Paris Session 2022

cigre
For power system expertise

Artificial Intelligence applications and technology in the power industry

D2.52 Tutorial for CIGRE session 2022
30th August, 2pm

PREPARED by
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Javier Mantilla / Florian Ainhirn/ Yishen Wang

Interactive Session QR Code

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Participation

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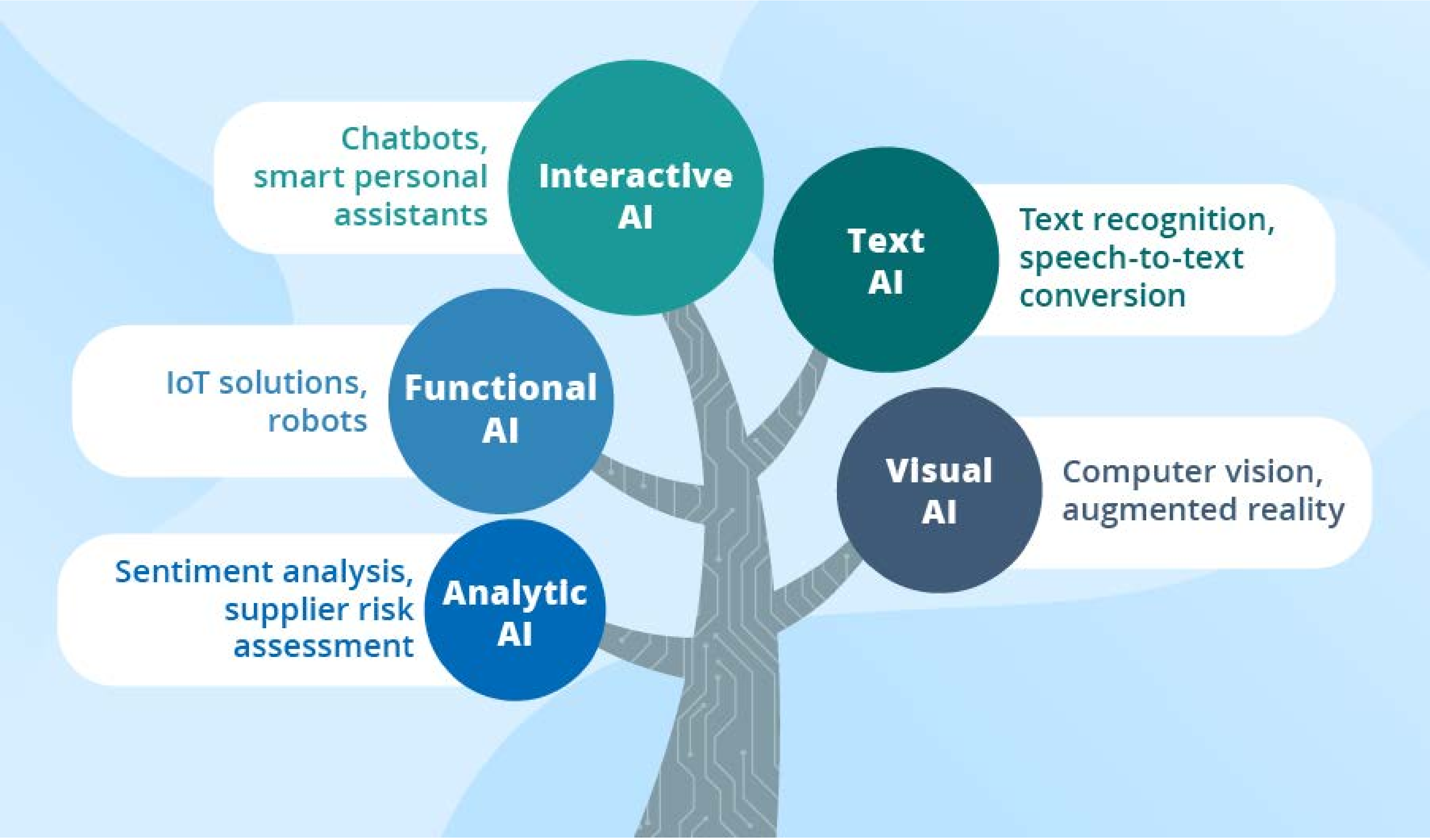
AI in Life



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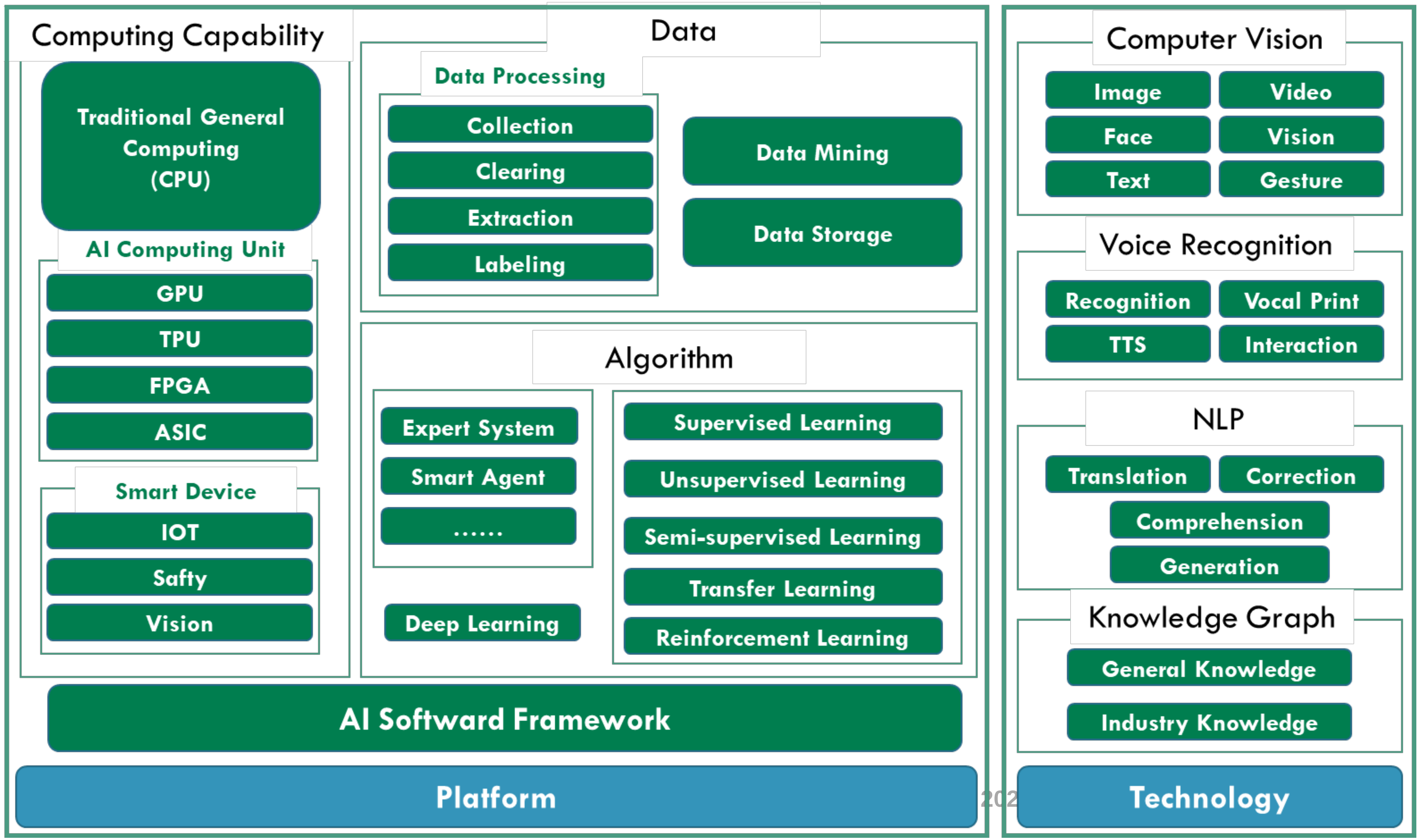
Glance at AI Technology



Scope of Working Group

Development and applicability of AI technology

- Technology and current development status of AI key fields
- Machine learning/Deep learning, data mining, computer vision
- Natural language processing, knowledge graph, etc
- Evaluation of technology maturity and its applicability in power industry

AI system architecture for power industry

- Heterogeneous computing platforms
- AI framework software, data management
- Model training and evaluation, inference service, application integration, etc

Scope of Working Group

- Typical practices and reference design of AI in power industry
  - Generation
  - Transmission
  - Substation
  - Distribution
  - Consumption
- New Challenges applying AI technologies in power industry
  - Data-related: the data silos, small sample, etc
  - Algorithm-related: safety and interpretability
  - Infrastructure-related: processor capabilities
  - Other challenges: privacy, trustworthiness, etc
- Advice for promoting AI suitability on power industry.

Working Group D2.52

Convener

Kunlun GAO

Deputy president, State Grid Smart Grid Research Institute Co. Ltd., SGCC

Regular member of CIGRE D2 China

Convener, CIGRE Working Group D2.55

Research Interests: Artificial Intelligence, Communication Technology

Secretary

Qixin CHEN

Associate Professor, Tsinghua University

Committee Member, CIGRE Working Group C5.21

Committee Member, CIGRE Working Group C5.32

Research Interests: Power Market, Low Carbon Electricity Technology

Working Group D2.52

Chapter Leaders / Presenters

John Ging

Luiz Cheim

Javier Mantilla

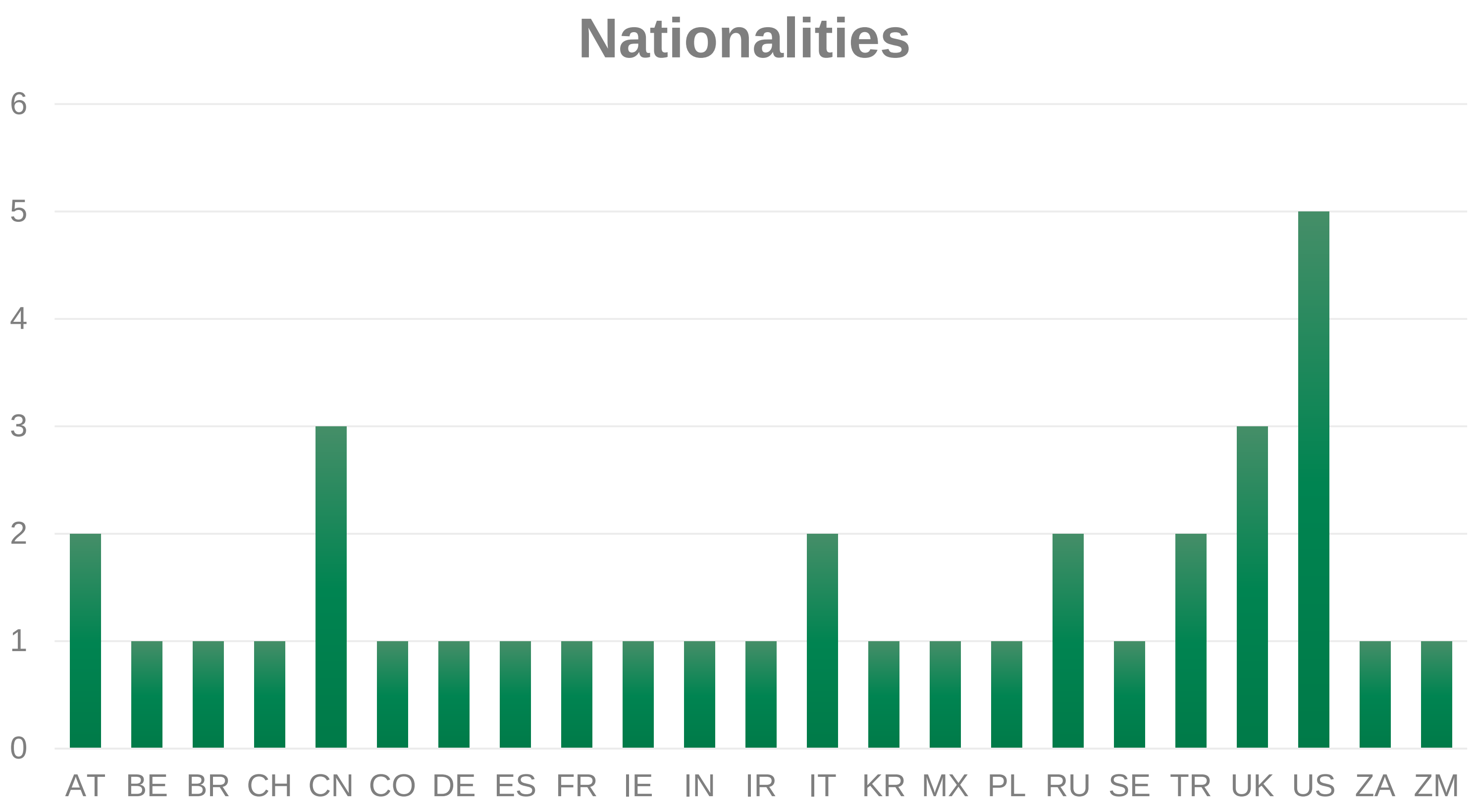
Marcelo Araujo

Florian Ainhirn

Rachel Berryman

Organization

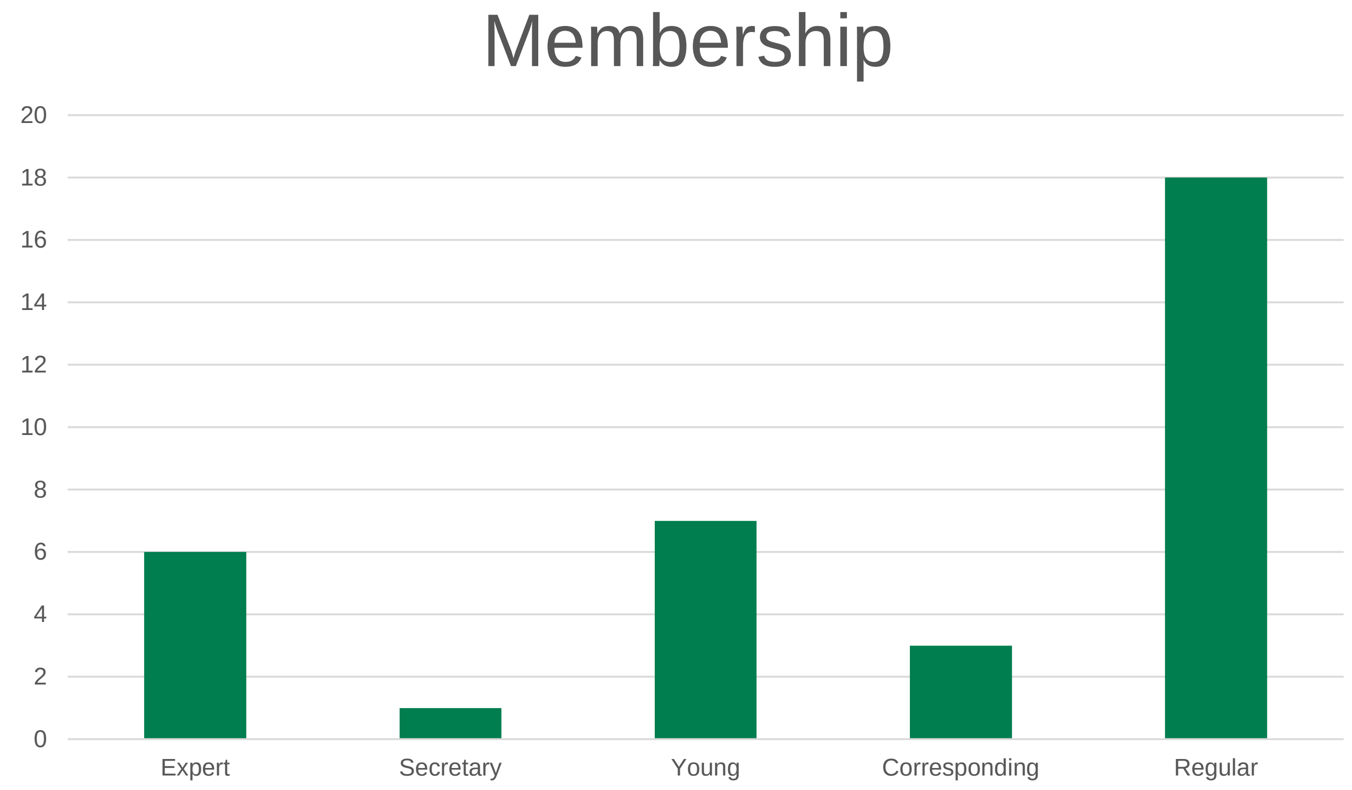
35 Members & Experts from 23 Countries



Experts included

Membership

Membership	Number
Secretary	1
Regular	18
Corresponding	3
Young	7
Expert	6



Organization

Name	NC	Membership
David Gopp	AT	Regular
Marcelo Costa de Araujo	BR	Regular
Xinqiao WANG	CN	Young
Qixin Chen	CN	Secretary
Laiz Souto	ES	Regular
Clément Goubet	FR	Regular
John Ging	IE	Regular
Praveen Kumar Agarwal	IN	Regular
Vahid Veysi	IR	Regular
Gustavo Arroyo Figueroa	MX	Regular
Mohamed Khalil	PL	Regular
Anton Nebera	RU	Corresponding
Evgeny Tsydenov	RU	Young
Giulio Riccardi	UK	Young
Mohammed Tageldin	UK	Regular
Sanam Mirzazad	US	Regular
Luiz Cheim	US	Corresponding
Michael Signorotti	US	Young

Name	NC	Membership
Anthony Chobela Mumba	ZM	Regular
Florian Ainhirn	AT	Young
Fraser Cook	UK	Expert
Javier Mantilla	CH	Regular
Anurag K Srivastava	US	Expert
Magnus Tarle	SE	Expert
Antonio Laudani	IT	Expert
Varun Perumalla	US	Expert
Sibusiso Reuben Bakana	ZA	Young
Elkin Leonardo	CO	Regular
Christian Kreischer	DE	Regular
Muhammed Fatih Gülsen	TR	Regular
Talya Tumer	TR	Corresponding
Sung-Chan Park	KR	Regular
Rachel Berryman	BE	Regular
Yishen Wang	CN	Expert
Edoardo Segatori	IT	Young

3 New members joined since this year

TB Organization

Chapter 1 **Introduction**	**WG Scope and Survey**
Chapter 2 **AI Requirements and Targets**	**Needs and Requirements**
Chapter 3 **AI Technology Frameworks**	**Frameworks and Algorithms**
Chapter 4 **Applicability and Maturity of AI Technologies**	**Technology Readiness Level Assessment**
Chapter 5 **Typical Practice**	**Case Studies**
Chapter 6 **New Challenges**	**Technology Challenges**
Chapter 7 **AI + Power Roadmap**	**Roadmap**
Chapter 8 **Summary of Findings and Recommendations**	**Summary**

TB Progress

Chapter	Title	Progress								Target Time
1	Introduction & Motivation									2023 Janurary
2	AI Requirements and Target									
3	AI Technology Framework									
4	Applicability & Maturity of AI Technologies									
5	Typical Practice									
6	New Challenges									
7	AI + Power Roadmap (2025, 2027, 2030...)									
8	Summary of Findings and Recommendations									
Appendix A	Definitions and Abbreviations									
Draft	Draft Group Internal Review and Proofread									2023 February
	Draft CIGRE Review									2023 April
	CIGRE Publication									2023 June

The WG is expected to finish the TB draft in April 2023.

Roadmap

Approval
2020.4
CIGRE'S technical committee gives official permission to the creation of WG D2.52.

Kickoff Meeting
2020.8.21
The roadmap of WG D2.52. Chapters of TB. The secretary and chapter leaders are announced.

Second Meeting
2020.12
Chapter 1, 2 drafted. Other chapters promoted.

Third Meeting
2021.8
More than 65% content has been finished.

Tutorial
2022.8
Present TB content.

Finishing
2023.03
Finalize TB.
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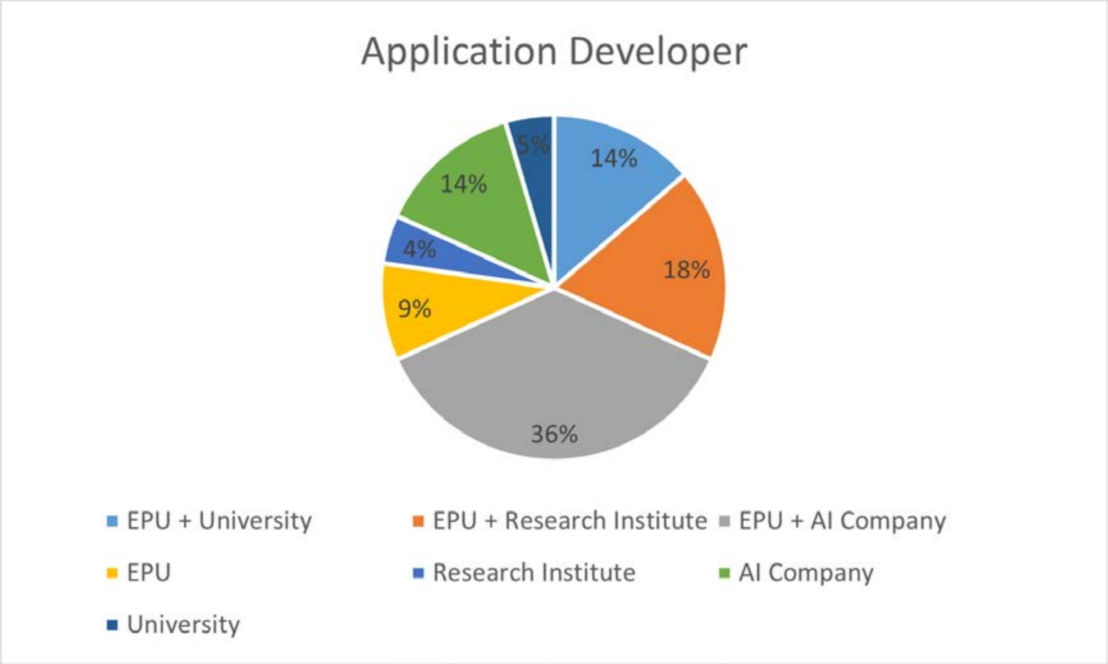
Survey

- A survey was sent out to collect the opinions on AI from academics, vendors, utilities, government and various related communities
- Collected power intelligence experts response from Mexico, South Korea, China, Sweden, United Kingdom, Spain, India, the United States, Colombia, Austria, France, Russia, Italy, Ireland, Switzerland, Egypt, Turkey and other countries



