Android Malware Detection

Machine Learning I

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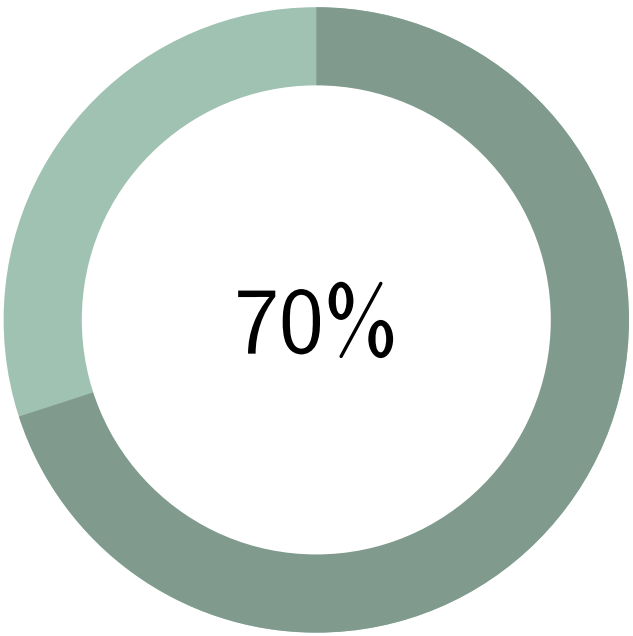
Introduction

Introduction

The problem



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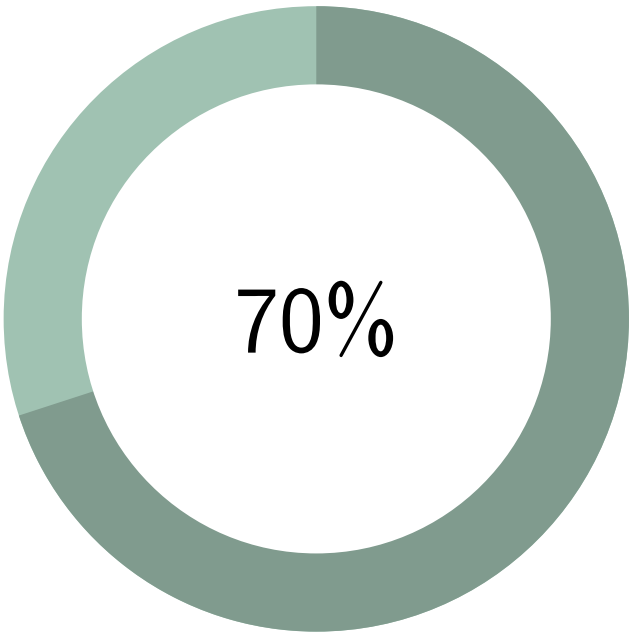

Introduction

About the dataset

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1. 355,630 rows

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2. 86 columns

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3. 4 classes

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1. 355,630 rows
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    - Android Adware

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   - Android Adware
   - Android Scareware

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4. Network flow characteristics

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   - IP (source and dest)

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5. Statistics of android apps behaviour
   - IP (source and dest)
   - Ports
   - Protocol
   - Packets details

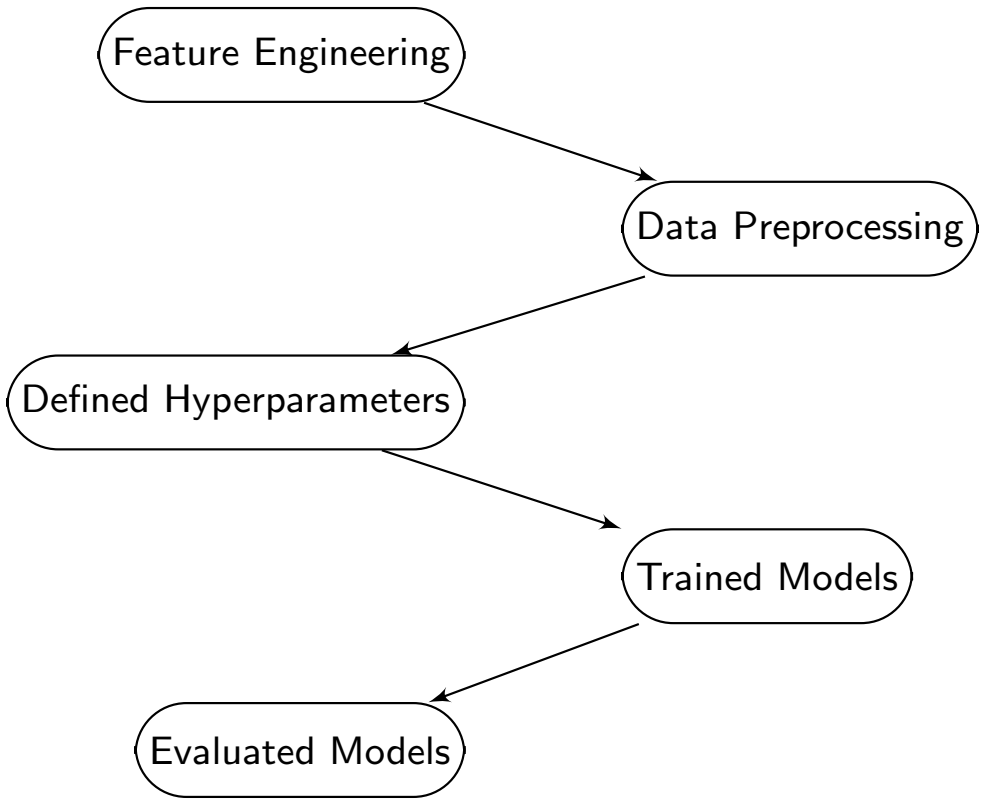
Introduction

Dataset

Label	Dataset Entries	Used Entries
Android_Adware	147,443	1,475
Android_Scareware	117,082	1,171
Android_SMS_Malware	67,397	674
Benign	23,708	237
Total size	355,630	3,557

