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Introduction to Gaussian Processes

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Linear Regression

- If we have a set of points in a space that comes from observations of an experiment and we want to predict other points, this could be done with **curve fitting**.
- So we could define some strategy to find our model.

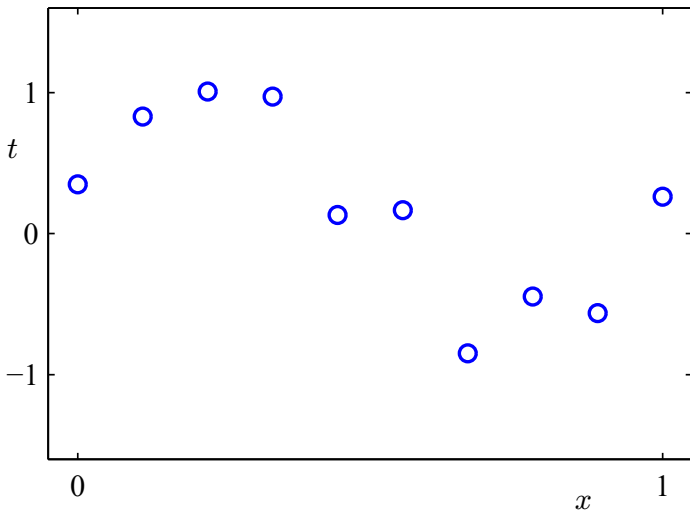
Strategy

- 1 Purpose a **model**, e.g. functions like exponential, polynomial and others.
- 2 Train our model with the training data set, finding the **unknown parameters** or **weights**.

Defining models

An initial curve fitting problem

- Let's take the points below generated from the function $y(x) = \sin(2\pi x)$.



- We can express the curve with a polynomial, being the **model**

$$y(x, \mathbf{w}) = w_0x^0 + w_1x^1 + w_2x^2 + \dots + w_{M-1}x^{M-1} = \sum_{j=1}^{M-1} w_jx^j$$

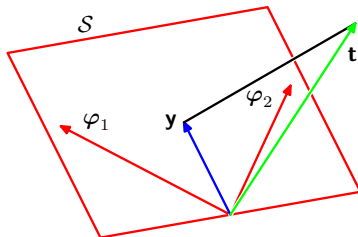
- In general, we could write this **weighted sum** with any other function. In other words, we can put this in terms of $\phi_n(x) = x^n$, where ϕ could be other **basis function**.
- e.g. we could have different $y(x)$ for different basis functions, or **features**.

$$\begin{aligned} y(x, \mathbf{w}) &= w_0\phi_0(x) + w_1\phi_1(x) + w_2\phi_2(x) + \dots + w_{M-1}\phi_{M-1}(x) \\ &= w_0 \exp \left\{ -\frac{(x - \mu_0)^2}{2\sigma^2} \right\} + w_1 \exp \left\{ -\frac{(x - \mu_1)^2}{2\sigma^2} \right\} + \\ &\dots + w_{M-1} \exp \left\{ -\frac{(x - \mu_{M-1})^2}{2\sigma^2} \right\} \\ &= w_0 \sin(0 \cdot x) + w_1 \cos(1 \cdot x) + \\ &\dots + w_{M_2} \sin((M - 2) \cdot x) + w_{M-1} \cos((M - 1) \cdot x) \end{aligned}$$

- For simplicity, we'll carry this notation along.

$$\begin{aligned} y(x, \mathbf{w}) &= w_0\phi_0(x) + w_1\phi_1(x) + \dots \\ &\quad + w_{M-1}\phi_{M-1}(x) \\ &= \sum_{j=1}^{M-1} w_j\phi_j(x) \end{aligned}$$

- We'll evaluate ϕ for all x , and then project it in the w vector space, the **feature-space**, then our model could be formed by **non-linear** functions. But, remaining **linear on parameters**.

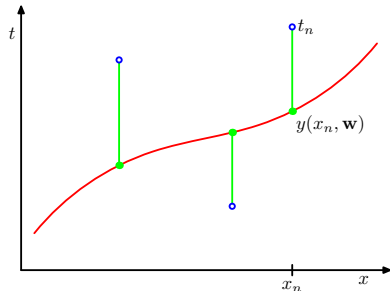


Optimizing the parameters

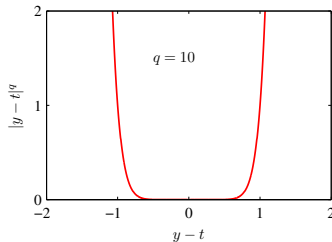
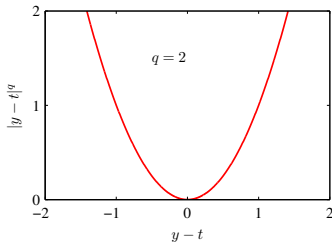
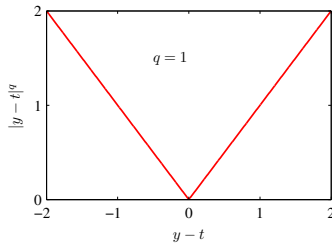
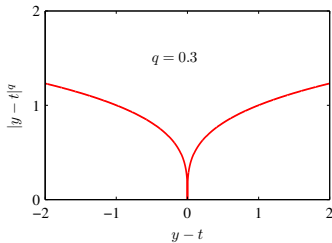
The model parameters

- The chosen model will give us some curve that is needed to adjust such that we'll **minimize its distance** to the **targets** t .
- This approach lead us to use the **least squares** to estimate the weights and minimize the **error** E .

$$E(\mathbf{w}) \triangleq \frac{1}{2} \sum_{n=1}^N \{y_n - t_n\}^2$$



Why choose a quadratic norm distance?



