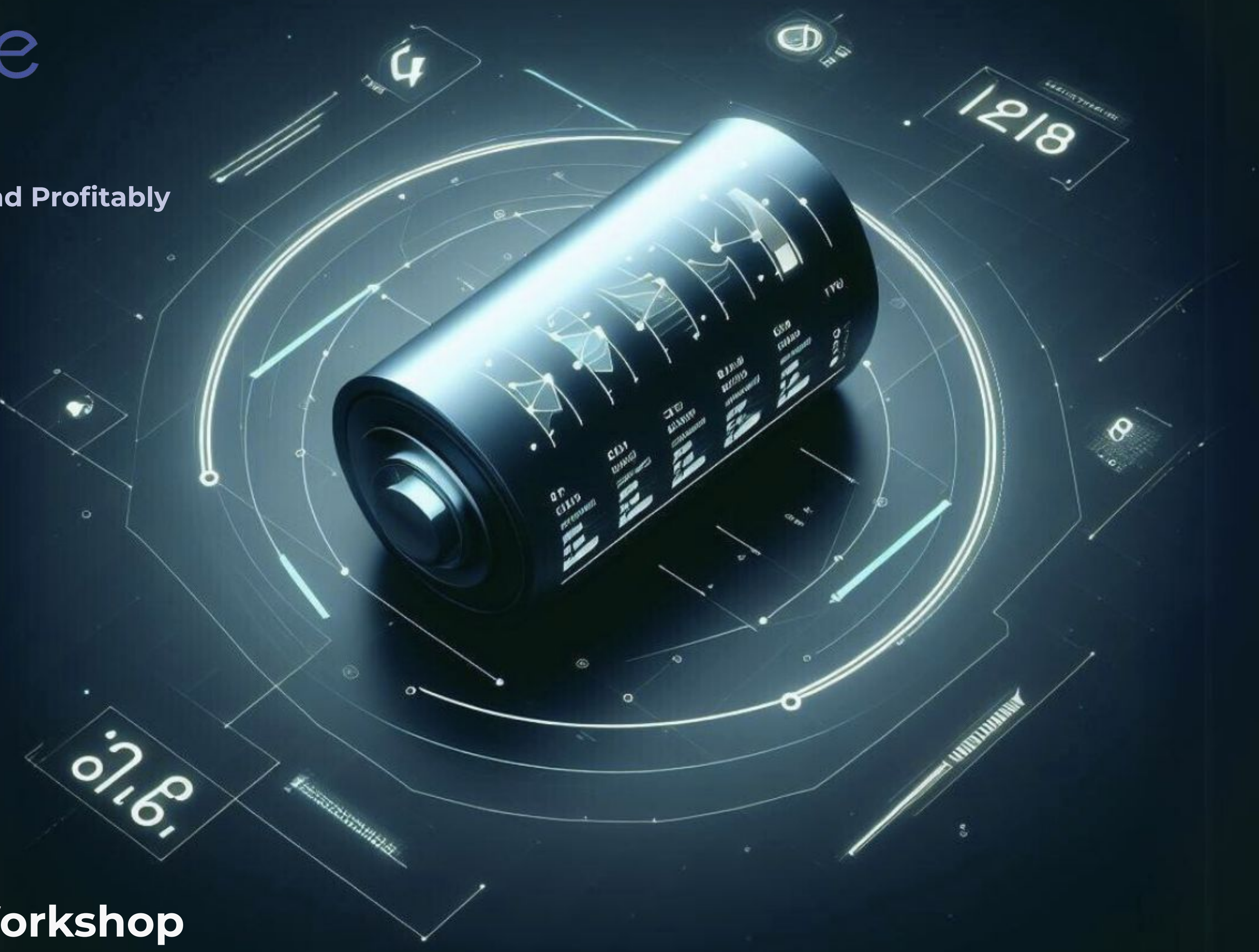
astrolabe analytics

Operating Batteries at the Limit - Safely and Profitably

Identification of Weak Cell Blocks in Electric Aircraft Battery Packs



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NASA Aerospace Battery Workshop
November 2023

Outline

1. Astrolabe Overview
2. Problem Statement
3. Approach
4. Algorithm Development
5. Results and Discussion
6. Conclusions and Future Work

About Astrolabe

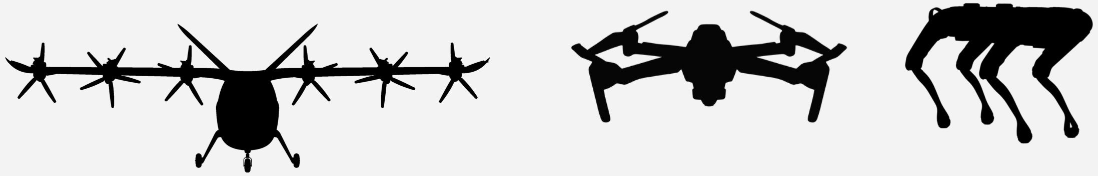
Established

2018

Based in Seattle, WA

Facts

Electrifying the unthinkable by enabling batteries to go beyond using Data Driven Battery Health and Performance Modeling.



Multiple commercial projects pertaining to eVTOL, drone, and ground assets

Mission & Technology

$2.3M in non-dilutive funding

SBIR ★ STTR
U.S. AIR FORCE ★ U.S. SPACE FORCE

NSF | America's SEED FUND SBIR.STTR

USAID FROM THE AMERICAN PEOPLE

Funding

Relevant Professional Memberships and Partners

Soteria Battery Innovation Group	Washington Cleantech Alliance	Vertical Flight Society	Military Power Sources Consortium	National Center for Manufacturing Sciences

High Level Problem Motivation

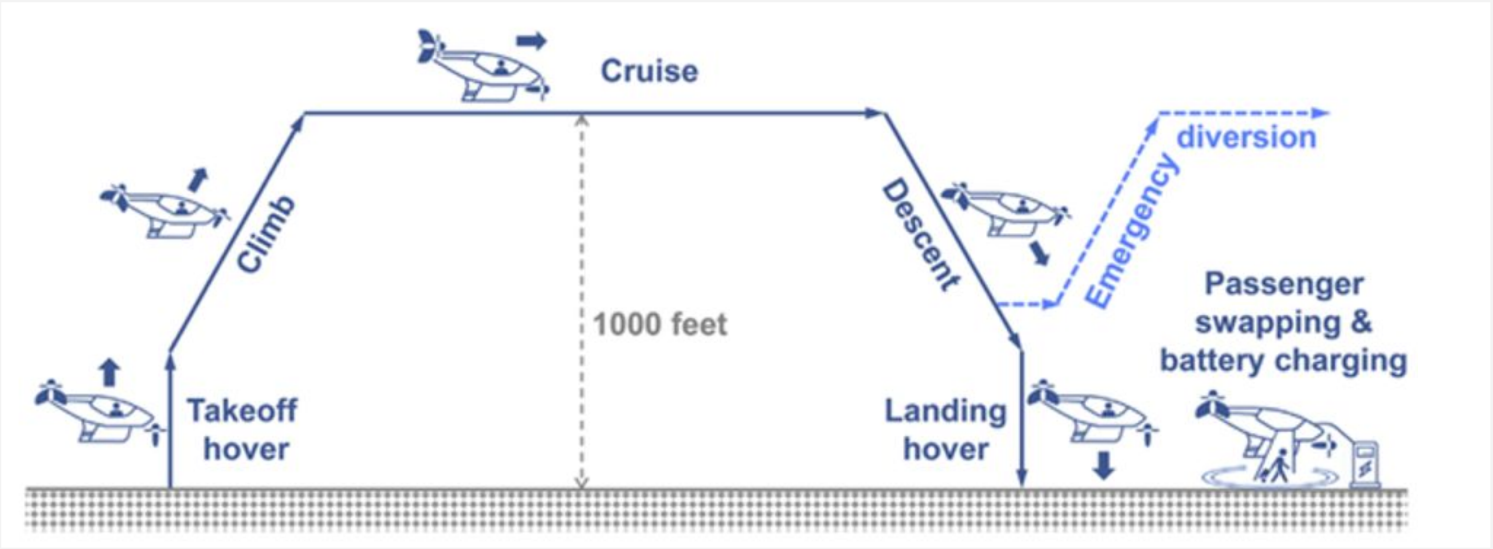
Electric aviation represents a new arena for battery engineering and development

