# Lecture 5: GPs and Streaming regression

- Gaussian Processes
- Information gain
- Confidence intervals

# Recall: Non-parametric regression

- Input space $\mathcal{X} \subseteq \mathbb{R}^n$, target space $\mathcal{Y} = \mathbb{R}$
- Input matrix $\mathbf{X}$ of size $m \times n$, target vector $\mathbf{y}$ of size $m \times 1$
- Feature mapping $\phi : \mathcal{X} \mapsto \mathbb{R}^d$
- Assumption: $\mathbf{y} = \mathbf{\Phi}\mathbf{w}$
- Minimize

$$J_\lambda(\mathbf{w}) = \frac{1}{2}(\mathbf{\Phi}\mathbf{w} - \mathbf{y})^\top(\mathbf{\Phi}\mathbf{w} - \mathbf{y}) + \frac{\lambda}{2}\mathbf{w}^\top\mathbf{w} \qquad \lambda \geq 0$$

- The solution is

$$\mathbf{w} = (\mathbf{\Phi}^\top\mathbf{\Phi} + \lambda\mathbf{I}_n)^{-1}\mathbf{\Phi}^\top\mathbf{y} = \mathbf{\Phi}^\top(\mathbf{\Phi}\mathbf{\Phi}^\top + \lambda\mathbf{I}_m)^{-1}\mathbf{y}$$

# Recall: Kernel regression

- Let $\mathbf{K} = \boldsymbol{\Phi}\boldsymbol{\Phi}^\top$ and $\mathbf{k}(\mathbf{x}) \in \mathbb{R}^m = \phi(\mathbf{x})^\top \boldsymbol{\Phi}^\top$ be the kernel matrix/vector:

$$\mathbf{K} = \begin{bmatrix} k(\mathbf{x}_1, \mathbf{x}_1) & k(\mathbf{x}_1, \mathbf{x}_2) & \ldots & k(\mathbf{x}_1, \mathbf{x}_m) \\ k(\mathbf{x}_2, \mathbf{x}_1) & k(\mathbf{x}_2, \mathbf{x}_2) & \ldots & k(\mathbf{x}_2, \mathbf{x}_m) \\ \vdots & \vdots & & \vdots \\ k(\mathbf{x}_m, \mathbf{x}_1) & k(\mathbf{x}_m, \mathbf{x}_2) & \ldots & k(\mathbf{x}_m, \mathbf{x}_m) \end{bmatrix} \qquad \mathbf{k}(\mathbf{x}) = \begin{bmatrix} k(\mathbf{x}, \mathbf{x}_1) \\ k(\mathbf{x}, \mathbf{x}_2) \\ \vdots \\ k(\mathbf{x}, \mathbf{x}_m) \end{bmatrix}$$

- The predictions for the input data are given by

$$\hat{\mathbf{y}} = \boldsymbol{\Phi}\boldsymbol{\Phi}^\top (\boldsymbol{\Phi}\boldsymbol{\Phi}^\top + \lambda \mathbf{I}_m)^{-1}\mathbf{y} = \mathbf{K}(\mathbf{K} + \lambda \mathbf{I}_m)^{-1}\mathbf{y}$$

- The prediction for a new input point $\mathbf{x}$ is given by

$$\hat{f}(\mathbf{x}) = \phi(\mathbf{x})^\top \boldsymbol{\Phi}^\top (\mathbf{K} + \lambda \mathbf{I}_m)^{-1}\mathbf{y} = \mathbf{k}(\mathbf{x})(\mathbf{K} + \lambda \mathbf{I}_m)^{-1}\mathbf{y}$$

# Recall: Bayesian view of regression

- Consider noisy observations $y = f(\mathbf{x}) + \epsilon = \phi(\mathbf{x})^\top \mathbf{w} + \epsilon$
- With Gaussian noise $\epsilon \sim \mathcal{N}(0, \sigma^2)$

$$P_\phi(\mathbf{y}|\mathbf{X}, \mathbf{w}) = \prod_{i=1}^{m} P_\phi(y_i|\mathbf{x}_i, \mathbf{w}) = \prod_{i=1}^{m} \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{(y_i - \phi(\mathbf{x}_i)^\top \mathbf{w})^2}{2\sigma^2}\right)$$

$$= \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{\|\mathbf{y} - \mathbf{\Phi}\mathbf{w}\|^2}{2\sigma^2}\right) = \mathcal{N}_m\left(\mathbf{\Phi}\mathbf{w}, \sigma^2 \mathbf{I}_m\right)$$

- Recall Bayes' rule: posterior $= \frac{\text{likelihood} \times \text{prior}}{\text{marginal likelihood}}$

$$P_\phi(\mathbf{w}|\mathbf{y}, \mathbf{X}) = \frac{P_\phi(\mathbf{y}|\mathbf{X}, \mathbf{w})P(\mathbf{w})}{P_\phi(\mathbf{y}|\mathbf{X})}$$

$\Rightarrow$ Marginal likelihood is independent of weights $\mathbf{w}$

# Posterior distribution on parameters

- With Gaussian prior on parameters $\mathbf{w} \sim \mathcal{N}_d(0, \Sigma_{\mathbf{w}})$

$$P_\phi(\mathbf{w}|\mathbf{y}, \mathbf{X}) \propto \exp\left(-\frac{\|\mathbf{y} - \boldsymbol{\Phi}\mathbf{w}\|^2}{2\sigma^2}\right) \exp\left(-\frac{\mathbf{w}^\top \Sigma_{\mathbf{w}}^{-1} \mathbf{w}}{2}\right)$$

$$= \exp\left(-\frac{\mathbf{y}^\top \mathbf{y} - \mathbf{y}^\top \boldsymbol{\Phi}\mathbf{w} - \mathbf{w}^\top \boldsymbol{\Phi}\mathbf{y} + \mathbf{w}^\top \boldsymbol{\Phi}^\top \boldsymbol{\Phi}\mathbf{w} + \sigma^2 \mathbf{w}^\top \Sigma_{\mathbf{w}}^{-1} \mathbf{w}}{2\sigma^2}\right)$$

$$= \exp\left(-\frac{\mathbf{y}^\top \mathbf{y} - \mathbf{y}^\top \boldsymbol{\Phi}\mathbf{w} - \mathbf{w}^\top \boldsymbol{\Phi}\mathbf{y} + \mathbf{w}^\top (\boldsymbol{\Phi}^\top \boldsymbol{\Phi} + \sigma^2 \Sigma_{\mathbf{w}}^{-1})\mathbf{w}}{2\sigma^2}\right)$$

$$\propto \exp\left((\mathbf{w} - \mathbf{b})^\top \mathbf{A}^{-1}(\mathbf{w} - \mathbf{b})\right)$$

where $\mathbf{A}^{-1} = \sigma^{-2}(\boldsymbol{\Phi}^\top \boldsymbol{\Phi} + \sigma^2 \Sigma_{\mathbf{w}}^{-1})$ and $\mathbf{b} = (\boldsymbol{\Phi}^\top \boldsymbol{\Phi} + \sigma^2 \Sigma_{\mathbf{w}}^{-1})^{-1} \boldsymbol{\Phi}^\top \mathbf{y}$

