AD-NEv: A Scalable Multi-Level Neuroevolution Framework for Multivariate Anomaly Detection

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I. Datasets

TABLE I: Statistics of the datasets

Dataset	Size of train datasets during evolution	Epochs evolution	Epochs final training
SWAT	9 933	25	90
WADI-2019	156 914	25	120
SMAP	138 004	25	70
MSl	58 317	25	70

II. Final subspaces and models

1) **SWAT** - [[5, 6, 7, 25, 26, 34, 36, 45], [0, 1, 2, 3, 8, 9, 12, 14, 16, 17, 20, 24, 43, 50], [4, 18, 21, 22, 23, 27, 28, 32, 33, 35, 37, 38, 39, 40, 41, 42, 44, 46, 49], [10, 11, 13, 15, 29], [19, 30, 31, 47, 48]]
2) **WADI** - [[8, 12, 20, 21, 29, 30, 41, 44, 52, 64, 67, 69, 75, 78, 87, 111, 112, 115, 119], [3, 4, 5, 6, 9, 10, 11, 13, 14, 15, 16, 17, 18, 19, 24, 27, 33, 36, 38, 40, 42, 43, 45, 46, 47, 49, 60, 61, 70, 72, 73, 81, 82, 83, 85, 86, 88, 89, 90, 96, 98, 118], [48, 50, 53, 54, 58, 68, 71, 72, 84, 94, 102, 105, 107, 108, 113, 116, 117], [1, 22, 23, 25, 26, 28, 31, 32, 34, 35, 37, 39, 59, 62, 63, 65, 66, 76, 77, 79, 80, 92, 93, 95, 106, 109, 110], [0, 2, 7, 51, 57, 74, 91, 97, 99, 100, 101, 103, 104, 114]]
3) **SMAP** - [[0],[2, 5, 6, 7, 12, 13, 14, 15, 17, 18, 19, 21, 22, 23], [10], [1, 3, 4, 9, 16, 20, 24], [11]]
4) **MSL** - [[0], [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 21, 22, 23, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 39, 40, 41, 42, 44, 45, 47, 48, 49, 50, 51], [43, 52], [24, 53, 54], [20, 25, 38, 46]]

TABLE II: Hyperparameters of the most effective CNN 1D model for the SWAT dataset (learning rate = 0.01). **C1D** means Conv1D layer, while **BN1D** means Batch Norm 1D layer

	Layer	Parameters		Layer	Parameters
1	C1D	$F[0]_{ic} = 5$ $F[0]_{oc} = 84$ $F[0]_K = 2$ $F[0]_P = 1$	7	C1D	$F[3]_{ic} = 205$ $F[3]_{oc} = 123$ $F[3]_K = 4$ $F[3]_P = 1$
2	BN1D	$F[0]_c^B = 84$	8	BN1D	$F[3]_c^B = 123$
3	C1D	$F[1]_{ic} = 84$ $F[1]_{oc} = 123$ $F[1]_K = 6$ $F[1]_P = 1$	9	C1D	$F[4]_{ic} = 123$ $F[4]_{oc} = 84$ $F[4]_K = 6$ $F[4]_P = 1$
4	BN1D	$F[1]_c^B = 123$	10	BN1D	$F[4]_c^B = 84$
5	C1D	$F[2]_{ic} = 123$ $F[2]_{oc} = 205$ $F[2]_K = 4$ $F[2]_P = 1$	11	C1D	$F[5]_{ic} = 84$ $F[5]_{ic} = 5$ $F[5]_K = 2$ $F[5]_P = 1$
6	BN1D	$F[2]_c^B = 205$	12	BN1D	$F[5]_c^B = 5$

TABLE III: Hyperparameters of the most effective CNN 1D model for the WADI dataset (learning rate = 0.01). **C1D** means Conv1D layer, while **BN1D** means Batch Norm 1D layer