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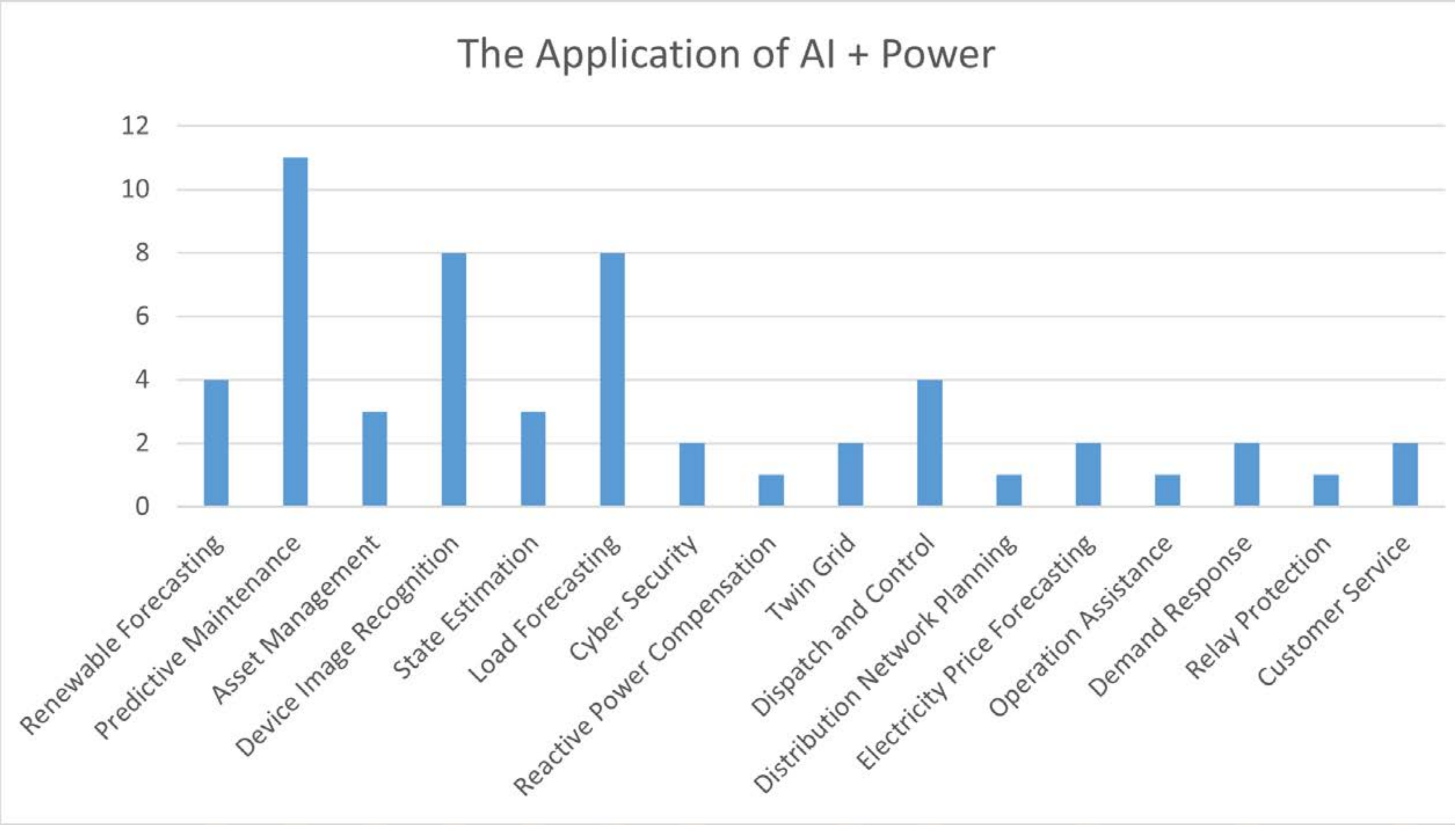
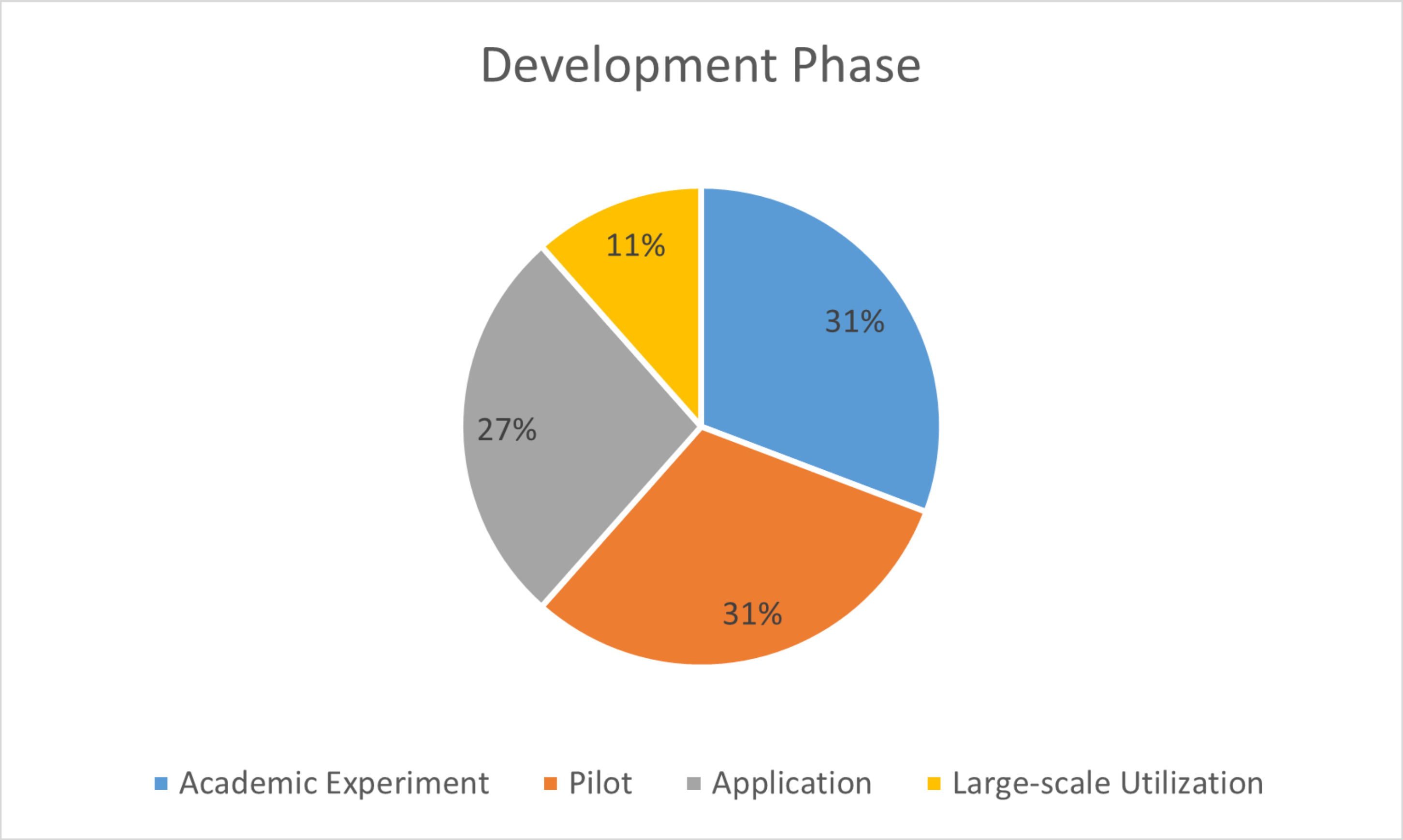
It is hard for EPUs to undertake R&D for AI applications. Most EPUs call for research institutes, software developers & universities to help.

Survey



There are lots of types of AI application in the power industry. To date, the most common ones are forecasting (regressor) & image recognition tasks

Survey



Most AI applications are under test/pilot phase and only a few can be implemented in large-scale utilization.

Survey

Featured Questions:

- **From your point of view, what is the bottleneck using AI technology in power industry?**
- **From your point of view, what kind of AI technology should be studied by power industry engineers / scientists?**
- **What is the significance of using AI technology in power industry (Efficiency \ Security \ Cost\ New business mode \ Others)?**
- **Is there an "AI in power industry standard in your country?**
- **Is there any AI regulations in your country?**
- **From your perspective, could AI applications be dangerous to power industry or its workers?**

Survey

Featured Answer

Question5

Q: ***From your point of view, what is the bottleneck using AI technology in power industry?***

Magnus Tarle (Sweden): Data infrastructure, meaning sufficient relevant sensors, management of data at site and cloud connection including cyber security.

Laiz Souto (Spain): lack of coordination between different stakeholders (e.g., householders, local authorities, companies) to understand how AI could benefit the power industry in different ways.

Michael Signorotti (USA): Most utility companies are not digitally native.

Florian Ainhirn (Austria): A lot of start-ups penetrate the market with highly sophisticated solutions, but with a lack of experience and most likely a lack of reference projects.

Clément Goubet (France): Few / coveted skilled collaborators for this area in power systems; Availability of acknowledged benchmark datasets; Availability of dedicated integrated solutions;

Giulio Riccardi (Italia): Not enough skills. Only few people know how to develop these technologies.

John Ging (Irish): Fear. Granting autonomy to a machine is considered imprudent since errors may lead to catastrophic repercussions, e.g. blackouts.

Javier Mantilla (Swiss): Education. The current workforce on utility level, is a knowledgeable and experienced workforce, yet the knowledge on AI and other modern techniques is seen -as with any new things- with some apprehension.

P.K. Agarwal (India): Power engineers are very conservative and do not want to go outside of their power system sphere.

- Finally, the featured answer, given by replier of questionnaire, is selected and showed in the TB. The different opinions coming from different countries matters a lot to our WG.

Thanks to every respondent for your contributions!

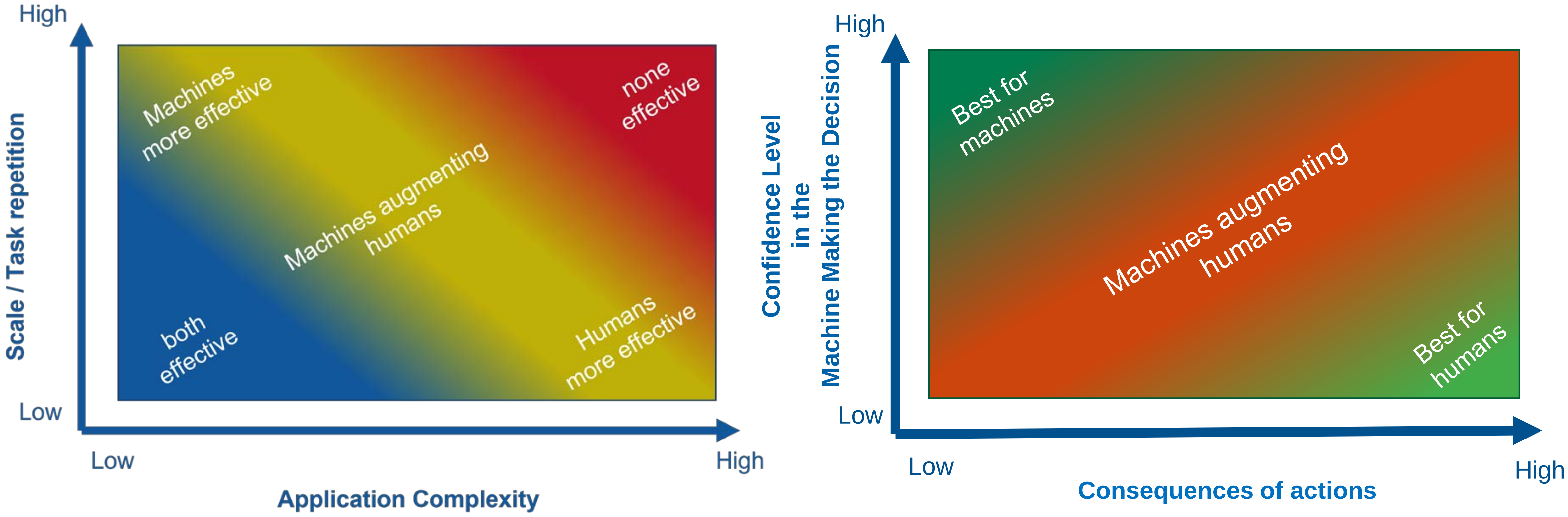
CONTENTS

Challenges driving the need for AI in the Power Industry

- Exponential increase in new types of plant and behaviours
- Complexity of the system increasing
- Equivalent increase in volume and complexity of information
  - Calculation
  - Diagnosis
  - Learning
  - Feedback
- Countered against an increase in
  - Computational time
  - Frequency of analysis
  - Accuracy of solution
  - Vast system data handling (inputs, models, results)

AI : Digital Expert to predict any outcome

Human – machine engagement



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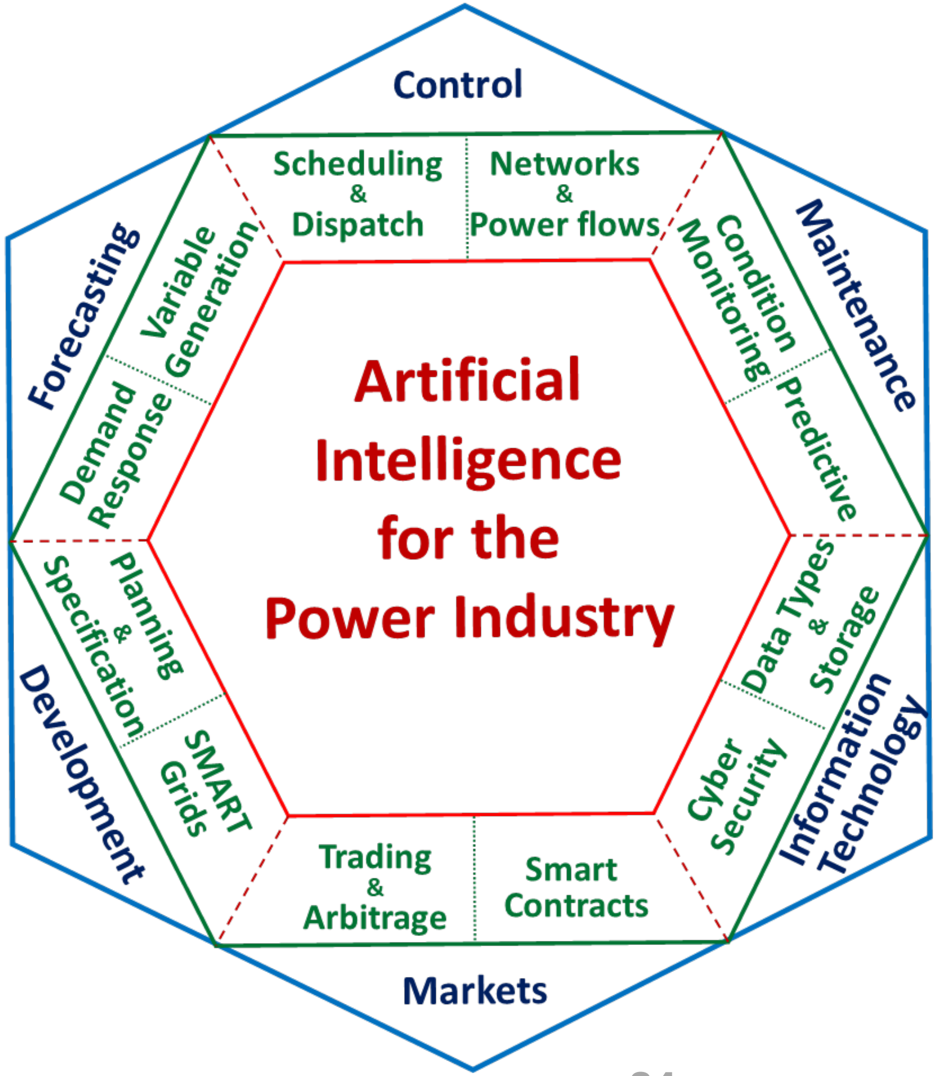
Why do we need AI in the Power Industry?

- Propose actions
- Prevent failures
- Provide insights
- Prosumer engagement
- Proactive evolution
- Predictive behaviour

- **Possibilities are limitless**



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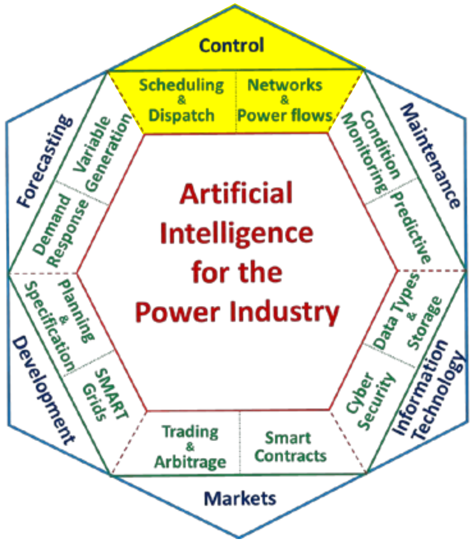
Defining the NEEDs – Control

- **Operational Control (Transmission and Distribution)**
  - Autonomous systems
  - Interpreting data
  - Monitoring and alarms
  - Networks and Power flows
    - Optimised automatic switching
    - Protection
    - Self Healing
    - Safety
  - Scheduling and Dispatch
    - Security assessments
    - Stability

- **Operational Control (Power Plant)**
  - Autonomous systems
  - Interpreting data
  - Monitoring and alarms
  - Responsive output

- **Operational Control (Consumer)**
  - Autonomous systems
  - Interpreting data
  - Responsive demand

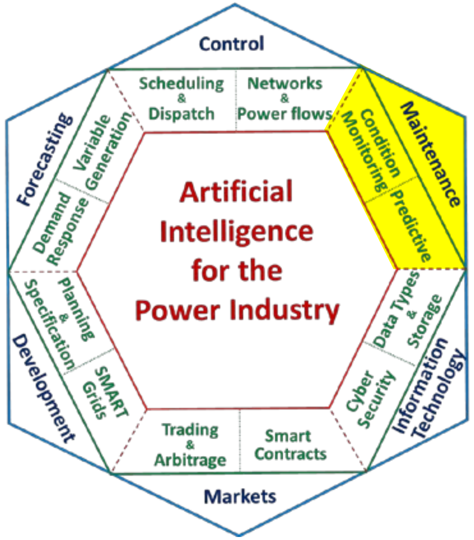


Defining the NEEDs – Maintenance

- **Plant awareness**
  - Digitalisation
  - System Integrity
  - Interpreting data and alarms
  - Fault finding

- **Asset Management**
  - Condition Monitoring
  - Predictive maintenance

- **Outage planning**
  - Optimisation of schedules
  - Outage interactions
  - Resource management



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Defining the NEEDs – Information Technology

- **Considerations**
  - Cyber-security
  - Visualisation
  - Governance and Audit
  - Data Identifiers and Frameworks

- **Requirements**
  - Customer engagement and support
  - Transparency and Access
  - Training sets and benchmarks
  - Policies and standards
  - Storage objectives

- **Enablers**
  - Hardware and computation
  - Networks and communication channels

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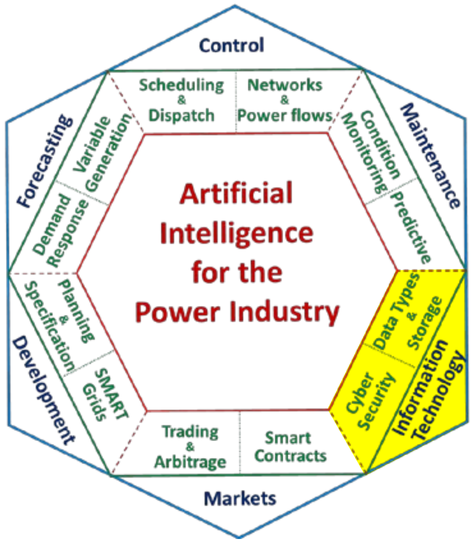
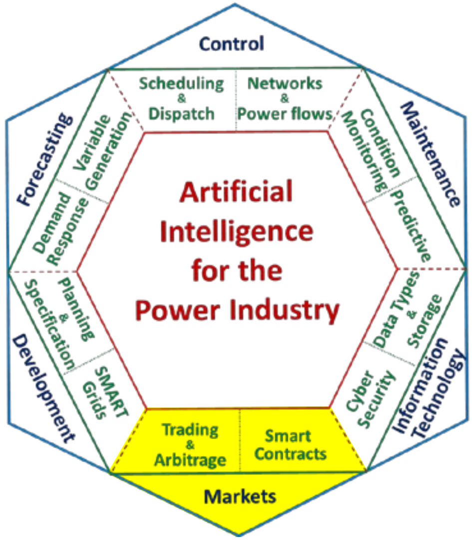


Defining the NEEDs – Markets

- **Electricity Markets**
  - Predictive pricing
  - Trading and Arbitrage
  - Scarcity and Administrative Pricing
  - Automated Matchmaking and Smart Contracts
  - Leverage decentralised assets
  - Market Monitoring and Reporting
  - Model Market behaviour
  - Provide Market signals

- **Sectoral Coupling**
  - Hydrocarbon market interactions (fuel prices)
  - Optimise Green Hydrogen production and utilisation
  - Enhance Energy storage opportunities



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Defining the NEEDs – Development

- **Infrastructure**
  - Digital Twins
  - Specifications and Technical parameters
  - Non-wires solutions
  - Smart Grids (Network)
- **Build out**
  - Expansion Planning and reinforcement
  - Interconnecting grids
  - Sector Coupling
- **Behaviour and Interactions**
  - Smart Grids (Response)
  - Costumer Engagement
  - Partnerships
  - Services
  - Technology development

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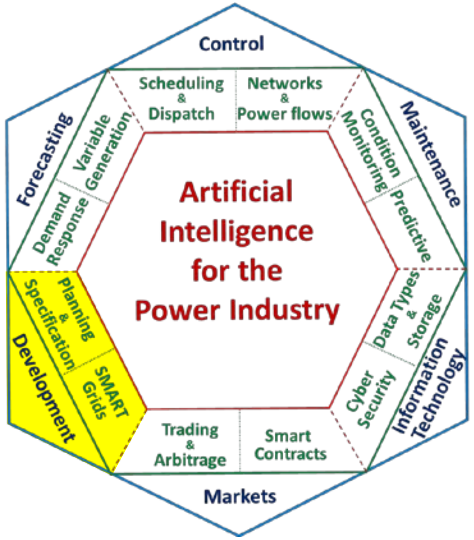
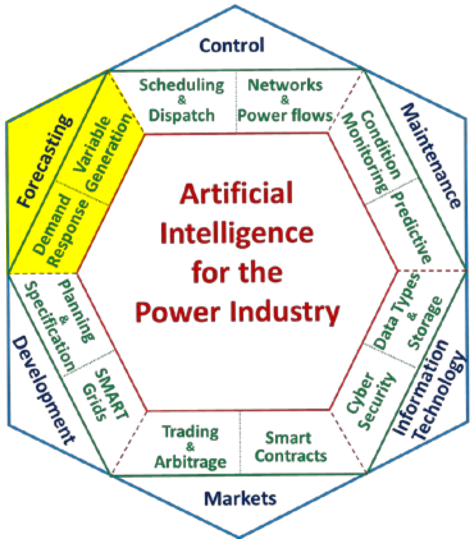


Defining the NEEDs – Forecasting

- **Predicting out-turns (Supply vs Demand)**
  - Variable generation e.g. Renewables (wind, solar)
  - Distributed Energy Resources
  - Day Ahead (ex-ante) cross-border flows
  - Load forecast
  - Demand response including EVs and BESS

- **Grid status**
  - Impact of Weather conditions
  - Potential Dynamic line ratings
  - Future powerflows and congestion
  - Future Reactive power consumption



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What do we need to realize Artificial Intelligence?

