ENHANCING ACCELERATORS MODELING, CONTROL AND ASSOCIATED TECHNOLOGY WITH AI APPLICATION

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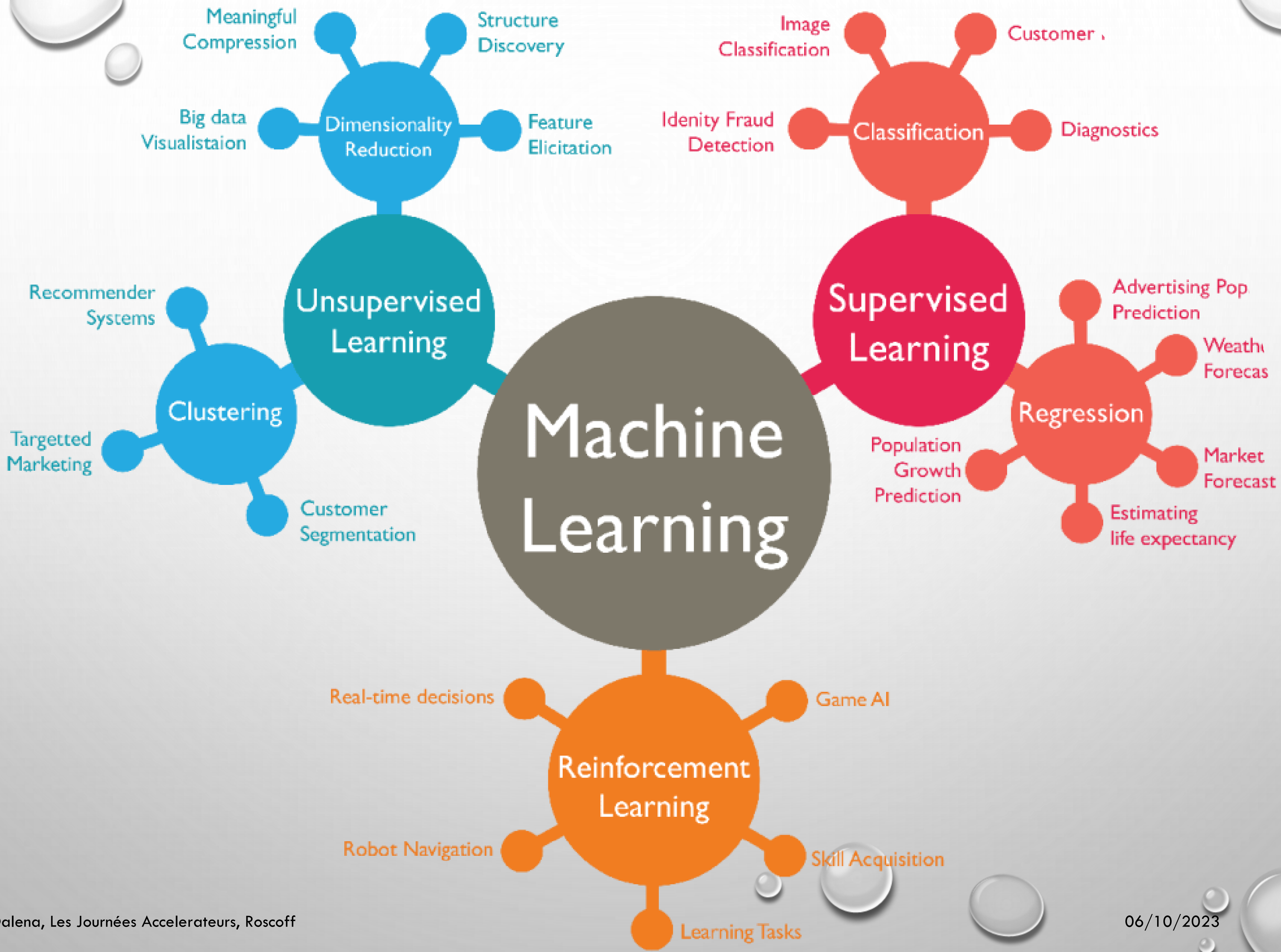
From whom I have taken some of the material for this presentation

I. Vidana, G. Valentino, G. Azzopardi, A. Eichler, S. Pioli, A. Edelen, E. Fol, K. Rajput, IDRIS

The list of examples given in this presentation is not exhaustive and is filtered by my personal analysis

OUTLINE

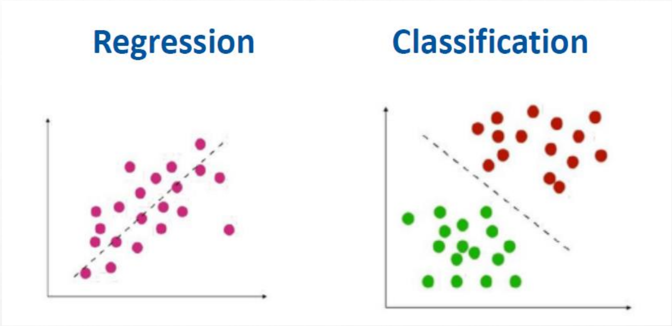
- Introduction to AI
- AI and Accelerators
  - Anomaly detection
  - Accelerator modeling
  - Accelerator control
- Example of national and international successful applications
- Perspectives


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
Idenity Fraud Detection
Diagnostics
Regression
Advertising Pop Prediction
Weath Forecas
Population Growth Prediction
Market Forecast
Estimating life expectancy
Reinforcement Learning
Real-time decisions
Game AI
Robot Navigation
Skill Acquisition
Learning Tasks

SOME DEFINITION

SUPERVISED LEARNING

Known input-output (feature-label) relations are given to the machine learning algorithm. Once the model is **trained based on the known data,** one can use unknown data into the model to get predictions.