	Layer	Parameters		Layer	Parameters
1	C1D	$F[0]_{ic} = 6$ $F[0]_{oc} = 91$ $F[0]_K = 7$ $F[0]_P = 1$	7	C1D	$F[3]_{ic} = 155$ $F[3]_{oc} = 153$ $F[3]_K = 4$ $F[3]_P = 1$
2	BN1D	$F[0]_c^B = 91$	8	BN1D	$F[3]_c^B = 153$
3	C1D	$F[1]_{ic} = 91$ $F[1]_{oc} = 153$ $F[1]_K = 3$ $F[1]_P = 1$	9	C1D	$F[4]_{ic} = 153$ $F[4]_{oc} = 91$ $F[4]_K = 3$ $F[4]_P = 1$
4	BN1D	$F[1]_c^B = 153$	10	BN1D	$F[4]_c^B = 91$
5	C1D	$F[2]_{ic} = 153$ $F[2]_{oc} = 155$ $F[2]_K = 4$ $F[2]_P = 1$	11	C1D	$F[5]_{ic} = 91$ $F[5]_{oc} = 6$ $F[5]_K = 7$ $F[5]_P = 1$
6	BN1D	$F[2]_c^B = 155$	12	BN1D	$F[5]_c^B = 6$

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TABLE IV: Hyperparameters of the most effective CNN 1D model for the MSL dataset (learning rate = 0.00001). **C1D** means Conv1D layer, while **BN1D** means Batch Norm 1D layer

	Layer	Parameters		Layer	Parameters
1	C1D	$F[0]_{ic}=4$ $F[0]_{oc}=95$ $F[0]_{K}=7$ $F[0]_{P}=3$	13	C1D	$F[6]_{ic}=927$ $F[6]_{oc}=685$ $F[6]_{K}=2$ $F[6]_{P}=1$
2	BN1D	$F[0]_{c}^{B}=95$	14	BN1D	$F[6]_{c}^{B}=685$
3	C1D	$F[1]_{ic}=95$ $F[1]_{oc}=126$ $F[1]_{K}=2$ $F[1]_{P}=1$	15	C1D	$F[7]_{ic}=685$ $F[7]_{oc}=261$ $F[7]_{K}=3$ $F[7]_{P}=1$
4	BN1D	$F[1]_{c}^{B}=126$	16	BN1D	$F[7]_{c}^{B}=261$
5	C1D	$F[2]_{ic}=126$ $F[2]_{oc}=138$ $F[2]_{K}=4$ $F[2]_{P}=1$	17	C1D	$F[8]_{ic}=261$ $F[8]_{oc}=138$ $F[8]_{K}=3$ $F[8]_{P}=1$
6	BN1D	$F[2]_{c}^{B}=138$	18	BN1D	$F[8]_{c}^{B}=138$
7	C1D	$F[3]_{ic}=138$ $F[3]_{oc}=261$ $F[3]_{K}=3$ $F[3]_{P}=1$	19	C1D	$F[9]_{ic}=138$ $F[9]_{oc}=126$ $F[9]_{ic}=4$ $F[9]_{ic}=1$
8	BN1D	$F[3]_{c}^{B}=261$	20	BN1D	$F[9]_{c}^{B}=126$
9	C1D	$F[4]_{ic}=261$ $F[4]_{oc}=685$ $F[4]_{K}=3$ $F[4]_{P}=1$	21	C1D	$F[10]_{ic}=126$ $F[10]_{oc}=95$ $F[10]_{K}=2$ $F[10]_{P}=1$
10	BN1D	$F[4]_{c}^{B}=685$	22	BN1D	$F[10]_{c}^{B}=95$
11	C1D	$F[5]_{ic}=685$ $F[5]_{oc}=927$ $F[5]_{K}=2$ $F[5]_{P}=1$	23	C1D	$F[11]_{ic}=95$ $F[11]_{oc}=4$ $F[11]_{K}=7$ $F[11]_{P}=3$
12	BN1D	$F[5]_{c}^{B}=927$	24	BN1D	$F[11]_{c}^{B}=4$

TABLE V: Hyperparameters of the most effective CNN 1D model for the SMAP dataset learning rate = 0.000001). **C1D** means Conv1D layer, while **BN1D** means Batch Norm 1D layer

