
Learning with Symmetric Label Noise: The Importance of Being Unhinged

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Abstract

Convex potential minimisation is the *de facto* approach to binary classification. However, Long and Servedio [2010] proved that under symmetric label noise (SLN), minimisation of *any* convex potential over a linear function class can result in classification performance equivalent to random guessing. This ostensibly shows that convex losses are not SLN-robust. In this paper, we propose a convex, classification-calibrated loss and prove that it *is* SLN-robust. The loss avoids the Long and Servedio [2010] result by virtue of being *negatively unbounded*. The loss is a modification of the hinge loss, where one does not clamp at zero; hence, we call it the *unhinged loss*. We show that the optimal unhinged solution is equivalent to that of a strongly regularised SVM, and is the limiting solution for *any* convex potential; this implies that strong ℓ_2 regularisation makes most standard learners SLN-robust. Experiments confirm the unhinged loss’ SLN-robustness is borne out in practice. So, with apologies to Wilde [1895], while the truth is rarely pure, it *can* be simple.

1 Learning with symmetric label noise

Binary classification is the canonical supervised learning problem. Given an instance space \mathcal{X} , and samples from some distribution D over $\mathcal{X} \times \{\pm 1\}$, the goal is to learn a scorer $s: \mathcal{X} \rightarrow \mathbb{R}$ with low *misclassification error* on future samples drawn from D . Our interest is in the more realistic scenario where the learner observes samples from some corruption \bar{D} of D , where labels have some constant probability of being flipped, and the goal is still to perform well with respect to D . This problem is known as learning from symmetric label noise (SLN learning) [Angluin and Laird, 1988].

Long and Servedio [2010] showed that there exist linearly separable D where, when the learner observes some corruption \bar{D} with symmetric label noise of *any nonzero rate*, minimisation of *any convex potential* over a linear function class results in classification performance on D that is equivalent to random guessing. Ostensibly, this establishes that convex losses are not “SLN-robust” and motivates the use of non-convex losses [Stempfel and Ralaivola, 2009, Masnadi-Shirazi et al., 2010, Ding and Vishwanathan, 2010, Denchev et al., 2012, Manwani and Sastry, 2013].

In this paper, we propose a convex loss and prove that it *is* SLN-robust. The loss avoids the result of Long and Servedio [2010] by virtue of being *negatively unbounded*. The loss is a modification of the hinge loss where one does not clamp at zero; thus, we call it the *unhinged loss*. This loss has several appealing properties, such as being the unique convex loss satisfying a notion of “strong” SLN-robustness (Proposition 5), being classification-calibrated (Proposition 6), consistent when minimised on \bar{D} (Proposition 7), and having an simple optimal solution that is the difference of two kernel means (Equation 8). Finally, we show that this optimal solution is equivalent to that of a strongly regularised SVM (Proposition 8), and *any* twice-differentiable convex potential (Proposition 9), implying that strong ℓ_2 regularisation endows most standard learners with SLN-robustness.

The classifier resulting from minimising the unhinged loss is not new [Devroye et al., 1996, Chapter 10], [Schölkopf and Smola, 2002, Section 1.2], [Shawe-Taylor and Cristianini, 2004, Section 5.1]. However, establishing this classifier’s (strong) SLN-robustness, uniqueness thereof, and its equivalence to a highly regularised SVM solution, to our knowledge is novel.

2 Background and problem setup

Fix an instance space \mathcal{X} . We denote by D a distribution over $\mathcal{X} \times \{\pm 1\}$, with random variables $(X, Y) \sim D$. Any D may be expressed via the *class-conditionals* $(P, Q) = (\mathbb{P}(X | Y = 1), \mathbb{P}(X | Y = -1))$ and *base rate* $\pi = \mathbb{P}(Y = 1)$, or via the *marginal* $M = \mathbb{P}(X)$ and *class-probability function* $\eta: x \mapsto \mathbb{P}(Y = 1 | X = x)$. We interchangeably write D as $D_{P,Q,\pi}$ or $D_{M,\eta}$.

2.1 Classifiers, scorers, and risks

A *scorer* is any function $s: \mathcal{X} \rightarrow \mathbb{R}$. A *loss* is any function $\ell: \{\pm 1\} \times \mathbb{R} \rightarrow \mathbb{R}$. We use ℓ_{-1}, ℓ_1 to refer to $\ell(-1, \cdot)$ and $\ell(1, \cdot)$. The ℓ -*conditional risk* $L_\ell: [0, 1] \times \mathbb{R} \rightarrow \mathbb{R}$ is defined as $L_\ell: (\eta, v) \mapsto \eta \cdot \ell_1(v) + (1 - \eta) \cdot \ell_{-1}(v)$. Given a distribution D , the ℓ -*risk* of a scorer s is defined as

$$\mathbb{L}_\ell^D(s) \doteq \mathbb{E}_{(X,Y) \sim D} [\ell(Y, s(X))], \quad (1)$$

so that $\mathbb{L}_\ell^D(s) = \mathbb{E}_{X \sim M} [L_\ell(\eta(X), s(X))]$. For a set \mathcal{S} , $\mathbb{L}_\ell^D(\mathcal{S})$ is the set of ℓ -risks for all scorers in \mathcal{S} .