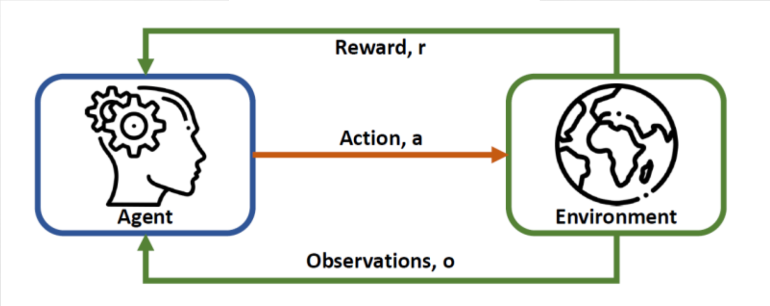


UNSUPERVISED LEARNING

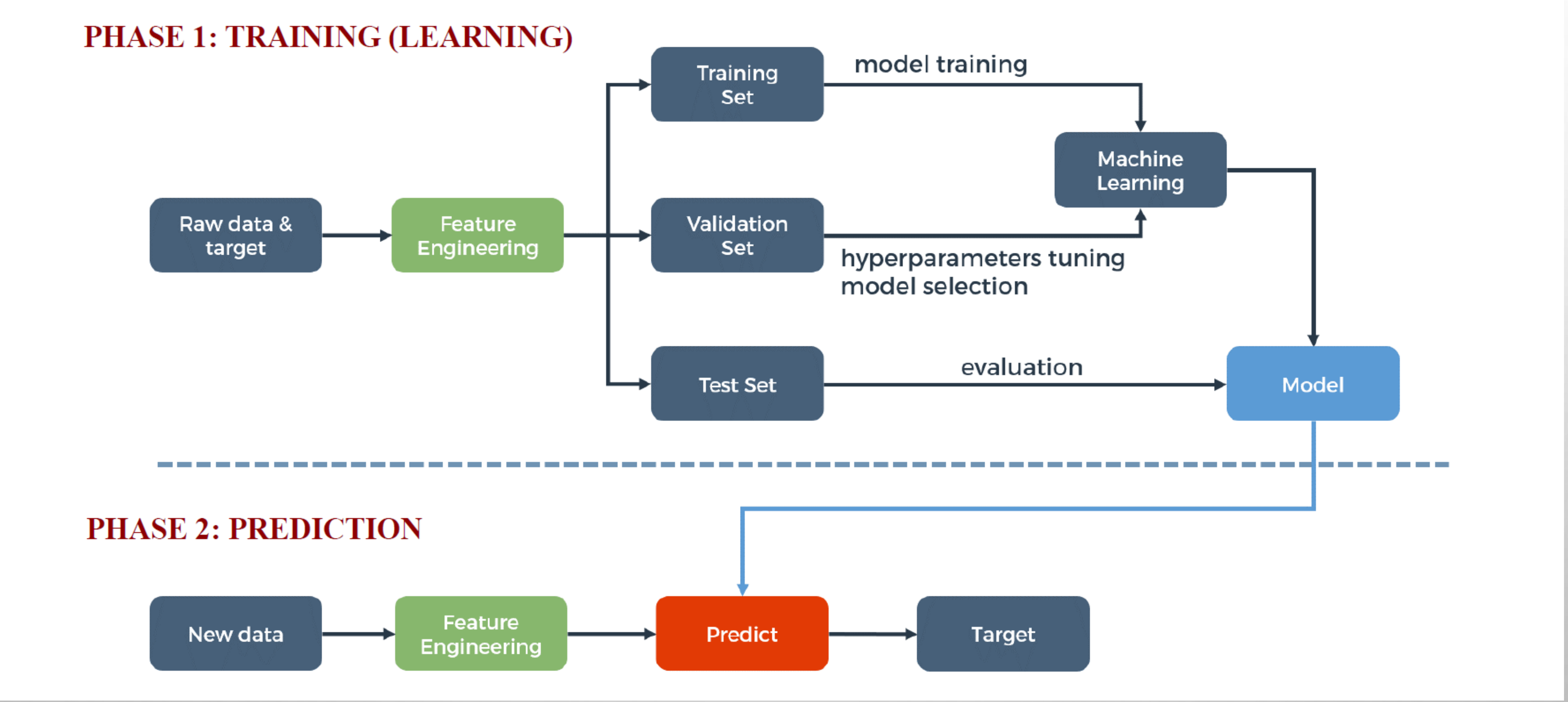
The output of the input training data is **unknown**. The input data is fed to the Machine Learning algorithm and is used to train the model which then is employed to **search for patterns in the data**.

REINFORCEMENT LEARNING

Given a **framework of rules and goals**, an **agent** (algorithm) **learns in an interactive environment** by **trial and error** using **feedback from its own actions and experiences** and it gets **rewarded** or **punished** depending on which strategy it uses. Each **reward** reinforces the current strategy, while **punishment** leads to an adaptation of its policy.



HOW MACHINE LEARN



SUCCESS FACTORS

1. DATA

   Huge amount of data to train algorithms and new techniques to label them, due to increasing digitization of environments

