# Lecture 21
# Theory of the Lasso II

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# Class Notes

- Midterm II - Available now, due next Monday
- Problem Set 7 - Available now, due December 11th (grace period through the 16th)

# Last time

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Today's goal is to establish a bound on $||\widehat{\beta} - \beta||_2^2$

The basic starting point from last time was the following decomposition, which had no assumptions beyond linearity of the true model:

$$||X(\beta - b)||_2^2 \leq 2\epsilon^t X(b - \beta) + \lambda \cdot (||\beta||_1 - ||b||_1)$$

Where can think of this decomposition as the loss to be minimized, the empirical part, and the penalty term.

I then defined the set

$$\mathcal{A} = \left\{2||\epsilon^t X||_\infty \leq \lambda\right\}$$

And showed that for any $A > 1$ we have $\mathbb{P}\mathcal{A} = 1 - A^{-1}$ whenever

$$\lambda \geq A \cdot \sqrt{8 \log(2p)\sigma^2}.$$

Today we will motivate a stronger assumption on the model and use these two results to establish bounds on the prediction of $\beta$.

# Bounds on estimation error

We already know that on $\mathcal{A}(\lambda_0)$ and with $\lambda > 2 \cdot \lambda_0$, we have:

$$\begin{aligned} ||X(b-\beta)||_2^2 + \lambda \cdot ||b||_1 &\leq 2\epsilon^t X(b-\beta) + \lambda \cdot ||\beta||_1 \\ &\leq \lambda_0 ||b-\beta||_1 + \lambda \cdot ||\beta||_1 \end{aligned}$$

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Now, multiplying by two gives:

$$2||X(b-\beta)||_2^2 + 2\lambda \cdot ||b||_1 \leq \lambda ||b-\beta||_1 + \lambda \cdot ||\beta||_1$$

Recall that we defined the notation: $S = \{j : \beta_j \neq 0\}$, $s$ is the size of the set $S$, and $v_S$ is the vector $v$ which has components not in $S$ set to zero.

Notice that:

$$||b||_1 = ||b_S||_1 + ||b_{S^c}||_1 \qquad \geq ||b_S||_1 - ||b_S - \beta||_1 + ||b_{S^c}||_1$$

Using the (reverse) triangle inequality and the fact that $\beta_{S^c}$ is zero by definition.

Similarly, we have:

$$||b - \beta||_1 = ||b_S - \beta_S||_1 + ||b_{S^c}||_1$$

Where clearly $\beta_S$ is redundant, but useful to keep the notation straight.

Plugging these in, we now get:

$$\begin{aligned} 2||X(b-\beta)||_2^2 + 2\lambda \cdot ||b_S||_1 - 2\lambda \cdot ||b_S - \beta||_1 + 2\lambda \cdot ||b_{S^c}||_1 \\ \leq \lambda ||b-\beta||_1 + \lambda \cdot ||b_S - \beta_S||_1 + \lambda \cdot ||b_{S^c}||_1 \end{aligned}$$

Plugging these in, we now get:

$$2||X(b-\beta)||_2^2+2\lambda\cdot||b_S||_1-2\lambda\cdot||b_S-\beta||_1+2\lambda\cdot||b_{S^c}||_1 \\ \leq \lambda||b-\beta||_1+\lambda\cdot||b_S-\beta_S||_1+\lambda\cdot||b_{S^c}||_1$$

Which cancels out as:

$$2||X(b-\beta)||_2^2+\lambda||b_{S^c}||_1\leq 3\cdot\lambda\cdot||b_S-\beta_S||_1$$

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Namely we have:

$$||b_{S^c}||_1 \leq 3 \cdot ||b_S - \beta_S||_1$$

Which implies that the amount of error in $b$ can not be too highly concentrated on $S^c$.

The other sub-result gives:

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If $\sigma_{min}$ is the minimum singular value of $X$, then the left hand side can be bounded below by:

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Using the Cauchy-Schwarz inequality, this becomes:

$$2\sigma_m^2 in||b-\beta||_2^2 \leq 3\lambda \cdot \sqrt{s}||b_S - \beta_S||_2$$

$$||b-\beta||_2 \leq \frac{3\lambda\sqrt{s}}{2\sigma_{min}^2}$$

Which gives a bound on the error of estimating $\beta$, which is exactly what we wanted to establish.

