TEA: Test-time Energy Adaptation

Paper Code

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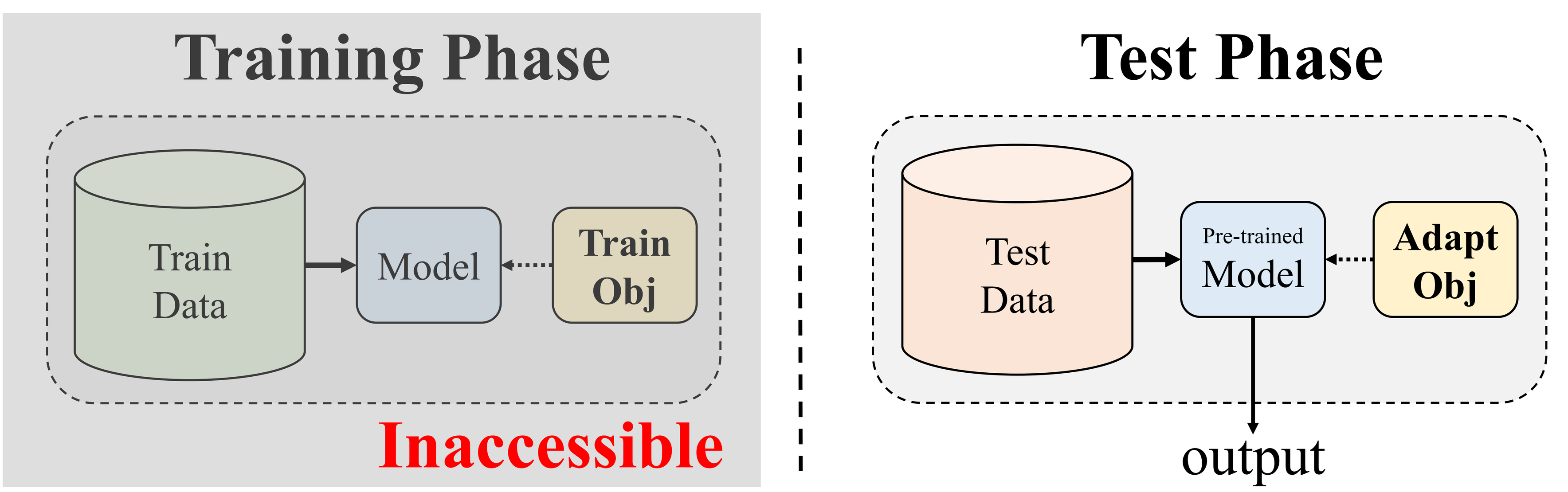
INTRODUCTION

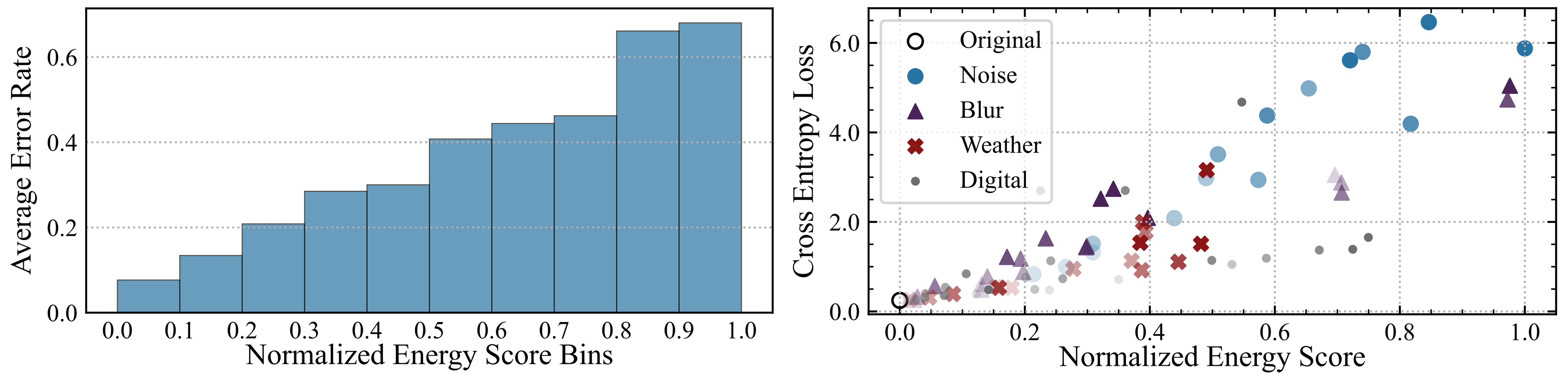
Objective: Improving model **generalizability** when test data diverges from training distribution, without requiring access to training data and processes.
Weakness of existing methods: Current TTA methods fail to address the fundamental issue: **covariate shift**, i.e., the decreased generalizability can be attributed to the model's reliance on the marginal distribution of the training data, which may impair model calibration and introduce confirmation bias.
Motivation: Transforming the trained classifier into an **energy-based** model and aligning the model's distribution with the test data's, enhancing its ability to perceive test distributions and thus improving overall generalizability.