Less mature and **requires higher safety** and **performance regulations** than automotive

Batteries are a looming certification challenge for electric aviation hopefuls

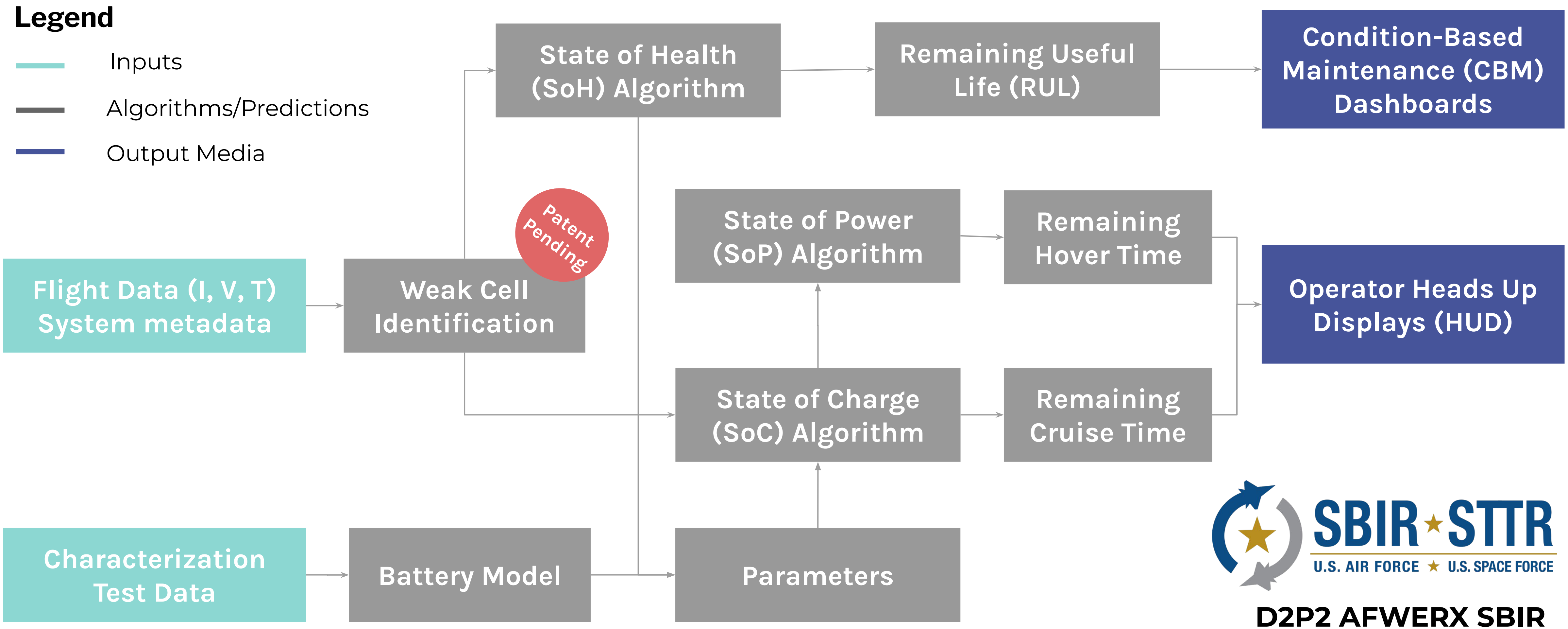
Elan Head,
The Air Current (2022)

Certification Basis Under Development



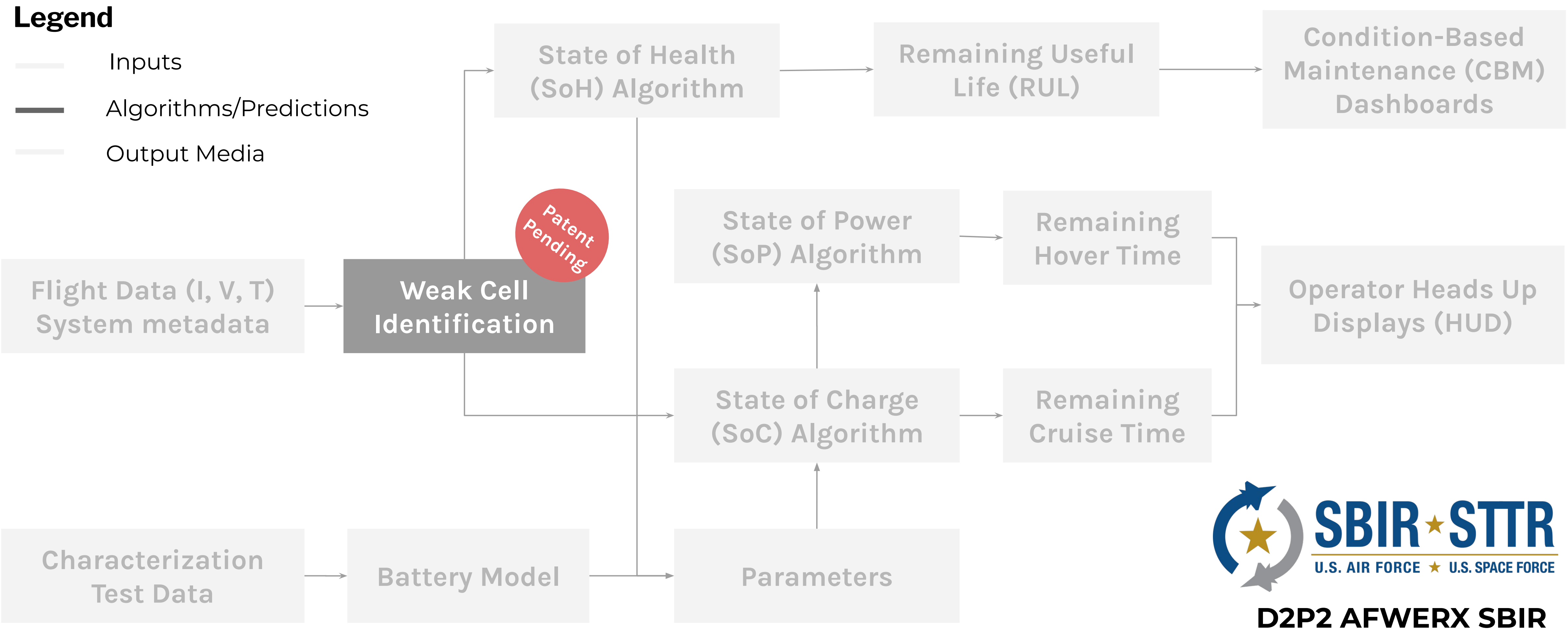
eVTOL very demanding on batteries
+1MW of power for take off and landing

Astrolabe eVTOL Analytics System



D2P2 AFWERX SBIR

Astrolabe eVTOL Analytics System



D2P2 AFWERX SBIR

Specific Problem - Weak Cell Block Identification

Problem

Weak cell blocks will **hurt overall pack-level safety** and performance. Low OCV at the end of flight indicates broken bond wires or imbalanced cell blocks (inter alia).