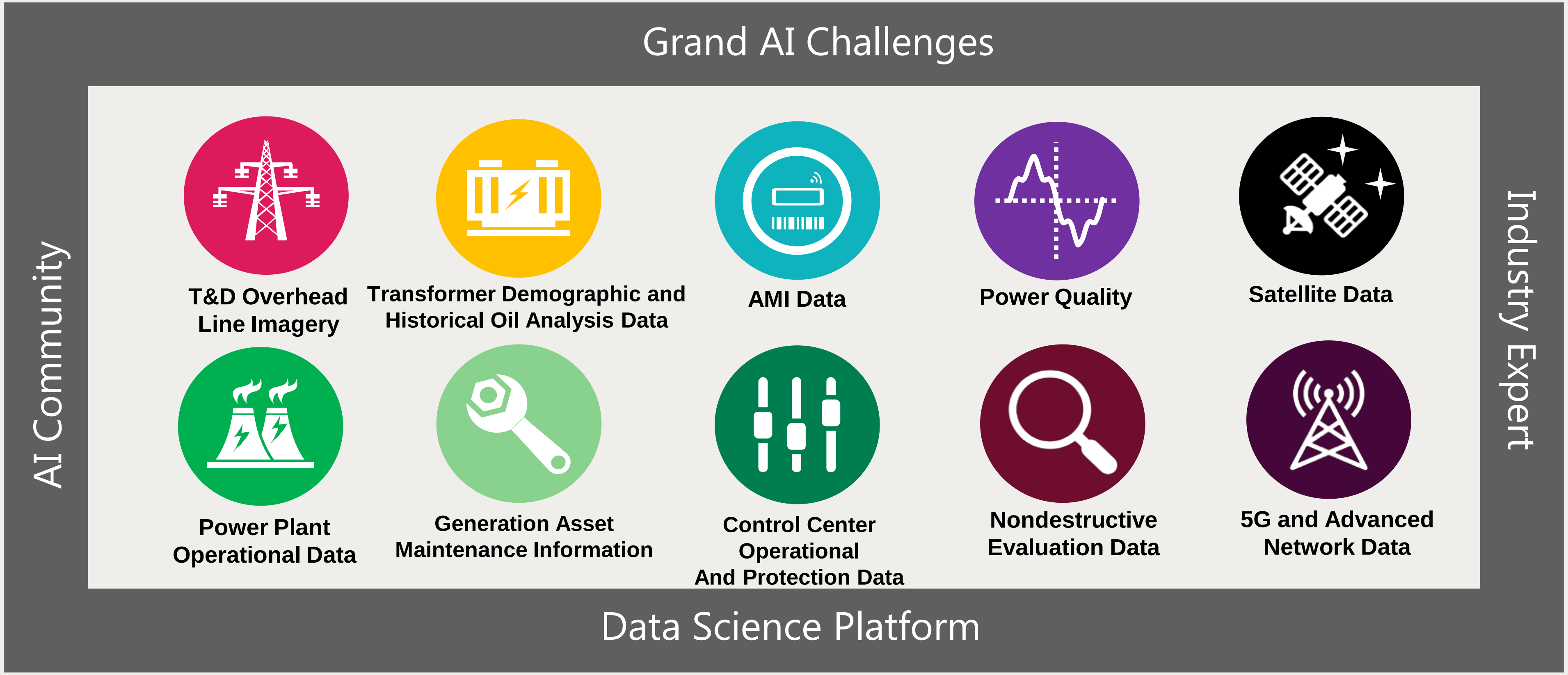
- General requirements for all systems that incorporate AI
- The EU Commission[1] has developed four basic ethical principles:
    1. AI should respect human autonomy
    2. AI should avoid social harm
    3. AI should be fair
    4. AI should be explainable
- For 'trustworthy' AI the EU commission[2] suggests 7 requirements to consider:
    1. Human agency and oversight
    2. Technical Robustness and safety
    3. Privacy and data governance
    4. Transparency
    5. Diversity, non-discrimination and fairness
    6. Societal and environmental well-being
    7. Accountability

[1]European Commission, Directorate-General for Communications Networks, Content & Tech., *Ethics guidelines for trustworthy AI*, 2019, https://data.europa.eu/doi/10.2759/346720
[2]European Commission, Directorate-General for Communications Networks, Content & Tech., *The Assessment List for Trustworthy Artificial Intelligence (ALTAI) for self assessment*, 2020, https://data.europa.eu/doi/10.2759/002360

What do we need to realize AI in the power industry?

- Consider the constraints specific to the power industry
  - Different requirements for AI used in different applications (e.g. condition assessment, protection systems, forecasting etc.)
  - Functional requirements
  - ICT requirements (data, security, storage, power, etc.)
- Consider solution validation
  - How does the customer/user know the AI being sold to them is fit for purpose?
  - How do developers/manufacturers prove to the customer that their systems work and meet requirements?
  - How is the solution supported?
  - Is there any fallback, contingency planning or disaster recovery?
- Consider applicability
  - Product lifetime and obsolescence
  - Difficult to stipulate the AI methods and design that must be used without stifling development
  - Overcome any temptation to apply AI/ML approaches when they are not the optimum solution
- Consider Principles
  - Are there any ethical constraints particular to the power industry? (e.g. use of data for purposes other than originally collected [such as re-use of smart meter data])
  - Jurisdictional requirements for data stored within country or transported on particular infrastructure

EPRI Artificial Intelligence Initiative



Data matters

Considerations for data gathering

- What data is required/available and what it will enable?
  - Characteristics based on data and what AI techniques it supports
    - Different forms of data (structured or unstructured)
    - Qualitative and Quantitative
    - Continuous and Discrete
    - Primary and Secondary Data

- Where does the data come from?
    - Provided data
    - Observed data
    - Derived data
    - Inferred data
    - Streaming data
    - Non-streaming data
  - Data from different data sources and attributes:
    - Data may come from Transmission, Distribution, generation, metering, market systems or other asset data.
    - Each with unique characteristics and ownership requiring classification of data before developing an application.
    - environmental data (e.g. weather data, seismic data, ...),
    - analog data (general sensor data/monitoring - voltage, current, power, vibration, ...),
    - digital data (communication, sensor data, ...)
    - composed data through physical models - white box, black box
  - This data will be collected with and stored with different techniques:
    - IOT, SQL, noSQL, Cloud

Digital Curation Centre Trilateral Research School of Informatics, The University of Edinburgh, *The Role of Data in AI: Report for the Data Governance Working Group of the Global Partnership of AI*, 2020
https://gpai.ai/projects/data-governance/role-of-data-in-ai.pdf

General Data Considerations

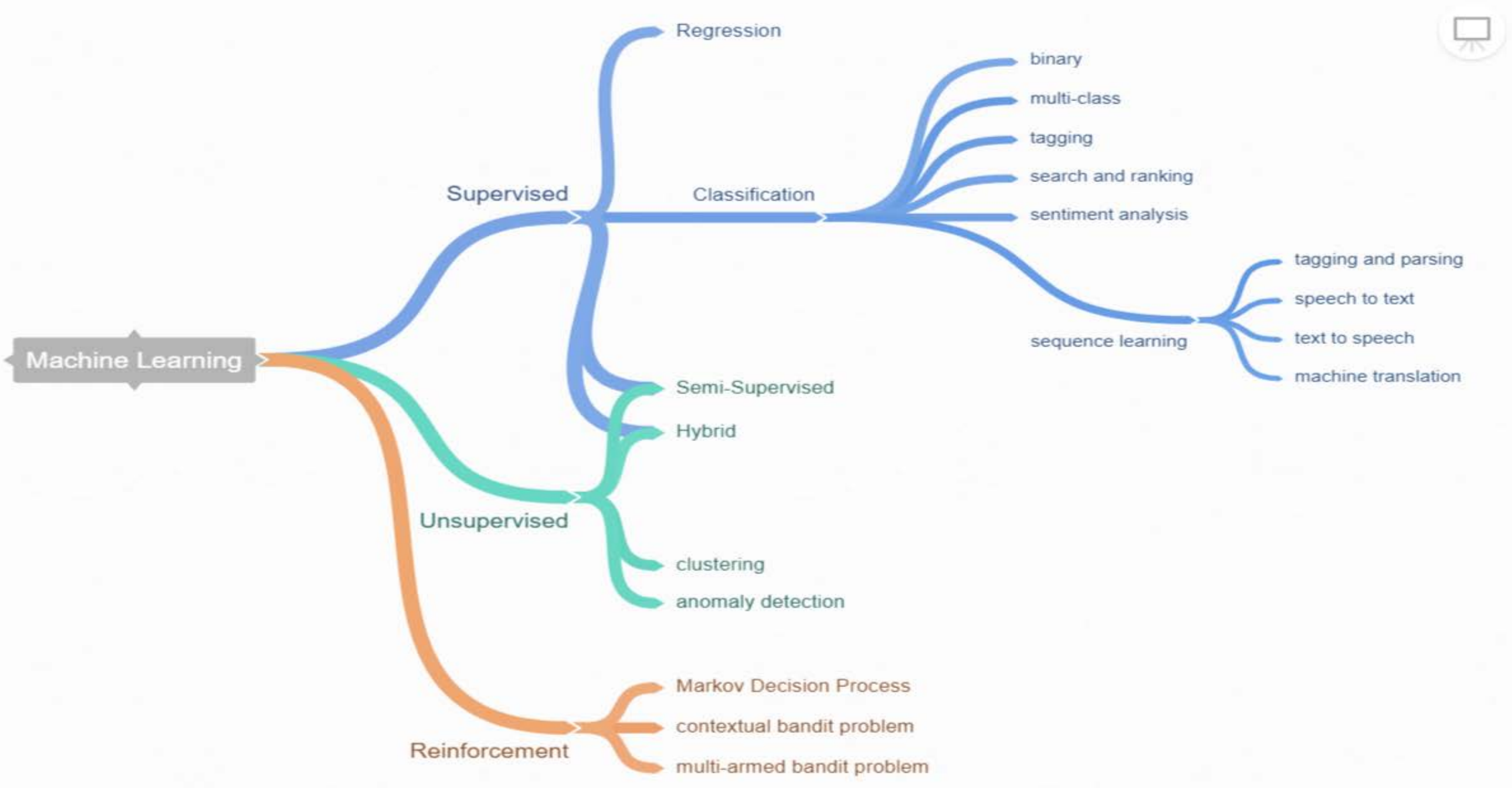
data + model → prediction

- Data set:
  - How much training and validation data is required?
  - What is the quality of the data available?
  - Is the data suitable and sufficient for the problem posed?
  - Is the data neutral or biased?
    - Ensure the data is not poisoned or manipulated
    - Data Security: Avoid the introduction of bias on the algorithm after or during the training
- Data readiness:
  - ***C band***: describes the ***accessibility*** of the individual data sets.
    - It includes limitations in terms of data protection, access restrictions due to topography, ethical and legal aspects.
  - ***B band:*** is concerned with the ***accuracy*** or integrity and presentation of the data.
    - It reflects the meaningfulness and compares it with the expectations.
    - A strategy is applied on how to deal with missing, noisy or manually incorrectly entered data sets.
  - ***A band:*** represents progress around the data in ***context***.
    - This category checks whether this data set is suitable for answering the respective question.
    - It follows that this category has some of the characteristics of a classical statistical analysis.
    - To successfully achieve this class, the data must be checked for distortion and possibly missing information.

L. D. Neil, *Data Readiness Levels,* Amazon Research Cambridge and University of Sheffield, 2017

Matching the AI model with Power system applications

Based on the **power system application** requirements and **data availability**, we should select unsupervised, supervised, semi-supervised or reinforcement learning



Considerations for your application

Machine learning approaches need to be applied after analyzing the power system problem carefully
→ It is important to match the strengths of ML / AI to the power system problem to be solved

Machine learning is only applicable in data-rich problems if no system model is available (e.g. forecasting)

If a model is available with rich data sets, typically it will be a two step approach:
1: apply machine learning to narrow down your possible options
2: refine it with model-based approach (e.g. event detection)

Machine learning will not (yet) give good results based on state of the art for highly complex & dynamic problems (e.g. transient stability, contingency analysis).

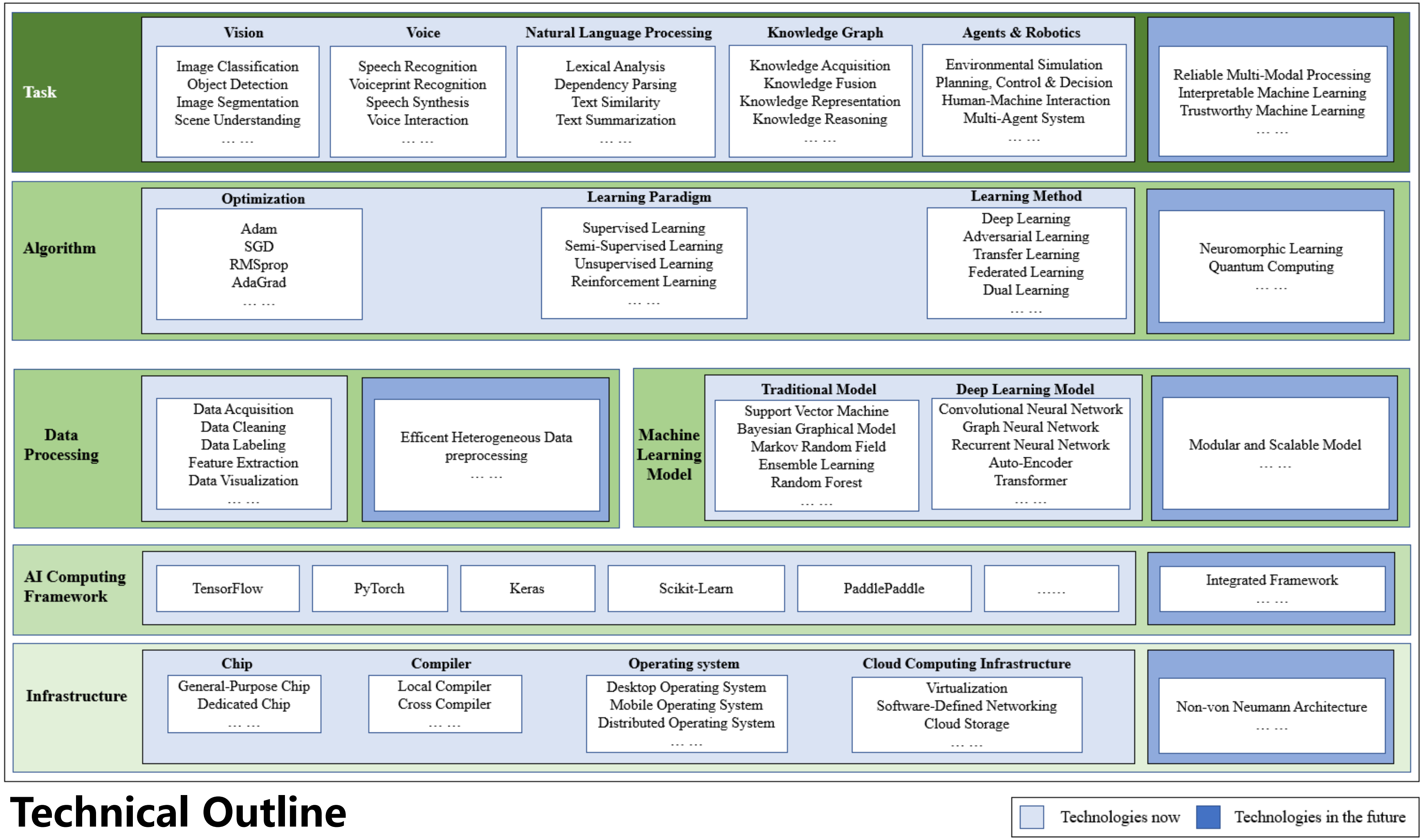
Validation and metrics are critical for these evolving solution technologies

CONTENTS

AI Technology Framework

- Covers all aspects of the technology needed for the development of AI application in the power field, including a limited outlook on possible future important technologies.

- Main purpose is to give power engineers and scientists who are not familiar with AI technology a basic understanding of AI, so as to lay the foundation for possible future work.



Technical Outline

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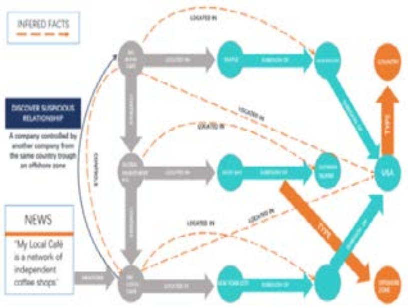
AI Tasks

- 4.1. TASK
  - 4.1.1. Vision
    - 4.1.1.1. Image classification
    - 4.1.1.2. Object detection
    - 4.1.1.3. Image segmentation
    - 4.1.1.4. Scene understanding
  - 4.1.2. Voice
    - 4.1.2.1. Speech recognition
    - 4.1.2.2. Voiceprint recognition
    - 4.1.2.3. Speech synthesis
  - 4.1.3. Natural language processing
    - 4.1.3.1. Semantic parsing
    - 4.1.3.2. Dependency parsing
    - 4.1.3.3. Text similarity
    - 4.1.3.4. Text summarization
  - 4.1.4. Knowledge graph
    - 4.1.4.1. Knowledge acquisition
    - 4.1.4.2. Knowledge embedding
    - 4.1.4.3. Knowledge reasoning
  - 4.1.5. Agents & Robotics
    - 4.1.5.1. Environmental simulation
    - 4.1.5.2. Planing, control, and decision
    - 4.1.5.3. Human-machine interaction
    - 4.1.5.4. Multi-agent system
  - 4.1.6. Future research
    - 4.1.6.1. Reliable multi-modal learning
    - 4.1.6.2. Trustworthy machine learning

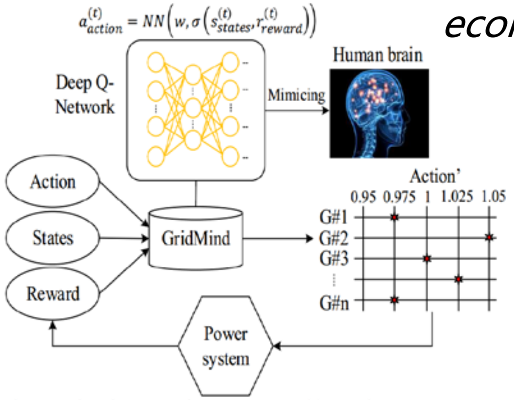
Object detection to improve system maintenance

Customer service robots to improve customer satisfaction and reduce human workloads



Knowledge graph to promote the efficiency for document reference

Smart dispatch to improve the system operational economics and reliability



Few common tasks to improve the power system are identified

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Vision

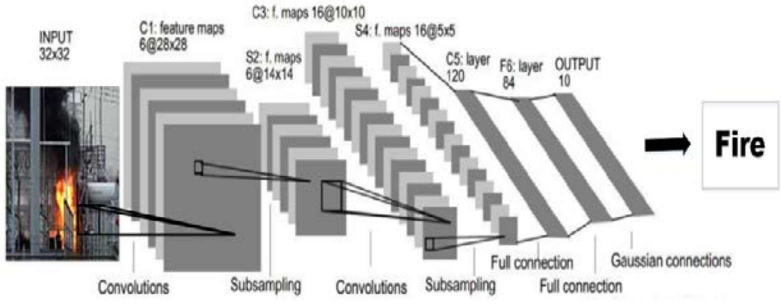


Image Classification

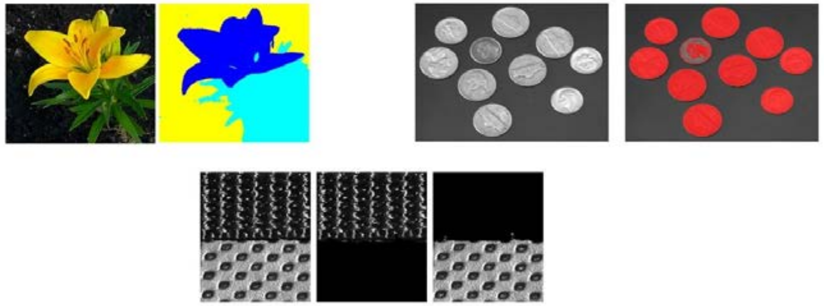
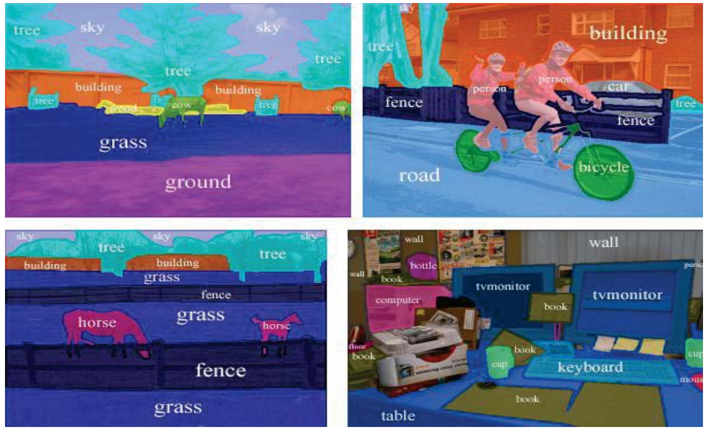


Image Segmentation

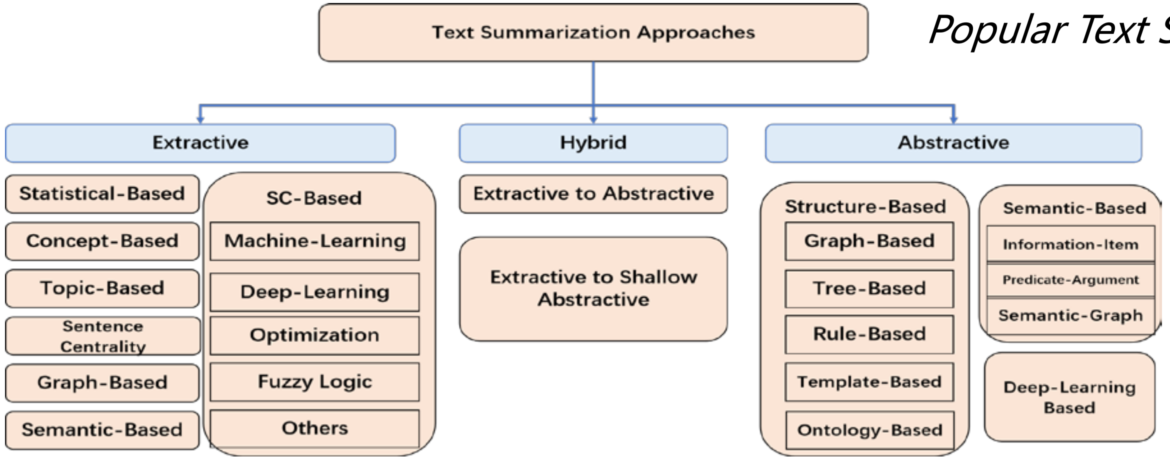
Object Detection



Scene Understanding

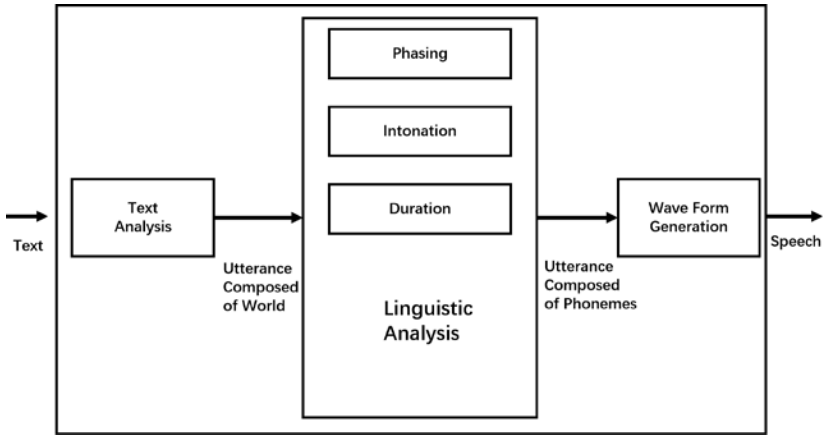
Voice / Natural Language Processing

- **Semantic parsing**
- **Dependency parsing**
- **Text similarity**
- **Text summarization**



Popular Text Summarization Methods

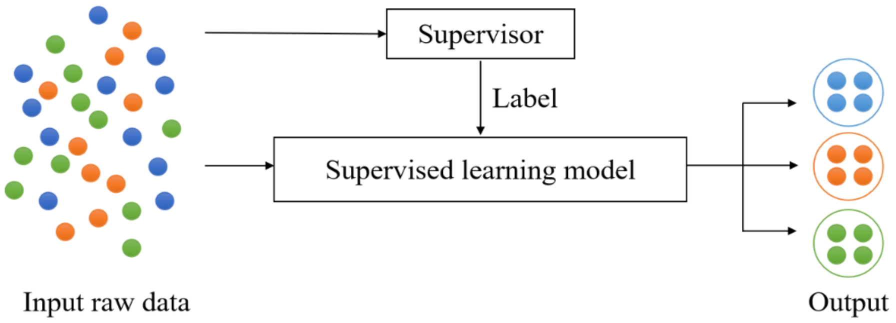
- **Speech recognition**
- **Voiceprint recognition**
- **Speech synthesis**



