

The A'allon koneoppimisen sanakirja

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Lists of Symbols

Sets and Functions

$a \in \mathcal{A}$ The object a is an element of the set \mathcal{A} .

$a := b$ We use a as a shorthand for b .

$|\mathcal{A}|$ The cardinality (i.e., number of elements) of a finite set \mathcal{A} .

$\mathcal{A} \subseteq \mathcal{B}$ \mathcal{A} is a subset of \mathcal{B} .

$\mathcal{A} \subset \mathcal{B}$ \mathcal{A} is a strict subset of \mathcal{B} .

$\mathcal{A} \times \mathcal{B}$ The Cartesian product of the sets \mathcal{A} and \mathcal{B} .

\mathbb{N} The natural numbers $1, 2, \dots$.

\mathbb{R} The real numbers x [1].

\mathbb{R}_+ The nonnegative real numbers $x \geq 0$.

\mathbb{R}_{++} The positive real numbers $x > 0$.

$\{0, 1\}$ The set consisting of the two real numbers 0 and 1.

$[0, 1]$ The closed interval of real numbers x with $0 \leq x \leq 1$.

$\arg \min_{\mathbf{w} \in \mathcal{C}} f(\mathbf{w})$	The set of minimizers for a real-valued function $f : \mathcal{C} \rightarrow \mathbb{R}$. See also: function.
$\mathbb{S}^{(n)}$	The set of unit-norm vectors in \mathbb{R}^{n+1} . See also: norm, vector.
$\exp(a)$	The exponential function evaluated at the real number $a \in \mathbb{R}$. See also: function.
$\log a$	The logarithm of the positive number $a \in \mathbb{R}_{++}$.
$f(\cdot) : \mathcal{A} \rightarrow \mathcal{B} : a \mapsto f(a)$	A function (or mapping) from a set \mathcal{A} to a set \mathcal{B} , which assigns to each input $a \in \mathcal{A}$ a well-defined output $f(a) \in \mathcal{B}$. The set \mathcal{A} is the domain of the function f and the set \mathcal{B} is the co-domain of f . Function approximation aims to learn a function h that maps points \mathbf{x} of a dataset to a response $h(\mathbf{x})$ for its label y . See also: function, mapping, output, domain, co-domain, function approximation, point, dataset, response, label.
$\text{epi}(f)$	The epigraph of a real-valued function $f : \mathbb{R}^d \rightarrow \mathbb{R}$. See also: epigraph, function.
$(a_r)_{r \in \mathbb{N}}, (a^{(r)})_{r \in \mathbb{N}}, \{a^{(r)}\}_{r \in \mathbb{N}}$	A sequence of elements. See also: sequence.

$\mathbb{I}_{\mathcal{A}}(x)$

The indicator funktio of a set \mathcal{A} delivers $f(x) = 1$ for any $x \in \mathcal{A}$ and $f(x) = 0$ otherwise.

See also: funktio.

$\frac{\partial f(w_1, \dots, w_d)}{\partial w_j}$

The partial derivative (if it exists) of a real-valued funktio $f : \mathbb{R}^d \rightarrow \mathbb{R}$ with respect to w_j [2, Ch. 9].

See also: partial derivative, funktio.

$\nabla f(\mathbf{w})$

The gradientti of a differentiable real-valued funktio $f : \mathbb{R}^d \rightarrow \mathbb{R}$ is the vektori $\nabla f(\mathbf{w}) = (\partial f / \partial w_1, \dots, \partial f / \partial w_d)^T \in \mathbb{R}^d$ [2, Ch. 9].

See also: gradientti, differentiable, funktio, vektori.

Matrices and Vectors

$\mathbf{x} = (x_1, \dots, x_d)^T$	A vektori of length d , with its j th entry being x_j . See also: vektori.
\mathbb{R}^d	The set of vektorit $\mathbf{x} = (x_1, \dots, x_d)^T$ consisting of d real-valued entries $x_1, \dots, x_d \in \mathbb{R}$. See also: vektori.
$\mathbf{I}_{l \times d}$	A generalized identity matriisi with l rows and d columns. The entries of $\mathbf{I}_{l \times d} \in \mathbb{R}^{l \times d}$ are equal to 1 along the main diagonal and otherwise equal to 0. See also: matriisi.
\mathbf{I}_d, \mathbf{I}	A square identity matriisi of size $d \times d$. If the size is clear from context, we drop the subscript. See also: matriisi.
$\ \mathbf{x}\ _2$	The Euclidean (or ℓ_2) normi of the vektori $\mathbf{x} = (x_1, \dots, x_d)^T \in \mathbb{R}^d$ defined as $\ \mathbf{x}\ _2 := \sqrt{\sum_{j=1}^d x_j^2}$. See also: normi, vektori.
$\ \mathbf{x}\ $	Some normi of the vektori $\mathbf{x} \in \mathbb{R}^d$ [3]. Unless otherwise specified, we mean the euklidinen normi $\ \mathbf{x}\ _2$. See also: normi, vektori, euklidinen normi.
\mathbf{x}^T	The transpose of a matriisi that has the vektori $\mathbf{x} \in \mathbb{R}^d$ as its single column. See also: matriisi, vektori.

\mathbf{X}^T The transpose of a matriisi $\mathbf{X} \in \mathbb{R}^{m \times d}$. A square real-valued matriisi $\mathbf{X} \in \mathbb{R}^{m \times m}$ is called symmetric if $\mathbf{X} = \mathbf{X}^T$.
See also: matriisi.

\mathbf{X}^{-1} The käänteismatriisi of a matriisi $\mathbf{X} \in \mathbb{R}^{d \times d}$.
See also: käänteismatriisi, matriisi.

$\mathbf{0} = (0, \dots, 0)^T$ The vektori in \mathbb{R}^d with each entry equal to zero.
See also: vektori.

$\mathbf{1} = (1, \dots, 1)^T$ The vektori in \mathbb{R}^d with each entry equal to one.
See also: vektori.

$(\mathbf{v}^T, \mathbf{w}^T)^T$ The vektori of length $d + d'$ obtained by concatenating the entries of vektori $\mathbf{v} \in \mathbb{R}^d$ with the entries of $\mathbf{w} \in \mathbb{R}^{d'}$.
See also: vektori.

$\text{span}(\mathbf{B})$ The span of a matriisi $\mathbf{B} \in \mathbb{R}^{a \times b}$, which is the subspace of all linear combinations of the columns of \mathbf{B} , such that $\text{span}(\mathbf{B}) = \{\mathbf{B}\mathbf{a} : \mathbf{a} \in \mathbb{R}^b\} \subseteq \mathbb{R}^a$.
See also: matriisi, subspace.

$\text{null}(\mathbf{A})$ The nolla-avaruuus of a matriisi $\mathbf{A} \in \mathbb{R}^{a \times b}$, which is the subspace of vektorit $\mathbf{a} \in \mathbb{R}^b$ such that $\mathbf{A}\mathbf{a} = \mathbf{0}$.
See also: nolla-avaruuus, matriisi, subspace, vektori.

$\det(\mathbf{C})$ The determinantti of the matriisi \mathbf{C} .
See also: determinantti, matriisi.

$\text{tr}(\mathbf{C})$ The trace of the matriisi \mathbf{C} .
See also: trace.

$\mathbf{A} \otimes \mathbf{B}$ The Kroneckerin tulo of \mathbf{A} and \mathbf{B} [4].
See also: Kroneckerin tulo.

Probability Theory

$\mathbf{x} \sim \mathbb{P}^{(\mathbf{z})}$	The satunnaismuuttuja \mathbf{x} is distributed according to the todennäköisyysjakauma $\mathbb{P}^{(\mathbf{z})}$ [5], [6]. See also: satunnaismuuttuja, todennäköisyysjakauma.
$\mathbb{E}_p\{f(\mathbf{z})\}$	The odotusarvo of an satunnaismuuttuja $f(\mathbf{z})$ that is obtained by applying a deterministic funktion f to an satunnaismuuttuja \mathbf{z} whose todennäköisyysjakauma is $\mathbb{P}^{(\mathbf{z})}$. If the todennäköisyysjakauma is clear from context, we just write $\mathbb{E}\{f(\mathbf{z})\}$. See also: odotusarvo, satunnaismuuttuja, funktion, todennäköisyysjakauma.
$\text{cov}(x, y)$	The kovarianssi between two real-valued satunnaismuuttujat defined over a common probability space. See also: kovarianssi, satunnaismuuttuja, todennäköisyysjakauma.
$\mathbb{P}^{(\mathbf{x}, y)}$	A (joint) todennäköisyysjakauma of an satunnaismuuttuja whose toteumat are tietopisteet with piirteet \mathbf{x} and nimiö y . See also: todennäköisyysjakauma, satunnaismuuttuja, toteuma, tietopiste, piirre, nimiö.
$\mathbb{P}^{(y \mathbf{x})}$	A conditional probability distribution of an satunnaismuuttuja y given (or conditioned on) the value of another satunnaismuuttuja \mathbf{x} [7, Sec. 3.5]. See also: conditional probability distribution, satunnaismuuttuja.
$\mathbb{P}(\mathcal{A})$	The todennäköisyys of the measurable event \mathcal{A} . See also: todennäköisyys, measurable, event.

	The moment generating function (MGF) of an satunnaismuuttuja x .
$M_x(t)$	See also: todennäköisyysjakauma, probability density function (pdf).
$\mathbb{P}^{(\mathcal{D})}$	The empirical distribution of a tietoaineisto \mathcal{D} . See also: empirical distribution, tietoaineisto, uusio-otanta.
$\mathbb{P}^{(\mathbf{x}; \mathbf{w})}$	A parameterized todennäköisyysjakauma of an satunnaismuuttuja \mathbf{x} . The todennäköisyysjakauma depends on a parameter vektori \mathbf{w} . For example, $\mathbb{P}^{(\mathbf{x}; \mathbf{w})}$ could be a moninormaalijakauma with the parameter vektori \mathbf{w} given by the entries of the keskiarvo vektori $\mathbb{E}\{\mathbf{x}\}$ and the kovarianssimatriisi $\mathbb{E}\left\{ (\mathbf{x} - \mathbb{E}\{\mathbf{x}\})(\mathbf{x} - \mathbb{E}\{\mathbf{x}\})^T \right\}$. See also: todennäköisyysjakauma, parameter, todennäköisyysmalli.
$\mathcal{N}(\mu, \sigma^2)$	The todennäköisyysjakauma of a normaalijakautunut satunnaismuuttuja $x \in \mathbb{R}$ with keskiarvo (or odotusarvo) $\mu = \mathbb{E}\{x\}$ and varianssi $\sigma^2 = \mathbb{E}\{(x - \mu)^2\}$. See also: todennäköisyysjakauma, normaalijakautunut satunnaismuuttuja.
$\mathcal{N}(\boldsymbol{\mu}, \mathbf{C})$	The moninormaalijakauma of a vektori-valued normaalijakautunut satunnaismuuttuja $\mathbf{x} \in \mathbb{R}^d$ with keskiarvo (or odotusarvo) $\boldsymbol{\mu} = \mathbb{E}\{\mathbf{x}\}$ and kovarianssimatriisi $\mathbf{C} = \mathbb{E}\{(\mathbf{x} - \boldsymbol{\mu})(\mathbf{x} - \boldsymbol{\mu})^T\}$. See also: moninormaalijakauma, normaalijakautunut satunnaismuuttuja.
Δ^k	The probability simplex, which consists of all vektorit $\mathbf{p} = (p_1, \dots, p_k)^T \in \mathbb{R}^k$ with nonnegative entries that sum to one, i.e., $p_c \geq 0$ for $c = 1, \dots, k$ and $\sum_{c=1}^k p_c = 1$. See also: probability mass function (pmf).

$H(x)$ The entropia of a discrete random variable (discrete RV) x .
See also: entropia, discrete RV.

Ω A otosavaruus of all possible outcomes of a satunnaiskoe.
See also: event.

Σ A collection of measurable subsets of a otosavaruus Ω .
See also: otosavaruus, event.

\mathcal{P} A probability space that consists of a otosavaruus Ω , a σ -algebra Σ of measurable subsets of Ω , and a todennäköisyysjakauma $\mathbb{P}(\cdot)$.
See also: otosavaruus, measurable, todennäköisyysjakauma.

Machine Learning

	An index $r = 1, 2, \dots$ that enumerates tietopisteet.
r	See also: tietopiste.
	The number of tietopisteet in (i.e., the size of) a tietoaineisto.
m	See also: tietopiste, tietoaineisto.
	A tietoaineisto $\mathcal{D} = \{\mathbf{z}^{(1)}, \dots, \mathbf{z}^{(m)}\}$ is a list of individual tietopisteet
\mathcal{D}	$\mathbf{z}^{(r)}$, for $r = 1, \dots, m$.
	See also: tietoaineisto, tietopiste.
	The number of piirteet that characterize a tietopiste.
d	See also: piirre, tietopiste.
	The j th piirre of a tietopiste. The first piirre is denoted by x_1 , the
x_j	second piirre x_2 , and so on.
	See also: tietopiste, piirre.
	The piirrevektori $\mathbf{x} = (x_1, \dots, x_d)^T$ of a tietopiste. The vektori's
\mathbf{x}	entries are the individual piirteet of a tietopiste.
	See also: piirrevektori, tietopiste, vektori, piirre.
	The piirreavaruus \mathcal{X} is the set of all possible values that the piirteet
\mathcal{X}	\mathbf{x} of a tietopiste can take on.
	See also: piirreavaruus, piirre, tietopiste.

Instead of the symbol \mathbf{x} , we sometimes use \mathbf{z} as another symbol to denote a vektori whose entries are the individual piirteet of a tietopiste. We need two different symbols to distinguish between raw and learned piirteet [8, Ch. 9].

See also: vektori, piirre, tietopiste.

$\mathbf{x}^{(r)}$ The piirrevektori of the r th tietopiste within a tietoaineisto.
See also: piirrevektori, tietopiste, tietoaineisto.

$x_j^{(r)}$ The j th piirre of the r th tietopiste within a tietoaineisto.
See also: piirre, tietopiste, tietoaineisto.

\mathcal{B} A mini-erä (or subset) of randomly chosen tietopisteet.
See also: erä, tietopiste.

B The size of (i.e., the number of tietopisteet in) a mini-erä.
See also: tietopiste, erä.

y The nimiö (or quantity of interest) of a tietopiste.
See also: nimiö, tietopiste.

$y^{(r)}$ The nimiö of the r th tietopiste.
See also: nimiö, tietopiste.

$(\mathbf{x}^{(r)}, y^{(r)})$ The piirteet and nimiö of the r th tietopiste.
See also: piirre, nimiö, tietopiste.

The label space \mathcal{Y} of an koneoppiminen method consists of all potential nimiö values that a tietopiste can carry. The nominal label space might be larger than the set of different nimiö values arising in a given tietoaineisto (e.g., a opetusaineisto). Koneoppiminen problems (or methods) using a numeric label space, such as $\mathcal{Y} = \mathbb{R}$ or $\mathcal{Y} = \mathbb{R}^3$, are referred to as regressio problems (or methods). Koneoppiminen problems (or methods) that use a discrete label space, such as $\mathcal{Y} = \{0, 1\}$ or $\mathcal{Y} = \{\text{cat}, \text{dog}, \text{mouse}\}$, are referred to as luokittelu problems (or methods).

See also: label space, koneoppiminen, nimiö, tietopiste, tietoaineisto, opetusaineisto, regressio, luokittelu.

η Oppimisnopeus (or step size) used by gradient-based methods.
See also: oppimisnopeus, step size, gradient-based method.

$h(\cdot)$ A hypoteesi kuvaus that maps the piirteet of a tietopiste to a ennuste $\hat{y} = h(\mathbf{x})$ for its nimiö y .

See also: hypoteesi, kuvaus, piirre, tietopiste, ennuste, nimiö.

$\mathcal{Y}^{\mathcal{X}}$ Given two sets \mathcal{X} and \mathcal{Y} , we denote by $\mathcal{Y}^{\mathcal{X}}$ the set of all possible hypoteesi kuvauskset $h : \mathcal{X} \rightarrow \mathcal{Y}$.

See also: hypoteesi, kuvaus.

\mathcal{H} A hypothesis space or malli used by an koneoppiminen method. The hypothesis space consists of different hypoteesi kuvauskset $h : \mathcal{X} \rightarrow \mathcal{Y}$, between which the koneoppiminen method must choose.

See also: hypothesis space, malli, koneoppiminen, hypoteesi, kuvaus.

$d_{\text{eff}}(\mathcal{H})$

The effective dimension of a hypothesis space \mathcal{H} .

See also: effective dimension, hypothesis space.

B^2

The squared harha of a learned hypoteesi \hat{h} , or its parameters.

Note that \hat{h} becomes an satunnaismuuttuja if it is learned from tietopisteet being satunnaismuuttujat themselves.

See also: harha, hypoteesi, parameter, satunnaismuuttuja, tietopiste.

V

The varianssi of a learned hypoteesi \hat{h} , or its parameters. Note that \hat{h} becomes an satunnaismuuttuja if it is learned from tietopisteet being satunnaismuuttujat themselves.

See also: varianssi, hypoteesi, parameter, satunnaismuuttuja, tietopiste.

$L((\mathbf{x}, y), h)$

The häviö incurred by predicting the nimiö y of a tietopiste using the ennuste $\hat{y} = h(\mathbf{x})$. The ennuste \hat{y} is obtained by evaluating the hypoteesi $h \in \mathcal{H}$ for the piirrevektori \mathbf{x} of the tietopiste.

See also: häviö, nimiö, tietopiste, ennuste, hypoteesi, piirrevektori.

E_v

The validointivirhe of a hypoteesi h , which is its average häviö incurred over a validointiaineisto.

See also: validointivirhe, hypoteesi, häviö, validointiaineisto.

$\widehat{L}(h|\mathcal{D})$

The empiirinen riski, or average häviö, incurred by the hypoteesi h on a tietoaineisto \mathcal{D} .

See also: empiirinen riski, häviö, hypoteesi, tietoaineisto.

E_t The opetusvirhe of a hypoteesi h , which is its average häviö incurred over a opetusaineisto.

See also: opetusvirhe, hypoteesi, häviö, opetusaineisto.

t A discrete-time index $t = 0, 1, \dots$ used to enumerate sequential events (or time instants).

See also: event.

t An index that enumerates oppimistehtävät within a monitehtävä-oppiminen problem.

See also: oppimistehtävä, monitehtäväoppiminen.

α A regularisointi parameter that controls the amount of regularisointi.

See also: regularisointi, parameter.

$\lambda_j(\mathbf{Q})$ The j th eigenvalue (sorted in either ascending or descending order) of a positive semi-definite (psd) matriisi \mathbf{Q} . We also use the shorthand λ_j if the corresponding matriisi is clear from context.

See also: eigenvalue, psd, matriisi.

$\sigma(\cdot)$ The aktivoointifunktio used by an artificial neuron within an neuroverkko.

See also: aktivoointifunktio, neuroverkko.

$\mathcal{R}_{\hat{y}}$ A päätösalue within a piirreavaruuus.

See also: päätösalue, piirreavaruuus.

w

A parameter vektori $\mathbf{w} = (w_1, \dots, w_d)^T$ of a malli, e.g., the weights of a lineaarinen malli or an neuroverkko.

See also: parameter, vektori, malli, weights, lineaarinen malli, neuroverkko.

$h^{(\mathbf{w})}(\cdot)$

A hypoteesi kuvaus that involves tunable model parameters w_1, \dots, w_d stacked into the vektori $\mathbf{w} = (w_1, \dots, w_d)^T$.

See also: hypoteesi, kuvaus, model parameter, vektori.

$\phi(\cdot)$

A piirrekartta $\phi : \mathcal{X} \rightarrow \mathcal{X}' : \mathbf{x} \mapsto \phi(\mathbf{x})$ that transforms the piirrevektori \mathbf{x} of a tietopiste into a new piirrevektori $\mathbf{x}' = \phi(\mathbf{x}) \in \mathcal{X}'$.

See also: piirrekartta.

$K(\cdot, \cdot)$

Given some piirreavaruuus \mathcal{X} , a ydinfunktio is a kuvaus $K : \mathcal{X} \times \mathcal{X} \rightarrow \mathbb{C}$ that is psd.

See also: piirreavaruuus, ydinfunktio, kuvaus, psd.

$\text{VCdim}(\mathcal{H})$

The Vapnik–Chervonenkis dimension (VC dimension) of the hypothesis space \mathcal{H} .

See also: VC dimension, hypothesis space.

Federated Learning

An undirected graph whose nodes $i \in \mathcal{V}$ represent devicet within a federated learning network (FL network). The undirected weighted edges \mathcal{E} represent connectivity between devices and $\mathcal{G} = (\mathcal{V}, \mathcal{E})$ statistical similarities between their tietoaineistot and oppimistehtävät.

See also: undirected graph, device, FL network, tietoaineisto, oppimistehtävä.

A node that represents some device within an FL network.
 $i \in \mathcal{V}$ The device can access a local dataset and train a local model.
 See also: device, FL network, local dataset, local model.

$\mathcal{G}^{(\mathcal{C})}$ The induced subgraph of \mathcal{G} using the nodes in $\mathcal{C} \subseteq \mathcal{V}$.

$\mathbf{L}^{(\mathcal{G})}$ The Laplacian matrix of a verkko \mathcal{G} .
 See also: Laplacian matrix, verkko.

$\mathbf{L}^{(\mathcal{C})}$ The Laplacian matrix of the induced verkko $\mathcal{G}^{(\mathcal{C})}$.
 See also: Laplacian matrix, verkko.

$\mathcal{N}^{(i)}$ The naapurusto of the node i in a verkko \mathcal{G} .
 See also: naapurusto, verkko.

$d^{(i)}$ The weighted solmun aste $d^{(i)} := \sum_{i' \in \mathcal{N}^{(i)}} A_{i,i'}$ of node i .
 See also: solmun aste.

$d_{\max}^{(\mathcal{G})}$ The maksimi weighted solmun aste of a verkko \mathcal{G} .
 See also: maksimi, solmun aste, verkko.

$\mathcal{D}^{(i)}$ The local dataset $\mathcal{D}^{(i)}$ carried by node $i \in \mathcal{V}$ of an FL network.

See also: local dataset, FL network.

m_i The number of tietopisteet (i.e., sample size) contained in the local dataset $\mathcal{D}^{(i)}$ at node $i \in \mathcal{V}$.

See also: tietopiste, sample size, local dataset.

$\mathbf{x}^{(i,r)}$ The piirteet of the r th tietopiste in the local dataset $\mathcal{D}^{(i)}$.

See also: piirre, tietopiste, local dataset.

$y^{(i,r)}$ The nimiö of the r th tietopiste in the local dataset $\mathcal{D}^{(i)}$.

See also: nimiö, tietopiste, local dataset.

$\mathbf{w}^{(i)}$ The local model parameters of device i within an FL network.

See also: model parameter, device, FL network.

$L_i(\mathbf{w})$ The local häviöfunktio used by device i to measure the usefulness of some choice \mathbf{w} for the local model parameters.

See also: häviöfunktio, device, model parameter.

$L^{(d)}(\mathbf{x}, h(\mathbf{x}), h'(\mathbf{x}))$ The häviö incurred by a hypoteesi h' on a tietopiste with piirteet \mathbf{x} and nimiö $h(\mathbf{x})$ that is obtained from another hypoteesi.

See also: häviö, hypoteesi, tietopiste, piirre, nimiö.

stack $\{\mathbf{w}^{(i)}\}_{i=1}^n$

The vektori $\left(\left(\mathbf{w}^{(1)}\right)^T, \dots, \left(\mathbf{w}^{(n)}\right)^T\right)^T \in \mathbb{R}^{dn}$ that is obtained by vertically pinoaminen the local model parameters $\mathbf{w}^{(i)} \in \mathbb{R}^d$, for $i = 1, \dots, n$.