Introduction

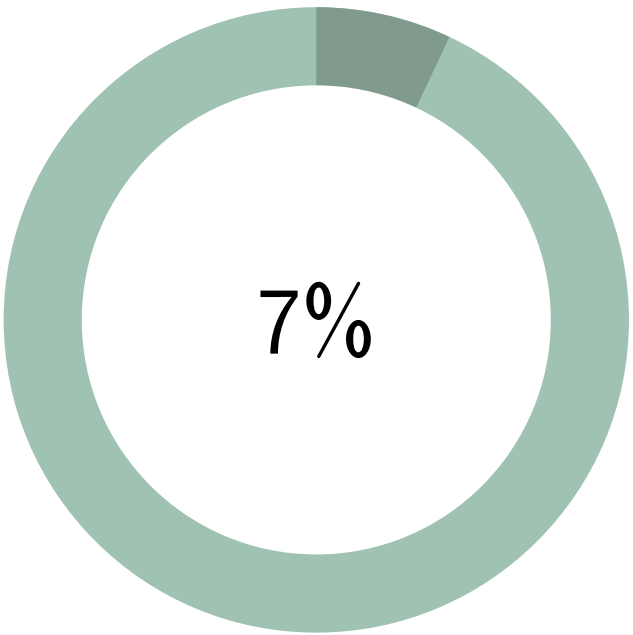
Pipeline



Approaches

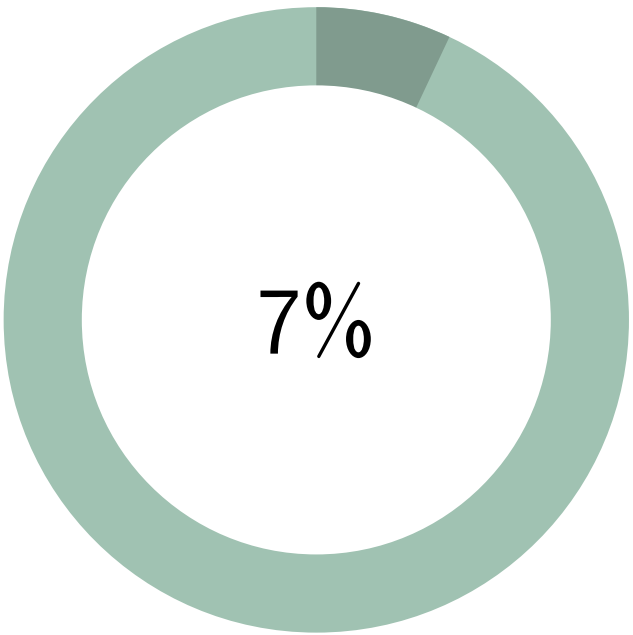
Approach 1: Binary Classification

Data Preprocessing



Approach 1: Binary Classification

Data Preprocessing



Label	Entries
Benign	237
Malware	3,320
Total size	3,557

Approach 1: Binary Classification

Results: ANN CV

Architecture	Accuracy	Recall	Specificity	F1-Score
20	93.71% *(0.0)*	100.0% *(0.0)*	0.0% *(0.0)*	96.75% *(0.0)*
40	93.71% *(0.0)*	100.0% *(0.0)*	0.0% *(0.0)*	96.75% *(0.0)*
80	93.71% *(0.0)*	100.0% *(0.0)*	0.0% *(0.0)*	96.75% *(0.0)*
100	93.71% *(0.0)*	100.0% *(0.0)*	0.0% *(0.0)*	96.75% *(0.0)*
60, 120	93.71% *(0.0)*	100.0% *(0.0)*	0.0% *(0.0)*	96.75% *(0.0)*
80, 50	93.71% *(0.0)*	100.0% *(0.0)*	0.0% *(0.0)*	96.75% *(0.0)*
80, 100	93.71% *(0.0)*	100.0% *(0.0)*	0.0% *(0.0)*	96.75% *(0.0)*
100, 40	93.71% *(0.0)*	100.0% *(0.0)*	0.0% *(0.0)*	96.75% *(0.0)*

Table: ANN metrics result for CrossValidation

Approach 1: Binary Classification

Results: ANN

Architecture	Accuracy	Recall	Specificity	F1-Score	CM
20	91.85%	100.0%	0.0%	95.75%	[654 58; 0 0]
40	91.85%	100.0%	0.0%	95.75%	[654 58; 0 0]
80	91.85%	100.0%	0.0%	95.75%	[654 58; 0 0]
100	91.85%	100.0%	0.0%	95.75%	[654 58; 0 0]
60, 120	91.85%	100.0%	0.0%	95.75%	[654 58; 0 0]
80, 50	91.85%	100.0%	0.0%	95.75%	[654 58; 0 0]
80, 100	91.85%	100.0%	0.0%	95.75%	[654 58; 0 0]
100, 40	91.85%	100.0%	0.0%	95.75%	[654 58; 0 0]

Table: ANN metrics result

Approach 1: Binary Classification

Results: kNN CV

k	Accuracy	Recall	Specificity	F1-Score
1	88.08% *(0.01)*	93.17% *(0.01)*	12.29% *(0.08)*	93.61% *(0.01)*
2	83.3% *(0.01)*	87.66% *(0.02)*	18.43% *(0.11)*	90.77% *(0.01)*
3	92.72% *(0.01)*	98.84% *(0.01)*	1.7% *(0.03)*	96.22% *(0.0)*
5	93.5% *(0.0)*	99.74% *(0.0)*	0.56% *(0.02)*	96.64% *(0.0)*
7	93.6% *(0.0)*	99.89% *(0.0)*	0.0% *(0.0)*	96.7% *(0.0)*
10	93.6% *(0.0)*	99.89% *(0.0)*	0.0% *(0.0)*	96.7% *(0.0)*
15	93.71% *(0.0)*	100.0% *(0.0)*	0.0% *(0.0)*	96.75% *(0.0)*

Table: kNN metrics result for CrossValidation

Approach 1: Binary Classification

Results: kNN

k	Accuracy	Recall	Specificity	F1-Score	CM
1	87.22%	94.19%	8.62%	93.12%	[616 53; 38 5]
2	80.48%	86.39%	13.79%	89.05%	[565 50; 89 8]
3	90.03%	97.86%	1.72%	94.74%	[640 57; 14 1]
5	91.43%	99.54%	0.0%	95.52%	[651 58; 3 0]
7	91.85%	100.0%	0.0%	95.75%	[654 58; 0 0]
10	91.85%	100.0%	0.0%	95.75%	[654 58; 0 0]
15	91.85%	100.0%	0.0%	95.75%	[654 58; 0 0]

Table: kNN metrics result

Approach 1: Binary Classification

Results: Decision Tree CV

MaxDepth	Accuracy	Recall	Specificity	F1-Score
3	93.6% *(0.0)*	99.89% *(0.0)*	0.0% *(0.0)*	96.7% *(0.0)*
5	93.15% *(0.0)*	99.36% *(0.0)*	0.56% *(0.02)*	96.45% *(0.0)*
7	92.34% *(0.0)*	98.39% *(0.0)*	2.22% *(0.03)*	96.01% *(0.0)*
10	91.42% *(0.01)*	97.22% *(0.01)*	5.03% *(0.04)*	95.5% *(0.01)*
15	88.96% *(0.01)*	94.26% *(0.02)*	10.03% *(0.06)*	94.11% *(0.01)*
nothing	87.1% *(0.02)*	92.08% *(0.02)*	12.88% *(0.08)*	93.04% *(0.01)*

Table: Decision Tree metrics result for CrossValidation

Approach 1: Binary Classification

Results: Decision Tree

MaxDepth	Accuracy	Recall	Specificity	F1-Score	CM
3	91.85%	100.0%	0.0%	95.75%	[654 58; 0 0]
5	91.71%	99.85%	0.0%	95.68%	[653 58; 1 0]
7	89.61%	97.55%	0.0%	94.52%	[638 58; 16 0]
10	88.06%	95.72%	1.72%	93.64%	[626 57; 28 1]
15	85.25%	92.66%	1.72%	92.03%	[606 57; 48 1]
nothing	84.55%	91.9%	1.72%	91.62%	[601 57; 53 1]

