

# Worksheet: Linear regression for the estimation of nonlinear receptive field models

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Following [Rapela et al. \[2006\]](#), to model responses of visual cell in animals to stimulation with natural images, we project these images into a small number of (learned) basis functions,  $\alpha_1, \dots, \alpha_L$ . Below we call *relevant dimensions* to these basis functions. We denote the projections of the  $n$ th image,  $\mathbf{v}_n$ , into the  $l$ th relevant dimension,  $\alpha_l$ , by  $x_{nl} = \alpha_l^\top \mathbf{v}_n$ . Then we model the number of spikes produced by the cell in response to the  $n$ th image,  $y_n$ , with a multivariate polynomial of degree  $D$ . Equation 1 shows a model of the response of a cell to the  $n$ th image with two basis functions,  $L = 2$ , and a multivariate polynomial of degree  $D = 3$ .

$$\begin{aligned} y_n &= \beta_0 + \beta_1 x_{n1} + \beta_2 x_{n2} + \\ &\quad \beta_{11} x_{n1}^2 + 2\beta_{12} x_{n1} x_{n2} + \beta_{22} x_{n2}^2 + \\ &\quad \beta_{111} x_{n1}^3 + 3\beta_{112} x_{n1}^2 x_{n2} + 3\beta_{122} x_{n1} x_{n2}^2 + \beta_{222} x_{n2}^3 \\ &= [1, x_{n1}, x_{n2}, x_{n1}^2, 2x_{n1}x_{n2}, x_{n2}^2, x_{n1}^3, 3x_{n1}^2x_{n2}, 3x_{n1}x_{n2}^2, x_{n2}^3] \begin{bmatrix} \beta_0 \\ \beta_1 \\ \beta_2 \\ \beta_{11} \\ \beta_{12} \\ \beta_{22} \\ \beta_{111} \\ \beta_{112} \\ \beta_{122} \\ \beta_{222} \end{bmatrix} \end{aligned} \quad (1)$$

Thus the above model is nonlinear on the input images, but linear on the model parameters. To estimate these parameters we use the method of least squares.

In this worksheet you will

1. do cross-validation to learn the optimal number of relevant dimensions,  $L$ , and the optimal degree of the multivariate polynomial,  $D$ .
2. plot residuals to check the goodness of fit of the model.
3. computer bootstrap confidence intervals to test the significance of model coefficients.

It is a good practice to first test your methods with simulated data, for which you know the ground truth. Thus, we will first perform this exercise on data from a simulated cell and then on data recorded from a complex cell in primary visual cortex of an anaesthetised cat [[Felsen et al., 2005](#)].

# 1 Simulated complex cell

We simulated responses of a complex cell using the energy model [Adelson and Bergen, 1985] in Eq. 2. This model uses two identical Gabor relevant dimensions,  $\alpha_1$  and  $\alpha_2$ , that are  $180^\circ$  out of phase. The relevant dimensions used for this simulation appear in Figure 1.

$$y_n = (\alpha_1^T \mathbf{v}_n)^2 + (\alpha_2^T \mathbf{v}_n)^2 \quad (2)$$

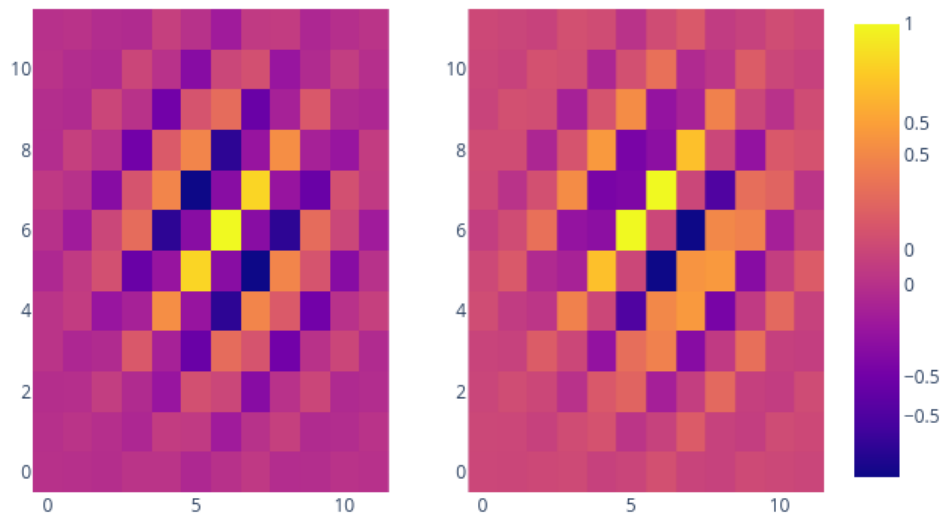


Figure 1: Relevant dimensions used for the complex cell simulation.

