Empirical Risk Minimization

Vojtěch Franc

March 8, 2022

Prediction task and its solution based on data

Empirical risk minimization

Statistical consistency

Uniform generalization bounds

XEP33SML – Structured Model Learning, Summer 2022

Structured Output Prediction: the statistical model

The setting

- $\mathcal{X}$ set of input observations
- $\mathcal{Y}$ finite set of hidden states, e.g.
  - Flat classification: $\mathcal{Y} = \{1, \ldots, K\}$
  - Structured classif.: $\mathcal{Y} = \mathcal{Y}_1 \times \cdots \times \mathcal{Y}_{|\mathcal{V}|}$ is a labeling of parts $\mathcal{V}$.
- $(x, y) \in \mathcal{X} \times \mathcal{Y}$ randomly drawn from r.v. with p.d.f. $p(x, y)$
- $\ell \colon \mathcal{Y} \times \mathcal{Y} \to [0, \infty)$ loss function

Structured Output Prediction: the statistical model

The setting

- $\mathcal{X}$ set of input observations
- $\mathcal{Y}$ finite set of hidden states, e.g.
  - Flat classification: $\mathcal{Y} = \{1, \ldots, K\}$
  - Structured classif.: $\mathcal{Y} = \mathcal{Y}_1 \times \cdots \times \mathcal{Y}_{|\mathcal{V}|}$ is a labeling of parts $\mathcal{V}$.
- $(x, y) \in \mathcal{X} \times \mathcal{Y}$ randomly drawn from r.v. with p.d.f. $p(x, y)$
- $\ell \colon \mathcal{Y} \times \mathcal{Y} \to [0, \infty)$ loss function

The task: find a strategy $h \colon \mathcal{X} \to \mathcal{Y}$ with the minimal expected risk

$$R^* = \min_{h \colon \mathcal{X} \to \mathcal{Y}} R(h) \qquad \text{where} \qquad R(h) = \mathbb{E}_{(x,y) \sim p}[\ell(y, h(x))]$$

Solving the prediction problem from examples

- **Assumption**: we have an access to examples

$$\{(x^1, y^1), (x^2, y^2), \ldots\}$$

drawn from i.i.d. r.v. distributed according to unknown $p(x, y)$.

Solving the prediction problem from examples

- **Assumption**: we have an access to examples

$$\{(x^1, y^1), (x^2, y^2), \dots\}$$

drawn from i.i.d. r.v. distributed according to unknown $p(x, y)$.

- a) **Evaluation**: Estimate $R(h)$ of a given $h\colon \mathcal{X} \to \mathcal{Y}$ using test set

$$\mathcal{S}^l = \{(x^i, y^i) \in (\mathcal{X} \times \mathcal{Y}) \mid i = 1, \dots, l\}$$

drawn i.i.d. from $p(x, y)$.

Solving the prediction problem from examples

- **Assumption**: we have an access to examples

$$\{(x^1, y^1), (x^2, y^2), \ldots\}$$

drawn from i.i.d. r.v. distributed according to unknown $p(x, y)$.

- a) **Evaluation**: Estimate $R(h)$ of a given $h\colon \mathcal{X} \to \mathcal{Y}$ using test set

$$\mathcal{S}^l = \{(x^i, y^i) \in (\mathcal{X} \times \mathcal{Y}) \mid i = 1, \ldots, l\}$$

drawn i.i.d. from $p(x, y)$.

- b) **Learning**: find $h\colon \mathcal{X} \to \mathcal{Y}$ with small $R(h)$ using training set

$$\mathcal{T}^m = \{(x^i, y^i) \in (\mathcal{X} \times \mathcal{Y}) \mid i = 1, \ldots, m\}$$

drawn i.i.d. from $p(x, y)$.

Evaluation: Estimation of the expected risk from examples

- Given a predictor $h\colon \mathcal{X} \to \mathcal{Y}$, compute the empirical risk

$$R_{\mathcal{S}^l}(h) = \frac{1}{l}\sum_{i=1}^{l} \ell(y^i, h(x^i))$$

and use it as a proxy for $R(h) = \mathbb{E}_{(x,y)\sim p}(\ell(y, h(x)))$.

Evaluation: Estimation of the expected risk from examples

- Given a predictor $h\colon \mathcal{X} \to \mathcal{Y}$, compute the empirical risk

$$R_{\mathcal{S}^l}(h) = \frac{1}{l}\sum_{i=1}^{l} \ell(y^i, h(x^i))$$

and use it as a proxy for $R(h) = \mathbb{E}_{(x,y)\sim p}(\ell(y, h(x)))$.

- The value of the empirical risk $R_{\mathcal{S}^l}(h)$ is a random number.

Evaluation: Estimation of the expected risk from examples

- Given a predictor $h\colon \mathcal{X} \to \mathcal{Y}$, compute the empirical risk

$$R_{\mathcal{S}^l}(h) = \frac{1}{l} \sum_{i=1}^{l} \ell(y^i, h(x^i))$$

and use it as a proxy for $R(h) = \mathbb{E}_{(x,y)\sim p}(\ell(y, h(x)))$.

- The value of the empirical risk $R_{\mathcal{S}^l}(h)$ is a random number.

- Application of Hoeffding inequality: for any $\varepsilon > 0$, the probability of the generalization error being at least ε can be bound by

$$\mathbb{P}_{\mathcal{S}^l \sim p}\Bigg(\underbrace{\Big| R_{\mathcal{S}^l}(h) - R(h) \Big| \geq \varepsilon}_{\text{high generalization error}} \Bigg) \leq 2e^{-\frac{2l\,\varepsilon^2}{(\ell_{\min} - \ell_{\max})^2}}$$

Learning algorithm

- **Learning:** find a strategy $h\colon \mathcal{X} \to \mathcal{Y}$ with a small $R(h)$ using the training set of examples

$$\mathcal{T}^m = \{(x^i, y^i) \in (\mathcal{X} \times \mathcal{Y}) \mid i = 1, \ldots, m\}$$

drawn from i.i.d. according to unknown $p(x, y)$.

- Use prior knowledge to select hypothesis space

$$\mathcal{H} \subseteq \mathcal{Y}^{\mathcal{X}} = \{h\colon \mathcal{X} \to \mathcal{Y}\}$$

- The learning algorithm

$$A\colon \cup_{m=1}^{\infty} (\mathcal{X} \times \mathcal{Y})^m \to \mathcal{H}$$

selects strategy $h_m = A(\mathcal{T}^m)$ based on the training set $\mathcal{T}^m$.

Generative learning (to come later)

1. Use the training set $\mathcal{T}^m = \{(x^i, y^i) \in \mathcal{X} \times \mathcal{Y} \mid i \in \{1, \ldots, m\}\}$ to approximate $p(x, y)$ by $\hat{p}(x, y)$.

   For example, use the Maximum-Likelihood method:

   (a) Guess the shape of the distribution, e.g.

$$\hat{p}_{\boldsymbol{w}}(x, y) = \frac{1}{Z(\boldsymbol{w})} \exp\langle \boldsymbol{w}, \boldsymbol{\phi}(x, y) \rangle \,, \qquad \boldsymbol{w} \in \mathcal{W}$$

   (b) Find the ML estimate

$$\boldsymbol{w}_m \in \operatorname*{argmax}_{\boldsymbol{w} \in \mathcal{W}} \sum_{i=1}^{m} \log \hat{p}_{\boldsymbol{w}}(x^i, y^i)$$

2. Construct a plug-in classifier

$$h_m(x) \in \operatorname*{argmin}_{h\colon \mathcal{X} \to \mathcal{Y}} \mathbb{E}_{(x,y) \sim \hat{p}_{\boldsymbol{w}_m}}[\ell(y, h(x))]$$

Discriminative learning by Empirical Risk Minimization

- Use the training set $\mathcal{T}^m = \{(x^i, y^i) \in \mathcal{X} \times \mathcal{Y} \mid i \in \{1, \ldots, m\}\}$ to approximate the expected risk $R(h)$ by the empirical risk

$$R_{\mathcal{T}^m}(h) = \frac{1}{m} \sum_{i=1}^{m} \ell(y^i, h(x^i))$$

- The ERM learning algorithm returns h_m such that

$$h_m \in \operatorname*{Argmin}_{h \in \mathcal{H}} R_{\mathcal{T}^m}(h) \tag{1}$$

- Depending on the choice of $\mathcal{H}$, ℓ and algorithm solving (1) we get individual instances, e.g.: Structured-Output Perceptron, Structured-Output Support Vector Machines, Logistic regression, Neural Networks learned by back-propagation, AdaBoost, ...

Errors characterizing a learning algorithm

The characters of the play:

- $R^* = \min_{h \in \mathcal{Y}^{\mathcal{X}}} R(h)$ best attainable (Bayes) risk
- $R(h_{\mathcal{H}})$ best risk in $\mathcal{H}$; $h_{\mathcal{H}} \in \mathrm{Argmin}_{h \in \mathcal{H}} R(h)$
- $R(h_m)$ risk of $h_m = A(\mathcal{T}_m)$ learned from $\mathcal{T}^m$

Errors characterizing a learning algorithm

The characters of the play:

- $R^* = \min_{h \in \mathcal{Y}^\mathcal{X}} R(h)$ best attainable (Bayes) risk
- $R(h_\mathcal{H})$ best risk in $\mathcal{H}$; $h_\mathcal{H} \in \operatorname{Argmin}_{h \in \mathcal{H}} R(h)$
- $R(h_m)$ risk of $h_m = A(\mathcal{T}_m)$ learned from $\mathcal{T}^m$

Excess error: the quantity we want to minimize

$$\underbrace{\Big(R(h_m) - R^*\Big)}_{\text{excess error}} = \underbrace{\Big(R(h_m) - R(h_\mathcal{H})\Big)}_{\text{estimation error}} + \underbrace{\Big(R(h_\mathcal{H}) - R^*\Big)}_{\text{approximation error}}$$

Errors characterizing a learning algorithm

The characters of the play:

- $R^* = \min_{h \in \mathcal{Y}^{\mathcal{X}}} R(h)$ best attainable (Bayes) risk
- $R(h_{\mathcal{H}})$ best risk in $\mathcal{H}$; $h_{\mathcal{H}} \in \operatorname{Argmin}_{h \in \mathcal{H}} R(h)$
- $R(h_m)$ risk of $h_m = A(\mathcal{T}_m)$ learned from $\mathcal{T}^m$

Excess error: the quantity we want to minimize

$$\underbrace{\Big(R(h_m) - R^*\Big)}_{\text{excess error}} = \underbrace{\Big(R(h_m) - R(h_{\mathcal{H}})\Big)}_{\text{estimation error}} + \underbrace{\Big(R(h_{\mathcal{H}}) - R^*\Big)}_{\text{approximation error}}$$

- The estimation error is random
- The estimation error depends on m and $\mathcal{H}$
- The approximation error depends only on $\mathcal{H}$

Statistically consistent learning algorithm

- The estimation error $R(h_m) - R(h_{\mathcal{H}})$ is random because it is a function of $h_m = A(\mathcal{T}^m)$ learned on $\mathcal{T}^m$ generated from $p(x, y)$.

Statistically consistent learning algorithm

- The estimation error $R(h_m) - R(h_{\mathcal{H}})$ is random because it is a function of $h_m = A(\mathcal{T}^m)$ learned on $\mathcal{T}^m$ generated from $p(x, y)$.

- We can derive bounds on the probability that the estimation error is above $\varepsilon > 0$, that is,

$$\mathbb{P}\Bigg(R(h_m) - R(h_{\mathcal{H}}) \geq \varepsilon \Bigg) \leq U(m, \varepsilon, \mathcal{H})$$

Statistically consistent learning algorithm

- The estimation error $R(h_m) - R(h_{\mathcal{H}})$ is random because it is a function of $h_m = A(\mathcal{T}^m)$ learned on $\mathcal{T}^m$ generated from $p(x,y)$.
- We can derive bounds on the probability that the estimation error is above $\varepsilon > 0$, that is,

$$\mathbb{P}\Big(R(h_m) - R(h_{\mathcal{H}}) \geq \varepsilon \Big) \leq U(m, \varepsilon, \mathcal{H})$$

Definition 1. *The algorithm* $A \colon \cup_{m=1}^{\infty} (\mathcal{X} \times \mathcal{Y})^m \to \mathcal{H}$ *is statistically consistent in* $\mathcal{H} \subseteq \mathcal{Y}^{\mathcal{X}}$ *if for any* $p(x,y)$ *it holds that*

$$\forall \varepsilon > 0 \colon \lim_{m \to \infty} \mathbb{P}\Big(R(h_m) - R(h_{\mathcal{H}}) \geq \varepsilon \Big) = 0$$

where $h_m = A(\mathcal{T}^m)$ *is learned from* $\mathcal{T}^m$ *generated from* $p(x,y)$*.*

Example: ERM is not consistent $\mathcal{H}$ is unconstrained

- Let $\mathcal{X} = [a, b] \subset \mathbb{R}$, $\mathcal{Y} = \{+1, -1\}$, $\ell(y, y') = [\![y \neq y']\!]$, $p(x \mid y = +1)$ and $p(x \mid y = -1)$ be uniform distributions on $\mathcal{X}$ and $p(y = +1) = 0.8$.

Example: ERM is not consistent $\mathcal{H}$ is unconstrained

- Let $\mathcal{X} = [a, b] \subset \mathbb{R}$, $\mathcal{Y} = \{+1, -1\}$, $\ell(y, y') = [\![y \neq y']\!]$, $p(x \mid y = +1)$ and $p(x \mid y = -1)$ be uniform distributions on $\mathcal{X}$ and $p(y = +1) = 0.8$.

- The optimal strategy is $h(x) = +1$ with the Bayes risk $R^* = 0.2$.

Example: ERM is not consistent $\mathcal{H}$ is unconstrained

- Let $\mathcal{X} = [a, b] \subset \mathbb{R}$, $\mathcal{Y} = \{+1, -1\}$, $\ell(y, y') = [\![y \neq y']\!]$, $p(x \mid y = +1)$ and $p(x \mid y = -1)$ be uniform distributions on $\mathcal{X}$ and $p(y = +1) = 0.8$.

- The optimal strategy is $h(x) = +1$ with the Bayes risk $R^* = 0.2$.

- Consider learning algorithm which for a given training set $\mathcal{T}^m = \{(x^1, y^1), \ldots, (x^m, y^m)\}$ returns strategy

$$h_m(x) = \begin{cases} y^j & \text{if } \; x = x^j \; \text{ for some } \; j \in \{1, \ldots, m\} \\ -1 & \text{otherwise} \end{cases}$$

Example: ERM is not consistent $\mathcal{H}$ is unconstrained

- Let $\mathcal{X} = [a,b] \subset \mathbb{R}$, $\mathcal{Y} = \{+1,-1\}$, $\ell(y,y') = [\![y \neq y']\!]$, $p(x \mid y = +1)$ and $p(x \mid y = -1)$ be uniform distributions on $\mathcal{X}$ and $p(y = +1) = 0.8$.

- The optimal strategy is $h(x) = +1$ with the Bayes risk $R^* = 0.2$.