Goal

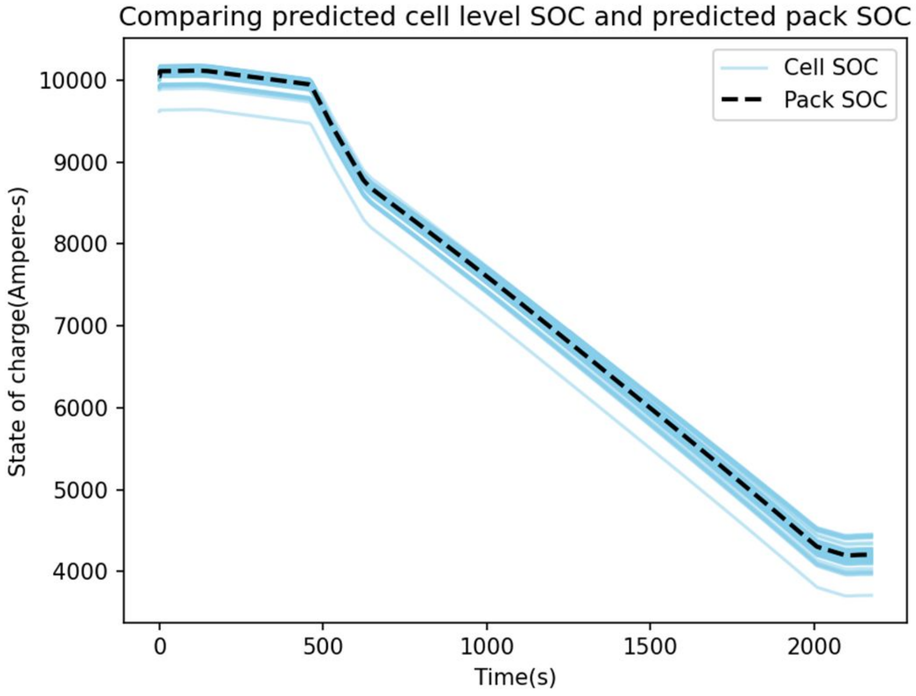
Accurately identify weak cells faster than status quo (~30min into flight test)

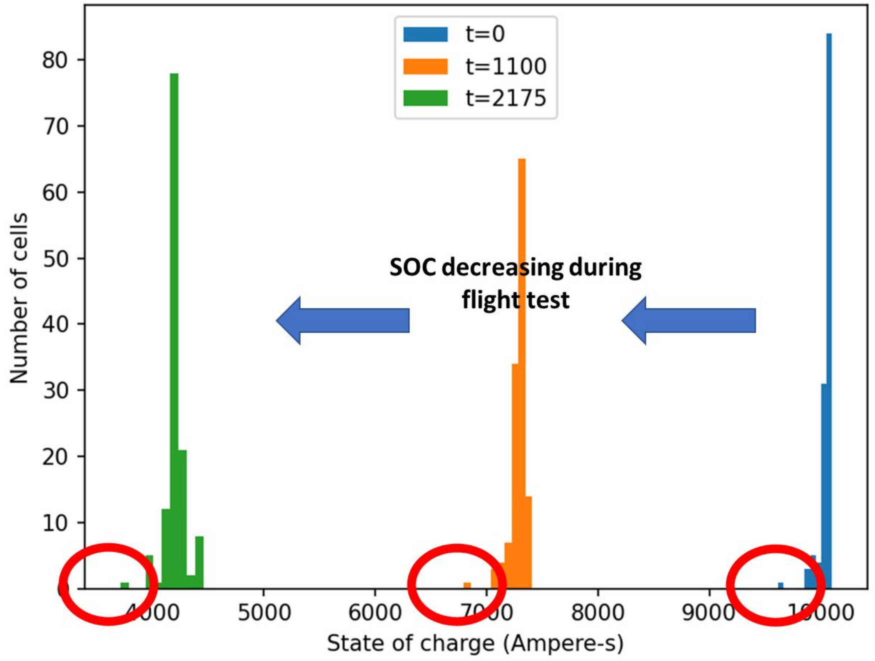
Specific Problem - Implications

Weak cell ID useful input for **RUE/RUL estimation**

Rationally downselect to a manageable set of cells (out of ~10,000)

The **SOC for the weakest cell** may be **appreciably lower** than the average SOC of the pack





Weak Cell Block Identification

Solution

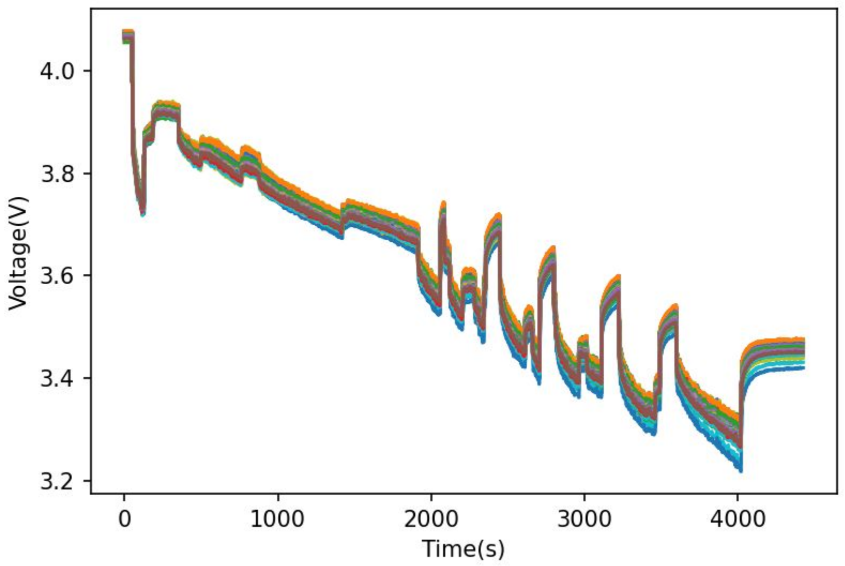
Outlier detection algorithm employed with **features derived from voltage data** to **identify weakest cell blocks** in battery pack

1. First step towards the **development of standards** for measuring remaining useful energy (RUE) and remaining useful life (RUL)
2. Considers first **5 minutes of data** (or less) and compares favorably against status quo
3. Validated against battery flight test data from **two different battery pack manufacturers**

Pack Characteristics

Manufacturer 1

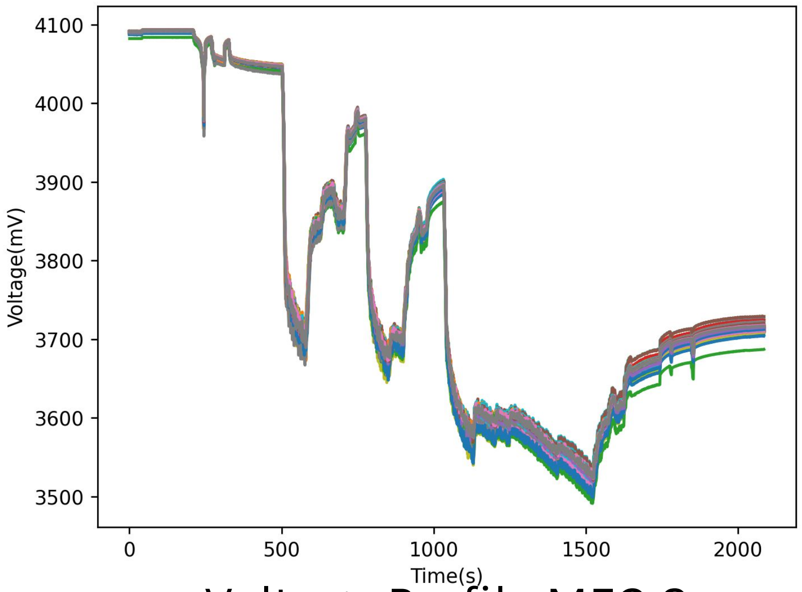
- 1 pack = 14 modules in series
- 1 module = 14 cell blocks in series
- 1 cell block = 16 cells in parallel
- 1 pack = 196s16p



Voltage Profile MFG 1

Manufacturer 2

- 1 pack = 8 modules in series
- 1 module = 16 cell blocks in series
- 1 cell block = 34 cells in parallel
- 1 pack = 128s 34p