Table: Decision Tree metrics result

Approach 1: Binary Classification

Results: SVM CV

Kernel	C	Accuracy	Recall	Specificity	F1-Score
rbf	0.1	93.71% *(0.0)*	100.0% *(0.0)*	0.0% *(0.0)*	96.75% *(0.0)*
rbf	1.0	93.71% *(0.0)*	100.0% *(0.0)*	0.0% *(0.0)*	96.75% *(0.0)*
rbf	10.0	93.6% *(0.0)*	99.89% *(0.0)*	0.0% *(0.0)*	96.7% *(0.0)*
poly	0.1	93.71% *(0.0)*	100.0% *(0.0)*	0.0% *(0.0)*	96.75% *(0.0)*
poly	1.0	93.67% *(0.0)*	99.96% *(0.0)*	0.0% *(0.0)*	96.73% *(0.0)*
linear	0.1	93.71% *(0.0)*	100.0% *(0.0)*	0.0% *(0.0)*	96.75% *(0.0)*
linear	1.0	93.71% *(0.0)*	100.0% *(0.0)*	0.0% *(0.0)*	96.75% *(0.0)*
linear	10.0	93.71% *(0.0)*	100.0% *(0.0)*	0.0% *(0.0)*	96.75% *(0.0)*

Table: SVM metrics result for CrossValidation

Approach 1: Binary Classification

Results: SVM

Kernel	C	Accuracy	Recall	Specificity	F1-Score	CM
rbf	0.1	91.85%	100.0%	0.0%	95.75%	[654 58; 0 0]
rbf	1.0	91.85%	100.0%	0.0%	95.75%	[654 58; 0 0]
rbf	10.0	91.71%	99.85%	0.0%	95.68%	[653 58; 1 0]
poly	0.1	91.85%	100.0%	0.0%	95.75%	[654 58; 0 0]
poly	1.0	91.71%	99.85%	0.0%	95.68%	[653 58; 1 0]
linear	0.1	91.85%	100.0%	0.0%	95.75%	[654 58; 0 0]
linear	1.0	91.85%	100.0%	0.0%	95.75%	[654 58; 0 0]
linear	10.0	91.85%	100.0%	0.0%	95.75%	[654 58; 0 0]

Table: SVM metrics result

Approach 1: Binary Classification

Results: Ensemble Model CV

Ensemble Model	Parameters	Accuracy	Recall	Specificity	F1-Score
Voting Hard		92.93% *(0.0)*	99.06% *(0.01)*	1.7% *(0.03)*	96.33% *(0.0)*
Stacking (DecisionTree)	Max Depth 10	92.06% *(0.01)*	98.16% *(0.02)*	1.11% *(0.02)*	95.86% *(0.01)*
Stacking (kNN)	numNeighboors = 2	82.88% *(0.04)*	87.96% *(0.04)*	7.32% *(0.09)*	90.54% *(0.03)*
Stacking (SVM)	C = 0.1, kernel = rbf	93.71% *(0.0)*	100.0% *(0.0)*	0.0% *(0.0)*	96.75% *(0.0)*

Table: Ensemble Model metrics result for CrossValidation

Approach 1: Binary Classification

Results: Ensemble Model

Ensemble Model	Final Estimator	Accuracy	Recall	Specificity	F1-Score	CM
Voting Hard		91.15%	99.08%	1.72%	95.36%	[648 57; 6 1]
Stacking (DecisionTree)	Max Depth 10	90.59%	98.62%	0.0%	95.06%	[645 58; 9 0]
Stacking (kNN)	numNeighboors = 2	81.18%	87.16%	13.79%	89.48%	[570 50; 84 8]
Stacking (SVM)	C = 0.1, kernel = rbf	91.85%	100.0%	0.0%	95.75%	[654 58; 0 0]

Table: Ensemble Model metrics result

Approach 1: Binary Classification

Conclusion

- Excellent recall.
- Poor specificity.
- Models predicting nearly every instance as malware.

Approach 2: Binary Classification with Balanced Classes

Data Preprocessing

Approach 2: Binary Classification with Balanced Classes

Data Preprocessing

Approach 2: Binary Classification with Balanced Classes

Data Preprocessing

Label	Entries
Benign	3,320
Malware	3,320
Total size	6,640

Approach 2: Binary Classification with Balanced Classes

Results: ANN CV

Architecture	Accuracy	Recall	Specificity	F1-Score
20	60.88% *(0.02)*	58.13% *(0.02)*	63.63% *(0.04)*	59.48% *(0.01)*
40	59.06% *(0.01)*	56.72% *(0.03)*	61.41% *(0.05)*	56.85% *(0.02)*
80	55.24% *(0.01)*	56.49% *(0.04)*	53.99% *(0.04)*	52.61% *(0.02)*
100	54.47% *(0.01)*	52.87% *(0.04)*	56.06% *(0.05)*	49.85% *(0.02)*
60, 120	53.94% *(0.01)*	59.53% *(0.08)*	48.36% *(0.09)*	49.12% *(0.04)*
80, 50	56.5% *(0.01)*	56.82% *(0.04)*	56.19% *(0.04)*	52.23% *(0.01)*
80, 100	54.67% *(0.01)*	55.69% *(0.05)*	53.65% *(0.06)*	47.75% *(0.03)*
100, 40	56.83% *(0.01)*	59.17% *(0.06)*	54.49% *(0.08)*	53.57% *(0.03)*

Table: ANN metrics result for CrossValidation

Approach 2: Binary Classification with Balanced Classes

Results: ANN

Architecture	Accuracy	Recall	Specificity	F1-Score	CM
20	59.64%	64.31%	54.97%	61.44%	[427 299; 237 365]
40	57.23%	77.41%	37.05%	64.41%	[514 418; 150 246]
80	54.29%	72.74%	35.84%	61.41%	[483 426; 181 238]
100	52.79%	62.5%	43.07%	56.97%	[415 378; 249 286]
60, 120	54.44%	16.27%	92.62%	26.31%	[108 49; 556 615]
80, 50	53.77%	11.14%	96.39%	19.42%	[74 24; 590 640]
80, 100	56.55%	25.0%	88.1%	36.52%	[166 79; 498 585]
100, 40	58.89%	83.89%	33.89%	67.11%	[557 439; 107 225]