- Consider learning algorithm which for a given training set $\mathcal{T}^m = \{(x^1,y^1),\ldots,(x^m,y^m)\}$ returns strategy

$$h_m(x) = \begin{cases} y^j & \text{if } \ x = x^j \ \text{ for some } \ j \in \{1,\ldots,m\} \\ -1 & \text{otherwise} \end{cases}$$

- The empirical risk is $R_{\mathcal{T}^m}(h_m) = 0$ with probability 1 for any m.

Example: ERM is not consistent $\mathcal{H}$ is unconstrained

- Let $\mathcal{X} = [a, b] \subset \mathbb{R}$, $\mathcal{Y} = \{+1, -1\}$, $\ell(y, y') = [\![y \neq y']\!]$, $p(x \mid y = +1)$ and $p(x \mid y = -1)$ be uniform distributions on $\mathcal{X}$ and $p(y = +1) = 0.8$.

- The optimal strategy is $h(x) = +1$ with the Bayes risk $R^* = 0.2$.

- Consider learning algorithm which for a given training set $\mathcal{T}^m = \{(x^1, y^1), \ldots, (x^m, y^m)\}$ returns strategy

$$h_m(x) = \begin{cases} y^j & \text{if } \; x = x^j \; \text{ for some } \; j \in \{1, \ldots, m\} \\ -1 & \text{otherwise} \end{cases}$$

- The empirical risk is $R_{\mathcal{T}^m}(h_m) = 0$ with probability 1 for any m.

- The expected risk is $R(h_m) = 0.8$ for any m.

Uniform Law of Large Numbers

- Law of Large Numbers: for any $p(x, y)$ generating $\mathcal{T}^m$, and $h \in \mathcal{H}$ fixed without seeing $\mathcal{T}^m$ we have

$$\forall\, \varepsilon > 0\colon\ \lim_{m\to\infty} \mathbb{P}\Big(\underbrace{\big|R(h) - R_{\mathcal{T}^m}(h)\big| \geq \varepsilon}_{\text{high generalization error}} \Big) = 0$$

Uniform Law of Large Numbers

- Law of Large Numbers: for any $p(x,y)$ generating $\mathcal{T}^m$, and $h \in \mathcal{H}$ fixed without seeing $\mathcal{T}^m$ we have

$$\forall\, \varepsilon > 0\colon \lim_{m\to\infty} \mathbb{P}\Big(\underbrace{\big|R(h) - R_{\mathcal{T}^m}(h)\big| \geq \varepsilon}_{\text{high generalization error}} \Big) = 0$$

- Uniform Law of Large Numbers: if for any $p(x,y)$ generating $\mathcal{T}^m$ it holds that

$$\forall\, \varepsilon > 0\colon \lim_{m\to\infty} \mathbb{P}\Bigg(\underbrace{\begin{array}{ll} \big|R(h_1) - R_{\mathcal{T}^m}(h_1)\big| \geq \varepsilon & \text{or} \\ \big|R(h_2) - R_{\mathcal{T}^m}(h_2)\big| \geq \varepsilon & \text{or} \\ \vdots & \\ \big|R(h_{|\mathcal{H}|}) - R_{\mathcal{T}^m}(h_{|\mathcal{H}|})\big| \geq \varepsilon & \end{array}}_{\substack{\text{high generalization error at least} \\ \text{for one strategy}}} \Bigg) = 0$$

we say that ULLN applies for $\mathcal{H}$.

Uniform Law of Large Numbers

- Law of Large Numbers: for any $p(x,y)$ generating $\mathcal{T}^m$, and $h \in \mathcal{H}$ fixed without seeing $\mathcal{T}^m$ we have

$$\forall\, \varepsilon > 0\colon\ \lim_{m\to\infty} \mathbb{P}\Big(\underbrace{\big|R(h) - R_{\mathcal{T}^m}(h)\big| \geq \varepsilon}_{\text{high generalization error}} \Big) = 0$$

- Uniform Law of Large Numbers: if for any $p(x,y)$ generating $\mathcal{T}^m$ it holds that

$$\forall\, \varepsilon > 0\colon\ \lim_{m\to\infty} \mathbb{P}\Big(\underbrace{\sup_{h\in\mathcal{H}} \big|R(h) - R_{\mathcal{T}^m}(h)\big| \geq \varepsilon}_{\substack{\text{high generalization error at least}\\ \text{for one strategy}}} \Big) = 0$$

we say that ULLN applies for $\mathcal{H}$.

Uniform Law of Large Numbers

- Law of Large Numbers: for any $p(x, y)$ generating $\mathcal{T}^m$, and $h \in \mathcal{H}$ fixed without seeing $\mathcal{T}^m$ we have

$$\forall \varepsilon > 0\colon \lim_{m \to \infty} \mathbb{P}\Big(\underbrace{\big| R(h) - R_{\mathcal{T}^m}(h) \big| \geq \varepsilon}_{\text{high generalization error}} \Big) = 0$$

- Uniform Law of Large Numbers: if for any $p(x, y)$ generating $\mathcal{T}^m$ it holds that

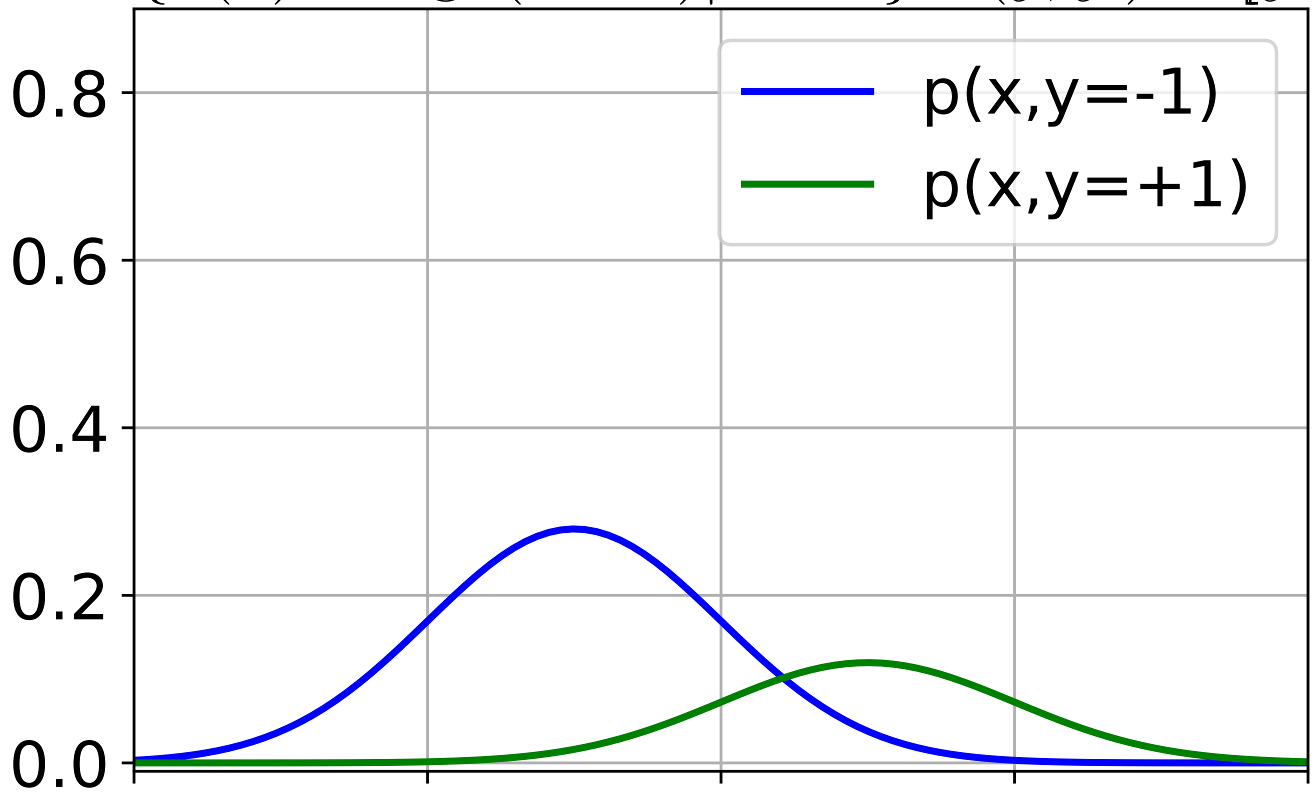
$$\forall \varepsilon > 0\colon \lim_{m \to \infty} \mathbb{P}\Big(\underbrace{\sup_{h \in \mathcal{H}} \big| R(h) - R_{\mathcal{T}^m}(h) \big| \geq \varepsilon}_{\substack{\text{high generalization error at least} \\ \text{for one strategy}}} \Big) = 0$$

we say that ULLN applies for $\mathcal{H}$.

Theorem 1. *If ULLN applies for $\mathcal{H}$ then ERM is statistically consistent in $\mathcal{H}$.*

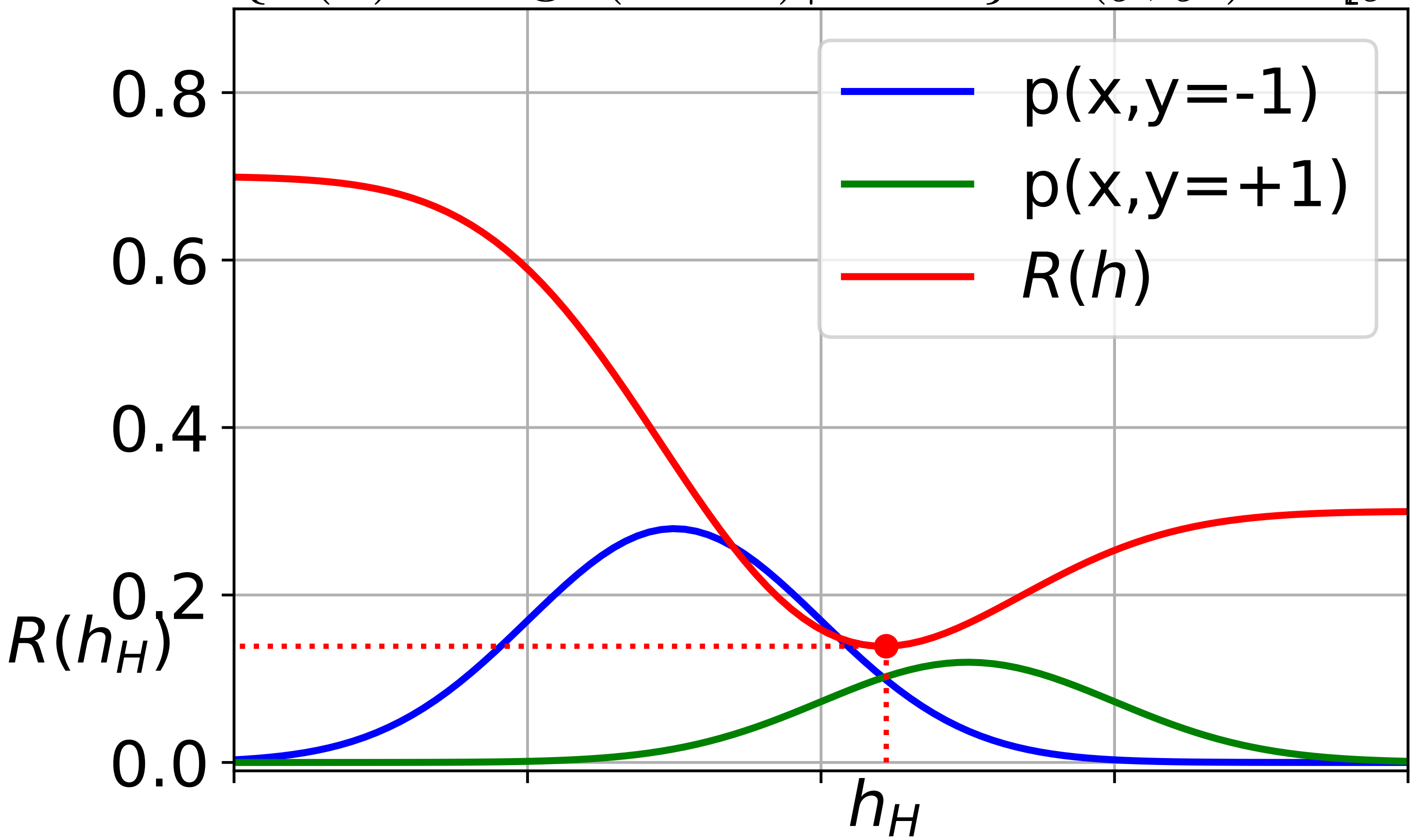
Uniform generalizaton bounds and the estimation error

$\mathcal{H} = \{h(x) = \mathrm{sign}(x - \theta) | \theta \in \mathbb{R}\}$, $\ell(y, y') = [\![y \neq y']\!]$



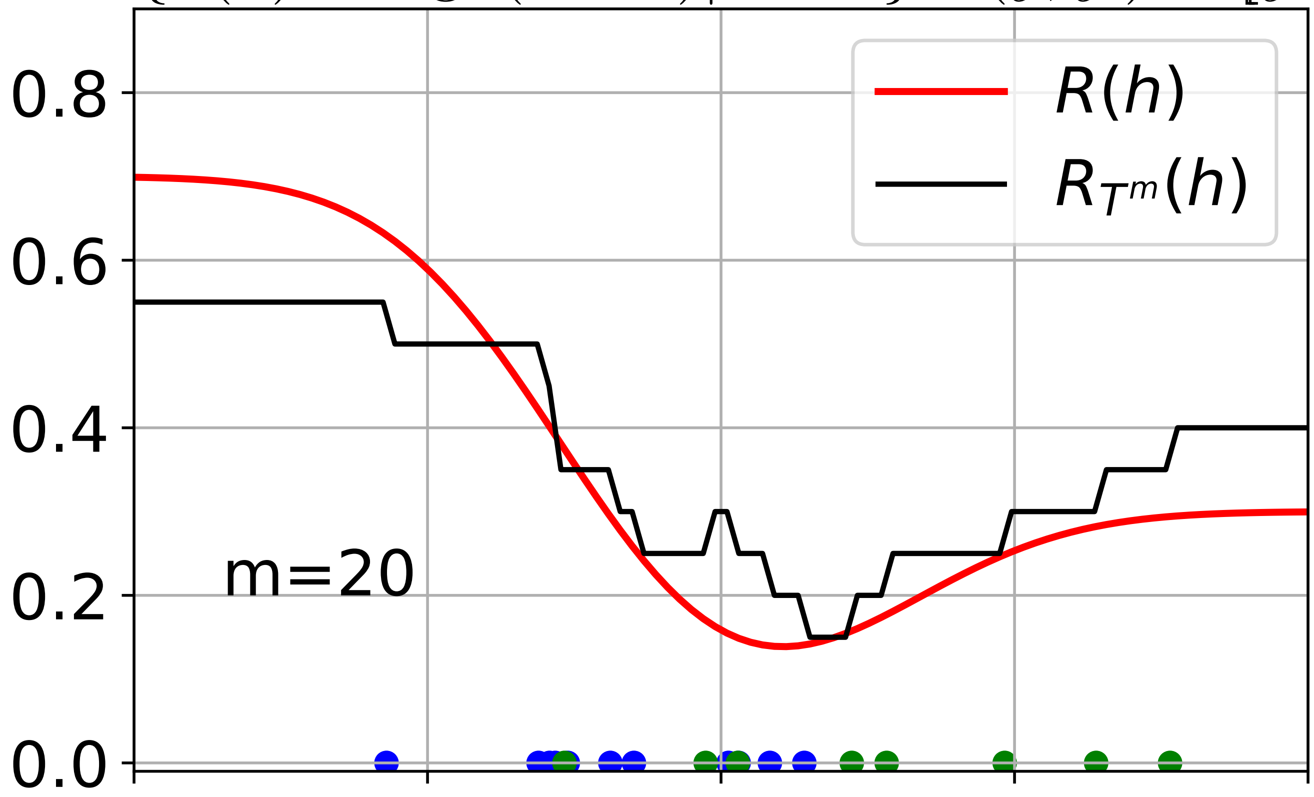
Uniform generalizaton bounds and the estimation error

$$\mathcal{H} = \{h(x) = \mathrm{sign}(x - \theta) | \theta \in \mathbb{R}\},\ \ell(y, y') = [\![y \neq y']\!]$$



