SEAMLESS ATE TEST PROGRAM GENERATION USING A ML APPROACH - MULTI-LABEL CLASSIFICATION

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Agenda

- Post Silicon Validation: Test program development overview
- Challenges in market
- Proposed Test Program Generation
- ML Approach - Multi label classification
- Results and Conclusion

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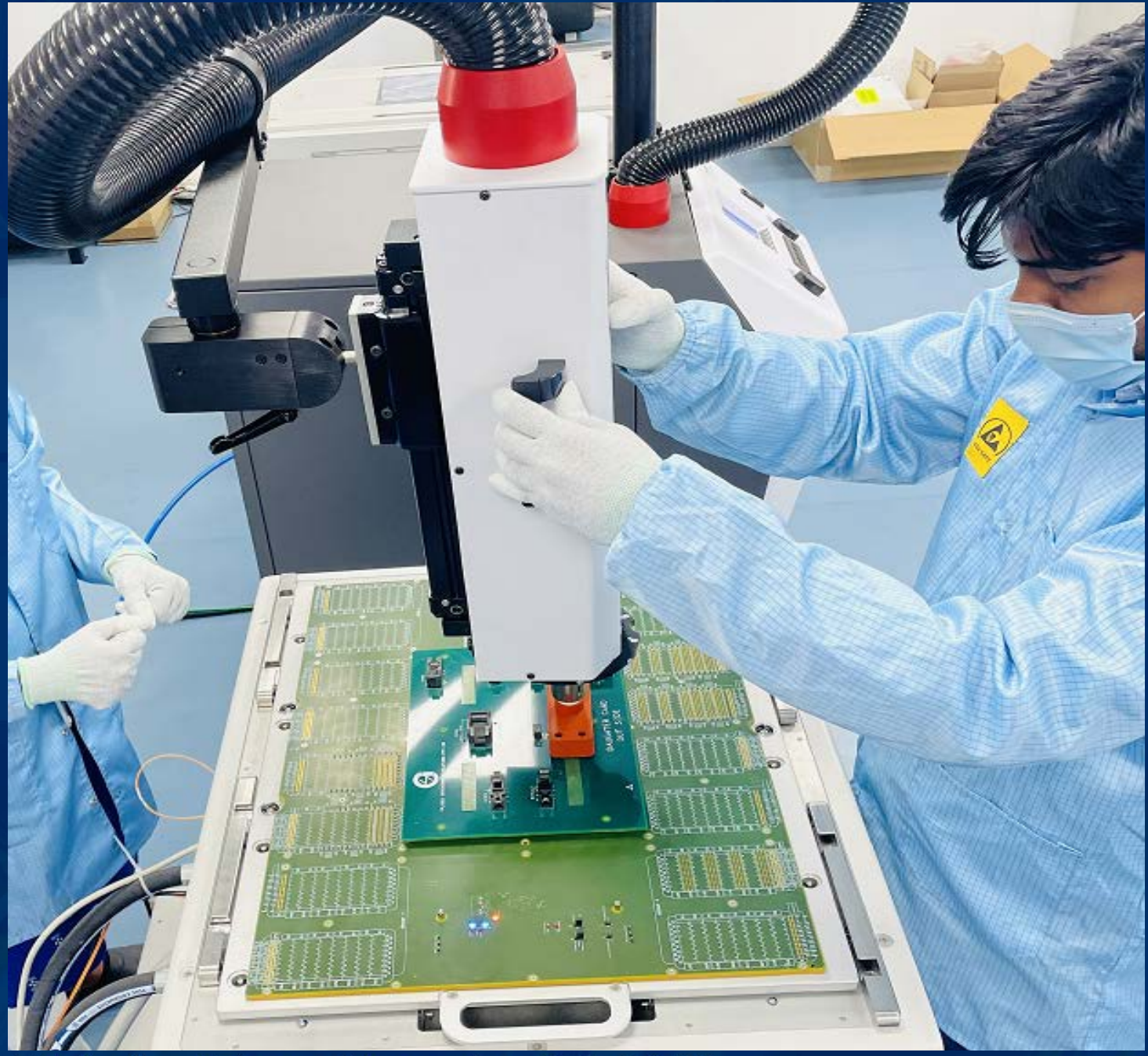
Post Silicon Validation Overview



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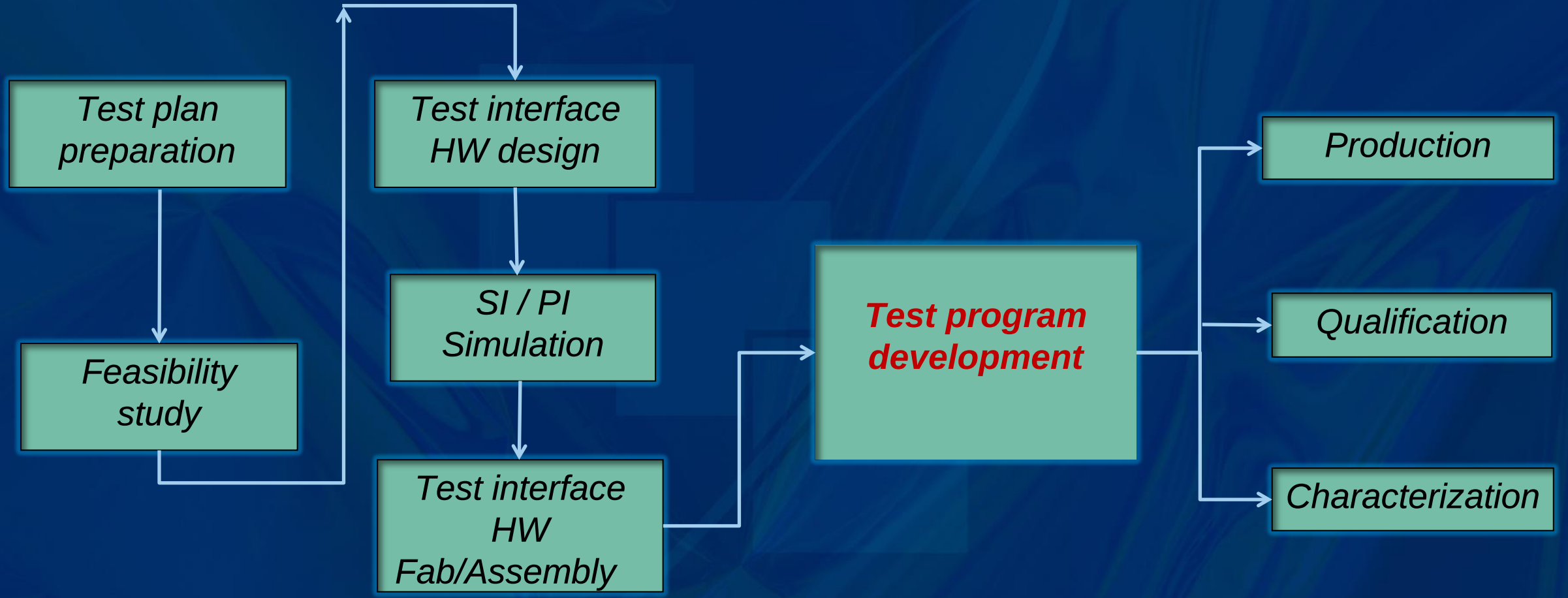
Post Silicon Validation Process