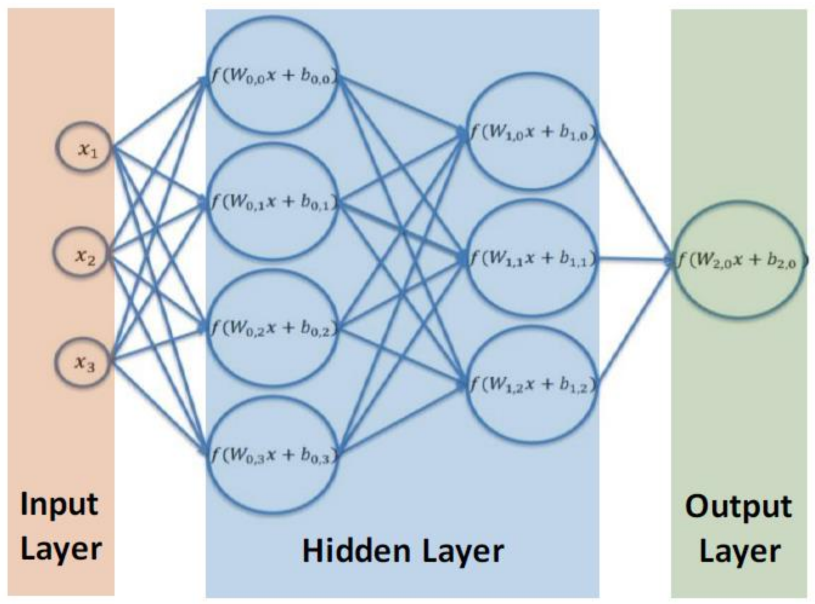
2. ENVIRONMENT/FRAMEWORK

   Facebook, google, Amazon, academic research, start-ups…

   Software layers: Torch, pyTorch, Keras, Tensorfow, cuda…

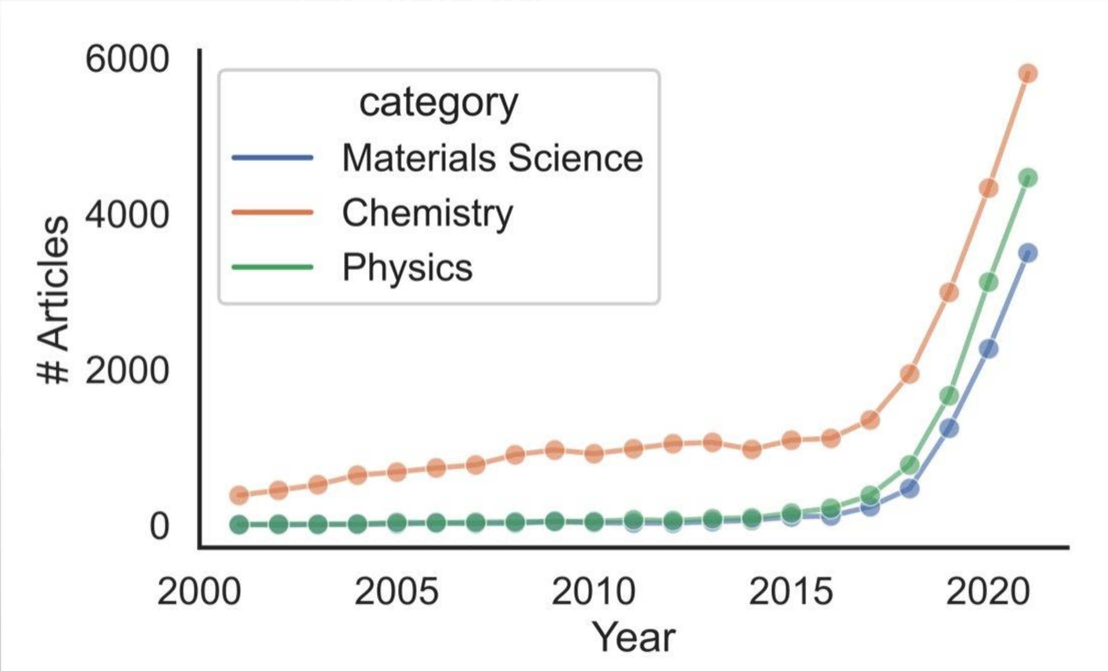
3. HARDWARE

   CPU, GPU, TPU, FPGA, SuperComputers

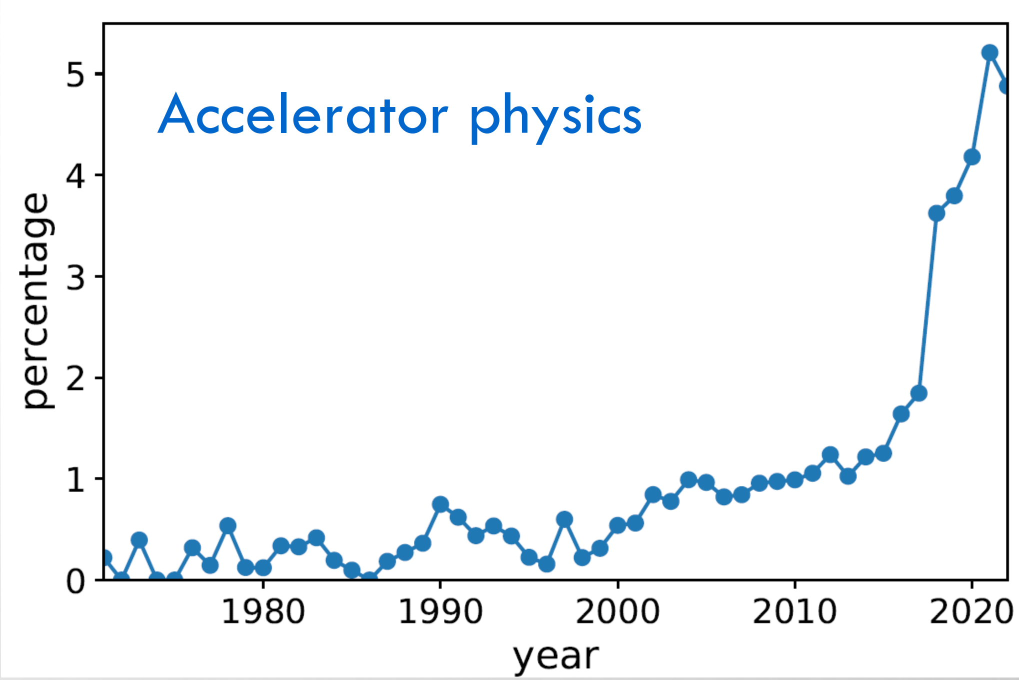


Neural networks

TREND OF ML IN SCIENTIFIC PUBLICATIONS



https://twitter.com/BenBlaiszik/status/1496509101915967490



Percentage of publication per year related with AI in most common Accelerator Physics journals from OpenAlex https://openalex.org (Courtesy of F. Gargiulo)

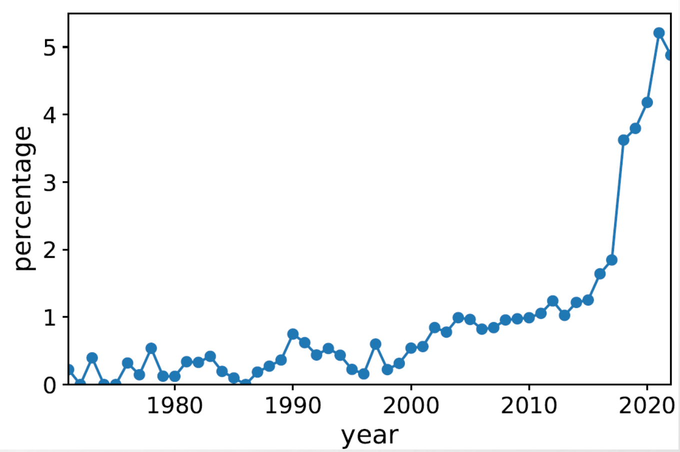
AI AND ACCELERATORS

WHY IS ML USEFUL FOR PARTICLE ACCELERATORS?