Table: ANN metrics result

Approach 2: Binary Classification with Balanced Classes

Results: kNN CV

k	Accuracy	Recall	Specificity	F1-Score
1	95.33% *(0.01)*	90.66% *(0.02)*	100.0% *(0.0)*	95.1% *(0.01)*
2	91.3% *(0.01)*	82.6% *(0.02)*	100.0% *(0.0)*	90.46% *(0.01)*
3	91.3% *(0.01)*	82.6% *(0.02)*	100.0% *(0.0)*	90.46% *(0.01)*
5	87.71% *(0.01)*	75.41% *(0.02)*	100.0% *(0.0)*	85.97% *(0.01)*
7	83.98% *(0.01)*	67.96% *(0.03)*	100.0% *(0.0)*	80.89% *(0.02)*
10	77.97% *(0.01)*	56.06% *(0.03)*	99.89% *(0.0)*	71.76% *(0.02)*
15	72.36% *(0.01)*	48.87% *(0.02)*	95.86% *(0.02)*	63.86% *(0.02)*

Table: kNN metrics result for CrossValidation

Approach 2: Binary Classification with Balanced Classes

Results: kNN

k	Accuracy	Recall	Specificity	F1-Score	CM
1	96.01%	92.02%	100.0%	95.84%	[611 0; 53 664]
2	91.49%	82.98%	100.0%	90.7%	[551 0; 113 664]
3	91.49%	82.98%	100.0%	90.7%	[551 0; 113 664]
5	87.73%	75.45%	100.0%	86.01%	[501 0; 163 664]
7	85.02%	70.03%	100.0%	82.37%	[465 0; 199 664]
10	80.12%	60.24%	100.0%	75.19%	[400 0; 264 664]
15	74.7%	50.45%	98.95%	66.6%	[335 7; 329 657]

Table: kNN metrics result

Approach 2: Binary Classification with Balanced Classes

Results: Decision Tree CV

MaxDepth	Accuracy	Recall	Specificity	F1-Score
3	56.85% *(0.02)*	42.33% *(0.22)*	71.37% *(0.22)*	46.65% *(0.13)*
5	61.8% *(0.02)*	42.16% *(0.12)*	81.44% *(0.14)*	51.67% *(0.06)*
7	67.28% *(0.02)*	51.42% *(0.13)*	83.14% *(0.09)*	60.14% *(0.08)*
10	77.59% *(0.03)*	64.57% *(0.08)*	90.62% *(0.05)*	74.01% *(0.05)*
15	88.57% *(0.02)*	78.77% *(0.04)*	98.38% *(0.01)*	87.28% *(0.03)*
None	95.29% *(0.01)*	90.59% *(0.02)*	100.0% *(0.0)*	95.05% *(0.01)*

Table: Decision Tree metrics result for CrossValidation

Approach 2: Binary Classification with Balanced Classes

Results: Decision Tree

MaxDepth	Accuracy	Recall	Specificity	F1-Score	CM
3	58.89%	43.52%	74.25%	51.42%	[289 171; 375 493]
5	63.03%	49.55%	76.51%	57.27%	[329 156; 335 508]
7	71.23%	58.73%	83.73%	67.13%	[390 108; 274 556]
10	81.4%	65.81%	96.99%	77.97%	[437 20; 227 644]
15	91.04%	82.08%	100.0%	90.16%	[545 0; 119 664]
None	96.31%	92.62%	100.0%	96.17%	[615 0; 49 664]

Table: Decision Tree metrics result

Approach 2: Binary Classification with Balanced Classes

Results: SVM CV

Kernel	C	Accuracy	Recall	Specificity	F1-Score
rbf	0.1	57.27% *(0.03)*	62.57% *(0.03)*	51.96% *(0.06)*	59.43% *(0.02)*
rbf	1.0	64.19% *(0.03)*	58.09% *(0.04)*	70.3% *(0.05)*	61.83% *(0.03)*
rbf	10.0	71.74% *(0.02)*	64.34% *(0.04)*	79.14% *(0.04)*	69.46% *(0.03)*
poly	0.1	57.46% *(0.02)*	90.14% *(0.02)*	24.78% *(0.05)*	67.95% *(0.01)*
poly	1.0	62.07% *(0.03)*	77.63% *(0.03)*	46.5% *(0.06)*	67.19% *(0.02)*
linear	0.1	57.32% *(0.01)*	56.81% *(0.05)*	57.83% *(0.06)*	57.0% *(0.02)*
linear	1.0	58.74% *(0.01)*	60.13% *(0.05)*	57.35% *(0.06)*	59.23% *(0.02)*
linear	10.0	59.32% *(0.02)*	62.72% *(0.04)*	55.92% *(0.06)*	60.63% *(0.02)*

Table: SVM metrics result for CrossValidation

Approach 2: Binary Classification with Balanced Classes

Results: SVM

Kernel	C	Accuracy	Recall	Specificity	F1-Score	CM
rbf	0.1	57.3%	59.49%	55.12%	58.22%	[395 298; 269 366]
rbf	1.0	63.18%	56.63%	69.73%	60.6%	[376 201; 288 463]
rbf	10.0	72.44%	61.75%	83.13%	69.14%	[410 112; 254 552]
poly	0.1	56.78%	89.31%	24.25%	67.39%	[593 503; 71 161]
poly	1.0	63.93%	76.96%	50.9%	68.09%	[511 326; 153 338]
linear	0.1	58.51%	54.52%	62.5%	56.78%	[362 249; 302 415]
linear	1.0	58.66%	57.08%	60.24%	58.0%	[379 264; 285 400]
linear	10.0	59.19%	60.54%	57.83%	59.73%	[402 280; 262 384]

Table: SVM metrics result

Approach 2: Binary Classification with Balanced Classes

Results: Ensembles CV

Ensemble Model	Parameters	Accuracy	Recall	Specificity	F1-Score
Hard Voting		94.33% *(0.01)*	88.67% *(0.02)*	100.0% *(0.0)*	93.98% *(0.01)*
Stacking (Decision Tree)	Max Depth = None	97.27% *(0.01)*	98.42% *(0.01)*	96.12% *(0.02)*	97.31% *(0.01)*
Stacking (kNN)	numNeighboors = 1	97.27% *(0.01)*	98.42% *(0.01)*	96.12% *(0.02)*	97.31% *(0.01)*
Stacking (SVM)	C = 10, kernel = rbf	99.1% *(0.0)*	98.19% *(0.01)*	100.0% *(0.0)*	99.09% *(0.0)*

Table: Ensemble Model metrics result for CrossValidation

Approach 2: Binary Classification with Balanced Classes

Results: Ensembles

Ensemble Model	Final Estimator	Accuracy	Recall	Specificity	F1-Score	CM
Hard Voting		95.11%	90.21%	100.0%	94.85%	[599 0; 65 664]
Stacking (Decision Tree)	Max Depth = None	95.26%	98.34%	92.17%	95.4%	[653 52; 11 612]
Stacking (kNN)	numNeighboors = 1	95.26%	98.34%	92.17%	95.4%	[653 52; 11 612]
Stacking (SVM)	C = 10, kernel = rbf	99.02%	98.04%	100.0%	99.01%	[651 0; 13 664]

