

Computational Cognitive Science

Lecture 3: Parameter Estimation

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Slide credits: Chris Lucas, Benjamin Peters

Reading: Chapter 3 of [Farrell and Lewandowsky \(2018\)](#).

(don't worry about bootstrapping or exact details of simplex algorithm)

Most models have free parameters.

Example:

- Decision threshold or criterion in the random-walk decision model

Example:

- Coefficients in a regression model

E.g., b_0 and b_1 in

$$y = b_0 + b_1x$$

Introduction

Example:

- ϵ in “ ϵ -greedy” models: The probability that someone chooses a random option over the best so far.

To model trade-offs between exploration and exploitation, like choosing between restaurants or foraging spots.



Example:

- Weights in a neural network

GPT4 has 1.8 trillion parameters.

Also, “hyperparameters”, e.g., learning rate, architectural decisions.

Why estimate parameters?

Usually necessary for precise and accurate predictions.

- A model with free parameters $\rightarrow$ a family or space of models.
- Sometimes we want to choose between model families – we can estimate parameters to pick a best representative of that family.
- Sometimes we want to identify better models **within** a family, e.g.,

$$b_0 + b_2x^2$$

in

$$b_0 + b_1x + b_2x^2 + b_3x^3$$

Why estimate parameters?

Some parameters are **interpretable**: They describe or explain behavior in a way that people can understand

- Random-walk model: Threshold, drift rate, standard deviation
- ϵ in ϵ -greedy: How conservative are people?

(Estimated parameters might tell us about populations, individuals, or both)

Parameter Estimation

The aim of parameter estimation is to find the parameter values that **minimize loss** (or error), according to some discrepancy function.

- If our goal is to have an accurate predictive model, we want to minimize predictive error.
- If our goal is to interpret parameters, we want the most likely or plausible values.

These goals go hand in hand. Today we'll focus on the first.

Quantifying error

A popular loss¹ function is **root mean squared deviation**:

$$RMSD = \sqrt{\frac{\sum_{j=1}^J (d_j - p_j)^2}{J}}$$

where

- J is the number of data points
- p_j (or $\hat{y}_j$) is the j^{th} prediction
- d_j (or y_j) is the j^{th} data point

Minimizing RMSD is equivalent to minimizing the sum squared error or the mean squared error; RMSD is easier to interpret.

¹or “discrepancy” or “error”. Can also call it RMSE.

RMSD has some appealing/intuitive features:

- Larger errors are worse than small errors
- Often easy to minimize
- Min RMSD $\rightarrow$ max likelihood in some cases

Quantifying error

Alternatives to RMSD:

- Mean absolute error: $\frac{1}{J} \sum_{j=1}^J |d_j - p_j|$
- 0/1 error: Can be useful in specific situations (e.g., roulette)
- R^2 (and adjusted R^2): Not scale-dependent (good) but blind to systematic bias (bad?)

Sometimes goal-appropriate loss functions are important, e.g.,

- It's better to deploy a parachute too early than too late.
- Medical diagnosis: Low-cost, low-precision tests can be useful.

Quantifying error: Discrete variables

Most loss functions for continuous variables aren't applicable to discrete variables (e.g., forced-choice judgments).

In psychological research, one popular discrepancy function for discrete variables is χ^2 :

$$\chi^2 = \sum_{j=1}^J \frac{(O_j - Np_j)^2}{Np_j}$$

where

- J is the number of response categories
- N is the total number of responses
- O_j is the observed number of responses in category j
- p_j is the predicted probability for response j

Quantifying error: Discrete variables

Another common choice is G^2 :

$$G^2 = 2 \sum_{j=1}^J O_j \log\left(\frac{O_j}{Np_j}\right)$$

These are popular in part because they are used in null hypothesis significance tests – we can quantify “badness of fit” of a model.

In both cases, zero indicates a perfect fit.

Quantifying error: Discrete variables

Issues:

- Not that easy to interpret
- Require not just predictions, but probabilities. What happens if a predicted probability is zero?

Also:

- Accuracy – proportion of correct predictions – is a simple, intuitive, and complementary measure.

Quantifying error: Binary variables

Many discrete loss functions focus on binary tasks, e.g., “ $y = 1$ iff x is in the target category, else $y = 0$ ”. We have:

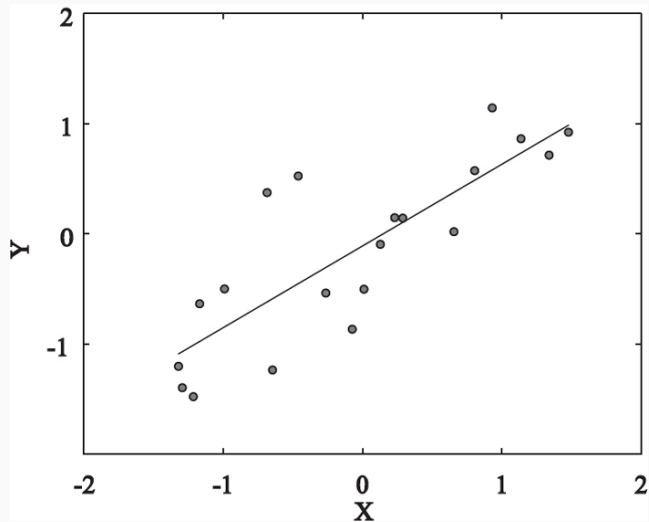
- true positives ($\hat{y}_i = 1, y_i = 1$)
- false positives ($\hat{y}_i = 1, y_i = 0$)
- true negatives ($\hat{y}_i = 0, y_i = 0$)
- false negatives ($\hat{y}_i = 0, y_i = 1$)

Quantifying error: Binary variables

We can use these to express several measures of goodness of fit:

- precision: $TP/(TP + FP)$ – useful, but easy to game
- recall: $TP/(TP + FN)$ – useful, but easy to game
- F1-score: $F_1 = 2 \frac{\text{precision} \cdot \text{recall}}{\text{precision} + \text{recall}}$
 - the harmonic mean of precision and recall; requires good performance in both

Example: Linear Regression



Linear Regression

Let's assume a simple model that describes a set of data points (x_i, y_i) as follows:

$$y_i = b_0 + b_1 x_i + e_i$$

i.e.,

$$\mathbf{y} = \mathbf{X}\mathbf{b} + \mathbf{e}$$

This equation describes **linear regression**. Here, b_0 and b_1 (intercept and slope) are the **parameters** of the model, and e_i is an error term – often assumed to be Gaussian.

How do we estimate these parameters?

How to minimize a loss function?

Suppose we want to minimize predictive RMSD.

A proxy: Minimize RMSD for the data we have.

Some approaches:

- Analytic solution
 - $\hat{\beta} = (\mathbf{X}^T \mathbf{X})^{-1} \mathbf{X}^T \mathbf{y}$
- “try them all” – look at a dense grid of possible parameters
- search selectively for an optimum

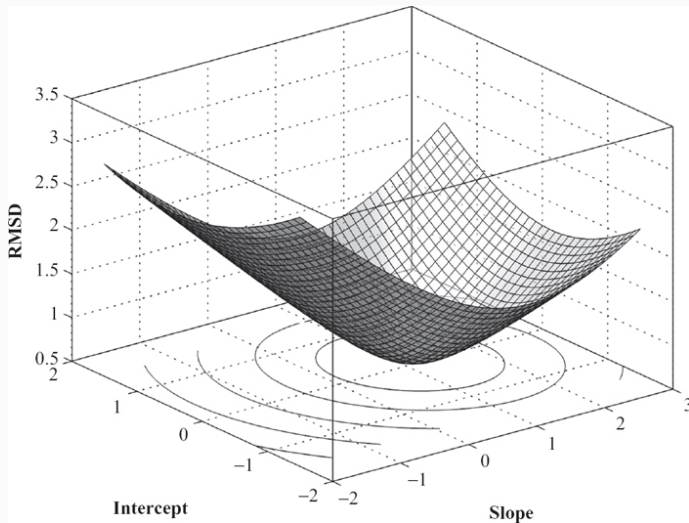
Optimization is covered in depth in other courses, e.g., MLP.²

²For a relevant reading, see Chapter 8 of [Goodfellow et al. \(2016\)](#).

Parameter Estimation: Analytic solutions

- Often the best approach, where available.
- Usually not available.

Parameter Estimation: Grid search



Parameter Estimation: Grid search

Pros:

- Easy to see how error changes as a function of 1-2 parameters.
- Easy to implement and parallelize.
- No issues with local optima.

Cons:

- Intractable for large parameter spaces or computationally expensive problems.
 - 5 parameters, 40 values per, 100ms to compute: 2844 hours.
- Doesn't find actual optimum.
- Bounds of grid aren't always known in advance.

If tractable, worth doing; complementary to other approaches.

Parameter Estimation: Sequential search/gradient descent

1. Determine a starting value for the parameters (randomly or educated guess)
2. Propose an adjustment to the parameters; use this adjustment if it reduces error
3. Iterate until no further error reduction is possible

Having gradients (i.e., how error changes locally as a function of parameters) can make this very efficient.

Parameter Estimation: Sequential search / gradient descent

See text for an example: the Nelder-Mead optimization algorithm.