AI AND ACCELERATOR

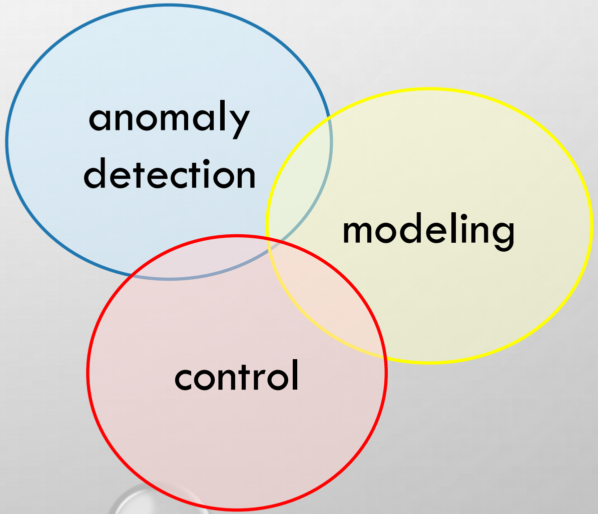
In US laboratories:

"ML techniques have been applied to particle accelerators since the late 1980s-1990s, for accelerator control and tuning […]
None of these systems were eventually used routinely as part of an accelerator's main control system due to limitations in the then-available hardware, algorithms, and software packages, as well as the limited accessibility of good data sets and simulation tools."



A. Edelen et al., arXiv:1811.03172 **[physics.acc-ph]**

Machine Learning (ML) can be useful for



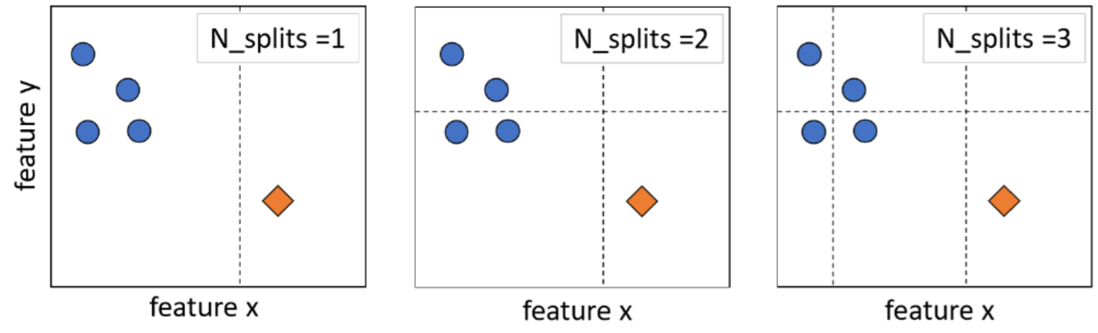
ANOMALY DETECTION

Accelerators are complex objects that require monitoring of many interacting subsystems:

- ML technique can be used to detect precursors of faults
  - Quench of superconductive magnets or superconductive RF cavities faults
  - Beam loss predictions
- Anomaly detection algorithms can also be used to identify bad signals:
  - Bad readings from beam position monitors
  - Assist to automated collimator alignment

⇒ improve beam quality, machine protection, availability of the accelerator

The less splits are needed, the more “anomalous”

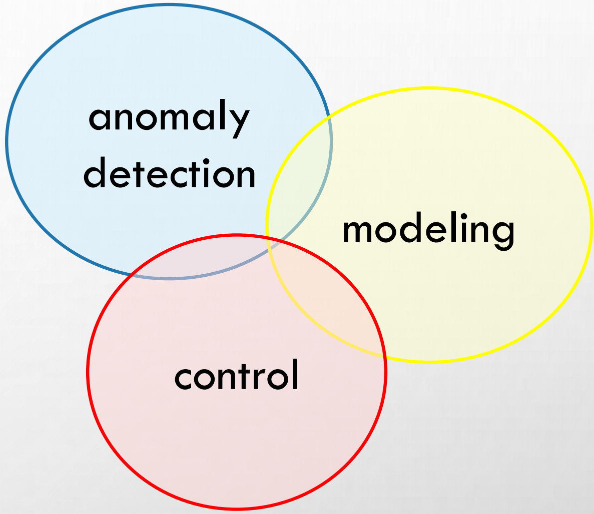


Conceptual illustration of Isolation Forest algorithm

ACCELERATOR MODELING
(SURROGATE MODELS AND OPTIMIZATION ALGORITHMS)

- Existing machine

  ML can learn models that combine information from physics-based simulations with measured data
  ⇒ provides real-time simulations in control rooms to improve beam time and quality (CONTROL)

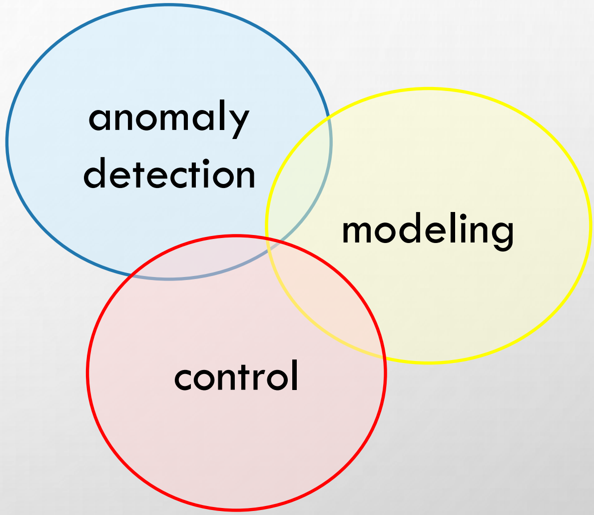


- Future accelerators

  Accurate simulations are essential for the design and the optimization of future machines
  - ✓ ML can speed up simulations and reduce CPU time, providing fast surrogate models of non-linear phenomena
  - ✓ ML can increase the extend of parameter space optimization for challenging accelerator design problems and allow faster exploration of various competing parameters (see talk F. Massimo and G. Kane)