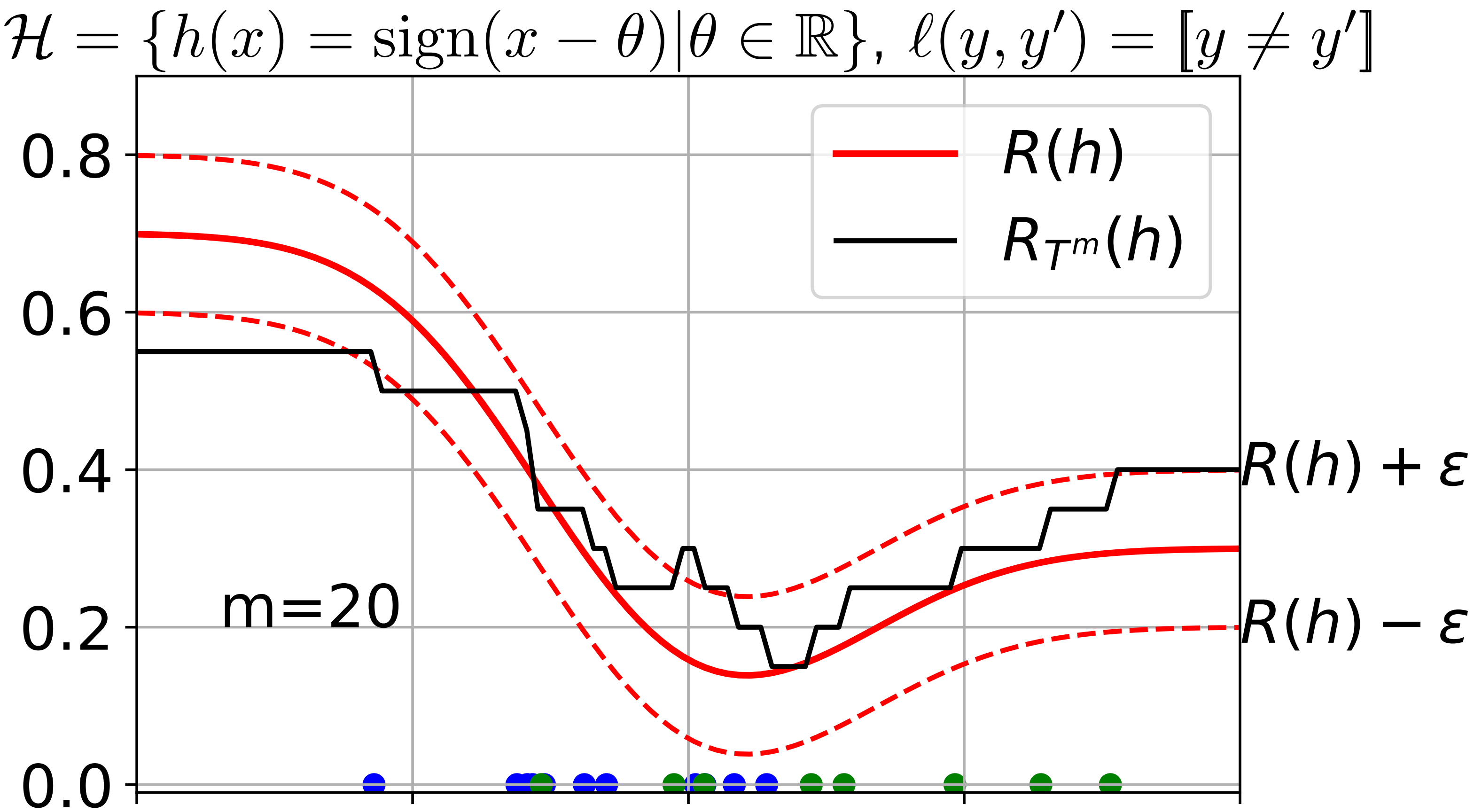
Uniform generalizaton bounds and the estimation error

$\mathcal{H} = \{h(x) = \mathrm{sign}(x - \theta) | \theta \in \mathbb{R}\}$, $\ell(y, y') = [\![y \neq y']\!]$



Uniform generalizaton bounds and the estimation error

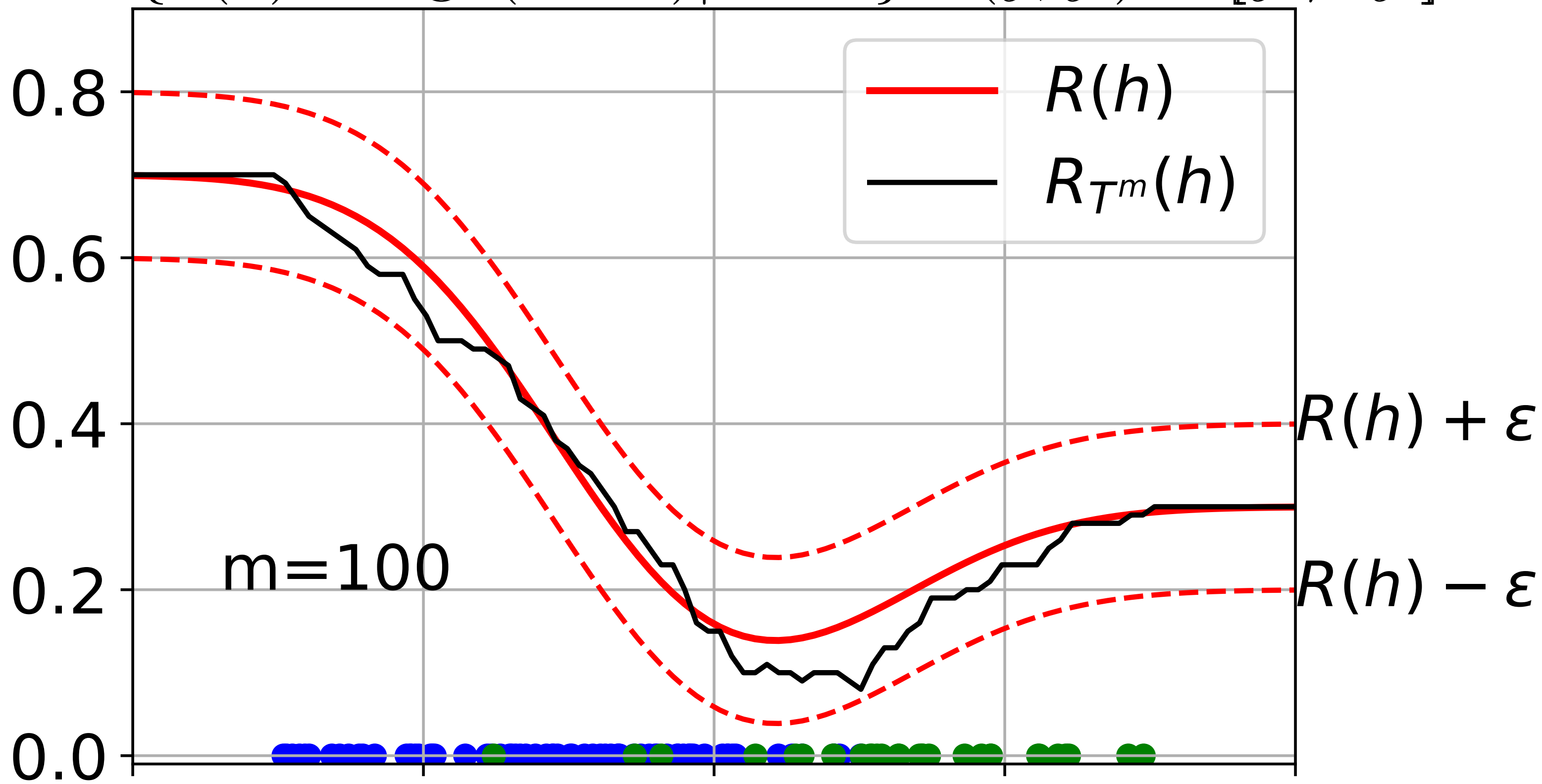
$$\mathbb{P}\Big(\underbrace{\sup_{h\in\mathcal{H}} \big|R(h) - R_{\mathcal{T}^m}(h)\big|}_{\text{worst generalization error}} \geq \varepsilon\Big) \leq B(m, \mathcal{H}, \varepsilon)$$



Uniform generalizaton bounds and the estimation error

$$\mathbb{P}\Big(\underbrace{\sup_{h\in\mathcal{H}} \big| R(h) - R_{\mathcal{T}^m}(h) \big|}_{\text{worst generalization error}} \geq \varepsilon \Big) \leq B(m, \mathcal{H}, \varepsilon)$$

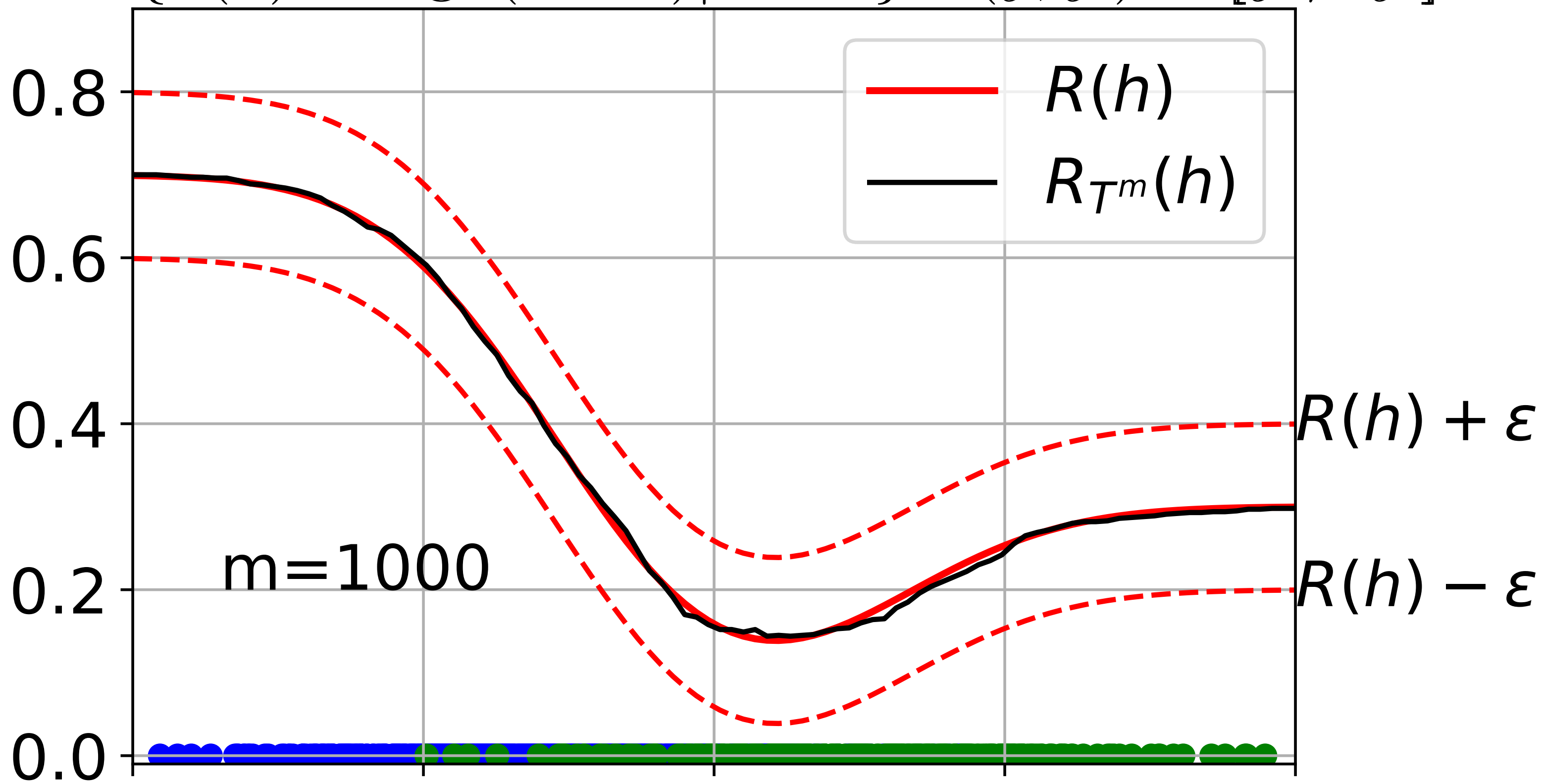
$\mathcal{H} = \{h(x) = \mathrm{sign}(x-\theta) | \theta \in \mathbb{R}\}$, $\ell(y,y') = [\![y \neq y']\!]$



Uniform generalizaton bounds and the estimation error

$$\mathbb{P}\Big(\underbrace{\sup_{h\in\mathcal{H}} \big|R(h) - R_{\mathcal{T}^m}(h)\big|}_{\text{worst generalization error}} \geq \varepsilon \Big) \leq B(m,\mathcal{H},\varepsilon)$$

