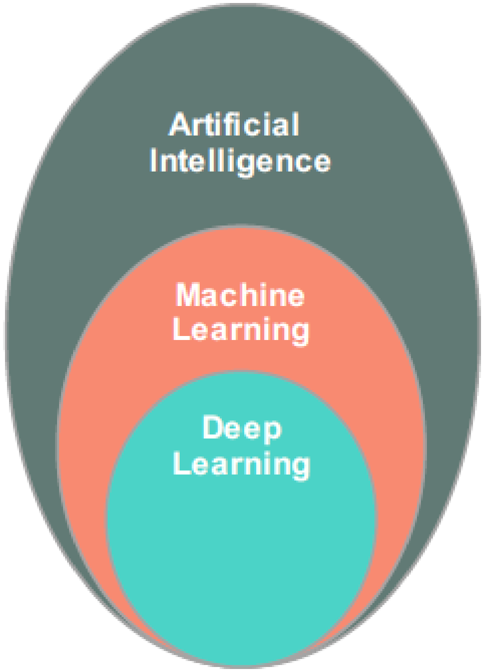


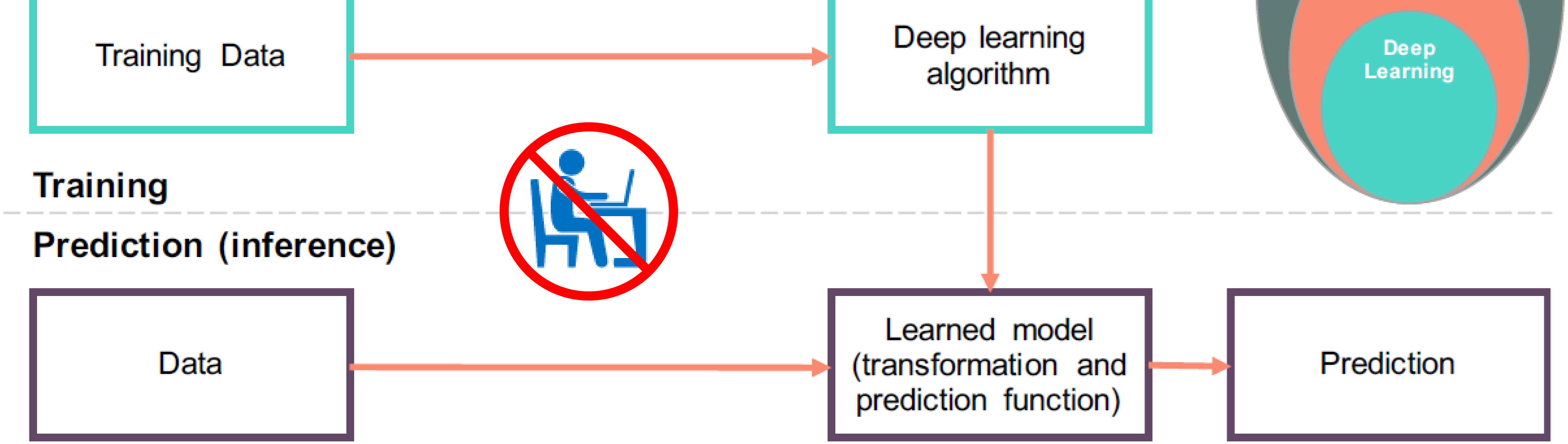


Modified from: Sorin Cheran's presentation titled 'About AI' (2018)

Artifial Intelligence – Machine learning

Deep learning does not require feature engineering: *algorithm automatically learns how to perform feature extraction and which features are important for the model*