ACCELERATOR CONTROL

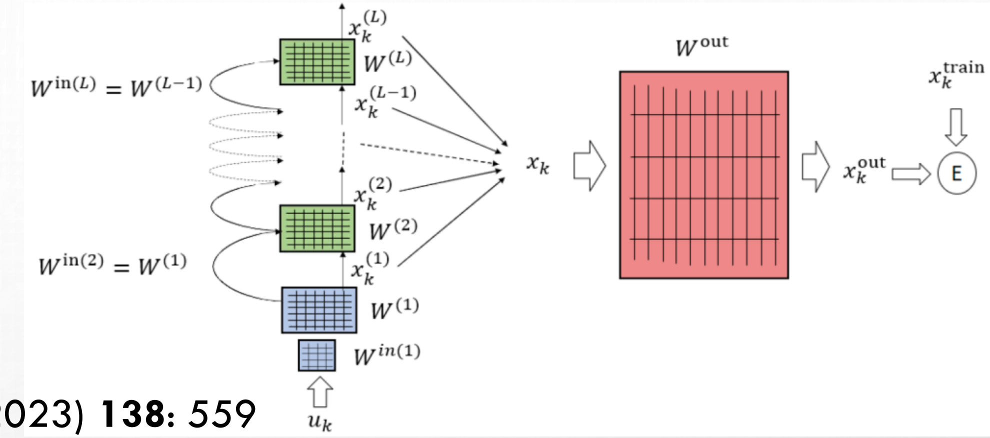
- TUNING, CONTROL
  - Complement and SPEED-UP fine-tuning of machine settings by operators or online optimization routines, and dedicated feedback
- VIRTUAL DIAGNOSTICS
  - Create new instruments or observations, exploiting correlations between cheap signals and beam quality (see C. Lassalle poster)
  - Provide estimate of beam parameters in case of missing instruments
- ADVANCED DATA ANALYSIS
  - Use image data, clustering and correlations algorithms to **automatically** detect beam losses, aberrant behavior, classify quench or modes of beam instabilities (ANOMALY DETECTION)



EXAMPLE OF NATIONAL AND INTERNATIONAL SUCCESSFUL APPLICATIONS

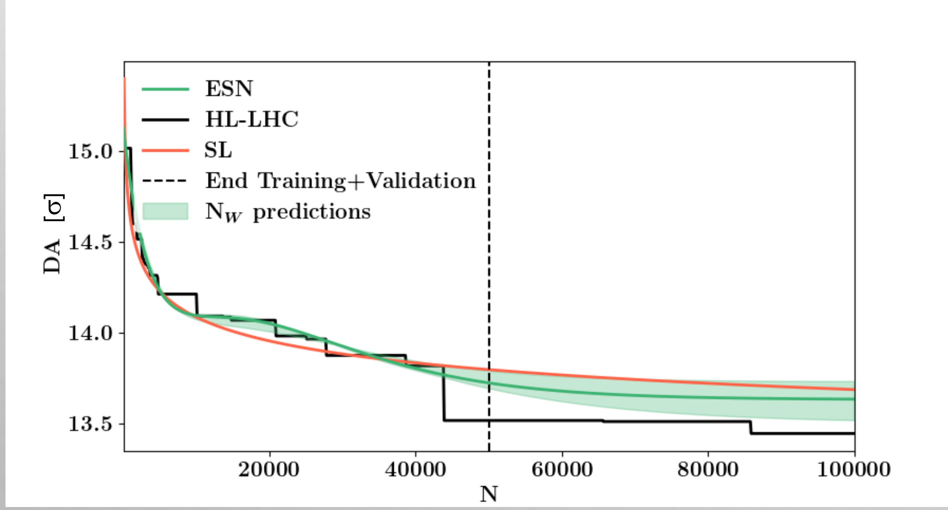
APPLICATION TO BEAM PHYSICS

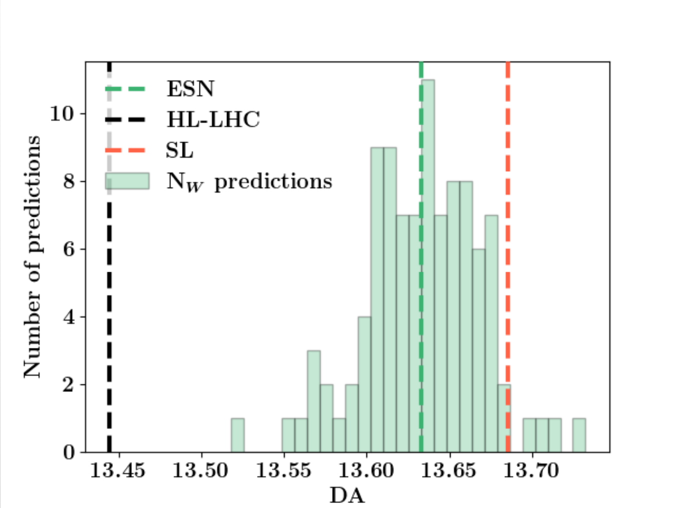
Reservoir Computing networks models and replicates the time evolution of Dynamic Aperture, allowing to speed–up tracking simulations for high energy hadron storage rings.



M. Casanova, B.D. et al. , Eur. Phys. J. Plus (2023) **138**: 559

Echo State Networks



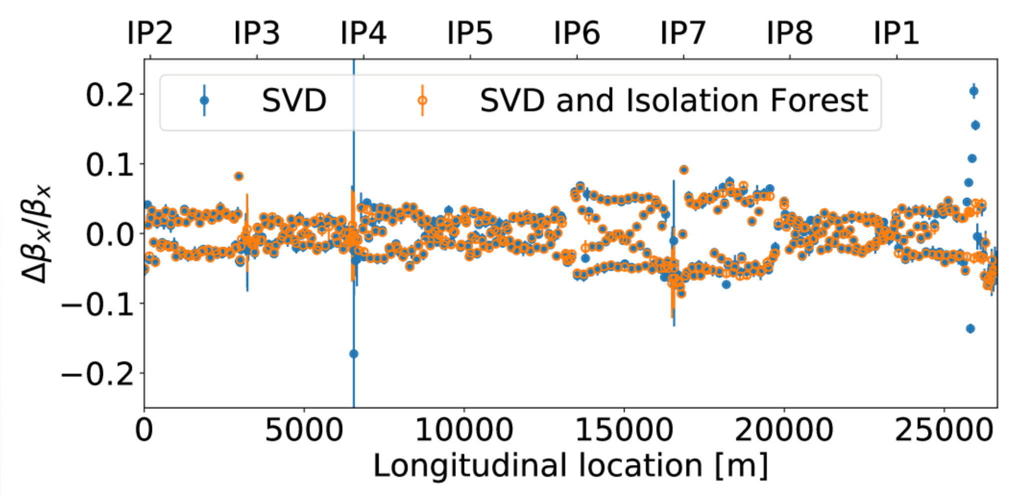


(⇒ see also Q. Bruant poster)

