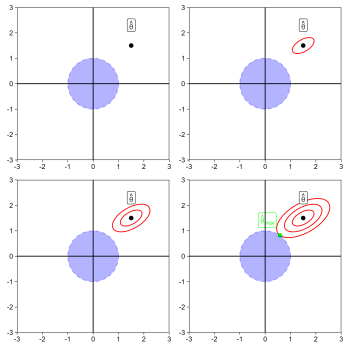


Introduction to Machine Learning

Regularization

Ridge Regression



Learning goals

- Regularized linear model
- Ridge regression / L_2 penalty
- Understand parameter shrinkage
- Understand correspondence to constrained optimization

REGULARIZATION IN LM

- Can also overfit if p large and n small(er)
- OLS estimator requires full-rank design matrix
- For highly correlated features, OLS becomes sensitive to random errors in response, results in large variance in fit
- We now add a complexity penalty to the loss:

$$\mathcal{R}_{\text{reg}}(\boldsymbol{\theta}) = \sum_{i=1}^n \left(y^{(i)} - \boldsymbol{\theta}^\top \mathbf{x}^{(i)} \right)^2 + \lambda \cdot J(\boldsymbol{\theta}).$$



RIDGE REGRESSION / L2 PENALTY

Intuitive measure of model complexity is deviation from 0-origin; coeffs then have no or a weak effect. So we measure $J(\theta)$ through a vector norm, shrinking coeffs closer to 0.



$$\begin{aligned}\hat{\theta}_{\text{ridge}} &= \arg \min_{\theta} \sum_{i=1}^n \left(y^{(i)} - \theta^T \mathbf{x}^{(i)} \right)^2 + \lambda \sum_{j=1}^p \theta_j^2 \\ &= \arg \min_{\theta} \|\mathbf{y} - \mathbf{X}\theta\|_2^2 + \lambda \|\theta\|_2^2\end{aligned}$$

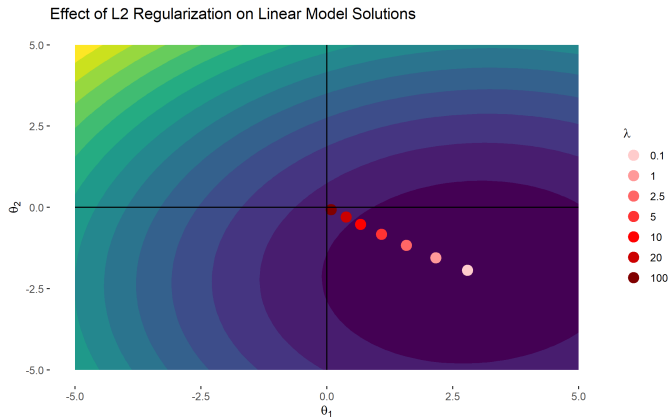
Can still analytically solve this:

$$\hat{\theta}_{\text{ridge}} = (\mathbf{X}^T \mathbf{X} + \lambda \mathbf{I})^{-1} \mathbf{X}^T \mathbf{y}$$

Name: We add pos. entries along the diagonal "ridge" of $\mathbf{X}^T \mathbf{X}$

RIDGE REGRESSION / L2 PENALTY / 2

Let $y = 3x_1 - 2x_2 + \epsilon$, $\epsilon \sim N(0, 1)$. The true minimizer is $\theta^* = (3, -2)^T$, with $\hat{\theta}_{\text{ridge}} = \arg \min_{\theta} \|\mathbf{y} - \mathbf{X}\theta\|^2 + \lambda \|\theta\|^2$.

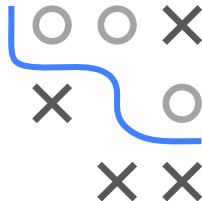
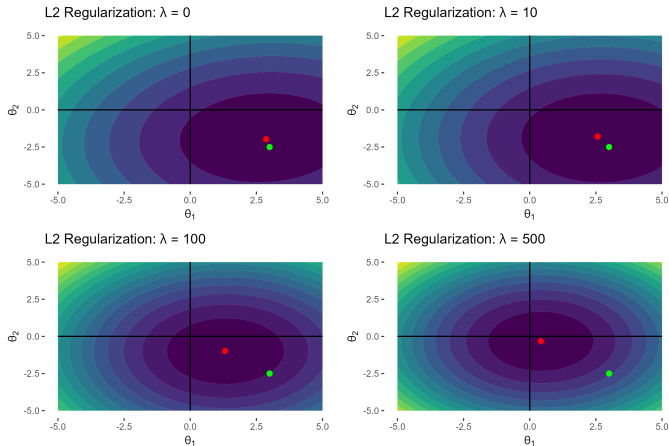


With increasing regularization, $\hat{\theta}_{\text{ridge}}$ is pulled back to the origin (contour lines show unregularized objective).