A *function class* is any $\mathcal{F} \subseteq \mathbb{R}^{\mathcal{X}}$. Given some \mathcal{F} , the set of *restricted Bayes-optimal scorers* for a loss ℓ are those scorers in \mathcal{F} that minimise the ℓ -risk:

$$\mathcal{S}_\ell^{D,\mathcal{F},*} \doteq \underset{s \in \mathcal{F}}{\text{Argmin}} \mathbb{L}_\ell^D(s).$$

The set of (unrestricted) Bayes-optimal scorers is $\mathcal{S}_\ell^{D,*} = \mathcal{S}_\ell^{D,\mathcal{F},*}$ for $\mathcal{F} = \mathbb{R}^{\mathcal{X}}$. The *restricted ℓ -regret* of a scorer is its excess risk over that of any restricted Bayes-optimal scorer:

$$\text{regret}_\ell^{D,\mathcal{F}}(s) \doteq \mathbb{L}_\ell^D(s) - \inf_{t \in \mathcal{F}} \mathbb{L}_\ell^D(t).$$

Binary classification is concerned with the *zero-one loss*, $\ell^{01}: (y, v) \mapsto \mathbb{I}[yv < 0] + \frac{1}{2}\mathbb{I}[v = 0]$. A loss ℓ is *classification-calibrated* if all its Bayes-optimal scorers are also optimal for zero-one loss: $(\forall D) \mathcal{S}_\ell^{D,*} \subseteq \mathcal{S}_{01}^{D,*}$. A *convex potential* is any loss $\ell: (y, v) \mapsto \phi(yv)$, where $\phi: \mathbb{R} \rightarrow \mathbb{R}_+$ is convex, non-increasing, differentiable with $\phi'(0) < 0$, and $\phi(+\infty) = 0$ [Long and Servedio, 2010, Definition 1]. All convex potentials are classification-calibrated [Bartlett et al., 2006, Theorem 2.1].

2.2 Learning with symmetric label noise (SLN learning)

The problem of learning with *symmetric label noise (SLN learning)* is the following [Angluin and Laird, 1988, Kearns, 1998, Blum and Mitchell, 1998, Natarajan et al., 2013]. For some notional “clean” distribution D , which we would like to observe, we instead observe samples from some corrupted distribution $\text{SLN}(D, \rho)$, for some $\rho \in [0, 1/2)$. The distribution $\text{SLN}(D, \rho)$ is such that the marginal distribution of instances is unchanged, but each label is independently flipped with probability ρ . The goal is to learn a scorer from these corrupted samples such that $\mathbb{L}_{01}^D(s)$ is small.

For any quantity in D , we denote its corrupted counterparts in $\text{SLN}(D, \rho)$ with a bar, e.g. \bar{M} for the corrupted marginal distribution, and $\bar{\eta}$ for the corrupted class-probability function; additionally, when ρ is clear from context, we will occasionally refer to $\text{SLN}(D, \rho)$ by \bar{D} . It is easy to check that the corrupted marginal distribution $\bar{M} = M$, and [Natarajan et al., 2013, Lemma 7]

$$(\forall x \in \mathcal{X}) \bar{\eta}(x) = (1 - 2\rho) \cdot \eta(x) + \rho. \quad (2)$$

3 SLN-robustness: formalisation

We consider learners (ℓ, \mathcal{F}) for a loss ℓ and a function class \mathcal{F} , with learning being the search for some $s \in \mathcal{F}$ that minimises the ℓ -risk. Informally, (ℓ, \mathcal{F}) is “robust” to symmetric label noise (SLN-robust) if minimising ℓ over \mathcal{F} gives the same classifier on both the clean distribution D , which

the learner would *like* to observe, and $\text{SLN}(D, \rho)$ for *any* $\rho \in [0, 1/2)$, which the learner *actually* observes. We now formalise this notion, and review what is known about SLN-robust learners.

3.1 SLN-robust learners: a formal definition

For some fixed instance space \mathcal{X} , let Δ denote the set of distributions on $\mathcal{X} \times \{\pm 1\}$. Given a notional “clean” distribution D , $\mathcal{N}_{\text{sln}} : \Delta \rightarrow 2^\Delta$ returns the *set* of possible corrupted versions of D the learner may observe, where labels are flipped with unknown probability ρ :

$$\mathcal{N}_{\text{sln}} : D \mapsto \left\{ \text{SLN}(D, \rho) \mid \rho \in \left[0, \frac{1}{2}\right) \right\}.$$

Equipped with this, we define our notion of SLN-robustness.

Definition 1 (SLN-robustness). *We say that a learner (ℓ, \mathcal{F}) is SLN-robust if*

$$(\forall D \in \Delta) (\forall \bar{D} \in \mathcal{N}_{\text{sln}}(D)) \mathbb{L}_{01}^D(\mathcal{S}_\ell^{D, \mathcal{F}, *}) = \mathbb{L}_{01}^{\bar{D}}(\mathcal{S}_\ell^{\bar{D}, \mathcal{F}, *}). \quad (3)$$

That is, SLN-robustness requires that for *any* level of label noise in the observed distribution \bar{D} , the classification performance (wrt D) of the learner is the same as if the learner directly observes D . Unfortunately, a widely adopted class of learners is *not* SLN-robust, as we will now see.