BACKGROUND

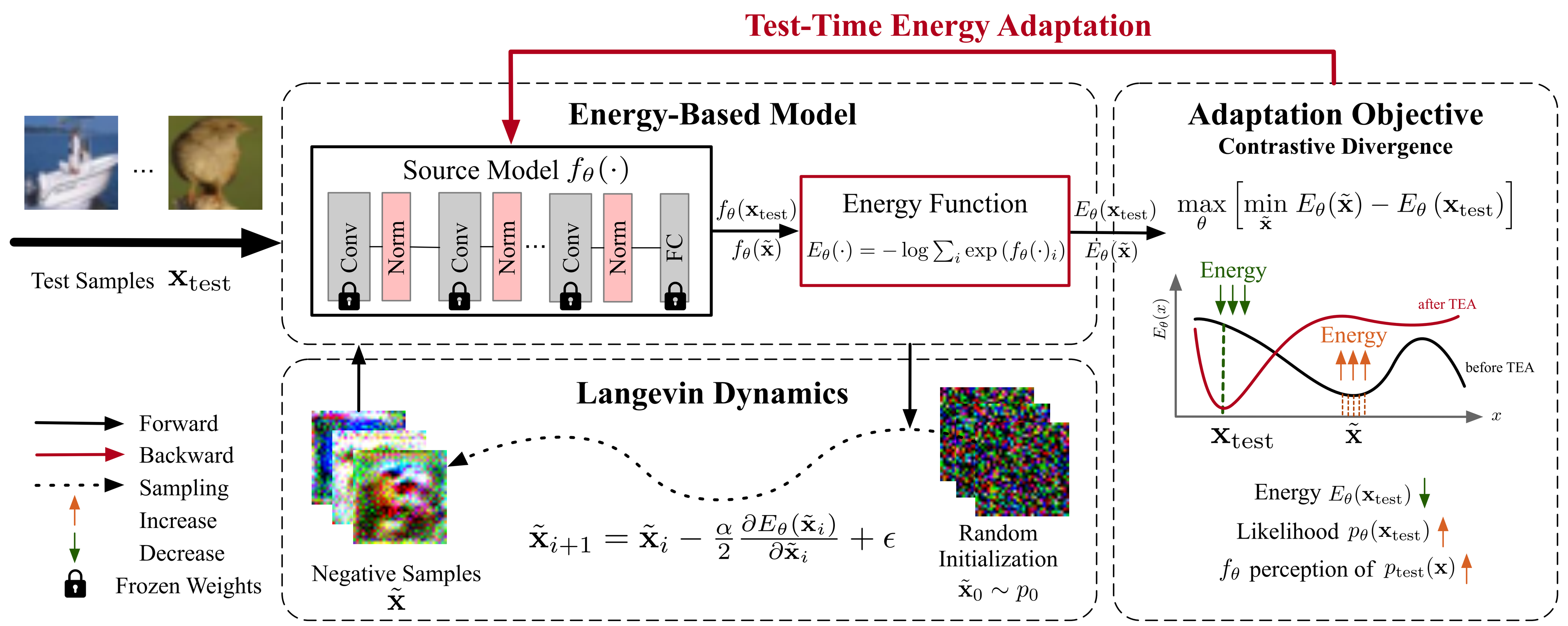


MOTIVATION

Low Energy ➡ High Probability High Performance
High Energy ➡ Low Probability Low Performance



METHOD



Treating Classifier As EBM

Pretrained Classifier

$$p_\theta(y \mid \mathbf{x}) = \frac{\exp(f_\theta(\mathbf{x})[y])}{\sum_{y'} \exp(f_\theta(\mathbf{x})[y'])}$$

introduce unknown normalizing constant Z_θ

$$p_\theta(\mathbf{x}, y) = \frac{\exp(f_\theta(\mathbf{x})[y])}{Z_\theta}$$

marginalize out y

$$p_\theta(\mathbf{x}) = \sum_y p_\theta(\mathbf{x}, y) = \frac{\sum_y \exp(f_\theta(\mathbf{x})[y])}{Z_\theta}$$

substitute E_θ

$$p_\theta(\mathbf{x}) = \frac{\exp(-E_\theta(\mathbf{x}))}{Z_\theta}$$

Energy Based Model