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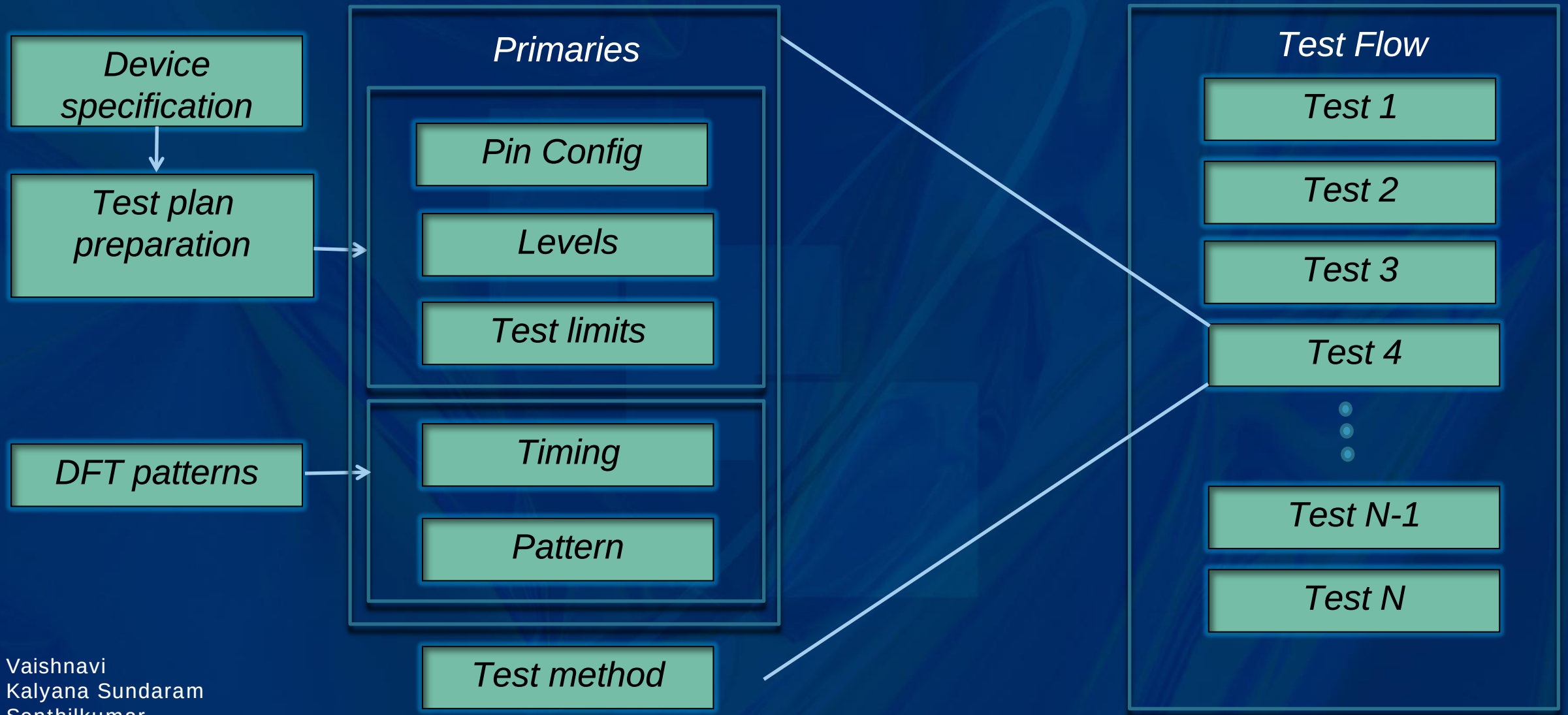
Conventional Test Program Generation



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Challenges in Market

Meeting the demands of intricate IC designs and faster time-to-market necessitates swift, and accurate test plan preparation followed by a production worthy test program development with a huge intervention of test engineer.