Why choose a quadratic norm distance?¹

- The first row figures could be used for the derivations, taking care with some **non-continuous derivatives**.
- We'll use the **quadratic norm** because its the minor integer q differentiable, and then the error measures E between the model $y(x, \mathbf{w})$ and the targets t will be euclidean.
- More, increasing the value of q , the smallests than 1 and bigger than 0 errors between the model and the targets that become irrelevant for E .

¹See Appendix ?

- Remembering that

$$y(x, \mathbf{w}) = w_0\phi_0(x) + w_1\phi_1(x) + w_2\phi_2(x) + \dots + w_{M-1}\phi_{M-1}(x)$$

- We'll evaluate for all x_i values, and then put $y_n(x_i, \mathbf{w})$ in the matrix form and get

$$y_n = [\phi_0(x_n) \quad \phi_1(x_n) \quad \dots \quad \phi_{M-1}(x_n)] [w_0 \quad w_1 \quad \dots \quad w_{M-1}]^\top$$

- And then

$$\underbrace{\begin{bmatrix} y_0 \\ y_1 \\ \vdots \\ y_{N-1} \end{bmatrix}}_{\mathbf{y}} = \underbrace{\begin{bmatrix} \phi_0(x_0) & \phi_1(x_0) & \dots & \phi_{M-1}(x_0) \\ \phi_0(x_1) & \phi_1(x_1) & \dots & \phi_{M-1}(x_1) \\ \vdots & \vdots & \ddots & \vdots \\ \phi_0(x_{N-1}) & \phi_1(x_{N-1}) & \dots & \phi_{M-1}(x_{N-1}) \end{bmatrix}}_{\Phi} \underbrace{\begin{bmatrix} w_0 \\ w_1 \\ \vdots \\ w_{N-1} \end{bmatrix}}_{\mathbf{w}}$$

where Φ is the **design matrix**.

- This represents the system $\mathbf{y} = \Phi\mathbf{w}$.

- If $E(\mathbf{w}) = \frac{1}{2} (\mathbf{y} - \mathbf{t})^\top (\mathbf{y} - \mathbf{t})$ where $\mathbf{t} = [t_1 \quad t_2 \quad \dots \quad t_n]^\top$
- Then we'll have

$$\begin{aligned} E(\mathbf{w}) &= \frac{1}{2} \left(\mathbf{y}^\top \mathbf{y} - \mathbf{t}^\top \mathbf{y} - \mathbf{y}^\top \mathbf{t} + \mathbf{t}^\top \mathbf{t} \right) \\ &= \frac{1}{2} \left((\Phi \mathbf{w})^\top (\Phi \mathbf{w}) - \mathbf{t}^\top (\Phi \mathbf{w}) - (\Phi \mathbf{w})^\top \mathbf{t} + \mathbf{t}^\top \mathbf{t} \right) \\ &= \frac{1}{2} \left(\mathbf{w}^\top \Phi^\top \Phi \mathbf{w} - 2\mathbf{t}^\top \Phi \mathbf{w} + \mathbf{t}^\top \mathbf{t} \right) \end{aligned}$$

- In sequence, we'll try to minimize it in terms of the weights (\mathbf{w}) by

$$\begin{aligned} 0 &= \frac{\partial E(\mathbf{w})}{\partial \mathbf{w}} = \frac{1}{2} \left(2\mathbf{w}^\top \Phi^\top \Phi - 2\mathbf{t}^\top \Phi + 0 \right) \\ \mathbf{w}^\top &= \mathbf{t}^\top \Phi \left(\Phi^\top \Phi \right)^{-1} \\ \mathbf{w}^* &= \left(\Phi^\top \Phi \right)^{-1} \Phi^\top \mathbf{t} \end{aligned}$$

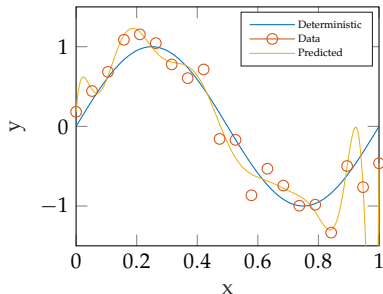
- Here, we've obtained the weights \mathbf{w}^* with the **best fit** of the curve.
- We could say that the model **learned** the parameters.

```
n = 20;
x = linspace(0,1,n)';
y = @(x) sin(2*pi*x);
e = .2*randn(size(x));
t = y(x) + e;

for M = 1:20
    phi = @(a)(bsxfun(@power,a,0:M-1));
    phix = phi(x);
    W = ((phix'*phix)\phix')*t;
end
```

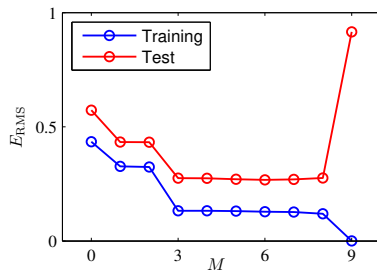
Why the prediction is so distant from the deterministic curve?