3.2 Convex potentials with linear function classes are not SLN-robust

Fix $\mathcal{X} = \mathbb{R}^d$, and consider learners with a convex potential ℓ , and a function class of linear scorers

$$\mathcal{F}_{\text{lin}} = \{x \mapsto \langle w, x \rangle \mid w \in \mathbb{R}^d\}.$$

This captures e.g. the linear SVM and logistic regression, which are widely studied in theory and applied in practice. Disappointingly, these learners are *not* SLN-robust: Long and Servedio [2010, Theorem 2] give an example where, when learning under symmetric label noise, for *any* convex potential ℓ , the corrupted ℓ -risk minimiser over \mathcal{F}_{lin} has classification performance equivalent to random guessing on D . This implies that $(\ell, \mathcal{F}_{\text{lin}})$ is not SLN-robust¹ as per Definition 1.

Proposition 1 (Long and Servedio [2010, Theorem 2]). *Let $\mathcal{X} = \mathbb{R}^d$ for any $d \geq 2$. Pick any convex potential ℓ . Then, $(\ell, \mathcal{F}_{\text{lin}})$ is not SLN-robust.*

3.3 The fallout: what learners are SLN-robust?

In light of Proposition 1, there are two ways to proceed in order to obtain SLN-robust learners: either we change the class of losses ℓ , or we change the function class \mathcal{F} .

The first approach has been pursued in a large body of work that embraces non-convex losses [Stempfel and Ralaivola, 2009, Masnadi-Shirazi et al., 2010, Ding and Vishwanathan, 2010, Denchev et al., 2012, Manwani and Sastry, 2013]. While such losses avoid the conditions of Proposition 1, this does not automatically imply that they are SLN-robust when used with \mathcal{F}_{lin} . In Appendix B, we present evidence that some of these losses are in fact *not* SLN-robust when used with \mathcal{F}_{lin} .

The second approach is to consider suitably rich \mathcal{F} that contains the Bayes-optimal scorer for \bar{D} , e.g. by employing a universal kernel. With this choice, one can still use a convex potential loss, and in fact, owing to Equation 2, *any* classification-calibrated loss.

Proposition 2. *Pick any classification-calibrated ℓ . Then, $(\ell, \mathbb{R}^{\mathcal{X}})$ is SLN-robust.*

Both approaches have drawbacks. The first approach has a computational penalty, as it requires optimising a non-convex loss. The second approach has a statistical penalty, as estimation rates with a rich \mathcal{F} will require a larger sample size. Thus, it appears that SLN-robustness involves a computational-statistical tradeoff. However, there is a variant of the first option: pick a loss that is convex, *but not a convex potential*. Such a loss would afford the computational and statistical advantages of minimising convex risks with linear scorers. Manwani and Sastry [2013] demonstrated that square loss, $\ell(y, v) = (1 - yv)^2$, is one such loss. We will show that there is a simpler loss that is convex and SLN-robust, but is not in the class of convex potentials by virtue of being *negatively unbounded*. To derive this loss, we first re-interpret robustness via a noise-correction procedure.

¹Even if we were content with a difference of $\epsilon \in [0, 1/2]$ between the clean and corrupted minimisers’ performance, Long and Servedio [2010, Theorem 2] implies that in the worst case $\epsilon = 1/2$.

4 A noise-corrected loss perspective on SLN-robustness

We now re-express SLN-robustness to reason about optimal scorers on the *same distribution*, but with two *different losses*. This will help characterise a set of “strongly SLN-robust” losses.

4.1 Reformulating SLN-robustness via noise-corrected losses

Given any $\rho \in [0, 1/2)$, Natarajan et al. [2013, Lemma 1] showed how to associate with a loss ℓ a *noise-corrected* counterpart $\bar{\ell}$ such that $\mathbb{L}_\ell^D(s) = \mathbb{L}_{\bar{\ell}}^{\bar{D}}(s)$. The loss $\bar{\ell}$ is defined as follows.

Definition 2 (Noise-corrected loss). *Given any loss ℓ and $\rho \in [0, 1/2)$, the noise-corrected loss $\bar{\ell}$ is*

$$(\forall y \in \{\pm 1\}) (\forall v \in \mathbb{R}) \bar{\ell}(y, v) = \frac{(1 - \rho) \cdot \ell(y, v) - \rho \cdot \ell(-y, v)}{1 - 2\rho}. \quad (4)$$

Since $\bar{\ell}$ depends on the unknown parameter ρ , it is not directly usable to design an SLN-robust learner. Nonetheless, it is a useful theoretical device, since, by construction, for any \mathcal{F} , $\mathcal{S}_\ell^{D, \mathcal{F}, *}$ = $\mathcal{S}_{\bar{\ell}}^{\bar{D}, \mathcal{F}, *}$. This means that a sufficient condition for (ℓ, \mathcal{F}) to be SLN-robust is for $\mathcal{S}_\ell^{\bar{D}, \mathcal{F}, *}$ = $\mathcal{S}_{\bar{\ell}}^{\bar{D}, \mathcal{F}, *}$. Ghosh et al. [2015, Theorem 1] proved a *sufficient* condition on ℓ such that this holds, namely,

$$(\exists C \in \mathbb{R}) (\forall v \in \mathbb{R}) \ell_1(v) + \ell_{-1}(v) = C. \quad (5)$$

Interestingly, Equation 5 is *necessary* for a *stronger* notion of robustness, which we now explore.

