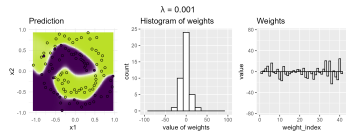
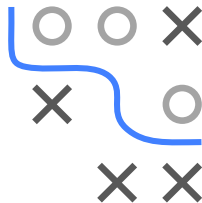


Introduction to Machine Learning

Regularization

Non-Linear Models and Structural Risk Minimization



Learning goals

- Regularization even more important in non-linear models
- Norm penalties applied similarly
- Structural risk minimization

SUMMARY: REGULARIZED RISK MINIMIZATION I

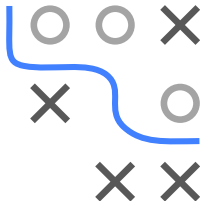
If we define (supervised) ML in one line, this might be it:

$$\min_{\theta} \mathcal{R}_{\text{reg}}(\theta) = \min_{\theta} \left(\sum_{i=1}^n L\left(y^{(i)}, f\left(\mathbf{x}^{(i)} \mid \theta\right)\right) + \lambda \cdot J(\theta) \right)$$

Can choose for task at hand:

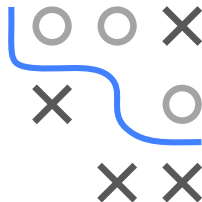
- **hypothesis space** of f , controls how features influence prediction
- **loss** function L , measures how errors are treated
- **regularizer** $J(\theta)$, encodes inductive bias

By varying these choices one can construct a huge number of different ML models. Many ML models follow this construction principle or can be interpreted through the lens of RRM.



REGULARIZATION IN NONLINEAR MODELS I

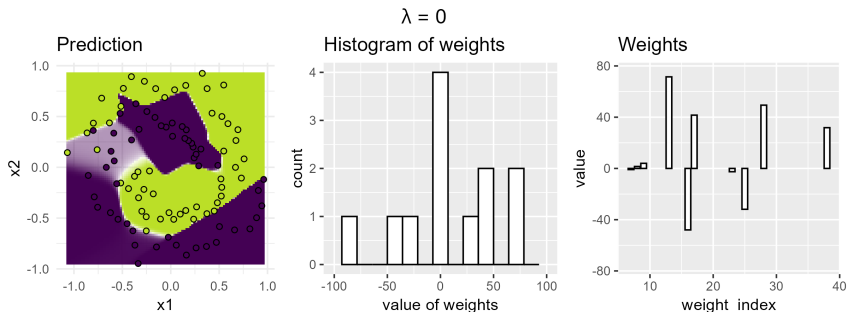
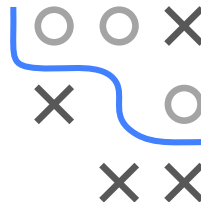
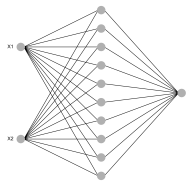
- So far we have mainly considered regularization in LMs
- Can in general also be applied to non-linear models; vector-norm penalties require numeric params
- Here, we typically use $L2$ regularization, which still results in parameter shrinkage and weight decay
- For non-linear models, regularization is even more important / basically required to prevent overfitting
- Commonplace in methods such as NNs, SVMs, or boosting
- Prediction surfaces / decision boundaries become smoother



REGULARIZATION IN NONLINEAR MODELS

Classification for spirals data.

NN with single hidden layer, size 10, L_2 penalty:

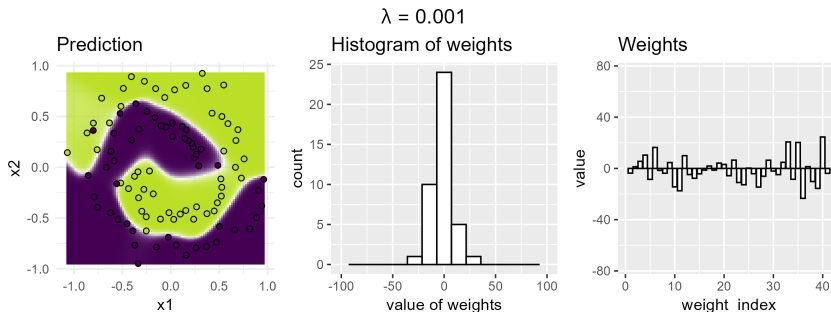
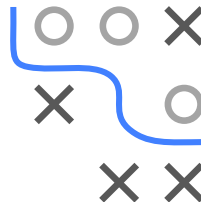
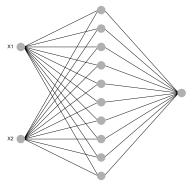


λ affects smoothness of decision boundary and magnitude of weights

REGULARIZATION IN NONLINEAR MODELS

Classification for spirals data.

NN with single hidden layer, size 10, L_2 penalty:

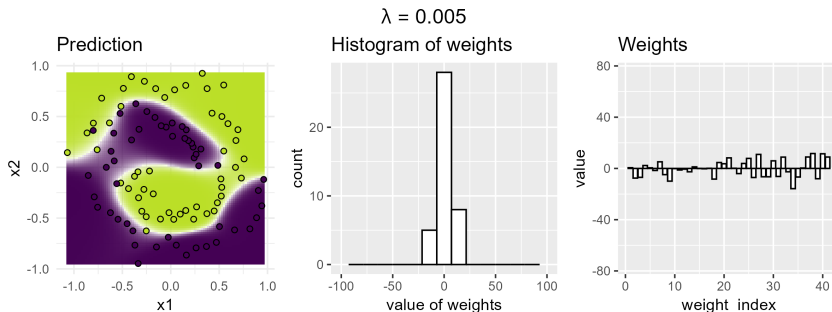
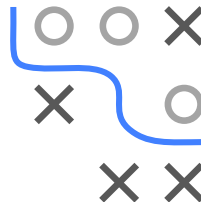
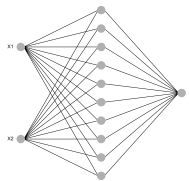


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REGULARIZATION IN NONLINEAR MODELS

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NN with single hidden layer, size 10, L_2 penalty:

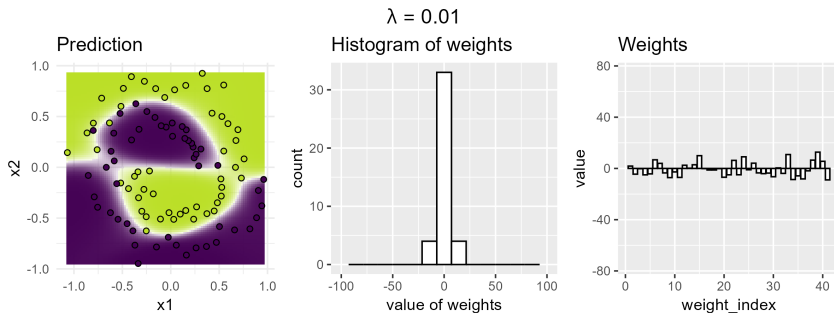
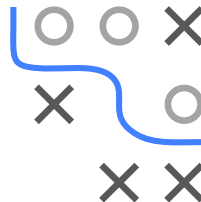
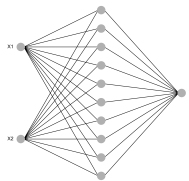


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REGULARIZATION IN NONLINEAR MODELS

Classification for spirals data.