- A visible effect of the **increase of the complexity** of the model, represented here by the M , is the **increase of the weights**.
- This means that the M number of basis functions is increasing too.
- It's easy to see that our model starts to differ from the y and starts to interpolate the noise. We call this of **over-fitting**.
- This phenomenon illustrates a method of always search for the **best estimation of the parameters**.



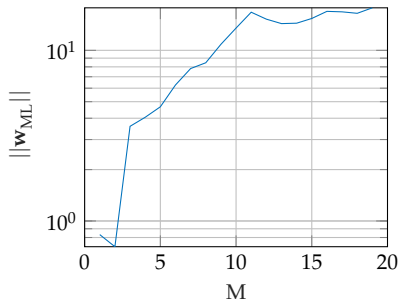
Could be over-fitting a problem?

- We could **train** our model, it means evaluate \mathbf{w}_{ML} , for only a part of our dataset.
- If the model be a good one, the error must be small when its **testing**.
- It means the error must be small when we evaluate all dataset with the \mathbf{w}_{ML} of the trained part.
- But this does not occur. So the **error increases**.



How to control the over-fitting?

- With the increase of the model complexity, the value of \mathbf{w}_{ML} increases too.
- A solution could be add a **penalty term** as the norm of the weights increases.



- To control the over-fitting, we try to **regularize** the weights by adding a penalty term (λ) to error function, by this we force the coefficients to not reach high values.

$$\begin{aligned}
 \tilde{E}(\mathbf{w}) &= \frac{1}{2}(\mathbf{y} - \mathbf{t})^\top (\mathbf{y} - \mathbf{t}) + \frac{\lambda}{2} \mathbf{w}^\top \mathbf{w} \\
 &= \frac{1}{2} \left(\mathbf{w}^\top \Phi^\top \Phi \mathbf{w} - 2\mathbf{t}^\top \Phi \mathbf{w} + \mathbf{t}^\top \mathbf{t} + \lambda \mathbf{w}^\top \mathbf{I} \mathbf{w} \right) \\
 \Rightarrow \frac{\partial E(\mathbf{w})}{\partial \mathbf{w}} &= \frac{1}{2} \left(2\mathbf{w}^\top \Phi^\top \Phi - 2\mathbf{t}^\top \Phi + 0 + 2\lambda \mathbf{w}^\top \mathbf{I} \right) \\
 0 &= \mathbf{w}^\top \Phi^\top \Phi - \mathbf{t}^\top \Phi + \lambda \mathbf{w}^\top \mathbf{I} \\
 \mathbf{w}_{ML} &= \left(\Phi^\top \Phi + \lambda \mathbf{I} \right)^{-1} \Phi^\top \mathbf{t}
 \end{aligned}$$

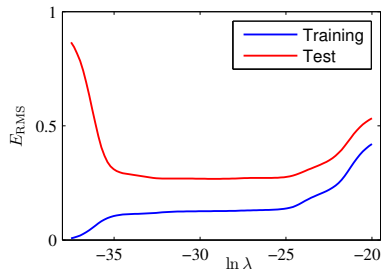
```

n = 10;
x = linspace(0,1,n)';
y = @(x) sin(2*pi*x);
e = .2*randn(size(x));
t = y(x) + e;
for lambda = 75:-1:1
    M = n;
    plot(Xp,y(Xp),'-');hold on; plot(x,t,'o');
    phi = @(a)(bsxfun(@power,a,0:M-1));
    phix = phi(x);
    W = ((phix'*phix+exp(-lambda)*eye(n))\phix')*t;
end

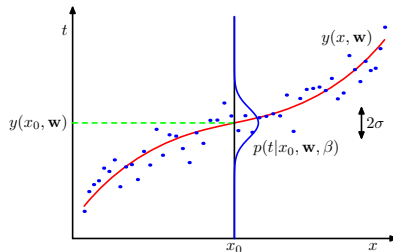
```

A more sophisticated approach?

- We could **train and test** and evaluate the error for several values of λ .
- Even yet, it's too wasteful partitionate and optimize data to find good model parameters or even a **flexible** one.
- We need a more sophisticated approach.



- Having an **uncertainty** in the measured value, we could represent it with a **probability distribution**.
- Now, each **target** could be expressed as a **random variable**.
- Its **mean** is given by $y(x, \mathbf{w})$, and the **variance** by $1/\sigma^2 = \beta$.
- β is known as **precision parameter** too.