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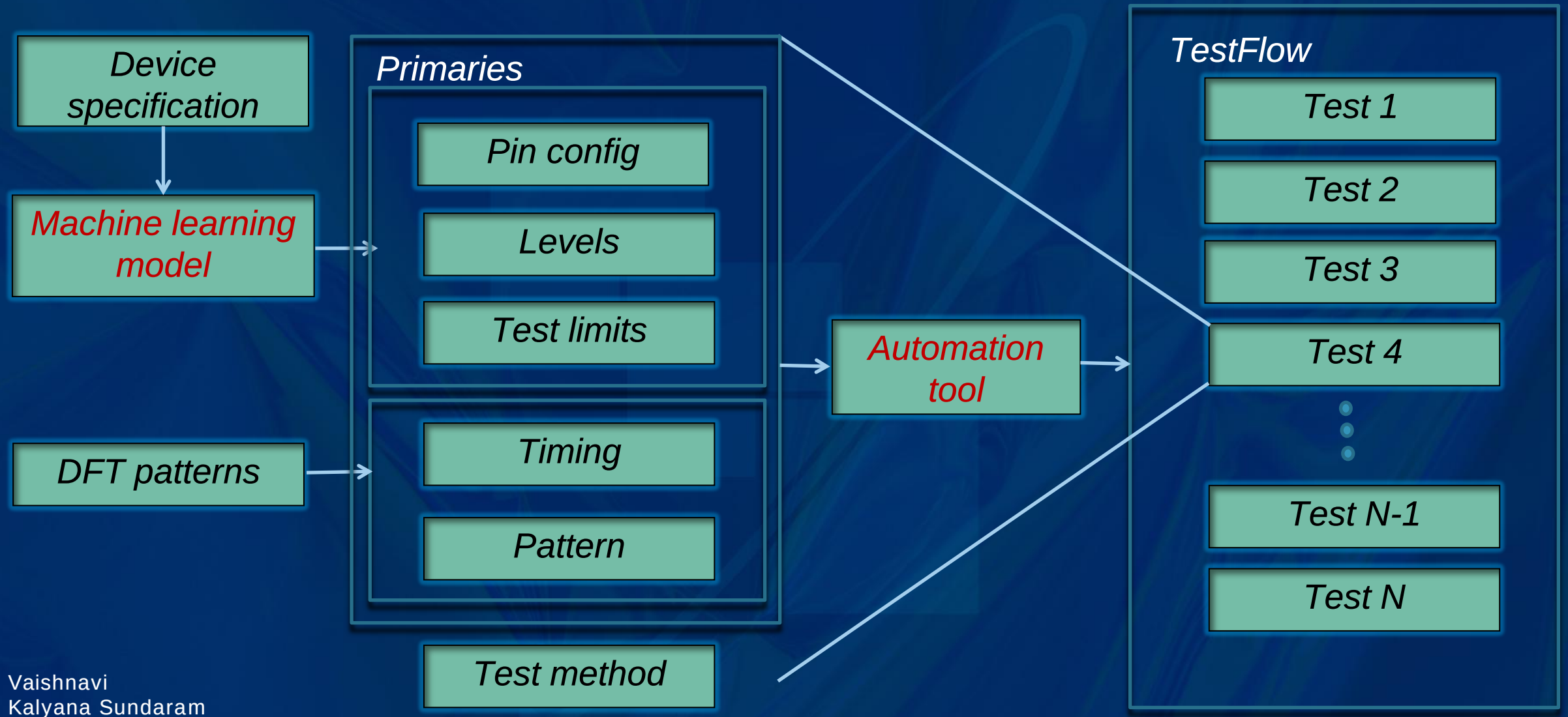
Proposed Solution



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TestGeni- Test Automation IP

- **Automation tool Introduced by Caliber**
- **To generate readily loadable Test files**
  - Pin Config
  - Levels
  - TestFlow
  - Test Limits

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Illustration-Device 1

10. Operating Ranges (Note)

Characteristics	Symbol	Test Condition	Rating	Unit
Supply voltage	V_{CC}		2.0 to 5.5	V
Input voltage	V_{IN}		0 to 5.5	V
Output voltage	V_{OUT}		0 to V_{CC}	V
Operating temperature	T_{opr}		-40 to 125	°C
Input rise and fall times	dt/dv	V_{CC} = 3.3 ± 0.3 V	0 to 100	ns/V
		V_{CC} = 5.0 ± 0.5 V	0 to 20	

Note: The operating ranges must be maintained to ensure the normal operation of the device.
Unused inputs must be tied to either V_{CC} or GND.

11.1. DC Characteristics (Unless otherwise specified, T_a = 25 °C)

Characteristics	Symbol	Test Condition		V_{CC} (V)	Min	Typ	Max	Unit
High-level input voltage	V_{IH}	—		2.0	1.50	—	—	V
				3.0 to 5.5	V_{CC} × 0.7	—	—	
Low-level input voltage	V_{IL}	—		2.0	—	—	0.50	V
				3.0 to 5.5	—	—	V_{CC} × 0.3	
High-level output voltage	V_{OH}	V_{IN} = V_{IH} or V_{IL}	I_{OH} = -50 μA	2.0	1.9	2.0	—	V
				3.0	2.9	3.0	—	
				4.5	4.4	4.5	—	
			I_{OH} = -4 mA	3.0	2.58	—	—	
			I_{OH} = -8 mA	4.5	3.94	—	—	
Low-level output voltage	V_{OL}	V_{IN} = V_{IH} or V_{IL}	I_{OL} = 50 μA	2.0	—	0.0	0.1	V
				3.0	—	0.0	0.1	
				4.5	—	0.0	0.1	
			I_{OL} = 4 mA	3.0	—	—	0.36	
			I_{OL} = 8 mA	4.5	—	—	0.36	
3-state output OFF-state leakage current	I_{OZ}	V_{IN} = V_{IH} or V_{IL} V_{OUT} = V_{CC} or GND		5.5	—	—	±0.25	μA
Input leakage current	I_{IN}	V_{IN} = 5.5 V or GND		0 to 5.5	—	—	±0.1	μA
Quiescent supply current	I_{CC}	V_{IN} = V_{CC} or GND		5.5	—	—	4.0	μA

Test 1

Sample Parameter - Test Setup
Test parameter: VOH
Test method: spec search
VCC=2V
VIL=0.50V
VIH=1.50V
IOL=50uA
IOH=-50uA
VOL=0.1V
Maxlimit= 2V
Minlimit=1.9V
startValue:1.5V
StopValue=2.5V
Step size= 0.01V
Temp=25degC

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Illustration-Device 1

10. Operating Ranges (Note)

Characteristics	Symbol	Test Condition	Rating	Unit
Supply voltage	V_{CC}		2.0 to 5.5	V
Input voltage	V_{IN}		0 to 5.5	V
Output voltage	V_{OUT}		0 to V_{CC}	V
Operating temperature	T_{opr}		-40 to 125	°C
Input rise and fall times	dt/dv	V_{CC} = 3.3 ± 0.3 V	0 to 100	ns/V
		V_{CC} = 5.0 ± 0.5 V	0 to 20	

Note: The operating ranges must be maintained to ensure the normal operation of the device.
Unused inputs must be tied to either V_{CC} or GND.