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We can get around this problem by defining a modified version of the minimum eigenvector (or squared singular value) by only considering $b - \beta$ such that:

$$||b_{S^c}||_1 \leq 3 \cdot ||b_S - \beta_S||_1$$

The (minimum) restricted eigenvalue $\phi_S$ on the set $S$ is defined as:

$$\phi_S = \arg\min_{v in \mathcal{V}_S} \frac{||Xb||_2}{||b||_2}$$

Where:

$$\mathcal{V}_S = \{v \in \mathbb{R}^p \text{ s.t. } ||v_{S^c}||_1 \leq 3 \cdot ||v_S||_1\}$$

Because we do not know $S$, it is impossible to calculate $\phi_S$ in practice. In theoretical work, often one considers **the** restricted eigenvalue $\phi$ defined as the smallest $\phi_S$ for all sets $S$ with size bounded by some predefined $s_0$.

Now, we can bound the following using our prior result:

$$\begin{aligned} 2||X(b-\beta)||_2^2 + \lambda \cdot ||b-\beta||_1 &= 2||X(b-\beta)||_2^2 + \lambda \cdot ||b_S - \beta_S||_1 + \lambda \cdot ||b_{S^c} \\ &= 4\lambda \cdot ||b_S - \beta_S||_1 \end{aligned}$$

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Using Cauchy-Schartz again, we can change the $\ell_1$-norm to an $\ell_2$-norm at the cost of a factor of $\sqrt{s}$:

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Finally, we now use the restricted eigenvalue $\phi$ to convert from $\beta$ space to $X\beta$ space:

$$2||X(b-\beta)||_2^2 + \lambda \cdot ||b-\beta||_1 \leq 4\lambda \cdot \sqrt{s} \cdot ||X(b_S - \beta_S)||_2/\phi$$

I am now going to use an inequality trick that is often pulled out in theoretical statistics proofs. For any $u$ and $v$, notice that $4uv \leq u^2 + 4v^2$.

For a proof, notice that it is trivially true at zero and negative values of $u$ and $v$. Then look at the derivatives and notice that the right hand side grows faster than the left hand side in the directions of both $u$ and $v$.

Setting $u = ||X(b_S - \beta_S)||_2$, we then have:

$$\begin{aligned} 2||X(b-\beta)||_2^2 + \lambda \cdot ||b-\beta||_1 &\leq ||X(b_S - \beta_S)||_2 + 4\lambda^2 \cdot s \cdot /\phi^2 \\ &\leq ||X(b-\beta)||_2 + 4\lambda^2 \cdot s \cdot /\phi^2 \end{aligned}$$

And when canceling one factor of $||X(b-\beta)||_2$:

$$||X(b-\beta)||_2^2 + \lambda \cdot ||b-\beta||_1 \leq 4\lambda^2 \cdot s \cdot /\phi^2$$

Which holds on the entire set $\mathcal{A}$.

This establishes two simultaneous bounds:

$$||X(b-\beta)||_2^2 \leq 4\lambda^2 \cdot s \cdot /\phi^2$$
$$||b-\beta||_1 \leq 4\lambda \cdot s \cdot /\phi^2$$

Though the first is slightly less satisfying than our result in last class as it relies on $\phi^2$, though it no longer requires the norm of $\beta$.

# Asymptotic analysis

As before, we can convert a more natural re-scaled problem by dividing all of the $\lambda$ parameters by $\sqrt{n}$

Also, remember that for some $A > 1$, we have $\mathbb{P}\mathcal{A} \geq 1 - A^{-1}$ for all $\lambda > A \cdot \sqrt{8n^{-1}\log(2p)\sigma^2}$.

Therefore, we have:

$$||b - \beta||_1 \leq 4\lambda \cdot s \cdot / \phi^2 \qquad \leq 4A2\sqrt{2}\sigma^2 / \phi^2 \cdot \frac{s_n^2 \log(2p_n)}{n}$$

So to establish consistency of the estimator under constant noise and restricted eigenvalues $\phi^2$, we need the following limit to go to zero:

$$\lim_{n \to \infty} \frac{s_n^2 \log(2p_n)}{n} = 0$$

Which can happen with a number of different scalings, such as a constant number of non-zero terms but an exponential number of non-zero terms. Or, $s_n$ growing like $n^{1/3}$ and $p_n$ growing linearly with $s_n$.

Some (personal) closing thoughts on the application of the lasso theory to data analysis:

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5. I have always been skeptical of the asymptotic results for the same reason; $\phi$ likely depends on $n$, $p_n$ and $s_n$ in complex ways that are not accounted for

For our next (and last) week we will:

1. use the lasso to encode more complex forms of linear sparsity (e.g., outlier detection and the fused lasso)
2. give an alternative approach to solving for the lasso solution at a particular value of $\lambda$