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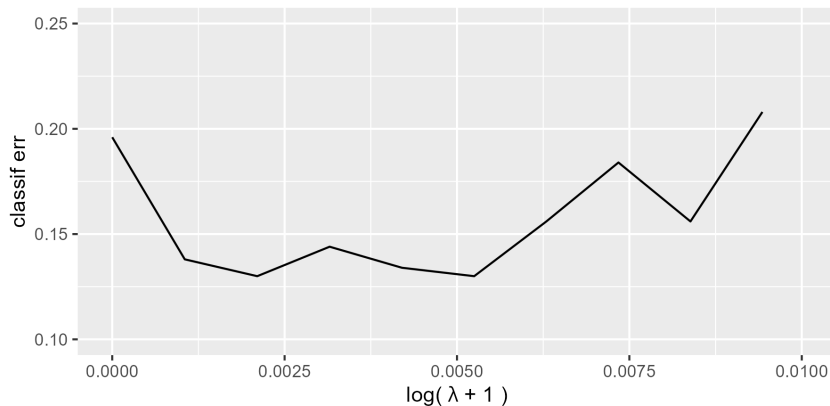


λ affects smoothness of decision boundary and magnitude of weights

REGULARIZATION IN NONLINEAR MODELS

Prevention of overfitting can also be seen in CV.

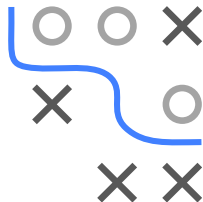
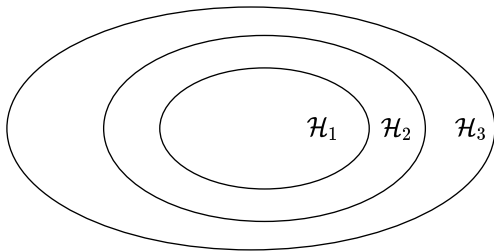
Same settings as before, but each λ is evaluated with 5x10 REP-CV



Typical U-shape with sweet spot between overfitting and underfitting

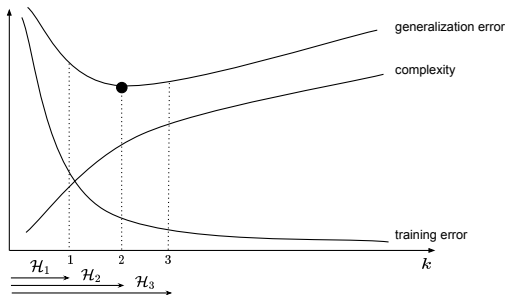
STRUCTURAL RISK MINIMIZATION I

- Can also see this as an iterative process; more a “discrete” view on things
- SRM assumes that \mathcal{H} can be decomposed into increasingly complex hypotheses: $\mathcal{H} = \cup_{k \geq 1} \mathcal{H}_k$
- Complexity parameters can be, e.g. the degree of polynomials in linear models or the size of hidden layers in neural networks



STRUCTURAL RISK MINIMIZATION II

- SRM chooses the smallest k such that the optimal model from \mathcal{H}_k found by ERM or RRM cannot significantly be outperformed by a model from a \mathcal{H}_m with $m > k$
- Principle of Occam's razor
- One challenge might be choosing an adequate complexity measure, as for some models, multiple exist



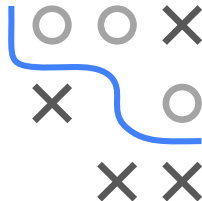
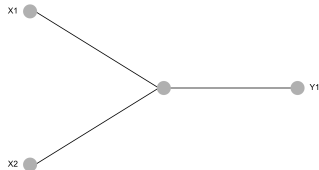
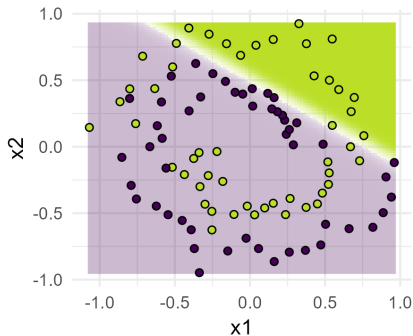
STRUCTURAL RISK MINIMIZATION

Again spirals.