	Layer	Parameters		Layer	Parameters
1	C1D	$F[0]_{ic}=5$ $F[0]_{oc}=75$ $F[0]_{K}=3$ $F[0]_{P}=1$	13	C1D	$F[6]_{ic}=1041$ $F[6]_{oc}=694$ $F[6]_{K}=2$ $F[6]_{P}=1$
2	BN1D	$F[0]_{c}^{B}=75$	14	BN1D	$F[6]_{c}^{B}=694$
3	C1D	$F[1]_{ic}=75$ $F[1]_{oc}=70$ $F[1]_{K}=2$ $F[1]_{P}=1$	15	C1D	$F[7]_{ic}=694$ $F[7]_{oc}=437$ $F[7]_{K}=2$ $F[7]_{P}=1$
4	BN1D	$F[1]_{c}^{B}=70$	16	BN1D	$F[7]_{c}^{B}=437$
5	C1D	$F[2]_{ic}=70$ $F[2]_{oc}=273$ $F[2]_{K}=5$ $F[2]_{P}=3$	17	C1D	$F[8]_{ic}=437$ $F[8]_{oc}=273$ $F[8]_{K}=3$ $F[8]_{P}=1$
6	BN1D	$F[2]_{c}^{B}=273$	18	BN1D	$F[8]_{c}^{B}=273$
7	C1D	$F[3]_{ic}=273$ $F[3]_{oc}=437$ $F[3]_{K}=3$ $F[3]_{P}=1$	19	C1D	$F[9]_{ic}=273$ $F[9]_{oc}=70$ $F[9]_{ic}=5$ $F[9]_{ic}=3$
8	BN1D	$F[3]_{c}^{B}=437$	20	BN1D	$F[9]_{c}^{B}=70$
9	C1D	$F[4]_{ic}=437$ $F[4]_{oc}=694$ $F[4]_{K}=2$ $F[4]_{P}=1$	21	C1D	$F[10]_{ic}=70$ $F[10]_{oc}=75$ $F[10]_{K}=2$ $F[10]_{P}=1$
10	BN1D	$F[4]_{c}^{B}=694$	22	BN1D	$F[10]_{c}^{B}=75$
11	C1D	$F[5]_{ic}=694$ $F[5]_{oc}=1041$ $F[5]_{K}=2$ $F[5]_{P}=1$	23	C1D	$F[11]_{ic}=75$ $F[11]_{oc}=5$ $F[11]_{K}=3$ $F[11]_{P}=1$
12	BN1D	$F[5]_{c}^{B}=1041$	24	BN1D	$F[11]_{c}^{B}=5$

III. Additional results and convergence plots

TABLE VI: F-1 score for all entities from SMAP datasets, 1-F_1 score, 2-F_1 score **after two steps**, 3-F_1 score **fine-tuned**

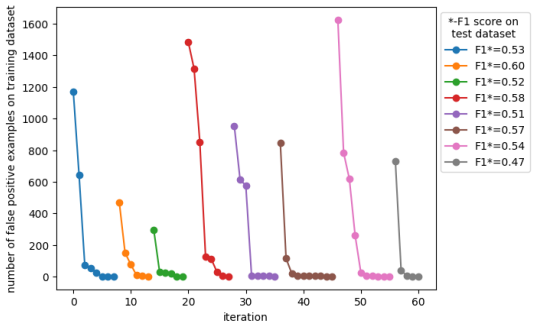
Entity Name	1	2	3	**Entity Name**	1	2	3
P-1	0.15	0.15	0.17	D-6	0.05	0.14	0.29
S-1	0.16	0.71	0.74	D-7	0.59	0.98	0.98
E-1	0.20	0.21	0.21	F-1	0.0	0.0	0.07
E-2	0.46	0.51	0.72	P-4	0.10	0.16	0.16
E-3	0.13	0.14	0.36	G-3	0.03	0.13	0.14
E-4	0.50	0.54	0.64	T-1	0.33	0.56	0.82
E-5	0.07	0.07	0.08	T-2	0.50	0.56	0.69
E-6	0.10	0.11	0.38	D-8	0.04	0.15	0.15
E-7	0.07	0.32	0.34	D-9	0.83	0.88	0.88
E-8	0.27	0.44	0.53	F-2	0.52	0.66	0.72
E-9	0.11	0.28	0.30	G-4	0.25	0.29	0.29
E-10	0.21	0.21	0.28	T-3	0.05	0.09	0.10
E-11	0.21	0.27	0.27	D-11	0.0	0.0	0.0
E-12	0.12	0.13	0.22	D-12	0.94	0.96	0.96
E-13	0.06	0.06	0.07	B-1	0.03	0.03	0.03
A-1	0.0	0.10	0.10	G-6	0.25	0.62	0.64
D-1	0.77	0.94	0.96	G-7	0.32	0.45	0.51
P-3	0.31	0.62	0.63	P-7	0.42	0.67	0.73
D-2	0.84	0.95	0.95	R-1	0.03	0.09	0.09
D-3	0.68	0.95	0.97	A-5	0.71	0.75	0.77
D-4	0.69	0.98	0.99	A-6	0.83	0.84	0.88
A-2	0.0	0.0	0.10	A-7	0.53	0.54	0.54
A-3	0.0	0.0	0.15	D-13	0.09	0.11	0.11
A-4	0.08	0.19	0.22	P-2	0.39	0.77	0.79
G-1	0.0	0.0	0.17	A-8	0.08	0.42	0.89
G-2	0.0	0.19	0.19	A-9	0.61	0.98	0.99
D-5	0.20	0.21	0.68	F-3	0.23	0.49	0.49