$$E_\theta(\mathbf{x}) = -\log \sum_y \exp(f_\theta(\mathbf{x})[y])$$

Inject Test Distribution Into Classifier

Contrastive Divergence

$$\frac{\partial \log p_\theta(\mathbf{x}_{\text{test}})}{\partial \theta} = \mathbb{E}_{\tilde{\mathbf{x}} \sim p_\theta}\left[\frac{\partial E_\theta(\tilde{\mathbf{x}})}{\partial \theta}\right] - \frac{\partial E_\theta(\mathbf{x}_{\text{test}})}{\partial \theta}$$

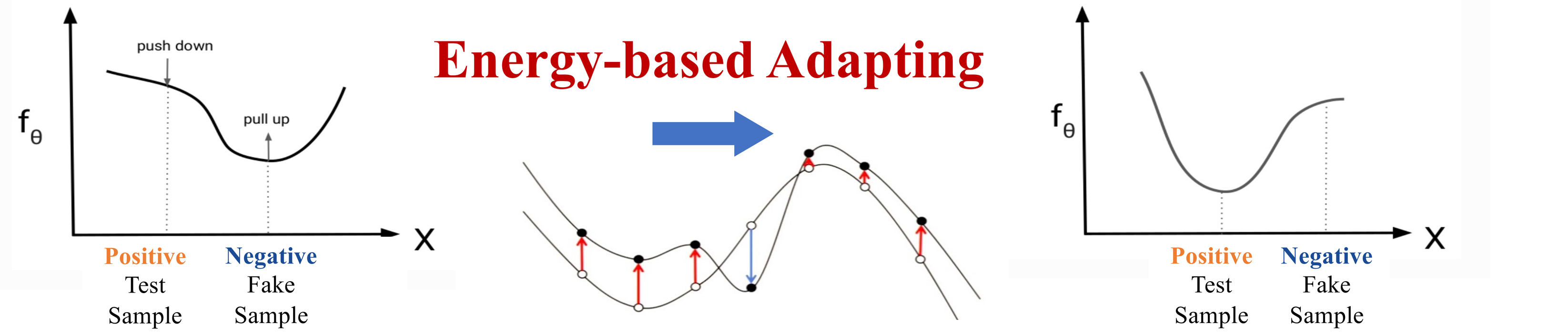
Stochastic Gradient Langevin Dynamics

$$\tilde{\mathbf{x}}_{t+1} = \mathbf{x}_t - \frac{\alpha}{2}\frac{\partial E_\theta(\tilde{\mathbf{x}}_t)}{\partial \tilde{\mathbf{x}}_t} + \sqrt{\alpha}\epsilon, \quad \epsilon \sim \mathcal{N}(\mathbf{0}, \mathbf{I}),$$