4.2 Characterising a stronger notion of SLN-robustness

As the first step towards a stronger notion of robustness, we rewrite (with a slight abuse of notation)

$$\mathbb{L}_\ell^D(s) = \mathbb{E}_{(X, Y) \sim D} [\ell(Y, s(X))] = \mathbb{E}_{(Y, S) \sim R(D, s)} [\ell(Y, S)] \doteq \mathbb{L}_\ell(R(D, s)),$$

where $R(D, s)$ is a distribution over labels and *scores*. Standard SLN-robustness requires that label noise does not change the ℓ -risk minimisers, i.e. that if s is such that $\mathbb{L}_\ell(R(D, s)) \leq \mathbb{L}_\ell(R(D, s'))$ for all s' , the same relation holds with \bar{D} in place of D . Strong SLN-robustness strengthens this notion by requiring that label noise does not affect the ordering of *all* pairs of joint distributions over labels and scores. (This of course trivially implies SLN-robustness.) As with the definition of \bar{D} , given a distribution R over labels and scores, let \bar{R} be the corresponding distribution where labels are flipped with probability ρ . Strong SLN-robustness can then be made precise as follows.

Definition 3 (Strong SLN-robustness). *Call a loss ℓ strongly SLN-robust if for every $\rho \in [0, 1/2)$,*

$$(\forall R, R') \mathbb{L}_\ell(R) \leq \mathbb{L}_\ell(R') \iff \mathbb{L}_\ell(\bar{R}) \leq \mathbb{L}_\ell(\bar{R}').$$

We now re-express strong SLN-robustness using a notion of *order equivalence* of loss pairs, which simply requires that two losses order all distributions over labels and scores identically.

Definition 4 (Order equivalent loss pairs). *Call a pair of losses $(\ell, \bar{\ell})$ order equivalent if*

$$(\forall R, R') \mathbb{L}_\ell(R) \leq \mathbb{L}_\ell(R') \iff \mathbb{L}_{\bar{\ell}}(R) \leq \mathbb{L}_{\bar{\ell}}(R').$$

Clearly, order equivalence of $(\ell, \bar{\ell})$ implies $\mathcal{S}_\ell^{D, \mathcal{F}, *}$ = $\mathcal{S}_{\bar{\ell}}^{\bar{D}, \mathcal{F}, *}$, which in turn implies SLN-robustness. It is thus not surprising that we can relate order equivalence to strong SLN-robustness of ℓ .

Proposition 3. *A loss ℓ is strongly SLN-robust iff for every $\rho \in [0, 1/2)$, $(\ell, \bar{\ell})$ are order equivalent.*

This connection now lets us exploit a classical result in decision theory about order equivalent losses being affine transformations of each other. Combined with the definition of $\bar{\ell}$, this lets us conclude that the sufficient condition of Equation 5 is also *necessary* for strong SLN-robustness of ℓ .

Proposition 4. *A loss ℓ is strongly SLN-robust if and only if it satisfies Equation 5.*

We now return to our original goal, which was to find a convex ℓ that is SLN-robust for \mathcal{F}_{lin} (and ideally more general function classes). The above suggests that to do so, it is reasonable to consider those losses that satisfy Equation 5. Unfortunately, it is evident that if ℓ is convex, non-constant, and bounded below by zero, then it cannot possibly be admissible in this sense. But we now show that removing the boundedness restriction allows for the existence of a convex admissible loss.

5 The unhinged loss: a convex, strongly SLN-robust loss

Consider the following simple, but non-standard convex loss:

$$\ell_1^{\text{unh}}(v) = 1 - v \text{ and } \ell_{-1}^{\text{unh}}(v) = 1 + v.$$

Compared to the hinge loss, the loss does not clamp at zero, i.e. it does not have a hinge. (Thus, peculiarly, it is negatively unbounded, an issue we discuss in §5.3.) Thus, we call this the *unhinged loss*². The loss has a number of attractive properties, the most immediate being its SLN-robustness.

5.1 The unhinged loss is strongly SLN-robust

Since $\ell_1^{\text{unh}}(v) + \ell_{-1}^{\text{unh}}(v) = 2$, Proposition 4 implies that ℓ^{unh} is strongly SLN-robust, and thus that $(\ell^{\text{unh}}, \mathcal{F})$ is SLN-robust for *any* \mathcal{F} . Further, the following uniqueness property is not hard to show.