Voltage Profile MFG 2

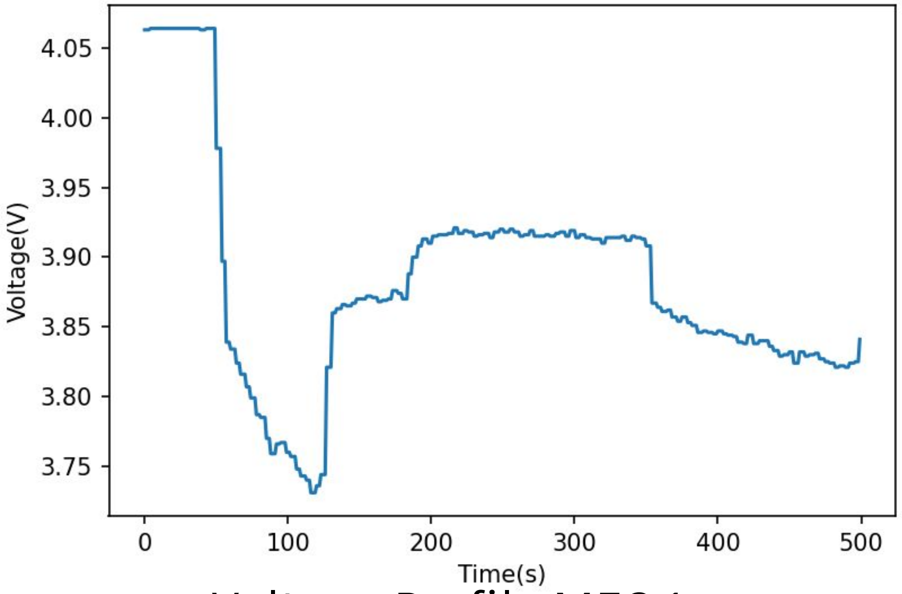
Input Data

Manufacturer 1

The first **300 seconds** of voltage data

Manufacturer 2

The first **200 seconds** of voltage data

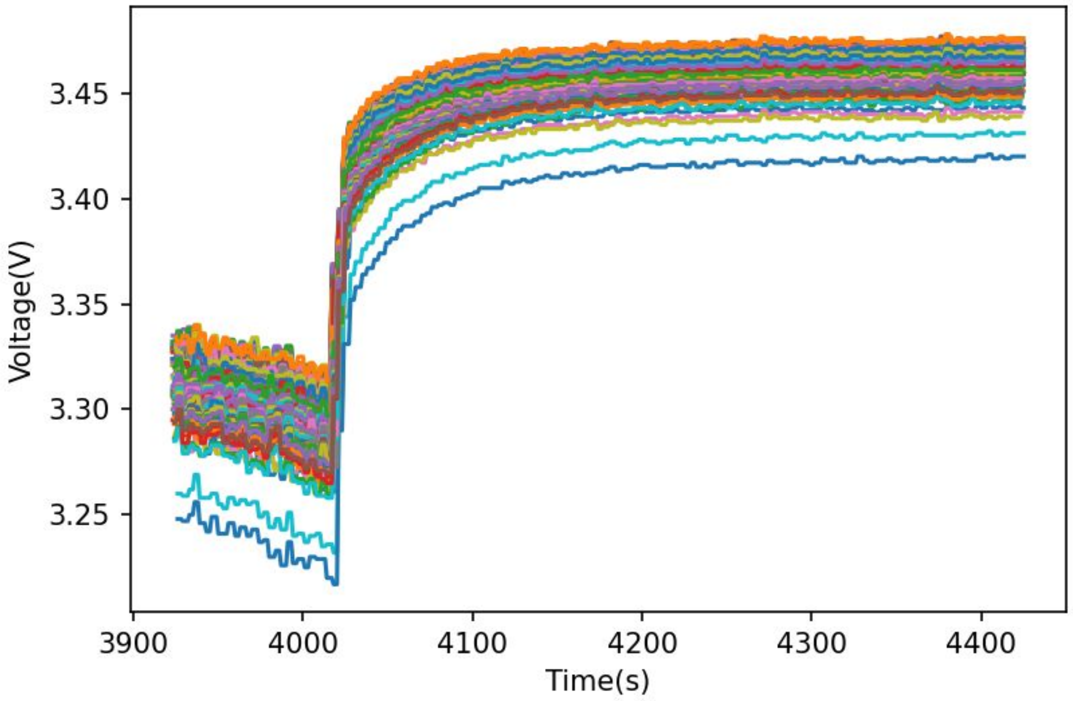


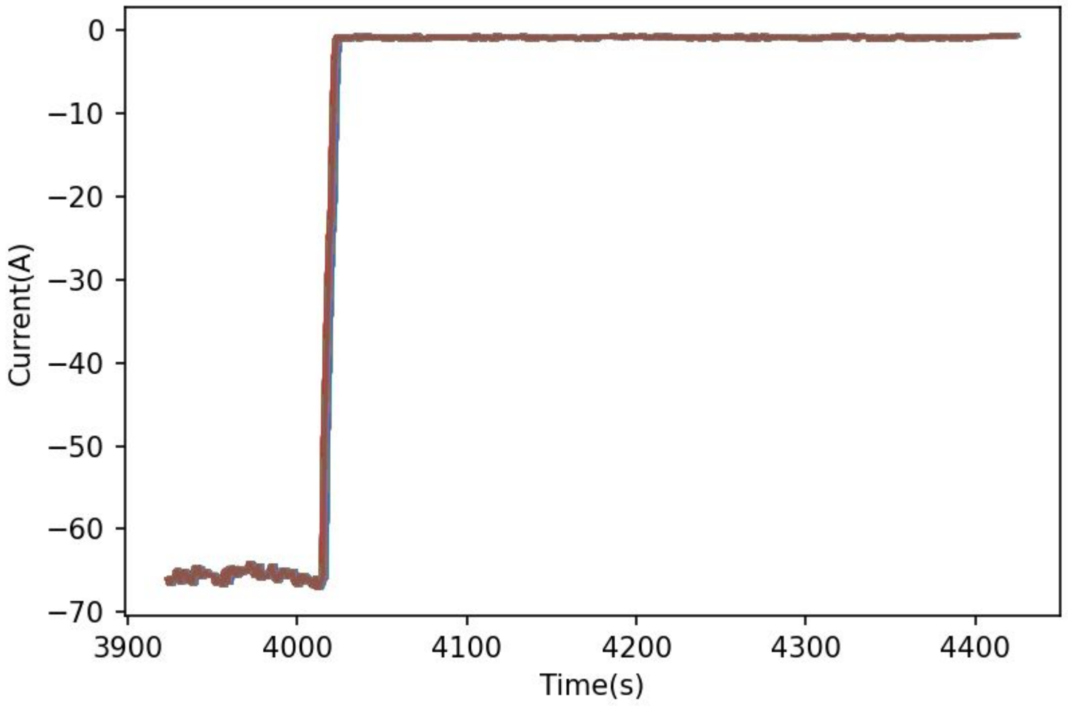
Voltage Profile MFG 1

Defining Weak Cells

Low OCV at the end of flight indicates broken bond wires or imbalanced cell blocks (inter alia)

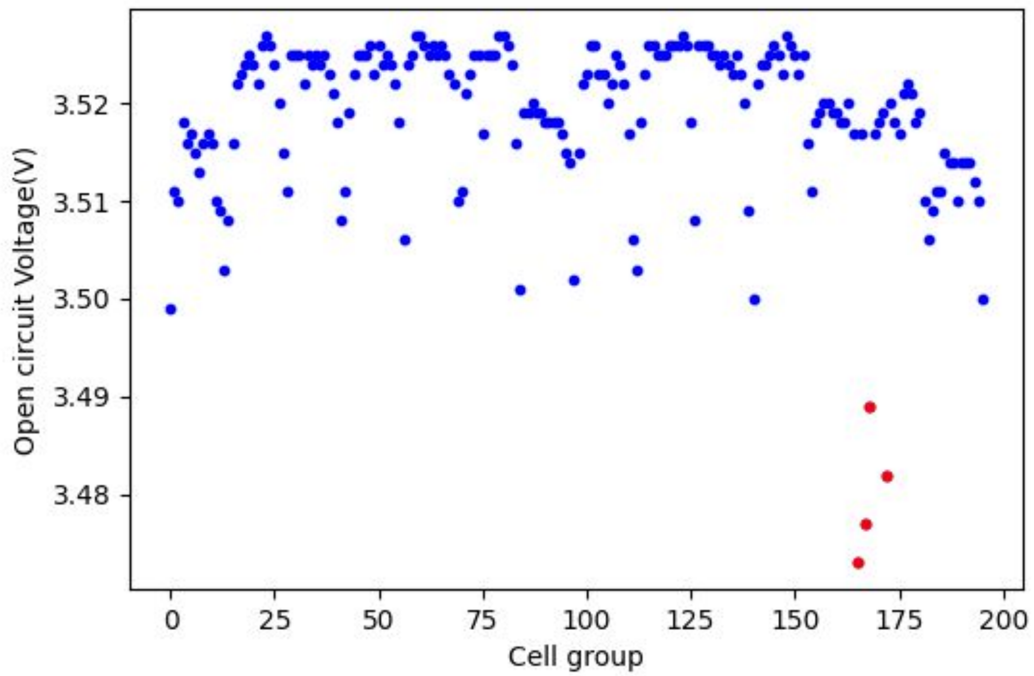
Cells with the lowest open circuit voltage at the end of the flight test are weak cells in a pack