$\Rightarrow$ The posterior distribution is Gaussian!

# Predictive distribution

- The pointwise posterior predictive distribution is a normal distribution

$$\tilde{f}(\mathbf{x})|\mathbf{x}_1, \ldots, \mathbf{x}_m, y_1, \ldots, y_m \sim \mathcal{N}\left(\hat{f}(\mathbf{x}), s^2(\mathbf{x})\right)$$

of expectation

$$\hat{f}(\mathbf{x}) = \phi(\mathbf{x})^\top (\mathbf{\Phi}^\top \mathbf{\Phi} + \sigma^2 \Sigma_{\mathbf{w}}^{-1})^{-1} \mathbf{\Phi}^\top \mathbf{y}$$

$$= \phi(\mathbf{x})^\top \Sigma_{\mathbf{w}} \mathbf{\Phi}^\top (\mathbf{\Phi} \Sigma_{\mathbf{w}} \mathbf{\Phi}^\top + \sigma^2 \mathbf{I}_m)^{-1} \mathbf{y}$$

and variance

$$s^2(\mathbf{x}) = \sigma^2 \phi(\mathbf{x})^\top (\mathbf{\Phi}^\top \mathbf{\Phi} + \sigma^2 \Sigma_{\mathbf{w}}^{-1})^{-1} \phi(\mathbf{x})$$

$$= \phi(\mathbf{x})^\top \Sigma_{\mathbf{w}} \phi(\mathbf{x}) - \phi(\mathbf{x})^\top \Sigma_{\mathbf{w}} \mathbf{\Phi}^\top (\mathbf{\Phi}^\top \Sigma_{\mathbf{w}} \mathbf{\Phi} + \sigma^2 \mathbf{I}_m)^{-1} \mathbf{\Phi} \Sigma_{\mathbf{w}} \phi(\mathbf{x})$$

$\rightarrow$ using Sherman-Morrison

# Reinterpreting regularization

- Recall kernel regression predictions:

$$\hat{f}(\mathbf{x}) = \mathbf{k}(\mathbf{x})^\top (\mathbf{K} + \lambda \mathbf{I}_m)^{-1} \mathbf{y}$$

- Using prior $\Sigma_{\mathbf{w}} = \frac{\sigma^2}{\lambda} \mathbf{I}_d$, the predictive mean rewrites as:

$$\hat{f}(\mathbf{x}) = \phi(\mathbf{x})^\top \Sigma_{\mathbf{w}} \mathbf{\Phi}^\top (\mathbf{\Phi} \Sigma_{\mathbf{w}} \mathbf{\Phi}^\top + \sigma^2 \mathbf{I}_m)^{-1} \mathbf{y}$$

$$= \phi(\mathbf{x})^\top \frac{\sigma^2}{\lambda} \mathbf{\Phi}^\top \left( \mathbf{\Phi} \frac{\sigma^2}{\lambda} \mathbf{\Phi}^\top + \sigma^2 \mathbf{I}_m \right)^{-1} \mathbf{y}$$

$$= \mathbf{k}(\mathbf{x})^\top (\mathbf{K} + \lambda \mathbf{I}_m)^{-1} \mathbf{y}$$

$\Rightarrow \lambda$ encodes some prior on weights $\mathbf{w}$

# Reinterpreting regularization (cont'd)

- Still using $\Sigma_{\mathbf{w}} = \frac{\sigma^2}{\lambda}\mathbf{I}_d$, the predictive variance rewrites as:

$$s^2(\mathbf{x}) = \phi(\mathbf{x})^\top \Sigma_{\mathbf{w}}\phi(\mathbf{x}) - \phi(\mathbf{x})^\top \Sigma_{\mathbf{w}}\boldsymbol{\Phi}^\top(\boldsymbol{\Phi}^\top\Sigma_{\mathbf{w}}\boldsymbol{\Phi} + \sigma^2\mathbf{I}_m)^{-1}\boldsymbol{\Phi}\Sigma_{\mathbf{w}}\phi(\mathbf{x})$$

$$= \phi(\mathbf{x})^\top\frac{\sigma^2}{\lambda}\phi(\mathbf{x}) - \phi(\mathbf{x})^\top\frac{\sigma^2}{\lambda}\boldsymbol{\Phi}^\top\left(\boldsymbol{\Phi}^\top\frac{\sigma^2}{\lambda}\boldsymbol{\Phi} + \sigma^2\mathbf{I}_m\right)^{-1}\boldsymbol{\Phi}\frac{\sigma^2}{\lambda}\phi(\mathbf{x})$$

$$= \frac{\sigma^2}{\lambda}k_\lambda(\mathbf{x}, \mathbf{x}) \qquad \text{with}$$