- Being the random variables independent and identically distributed, we can say that our **joint probability** is given by

$$p(\mathbf{t}|\mathbf{x}, \mathbf{w}, \beta) = \prod_{n=1}^N p(t_n|x_n, \mathbf{w}, \beta)$$

- Our goal is, given the **parameters** \mathbf{w} , maximize the **probability** of the **targets**.
- Before, consider a property of the probability distributions

$$\int_{-\infty}^{\infty} p(x)dx = 1 \text{ and } p(x) \geq 0$$

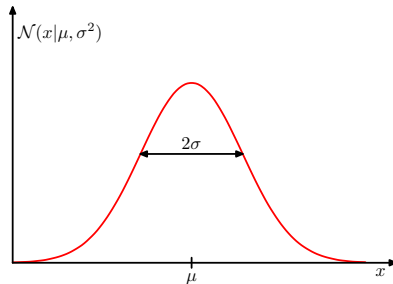
- Then, to avoid computational singularity and obtain a monotonically increasing function, we apply

$$\ln(p(\mathbf{t}|\mathbf{x}, \mathbf{w}, \beta)) = \sum_{n=1}^N \ln(p(t_n|x_n, \mathbf{w}, \beta))$$

- We'll choose the **Gaussian distribution** just for convenience.
- Then we can state the distribution for each target and then

$$p(t|\mathbf{x}, \mathbf{w}, \beta) = \mathcal{N}\left(t|y(\mathbf{x}, \mathbf{w}), \beta^{-1}\right)$$

- And we'll try to **maximize** the targets probability.



One-dimensional Gaussian distribution

$$\mathcal{N}(x|\mu, \sigma^2) = \frac{1}{(2\pi\sigma^2)^{1/2}} \exp\left\{-\frac{1}{2\sigma^2}(x - \mu)^2\right\} > 0$$

where μ is the mean and σ^2 the variance.

- From the **joint probability** of the Gaussians distributions we have

$$\begin{aligned}\ln(p(\mathbf{t}|\mathbf{x}, \mathbf{w}, \beta)) &= \mathcal{N}\left(t|y(\mathbf{x}, \mathbf{w}), \beta^{-1}\right) \\ &= \sum_{n=1}^N -\frac{1}{2} \ln(2\pi) + \sum_{n=1}^N \frac{1}{2} \ln \beta - \sum_{n=1}^N \frac{\beta}{2} (x_n - y(x_n, \mathbf{w}))^2\end{aligned}$$

- If we make

$$\frac{\partial}{\partial \mathbf{w}} \ln(p(\mathbf{t}|\mathbf{x}, \mathbf{w}, \beta)) = 0$$

we'll obtain the **cost function** obtained before in the linear regression.

- In other words, we'll obtain the weights \mathbf{w}_{ML} that **maximize** the log probability of the targets, as β_{ML} .
- With this approach, we expect to obtain too the same **over-fitting** problem.²
- Next we'll take a step towards to a **Bayesian** approach.

²See Appendix ?

Bayesian Linear Regression

At this point, we have a probabilistic model and we may want to predict values for x . Then, we need a *predictive distribution*.

Let's say we have the probabilities of some idea we desire to update it in the light of some new evidence. This could be done with **Bayes' Rule**, to convert a *prior* probability in a *posterior* probability and put some uncertainty in the parameters too.

Mathematically, by Bayes' Rule, we could infer

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$$\underbrace{p(\mathbf{w}|\mathbf{x}, \mathbf{t}, \alpha, \beta)}_{\text{posterior}} \propto \underbrace{p(\mathbf{t}|\mathbf{w}, \mathbf{x}, \beta)}_{\text{likelihood}} \underbrace{p(\mathbf{w}|\alpha)}_{\text{prior}}$$

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and for simplicity, consider the follow prior for \mathbf{w}

$$p(\mathbf{w}|\alpha) = \mathcal{N}(\mathbf{w}|\mathbf{0}, \alpha^{-1}\mathbf{I}) = \left(\frac{\alpha}{2\pi}\right)^{(M+1)/2} \exp\left\{-\frac{\alpha}{2}\mathbf{w}^\top \mathbf{w}\right\}$$

where α the precision of the distribution and $M + 1$ is the dimension of \mathbf{w} , for a polynomial of M^{th} order. Variables such α are called *hyperparameters* and control the distribution of model parameters.

By this, we can find a distribution and its maximum, or most probable value of \mathbf{w} given the data taking the minimum of the negative logarithm of the inferred expression, that will lead us to a term

$$\sum_{n=1}^N \{y(x_n, \mathbf{w}) - t_n\}^2 + \frac{\alpha}{2} \mathbf{w}^\top \mathbf{w} + \text{const.}$$

Note that if we consider $\lambda = \alpha/\beta$, this will back to the regularized form of *least squares*. This technique is called *maximum posterior* (MAP).

So, observe that even making some probabilistic assumptions, we don't have yet a fully bayesian model, given that finding the *maximum likelihood*, we're finding only the parameters given one model such that maximize our targets probabilities. Furthermore, even with some probabilistic assumptions, our model still have a **over-fitting** problem, given that we obtained the same expressions for the simple regression, adding some constants.

