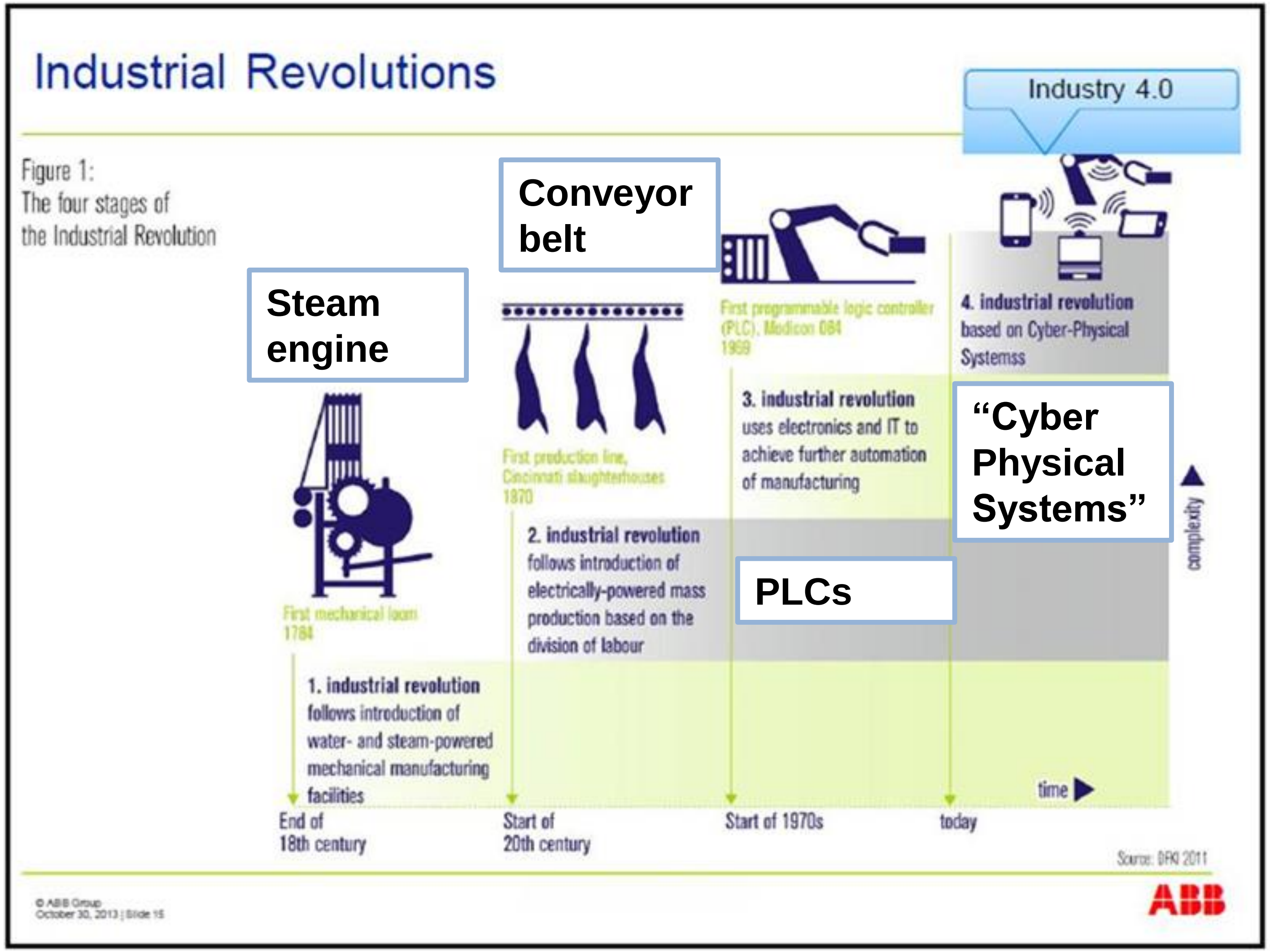
Predictive Maintenance with MATLAB for the Industry 4.0

Sergio E. Obando Quintero, Ph.D.
Application Engineering

Operation Optimization
Predictive Maintenance
Risk Management…

What is *Industry 4.0*



Source: ABB

Definition:

Production equipment, automation components and entire process lines are **connected** with each other and exchange information (= data). They build the "*Industrial Internet-of-Things*".

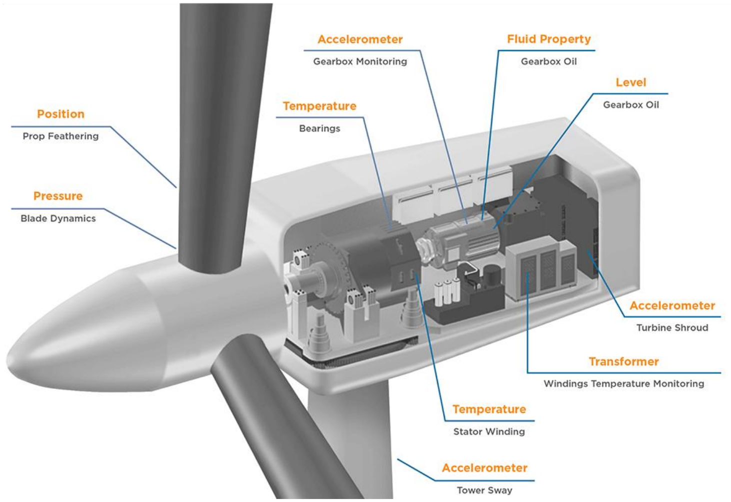
The goal is to **optimize** the entire process (for minimum energy consumption, maximum throughput, feedstock quality, etc.) and to make the production of small lots **more flexible** ("*mass customization*").

Megatrend: Digital Transformation and IoT

Goals:

By connecting machines in operation you can use data, algorithms, and models to make better decisions, improve processes, reduce cost, improve customer experience.

- **Industrial IoT**
- **Digital Twin**
- **Industry 4.0**
- **Smart 'XYZ'**
- **Digital Transformation**



Great ideas. But how to get there?

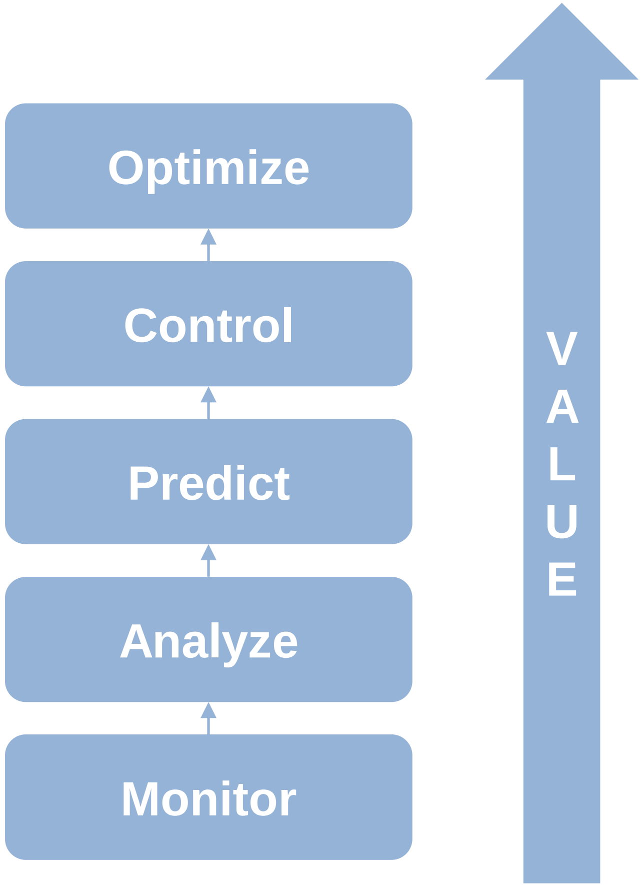
Identifying IoT Applications that Provide Business Value

List of typical IoT applications:

- Asset Performance Management
- Operations Optimization
- Predictive Maintenance
- Power Systems Studies
- Operational Technology
- Cyber Physical Systems
- Edge Computing
- Fleet Management
- Supervisory Control or SCADA
- Anomaly Detection
- Fault Isolation
- Streaming Analytics

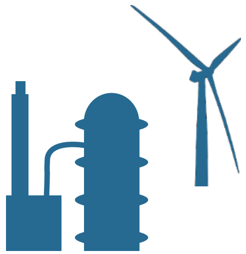
How do you determine the potential value of applications?

The Value of IoT Applications



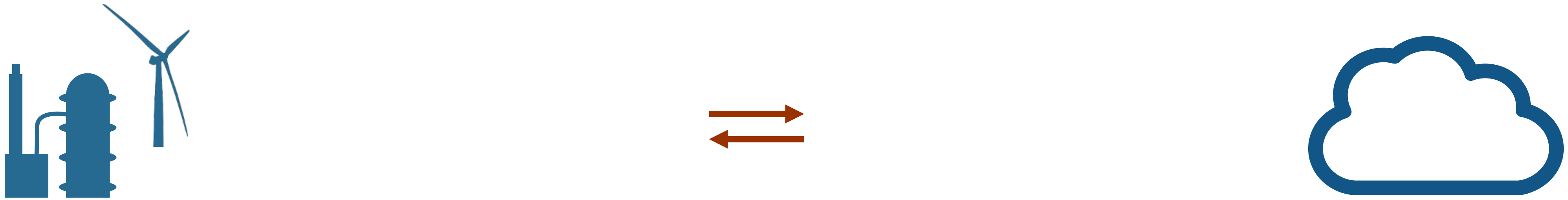
MATLAB® & SIMULINK®

IIoT: Systems of Physical Assets in Operation

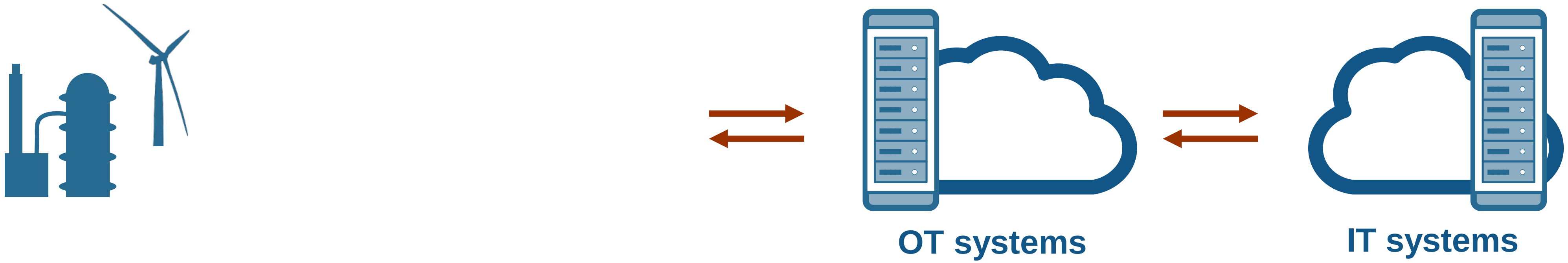


Do you intend to connect your asset in operation?

IIoT: Systems of Physical Assets in Operation



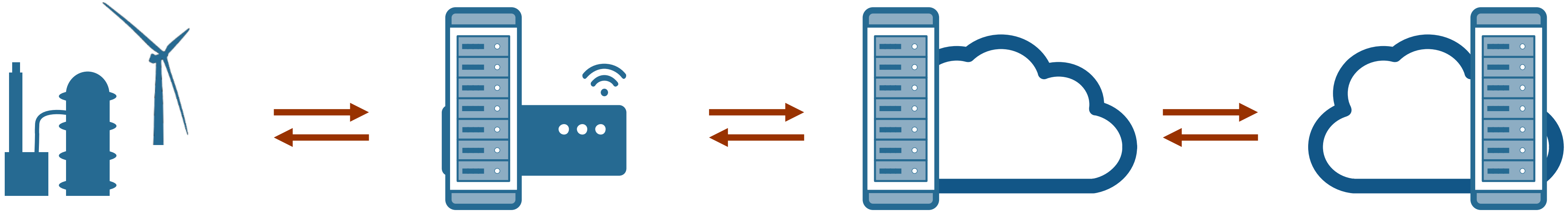
IIoT: Systems of Physical Assets in Operation



Operational Technology (OT) – technology needed to run, manage, and optimize/tune the assets in operation at systems and business levels

Enterprise Integration a large part of systems and interface integration for the business

IIoT: Systems of Physical Assets in Operation



Edge systems

Edge Computing highly accelerating business value by adding a closer compute node to assets which compliments either side, asset or cloud, of diagram

Computing Near the Asset

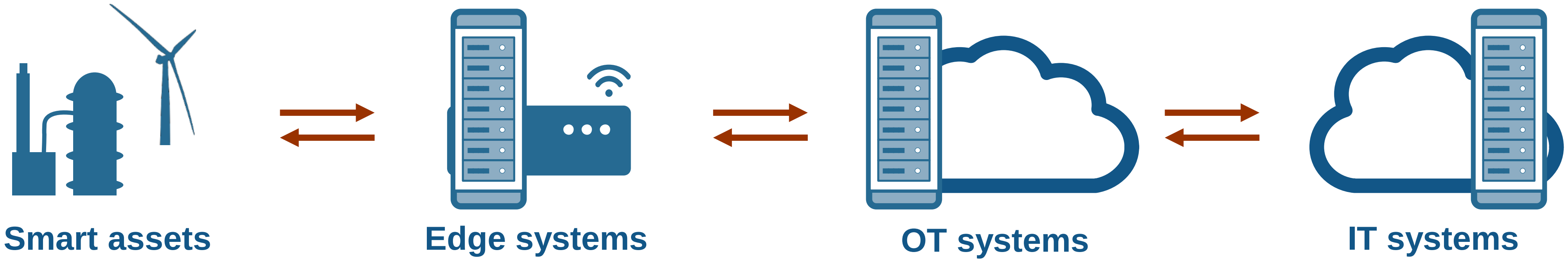
R-Pi

SCADA

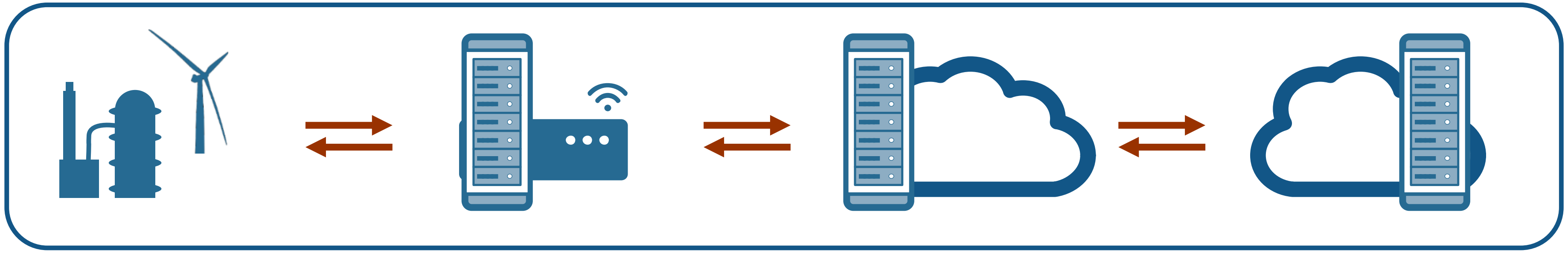
Server-class
Linux system

Increasing Compute Power →

Common IoT Application Topology



Applying Digital Twin Strategies



Optimize

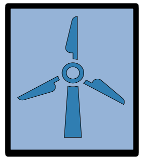
Control

Predict

Analyze

Monitor

What is a Digital Twin?