$$k_\lambda(\mathbf{x}, \mathbf{x}') = k(\mathbf{x}, \mathbf{x}') - \mathbf{k}(\mathbf{x})^\top(\mathbf{K} + \lambda\mathbf{I}_m)^{-1}\mathbf{k}(\mathbf{x}')$$
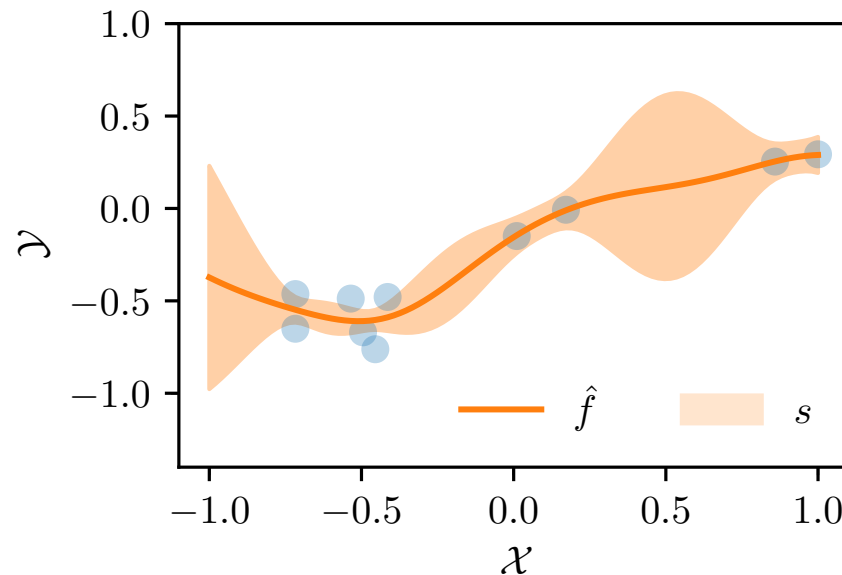
# Summary

- Using prior $\Sigma_{\mathbf{w}} = \frac{\sigma^2}{\lambda} \mathbf{I}_d$, we have

$$\hat{f}(\mathbf{x}) = \mathbf{k}(\mathbf{x})^\top (\mathbf{K} + \lambda \mathbf{I}_m)^{-1} \mathbf{y}$$

$$s^2(\mathbf{x}) = \frac{\sigma^2}{\lambda} k_\lambda(\mathbf{x}, \mathbf{x}) \qquad \text{with}$$

$$k_\lambda(\mathbf{x}, \mathbf{x}') = k(\mathbf{x}, \mathbf{x}') - \mathbf{k}(\mathbf{x})^\top (\mathbf{K} + \lambda \mathbf{I}_m)^{-1} \mathbf{k}(\mathbf{x}')$$

- Providing pointwise posterior prediction

$$\tilde{f}(\mathbf{x}) | \mathbf{x}_1, \ldots, \mathbf{x}_m, y_1, \ldots, y_m \sim \mathcal{N}\left(\hat{f}(\mathbf{x}), s^2(\mathbf{x})\right)$$

$\Rightarrow$ What does it mean to use $\lambda \in \mathbb{R}_{\geq 0}$?

# Pointwise posterior distribution

- At each point $\mathbf{x} \in \mathcal{X}$, we have a distribution $\mathcal{N}\left(\hat{f}(\mathbf{x}), s^2(\mathbf{x})\right)$

- We can sample from these $\tilde{f}(\mathbf{x}) \sim \mathcal{N}\left(\hat{f}(\mathbf{x}), s^2(\mathbf{x})\right)$

# Joint distribution

- Suppose you *query* your model at locations $\mathbf{X}_*$

- Extend the prior to include query points:

$$\begin{bmatrix} \mathbf{f} \\ \mathbf{f}_* \end{bmatrix} | \mathbf{X}, \mathbf{X}_* \sim \mathcal{N}\left( \mathbf{0}, \begin{bmatrix} \mathbf{K}_{\mathbf{X},\mathbf{X}}+ & \mathbf{K}_{\mathbf{X},\mathbf{X}_*} \\ \mathbf{K}_{\mathbf{X}_*,\mathbf{X}} & \mathbf{K}_{\mathbf{X}_*,\mathbf{X}_*} \end{bmatrix} \right)$$

$$\mathbf{y}|\mathbf{f} \sim \mathcal{N}_m(\mathbf{f}, \sigma^2\mathbf{I}_m)$$

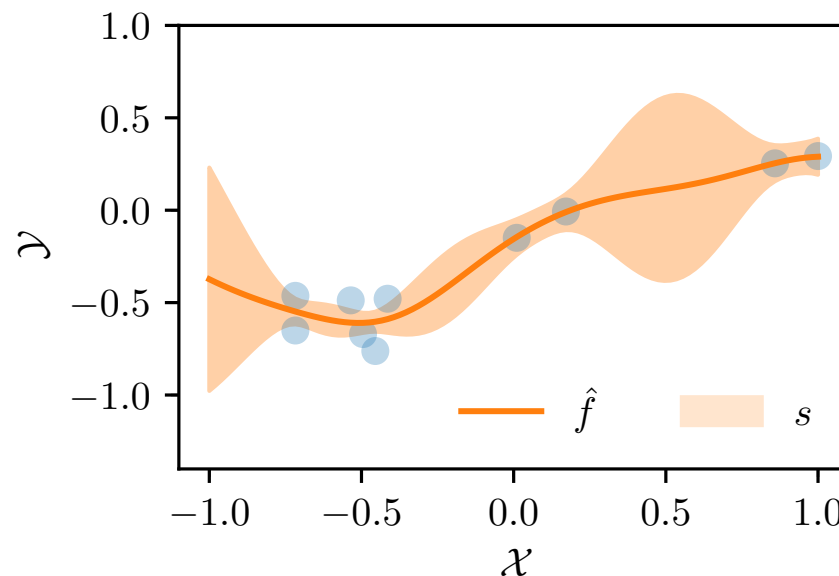- Using joint normality of $\mathbf{f}_*$ and $\mathbf{y}$:

