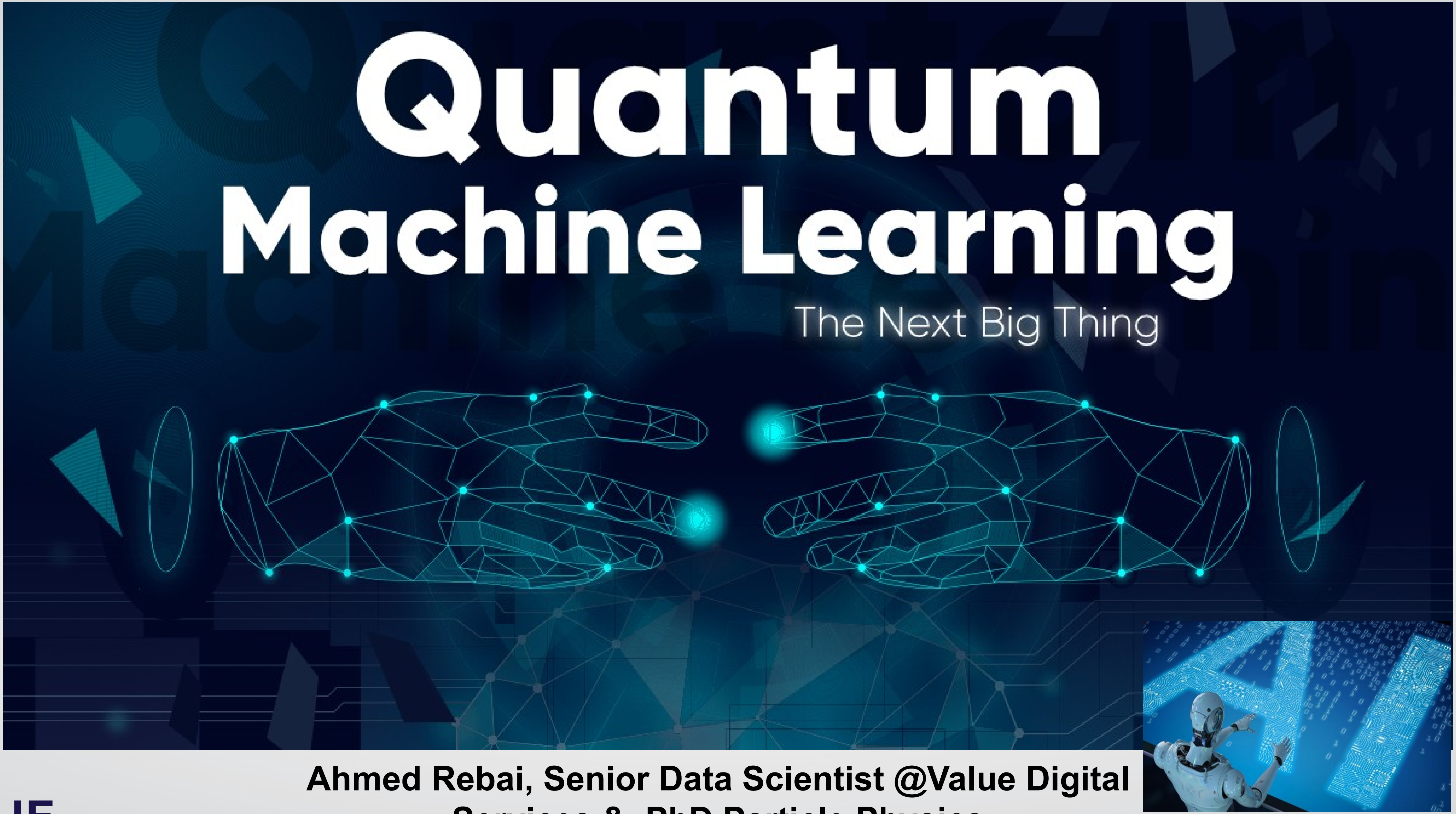
A shallow introduction to quantum machine learning



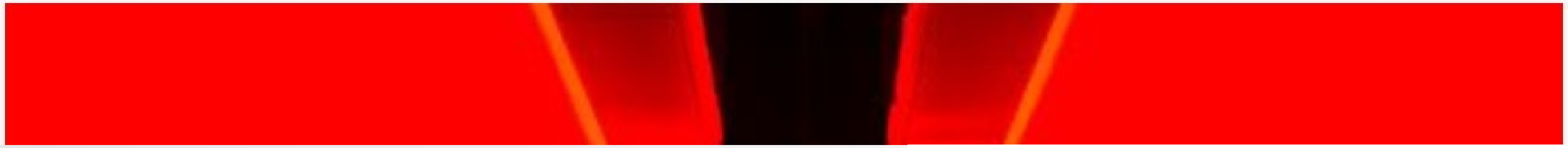
Ahmed Rebai, Senior Data Scientist @Value Digital Services & PhD Particle Physics

VALUE

Quantum computers are here! First business contracts: investment banks, defense, aircraft manufacturers

How Goldman Sachs and JPMorgan are using quantum computing

by Sarah Butcher 10 December 2020



Recent news

CLSA is hiring in Hong Kong after staff quit

Goldman Sachs is picking up SocGen's equity derivatives professionals in Paris

Two Sigma's chief technology officer: finding talent is the hardest thing

Quantum algorithms are coming to finance, slowly

by Sarah Butcher 26 November 2020

Something is happening on the fringes of financial services. Away from trading floors, in banks' Google-style 'moonshot research labs', PhD students are experimenting with the application of quantum computing and quantum algorithms to financial services. No one is saying that quantum

PUBLICATION

The Military Balance 2019
February 2019

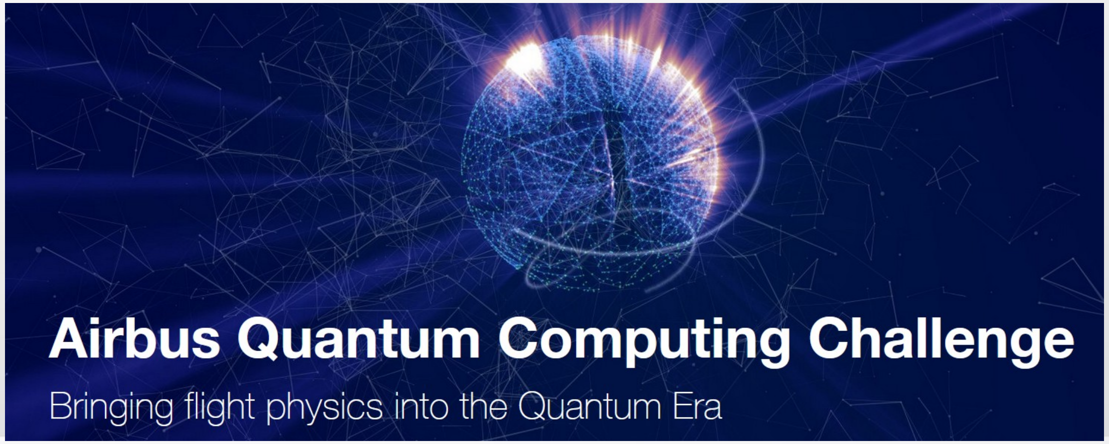
QUANTUM COMPUTING AND DEFEN… SEE CHAPTER LIST ◄ PREVIOUS NEXT ►

CHAPTER ONE, PART III

Quantum computing and defence

Potential military applications; National programmes; Quantum supremacy

The integration of quantum technologies currently represents one of the most



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Plan

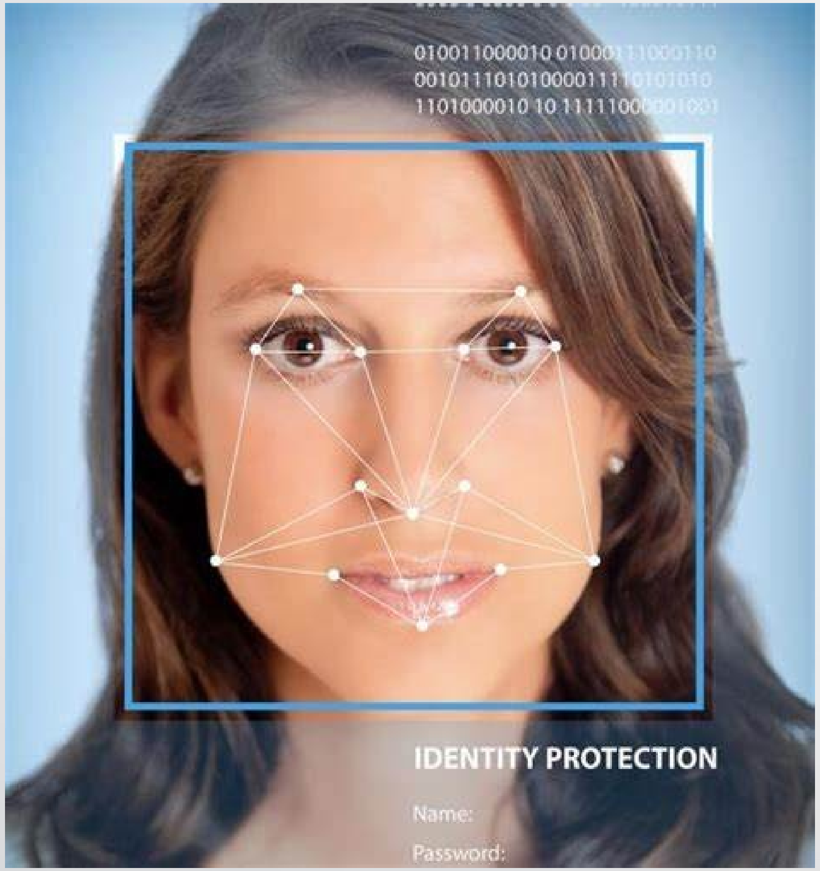
-AI applications
-AI history
-Machine Learning methods
-Deep Learning methods
-Quantum Machine Learning
-Live coding session (GoogleColab or JupyterNotebook)

AI is changing our lives

Let’s start with some real applications

AI is changing our lives

Facial recognition for security



Facial personality analysis

AI is changing our lives

Since DARPA Grand Challenge 2005

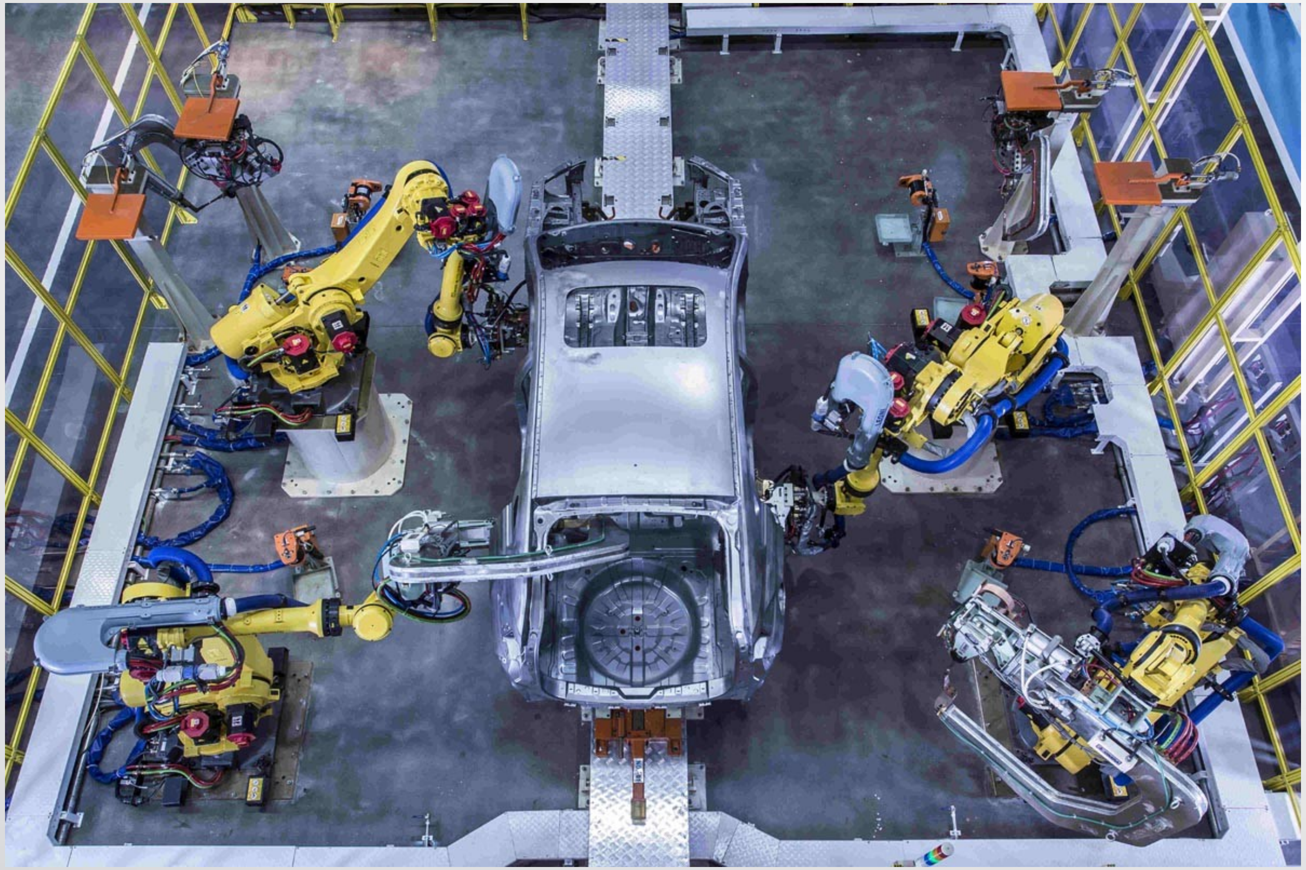
And now

Google autonomous car

Tesla autonomous car

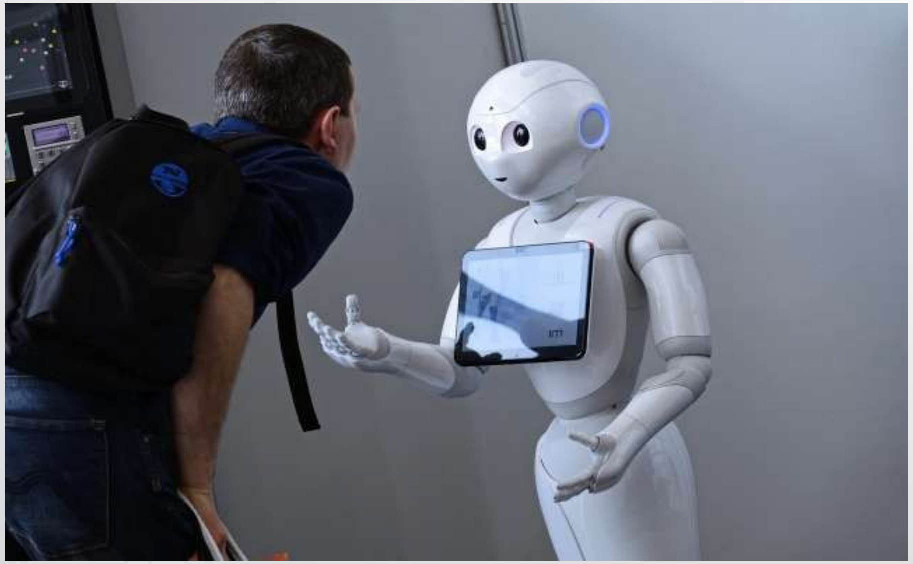
AI is changing our lives

AI in manufacturing for a smart factories



AI is changing our lives

Discreet and helpful personal assistants (example: rasa, ...)