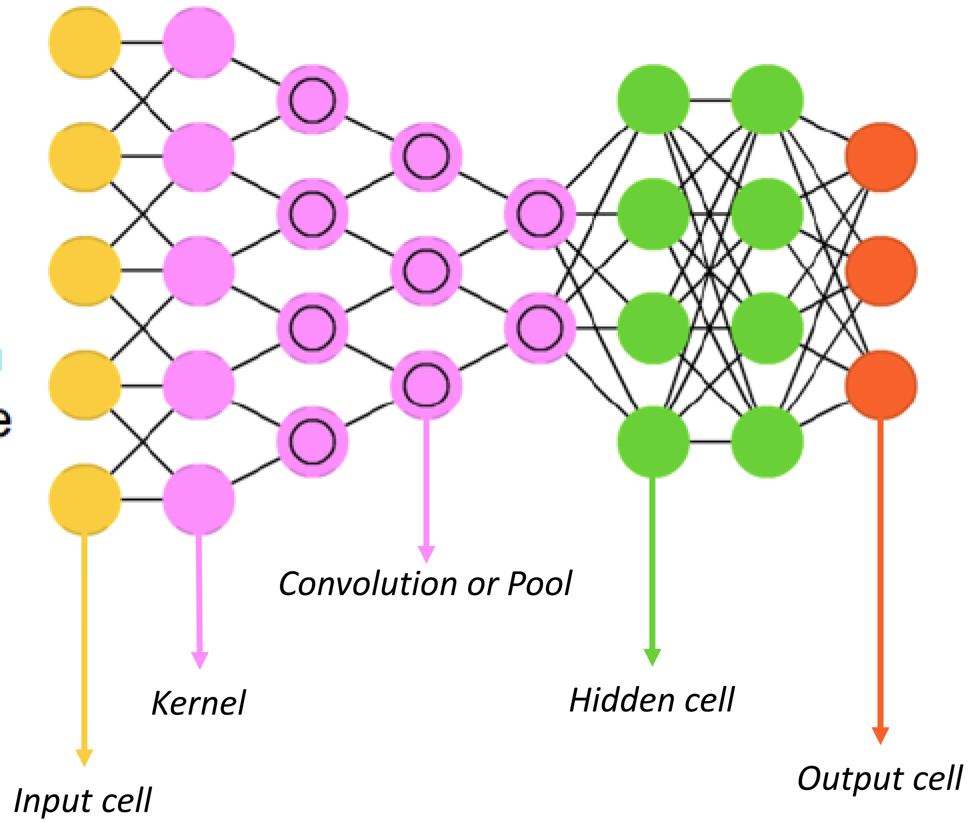
Modified from: Sorin Cheran's presentation titled 'About AI' (2018)

ANN and CV – Convolutional Neural Networks

Scope : Mainly used for images and video, could easily cover text and audio.

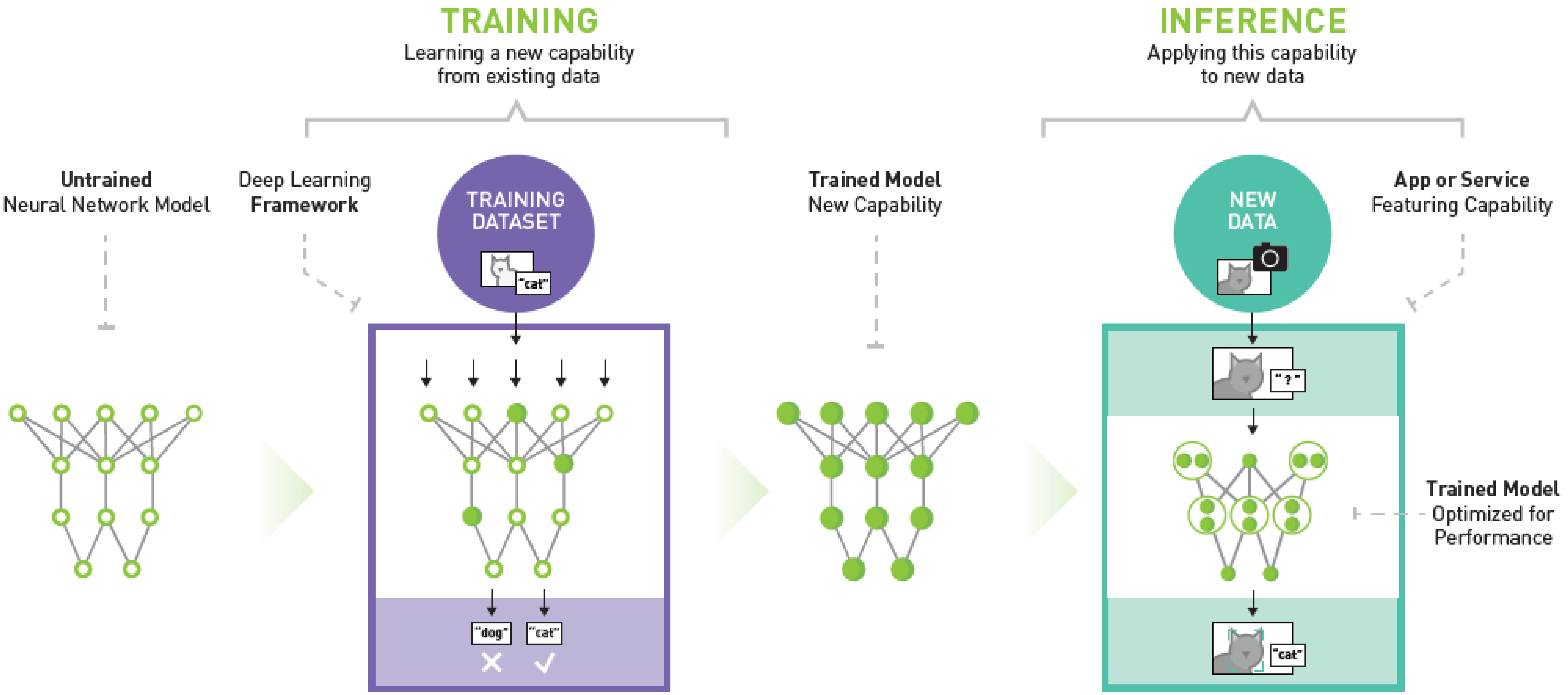
Typical use: Feed in images and the network that classifies the data. They can identify object, faces, cars, animals an so on.