$$\begin{bmatrix} \mathbf{y} \\ \mathbf{f}_* \end{bmatrix} \sim \mathcal{N}_{m+m_*}\left( \mathbf{0}, \begin{bmatrix} \mathbf{K}_{\mathbf{X},\mathbf{X}} + \lambda\mathbf{I}_m & \mathbf{K}_{\mathbf{X},\mathbf{X}_*} \\ \mathbf{K}_{\mathbf{X}_*,\mathbf{X}} & \mathbf{K}_{\mathbf{X}_*,\mathbf{X}_*} \end{bmatrix} \right)$$
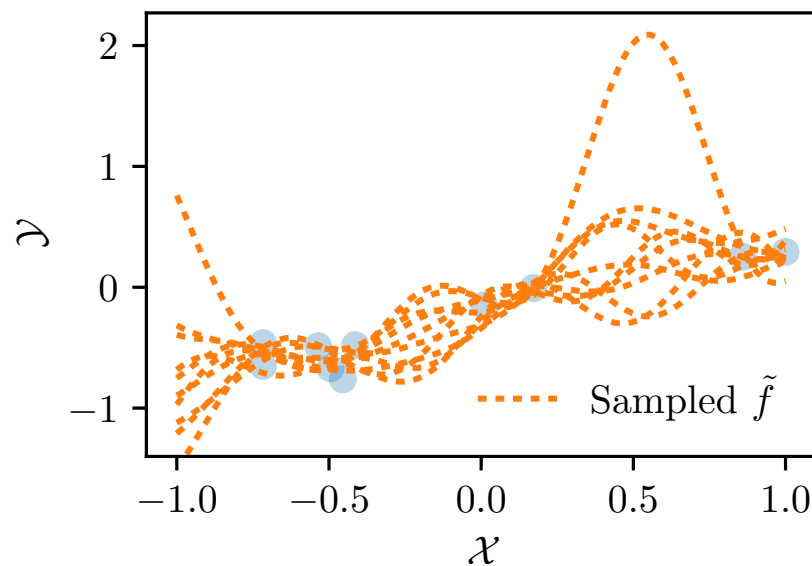
# Gaussian Process (GP)

- By considering the covariance between *every points in the space*, we get a distribution over functions!
- Posterior distribution on $f$:

$$P[f|\mathbf{X}, \mathbf{y}] \sim \mathcal{N}_{|\mathcal{X}|} \left( \left[ \hat{f}(\mathbf{x}) \right]_{\mathbf{x} \in \mathcal{X}}, \frac{\sigma^2}{\lambda} \left[ k_\lambda(\mathbf{x}, \mathbf{x}') \right]_{\mathbf{x}, \mathbf{x}' \in \mathcal{X}} \right)$$

# Sampling from a Gaussian Process

- Generalization of normal probability distribution to the function space
  - From a normal distribution we sample variables
  - From a GP we sample *functions*!

# Sampling from a Gaussian Process: How to

- Observe that

$$\mathcal{N}_{|\mathcal{X}|}\left(\left[\hat{f}(\mathbf{x})\right]_{\mathbf{x}\in\mathcal{X}}, \frac{\sigma^2}{\lambda}\left[k_\lambda(\mathbf{x}, \mathbf{x}')\right]_{\mathbf{x},\mathbf{x}'\in\mathcal{X}}\right)$$

  defines a $|\mathcal{X}|$-dimensional multivariate Gaussian distribution

$\rightarrow$ What if $|\mathcal{X}| = \infty$ (e.g. $\mathcal{X} = [-1, 1]$)?

- We can consider a discrete, finite, set $\mathbb{X} \subset \mathcal{X}$ and sample from

$$\mathcal{N}_{|\mathbb{X}|}\left(\left[\hat{f}(\mathbf{x})\right]_{\mathbf{x}\in\mathbb{X}}, \frac{\sigma^2}{\lambda}\left[k_\lambda(\mathbf{x}, \mathbf{x}')\right]_{\mathbf{x},\mathbf{x}'\in\mathbb{X}}\right)$$

- This will result in a function $\tilde{f}$ evaluated at every $\mathbf{x} \in \mathbb{X}$

# Learning the hyperparameters

- If we assume that $\Sigma_{\mathbf{w}} = \mathbf{I}_d$, then we have $\lambda = \sigma^2$

- In practice you may not know the noise and the *optimal* kernel hypers

- Let $\boldsymbol{\theta}$ denote the kernel hyperparameters (e.g. $\rho$) and noise $\sigma$

- Recall: multivariate normal density

$$P(\mathbf{y}|\boldsymbol{\theta}) = \frac{\exp\left(-\frac{1}{2}\mathbf{y}^\top(\mathbf{K}_{\boldsymbol{\theta}} + \sigma^2\mathbf{I}_m)^{-1}\mathbf{y}\right)}{\sqrt{(2\pi)^D|\mathbf{K}_{\boldsymbol{\theta}} + \sigma^2\mathbf{I}_m|}}$$

- Maximize the marginal likelihood $\mathcal{L} = \log P(\mathbf{y}|\boldsymbol{\theta})$:
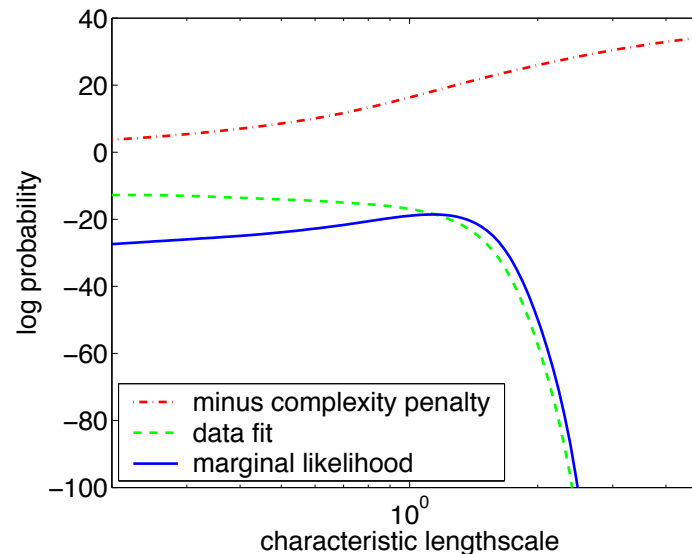
$$\mathcal{L} = -\frac{1}{2}\mathbf{y}^\top(\mathbf{K}_{\boldsymbol{\theta}} + \sigma^2\mathbf{I}_m)^{-1}\mathbf{y} - \frac{D}{2}\log(2\pi) - \frac{1}{2}\log|\mathbf{K}_{\boldsymbol{\theta}} + \sigma^2\mathbf{I}_m|$$

# Anatomy of marginal likelihood

- Marginal likelihood:

$$\mathcal{L} = \log P(\mathbf{y}|\boldsymbol{\theta}) \propto -\frac{1}{2}\mathbf{y}^{\top}(\mathbf{K}_{\boldsymbol{\theta}} + \sigma^2\mathbf{I}_m)^{-1}\mathbf{y} - \frac{1}{2}\log|\mathbf{K}_{\boldsymbol{\theta}} + \sigma^2\mathbf{I}_m|$$