11.1. DC Characteristics (Unless otherwise specified, T_a = 25 °C)

Characteristics	Symbol	Test Condition		V_{CC} (V)	Min	Typ	Max	Unit
High-level input voltage	V_{IH}	—		2.0	1.50	—	—	V
				3.0 to 5.5	V_{CC} × 0.7	—	—	
Low-level input voltage	V_{IL}	—		2.0	—	—	0.50	V
				3.0 to 5.5	—	—	V_{CC} × 0.3	
High-level output voltage	V_{OH}	V_{IN} = V_{IH} or V_{IL}	I_{OH} = -50 μA	2.0	1.9	2.0	—	V
				3.0	2.9	3.0	—	
				4.5	4.4	4.5	—	
			I_{OH} = -4 mA	3.0	2.58	—	—	
			I_{OH} = -8 mA	4.5	3.94	—	—	
Low-level output voltage	V_{OL}	V_{IN} = V_{IH} or V_{IL}	I_{OL} = 50 μA	2.0	—	0.0	0.1	V
				3.0	—	0.0	0.1	
				4.5	—	0.0	0.1	
			I_{OL} = 4 mA	3.0	—	—	0.36	
			I_{OL} = 8 mA	4.5	—	—	0.36	
3-state output OFF-state leakage current	I_{OZ}	V_{IN} = V_{IH} or V_{IL} V_{OUT} = V_{CC} or GND		5.5	—	—	±0.25	μA
Input leakage current	I_{IN}	V_{IN} = 5.5 V or GND		0 to 5.5	—	—	±0.1	μA
Quiescent supply current	I_{CC}	V_{IN} = V_{CC} or GND		5.5	—	—	4.0	μA

Test 1:
Test parameter: VOH
Test method: spec search
VCC=2V
VIL=0.50V
VIH=1.50V
IOL=50uA
IOH=-50uA
VOL=0.1V
Maxlimit= 2V
Minlimit=1.9V
startValue:1.5V
StopValue=2.5V
Step size= 0.01V
Temp=25degC

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Illustration-Device 1

10. Operating Ranges (Note)

Characteristics	Symbol	Test Condition	Rating	Unit
Supply voltage	V_{CC}		2.0 to 5.5	V
Input voltage	V_{IN}		0 to 5.5	V
Output voltage	V_{OUT}		0 to V_{CC}	V
Operating temperature	T_{opr}		-40 to 125	°C
Input rise and fall times	dt/dv	V_{CC} = 3.3 ± 0.3 V	0 to 100	ns/V
		V_{CC} = 5.0 ± 0.5 V	0 to 20	

Note: The operating ranges must be maintained to ensure the normal operation of the device.
Unused inputs must be tied to either V_{CC} or GND.

11.1. DC Characteristics (Unless otherwise specified, T_a = 25 °C)

Characteristics	Symbol	Test Condition		V_{CC} (V)	Min	Typ	Max	Unit
High-level input voltage	V_{IH}	—		2.0	1.50	—	—	V
				3.0 to 5.5	V_{CC} × 0.7	—	—	
Low-level input voltage	V_{IL}	—		2.0	—	—	0.50	V
				3.0 to 5.5	—	—	V_{CC} × 0.3	
High-level output voltage	V_{OH}	V_{IN} = V_{IH} or V_{IL}	I_{OH} = -50 μA	2.0	1.9	2.0	—	V
				3.0	2.9	3.0	—	
				4.5	4.4	4.5	—	
			I_{OH} = -4 mA	3.0	2.58	—	—	
			I_{OH} = -8 mA	4.5	3.94	—	—	
Low-level output voltage	V_{OL}	V_{IN} = V_{IH} or V_{IL}	I_{OL} = 50 μA	2.0	—	0.0	0.1	V
				3.0	—	0.0	0.1	
				4.5	—	0.0	0.1	
			I_{OL} = 4 mA	3.0	—	—	0.36	
			I_{OL} = 8 mA	4.5	—	—	0.36	
3-state output OFF-state leakage current	I_{OZ}	V_{IN} = V_{IH} or V_{IL} V_{OUT} = V_{CC} or GND		5.5	—	—	±0.25	μA
Input leakage current	I_{IN}	V_{IN} = 5.5 V or GND		0 to 5.5	—	—	±0.1	μA
Quiescent supply current	I_{CC}	V_{IN} = V_{CC} or GND		5.5	—	—	4.0	μA

Sample Parameter - Test Setup

Test 1:

Test parameter: VOH

Test method: spec search

VCC=2V

VIL=0.50V

VIH=1.50V

IOL=50uA

IOH=-50uA

VOL=0.1V

Maxlimit= 2V

Minlimit=1.9V

startValue:1.5V

StopValue=2.5V

Step size= 0.01V

Temp=25degC

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Illustration - Device 2

10. Operating Ranges (Note)

Characteristics	Symbol	Note	Rating	Unit
Supply voltage	V_{CC}		4.5 to 5.5	V
Input voltage	V_{IN}		0 to 5.5	V
Output voltage	V_{OUT}	(Note 1)	0 to 5.5	V
		(Note 2)	0 to V_{CC}	
Operating temperature	T_{opr}		-40 to 125	°C
Input rise and fall times	dt/dv		0 to 20	ns/V