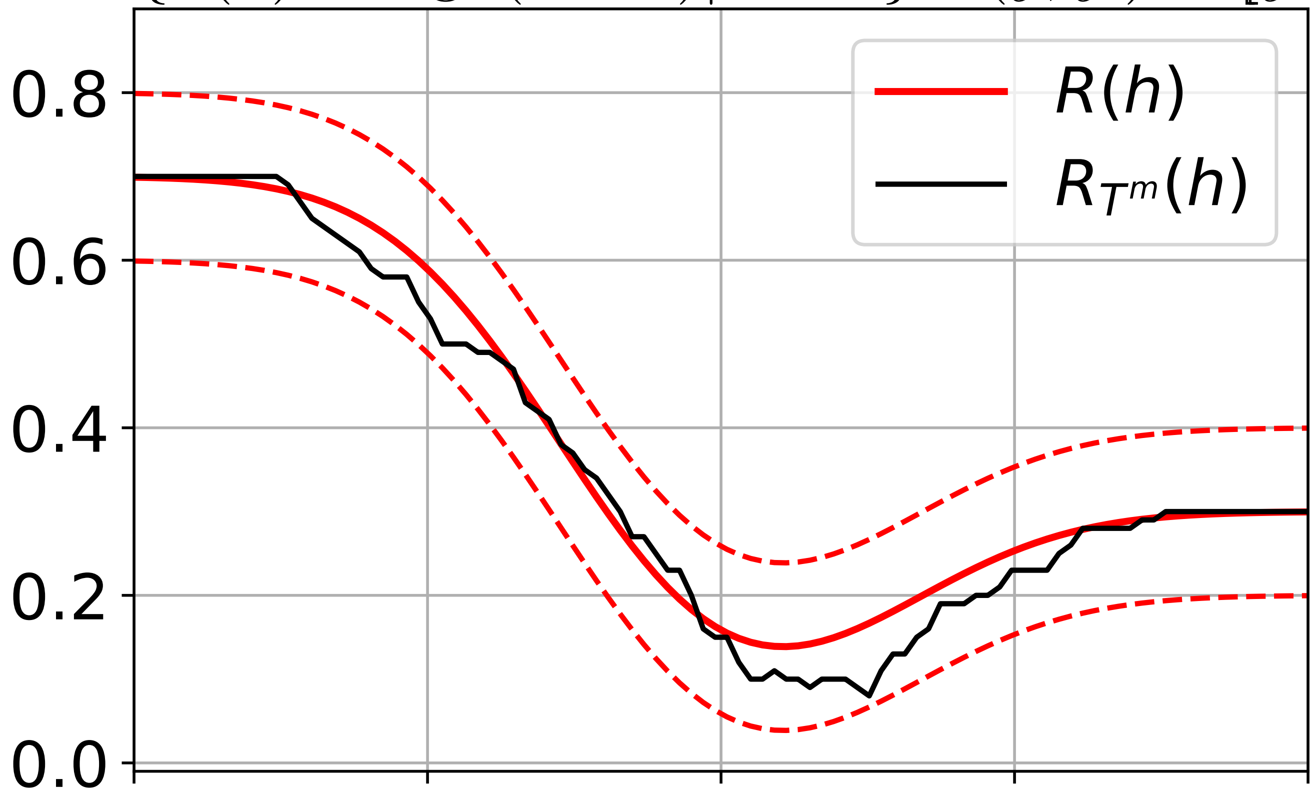
$\mathcal{H} = \{h(x) = \text{sign}(x-\theta) | \theta \in \mathbb{R}\}$, $\ell(y,y') = [\![y \neq y']\!]$



Uniform generalizaton bounds and the estimation error

$$\mathbb{P}\Big(\underbrace{\sup_{h\in\mathcal{H}} \big|R(h) - R_{\mathcal{T}^m}(h)\big|}_{\text{worst generalization error}} \geq \varepsilon\Big) \leq B(m,\mathcal{H},\varepsilon)$$

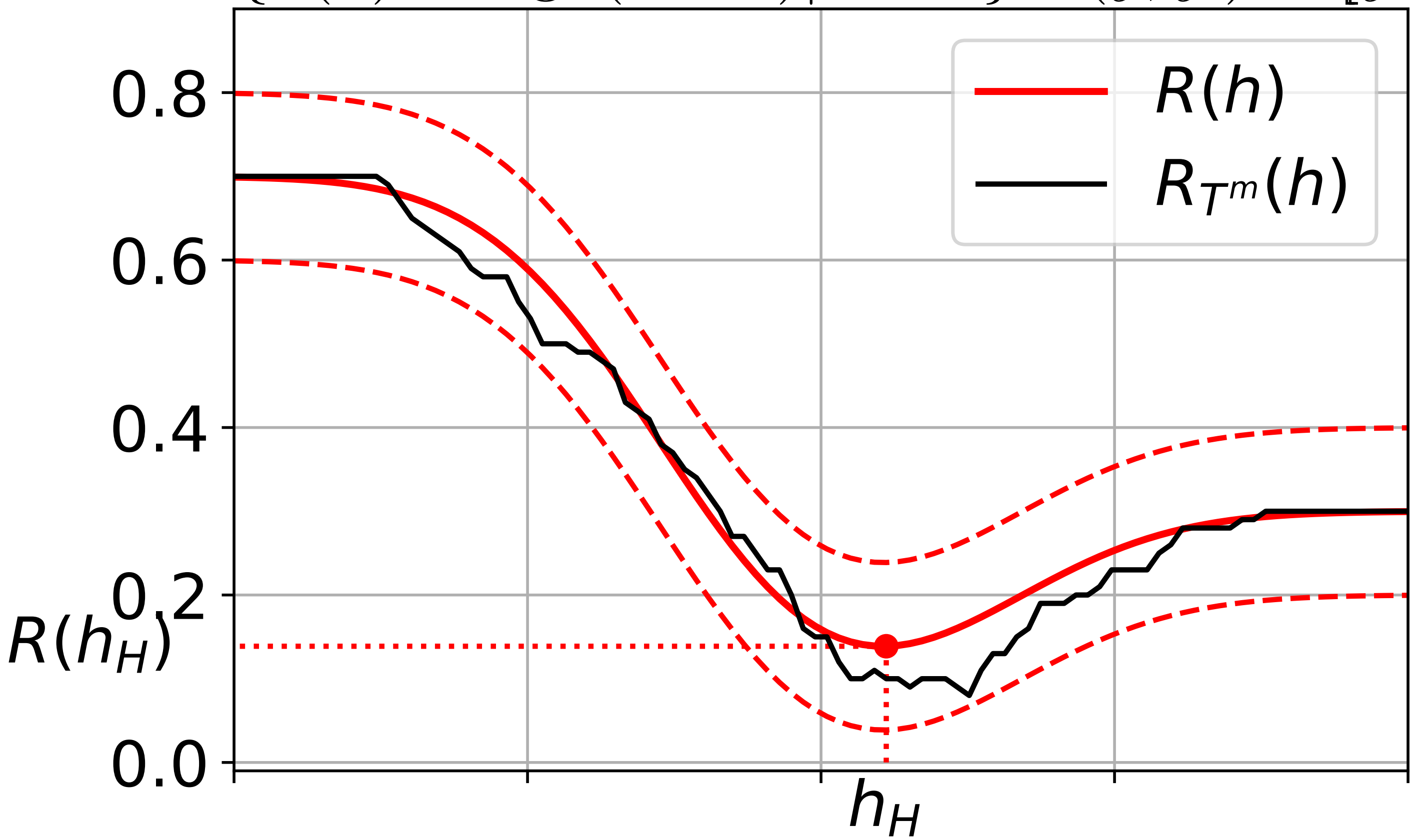
$\mathcal{H} = \{h(x) = \operatorname{sign}(x-\theta) | \theta \in \mathbb{R}\}$, $\ell(y,y') = [\![y \neq y']\!]$



Uniform generalizaton bounds and the estimation error

$$\mathbb{P}\Big(\underbrace{\sup_{h\in\mathcal{H}}\big|R(h) - R_{\mathcal{T}^m}(h)\big|}_{\text{worst generalization error}} \geq \varepsilon\Big) \leq B(m,\mathcal{H},\varepsilon)$$

$\mathcal{H} = \{h(x) = \mathrm{sign}(x-\theta) | \theta \in \mathbb{R}\}$, $\ell(y,y') = [\![y \neq y']\!]$

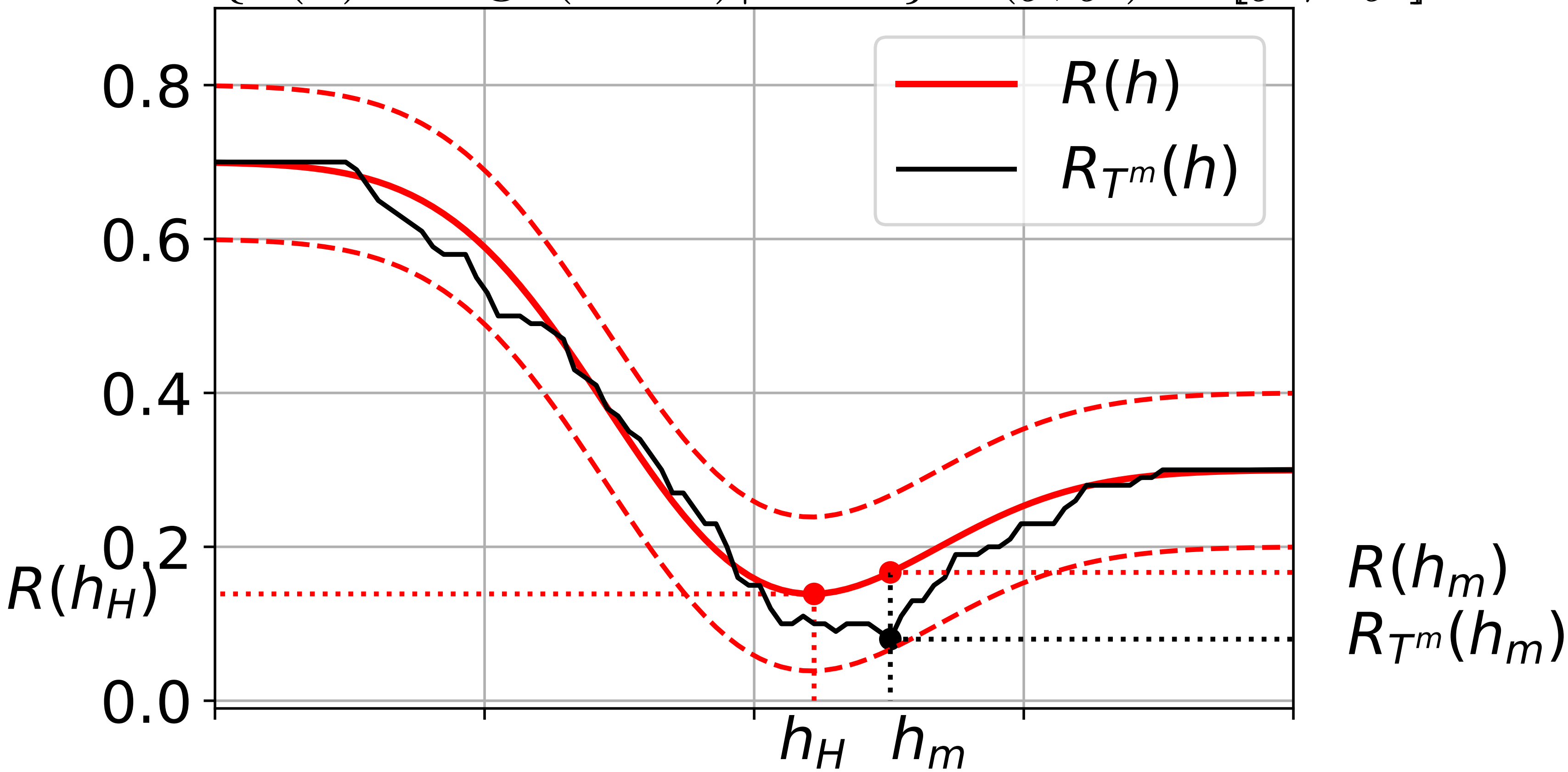


Uniform generalizaton bounds and the estimation error

$$\mathbb{P}\Big(\underbrace{\sup_{h\in\mathcal{H}}\big|R(h)-R_{\mathcal{T}^m}(h)\big|}_{\text{worst generalization error}}\geq\varepsilon\Big)\leq B(m,\mathcal{H},\varepsilon)$$

$$\underbrace{R(h_m)-R(h_{\mathcal{H}})}_{\text{estimation error}}$$

$$\mathcal{H}=\{h(x)=\text{sign}(x-\theta)|\theta\in\mathbb{R}\},\ \ell(y,y')=[\![y\neq y']\!]$$

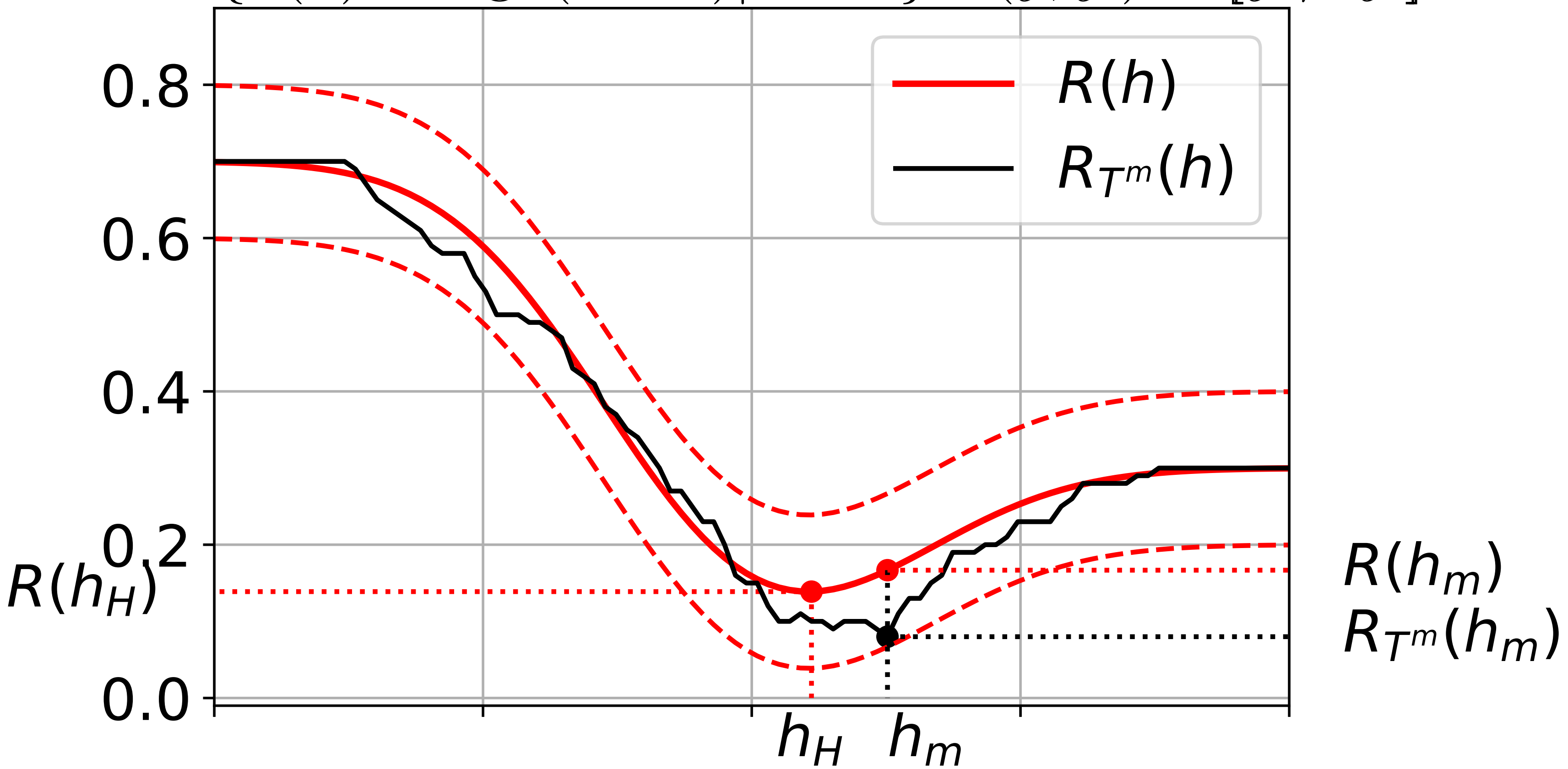


Uniform generalizaton bounds and the estimation error

$$\mathbb{P}\Big(\underbrace{\sup_{h\in\mathcal{H}}\big|R(h)-R_{\mathcal{T}^m}(h)\big|}_{\text{worst generalization error}}\geq\varepsilon\Big)\leq B(m,\mathcal{H},\varepsilon)$$

$$\underbrace{R(h_m)-R(h_{\mathcal{H}})}_{\text{estimation error}}\leq 2\underbrace{\sup_{h\in\mathcal{H}}\big|R(h)-R_{\mathcal{T}^m}(h)\big|}_{\text{worst generalizaton error}}$$

$$\mathcal{H}=\{h(x)=\text{sign}(x-\theta)|\theta\in\mathbb{R}\},\ \ell(y,y')=[\![y\neq y']\!]$$