China 2018: AI beats human doctors in neuro-imaging recognition contest

- **Cut Medical cost?**
- **Improve work efficiency?**
- **Replace doctor’s work?**
- **Standardized treatment of patients?**
- **… AI doctors?**

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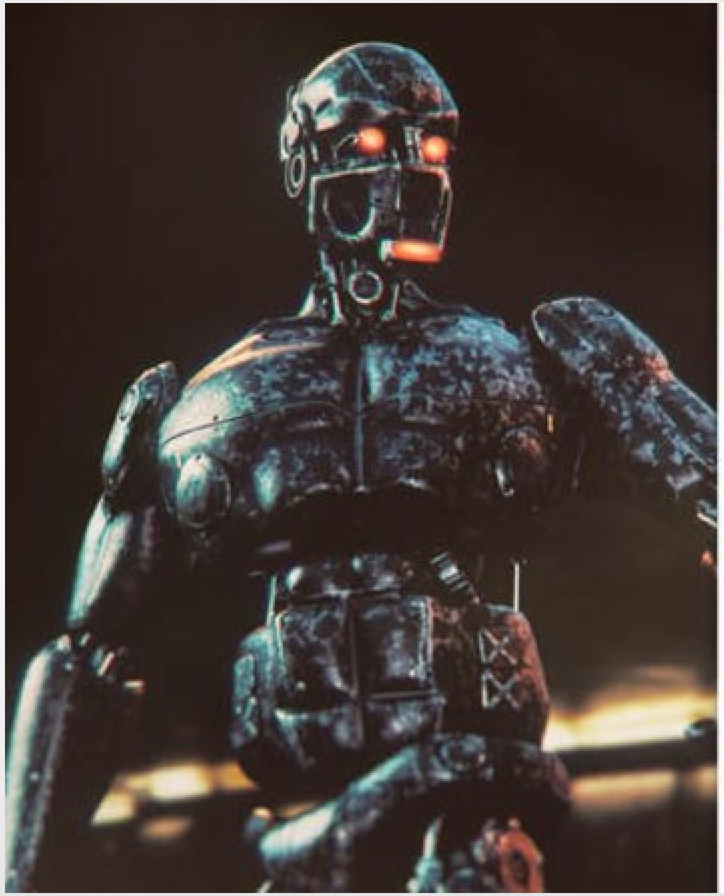
AI is changing our lives

UAV drones

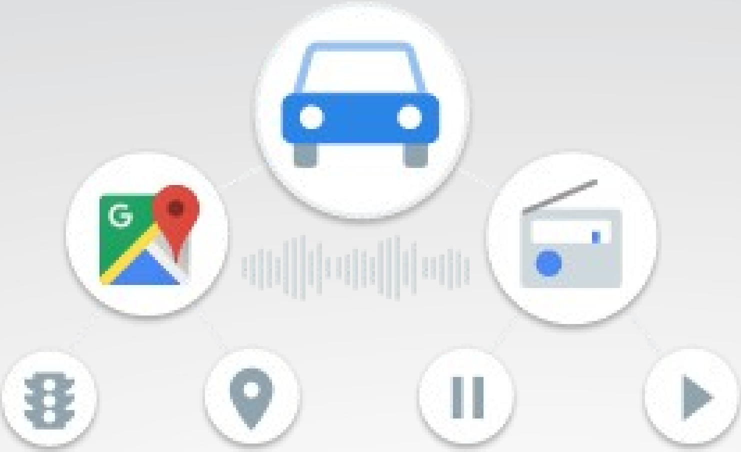
Automatic tanks

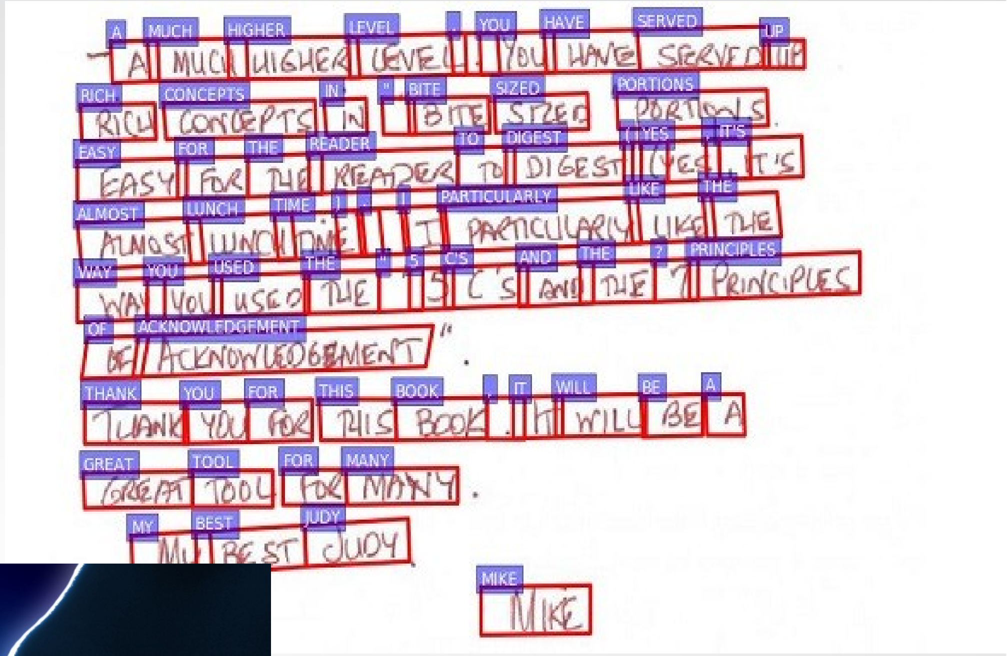
Military soldiers! (Boston Dynamics)

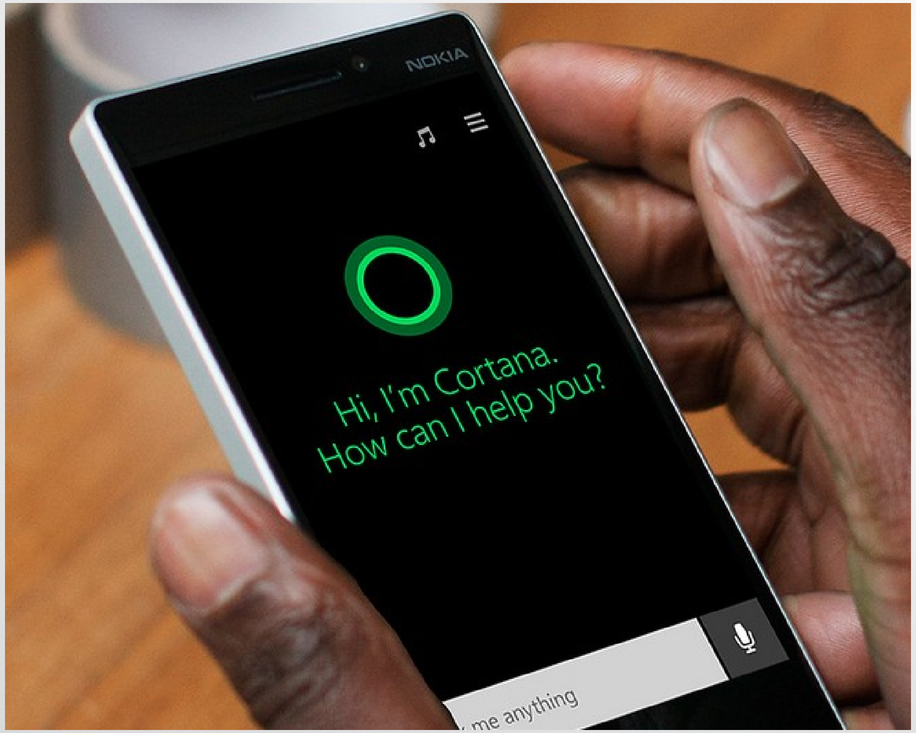


AI is changing our lives

Speech to text
Text to speech
Speech recognition







But what's AI?

AI stands for Artificial Intelligence

The ability of a **digital computer or computer-controlled robot** to perform **tasks** commonly associated with **intelligent beings**.

Imitating the intellectual processes characteristic of humans, such as the ability to reason, discover meaning, generalize, or learn from past experience.

Theoretical development began in the early 1940s with the english mathematician Alan Turing

Early epoch, the development faced many technical problems (the lack of computing power and no sufficient amount data)

Artificial Intelligence

Machine learning

Statistical learning & Reinforcement learning

Data science

Deep learning

Artificial general intelligence AGI

Deep reinforcement learning

Quantum machine learning

Avènement de l’intelligence artificielle: test de Turing, premier réseau de neurones inspiré de la biologie mais manque de ressources informatiques

Années: 1950 1980 1990 2000 2010 2020

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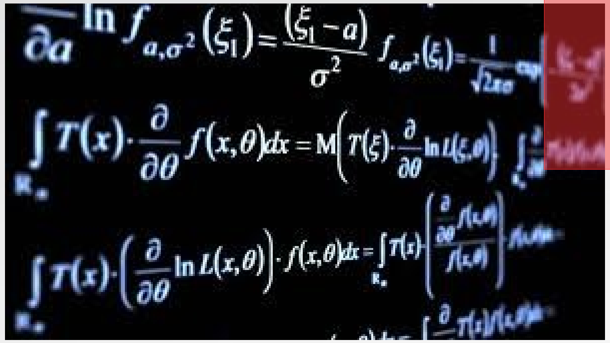
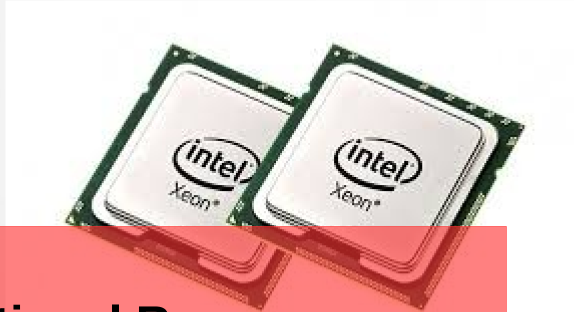
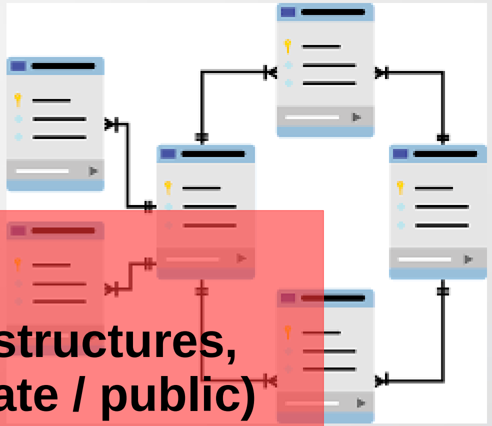
AI a history of a closed triangle

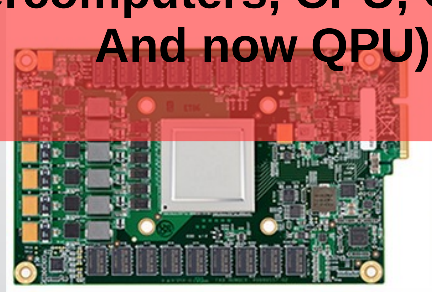


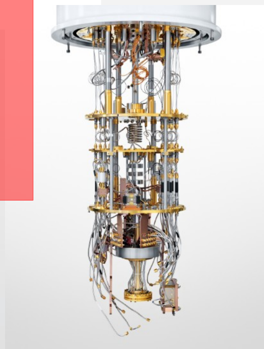
Mathematical models
Algorithms





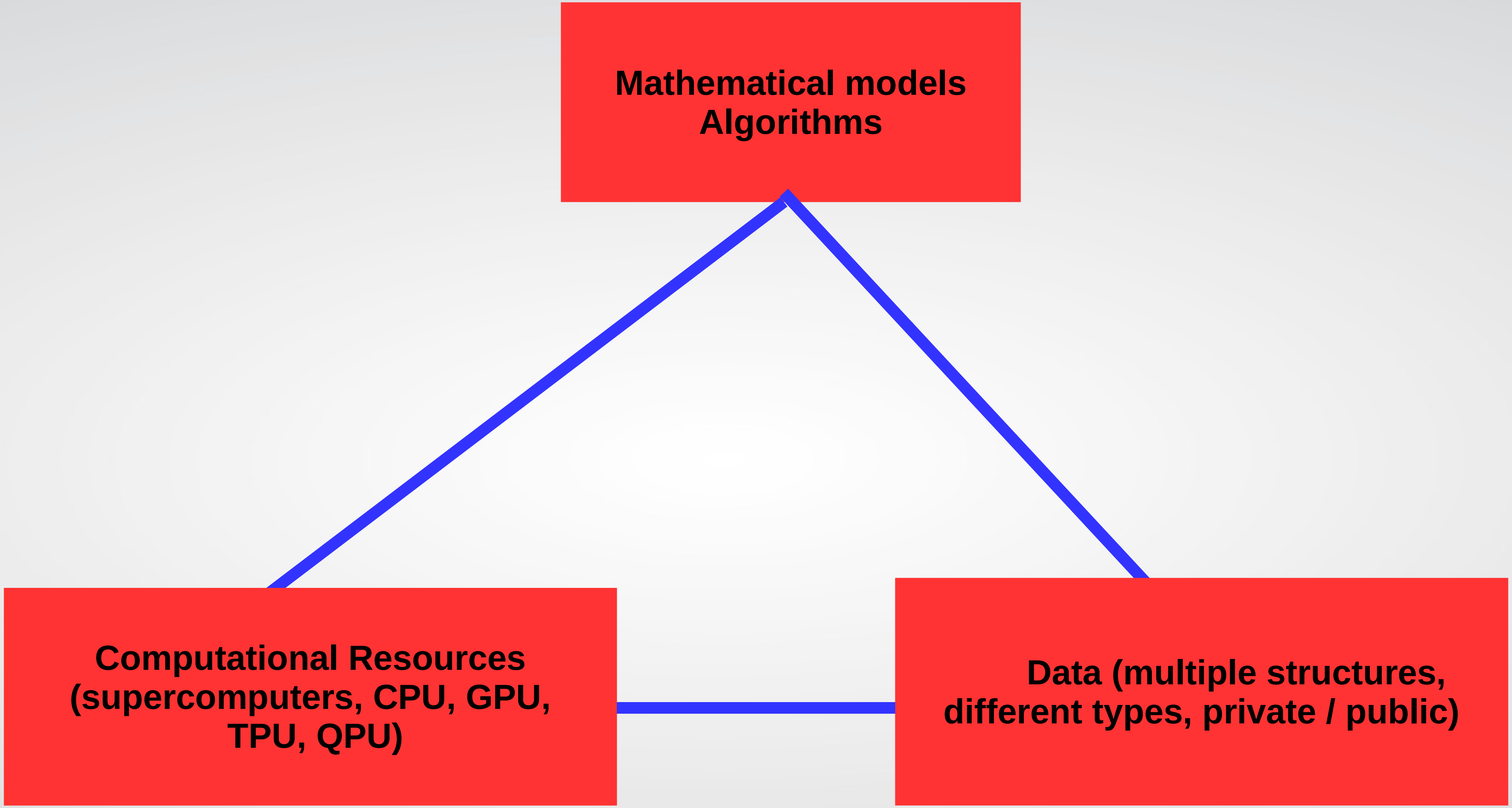
Computational Resources
(supercomputers, CPU, GPU, TPU
And now QPU)