Proposition 5. *Pick any convex loss ℓ . Then,*

$$(\exists C \in \mathbb{R}) \ell_1(v) + \ell_{-1}(v) = C \iff (\exists A, B, D \in \mathbb{R}) \ell_1(v) = -A \cdot v + B, \ell_{-1}(v) = A \cdot v + D.$$

That is, up to scaling and translation, ℓ^{unh} is the only convex loss that is strongly SLN-robust.

Returning to the case of linear scorers, the above implies that $(\ell^{\text{unh}}, \mathcal{F}_{\text{lin}})$ is SLN-robust. This does not contradict Proposition 1, since ℓ^{unh} is not a convex potential as it is negatively unbounded. Intuitively, this property allows the loss to offset the penalty incurred by instances that are misclassified with high margin by awarding a “gain” for instances that correctly classified with high margin.

5.2 The unhinged loss is classification calibrated

SLN-robustness is by itself insufficient for a learner to be useful. For example, a loss that is uniformly zero is strongly SLN-robust, but is useless as it is not classification-calibrated. Fortunately, the unhinged loss is classification-calibrated, as we now establish. For technical reasons (see §5.3), we operate with $\mathcal{F}_B = [-B, +B]^{\mathcal{X}}$, the set of scorers with range bounded by $B \in [0, \infty)$.

Proposition 6. *Fix $\ell = \ell^{\text{unh}}$. For any $D_{M,\eta}, B \in [0, \infty)$, $\mathcal{S}_{\ell}^{D, \mathcal{F}_B, *} = \{x \mapsto B \cdot \text{sign}(2\eta(x) - 1)\}$.*

Thus, for every $B \in [0, \infty)$, the restricted Bayes-optimal scorer over \mathcal{F}_B has the same sign as the Bayes-optimal classifier for 0-1 loss. In the limiting case where $\mathcal{F} = \mathbb{R}^{\mathcal{X}}$, the optimal scorer is attainable if we operate over the extended reals $\mathbb{R} \cup \{\pm\infty\}$, so that ℓ^{unh} is classification-calibrated.

5.3 Enforcing boundedness of the loss

While the classification-calibration of ℓ^{unh} is encouraging, Proposition 6 implies that its (unrestricted) Bayes-risk is $-\infty$. Thus, the regret of every non-optimal scorer s is identically $+\infty$, which hampers analysis of consistency. In orthodox decision theory, analogous theoretical issues arise when attempting to establish basic theorems with unbounded losses [Ferguson, 1967, pg. 78].

We can side-step this issue by restricting attention to bounded scorers, so that ℓ^{unh} is effectively bounded. By Proposition 6, this does not affect the classification-calibration of the loss. In the context of linear scorers, boundedness of scorers can be achieved by regularisation: instead of working with \mathcal{F}_{lin} , one can instead use $\mathcal{F}_{\text{lin},\lambda} = \{x \mapsto \langle w, x \rangle \mid \|w\|_2 \leq 1/\sqrt{\lambda}\}$, where $\lambda > 0$, so that $\mathcal{F}_{\text{lin},\lambda} \subseteq \mathcal{F}_{R/\sqrt{\lambda}}$ for $R = \sup_{x \in \mathcal{X}} \|x\|_2$. Observe that as $(\ell^{\text{unh}}, \mathcal{F})$ is SLN-robust for *any* \mathcal{F} , $(\ell^{\text{unh}}, \mathcal{F}_{\text{lin},\lambda})$ is SLN-robust for any $\lambda > 0$. As we shall see in §6.3, working with $\mathcal{F}_{\text{lin},\lambda}$ also lets us establish SLN-robustness of the hinge loss when λ is large.

5.4 Unhinged loss minimisation on corrupted distribution is consistent

Using bounded scorers makes it possible to establish a surrogate regret bound for the unhinged loss. This shows classification consistency of unhinged loss minimisation on the *corrupted* distribution.

²This loss has been considered in Sriperumbudur et al. [2009], Reid and Williamson [2011] in the context of maximum mean discrepancy; see the Appendix. The analysis of its SLN-robustness is to our knowledge novel.

Proposition 7. Fix $\ell = \ell^{\text{unh}}$. Then, for any $D, \rho \in [0, 1/2)$, $B \in [1, \infty)$, and scorer $s \in \mathcal{F}_B$,

$$\text{regret}_{01}^D(s) \leq \text{regret}_{\ell}^{D, \mathcal{F}_B}(s) = \frac{1}{1 - 2\rho} \cdot \text{regret}_{\ell}^{\bar{D}, \mathcal{F}_B}(s).$$

Standard rates of convergence via generalisation bounds are also trivial to derive; see the Appendix.

6 Learning with the unhinged loss and kernels

We now show that the optimal solution for the unhinged loss when employing regularisation and kernelised scorers has a simple form. This sheds further light on SLN-robustness and regularisation.