See also: vektori, pinoaminen, model parameter.

Mathematical Tools

algebraic connectivity The algebraic connectivity of an undirected graph is the second-smallest eigenvalue λ_2 of its Laplacian matrix. An undirected graph is kytketty verkko if and only if $\lambda_2 > 0$ (see Fig. 1) [9], [10].

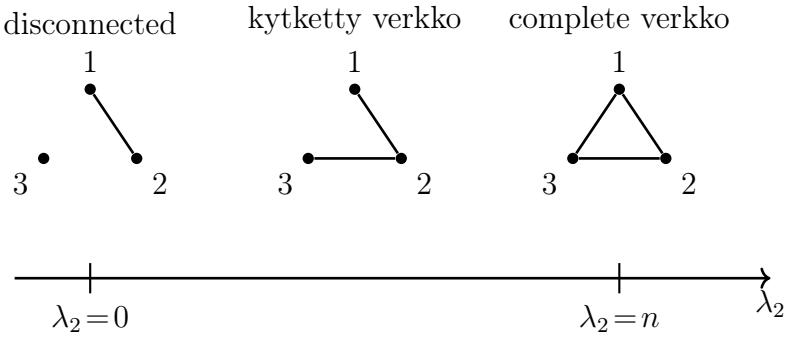


Fig. 1. Three examples of undirected graphs.

See also: undirected graph, eigenvalue, Laplacian matrix, kytketty verkko.

Banach's fixed-point theorem Banach's fixed-point theorem (also referred to as the contraction principle [2, Th. 9.23], [11]) states that every contractive operator \mathcal{F} on a complete metric space \mathcal{W} has a unique fixed point. Formally, let $(\mathcal{W}, d(\cdot, \cdot))$ be a non-empty complete metric space and let $\mathcal{F} : \mathcal{W} \rightarrow \mathcal{W}$ satisfy

$$d(\mathcal{F}\mathbf{w}, \mathcal{F}\mathbf{w}') \leq \kappa \cdot d(\mathbf{w}, \mathbf{w}') \quad \forall \mathbf{w}, \mathbf{w}' \in \mathcal{W}$$

for some constant $\kappa \in [0, 1)$. Then, \mathcal{F} has a unique fixed point, i.e., there exists a unique $\mathbf{w}^* \in \mathcal{W}$ with $\mathcal{F}\mathbf{w}^* = \mathbf{w}^*$. Moreover, for any initial $\mathbf{w}^{(0)} \in \mathcal{W}$, the fixed-point iteration $\mathbf{w}^{(t)} = \mathcal{F}\mathbf{w}^{(t-1)}$, for $t = 1, 2, \dots$, converges to \mathbf{w}^* at a rate governed by κ . In particular,

$$d(\mathbf{w}^{(t)}, \mathbf{w}^*) \leq \kappa^t \cdot d(\mathbf{w}^{(0)}, \mathbf{w}^*), \text{ for } t = 1, 2, \dots$$

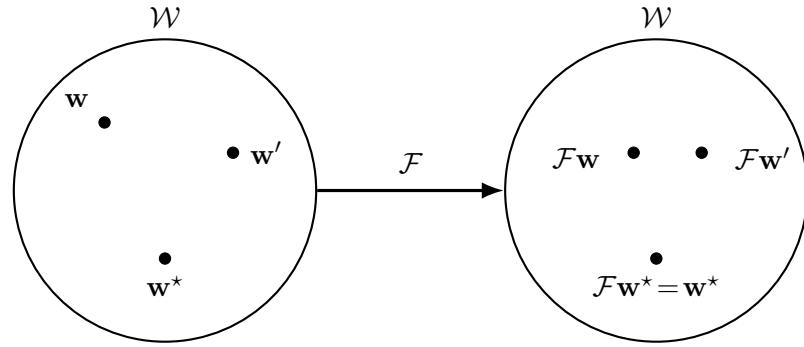


Fig. 2. A contractive operator $\mathcal{F} : \mathcal{W} \rightarrow \mathcal{W}$ has a unique fixed point \mathbf{w}^* with $\mathcal{F}\mathbf{w}^* = \mathbf{w}^*$.

See also: contractive operator, fixed-point iteration.

basis A basis of a vektoriavaruus \mathcal{V} is a set of linearly independent vektorit $\{\mathbf{a}^{(1)}, \dots, \mathbf{a}^{(d)}\}$ such that any vektori $\mathbf{a} \in \mathcal{A}$ can be expressed as a linear combination of the basis vektorit, i.e.,

$$\mathbf{a} = \sum_{j=1}^d \alpha_j \mathbf{a}^{(j)} \quad \text{for some } \alpha_1, \dots, \alpha_d \in \mathbb{R}.$$

See also: vektoriavaruus, linearly independent, vektori.

Bregman divergence The Bregman divergence induced by a convex, differentiable function $\phi(\cdot)$ is defined as

$$D_\phi(\mathbf{w}, \mathbf{w}') := \phi(\mathbf{w}) - \phi(\mathbf{w}') - \langle \nabla \phi(\mathbf{w}'), \mathbf{w} - \mathbf{w}' \rangle,$$

for \mathbf{w}, \mathbf{w}' in the domain \mathcal{W} of ϕ . It measures the deviation of $\phi(\mathbf{w})$ from its first-order Taylor approximation around \mathbf{w}' and is in general neither symmetric nor a metric. For twice differentiable ϕ , the divergence

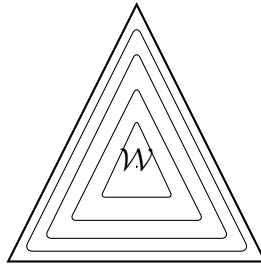


Fig. 3. Contour lines of a convex function $\phi(\cdot)$ defined on a convex set \mathcal{W} . The density of the contour lines can be used to steer the step size used in a gradient task: If the current model parameter lies in a region with dense contour lines, a smaller step size is preferable

$D_\phi(\cdot, \cdot)$ behaves locally like a quadratic form

$$D_\phi(\mathbf{w}, \mathbf{w}') \approx \frac{1}{2} (\mathbf{w} - \mathbf{w}')^T \nabla^2 \phi(\mathbf{w}') (\mathbf{w} - \mathbf{w}').$$

which can be interpreted as a squared norm of the displacement $\mathbf{w} - \mathbf{w}'$ induced by $\nabla^2 \phi(\mathbf{w}')$.

See also: gradient task, proximal operator.

Cauchy sequence A Cauchy sequence is a sequence $(\mathbf{x}^{(r)})_{r \in \mathbb{N}}$ in a metric space $(\mathcal{X}, d(\cdot, \cdot))$ such that the elements $\mathbf{x}^{(r)} \in \mathcal{X}$ become arbitrarily close to each other eventually. In other words [2, Def. 3.8],

$$\forall \epsilon > 0, \exists N \in \mathbb{N} \text{ such that } \forall r, r' \geq N, d(\mathbf{x}^{(r)}, \mathbf{x}^{(r')}) < \epsilon.$$

Fig. 4 shows a Cauchy sequence in the metric space $(\mathbb{Q}, |\cdot|)$ of rational numbers.

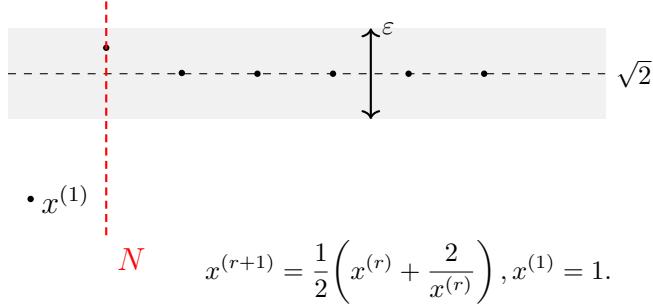


Fig. 4. A Cauchy sequence $(x^{(r)})_{r \in \mathbb{N}}$ in the metric space $(\mathbb{Q}, |\cdot|)$. This sequence is generated by a fixed-point iteration used to approximate $\sqrt{2}$. For all $r \geq N$, the sequence elements lie within a band of width ε . Note that the sequence does not converge in \mathbb{Q} , since $\sqrt{2} \notin \mathbb{Q}$ [2, Example 1.1].

See also: sequence, metric space.

Chebyshev's inequality Consider a real-valued satunnaismuuttuja x for which the second moment $\mathbb{E}\{x^2\}$ exists (and is finite). The existence of the second moment implies the existence of a finite odotusarvo $\mu := \mathbb{E}\{x\}$ and a finite varianssi $\sigma^2 := \mathbb{E}\{(x - \mu)^2\}$ [12, Proposition 6.12]. Chebyshev's inequality refers to the following upper bound on the

todennäköisyyss that x deviates from μ by more than a given threshold η [13, Ch. 4]. In particular,

$$\mathbb{P}(|x - \mu| \geq \eta) \leq \frac{\sigma^2}{\eta^2} \quad \text{for some } \eta > 0.$$

This upper bound can be obtained by applying Markov's inequality to the new satunnaismuuttuja $\tilde{x} := (x - \mu)^2$.

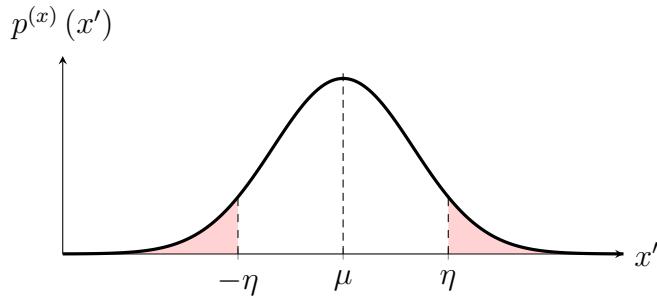


Fig. 5. Chebyshev's inequality provides an upper bound on the tail todennäköisyyss $\mathbb{P}(|x - \mu| \geq \eta)$ (i.e., shaded area) of a real-valued satunnaismuuttuja x with a finite second moment.

See also: odotusarvo, Markov's inequality, concentration inequality.

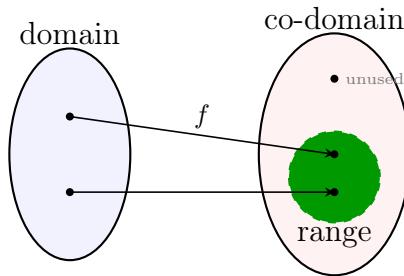
Chernoff bound The Chernoff bound is a concentration inequality derived as a direct application of Markov's inequality [14, Ch. 2]. Let x be a real-valued satunnaismuuttuja such that its MGF $M_x(t) = \mathbb{E}\{\exp(tx)\}$ exists for some $t > 0$. Applying Markov's inequality to the nonnegative satunnaismuuttuja $\exp(tx)$ yields, for any $\eta \in \mathbb{R}$,

$$\mathbb{P}(x \geq \eta) = \mathbb{P}(\exp(tx) \geq \exp(t\eta)) \leq \exp(-t\eta) \mathbb{E}\{\exp(tx)\}.$$

Note that this is actually an entire family of upper bounds, parameterized by all valid choices for $t > 0$ (i.e., $M_x(t)$ must exist).

See also: Markov's inequality, Chebyshev's inequality, Hoeffding's inequality, concentration inequality.

co-domain The co-domain of a function $f : \mathcal{U} \rightarrow \mathcal{V}$ is the set \mathcal{V} into which f maps elements of its domain \mathcal{U} .



See also: domain, function, mapping.

column space The column space of a matrix $\mathbf{A} \in \mathbb{R}^{m \times d}$, denoted by $\text{span}(\mathbf{A})$, is the set of all linear combinations of the columns of \mathbf{A} . In other words,

$$\text{span}(\mathbf{A}) = \{\mathbf{A}\mathbf{w} : \mathbf{w} \in \mathbb{R}^d\}.$$

The column space $\text{span}(\mathbf{A})$ of the matrix \mathbf{A} is a subspace of the Euclidean space \mathbb{R}^m .

See also: matrix, vector space.

concentration inequality An upper bound on the probability that a random variable deviates more than a prescribed amount from its expected value [15].

See also: probability, random variable, expected value.

condition number The condition number $\kappa(\mathbf{Q}) \geq 1$ of a positive definite matriisi $\mathbf{Q} \in \mathbb{R}^{d \times d}$ is the ratio α/β , where α and β denote the largest and smallest eigenvalues of \mathbf{Q} , respectively. The condition number is useful for the analysis of koneoppiminen methods. The computational complexity of gradient-based methods for lineaarinen regressio depends crucially on the condition number of the matriisi $\mathbf{Q} = \mathbf{X}\mathbf{X}^T$, where \mathbf{X} is the feature matrix of the opetusaineisto. These methods converge faster when the condition number $\kappa(\mathbf{Q})$ is close to 1.

See also: matriisi, eigenvalue, gradient-based method.

conditional expectation Consider a numeric satunnaismuuttuja $\mathbf{x} \in \mathbb{R}^d$ defined on a probability space $\mathcal{P} = (\Omega, \mathcal{F}, \mathbb{P})$. Let $\Sigma' \subseteq \Sigma$ be a (sub-) σ -algebra that represents partial information about the outcome of a satunnaiskoe. The conditional odotusarvo of \mathbf{x} given (or conditioned on) Σ' , denoted $\mathbb{E}\{\mathbf{x} | \Sigma'\}$, is a numeric satunnaismuuttuja that [6], [16]: 1) is measurable with respect to Σ' ; and 2) satisfies

$$\int_{\mathcal{A}} \mathbb{E}\{\mathbf{x} | \Sigma'\} d\mathbb{P} = \int_{\mathcal{A}} \mathbf{x} d\mathbb{P} \quad \text{for any } \mathcal{A} \in \Sigma'.$$

Intuitively, $\mathbb{E}\{\mathbf{x} | \mathcal{F}'\}$ summarizes the average value of \mathbf{x} using only information contained in the (typically smaller) σ -algebra Σ' [6], [17], [18].

See also: probability space, σ -algebra, odotusarvo.

conditional probability distribution Consider a satunnaisprosessi consisting of two satunnaismuuttujat \mathbf{x} and y with todennäköisyysjakauma $\mathbb{P}^{(\mathbf{x},y)}$. The conditional todennäköisyysjakauma of y given (or conditioned on) \mathbf{x} is denoted by $\mathbb{P}^{(y|\mathbf{x})}$. It is defined via the conditional expectations

of the indicator funktiot of measurable sets in the σ -algebra generated by the satunnaismuuttuja y [6], [19].

See also: todennäköisyysjakauma, conditional expectation.

conditional probability mass function (conditional pmf) Consider two discrete RVs y and x defined on the same probability space $(\Omega, \mathcal{F}, \mathbb{P}(\cdot))$. The conditional pmf of y given (or conditioned on) x is denoted $p^{(y|x)}(\cdot | \cdot)$ and is defined by

$$p^{(y|x)}(y' | x') := \mathbb{P}(y = y' | x = x'),$$

for all realizations y', x' with $\mathbb{P}(x = x') > 0$. Equivalently, the conditional pmf can be expressed using conditional expectation as

$$p^{(y|x)}(y' | x') = \mathbb{E}\{\mathbb{I}_{y=y'} | \Sigma(x)\}(x'),$$

where $\Sigma(x)$ denotes the σ -algebra generated by the satunnaismuuttuja x .

See also: conditional expectation, pmf, probability space.

conjugate transpose The conjugate transpose of a matriisi is obtained by transposing the matriisi and taking the complex conjugate of each entry. For a matrix $\mathbf{A} \in \mathbb{C}^{m \times d}$, its conjugate transpose is denoted by $\mathbf{A}^H \in \mathbb{C}^{d \times m}$ and is defined entrywise by

$$(\mathbf{A}^H)_{j,r} = \overline{(\mathbf{A})_{r,j}},$$

where $\overline{(\cdot)}$ denotes complex conjugation.

contractive operator An operator $\mathcal{F} : \mathbb{R}^d \rightarrow \mathbb{R}^d$ is a contraction (or contractive) if, for some $\kappa \in [0, 1)$, [20], [21]

$$\|\mathcal{F}\mathbf{w} - \mathcal{F}\mathbf{w}'\|_2 \leq \kappa \|\mathbf{w} - \mathbf{w}'\|_2 \text{ holds for any } \mathbf{w}, \mathbf{w}' \in \mathbb{R}^d.$$

The notion of a contractive operator generalizes naturally from \mathbb{R}^d to arbitrary metric spaces [20].

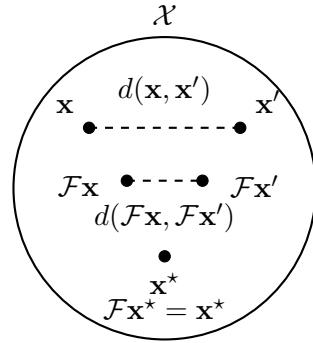


Fig. 6. A contractive operator $\mathcal{F} : \mathcal{X} \rightarrow \mathcal{X}$ has a unique fixed point \mathbf{x}^* with $\mathcal{F}\mathbf{x}^* = \mathbf{x}^*$. For any two points \mathbf{x}, \mathbf{x}' in the same space, the distance between their images $\mathcal{F}\mathbf{x}$ and $\mathcal{F}\mathbf{x}'$ is strictly smaller.

Intuitively, a contractive operator brings any two points from its domain closer together by at least a factor of κ .

See also: operator, metric space.

convergence Consider a sequence $(a_r)_{r \in \mathbb{N}}$ with numeric values $a_r \in \mathbb{R}$. This sequence is said to converge to a value a^* if the values a_r become arbitrarily close to a^* for sufficiently large indices r . Mathematically speaking, the sequence converges to a^* if [1], [2]

$$\forall \epsilon > 0, \exists N \in \mathbb{N} : r > N \Rightarrow |a_r - a^*| < \epsilon.$$

We denote the convergence of a sequence to a^* by

$$\lim_{r \rightarrow \infty} a_r = a^*.$$

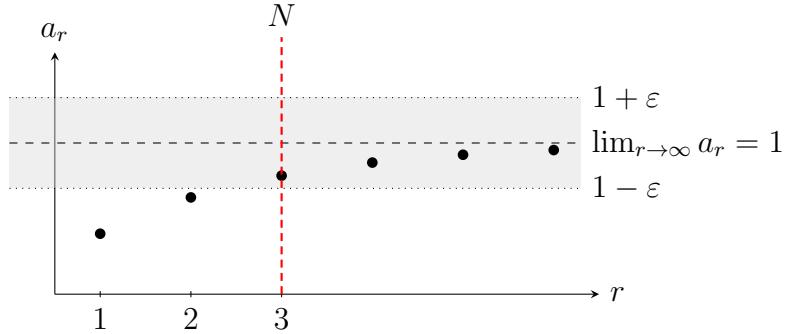


Fig. 7. A real-valued sequence $(a_r)_{r \in \mathbb{N}}$ converging to the limit $a^* = 1$.

The concept of convergence of a real-valued sequence (where $\mathcal{A} = \mathbb{R}$) extends naturally to a sequence in an arbitrary metric space \mathcal{A} . Indeed, we just need to replace the absolute difference $|a_r - a^*|$ by the metric $d(a_r, a^*)$. Note that a sequence can only converge if it is a Cauchy sequence [2]. However, not every Cauchy sequence is converging unless the underlying metric space is complete.

See also: sequence, metric space, Cauchy sequence.

convex A subset $\mathcal{C} \subseteq \mathbb{R}^d$ of the euklidinen avaruuus \mathbb{R}^d is referred to as convex if it contains the line segment between any two points $\mathbf{x}, \mathbf{y} \in \mathcal{C}$ in that set, i.e.,

$$\alpha\mathbf{x} + (1 - \alpha)\mathbf{y} \in \mathcal{C}, \text{ for any } \alpha \in [0, 1].$$

Similarly, a funktion $f: \mathbb{R}^d \rightarrow \mathbb{R}$ is convex if its epigrafi $\{(\mathbf{w}^T, t)^T \in \mathbb{R}^{d+1} : f(\mathbf{w}) \leq t\}$

$t \geq f(\mathbf{w})\}$ is a convex set [22]. We illustrate one example of a convex set and a convex function in Fig. 8.



Fig. 8. (a) A convex set $\mathcal{C} \subseteq \mathbb{R}^d$. (b) A convex function $f: \mathbb{R}^d \rightarrow \mathbb{R}$.

See also: euklidinen avaruuus, funktio, epigrafi.

convex optimization problem See konveksi optimointi.

countable A set is called countable if its elements can be put into a one-to-one correspondence with the natural numbers $\mathbb{N} = \{1, 2, 3, \dots\}$ or with a finite subset of \mathbb{N} [23]. Equivalently, a set \mathcal{A} is countable if there exists an injective function $f: \mathcal{A} \rightarrow \mathbb{N}$.

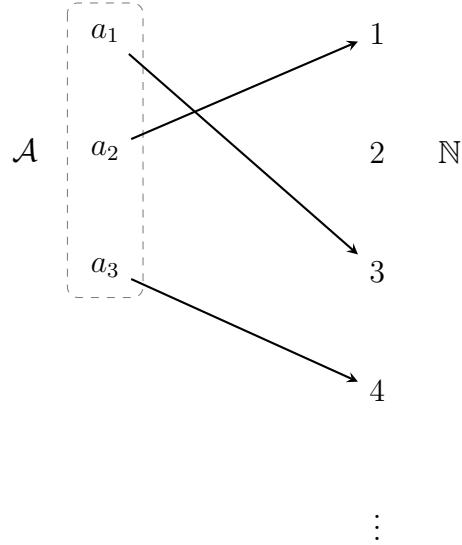


Fig. 9. An injective funktion that maps the elements of a finite set \mathcal{A} to the natural numbers \mathbb{N} , which implies that \mathcal{A} is countable.

Typical examples include the set of integers \mathbb{Z} and rational numbers \mathbb{Q} . In contrast, the set of real numbers \mathbb{R} is not countable, meaning no such one-to-one correspondence with \mathbb{N} exists.

See also: injective, funktion.

Courant–Fischer–Weyl min–max characterization (CFW min–max characterization)

Consider a psd matriisi $\mathbf{Q} \in \mathbb{R}^{d \times d}$ with eigenvalue decomposition (EVD) (or spectral decomposition), i.e.,

$$\mathbf{Q} = \sum_{j=1}^d \lambda_j \mathbf{u}^{(j)} (\mathbf{u}^{(j)})^T.$$

Here, we use the ordered (in ascending order) eigenvalues

$$\lambda_1 \leq \dots \leq \lambda_n.$$

The CFW min–max characterization [3, Th. 8.1.2] represents the eigenvalues of \mathbf{Q} as the solutions to certain optimointitehtävät.