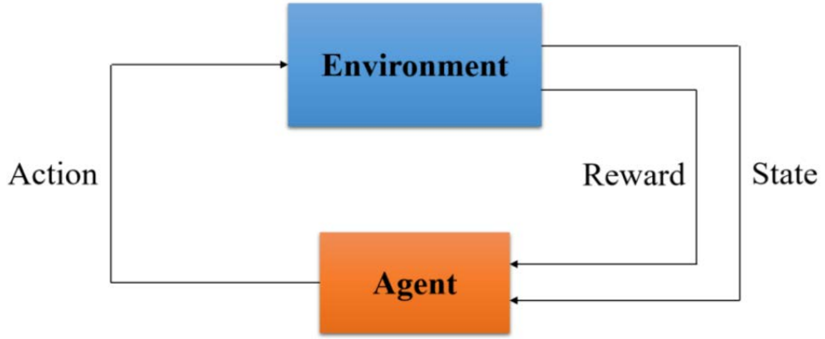
Pipeline of a typical TTS system

Algorithms & Data Processing

- 4.2. ALGORITHM
  - 4.2.1. Optimization
    - 4.2.1.1. First-order optimization
    - 4.2.1.2. High-order optimization
    - 4.2.1.3. Derivative-free optimization
  - 4.2.2. Classic learning paradigms
    - 4.2.2.1. Supervised learning
    - 4.2.2.2. Unsupervised learning
    - 4.2.2.3. Semi-supervised learning
    - 4.2.2.4. Weakly-supervised learning
    - 4.2.2.5. Reinforcement learning
  - 4.2.3. Advanced learning techniques
    - 4.2.3.1. Deep learning
    - 4.2.3.2. Adversarial learning
    - 4.2.3.3. Transfer learning
    - 4.2.3.4. Federated learning
  - 4.2.4. Future research
    - 4.2.4.1. Neuromorphic computing
    - 4.2.4.2. Quantum computing
- 4.3. DATA PROCESSING
  - 4.3.1. Data acquisition
  - 4.3.2. Data cleaning
  - 4.3.3. Data labeling
  - 4.3.4. Feature extraction
  - 4.3.5. Data visualization
  - 4.3.6. Future: Efficient heterogeneous data preprocessing



Supervised Learning Principle



Reinforced Learning Principle

Key algorithms, including optimization, learning paradigms, advanced techniques have been introduced

Some data processing techniques are introduced

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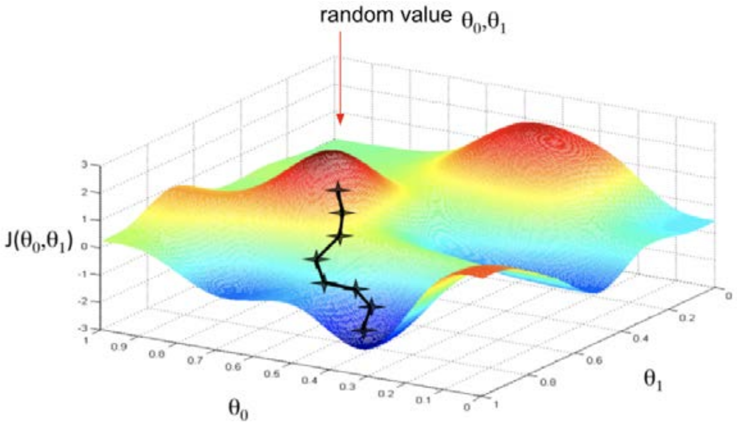
Optimization

First-order optimization:

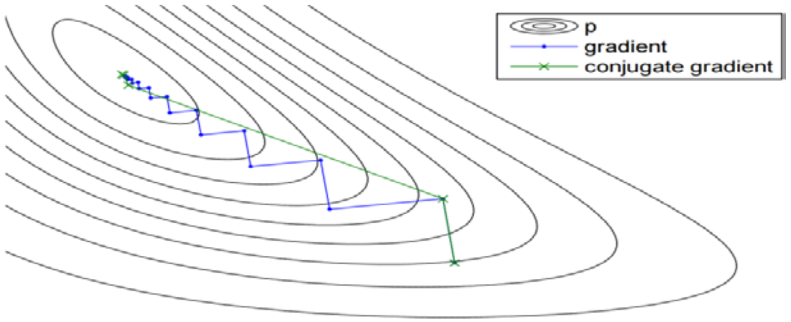
- iteratively explores gradient information to minimize a loss function
- require significantly less data information and have lower implementation complexity
- Stochastic gradient descent (SGD), Adaptive Moment Estimation (Adam), Root Mean Square prop (RMSProp), and Adaptive Sub-gradient (AdaGrad)



Minimizing a loss function with gradient descent

High-order optimization

- generally refers to second-order optimization
- faster convergence speed with greatly increased complexity
- Newton’s method, Conjugate Gradient Method, Quasi-Newton Method, and Trust Region Method



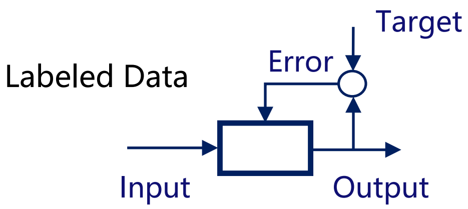
Gradient vs. Conjugate gradient

Derivative-free optimization

- derivative of an objective function is unavailable, unreliable, or impractical to obtain
- Heuristics algorithms

Classic Learning Paradigms

Supervised Learning



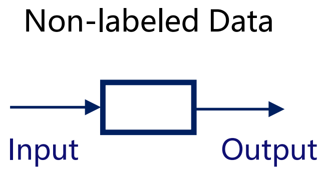
Applications

- ✓ Classification
- ✓ Regression

Algorithms

- o *k*-NN
- o Linear regression
- o Decision tree
- o Logistic regression
- o SVM
- o Neural network

Unsupervised Learning



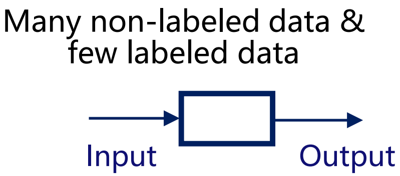
Applications

- ✓ Clustering
- ✓ Dimensionality reduction
- ✓ Visualization

Algorithms

- o *k*-Means
- o Hierarchical clustering
- o PCA

Semi-supervised Learning



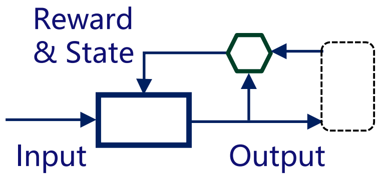
Applications

- ✓ Google photo
- ✓ Page rank

Algorithms

- o Graph algorithms
- o Self-training
- o Co-training

Reinforcement Learning



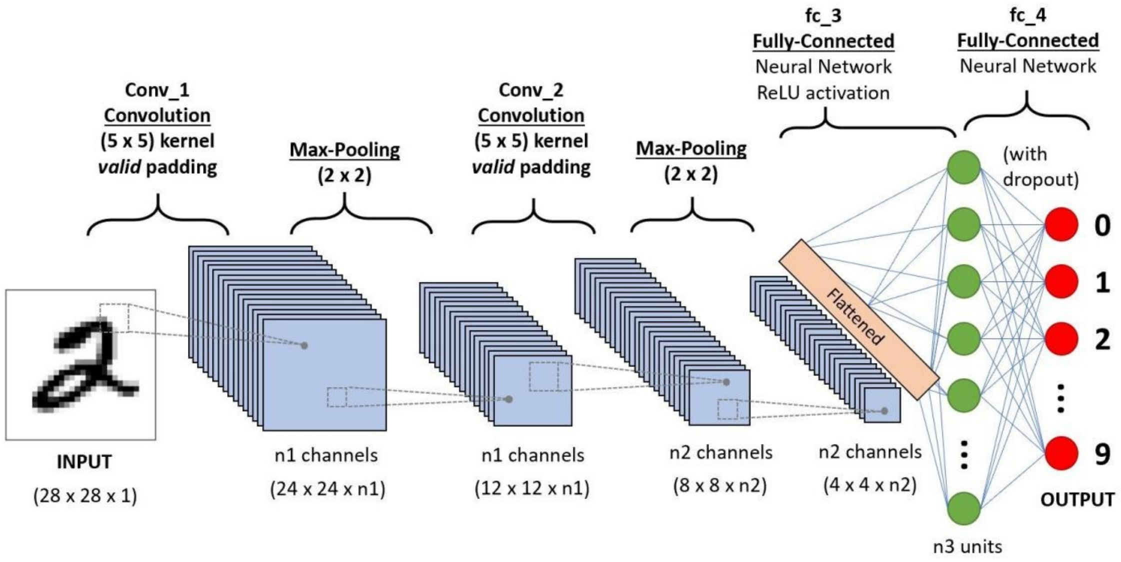
Applications

- ✓ AlphaGo
- ✓ Autonomous driving
- ✓ Control & Optimization

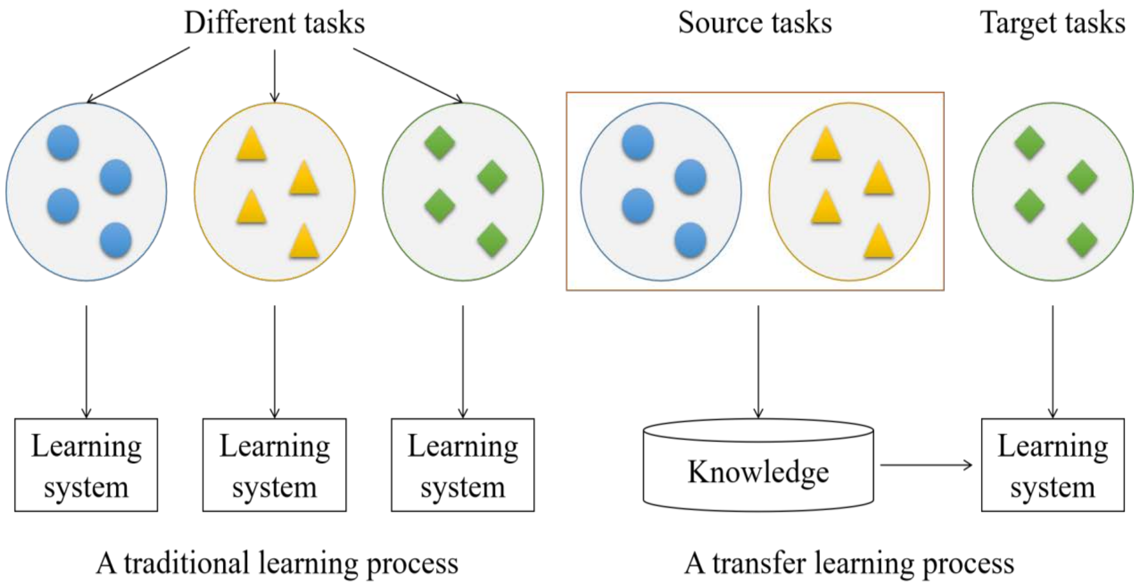
Algorithms

- o Dynamics programming
- o Temporal differences
  - ✓ Q-learning
  - ✓ SARSA

Advanced Learning Techniques



Deep learning

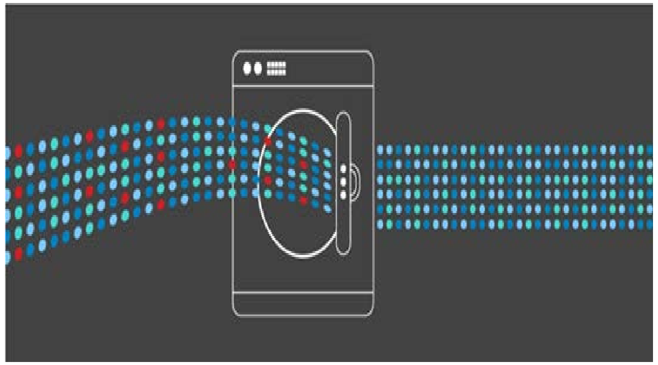


Transfer learning

- **Adversarial learning**
- **Federated learning**
- **Neuromorphic Computing**
- **Quantum computing**

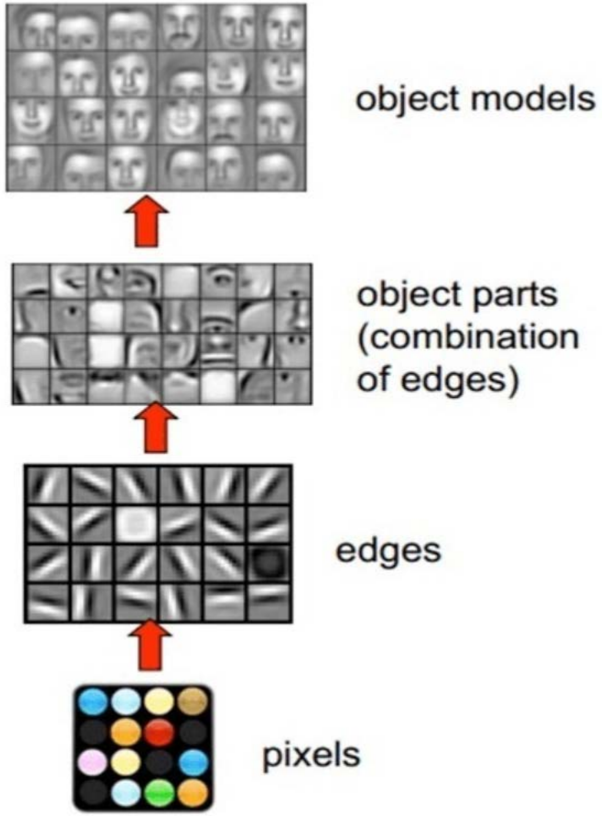
Data Processing

- **Data Acquisition**
- **Data cleaning**
- **Data labeling**
- **Feature extraction**
- **Data visualization**



Data cleaning

Data labeling



Feature extraction

Machine Learning Models & Framework

- 4.4. Machine Learning Models
  - 4.4.1. Traditional Models
    - 4.4.1.1. Linear Regression
    - 4.4.1.2. Logistic Regression
    - 4.4.1.3. Decision Tree/Forests
    - 4.4.1.4. Neural Network (shallow)
    - 4.4.1.5. Support Vector Machine
    - 4.4.1.6. Neural network
    - 4.4.1.7. K-nearest neighbor
    - 4.4.1.8. Support vector machine
    - 4.4.1.9. Ensemble learning
    - 4.4.1.10. Decision tree
    - 4.4.1.11. Random forest
    - 4.4.1.12. Markov random field
  - 4.4.2. Deep learning model
    - 4.4.2.1. Deep neural network
    - 4.4.2.2. Convolutional neural network
    - 4.4.2.3. Recurrent neural network
    - 4.4.2.4. Graph neural network
    - 4.4.2.5. Transformer
  - 4.4.3. Future: Bio-inspired interpretable model
- 4.5. AI COMPUTING FRAMEWORK
  - 4.5.1. Tensorflow
  - 4.5.2. Pytorch
  - 4.5.3. Keras
  - 4.5.4. Scikit-learn
  - 4.5.5. PaddlePaddle
  - 4.5.6. Future: Human-Machine interactive framework

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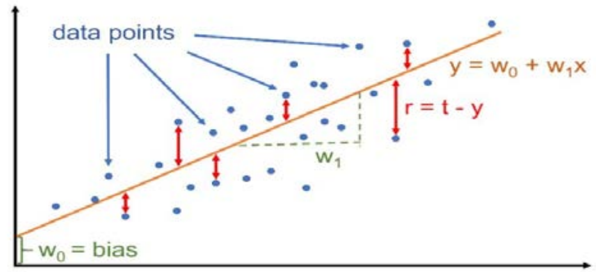
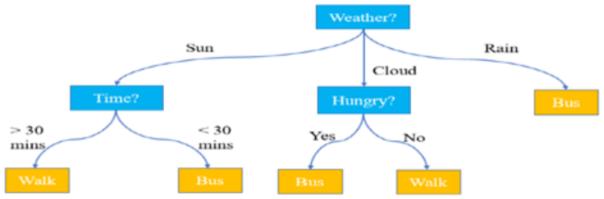
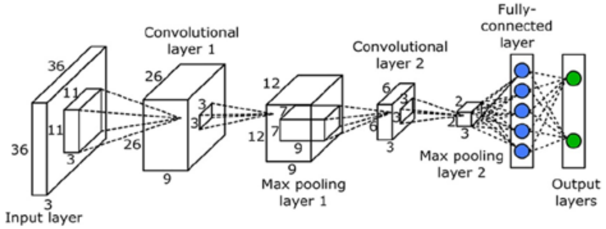


Basic: linear regression



Intermediate: decision tree

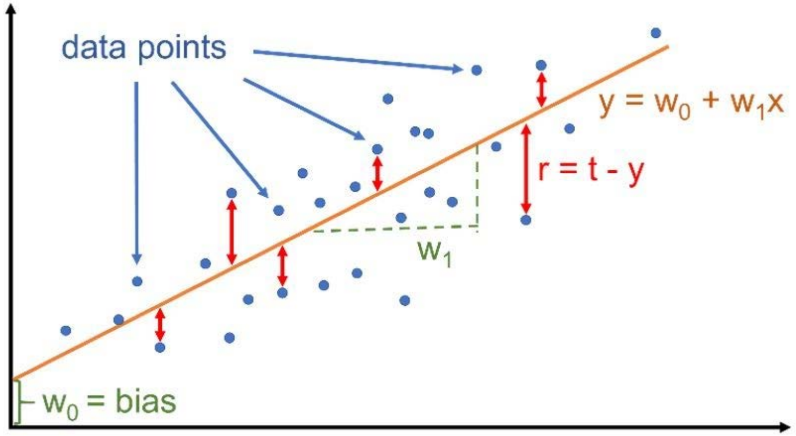


Advanced: convolutional neural network (CNN)

- **Widely applied machine learning models are covered, from the basic linear models to advanced deep models**
- **Public computing framework are mentioned to guide interested readers**

Linear Regression

- **Map the relationship between variables by fitting a linear equation to the data,**
- **One target variable is the variable being studied, and it is what the regression models trying to predict**
- **The other variables are considered to be predictors, independent variables or features**
- **Multiple features in which case we speak of multiple linear regression**



Basic principle of linear regression

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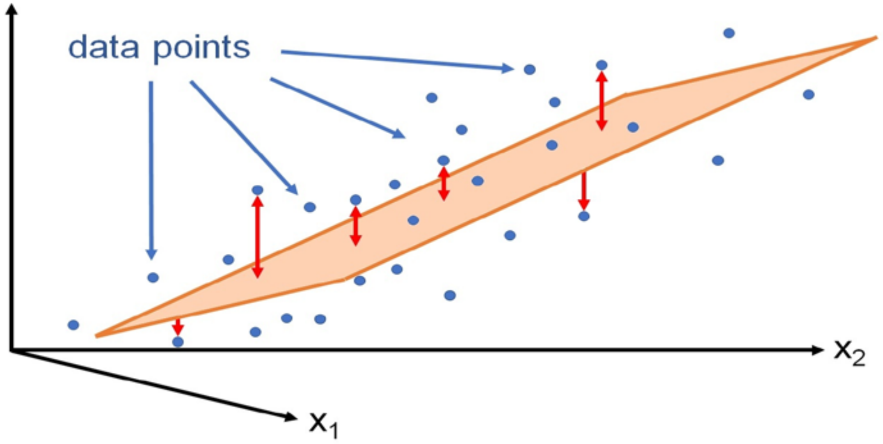
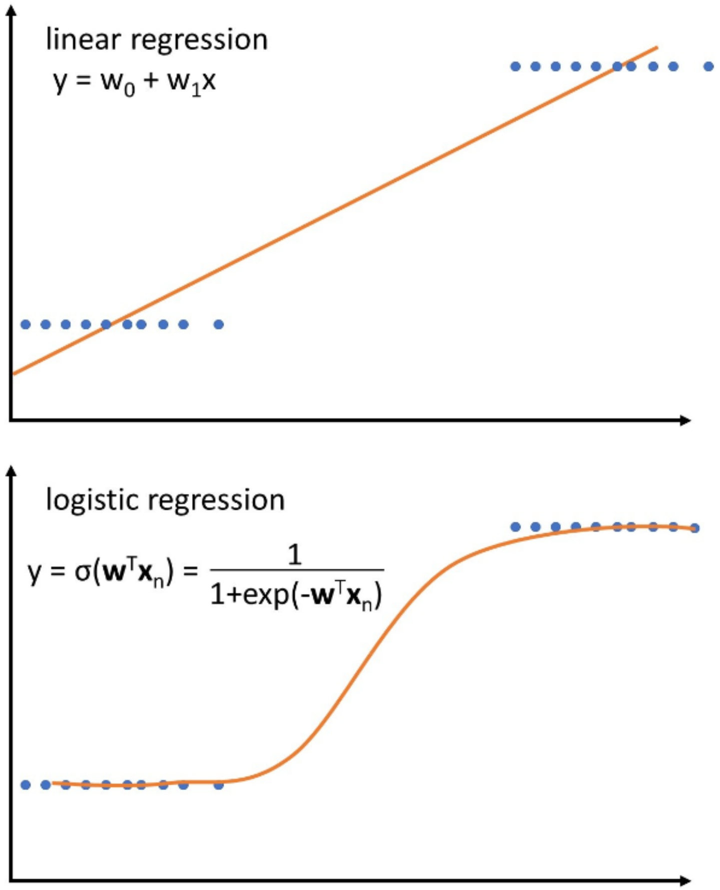


Multiple linear regression with two features

Logistic Regression

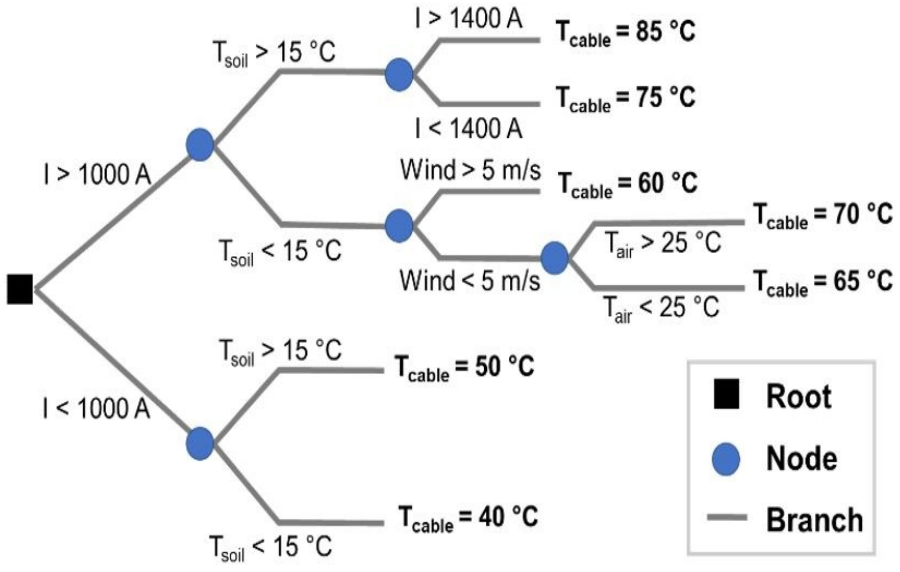
- **Commonly use for supervised classification**
- **Use sigmoid function to return probabilities**
- **Non-convex cost function**
- **Iterative optimization approaches such as gradient descent**