The next step is put some **uncertainty in predictive model**, and makes adjustments in the light of our new evidences. By that we could obtain a "more Bayesian" model, in other words, a **Bayesian Linear Regression**.

Seeking a Bayesian approach, the next steps consists to apply the **sum** and **product** rules of probability to evaluate the predictive distribution. By now we assume that the hyperparameters are fixed, but they could assume a distribution too.

We saw that the posterior distribution for \mathbf{w} could be given by

$$\underbrace{p(\mathbf{w}|\mathbf{x}, \mathbf{t})}_{\text{posterior}} \propto \underbrace{p(\mathbf{t}|\mathbf{w}, \mathbf{x})}_{\text{likelihood}} \underbrace{p(\mathbf{w})}_{\text{prior}}$$

Remember the One-dimensional Gaussian distribution

One-dimensional Gaussian distribution

$$\mathcal{N}(x|\mu, \sigma^2) = \frac{1}{(2\pi\sigma^2)^{1/2}} \exp \left\{ -\frac{1}{2\sigma^2} (x - \mu)^2 \right\} > 0$$

where μ is the mean and σ^2 the variance.

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where μ is the mean and σ^2 the variance.

First we'll consider a geometrical approach by the quadratic distance $(x - \mu)^2$ normalized by the variance σ^2 . This comprehension will help us with the D-dimensional case.

To more than one dimensions, we'll consider the points (\mathbf{x}) distance for the mean of the distribution, as we done in the one dimensional case, by adding a term to prioritize some dimension distribution in particular. Then

$$\Delta^2 = (\mathbf{x} - \boldsymbol{\mu})^\top \boldsymbol{\Sigma}^{-1} (\mathbf{x} - \boldsymbol{\mu})$$

called *Mahalanobis distance*. And it's becomes the *Euclidean distance*, when $\boldsymbol{\Sigma}$ is the identity matrix. This means that the all the distances are equally normalized. The matrix $\boldsymbol{\Sigma}$ is the covariance matrix of the distributions, by definition.

And then

D-dimensional Gaussian distribution

$$\mathcal{N}(\mathbf{x}|\boldsymbol{\mu}, \boldsymbol{\Sigma}) = \frac{1}{(2\pi)^{D/2}} \frac{1}{|\boldsymbol{\Sigma}|^{1/2}} \exp \left\{ -\frac{1}{2} (\mathbf{x} - \boldsymbol{\mu})^\top \boldsymbol{\Sigma}^{-1} (\mathbf{x} - \boldsymbol{\mu}) \right\}$$

where $\boldsymbol{\mu}$ is the D-dimensional mean vector, $\boldsymbol{\Sigma}$ the $D \times D$ -dimensional variance matrix and $|\boldsymbol{\Sigma}|$ its determinant.

Partitioned Gaussians

Given a joint Gaussian distribution $\mathcal{N}(\mathbf{x}|\boldsymbol{\mu}, \boldsymbol{\Sigma})$ with $\boldsymbol{\Lambda} \equiv \boldsymbol{\Sigma}^{-1}$ and

$$\mathbf{x} = \begin{pmatrix} \mathbf{x}_a \\ \mathbf{x}_b \end{pmatrix}, \boldsymbol{\mu} = \begin{pmatrix} \boldsymbol{\mu}_a \\ \boldsymbol{\mu}_b \end{pmatrix}, \boldsymbol{\Sigma} = \begin{pmatrix} \boldsymbol{\Sigma}_{aa} & \boldsymbol{\Sigma}_{ab} \\ \boldsymbol{\Sigma}_{ba} & \boldsymbol{\Sigma}_{bb} \end{pmatrix}, \boldsymbol{\Lambda} = \begin{pmatrix} \boldsymbol{\Lambda}_{aa} & \boldsymbol{\Lambda}_{ab} \\ \boldsymbol{\Lambda}_{ba} & \boldsymbol{\Lambda}_{bb} \end{pmatrix}.$$

Will give us

- Conditional distribution:

$$p(\mathbf{x}_a|\mathbf{x}_b) = \mathcal{N}(\mathbf{x}_a|\boldsymbol{\mu}_{a|b}, \boldsymbol{\Lambda}_{aa}^{-1}), \boldsymbol{\mu}_{a|b} = \boldsymbol{\mu}_a - \boldsymbol{\Lambda}_{aa}^{-1}\boldsymbol{\Lambda}_{ab}(\mathbf{x}_b - \boldsymbol{\mu}_b)$$

- Marginal distribution:

$$p(\mathbf{x}_a) = \mathcal{N}(\mathbf{x}_a|\boldsymbol{\mu}_a, \boldsymbol{\Sigma}_{aa})$$

To proceed we'd like to prove that the Gaussians are **closed under linear transformations**. This will allow us to transform the Gaussians under the likelihood distribution given a prior. For example, given a distribution

$$p(\mathbf{z}) = p(\mathbf{x}, \mathbf{y})$$

In other words, we're trying to find the marginal distribution $p(\mathbf{y})$ and the conditional distribution $p(\mathbf{x}|\mathbf{y})$, given

$$p(\mathbf{x}) = \mathcal{N}(\mathbf{x}|\boldsymbol{\mu}, \boldsymbol{\Lambda}^{-1})$$

$$p(\mathbf{y}|\mathbf{x}) = \mathcal{N}(\mathbf{y}|\mathbf{Ax} + \mathbf{b}, \mathbf{L}^{-1})$$