See also: psd, matriisi, EVD, eigenvalue, optimointitehtävä.

cumulative distribution function (cdf) The cdf $F^{(x)}(\eta)$ of a real-valued satunnaismuuttuja x is [24], [25]

$$F^{(x)}(\eta) := \mathbb{P}(x \leq \eta).$$

See also: satunnaismuuttuja, pdf, todennäköisyysjakauma.

derivative See partial derivative.

determinantti The determinant $\det(\mathbf{A})$ of a square matriisi $\mathbf{A} = (\mathbf{a}^{(1)}, \dots, \mathbf{a}^{(d)}) \in \mathbb{R}^{d \times d}$ is a funktio of its columns $\mathbf{a}^{(1)}, \dots, \mathbf{a}^{(d)} \in \mathbb{R}^d$, i.e., it satisfies the following properties [26]:

- Normalized:

$$\det(\mathbf{I}) = 1$$

- Multilinear:

$$\begin{aligned} \det(\mathbf{a}^{(1)}, \dots, \alpha\mathbf{u} + \beta\mathbf{v}, \dots, \mathbf{a}^{(d)}) &= \alpha \det(\mathbf{a}^{(1)}, \dots, \mathbf{u}, \dots, \mathbf{a}^{(d)}) \\ &\quad + \beta \det(\mathbf{a}^{(1)}, \dots, \mathbf{v}, \dots, \mathbf{a}^{(d)}) \end{aligned}$$

- Antisymmetric:

$$\det(\dots, \mathbf{a}^{(j)}, \dots, \mathbf{a}^{(j')}, \dots) = -\det(\dots, \mathbf{a}^{(j')}, \dots, \mathbf{a}^{(j)}, \dots).$$

We can interpret a matrix \mathbf{A} as a linear transformation on \mathbb{R}^d . The determinant $\det(\mathbf{A})$ characterizes how volumes in \mathbb{R}^d (and their orientation) are altered by this transformation (see Fig. 10) [3], [27]. In particular, $\det(\mathbf{A}) > 0$ preserves orientation, $\det(\mathbf{A}) < 0$ reverses orientation, and $\det(\mathbf{A}) = 0$ collapses volume entirely, indicating that \mathbf{A} is non-invertible. The determinant also satisfies $\det(\mathbf{AB}) = \det(\mathbf{A}) \cdot \det(\mathbf{B})$, and if \mathbf{A} is diagonalizable with eigenvalues $\lambda_1, \dots, \lambda_d$, then $\det(\mathbf{A}) = \prod_{j=1}^d \lambda_j$ [28]. For the special cases $d = 2$ (i.e., two-dimensional or 2-D) and $d = 3$ (i.e., three-dimensional or 3-D), the determinant can be interpreted as an oriented area or volume spanned by the column vectors of \mathbf{A} .

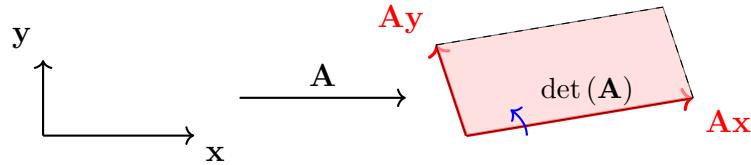


Fig. 10. We can interpret a square matrix \mathbf{A} as a linear transformation of \mathbb{R}^d into itself. The determinant $\det(\mathbf{A})$ characterizes how this transformation alters an oriented volume.

See also: eigenvalue, käänne-matriisi.

diagonalizable A square matrix $\mathbf{A} \in \mathbb{C}^{d \times d}$ is called diagonalizable if it is similar to a diagonal matrix [28], [29]. Formally, \mathbf{A} is diagonalizable if there exists an invertible matrix $\mathbf{P} \in \mathbb{C}^{d \times d}$ such that

$$\mathbf{A} = \mathbf{P}\mathbf{D}\mathbf{P}^{-1}$$

where $\mathbf{D} \in \mathbb{C}^{d \times d}$ is a diagonal matriisi whose main diagonal entries are the eigenvalues of \mathbf{A} . A matriisi $\mathbf{A} \in \mathbb{R}^{d \times d}$ is diagonalizable if and only if it has d linearly independent eigenvectort [28].

See also: matriisi, eigenvalue, EVD.

differentiable A real-valued funktilo $f : \mathbb{R}^d \rightarrow \mathbb{R}$ is differentiable if it can be approximated locally at any point by a linear funktilo. The local linear approximation at the point \mathbf{x} is determined by the gradientti $\nabla f(\mathbf{x})$ [2].
See also: funktilo, gradientti.

differential entropy For an satunnaismuuttuja $\mathbf{x} \in \mathbb{R}^d$ with a pdf $p^{(x)}(\cdot)$, the differential entropia is defined as [30]

$$h(\mathbf{x}) := - \int_{\mathbf{x}' \in \mathbb{R}^d} \log p(\mathbf{x}') \, dp^{(\mathbf{x})}(\mathbf{x}').$$

Differential entropia can be negative and lacks some properties of entropia for discrete-valued satunnaismuuttujat, such as invariance under a change of variables [30]. Among all satunnaismuuttujat with a given keskiarvo $\boldsymbol{\mu}$ and kovarianssimatriisi \mathbf{C} , $h(\mathbf{x})$ is maximized by $\mathbf{x} \sim \mathcal{N}(\boldsymbol{\mu}, \mathbf{C})$.

See also: epävarmuus, todennäköisyysmalli.

dimension The dimension $\dim \mathcal{A}$ of a vektoriavaruus \mathcal{A} is the cardinality of any basis of \mathcal{A} [31]. Strictly speaking, this definition applies only to finite-dimensional vektoriavaruudet, i.e., those that possess a finite basis.

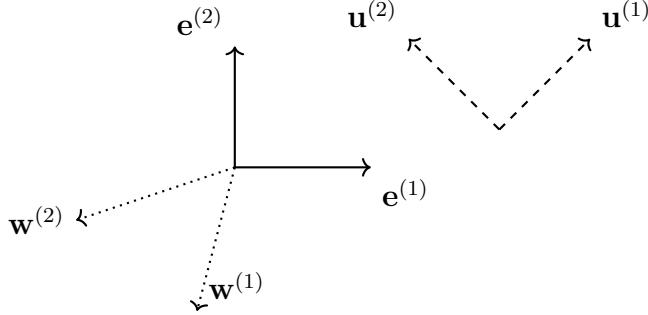


Fig. 11. Three bases, $\{\mathbf{e}^{(1)}, \mathbf{e}^{(2)}\}$, $\{\mathbf{u}^{(1)}, \mathbf{u}^{(2)}\}$, $\{\mathbf{w}^{(1)}, \mathbf{w}^{(2)}\}$, for the vektoriavaruus \mathbb{R}^2 .

For such spaces, all bases have the same cardinality, which is the dimension of the space [29, Ch. 2].

See also: vektoriavaruus, basis.

directed acyclic graph (DAG) A DAG is a directed graph which contains no directed cycles. Formally, a DAG $\mathcal{G} = (\mathcal{V}, \mathcal{E})$ satisfies that, for any sequence of distinct nodes (i_1, \dots, i_k) , the presence of directed edges $(i_1, i_2), (i_2, i_3), \dots, (i_{k-1}, i_k)$ implies that $(i_k, i_1) \notin \mathcal{E}$.



Fig. 12. (a) A DAG defined on three nodes $\mathcal{V} = \{1, 2, 3\}$. (b) Another directed graph on the same nodes that is not a DAG, since it contains a directed cycle.

The absence of directed cycles allows for a topological ordering of nodes such that all edges point from earlier to later nodes in this order. Several

koneoppiminen mallit, such as neuroverkot or päätöspuut, are naturally represented as DAGs.

See also: directed graph, neuroverkko, päätöspuu.

directed cycle A directed cycle in a directed graph $\mathcal{G} = (\mathcal{V}, \mathcal{E})$ is a sequence of distinct nodes (i_1, i_2, \dots, i_k) such that $(i_1, i_2), (i_2, i_3), \dots, (i_{k-1}, i_k), (i_k, i_1) \in \mathcal{E}$. In a directed cycle, following the direction of each edge eventually leads back to the starting node, creating a closed loop.

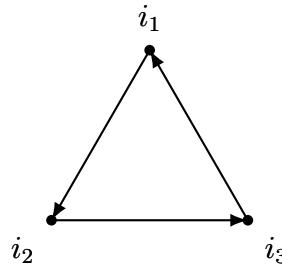


Fig. 13. A directed cycle consisting of three nodes kytetty verkko in a closed loop.

The presence of a directed cycle prevents a directed graph from being a directed acyclic graph (DAG).

See also: directed graph, DAG.

directed graph A directed verkko contains edges that have an orientation (or direction). Mathematically, a directed verkko $\mathcal{G} = (\mathcal{V}, \mathcal{E})$ consists of nodes \mathcal{V} and a set $\mathcal{E} \subseteq \mathcal{V} \times \mathcal{V}$ of directed edges.



Fig. 14. The edges of a directed verkko have an orientation (or direction). We can indicate the orientation by an arrow head.

We can represent a directed edge from node $i \in \mathcal{V}$ to node $i' \in \mathcal{V}$ by an ordered pair (i, i') . Directed verkot are widely used to model interconnected systems or networks, such as transportation systems, electronic circuits, and biological processes [32].

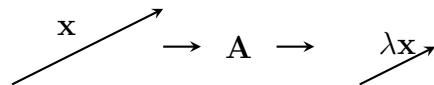
See also: verkko.

discrete random variable (discrete RV) A satunnaismuuttuja, i.e., a funktio that maps the outcomes of a satunnaiskoe to elements of a measurable space \mathcal{X} , is referred to as discrete if its value space \mathcal{X} countable [6].
See also: satunnaismuuttuja, todennäköisyys, todennäköisyysjakauma.

domain The domain of a funktio $f : \mathcal{U} \rightarrow \mathcal{V}$ is the set \mathcal{U} from which f takes its inputs.

See also: funktio, co-domain, kuvaus.

eigenvalue We refer to a number $\lambda \in \mathbb{R}$ as an eigenvalue of a square matriisi $\mathbf{A} \in \mathbb{R}^{d \times d}$ if there exists a nonzero vektori $\mathbf{x} \in \mathbb{R}^d \setminus \{\mathbf{0}\}$ such that $\mathbf{Ax} = \lambda\mathbf{x}$.



This vector is the eigenvector corresponding to the eigenvalue λ .

See also: matriisi, vektori.

eigenvalue decomposition (EVD) The EVD for a square matriisi $\mathbf{A} \in \mathbb{R}^{d \times d}$ is a factorization of the form

$$\mathbf{A} = \mathbf{V}\Lambda\mathbf{V}^{-1}.$$

The columns of the matriisi $\mathbf{V} = (\mathbf{v}^{(1)}, \dots, \mathbf{v}^{(d)})$ are the eigenvectors of the matriisi \mathbf{V} . The diagonal matriisi $\Lambda = \text{diag}\{\lambda_1, \dots, \lambda_d\}$ contains the eigenvalues λ_j corresponding to the eigenvectors $\mathbf{v}^{(j)}$. Note that the above decomposition exists only if the matriisi \mathbf{A} is diagonalizable.

See also: matriisi, eigenvector, eigenvalue, diagonalizable.

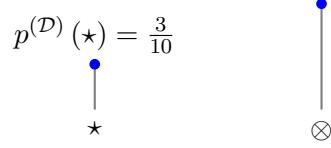
empirical distribution Consider a tietoaineisto $\mathcal{D} = \{\mathbf{x}^{(1)}, \dots, \mathbf{x}^{(m)}\}$ consisting of m distinct tietopisteet, each characterized by the piirrevektori $\mathbf{x}^{(r)} \in \mathcal{X}$ for $r = 1, \dots, m$. For a given σ -algebra Σ over the piirreavaruus \mathcal{X} , the empirical distribution of \mathcal{D} is the todennäköisyysjakauma $\mathbb{P}^{(\mathcal{D})}$ defined via

$$\mathbb{P}^{(\mathcal{D})}(\mathcal{A}) = (1/m) |\{r : \mathbf{x}^{(r)} \in \mathcal{A}\}|, \quad \text{for any event } \mathcal{A} \in \Sigma.$$

In other words, the empirical distribution assigns to any measurable set $\mathcal{A} \in \Sigma$ the fraction of tietopisteet in \mathcal{D} that fall into \mathcal{A} . If the piirreavaruus is ordered, the empirical distribution can also be characterized by its empirical cumulative distribution function (cdf)

$$F^{(\mathcal{D})}(\mathbf{x}) = (1/m) |\{r : \mathbf{x}^{(r)} \preceq \mathbf{x}\}|, \quad \text{for any } \mathbf{x} \in \mathcal{X}$$

where \preceq denotes the ordering relation on \mathcal{X} .



$$\mathcal{D} = (\star, \star, \star, \otimes, \otimes, \otimes, \otimes, \otimes, \otimes, \otimes)$$

Fig. 15. A tietoaineisto \mathcal{D} consisting of $m = 10$ tietopisteet, each characterized by a value from the finite piirreavaruus $\mathcal{X} = \{\star, \otimes\}$. The empirical pmf $p^{(\mathcal{D})}(\mathbf{x})$ assigns to each possible value $\mathbf{x} \in \mathcal{X}$ the fraction of tietopisteet in \mathcal{D} whose piirre takes on this value. Here, three out of ten tietopisteet take on the piirre value \star , resulting in $p^{(\mathcal{D})}(\star) = 3/10$.

If the piirreavaruus \mathcal{X} is finite, the empirical distribution of \mathcal{D} can also be characterized by the empirical pmf

$$p^{(\mathcal{D})}(\mathbf{x}) = (1/m)|\{r : \mathbf{x}^{(r)} = \mathbf{x}\}|, \quad \text{for any } \mathbf{x} \in \mathcal{X}.$$

See also: σ -algebra, todennäköisyysjakauma.

entropia Entropy quantifies the epävarmuus or unpredictability associated with an satunnaismuuttuja [30]. For a discrete RV x taking on values in a finite set $\mathcal{S} = \{x_1, \dots, x_k\}$ with a pmf $p^{(x)}(x_c) (= \mathbb{P}(x = x_c))$, the entropy is defined as [30]

$$H(x) := - \sum_{c=1}^k p^{(x)}(x_c) \log p^{(x)}(x_c).$$

For a given set of values \mathcal{S} , the entropy is maximized for a uniformly distributed satunnaismuuttuja, where $p^{(x)}(x_c) = 1/k$. The minimal

entropy, which is zero, is obtained when $p^{(x)}(x_c) = 1$ for some $x_c \in \mathcal{S}$. Differential entropy generalizes the concept of entropia from discrete RVs to jatkuva satunnaismuuttujat.

See also: epävarmuus, todennäköisyysmalli.

epigrafi The epigraph of a real-valued funktio $f : \mathbb{R}^d \rightarrow \mathbb{R} \cup \{+\infty\}$ is the set of points lying on or above its graph (see Fig. 16), i.e.,

$$\text{epi}(f) = \{(\mathbf{w}, t) \in \mathbb{R}^d \times \mathbb{R} \mid f(\mathbf{x}) \leq t\}.$$

A funktio is convex if and only if its epigraph is a convex set [22], [33].

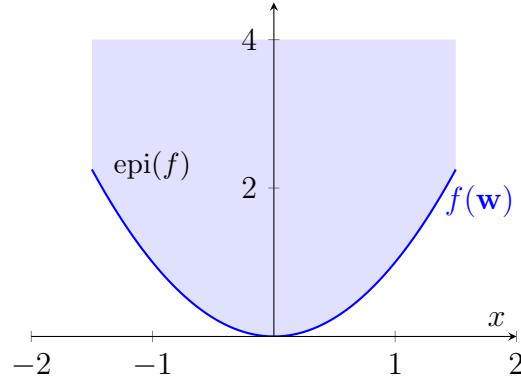


Fig. 16. Epigraph of the funktio $f(w) = w^2$ (i.e., the shaded area).

See also: funktio, convex.

Erdős–Rényi -verkko (ER-verkko) An ER verkko [34], [35] is a todennäköisyysmalli for verkot defined over a given node set $i = 1, \dots, n$. One way to define the ER verkko is via the collection of independent and identically distributed (i.i.d.) binary satunnaismuuttujat $b^{(\{i,i'\})} \in \{0, 1\}$,

for each pair of different nodes i, i' . A specific toteuma of an ER verkko contains an edge $\{i, i'\}$ if and only if $b^{\{i, i'\}} = 1$. The ER verkko is parameterized by the number n of nodes and the todennäköisyys $\mathbb{P}(b^{\{i, i'\}} = 1)$.

See also: verkko, todennäköisyyssmalli, i.i.d., satunnaismuuttuja, toteuma, todennäköisyys.

event Consider an satunnaismuuttuja \mathbf{x} , defined on some probability space, which takes values in a measurable space \mathcal{X} . An event $\mathcal{A} \subseteq \mathcal{X}$ is a subset of \mathcal{X} such that the todennäköisyys $\mathbb{P}(\mathbf{x} \in \mathcal{A})$ is well defined. In other words, the preimage $\mathbf{x}^{-1}(\mathcal{A})$ of an event belongs to the underlying σ -algebra, i.e., the preimage is a measurable subset of the otosavaruus [1], [6], [16]. Roughly speaking, an event represents a set of possible outcomes of some process. One example of such a process could also be the treatment of a health-care patient.

See also: satunnaismuuttuja, tietopiste, riippumaton ja samoin jakautunut -olettamus (i.i.d. olettamus), todennäköisyyssmalli.

firmly non-expansive operator An operator $\mathcal{F} : \mathcal{H} \rightarrow \mathcal{H}$ defined on a Hilbert space \mathcal{H} is called firmly non-expansive if it satisfies

$$\|\mathcal{F}\mathbf{w} - \mathcal{F}\mathbf{w}'\|_2^2 \leq \langle \mathbf{w} - \mathbf{w}', \mathcal{F}\mathbf{w} - \mathcal{F}\mathbf{w}' \rangle \text{ for any } \mathbf{w}, \mathbf{w}' \in \mathcal{H}.$$

Any firmly non-expansive operator is necessarily also a non-expansive operator [20]. Every fixed-point iteration that uses a firmly non-expansive operator converges to a fixed point of the operator [20].

See also: fixed-point iteration, contractive operator.

fixed point Consider some operator $\mathcal{F} : \mathcal{H} \rightarrow \mathcal{H}$ defined on a Hilbert space \mathcal{H} . A vektori $\hat{\mathbf{w}} \in \mathcal{H}$ is called a fixed point of the operator \mathcal{F} if it satisfies

$$\mathcal{F}\hat{\mathbf{w}} = \hat{\mathbf{w}}.$$

In other words, applying the operator \mathcal{F} to its fixed point $\hat{\mathbf{w}}$ returns the same vektori $\hat{\mathbf{w}}$. Finding a fixed point of a suitable operator \mathcal{F} is a common approach for solving various optimointitehtävät (e.g., an instance of empirical risk minimization (ERM)). A popular method for computing approximations of a fixed point is the fixed-point iteration. See also: fixed-point iteration.

fixed-point equation A fixed-point equation is an equation of the form

$$\mathbf{w} = \mathcal{F}(\mathbf{w}),$$

where $\mathcal{F} : \mathcal{H} \rightarrow \mathcal{H}$ is an operator defined on a Hilbert space \mathcal{H} . Solving a fixed-point equation amounts to finding the fixed points of \mathcal{F} . Many , including instances of ERM, can be cast in this form. For example, minimizing a smooth convex funktio f is equivalent to solving the fixed-point equation

$$\mathbf{w} = \mathcal{F}\mathbf{w} \text{ with } \mathcal{F} : \mathbf{w} \mapsto \mathbf{w} - \eta \nabla f(\mathbf{w})$$

. Here, $\eta > 0$ can be choosen freely. The above fixed-point equation is nothing but the zero-gradient condition for the minimizer of f [22]. Similarly, one can reforulate the optimality conditions (KKT conditions) of optimointitehtävät with constraints as a fixed-point equation [22, 36]

fixed-point iteration A fixed-point iteration is an iterative method for solving an optimointitehtävä. It constructs a sequence $\mathbf{w}^{(0)}, \mathbf{w}^{(1)}, \dots$ by repeatedly applying an operator \mathcal{F} , i.e.,

$$\mathbf{w}^{(t+1)} = \mathcal{F}\mathbf{w}^{(t)}, \text{ for } t = 0, 1, \dots \quad (1)$$

The operator \mathcal{F} is chosen such that any of its fixed points is a solution $\hat{\mathbf{w}}$ to the given optimointitehtävä. For example, given a differentiable and convex function $f(\mathbf{w})$, the fixed points of the operator $\mathcal{F} : \mathbf{w} \mapsto \mathbf{w} - \nabla f(\mathbf{w})$ coincide with the minimizers of $f(\mathbf{w})$. In general, for a given optimointitehtävä with solution $\hat{\mathbf{w}}$, there are many different operators \mathcal{F} whose fixed points are $\hat{\mathbf{w}}$. Clearly, we should use an operator \mathcal{F} in (1) that reduces the distance to a solution such that

$$\underbrace{\|\mathbf{w}^{(t+1)} - \hat{\mathbf{w}}\|_2}_{\stackrel{(1)}{=} \|\mathcal{F}\mathbf{w}^{(t)} - \mathcal{F}\hat{\mathbf{w}}\|_2} \leq \|\mathbf{w}^{(t)} - \hat{\mathbf{w}}\|_2.$$

Thus, we require \mathcal{F} to be at least a non-expansive operator, i.e., the iteration (1) should not result in worse model parameters that have a larger distance to a solution $\hat{\mathbf{w}}$. Furthermore, each iteration (1) should also make some progress, i.e., reduce the distance to a solution $\hat{\mathbf{w}}$. This requirement can be made precise using the notion of a contractive operator [37], [38]. The operator \mathcal{F} is a contractive operator if, for some $\kappa \in [0, 1)$,

$$\|\mathcal{F}\mathbf{w} - \mathcal{F}\mathbf{w}'\|_2 \leq \kappa \|\mathbf{w} - \mathbf{w}'\|_2 \text{ holds for any } \mathbf{w}, \mathbf{w}'.$$

For a contractive operator \mathcal{F} , the fixed-point iteration (1) generates a sequence $\mathbf{w}^{(t)}$ that converges quite rapidly. In particular [2, Th. 9.23],

$$\|\mathbf{w}^{(t)} - \hat{\mathbf{w}}\|_2 \leq \kappa^t \|\mathbf{w}^{(0)} - \hat{\mathbf{w}}\|_2.$$

Here, $\|\mathbf{w}^{(0)} - \hat{\mathbf{w}}\|_2$ is the distance between the initialization $\mathbf{w}^{(0)}$ and the solution $\hat{\mathbf{w}}$. It turns out that a fixed-point iteration (1) with a firmly non-expansive operator \mathcal{F} is guaranteed to converge to a fixed point of \mathcal{F} [37, Corollary 5.16]. Fig. 17 depicts examples of a non-expansive operator, a firmly non-expansive operator, and a contractive operator. All of these operators are defined on the 1-D space \mathbb{R} . Another example of a firmly non-expansive operator is the proximal operator of a convex function [21], [37].

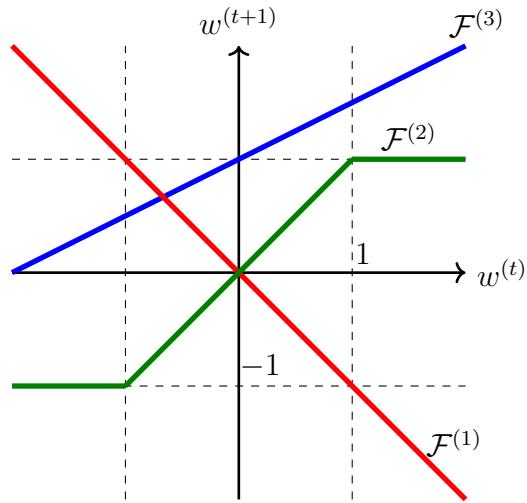


Fig. 17. Example of a non-expansive operator $\mathcal{F}^{(1)}$, a firmly non-expansive operator $\mathcal{F}^{(2)}$, and a contractive operator $\mathcal{F}^{(3)}$.

See also: contractive operator, proximal operator.

full-rank A matriisi $\mathbf{A} \in \mathbb{R}^{m \times d}$ is full-rank if it has maksimi rank [31]. For a tall matrix, i.e., when $d < m$, being full-rank means that its rank is equal to d .

$$\begin{array}{ll}
\mathbf{A} = \begin{pmatrix} 1 & 2 \\ 3 & 4 \end{pmatrix} & \mathbf{B} = \begin{pmatrix} 1 & 2 \\ 2 & 4 \end{pmatrix} \\
\text{full-rank square} & \text{rank-deficient square} \\
\\
\mathbf{C} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \\ 1 & 1 \end{pmatrix} & \mathbf{D} = \begin{pmatrix} 1 & 2 & 3 \\ 2 & 4 & 6 \end{pmatrix} \\
\text{full-rank tall matrix} & \text{rank-deficient wide matrix}
\end{array}$$

Fig. 18. Examples of full-rank and rank-deficient matriisit.