- 1st term: quality of predictions; 2nd term: model complexity
- Trade-off (from Rasmussen & Williams, 2006):

# Gradient-based optimization

- Compute gradients:

$$\frac{\partial \mathcal{L}}{\partial \theta_i} = \frac{1}{2} \mathbf{y}^\top (\mathbf{K}_{\boldsymbol{\theta}} + \sigma^2 \mathbf{I}_m)^{-1} \frac{\partial (\mathbf{K}_{\boldsymbol{\theta}} + \sigma^2 \mathbf{I}_m)}{\partial \theta_i} (\mathbf{K}_{\boldsymbol{\theta}} + \sigma^2 \mathbf{I}_m)^{-1} \mathbf{y}$$

$$- \frac{1}{2} \mathrm{Tr} \left( (\mathbf{K}_{\boldsymbol{\theta}} + \sigma^2 \mathbf{I}_m)^{-1} \frac{\partial (\mathbf{K}_{\boldsymbol{\theta}} + \sigma^2 \mathbf{I}_m)}{\partial \theta_i} \right)$$

- Minimize the negative
- Non-convex optimization task

# Summary

- Normal priors on the weights distribution $\rightarrow$ Gaussian Process

- Regularization $\rightarrow$ prior on the weights covariance

- GP provides a posterior distribution on functions

  - Expectation: kernel regression model
  - Covariance $\rightarrow$ confidence intervals

- Sample discretized functions from a GP

# Typical supervised setting

- Have dataset $(\mathbf{X}, \mathbf{y})$ of previously acquired data

- Learn model $\mathbf{w}$ on $(\mathbf{X}, \mathbf{y})$

- Apply model $\mathbf{w}$ to provide predictions at new data points

- Samples $(\mathbf{X}, \mathbf{y})$ are often assumed to be i.i.d.

# Streaming setting

- Start with (possibly empty) dataset $(\mathbf{X}_0, \mathbf{y}_0)$

- For each time step $t = 1, \ldots$:

  - Fit model $\mathbf{w}_t$ on $\mathbf{X}_{t-1}$ and $\mathbf{y}_{t-1}$
  - Acquire a new sample $(\mathbf{x}_t, y_t)$ (possibly using $\mathbf{w}_t$)
  - Define $\mathbf{X}_t = [\mathbf{x}_i]_{i=1\ldots t}$, $\mathbf{y}_t = [y_i]_{i=1\ldots t}$

- Samples may be dependent of model (not i.i.d.)

$\rightarrow$ Samples influence model / Samples depend on model

# Application: Online function optimization
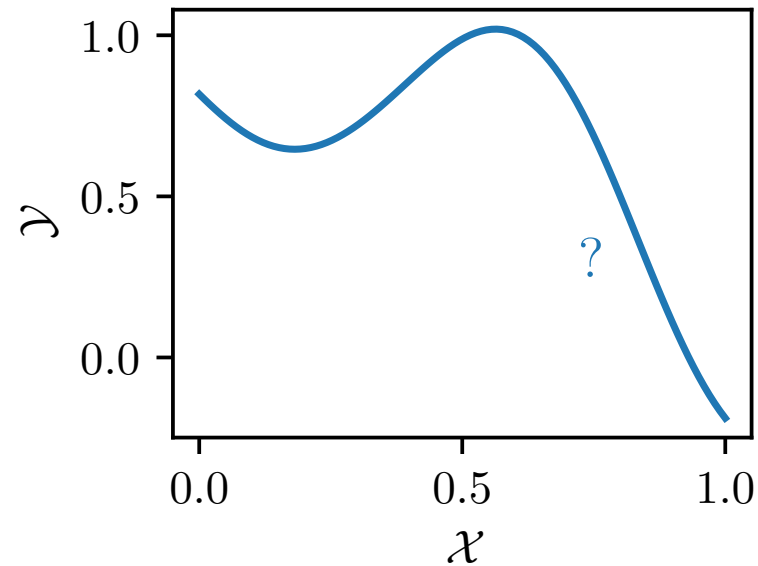


- Unknown function $f : \mathcal{X} \mapsto \mathbb{R}$
- Sequentially select locations $(\mathbf{x}_t)_{t \geq 1}$ at which to observe the function $y_t$
- Try to maximize/minimize the observations

# Example

What is the optimal treatment dosage for a given disease?

- For each time step $t = 1, \ldots$:
    - New patient $t$ comes in
    - We decide on treatment dosage $\mathbf{x}_t$
    - We observe the patient's response to treatement, $y_t$
- Our goal is to cure patients as effectively as possible
- What you don't want: give bad dosages that *were known to be bad*
- What you want:
    - give *good* dosages
    - try *informative* dosages

# Information

- An informative sample improves the model by reducing its uncertainty
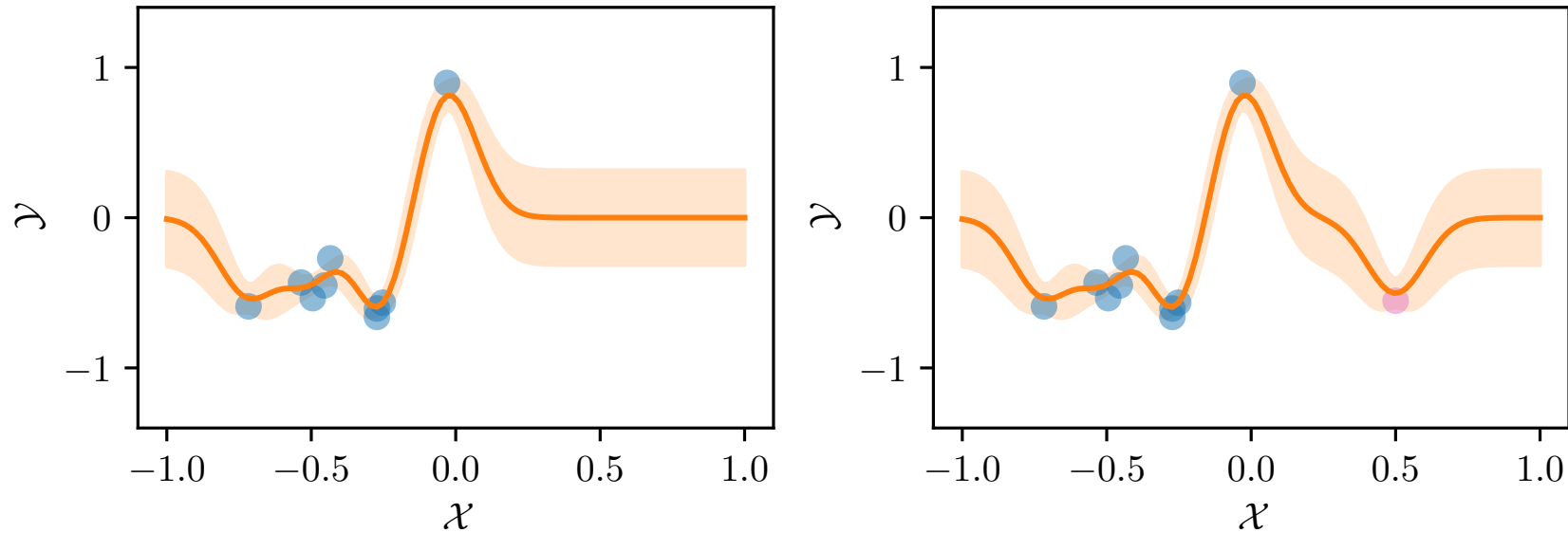