In other words, we're trying to find the parginal distribution $p(\mathbf{y})$ and the conditional distribution $p(\mathbf{x}|\mathbf{y})$, given

$$p(\mathbf{x}) = \mathcal{N}(\mathbf{x}|\boldsymbol{\mu}, \boldsymbol{\Lambda}^{-1})$$

$$p(\mathbf{y}|\mathbf{x}) = \mathcal{N}(\mathbf{y}|\mathbf{Ax} + \mathbf{b}, \mathbf{L}^{-1})$$

So, applying the joint distribution and the its ln after

$$p(\mathbf{z}) = p(\mathbf{x}, \mathbf{y}) = p(\mathbf{y}|\mathbf{x}) p(\mathbf{x})$$

$$\ln p(\mathbf{z}) = \ln p(\mathbf{y}|\mathbf{x}) + \ln p(\mathbf{x})$$

$$= -\frac{1}{2} (\mathbf{x} - \boldsymbol{\mu})^\top \boldsymbol{\Lambda} (\mathbf{x} - \boldsymbol{\mu})$$

$$- \frac{1}{2} (\mathbf{y} - \mathbf{Ax} - \mathbf{b})^\top \mathbf{L} (\mathbf{y} - \mathbf{Ax} - \mathbf{b}) + \text{const}$$

The "const" is the term independent of \mathbf{x} and \mathbf{y} . Then, expanding the quadratic form

$$\begin{aligned}\ln p(\mathbf{z}) &= -\frac{1}{2}\mathbf{x}^\top \left(\mathbf{\Lambda} + \mathbf{A}^\top \mathbf{L} \mathbf{A} \right) \mathbf{x} - \frac{1}{2}\mathbf{y}^\top \mathbf{L} \mathbf{y} + \frac{1}{2}\mathbf{y}^\top \mathbf{L} \mathbf{A} \mathbf{x} + \frac{1}{2}\mathbf{x}^\top \mathbf{A}^\top \mathbf{L} \mathbf{y} \\ &= -\frac{1}{2} \begin{pmatrix} \mathbf{x} \\ \mathbf{y} \end{pmatrix}^\top \begin{pmatrix} \mathbf{\Lambda} + \mathbf{A}^\top \mathbf{L} \mathbf{A} & -\mathbf{A}^\top \mathbf{L} \\ -\mathbf{L} \mathbf{A} & \mathbf{L} \end{pmatrix} \begin{pmatrix} \mathbf{x} \\ \mathbf{y} \end{pmatrix} = -\frac{1}{2} \mathbf{z}^\top \mathbf{R} \mathbf{z}\end{aligned}$$

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We'll apply the partitioned matrices inversion to obtain \mathbf{R}^{-1}

$$\mathbf{R}^{-1} = \begin{pmatrix} \mathbf{\Lambda}^{-1} & \mathbf{\Lambda}^{-1} \mathbf{A}^\top \\ \mathbf{A} \mathbf{\Lambda}^{-1} & \mathbf{L}^{-1} + \mathbf{A} \mathbf{\Lambda}^{-1} \mathbf{A}^\top \end{pmatrix}$$

The expanded form of $\ln p(\mathbf{z})$ give us the mean too by the linear terms, then

$$\mathbf{x}^\top \Lambda \boldsymbol{\mu} - \mathbf{x}^\top \mathbf{A}^\top \mathbf{L} \mathbf{b} + \mathbf{y}^\top \mathbf{L} \mathbf{b} = \begin{pmatrix} \mathbf{x} \\ \mathbf{y} \end{pmatrix}^\top \begin{pmatrix} \Lambda \boldsymbol{\mu} - \mathbf{A}^\top \mathbf{L} \mathbf{b} \\ \mathbf{L} \mathbf{b} \end{pmatrix}$$

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By inspection of the linear terms

$$\mathbb{E}[\mathbf{z}] = \mathbf{R}^{-1} \begin{pmatrix} \mathbf{\Lambda} \boldsymbol{\mu} - \mathbf{A}^\top \mathbf{L} \mathbf{b} \\ \mathbf{L} \mathbf{b} \end{pmatrix} = \begin{pmatrix} \boldsymbol{\mu} \\ \mathbf{A} \boldsymbol{\mu} + \mathbf{b} \end{pmatrix}$$

And then we we'll have that

$$\begin{aligned}\mathbb{E}[\mathbf{y}] &= \mathbf{A}\boldsymbol{\mu} + \mathbf{b} \\ \text{cov}[\mathbf{y}] &= \mathbf{L}^{-1} + \mathbf{A}\boldsymbol{\Lambda}^{-1}\mathbf{A}^\top\end{aligned}$$