Comparison of linear regression and logistic regression

Decision Trees

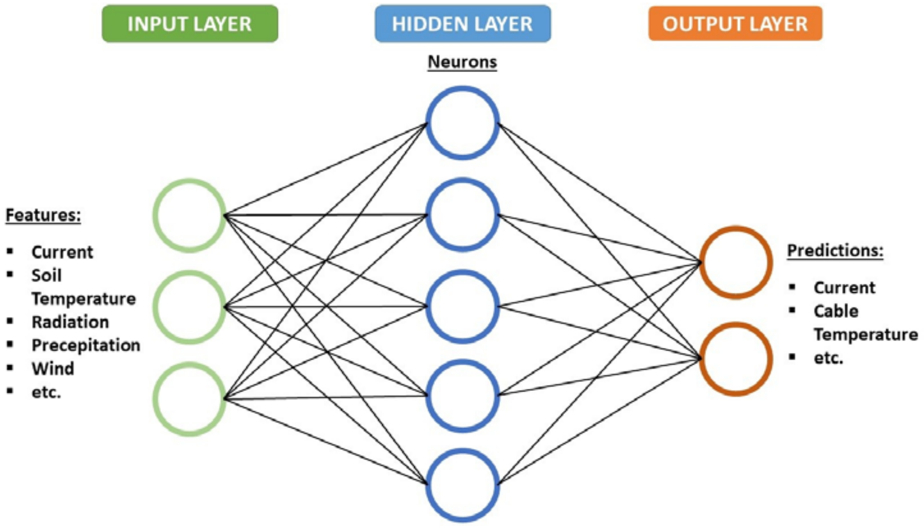
- **A list of if-then checks, where every node represents a check or evaluation**
- **Every branch is a decision and the end of a branch a consequence**
- **A recursive portioning of the data**
- **Extensions include gradient boosting tree, random forests**



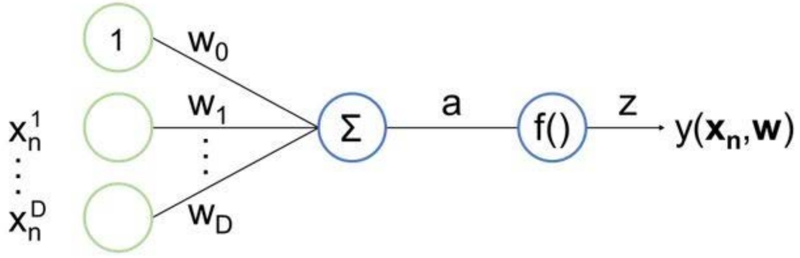
Basic architecture of decision tree

Neural Networks

- **A collection of connected nodes or artificial neurons, similarly to the neurons in a biological brain**
- **An input layer, one hidden layer (shallow neural networks) or multiple hidden layers (deep neural networks) and an output layer.**
- **Represent a vast variety of functions if they are given appropriate weights (universal approximation theorem)**
- **virtually any function can be represented by a neural network with a sufficient number of neurons and corresponding weights.**



Basic architecture of shallow neural network



Perceptron

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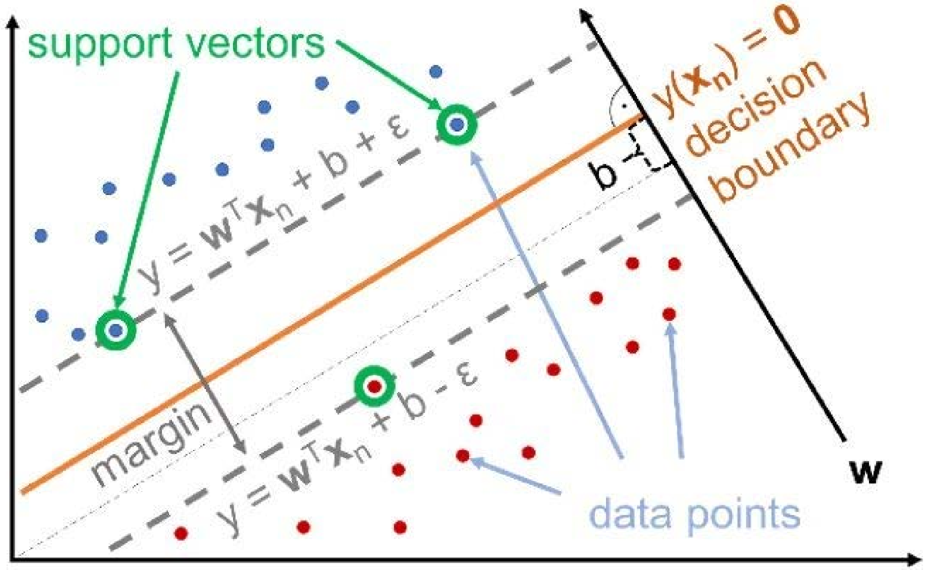
Support Vector Machine

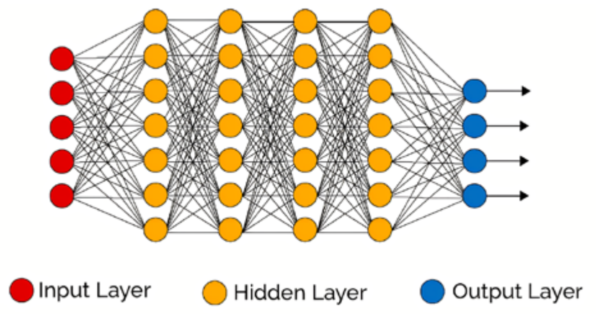
- **Decision boundary finds a function that separates the data into its classes**
- **To find the "best" line, the SVM algorithm uses a margin as an optimization quantity**
- **The line separating the data is defined by the data points closest to it, called support vectors**
- **The distance between these support vectors and the line is called the margin**
- **To find the "best" hyperplane, the support vector machine algorithm maximizes this margin**



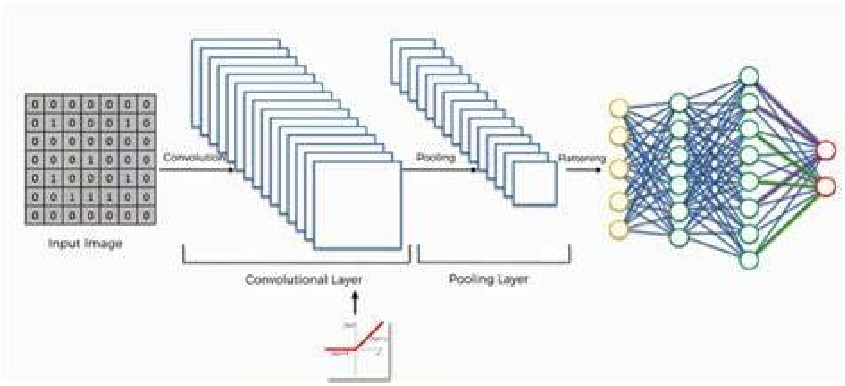
Basic principle of support vector machine

Deep Learning

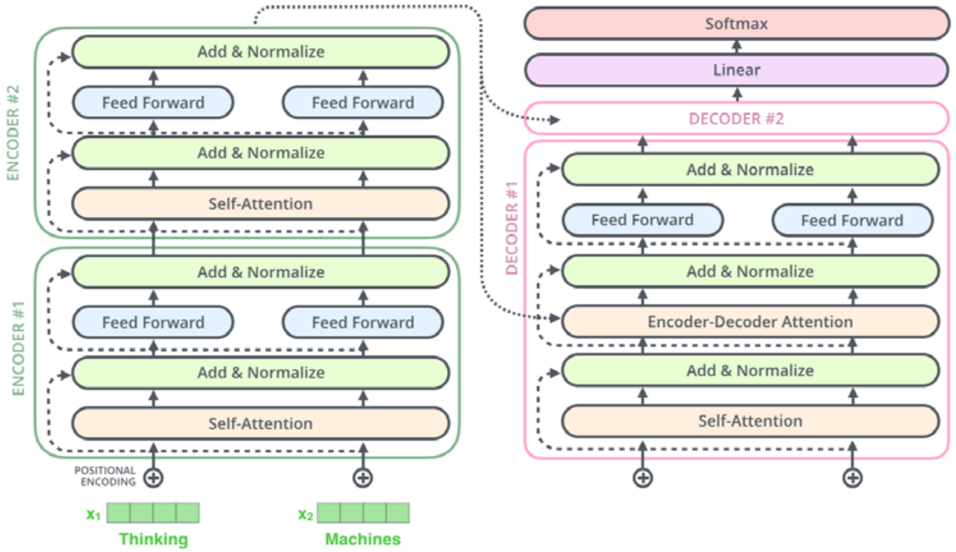
DNN



CNN



Transformer



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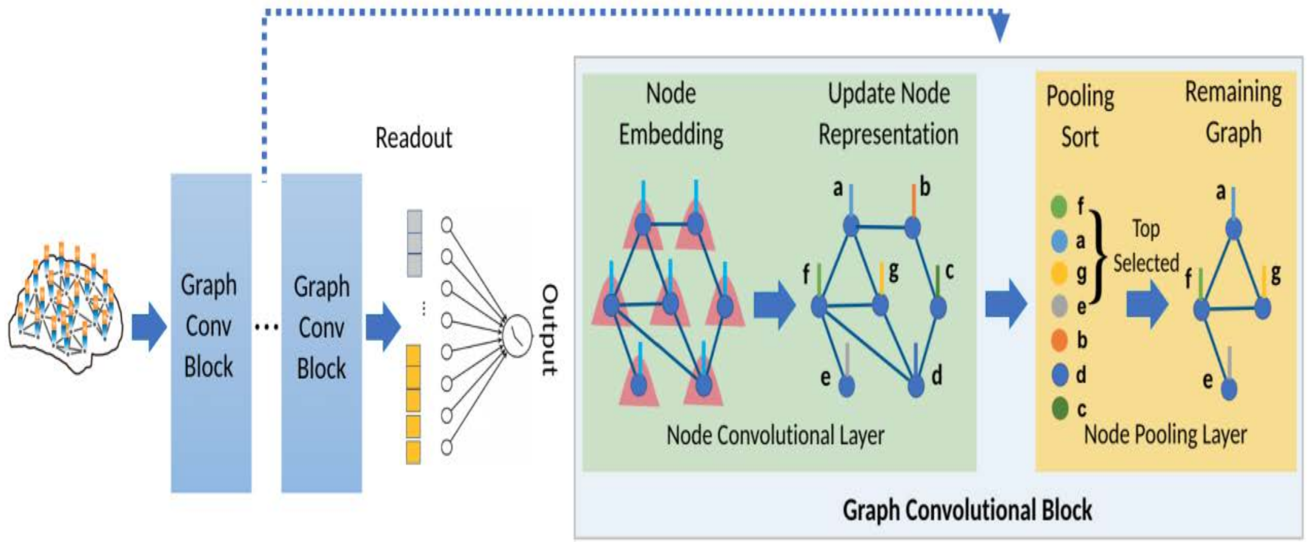
GNN

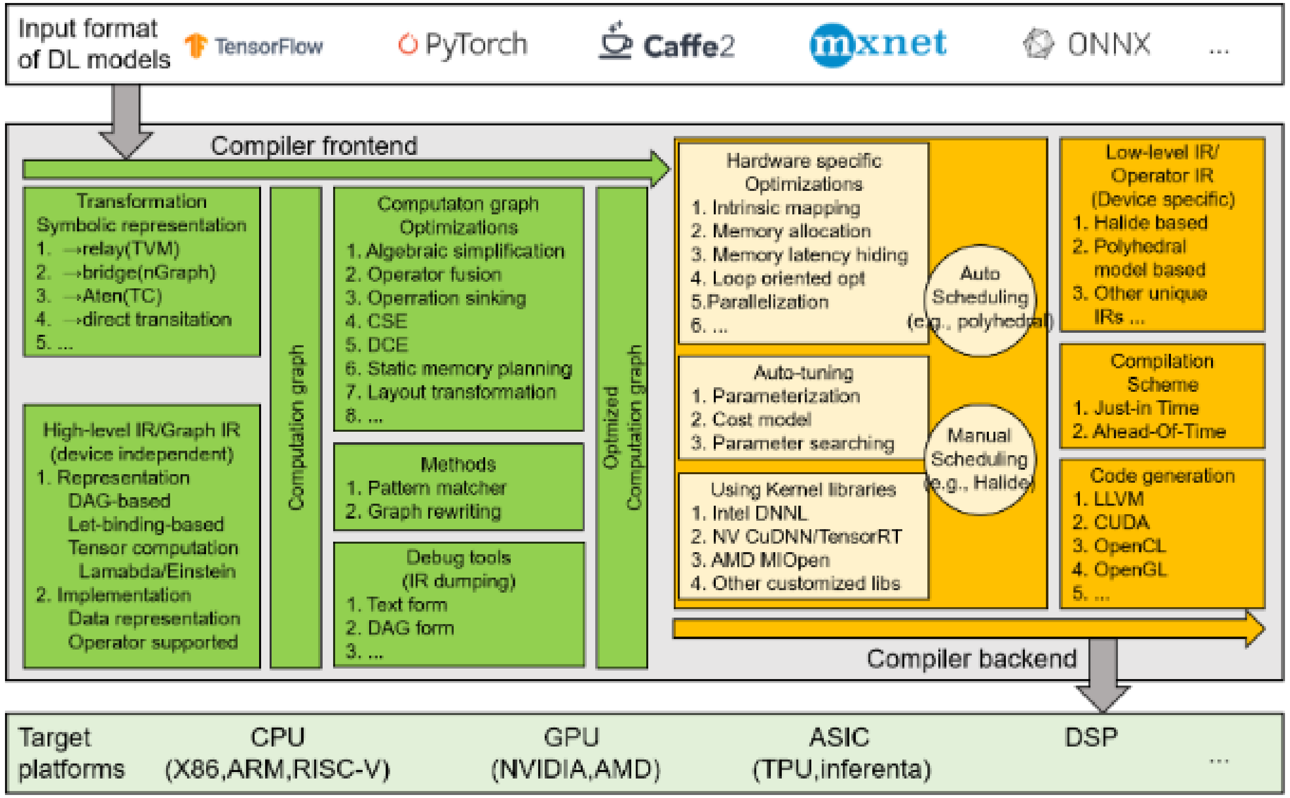


Computing Frameworks

- **Tensorflow**
- **Pytorch**
- **Keras**
- **Scikit-learn**
- **PaddlePaddle**

Infrastructure

Overview of commonly adopted design architecture of AI dedicated compilers



Software is not everything, and another critical component in AI technology is hardware

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CONTENTS

Main Areas of Application

- Operations (economic dispatch, congestion management, state estimation and maintenance scheduling)
- Control (voltage control, stability control, power flow control, load frequency control)
- Planning (short-term and long-term load forecast, solar and wind power forecasting, electricity market strategies (example: bidding strategies)
- Automation of power systems like fault diagnosis and/or restoration
- System stability analysis and enhancement
- Reactive power planning and control
- Asset management and online asset monitoring systems
- Asset failure prediction and identification

Discussion of Applicability

Important aspects to consider:

- IT requirements (infrastructures, hardware, integration)
- Data availability and quality
- Ethical and environmental concerns
- Scalability or the ability to adapt to users' requirements, irrespective of size or volume

Assessing Maturity

Assessing the maturity of a particular technology on a global scale is not easy since there could be several localized applications in different parts of the world, some more successful than others, some not so much publicly described for intellectual property reasons or other matters that are difficult to overcome for each individual solution. In general terms one can say that maturity of a technology may be assessed by the determination of how advanced its developments are considering the specificities of its field of application.

NASA Technology Readiness Approach[1]

As an example of a methodology to assess maturity, NASA has proposed a scale for the so-called Technology Readiness Level (TRL) that has been applied to various technologies and industries. TRL principles were generalized in the norm ISO 16290:2013, and consist of:

1. Basic principles observed and reported
2. Technology concept and/or application formulated
3. Analytical and experimental critical function and/or characteristic proof-of-concept
4. Component and/or breadboard functional verification in laboratory environment
5. Component and/or breadboard critical function verification in a relevant environment
6. Model demonstrating the critical functions of the element in a relevant environment
7. Model demonstrating the element performance for the operational environment
8. Actual system completed and accepted for flight (“flight qualified”) - deployment
9. Actual system “flight proven” through successful mission operations – large scale

(1) Technolgy Readiness Levels: a White Paper.
NASA Office of Space Access and Technology Advanced Concepts Office, 1995

Technology Readiness for Machine Learning (TR4ML) (2)

The NASA framework was adapted to the peculiarities of AI/Machine Learning applications, incorporating the required process of Software development, iterations, from research to industrialization. Technology Readiness for Machine Learning (TR4ML) spans the stages of a project development through prototyping, productization and deployment with 9 levels, which represents the maturity of a model or algorithm, data pipelines, software module, or composition thereof. A typical ML system consists of many interconnected subsystems and components, and the TRL of the system is the lowest level of its constituent parts. The levels are defined with the following considerations:

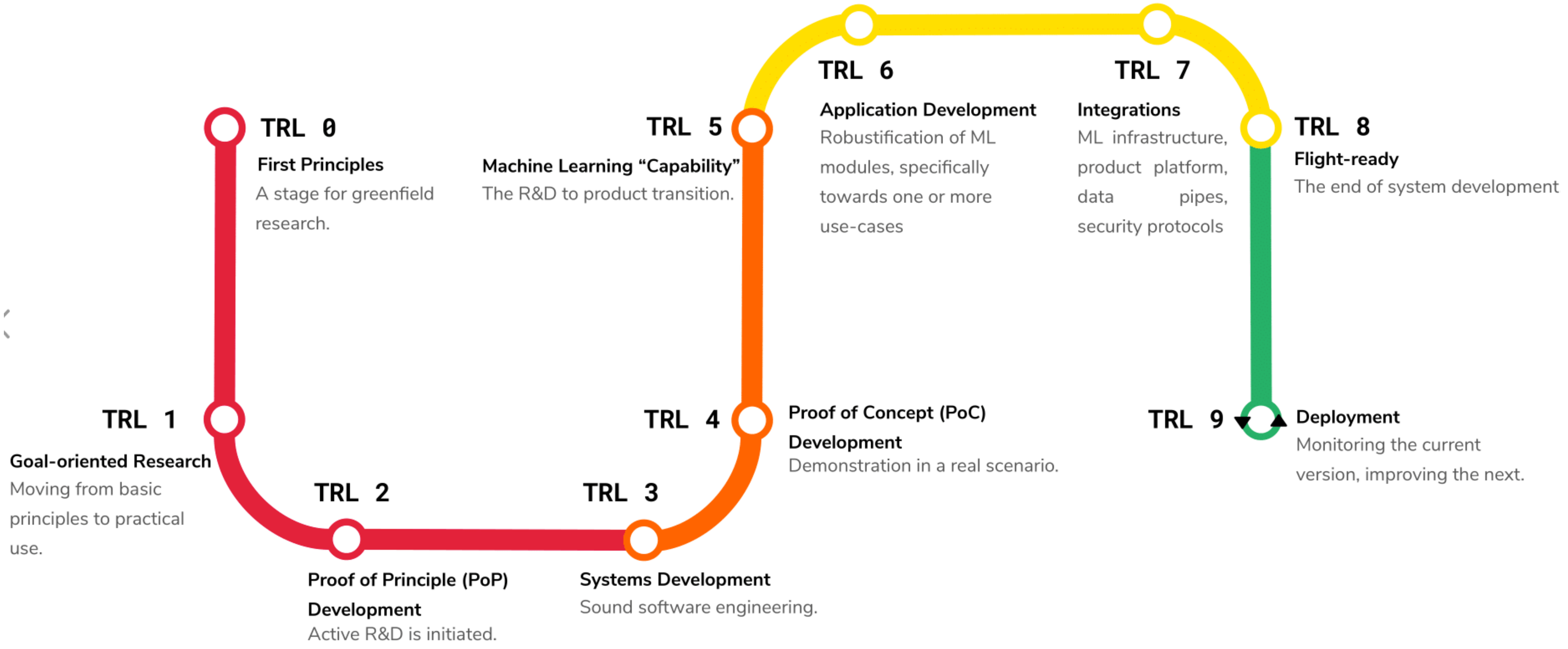
(2) A. Lavin et al., "Technology Readiness Levels for Machine Learning Systems" [arXiv, 2021]

Technology Readiness for Machine Learning (TR4ML)

1. Goal-oriented research - first experiments presented to peers
2. Proof of Principle development - run of testbeds with benchmark datasets
3. System development - interoperability and maintainability, code documentation and versioning.
4. Proof of Concept (PoC) development - use-case examples
5. Machine learning "capability" - data pipelines scaling, data governance, draft of product requirements,
6. Application development - code quality to reach product-caliber level, regulatory compliance, robustness.
7. Integrations - review of data pipelines and tests suites in targeted production environments
8. Flight-ready - walkthrough every technical requirement, showing validations, demo to stakeholders
9. Deployment - monitoring of the current version, regular monitoring of performance

Technology Readiness Diagram

TR4ML Diagram



TR4ML Case Studies

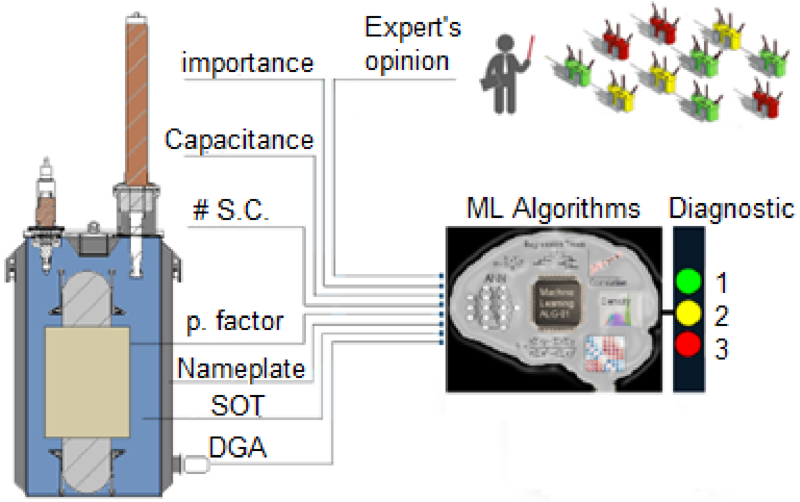
1. PD Pattern Recognition in Online Monitoring
2. Transformer Condition Assessment with ML
3. Image Classification of Transmission Lines
4. Reinforcement Learning for Electrical Grid Operations
5. Ampacity Calculation for Power Cables with ML

Example: Transformer Condition Assessment with ML[3]

Consider the case of a large number of power transformers, say 1,000 units of different sizes and manufacturing, for which we have 24 parameters (features) indicating the operating condition of the units (oil quality, DGA, bushing power factor, ratings, etc.)

Based on the data above human experts classified all units into 3 groups: green = good condition, yellow = acceptable but needs action, and red = high risk units, requiring immediate action.

ML algorithms were trained by the expert judgement and "learned" to classify the transformer conditions with an accuracy of 97% on a test set with 200 unseen cases.



