XCS Classifier System with Experience Replay

Supplemental Material

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A EXPERIMENT CONFIGURATIONS

Environment Modifications. For the **n-Chain** environment, the episode length was reduced from 1000 to only 200, what increases the problem difficulty.

For the **CartPole** environment, the input parameters have been re-scaled to the interval $[0,1]$ (using reasonable lower and upper bounds as determined in preliminary runs) since the utilized XCS implementation expects normalized inputs. The reward scheme was slightly modified to deliver +1 every time the pole keeps balanced by the cart and 0 if it has fallen. This provides a clearer reward signal and facilitates quicker learning for each of the compared algorithms.

Regarding the **MountainCar** environment, we again changed the episode length from 200 to 500, since both XCS variants encountered problems in randomly stumbling into the goal state within only 200 steps. Further, the reward scheme was made binary, i.e., instead of paying -1 for every step (includes reaching the terminal/goal state), we chose to apply a 0/1000 scheme. The latter only pays a reward of 1000 when reaching the goal, otherwise 0. This modification essentially increases the problem difficulty, since it renders the reward signal sparse.

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Table 1. Configured hyperparameter settings. Abbreviations used: TS = tournament selection, UBR = unordered bound hyperrectangular representation, WH = Widrow-Hoff learning rule, RLS = recursive least square learning rule

Parameter	Mario	6-RMP	WBC	16chain	CartPole	M.Car
Learning steps	100k	40k	50k	50k	50k	60k
N_{max}	7000	800	6400	1000	5000	3000
β	0.3	0.2	0.2	0.1	0.1	0.1
γ	-	-	-	0.9	0.99	0.99
Fitness parameters:						
α	0.1	0.1	0.1	0.1	0.1	0.1
ϵ_0	10	10	1	0.1	8.0	0.1
ν	5	5	5	5	5	5
Deletion parameters:						
θ_{del}	50	20	50	20	200	200
δ	0.1	0.1	0.1	0.1	0.1	0.1
Covering parameters:						
θ_{mna}	7	2	2	2	2	3
p_{ini}	10	10	10	10	0.01	0.01
ϵ_{ini}	0	0	0	10	0.01	0.01
F_{ini}	0.01	0.01	0.01	0.01	0.01	0.01
GA parameters:						
μ	0.04	0.04	0.04	0.04	0.04	0.04
χ	0.8	0.8	0.8	0.8	0.8	0.8
θ_{GA}	30	12	48	50	25	50
θ_{sub}	50	20	50	200	20	20
GA-selection	TS	TS	TS	TS	TS	TS
F_{reduce}	0.1	0.1	0.1	0.1	0.1	0.1
ϵ_{reduce}	1.0	1.0	1.0	0.25	0.25	0.25
Condition parameters:						
Condition	UBR	UBR	UBR	UBR	UBR	UBR
m_0	0.1	0.1	0.2	0.1	0.1	0.1
r_0	0.1	1.0	0.4	0.2	0.2	0.33
Prediction parameters:						
Prediction	scalar	scalar	scalar	scalar	linear	linear
Learning rule	WH	WH	WH	WH	RLS	RLS
δ_{RLS}	-	-	-	-	1.0	500
λ_{RLS}	-	-	-	-	1.0	1.0

For all experiments a maximum capacity for the Replay Memory (RM) of $N = 50k$ has been chosen. The mini-batch size was set to $m = 4$. In all experiments, a warm-up phase to fill the RM was conducted during the initial 1000 steps. No learning happened in this phase.

B ADDITIONAL STATISTICS

Fig. 1. XCS vs. XCS-ER on Mario pixel art.

Table 2. Shapiro-Wilk tests for normality on the Mario problem. The resulting p-values are given in the cells. * (**) indicates a p-value $< \alpha = 0.05$ (0.01), i.e. a high likelihood that the null hypothesis (normality) can be rejected. p-values below 0.05 are marked in bold.