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$$\begin{aligned}\mathbb{E}[\mathbf{x}|\mathbf{y}] &= \left(\boldsymbol{\Lambda} + \mathbf{A}^\top\mathbf{L}\mathbf{A}\right)^{-1} \left\{ \mathbf{A}^\top\mathbf{L}(\mathbf{y} - \mathbf{b}) + \boldsymbol{\Lambda}\boldsymbol{\mu} \right\} \\ \text{cov}[\mathbf{x}|\mathbf{y}] &= \left(\boldsymbol{\Lambda} + \mathbf{A}^\top\mathbf{L}\mathbf{A}\right)^{-1}\end{aligned}$$

In the next step, we'll assume a **prior distribution over parameters**, $p(\mathbf{w})$, and define it as a Gaussian distribution, then

$$p(\mathbf{w}) = \mathcal{N}(\mathbf{w}|\mathbf{m}_0, \mathbf{S}_0)$$

with mean \mathbf{m}_0 and variance \mathbf{S}_0 .

Marginal and Conditioned Gaussians

- For \mathbf{y} given \mathbf{x} :

$$p(\mathbf{x}) = \mathcal{N}(\mathbf{x} | \boldsymbol{\mu}, \boldsymbol{\Lambda}^{-1})$$

$$p(\mathbf{y} | \mathbf{x}) = \mathcal{N}(\mathbf{y} | \mathbf{A}\mathbf{x} + \mathbf{b}, \mathbf{L}^{-1})$$

- For \mathbf{x} given \mathbf{y} :

$$p(\mathbf{x} | \mathbf{y}) = \mathcal{N}(\mathbf{y} | \boldsymbol{\Sigma} \{ \mathbf{A}^\top \mathbf{L}(\mathbf{y} - \mathbf{b} + \boldsymbol{\Sigma} \boldsymbol{\mu}) \}, \boldsymbol{\Sigma})$$

$$p(\mathbf{y}) = \mathcal{N}(\mathbf{y} | \mathbf{A} \boldsymbol{\mu} + \mathbf{b}, \mathbf{L}^{-1} + \mathbf{A} \boldsymbol{\Lambda}^{-1} \mathbf{A}^\top), \text{ where } \boldsymbol{\Sigma} = (\boldsymbol{\Lambda} + \mathbf{A}^\top \mathbf{L} \mathbf{A})^{-1}$$

By the derivations, we make the assumptions of given $p(\mathbf{w})$ and for $p(\mathbf{t}|\mathbf{w})$ such that

$$\begin{aligned} p(\mathbf{t}|\mathbf{w}) &= \mathcal{N}(\mathbf{t}|y(\mathbf{x}, \mathbf{w}), \beta^{-1}) \\ &= \mathcal{N}(\mathbf{t}|\Phi^\top \mathbf{w}, \beta^{-1}) \end{aligned}$$

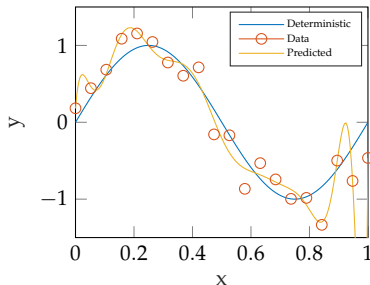
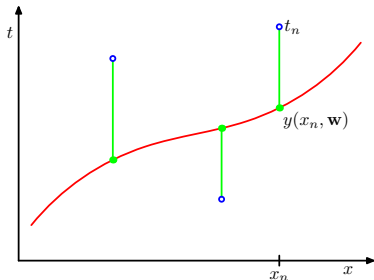
And then $p(\mathbf{w}|\mathbf{t}) = \mathcal{N}(\mathbf{w}|\mathbf{m}_N, \mathbf{S}_N)$ where

$$\begin{aligned} \mathbf{m}_N &= \mathbf{S}_N (\mathbf{S}_0^{-1} \mathbf{m}_0 + \beta \Phi^\top \mathbf{t}) \\ \mathbf{S}_N^{-1} &= \mathbf{S}_0^{-1} + \beta \Phi^\top \Phi \end{aligned}$$

Gaussian Processes

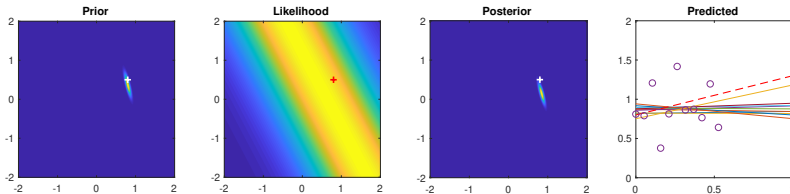
What was done until here?

- We assumed that our targets t were **i.i.d.** and given by $t = y(\mathbf{x}) + \varepsilon$, where $\varepsilon \sim \mathcal{N}(0, \beta)$.
- Our model is given by $y(\mathbf{x}) = \Phi^\top \mathbf{w}$, where Φ is the **design matrix**, and this characterizes our model as **linear in parameters**.
- The **design matrix** was defined as $\phi_{i,j} = \phi_i(\mathbf{x}_j)$.
- The **parameters** were given by $\mathbf{w} = (\Phi^\top \Phi)^{-1} \Phi^\top \mathbf{t}$.
- These **parameters** calculated at the minimum of the cost function are called **maximum likelihood**.