Overall Objective

$$\max p_\theta(\mathbf{x}_{\text{test}}) = \max_\theta \left[\min_{\tilde{\mathbf{x}}} E_\theta(\tilde{\mathbf{x}}) - E_\theta(\mathbf{x}_{\text{test}})\right]$$

Energy-based Adapting

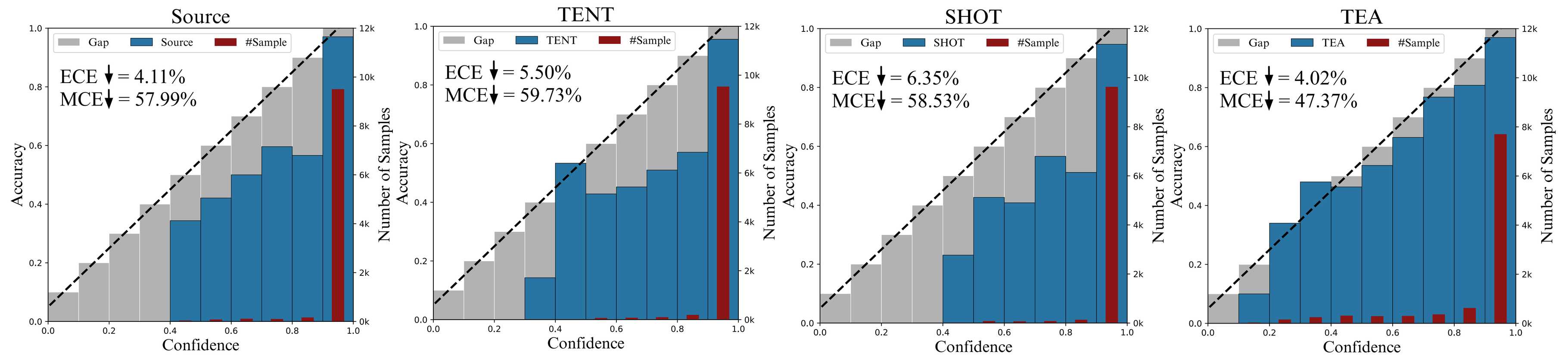


EXPERIMENTS

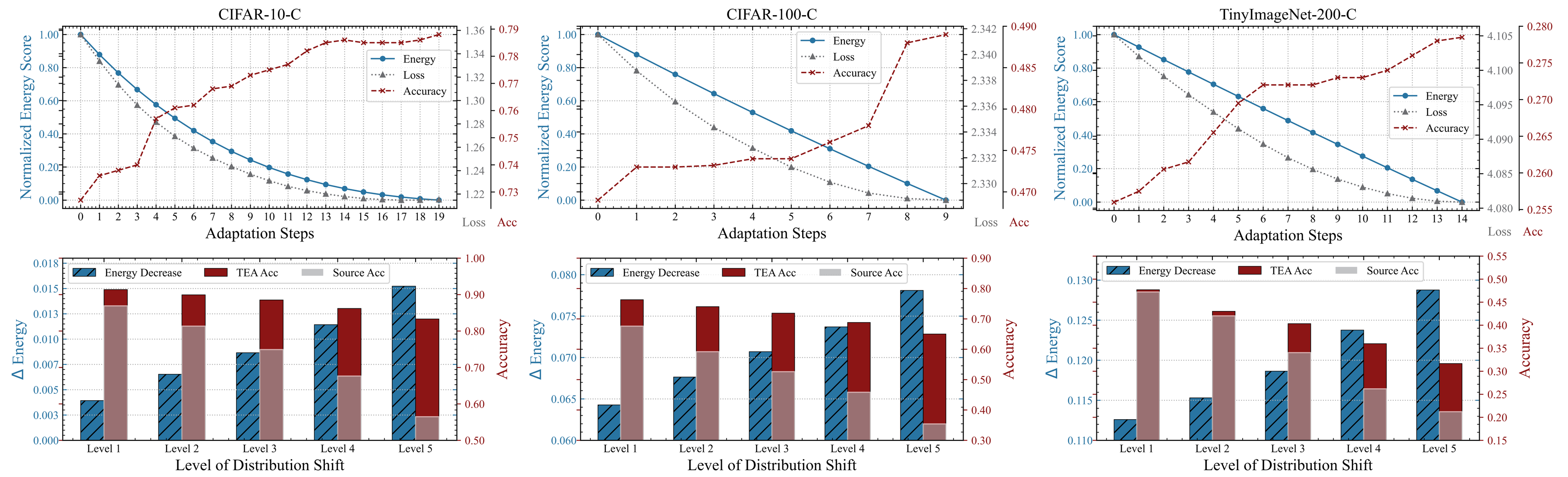
TEA's Adaptation Performance

WRN-28-10 BatchNorm		CIFAR-10(C) Clean	CIFAR-10(C) Corr Severity 5		CIFAR-10(C) Corr Severity 1-5		CIFAR-100(C) Clean	CIFAR-100(C) Corr Severity 5		CIFAR-100(C) Corr Severity 1-5		Tiny-ImageNet(C) Clean	Tiny-ImageNet(C) Corr Severity 5		Tiny-ImageNet(C) Corr Severity 1-5	
		Acc (↑)	Acc (↑)	mCE (↓)	Acc (↑)	mCE (↓)	Acc (↑)	Acc (↑)	mCE (↓)	Acc (↑)	mCE (↓)	Acc (↑)	Acc (↑)	mCE (↓)	Acc (↑)	mCE (↓)
Source		94.77	56.47	100.00	73.45	100.00	81.79	35.39	100.00	52.12	100.00	63.19	21.21	100.00	34.13	100.00
Norm	BN [52]	93.97	79.56	52.65	85.63	60.00	80.83	60.06	63.54	68.11	69.42	45.04	27.74	93.42	34.27	100.96
	DUA* [41]	-	80.10	50.78	-	-	-	-	-	-	-	-	-	-	-	-