TABLE VII: F-1 score for all entities from MSL datasets, 1-F_1 score, 2-F_1 score **after two steps**, 3-F_1 score **fine-tuned**

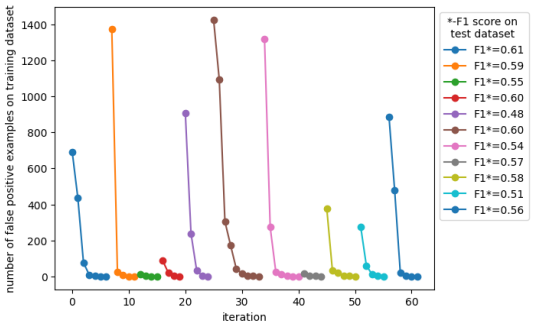
Entity Name	1	2	3	**Entity Name**	1	2	3
M-6	0.15	0.91	0.92	T-13	0.35	0.35	0.35
M-1	0.58	0.59	0.67	F-4	0.11	0.27	0.27
M-2	0.75	0.78	0.80	F-5	0.47	0.70	0.70
P-10	0.34	0.38	0.38	P-14	0.31	0.48	0.49
T-4	0.07	0.08	0.19	T-8	0.12	0.17	0.17
T-5	0.41	0.48	0.49	P-11	0.11	0.17	0.17
F-7	0.26	0.29	0.35	D-15	0.66	0.71	0.82
M-3	0.20	0.29	0.29	D-16	0.31	0.32	0.33
M-4	0.37	0.52	0.52	M-7	0.09	0.73	0.73
M-5	0.29	0.15	0.20	F-8	0.32	0.32	0.42
P-15	0.6	0.06	0.09	D-14	0.86	0.93	0.93
C-1	0.25	0.27	0.28	T-9	0.23	0.40	0.47
C-2	0.23	0.14	0.27	T-12	0.11	0.13	0.13
S-2	0.23	0.63	0.63				

TABLE VIII: Experimental results with additional metrics.

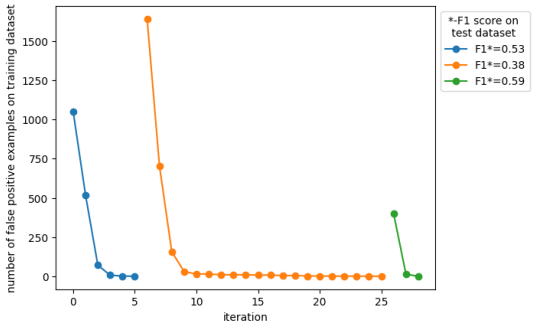
Dataset	Precision	Recall	F1-Score
SMAP	0.8554	0.6988	0.7692
MSL	0.6199	0.5205	0.5659
WADI	0.7938	0.5103	0.6213
SWAT	0.9767	0.7051	0.8190



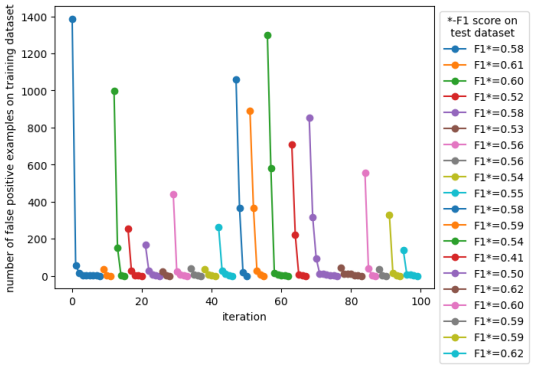
(a) Fine tuning convergence for the WADI dataset with a population size of 8, 64 iterations, $\tau = \frac{1}{256}$, and a mutation probability of 0.02.