RIDGE REGRESSION / L2 PENALTY / 3

Contours of regularized objective for different λ values.

$$\hat{\theta}_{\text{ridge}} = \arg \min_{\theta} \|\mathbf{y} - \mathbf{X}\theta\|^2 + \lambda \|\theta\|^2.$$

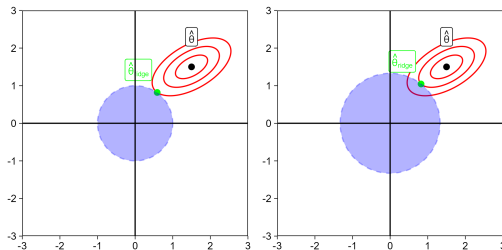


Green = true coefs of the DGP and red = ridge solution.

RIDGE REGRESSION / L2 PENALTY / 4

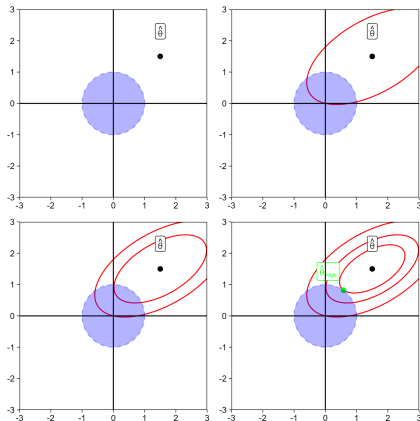
We understand the geometry of these 2 mixed components in our regularized risk objective much better, if we formulate the optimization as a constrained problem (see this as Lagrange multipliers in reverse).

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

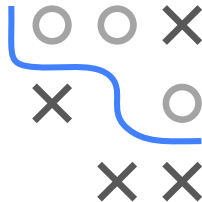


NB: There is a bijective relationship between λ and t : $\lambda \uparrow \Rightarrow t \downarrow$ and vice versa.

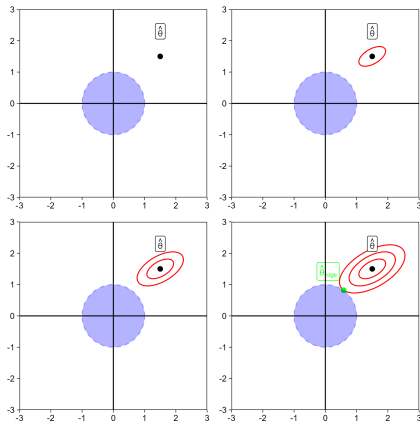
RIDGE REGRESSION / L2 PENALTY / 5



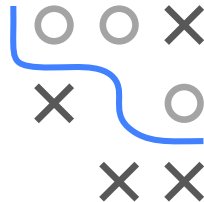
- Inside constraints perspective: From origin, jump from contour line to contour line (better) until you become infeasible, stop before.
- We still optimize the $\mathcal{R}_{\text{emp}}(\theta)$, but cannot leave a ball around the origin.
- $\mathcal{R}_{\text{emp}}(\theta)$ grows monotonically if we move away from $\hat{\theta}$ (elliptic contours).
- Solution path moves from origin to border of feasible region with minimal L_2 distance.



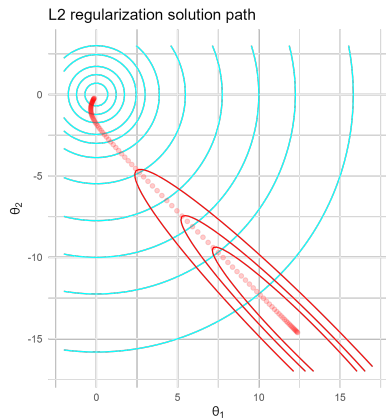
RIDGE REGRESSION / L2 PENALTY / 6



- Outside constraints perspective:
From $\hat{\theta}$, jump from contour line to contour line (worse) until you become feasible, stop then.
- So our new optimum will lie on the boundary of that ball.
- Solution path moves from unregularized estimate to feasible region of regularized objective with minimal L_2 distance.



RIDGE REGRESSION / L2 PENALTY / 7



- Here we can see entire solution path for ridge regression
- Cyan contours indicate feasible regions induced by different λ s
- Red contour lines indicate different levels of the unreg. objective
- Ridge solution (red points) gets pulled toward origin for increasing λ



EXAMPLE: POLYNOMIAL RIDGE REGRESSION

Let's use a d th-order polynomial

Using model complexity $d = 10$ overfits:



A 3x3 grid with a blue path starting at the top-left cell and ending at the bottom-right cell. The path is composed of three segments: a vertical segment from (1,1) to (2,1), a horizontal segment from (2,1) to (2,2), and a diagonal segment from (2,2) to (3,3). The cells (1,2), (1,3), (2,3), and (3,1) are empty.

λ	θ_0	θ_1	θ_2	θ_3	θ_4	θ_5	θ_6	θ_7	θ_8	θ_9	θ_{10}
0.00	12.00	-16.00	4.80	23.00	-5.40	-9.30	4.20	0.53	-0.63	0.13	-0.01
10.00	5.20	1.30	3.70	0.69	1.90	-2.00	0.47	0.20	-0.14	0.03	-0.00
100.00	1.70	0.46	1.80	0.25	1.80	-0.94	0.34	-0.01	-0.06	0.02	-0.00