Pseudo	PL [34]	93.75	51.42	106.98	72.62	99.37	80.52	53.40	72.12	64.53	75.29	47.84	28.26	91.22	39.83	91.67
	SHOT [36]	93.25	74.77	63.19	82.35	72.61	80.52	56.53	68.01	66.00	73.28	47.95	29.14	90.16	**40.01**	**91.41**
Entropy	TENT [60]	93.66	81.41	48.13	86.75	56.17	80.14	63.09	59.42	69.47	67.80	39.54	26.31	95.52	32.03	104.49
	ETA [45]	93.96	79.58	52.64	85.63	59.99	80.65	59.82	64.52	67.17	72.40	43.20	27.28	94.12	33.46	102.25
	EATA [45]	93.96	79.59	52.62	85.64	59.98	80.68	60.24	63.75	67.48	71.66	43.42	27.28	94.09	33.47	102.24
	SAR [46]	93.97	79.77	51.94	85.83	58.97	80.84	62.95	59.37	70.01	65.99	41.58	28.21	92.82	34.60	100.47
Energy	TEA	**94.09**	**83.34**	**43.69**	**87.88**	**52.00**	**80.88**	**65.10**	**56.07**	**71.22**	**63.72**	**51.65**	**31.67**	**87.99**	39.96	92.12

TEA's Improvements in Confidence Calibration



Relation between TEA's Energy Reduction and Generalizability Enhancement



TEA's Distribution Perception and Generation