ANOMALY DETECTION ANALYSIS

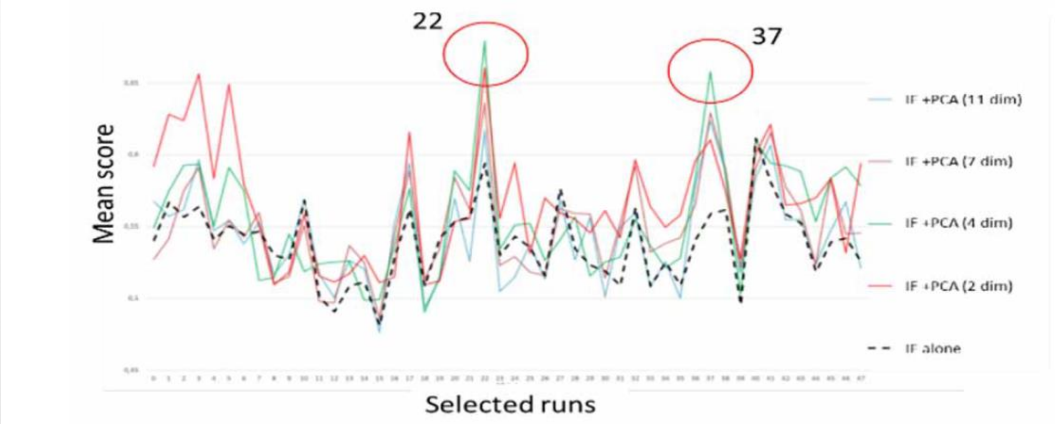
Isolation Forest with **decision tree** is used by at **CERN** to detect faulty BPMs signals that remain after SVD cleaning of turn by turn **optics measurements data.**

E. Fol et al. **WEPGW081** IPAC 2019



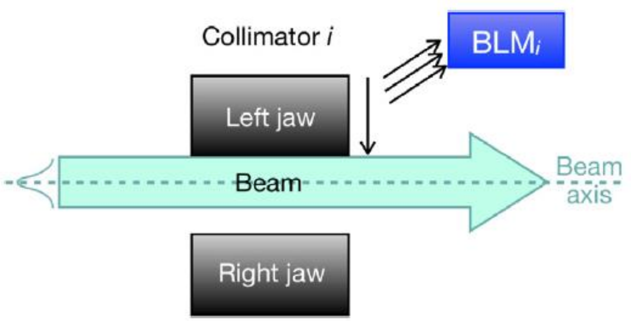
K-mean, Density-Based Spatial Clustering and Isolation Forest in combination with PCA is used by F. Poirier et al. at ARRONAX Cyclotron to **identify anomalies** that occur for non-labelled multi-variate data **during radio-isotopes production.**

F. Poirier et al. TUPM036 IPAC2023

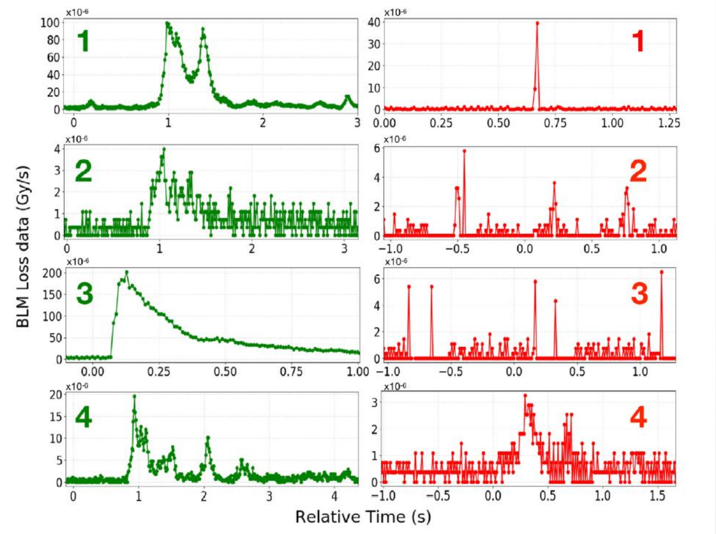


AUTOMATED ANOMALY DETECTION

Establish the operational settings of ~100 **LHC** collimators by automatically detect true and false alignment-spikes.
Successfully deployed in operation with a gain of a factor three in alignment time.

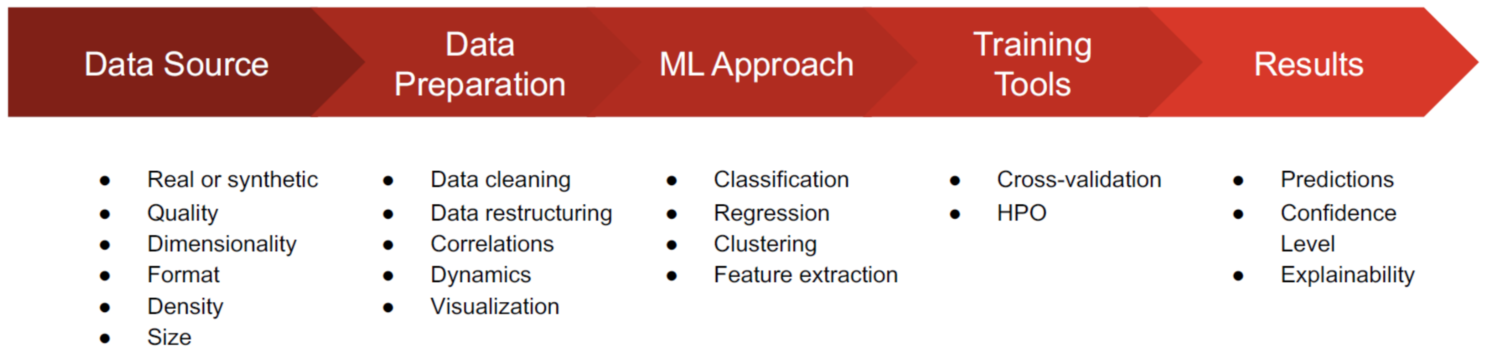


G. Azzopardi et al. NIMA 934, 2019, 10



Errant beam prediction at SNS accelerator

- Predict an upcoming machine trip before it occurs to potentially allow the crew to change settings to avoid it
- Use pulses leading to a trip (tagged "Before") and identify features that indicate an upcoming failure
- Data science pipeline:



identify accelerator failures with > 80% accuracy

K. Rajput

OPTIMIZATION IN CONTROL ROOM

Machine Learning Frameworks/tools for accelerators:

Xopt+BADGER (SLAC)

- For simulations (models) or experiments (data)
- Independent of optimization algorithm + easy to incorporate custom algorithm
- Provides interface for operation in control room

⇒ Used at **ESRF** in collaboration with **DESY**, **LNBL** and **SLAC** for tuning of the EBS storage ring lifetime and injection efficiency with Bayesian techniques (S.Liuzzo et al., MO3AO01, ICALEPCS 2023)