6.1 The centroid classifier optimises the unhinged loss

Consider minimising the unhinged risk over the class of kernelised scorers $\mathcal{F}_{\mathcal{H}, \lambda} = \{s: x \mapsto \langle w, \Phi(x) \rangle_{\mathcal{H}} \mid \|w\|_{\mathcal{H}} \leq 1/\sqrt{\lambda}\}$ for some $\lambda > 0$, where $\Phi: \mathcal{X} \rightarrow \mathcal{H}$ is a feature mapping into a reproducing kernel Hilbert space \mathcal{H} with kernel k . Equivalently, given a distribution³ D , we want

$$w_{\text{unh}, \lambda}^* = \underset{w \in \mathcal{H}}{\text{argmin}} \mathbb{E}_{(X, Y) \sim D} [1 - Y \cdot \langle w, \Phi(X) \rangle] + \frac{\lambda}{2} \langle w, w \rangle_{\mathcal{H}}. \quad (6)$$

The first-order optimality condition implies that

$$w_{\text{unh}, \lambda}^* = \frac{1}{\lambda} \cdot \mathbb{E}_{(X, Y) \sim D} [Y \cdot \Phi(X)], \quad (7)$$

which is the *kernel mean map* of D [Smola et al., 2007], and thus the optimal unhinged scorer is

$$s_{\text{unh}, \lambda}^*: x \mapsto \frac{1}{\lambda} \cdot \mathbb{E}_{(X, Y) \sim D} [Y \cdot k(X, x)] = x \mapsto \frac{1}{\lambda} \cdot \left(\pi \cdot \mathbb{E}_{X \sim P} [k(X, x)] - (1 - \pi) \cdot \mathbb{E}_{X \sim Q} [k(X, x)] \right). \quad (8)$$

From Equation 8, the unhinged solution is equivalent to a *nearest centroid classifier* [Manning et al., 2008, pg. 181] [Tibshirani et al., 2002] [Shawe-Taylor and Cristianini, 2004, Section 5.1]. Equation 8 gives a simple way to understand the SLN-robustness of $(\ell^{\text{unh}}, \mathcal{F}_{\mathcal{H}, \lambda})$, as the optimal scorers on the clean and corrupted distributions only differ by a scaling (see the Appendix):

$$(\forall x \in \mathcal{X}) \mathbb{E}_{(X, Y) \sim D} [Y \cdot k(X, x)] = \frac{1}{1 - 2\rho} \cdot \mathbb{E}_{(X, \bar{Y}) \sim \bar{D}} [\bar{Y} \cdot k(X, x)]. \quad (9)$$

Interestingly, Servadio [1999, Theorem 4] established that a nearest centroid classifier (which they termed ‘‘AVERAGE’’) is robust to a general class of label noise, but required the assumption that M is uniform over the unit sphere. Our result establishes that SLN robustness of the classifier holds without any assumptions on M . In fact, Ghosh et al. [2015, Theorem 1] lets one quantify the unhinged loss’ performance under a more general noise model; see the Appendix for discussion.

6.2 Practical considerations

We note several points relating to practical usage of the unhinged loss with kernelised scorers. First, cross-validation is not required to select λ , since changing λ only changes the magnitude of scores, *not their sign*. Thus, for the purposes of classification, one can simply use $\lambda = 1$.

Second, we can easily extend the scorers to use a bias regularised with strength $0 < \lambda_b \neq \lambda$. Tuning λ_b is equivalent to computing $s_{\text{unh}, \lambda}^*$ as per Equation 8, and tuning a threshold on a holdout set.

Third, when $\mathcal{H} = \mathbb{R}^d$ for d small, we can store $w_{\text{unh}, \lambda}^*$ explicitly, and use this to make predictions. For high (or infinite) dimensional \mathcal{H} , we can either make predictions directly via Equation 8, or use random Fourier features [Rahimi and Recht, 2007] to (approximately) embed \mathcal{H} into some low-dimensional \mathbb{R}^d , and then store $w_{\text{unh}, \lambda}^*$ as usual. (The latter requires a translation-invariant kernel.)

We now show that under some assumptions, $w_{\text{unh}, \lambda}^*$ coincides with the solution of two established methods; the Appendix discusses some further relationships, e.g. to the maximum mean discrepancy.

³Given a training sample $S \sim D^n$, we can use plugin estimates as appropriate.

6.3 Equivalence to a highly regularised SVM and other convex potentials

There is an interesting equivalence between the unhinged solution and that of a *highly regularised SVM*. This has been noted in e.g. [Hastie et al. \[2004, Section 6\]](#), which showed how SVMs approach a nearest centroid classifier, which is of course the optimal unhinged solution.

Proposition 8. *Pick any D and $\Phi: \mathcal{X} \rightarrow \mathcal{H}$ with $R = \sup_{x \in \mathcal{X}} \|\Phi(x)\|_{\mathcal{H}} < \infty$. For any $\lambda > 0$, let*

$$w_{\text{hinge}, \lambda}^* = \operatorname{argmin}_{w \in \mathcal{H}} \mathbb{E}_{(X, Y) \sim D} [\max(0, 1 - Y \cdot \langle w, \Phi(x) \rangle_{\mathcal{H}})] + \frac{\lambda}{2} \langle w, w \rangle_{\mathcal{H}}$$

be the soft-margin SVM solution. Then, if $\lambda \geq R^2$, $w_{\text{hinge}, \lambda}^ = w_{\text{unh}, \lambda}^*$.*