Data (multiple structures,
different types, private / public)

AI a history of a closed triangle



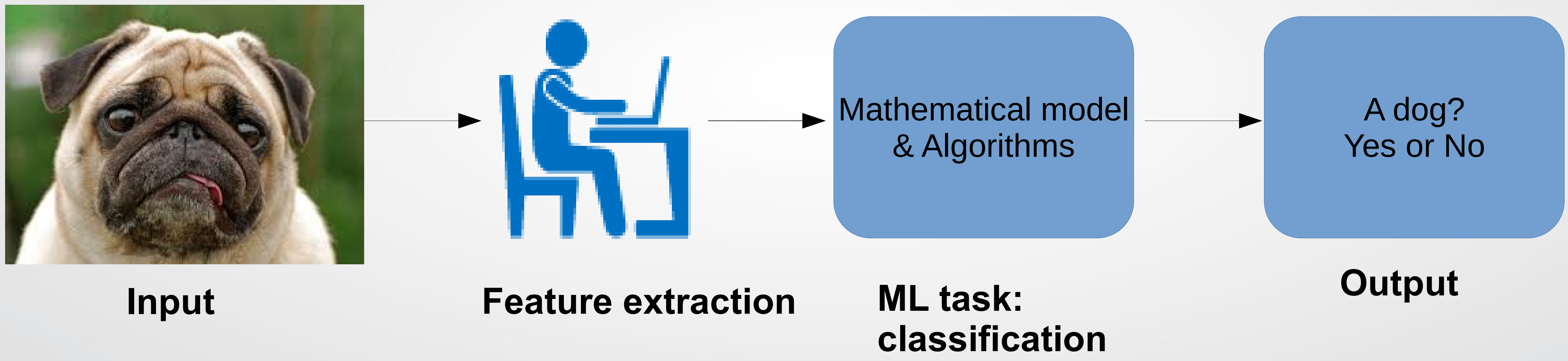
AI in action: machine learning (ML)

What is machine learning?

Machine learning is a subset of artificial intelligence.

Machines have the ability to learn without being explicitly programmed but we need to provide a mathematical model, a database and a set of features.

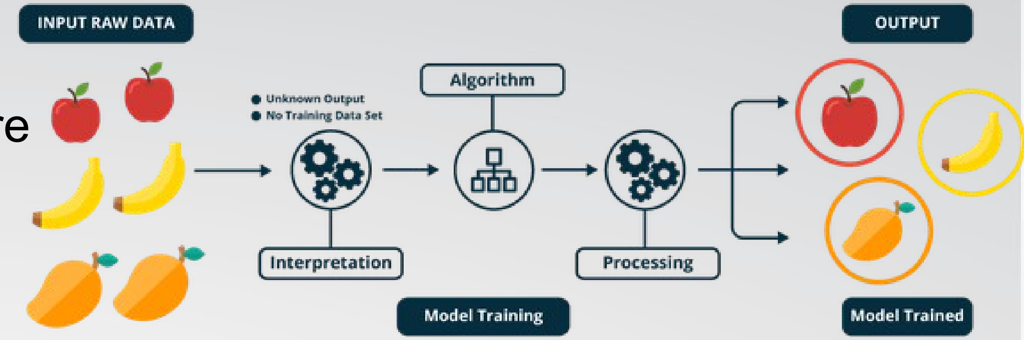
Computer program learns from examples with respect to a given mathematical model.



Machine learning methods

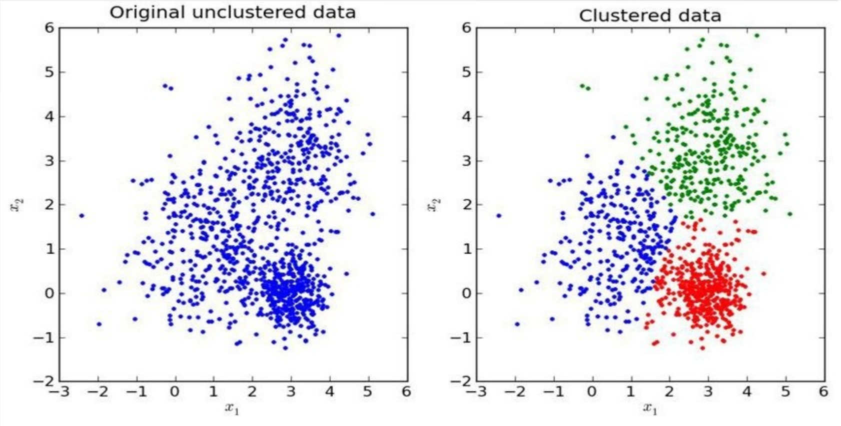
- Supervised machine learning:

- Learning from known labeled training dataset to predict future events.
- Use mathematical models.



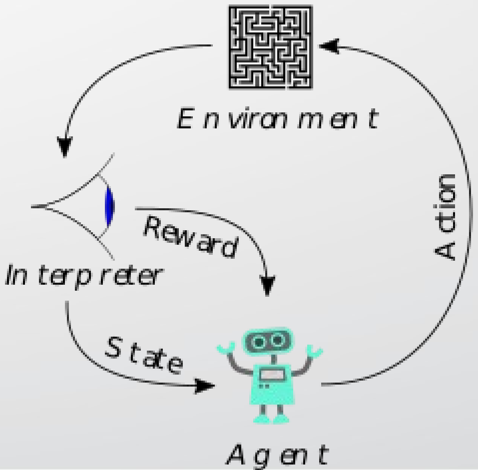
- Unsupervised machine learning:

- Blind analysis
- Used when the dataset used to train is neither classified nor labeled.
- Use mathematical models.
- Use similarity.



- Reinforcement machine learning:

- Absence of training dataset only learn from its experience.
- Taking suitable action to maximize reward in a particular situation.



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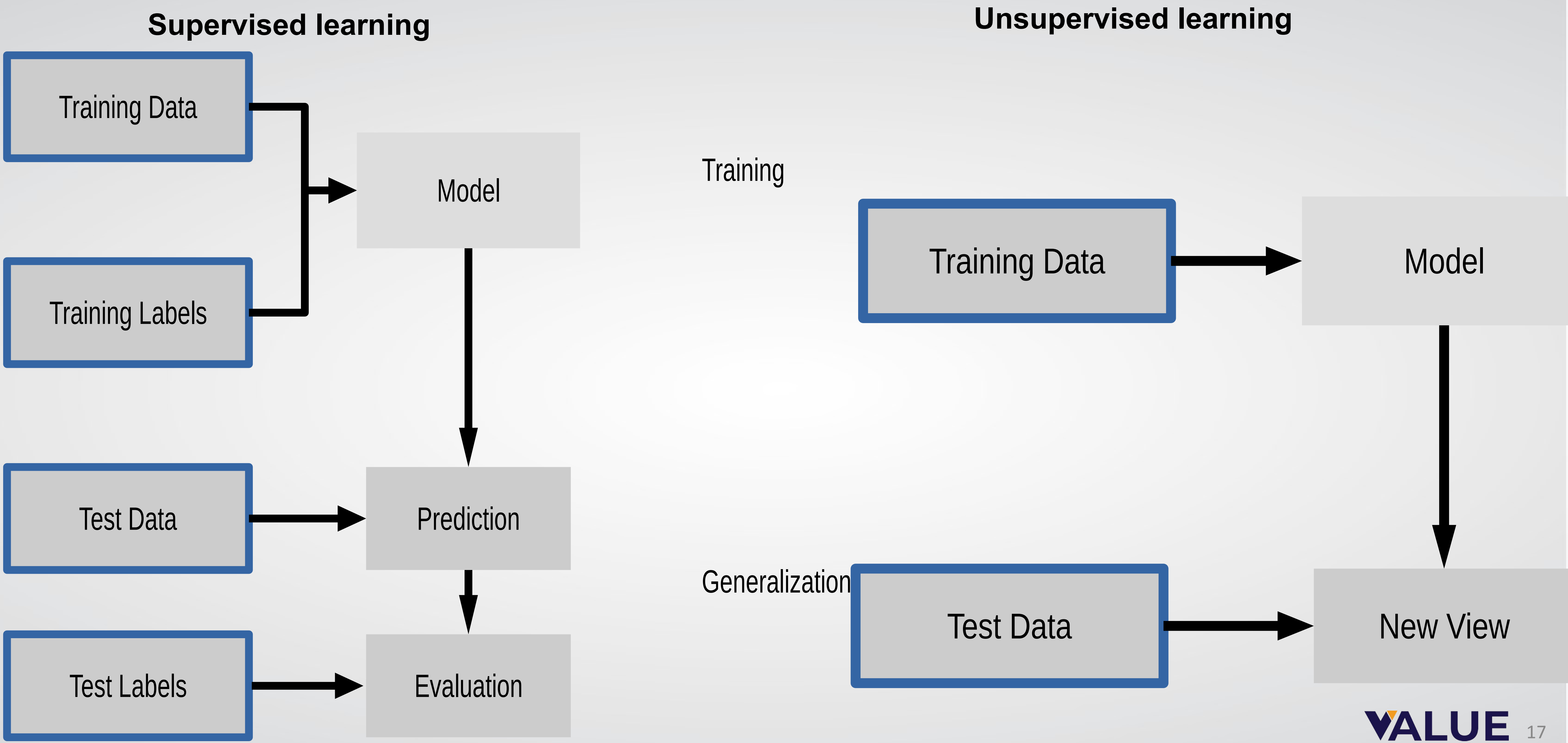
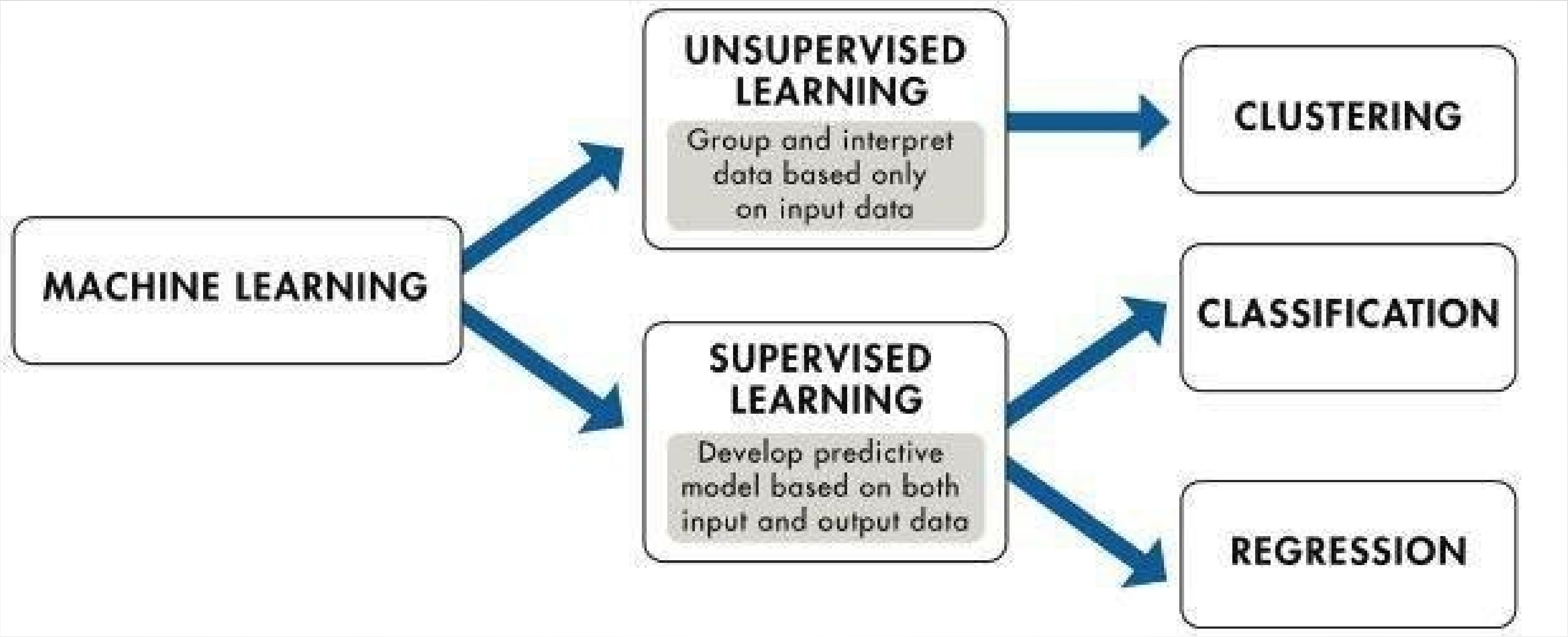
Machine learning: How to learn?



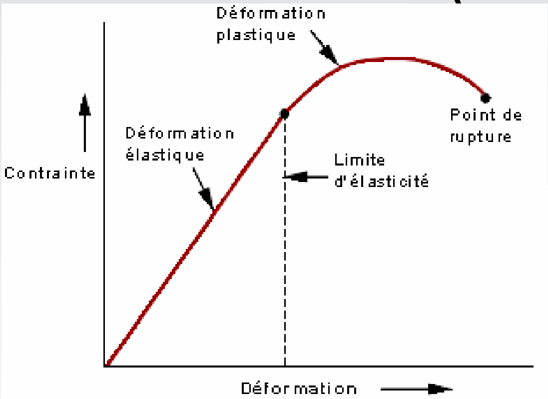
Machine learning methods: more in depth

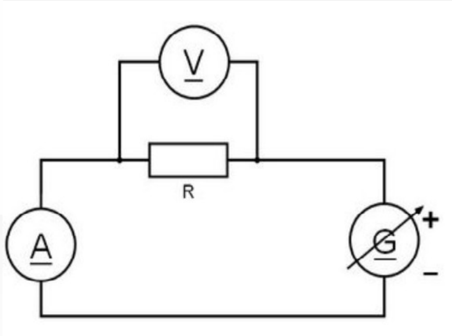


- **Regression:** Used to predict a continuous value
  -
- **Classification:** Used to predict discrete value (a discrete class label output for an example)
- **Clustering:** Based on similarity, grouping a set of objects the same group

Machine learning methods: Regression

Start from a simple problem:
Can we predict house price? Electric potential difference? (Ohm's law)
The mechanical stress (Hooke's law)?