A square matriisi is full-rank if and only if it is invertible.

See also: matriisi, rank, dimension, lineaarikuvaus, column space.

funktio A function between two sets \mathcal{U} and \mathcal{V} assigns each element $u \in \mathcal{U}$ exactly one element $f(u) \in \mathcal{V}$ [2]. We write this as

$$f : \mathcal{U} \rightarrow \mathcal{V} : u \mapsto f(u)$$

where \mathcal{U} is the domain and \mathcal{V} the co-domain of f . That is, a function f defines a unique tuotos $f(u) \in \mathcal{V}$ for every input $u \in \mathcal{U}$ (see Fig. 19).

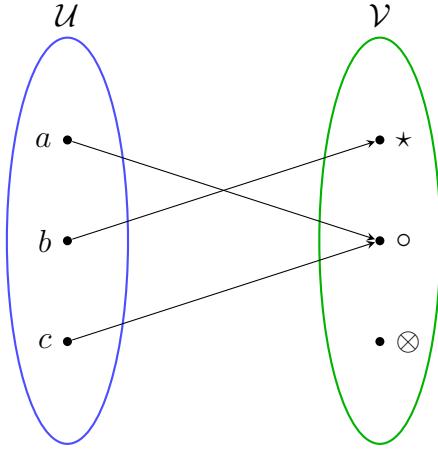


Fig. 19. A function $f: \mathcal{U} \rightarrow \mathcal{V}$ mapping each element of the domain $\mathcal{U} = \{a, b, c\}$ to exactly one element of the co-domain $\mathcal{V} = \{\star, \circ, \otimes\}$.

See also: domain, co-domain, tuotos.

Gaussian See normaalijakautunut satunnaismuuttuja.

Gaussian prosessi A GP is a collection of satunnaismuuttujat $\{f(\mathbf{x})\}_{\mathbf{x} \in \mathcal{X}}$ indexed by input values \mathbf{x} from some input space \mathcal{X} such that, for any finite subset $\mathbf{x}^{(1)}, \dots, \mathbf{x}^{(m)} \in \mathcal{X}$, the corresponding satunnaismuuttujat $f(\mathbf{x}^{(1)}, \dots, \mathbf{x}^{(m)})$ have a joint moninormaalijakauma

$$f(\mathbf{x}^{(1)}, \dots, \mathbf{x}^{(m)}) \sim \mathcal{N}(\boldsymbol{\mu}, \mathbf{K}).$$

For a fixed input space \mathcal{X} , a GP is fully specified (or parameterized) by: 1) a keskiarvo funktio $\mu(\mathbf{x}) = \mathbb{E}\{f(\mathbf{x})\}$; and 2) a kovarianssi funktio $K(\mathbf{x}, \mathbf{x}') = \mathbb{E}\{(f(\mathbf{x}) - \mu(\mathbf{x}))(f(\mathbf{x}') - \mu(\mathbf{x}'))\}$.

Example: We can interpret the temperature distribution across Finland (at a specific point in time) as the toteuma of a GP $f(\mathbf{x})$, where

each input $\mathbf{x} = (\text{lat}, \text{lon})$ denotes a geographic location. Temperature observations from Ilmatieteen laitos weather stations provide values $f(\mathbf{x})$ at specific locations (see Fig. 20). A GP allows us to predict the temperature nearby Ilmatieteen laitos weather stations and to quantify the epävarmuus of these ennusteet.

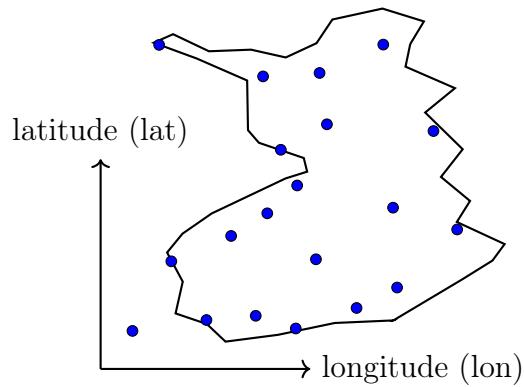


Fig. 20. For a given point in time, we can interpret the current temperature distribution over Finland as a toteuma of a GP indexed by geographic coordinates and sampled at Ilmatieteen laitos weather stations. The weather stations are indicated by blue dots.

See also: moninormaalijakauma, epävarmuus, normaalijakautunut satunnaismuuttuja.

gradientti For a real-valued funktion $f : \mathbb{R}^d \rightarrow \mathbb{R} : \mathbf{w} \mapsto f(\mathbf{w})$, if a vektori \mathbf{g} exists such that $\lim_{\mathbf{w} \rightarrow \mathbf{w}'} f(\mathbf{w}) - (f(\mathbf{w}') + \mathbf{g}^T(\mathbf{w} - \mathbf{w}')) / \|\mathbf{w} - \mathbf{w}'\| = 0$, it is referred to as the gradient of f at \mathbf{w}' . If it exists, the gradient is unique and denoted by $\nabla f(\mathbf{w}')$ or $\nabla f(\mathbf{w})|_{\mathbf{w}'}$ [2].

See also: funktio, vektori.

gradienttiaaskel Given a differentiable real-valued funktion $f(\cdot) : \mathbb{R}^d \rightarrow \mathbb{R}$ and a vektori $\mathbf{w} \in \mathbb{R}^d$, the gradientti step updates \mathbf{w} by adding the scaled negative gradientti $\nabla f(\mathbf{w})$ to obtain the new vektori (see Fig. 21)

$$\hat{\mathbf{w}} := \mathbf{w} - \eta \nabla f(\mathbf{w}). \quad (2)$$

The gradientti step amounts to applying the operator

$$\mathcal{T}^{(f,\eta)}(\cdot) : \mathbb{R}^d \rightarrow \mathbb{R}^d : \mathbf{w} \mapsto \mathbf{w} - \eta \nabla f(\mathbf{w}).$$

For a convex funktion $f(\cdot)$ that is sufficiently smooth and a sufficiently small oppimisnopeus $\eta > 0$, one can verify that $\mathcal{T}^{(f,\eta)}$ becomes a firmly non-expansive operator [20, Cor. 18.16]. If a strongly convex and smooth funktion $f(\cdot)$ and an appropriate choice of oppimisnopeus, one can verify that $\mathcal{T}^{(f,\eta)}$ is a contractive operator [39, Thm. 2.1.14.]. In these cases, gradient-based methods are instances of a fixed-point iteration since the operator $\mathcal{T}^{(f,\eta)}$ has a fixed point that coincides with the minimizer of $f(\cdot)$ (see zero-gradient condition).

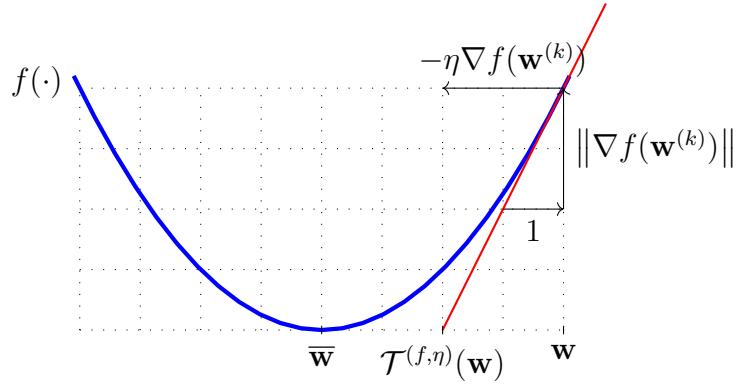


Fig. 21. The basic gradientti step (2) maps a given vektori \mathbf{w} to the updated vektori \mathbf{w}' .

Note that the gradientti step (2) optimizes locally—in a naapurusto whose size is determined by the step size η —a linear approximation to the funktilo $f(\cdot)$. A natural yleistys of (2) is to locally optimize the funktilo itself—instead of its linear approximation—such that

$$\hat{\mathbf{w}} = \arg \min_{\mathbf{w}' \in \mathbb{R}^d} f(\mathbf{w}') + \frac{1}{\eta} \|\mathbf{w} - \mathbf{w}'\|_2^2. \quad (3)$$

We intentionally use the same symbol η for the parameter in (3) as we used for the step size in (2). The larger the η we choose in (3), the more progress the update will make toward reducing the funktilo value $f(\hat{\mathbf{w}})$. Note that, much like the gradientti step (2), the update (3) also defines an operator that is parameterized by the funktilo $f(\cdot)$ and the oppimisnopeus η . For a convex funktilo $f(\cdot)$, this operator is known as the proximal operator of $f(\cdot)$ [21].

See also: differentiable, gradientti, step size, proximal operator.

graph of a function Given a funktion $f : \mathcal{X} \rightarrow \mathcal{Y}$, the graph of f is the subset of $\mathcal{X} \times \mathcal{Y}$ defined as

$$\{(\mathbf{x}, f(\mathbf{x})) : \mathbf{x} \in \mathcal{X}\}.$$

The graph of a funktion provides a geometric representation that is widely used in analysis, topology, and optimization.

halfspace See hyperplane.

Hermitian (matrix) A square matrix $\mathbf{A} \in \mathbb{C}^{d \times d}$ is Hermitian if it coincides with its conjugate transpose, i.e., $\mathbf{A} = \mathbf{A}^H$. Trivially, a Hermitian matrix is also a normal matrix.

Hessen matriisi Consider a funktion $f : \mathbb{R}^d \rightarrow \mathbb{R}$ for which the second-order partial derivatives exist at \mathbf{x}' . Then, the Hessian $\nabla^2 f(\mathbf{x}')$ of f at \mathbf{x} is defined as the matriisi of second-order partial derivatives of f at \mathbf{x}' , i.e.,

$$\nabla^2 f(\mathbf{x}') = \begin{pmatrix} \frac{\partial^2 f}{\partial x_1^2} & \frac{\partial^2 f}{\partial x_1 \partial x_2} & \cdots & \frac{\partial^2 f}{\partial x_1 \partial x_d} \\ \frac{\partial^2 f}{\partial x_2 \partial x_1} & \frac{\partial^2 f}{\partial x_2^2} & \cdots & \frac{\partial^2 f}{\partial x_2 \partial x_d} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial^2 f}{\partial x_d \partial x_1} & \frac{\partial^2 f}{\partial x_d \partial x_2} & \cdots & \frac{\partial^2 f}{\partial x_d^2} \end{pmatrix}.$$

If the second-order partial derivatives are jatkuva in a naapurusto around \mathbf{x}' , then the Hessian is a symmetric matriisi, i.e., $\partial^2 f / \partial x_j \partial x_{j'} = \partial^2 f / \partial x_{j'} \partial x_j$ for all j, j' [2]. If additionally f is convex, then the Hessian is a psd matriisi [22].

The Hessian $\nabla^2 f(\mathbf{x}')$ can be used to compute a kvadraattinen funktion

$$q(\mathbf{x}) = \frac{1}{2}(\mathbf{x} - \mathbf{x}')^T \underbrace{\nabla^2 f(\mathbf{x}')}_{\text{Hessian}} (\mathbf{x} - \mathbf{x}') + (\mathbf{x} - \mathbf{x}')^T \underbrace{\nabla f(\mathbf{x}')}_{\text{gradientti}} + f(\mathbf{x}')$$

that approximates f locally around \mathbf{x}' (see also Fig. 22).

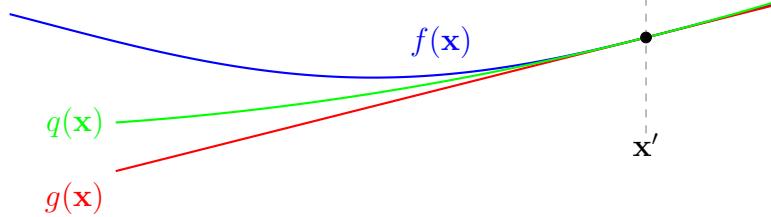


Fig. 22. A funktion $f(\mathbf{x})$ that is sufficiently smooth at a point \mathbf{x}' can be locally approximated by a kvadraattinen funktion $q(\mathbf{x})$, which provides a more accurate approximation compared to a linear funktion $g(\mathbf{x})$.

See also: funktion, matriisi, kvadraattinen funktion, differentiable.

Hilbert space A Hilbert space \mathcal{H} is a complete inner product space. Thus,

\mathcal{H} is a vektoriavaruus equipped with an inner product $\langle \cdot, \cdot \rangle$. The inner product induces a normi $\|\cdot\|_2$ via $\|\mathbf{w}\|_2 = \sqrt{\langle \mathbf{w}, \mathbf{w} \rangle}$. Furthermore, \mathcal{H} is complete in the sense that every Cauchy sequence $(\mathbf{w}^{(r)})_{r \in \mathbb{N}}$ in \mathcal{H} converges to a limit $\lim_{r \rightarrow \infty} \mathbf{w}^{(r)}$ that is also contained in \mathcal{H} .

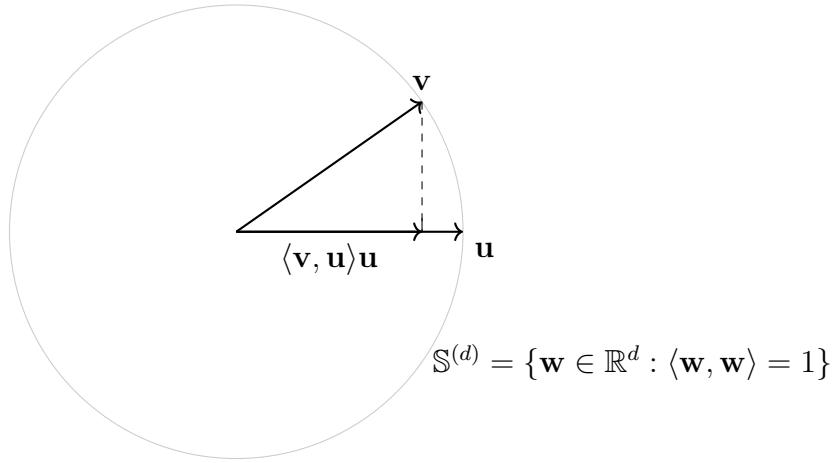


Fig. 23. For two unit-normi vektorit $\mathbf{u}, \mathbf{v} \in S^{(d)} \subseteq \mathbb{R}^d$ the inner product $\langle \mathbf{u}, \mathbf{v} \rangle$ is the expansion coefficient for the projektio of \mathbf{v} onto the subspace $\{c\mathbf{u} : c \in \mathbb{R}\}$ spanned by \mathbf{u} . The absolute value $|\langle \mathbf{u}, \mathbf{v} \rangle|$ measures the normi of this projektio.

One important example of a Hilbert space is the euklidinen avaruuus \mathbb{R}^d with the inner product $\langle \mathbf{w}, \mathbf{w}' \rangle = \mathbf{w}^\top \mathbf{w}'$.

See also: vektoriavaruuus.

Hoeffding's inequality Hoeffding's inequality [40] is a fundamental concentra-tion inequality that provides an upper bound on the todennäköisyys that a sum (or average) of independent, bounded satunnaismuuttujat de-viates from its keskiarvo by more than some threshold. Let x_1, \dots, x_n be independent real-valued satunnaismuuttujat x_i taking values in $[a_i, b_i] \subset \mathbb{R}$, and $S_n := \sum_{i=1}^n x_i$ and $\mathbb{E}\{S_n\} = \sum_{i=1}^n \mathbb{E}\{x_i\}$. Then, Hoeff-

ding's inequality [14, Th. 2.2.6] states that

$$\mathbb{P}(|S_n - \mathbb{E}\{S_n\}| \geq t) \leq 2 \exp \left(-\frac{2t^2}{\sum_{i=1}^n (b_i - a_i)^2} \right) \quad \forall t > 0.$$

Hoeffding's inequality typically provides sharper bounds than Chebyshev's inequality, but it is more restrictive by assuming bounded satunnaismuuttujat. In the context of koneoppiminen, this result is useful for deriving guarantees for ERM and in the context of monikäinen rosvo. See also: concentration inequality, todennäköisyys, satunnaismuuttuja, Chebyshev's inequality, odotusarvo, probability space, Markov's inequality.

hyperplane A hyperplane is an $(d - 1)$ -dimensional affine subspace of a d -dimensional vektoriavaruus. In the context of a euklidinen avaruus \mathbb{R}^d , a hyperplane is a set of the form

$$\{\mathbf{x} \in \mathbb{R}^d : \mathbf{w}^\top \mathbf{x} = b\}$$

where $\mathbf{w} \in \mathbb{R}^d \setminus \{0\}$ is a normal vektori and $b \in \mathbb{R}$ is an offset. Such a hyperplane partitions \mathbb{R}^d into two halfspaces

$$\{\mathbf{x} \in \mathbb{R}^d : \mathbf{w}^\top \mathbf{x} \leq b\} \quad \text{and} \quad \{\mathbf{x} \in \mathbb{R}^d : \mathbf{w}^\top \mathbf{x} \geq b\}.$$

Hyperplanes arise as the päätöspinnat of lineaarinen luokitint.

See also: subspace, vektoriavaruus, euklidinen avaruus, päätöspinta.

independent and identically distributed (i.i.d.) A collection of satunnaismuuttujat

$\mathbf{z}^{(1)}, \dots, \mathbf{z}^{(m)}$ is referred to as i.i.d. if each $\mathbf{z}^{(r)}$ follows the same todennäköisyysjakauma, and the satunnaismuuttujat are mutually independent. That is, for any collection of events $\mathcal{A}_1, \dots, \mathcal{A}_m$, we have

$$\mathbb{P}(\mathbf{z}^{(1)} \in \mathcal{A}_1, \dots, \mathbf{z}^{(m)} \in \mathcal{A}_m) = \prod_{r=1}^m \mathbb{P}(\mathbf{z}^{(r)} \in \mathcal{A}_r).$$

See also: satunnaismuuttuja, todennäköisyysjakauma, event, tietopiste, i.i.d. olettamus.

injective A funktio $f : \mathcal{U} \rightarrow \mathcal{V}$ is injective if it maps distinct elements of its domain to distinct elements of its co-domain, i.e., if $f(u_1) = f(u_2)$ implies $u_1 = u_2$ for all $u_1, u_2 \in \mathcal{U}$ [23]. Equivalently, no two different funktio inputs are mapped to the same funktio tuotos.

See also: funktio.

inner product Consider a vektoriavaruus \mathcal{X} over the field \mathbb{F} , where \mathbb{F} is either the field of real numbers \mathbb{R} or the field of complex numbers \mathbb{C} . An inner product in \mathcal{X} is a funktio

$$\langle \cdot, \cdot \rangle : \mathcal{X} \times \mathcal{X} \rightarrow \mathbb{F},$$

that satisfies the following properties for all $\mathbf{x}, \mathbf{x}', \mathbf{x}'' \in \mathcal{X}$ and all scalars $\alpha \in \mathbb{F}$ [29]:

- (i) Conjugate symmetry: $\langle \mathbf{x}, \mathbf{x}' \rangle = \overline{\langle \mathbf{x}', \mathbf{x} \rangle}$,
- (ii) Linearity in the first argument: $\langle \alpha \mathbf{x} + \mathbf{x}'', \mathbf{x}' \rangle = \alpha \langle \mathbf{x}, \mathbf{x}' \rangle + \langle \mathbf{x}'', \mathbf{x}' \rangle$,
- (iii) Positive-definiteness: $\langle \mathbf{x}, \mathbf{x} \rangle \geq 0$, with equality if and only if $\mathbf{x} = \mathbf{0}$.

The pair $(\mathcal{X}, \langle \cdot, \cdot \rangle)$ is called an inner product space. Each inner product induces a norm via $\|\mathbf{x}\| := \sqrt{\langle \mathbf{x}, \mathbf{x} \rangle}$ for all $\mathbf{x} \in \mathcal{X}$, which in turn induces a metric via $d(\mathbf{x}, \mathbf{x}') := \|\mathbf{x} - \mathbf{x}'\|$ for all $\mathbf{x}, \mathbf{x}' \in \mathcal{X}$.

See also: vektori, normi, metric space.

integrable A measurable funktion $f : \Omega \rightarrow \mathbb{R}$ defined on a measure space (Ω, Σ, μ) is called integrable if the Lebesgue integral of its absolute value is finite, i.e.,

$$\int_{\Omega} |f(x)| d\mu < \infty.$$

In this case, the Lebesgue integral $\int_{\Omega} f(x) d\mu$ is well-defined and finite. An satunnaismuuttuja x defined on the otosavaruus of a probability space $(\Omega, \Sigma, \mathbb{P})$ is integrable if

$$\mathbb{E}\{|x|\} = \int_{\Omega} |x(\omega)| d\mathbb{P} < \infty$$

which ensures that the odotusarvo $\mathbb{E}\{|x|\}$ exists and is finite.

See also: measure space, measure.

jatkuva A funktion $f : \mathbb{R}^d \rightarrow \mathbb{R}$ is continuous at a point $\mathbf{x}' \in \mathbb{R}^d$ if, for every $\epsilon > 0$, there is a $\delta > 0$ such that, for all $\mathbf{x} \in \mathbb{R}^d$ with $\|\mathbf{x} - \mathbf{x}'\|_2 < \delta$, it holds that $|f(\mathbf{x}) - f(\mathbf{x}')| < \epsilon$ [2]. In other words, we can make $f(\mathbf{x})$ arbitrarily close to $f(\mathbf{x}')$ by choosing \mathbf{x} sufficiently close to \mathbf{x}' .

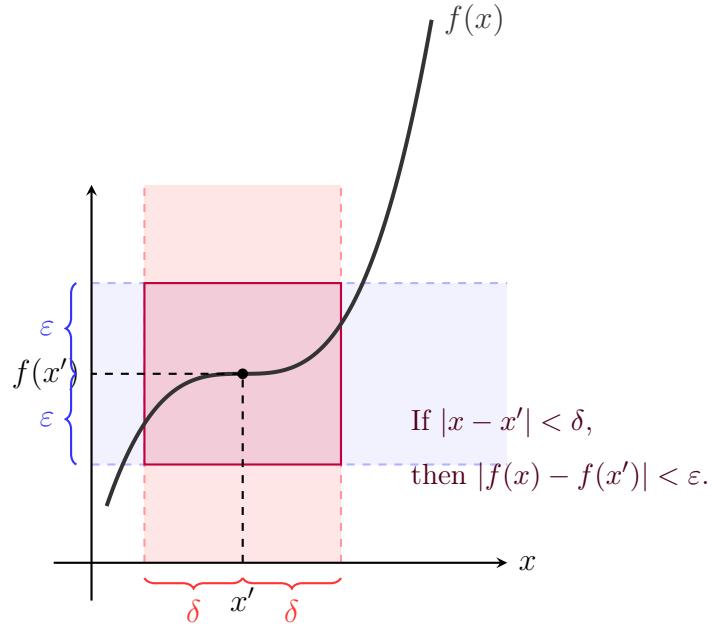


Fig. 24. The funktion $f(x) = 0.3(x - 2)^3 + 2.5$ is continuous at every x' .

If f is continuous at every point $\mathbf{x}' \in \mathbb{R}^d$, then f is said to be continuous on \mathbb{R}^d . The notion of a continuous funktion can be naturally extended to funktioner between general metric spaces [2].

See also: euklidinen avaruus, metric.