Table: Ensemble Model metrics result

Approach 2: Binary Classification with Balanced Classes

Conclusion

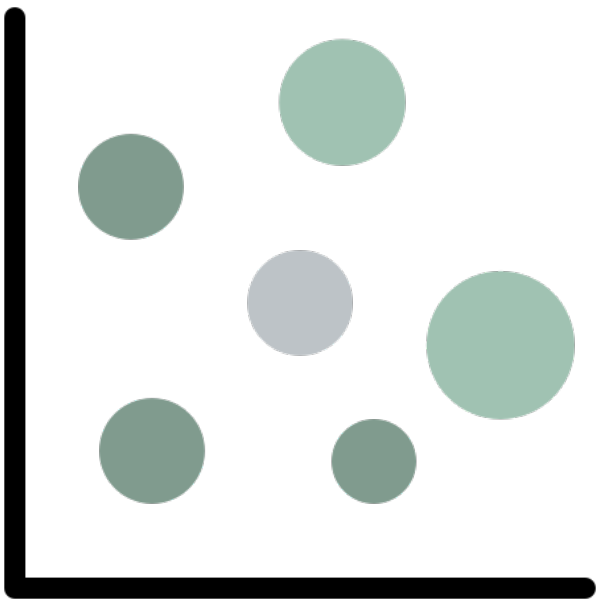
- Significant enhancement in binary classification.
- Ensembles as the top performer:
  - Combining base models.
  - Enhanced knowledge representation.

Approach 3: Multiclass Classification

Data Preprocessing

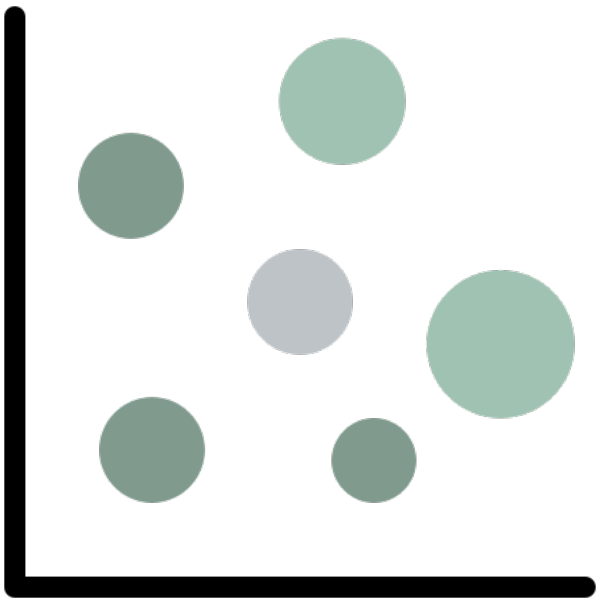
Approach 3: Multiclass Classification

Data Preprocessing



Approach 3: Multiclass Classification

Data Preprocessing



Label	Entries
Benign	1,475
Android_Scareware	1,475
Android_SMS_Malware	1,475
Android_Adware	1,475
Total size	5,900

Approach 3: Multiclass Classification

Results: ANN CV

Architecture	Accuracy	Recall	Specificity	F1-Score
20	33.21% *(0.01)*	33.21% *(0.01)*	77.75% *(0.0)*	32.2% *(0.01)*
40	32.82% *(0.01)*	32.82% *(0.01)*	77.61% *(0.0)*	30.85% *(0.01)*
80	31.43% *(0.01)*	31.43% *(0.01)*	77.13% *(0.0)*	27.34% *(0.01)*
100	30.83% *(0.01)*	30.83% *(0.01)*	76.95% *(0.0)*	26.02% *(0.01)*
60, 120	30.2% *(0.0)*	30.2% *(0.0)*	76.71% *(0.0)*	21.09% *(0.01)*
80, 50	31.67% *(0.01)*	31.67% *(0.01)*	77.22% *(0.0)*	25.56% *(0.01)*
80, 100	30.12% *(0.01)*	30.12% *(0.01)*	76.71% *(0.0)*	21.38% *(0.01)*
100, 40	31.61% *(0.01)*	31.61% *(0.01)*	77.21% *(0.0)*	25.89% *(0.01)*

Table: ANN metrics result for CrossValidation

Approach 3: Multiclass Classification

Results: ANN

Architecture	Accuracy	Recall	Specificity	F1-Score	CM
20	22.37%	22.37%	73.78%	20.66%	[67 104 105 26; 78 56 135 35; 76 64 124 32; 117 48 96 17]
40	20.59%	20.59%	72.99%	17.85%	[147 80 55 20; 166 35 68 35; 171 61 43 21; 175 48 37 18]
80	23.9%	23.9%	74.66%	23.48%	[78 87 51 86; 86 86 36 96; 69 97 41 89; 87 88 26 77]
100	21.44%	21.44%	73.11%	17.1%	[74 200 15 13; 105 155 12 32; 107 153 9 27; 128 120 15 15]
60, 120	23.64%	23.64%	75.28%	17.65%	[3 44 132 123; 7 12 137 148; 8 21 115 152; 8 18 103 149]
80, 50	21.44%	21.44%	74.18%	16.98%	[12 169 20 101; 28 99 10 167; 22 115 10 149; 31 101 14 132]
80, 100	25.42%	25.42%	74.6%	17.27%	[239 24 31 8; 208 7 65 24; 220 12 45 19; 219 7 43 9]
100, 40	23.9%	23.9%	75.43%	17.48%	[6 29 126 141; 12 5 139 148; 9 15 119 153; 20 8 98 152]

Table: ANN metrics result

Approach 3: Multiclass Classification

Results: kNN CV

k	Accuracy	Recall	Specificity	F1-Score
1	71.65% *(0.02)*	71.65% *(0.02)*	90.54% *(0.01)*	70.28% *(0.02)*
2	62.31% *(0.02)*	62.31% *(0.02)*	87.44% *(0.01)*	60.55% *(0.02)*
3	57.35% *(0.02)*	57.35% *(0.02)*	85.78% *(0.01)*	55.48% *(0.02)*
5	52.04% *(0.02)*	52.04% *(0.02)*	84.0% *(0.01)*	49.75% *(0.02)*
7	47.67% *(0.03)*	47.67% *(0.03)*	82.57% *(0.01)*	45.61% *(0.03)*
10	41.42% *(0.03)*	41.42% *(0.03)*	80.48% *(0.01)*	40.28% *(0.03)*
15	39.47% *(0.03)*	39.47% *(0.03)*	79.83% *(0.01)*	38.99% *(0.03)*