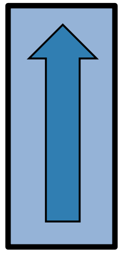


Create representation of asset in operation

- MATLAB or Simulink models
- Reuse models from development process (e.g. MBD)
- Kept up-to-date during asset operation (e.g. aging, wear, environment)

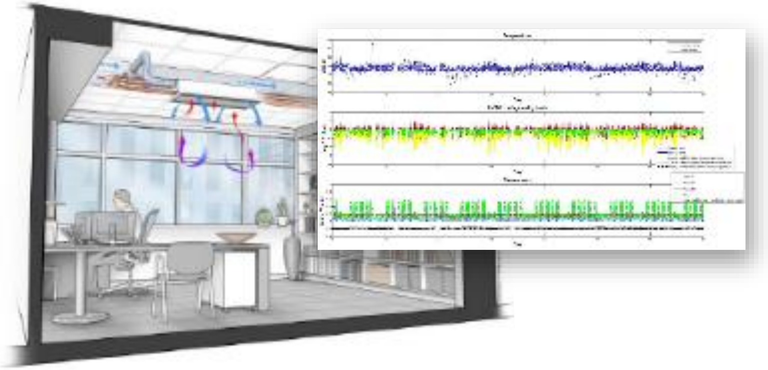
Use Digital Twin in-operation

- Optimize fleet or system behavior
- Calculate control setpoints or parameters
- Predict future behavior or events



Prescriptive Analytics

Predict and Optimize Energy production



Online optimization of building energy use

Advanced Emergency Braking

Recommendation — **Supervisory Control** — **Embedded system**

Decision support — **Decision automation**

Customer Example: BuildingIQ

Predictive Energy Optimization

User Story

Opportunity

- **Real-time, cloud-based system** for commercial building owners to reduce energy consumption of HVAC operation

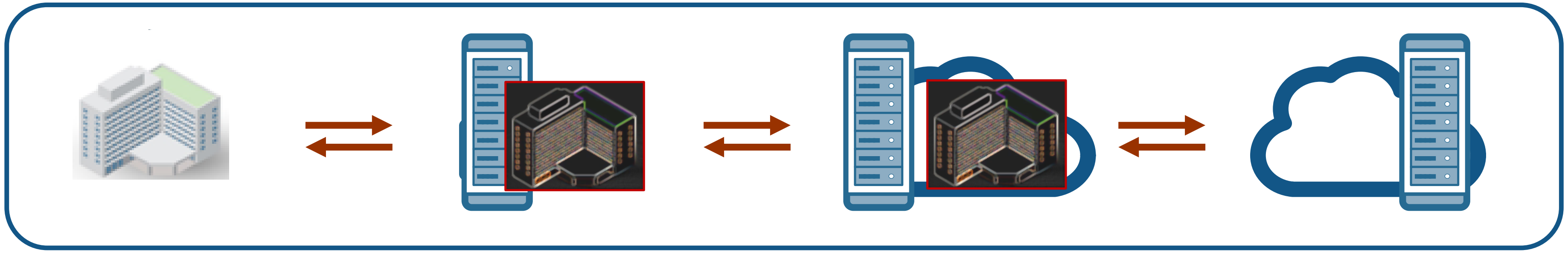
Analytics Use

- **Data:** 3 to 12 months of data from power meters, thermometers, and pressure sensors, as well as weather and energy cost, comprising billions of data points
- **Machine learning:** SVM regression, Gaussian mixture models, k-means clustering
- **Optimization:** multi-objective, constrained
- **Controls:** analyze system-response dynamics

Benefit

- Typical energy consumption reduced 15-25%

Case Study: BuildingIQ (Operations Optimization)



- Optimize
- Control
- Predict
- Analyze
- Monitor

HVAC hard-real-time closed-loop control ⟷ Digital Twin used for control tuning and supervisory control ⟷ Digital Twin used for optimal energy efficiency (load, weather, pricing, etc)

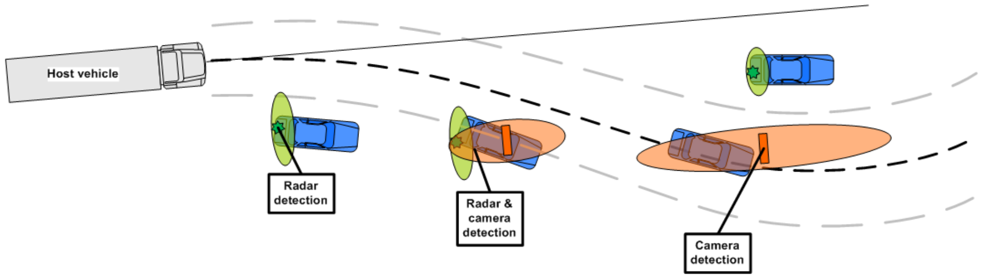
Objective: Optimally control HVAC building systems based on real-time operational constraints and state.

Digital Twin: Digital Twin is MATLAB system model and tuned from real data periodically. Then used continuously to implement robust control strategies and optimize system behavior.

Outcome: 10% to 25% energy savings reported daily.

Customer Example: Scania

Automatic Emergency Braking



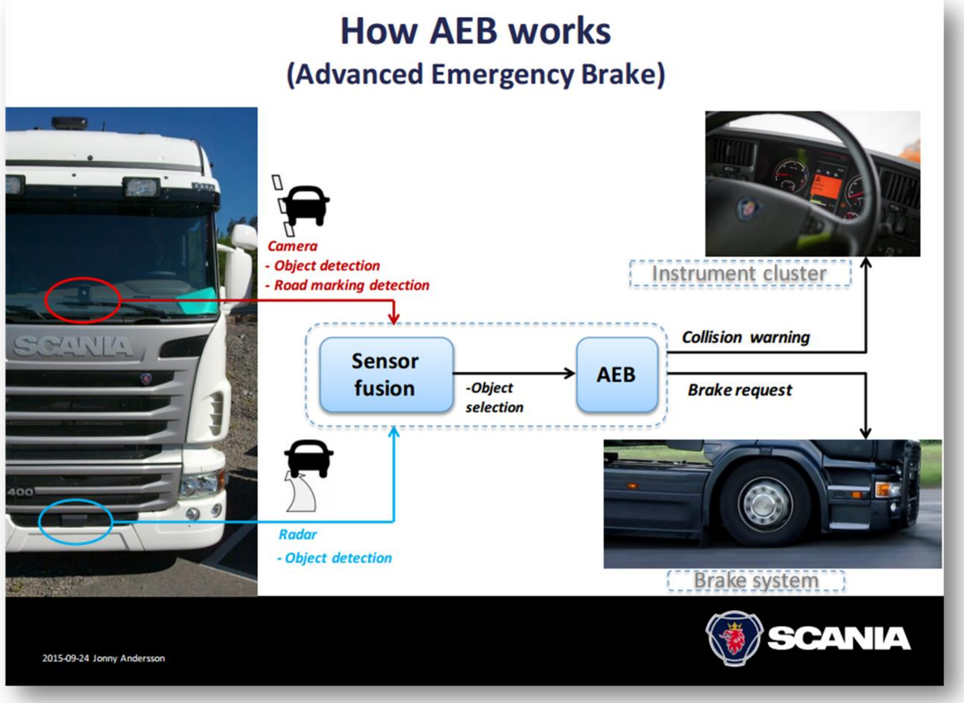
Radar and camera for object-detection and real-time collision warning and braking.

Opportunity

Real-time crash avoidance by detecting imminent collisions and automatically taking action

Analytics Use

- **Data:** 80 TB – 1.5 million km of driving
- **Machine Learning:** Object detection
- **Control Systems:** Brake application
- **Test and Verify:** System model with simulated, recorded, and live data.



Perception → Prediction → Action

Benefit

- Reduced accidents
- Meet EU Regulations

AEB (Advanced Emergency Brake)

Use In Operations

- Use models for health monitoring and predictive maintenance
- Reproduce errors from field data
- Train operators on new systems
- Use machine vision for non-invasive quality control

Why perform predictive maintenance?

- Example: faulty braking system leads to wind turbine disaster
  - https://youtu.be/7nSB1SdVHqQ

- Wind turbines cost millions of dollars

- Failures can be dangerous

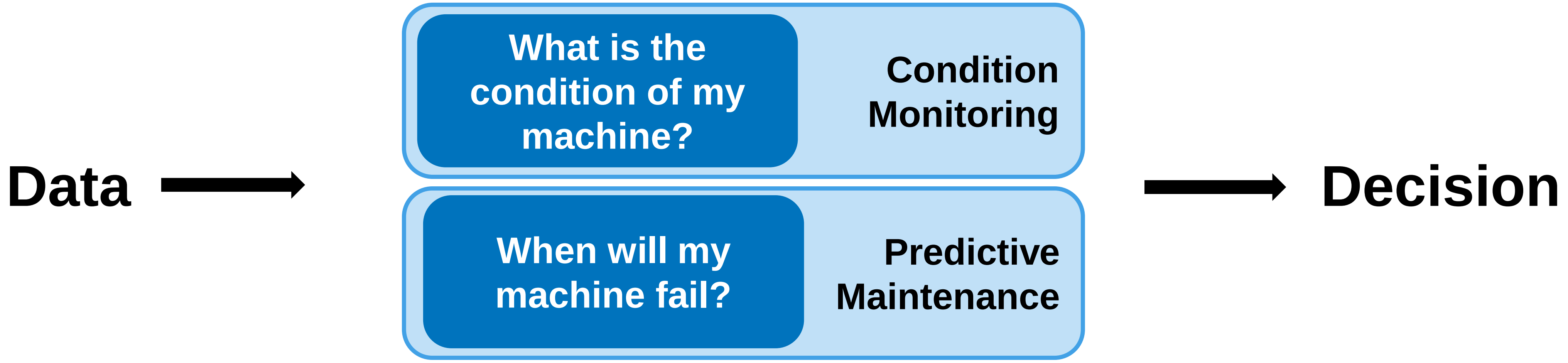
- Maintenance also very expensive and dangerous

Types of Maintenance

- Reactive – Do maintenance once there’s a problem
  - Example: replace car battery when it fails
  - Problem: unexpected failures can be expensive and potentially dangerous
- Scheduled – Do maintenance at a regular rate
  - Example: change car’s oil every 5,000 miles
  - Problem: unnecessary maintenance can be wasteful; may not eliminate all failures
- Predictive – Forecast when problems will arise
  - Example: certain GM car models forecast problems with the battery, fuel pump, and starter motor
  - Problem: difficult to make accurate forecasts for complex equipment

What does a Predictive Maintenance algorithm do?