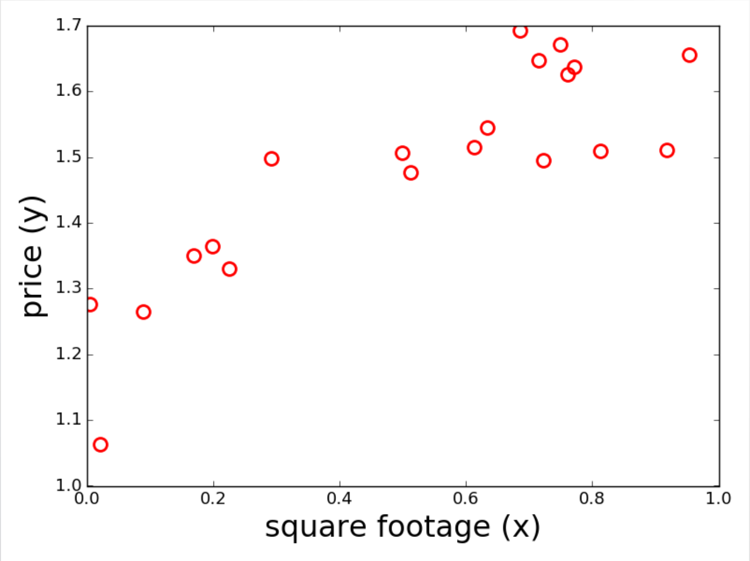


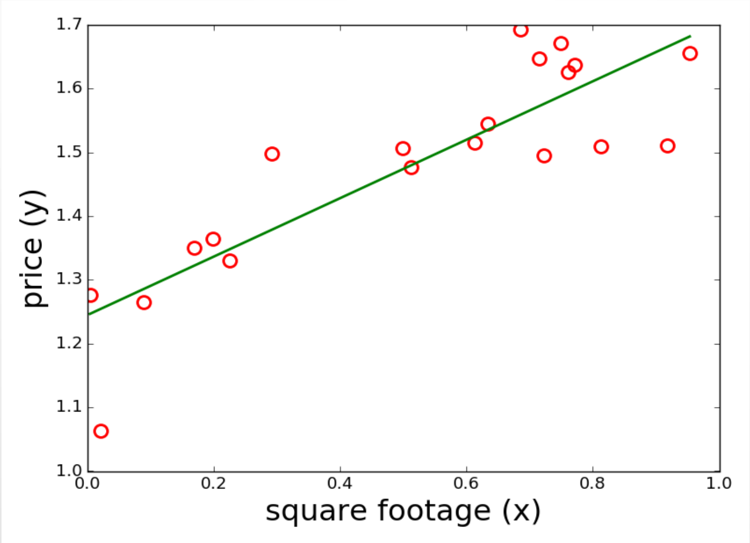


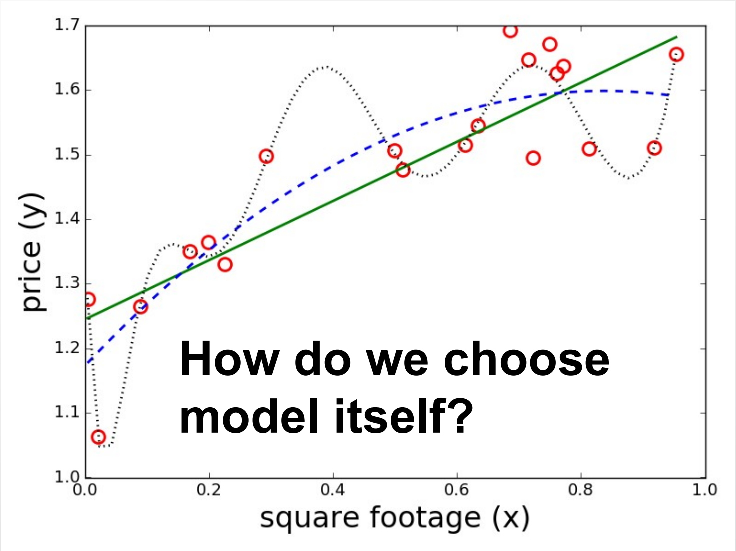
Least Squares Regression

- "Training set" consists of *m* examples
- Each example has *n* attributes (**x**) and one label (y)

Our goal: given a new example, x', can we predict its label, y'?







Machine learning methods: Least Square Regression

Start from a simple problem: can we predict house price?

- "Training set" consists of *m* examples
- Each example has *n* attributes (**x**) and one label (y)

Our goal: given a new example, x', can we predict its label, y'?

Hypothesis:

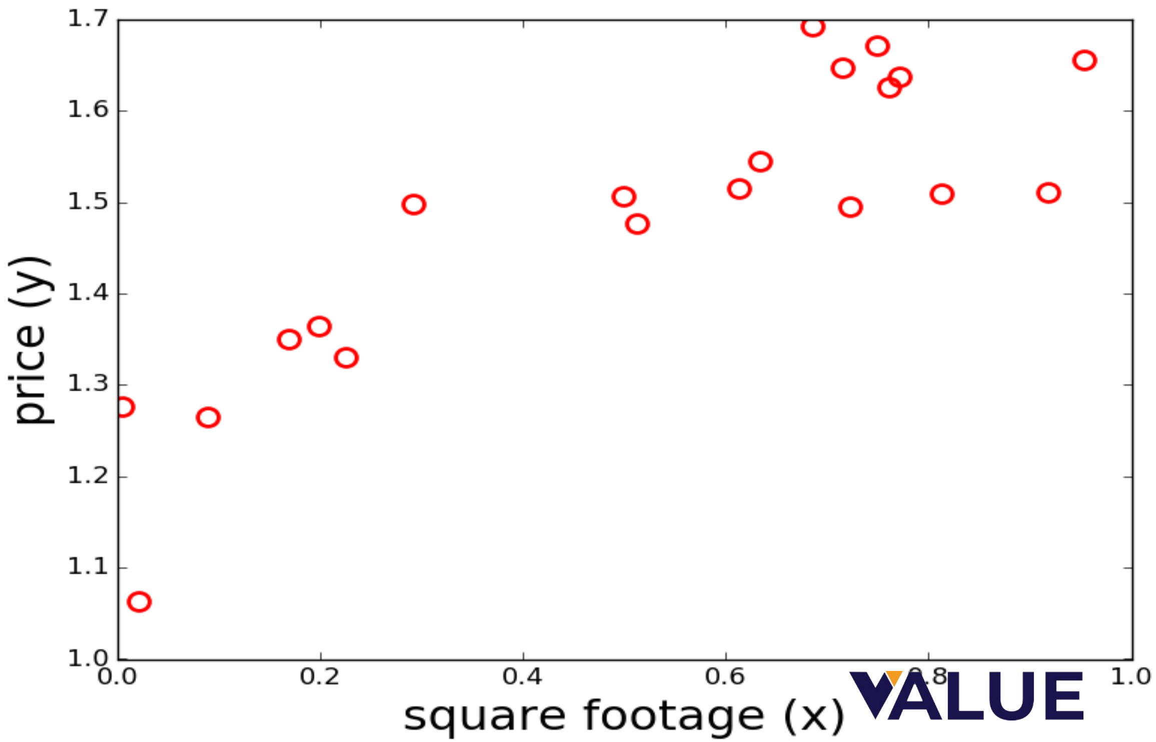
example *i*

sum over *n* attributes

$$h_\theta(x^{(i)}) = \sum_{j=0}^{n} \theta_j x_j^{(i)} = \theta^T x^{(i)}$$

guess for y

$$h_\theta(x^{(i)}) = \theta_0 + \theta_1 x_1^{(i)}$$



VALUE

The core of machine learning: how do we learn best θ given data x,y?

Need a metric for “best”: Cost/Loss function

$$h_\theta(x^{(i)}) = \theta^T x^{(i)}$$

Examples: mean square error (MSE), absolute error, etc.

MSE:

# of examples

groundtruth=label

$$J(\theta) = \frac{1}{2}\sum_{i=1}^{m}(h_\theta(x^{(i)}) - y^{(i)})^2$$

$$= \frac{1}{2}(X\theta - \vec{y})^T(X\theta - \vec{y})$$

n+1 x 1

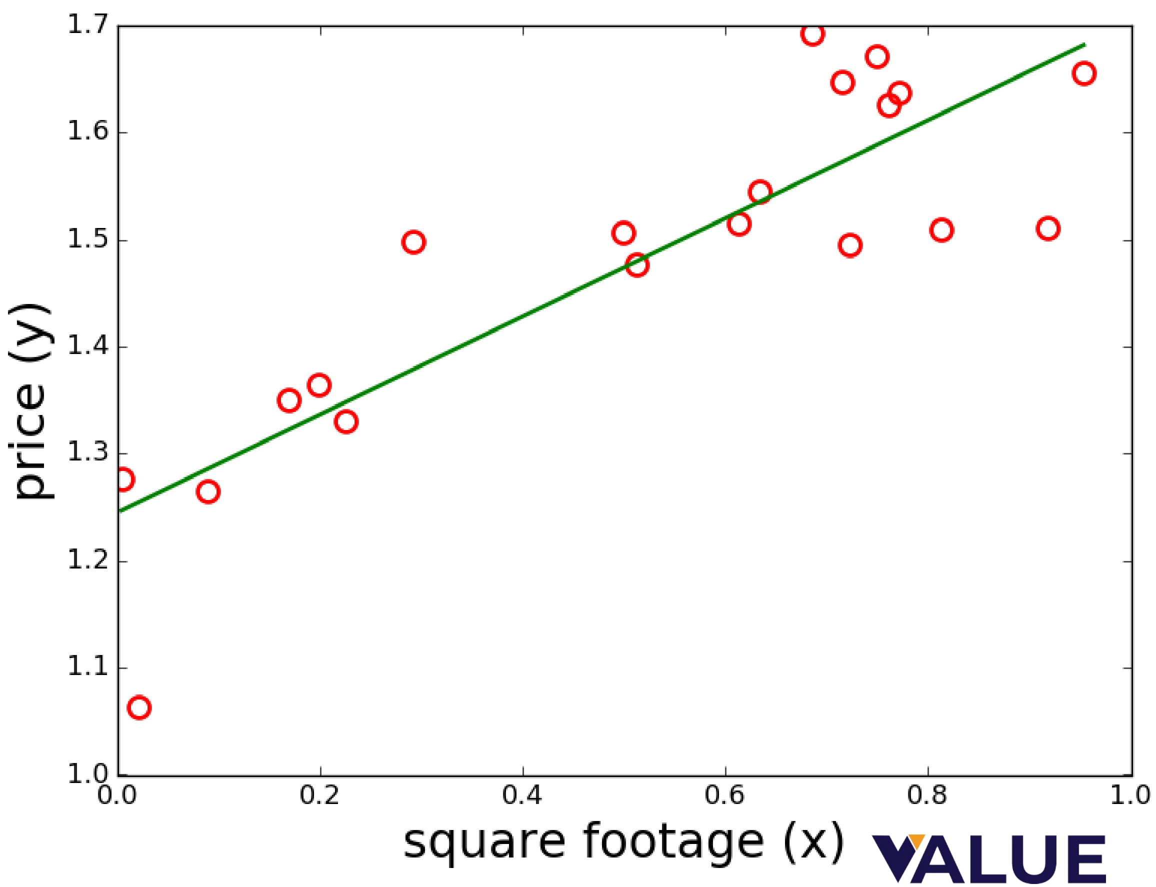
m x n+1

m x 1

Optimal θ:

$$\theta = (X^TX)^{-1}X^T\vec{y}.$$

Least Squares Regression



The core of machine learning: how do we learn best θ given data x,y?

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MSE:

# of examples

groundtruth=label

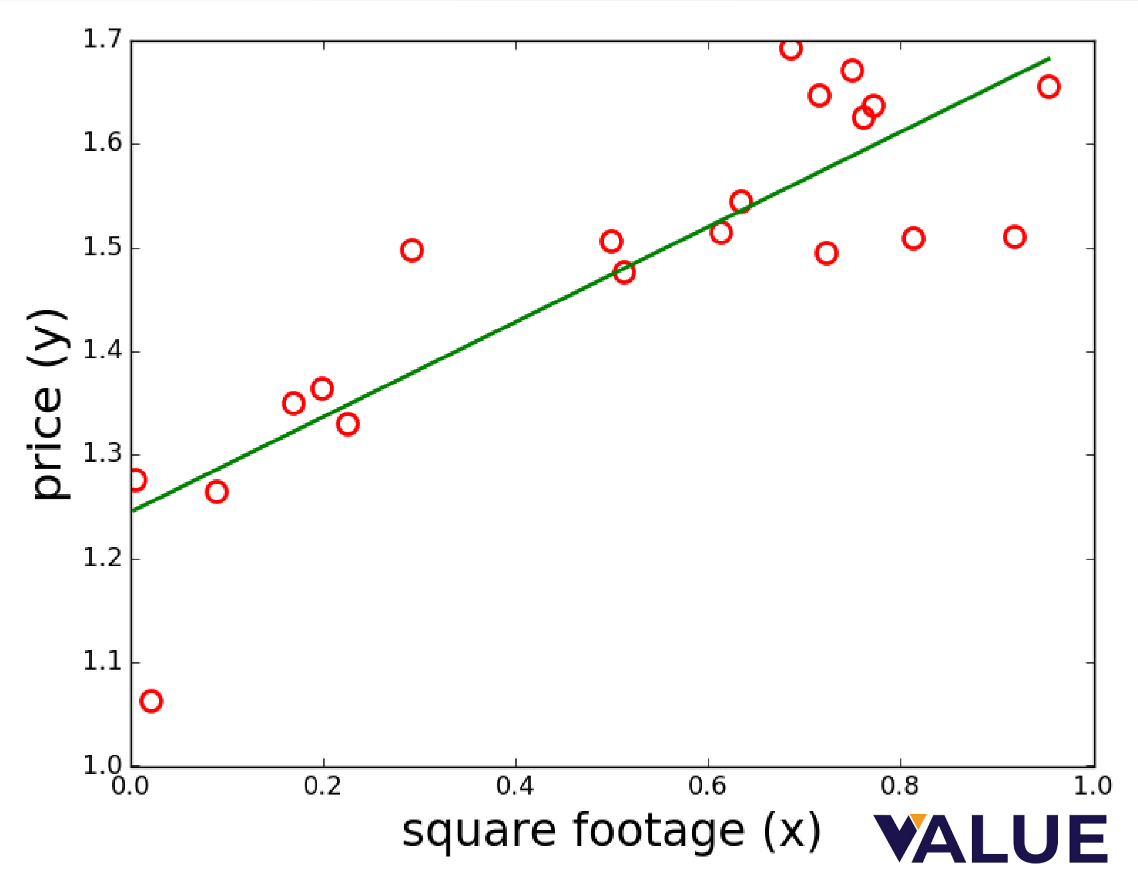
$$J(\theta) = \frac{1}{2}\sum_{i=1}^{m}(h_\theta(x^{(i)}) - y^{(i)})^2$$

$$\theta_j := \theta_j - \alpha \underbrace{\frac{\partial}{\partial\theta_j} J(\theta)}_{\sum_{i=1}^{m}\left(y^{(i)} - h_\theta(x^{(i)})\right) x_j^{(i)}}$$

Learning rate

“Stochastic gradient descent”: update θ after each *i*

Least Squares Regression



VALUE

“Hyper-parameters”: how do we choose model itself?

e.g. pick model architecture, cost function, learning rate, etc.