Table: kNN metrics result for CrossValidation

Approach 3: Multiclass Classification

Results: kNN

k	Accuracy	Recall	Specificity	F1-Score	CM
1	71.78%	71.78%	90.64%	70.38%	[302 0 0 0; 22 143 85 54; 14 86 154 42; 4 10 16 248]
2	63.73%	63.73%	87.91%	61.89%	[297 5 0 0; 22 172 45 65; 14 133 82 67; 4 67 6 201]
3	57.97%	57.97%	86.01%	56.11%	[297 5 0 0; 35 127 70 72; 43 85 100 68; 17 62 39 160]
5	56.19%	56.19%	85.36%	54.22%	[285 5 8 4; 46 128 68 62; 65 72 100 59; 35 53 40 150]
7	50.42%	50.42%	83.37%	48.24%	[270 14 8 10; 67 112 73 52; 81 72 87 56; 48 54 50 126]
10	43.98%	43.98%	81.21%	42.53%	[216 30 28 28; 84 109 60 51; 91 72 74 59; 52 58 48 120]
15	40.0%	40.0%	79.94%	39.13%	[182 36 46 38; 78 100 72 54; 81 70 75 70; 66 49 48 115]

Table: kNN metrics result

Approach 3: Multiclass Classification

Results: Decision Tree CV

MaxDepth	Accuracy	Recall	Specificity	F1-Score
3	33.41% *(0.02)*	33.41% *(0.02)*	77.87% *(0.01)*	29.11% *(0.03)*
5	36.65% *(0.03)*	36.65% *(0.03)*	78.93% *(0.01)*	34.46% *(0.03)*
7	40.68% *(0.02)*	40.68% *(0.02)*	80.28% *(0.01)*	39.03% *(0.02)*
10	48.6% *(0.02)*	48.6% *(0.02)*	82.9% *(0.01)*	47.87% *(0.02)*
15	62.88% *(0.03)*	62.88% *(0.03)*	87.64% *(0.01)*	62.15% *(0.03)*
nothing	71.95% *(0.02)*	71.95% *(0.02)*	90.64% *(0.01)*	70.58% *(0.02)*

Table: Decision Tree metrics result for CrossValidation

Approach 3: Multiclass Classification

Results: Decision Tree

MaxDepth	Accuracy	Recall	Specificity	F1-Score	CM
3	34.92%	34.92%	78.14%	29.99%	[142 99 0 61; 104 133 0 67; 104 121 0 71; 74 67 0 137]
5	37.29%	37.29%	78.86%	35.23%	[200 45 31 26; 125 69 59 51; 142 60 51 43; 89 26 43 120]
7	42.46%	42.46%	80.56%	40.53%	[212 56 22 12; 122 83 55 44; 124 69 58 45; 62 33 35 148]
10	49.92%	49.92%	83.14%	49.06%	[205 62 20 15; 65 117 80 42; 79 83 88 46; 24 39 36 179]
15	67.2%	67.2%	89.11%	65.99%	[264 19 15 4; 38 146 72 48; 35 62 142 57; 5 12 20 241]
nothing	73.39%	73.39%	91.19%	71.85%	[302 0 0 0; 31 144 84 45; 17 65 164 50; 2 8 12 256]

Table: DecisionTree metrics result

Approach 3: Multiclass Classification

Results: SVM CV

Kernel	C	Accuracy	Recall	Specificity	F1-Score
rbf	0.1	30.87% *(0.02)*	30.87% *(0.02)*	77.01% *(0.01)*	27.17% *(0.02)*
rbf	1.0	35.93% *(0.02)*	35.93% *(0.02)*	78.71% *(0.01)*	35.01% *(0.02)*
rbf	10.0	42.2% *(0.01)*	42.2% *(0.01)*	80.79% *(0.0)*	41.5% *(0.01)*
poly	0.1	32.12% *(0.02)*	32.12% *(0.02)*	77.42% *(0.01)*	27.33% *(0.02)*
poly	1.0	35.42% *(0.02)*	35.42% *(0.02)*	78.6% *(0.0)*	33.2% *(0.02)*
linear	0.1	32.5% *(0.02)*	32.5% *(0.02)*	77.56% *(0.01)*	31.06% *(0.02)*
linear	1.0	33.2% *(0.01)*	33.2% *(0.01)*	77.8% *(0.0)*	31.9% *(0.01)*
linear	10.0	32.86% *(0.02)*	32.86% *(0.02)*	77.69% *(0.01)*	31.61% *(0.02)*

Table: SVM metrics result for CrossValidation

Approach 3: Multiclass Classification

Results: SVM

Kernel	C	Accuracy	Recall	Specificity	F1-Score	CM
rbf	0.1	29.07%	29.07%	76.08%	25.62%	[91 140 7 64; 56 165 15 68; 66 163 10 57; 68 127 6 77]
rbf	1.0	34.66%	34.66%	77.94%	33.64%	[151 84 42 25; 75 125 55 49; 95 100 50 51; 66 88 41 83]
rbf	10.0	40.93%	40.93%	80.06%	40.44%	[171 67 50 14; 71 131 61 41; 74 105 69 48; 46 71 49 112]
poly	0.1	29.49%	29.49%	76.22%	24.41%	[39 184 8 71; 8 211 20 65; 15 209 13 59; 15 172 6 85]
poly	1.0	35.08%	35.08%	77.86%	33.23%	[81 162 43 16; 25 209 40 30; 30 191 45 30; 20 147 32 79]
linear	0.1	30.68%	30.68%	76.63%	28.68%	[111 115 24 52; 63 152 29 60; 86 129 28 53; 63 111 33 71]
linear	1.0	30.85%	30.85%	76.68%	29.24%	[114 104 41 43; 61 147 37 59; 81 131 32 52; 61 105 41 71]
linear	10.0	30.93%	30.93%	76.65%	29.2%	[117 108 43 34; 59 151 43 51; 84 133 31 48; 62 110 40 66]

Table: SVM metrics result

Approach 3: Multiclass Classification

Results: Ensembles CV

Ensemble Model	Parameters	Accuracy	Recall	Specificity	F1-Score
Hard Voting		72.63% *(0.02)*	72.63% *(0.02)*	90.89% *(0.01)*	71.53% *(0.02)*
Stacking (Decision Tree)	Max Depth = None	65.11% *(0.03)*	65.11% *(0.03)*	88.38% *(0.01)*	65.13% *(0.03)*
Stacking (kNN)	numNeighboors = 1	65.32% *(0.03)*	65.32% *(0.03)*	88.45% *(0.01)*	65.25% *(0.03)*
Stacking (SVM)	C = 10, kernel = rbf	74.56% *(0.02)*	74.56% *(0.02)*	91.55% *(0.01)*	74.47% *(0.02)*

Table: Ensemble Model metrics result for CrossValidation

Approach 3: Multiclass Classification

Results: Ensembles

Ensemble Model	Final Estimator	Accuracy	Recall	Specificity	F1-Score	CM
Hard Voting		74.24%	74.24%	91.38%	73.11%	[302 0 0 0; 23 187 59 35; 13 106 139 38; 0 16 14 248]
Stacking (Decision Tree)	Max Depth = None	68.98%	68.98%	89.6%	69.16%	[284 18 0 0; 8 162 102 32; 2 99 160 35; 0 34 36 208]
Stacking (kNN)	numNeighboors = 1	69.49%	69.49%	89.78%	69.48%	[288 12 2 0; 8 156 112 28; 2 98 157 39; 0 38 21 219]
Stacking (SVM)	C = 10, kernel = rbf	77.37%	77.37%	92.38%	77.22%	[302 0 0 0; 7 198 83 16; 2 104 171 19; 0 6 30 242]

Table: Ensemble Model metrics result

Approach 3: Multiclass Classification

Conclusion

- Data balancing remains crucial.
- Ensembles keeps demonstrating superior outcomes.
- Remarkably good results for a 4-class problem.