Johnson–Lindenstrauss lemma (JL lemma) The JL lemma describes conditions for the existence of a piirrekartta $\Phi : \mathbb{R}^d \rightarrow \mathbb{R}^{d'}$ with $d' \ll d$ such that the pairwise euklidinen etäisyys between piirrevektorit of a finite tietoaineisto is approximately preserved [14], [41], [42]. Consider a tietoaineisto $\mathcal{D} = \{\mathbf{x}^{(1)}, \dots, \mathbf{x}^{(m)}\}$ with tietopisteet characterized by piirrevektorit in \mathbb{R}^d . Then, for any d' that satisfies

$$d' \geq \frac{4 \ln(m)}{\varepsilon^2/2 - \varepsilon^3/3} \text{ for some } 0 < \varepsilon < 1$$

there is a piirrekartta Φ such that [43]

$$(1-\varepsilon) \|\mathbf{x}^{(r)} - \mathbf{x}^{(r')}\|_2 \leq \|\Phi(\mathbf{x}^{(r)}) - \Phi(\mathbf{x}^{(r')})\|_2 \leq (1+\varepsilon) \|\mathbf{x}^{(r)} - \mathbf{x}^{(r')}\|_2 \quad (4)$$

for all $\mathbf{x}^{(r)}, \mathbf{x}^{(r')} \in \mathcal{D}$.

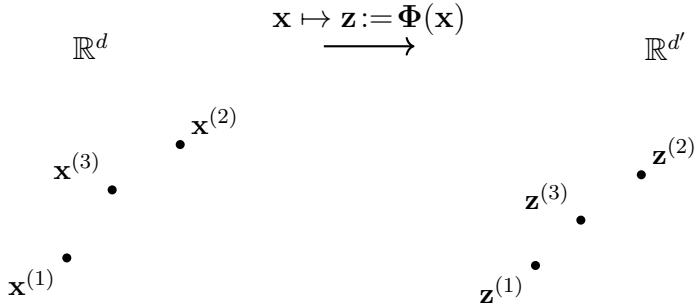


Fig. 25. The JL lemma offers precise conditions that guarantee the existence of a piirrekartta $\Phi : \mathbb{R}^d \rightarrow \mathbb{R}^{d'}$ such that pairwise euklidiset etäisyydet between (the piirrevektorit of) tietopisteet are approximately preserved. Roughly speaking, Φ maps neighboring points in the original piirreavaruus to neighboring points in the new piirreavaruus.

The piirrekartta Φ can be obtained from a random matriisi $\mathbf{A} \in \mathbb{R}^{d' \times d}$ whose entries are i.i.d. normaalijakautuneet satunnaismuuttujat $A_{i,j} \sim \mathcal{N}(0, 1/d')$. It can be shown that the piirrekartta $\mathbf{x} \mapsto \underbrace{\mathbf{Ax}}_{\Phi(\mathbf{x})}$ satisfies (4) with todennäköisyys at least $1 - 1/m$ [43].

See also: matriisi, normi, vektoriavaruus, euklidinen avaruuus, ulottuvuuksien vähentäminen, principal component analysis (PCA).

kaksoisnormi Every normi $\|\cdot\|$ defined on a euklidinen avaruuus \mathbb{R}^d has an associated dual normi, which is denoted by $\|\cdot\|_*$ and defined as

$\|\mathbf{y}\|_* := \sup_{\|\mathbf{x}\| \leq 1} \mathbf{y}^T \mathbf{x}$. The dual normi measures the largest possible inner product between \mathbf{y} and any vektori in the unit ball of the original normi. For further details, see [22, Sec. A.1.6].

See also: normi, euklidinen avaruuus, vektori.

keskeinen raja-arvolause Consider a sequence of i.i.d. satunnaismuuttujat $x^{(r)}$, for $r = 1, 2, \dots$, each with keskiarvo zero and finite varianssi $\sigma^2 > 0$. The CLT states that the normalized sum

$$s^{(m)} := \frac{1}{\sqrt{m}} \sum_{r=1}^m x^{(r)}$$

converges in distribution to a normaalijakautunut satunnaismuuttuja with keskiarvo zero and varianssi σ^2 as $m \rightarrow \infty$ [44, Proposition 2.17]. One elegant way to derive the CLT is via the ominaisfunktio of the normalized sum $s^{(m)}$. Let $\phi(t) = \mathbb{E}\{\exp(jtx)\}$ (with the imaginary unit $j = \sqrt{-1}$) be the common ominaisfunktio of each sum and $x^{(r)}$, and let $\phi^{(m)}(t)$ denote the ominaisfunktio of $s^{(m)}$. Define an operator \mathcal{T} acting on ominaisfunktiot such that

$$\phi^{(m)}(t) = \mathcal{T}(\phi^{(m-1)})(t) := \phi\left(\frac{t}{\sqrt{m}}\right) \cdot \phi^{(m-1)}\left(\frac{\sqrt{m-1}}{\sqrt{m}}t\right).$$

This fixed-point iteration captures the effect of recursively adding an i.i.d. satunnaismuuttuja $\mathbf{x}^{(m)}$ and rescaling. Iteratively applying \mathcal{T} leads to convergence of $\phi^{(m)}(t)$ toward the fixed point

$$\phi^*(t) = \exp(-t^2\sigma^2/2)$$

which is the ominaisfunktio of a normaalijakautunut satunnaismuuttuja with keskiarvo zero and varianssi σ^2 . Yleistykset of the CLT allow

for dependent or nonidentically distributed satunnaismuuttujat [44, Sec. 2.8].

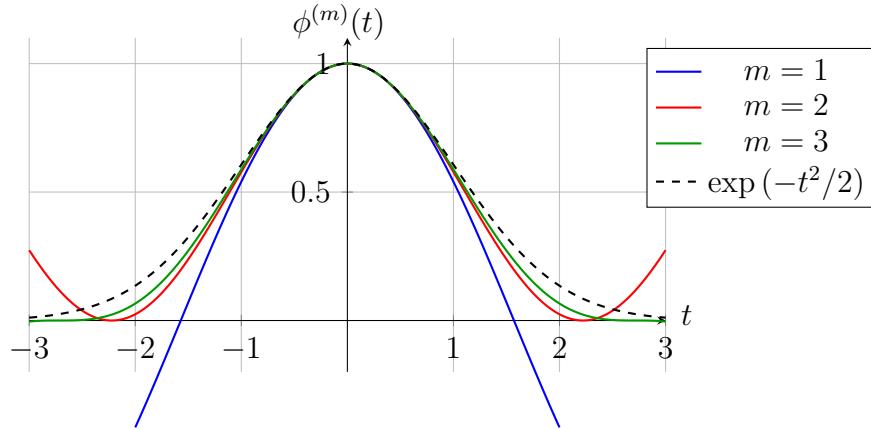


Fig. 26. Ominaisfunktiot of normalized sums of i.i.d. satunnaismuuttujat $x^{(r)} \in \{-1, 1\}$ for $r = 1, \dots, m$ compared to the Gaussian limit.

See also: satunnaismuuttuja, normaalijakautunut satunnaismuuttuja.

keskiarvo The mean of a satunnaismuuttuja \mathbf{x} , which takes on values in a euklidinen avaruus \mathbb{R}^d , is its odotusarvo $\mathbb{E}\{\mathbf{x}\}$. It is defined as the Lebesgue integral of \mathbf{x} with respect to the underlying todennäköisyysjakauma P (e.g., see [2] or [6]), i.e.,

$$\mathbb{E}\{\mathbf{x}\} = \int_{\mathbb{R}^d} \mathbf{x} dP(\mathbf{x}).$$

We also use the term to refer to the average of a finite tietoaineisto $\mathcal{D} = \{\mathbf{x}^{(1)}, \dots, \mathbf{x}^{(m)} \in \mathbb{R}^d\}$. However, these two definitions are essentially the same. Indeed, we can use a tietoaineisto to construct a discrete satunnaismuuttuja $\tilde{\mathbf{x}}^{(\mathcal{D})} = \mathbf{x}^{(I)}$ on the otosavaruus $\{1, \dots, m\}$. Here,

the index I is chosen uniformly at random, $\mathbb{P}(I = r) = 1/m$ for all $r = 1, \dots, m$. The mean of $\tilde{\mathbf{x}}^{(\mathcal{D})}$ is precisely the average $(1/m) \sum_{r=1}^m \mathbf{x}^{(r)}$. For a satunnaismuuttuja with finite second-order moment, i.e., $\mathbb{E}\{\|\mathbf{x}\|_2^2\}$ is well-defined and finite, the mean is characterized as the solution of the following riski minimization problem [7]:

$$\mathbb{E}\{\mathbf{x}\} = \arg \min_{\mathbf{c} \in \mathbb{R}^d} \mathbb{E}\{\|\mathbf{x} - \mathbf{c}\|_2^2\}.$$

For the satunnaismuuttuja $\tilde{\mathbf{x}}^{(\mathcal{D})}$, associated with a tietoaineisto, this optimointitehtävä reduces to ERM with neliövirhehäviö on \mathcal{D} .

See also: satunnaismuuttuja, odotusarvo, todennäköisyysjakauma, ERM.

konveksi optimointi Convex optimization studies the formulation, properties, and efficient solution methods for convex optimointitehtävät [22]. A convex optimointitehtävä (defined on the euklidinen avaruus \mathbb{R}^d) consists of a convex kohdefunktio $f : \mathbb{R}^d \rightarrow \mathbb{R}$ and a convex constraint set \mathcal{C} for the optimization variable \mathbf{w} . It can be written compactly as [22]

$$\min_{\mathbf{w} \in \mathcal{C}} f(\mathbf{w}).$$

Alternatively, a convex optimointitehtävä can be expressed in terms of convex constraint funktiot g_1, \dots, g_k as

$$\begin{aligned} & \min_{\mathbf{w} \in \mathbb{R}^d} f(\mathbf{w}) \\ & \text{s.t. } g_r(\mathbf{w}) \leq 0, \quad r = 1, \dots, k. \end{aligned} \tag{5}$$

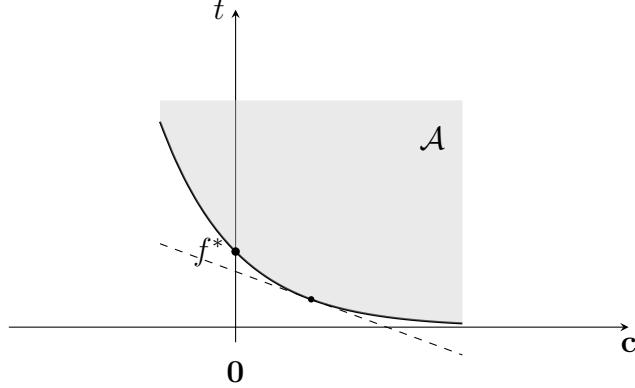


Fig. 27. A convex optimointitehtävä (5) can be represented by a set \mathcal{A} that consists of objective values t and constraint values $\mathbf{c} = (c_1, \dots, c_d)^T$ that are achievable, i.e., $f(\mathbf{w}) \leq t, g_1(\mathbf{w}) \leq c_1, \dots, g_k(\mathbf{w}) \leq c_k$ by some $\mathbf{w} \in \mathbb{R}^d$. The optimal value f^* of the optimointitehtävä is the smallest t for which $(\mathbf{0}, t) \in \mathcal{A}$.

The formulation (5) lends, in turn, to the epigrafi form of [22, Sec. 5.3]

$$\inf \{t \in \mathbb{R} : (\mathbf{0}, t) \in \mathcal{A}\}$$

with the set

$$\begin{aligned} \mathcal{A} := \{(\mathbf{c}, t) \in \mathbb{R}^d \times \mathbb{R} : f(\mathbf{w}) \leq t, \\ g_r(\mathbf{w}) \leq c_r, r = 1, \dots, k, \text{ for some } \mathbf{w} \in \mathbb{R}^d\}. \end{aligned}$$

It can be shown that, since f, g_1, \dots, g_k are convex funktiot, \mathcal{A} is a convex set [22, Ch. 2]. The set \mathcal{A} fully characterizes the optimointitehtävä (5) and can be interpreted as the epigrafi of the kohdefunktio f over the feasible region defined by the constraint funktiot g_1, \dots, g_k . See also: convex, optimointitehtävä, optimointimenetelmä.

kovarianssi The covariance between two real-valued satunnaismuuttujat x and y , defined on a common probability space, measures their linear dependence. It is defined as

$$\text{cov}(x, y) = \mathbb{E}\{(x - \mathbb{E}\{x\})(y - \mathbb{E}\{y\})\}.$$

A positive covariance indicates that x and y tend to increase together, while a negative covariance suggests that one tends to increase as the other decreases. If $\text{cov}(x, y) = 0$, the satunnaismuuttujat are said to be uncorrelated, though not necessarily statistically independent. See Fig. 28 for visual illustrations.

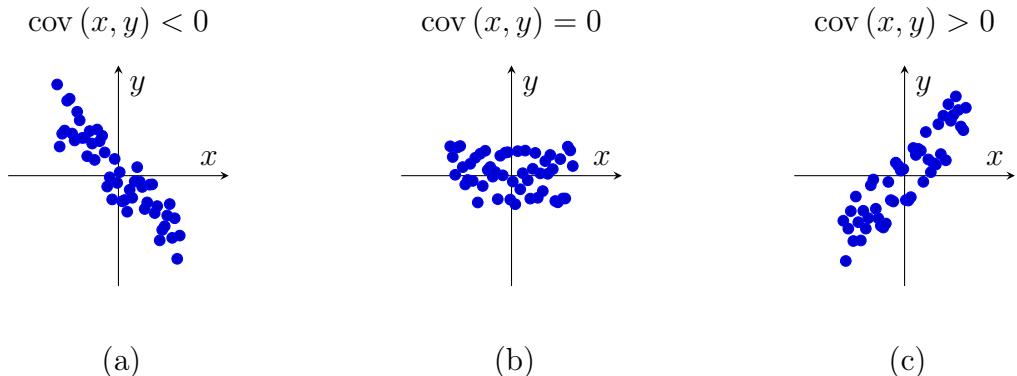


Fig. 28. Hajontakuviot illustrating toteumat from three different todennäköisyysmallit for two satunnaismuuttujat with different covariance values. (a) Negative. (b) Zero. (c) Positive.

See also: todennäköisyysmalli, odotusarvo.

kovarianssimatriisi The kovarianssi matriisi of an satunnaismuuttuja $\mathbf{x} \in$

\mathbb{R}^d is defined as the odotusarvo (if it exists)

$$\mathbf{C}^{(\mathbf{x})} := \mathbb{E} \left\{ (\mathbf{x} - \mathbb{E}\{\mathbf{x}\})(\mathbf{x} - \mathbb{E}\{\mathbf{x}\})^T \right\}.$$

See also: kovarianssi, matriisi, satunnaismuuttuja.

kuvaus We use the term map as a synonym for funktio.

See also: funktio.

kytketty verkko An undirected graph $\mathcal{G} = (\mathcal{V}, \mathcal{E})$ is connected if, for every non-empty subset $\mathcal{V}' \subset \mathcal{V}$, we can find at least one edge connecting a node in \mathcal{V}' with some node in $\mathcal{V} \setminus \mathcal{V}'$. We illustrate two examples of undirected graphs in Fig. 29.

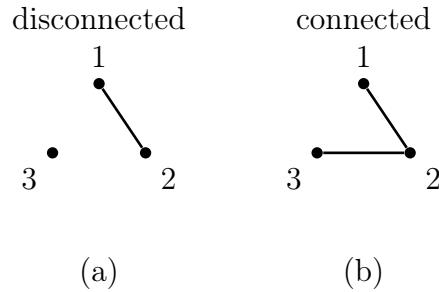


Fig. 29. (a) A verkko that is disconnected. (b) A verkko that is connected.

See also: undirected graph, algebraic connectivity.

käänteismatriisi An inverse matriisi \mathbf{A}^{-1} is defined for a square matriisi $\mathbf{A} \in \mathbb{R}^{n \times n}$ that is of full-rank, meaning its columns are linearly independent. In this case, \mathbf{A} is said to be invertible, and its inverse satisfies

$$\mathbf{A}\mathbf{A}^{-1} = \mathbf{A}^{-1}\mathbf{A} = \mathbf{I}.$$

A square matriisi is invertible if and only if its determinantti is nonzero. Inverse matriisit are fundamental in solving systems of linear equations and in the closed-form solution of lineaarinen regressio [27], [45]. The concept of an inverse matriisi can be extended to matriisit that are not square or do not have full-rank. One may define a “left inverse” \mathbf{B} satisfying $\mathbf{BA} = \mathbf{I}$ or a “right inverse” \mathbf{C} satisfying $\mathbf{AC} = \mathbf{I}$. For general rectangular or singular matriisit, the Moore–Penrose pseudokäänteisluku \mathbf{A}^+ provides a unified concept of a generalized inverse matriisi [3].

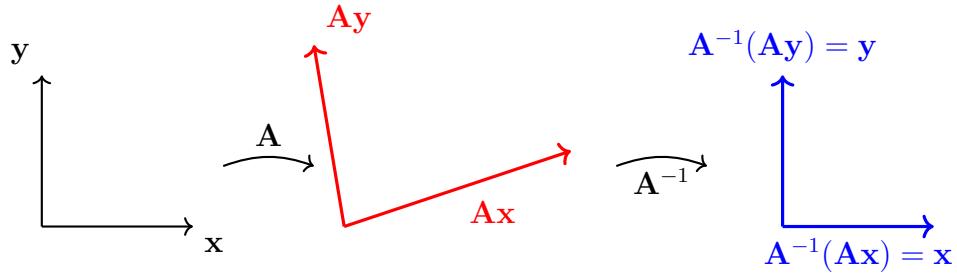


Fig. 30. A matriisi \mathbf{A} represents a linear transformation of \mathbb{R}^2 . The inverse matriisi \mathbf{A}^{-1} represents the inverse transformation.

See also: matriisi, determinanti, lineaarinen regressio, pseudokäänteisluku.

Lagrange dual problem The Lagrangian of an optimointitehtävä of form

$$\begin{aligned} & \min_{\mathbf{w} \in \mathbb{R}^d} f_0(\mathbf{w}) \\ \text{s.t. } & f_i(\mathbf{w}) \leq 0, \quad i = 1, \dots, k \end{aligned} \tag{6}$$

$$g_j(\mathbf{w}) = 0, \quad j = 1, \dots, l \tag{7}$$

is

$$\max_{\lambda \in \mathbb{R}^k, \nu \in \mathbb{R}^l} \inf_{\mathbf{w} \in \mathbb{R}^d} L(\mathbf{w}, \lambda, \nu) \text{ s.t. } \lambda \leq 0, \quad (8)$$

where L is the Lagrangian of the optimointitehtävä.

See also: konveksi optimointi, optimointitehtävä, Lagrangian.

Lagrangian The Lagrangian of an optimointitehtävä of form

$$\begin{aligned} & \min_{\mathbf{w} \in \mathbb{R}^d} f_0(\mathbf{w}) \\ \text{s.t. } & f_i(\mathbf{w}) \leq 0, \quad i = 1, \dots, k \end{aligned} \quad (9)$$

$$g_j(\mathbf{w}) = 0, \quad j = 1, \dots, l \quad (10)$$

is

$$L(\mathbf{w}, \lambda, \nu) := f_0(\mathbf{w}) + \sum_{i=1}^k \lambda_i f_i(\mathbf{w}) + \sum_{j=1}^l \nu_j g_j(\mathbf{w}). \quad (11)$$

The Lagrangian is most often used to formulate the Lagrange dual problem.

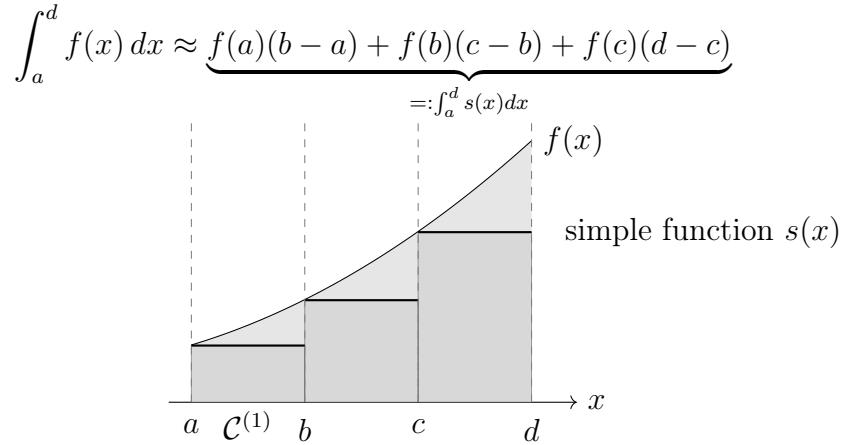
See also: konveksi optimointi, optimointitehtävä, dual.

law of large numbers The law of large numbers refers to the convergence of the average of an increasing (large) number of i.i.d. satunnaismuuttujat to the keskiarvo of their common todennäköisyysjakauma. Different instances of the law of large numbers are obtained by using different notions of convergence [25].

See also: convergence, i.i.d., satunnaismuuttuja, keskiarvo, todennäköisyysjakauma.

Lebesgue integral The Lebesgue integral assigns each integrable funktio $f : \mathbb{R}^d \rightarrow \mathbb{R}$ a number $\int_{\mathbf{x}} f(\mathbf{x}) d\mathbf{x}$ that is referred to as the integral of

f . The integral of f can be interpreted as the volume that is enclosed by the funktion f in the space \mathbb{R}^{d+1} . We can compute it by increasingly accurate approximations by simple functions [1, Ch. 1].



It is useful to think of the Lebesgue integral as a funktion that maps an integrable funktion f to the value of its integral,

$$f \mapsto \int_{\mathbf{x}} f(\mathbf{x}) d\mathbf{x}.$$

The precise definition of this funktion, whose domain consists of the integrable funktioner, is a cornerstone of measure theory [1, Ch. 1].

See also: funktion.

lineaarikuvaus A linear kuvaus $f : \mathbb{R}^d \rightarrow \mathbb{R}^m$ is a funktion that satisfies additivity, i.e., $f(\mathbf{x} + \mathbf{y}) = f(\mathbf{x}) + f(\mathbf{y})$, and homogeneity, i.e., $f(c\mathbf{x}) = cf(\mathbf{x})$, for all vektorit $\mathbf{x}, \mathbf{y} \in \mathbb{R}^d$ and scalars $c \in \mathbb{R}$. In particular, $f(\mathbf{0}) = \mathbf{0}$. Any linear kuvaus can be represented as a matriisi multiplication $f(\mathbf{x}) = \mathbf{Ax}$, for some matriisi $\mathbf{A} \in \mathbb{R}^{m \times n}$. The collection of real-valued linear kuvauksset (where $m = 1$), for a given dimension d , constitute a

lineaarinen malli. The notion of a linear kuvaus can be generalized from the domain \mathbb{R}^d and co-domain \mathbb{R}^m to arbitrary vektoriavaruudet.