Helps make maintenance decisions based on large volumes of complex data



Condition Monitoring
Process of monitoring sensor data from machines (vibration, temperature etc.) in order to identify significant changes which can indicate developing faults

Predictive Maintenance
Technique that determines **time-to-failure/remaining useful life (RUL)** from sensor data & historical data in order to predict when maintenance should be performed

Predictive Maintenance
Customer Examples

Pump Health Monitoring System

- Spectral analysis and filtering on binary sensor data and neural network model prediction
- More than $10 million projected savings

Online engine health monitoring

- Real-time analytics integrated with enterprise service systems
- Predict sub-system performance (oil, fuel, liftoff, mechanical health, controls

Production machinery failure warning

- Reduce waste and machine downtime
- MATLAB based HMI warns operators of potential failures
- > 200,000 € savings per year

Customer Example: Baker Hughes

Pump Health Monitoring System

Challenge

- As many as 20 trucks operate around the clock at a well site
- A truck with a pump failure must be immediately replaced
- Accurate prediction prevents damage and maintains operation

Solution

- Analyzed a **terabyte of data** collected at 50,000 samples per second from sensors installed on 10 trucks
- Read and parsed sensor data in **proprietary binary file format**
- Performed **FFTs and spectral analysis** to filter large movements of the truck, pump, and fluids
- Best model was a **neural network** using pressure, vibration, and timing sensor data of the valves and valve seats

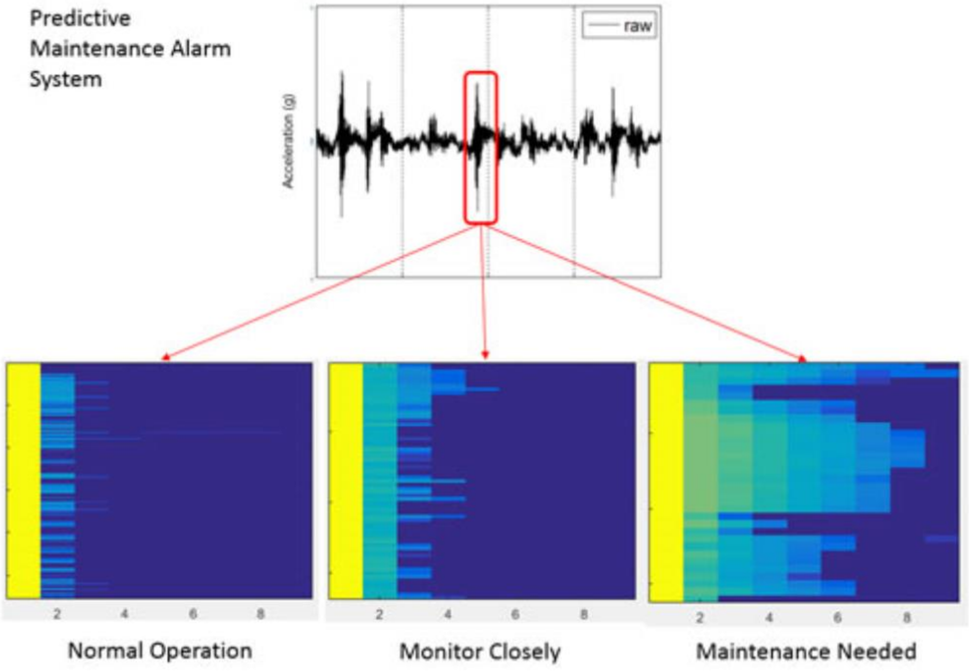
Results

- Savings of **more than $10 million** projected
- Development time reduced tenfold

BAKER HUGHES

- one of the world's largest oil field services companies.
- ~34k employees

Positive displacement pumps inject a mixture of water and sand at high pressure into drilled wells.



MATLAB based predictive maintenance alarm system

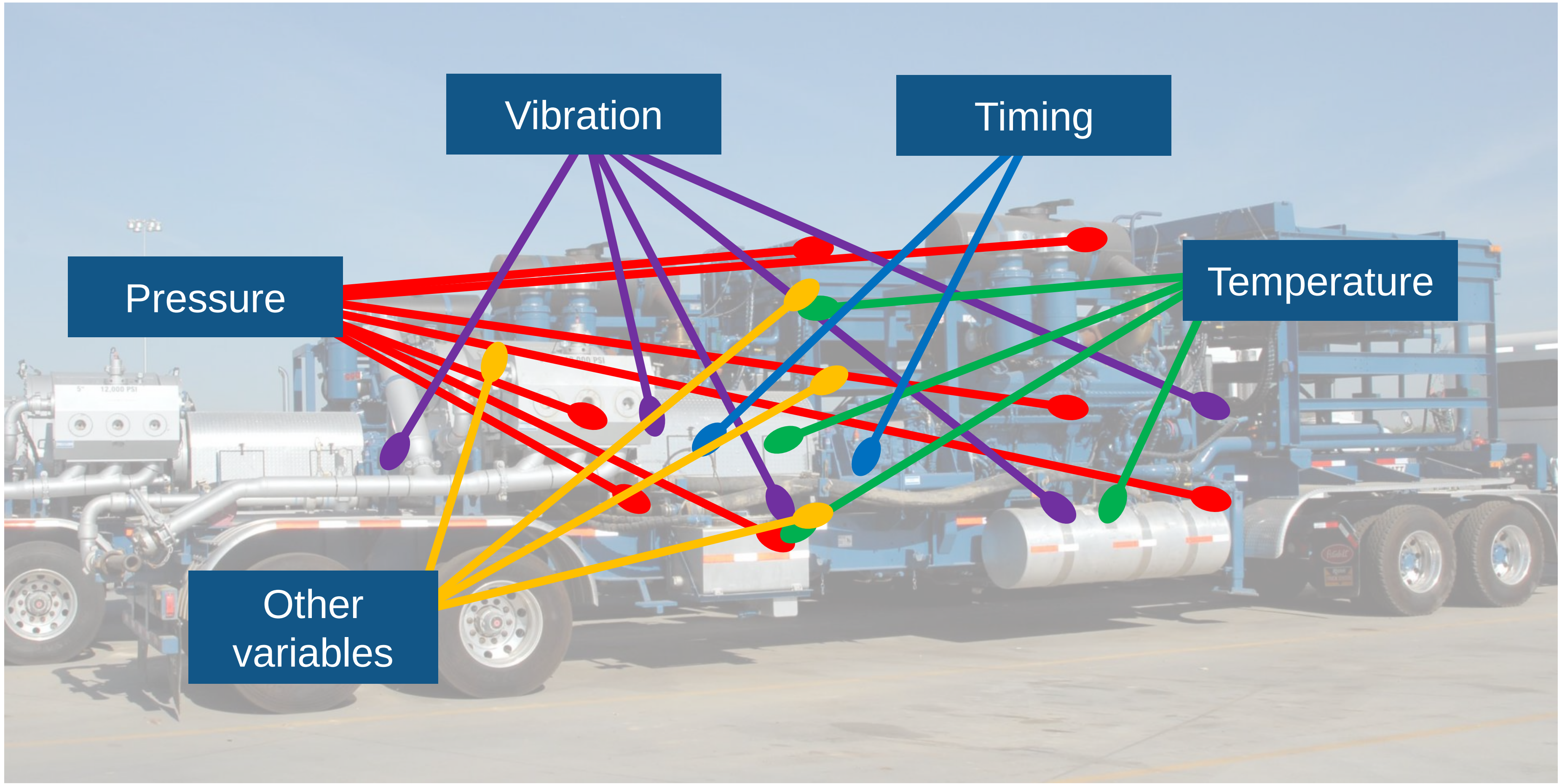
[Link to User Story]

Service for Predictive Maintenance

010010
100001
011100
100101

Data & Information

Which sensor values should they use?



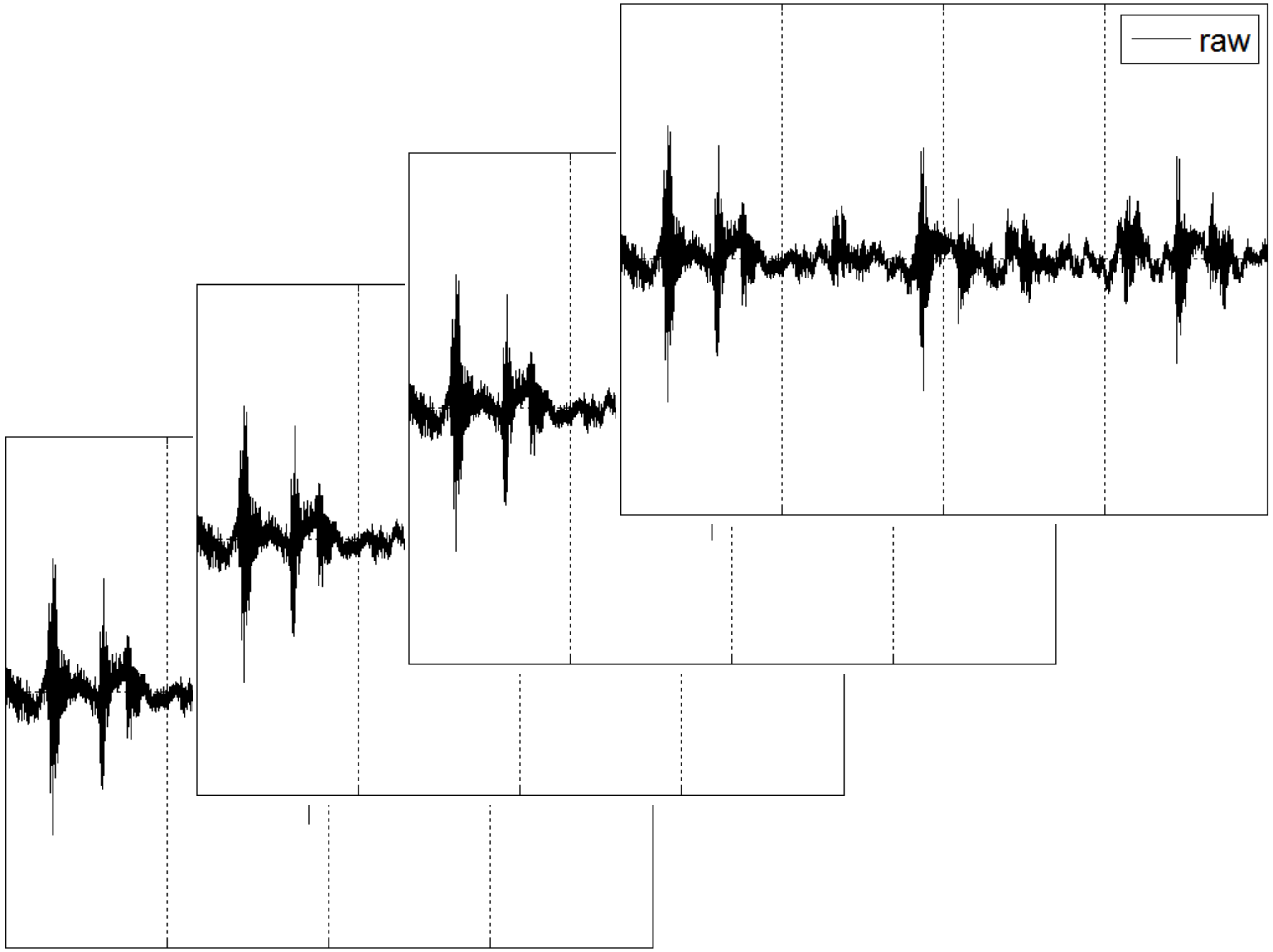
[Link to User Story]

Service for Predictive Maintenance

010010
100001
011100
100101

Data & Information

Knowledge



[Link to User Story](#)

Service for Predictive Maintenance

010010
100001
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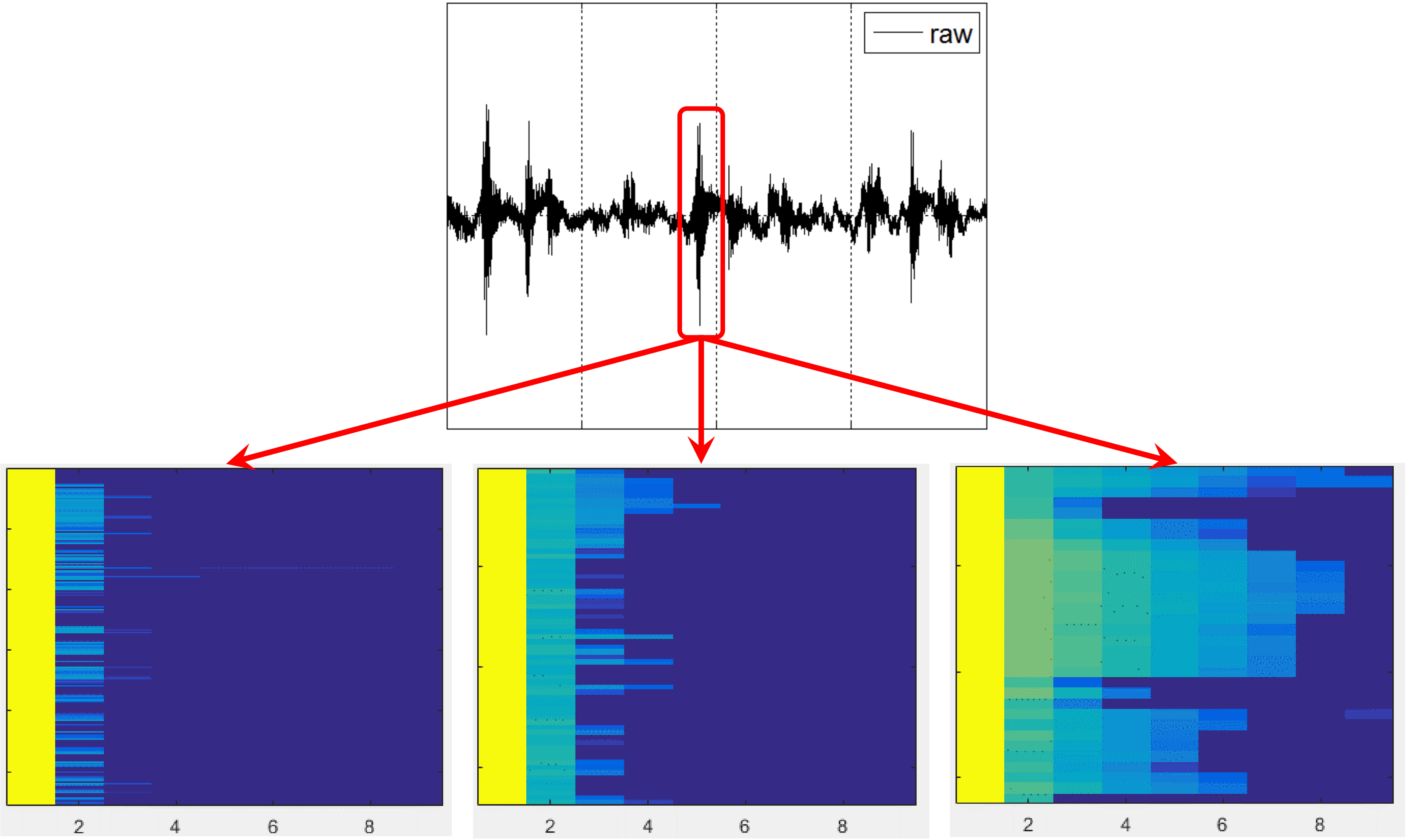
Data & Information