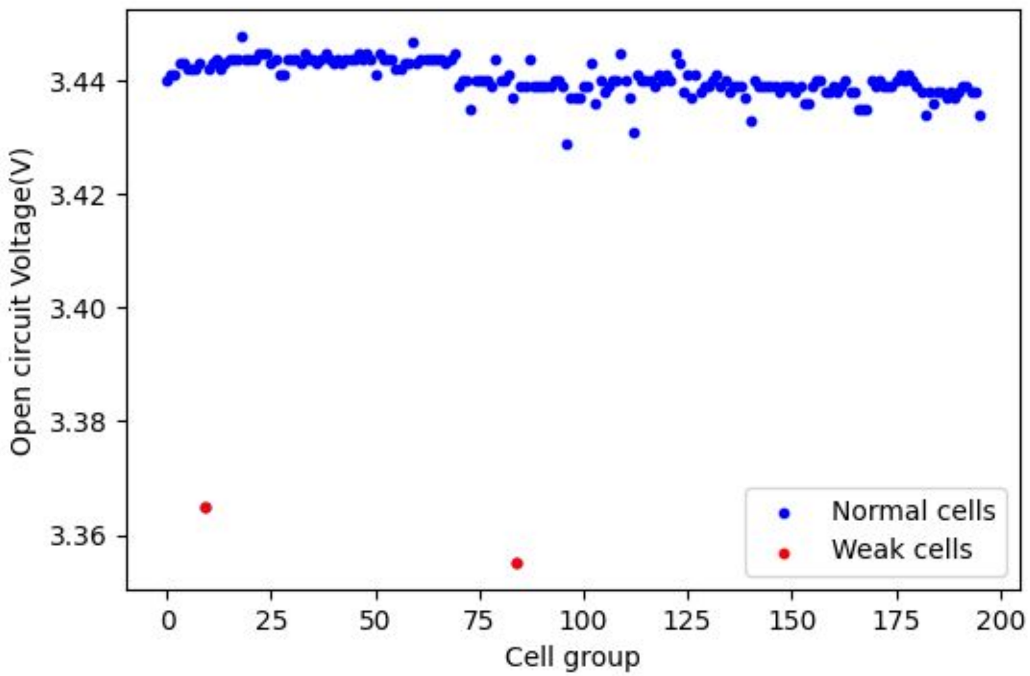




Outlier Detection

The open circuit voltage for weak cells is **noticeably lesser than the median value** and thus they can be considered as outliers





Feature Engineering

Two features produced the most accurate results for 300s of input data

1 Maximum Voltage

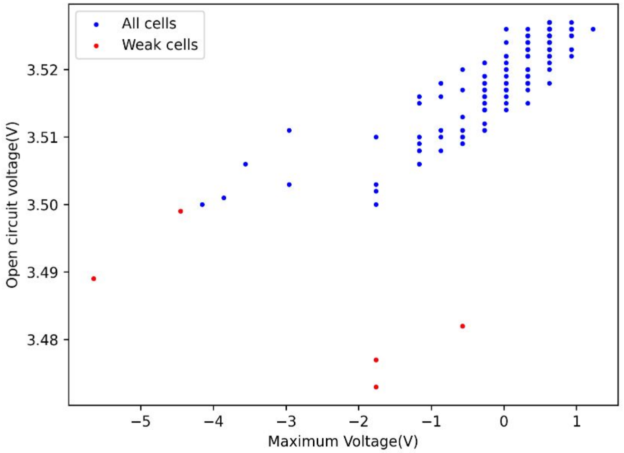
The (standardized) maximum voltage for each cell group in a pack.

2 Voltage Integral

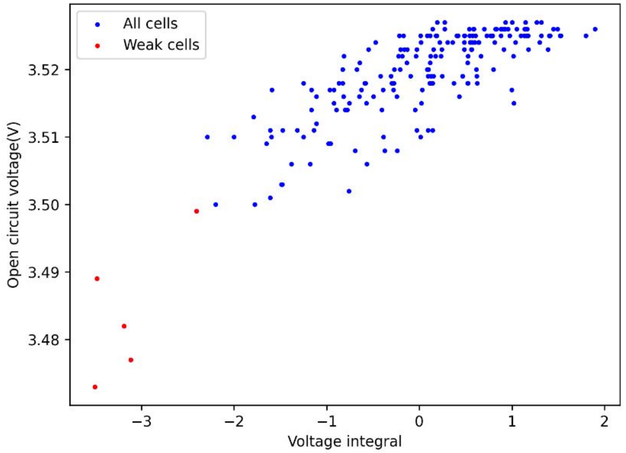
(Standardized) Trapezoidal integral of voltage for each cell group in a pack.

MFG 1

Maximum Voltage

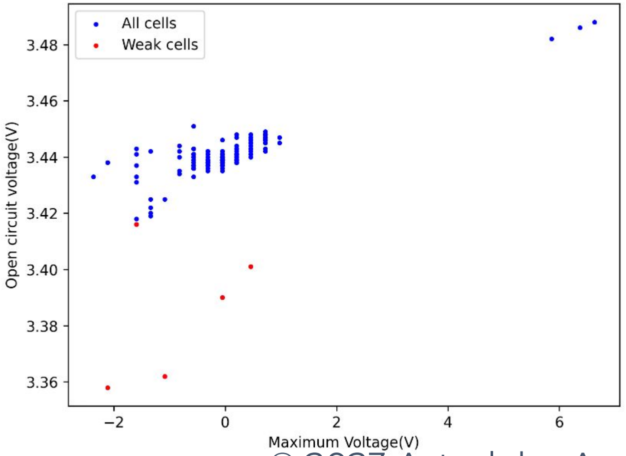


Voltage Integral

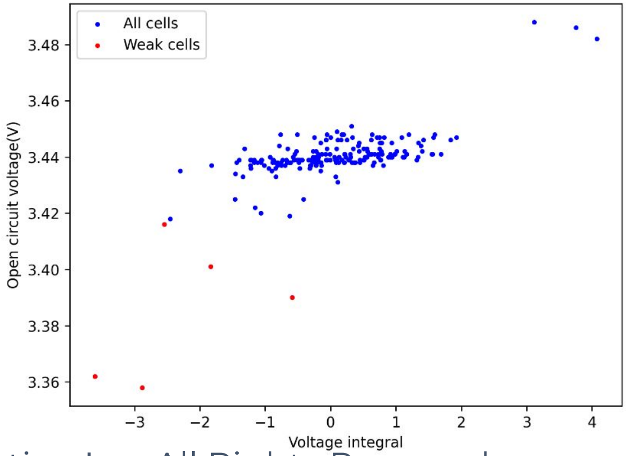


MFG 2

Maximum Voltage



Voltage Integral



Feature Engineering

The features were standardized by removing the mean and scaling to unit variance.

The standard score (z) of a sample (x) is calculated as shown right, where μ is the mean of the training samples and σ is the standard deviation of the training samples.

$$z = \frac{x - \mu}{\sigma}$$

$\mu =$ Mean

$\sigma =$ Standard Deviation

Local Outlier Factor

Local Outlier Factor is a **density-based** outlier detection algorithm. The following parameters were used to detect the weak cells:

1 **n_neighbors: 35**

Finds the n nearest neighbors of a point and returns the distance to each point (Nearest neighbor search)

2 **contamination: 0.15**

The amount of contamination of the data set, i.e., the proportion of outliers in the data set. When fitting this is used to define the threshold on the scores of the samples.