All the code for this worksheet appears in the subdirectory `worksheets/06_linearRegression/code/scripts` of the class `repo`. In particular, the code to simulate a complex cells is in script `doSimulateComplexCell.py`. Prior to running this code install the required dependencies by running

```
pip install -r requirements.txt
```

from the subdirectory `worksheets/06_linearRegression/code/scripts`.

The script `doLinearRegressionVisualCell.py` implements all the functionality required for this worksheet, but it has a few lines that you will need to complete to make it work.

The first section you will have to complete is on file `doLinearRegressionVisualCell.py`:

```
1 # calculate regression coefficients with train data using L2 regularisation
2 X = utils.buildDataMatrix(px=px, order=order, nRDs=n_RDs)
3 X_train, X_test, Y_train, Y_test = \
4     sklearn.model_selection.train_test_split(X, Y,
5                                             test_size=test_percentage)
6
7 coefs = ...
```

Lines 3-5 partition the data into train and test sets. We will use the train set to estimate model parameters and the test set to assess the model predictive power without overfitting.

You will need to complete line 6 to calculate the coefficients using the train set and the formula given in class to compute regression coefficients using L2 regularisation. You may want to use functions `np.matmul` for matrix-matrix or matrix-vector multiplication, `np.transpose` to transpose an array, `np.linalg.inv` for matrix inversion and/or `np.linalg.solve` to solve systems of equations.

The second section you will have to complete is on file `utils.py`:

```
1 def computeBootstrapCIs(resamples, alpha):
2     """Computes bootstrap confidence intervals at a significance level alpha
3     from bootstrap resamples.
4
5     :param resamples: bootstrap resamples
6
7     :type resamples: list like
8
9     :param alpha: significance level
10
11     :type float
12
13     :return: a 2-tuple containing the lower and upper bound of the confidence
14     interval.
15     :rtype: tuple
16     """
17     ...
18     lower = ...
19     upper = ...
20     return lower, upper
```

You need to complete lines 16-18 to calculate the lower and upper values of the bootstrap confidence intervals from the bootstrap resamples `resamples` and at the significance level `alpha`.

The third section you will have to complete is on file `doLinearRegressionVisualCell.py`:

```
1     # calculate residuals
2     fitted_train = ...
3     residuals_train = Y_train - fitted_train
4
5     # compute correlation coefficient on test data
6     fitted_test = ...
7     rho_test = np.corrcoef(Y_test, fitted_test)[0, 1]
```

Given the coefficients estimated above, here you need to compute the fitted response (or dependent variable) for the train and test segments. We use the fitted train response to calculate the residuals for the train data. We use the fitted test response to calculate their correlation coefficients with the observed test dependent variable.

After you complete the missing parts of the code, you can run it with the parameters set for the simulated complex cell specified in the shell script `doAnalyzeSimulatedComplexCell.csh`. In this script you can specify the number of relevant dimensions (parameter `--nRDs`) and the polynomial order (parameter `--order`) that you want to use. Running this script with two relevant dimensions and with a polynomial order 2 (i.e., parameters `--order=2 --nRDs=2`) I obtained the estimated relevant dimensions in Figure 2, the coefficients in Figure 3, the histogram of residuals in Figure 4 and the fitted responses in Figure 5.