(3) Machine Learning Tools in Support of Transformer Diagnostics, Luiz Cheim, SCA2 PS2 Best Paper Award, Paris Cigre Session 2018

Power System Fault Diagnostics with Machine Learning

IEEE Explore

2015	2016	2017	2018	2019	2020	2021
176	251	372	537	835	982	1100

Google Scholar

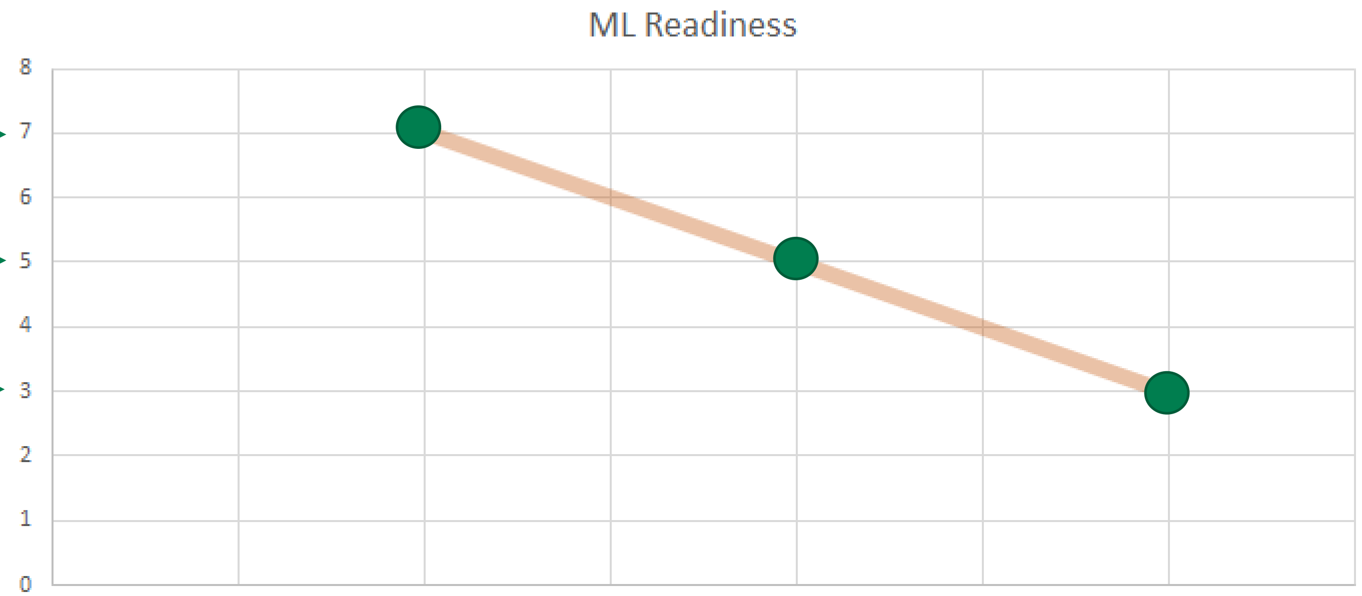
2015	2016	2017	2018	2019	2020	2021
158	232	337	471	736	1050	1460

Technology Readiness

ML Integration
Data pipes in place

Transitioning
R&D to Product

Proof of Concept



Fault Detection Identification

Failure Cause Analysis

System restoration Actionable recommendation

Technology Readiness

TRL 3
Efforts taking place in the area of system restoration, actionable recommendations, root cause analysis through automated systems. Still in early stages. *Power equipment Digital Twin playing important role*.

TRL 5
Failure identification through NN, Deep Learning, Gradient Boosting Machine already a common place

TRL 7
"Productization" /Integration into IT infrastructure of fault detection/identification already happening in multiple types of applications

Data Readiness

Companies still struggling to move into AI/ML data-ready.
A lot of “experimentation” with powerful applications but data readiness require serious “rethinking” of the whole data governance process.

CONTENTS

Typical Practice - Included Cases

1. **Condition Assessment of Power Transformers**
2. **AI Techniques for the Classification of UHF PD Signals**
3. **GIS / Transformer PD Analysis**
4. **AI in Thermal Rating and Monitoring of HV Power Cables**
5. **Power Market Bidding Pattern Analysis**

Typical Practice – Outline / Aim

For each case the general outline is:

- **Introduction / Evaluation on problem**
- **Data set and preparation**
- **Methodology**
- **Practice validation / Case study**
- **Discussion**

The chapter *Typical Practice* is focusing on specific problem cases and how they are solved using AI.

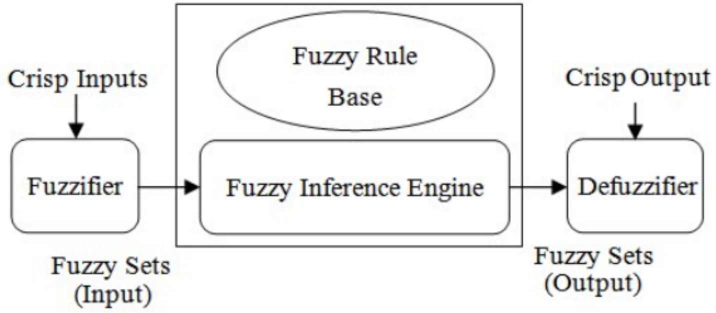
For the evaluation of applicability, examples are given in the chapter *Applicability and Maturity*, which are:

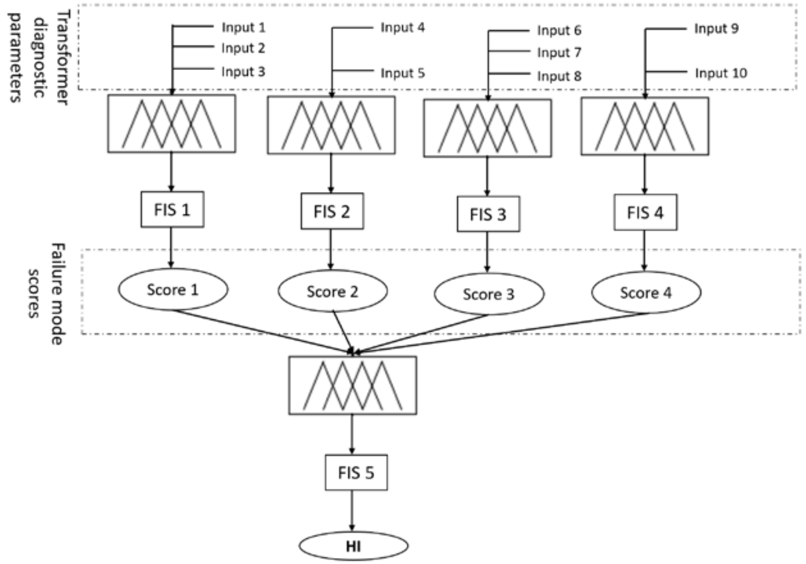
1. PD Pattern Recognition in Online Monitoring
2. Transformer Condition Assessment with ML
3. Image Classification of Transmission Lines
4. Reinforcement Learning for Electrical Grid Operation
5. Ampacity Calculation for Power Cables

Condition Assessment of Power Transformers | **Data set / Preparation**

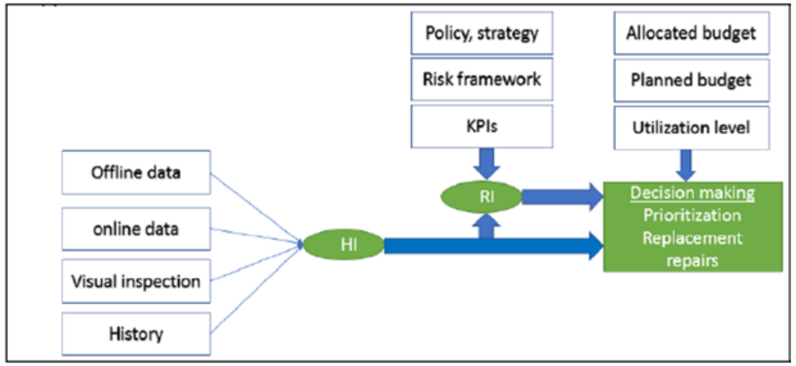
Health index determination for power transformers with fuzzy logic.

- data from DGA and oil-quality tests





Online Monitoring / Operations



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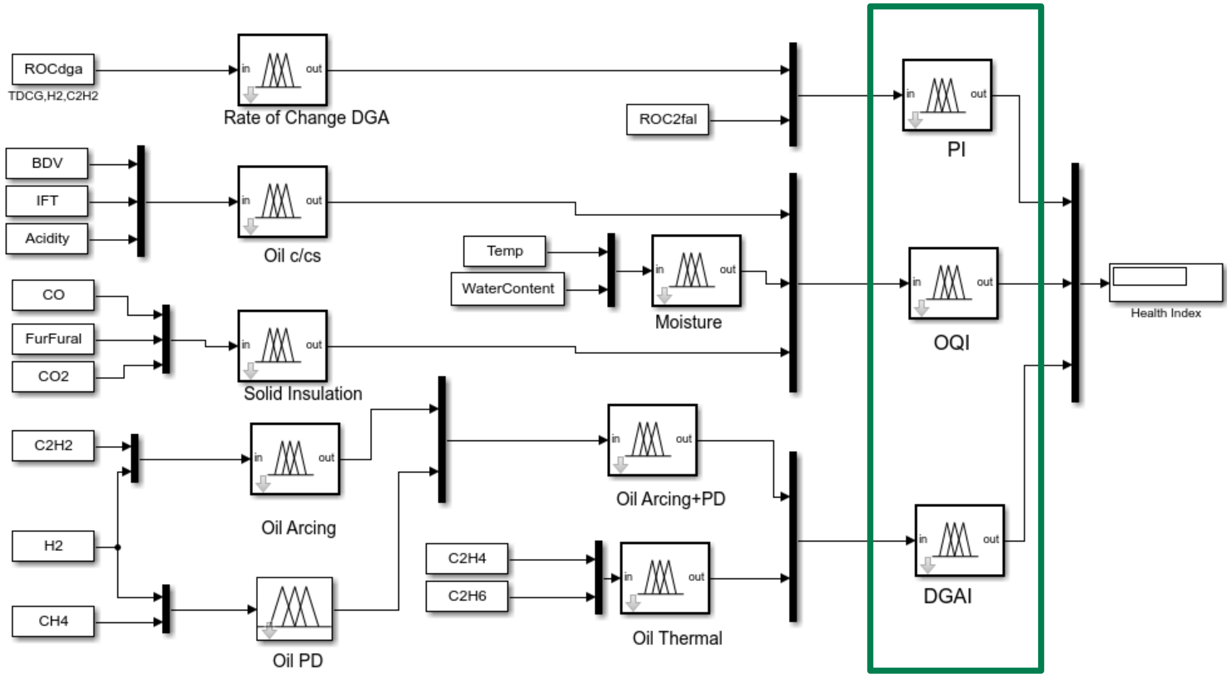
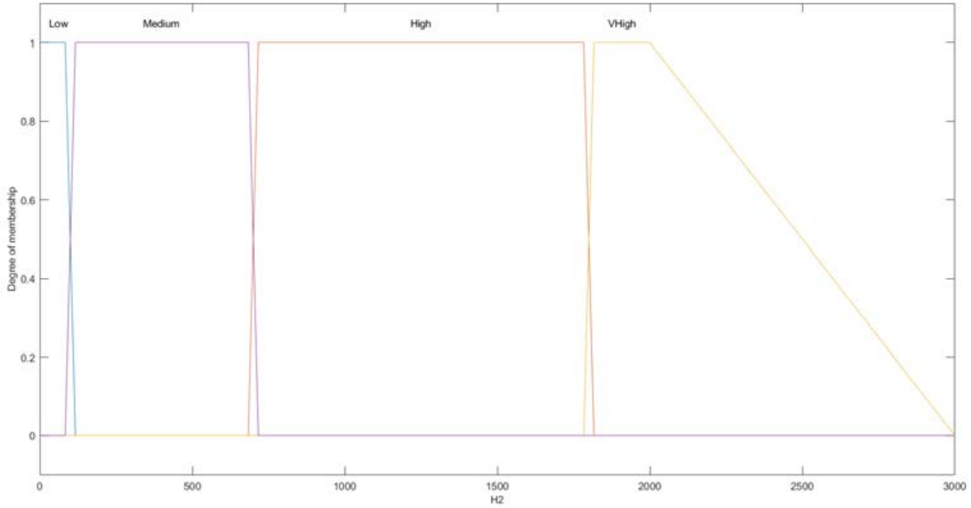
Typical Practice - Case 1

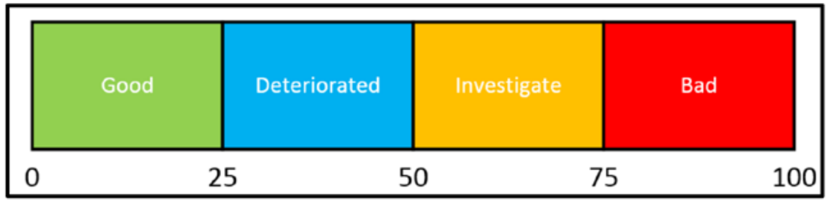
Condition Assessment of Power Transformers | **Methodology / Case Study**

PI…prognostic index
OQI…oil-quality index
DGAI…DGA-index



model output: fuzzy sets for H2-level





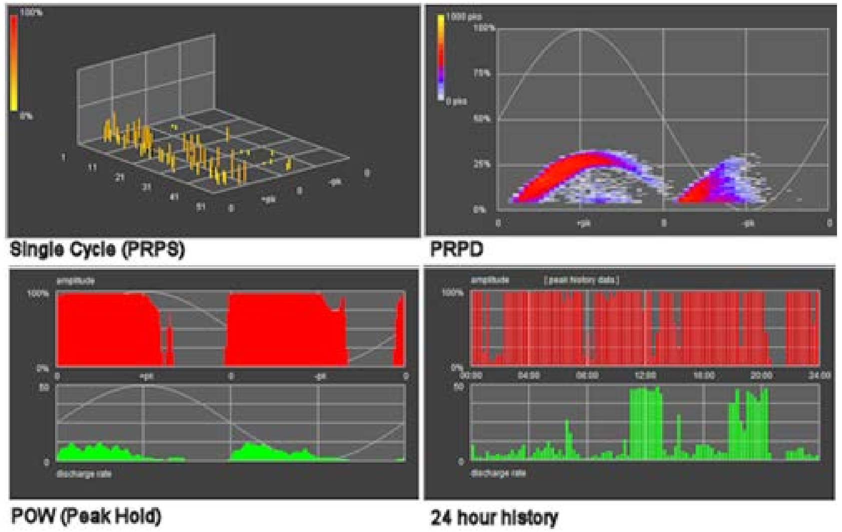
final model output: HI value

Typical Practice - Case 2

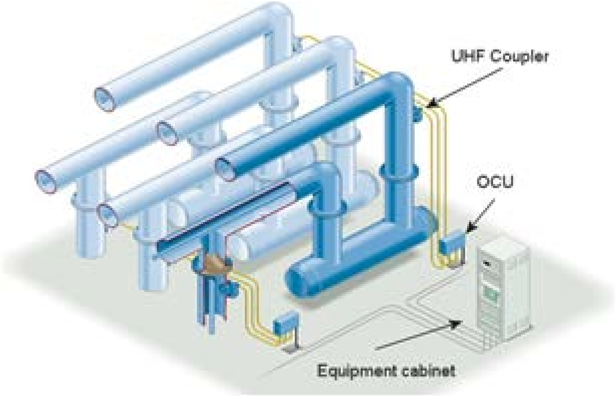
AI Techniques for the Classification of UHF PD Signals | **Data set / Preparation**

Automated GIS PD classification and alarm generation.

- labelled data
- large database of real data from substations (>3.5 Mio. examples)
- 75% training, 25% validation



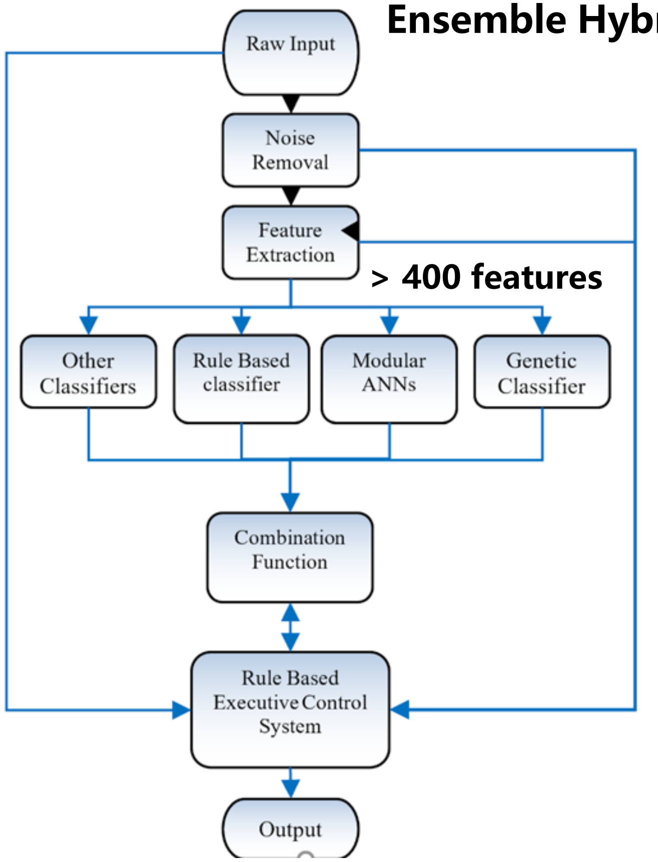
Online Monitoring / Operations



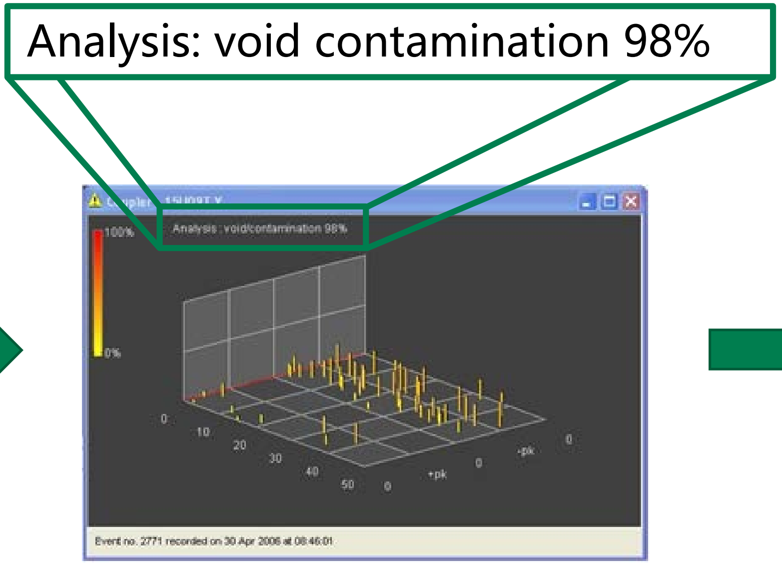
Typical Practice - Case 2

AI Techniques for the Classification of UHF PD Signals | **Methodology / Case Study**

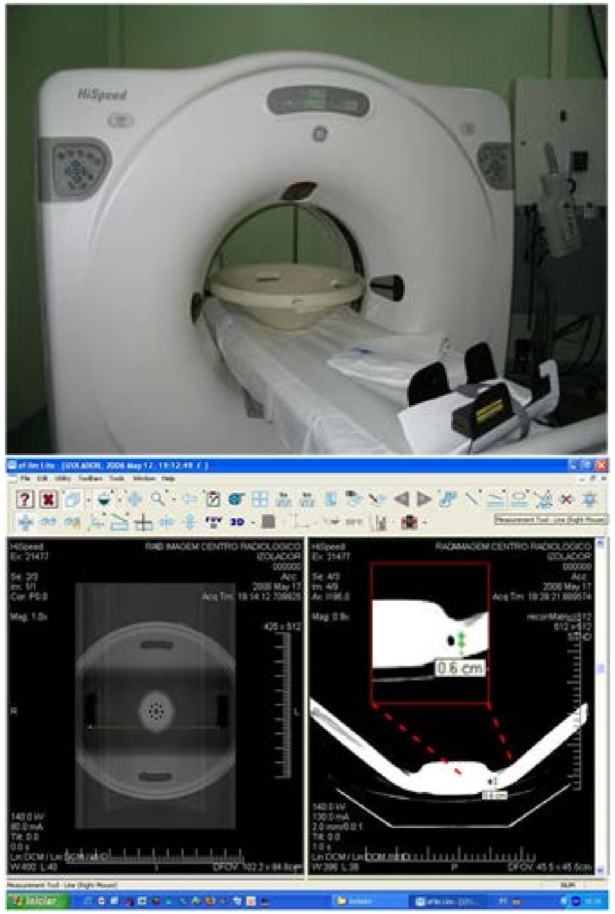
Ensemble Hybrid Classifier



> 400 features



overall accuracy > 93%

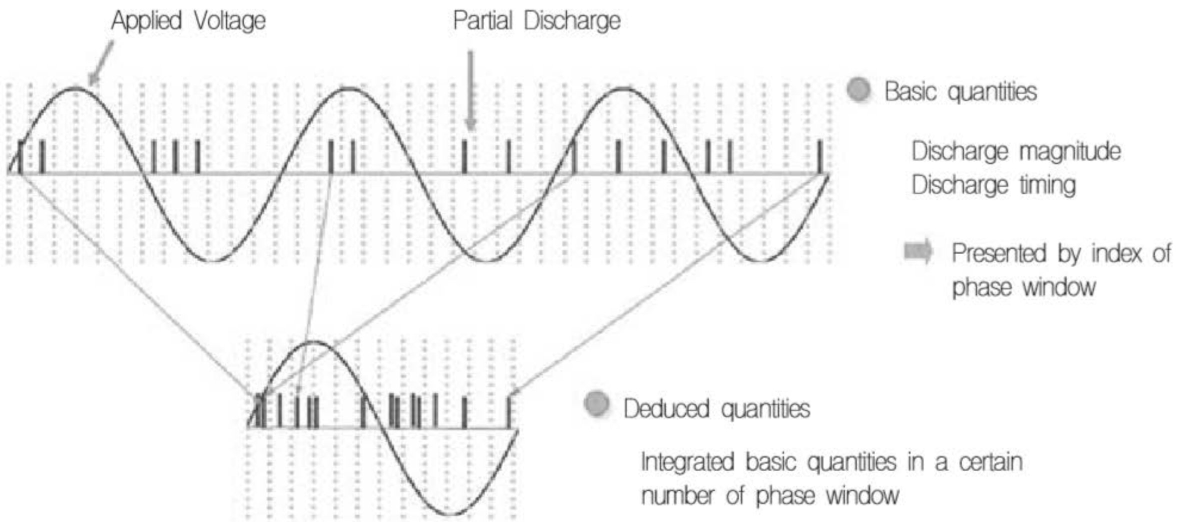


Typical Practice - Case 3

GIS / Transformer PD Analysis | **Data set / Preparation**

PD analysis for GIS and transformers.