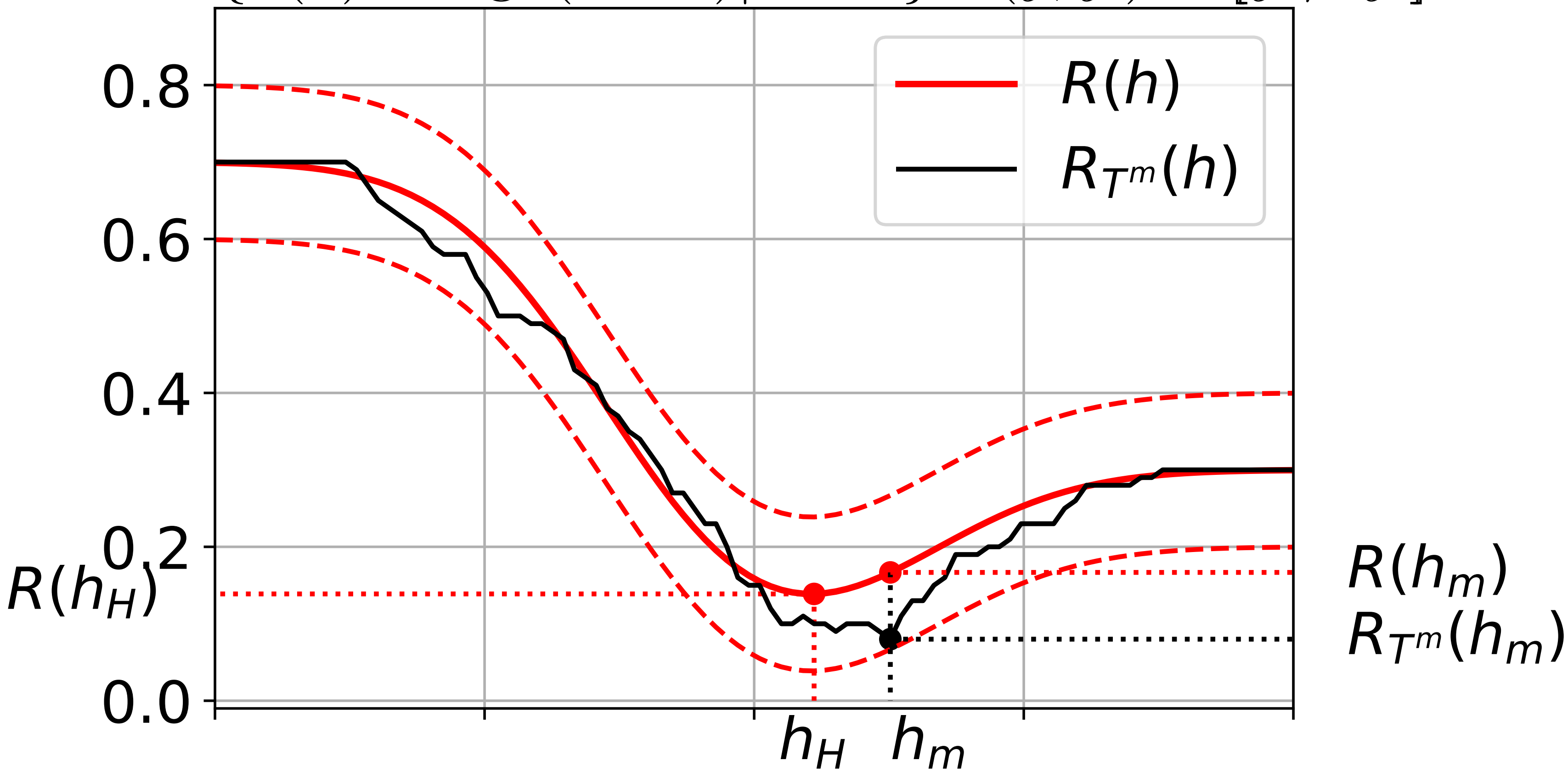


Uniform generalizaton bounds and the estimation error

$$\mathbb{P}\Big(\underbrace{\sup_{h\in\mathcal{H}} \big|R(h) - R_{\mathcal{T}^m}(h)\big|}_{\text{worst generalization error}} \geq \varepsilon \Big) \leq B(m,\mathcal{H},\varepsilon)$$

$$\mathbb{P}\Big(\underbrace{R(h_m) - R(h_{\mathcal{H}})}_{\text{estimation error}} \geq \varepsilon \Big) \leq \mathbb{P}\Big(\underbrace{\sup_{h\in\mathcal{H}} \big|R(h) - R_{\mathcal{T}^m}(h)\big|}_{\text{worst generalizaton error}} \geq \tfrac{\varepsilon}{2} \Big)$$

$\mathcal{H} = \{h(x) = \mathrm{sign}(x-\theta) | \theta \in \mathbb{R}\}$, $\ell(y,y') = [\![y \neq y']\!]$



Proof: ULLN implies consistency of ERM

For fixed $\mathcal{T}^m$ and $h_m \in \operatorname{Argmin}_{h\in\mathcal{H}} R_{\mathcal{T}^m}(h)$ we have:

$$\begin{aligned} R(h_m) - R(h_{\mathcal{H}}) &= \Big(R(h_m) - R_{\mathcal{T}^m}(h_m) \Big) + \Big(R_{\mathcal{T}^m}(h_m) - R(h_{\mathcal{H}}) \Big) \\ &\leq \Big(R(h_m) - R_{\mathcal{T}^m}(h_m) \Big) + \Big(R_{\mathcal{T}^m}(h_{\mathcal{H}}) - R(h_{\mathcal{H}}) \Big) \\ &\leq 2 \sup_{h\in\mathcal{H}} \Big| R(h) - R_{\mathcal{T}^m}(h) \Big| \end{aligned}$$

Therefore $\varepsilon \leq R(h_m) - R(h_{\mathcal{H}})$ implies $\frac{\varepsilon}{2} \leq \sup_{h\in\mathcal{H}} \Big| R(h) - R_{\mathcal{T}^m}(h) \Big|$ and

$$\mathbb{P}\Big(R(h_m) - R(h_{\mathcal{H}}) \geq \varepsilon \Big) \leq \mathbb{P}\Big(\sup_{h\in\mathcal{H}} \Big| R(h) - R_{\mathcal{T}^m}(h) \Big| \geq \frac{\varepsilon}{2} \Big)$$

Two examples of uniform generalization bounds

1. $\mathcal{H}$ is a finite set and $\ell\colon \mathcal{Y}\times\mathcal{Y}\to[\ell_{min},\ell_{max}]$. Then,

$$\mathbb{P}_{\mathcal{T}\sim p^m}\left(\max_{h\in\mathcal{H}}\left|R(h)-R_{\mathcal{T}^m}(h)\right|\geq\varepsilon\right)\leq 2|\mathcal{H}|\exp\left(\frac{-2m\,\varepsilon^2}{(\ell_{max}-\ell_{min})^2}\right)$$

holds for any $\varepsilon>0$ and $m\in\mathcal{N}$.

Two examples of uniform generalization bounds

1. $\mathcal{H}$ is a finite set and $\ell\colon \mathcal{Y} \times \mathcal{Y} \to [\ell_{min}, \ell_{max}]$. Then,

$$\mathbb{P}_{\mathcal{T}\sim p^m}\left(\max_{h\in\mathcal{H}} \left| R(h) - R_{\mathcal{T}^m}(h) \right| \geq \varepsilon \right) \leq 2|\mathcal{H}| \exp\left(\frac{-2m\,\varepsilon^2}{(\ell_{max} - \ell_{min})^2} \right)$$

holds for any $\varepsilon > 0$ and $m \in \mathcal{N}$.

2. $\ell(y, y') = [\![y \neq y']\!]$, $\mathcal{Y} = \{+1, -1\}$ and VC-dimension of $\mathcal{H}$ is finite. VC-dimension d of $\mathcal{H}$ is the maximal number of inputs which can be classified by strategies from $\mathcal{H}$ in all possible (that is 2^d) ways. Then,

$$\mathbb{P}_{\mathcal{T}\sim p^m}\left(\sup_{h\in\mathcal{H}} \left| R(h) - R_{\mathcal{T}^m}(h) \right| \geq \varepsilon \right) \leq 4 \left(\frac{2\,e\,m}{d} \right)^d e^{-\frac{m\,\varepsilon^2}{8}}$$

Rademacher Complexity

- Let $z = (x, y) \in \mathcal{Z} = \mathcal{X} \times \mathcal{Y}$, $p(z) = p(x, y)$ and $g(z) = \ell(y, h(x))$.

Rademacher Complexity

- Let $z = (x, y) \in \mathcal{Z} = \mathcal{X} \times \mathcal{Y}$, $p(z) = p(x, y)$ and $g(z) = \ell(y, h(x))$.

Definition 2. *Let* $\mathcal{G} \subseteq [a, b]^{\mathcal{Z}}$ *be a set of functions* $g \colon \mathcal{Z} \to [a, b]$ *where* $a, b \in \mathbb{R}$ *and* $a < b$. *Let* $\mathcal{U}^m = \{z^1, \ldots, z^m\} \in \mathcal{Z}^m$ *be drawn i.i.d. from* $p(z)$.

Rademacher Complexity

- Let $z = (x, y) \in \mathcal{Z} = \mathcal{X} \times \mathcal{Y}$, $p(z) = p(x, y)$ and $g(z) = \ell(y, h(x))$.

Definition 2. *Let $\mathcal{G} \subseteq [a, b]^{\mathcal{Z}}$ be a set of functions $g \colon \mathcal{Z} \to [a, b]$ where $a, b \in \mathbb{R}$ and $a < b$. Let $\mathcal{U}^m = \{z^1, \dots, z^m\} \in \mathcal{Z}^m$ be drawn i.i.d. from $p(z)$.*

The empirical Rademacher complexity of $\mathcal{G}$ w.r.t. to the sample $\mathcal{U}^m$ is

$$\hat{\mathfrak{R}}_m(\mathcal{G}, \mathcal{U}^m) = \mathbb{E}_{\sigma \sim \mathrm{Unif}\{-1,+1\}} \left[\sup_{g \in \mathcal{G}} \frac{1}{m} \sum_{i=1}^{m} \sigma_i \, g(z_i) \right]$$

Rademacher Complexity

- Let $z = (x, y) \in \mathcal{Z} = \mathcal{X} \times \mathcal{Y}$, $p(z) = p(x, y)$ and $g(z) = \ell(y, h(x))$.

Definition 2. *Let $\mathcal{G} \subseteq [a, b]^{\mathcal{Z}}$ be a set of functions $g \colon \mathcal{Z} \to [a, b]$ where $a, b \in \mathbb{R}$ and $a < b$. Let $\mathcal{U}^m = \{z^1, \ldots, z^m\} \in \mathcal{Z}^m$ be drawn i.i.d. from $p(z)$.*

The empirical Rademacher complexity of $\mathcal{G}$ w.r.t. to the sample $\mathcal{U}^m$ is

$$\hat{\mathfrak{R}}_m(\mathcal{G}, \mathcal{U}^m) = \mathbb{E}_{\sigma \sim \mathrm{Unif}\{-1,+1\}} \left[\sup_{g \in \mathcal{G}} \frac{1}{m} \sum_{i=1}^{m} \sigma_i \, g(z_i) \right]$$

The Rademacher complexity of $\mathcal{G}$ w.r.t. distribution $p(z)$ is

$$\mathfrak{R}_m(\mathcal{G}) = \mathbb{E}_{\mathcal{U}^m \sim p^m(z)} \left[\hat{\mathfrak{R}}_m(\mathcal{G}, \mathcal{U}^m) \right]$$

Rademacher-based uniform convergence bounds

- Let $\mathcal{G} \subseteq [a,b]^{\mathcal{Z}}$ be a set of functions. Then, for every $\delta \in (0,1)$

$$\sup_{g \in \mathcal{G}} \left| \mathbb{E}_{z \sim p}(g(z)) - \frac{1}{m} \sum_{i=1}^{m} g(z_i) \right| \leq 2\, \mathfrak{R}_m(\mathcal{G}) + (b-a) \sqrt{\frac{\log 2/\delta}{2\,m}}$$

holds with probability $1-\delta$ at least, w.r.t. $\mathcal{U}^m = \{z^1, \ldots, z^m\} \sim p^m(z)$.

Rademacher-based uniform convergence bounds

- Let $\mathcal{G} \subseteq [a,b]^{\mathcal{Z}}$ be a set of functions. Then, for every $\delta \in (0,1)$

$$\sup_{g \in \mathcal{G}} \left| \mathbb{E}_{z \sim p}(g(z)) - \frac{1}{m} \sum_{i=1}^{m} g(z_i) \right| \leq 2\, \mathfrak{R}_m(\mathcal{G}) + (b-a) \sqrt{\frac{\log 2/\delta}{2\,m}}$$

holds with probability $1-\delta$ at least, w.r.t. $\mathcal{U}^m = \{z^1, \ldots, z^m\} \sim p^m(z)$.

- For every $\delta \in (0,1)$

$$\sup_{g \in \mathcal{G}} \left| \mathbb{E}_{z \sim p}(g(z)) - \frac{1}{m} \sum_{i=1}^{m} g(z_i) \right| \leq 3\, \hat{\mathfrak{R}}_m(\mathcal{G}, \mathcal{U}^m) + (b-a) \sqrt{\frac{\log 4/\delta}{2\,m}}$$

holds with probability $1-\delta$ at least, w.r.t. $\mathcal{U}^m = \{z^1, \ldots, z^m\} \sim p^m(z)$.

Example: Rademacher complexity of linear functions

- Assume that $\mathcal{X} \subseteq \mathbb{R}^n$ and $p(\boldsymbol{x}, y)$ is such that $\|\boldsymbol{x}\| \leq R$.
- Assume that
$$\mathcal{G} = \left\{ \psi(\langle \boldsymbol{w}, \boldsymbol{x} \rangle, y) \mid \|\boldsymbol{w}\|_2 \leq B \right\}$$
where $\psi \colon \mathbb{R} \times \mathcal{Y} \to \mathbb{R}$ is such that $f(t) = \psi(t, y)$ is ρ-Lipschitz continuous for all $y \in \mathcal{Y}$.