Local Outlier Factor

Local Outlier Factor is a **density-based** outlier detection algorithm. The following parameters were used to detect the weak cells:

3 **p: 1**

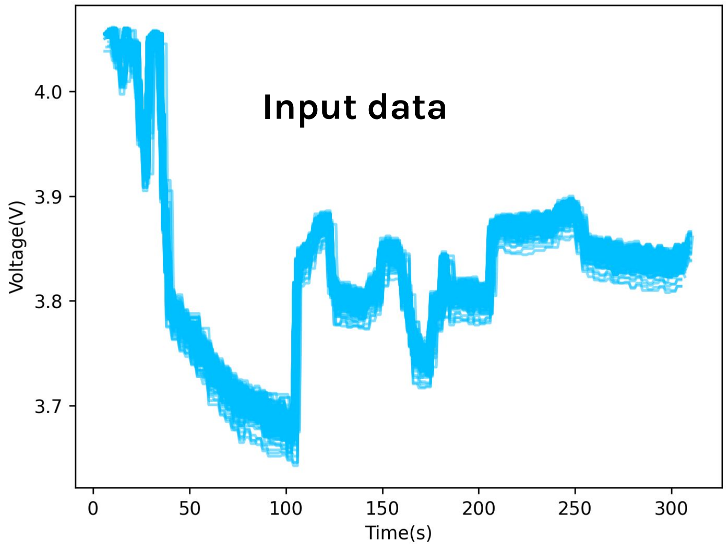
Parameter for the metric used to calculate distance, p=1 is equivalent to using the Manhattan distance, that is the distance between two points measured along axes at right angles.
In a plane with point p1 at (x1, y1) and point p2 at (x2, y2), it is |x1 - x2| + |y1 - y2|

4 **Algorithm: ‘brute’**

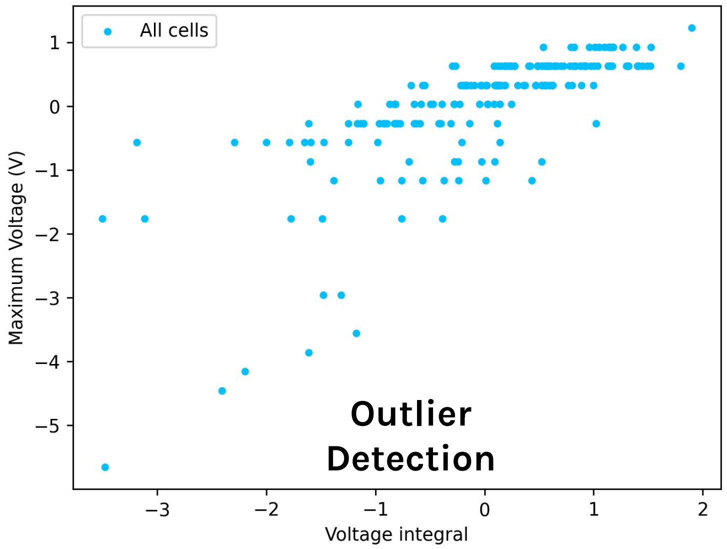
Algorithm used to compute the nearest neighbors. It is usually used for low dimensional data.

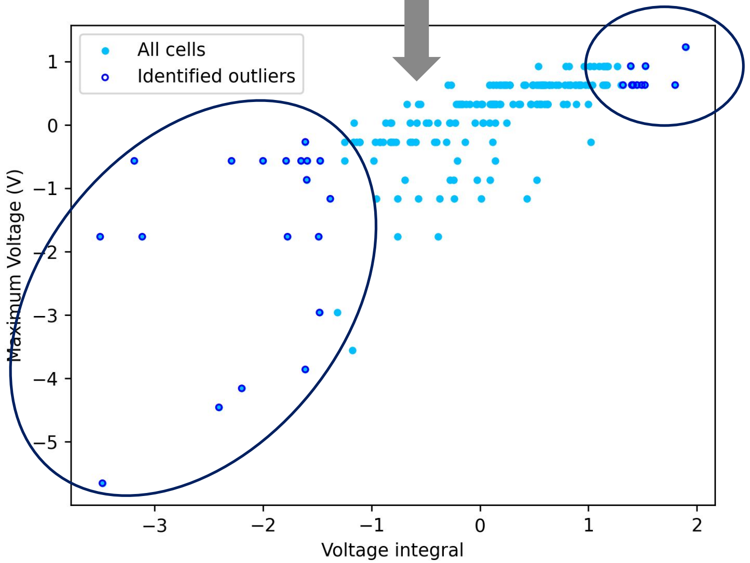
Features used: The feature ‘Voltage integral’ was used as x-axis data and ‘Minimum voltage’ was used as y-axis data.

Algorithm Demonstration

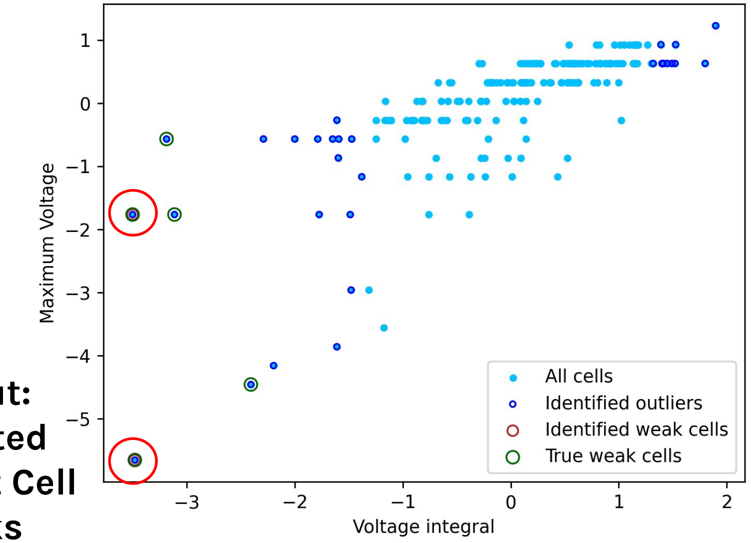


Feature Engineering





Filtering the outliers



Output: Predicted Weakest Cell Blocks

Repeatability

Same 3 packs tested 27 times for Manufacturer 2

ID's weak cells with 85% accuracy

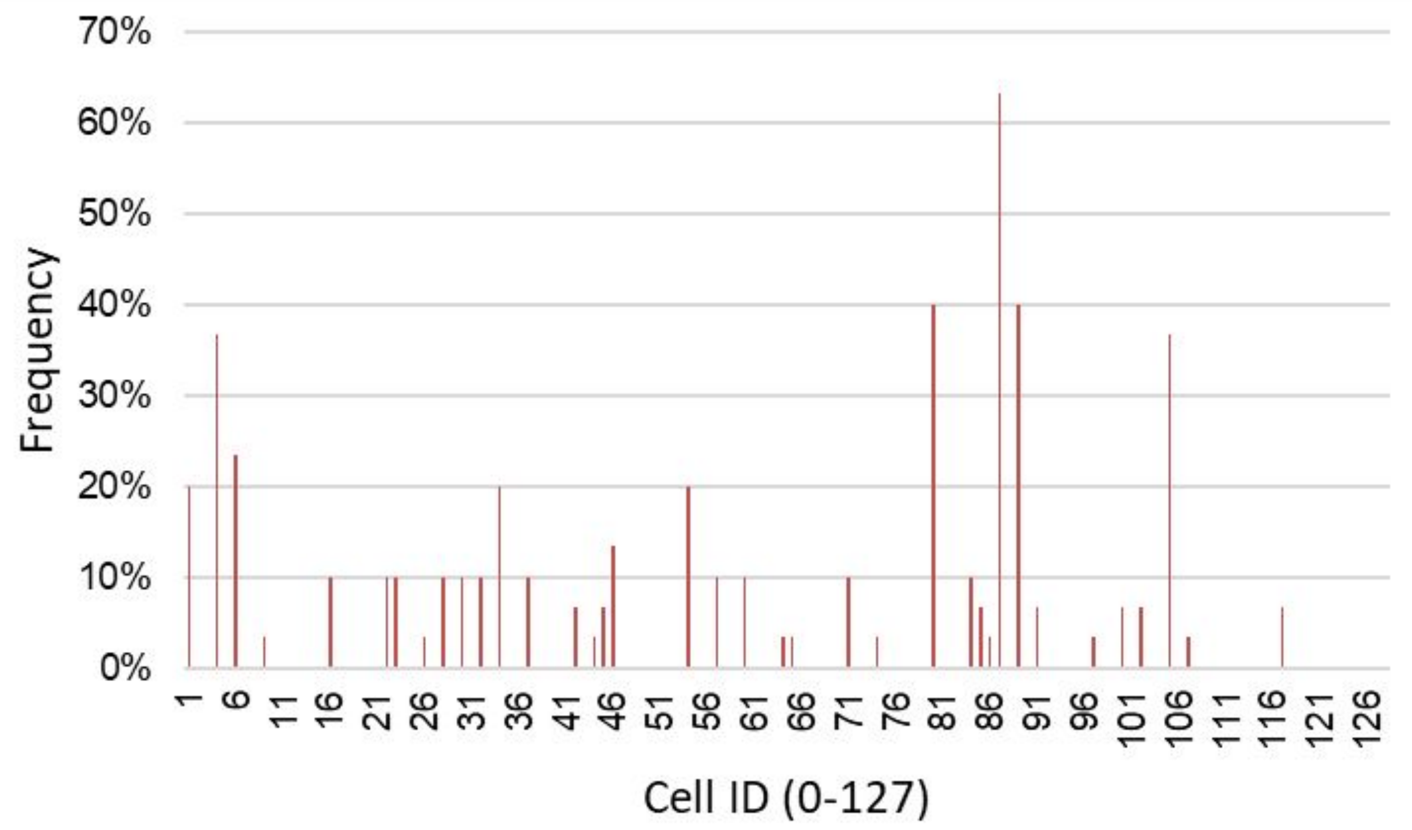
Pack type	Number of battery packs	Correct results	Incorrect results	Percent Error
Mfg 2	81	69	12	14.8%