- labelled data (300 data sets)
- challenge of imbalanced data
- data from 170 kV GIS
- train/test 7/3



Online Monitoring / Operations

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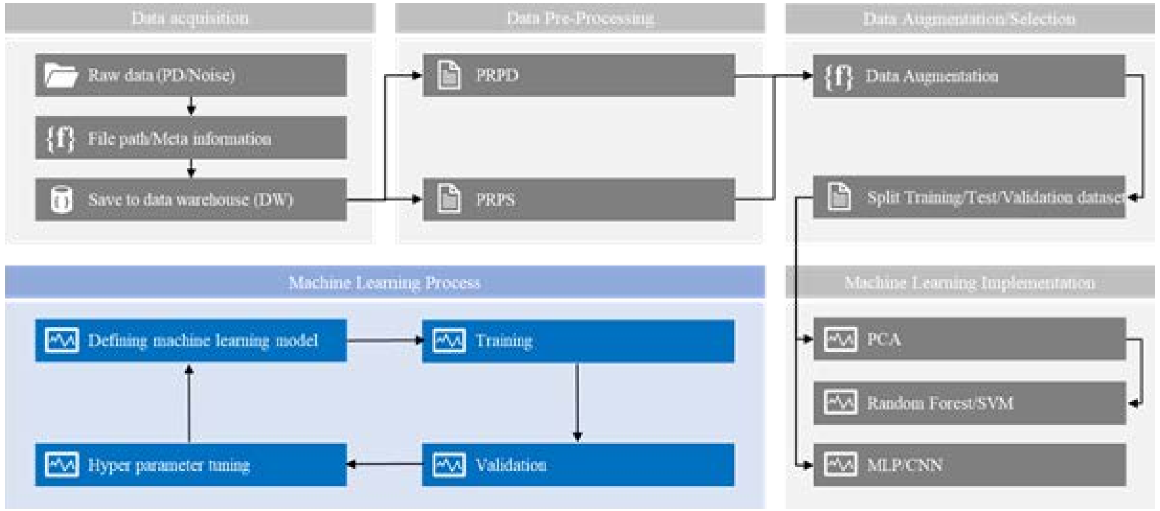
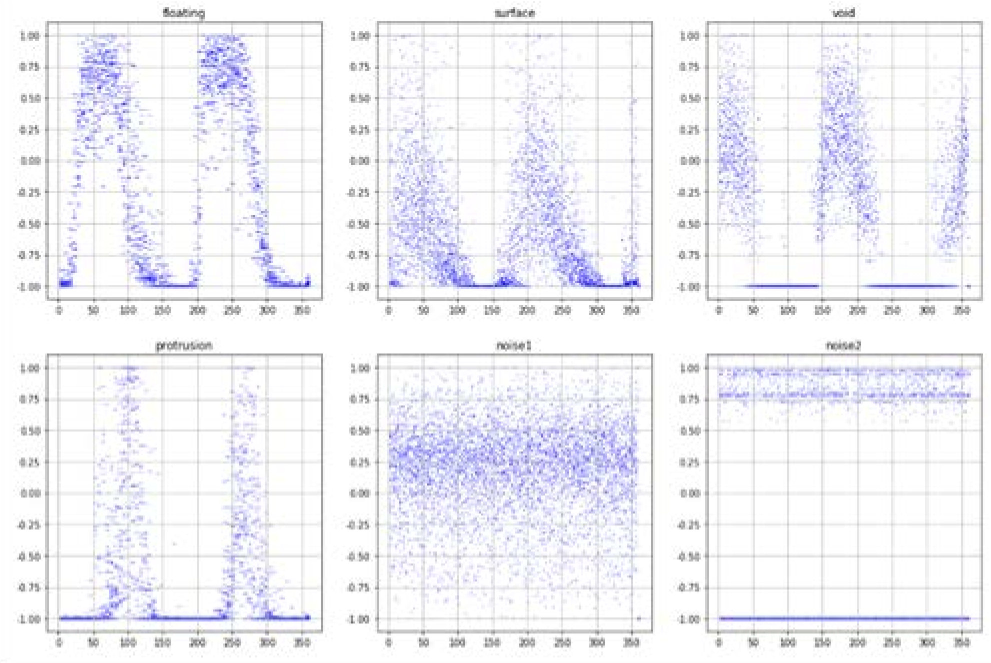
Typical Practice - Case 3

GIS / Transformer PD Analysis | **Methodology / Case Study**





different algorithms tested on same data set: multi-layer perceptron → 87.2% CNN → 100%

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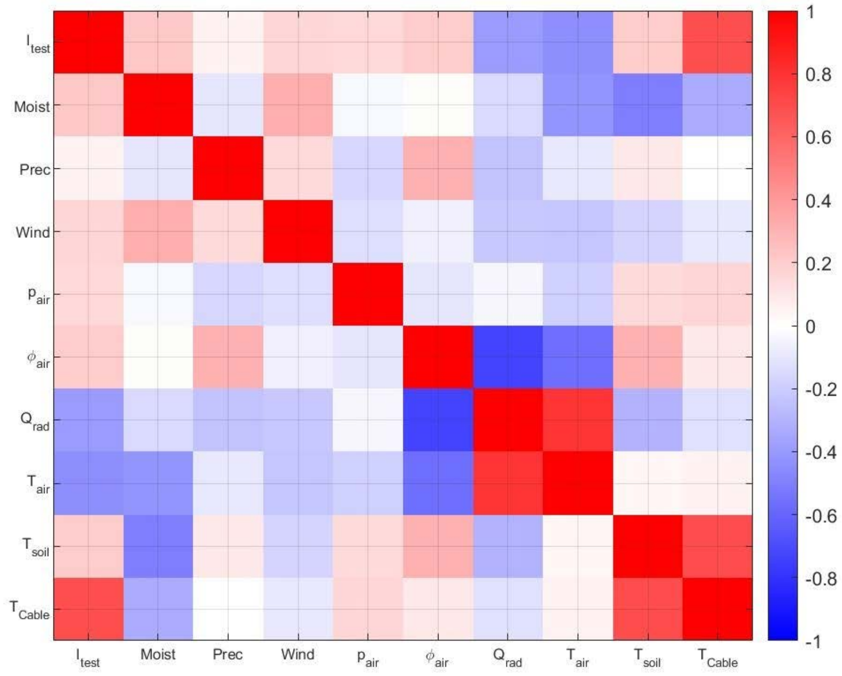
Typical Practice - Case 4

AI in Thermal Rating and Monitoring of HV Power Cables | **Data set / Preparation**

Thermal rating of 400 kV power cable
based on empirical data.

- labelled data
- large database of real data (> 70 Mio. data points → load data, temperatures, climate data, etc.)
- train/test/validation 40/40/20

Abbreviation	Description	Unit
I_{test}	Cable current	[A]
Moist	Relative soil moisture content	[%]
Prec	Precipitation	[mm/h]
Wind	Wind speed	[m/s]
p_{air}	Absolut air pressure	[hPa]
φ_{air}	Relative air humidity	[%]
Q_{rad}	Global radiaton	[W/m²]
T_{air}	Air temperature	[°C]
T_{soil}	Soil temperature (cable depth)	[°C]
T_{cable}	Cable temperature (outer sheath)	[°C]



Real-time control/ Operations

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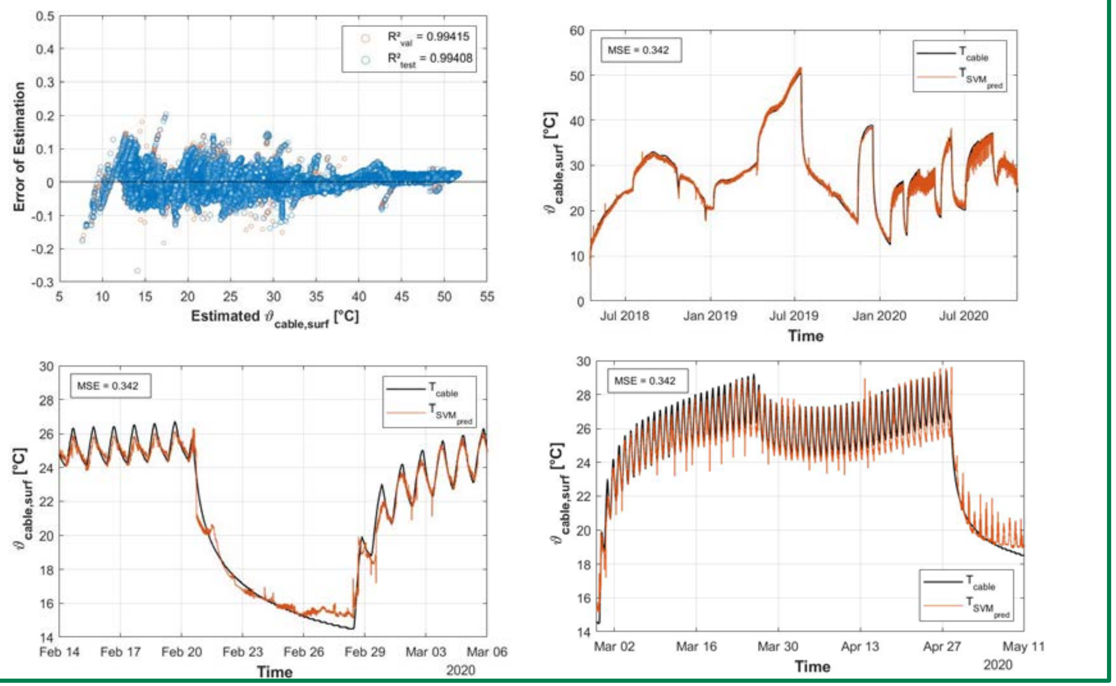
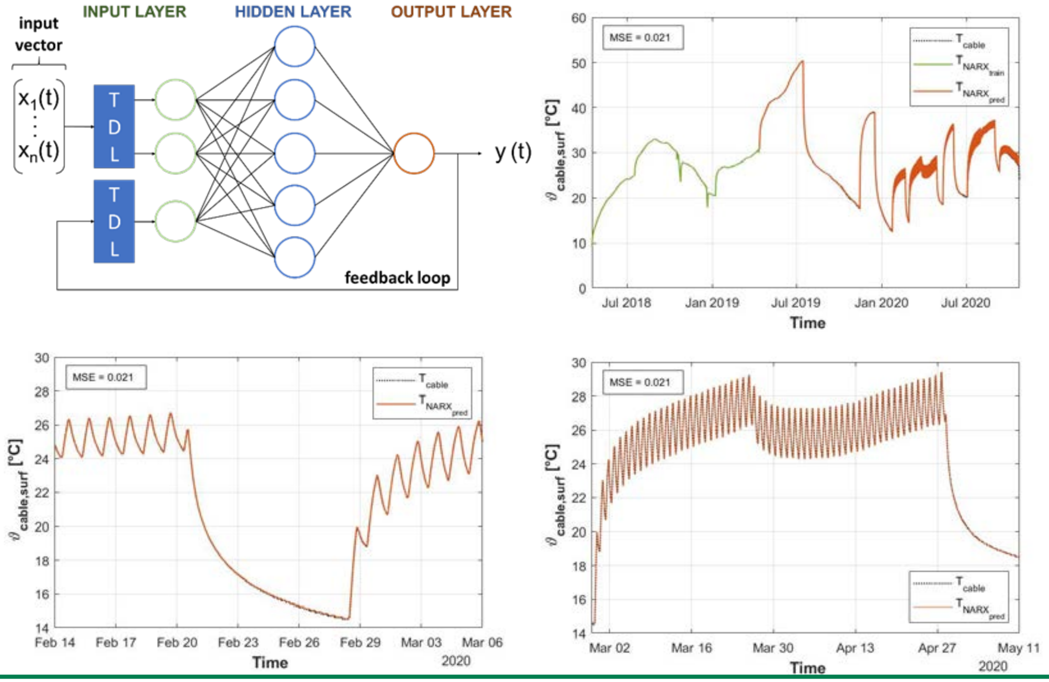
Typical Practice - Case 4

AI in Thermal Rating and Monitoring of HV Power Cables | **Methodology / Case Study**

STATIC MODELS



DYNAMIC MODELS (TIME SERIES)



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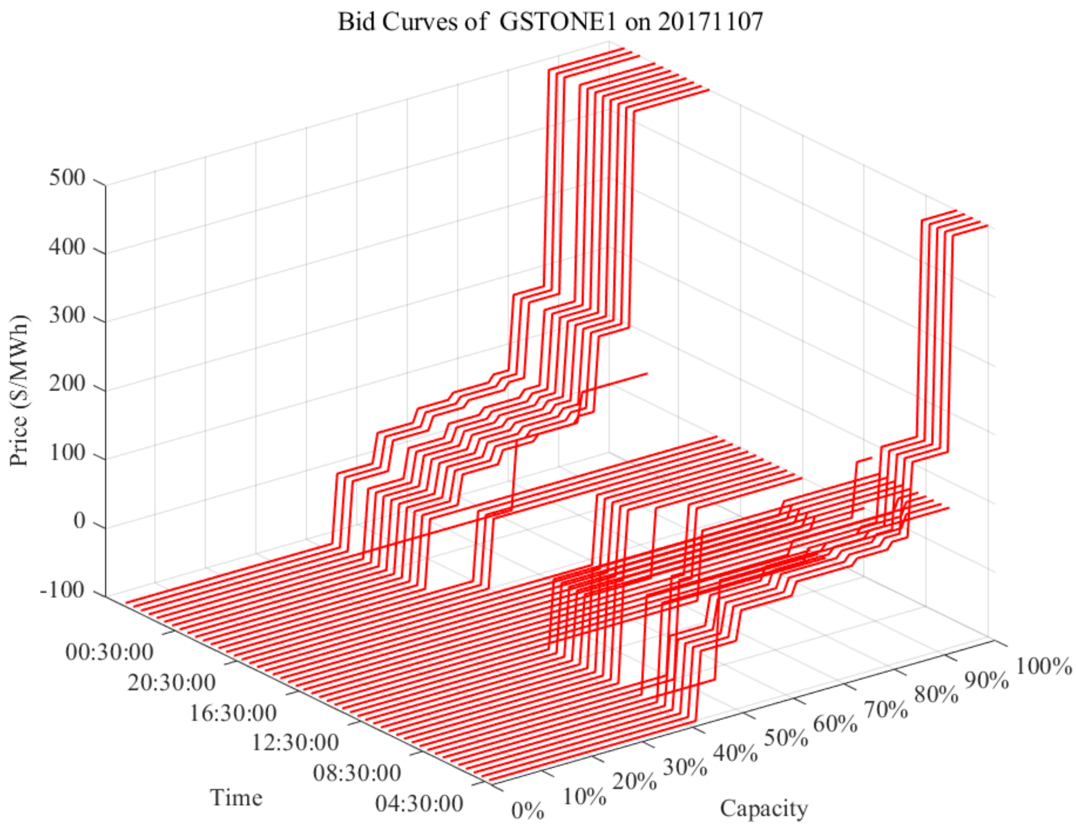
overall accuracy > 95%

Typical Practice - Case 5

Power Market Bidding Pattern Analysis | **Data set / Preparation**

Bidding Pattern Extraction of a Generator.

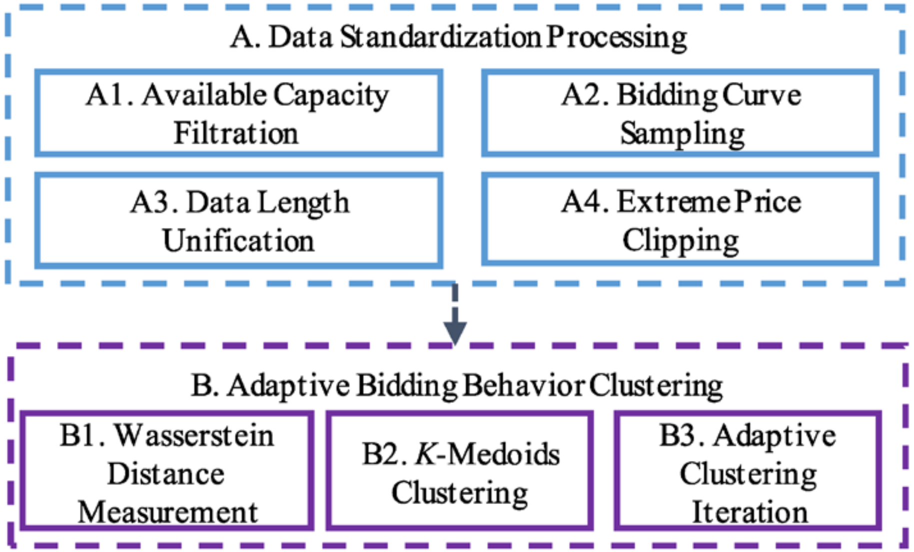
- labelled data
- bidding data of AEM (120 GENCOs – 188 fossil, 82 hydro, 72 wind, 44 solar, 50 others) → 3.25 Mio. bids

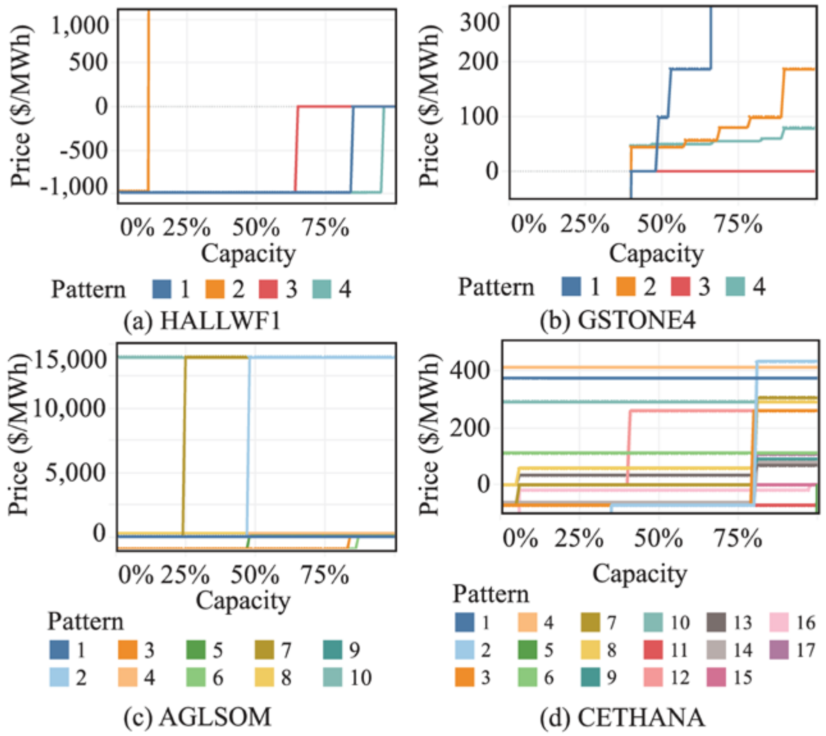


Operations planning / studies

Typical Practice - Case 5

Power Market Bidding Pattern Analysis | **Methodology / Case Study**





Step-by-step analysis of bidding patterns for various fuel-type generators showing stategic bidding behaviours of GENCOs.

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CONTENTS

New Challenges – What is about?

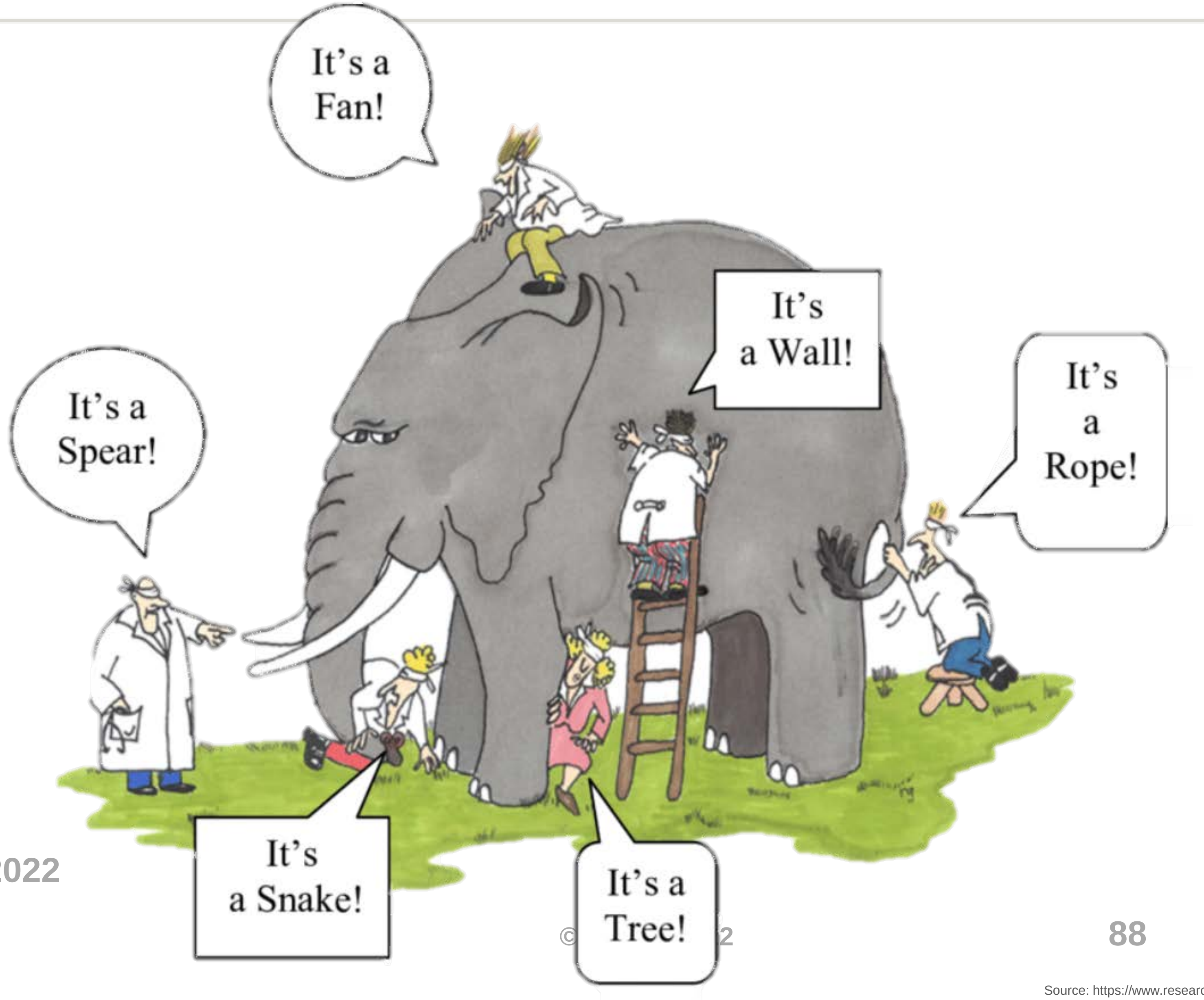
The main current and foreseen challenges are discussed:

1. Use and understanding of Data
2. Tools robustness and maturity
3. User and system security
4. Experts roles
5. Ethic dilemmas

Also included in the chapter are the identified gaps that despite discussed are not in the scope of the WG

#!/ **New Challenges chapter roster:** R. Berryman (Elia Group), D. Gopp (Omicron), L. Souto (University of Bristol), J. Mantilla (Hyundai Electric Switzerland)-*-

New Challenges – Defining AI is itself a challenge!



Source: https://www.researchgate.net/figure/The-Blind-Men-and-the-Elephant_fig1_290127733

New Challenges – Data

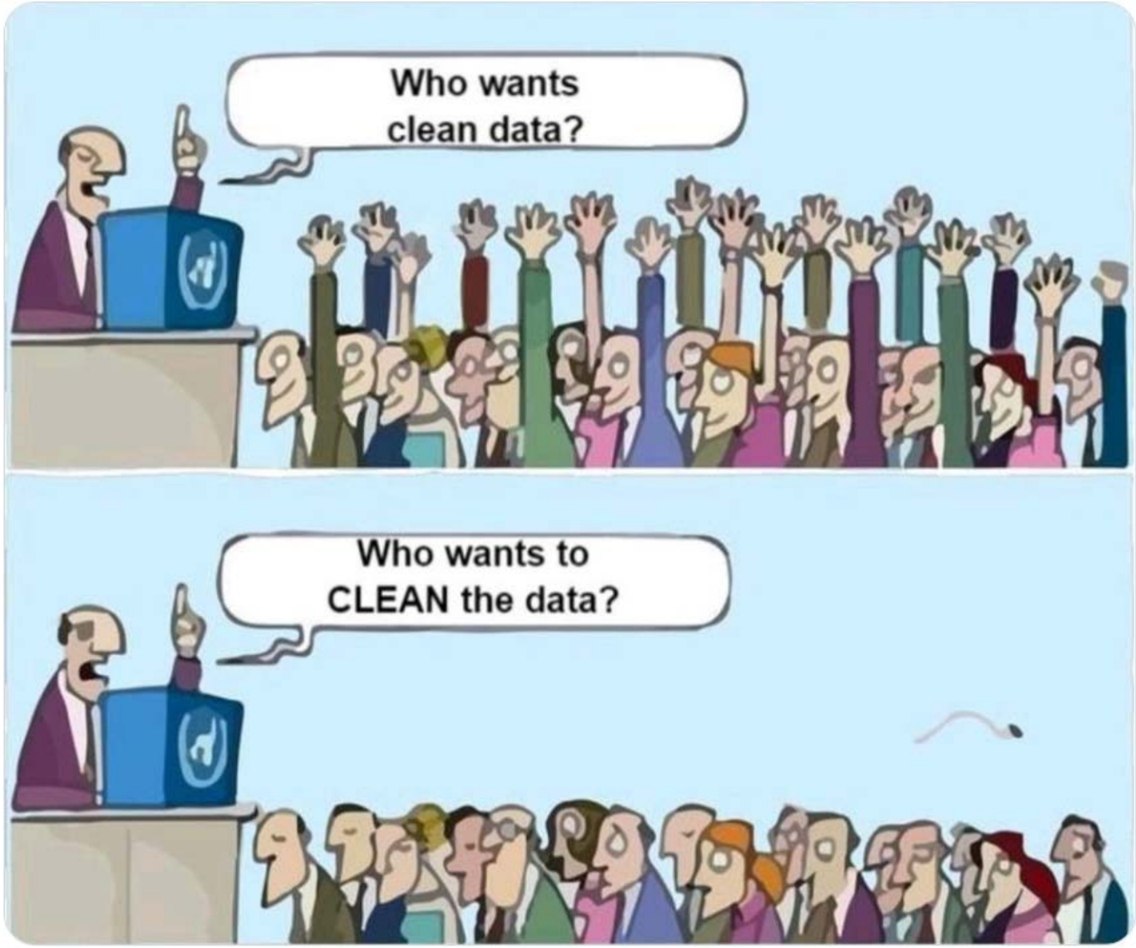
Main topics addressed:

i. Availability, collection, processing and selection:
   - The amount of information, formats and frequency will keep being a variable. Hardware and storage capacity will be a challenge.
   - Exhaustive data collection. Strict requirements (measured quantities, sampling frequency, storage, etc.) defined according to the application.
   - Increased availability of historical data for training AI and ML models with higher accuracy requirements.

ii. Literacy
   - Increase literacy in AI and ML applications in power systems as they become widespread.

iii. Governance
   - Established structure and regulations constantly evolving to accommodate new data and applications.

iv. Legacy
   - More efforts and tools required as AI penetrates all aspects of the T&D industry.