The biological inspiration for CNNs is the visual cortex in different animals. The cells in the visual cortex are sensitive to small regions of the input. We call this the *visual field.* These smaller regions are unified together to cover all the visual field.



Modified from: Sorin Cheran's presentation titled 'About AI' (2018)

How inference works



Prof. Roberto Moscetti, PhD

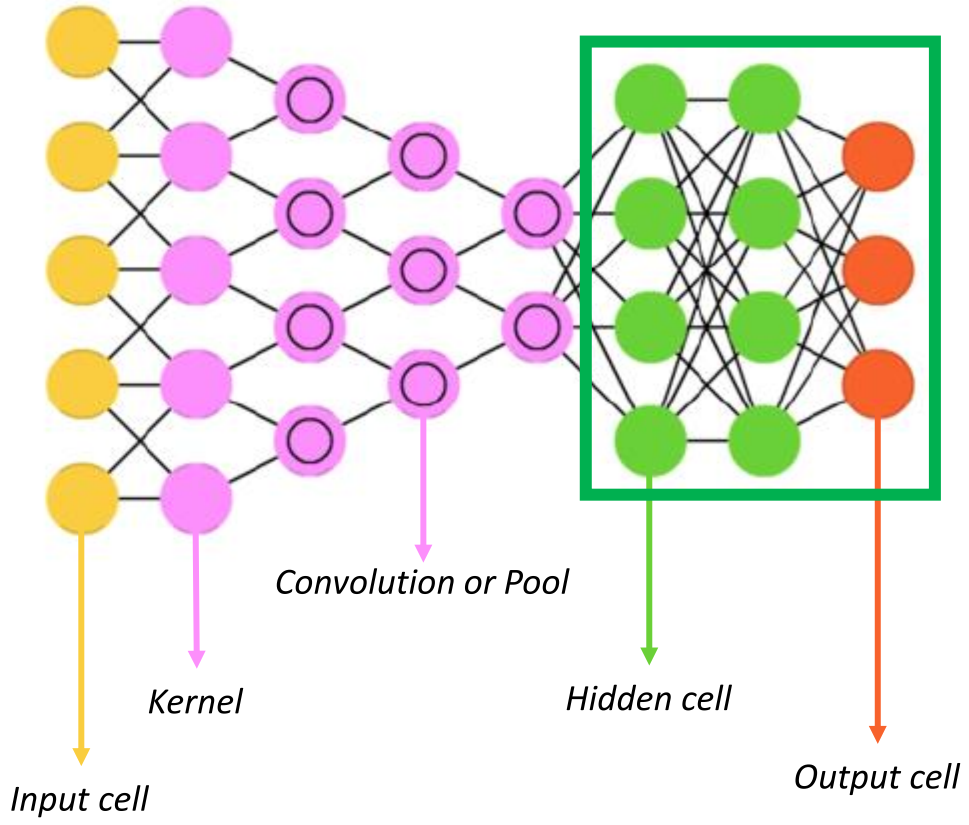
How to make model training much easier

Transfer learning is a technique that shortcuts much of this by taking a piece of a model that has already been trained on a related task and reusing it in a new model (source: Google Tensorflow website, 2019)

Name	Type	Model size (# params)	Model size (MB)	GFLOPs (forward pass)
AlexNet	CNN	60,965,224	233 MB	0.7
GoogleNet	CNN	6,998,552	27 MB	1.6
VGG-16	CNN	138,357,544	528 MB	15.5
VGG-19	CNN	143,667,240	548 MB	19.6
ResNet50	CNN	25,610,269	98 MB	3.9
ResNet101	CNN	44,654,608	170 MB	7.6
ResNet152	CNN	60,344,387	230 MB	11.3
Eng Acoustic Model	RNN	34,678,784	132 MB	0.035
TextCNN	CNN	151,690	0.6 MB	0.009

How to make model training much easier

Transfer learning is a technique that shortcuts much of this by taking a piece of a model that has already been trained on a related task and reusing it in a new model (source: Google Tensorflow website, 2019)