11.1. DC Characteristics (Unless otherwise specified, T_a = 25 °C)

Characteristics	Symbol	Test Condition		V_{CC} (V)	Min	Typ.	Max	Unit
High-level input voltage	V_{IH}	—		4.5 to 5.5	2.0	—	—	V
Low-level input voltage	V_{IL}	—		4.5 to 5.5	—	—	0.8	V
High-level output voltage	V_{OH}	V_{IN} = V_{IH} or V_{IL}	I_{OH} = -50 μA	4.5	4.4	4.5	—	V
			I_{OH} = -8 mA	4.5	3.94	—	—	
Low-level output voltage	V_{OL}	V_{IN} = V_{IH} or V_{IL}	I_{OL} = 50 μA	4.5	—	0.0	0.1	V
			I_{OL} = 8 mA	4.5	—	—	0.36	
3-state output OFF-state leakage current	I_{OZ}	V_{IN} = V_{IH} or V_{IL} V_{OUT} = V_{CC} or GND		5.5	—	—	±0.25	μA
Input leakage current	I_{IN}	V_{IN} = 5.5 V or GND		0 to 5.5	—	—	±0.1	μA
Quiescent supply current	I_{CC}	V_{IN} = V_{CC} or GND		5.5	—	—	4.0	μA
	I_{CCT}	Per input: V_{IN} = 3.4 V Other input: V_{CC} or GND		5.5	—	—	1.35	mA
Output leakage current (Power-OFF)	I_{OPD}	V_{OUT} = 5.5 V		0	—	—	0.5	μA

Test 1:
Test parameter: VOH
Test method: Spec search
VCC = 4.5V
VIL = 0.50V
VIH = 1.50V
IOL = 50uA
IOH = -50uA
VOL = 0.1V
Max limit = 4.4V
Min limit = 4.5V
Start value = 4V
Stop value = 5V
Step size = 0.01V
Temp = 25degC

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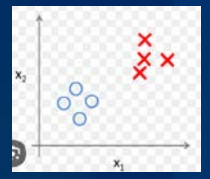
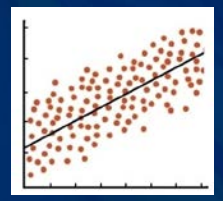
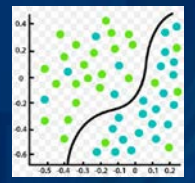
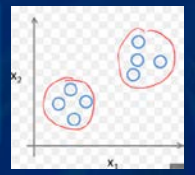
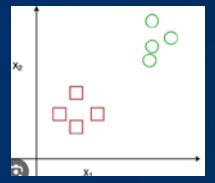
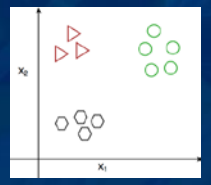
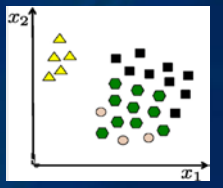
Machine Learning and Proposed Approach

- Machine learning algorithms
  - Supervised learning (labeled data)
    - Regression
    - Classification
      - Binary Classification
      - Multi class Classification
      - Multi label Classification
        - LP,PS,DBPNN,PSt,BCC, CDN,BPNN, RakEL,BRq, etc..
  - Semi supervised learning
  - Unsupervised learning (Unlabeled data)
    - Clustering
    - Dimensionality reduction

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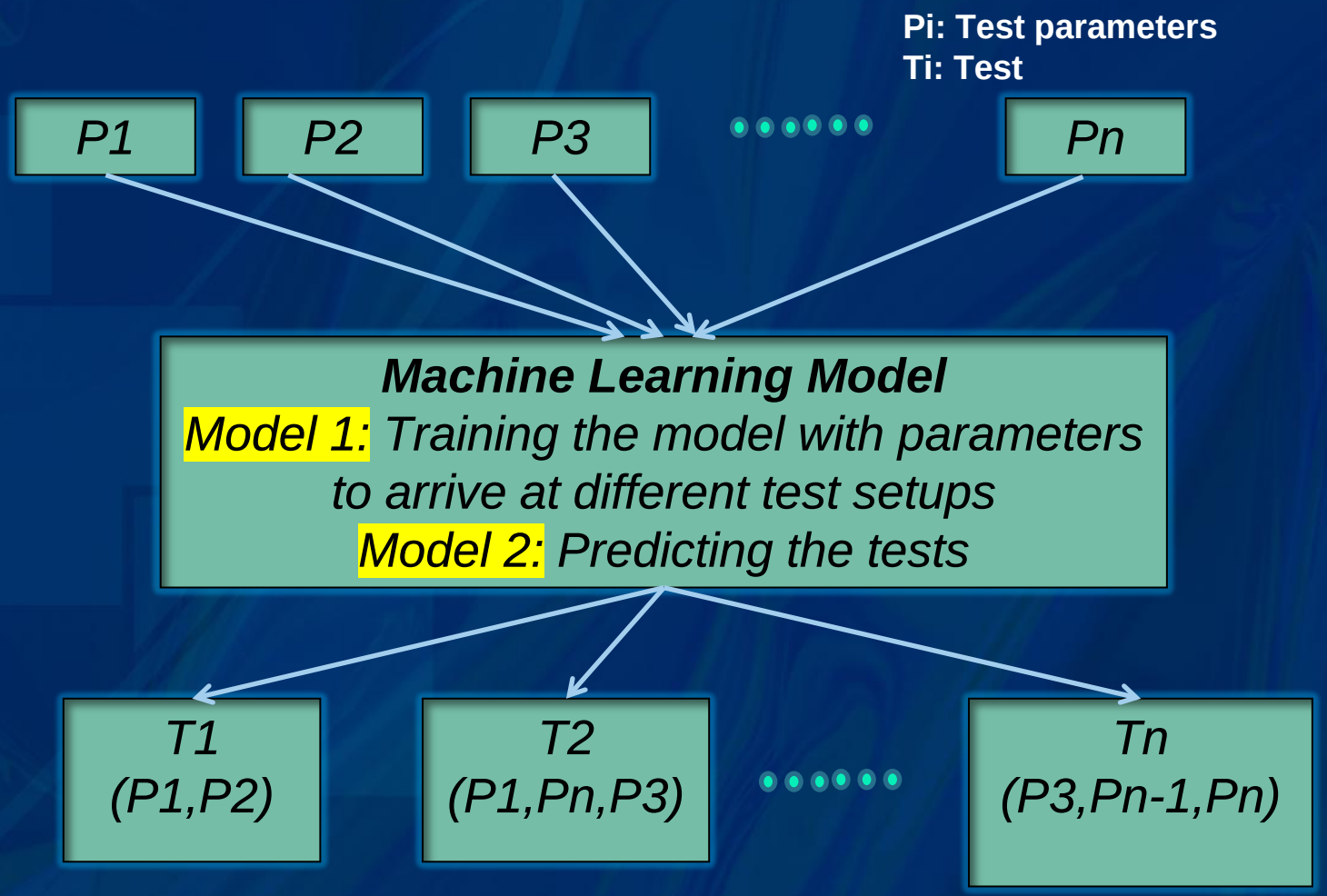
Multi-label Classification Model