Knowledge

Wisdom



Normal Operation

Monitor Closely

Maintenance Needed

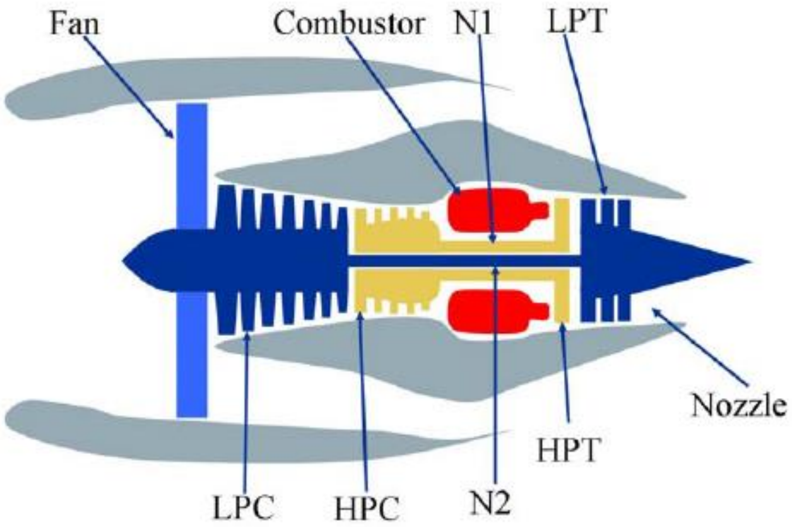
[Link to User Story]

Predictive Maintenance of Turbofan Engine

Sensor data from 100 engines of the same model

Predict and fix failures before they arise

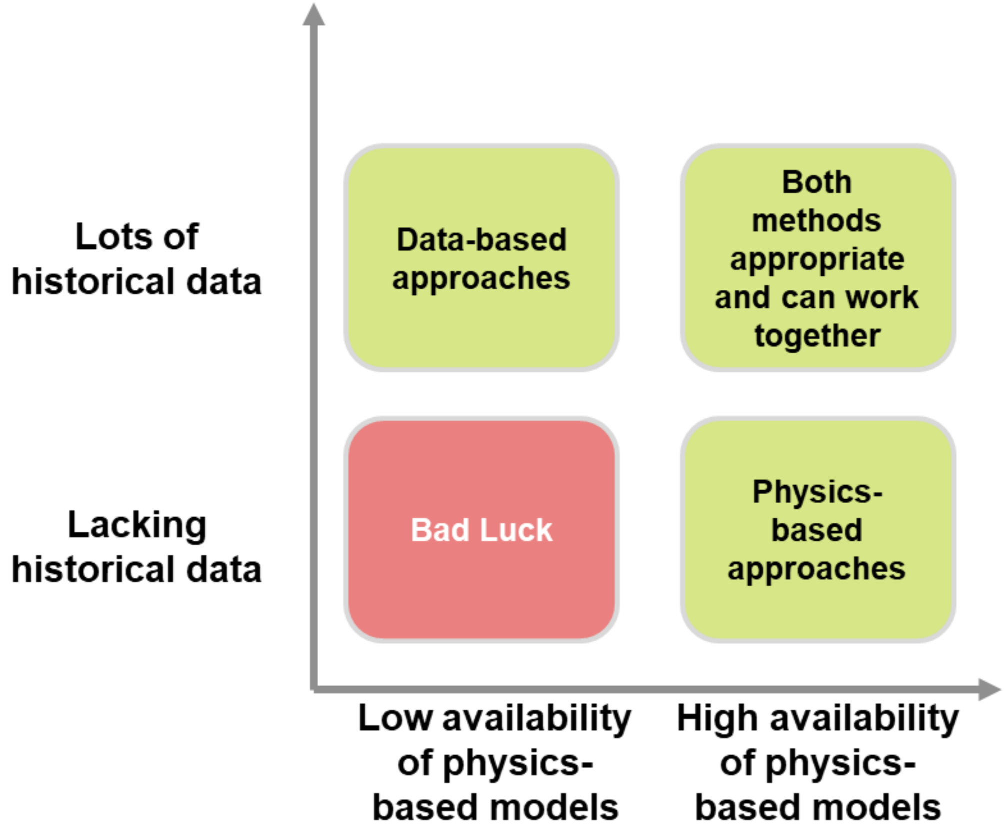
- Import and analyze historical sensor data
- Train model to predict when failures will occur
- Deploy model to run on live sensor data
- Predict failures in real time



Data provided by NASA PCoE
http://ti.arc.nasa.gov/tech/dash/pcoe/prognostic-data-repository/

Different Approaches to Predictive Maintenance

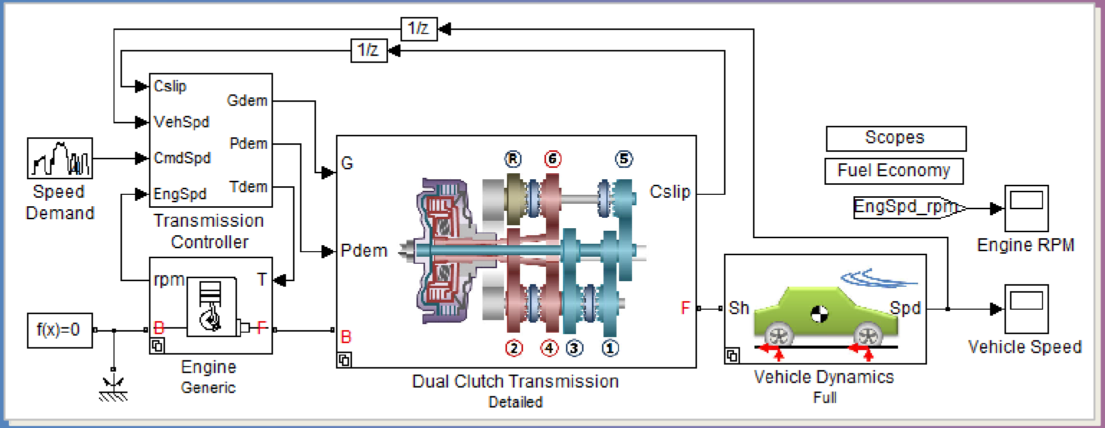
- Data-Based Approaches: Classical statistics & machine learning methods
- Model-Based / Physics-Based Approaches: Fitting a model to your data and analyzing the properties of the model
  - E.g Fit a curve to data and track how the coefficients of the curve change over time
  - E.g Fit transfer function to data and analyze Bode response plot over time

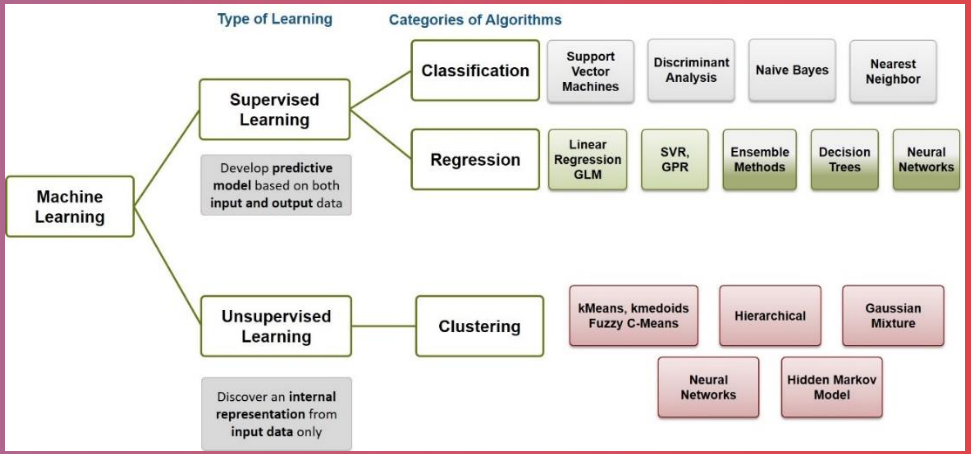


Modeling Approaches

First Principles Modeling

Data-Driven Modeling



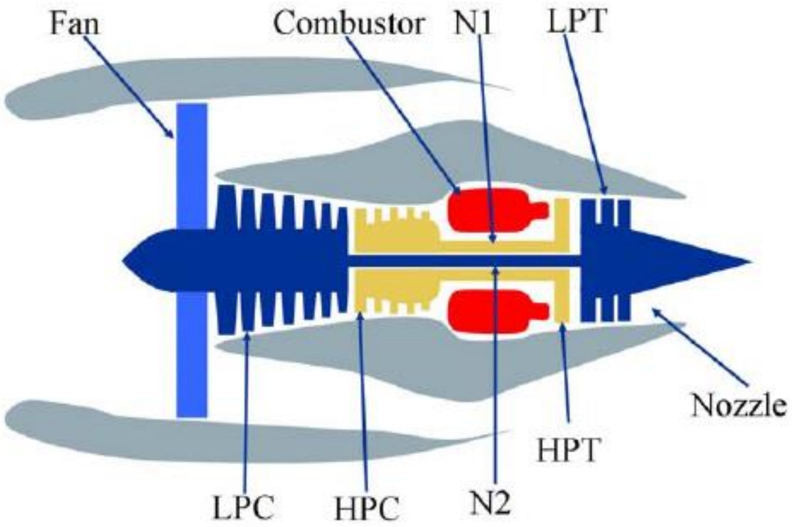


Predictive Maintenance of Turbofan Engine

Sensor data from 100 engines of the same model

Scenario 1: Condition Monitoring

- May or may not have failure data
- Used together with scheduled or predictive maintenance
- In this example:
  - Performing scheduled maintenance often enough no failures have occurred
  - Maintenance crews tell us most engines could run for longer
- Can we be smarter about how to schedule maintenance **without** knowing what failure looks like?



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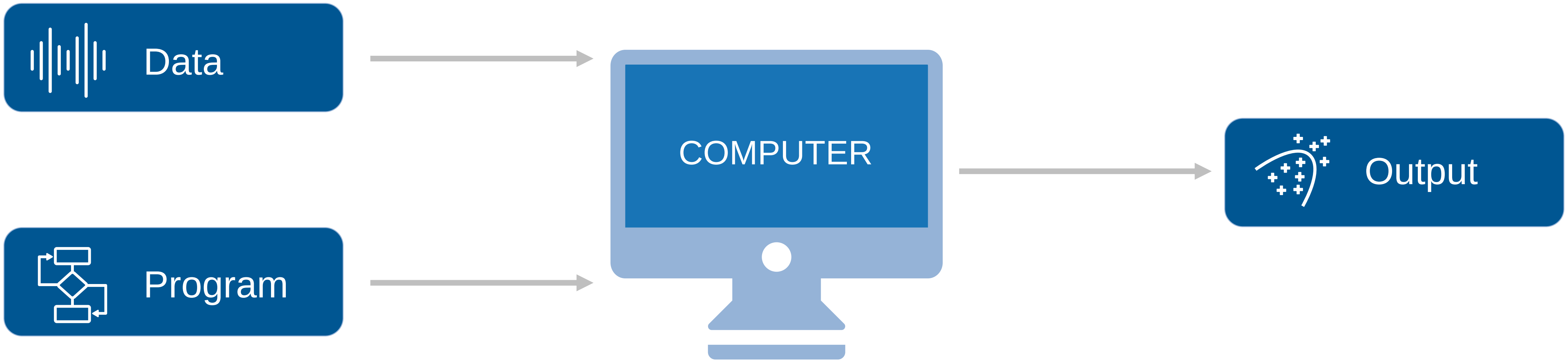
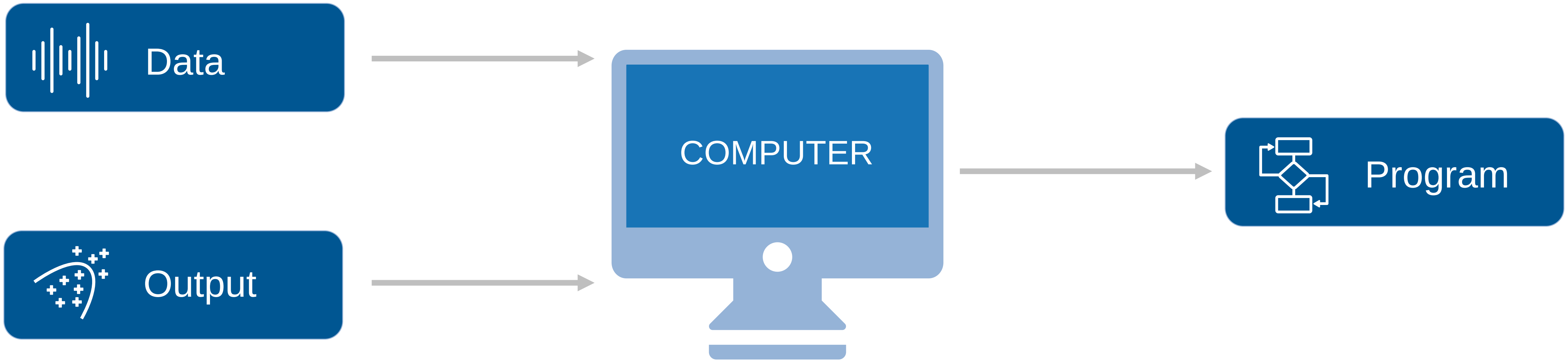
How does Machine Learning work