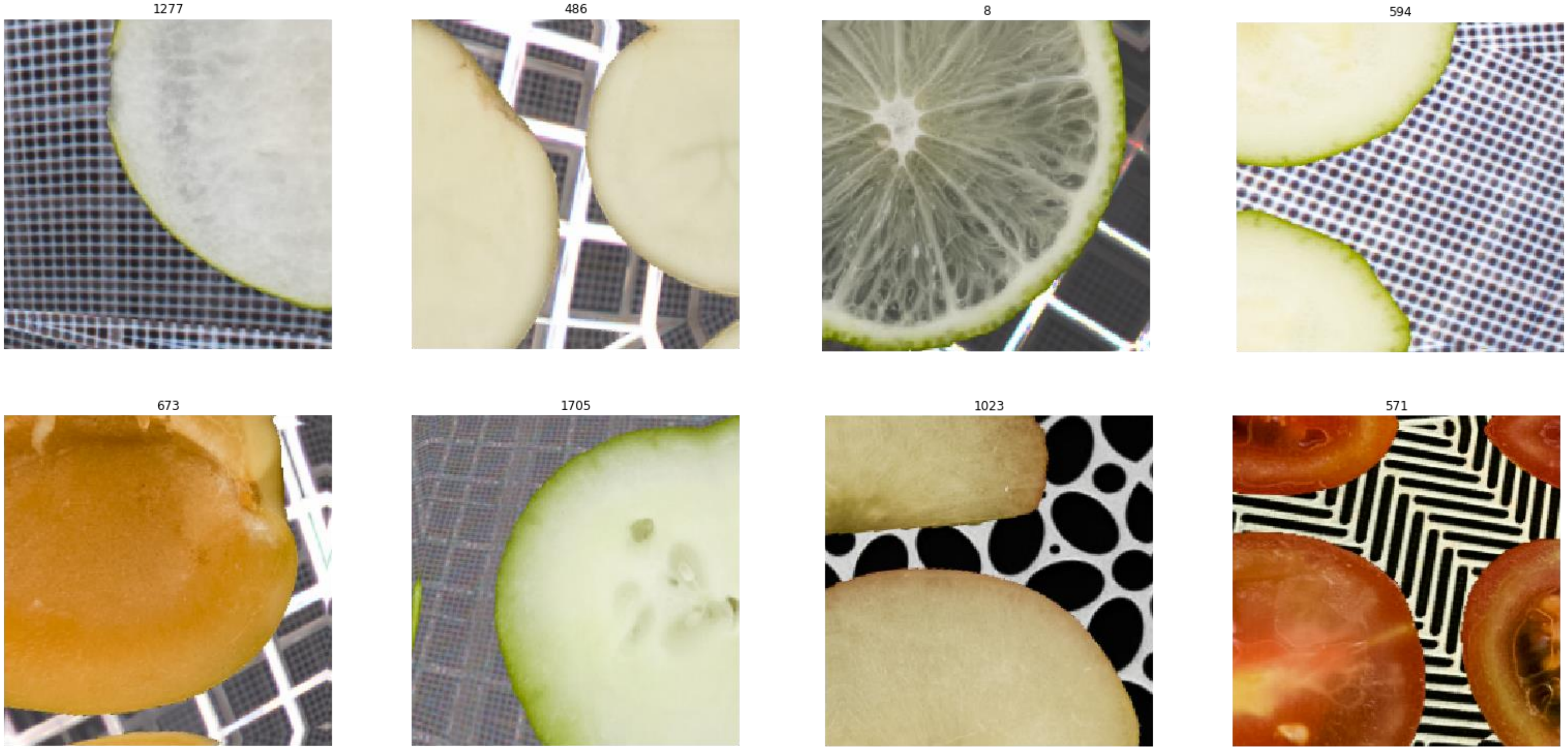


Last layers are the only ones that are retrained