Mario	XCS-ER-8	XCS-ER-4	XCS
Reward mean	0.783	0.637	0.936
System error mean	0.467	0.858	0.065
Macroclassifiers mean	0.209	0.863	0.235
Generality mean	0.213	0.586	0.110

Table 3. Paired one-sided t-tests for XCS vs. XCS-ER on the Mario problem. The resulting p-values are given in the cells. * (**) indicates a p-value $< \alpha = 0.05$ (0.01), i.e. a high likelihood the deviation is statistically significant. p-values below 0.05 are marked in bold.

Mario	XCS-ER-8	XCS-ER-4
Reward mean	0.000**	0.000**
System error mean	0.000**	0.000**
Macroclassifiers mean	0.000**	0.000**
Generality mean	0.000**	0.000**

Fig. 2. XCS vs. XCS-ER on 6-Real Multiplexer

Table 4. Shapiro-Wilk tests for normality for the 6-RMP problem. The resulting p-values are given in the cells. * (**) indicates a p-value $< \alpha = 0.05$ (0.01), i.e. a high likelihood that the null hypothesis (normality) can be rejected. p-values below 0.05 are marked in bold.

6-Real Multiplexer	XCS-ER	XCS
Reward mean	0.060	0.872
System error mean	0.143	0.714
Macroclassifiers mean	0.037*	0.882
Generality mean	0.846	0.117

Table 5. Paired one-sided t-tests for XCS vs. XCS-ER on the 6-RMP problem. The resulting p-values are given in the cells. * (**) indicates a p-value $< \alpha = 0.05$ (0.01), i.e. a high likelihood the deviation from the baseline (XCS without ER) is statistically significant. p-values below 0.05 are marked in bold.

6-Real Multiplexer	XCS-ER
Reward mean	0.000**
System error mean	0.000**
Macroclassifiers mean	0.000**
Generality mean	0.000**

Fig. 3. XCS vs. XCS-ER on WBC classification

Table 6. Shapiro-Wilk tests for normality on the WBC data set. The resulting p-values are depicted in the cells. * (**) indicates a p-value $< \alpha = 0.05$ (0.01), i.e. a high likelihood that the null hypothesis (normality) can be rejected. p-values below 0.05 are marked in bold.

WBC	XCS-ER	XCS
Reward mean	0.458	0.333
System error mean	0.195	0.316
Macroclassifiers mean	0.096	0.458
Generality mean	0.026*	0.003**

Table 7. Paired one-sided t-tests for XCS vs. XCS-ER on the WBC data set. The resulting p-values are given in the cells. * (**) indicates a p-value $< \alpha = 0.05$ (0.01), i.e. a high likelihood the deviation from the baseline (XCS without ER) is statistically significant. p-values below 0.05 are marked in bold.

WBC	XCS-ER
Reward mean	0.000**
System error mean	0.000**
Macroclassifiers mean	0.000**
Generality mean	0.000**

Table 8. Overall results for the multi-step environments: Reward, prediction error, population size in macroclassifiers, generality, OTM and Divergences are shown. Table entries indicate the overall means $\pm 1SD$ over the 30 repetitions. Divergence criteria for individual repetitions for 16Chain, CartPole, MountainCar are OTM values below 1, 70 and 200 respectively. 'T' indicates active teletransportation. Arrows show whether the metric increased up or decreased. Statistical significance when compared to the regular XCS is determined via the Wilcoxon signed-rank test. * (**) indicates a p-value $< \alpha = 0.05$ (0.01). p-values below 0.05 confirming improvements are given in bold.