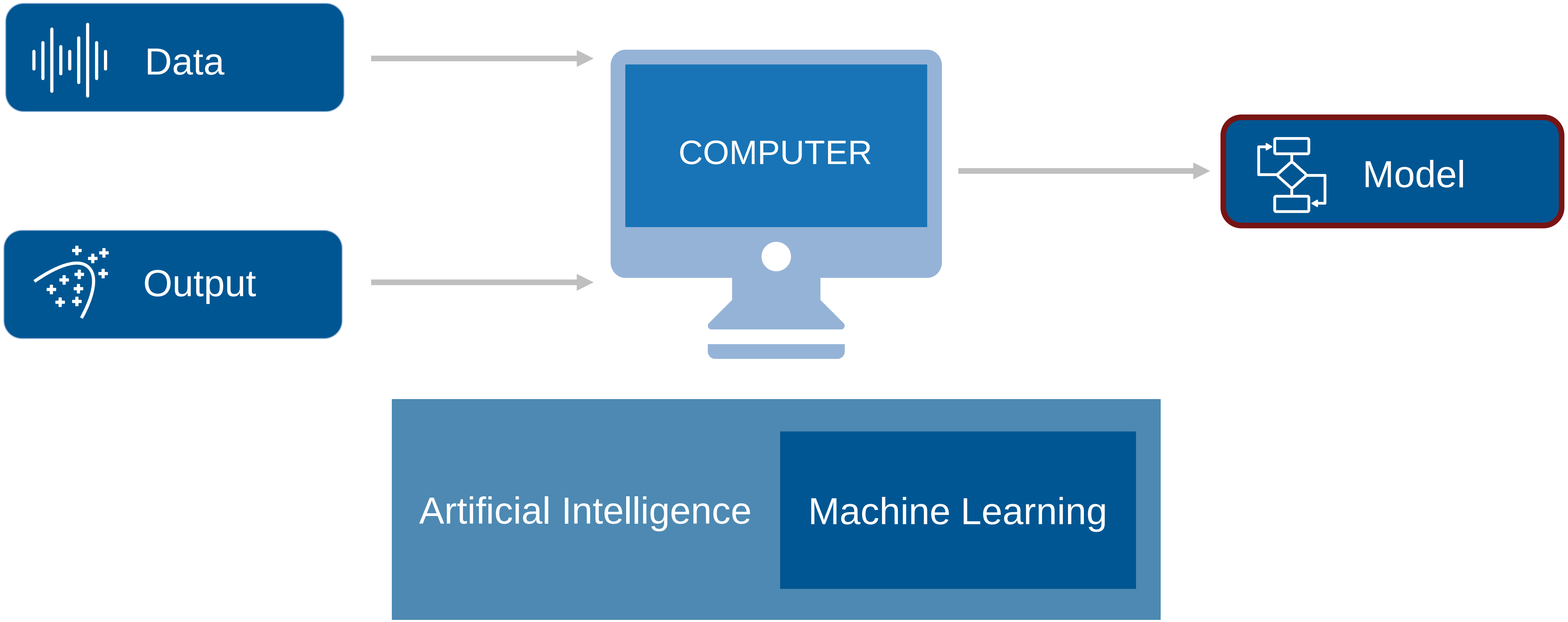


How does Machine Learning work



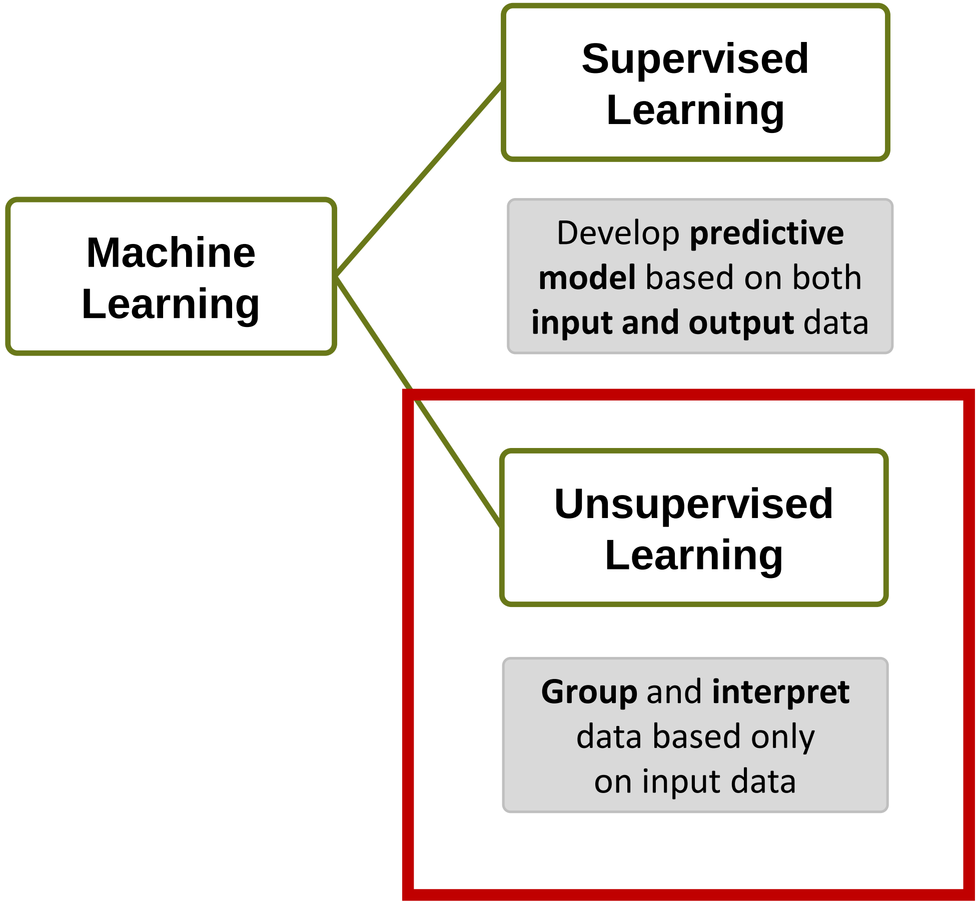
How does Machine Learning work

What if you don't have enough (failure) data to train your model?

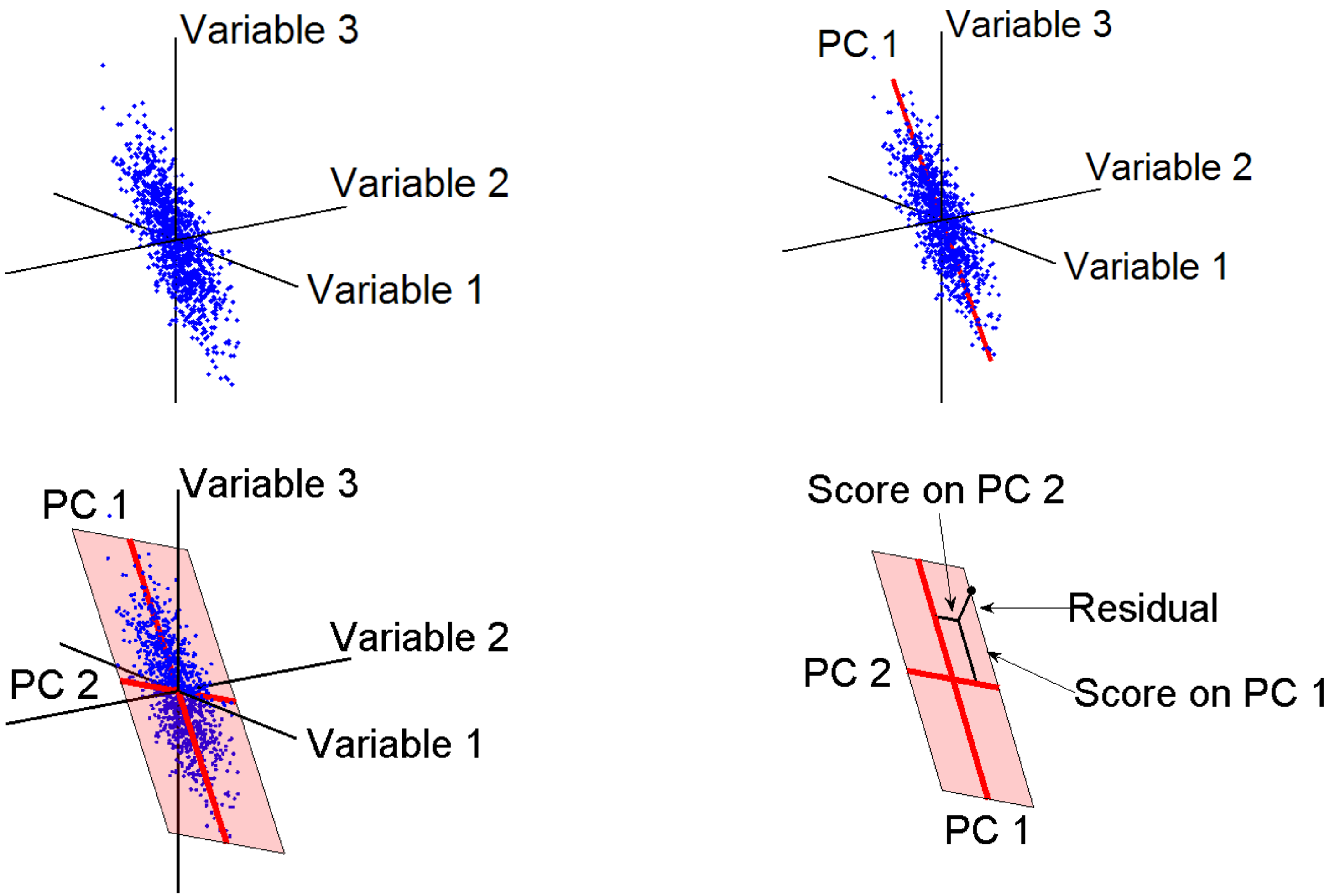


Overview – Machine Learning

Type of Learning

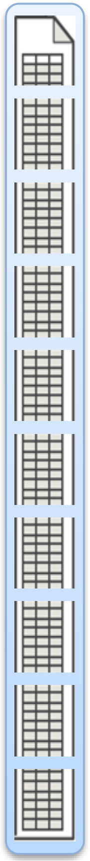


Principal Components Analysis – what is it doing?



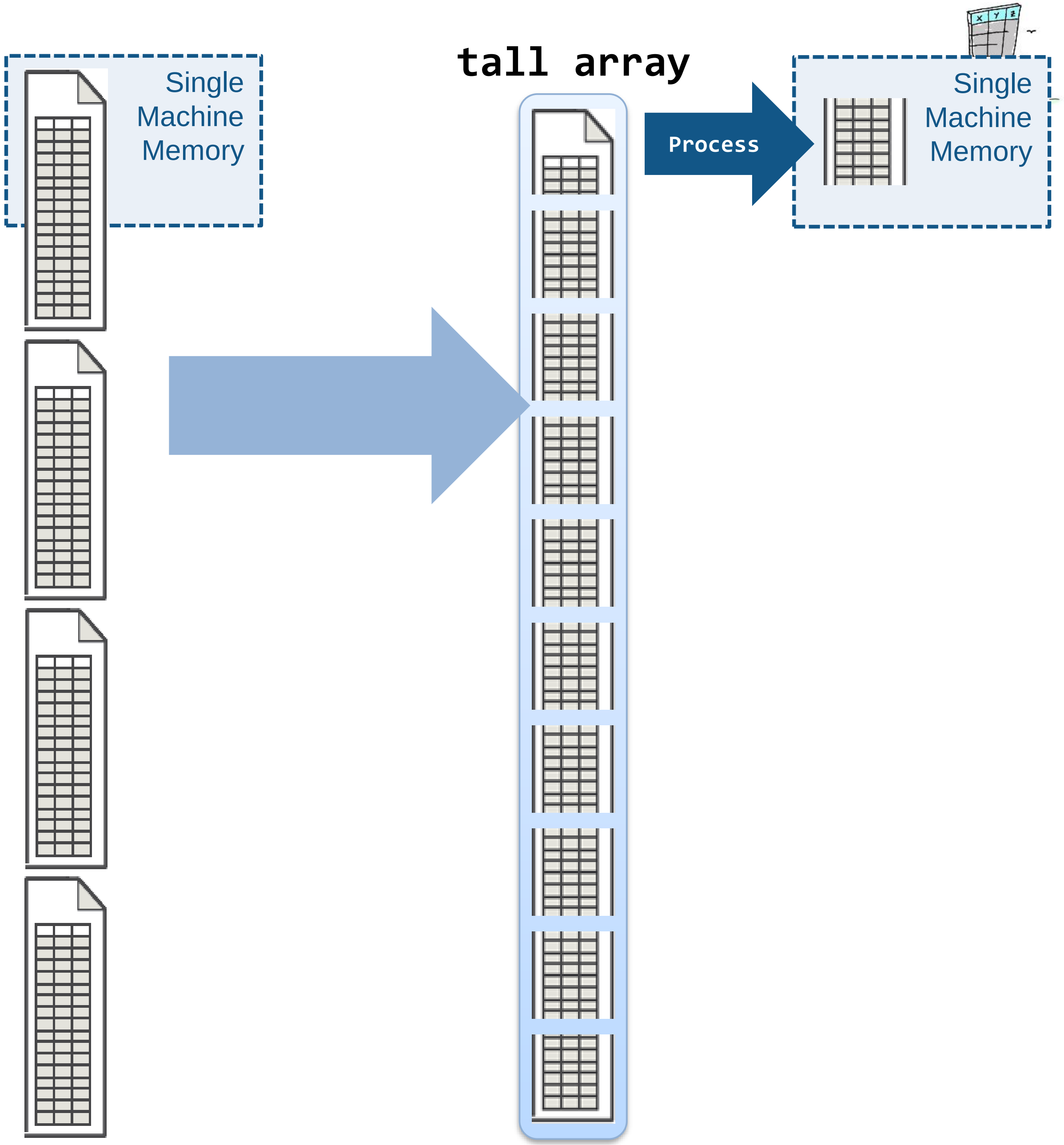
`tall` arrays R2016b

- New data type designed for data that doesn't fit into memory
- Lots of observations (hence "tall")
- Looks like a normal MATLAB array
  - Supports numeric types, tables, datetimes, strings, etc…
  - Supports several hundred functions for basic math, stats, indexing, etc.
  - **Statistics and Machine Learning Toolbox** support (clustering, classification, etc.)