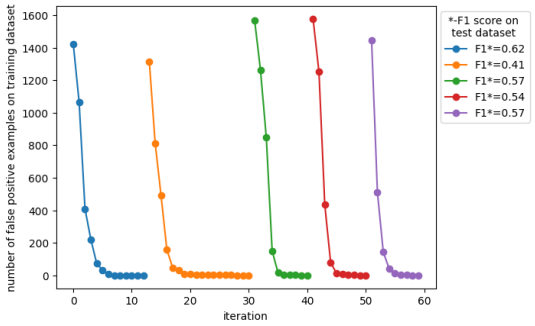
(b) Fine tuning convergence for the WADI dataset with a population size of 16, 64 iterations, $\tau = \frac{1}{256}$, and a mutation probability of 0.02.



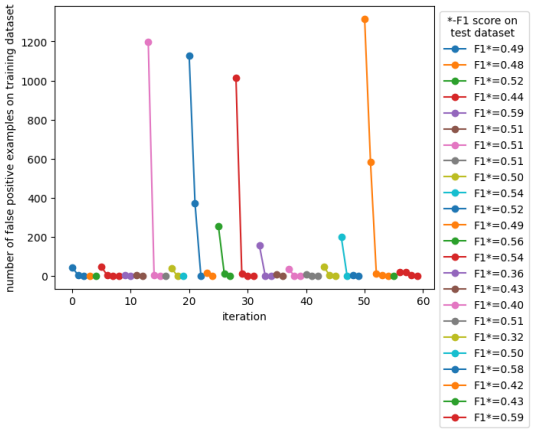
(c) Fine tuning convergence for the WADI dataset with a population size of 24, 32 iterations, $\tau = \frac{1}{256}$, and a mutation probability of 0.02.



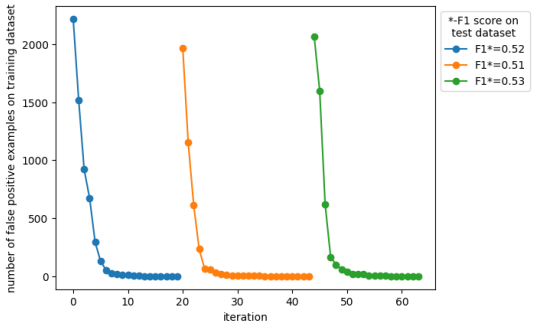
(d) Fine tuning convergence for the WADI dataset with a population size of 24, 100 iterations, $\tau = \frac{1}{256}$, and a mutation probability of 0.02



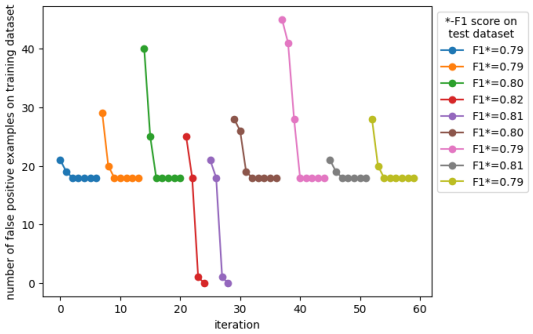
(e) Fine tuning convergence for the WADI dataset with a population size of 24, 64 iterations, $\tau = \frac{1}{512}$, and a mutation probability of 0.02.



(f) Fine tuning convergence for the WADI dataset with a population size of 24, 64 iterations, $\tau = \frac{1}{128}$, and a mutation probability of 0.02.



(g) Fine tuning convergence for the WADI dataset with a population size of 24, 64 iterations, $\tau = \frac{1}{256}$, and a mutation probability of 0.05.



(h) Fine tuning convergence for the SWAT dataset with a population size of 24, 64 iterations, $\tau = \frac{1}{256}$, and a mutation probability of 0.02.

Fig. 1: Additional convergence plots