Weak Cells are Not Randomly Distributed

30 Tests from Pack 1 from Mfg 2

Considering 5 cells with the lowest final voltage for each test:

- 1 cell appears 63% of the time
- 4 other cells appear >30% of the time
- 91 cells never among 5 weakest cells



Reproducibility

Algorithm achieves >85% accuracy with both manufacturers

Pack type	Number of tests	Correct results	Incorrect results	Percent Error
Mfg 1	53	46	7	13.2%
Mfg 2	81	69	12	14.8%
Total:	**134**	**115**	**19**	**14.1%**

Error Analysis

3 categories of errors

Reasoning

The two cell groups with the lowest voltage integral in the outliers are picked as weak cell groups while that is not always the case.

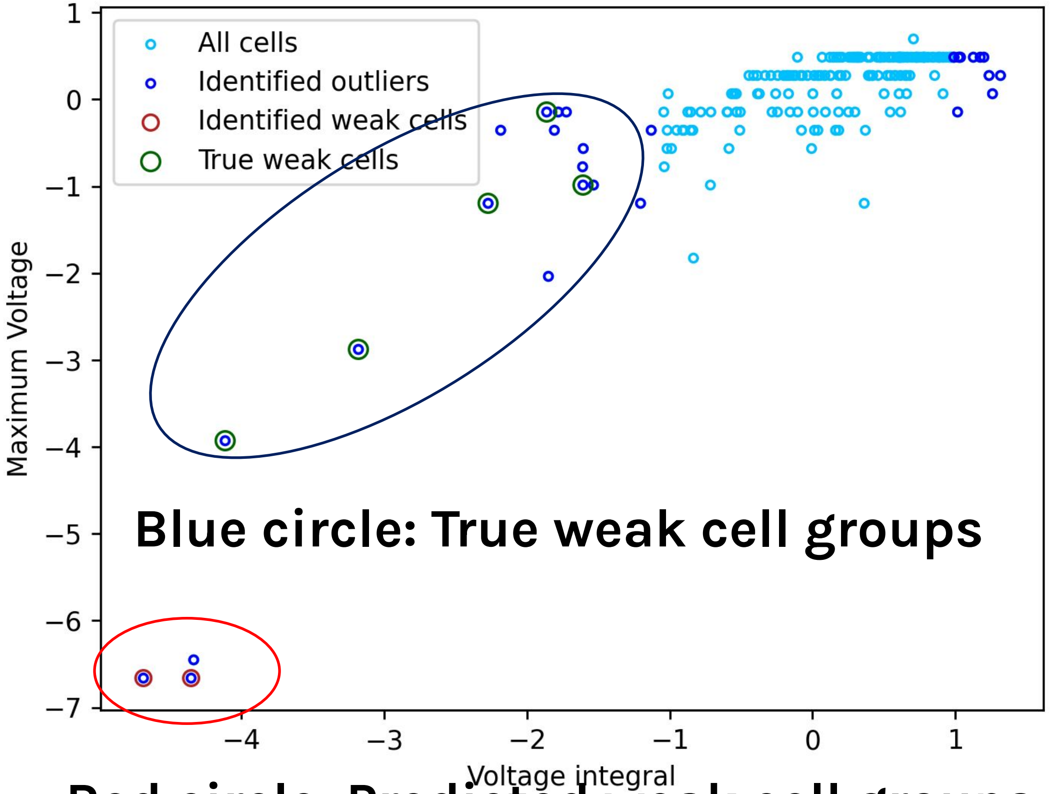
Future Work

What is the optimal set of features and data required to maximize accuracy?