NN with 1 hidden layer, and fixed (small) L2 penalty.

size of hidden layer = 1

Prediction



Size affects complexity and smoothness of decision boundary

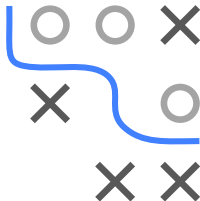
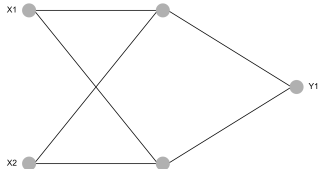
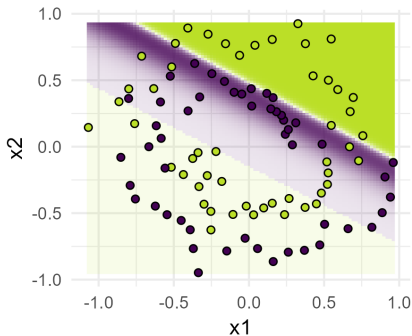
STRUCTURAL RISK MINIMIZATION

Again spirals.

NN with 1 hidden layer, and fixed (small) L2 penalty.

size of hidden layer = 2

Prediction



Size affects complexity and smoothness of decision boundary

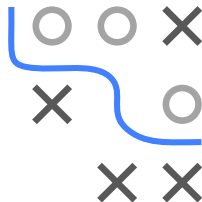
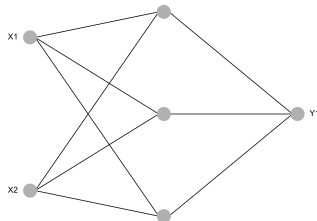
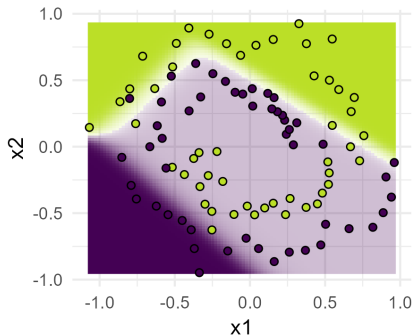
STRUCTURAL RISK MINIMIZATION

Again spirals.

NN with 1 hidden layer, and fixed (small) L2 penalty.

size of hidden layer = 3

Prediction



Size affects complexity and smoothness of decision boundary

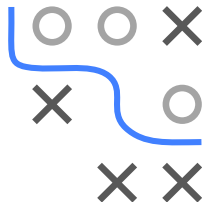
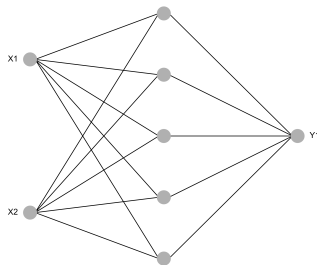
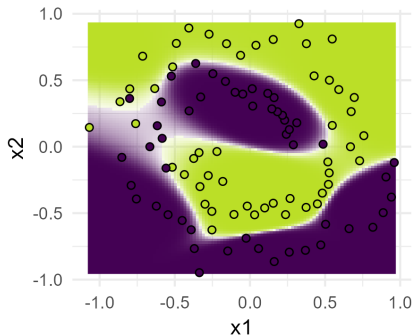
STRUCTURAL RISK MINIMIZATION

Again spirals.

NN with 1 hidden layer, and fixed (small) L2 penalty.

size of hidden layer = 5

Prediction



Size affects complexity and smoothness of decision boundary

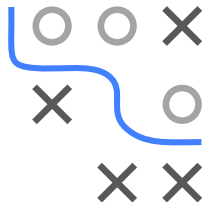
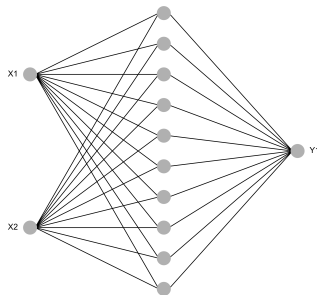
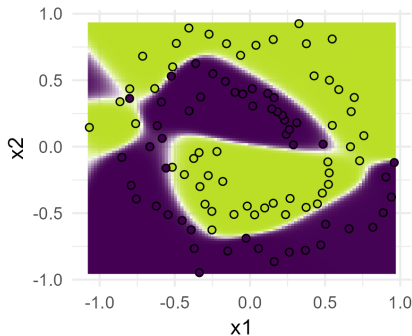
STRUCTURAL RISK MINIMIZATION

Again spirals.