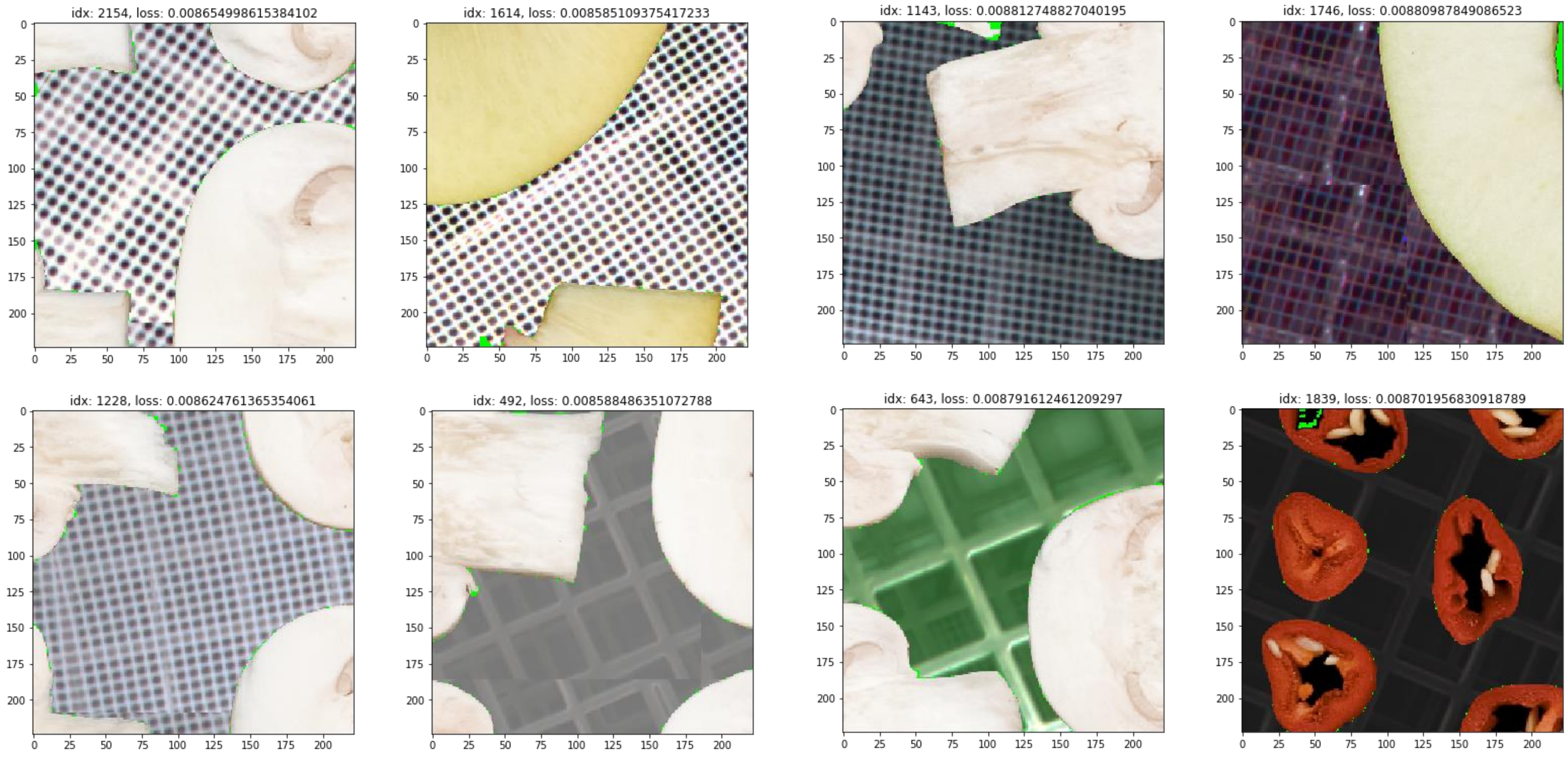
The dataset – 100+ images per class of product