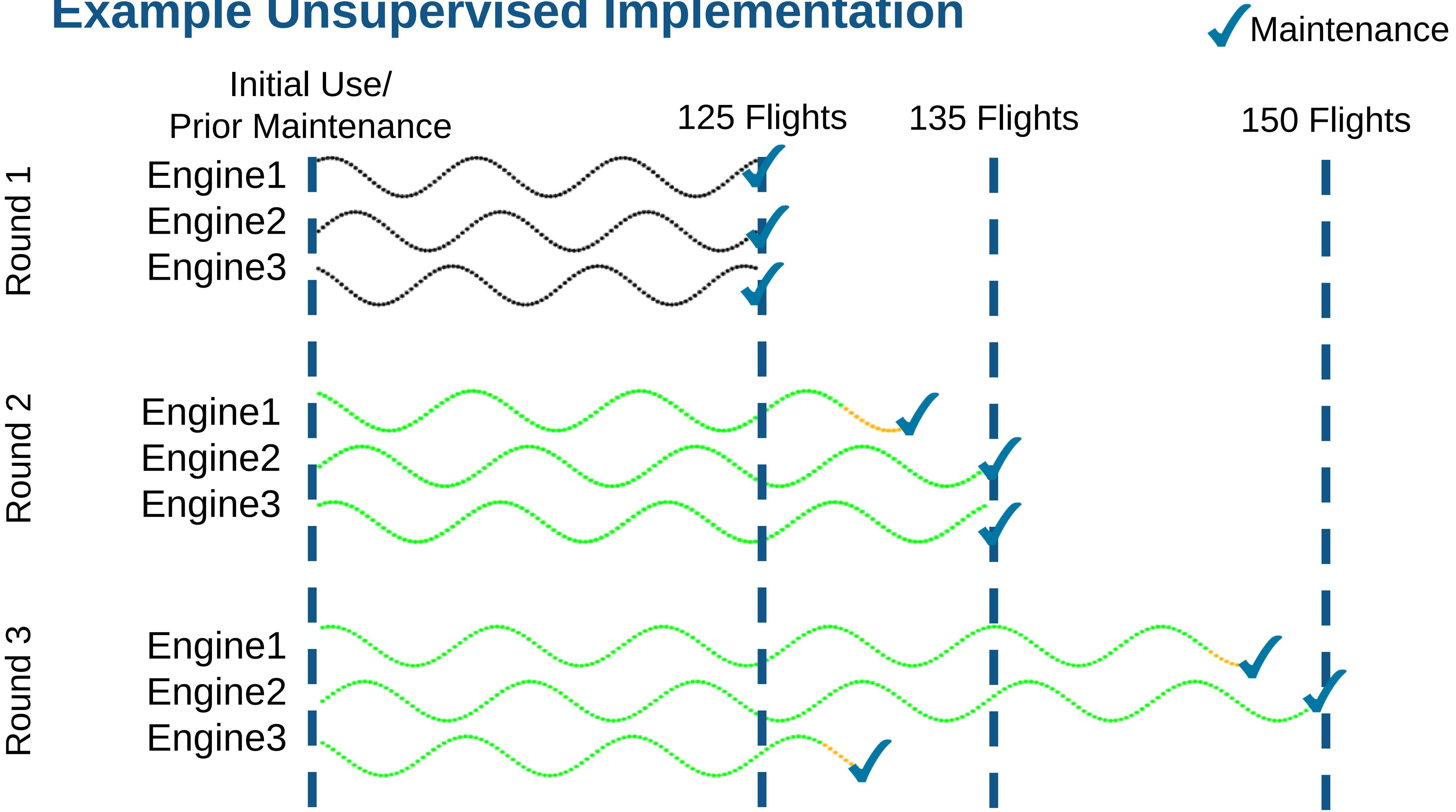


`tall` arrays R2016b

- Automatically breaks data up into small “chunks” that fit in memory
- Tall arrays scan through the dataset one “chunk” at a time
- Processing code for tall arrays is the same as ordinary arrays



Example Unsupervised Implementation



Condition monitoring at MONDI

Challenge

Reduce waste and machine downtime in plastics manufacturing

Solution

Use MATLAB to develop and deploy monitoring and predictive maintenance using machine learning to predict machine failures

Results

- > 200,000 € savings per year expected when in full production
- Prototype completed in six months
- MATLAB-based Production software runs 24/7

- International packaging and paper
- ~25k employees
- Revenues of €6.4 billion in 2014

One of Mondi's plastic production machines, which deliver 18 million tons of plastic and thin film products annually.

MATLAB based HMI that enables equipment operators to receive warnings about potential failures before they occur

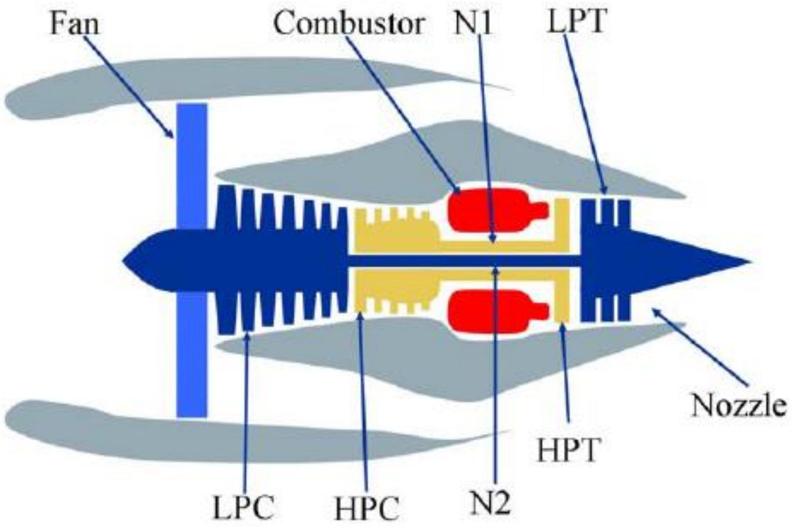
[Link to User Story]

Predictive Maintenance of Turbofan Engine

Sensor data from 100 engines of the same model

Scenario 2: Have failure data

- Performing scheduled maintenance
- Failures still occurring (maybe by design)
- Search records for when failures occurred and gather data preceding the failure events
- Can we predict how long until failures will occur?



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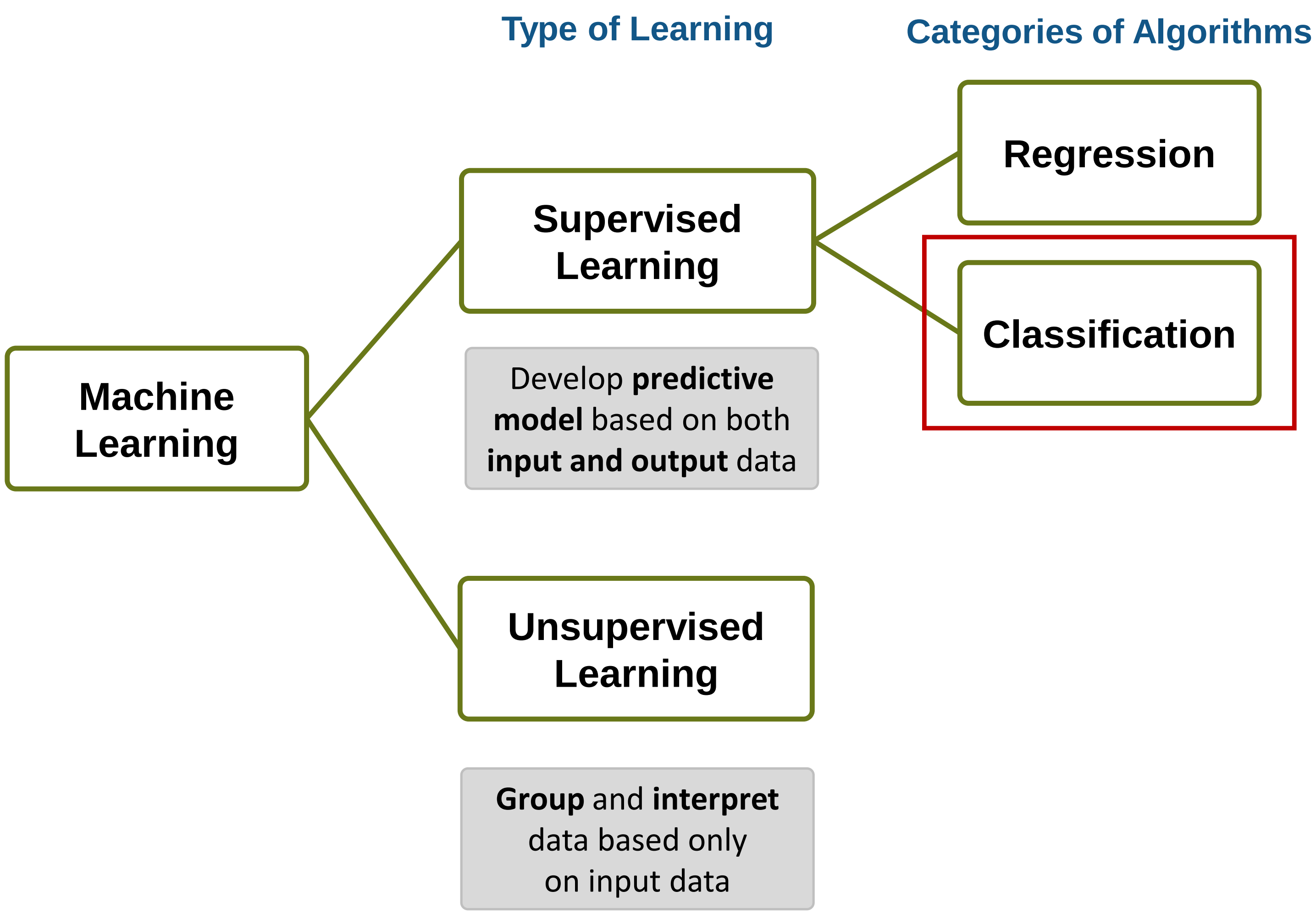
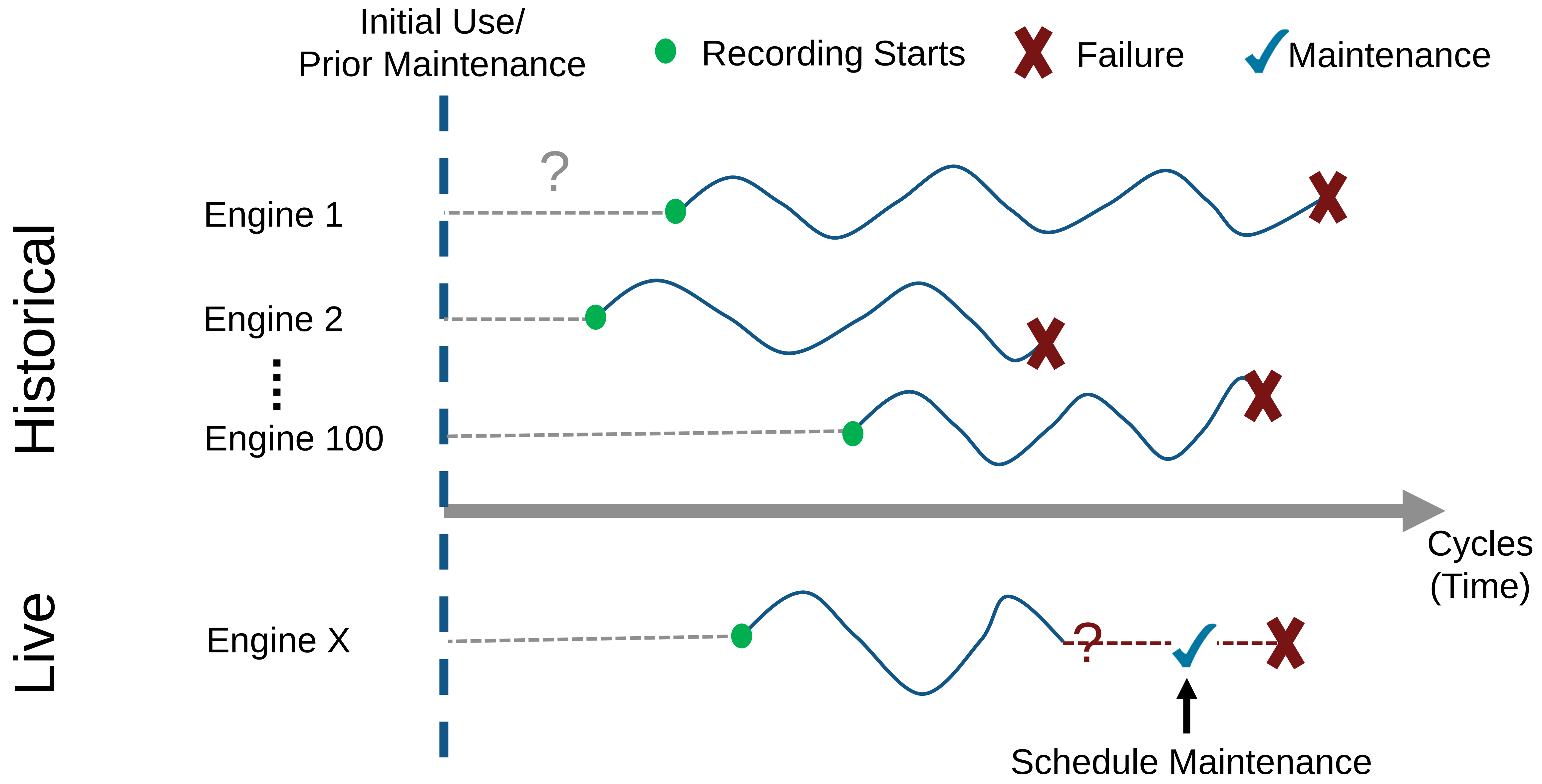
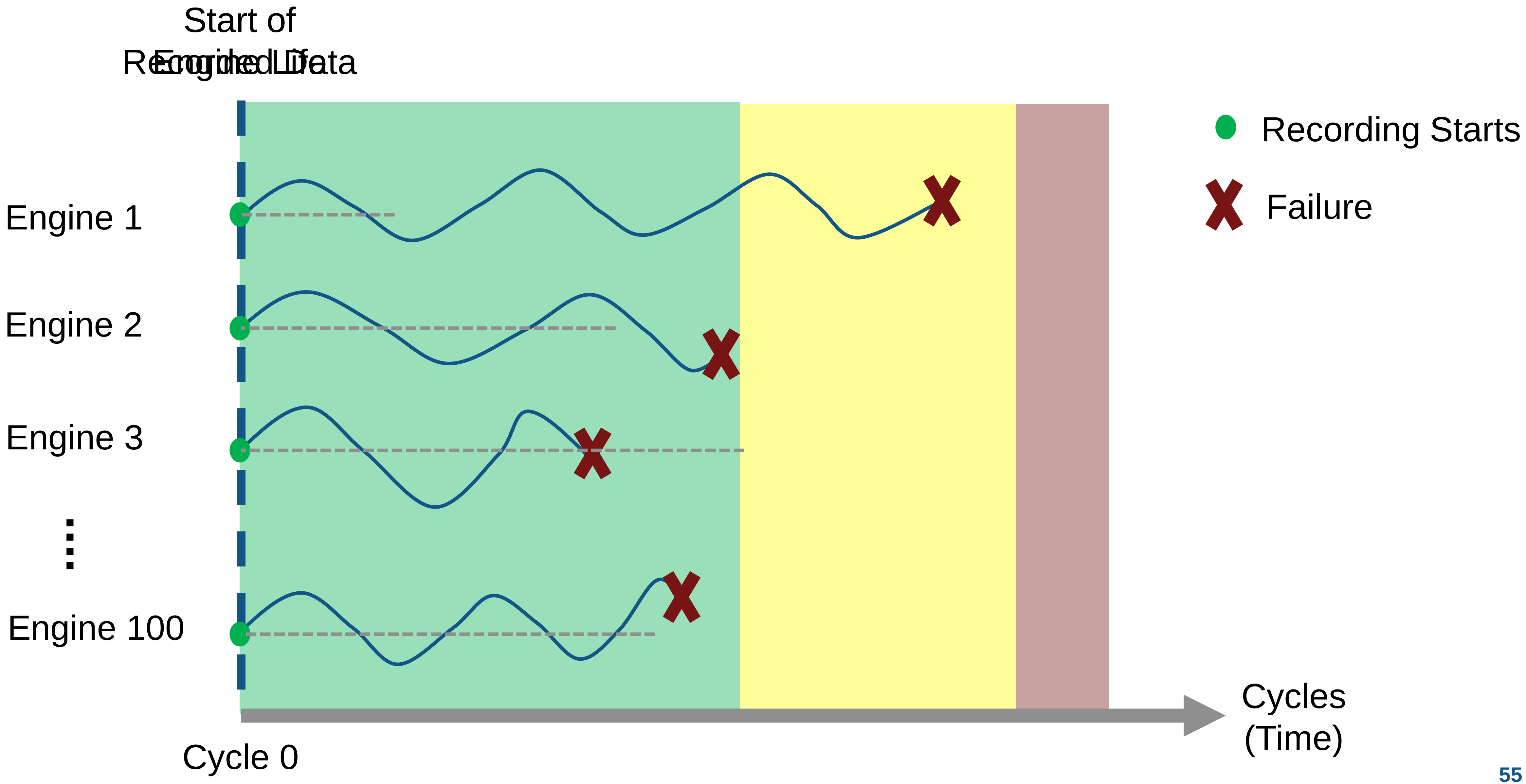