See also: kuvaus, funktio, vektori, matriisi, lineaarinen malli.

linearly independent A subset $\{\mathbf{a}^{(1)}, \dots, \mathbf{a}^{(d)}\} \in \mathcal{V}$ of a vektoriavaruus is linearly independent if there is no nontrivial linear combination of these vektorit that equals the zero vektori [31]. In other words,

$$\sum_{j=1}^d \alpha_j \mathbf{a}^{(j)} = \mathbf{0} \quad \text{implies} \quad \alpha_1 = \alpha_2 = \dots = \alpha_k = 0.$$

See also: vektoriavaruus, vektori, dimension, basis.

majorize-minimize (MM) Consider an optimointitehtävä $\min_{\mathbf{w} \in \mathcal{W}} f(\mathbf{w})$ with some complicated (potentially non-convex and non-smooth) kohdefunktio. One important example of such an optimointitehtävä is ERM, which is used to learn the model parameters of a nonlinear malli. An MM method is an iterative optimointimenetelmä that constructs a sequence $\mathbf{w}^{(1)}, \mathbf{w}^{(2)}, \dots \in \mathcal{W}$ of model parameters as follows [46], [47], [48] (see also Fig. 31):

- During the t th iteraatio, the kohdefunktio $f(\cdot)$ is approximated by another funktio $g(\cdot; \mathbf{w}^{(t)})$. This approximation must be an upper bound for (i.e., must majorize) the original kohdefunktio, i.e., $g(\mathbf{w}; \mathbf{w}^{(t)}) \geq f(\mathbf{w})$ for all $\mathbf{w} \in \mathcal{W}$, and it must be tight for $\mathbf{w}^{(t)}$, i.e., $g(\mathbf{w}^{(t)}; \mathbf{w}^{(t)}) = f(\mathbf{w}^{(t)})$.
- The new model parameters $\mathbf{w}^{(t+1)}$ are then obtained by minimizing the approximation, i.e., $\mathbf{w}^{(t+1)} \in \arg \min_{\mathbf{w} \in \mathcal{W}} g(\mathbf{w}; \mathbf{w}^{(t)})$.

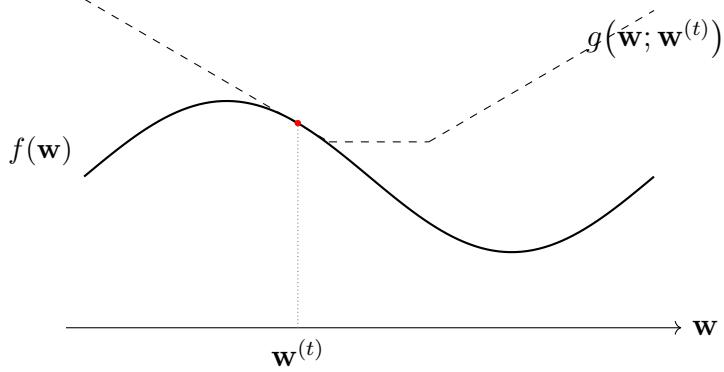


Fig. 31. The construction of model parameters based on the iterative MM method.

Similar to gradient-based methods, the MM principle is also based on approximating a function locally, around the current model parameters, and then optimizing this approximation to obtain new model parameters. However, the construction of local approximations is very different. While gradient-based methods use linear functions for these approximations, MM methods can use nonlinear functions as long as they are upper bounds for the original function.

See also: gradient-based method, odotusarvon maksimointi.

maksimi The maximum of a set $\mathcal{A} \subseteq \mathbb{R}$ of real numbers is the greatest element in that set, if such an element exists. A set \mathcal{A} has a maximum if it is bounded above and attains its supremum (or least upper bound) [2, Sec. 1.4].

See also: supremum.

Markov chain A Markov chain is a satunnaisprosessi $\{X_t\}_{t \in \mathbb{N}}$, defined on a

common probability space and using the index set \mathbb{N} . The satunnaismuuttuja X_t might represent (the generation of) a state of a physical system at the time instant t . The defining property of a Markov chain is the Markov property [16, 25, 49]: For all $t \in \mathbb{N}$,

$$\mathbb{P}(X_{t+1}|X_t, \dots, X_1) = \mathbb{P}(X_{t+1}|X_t).$$

In other words, the conditional probability distribution of the next state X_{t+1} depends on the past X_t, X_{t-1}, \dots, X_1 only through the current state X_t . The concept of a Markov chain can be generalized from discrete time (with index set \mathbb{N}) to continuous time (with index set \mathbb{R}) [49].

See also: satunnaisprosessi, conditional probability distribution.

Markov property See Markov chain.

Markov's inequality Consider a real-valued nonnegative satunnaismuuttuja x for which the odotusarvo $\mathbb{E}\{x\}$ exists. Markov's inequality provides an upper bound on the todennäköisyys $\mathbb{P}(x \geq a)$ that x exceeds a given positive threshold $a > 0$. In particular,

$$\mathbb{P}(x \geq a) \leq \frac{\mathbb{E}\{x\}}{a} \quad \text{holds for any } a > 0.$$

This inequality can be verified by noting that $\mathbb{P}(x \geq a)$ is the odotusarvo $\mathbb{E}\{g(x)\}$ with the funktio

$$g : \mathbb{R} \rightarrow \mathbb{R} : x' \mapsto \mathbb{I}_{\{x \geq a\}}(x').$$

As illustrated in Fig. 32, for any positive $a > 0$,

$$g(x') \leq x'/a \text{ for all } x' \in \mathbb{R}.$$

This implies Markov's inequality via the monotonicity property of the Lebesgue integral [12, p. 50].

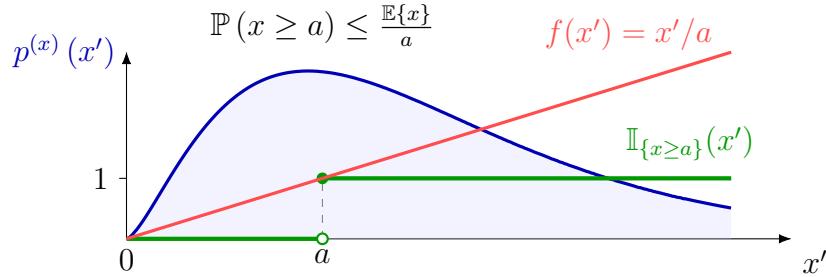


Fig. 32. The odotusarvo $\mathbb{E}\{x\}$ and the todennäköisyys $\mathbb{P}(x \geq a)$ of a nonnegative satunnaismuuttuja x with a pdf $p^{(x)}(\cdot)$ can be obtained via Lebesgue integrals of $f(x') = x'/a$ and $g(x') = \mathbb{I}_{\{x \geq a\}}(x')$, respectively.

See also: odotusarvo, todennäköisyys, concentration inequality.

matriisi A matrix of size $m \times d$ is a 2-D array of numbers, which is denoted by

$$\mathbf{A} = \begin{pmatrix} A_{1,1} & A_{1,2} & \dots & A_{1,d} \\ A_{2,1} & A_{2,2} & \dots & A_{2,d} \\ \vdots & \vdots & \ddots & \vdots \\ A_{m,1} & A_{m,2} & \dots & A_{m,d} \end{pmatrix} \in \mathbb{R}^{m \times d}.$$

Here, $A_{r,j}$ denotes the matrix entry in the r th row and the j th column. Matrices are useful representations of various mathematical objects [31], including the following:

- Systems of linear equations: We can use a matrix to represent a

system of linear equations

$$\begin{pmatrix} A_{1,1} & A_{1,2} \\ A_{2,1} & A_{2,2} \end{pmatrix} \begin{pmatrix} w_1 \\ w_2 \end{pmatrix} = \begin{pmatrix} y_1 \\ y_2 \end{pmatrix} \quad \text{compactly as} \quad \mathbf{A}\mathbf{w} = \mathbf{y}.$$

One important example of systems of linear equations is the optimality condition for the model parameters within lineaarinen regressio.

- Lineaarikuvauskset: Consider a d -dimensional vektoriavaruus \mathcal{U} and a m -dimensional vektoriavaruus \mathcal{V} . If we fix a basis $\mathbf{u}^{(1)}, \dots, \mathbf{u}^{(d)}$ for \mathcal{U} and a basis $\mathbf{v}^{(1)}, \dots, \mathbf{v}^{(m)}$ for \mathcal{V} , each matrix $\mathbf{A} \in \mathbb{R}^{m \times d}$ naturally defines a lineaarikuvaus $\alpha : \mathcal{U} \rightarrow \mathcal{V}$ (see Fig. 33) such that

$$\mathbf{u}^{(j)} \mapsto \sum_{r=1}^m A_{r,j} \mathbf{v}^{(r)}.$$

- Tietoaineistot: We can use a matrix to represent a tietoaineisto. Each row corresponds to a single tietopiste, and each column corresponds to a specific piirre or nimiö of a tietopiste.

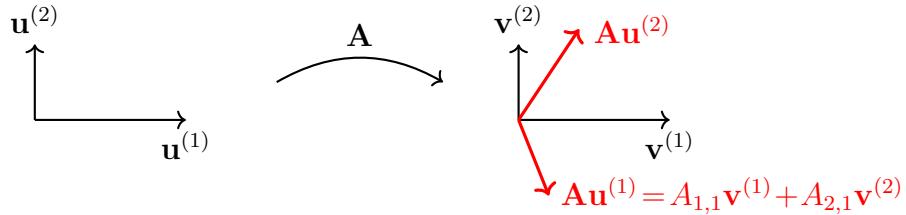


Fig. 33. A matrix \mathbf{A} defines a lineaarikuvaus between two vektoriavaruudet.

See also: lineaarikuvaus, tietoaineisto, lineaarinen malli.

measurable Consider a satunnaiskoe, such as recording the air temperature at an Ilmatieteen laitos weather station. The corresponding otosavaruus Ω consists of all possible outcomes ω (e.g., all possible temperature values in degree Celsius). In many koneoppiminen applications, we are not interested in the exact outcome ω , but only whether it belongs to a subset $\mathcal{A} \subseteq \Omega$ (e.g., determining whether the temperature is below zero degrees). We call such a subset \mathcal{A} measurable if it is possible to decide, for any outcome ω , whether $\omega \in \mathcal{A}$ or not (see Fig. 34).

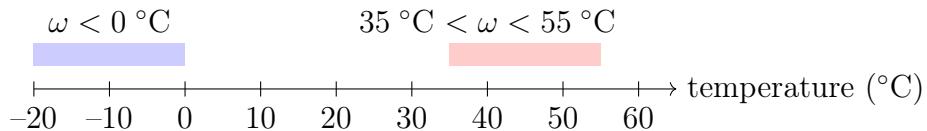


Fig. 34. A otosavaruus constituted by all possible temperature values ω that can occur at an Ilmatieteen laitos station. Two measurable subsets of temperature values, denoted by $\mathcal{A}^{(1)}$ and $\mathcal{A}^{(2)}$, are highlighted. For any actual temperature value ω , it is possible to determine (via some equipment) whether $\omega \in \mathcal{A}^{(1)}$ and whether $\omega \in \mathcal{A}^{(2)}$.

In principle, measurable sets could be chosen freely (e.g., depending on the resolution of the measuring equipment). However, it is often useful to impose certain completeness requirements on the collection of measurable sets. For example, the otosavaruus itself should be measurable, and the union of two measurable sets should also be measurable.

These completeness requirements can be formalized via the concept of a σ -algebra (or σ -field) [1], [6], [16]. A measurable space is a pair $(\mathcal{X}, \mathcal{F})$ that consists of an arbitrary set \mathcal{X} and a collection \mathcal{F} of measurable subsets of \mathcal{X} that form a σ -algebra.

See also: otosavaruus, outcome, σ -algebra, todennäköisyys.

measure A measure μ on a set Ω equipped with a σ -algebra Σ is a funktion $\mu : \Sigma \rightarrow [0, \infty)$ that assigns a nonnegative value to each measurable set $\mathcal{A} \in \Sigma$ such that [2], [6], [50]: 1) $\mu(\emptyset) = 0$; and 2) for any countable collection $\{\mathcal{A}_i\}_{i=1}^{\infty}$ of pairwise disjoint sets in Σ ,

$$\mu\left(\bigcup_{i=1}^{\infty} \mathcal{A}_i\right) = \sum_{i=1}^{\infty} \mu(\mathcal{A}_i)$$

which is referred to as “countable additivity”.

See also: measurable, countable.

measure space A measure space is a triple (Ω, Σ, μ) consisting of a set Ω , a σ -algebra Σ of subsets of Ω , and a measure $\mu : \Sigma \rightarrow [0, \infty)$. The measure μ assigns a nonnegative number to each measurable set $\mathcal{A} \in \Sigma$, generalizing the notions of length, area, or volume in euklidinen avaruust [2], [50]. Measure spaces provide the mathematical foundation for the Lebesgue integral or the definition of satunnaismuuttujat as measurable mappings between measure spaces. A probability space is a special case of a measure space where the total measure of the otosavaruus is normalized to one, i.e., $\mu(\Omega) = 1$. In this case, μ is called a todennäköisyysjakauma.

See also: measurable, probability space, todennäköisyysjakauma.

mediaani A median $\text{med}(x)$ of a real-valued satunnaismuuttuja x is any number $M \in \mathbb{R}$ such that $\mathbb{P}(x \leq M) \geq 1/2$ and $\mathbb{P}(x \geq M) \geq 1/2$ (see Fig. 35) [51].

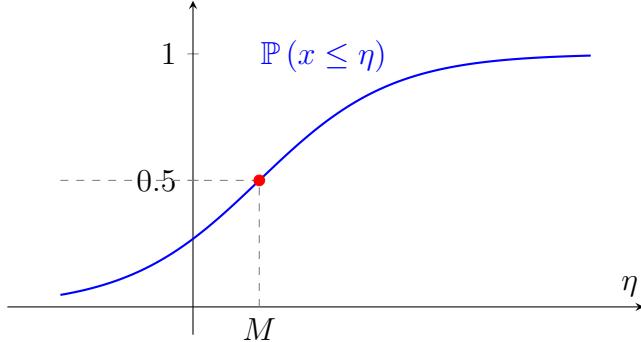


Fig. 35. The median of a real-valued satunnaismuuttuja is any number M that partitions \mathbb{R} into two rays with equal todennäköisyys.

We can define the median $\text{med}(\mathcal{D})$ of a tietoaineisto $\mathcal{D} = \{x^{(1)}, \dots, x^{(m)} \in \mathbb{R}\}$ via a specific satunnaismuuttuja $\tilde{x}^{(\mathcal{D})}$ that is naturally associated with \mathcal{D} . In particular, this satunnaismuuttuja is defined on the otosavaruus $\{1, \dots, m\}$ via $\tilde{x}^{(\mathcal{D})} := x^{(I)}$. Here, the index I is chosen uniformly at random, i.e., $\mathbb{P}(I = r) = 1/m$ for all $r = 1, \dots, m$. If the satunnaismuuttuja x is integrable, any median of x solves the optimointitehtävä:

$$\min_{x' \in \mathbb{R}} \mathbb{E}|x - x'|.$$

For a the above satunnaismuuttuja \tilde{x} (constructed from a tietoaineisto \mathcal{D}), this optimointitehtävä is ERM on \mathcal{D} using absolute error loss. Like the keskiarvo, the median of a tietoaineisto \mathcal{D} can also be used to estimate parameters of an underlying todennäköisyysmalli. Compared

with the keskiarvo, the median is more robust to poikkeava havaintot. For example, a median of a tietoaineisto \mathcal{D} with more than one tietopiste does not change even if we arbitrarily increase the largest element of \mathcal{D} (see Fig. 36). In contrast, the keskiarvo will increase arbitrarily.

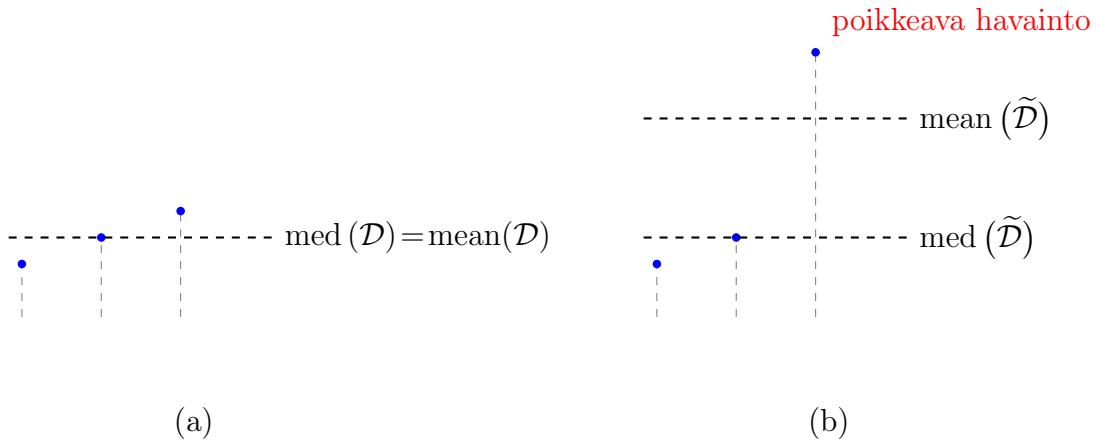


Fig. 36. The median is robust against poikkeava havainto contamination. (a) Original tietoaineisto \mathcal{D} . (b) Noisy tietoaineisto $\tilde{\mathcal{D}}$ including an poikkeava havainto.

See also: keskiarvo, poikkeava havainto, vakaus, least absolute deviation regression.

metric space A metric space is a set \mathcal{X} equipped with a funkatio (referred to as a metric) $d(\cdot, \cdot) : \mathcal{X} \times \mathcal{X} \rightarrow \mathbb{R}_+$ that satisfies the following requirements for all $\mathbf{x}, \mathbf{x}', \mathbf{x}'' \in \mathcal{X}$:

1. Nonnegativity: $d(\mathbf{x}, \mathbf{x}') \geq 0$;
2. Identity: $d(\mathbf{x}, \mathbf{x}') = 0$ if and only if $\mathbf{x} = \mathbf{x}'$;

3. Symmetry: $d(\mathbf{x}, \mathbf{x}') = d(\mathbf{x}', \mathbf{x});$
4. Triangle inequality: $d(\mathbf{x}, \mathbf{x}'') \leq d(\mathbf{x}, \mathbf{x}') + d(\mathbf{x}', \mathbf{x}'').$

Formally, a metric space is a pair $(\mathcal{X}, d(\cdot, \cdot))$ that satisfies the above requirements.

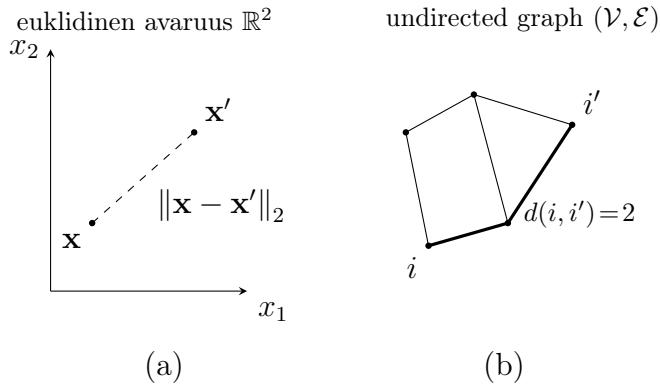


Fig. 37. Examples of metric spaces. (a) euklidinen avaruuus \mathbb{R}^2 with the euklidinen etäisyys as a metric. (b) Undirected graph $(\mathcal{V}, \mathcal{E})$ with the shortest-path distance as a metric.

A prominent example of a metric space is the euklidinen avaruuus equipped with a metric given by the euklidinen etäisyys $d(\mathbf{x}, \mathbf{x}') = \|\mathbf{x} - \mathbf{x}'\|_2$. Another well-known example of a metric space is an undirected graph $\mathcal{G} = (\mathcal{V}, \mathcal{E})$, with the metric $d(i, i')$ defined by the length of the shortest path connecting nodes i and i' .

See also: euklidinen avaruuus, undirected graph, piirreavaruuus.

minimi Given a set of real numbers, the minimum is the smallest of those numbers. Note that for some sets, such as the set of negative real numbers, the minimum does not exist.

mirror descent Mirror descent is an iterative optimointimenetelmä obtained by generalizing the gradienttiaskel. The gradienttiaskel for minimizing a differentiable kohdefunktio $f(\mathbf{w})$, can be written as

$$\mathbf{w}^{(k+1)} = \arg \min_{\mathbf{w}} \langle \nabla f(\mathbf{w}^{(k)}), \mathbf{w} \rangle + \frac{1}{\eta} \|\mathbf{w} - \mathbf{w}^{(k)}\|_2^2.$$

Thus, a gradienttiaskel minimizes a linearization of $f(\cdot)$ penalized by a scaled squared euklidinen normi $\frac{1}{\eta} \|\mathbf{w} - \mathbf{w}^{(k)}\|_2^2$. The scaling factor if the inverse of the oppimisnopeus η used in the gradienttiaskel. Mirror descent replaces the squared euklidinen normi by a Bregman divergence $D_\phi(\cdot, \cdot)$ induced by a strictly convex funkatio $\phi(\cdot)$. This mirror map is typically defined on a convex set $\mathcal{W} \subseteq \mathbb{R}^d$ and is differentiable and strictly convex on the interior of \mathcal{W} [52]. The resulting update becomes

$$\mathbf{w}^{(k+1)} = \arg \min_{\mathbf{w} \in \mathcal{W}} \langle \mathbf{g}^{(k)}, \mathbf{w} \rangle + \frac{1}{\eta} D_\phi(\mathbf{w}, \mathbf{w}^{(k)}).$$

See also: gradienttiaskel, proximal operator, Bregman divergence.

moment generating function (MGF) Consider the MGF $M_x(t)$ of a real-valued satunnaismuuttuja x , which is defined as $M_x(t) = \mathbb{E}\{\exp(t \cdot x)\}$ for any $t \in \mathbb{R}$ for which this odotusarvo exists [6, Sec. 21]. As its name indicates, the MGF allows us to compute the moments $\mathbb{E}\{x^k\}$ for $k \in \mathbb{N}$. In particular, the k th moment is obtained by evaluating the k th derivative of $M_x(t)$ for $t = 0$, i.e., $\mathbb{E}\{x^k\} = M_x^{(k)}(0)$. This fact can be

verified by the following identities:

$$\begin{aligned} M_x(t) &= \mathbb{E}\{\exp(t \cdot x)\} \\ &\stackrel{(a)}{=} \mathbb{E}\left\{\sum_{k=0}^{\infty} \frac{t^k}{k!} x^k\right\} \\ &\stackrel{(b)}{=} \sum_{k=0}^{\infty} \frac{t^k}{k!} \mathbb{E}\{x^k\}. \end{aligned}$$

Here, step (a) is due to the Taylor series expansion of $\exp(t \cdot x)$ and step (b) is valid when the MGF exists for all t in some interval $(-t_0, t_0)$ [6, p. 278].

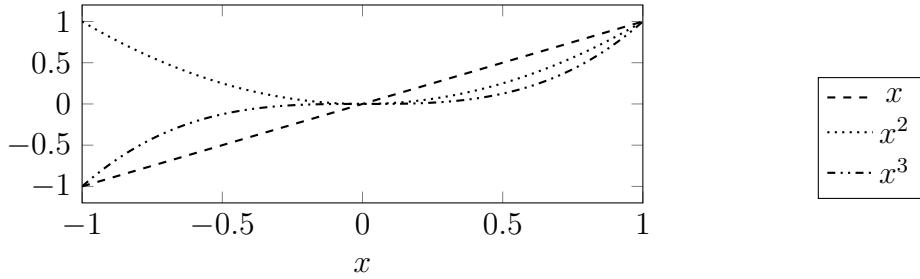


Fig. 38. The first few powers of an satunnaismuuttuja x . The MGF encodes the moments of x , which are the odotusarvot of the powers x^k for $k = 1, 2, \dots$

The MGF is a useful tool for the study of sums of independent satunnaismuuttujat. As a case in point, if x and y are independent satunnaismuuttujat, then the MGF of their sum $z = x + y$ typically satisfies $M_z(t) = M_x(t) M_y(t)$, i.e., the MGF of the sum is typically the pointwise product of the individual MGFs [6, p. 280].