NN with 1 hidden layer, and fixed (small) L2 penalty.

size of hidden layer = 10

Prediction



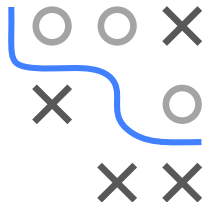
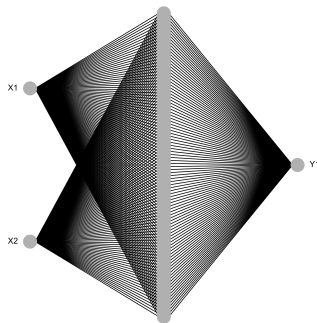
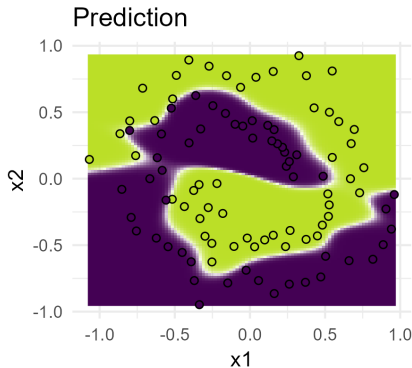
Size affects complexity and smoothness of decision boundary

STRUCTURAL RISK MINIMIZATION

Again spirals.

NN with 1 hidden layer, and fixed (small) L2 penalty.

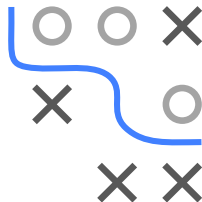
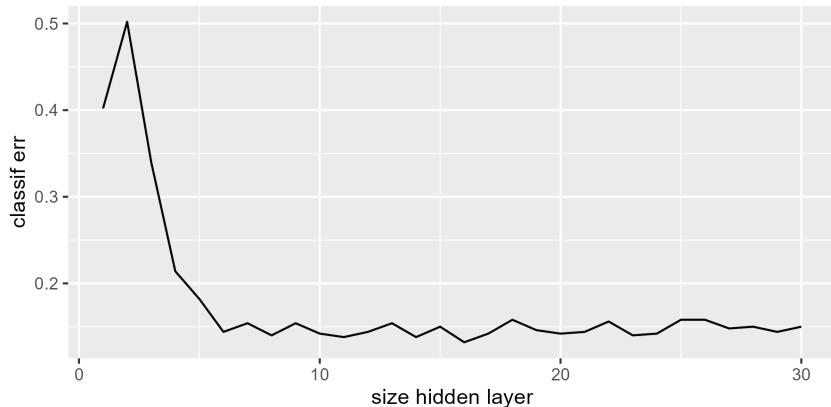
size of hidden layer = 100



Size affects complexity and smoothness of decision boundary

STRUCTURAL RISK MINIMIZATION

Again, complexity vs CV score.

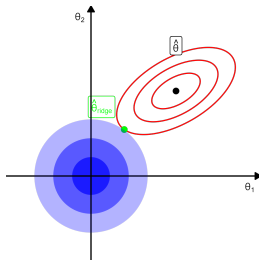


Minimal model with good generalization seems to size=10

STRUCTURAL RISK MINIMIZATION AND RRM

RRM can also be interpreted through SRM,
if we rewrite it in constrained form:

$$\begin{aligned} \min_{\boldsymbol{\theta}} \quad & \sum_{i=1}^n L\left(y^{(i)}, f\left(\mathbf{x}^{(i)} \mid \boldsymbol{\theta}\right)\right) \\ \text{s.t.} \quad & \|\boldsymbol{\theta}\|_2^2 \leq t \end{aligned}$$



Can interpret going through λ from large to small as through t from small to large. Constructs series of ERM problems with hypothesis spaces \mathcal{H}_λ , where we constrain norm of $\boldsymbol{\theta}$ to unit balls of growing sizes.