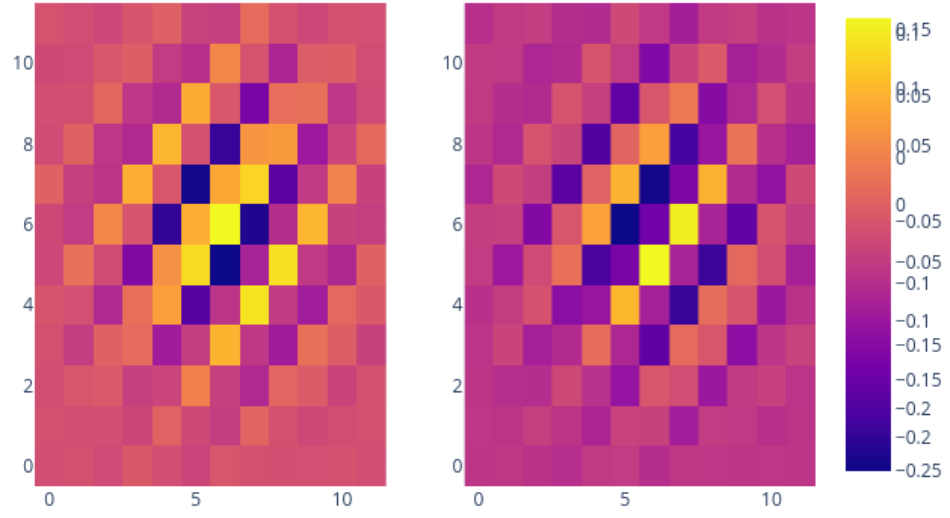


Figure 2: Relevant dimensions estimated for simulated data of a complex cell. Compare with Figure 1

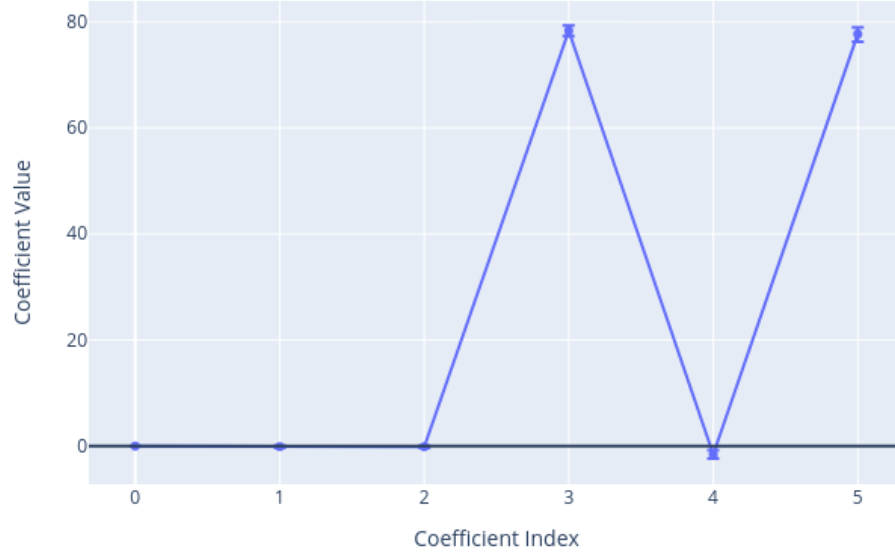


Figure 3: Coefficients estimated for simulated data of a complex cell. Only the coefficient 2 and 4, corresponding to  $\beta_{11}$  and  $\beta_{22}$  (Eq. 1) are significantly different from zero.