Category 1

Empirical errors in engineered features

5 of 19 total errors



Red circle: Predicted weak cell groups

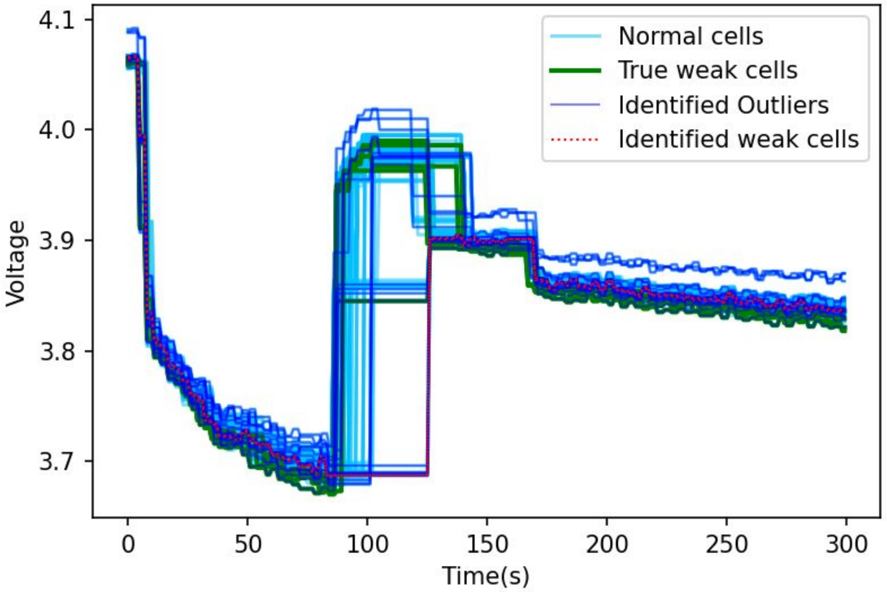
Error Analysis

3 categories of errors

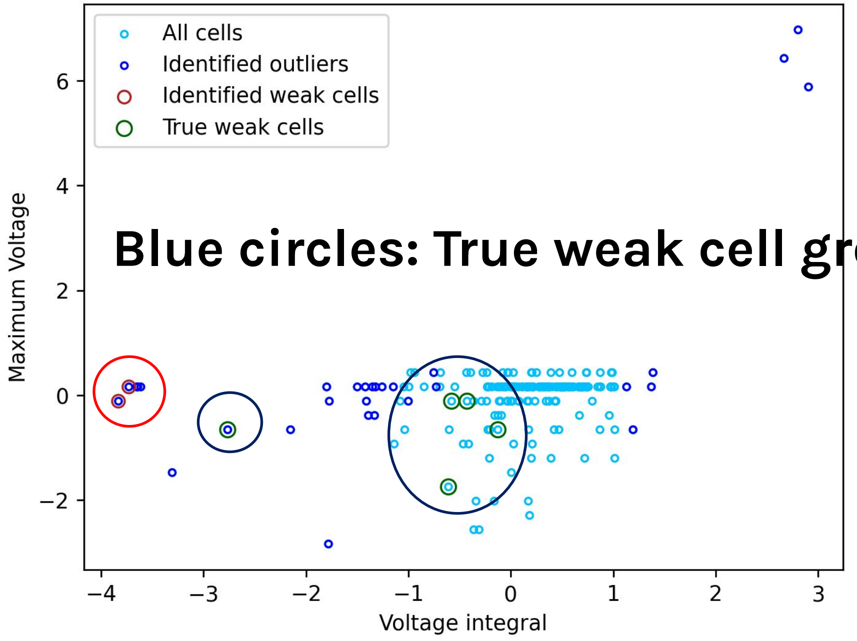
Category 2

Time lag in data logging

3 of 7 errors from Mfg 1



Offset in data logging **throws off calculation** of voltage integral



Blue circles: True weak cell groups

Red circle: Predicted weak cell groups

Error Analysis

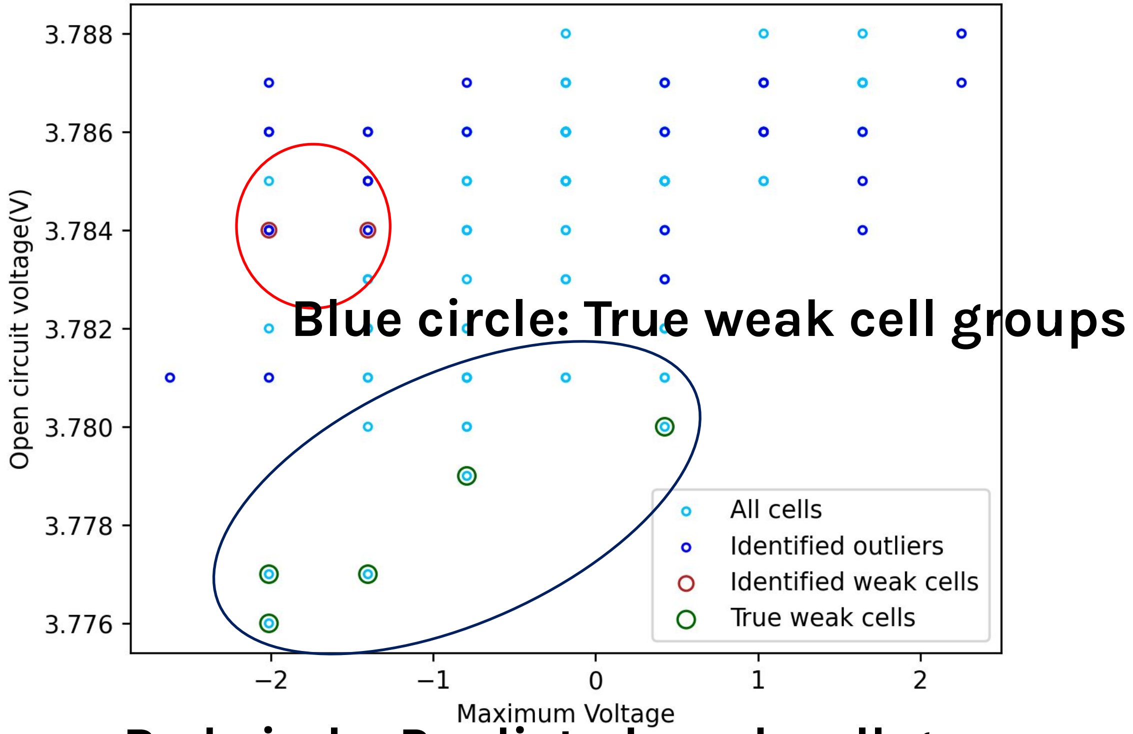
3 categories of errors

Only 12mV delta between highest and lowest cell blocks

Category 3

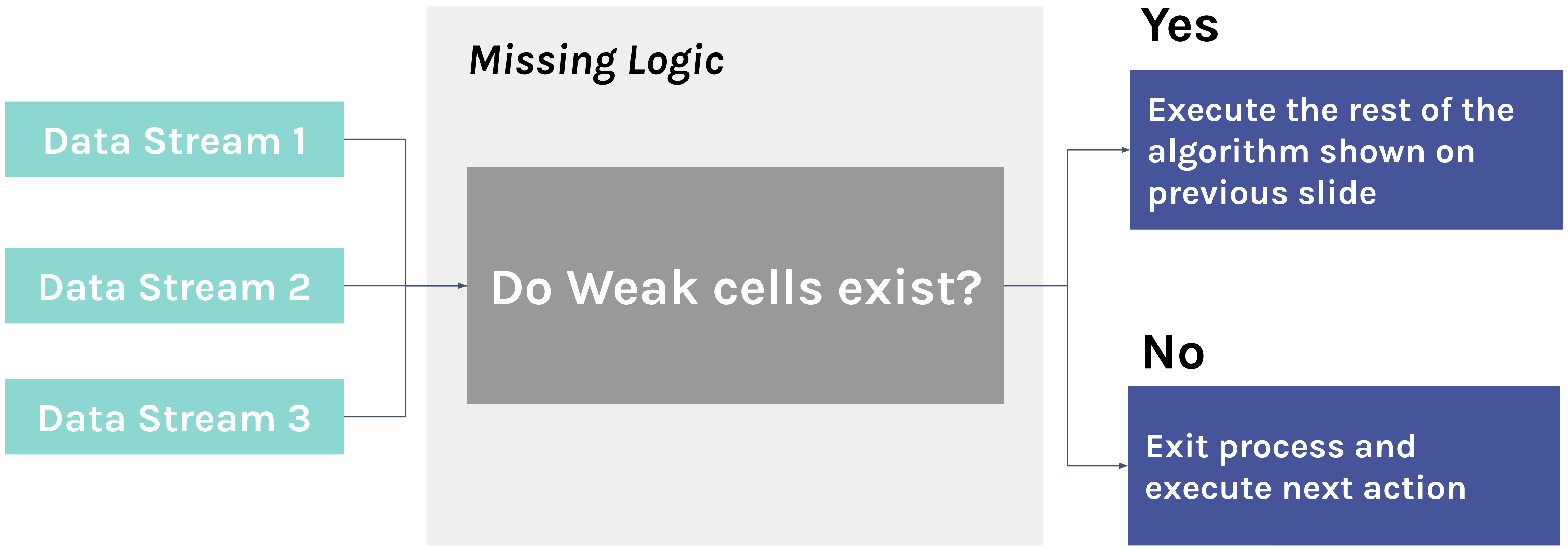
Narrow delta between high and low voltage cells

10 of 19 total errors



Red circle: Predicted weak cell groups

Logic to be added



Reproducibility

Accuracy improves to <5% error after excluding hardware and including added logic

Pack type	Number of tests	Correct results	Hardware Error	No Weak Cells	Algorithm Empirical Error	Percent Error
Mfg 1	53	46	3	2	2	3.8%
Mfg 2	81	69	0	8	4	4.9%
Total:	134	115	3	10	6	4.4%

Features Considered

Voltage features most correlated to final voltage

V_{max}:
$R^2 \sim 0.59$

Voltage integral
(related to V_{avg}):
$R^2 \sim 0.51$

V_{min}:
$R^2 \sim 0.48$

Other features had no or low correlation

Temperature:
$R^2 \sim 0.01$

Resistance:
$R^2 \sim 0.13$

Takeaways

1. Simple features derived from voltage data at the beginning of the flight can be used to identify weak cells.
2. 6x faster than status quo (5 min vs 30 min)
3. Algorithm is 85% accurate using data from 2 different battery packs
4. Can be improved to +95% accuracy after additional error handling logic implemented

Future Work

Answer

What is so special about these features?

Find

Features with maximum predictive power for Minimum timeframe

What is minimum dataset needed, or acceptable tradeoff between speed and accuracy?

Integrate

Embed onto real-time operating system (RTOS) for operational testing

Opportunities

Let's team on proposals or help build your next aerospace battery

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Questions?

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