How do we quantity the reduction of uncertainty
after observing $y_1, \ldots, y_t$ at locations $\mathbf{x}_1, \ldots, \mathbf{x}_t$?

# A little bit of information theory

- *Mutual information* between underlying function $f$ and observations $y_1, \ldots, y_t$ at locations $\mathbf{x}_1, \ldots, \mathbf{x}_t$:

$$I(y_1, \ldots, y_t; f) = \underbrace{H(y_1, \ldots, y_t)}_{\text{Marginal entropy}} - \underbrace{H(y_1, \ldots, y_t | f)}_{\text{Conditional entropy}}$$

- It quantifies the "amount of information" obtained about one random variable, through the other random variable

- *Entropy* is the "amount of information" held by a random variable

- $H(Y|X) = 0$ if and only if the value of $Y$ is completely determined by the value of $X$

- $H(Y|X) = H(Y)$ if and only if $Y$ and $X$ are independent random variables

# Amount of information

$$H(X) = \mathbb{E}[-\ln P_X] \sum_{i=1}^{n} p(x_i) \log_b (p(x_i))$$

Example: Tossing a coin
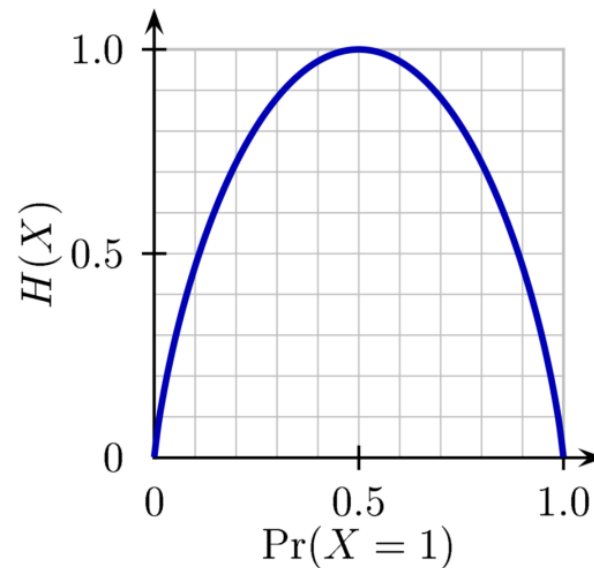


- A fair coin has maximal entropy: it is the less predictable!
- Every new sample that you get changes your *model* the most

# Mutual information

- Entropy of $X \sim \mathcal{N}_D(\boldsymbol{\mu}, \boldsymbol{\Sigma})$:

$$H(X) = \mathbb{E}\left[-\ln \frac{\exp\left(-\frac{1}{2}(\mathbf{x} - \boldsymbol{\mu})^\top \boldsymbol{\Sigma}^{-1}(\mathbf{x} - \boldsymbol{\mu})\right)}{\sqrt{(2\pi)^D |\boldsymbol{\Sigma}|}}\right] = \frac{D}{2} + \frac{D}{2}\ln 2\pi + \frac{1}{2}\ln|\boldsymbol{\Sigma}|$$

$\rightarrow$ Using $\mathbb{E}\left[\mathbf{a}^\top \mathbf{M}^{-1} \mathbf{a}\right] = \mathbb{E}\left[\text{Tr}\left(\mathbf{a}^\top \mathbf{M}^{-1} \mathbf{a}\right)\right] = \mathbb{E}\left[\text{Tr}\left(\mathbf{a}\mathbf{a}^\top \mathbf{M}^{-1}\right)\right] = D$

- Recall the joint distribution between $m$ observations $\mathbf{y}$ and $m_*$ query points $\mathbf{X}_*$:

$$\begin{bmatrix} \mathbf{y} \\ \mathbf{f}_* \end{bmatrix} \sim \mathcal{N}_{m+m_*}\left(\mathbf{0}, \begin{bmatrix} \mathbf{K}_{\mathbf{X},\mathbf{X}} + \lambda \mathbf{I}_m & \mathbf{K}_{\mathbf{X},\mathbf{X}_*} \\ \mathbf{K}_{\mathbf{X}_*,\mathbf{X}} & \mathbf{K}_{\mathbf{X}_*,\mathbf{X}_*} \end{bmatrix}\right)$$

- Then $I(y_1, \ldots, y_t; f) = \frac{1}{2}\ln|\mathbf{K}_t + \lambda \mathbf{I}_t|$

# Another decomposition of mutual information

- Recall that $y_1, \ldots, y_t | f(x_1), \ldots, f(x_t) \sim \mathcal{N}_t \left( (f(x_1), \ldots, f(x_t)), \sigma^2 \mathbf{I}_t \right)$

$\rightarrow$ Using that $y_i = f(x_i) + \epsilon$ with $\epsilon \sim \mathcal{N}(0, \sigma^2)$

- Pluging-in the conditional entropy of a multivariate normal distribution:

$$I(y_1, \ldots, y_t; f) = H(y_1, \ldots, y_t) - \frac{1}{2} \ln |2\pi e \sigma^2 \mathbf{I}_t|$$

$$= H(y_1, \ldots, y_t) - \frac{t}{2} \ln 2\pi e - \frac{t}{2} \sigma^2$$

- What is the marginal entropy $H(y_1, \ldots, y_t)$?