What was done until here?

- We put an **uncertainty** over the targets t and the parameters \mathbf{w} .
- We assumed that targets being **distributed** as $p(t|\mathbf{x}, \mathbf{w}, \beta) = \mathcal{N}(t|y(\mathbf{x}, \mathbf{w}), \beta^{-1})$.
- By **Bayes' Rule** we obtained that $p(\mathbf{w}|\mathbf{x}, \mathbf{t}, \alpha, \beta) \propto p(\mathbf{t}|\mathbf{w}, \mathbf{x}, \beta) p(\mathbf{w}|\alpha)$
- This allowed to make an **inference** to obtain a **prediction** of the parameters in the **weight-space**.



Recap

A more clear way to see what is happening...

From Bayesian inference

- We have

$$p(\mathbf{w}|\mathbf{x}, \mathbf{t}, \alpha, \beta) \propto p(\mathbf{t}|\mathbf{x}, \mathbf{w}, \beta)p(\mathbf{w}|\alpha)$$

- We'll change from **weight-space**

$$p(\mathbf{t}_*|\mathbf{x}_*, \mathbf{x}, \mathbf{t}) = \int p(\mathbf{t}_*|\mathbf{x}_*, \mathbf{w})p(\mathbf{w}|\mathbf{x}, \mathbf{t})d\mathbf{w}$$

- To **feature-space**

$$\begin{aligned} p(f_*|\mathbf{x}_*, \Phi, \mathbf{t}) &= \int p(f_*|\mathbf{x}_*, \mathbf{w})p(\mathbf{w}|\Phi, \mathbf{t})d\mathbf{w} = \int \mathbf{x}_*^\top \mathbf{w} p(\mathbf{w}|\Phi, \mathbf{t})d\mathbf{w} \\ &= \mathcal{N}\left(\beta \phi(\mathbf{x}_*)^\top \mathbf{S}_N \Phi \mathbf{t}, \phi(\mathbf{x}_*)^\top \mathbf{S}_N^{-1} \phi(\mathbf{x}_*)\right) \end{aligned}$$

where $f_* \triangleq f(\mathbf{x}_*)$ at \mathbf{x}_* and $\Phi = \Phi(\mathbf{x})$

Alternative formulation

$$f_* | \mathbf{x}_*, \Phi, \mathbf{t} \sim \mathcal{N} \left(\phi_*^\top \mathbf{S}_0 \Phi \left(K + \beta^{-2} I \right)^{-1} \mathbf{t}, \phi_*^\top \mathbf{S}_0 \phi_* - \phi_*^\top \mathbf{S}_0 \Phi \left(K + \beta^{-2} I \right)^{-1} \Phi^\top \mathbf{S}_0 \phi_* \right)$$

where $K = \Phi^\top \mathbf{S}_0 \Phi$

What is kernel?

$$f_* | \mathbf{x}_*, \Phi, \mathbf{t} \sim \mathcal{N} \left(\phi_*^\top \mathbf{S}_0 \Phi \left(K + \beta^{-2} I \right)^{-1} \mathbf{t}, \phi_*^\top \mathbf{S}_0 \phi_* - \phi_*^\top \mathbf{S}_0 \Phi \left(K + \beta^{-2} I \right)^{-1} \Phi^\top \mathbf{S}_0 \phi_* \right)$$

- We could observe the appearance of terms like $\Phi^\top \mathbf{S}_0 \Phi$, $\phi_*^\top \mathbf{S}_0 \Phi$, or $\phi_*^\top \mathbf{S}_0 \phi_*$.
- The common term between these operations is $k(\mathbf{x}, \mathbf{x}') = \phi(\mathbf{x})^\top \mathbf{S}_0 \phi(\mathbf{x}')$
- Then we define $k(\cdot, \cdot)$ as **kernel function**
- This technique is particularly valuable in situations where it is more convenient to compute the kernel than the design matrix vectors themselves.

- Previously we make the inference in the **feature-space** and then we find the function distribution.
- Now we'll make the inference directly on **function-space**.
- Let's define

Definition

*A **Gaussian process** is a collection of random variables which any finite number of them have a joint Gaussian distribution.*

Mean and covariance function

- As the Gaussian distribution, the \mathcal{GP} is characterized by its **mean function** $m(\mathbf{x})$ and its **covariance function** $k(\mathbf{x}, \mathbf{x}')$ of a real process $f(\mathbf{x})$.
- For a Gaussian processes

$$f(\mathbf{x}) \sim \mathcal{GP}(m(\mathbf{x}), k(\mathbf{x}, \mathbf{x}'))$$

- We have

$$m(\mathbf{x}) = \mathbb{E}[f(\mathbf{x})]$$

$$k(\mathbf{x}, \mathbf{x}') = \mathbb{E}[(f(\mathbf{x}) - m(\mathbf{x}))(f(\mathbf{x}') - m(\mathbf{x}'))]$$

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