16Chain	Reward	Pr.Err.	$ P $	Gen.	OTM	Div
XCS-ER	0.56 $\downarrow^{**}$ ± 0.37	0.23 $\uparrow^{**}$ ± 0.01	92.92$\downarrow^{**}$ ± 25.81	0.13$\uparrow^{**}$ ± 0.06	95.3 $\downarrow^{**}$ ± 63.6	9 $\uparrow$
DQN	n/a	n/a	n/a	n/a	143.1 $\uparrow$ ± 1.4	0 $\downarrow$
XCS	0.82 ± 0.15	0.14 ± 0.03	152.68 ± 22.16	0.07 ± 0.02	138.6 ± 25.7	1
16Chain T	Reward	Pr.Err.	$ P $	Gen.	OTM	Div
XCST-ER	0.86 $\downarrow$ ± 0.03	0.24 $\uparrow^{**}$ ± 0.01	111.65 $\downarrow$ ± 21.94	0.10 $\uparrow$ ± 0.05	147.6 $\downarrow$ ± 4.2	0
DQNT	n/a	n/a	n/a	n/a	148.0 $\downarrow$ ± 5.8	0
XCST	0.88 ± 0.00	0.20 ± 0.03	117.90 ± 13.54	0.09 ± 0.01	149.2 ± 0.6	0
CartPole	Reward	Pr.Err.	$ P $	Gen.	OTM	Div
XCS-ER	0.98 $\downarrow$ ± 0.03	1.92 $\uparrow^{**}$ ± 0.11	1937.44 $\uparrow^{**}$ ± 106.85	0.0004$\uparrow^{**}$ ± 0.0000	93.0 $\downarrow$ ± 47.6	9 $\uparrow$
DQN	n/a	n/a	n/a	n/a	122.2 $\uparrow$ ± 13.4	0 $\downarrow$
XCS	0.99 ± 0.01	1.62 ± 0.25	1703.42 ± 161.46	0.0003 ± 0.0000	110.6 ± 46.5	7
CartPole T	Reward	Pr.Err.	$ P $	Gen.	OTM	Div
XCST-ER	0.94$\uparrow^{**}$ ± 0.02	2.17 $\uparrow^{**}$ ± 0.12	2162.30$\downarrow^{**}$ ± 51.94	0.0013$\uparrow^{**}$ ± 0.0000	18.29$\uparrow^{**}$ ± 6.22	30
DQNT	n/a	n/a	n/a	n/a	38.75$\uparrow^{**}$ ± 2.19	30
XCST	0.92 ± 0.02	1.90 ± 0.09	2640.10 ± 70.37	0.0005 ± 0.0001	13.76 ± 3.59	30
M.Car	Reward	Pr.Err.	$ P $	Gen.	OTM	Div
XCS-ER	0.13 $\uparrow$ ± 0.06	1.73$\downarrow^{**}$ ± 2.77	383.25 $\uparrow$ ± 204.68	0.05$\uparrow^{**}$ ± 0.01	38.57 $\uparrow$ ± 86.37	29
DQN	n/a	n/a	n/a	n/a	504.96$\uparrow^{**}$ ± 216.03	3 $\downarrow$
XCS	0.06 ± 0.15	3.5E5 $\pm 1.8E6$	325.17 ± 162.39	0.04 ± 0.01	29.15 ± 63.27	29
M.Car T	Reward	Pr.Err.	$ P $	Gen.	OTM	Div
XCST-ER	4.33$\uparrow^*$ ± 1.3	12.40$\downarrow^{**}$ ± 3.69	1150.36 $\uparrow$ ± 88.24	0.01 $\downarrow^{**}$ ± 0.00	626.3 $\uparrow$ ± 132.4	0 $\downarrow$
DQNT	n/a	n/a	n/a	n/a	814.5$\uparrow^{**}$ ± 90.9	0 $\downarrow$
XCST	3.22 ± 2.17	1.2E21 $\pm 6.3E21$	1041.51 ± 114.82	0.02 ± 0.00	511.2 ± 219.5	5

Table 9. Shapiro-Wilk tests for normality on the multi-step environments. The resulting p-values are given in the cells. * (**) indicates a p-value $< \alpha = 0.05$ (0.01), i.e. a high likelihood that the null hypothesis (normality) can be rejected. p-values below 0.05 are marked in bold.