# Entropy of observations

- Recursively decompose

$$H(y_1, \ldots, y_t) = H(y_1, \ldots, y_{t-1}) + H(y_t | y_1, \ldots, y_{t-1})$$

$$= H(y_1, \ldots, y_{t-1}) + \frac{1}{2} \ln \left[ 2\pi e \left( \sigma^2 + \frac{\sigma^2}{\lambda} k_{\lambda, t-1}(x_t, x_t) \right) \right]$$

$$\vdots$$

$$= H(y_1) + H(y_2 | y_1) + \cdots + \frac{1}{2} \ln \left[ 2\pi e \left( \sigma^2 + \frac{\sigma^2}{\lambda} k_{\lambda, t-1}(x_s, x_s) \right) \right]$$

$$= \sum_{s=1}^{t} \frac{1}{2} \ln \left[ 2\pi e \sigma^2 \left( 1 + \frac{1}{\lambda} k_{\lambda, s-1}(x_s, x_s) \right) \right]$$

$\rightarrow$ Still using that $y_i = f(x_i) + \epsilon$ with $\epsilon \sim \mathcal{N}(0, \sigma^2)$
$\rightarrow$ Also using the uncertainty about the location of the *true* $f$

# Information gain

$$I(y_1, \ldots, y_t; f) = \sum_{s=1}^{t} \frac{1}{2} \ln \left[ 2\pi e \sigma^2 \left( 1 + \frac{1}{\lambda} k_{\lambda, s-1}(x_s, x_s) \right) \right] - \frac{t}{2} \ln(2\pi e) - \frac{t}{2} \sigma^2$$

$$= \sum_{s=1}^{t} \frac{1}{2} \ln \left[ 1 + \frac{1}{\lambda} k_{\lambda, s-1}(x_s, x_s) \right]$$

- Information gain $\gamma_t(\lambda) = I(y_1, \ldots, y_t; f)$: reduction of uncertainty on $f$ after observing $y_1, \ldots, y_t$
- Information gain is inversely proportionnal to $\lambda$
$\rightarrow$ Limiting changes in function limits the contribution of samples

# Information gain vs regularization
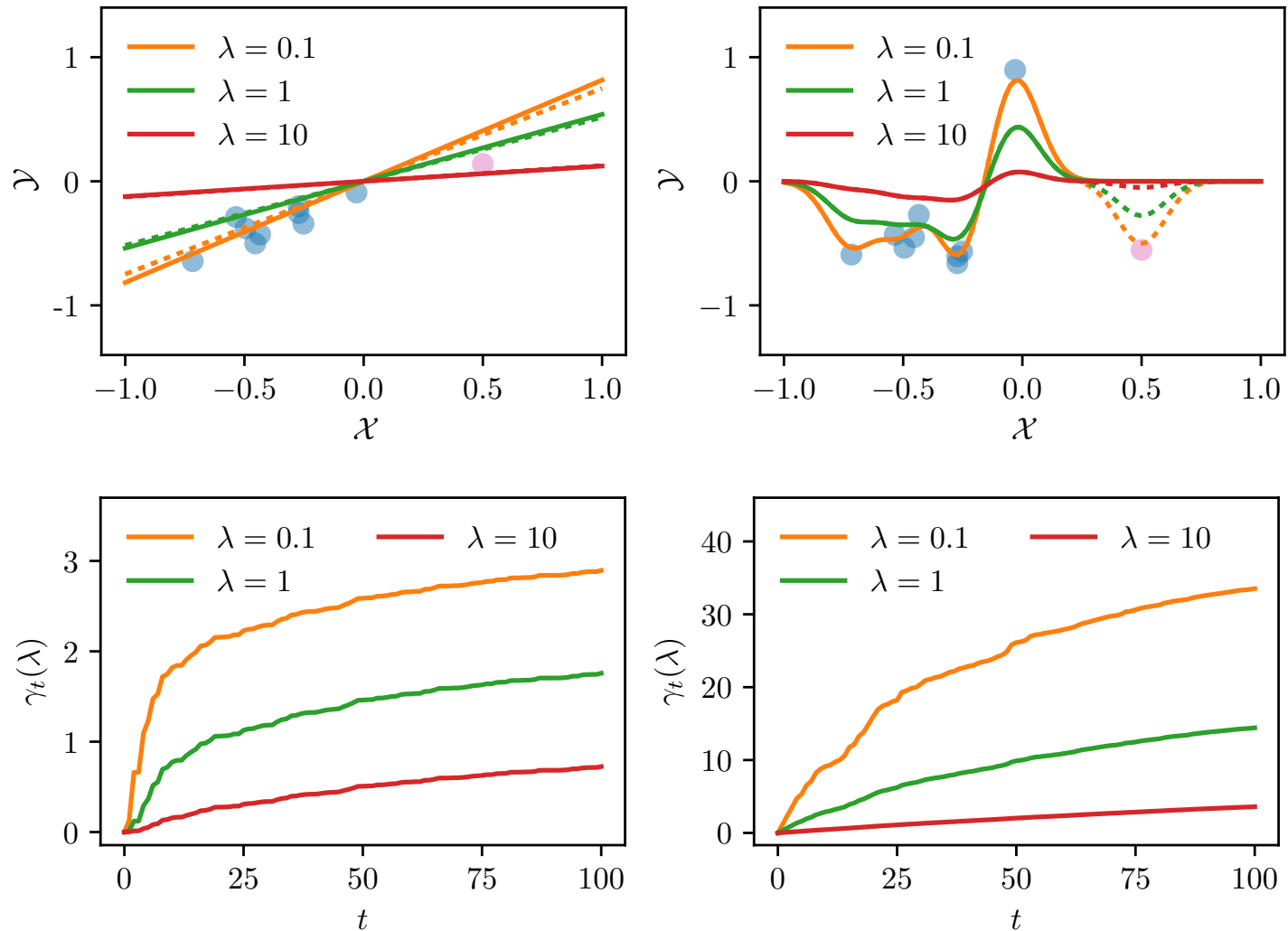
# Summary

- Streaming regression: sequentially gather (potentially non-i.i.d) samples

- Information gain measures the total information that could result from adding a new sample (observation) to the model

- Information gain is controlled by the *information sharing* capability of the kernel

- Information gain is controlled by the changes in model admitted by regularization

- Information gain will play a part in confidence intervals

# Confidence intervals

- Given that we have gathered $t$ samples under the streaming setting, what kind of guarantees can we have on the resulting model?