GeOFF and the Machine Learning Platform (CERN)

Framework for operational use of RL and numerical optimization

- provide ecosystem for accelerator optimization and control
- provide compatibility with as many algorithms as possible
- facilitate the progression
  manual tuning → numerical optimization → machine learning

⇒ Used at CERN for almost all accelerators (see talk A. *Lasheen*)

EURO-LABS project supports efforts towards agnostic usage and portability

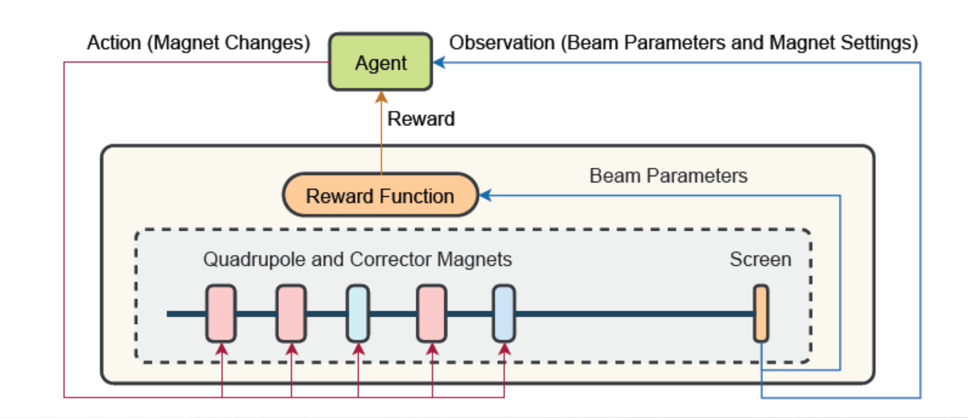
TOWARDS AN AUTONOMOUS ACCELERATOR

Autonomous operation of FLUTE, ARES LINACs

Deep Deterministic Policy Gradient algorithm and Twin Delayed Deep Deterministic policy gradient demonstrate ability to solve beam optimization tasks on simulated data.

DESY KIT Karlsruher Institut für Technologie

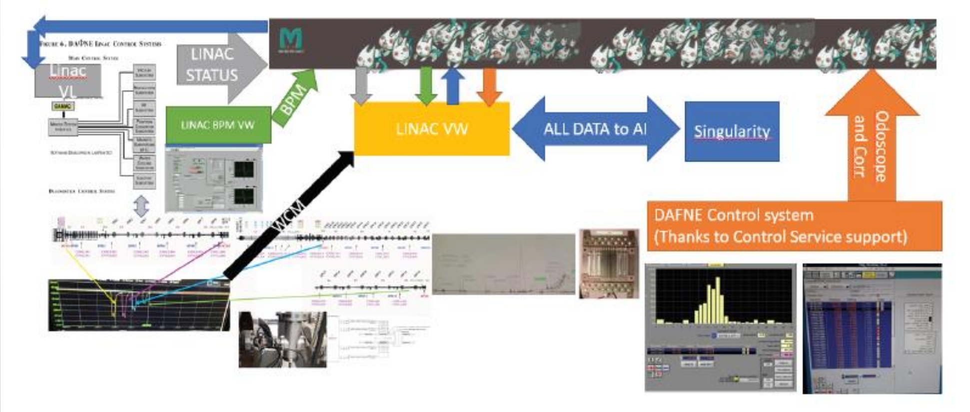
A. Eichler et al. TUPAB298 IPAC 2021



Q-learning algorithm (Markov decision process) applied to automatically optimize energy and charge of the DAΦNE LINAC, coupled with DBSCAN Algorithm used to detect RF fault and stop automated operation, within few days of dedicated operation.

INFN

S. Pioli et al. THAL03 ICALEPCS 2021



PERSPECTIVES

WHAT CAN WE DO MORE ?

EXAMPLE: INTHEART

- Les objectifs :
    - Partager les connaissances et appréhender les nouvelles techniques en IA
    - Discuter et travailler ensemble à travers un groupe ouvert, transverse au CEA et au-delà
- Participants (~150 personnes):
    - **CEA** : DAM, DES, DRF, DRT
    - **CNRS**
    - **Université Paris-Saclay**
- Financement PTC (Programme Transverse de Compétence – CEA)
- Pour y participer/contribuer : Valerie.gautard@cea.fr

- Des seminaries (https://indico.in2p3.fr/event/17858/page/2883-2022)
- Des formations
- Des workshops
- Web sites: IntheArt : https://indico.in2p3.fr/event/17858/page/1967-intheart
  GitLab : https://drf-gitlab.cea.fr/InTheArt
  Redmine : https://forge.in2p3.fr/projects/intheart?jump=welcome

Coutesy of V. Gautard

A NEW SYNERGETIC APPROACH

- Unlock the use of artificial intelligence in particle and nuclear accelerators as well as in light/neutron sources;
- Tackle all challenges of particle accelerators.