Since $(\ell^{\text{unh}}, \mathcal{F}_{\mathcal{H}, \lambda})$ is SLN-robust, it follows that for $\ell^{\text{hinge}}: (y, v) \mapsto \max(0, 1 - yv)$, $(\ell^{\text{hinge}}, \mathcal{F}_{\mathcal{H}, \lambda})$ is similarly SLN-robust *provided λ is sufficiently large*. That is, strong ℓ_2 regularisation (and a bounded feature map) endows the hinge loss with SLN-robustness⁴. Proposition 8 can be generalised to show that $w_{\text{unh}, \lambda}^*$ is the limiting solution of *any* twice differentiable convex potential. This shows that *strong ℓ_2 regularisation endows most learners with SLN-robustness*. Intuitively, with strong regularisation, one only considers the behaviour of a loss near zero; since a convex potential ϕ has $\phi'(0) < 0$, it will behave similarly to its linear approximation around zero, viz. the unhinged loss.

Proposition 9. *Pick any D , bounded feature mapping $\Phi: \mathcal{X} \rightarrow \mathcal{H}$, and twice differentiable convex potential ϕ with $\phi''([-1, 1])$ bounded. Let $w_{\phi, \lambda}^*$ be the minimiser of the regularised ϕ risk. Then,*

$$\lim_{\lambda \rightarrow \infty} \left\| \frac{w_{\phi, \lambda}^*}{\|w_{\phi, \lambda}^*\|_{\mathcal{H}}} - \frac{w_{\text{unh}, \lambda}^*}{\|w_{\text{unh}, \lambda}^*\|_{\mathcal{H}}} \right\|_{\mathcal{H}}^2 = 0.$$

6.4 Equivalence to Fisher Linear Discriminant with whitened data

For binary classification on $D_{M, \eta}$, the Fisher Linear Discriminant (FLD) finds a weight vector proportional to the minimiser of square loss $\ell^{\text{sq}}: (y, v) \mapsto (1 - yv)^2$ [[Bishop, 2006, Section 4.1.5](#)],

$$w_{\text{sq}, \lambda}^* = (\mathbb{E}_{X \sim M} [XX^T] + \lambda I)^{-1} \cdot \mathbb{E}_{(X, Y) \sim D} [Y \cdot X]. \quad (10)$$

By Equation 9, and the fact that the corrupted marginal $\bar{M} = M$, $w_{\text{sq}, \lambda}^*$ is only changed by a scaling factor under label noise. This provides an alternate proof of the fact that $(\ell^{\text{sq}}, \mathcal{F}_{\text{lin}})$ is SLN-robust⁵ [[Manwani and Sastry, 2013, Theorem 2](#)]. Clearly, the unhinged loss solution $w_{\text{unh}, \lambda}^*$ is equivalent to the FLD and square loss solution $w_{\text{sq}, \lambda}^*$ when the input data is whitened i.e. $\mathbb{E}_{X \sim M} [XX^T] = I$. With a well-specified \mathcal{F} , e.g. with a universal kernel, both the unhinged and square loss asymptotically recover the optimal classifier, but the unhinged loss does not require a matrix inversion. With a misspecified \mathcal{F} , one cannot in general argue for the superiority of the unhinged loss over square loss, or vice-versa, as there is no universally good surrogate to the 0-1 loss [[Reid and Williamson, 2010, Appendix A](#)]; the Appendix illustrate examples where both losses may underperform.

7 SLN-robustness of unhinged loss: empirical illustration

We now illustrate that the unhinged loss' SLN-robustness is empirically manifest. We reiterate that with high regularisation, the unhinged solution is equivalent to an SVM (and in the limit any classification-calibrated loss) solution. Thus, we do *not* aim to assert that the unhinged loss is "better" than other losses, but rather, to demonstrate that its SLN-robustness is not *purely* theoretical.

We first show that the unhinged risk minimiser performs well on the example of [Long and Servedio \[2010\]](#) (henceforth LS10). Figure 1 shows the distribution D , where $\mathcal{X} = \{(1, 0), (\gamma, 5\gamma), (\gamma, -\gamma)\} \subset \mathbb{R}^2$, with marginal distribution $M = \{\frac{1}{4}, \frac{1}{4}, \frac{1}{2}\}$ and all three instances are deterministically positive. We pick $\gamma = 1/2$. The unhinged minimiser perfectly classifies all three points, regardless of the level of label noise (Figure 1). The hinge minimiser is perfect when there is no noise, but with even a small amount of noise, achieves a 50% error rate.

⁴Long and Servedio [2010, Section 6] show that ℓ_1 regularisation does not endow SLN-robustness.

⁵Square loss escapes the result of Long and Servedio [2010] since it is not monotone decreasing.

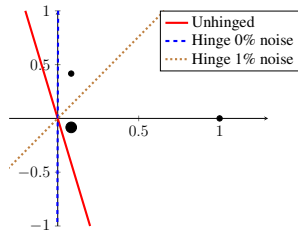


Figure 1: LS10 dataset.

