You want to hire someone, and you evaluate candidates by asking them ten technical yes/no questions.

Would you feel confident if you interviewed one candidate and s/he makes a perfect score?

What about interviewing ten candidates and picking the best? What about interviewing one thousand?

Here the candidates are our models and the questions are the training examples used to pick the best one.
With
\[ Q^n_k \sim \mathcal{B}(0.5), \; n = 1, \ldots, 1000, \; k = 1, \ldots, 10, \]
independent standing for “candidate \( n \) answered question \( k \) correctly”, we have
\[ \forall n, \; P(\forall k, Q^n_k = 1) = \frac{1}{1024} \]
and
\[ P(\exists n, \forall k, Q^n_k = 1) \approx 0.62. \]
So there is 62% chance that among 1,000 candidates answering completely at random, at least one will score perfectly.

**Selecting a candidate based on a statistical estimator biases the said estimator for that candidate.** And you need a greater number of “competence checks” if you have a larger pool of candidates.

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**Over and under-fitting, capacity.** \( K \)-nearest-neighbors
A simple classification procedure is the "K-nearest neighbors."

Given
\[(x_n, y_n) \in \mathbb{R}^D \times \{1, \ldots, C\}, \; n = 1, \ldots, N\]
to predict the \(y\) associated to a new \(x\), take the \(y_n\) of the closest \(x_n\):
\[
n^*(x) = \arg\min_n \|x_n - x\|
\]
\[
f^*(x) = y_{n^*(x)}.
\]
This recipe corresponds to \(K = 1\), and makes the empirical training error zero.
Under mild assumptions of regularities of $\mu_X, Y$, for $N \to \infty$ the asymptotic error rate of the 1-NN is less than twice the (optimal!) Bayes' Error rate.

It can be made more stable by looking at the $K > 1$ closest training points, and taking the majority vote.

If we let also $K \to \infty$ “not too fast”, the error rate is the (optimal!) Bayes’ Error rate.
Training set

Prediction (K=1)

Training set

Votes (K=51)  Prediction (K=51)
Training set

Votes (K=51)

Prediction (K=51)

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Deep learning / 2.2. Over and under fitting

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Over and under-fitting, capacity, polynomials

Given a polynomial model

$$\forall x, \alpha_0, \ldots, \alpha_D \in \mathbb{R}, \quad f(x; \alpha) = \sum_{d=0}^{D} \alpha_d x^d.$$  

and training points $$(x_n, y_n) \in \mathbb{R}^2, n = 1, \ldots, N$$, the quadratic loss is

$$\mathcal{L}(\alpha) = \sum_n (f(x_n; \alpha) - y_n)^2$$

$$= \sum_n \left( \sum_{d=0}^{D} \alpha_d x_n^d - y_n \right)^2$$

$$= \left\| \begin{pmatrix} x_1^0 & \cdots & x_1^D \\ \vdots & \ddots & \vdots \\ x_N^0 & \cdots & x_N^D \end{pmatrix} \begin{pmatrix} \alpha_0 \\ \vdots \\ \alpha_D \end{pmatrix} - \begin{pmatrix} y_1 \\ \vdots \\ y_N \end{pmatrix} \right\|^2.$$  

Hence, minimizing this loss is a standard quadratic problem, for which we have efficient algorithms.
\[
\arg\min_{\alpha} \left\| \begin{pmatrix}
    x_1^0 & \cdots & x_1^D \\
    \vdots & \ddots & \vdots \\
    x_N^0 & \cdots & x_N^D \\
\end{pmatrix}
\begin{pmatrix}
    \alpha_0 \\
    \vdots \\
    \alpha_D \\
\end{pmatrix}
- \begin{pmatrix}
    y_1 \\
    \vdots \\
    y_N \\
\end{pmatrix}
\right\|^2
\]

```python
def fit_polynomial(D, x, y):
    X = torch.empty(x.size(0), D + 1)
    for d in range(D + 1):
        X[:, d] = x**d
    # lstsq expects a matrix for target
    Y = y.view(-1, 1)
    # Least square solution
    alpha, _ = torch.lstsq(Y, X)
    return alpha[:D+1, 0]
```

```
D, N = 4, 100
x = torch.linspace(-math.pi, math.pi, N)
y = x.sin()
alpha = fit_polynomial(D, x, y)
X = torch.empty(N, D + 1)
for d in range(D + 1):
    X[:, d] = x.pow(d)
y_hat = X.mv(alpha)
for k in range(N):
    print(x[k].item(), y[k].item(), y_hat[k].item())
```

![Graph showing the fit of a polynomial to a sine function](image.png)
We can use this model to illustrate how the prediction changes when we increase the degree or the regularization.
We can visualize the influence of the noise by generating multiple training sets $\mathcal{D}_1, \ldots, \mathcal{D}_M$ with different noise, and training one model on each.
We can reformulate this control of the degree with a penalty

\[ \mathcal{L}(\alpha) = \sum_n (f(x_n; \alpha) - y_n)^2 + \sum_d l_d(\alpha_d) \]

where

\[ l_d(\alpha) = \begin{cases} 
0 & \text{if } d \leq D \text{ or } \alpha = 0 \\
+\infty & \text{otherwise.} 
\end{cases} \]

Such a penalty kills any term of degree \( > D \).

This suggests more subtle variants. For instance, to keep all this quadratic

\[ \mathcal{L}(\alpha) = \sum_n (f(x_n; \alpha) - y_n)^2 + \rho \sum_d \alpha_d^2. \]
$D = 9, \rho = 1 \times 10^{-1}, f^* f$
We define the **capacity** of a set of predictors as its ability to model an arbitrary functional. This is a vague definition, difficult to make formal.

A mathematically precise notion is the Vapnik–Chervonenkis dimension of a set of functions, which, in the Binary classification case, is the cardinality of the largest set that can be labeled arbitrarily (Vapnik, 1995).

It is a very powerful concept, but is poorly adapted to neural networks. We will not say more about it in this course.

Although the capacity is hard to define precisely, it is quite clear in practice how to modulate it for a given class of models.

In particular one can control over-fitting either by

- Reducing the space $\mathcal{F}$ (less functionals, constrained or degraded optimization), or

- Making the choice of $f^*$ less dependent on data (penalty on coefficients, margin maximization, ensemble methods).
References