A French network: M4CAST

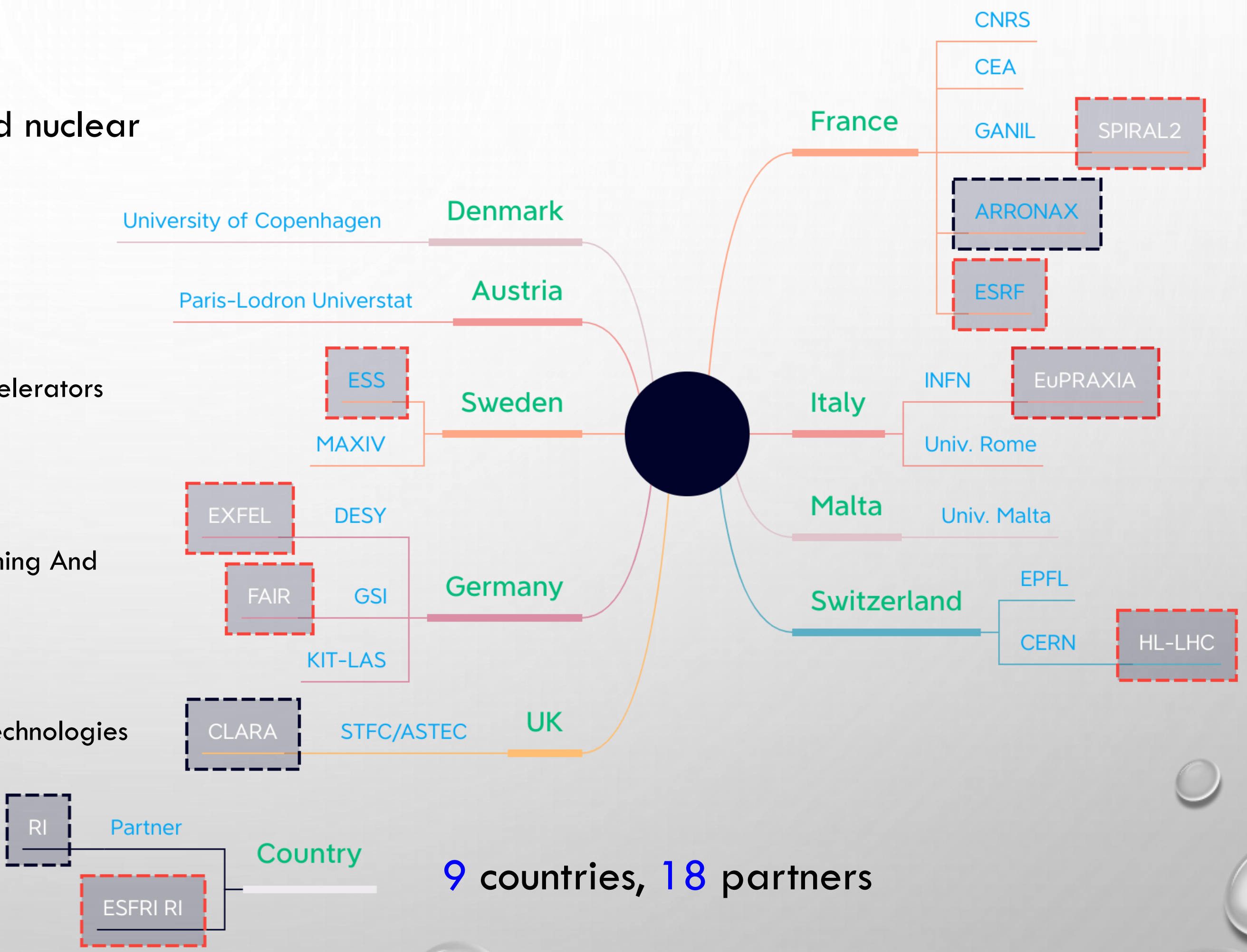
Multiphysics Modeling, Machine learning and Model-based Control in Accelerators Science and Technology

A European network: TRAINABLE

TowaRds An International network for multiphysics modelling, machine learning And model-Based control in accelerator sciences and technoLogiEs

target an Horizon Europe project ARTIFACT

ARTificial Intelligence For Accelerators, user Communities and associated Technologies

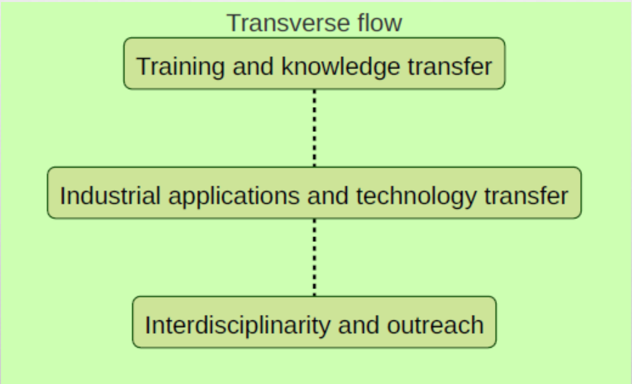


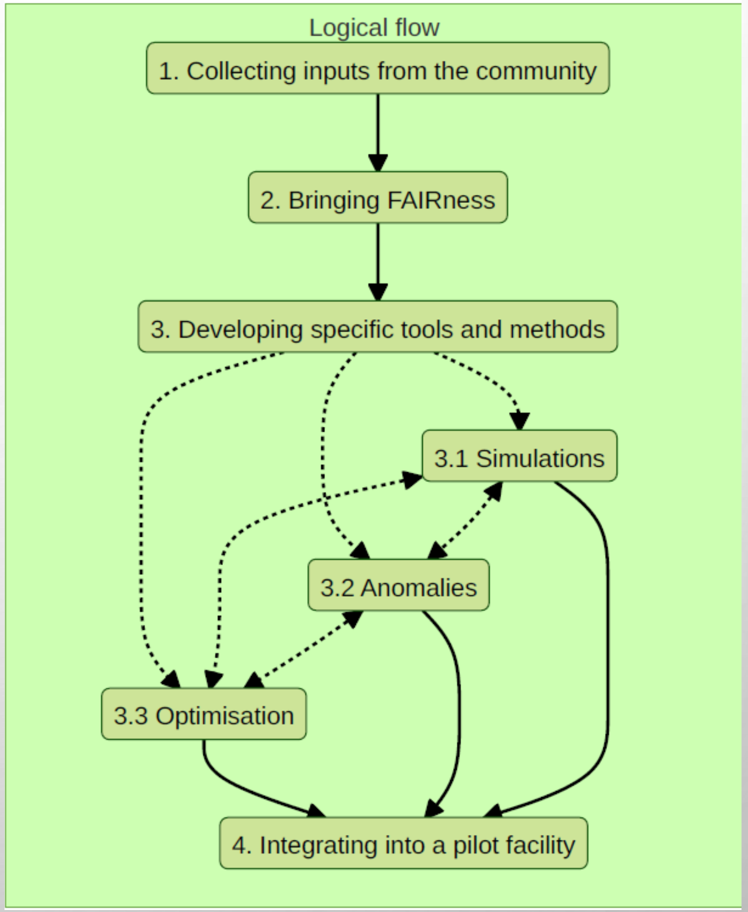
9 countries, 18 partners

Courtesy of A. Ghribi

STRATEGY

- Guidelines to unclock the use of AI in accelerators
- Standardize and open our data and approaches
- Structure ourselves to work in a fertile collaborative space
- Transfer links (astrop, HEP, medecine, …)
- Training: students as well as professionals





Courtesy of A. Ghribi

TOWARDS A MORE SUSTANAIBLE DEVELOPMENT

Outcomes:

- Enhance scientific competitiveness of Research Infrastructures (RI)
- Enhanced RI capacities to address research challenges and EU policy priorities ;
- Increase collaboration of research infrastructures with universities, research organization and industry
- Increase of technological level of industries
- Integration of research infrastructures into local, regional and global innovation systems and promotion of entrepreneurial culture

Courtesy of A. Ghribi

THANK YOU