Use historical data to predict when failures will occur

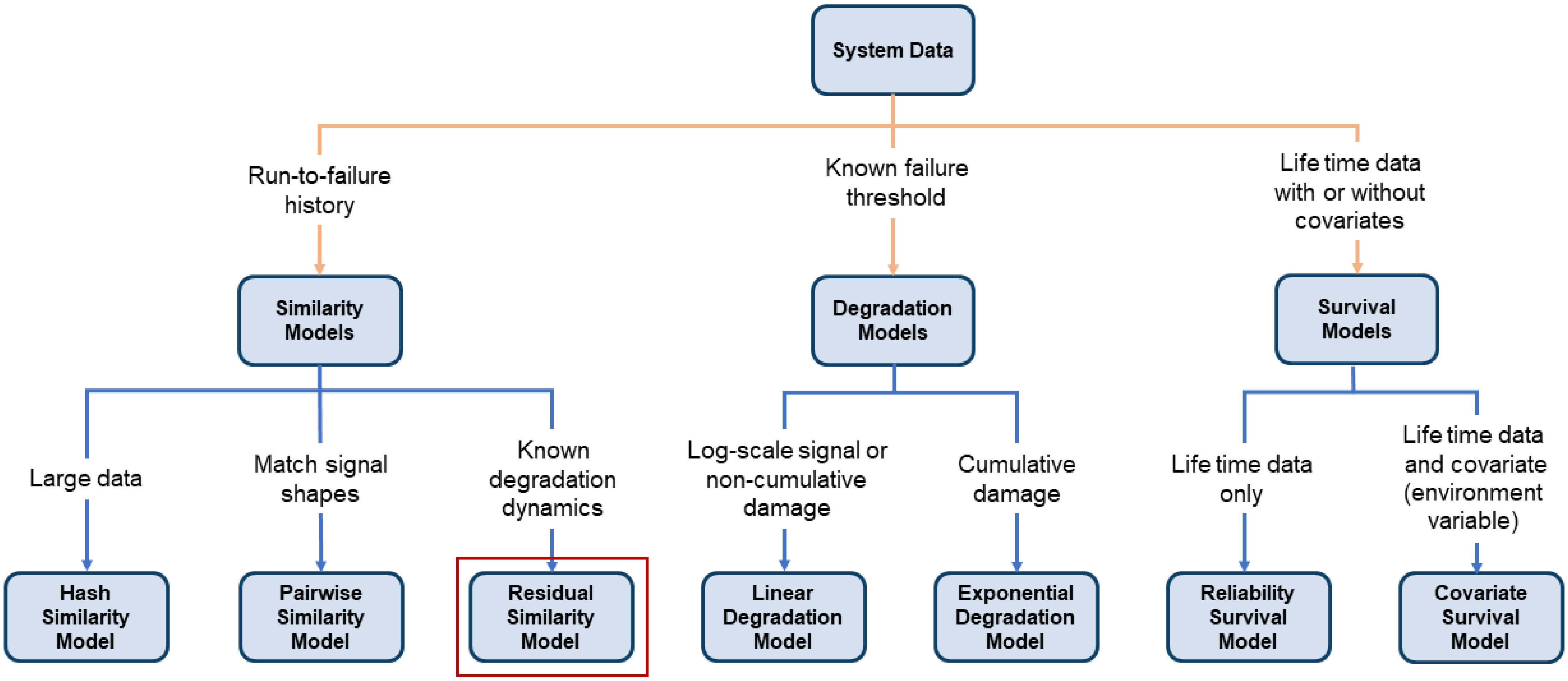


Preprocessing and Classifying our Input Data



RUL Methods and when to use them

Requirement: Need to know what constitutes failure data

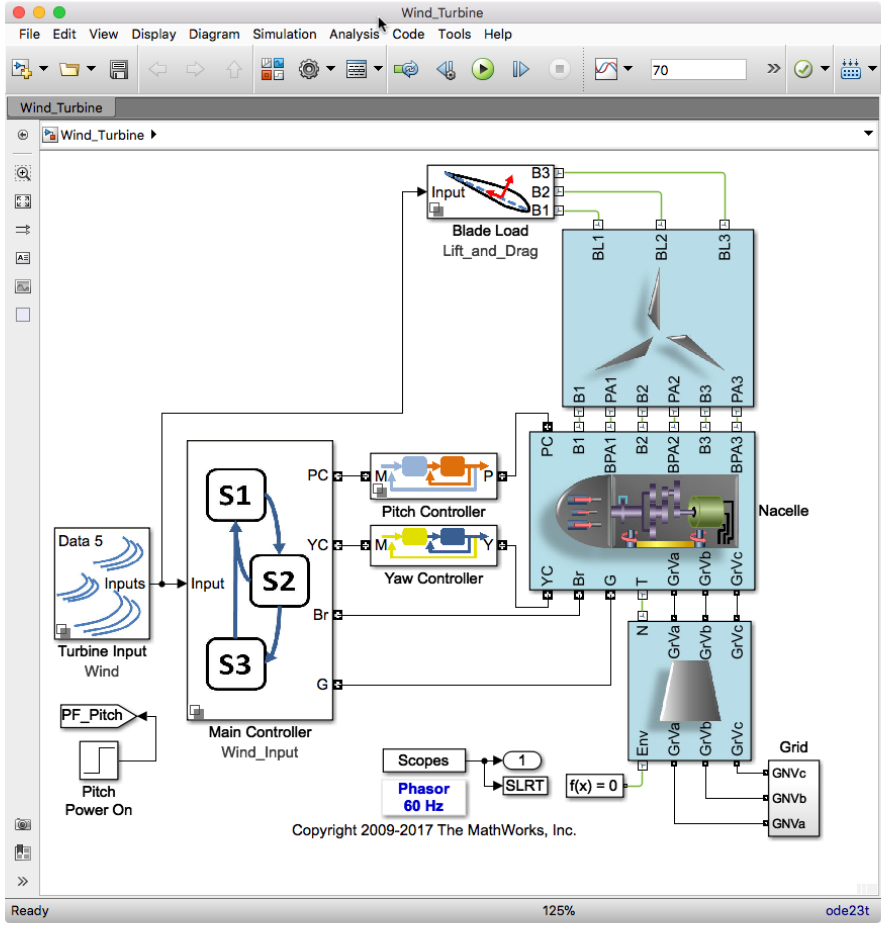


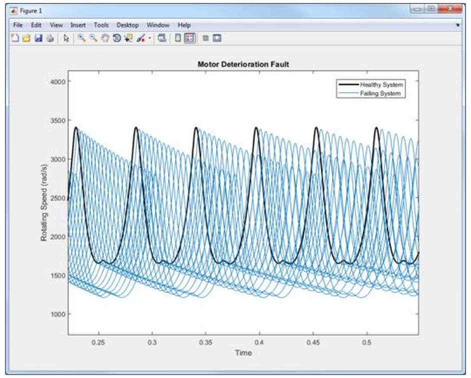
[Details on model selection in the documentation]

Predictive Maintenance

- Measure the wear of each blade
- Predict and fix failures before they happen
- Can’t rely on failures in the field

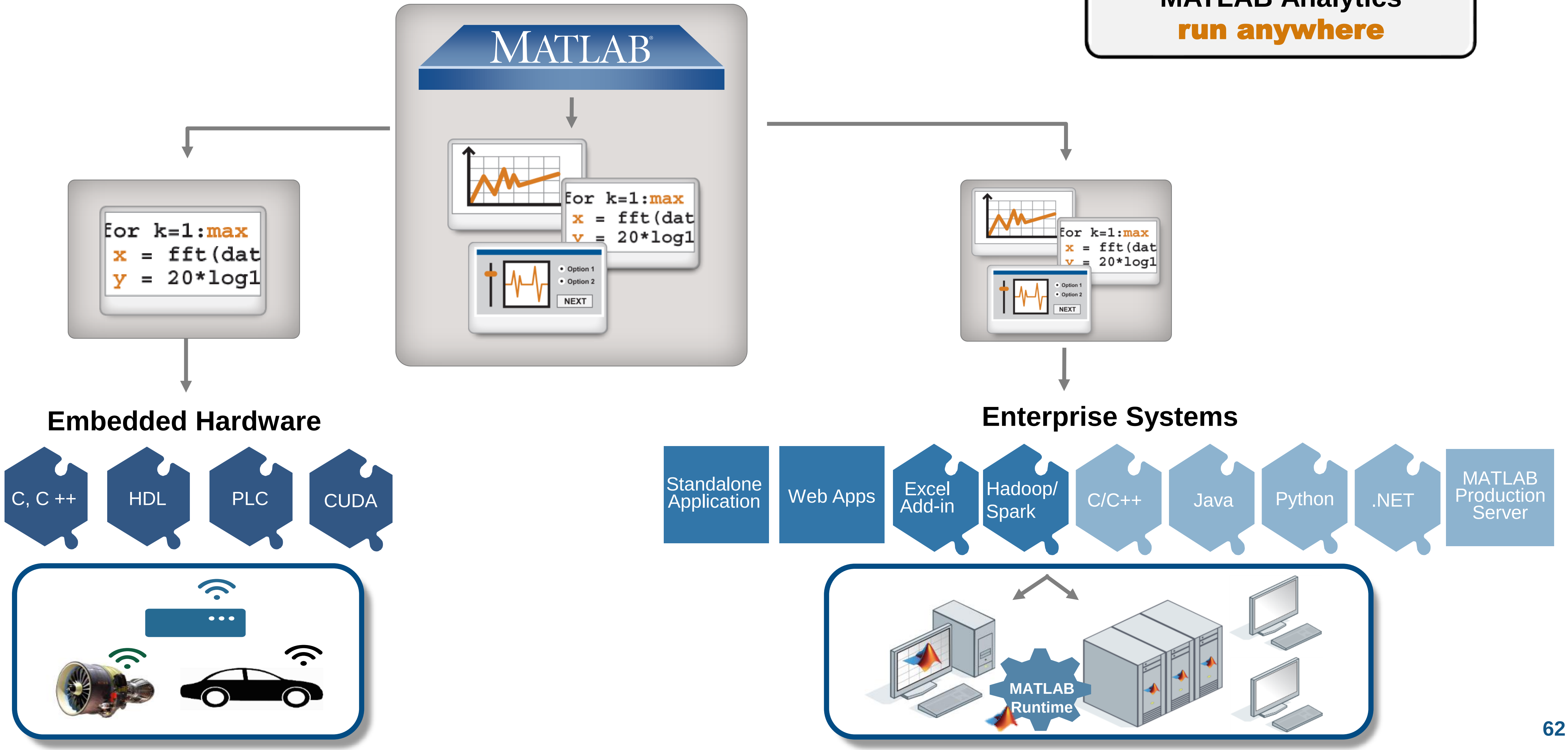
Predictive Maintenance with synthetic failure data from simulation