- More specifically, could we guarantee that

$$|f(\mathbf{x}) - \hat{f}_t(\mathbf{x})| \leq \text{something}$$

  simultaneously for all $\mathbf{x} \in \mathcal{X}$ and for all $t \geq 0$?

- Motivations:
  - Control bad behaviours in critical applications
  - Help selecting the next sample location
    * Maximize/minimize function?
    * Maximize model improvement?
  - Derive sound algorithms

# Result (Maillard, 2016)

- Under the assumption of subgaussian noise...

$$|f(x) - \hat{f}_t(x)| \leq \sqrt{\frac{k_{\lambda,t}(x,x)}{\lambda}} \left[ \sqrt{\lambda} \|f\|_{\mathcal{K}} + \sigma \sqrt{2\ln(1/\delta) + 2\gamma_t(\lambda)} \right]$$

- With probability higher than $1 - \delta$
- Simultaneously for all $t \geq 0$, for all $x \in \mathcal{X}$
$\Rightarrow$ Observe that the error scales with the information gain!

# Subgaussian noise

- A real-valued random variable $X$ is $\sigma^2$-subgaussian if $\mathbb{E}\left[e^{\gamma X}\right] \leq e^{\gamma^2 \sigma^2/2}$

$\rightarrow$ The Laplace transform of $X$ is dominated by the Laplace transform of a random variable sampled from $\mathcal{N}(0, \sigma^2)$

- Require that the tails of the noise distribution are dominated by the tails of a Gaussian distribution

- For example, true for

  - Gaussian noise
  - Bounded noise

# Confidence envelope
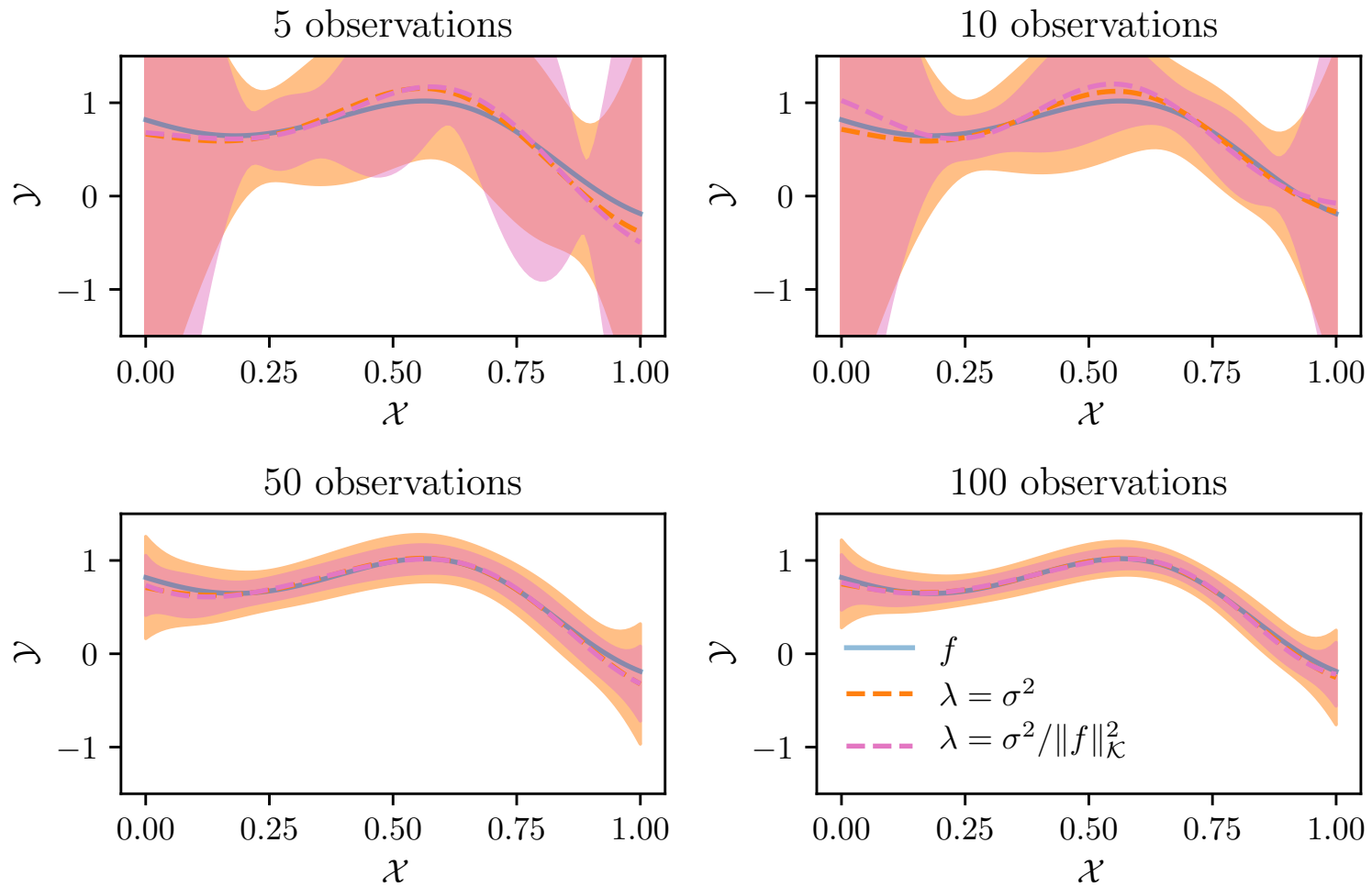
# Summary

- It is possible to have guarantees even with non-i.i.d. data

- The predition error depends on

  - How well your model shares information across observations
  - How well your model is adapted to the function
  - How noisy the observations are
  - Regularization $\rightarrow$ prior on $\Sigma_{\mathbf{w}}$

- Confidence intervals/envelopes will be really useful for deriving algorithms (we will see that later)