Example: Rademacher complexity of linear functions

- Assume that $\mathcal{X} \subseteq \mathbb{R}^n$ and $p(\boldsymbol{x}, y)$ is such that $\|\boldsymbol{x}\| \leq R$.
- Assume that
$$\mathcal{G} = \Big\{\psi(\langle \boldsymbol{w}, \boldsymbol{x}\rangle, y) \mid \|\boldsymbol{w}\|_2 \leq B\Big\}$$
where $\psi\colon \mathbb{R} \times \mathcal{Y} \to \mathbb{R}$ is such that $f(t) = \psi(t, y)$ is ρ-Lipschitz continuous for all $y \in \mathcal{Y}$.

  E.g. $\psi(t, y) = \max\{0, 1 - t\, y\}$ and $\psi(t) = |t - y|$ are 1-Lipschitz.

Example: Rademacher complexity of linear functions

- Assume that $\mathcal{X} \subseteq \mathbb{R}^n$ and $p(\boldsymbol{x}, y)$ is such that $\|\boldsymbol{x}\| \leq R$.
- Assume that

$$\mathcal{G} = \left\{ \psi(\langle \boldsymbol{w}, \boldsymbol{x} \rangle, y) \mid \|\boldsymbol{w}\|_2 \leq B \right\}$$

where $\psi\colon \mathbb{R} \times \mathcal{Y} \to \mathbb{R}$ is such that $f(t) = \psi(t, y)$ is ρ-Lipschitz continuous for all $y \in \mathcal{Y}$.

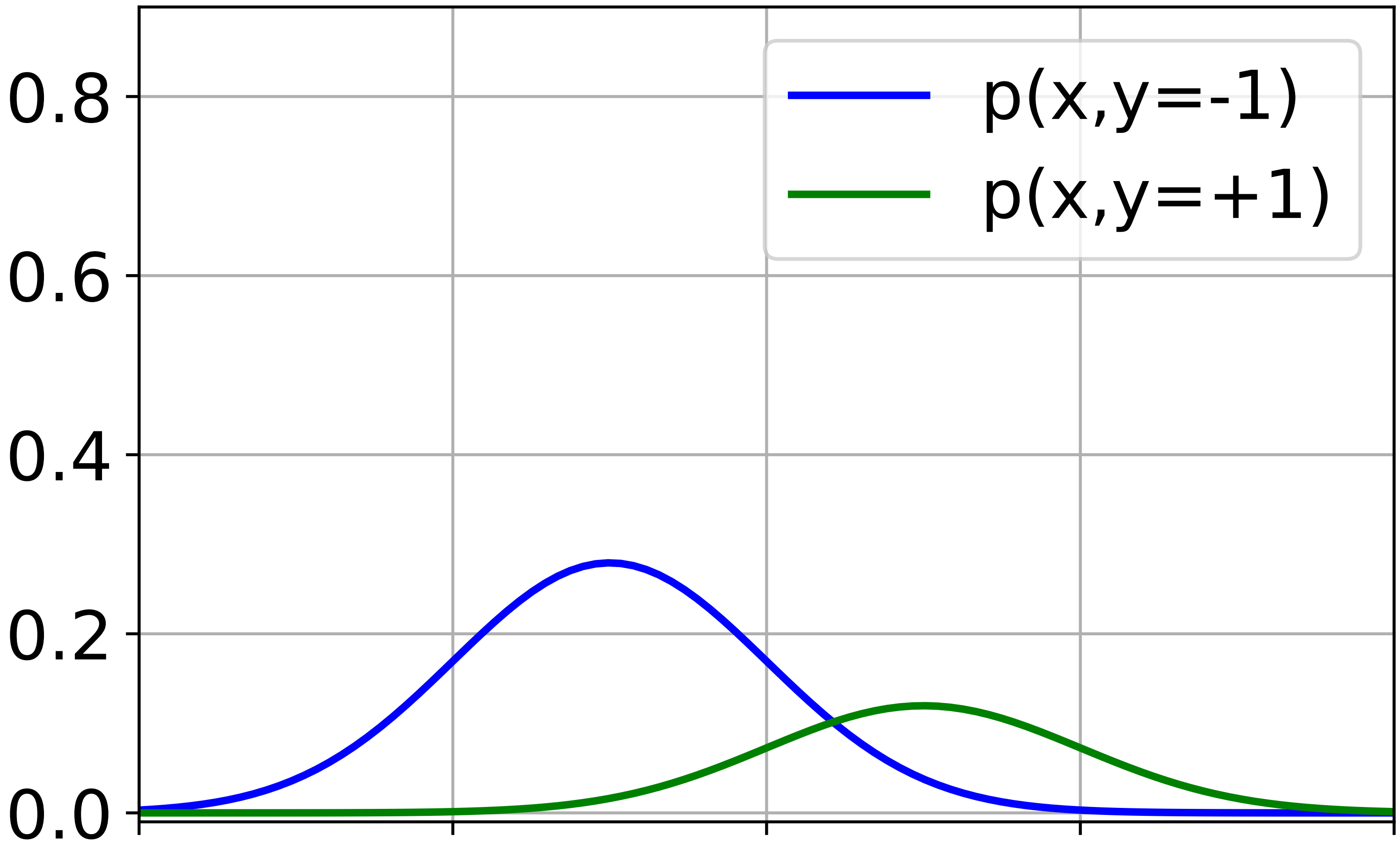
E.g. $\psi(t, y) = \max\{0, 1 - t\, y\}$ and $\psi(t) = |t - y|$ are 1-Lipschitz.

- Then,

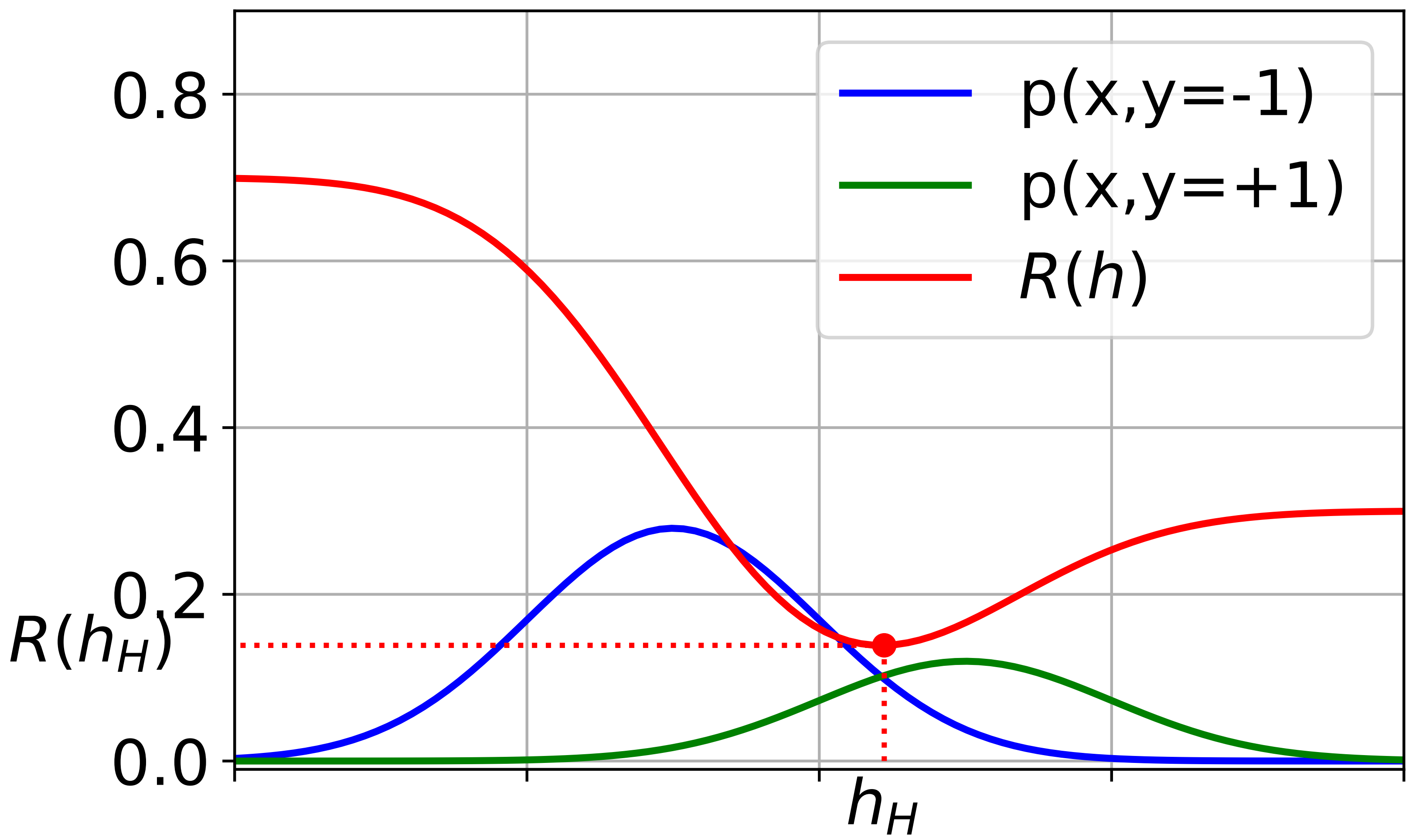
$$\hat{\mathfrak{R}}_m(\mathcal{G}) \leq \frac{\rho\, B\, R}{\sqrt{m}}$$

- We can also compute

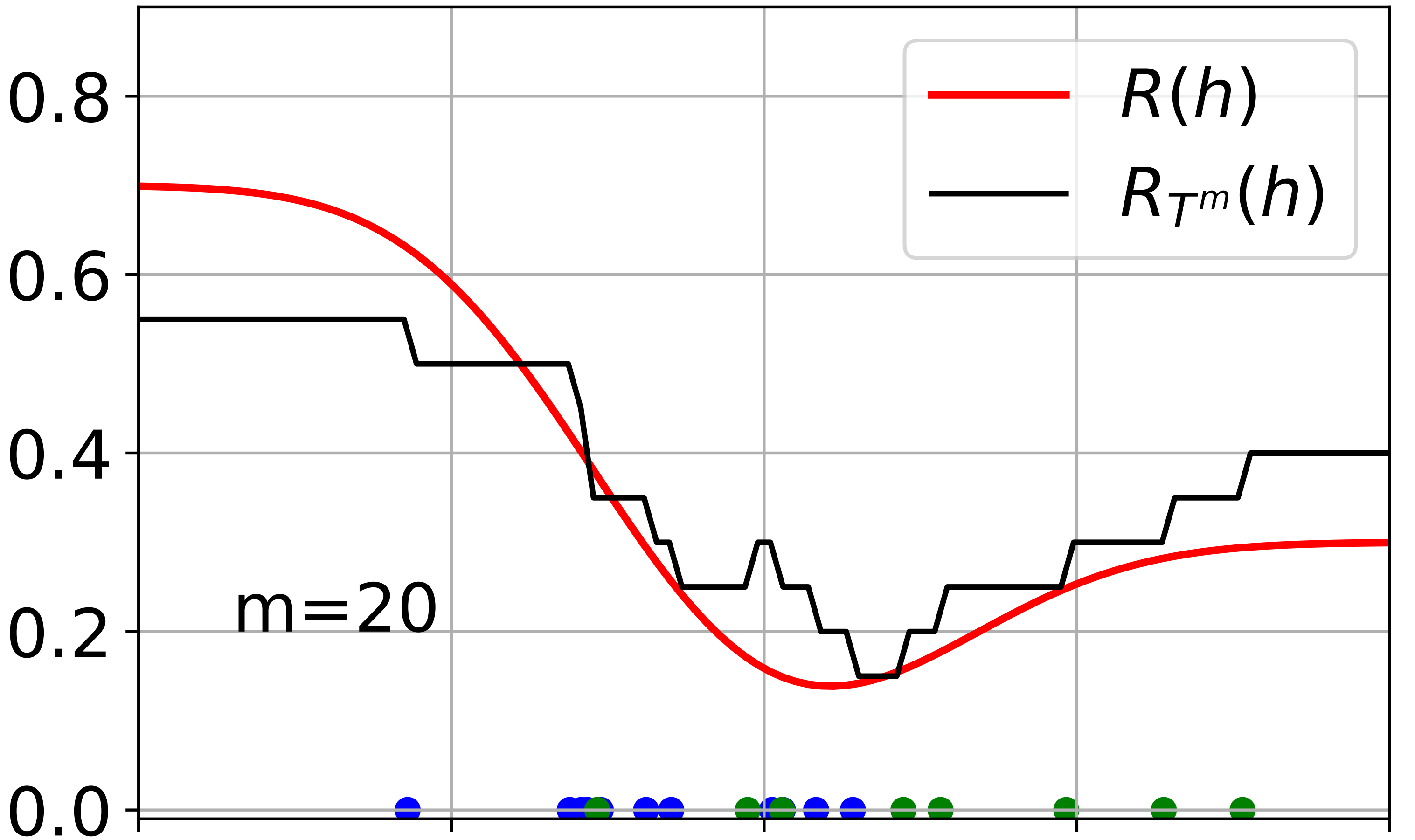
$$b = \max_{t \in [-BR, BR]} \psi(t, y) \qquad \text{and} \qquad a = \min_{t \in [-BR, BR]} \psi(t, y)$$