See also: satunnaismuuttuja, odotusarvo.

moninormaalijakauma The multivariate normal distribution, which is de-

noted by $\mathcal{N}(\boldsymbol{\mu}, \mathbf{C})$, is a fundamental todennäköisyysmalli for numerical piirrevektorit of fixed dimension d . It defines a family of todennäköisyysjakaumat over vektori-valued satunnaismuuttujat $\mathbf{x} \in \mathbb{R}^d$ [7], [17], [53]. Each distribution in this family is fully specified by its kesiarvo vektori $\boldsymbol{\mu} \in \mathbb{R}^d$ and kovarianssimatriisi $\mathbf{C} \in \mathbb{R}^{d \times d}$. When the kovarianssimatriisi \mathbf{C} is invertible, the corresponding todennäköisyysjakauma is characterized by the following pdf:

$$p(\mathbf{x}) = \frac{1}{\sqrt{(2\pi)^d \det(\mathbf{C})}} \exp \left[-\frac{1}{2} (\mathbf{x} - \boldsymbol{\mu})^T \mathbf{C}^{-1} (\mathbf{x} - \boldsymbol{\mu}) \right].$$

Note that this pdf is only defined when \mathbf{C} is invertible. More generally, any satunnaismuuttuja $\mathbf{x} \sim \mathcal{N}(\boldsymbol{\mu}, \mathbf{C})$ admits the following representation:

$$\mathbf{x} = \mathbf{A}\mathbf{z} + \boldsymbol{\mu}$$

where $\mathbf{z} \sim \mathcal{N}(\mathbf{0}, \mathbf{I})$ is a standard normal random vector and $\mathbf{A} \in \mathbb{R}^{d \times d}$ satisfies $\mathbf{A}\mathbf{A}^\top = \mathbf{C}$. This representation remains valid even when \mathbf{C} is singular, in which case \mathbf{A} is not full-rank [54, Ch. 23]. The family of multivariate normal distributions is exceptional among todennäköisyysmallit for numerical quantities, at least for the following reasons. First, the family is closed under affine transformations, i.e.,

$$\mathbf{x} \sim \mathcal{N}(\boldsymbol{\mu}, \mathbf{C}) \text{ implies } \mathbf{B}\mathbf{x} + \mathbf{c} \sim \mathcal{N}(\mathbf{B}\boldsymbol{\mu} + \mathbf{c}, \mathbf{B}\mathbf{C}\mathbf{B}^T).$$

Second, the todennäköisyysjakauma $\mathcal{N}(\mathbf{0}, \mathbf{C})$ maximizes the differential entropy among all distributions with the same kovarianssimatriisi \mathbf{C} [30].

See also: todennäköisyysmalli, todennäköisyysjakauma, standard normal

random vector, differential entropy, normaalijakautunut satunnaismuuttuja.

Newtonin menetelmä Newton's method is an iterative optimointimenetelmä for finding local minimi or maksimi of a differentiable kohdefunktio $f(\mathbf{w})$. Like gradient-based methods, Newton's method also computes a new estimate $\hat{\mathbf{w}}_{t+1}$ by optimizing a local approximation of $f(\mathbf{w})$ around the current estimate $\hat{\mathbf{w}}_t$. In contrast to gradient-based methods, which use the gradientti to build a local linear approximation, Newton's method uses the Hessen matriisi matriisi to build a local quadratic approximation. In particular, starting from an initial estimate $\hat{\mathbf{w}}_0$, Newton's method iteratively updates the estimate according to

$$\hat{\mathbf{w}}_{t+1} = \hat{\mathbf{w}}_t - (\nabla^2 f(\hat{\mathbf{w}}_t))^{-1} \nabla f(\hat{\mathbf{w}}_t), \text{ for } t = 0, 1, \dots$$

Here, $\nabla f(\hat{\mathbf{w}}_t)$ is the gradientti, and $\nabla^2 f(\mathbf{w}^{(t)})$ is the Hessen matriisi of the kohdefunktio f . Since using a kvadraattinen funktilo as local approximation is more accurate than using a linear funktilo (which is a special case of a kvadraattinen funktilo), Newton's method tends to converge faster than gradient-based methods (see Fig. 39). However, this faster convergence comes at the increased computational complexity of the iteraatiot. Indeed, each iteraatio of Newton's method requires the inversion of the Hessen matriisi.

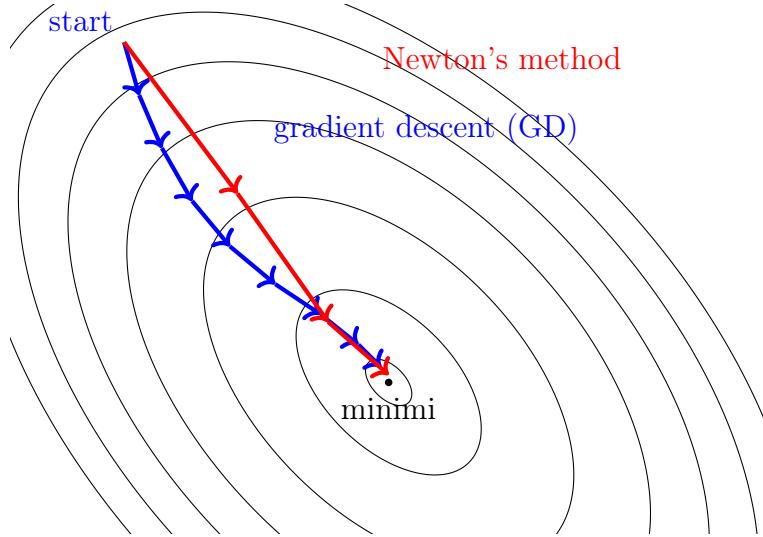


Fig. 39. Comparison of GD (blue) and Newton's method (red) paths toward the minimi of a häviöfunktio.

See also: optimointimenetelmä, gradientti, Hessen matriisi, GD.

nolla-avaruus The nullspace of a matriisi $\mathbf{A} \in \mathbb{R}^{d' \times d}$, denoted by $\text{null}(\mathbf{A})$, is the set of all vektorit $\mathbf{n} \in \mathbb{R}^d$ such that

$$\mathbf{A}\mathbf{n} = \mathbf{0}.$$

Consider a piirreoptimointi method that uses the matriisi \mathbf{A} to transform a piirrevektori $\mathbf{x} \in \mathbb{R}^d$ of a tietopiste into a new piirrevektori $\mathbf{z} = \mathbf{Ax} \in \mathbb{R}^{d'}$. The nullspace $\text{null}(\mathbf{A})$ characterizes all directions in the original piirreavaruus \mathbb{R}^d along which the transformation \mathbf{Ax} remains unchanged. In other words, adding any vektori from the nullspace to a piirrevektori \mathbf{x} does not affect the transformed representation \mathbf{z} . This property can be exploited to enforce invariances in the ennusteet (computed from

\mathbf{Ax}). Fig. 40 illustrates one such invariance. It shows rotated versions of two handwritten digits, which approximately lie along 1-D curves in the original piirreavaruus. These curves are aligned with a direction vektori $\mathbf{n} \in \mathbb{R}^d$. To ensure that the trained malli is invariant to such rotations, we can choose the transformation matriisi \mathbf{A} such that $\mathbf{n} \in \text{null}(\mathbf{A})$. This ensures that \mathbf{Ax} , and hence the resulting ennuste, is approximately insensitive to rotations of the input image.

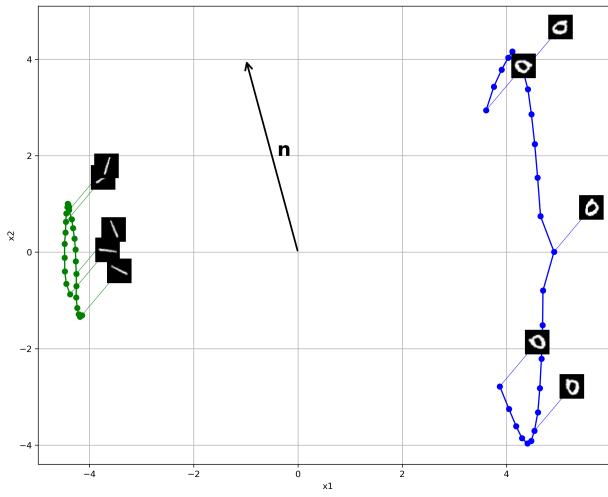


Fig. 40. Rotated handwritings of two different digits. The rotations are approximately aligned along straight lines parallel to the vektori \mathbf{n} . For a binary luokitin distinguishing between these digits, a natural choice is a linear piirrekartta $\mathbf{x} \mapsto \mathbf{Ax}$ with a matriisi \mathbf{A} whose nullspace contains \mathbf{n} , i.e., $\mathbf{n} \in \text{null}(\mathbf{A})$.

See also: matriisi, piirrekartta, piirreoptimointi.

Python demo: [click me](#)

non-expansive operator An operator $\mathcal{F} : \mathcal{H} \rightarrow \mathcal{H}$ defined on a Hilbert

space \mathcal{H} is called non-expansive if it does not increase distances. In other words,

$$\|\mathcal{F}\mathbf{w} - \mathcal{F}\mathbf{w}'\|_2 \leq \|\mathbf{w} - \mathbf{w}'\|_2 \text{ for any } \mathbf{w}, \mathbf{w}' \in \mathcal{H}.$$

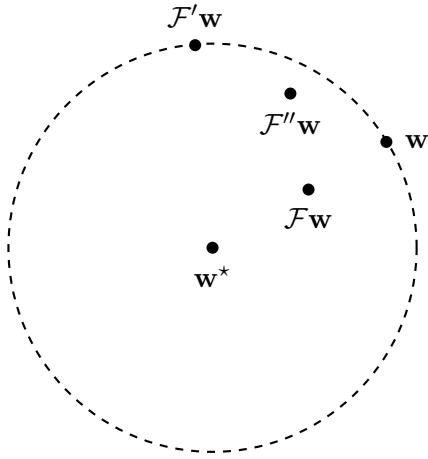


Fig. 41. The result of applying a contractive operator \mathcal{F} , a non-expansive operator \mathcal{F}' and a firmly non-expansive operator \mathcal{F}'' . These operators have the common fixed point \mathbf{w}^* .

Non-expansiveness is not sufficient to guarantee convergence of a fixed-point iteration that uses \mathcal{F} (see Fig. 41).

See also: fixed-point iteration, contractive operator.

non-smooth We refer to a function as non-smooth if it is not smooth [39].

See also: function, smooth.

normaalijakautunut satunnaismuuttuja A standard Gaussian satunnaismuuttuja is a real-valued satunnaismuuttuja x with pdf [7], [25], [17]

$$p(x) = \frac{1}{\sqrt{2\pi}} \exp(-x^2/2).$$

Given a standard Gaussian satunnaismuuttuja x , we can construct a general Gaussian satunnaismuuttuja x' with keskiarvo μ and varianssi σ^2 via $x' := \sigma x + \mu$. The todennäköisyysjakauma of a Gaussian satunnaismuuttuja is referred to as normal distribution, denoted by $\mathcal{N}(\mu, \sigma^2)$.

A Gaussian random vektori $\mathbf{x} \in \mathbb{R}^d$ with kovarianssimatriisi \mathbf{C} and keskiarvo $\boldsymbol{\mu}$ can be constructed as [17], [25], [53]

$$\mathbf{x} := \mathbf{A}\mathbf{z} + \boldsymbol{\mu}$$

where $\mathbf{z} := (z_1, \dots, z_d)^T$ is a vektori of i.i.d. standard Gaussian satunnaismuuttujat, and $\mathbf{A} \in \mathbb{R}^{d \times d}$ is any matriisi satisfying $\mathbf{A}\mathbf{A}^T = \mathbf{C}$. The todennäköisyysjakauma of a Gaussian random vektori is referred to as the moninormaalijakauma, denoted by $\mathcal{N}(\boldsymbol{\mu}, \mathbf{C})$.

We can interpret a Gaussian random vektori $\mathbf{x} = (x_1, \dots, x_d)$ as a satunnaisprosessi indexed by the set $\mathcal{I} = \{1, \dots, d\}$. A Gaussin prosessit is a satunnaisprosessi over an arbitray index set \mathcal{I} such that any restriction to a finite subset $\mathcal{I}' \subseteq \mathcal{I}$ yields a Gaussian random vektori [55].

Gaussian satunnaismuuttujat are widely used todennäköisyysmallit in the statistical analysis of koneoppiminen methods. Their significance arises partly from the keskeinen raja-arvolause which provides conditions under which the average of many independent satunnaismuuttujat (not necessarily Gaussian themselves) tends toward a Gaussian satunnaismuuttuja [18].

The moninormaalijakauma is also distinct in that it represents maksimi epävarmuus. Among all vektori-valued satunnaismuuttujat with a given kovarianssimatriisi \mathbf{C} , the satunnaismuuttuja $\mathbf{x} \sim \mathcal{N}(\boldsymbol{\mu}, \mathbf{C})$ maximizes differential entropy [30, Th. 8.6.5]. This makes Gaussin prosessit a natu-

ral choice for capturing epävarmuus or the lack of (domain) knowledge. See also: moninormaalijakauma, Gaussian prosessi, todennäköisyysmalli, keskeinen raja-arvolause, differential entropy.

normal distribution See normaalijakautunut satunnaismuuttuja.

normal matrix A square matrix $\mathbf{A} \in \mathbb{C}^{d \times d}$ that commutes with its conjugate transpose, i.e., $\mathbf{A}\mathbf{A}^H = \mathbf{A}^H\mathbf{A}$. Normal matrices admit an orthonormal basis of eigenvectors and are unitarily diagonalizable.

normal vector See hyperplane.

normi A norm is a funktion that maps each (vektori) element of a vektoriavaruus to a nonnegative real number. This funktion must be homogeneous and definite, and it must satisfy the triangle inequality [28].
See also: funktion, vektori, vektoriavaruus.

odotusarvon maksimointi The EM algoritmi [56] is an iterative optimointimenetelmä for approximately solving certain suurimman uskottavuuden menetelmä optimointitehtävät that are difficult to solve directly [47, Sec. 9.4], [57, Sec. 11.4.7]. To motivate the EM algoritmi and explain its construction, consider a koneoppiminen application involving a single observed tietopiste with piirre $x \in \mathcal{X}$, where \mathcal{X} is a finite piirreavaruus. The data generation is modeled via a todennäköisyysmalli that consists of a satunnaismuuttuja x' with pmf $p^{(x')}(\cdot; \mathbf{w})$. Here, the actual model parameters $\mathbf{w} \in \mathcal{W}$ - used for the data generation via sampling from $p^{(x')}(\cdot; \mathbf{w})$ - are unknown. A widely used approach for

estimating these model parameters is via the solutions of the suurimman uskottavuuden menetelmä problem

$$\min_{\mathbf{w} \in \mathcal{W}} -\log p^{(x')}(\mathbf{x}; \mathbf{w}). \quad (12)$$

For some todennäköisyysmallit, such as a Gaussian sekoitemalli, this optimointitehtävä can be difficult to solve directly. As a work-around, one can often introduce an auxiliary attribute $y \in \mathcal{Y}$, generated via some satunnaismuuttuja y' , such that the corresponding todennäköisyysmalli $p^{(x',y')}(\cdot, \cdot; \mathbf{w})$ yields a much easier suurimman uskottavuuden menetelmä problem

$$\min_{\mathbf{w} \in \mathcal{W}} -\log p^{(x',y')}(\mathbf{x}, y; \mathbf{w}). \quad (13)$$

The attribute y is introduced solely to simplify (13), but it is not observed in practice—only the feature x is available. Thus, we cannot solve (13) directly as we do not know which value y to plug into the pmf $p^{(x',y')}(\mathbf{x}, y; \mathbf{w})$. The EM method resolves this dilemma by alternating between two steps:

- (**E-step**) computing a “soft” estimate of the auxiliary attribute y in the form of the posterior $p^{(y'|x')}(\cdot; \widehat{\mathbf{w}})$ using the current choice $\widehat{\mathbf{w}}$ for the model parameters, and
- (**M-step**) minimizing a surrogate kohdefunktio derived from this posterior.

The completion of these two steps constitutes one full iteraatio of the EM method. In more detail, the E-step produces the funkatio

$$Q(\mathbf{w} | \widehat{\mathbf{w}}) := - \sum_{y \in \mathcal{Y}} p^{(y'|x')}(\mathbf{y}; \widehat{\mathbf{w}}) \log \left(p^{(x',y')}(\mathbf{x}, \mathbf{y}; \mathbf{w}) / p^{(y'|x')}(\mathbf{y}; \widehat{\mathbf{w}}) \right),$$

and the M-step minimizes $Q(\mathbf{w} \mid \hat{\mathbf{w}})$ over $\mathbf{w} \in \mathcal{W}$. This funktion satisfies two key properties [47, Sec. 9.4], [57, Sec. 11.4.7]:

- **Upper bound:**

$$Q(\mathbf{w} \mid \hat{\mathbf{w}}) \geq -\log p^{(x')}(\mathbf{x}; \mathbf{w}) \quad \text{for all } \mathbf{w} \in \mathcal{W}. \quad (14)$$

- **Tightness:**

$$Q(\hat{\mathbf{w}} \mid \hat{\mathbf{w}}) = -\log p^{(x')}(\mathbf{x}; \hat{\mathbf{w}}). \quad (15)$$

To summarize, during each iteraatio, EM minimizes an upper-bounding surrogate kohdefunktio that is tight at the current iterate $\hat{\mathbf{w}}$. Thus, EM is a majorize–minimize (MM) method for approximately solving (12). The above construction and analysis of EM can be extended to more general settings involving multiple tietopisteet and infinite piirreavaruust such as \mathbb{R}^d ; see [57, Sec. 11.4.7] for details.

See also: todennäköisyysmalli, suurimman uskottavuuden menetelmä, optimointitehtävä.

ominaisfunktio The characteristic funktion of a real-valued satunnaismuuttuja x is the funktion [6, Sec. 26]

$$\phi_x(t) := \mathbb{E}\exp(jtx) \text{ with } j = \sqrt{-1}.$$

The characteristic funktion uniquely determines the todennäköisyysjakauma of x .

See also: satunnaismuuttuja, todennäköisyysjakauma.

operator An operator is a funktion whose domain and co-domain have a specific mathematical structure such as a vektoriavaruus, a Hilbert

space, or a metric space [37], [58]. Many koneoppiminen methods involve operators whose domain and co-domain are euklidinen avaruust.

See also: funktio, vektoriavaruus, Hilbert space.

optimointimenetelmä An optimization method is an algoritmi that takes a representation of an optimointitehtävä as input and computes an (approximate) solution as its tuotos. A central example of an optimointitehtävä in koneoppiminen is ERM. By applying an appropriate optimization method to ERM, we obtain a concrete learning algoritmi [22], [59], [39].

See also: algoritmi, optimointitehtävä.

optimointitehtävä An optimization problem is a mathematical structure consisting of an kohdefunktio $f : \mathcal{U} \rightarrow \mathcal{V}$ defined over an optimization variable $\mathbf{w} \in \mathcal{U}$, together with a feasible set $\mathcal{W} \subseteq \mathcal{U}$. The co-domain \mathcal{V} is assumed to be ordered, meaning that for any two elements $\mathbf{a}, \mathbf{b} \in \mathcal{V}$, we can determine whether $\mathbf{a} \leq \mathbf{b}$ or not. Here, “ \leq ” denotes a general partial order relation, which may differ from the standard numerical order on real numbers [22, Sec. 2.4.]. The goal in optimization is to find those values $\mathbf{w} \in \mathcal{W}$ for which the objective $f(\mathbf{w})$ is extremal—i.e., minimal or maximal [22], [59], [39].

See also: kohdefunktio.

outcome Outcome is one possible result of a physical process. Such a process could be the observation of a physical phenomenon, a computation performed by an algoritmi, or a satunnaiskoe [6].

See also: otosavaruus.

partial derivative Consider a real-valued funktion $f : \mathbb{R}^d \rightarrow \mathbb{R} : \mathbf{x} \mapsto f(\mathbf{x})$.

The partial derivative of $f(\mathbf{x})$ with respect to the entry x_j measures how f changes when x_j varies while all other entries $x_{j'}$, for $j' \in [d] \setminus \{j\}$, are held fixed. It is defined as [2]

$$\frac{\partial f(\mathbf{x})}{\partial x_j} = \lim_{\varepsilon \rightarrow 0} \frac{f(x_1, \dots, x_j + \varepsilon, \dots, x_d) - f(x_1, \dots, x_j, \dots, x_d)}{\varepsilon}.$$

Note that the partial derivative is only defined if this limit exists. For a differentiable funktion, the partial derivatives of f are the entries of the gradientti ∇f .

See also: funktion, derivative, gradientti.

positive semi-definite (psd) A (real-valued) symmetric matrix $\mathbf{Q} = \mathbf{Q}^T \in \mathbb{R}^{d \times d}$ is referred to as psd if $\mathbf{x}^T \mathbf{Q} \mathbf{x} \geq 0$ for every vektori $\mathbf{x} \in \mathbb{R}^d$. A psd matrix \mathbf{Q} admits a spectral decomposition with nonnegative eigenvalues $\lambda_1, \dots, \lambda_d \geq 0$ [28], [29]. The notion of being psd can be extended from matriisit to (real-valued) symmetric ydinfunktio kuvaukset $K : \mathcal{X} \times \mathcal{X} \rightarrow \mathbb{R}$ (with $K(\mathbf{x}, \mathbf{x}') = K(\mathbf{x}', \mathbf{x})$) as follows: For any finite set of piirrevektorit $\mathbf{x}^{(1)}, \dots, \mathbf{x}^{(m)}$, the resulting matriisi $\mathbf{Q} \in \mathbb{R}^{m \times m}$ with entries $Q_{r,r'} = K(\mathbf{x}^{(r)}, \mathbf{x}^{(r')})$ is psd [60].

See also: symmetric matrix, ydinfunktio.

posterior The study and design of koneoppiminen methods is often based on a todennäköisyysmalli for the data generation process. Within a todennäköisyysmalli, we view (the generation of) a tietopiste with piirteet \mathbf{x} and nimiö y as an satunnaismuuttuja with todennäköisyysjakauma $\mathbb{P}^{(\mathbf{x},y)}$. It turns out that the optimal ennuste for the nimiö y , given the

piirrevektori \mathbf{x} , is fully determined by the conditional probability distribution of y given (or conditioned on) \mathbf{x} .

See also: todennäköisyysmalli, conditional probability distribution.

preimage Consider a funktion $f: \mathcal{U} \rightarrow \mathcal{V}$ between two sets. The preimage $f^{-1}(\mathcal{B})$ of a subset $\mathcal{B} \subseteq \mathcal{V}$ is the set of all inputs $u \in \mathcal{U}$ that are mapped into \mathcal{B} by f , i.e.,

$$f^{-1}(\mathcal{B}) := \{u \in \mathcal{U} \mid f(u) \in \mathcal{B}\}.$$

The preimage is well defined even if the funktion f is non-invertible [2].

See also: funktion.

probabilistic principal component analysis (PPCA) PPCA extends basic PCA by using a todennäköisyysmalli for tietopisteet. The todennäköisyysmalli of PPCA frames the task of ulottuvuuksien vähentäminen as an estimation problem that can be solved using odotusarvon maksimointi [61].

See also: PCA, todennäköisyysmalli, ulottuvuuksien vähentäminen, odotusarvon maksimointi.

probability density function (pdf) The pdf $p^{(x)}(\cdot)$ of a continuous real-valued satunnaismuuttuja $x \in \mathbb{R}$ allows to compute the todennäköisyys $\mathbb{P}(x \in \mathcal{B})$ (of the event $\mathcal{B} \subseteq \mathbb{R}$) via a Lebesgue integral [7, Ch. 3]

$$\mathbb{P}(x \in \mathcal{B}) = \int_{\mathcal{B}} p^{(x)}(\eta) d\eta.$$

This definition extends naturally to a (continuous) vector-valued satunnaismuuttuja $\mathbf{x} \in \mathbb{R}^d$ as the Lebesgue integral is defined for \mathbb{R}^d with

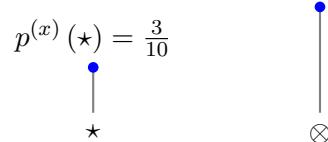
any dimension d .