Approach 4: Multiclass Classification with data dimensionality reduction

Data Preprocessing

Approach 4: Multiclass Classification with data dimensionality reduction

Data Preprocessing

Approach 4: Multiclass Classification with data dimensionality reduction

Data Preprocessing

Label	Entries
Benign	1,475
Android_Scareware	1,475
Android_SMS_Malware	1,475
Android_Adware	1,475
Total size	5,900

Approach 4: Multiclass Classification with data dimensionality reduction

Results: ANN CV

Architecture	Accuracy	Recall	Specificity	F1-Score
20	29.31% *(0.01)*	29.31% *(0.01)*	76.42% *(0.0)*	26.94% *(0.01)*
40	28.93% *(0.01)*	28.93% *(0.01)*	76.29% *(0.0)*	25.32% *(0.01)*
80	28.04% *(0.01)*	28.04% *(0.01)*	76.0% *(0.0)*	22.05% *(0.01)*
100	27.94% *(0.01)*	27.94% *(0.01)*	75.97% *(0.0)*	21.27% *(0.01)*
60, 120	27.55% *(0.01)*	27.55% *(0.01)*	75.83% *(0.0)*	17.43% *(0.01)*
80, 50	28.04% *(0.01)*	28.04% *(0.01)*	76.0% *(0.0)*	19.56% *(0.01)*
80, 100	27.5% *(0.01)*	27.5% *(0.01)*	75.85% *(0.0)*	17.23% *(0.01)*
100, 40	27.92% *(0.01)*	27.92% *(0.01)*	75.98% *(0.0)*	19.62% *(0.01)*

Table: ANN metrics result for CrossValidation

Approach 4: Multiclass Classification with data dimensionality reduction

Results: ANN

Architecture	Accuracy	Recall	Specificity	F1-Score	CM
20	24.92%	24.92%	74.6%	19.58%	[119 38 129 16; 117 11 165 11; 101 23 156 16; 123 27 120 8]
40	26.36%	26.36%	75.06%	19.43%	[144 12 136 10; 129 2 164 9; 131 4 155 6; 145 5 118 10]
80	20.59%	20.59%	72.66%	15.58%	[98 187 10 7; 152 133 12 7; 143 139 5 9; 152 113 6 7]
100	24.24%	24.24%	73.94%	18.08%	[123 158 9 12; 137 152 7 8; 143 138 5 10; 143 120 9 6]
60, 120	23.56%	23.56%	76.42%	9.45%	[0 0 5 297; 0 0 1 303; 0 0 3 293; 0 0 3 275]
80, 50	22.63%	22.63%	75.09%	14.61%	[0 120 0 182; 0 96 0 208; 0 95 0 201; 0 106 1 171]
80, 100	22.12%	22.12%	75.32%	15.08%	[26 20 25 231; 46 2 30 226; 39 7 29 221; 42 3 29 204]
100, 40	25.0%	25.0%	75.84%	18.54%	[12 20 130 140; 15 4 129 156; 13 3 125 155; 15 4 105 154]

Table: ANN metrics result

Approach 4: Multiclass Classification with data dimensionality reduction

Results: kNN CV

k	Accuracy	Recall	Specificity	F1-Score
1	70.96% *(0.02)*	70.96% *(0.02)*	90.3% *(0.01)*	69.58% *(0.02)*
2	60.53% *(0.02)*	60.53% *(0.02)*	86.85% *(0.01)*	58.97% *(0.02)*
3	55.3% *(0.02)*	55.3% *(0.02)*	85.1% *(0.01)*	53.46% *(0.02)*
5	50.93% *(0.01)*	50.93% *(0.01)*	83.65% *(0.0)*	48.64% *(0.02)*
7	46.38% *(0.01)*	46.38% *(0.01)*	82.14% *(0.0)*	44.3% *(0.02)*
10	41.87% *(0.02)*	41.87% *(0.02)*	80.63% *(0.01)*	40.58% *(0.02)*
15	39.11% *(0.03)*	39.11% *(0.03)*	79.71% *(0.01)*	38.46% *(0.03)*

Table: kNN metrics result for CrossValidation

Approach 4: Multiclass Classification with data dimensionality reduction

Results: kNN

k	Accuracy	Recall	Specificity	F1-Score	CM
1	70.34%	70.34%	90.17%	68.79%	[302 0 0 0; 25 130 89 60; 13 83 156 44; 6 12 18 242]
2	61.36%	61.36%	87.08%	59.74%	[297 5 0 0; 25 169 50 60; 13 134 81 68; 6 85 10 177]
3	54.58%	54.58%	84.87%	52.79%	[297 5 0 0; 39 110 77 78; 36 92 98 70; 15 80 44 139]
5	50.68%	50.68%	83.61%	48.47%	[281 5 12 4; 53 104 73 74; 49 78 80 89; 28 68 49 133]
7	47.54%	47.54%	82.49%	45.1%	[264 11 20 7; 75 92 66 71; 73 68 78 77; 44 58 49 127]
10	40.42%	40.42%	80.11%	38.67%	[208 39 27 28; 88 86 58 72; 78 71 64 83; 62 58 39 119]
15	35.42%	35.42%	78.47%	34.56%	[157 52 52 41; 86 81 64 73; 77 76 61 82; 51 55 53 119]

Table: kNN metrics result

Approach 4: Multiclass Classification with data dimensionality reduction

Results: Decision Tree CV

MaxDepth	Accuracy	Recall	Specificity	F1-Score
3	29.54% *(0.02)*	29.54% *(0.02)*	76.47% *(0.01)*	25.2% *(0.02)*
5	33.03% *(0.02)*	33.03% *(0.02)*	77.66% *(0.01)*	29.97% *(0.03)*
7	36.16% *(0.02)*	36.16% *(0.02)*	78.74% *(0.01)*	34.58% *(0.02)*
10	45.68% *(0.02)*	45.68% *(0.02)*	81.89% *(0.01)*	44.73% *(0.02)*
15	59.39% *(0.03)*	59.39% *(0.03)*	86.45% *(0.01)*	58.37% *(0.03)*
nothing	70.55% *(0.03)*	70.55% *(0.03)*	90.17% *(0.01)*	69.12% *(0.03)*