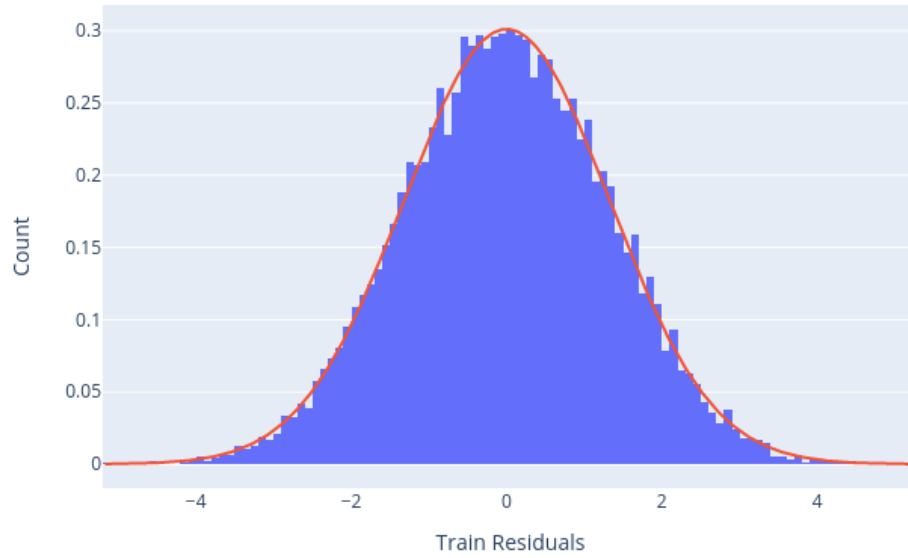


Figure 4: Histogram of train residuals for the simulated complex cell (blue) and density of Normal distribution with the same mean and variance as that of the train residuals (red).

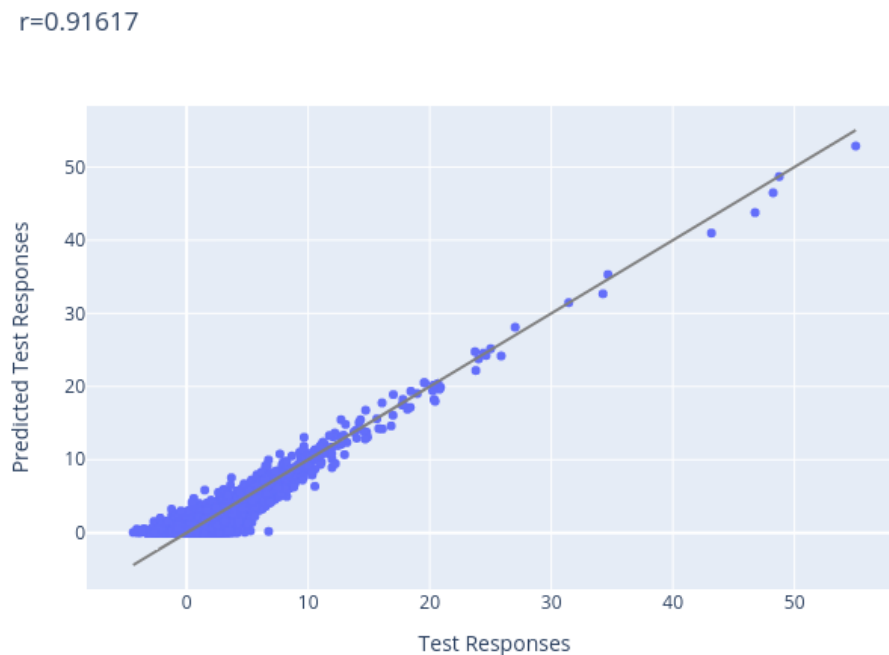


Figure 5: Cell responses versus predictions for the simulated complex cell. Their correlation coefficient appears in the title.

Vary the number of relevant dimensions (parameter `--nRDs` in `doAnalyzeSimulatedComplexCell.csh`) and model order (parameter `--order` in `doAnalyzeSimulatedComplexCell.csh`) to select their optimal values. Plot Figure 2-5 for the best and a poor set of parameters.

## 2 Real complex cell

The shell script `doAnalyzeRealComplexCell.csh` contains the parameters required to characterise a complex cell in primary visual cortex of an anaesthetised cat [Felsen et al., 2005]. Find the best set of parameters to characterise this cell. Plot Figure 2-5 for the best and a poor set of parameters.

## References

- E.H. Adelson and J.R. Bergen. Spatiotemporal energy models for the perception of motion. *Journal of the Optical Society of America A*, 2:284–299, 1985.
- G. Felsen, J. Touryan, F. Han, and Y. Dan. Cortical sensitivity to visual features in natural scenes. *PLoS Biology*, 3(10):e342, 9 2005. doi: 10.1371/journal.pbio.0030342. URL <http://dx.doi.org/10.1371%2Fjournal.pbio.0030342>.
- J. Rapela, J.M. Mendel, and N.M. Grzywacz. Estimating nonlinear receptive fields from natural images. *Journal of Vision*, 6(4):441–474, 2006.