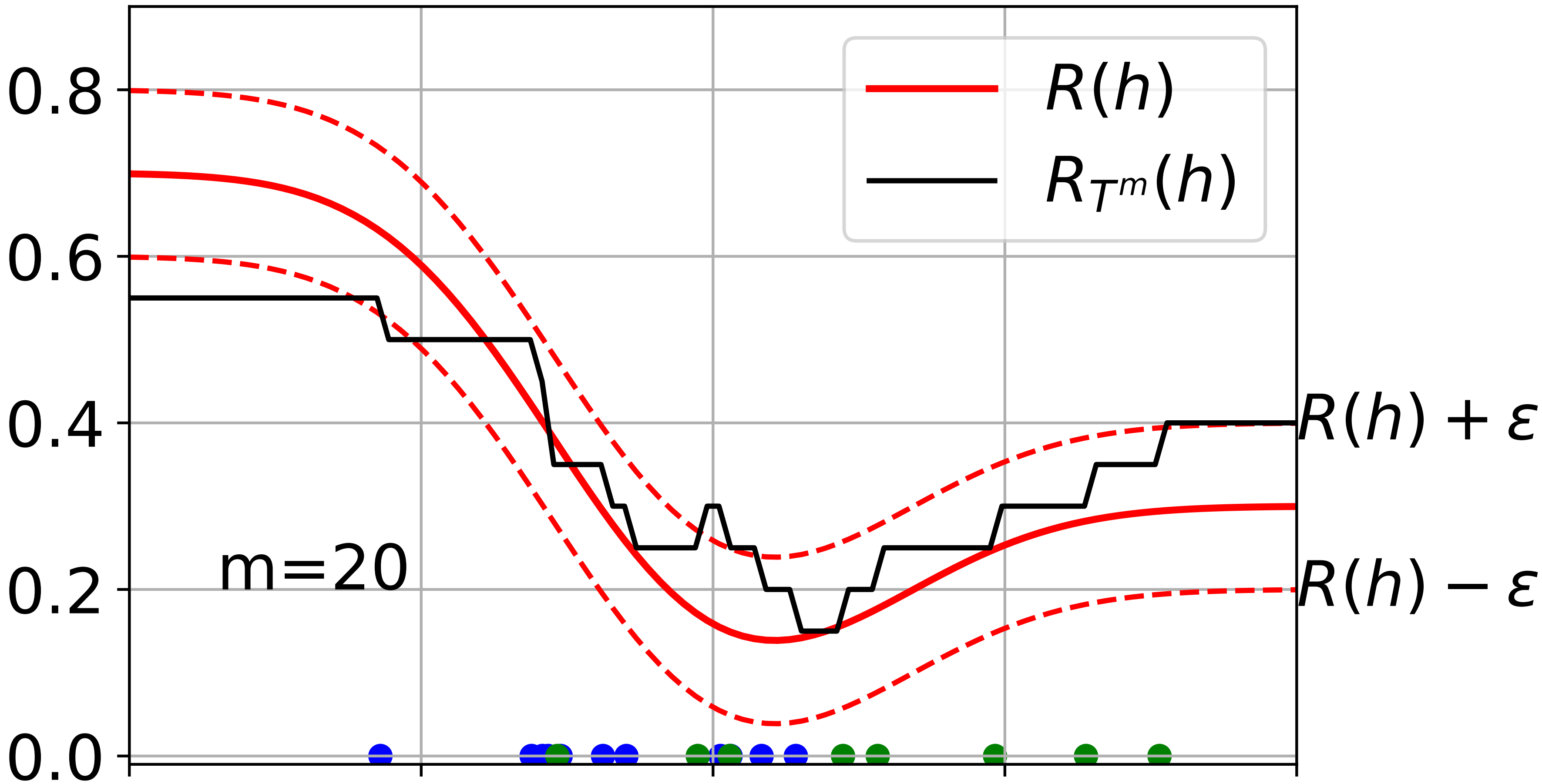
0.8
0.6
0.4
0.2
0.0
p(x,y=-1)
p(x,y=+1)



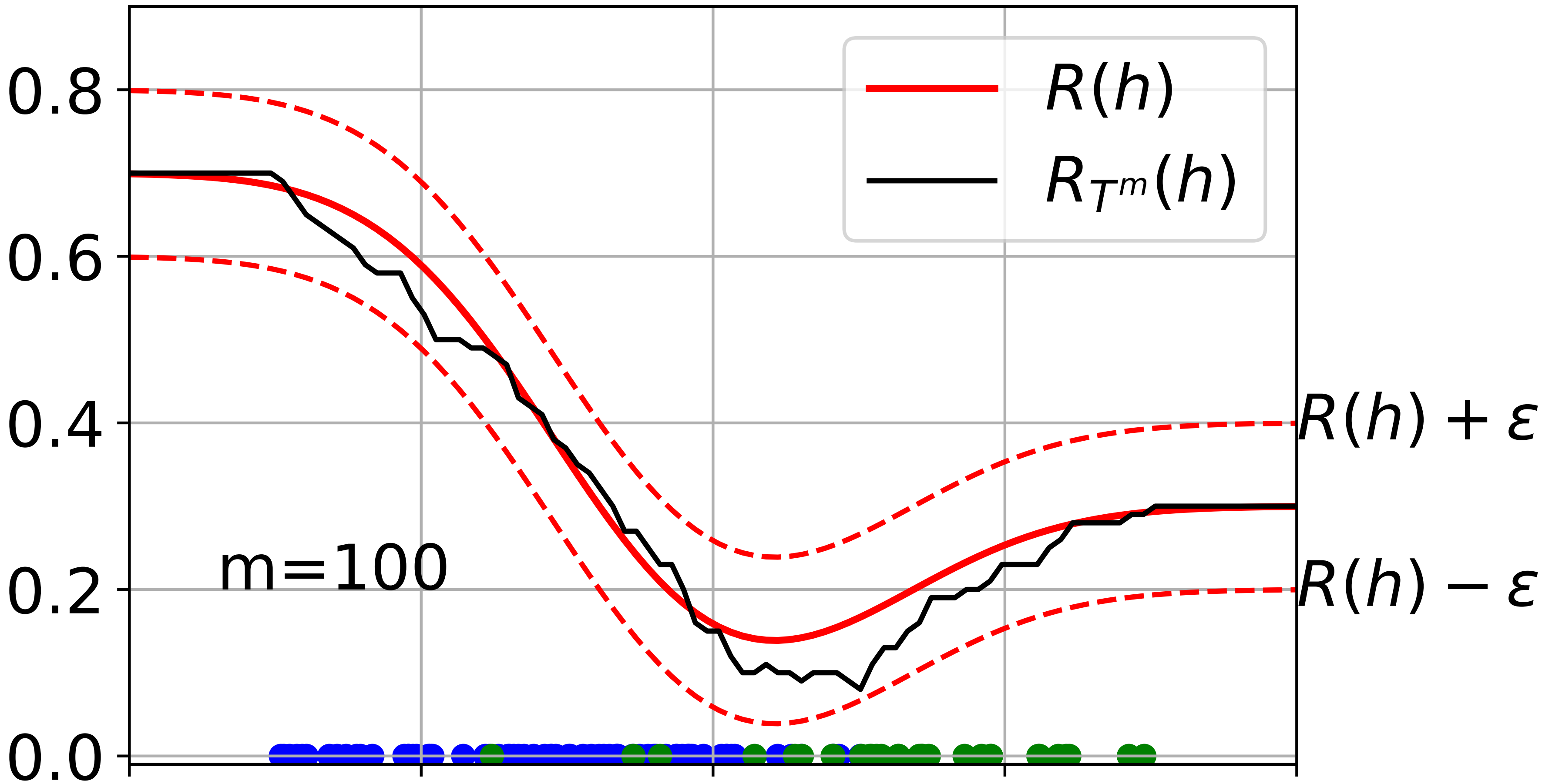
0.8
0.6
0.4
0.2
0.0
$R(h_H)$
h_H
p(x,y=-1)
p(x,y=+1)
$R(h)$



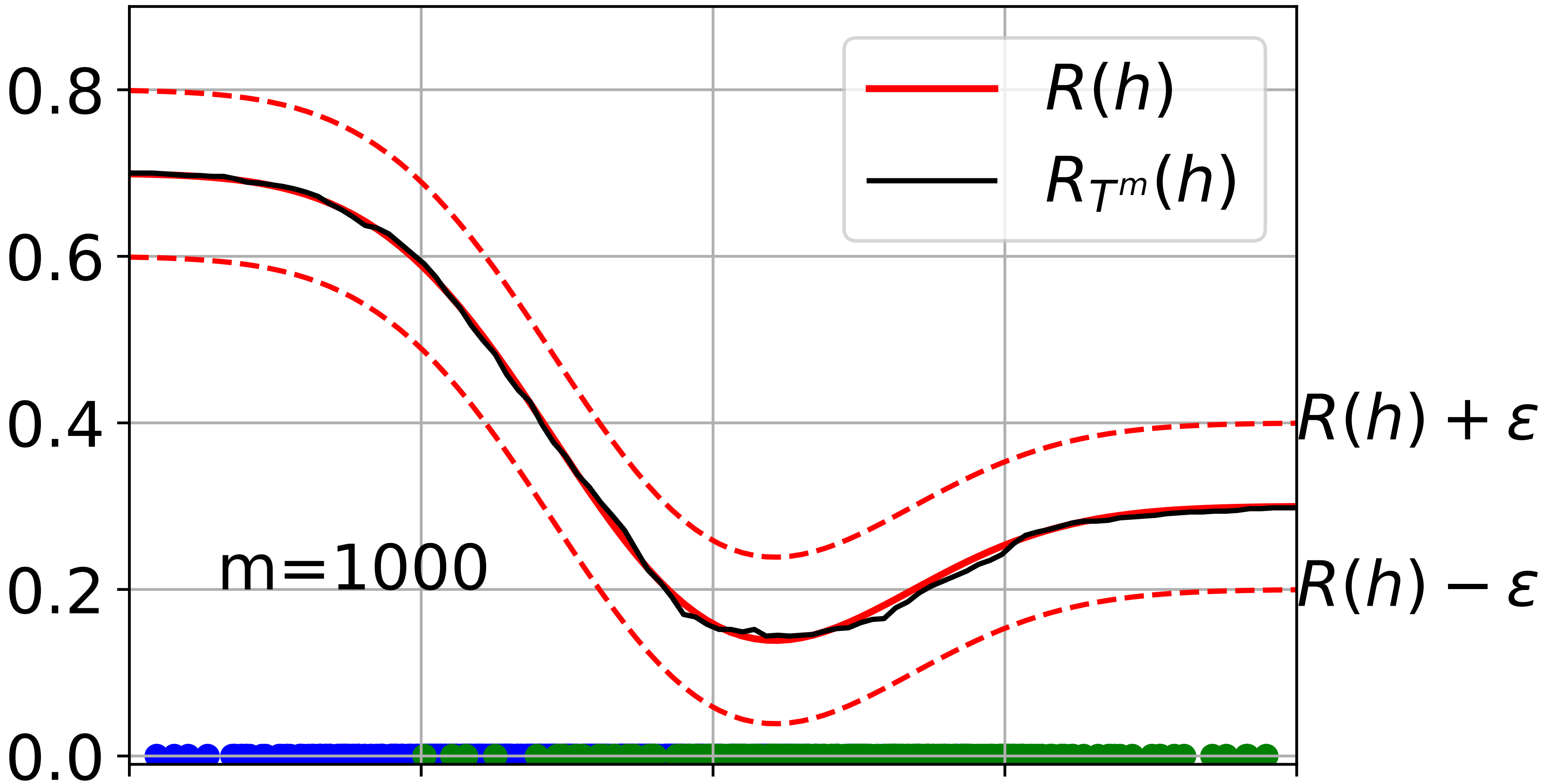
0.8
0.6
0.4
0.2
0.0
$R(h)$
$R_{T^m}(h)$
m=20



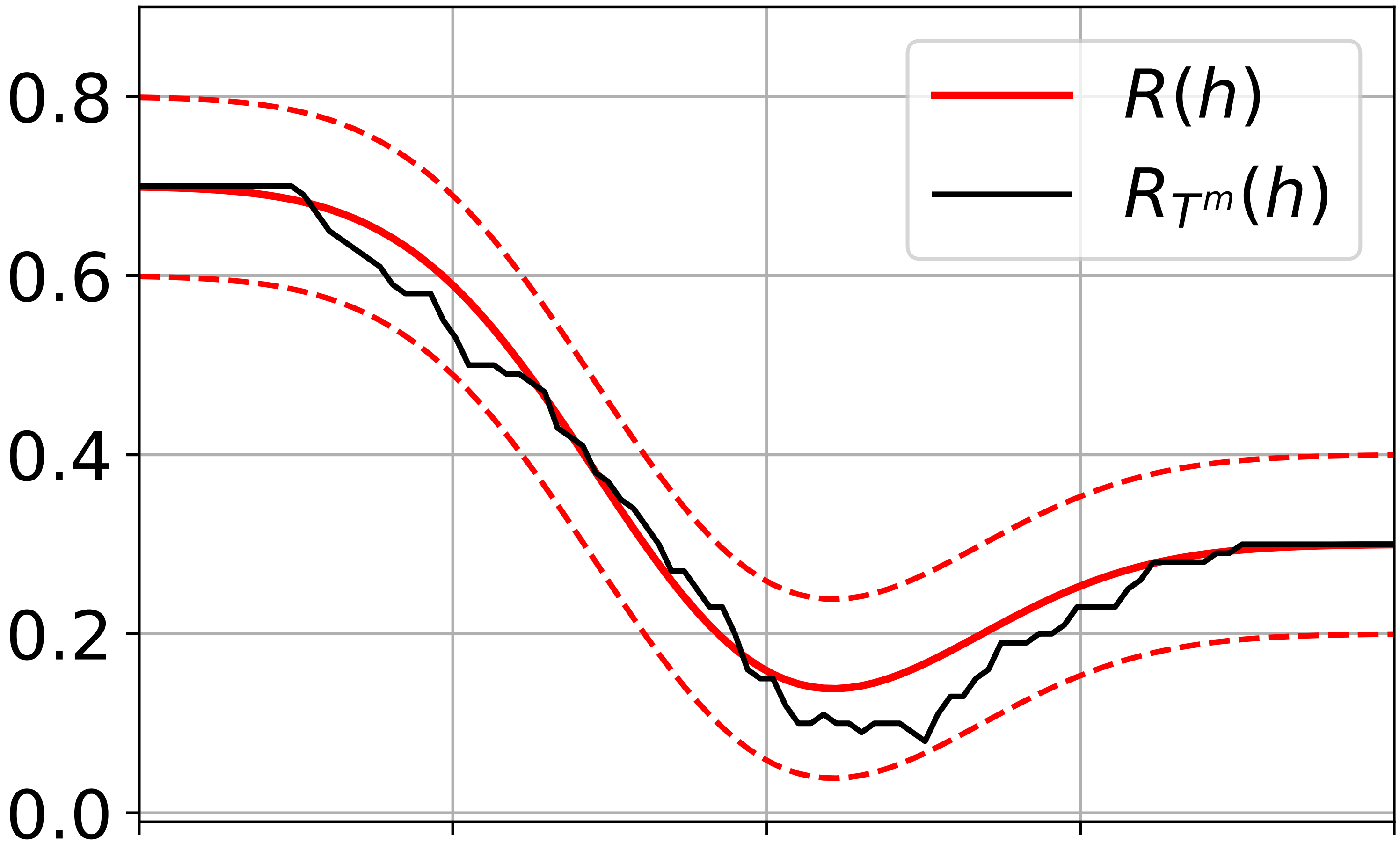
0.8
0.6
0.4
0.2
0.0
m=20
$R(h)$
$R_{T^m}(h)$
$R(h)+\varepsilon$
$R(h)-\varepsilon$