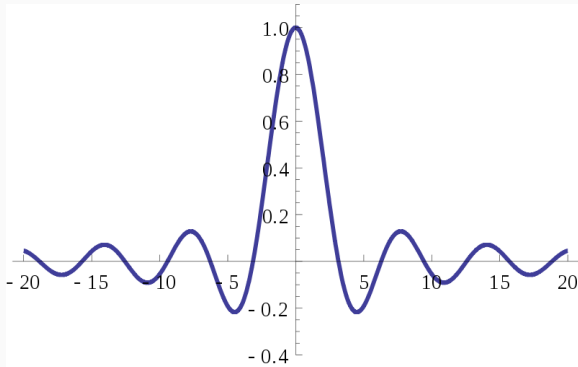
This algorithm is simple and popular, but has some disadvantages:

- Deals poorly with high-dimensional problems
- Deals poorly with stochastic loss functions (e.g., simulation-based models)
- Deals poorly with constraints on variables
- Can't deal with discrete variables
- Not very good at dealing with local optima

Pitfall: Local optima

Most efficient methods for optimizing non-trivial functions only guarantee finding *local* optima.

These may not be the same as the *global* optimum.



Pitfall: Local optima

There is no magic solution to the problem of local optima.

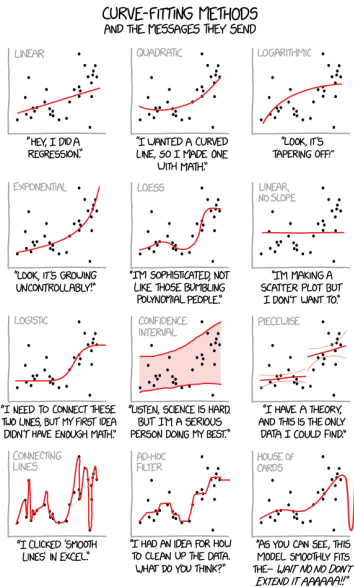
Many methods exist to mitigate it.

- See the text for a discussion of one of these: **simulated annealing**. Intuitively:
 - With certain probability, accept a parameter proposal that is worse than the current one.
 - Decrease this probability (related to “temperature”) slowly over the time of the optimization process.
- Repeating optimization many times with random initializations also helps.

Pitfall: Overfitting and predictive accuracy

We care about *predictive* error, not post-hoc error on our old data. The latter is not always a good proxy for the former.

Pitfall: Overfitting and predictive accuracy



Pitfall: Overfitting and predictive accuracy

How do we find parameters that maximize predictive accuracy?

- If data set is large and representative of all data sets we want to generalize to, fits can be a reasonable proxy.
 - This is rarely true for experimental data.
- We can use prior knowledge, e.g., in regression:
 - parameters in a regression model are likely to be close to zero.
 - most features are likely to be irrelevant.
- “regularized” or “penalized” models, e.g., minimize $\text{RMSD} + f(\mathbf{b})$.
- Other tricks: “drop-out”, early stopping, ...
- Ideally, we should be able to take our uncertainty about parameter values and predictions given data into account – be Bayesian

Pitfall: Overfitting and predictive accuracy

How do we assess the predictive accuracy of a model?

- Predict! Set aside representative data. Test after model is final.

Failing that, there are some approximations, e.g., penalties for model complexity.

Doing this well is important for model selection – discussed in a future lecture.

Discrepancy functions and fitting: What are the data?

We've been assuming we know what our data are. Do we?

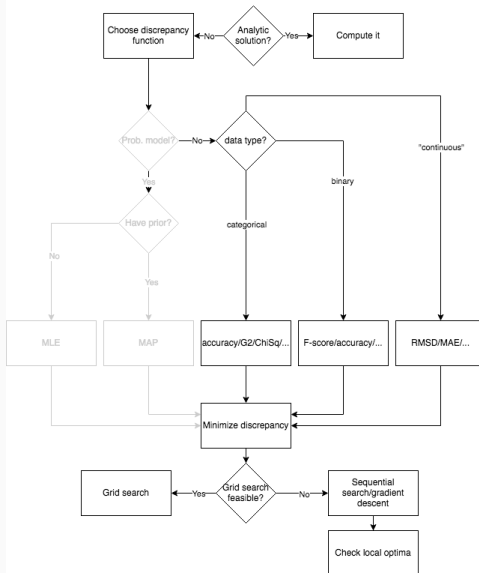
Consider the reaction-time experiment:

- Are all participants the same, e.g., same threshold for evidence?
- Is it realistic to predict the accuracy and reaction time for every judgment?
- What if we take averages per condition as our data?
 - This is common in psychological research.
 - Is it safe to do? Not always.
 - Later: Data aggregation.

Summary

- Cognitive models often have parameters that need to be estimated
- These are optimized relative to a discrepancy or loss function
 - RMSD is a popular choice, but loss function should be carefully considered
- Many optimization methods exist
 - Analytic
 - Exhaustive/gridded
 - Sequential, e.g., Nelder-Mead and new alternatives
- Beware local optima; restarts/annealing
- Post-hoc error not always a good indicator of predictive error

Parameters: Point estimates



- Farrell, Simon and Stephan Lewandowsky. 2018. *Computational Modeling of Cognition and Behavior*. Cambridge University Press, Cambridge.
- Goodfellow, Ian, Yoshua Bengio, and Aaron Courville. 2016. *Deep Learning*. MIT Press, Cambridge, MA.