Table: Decision Tree metrics result for CrossValidation

Approach 4: Multiclass Classification with data dimensionality reduction

Results: Decision Tree

MaxDepth	Accuracy	Recall	Specificity	F1-Score	CM
3	28.22%	28.22%	76.38%	24.56%	[64 106 4 128; 36 137 4 127; 24 139 7 126; 34 115 4 125]
5	32.37%	32.37%	77.96%	30.92%	[112 37 33 120; 50 83 38 133; 36 85 34 141; 35 62 28 153]
7	35.59%	35.59%	78.81%	34.47%	[160 28 35 79; 73 60 71 100; 64 54 72 106; 50 39 61 128]
10	45.85%	45.85%	81.89%	44.12%	[233 32 6 31; 76 107 58 63; 62 90 74 70; 52 68 31 127]
15	60.68%	60.68%	86.92%	59.9%	[265 17 10 10; 29 125 87 63; 24 81 136 55; 14 44 30 190]
nothing	70.76%	70.76%	90.33%	69.26%	[302 0 0 0; 25 134 88 57; 17 67 161 51; 8 16 16 238]

Table: DecisionTree metrics result

Approach 4: Multiclass Classification with data dimensionality reduction

Results: SVM CV

Kernel	C	Accuracy	Recall	Specificity	F1-Score
rbf	0.1	27.65% *(0.02)*	27.65% *(0.02)*	75.97% *(0.01)*	21.56% *(0.02)*
rbf	1.0	28.73% *(0.02)*	28.73% *(0.02)*	76.31% *(0.01)*	24.59% *(0.02)*
rbf	10.0	30.15% *(0.02)*	30.15% *(0.02)*	76.75% *(0.01)*	27.09% *(0.02)*
poly	0.1	26.19% *(0.01)*	26.19% *(0.01)*	74.94% *(0.0)*	13.41% *(0.01)*
poly	1.0	26.23% *(0.01)*	26.23% *(0.01)*	74.96% *(0.0)*	13.51% *(0.01)*
linear	0.1	26.59% *(0.02)*	26.59% *(0.02)*	75.63% *(0.01)*	17.33% *(0.02)*
linear	1.0	26.59% *(0.02)*	26.59% *(0.02)*	75.62% *(0.01)*	17.32% *(0.02)*
linear	10.0	26.59% *(0.02)*	26.59% *(0.02)*	75.62% *(0.01)*	17.32% *(0.02)*

Table: SVM metrics result for CrossValidation

Approach 4: Multiclass Classification with data dimensionality reduction

Results: SVM

Kernel	C	Accuracy	Recall	Specificity	F1-Score	CM
rbf	0.1	28.39%	28.39%	75.76%	22.23%	[51 189 0 62; 23 217 2 62; 23 217 1 55; 42 170 0 66]
rbf	1.0	26.86%	26.86%	75.37%	23.77%	[37 161 38 66; 15 183 42 64; 13 192 34 57; 25 151 39 63]
rbf	10.0	29.66%	29.66%	76.46%	27.31%	[67 132 21 82; 35 167 17 85; 37 161 28 70; 41 127 22 88]
poly	0.1	24.07%	24.07%	76.47%	12.1%	[16 6 0 280; 5 4 2 293; 7 5 1 283; 7 6 2 263]
poly	1.0	24.07%	24.07%	76.47%	12.11%	[16 6 0 280; 5 4 2 293; 7 5 1 283; 6 7 2 263]
linear	0.1	26.61%	26.61%	75.22%	16.94%	[0 220 0 82; 0 234 1 69; 0 235 2 59; 0 200 0 78]
linear	1.0	26.69%	26.69%	75.24%	17.13%	[0 220 0 82; 0 234 2 68; 0 236 3 57; 0 200 0 78]
linear	10.0	26.69%	26.69%	75.24%	17.13%	[0 220 0 82; 0 234 2 68; 0 236 3 57; 0 200 0 78]

Table: SVM metrics result

Approach 4: Multiclass Classification with data dimensionality reduction

Results: Ensembles CV

Ensemble Model	Parameters	Accuracy	Recall	Specificity	F1-Score
Hard Voting		73.41% *(0.02)*	73.41% *(0.02)*	91.15% *(0.01)*	72.32% *(0.03)*
Stacking (Decision Tree)	Max Depth = None	65.49% *(0.01)*	65.49% *(0.01)*	88.5% *(0.0)*	65.46% *(0.01)*
Stacking (kNN)	numNeighboors = 1	66.38% *(0.02)*	66.38% *(0.02)*	88.8% *(0.01)*	66.3% *(0.02)*
Stacking (SVM)	C = 10, kernel = rbf	74.92% *(0.02)*	74.92% *(0.02)*	91.67% *(0.01)*	74.81% *(0.02)*

Table: Ensemble Model metrics result for CrossValidation

Approach 4: Multiclass Classification with data dimensionality reduction

Results: Ensembles

Ensemble Model	Final Estimator	Accuracy	Recall	Specificity	F1-Score	CM
Hard Voting		74.41%	74.41%	91.43%	73.22%	[302 0 0 0; 23 192 55 34; 13 108 136 39; 2 20 8 248]
Stacking (Decision Tree)	Max Depth = None	68.14%	68.14%	89.4%	67.93%	[288 8 4 2; 7 153 90 54; 1 104 148 43; 0 35 28 215]
Stacking (kNN)	numNeighboors = 1	66.86%	66.86%	88.92%	66.74%	[290 8 4 0; 8 152 104 40; 1 116 136 43; 0 35 32 211]
Stacking (SVM)	C = 10, kernel = rbf	74.83%	74.83%	91.47%	74.6%	[302 0 0 0; 7 194 89 14; 1 135 143 17; 0 22 12 244]

Table: Ensemble Model metrics result

Approach 4: Multiclass Classification with data dimensionality reduction

Conclusion

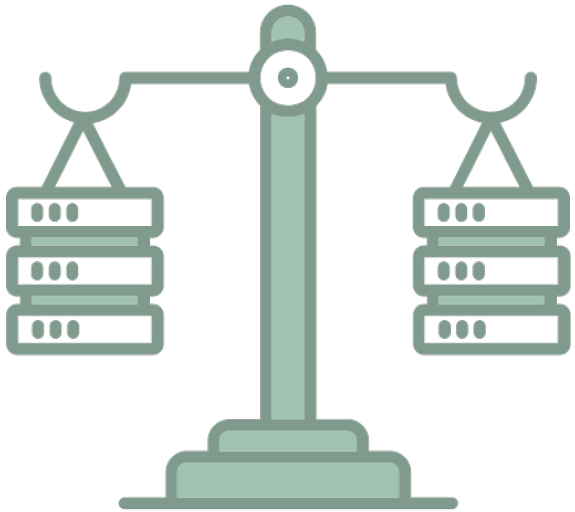
- Slightly varied outcomes using nearly half the features.
- Reduced training time.

Conclusions and future work

Conclusions

Conclusions

Conclusions



Future work

Future work

Android Malware Detection

Machine Learning I

Abel Juncal Suárez
Alejandro Dopico Castro
Javier Torón Artiles
Lucía María Álvarez Crespo

Master in Artificial Intelligence 2023/2024

Group C

December 19, 2023