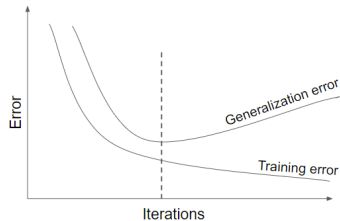
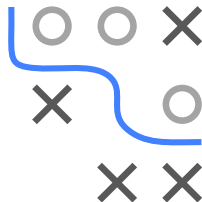


# Introduction to Machine Learning

## Regularization Early Stopping

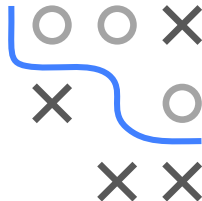
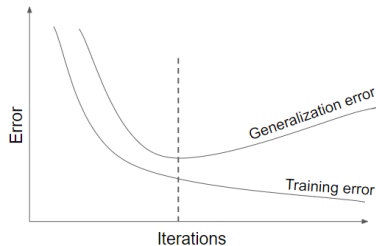


### Learning goals

- Know how early stopping works
- Understand how early stopping acts as a regularizer

# EARLY STOPPING

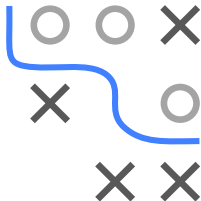
- Especially for complex nonlinear models we can easily overfit
- In optimization: Often, after a certain number of iterations, generalization error begins to increase even though training error continues to decrease



## EARLY STOPPING / 2

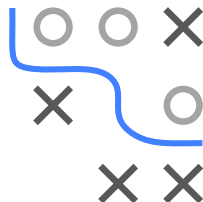
For iterative optimizers like SGD,  
we can monitor this step-by-step over small iterations:

- 1 Split train data  $\mathcal{D}_{\text{train}}$  into  $\mathcal{D}_{\text{subtrain}}$  and  $\mathcal{D}_{\text{val}}$  (e.g. with ratio of 2:1)
- 2 Train on  $\mathcal{D}_{\text{subtrain}}$  and eval model on  $\mathcal{D}_{\text{val}}$
- 3 Stop when validation error stops decreasing  
(after a range of “patience” steps)
- 4 Use parameters of the previous step for the actual model



More sophisticated forms also apply cross-validation.

Strengths	Weaknesses
Effective and simple	Periodical evaluation of validation error
Applicable to almost any model without adjustment	Temporary copy of $\theta$ (we have to save the whole model each time validation error improves)
Combinable with other regularization methods	Less data for training $\rightarrow$ include $\mathcal{D}_{\text{val}}$ afterwards

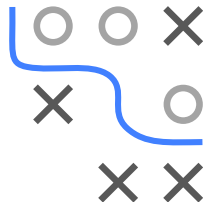


- For simple case of LM with squared loss and GD optim initialized at  $\theta = 0$ : Early stopping has exact correspondence with  $L_2$  regularization/WD: optimal early-stopping iter  $T_{\text{stop}}$  inversely proportional to  $\lambda$  scaled by step-size  $\alpha$

$$T_{\text{stop}} \approx \frac{1}{\alpha \lambda} \Leftrightarrow \lambda \approx \frac{1}{T_{\text{stop}} \alpha}$$

- Small  $\lambda$  ( regu.  $\downarrow$ )  $\Rightarrow$  large  $T_{\text{stop}}$  (complexity  $\uparrow$ ) and vice versa

► Goodfellow, Bengio, and Courville 2016 / 2

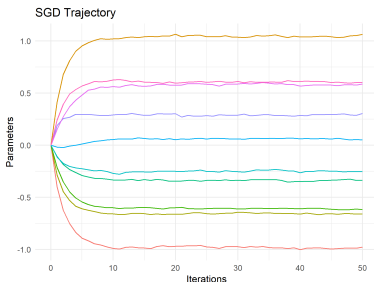
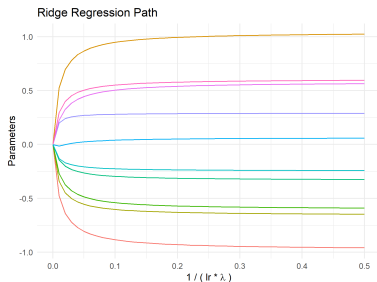
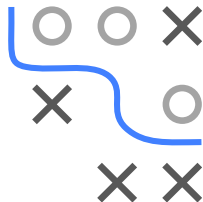


- Solid lines are  $\mathcal{R}_{\text{emp}}(\theta)$
- LHS: Trajectory of GD early stopped, initialized at origin
- RHS: Constrained form of ridge regularization

# SGD TRAJECTORY AND $L_2$

► Ali, Dobriban, and Tibshirani 2020

Solution paths for  $L_2$  regularized linear model closely matches SGD trajectory of unregularized LM initialized at  $\theta = 0$



**Caveat:** Initialization at the origin is crucial for this equivalence to hold, which is almost never exactly used in practice in ML/DL applications