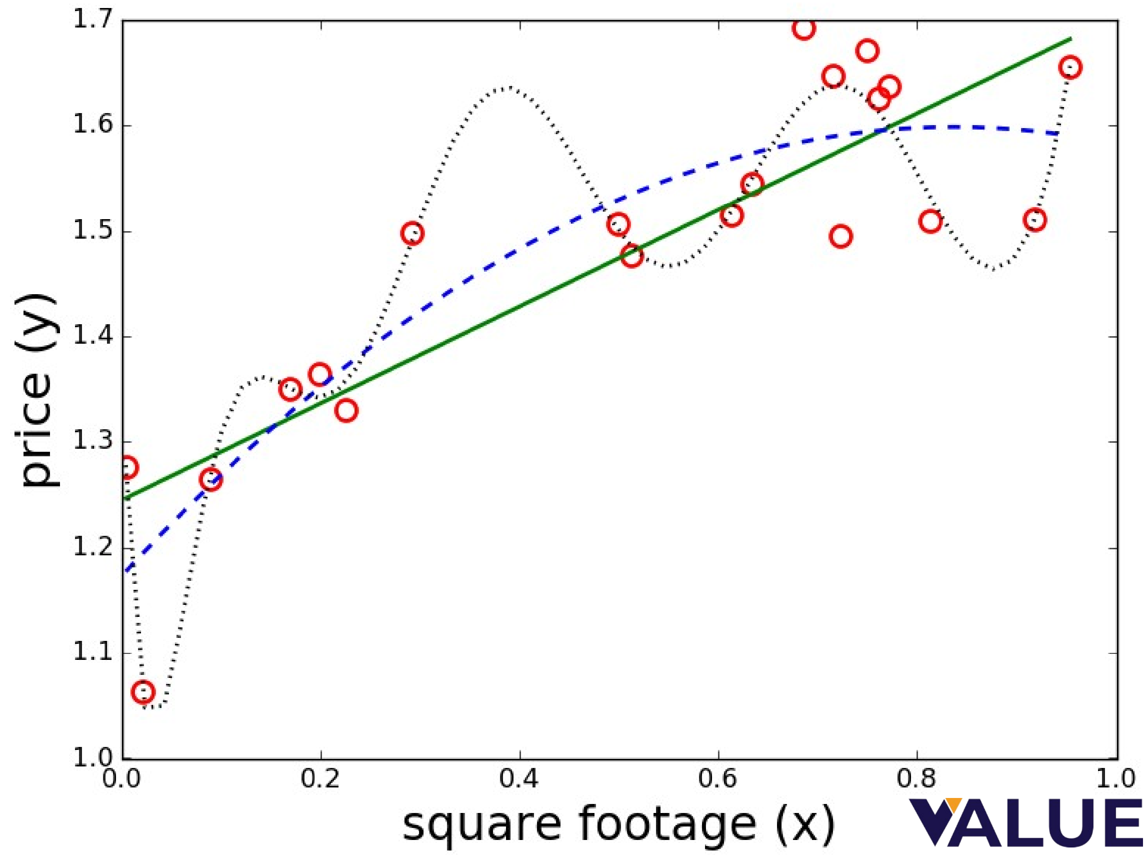
Least Squares Regression

$$h_\theta(x) = \theta_0 + \theta_1 x + \theta_2 x^2$$
$$= \sum_{k=0}^{p} \theta_k x^k$$

$$x \to \phi(x) = [x, x^2, ...]$$

attributes features

Least Squares Regression



VALUE

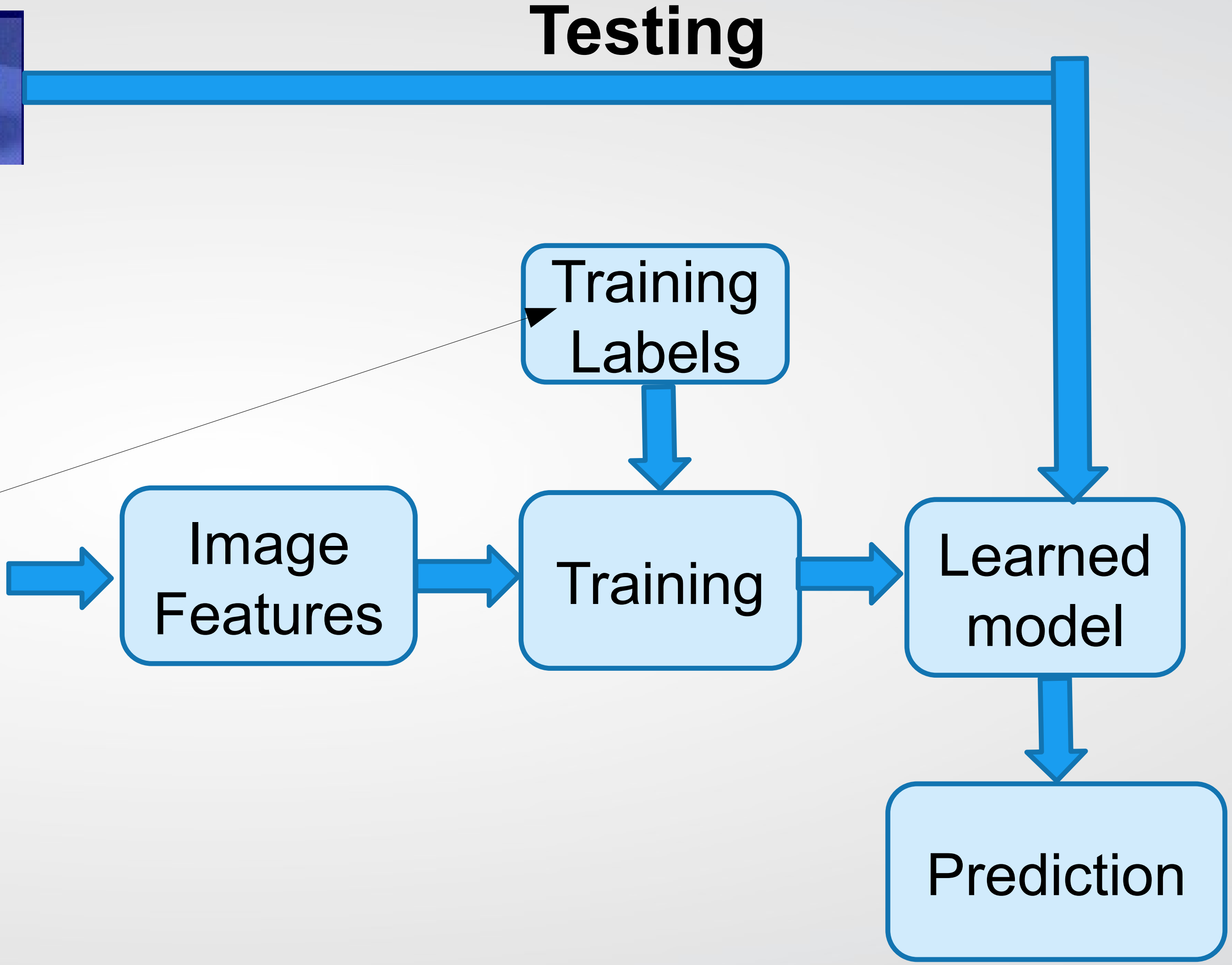
Machine learning methods: Classification

- Task T: Can you identify this object?

Training

Training Images:

- Experience E:
  Training Examples



Generalization of mathematical approach for regression and classification: Multilinear regression, Logistic regression, Poisson regression, Probit regression

$$p(y|\cancel{X};\vec{\theta}) = f(y|g(\vec{w}^T\cdot\vec{\phi}(X));\sigma^2)$$

$$\boxed{y = Y = \vec{y}} \in \mathcal{M}_{n,1}(\mathbb{R} \text{ ou } \mathbb{Z})$$

$$\vec{x} = X \in \mathcal{M}_{n,m}(\mathbb{R})$$

$$\vec{w} = \begin{pmatrix} w_1 \\ w_2 \\ \vdots \\ w_d \end{pmatrix}$$

$$\sigma^2(X) = \sigma^2$$

$$\vec{\theta} = (\vec{w};\sigma^2) = \begin{pmatrix} \vec{w} \\ \sigma^2 \end{pmatrix}$$

$$\vec{\Phi}(X) = [1, x, x^2, \dots, x^d]$$

$$g(z) = z$$

$$g(z) = \mathrm{sigm}(z) = \frac{1}{1+e^{-z}}$$

$$g(z) = e^{z}$$

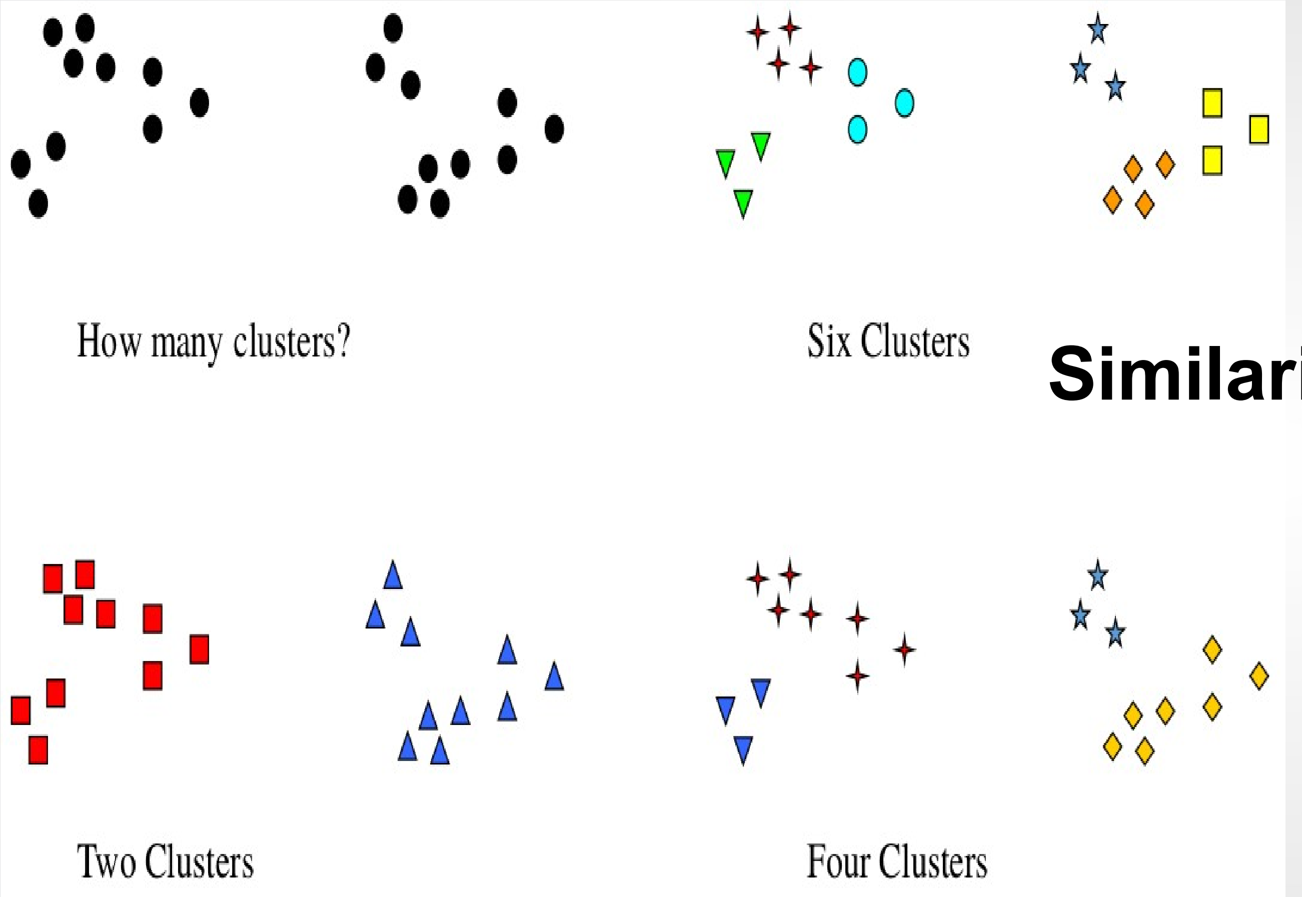
$$g(z) = \frac{\varphi^{-1}(z)}{\sqrt{\frac{\pi}{8}}}$$

LINEA

$$L(\vec{\theta}) = \left(\frac{1}{2\pi\sigma^2}\right)^{\frac{n}{2}} e^{-\frac{1}{2\sigma^2}\sum_{i=1}^{n}\left(y_i - \underbrace{(w_0 + w_1 x_i)}_{X\vec{w}}\right)^2}$$