Supervised learning method - Multilabel classification:

- Classify data with more than one target variable
- Designed to handle complex tasks where items can belong to multiple categories simultaneously

Ensemble method can give better accuracy



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Machine Learning Model 1

Phase 1:

Feature Engineering:

- Extracting unique features from device specifications
- Creating dictionary with parameters and its levels as “key - value” pair
  - Features extracted - 715
- Reducing overfitting through Principal Component Analysis(PCA) technique
  - Features scaled down - 355
- Zero imputation to make the sparse data as clean data

Phase 2:

- Classify objects using PS: Pruned sets algorithm(Ensemble method)
  - Base classifier:J48
  - Pruning value(pv): It defines an infrequent labelset as one which occurs less than ‘p’ times in the data.{pv ∈ Z | 1 ≤ pv ≤ 5}.
  - Subsampling value (sv)[-N] :Subsample value defines the (maximum) number of frequent labelsets to subsample from the infrequent labelsets.

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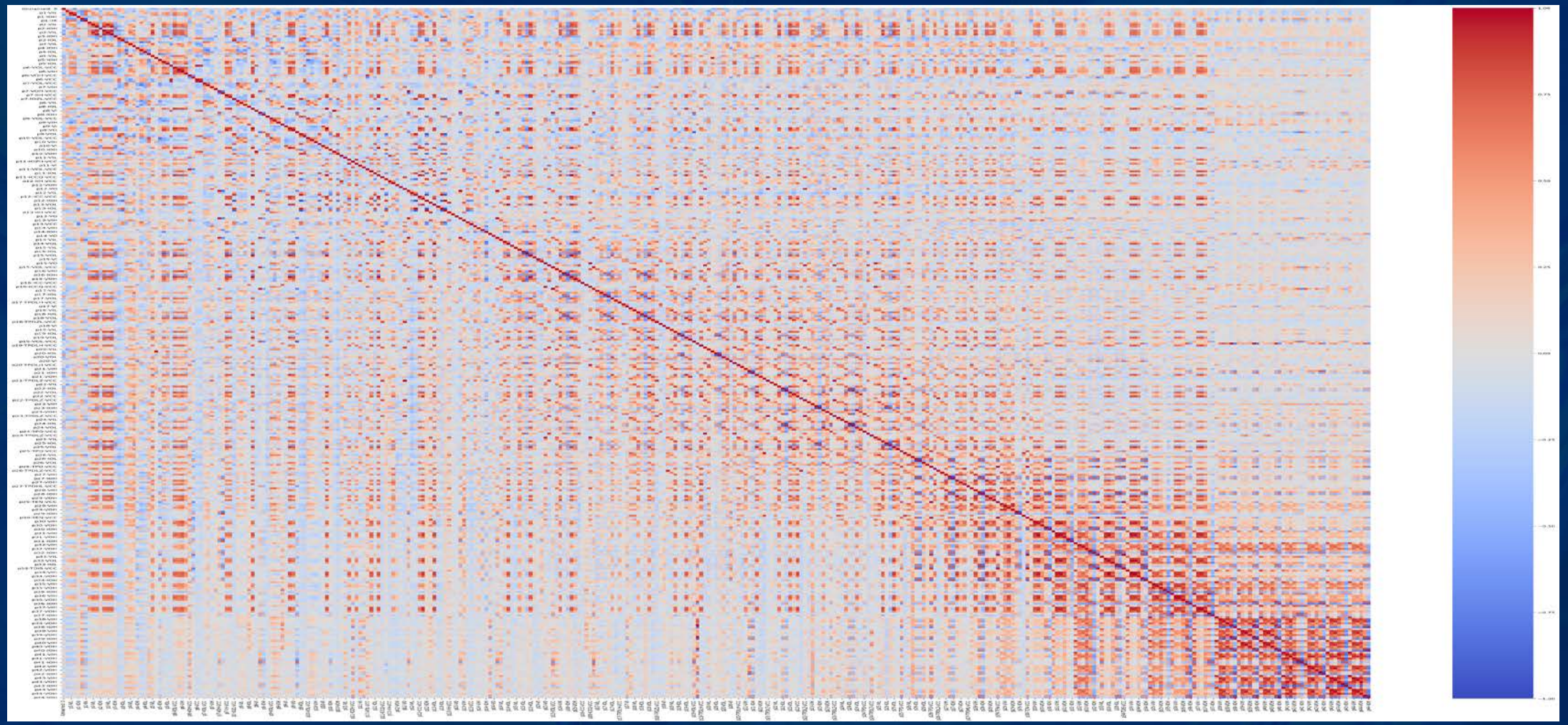
Correlation Analysis of Features



Highly correlated

Least correlated

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Comparative Model Evaluation

Sl.No	Algorithm	Accuracy(%)	Jaccard index	Hamming score	Avg precision
1	PS(Pruned Sets)	62.9	0.371	0.014	0.876
2	RakEL (Random K-Label Pruned Sets)	56	0.44	0.985	0.594
3	DBPNN (Back Propagation Neural Networks)	41.7	0.583	0.981	0.992
4	PSt (Pruned Sets with Threshold)	43	0.43	0.889	0.471