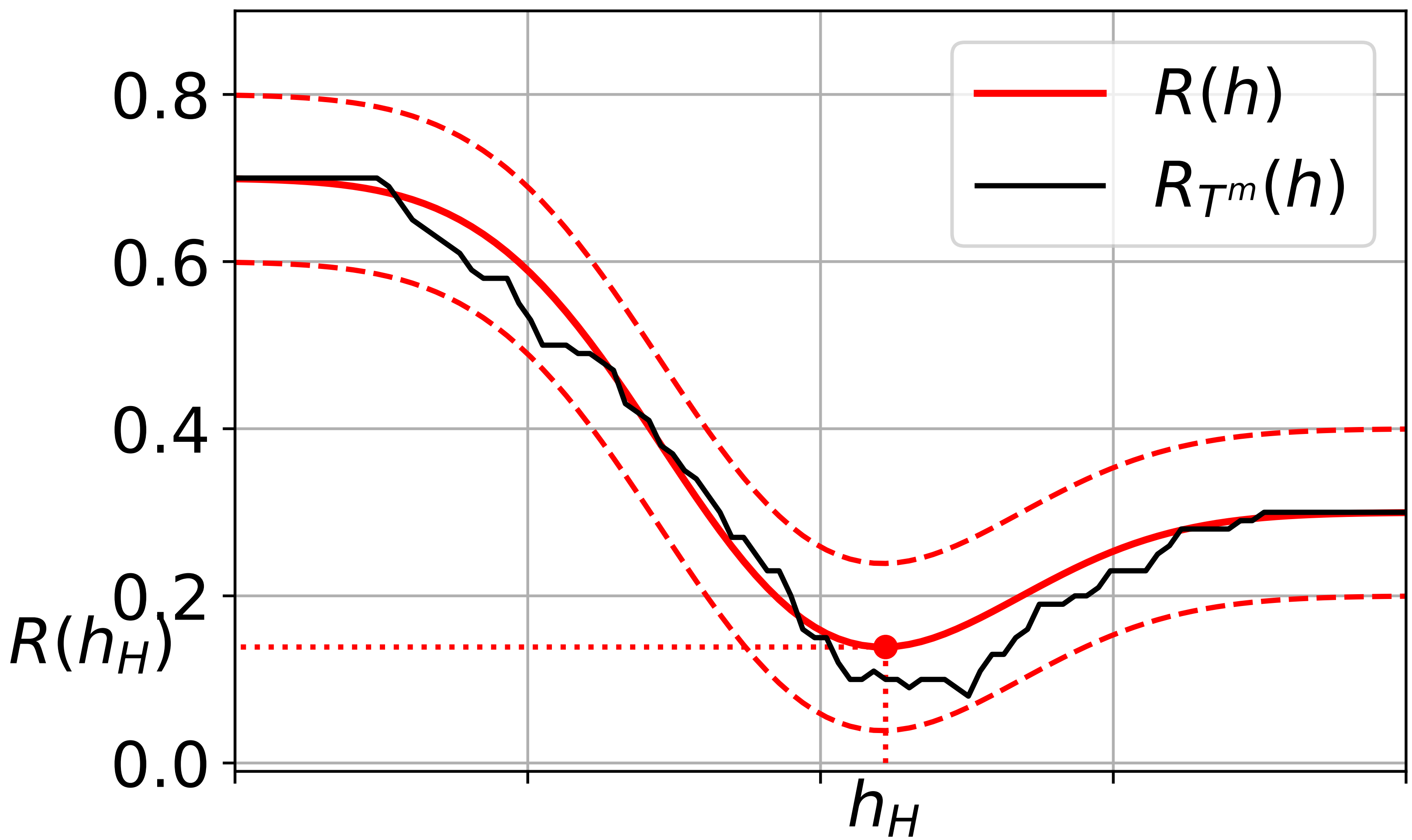


0.8
0.6
0.4
0.2
0.0
$R(h)$
$R_{T^m}(h)$
m=100
$R(h)+\varepsilon$
$R(h)-\varepsilon$

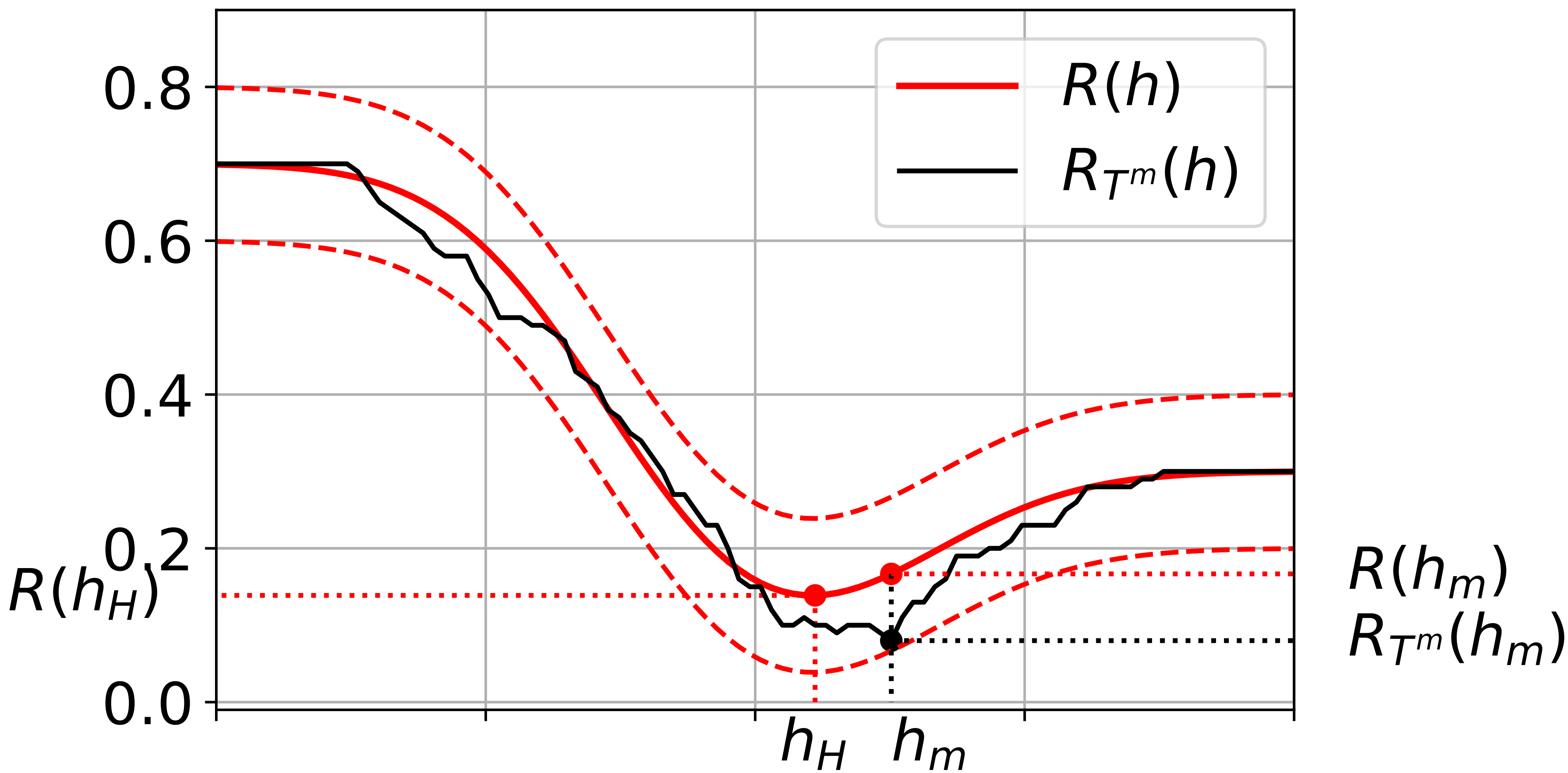


0.8
0.6
0.4
0.2
0.0
$R(h)$
$R_{T^m}(h)$
$R(h)+\varepsilon$
$R(h)-\varepsilon$
m=1000

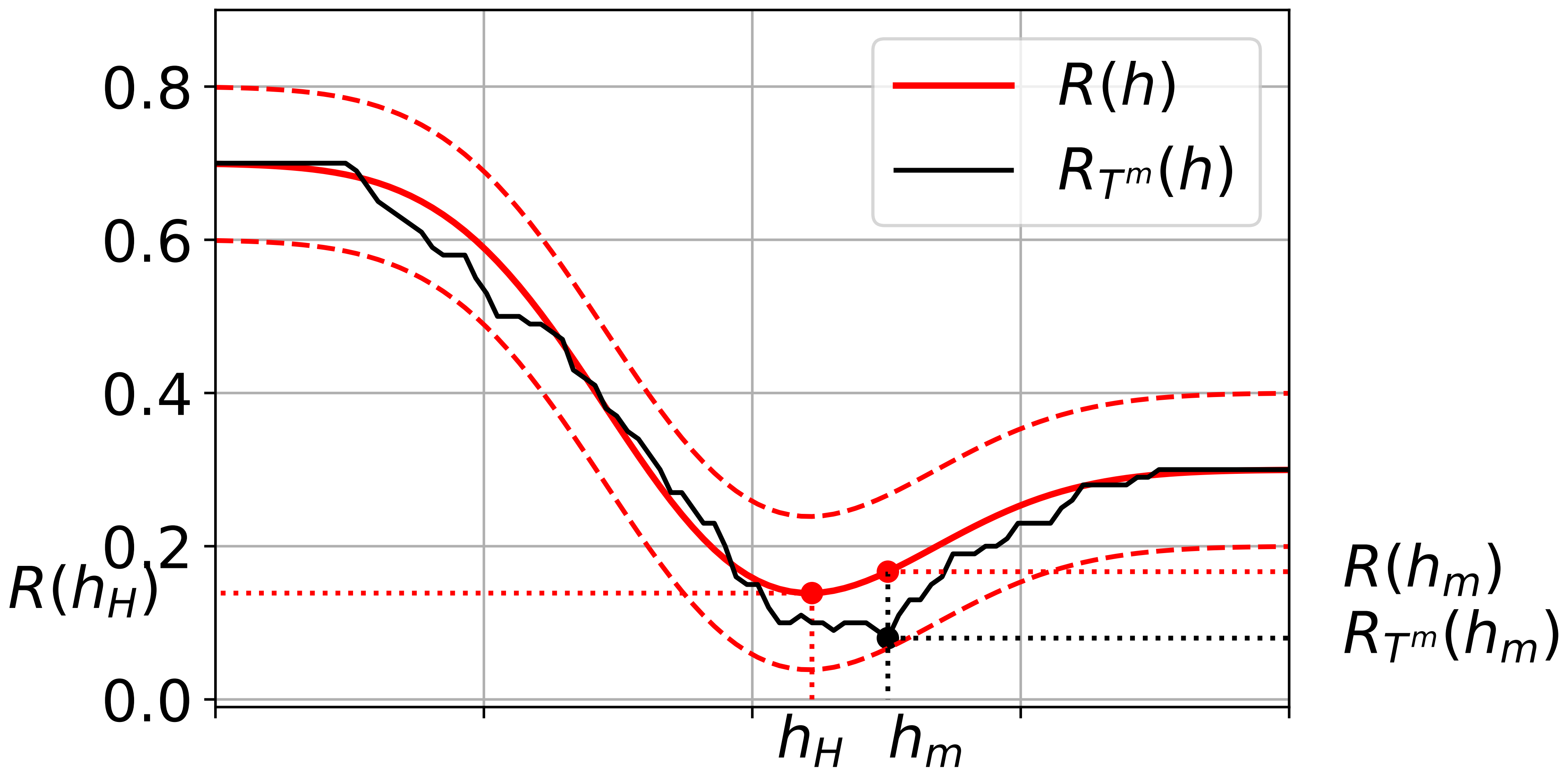

0.8
0.6
0.4
0.2
0.0
R(h)
R_{T^m}(h)



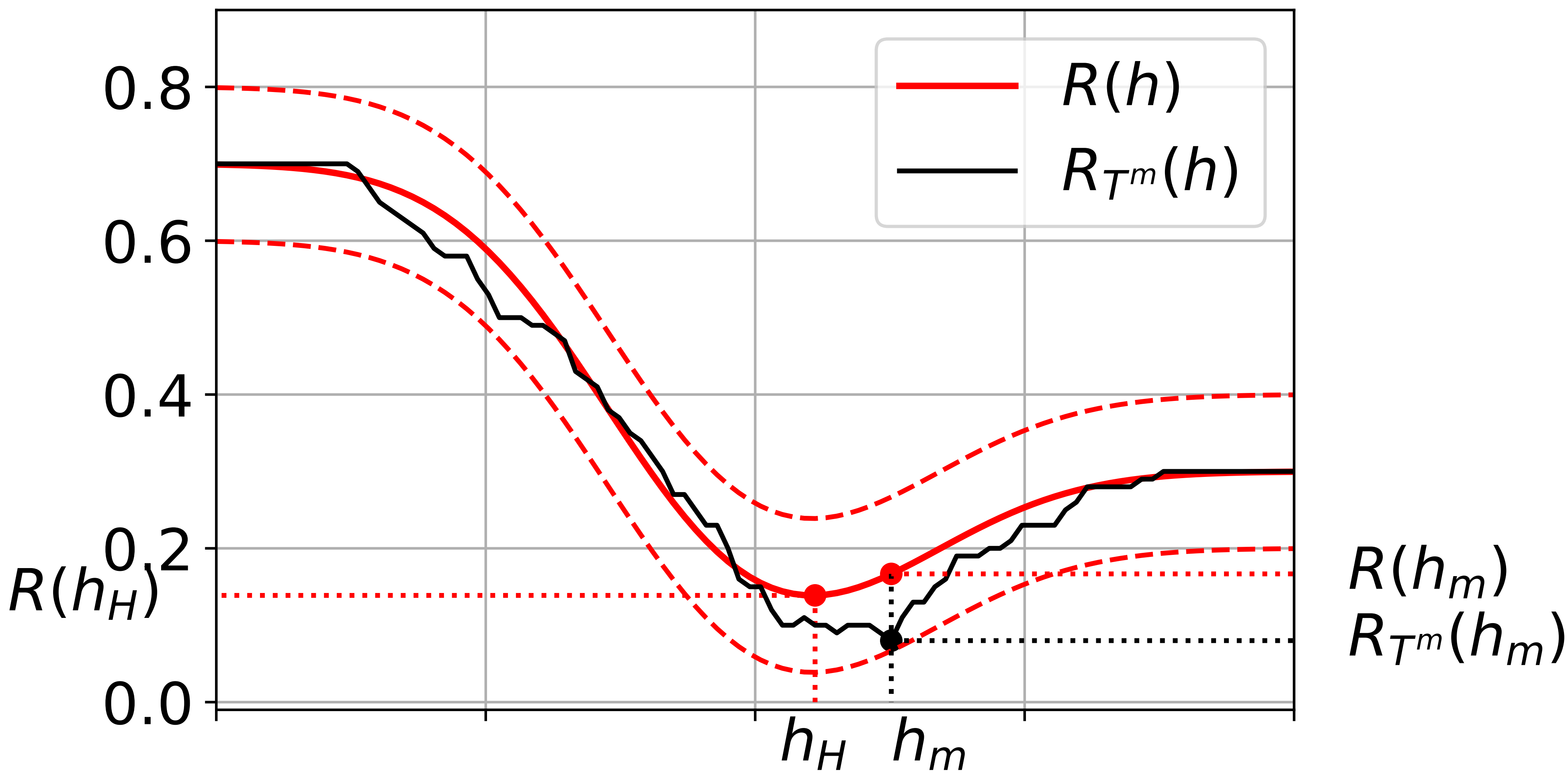
0.8
0.6
0.4
0.2
0.0
$R(h_H)$
h_H
$R(h)$
$R_{T^m}(h)$



0.8
0.6
0.4
0.2
0.0
$R(h)$
$R_{T^m}(h)$
$R(h_H)$
$R(h_m)$
$R_{T^m}(h_m)$
h_H
h_m



0.8
0.6
0.4
0.2
0.0
$R(h)$
$R_{T^m}(h)$
$R(h_H)$
$R(h_m)$
$R_{T^m}(h_m)$
h_H
h_m



0.8
0.6
0.4
0.2
0.0
$R(h)$
$R_{T^m}(h)$
$R(h_H)$
$R(h_m)$
$R_{T^m}(h_m)$
h_H
h_m