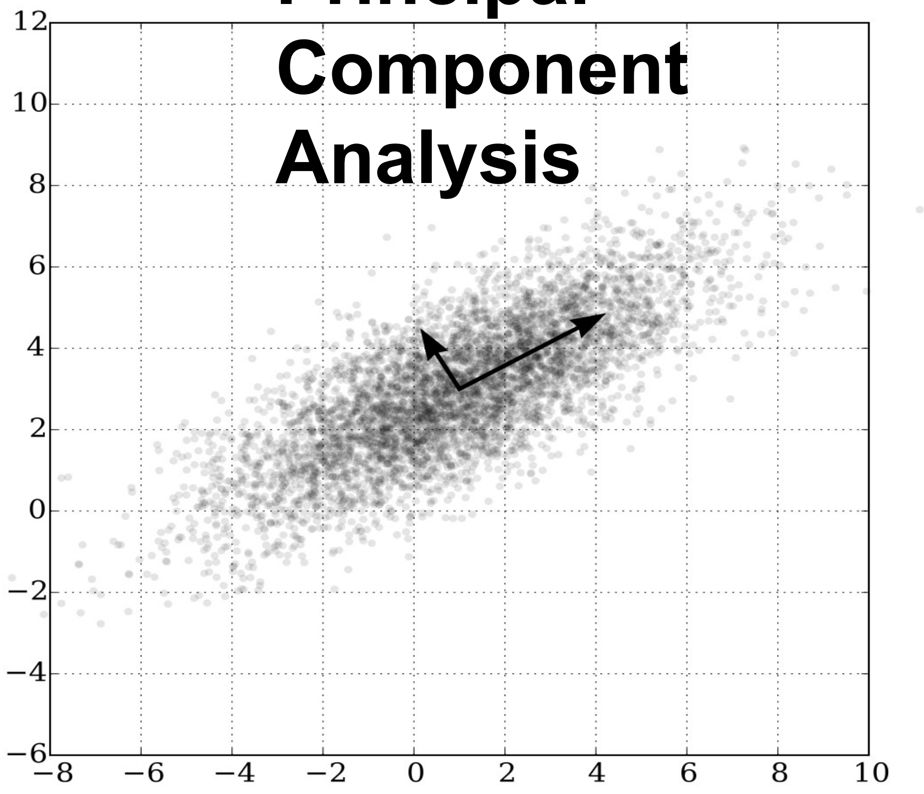
$$\vec{\theta} = (\vec{w};\sigma^2)$$

Machine learning methods: Clustering/Reduction of dimensions



Similarity

Principal Component Analysis

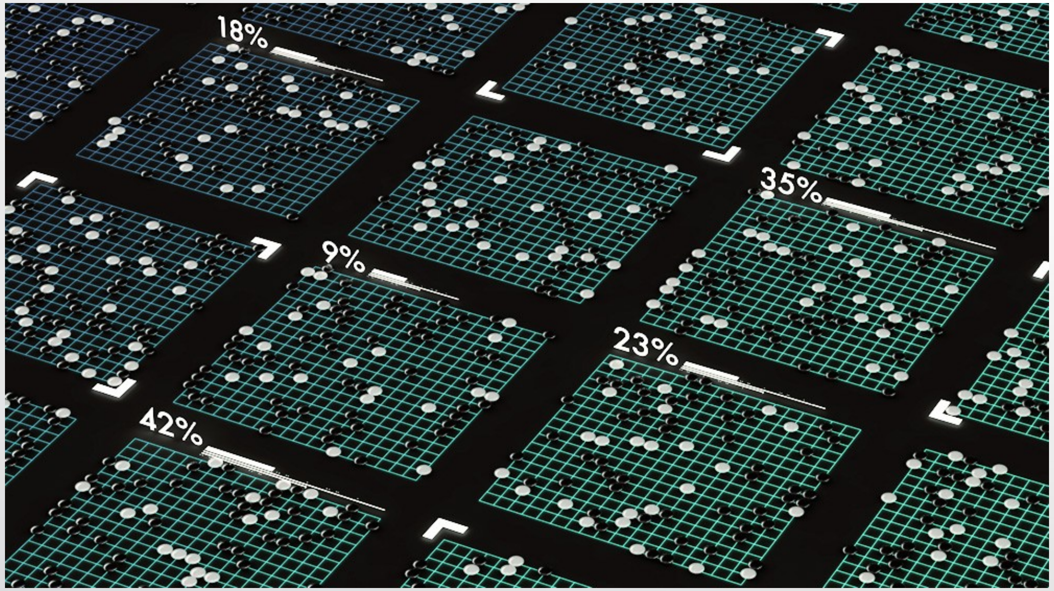


AI methods: Reinforcement learning

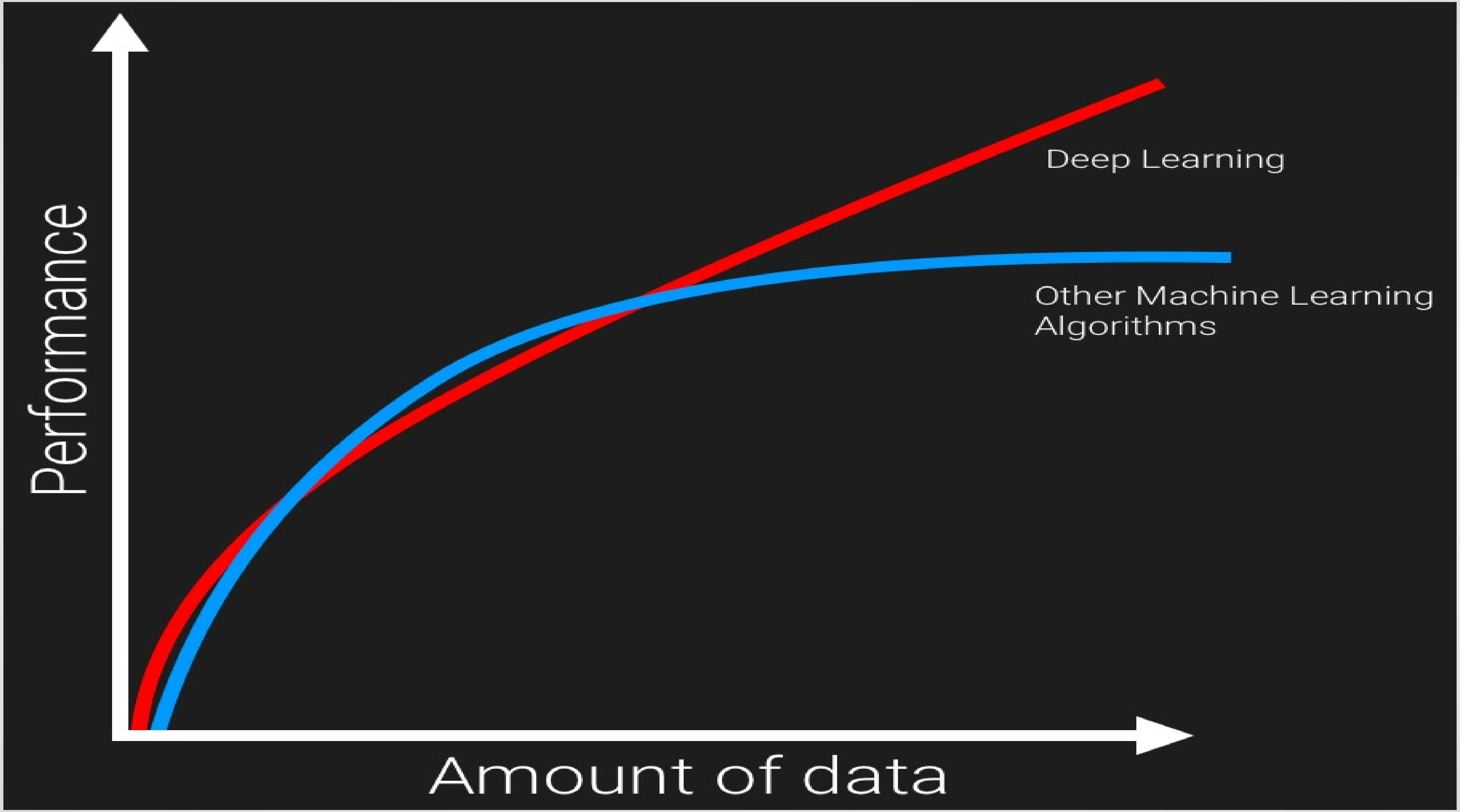
Google's machine AlphaGo wins Go master players

The machine plays against itself

Parties simulation



Machine learning limitations: Performance saturation

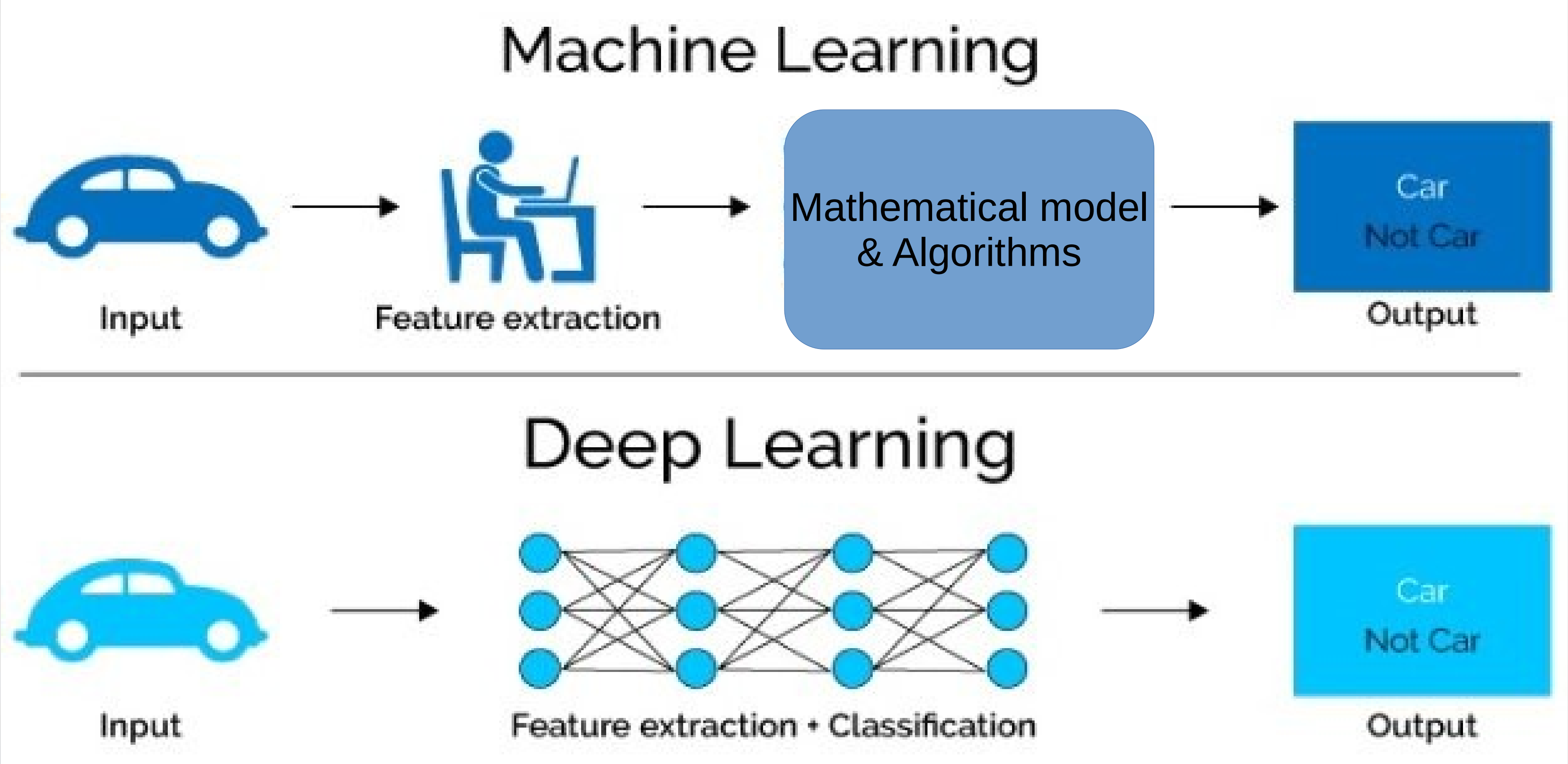


VALUE

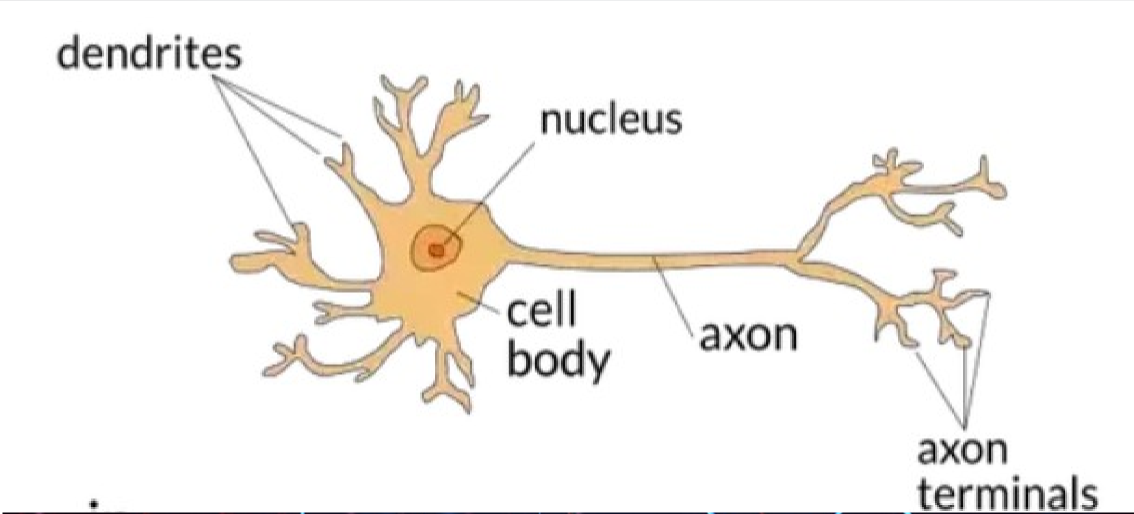
Deep learning

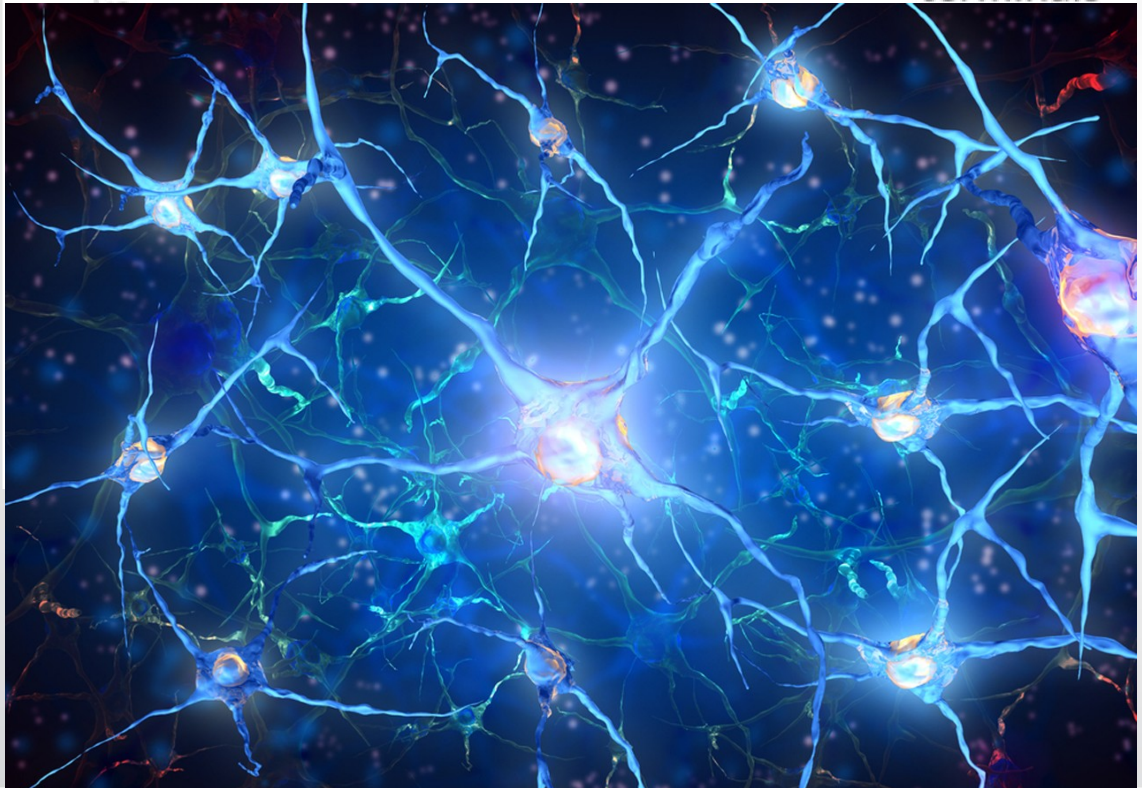
- Deep learning is subfield of machine learning based on artificial neural networks.