	Hinge	t -logistic	Unhinged
$\rho = 0$	0.00 \pm 0.00	0.00 \pm 0.00	0.00 \pm 0.00
$\rho = 0.1$	0.15 \pm 0.27	0.00 \pm 0.00	0.00 \pm 0.00
$\rho = 0.2$	0.21 \pm 0.30	0.00 \pm 0.00	0.00 \pm 0.00
$\rho = 0.3$	0.38 \pm 0.37	0.22 \pm 0.08	0.00 \pm 0.00
$\rho = 0.4$	0.42 \pm 0.36	0.22 \pm 0.08	0.00 \pm 0.00
$\rho = 0.49$	0.47 \pm 0.38	0.39 \pm 0.23	0.34 \pm 0.48

Table 1: Mean and standard deviation of the 0-1 error over 125 trials on LS10. Grayed cells denote the best performer at that noise rate.

We next consider empirical risk minimisers from a random training sample: we construct a training set of 800 instances, injected with varying levels of label noise, and evaluate classification performance on a test set of 1000 instances. We compare the hinge, t -logistic (for $t = 2$) [Ding and Vishwanathan, 2010] and unhinged minimisers using a linear scorer *without* a bias term, and regularisation strength $\lambda = 10^{-16}$. From Table 1, even at 40% label noise, the unhinged classifier is able to find a perfect solution. By contrast, both other losses suffer at even moderate noise rates.

We next report results on some UCI datasets, where we additionally tune a threshold so as to ensure the best training set 0-1 accuracy. Table 2 summarises results on a sample of four datasets. (The Appendix contains results with more datasets, performance metrics, and losses.) Even at noise close to 50%, the unhinged loss is often able to learn a classifier with some discriminative power.

	Hinge	t -Logistic	Unhinged
$\rho = 0$	0.00 \pm 0.00	0.00 \pm 0.00	0.00 \pm 0.00
$\rho = 0.1$	0.01 \pm 0.03	0.01 \pm 0.03	0.00 \pm 0.00
$\rho = 0.2$	0.06 \pm 0.12	0.04 \pm 0.05	0.00 \pm 0.01
$\rho = 0.3$	0.17 \pm 0.20	0.09 \pm 0.11	0.02 \pm 0.07
$\rho = 0.4$	0.35 \pm 0.24	0.24 \pm 0.16	0.13 \pm 0.22
$\rho = 0.49$	0.60 \pm 0.20	0.49 \pm 0.20	0.45 \pm 0.33

(a) iris.

	Hinge	t -Logistic	Unhinged
$\rho = 0$	0.05 \pm 0.00	0.05 \pm 0.00	0.05 \pm 0.00
$\rho = 0.1$	0.06 \pm 0.01	0.07 \pm 0.02	0.05 \pm 0.00
$\rho = 0.2$	0.06 \pm 0.01	0.08 \pm 0.03	0.05 \pm 0.00
$\rho = 0.3$	0.08 \pm 0.04	0.11 \pm 0.05	0.05 \pm 0.01
$\rho = 0.4$	0.14 \pm 0.10	0.24 \pm 0.13	0.09 \pm 0.10
$\rho = 0.49$	0.45 \pm 0.26	0.49 \pm 0.16	0.46 \pm 0.30

(b) housing.

	Hinge	t -Logistic	Unhinged
$\rho = 0$	0.00 \pm 0.00	0.00 \pm 0.00	0.00 \pm 0.00
$\rho = 0.1$	0.10 \pm 0.08	0.11 \pm 0.02	0.00 \pm 0.00
$\rho = 0.2$	0.19 \pm 0.11	0.15 \pm 0.02	0.00 \pm 0.00
$\rho = 0.3$	0.31 \pm 0.13	0.22 \pm 0.03	0.01 \pm 0.00
$\rho = 0.4$	0.39 \pm 0.13	0.33 \pm 0.04	0.02 \pm 0.02
$\rho = 0.49$	0.50 \pm 0.16	0.48 \pm 0.04	0.34 \pm 0.21

(c) usps0v7.

	Hinge	t -Logistic	Unhinged
$\rho = 0$	0.05 \pm 0.00	0.04 \pm 0.00	0.19 \pm 0.00
$\rho = 0.1$	0.15 \pm 0.03	0.24 \pm 0.00	0.19 \pm 0.01
$\rho = 0.2$	0.21 \pm 0.03	0.24 \pm 0.00	0.19 \pm 0.01
$\rho = 0.3$	0.25 \pm 0.03	0.24 \pm 0.00	0.19 \pm 0.03
$\rho = 0.4$	0.31 \pm 0.05	0.24 \pm 0.00	0.22 \pm 0.05
$\rho = 0.49$	0.48 \pm 0.09	0.40 \pm 0.24	0.45 \pm 0.08

(d) splice.

Table 2: Mean and standard deviation of the 0-1 error over 125 trials on UCI datasets.

8 Conclusion and future work

We proposed a convex, classification-calibrated loss, proved that is robust to symmetric label noise (SLN-robust), showed it is the unique loss that satisfies a notion of strong SLN-robustness, established that it is optimised by the nearest centroid classifier, and showed that most convex potentials, such as the SVM, are also SLN-robust when highly regularised. So, with apologies to Wilde [1895]:

While the truth is rarely pure, it *can* be simple.

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