1. Apricot
2. Banana
3. Carrot (unpeeled)
4. Carrot (peeled)
5. Cucumber
6. Champignon (or white button, mushroom)
7. Onion
8. Kiwifruit
9. Lime
10. Apple
11. Potato
12. Chilli pepper
13. Pear
14. Peach
15. Red plum
16. Zucchini
17. Cherry tomato
18. San Marzano tomato

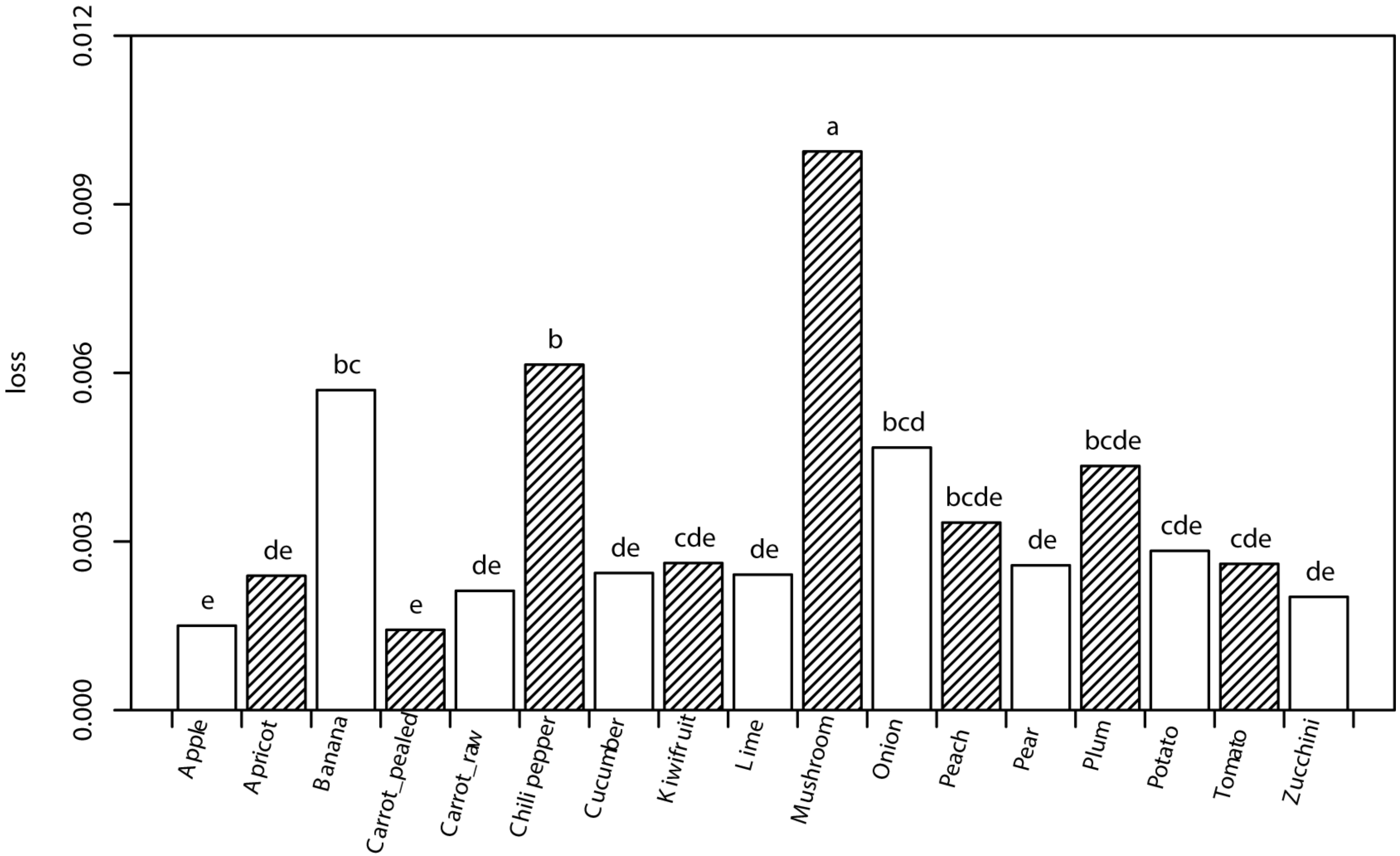
The data augmentation approch

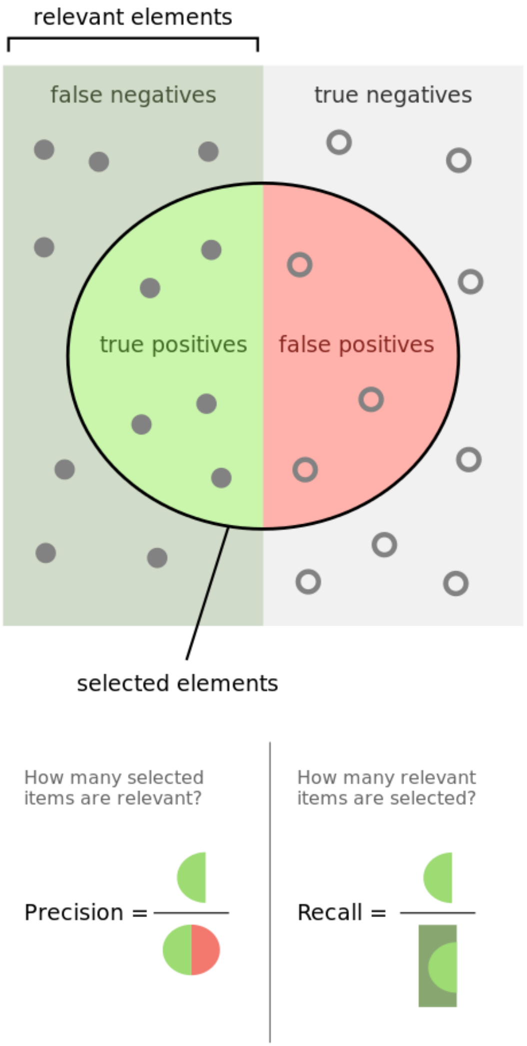


The Semantic Segmentation Model (SSM)



The Classification Model (CM)





Prof. Roberto Moscetti, PhD
Lecture: University of Teramo 19-03-24

Some final considerations

- ICT and PAT solutions can enable innovation in the food processing in terms of sustainability
- Most of SMART solutions are small or prototypal: investment in scale-up is needed
- Industry will benefit enormously by reducing GHG emissions and dependence on fossil fuels
- In order to achieve the objective, an interdisciplinary approach is required that takes into account the dynamics of a process, the environmental impact, the economic aspects related to the cost of the plant and the operating costs
- Pursuing sustainability is not possible without high quality, healthy and safe products

THANK YOU FOR THE ATTENTION!

Prof. Roberto Moscetti
rmoscetti@unitus.it