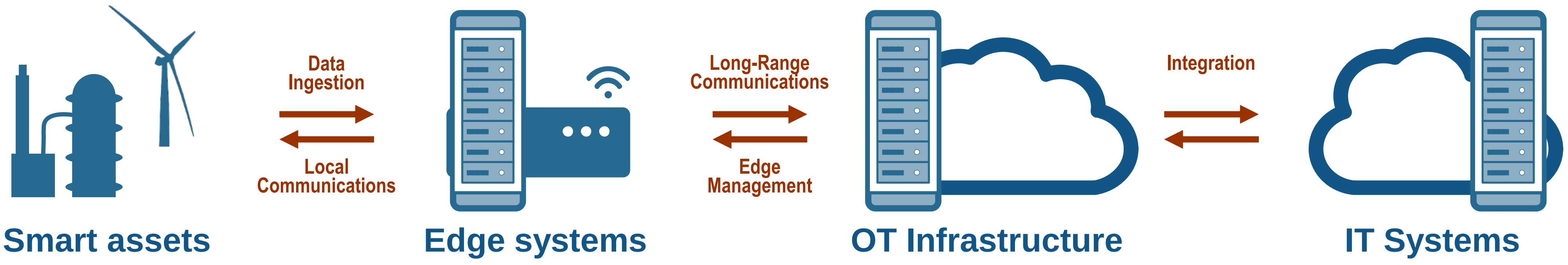


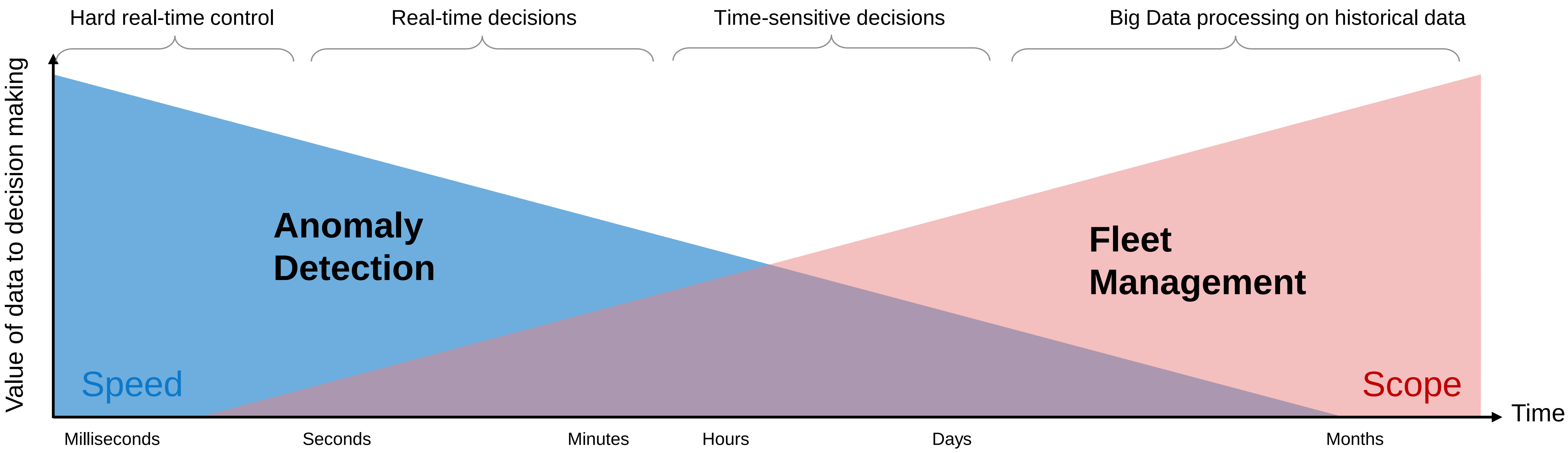
Integrate Analytics with Systems

MATLAB Analytics
run anywhere



Preventive, Predictive, Reactive, Actionable

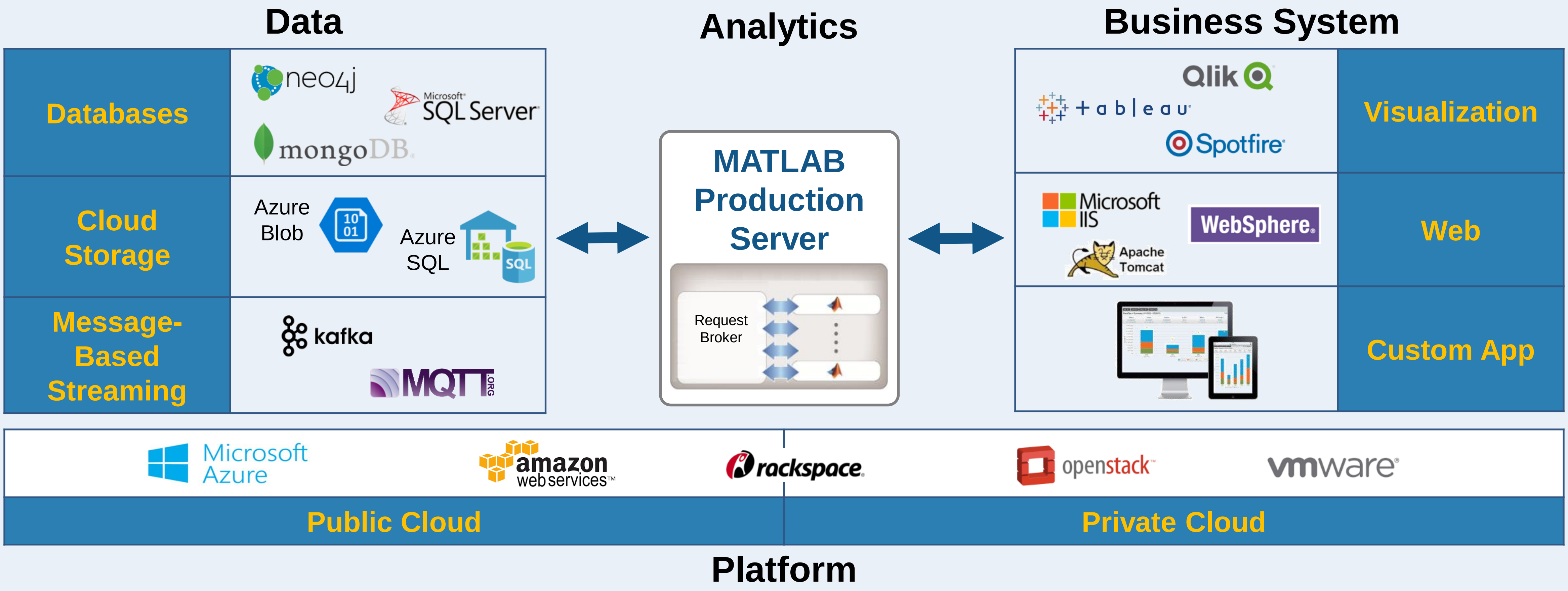




MATLAB and Simulink: Key Capabilities for Digital Twins

Integration with enterprise systems

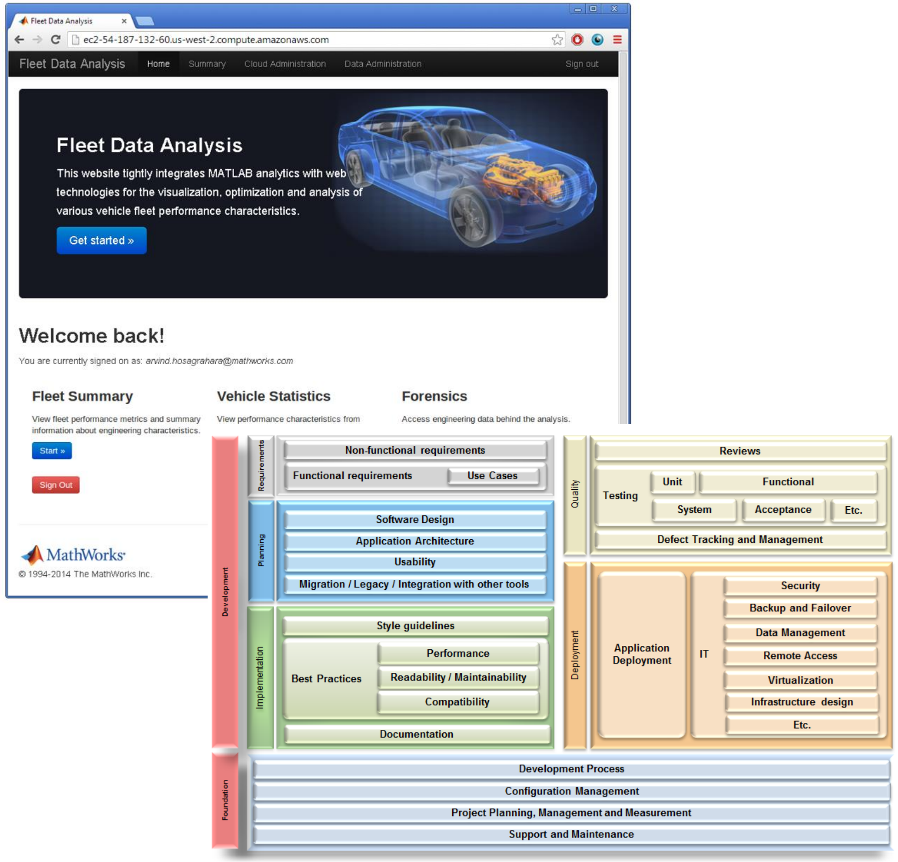
- MathWorks Consulting enables integration for customer workflows



MathWorks Services

- Consulting
  - Integration
  - Data analysis/visualization
  - Unify workflows, models, data

www.mathworks.com/services/consulting/

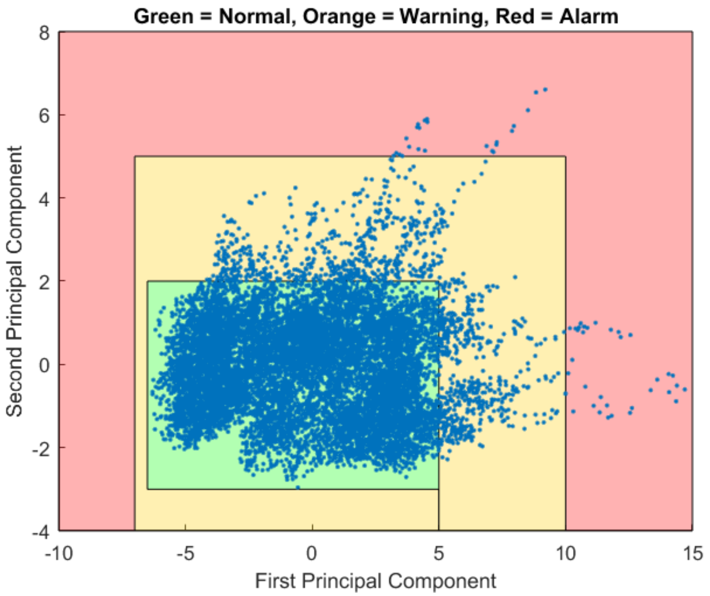


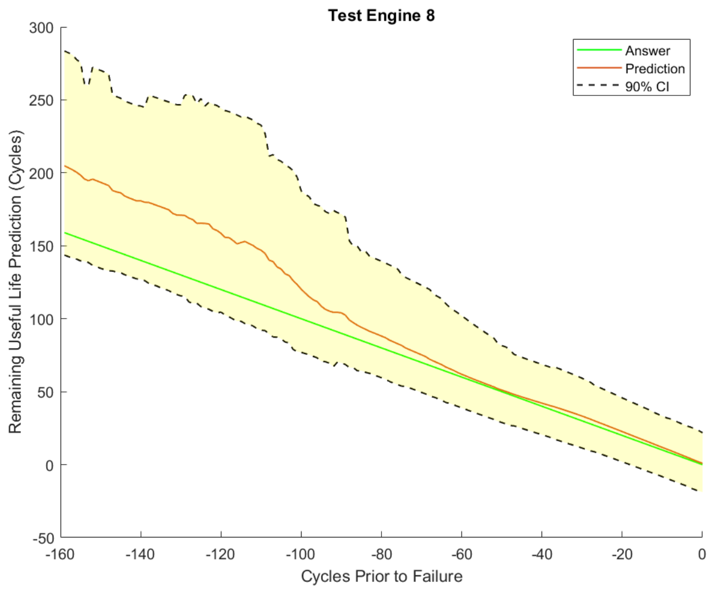
- Training
  - Classroom, online, on-site
  - Data Processing, Visualization, Deployment, Parallel Computing

www.mathworks.com/services/training/

Key Takeaways

- Frequent maintenance and unexpected failures are a large cost in many industries
- MATLAB enables engineers and data scientists to quickly create, test and implement predictive maintenance programs
- Predictive maintenance
  – Saves money for equipment operators
  – Increases reliability and safety of equipment
  – Creates opportunities for new services that equipment manufacturers can provide





Key Takeaway

- Industrial IoT is real and is already used in practical applications
- There is not "the one" IIoT application
- Know your business case before implementing your IIoT application
- MathWorks has key building blocks for developing IIoT applications: Modeling, Simulation, Codegen, Data Analytics, Application Deployment, and Enterprise Integration

IIoT and Digital Twin Relevant Solution Pages

- www.mathworks.com/iot
- www.mathworks.com/cloud
- https://www.mathworks.com/solutions/physical-modeling.html
- https://www.mathworks.com/solutions/predictive-maintenance.html
- https://www.mathworks.com/solutions/data-science.html

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