16Chain	XCS-ER	XCS	DQN
Reward mean	0.000**	0.000**	n/a
Prediction error mean	0.003**	0.366	n/a
Macroclassifiers mean	0.058	0.008**	n/a
Generality mean	0.000**	0.000**	n/a
OTM	0.000**	0.000**	0.000**
16Chain Tele.	XCS-ER	XCS	DQN
Reward mean	0.000**	0.037*	n/a
Prediction error mean	0.001**	0.531	n/a
Macroclassifiers mean	0.000**	0.597	n/a
Generality mean	0.000**	0.733	n/a
OTM	0.000**	0.02*	0.000**
CartPole	XCS-ER	XCS	DQN
Reward mean	0.000**	0.000**	n/a
Prediction error mean	0.625	0.023*	n/a
Macroclassifiers mean	0.875	0.222	n/a
Generality mean	0.432	0.618	n/a
OTM	0.006**	0.000**	0.099
CartPole Tele.	XCS-ER	XCS	DQN
Reward mean	0.056	0.639	n/a
Prediction error mean	0.184	0.167	n/a
Macroclassifiers mean	0.026*	0.976	n/a
Generality mean	0.594	0.240	n/a
OTM	0.177	0.002**	0.370
MountainCar	XCS-ER	XCS	DQN
Reward mean	0.000**	0.000**	n/a
Prediction error mean	0.000**	0.000**	n/a
Macroclassifiers mean	0.000**	0.006**	n/a
Generality mean	0.367	0.303	n/a
OTM	0.000**	0.000**	0.023*
MountainCar Tele.	XCS-ER	XCS	DQN
Reward mean	0.673	0.067	n/a
Prediction error mean	0.641	0.000**	n/a
Macroclassifiers mean	0.024*	0.023*	n/a
Generality mean	0.070	0.000**	n/a
OTM	0.004**	0.042	0.005**

As can be noticed, most of the metrics do not follow a normal distribution. Even if normality can be confirmed in certain cases, a parametric test is still not plausibly applicable when the sample considered for comparison violates this assumption. For that reason, we decided to exclusively conduct non-parametric Wilcoxon tests across all multi-step experiments.

Table 10. Wilcoxon signed-rank tests for the multi-step environments. The resulting p-values are given in the cells. * (**) indicates a p-value $< \alpha = 0.05$ (0.01), i.e. a high likelihood that the deviation from the baseline (XCS without ER) is statistically significant. p-values below 0.05 are marked in bold.

16Chain	XCS-ER	DQN
Reward mean	0.000**	n/a
Prediction error mean	0.000**	n/a
Macroclassifiers mean	0.000**	n/a
Generality mean	0.000**	n/a
OTM	0.000**	0.959
16Chain Tele.	XCS-ER	DQN
Reward mean	0.254	n/a
Prediction error mean	0.000**	n/a
Macroclassifiers mean	0.349	n/a
Generality mean	0.644	n/a
OTM	0.394	0.504
CartPole	XCS-ER	DQN
Reward mean	0.136	n/a
Prediction error mean	0.000**	n/a
Macroclassifiers mean	0.000**	n/a
Generality mean	0.000**	n/a
OTM	0.111	0.428
CartPole Tele.	XCS-ER	DQN
Reward mean	0.000**	n/a
Prediction error mean	0.000**	n/a
Macroclassifiers mean	0.000**	n/a
Generality mean	0.000**	n/a
OTM	0.000**	0.000**
MountainCar	XCS-ER	DQN
Reward mean	0.178	n/a
Prediction error mean	0.002**	n/a
Macroclassifiers mean	0.360	n/a
Generality mean	0.001**	n/a
OTM	0.550	0.000**
MountainCar Tele.	XCS-ER	DQN
Reward mean	0.014*	n/a
Prediction error mean	0.000**	n/a
Macroclassifiers mean	0.000**	n/a
Generality mean	0.000**	n/a
OTM	0.060	0.000**