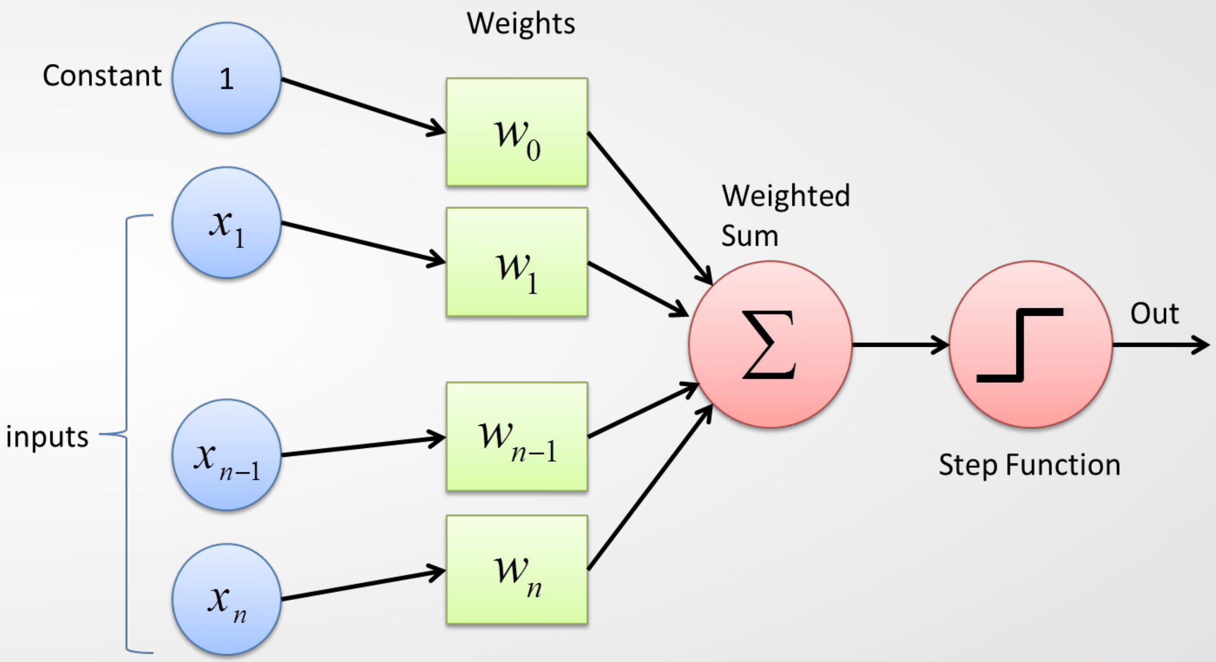
- Deep learning is inspired from the humain brain



Deep learning: origins







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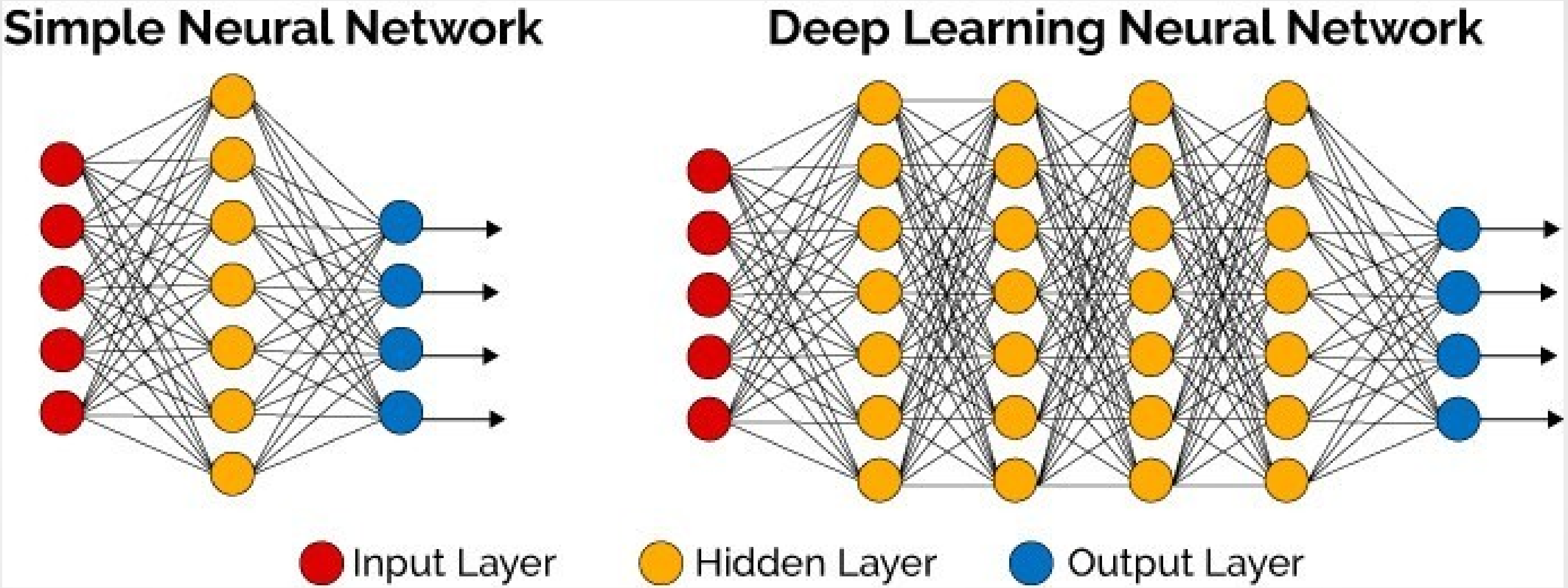
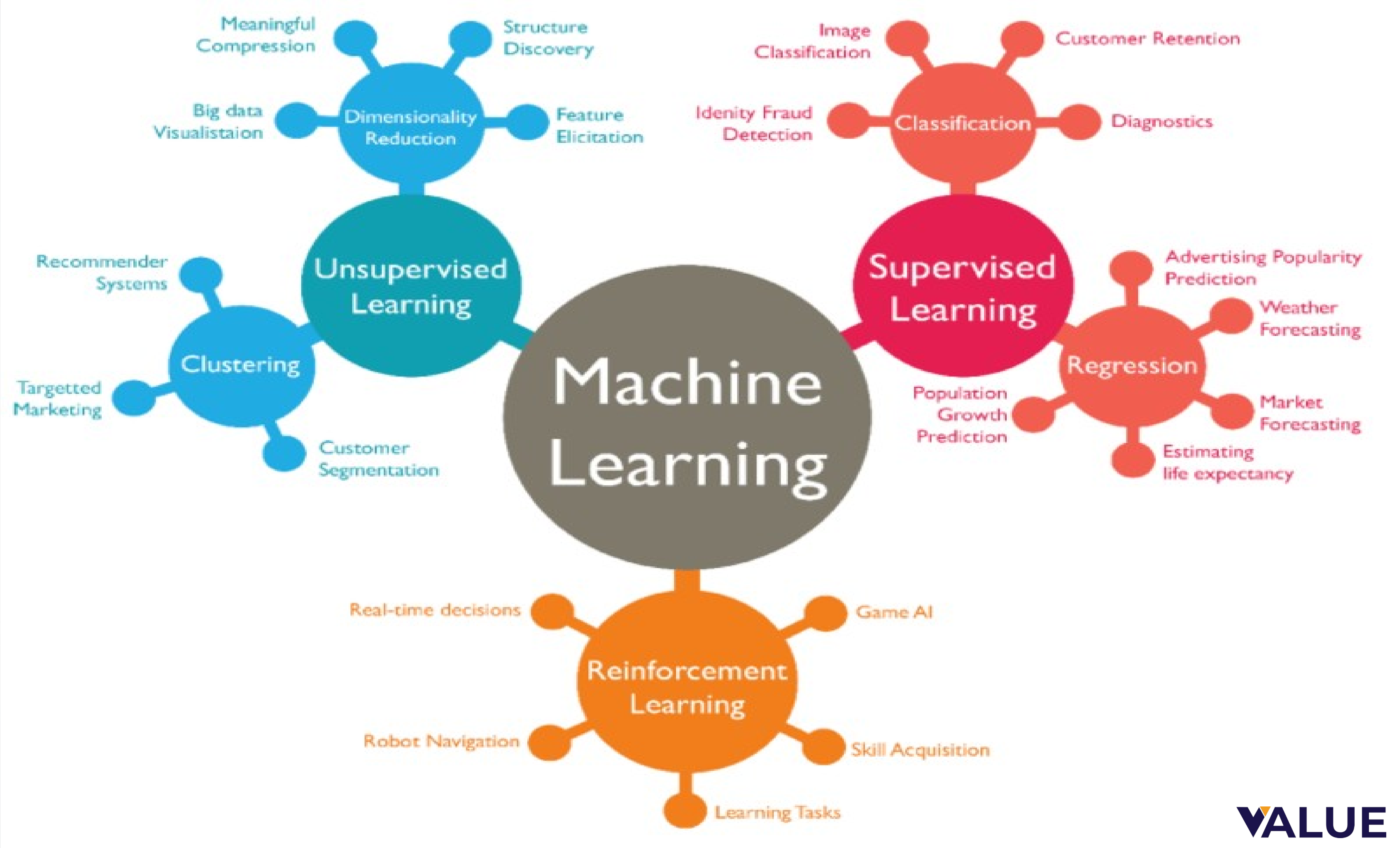
Deep learning: Imitation of the humain brain

Input



Output


Machine Learning
Unsupervised Learning
Dimensionality Reduction
Meaningful Compression
Structure Discovery
Big data Visualistaion
Feature Elicitation
Clustering
Recommender Systems
Targetted Marketing
Customer Segmentation
Supervised Learning
Classification
Image Classification
Customer Retention
Idenity Fraud Detection
Diagnostics
Regression
Advertising Popularity Prediction
Weather Forecasting
Population Growth Prediction
Market Forecasting
Estimating life expectancy
Reinforcement Learning
Real-time decisions
Game AI
Robot Navigation
Skill Acquisition
Learning Tasks