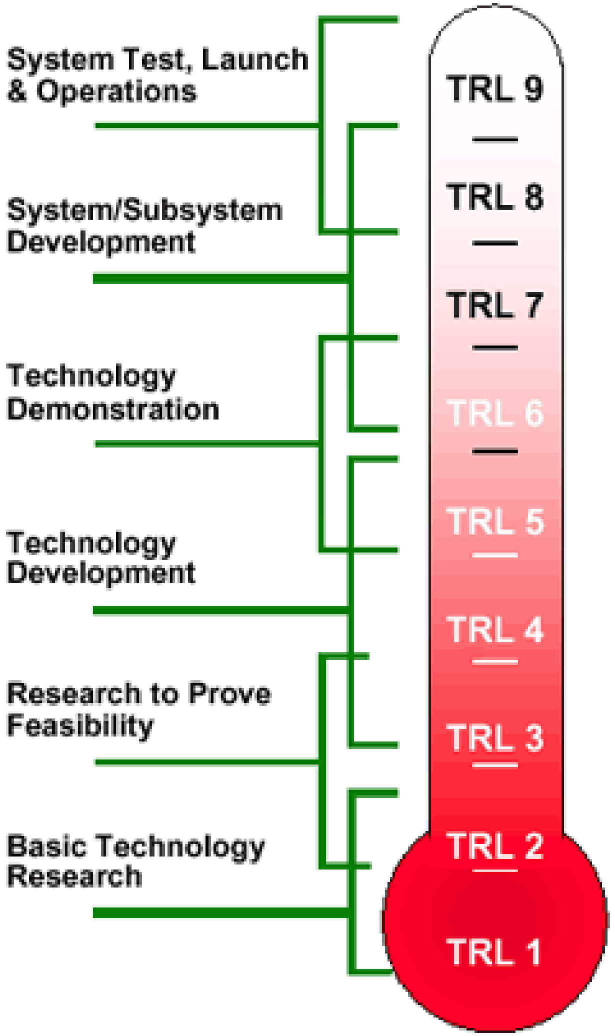
New Challenges – Tools

Main topics addressed:

i. The TRL of the different tools is NOT addressed in this chapter, that is the topic of an earlier one.

ii. The main challenge addressed is the constant evolutive nature to the tools (e.g. SW, HW) and the perceived and real level of maturity that could be assymetric depending on the application.

iii. The tools use and acceptance presents also a challenge. What is good today might/likely not be tomorrow. Risk of confussion…



Source: Wikipedia: TRL

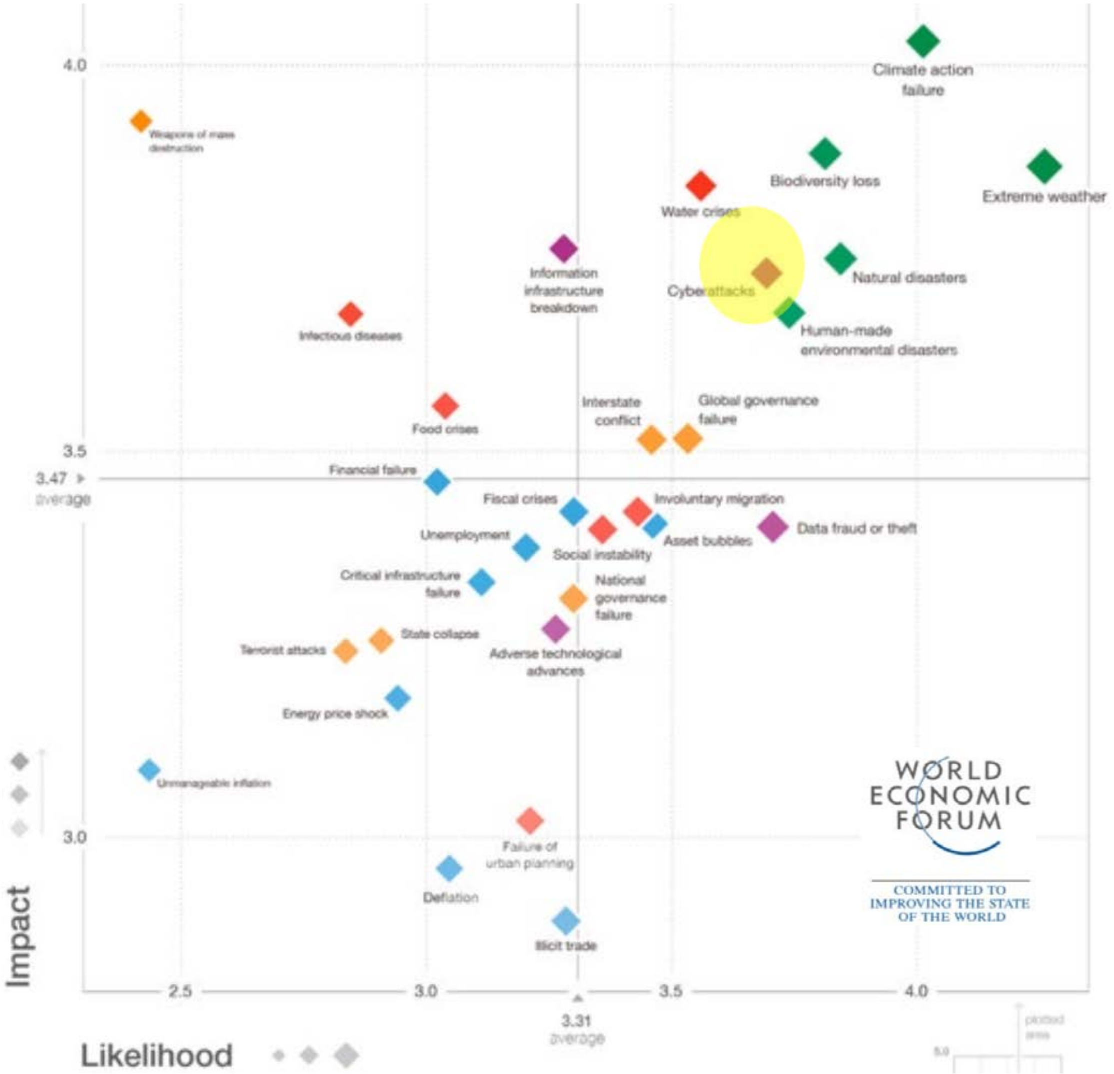
New Challenges – Security

Main topics addressed:

i. Cybersecurity
   - Power systems must be resilient to cyber-attacks of different nature, defined in the STRIDE threat model.

ii. Data collection and storage

iii. Others/ongoing…



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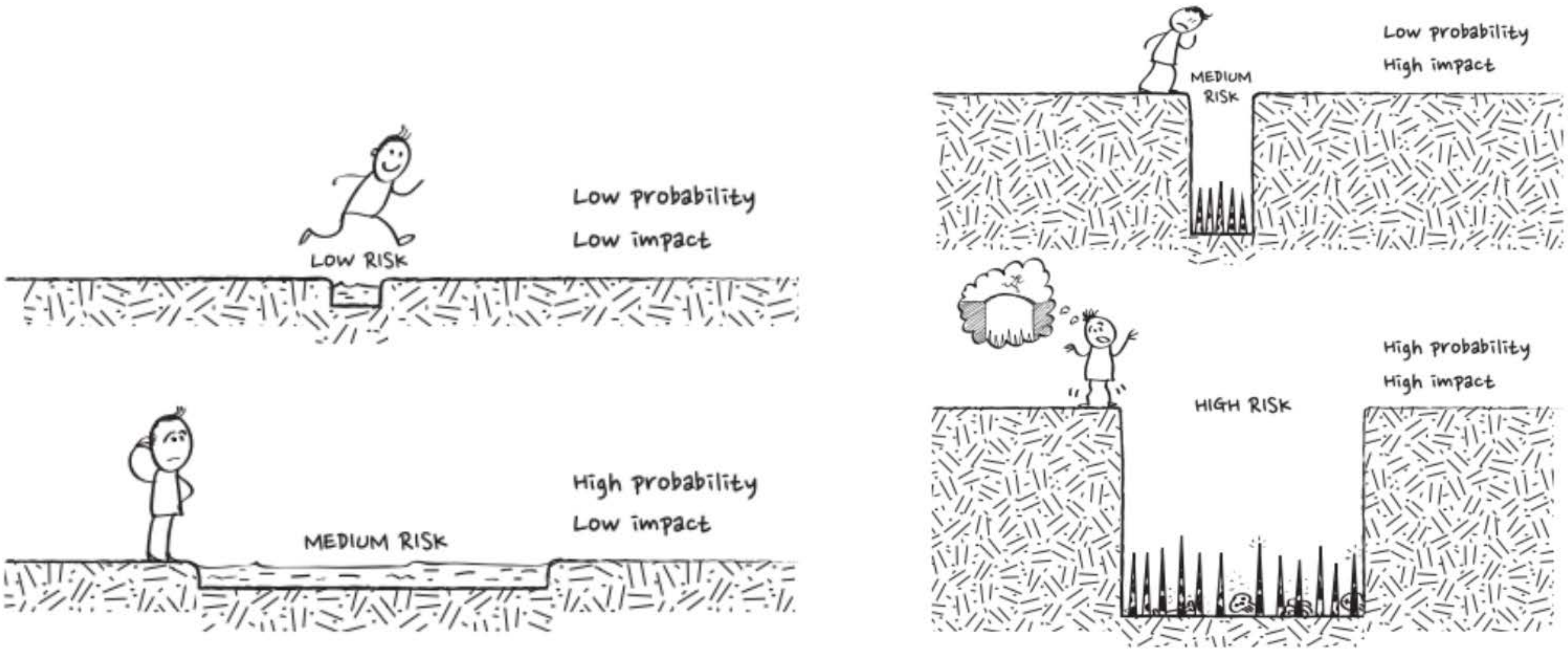
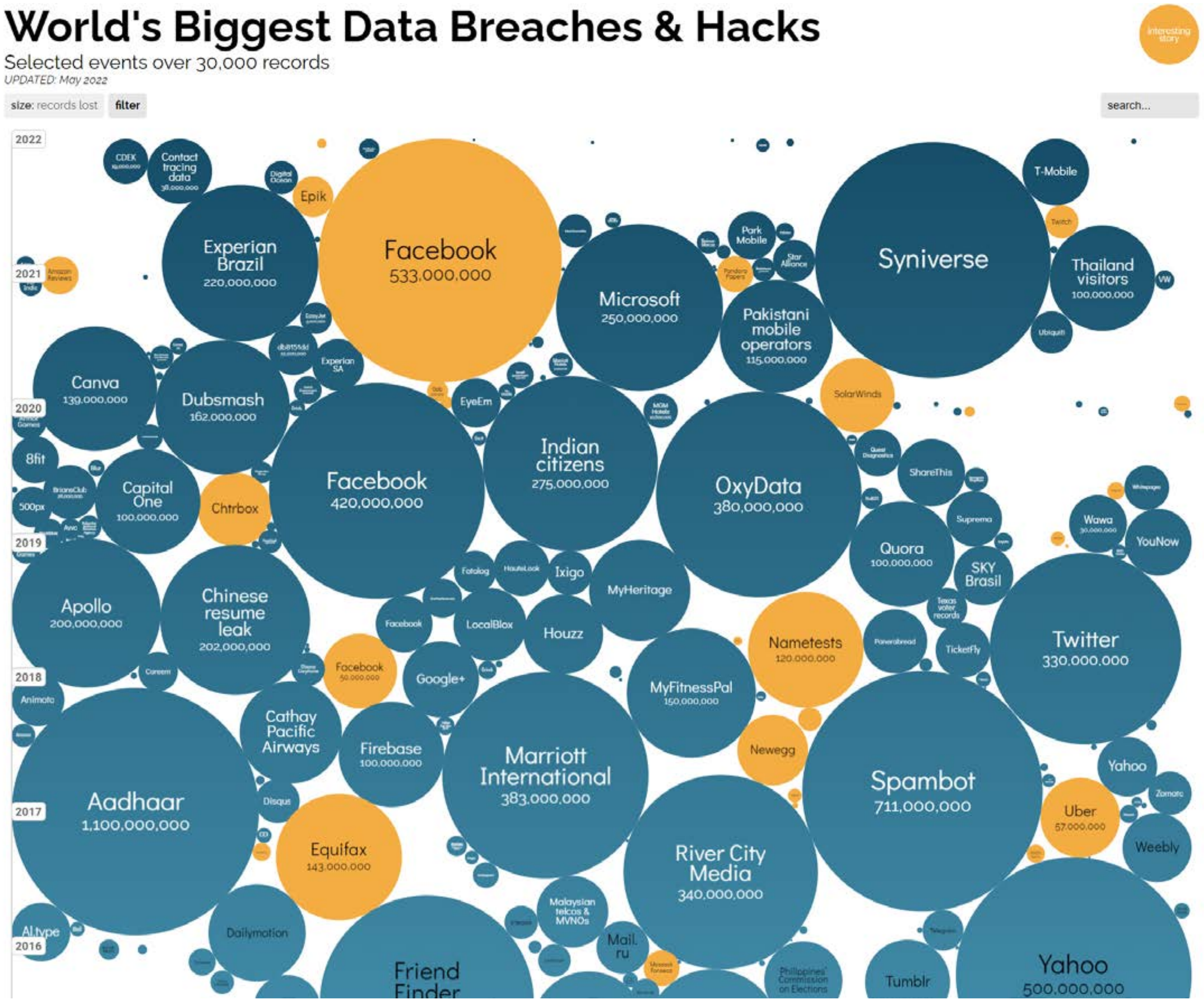
New Challenges – Security

Cybersecurity Risk = Probability X Impact



Source: Christian Espinosa, The Smartest Person in the Room

New Challenges – Security



Source: https://www.informationisbeautiful.net/visualizations/worlds-biggest-data-breaches-hacks/

New Challenges – Security

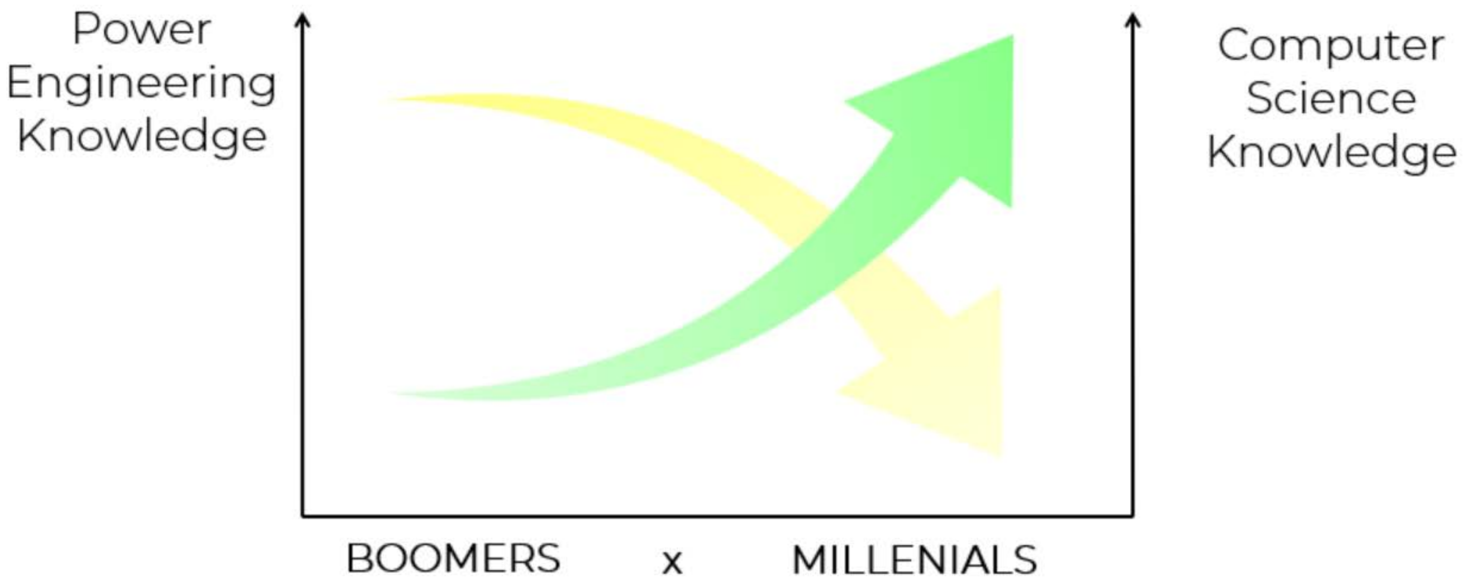
Top 10 industries targeted 2019 vs. 2020

Top 10 industries ranked by attack volume, 2020 vs. 2019 | Source: IBM Security X-Force

Sector	2020 rank	2019 rank
Finance and insurance	1	1
Manufacturing	2	8
Energy	3	9
Retail	4	2
Professional services	5	5
Government	6	6
Healthcare	7	10
Media	8	4
Transportation	9	3
Education	10	7

Source: Verizon 2020 Data Breach Investigations Report

New Challenges – Experts



‘The industry environment has changed radically in the last years. There used to be a large powerful workforce and a depth of knowledge with limited computer power. Now there are large powerful computers and a small workforce with a limited depth of knowledge’ [TB 737]

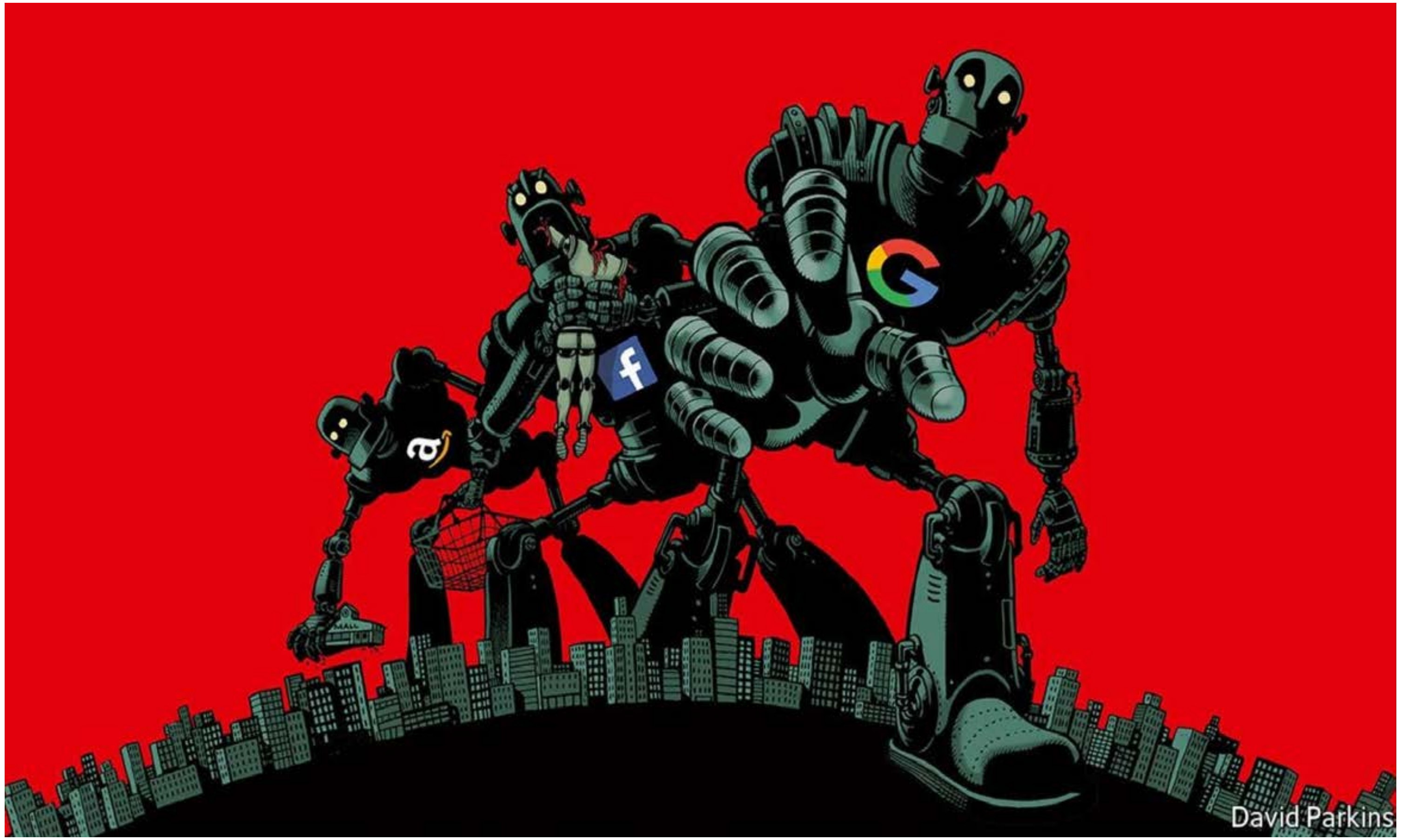
New Challenges – Ethics

There is not yet consensus on what constitutes “Ethical AI”: just as there are very many ethical schools in philosophy, each of which with their own definition of what is “ethical”.

Main topics addressed:

i. Privacy
   - Applications of AI techniques to power systems must comply with strict data privacy requirements to prevent all possible sorts of data breaches.

ii. Monopolistic AI
iii. Ownership (Web 3.0)
iv. Environmental
v. Others/ongoing…



Source: Christian Espinosa, The Smartest Person in the Room

CONTENTS

Summary

- **AI and machine learning techniques have made advances allowing for their consideration in many power applications**

- **AI is powerful with its analysis and inference capabilities, and data-driven methods will play a more important role in the power industry**

- **Many current AI and machine learning techniques are still in the stage of “blackbox”, the explainability and robustness cannot meet the requirements of operation in the field yet**

- **Further work is needed to lead the next-generation AI+Power**

Summary

- **In this tutorial, we have reviewed the scope, organization, featured activities, motivation, survey and findings of SC.D2 WG D2.52**

- **The main contents for the Technical Brochure including AI requirements and target, AI Technology Framework, Applicability and Maturity of AI, Typical Practice, and New Challenges has been summarized and presented in this tutorial**

- **This tutorial is intended as a high-level introduction to AI applications in the power industry**

- **For more detailed information, please refer to the TB to be published next year**

THANK YOU!

Questions?