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Resultant Features

	p1-VOH-VCC	p1-VIL	p1-VIH	p1-IOH	p1-VIK-VCC	p1-IIK	p2-VOH-VCC	p2-VIL	p2-VIH	p2-IOH	p3-VOH-VCC	p3-VIL	p3-VIH	p3-IOH	p3-VOL-VCC	p3-IOL	p4-VOH-VCC	p4-VIL	p4-VIH	p4-IOH
0	2.0	0.00	2.00	-20.00	0.0	0.0	4.50	0.0000	4.5000	-20.00	6.0	0.00	6.00	-20.00	0.0	0.00	4.50	0.0000	4.5000	-6.00
1	2.0	0.50	1.50	-0.05	0.0	0.0	3.00	0.9000	2.1000	-0.05	4.5	1.35	3.15	-0.05	0.0	0.00	3.00	0.9000	2.1000	-4.00
2	0.0	1.65	3.85	0.00	0.0	0.0	0.00	0.4950	1.0725	0.00	0.0	0.70	1.70	0.00	2.3	8.00	0.00	0.7000	1.7000	0.00
3	2.0	0.50	1.50	-0.05	0.0	0.0	3.00	0.9000	2.1000	-0.05	4.5	1.65	3.85	-0.05	0.0	0.00	3.00	0.9000	2.1000	-4.00
4	1.8	0.15	1.65	-0.05	0.0	0.0	3.00	0.9000	2.2000	-0.05	4.5	1.35	3.15	-0.05	0.0	0.00	3.00	0.9000	2.2000	-8.00
5	1.8	0.15	1.65	-0.05	0.0	0.0	3.00	0.9000	2.2000	-0.05	4.5	1.35	3.15	-0.05	0.0	0.00	3.00	0.9000	2.2000	-8.00
6	3.6	0.80	2.00	-0.10	0.0	0.0	1.65	0.5775	1.0725	-6.00	2.3	0.70	1.70	-12.00	0.0	0.00	2.30	0.7000	1.7000	-18.00
7	0.0	0.90	2.00	0.00	0.0	0.0	0.00	0.3850	0.7150	0.00	0.0	0.49	0.91	0.00	1.4	1.70	0.00	0.5775	1.0725	0.00
8	5.0	1.50	3.50	-10.00	0.0	0.0	10.00	3.0000	7.0000	-15.00	15.0	4.00	11.00	-20.00	0.0	0.00	0.00	1.5000	3.5000	0.00
9	3.0	0.90	2.10	-12.00	0.0	0.0	4.50	1.3500	3.1500	-24.00	5.5	1.65	3.85	-24.00	0.0	0.00	0.00	0.9000	2.1000	0.00
10	3.0	0.90	2.10	-12.00	0.0	0.0	4.50	1.3500	3.1500	-24.00	5.5	1.65	3.85	-24.00	0.0	0.00	0.00	0.9000	2.1000	0.00
11	3.0	0.90	2.10	-3.60	0.0	0.0	4.50	1.3500	3.1500	-6.00	6.0	1.80	4.20	-7.80	0.0	0.00	0.00	0.9000	2.1000	0.00
12	0.0	0.70	1.70	0.00	0.0	0.0	0.00	0.8000	2.0000	0.00	0.0	0.80	2.00	0.00	3.0	16.00	0.00	0.8000	2.0000	0.00
13	2.7	0.80	2.00	-12.00	0.0	0.0	3.00	0.8000	2.0000	-18.00	3.0	0.80	2.00	-24.00	0.0	0.00	3.60	0.8000	2.0000	-0.10
14	2.0	0.50	1.50	-0.05	0.0	0.0	3.00	0.9000	2.1000	-0.05	4.5	1.35	3.15	-0.05	0.0	0.00	3.00	0.9000	2.1000	-4.00
15	2.0	0.50	1.50	-0.05	0.0	0.0	3.00	0.9000	2.1000	-0.05	4.5	1.35	3.15	-0.05	0.0	0.00	3.00	0.9000	2.1000	-4.00
16	3.0	0.53	1.20	-0.05	0.0	0.0	4.50	0.8000	2.0000	-0.05	3.0	0.53	1.20	-4.00	0.0	0.00	4.50	0.8000	2.0000	-8.00
17	2.0	0.50	1.50	-0.05	0.0	0.0	3.00	0.9000	2.1000	-0.05	4.5	1.35	3.15	-0.05	0.0	0.00	3.00	0.9000	2.1000	-4.00
18	0.0	0.00	0.00	0.00	2.7	-18.0	2.70	0.8000	2.0000	-0.10	2.7	0.80	2.00	-8.00	0.0	0.00	3.00	0.8000	2.0000	-32.00
19	0.0	0.00	0.00	0.00	2.0	-18.0	2.00	0.5000	1.5000	-0.05	3.0	0.90	2.10	-0.05	0.0	0.00	4.50	1.3500	3.1500	-0.05

Resultant Targets

	DPS-short	ICC-VCC=6	VIL=0	VIH=6	IOL=0	IOH=0	VOL=0	VOH=6	FUNCGR-VCC=6	VOL=3	VOH=3	FUNCSTR-VCC=2	VIH=2	VOL=0.1	VOH=1.9	FUNCSTR-VCC=4.5
0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	0	1	0	1	1	1	1	0	0	0	1	0	1	1	1
2	1	0	1	0	1	1	0	0	0	0	0	0	1	0	0	0
3	1	0	1	0	0	0	0	0	0	0	0	1	1	1	1	1
4	1	0	1	0	0	0	0	0	0	0	0	0	0	1	0	1
5	1	0	1	0	0	0	0	0	0	0	0	0	0	1	0	1
6	1	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0
7	1	0	1	0	0	0	0	0	0	0	0	0	1	1	0	0
8	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
9	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
10	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
11	1	1	1	1	0	0	0	0	1	1	1	1	1	1	1	0
12	1	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0
13	1	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0
14	1	0	1	0	1	1	0	0	0	0	0	1	0	1	0	1
15	1	0	1	0	1	1	0	0	0	0	0	1	0	1	0	1
16	1	0	1	0	1	1	0	0	0	0	0	0	1	0	0	1
17	1	0	1	0	1	1	0	0	0	0	0	1	1	1	0	1
18	1	0	1	0	1	1	0	0	0	0	0	0	1	0	0	0
19	1	0	1	0	1	1	0	0	0	0	0	1	0	1	0	1
20	1	0	1	0	1	1	0	0	0	0	0	1	0	1	0	1
21	1	0	1	0	1	1	0	0	0	0	0	1	0	1	0	1
22	1	0	1	0	1	1	0	0	0	0	0	0	1	0	0	1
23	1	0	1	0	1	1	0	0	0	0	0	0	1	0	0	1
24	1	0	1	0	1	1	0	0	0	0	0	0	1	0	0	1
25	1	0	1	1	1	1	0	0	1	1	1	1	0	1	1	1