VALUE

Quantum machine learning

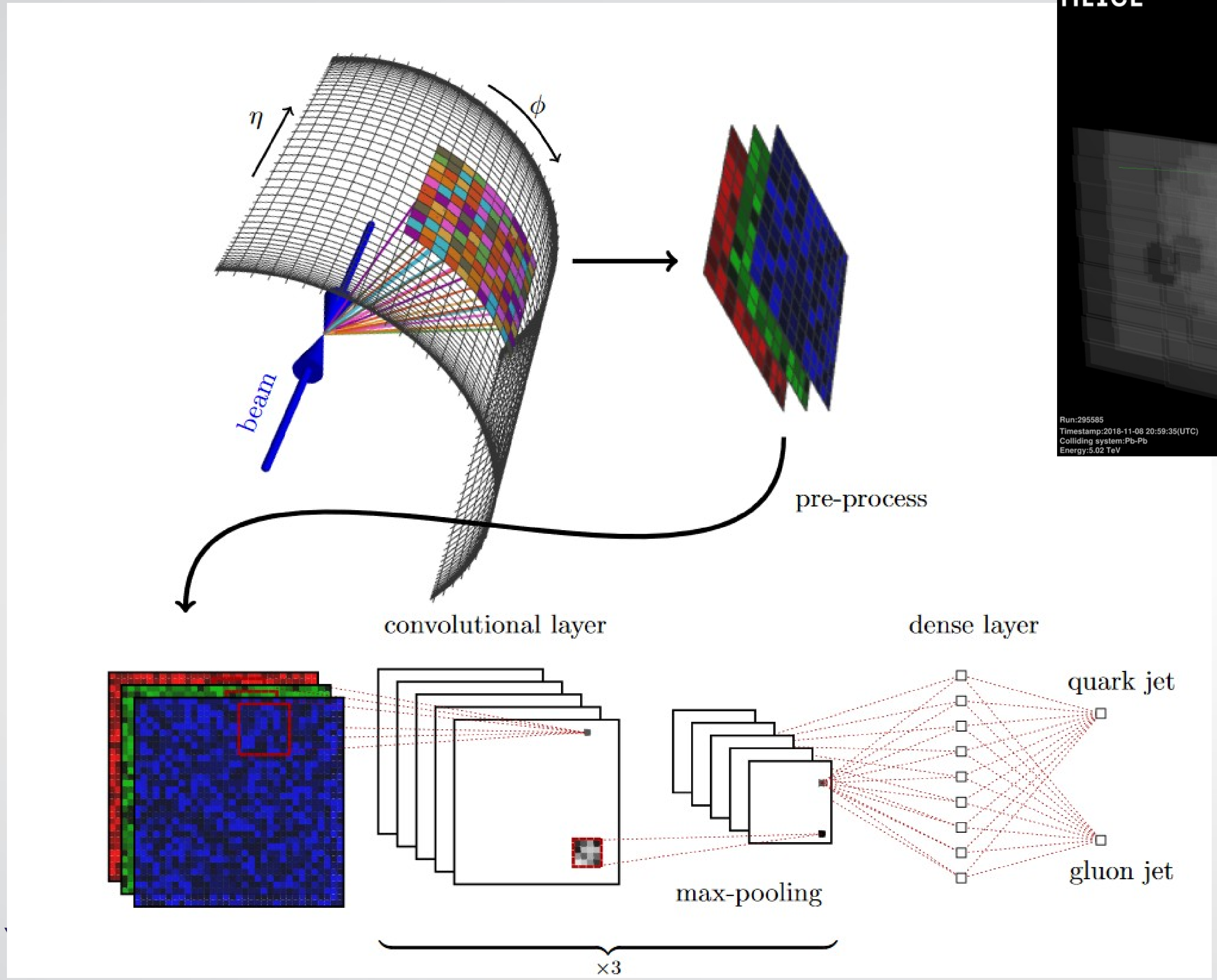
Classical data
+
Classical computing

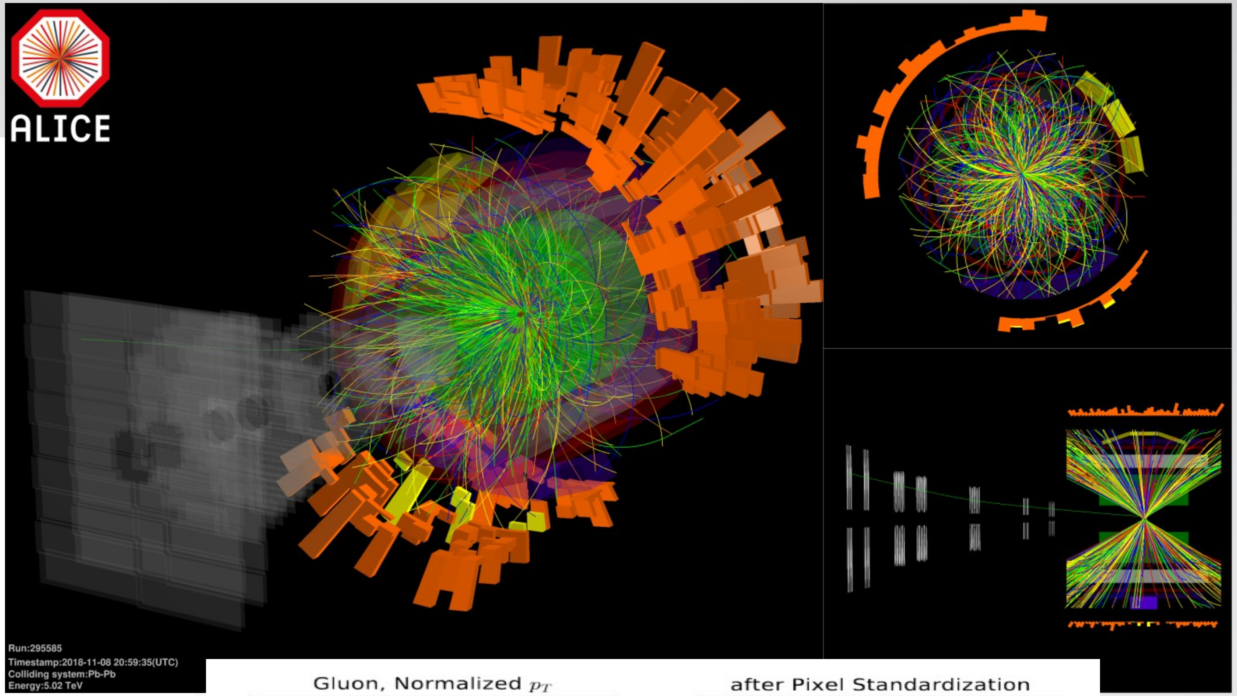
Quantum data
+
Classical computing

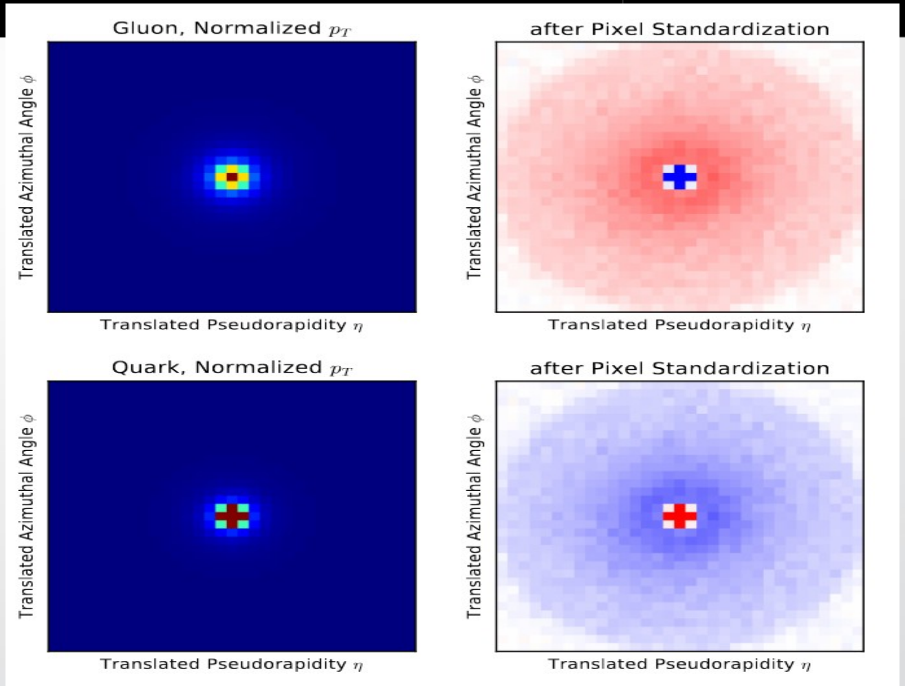
Classical data
+
Quantum computing

Quantum data
+
Quantum computing

Quantum data/Classical computing: reconstruction the data of a quantum experiment with CNN network







Deep learning in color: towards automated quark/gluonjet discrimination arXiv:1612.01551v3 [hep-ph] 4 Sep 2018

Classical data/Quantum computing: three families of algorithms

Gate circuits:

Search - Grover
QFT - Shor
Deutsch

Annealing:

Direct Annealing
Adiabatic Evolution

Variational:

Eigensolvers
Classifiers
Autoencoders

Classical data/Quantum computing: Eigensolvers

En mécanique quantique, une mesure réalisée sur un système quantique permet de déterminer à chaque fois les valeurs propres et les vecteurs propres de l'observable qui est représentée par une matrice.

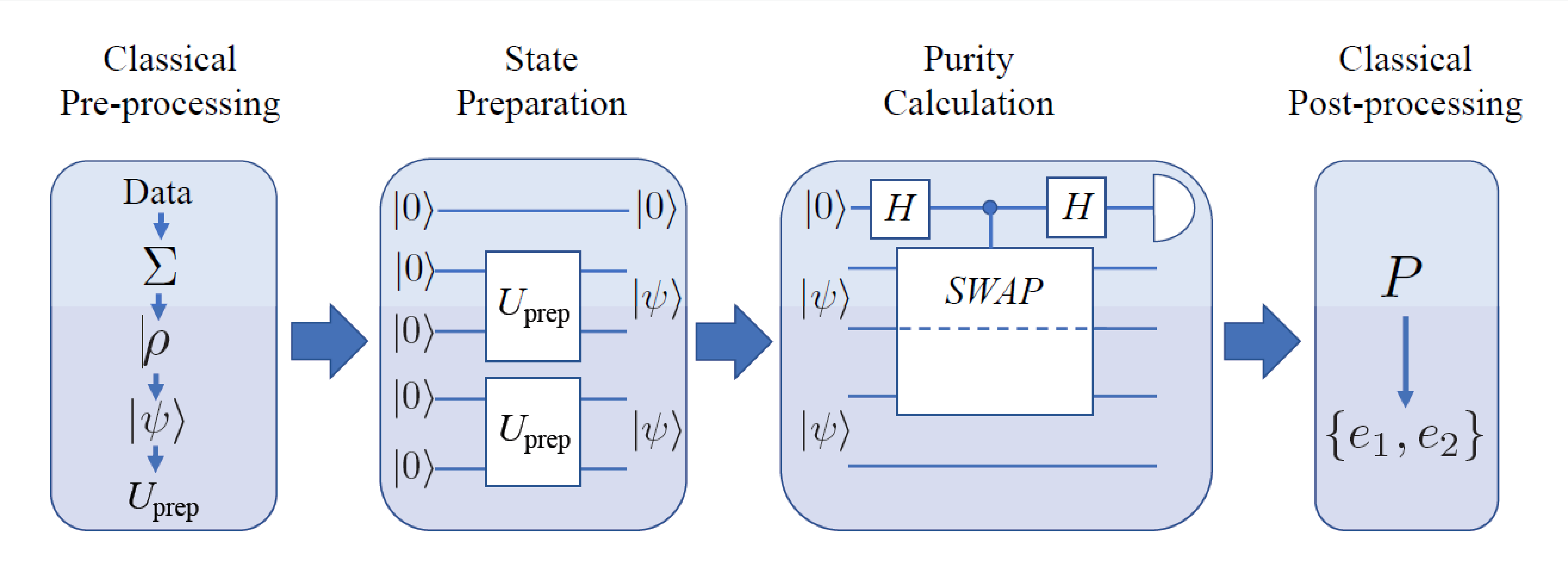
$$A\vec{x} = \vec{b}. \qquad A^{-1}|b\rangle = |x\rangle$$

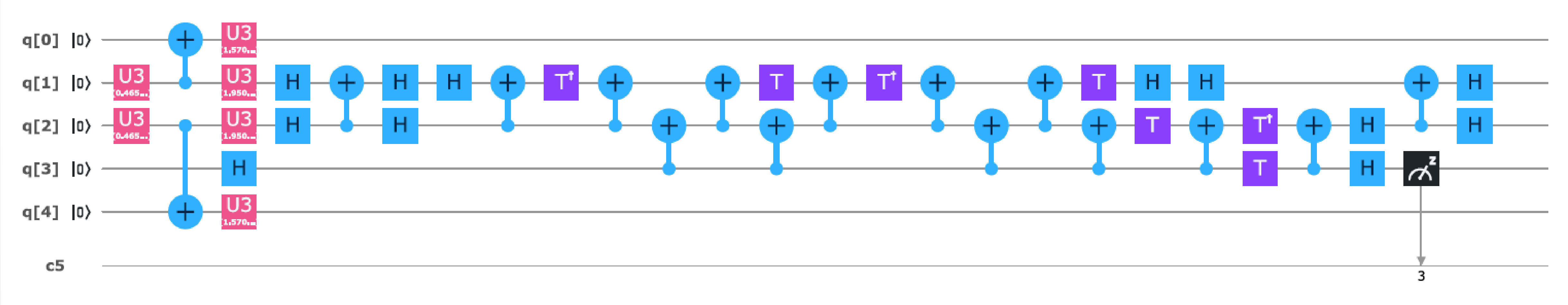
1 - On prépare un système quantique (circuit) vérifiant la matrice A.
2 – On effecture une série de mesures permettant d'obtenir les valeurs propres et les vecteurs propres.

==> Amélioration considérable de la complexité algorithmique $\log_2(n)$

D'après l'algorithme quantique HHL A. W. Harrow, A. Hassidim, and S. Lloyd, Phys. Rev. Lett. 103, 150502 (2009), e-print arXiv 0811.3171

Classical data/Quantum computing: PCA





Classical data/Quantum computing: Support Vector Machine

Algorithm 13 Quantum SVM [84]

Input:

- Training data set $\{(\vec{x}_j, y_j) : j = 1, 2, \ldots, M\}$.
- A query data $\vec{x}$.

Output:

- Classification of $\vec{x}$: $+1$ or -1.

Procedure:

Step 1. Calculate kernel matrix $K_{ij} = \vec{x}_i \cdot \vec{x}_j$ using quantum inner product algorithm [69].

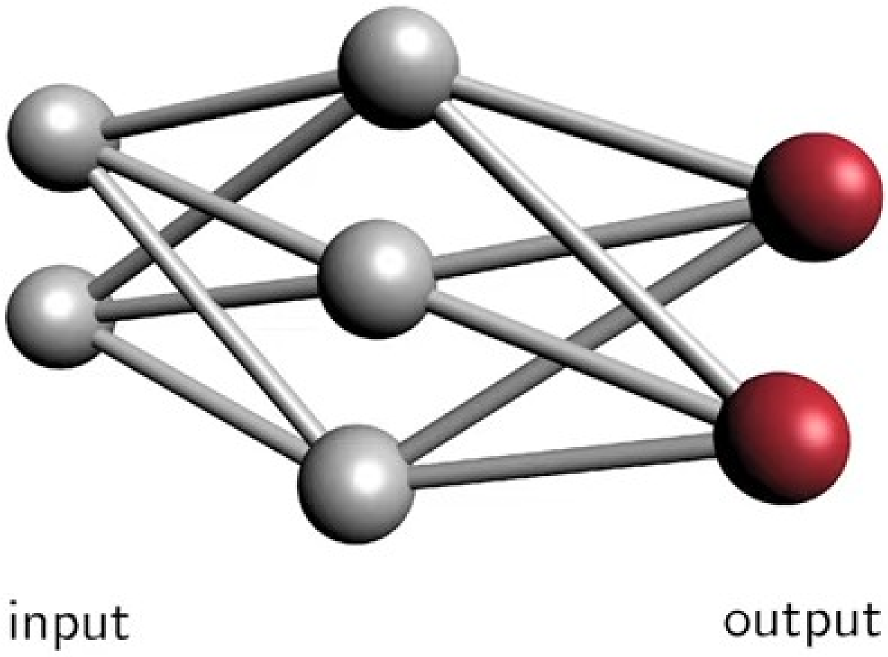
Step 2. Solve linear equation Eq. (87) and find $|b, \vec{\alpha}\rangle$ using a quantum algorithm for solving linear equations [50] (training step).

Step 3. Perform classification of the query data $\vec{x}$ against the training results $|b, \vec{\alpha}\rangle$ using a quantum algorithm [84].

Seth Lloyd, Masoud Mohseni, and Patrick Rebentrost. Quantum algorithms for supervised and unsupervised machine learning. arXiv preprint arXiv:1307.0411, 2013. [69]

Patrick Rebentrost, Masoud Mohseni, and Seth Lloyd. Quantum support vector machine for big data classification. Physical review letters, 113(13):130503, 2014. [84]

Quantum data/Quantum computing: Quantum Neural Network



$$\mathrm{tr}_1\left(U_2^{\mathrm{out}}U_1^{\mathrm{out}}\left(\mathrm{tr}_{\mathrm{in}}\left(U_3^1U_2^1U_1^1\left(\rho^{\mathrm{in}}\otimes|000\rangle_1\langle000|\right)U_1^{1\dagger}U_2^{1\dagger}U_3^{1\dagger}\right)\otimes|00\rangle_{\mathrm{out}}\langle00|\right)U_1^{\mathrm{out}\dagger}U_2^{\mathrm{out}\dagger}\right)$$

arXiv:1902.10445v1 [quant-ph] 27 Feb 2019 Efficient Learning for Deep Quantum Neural Networks

Training deep quantum neural networks, Nature Communications volume 11, Article number: 808 (2020)

Live coding session

- Classification with Classical SVM and Quantum SVM

- Portfolio Diversification : an application in finance