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Machine Learning Model 2

Phase 1:

- Targets of Phase 1 is the features for ML model 2
- One hot encoding is used to change it as feature for next phase

Phase 2:

Classify objects using LC: Label Powerset

Base classifier:J48

Require_dense – whether the base classifier requires dense representations for input features and classes/labels matrices in fit/predict.(Total targets 797)

Phase 3:

Associate the tests using MMAC(Multiclass Multilabel Associative Classification) Apriori

Produce rule set using frequent items

Rank the rule set based on support and confidence

Repeat untill no frequent item is found

Merge rules and classify objects

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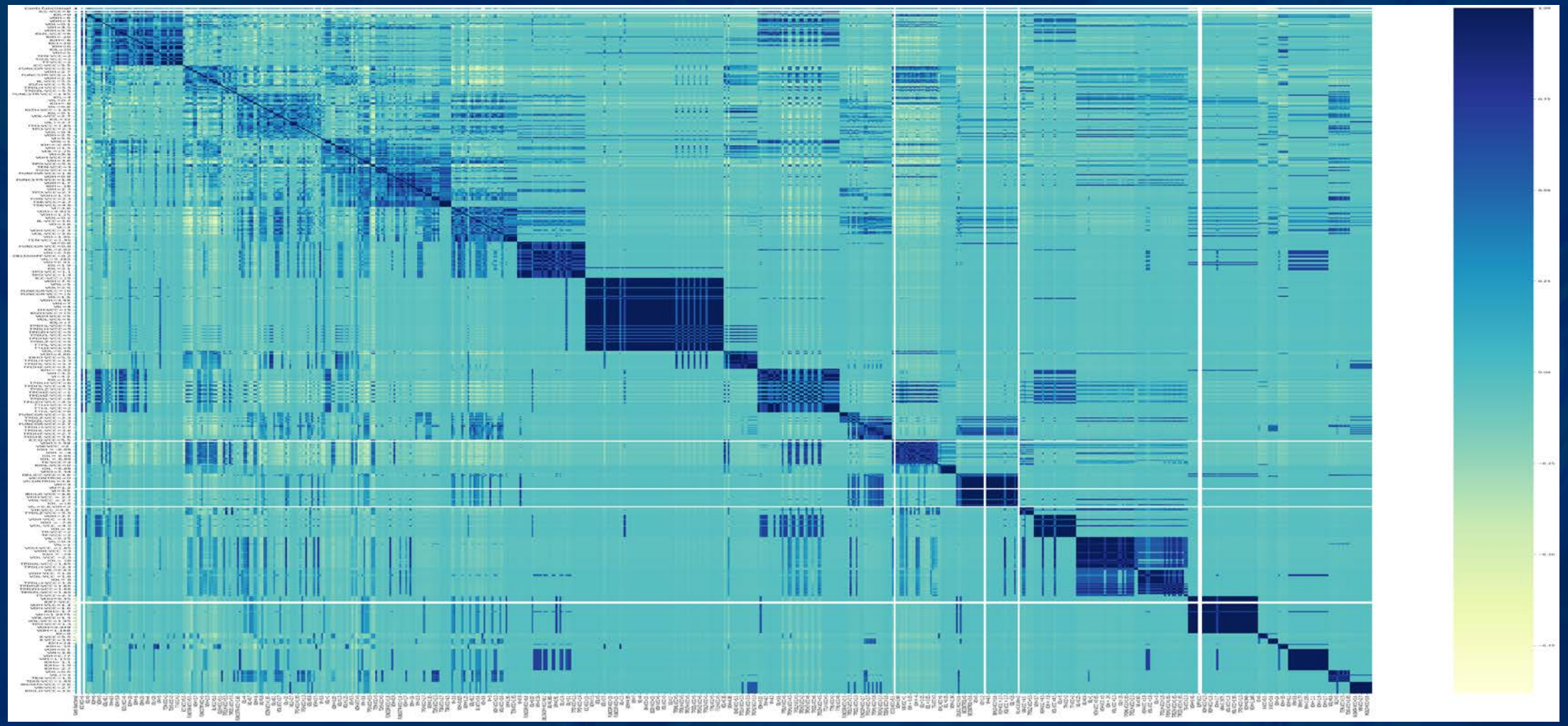
Correlation Matrix of the Targets



Highly correlated

Least correlated

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Comparative Model Evaluation

Sl.No	Algorithm	Accuracy(%)	Jaccard index	Hamming score	Avg precision
1	LC(Label Powerset)	76.9	0.231	0.992	0.8
2	BCC (Bayesian Classifier Chain)	76.9	0.231	0.992	0.8
3	CDN (Conditional Dependency Networks)	54.1	0.451	0.986	0.88
4	BRq (Binary Relevance – Quick Version)	75.6	0.244	0.67	0.7998

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Test Program Generation Summary

Use case:

Device : ASIC ICs

ATE platform: Advantest V93K

Total devices: 250

ATE loadable files

Pin Config files:	TestGeni
Levels:	ML and TestGeni
Timing:	Vector conversion
Pattern:	Vector conversion
Test limits:	ML and TestGeni
Test flow:	ML and TestGeni

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Conclusion and Future Work

- In the quest for precision, a symphony of AI automation plays its part, yet the conductor's touch of human intervention ensures the perfect performance.

- Test development time slashed significantly.

Future work:
Training the model to generate the schematic design from test specifications

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Thank you

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