See also: satunnaismuuttuja, todennäköisyysjakauma, todennäköisyys, measurable, vektori.

probability mass function (pmf) The pmf of a discrete RV x is a funktion $p^{(x)}(\cdot) : \mathcal{X} \rightarrow [0, 1]$ that assigns to each possible value $x' \in \mathcal{X}$ of the satunnaismuuttuja x the todennäköisyys $p^{(x)}(x') = \mathbb{P}(x' = x)$ [25]. Fig. 42 illustrates the pmf of a discrete RV x .

$$\mathcal{D}'' = (\otimes, \otimes, \otimes, \star, \otimes, \star, \otimes, \otimes, \star, \otimes)$$

$$\mathcal{D}' = (\otimes, \star, \otimes, \star, \otimes, \star, \otimes, \otimes, \otimes)$$



$$\mathcal{D} = (\star, \star, \star, \otimes, \otimes, \otimes, \otimes, \otimes, \otimes)$$

Fig. 42. The pmf $p^{(x)}(\cdot)$ of a discrete RV x taking values in the set $\mathcal{X} = \{\star, \otimes\}$. Three tietoaineistot are also shown whose relative frequencies of tietopisteet match this pmf exactly. Such tietoaineistot could arise as toteumat of i.i.d. satunnaismuuttujat sharing the common pmf $p^{(x)}(\cdot)$.

A pmf always satisfies $\sum_{x' \in \mathcal{X}} p^{(x)}(x') = 1$. We can view a pmf as representing a collection of (sufficiently long) tietoaineistot. This collection contains any $\mathcal{D} = \{x^{(1)}, \dots, x^{(m)}\}$, with the relative frequencies of every value $x' \in \mathcal{X}$ being close to the corresponding pmf value $p^{(x)}(x')$,

$$\frac{|r \in \{1, \dots, m\} : x^{(r)} = x'|}{m} \approx p^{(x)}(x').$$

Note that requiring relative frequencies to be close to the pmf values implies that the empirical entropia of such a tietoaineisto is close to the entropia of the pmf $p^{(x)}(\cdot)$. Information theory refers to the collection of such tietoaineistot as the typical set corresponding to the pmf $p^{(x)}(\cdot)$ [30]. A main result of information theory states that a tietoaineisto generated by i.i.d. sampling from $p^{(x)}(\cdot)$ belongs, with high todennäköisyys, to the typical set with respect to $p^{(x)}(\cdot)$ [30, Th. 3.1.2]. See also: discrete RV, todennäköisyys, todennäköisyysjakauma, todennäköisyysmalli.

probability simplex The todennäköisyys simplex Δ^{k-1} is the set of all vektorit in \mathbb{R}^k with nonnegative entries that sum to one [22]. Each element of Δ^{k-1} represents a pmf of an satunnaismuuttuja $y \in \{1, \dots, k\}$.
See also: todennäköisyys, vektori, pmf, satunnaismuuttuja.

probability space A todennäköisyys space is a mathematical structure that allows us to reason about a satunnaiskoe, e.g., the observation of a physical phenomenon. Formally, a todennäköisyys space \mathcal{P} is a triplet $(\Omega, \mathcal{F}, \mathbb{P}(\cdot))$ where

- Ω is a otosavaruus containing all possible outcomes of a satunnaiskoe;
- \mathcal{F} is a σ -algebra, i.e., a collection of subsets of Ω (called events) that satisfies certain closure properties under set operations;
- $\mathbb{P}(\cdot)$ is a todennäköisyysjakauma, i.e., a funktion that assigns a todennäköisyys $\mathbb{P}(\mathcal{A}) \in [0, 1]$ to each event $\mathcal{A} \in \mathcal{F}$. This funktion

must satisfy $\mathbb{P}(\Omega) = 1$ and $\mathbb{P}(\bigcup_{i=1}^{\infty} \mathcal{A}_i) = \sum_{i=1}^{\infty} \mathbb{P}(\mathcal{A}_i)$ for any countable sequence of pairwise disjoint events $\mathcal{A}_1, \mathcal{A}_2, \dots$ in \mathcal{F} .

Todennäköisyys spaces provide the foundation of todennäköisyysmallit that can be used to study the behavior of koneoppiminen methods [6], [17], [18].

See also: todennäköisyys, satunnaiskoe, otosavaruus, event, todennäköisyysjakauma, funktio, todennäköisyysmalli, koneoppiminen.

projected gradient descent (projected GD) Consider an ERM-based method that uses a parameterized malli with parameter space $\mathcal{W} \subseteq \mathbb{R}^d$. Even if the kohdefunktio of ERM is smooth, we cannot use basic GD, as it does not take into account constraints on the optimization variable (i.e., the model parameters). Projected GD extends basic GD to address this issue. A single iteration of projected GD consists of first taking a gradienttiaskel and then projecting the result back onto the parameter space. See Fig. 43 for a visual illustration.

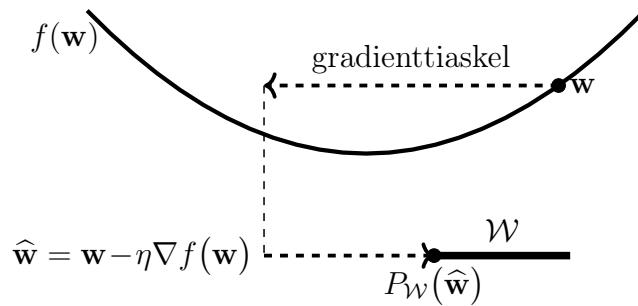


Fig. 43. Projected GD augments a basic gradienttiaskel with a projektio back onto the constraint set \mathcal{W} .

See also: ERM, malli, parameter space, kohdefunktio, smooth, GD, model parameter, gradienttiaskel, projektio.

projektiot Consider a bounded subset $\mathcal{W} \subseteq \mathbb{R}^d$ of the d -dimensional euklidinen avaruuus. We define the projection $P_{\mathcal{W}}(\mathbf{w})$ of a vektori $\mathbf{w} \in \mathbb{R}^d$ onto \mathcal{W} as

$$P_{\mathcal{W}}(\mathbf{w}) = \arg \min_{\mathbf{w}' \in \mathcal{W}} \|\mathbf{w} - \mathbf{w}'\|_2.$$

In other words, $P_{\mathcal{W}}(\mathbf{w})$ is the vektori in \mathcal{W} that is closest to \mathbf{w} . The projection is only well defined for subsets \mathcal{W} for which the above minimi exists [22].

See also: euklidinen avaruuus, vektori, minimi.

proximable A convex funktilo for which the proximal operator can be computed efficiently is sometimes referred to as proximable or simple [62].
See also: convex, funktilo, proximal operator.

proximal operator Given a convex funktilo $f(\mathbf{w}')$, we define its proximal operator as [37], [21]

$$\text{prox}_{f(\cdot), \rho}(\mathbf{w}) := \arg \min_{\mathbf{w}' \in \mathbb{R}^d} \left[f(\mathbf{w}') + \frac{\rho}{2} \|\mathbf{w} - \mathbf{w}'\|_2^2 \right] \text{ with } \rho > 0.$$

As illustrated in Fig. 44, evaluating the proximal operator amounts to minimizing a penalized variant of $f(\mathbf{w}')$. The penalty term is the scaled squared euklidinen etäisyys to a given vektori \mathbf{w} (which is the input to the proximal operator). The proximal operator can be interpreted as a yleistys of the gradienttiaskel, which is defined for a smooth convex funktilo $f(\mathbf{w}')$. Indeed, taking a gradienttiaskel with step size η at the

current vektori \mathbf{w} is the same as applying the proximal operator of the funktio $\tilde{f}(\mathbf{w}') = (\nabla f(\mathbf{w}))^T(\mathbf{w}' - \mathbf{w})$ and using $\rho = 1/\eta$.

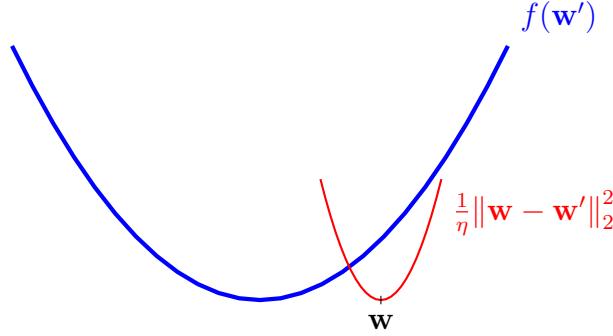


Fig. 44. The proximal operator updates a vektori \mathbf{w} by minimizing a penalized version of the funktio $f(\cdot)$. The penalty term is the scaled squared euklidinen etäisyys between the optimization variable \mathbf{w}' and the given vektori \mathbf{w} .

See also: convex, funktio, gradienttiaskel.

pseudokäänteisluku The Moore–Penrose pseudoinverse \mathbf{A}^+ of a matriisi $\mathbf{X} \in \mathbb{R}^{m \times d}$ generalizes the notion of an käänteismatriisi [3]. The pseudoinverse arises naturally in harjaregressio for a tietoaineisto with feature matrix \mathbf{X} and label vector \mathbf{y} [63, Ch. 3]. The model parameters learned by harjaregressio are given by

$$\hat{\mathbf{w}}^{(\alpha)} = (\mathbf{X}^T \mathbf{X} + \alpha \mathbf{I})^{-1} \mathbf{X}^T \mathbf{y}, \quad \alpha > 0.$$

We can then define the pseudoinverse $\mathbf{X}^+ \in \mathbb{R}^{d \times m}$ via the limit [64, Ch. 3]

$$\lim_{\alpha \rightarrow 0^+} \hat{\mathbf{w}}^{(\alpha)} = \mathbf{X}^+ \mathbf{y}.$$

See also: matriisi, käänteismatriisi, harjaregressio.

random geometric graph (RGG) An RGG is a todennäköisyysmalli for verkot built from nodes randomly placed in a metric space. Given a metric space, the RGG is characterized by the number of nodes, the connection radius, and the todennäköisyysjakauma describing the node placement. More precisely, for a node set $i = 1, \dots, n$, each node i is assigned to a random position $\mathbf{x}^{(i)} \in \mathcal{X}$, typically as toteumat of i.i.d. satunnaismuuttujat taking values in a set \mathcal{X} . Together with a metric, this forms a metric space, often with the metric induced by a normi. A specific toteuma of an RGG contains an edge $\{i, i'\}$ if and only if the distance between the nodes with respect to the metric is smaller than some threshold, i.e., when $d(\mathbf{x}^{(i)}, \mathbf{x}^{(i')}) \leq r$ for some threshold $r > 0$, as illustrated in Fig. 45.

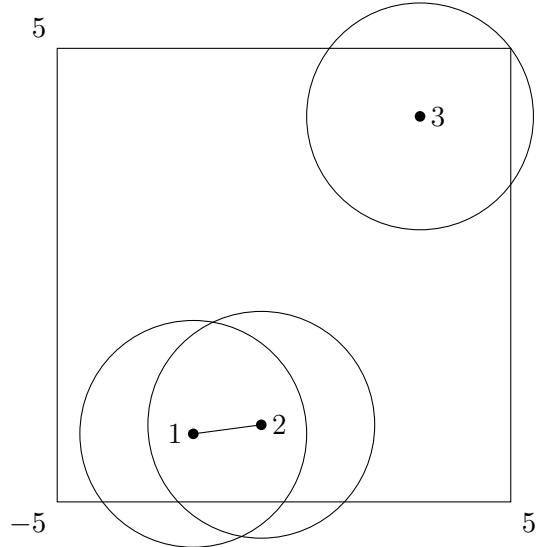


Fig. 45. Illustration of an RGG with $\mathcal{X} = [-5, 5] \times [-5, 5] \subset \mathbb{R}^2$ and radius $r = 2.5$ (with respect to the euklidinen etäisyys), where nodes 1 and 2 (corresponding to $(-2.0, -3.5)^T$ and $(-0.5, -3.3)^T$, within radius $r = 2.5$) are connected, while node 3 (corresponding to $(3.0, 3.5)^T$) has no other node within that distance.

See also: verkko, stokastinen lohkomalli, Erdős–Rényi -verkko (ER-verkko).

rank The rank of a matriisi $\mathbf{A} \in \mathbb{R}^{m \times d}$, denoted as $\text{rank } \mathbf{A}$, is the maksimi number of linearly independent columns of \mathbf{A} [31]. Equivalently, the rank can be defined as the dimension of the column space $\text{span}(\mathbf{A}) = \{\mathbf{Aw} \text{ for some } \mathbf{w} \in \mathbb{R}^d\}$. The rank of a matriisi $\mathbf{A} \in \mathbb{R}^{m \times d}$ can neither exceed the number of rows nor the number of columns of \mathbf{A} [45], [65], i.e., $\text{rank } \mathbf{A} \leq \min\{m, d\}$.

See also: matriisi, dimension, column space, lineaarikuvaus.

rank-deficient A matriisi $\mathbf{A} \in \mathbb{R}^{m \times d}$ is rank-deficient if it is not full-rank, i.e., when $\text{rank } \mathbf{A} < \min\{m, d\}$.

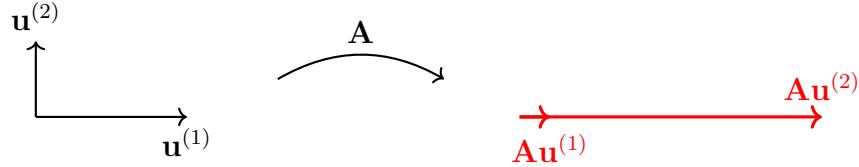


Fig. 46. Example of a rank-deficient matriisi $\mathbf{A} \in \mathbb{R}^{2 \times 2}$.

In lineaarinen regressio, the solution of the ERM problem is not unique whenever the feature matrix \mathbf{X} is such that the matriisi $\mathbf{X}^\top \mathbf{X}$ is rank-deficient.

See also: full-rank, dimension, vektoriavaruus.

Rényi divergence The Rényi divergence measures the (dis)similarity between two todennäköisyysjakaumat [66].

See also: todennäköisyysjakauma.

sample In the context of koneoppiminen, a sample is a finite sequence (of length m) of tietopisteet $\mathbf{z}^{(1)}, \dots, \mathbf{z}^{(m)}$. The number m is called the sample size. ERM-based methods use a sample to train a malli (or learn a hypoteesi) by minimizing the average häviö (i.e., the empiirinen riski) over that sample. Since a sample is defined as a sequence, the same tietopiste may appear more than once. By contrast, some authors in statistics define a sample as a set of tietopisteet, in which case duplicates are not allowed [67], [68]. These two views (i.e., sequence versus set)

can be reconciled by regarding a sample as a sequence of piirre–nimiö pairs, $(\mathbf{x}^{(1)}, y^{(1)})$, \dots , $(\mathbf{x}^{(m)}, y^{(m)})$. The r th pair consists of the piirteet $\mathbf{x}^{(r)}$ and the nimiö $y^{(r)}$ of an unique underlying tietopiste $\tilde{\mathbf{z}}^{(r)}$. While the underlying tietopisteet $\tilde{\mathbf{z}}^{(1)}, \dots, \tilde{\mathbf{z}}^{(m)}$ are unique, some of them can have identical piirteet and nimiöt.

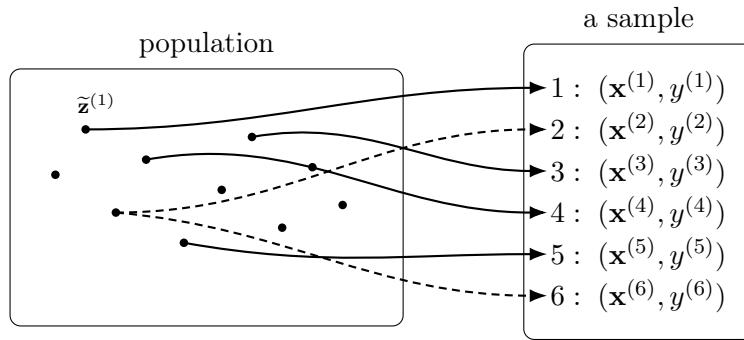


Fig. 47. A sample viewed as a finite sequence. Each element of this sample consists of the piirrevektori and the nimiö of a tietopiste from an underlying population. The same tietopiste may occur more than once in the sample.

For the analysis of koneoppiminen methods, it is common to interpret (the generation of) a sample as the toteuma of a satunnaisprosessi indexed by $\{1, \dots, m\}$. A widely used assumption is the i.i.d. olettamus, where sample elements $(\mathbf{x}^{(r)}, y^{(r)})$, for $r = 1, \dots, m$, are i.i.d. satunnaismuuttujat with a common todennäköisyysjakauma.

See also: sequence, i.i.d. olettamus, tietoaineisto.

sample covariance matrix Consider a tietoaineisto consisting of tietopisteet characterized by piirrevektorit $\mathbf{x}^{(1)}, \dots, \mathbf{x}^{(m)} \in \mathbb{R}^d$. The sample

kovarianssi matriisi of \mathcal{D} is defined as the kovarianssimatriisi with respect to the empirical distribution $\mathbb{P}^{(\mathcal{D})}$ induced by \mathcal{D} . It is given explicitly by

$$\widehat{\mathbf{C}} = \frac{1}{m} \sum_{r=1}^m (\mathbf{x}^{(r)} - \widehat{\mathbf{m}})(\mathbf{x}^{(r)} - \widehat{\mathbf{m}})^T.$$

Here, we use the otoskeskiarvo $\widehat{\boldsymbol{\mu}}$.

See also: kovarianssi, matriisi, satunnaismuuttuja.

satunnaiskoe A random experiment is a physical (or abstract) process that produces an outcome ω from a set Ω of possibilities. This set of all possible outcomes is referred to as the otosavaruus of the experiment. The key characteristic of a random experiment is that its outcome is unpredictable (or uncertain). Any measurement or observation of the outcome is a satunnaismuuttuja, i.e., a funktion of the outcome $\omega \in \Omega$. Todennäköisyys theory uses a probability space as a mathematical structure for the study of random experiments. A key conceptual property of a random experiment is that it can be repeated under identical conditions. Strictly speaking, repeating a random experiment a given number of m times defines a new random experiment. The outcomes of this new experiment are length- m sequences of outcomes from the original experiment (see Fig. 48). While the outcome of a single experiment is uncertain, the long-run behaviour of the outcomes of repeated experiments tends to become increasingly predictable. This informal claim can be made precise via fundamental results of todennäköisyys theory, such as the law of large numbers and the keskeinen raja-arvolause.

new random experiment with $\Omega' = \Omega \times \dots \times \Omega$

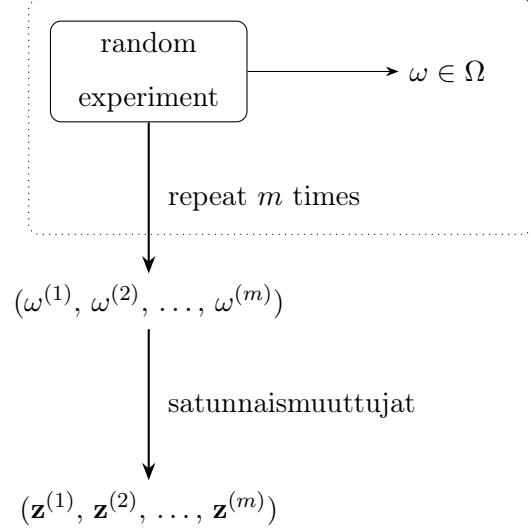


Fig. 48. A random experiment produces an outcome $\omega \in \Omega$ from a set of possibilities (i.e., a otosavaruus) Ω . Repeating the experiment m times yields another random experiment, whose outcomes are sequences $(\omega^{(1)}, \omega^{(2)}, \dots, \omega^{(m)}) \in \Omega \times \dots \times \Omega$. One example of a random experiment arising in many koneoppiminen applications is the gathering of a opetusaineisto $\mathbf{z}^{(1)}, \dots, \mathbf{z}^{(m)}$.

Examples for random experiments arising in koneoppiminen applications include the following:

- Data collection: The tietopisteet collected in ERM-based methods can be interpreted as satunnaismuuttujat, i.e., as funktiot of the outcome $\omega \in \Omega$ of a random experiment.
- Stochastic gradient descent (SGD) uses a random experiment at

each iteration to select a subset of the opetusaineisto.

- Yksityisyyden suoja methods use random experiments to perturb the tuotokset of an koneoppiminen method to ensure differentiaali-nen yksityisyyss.

See also: outcome, otosavaruus, satunnaismuuttuja, todennäköisyys, probability space.

satunnaismuuttuja An RV is a funktion that maps the outcomes of a satunnaiskoe to elements of a measurable space [6], [17]. Mathematically, an RV is a funktion $x : \Omega \rightarrow \mathcal{X}$ whose domain is the otosavaruus Ω of a probability space and whose co-domain is a measurable space \mathcal{X} . Different types of RVs include

- binary RVs, which map each outcome to an element of a binary set (e.g., $\{-1, 1\}$ or $\{\text{cat}, \text{no cat}\}$);
- discrete RVs, which take on values in a countable set (which can be finite or countably infinite);
- real-valued RVs, which take on values in the real numbers \mathbb{R} ;
- vektori-valued RVs, which map outcomes to the euklidinen avaruuus \mathbb{R}^d .

Todennäköisyys theory uses the concept of measurable spaces to rigorously define and study the properties of collections of RVs [6].

See also: funktion, satunnaiskoe, otosavaruus, probability space, vektori, euklidinen avaruuus, todennäköisyys, measurable.

satunnaisprosessi A stokastinen process is a collection of satunnaismuuttujat defined on a common probability space and indexed by some set \mathcal{I} [17], [25], [69]. The index set \mathcal{I} typically represents time or space, allowing us to represent random phenomena that evolve across time or spatial dimensions—for example, sensor noise or financial time series. Stokastinen processes are not limited to temporal or spatial settings. For instance, random verkot such as the ER-verkko or the stokastinen lohkomalli can also be viewed as stokastinen processes. Here, the index set \mathcal{I} consists of node pairs that index satunnaismuuttujat whose values encode the presence or weight of an edge between two nodes. Moreover, stokastinen processes naturally arise in the analysis of satunnaisalgoritmit, such as SGD, which construct a sequence of satunnaismuuttujat. See also: satunnaismuuttuja, stokastinen lohkomalli, SGD, epävarmuus, todennäköisyyssmalli.

Schur decomposition Every square matriisi $\mathbf{A} \in \mathbb{C}^{d \times d}$ admits a Schur decomposition [3, Thm. 7.1.3]

$$\mathbf{A} = \mathbf{U}\mathbf{T}\mathbf{U}^H.$$

Here, $\mathbf{U} \in \mathbb{C}^{d \times d}$ is a unitary matrix (i.e., $\mathbf{U}^H\mathbf{U} = \mathbf{I}$) and \mathbf{T} is upper triangular with the eigenvalues of \mathbf{A} on its diagonal. Carefully note that the Schur decomposition exists also for a matriisi \mathbf{A} that is not diagonalizable,

See also: EVD, eigenvalue, matriisi.

sequence A sequence is an ordered collection of values from a set \mathcal{A} . For

$$(\mathbf{U}^{(1)})^H \mathbf{A} \mathbf{U}^{(1)} = \begin{pmatrix} (\mathbf{x}^{(1)})^H \\ (\mathbf{X}^{(2)})^H \end{pmatrix} \mathbf{A} \begin{pmatrix} \mathbf{x}^{(1)} & \mathbf{X}^{(2)} \end{pmatrix} = \begin{pmatrix} \lambda_1 & \mathbf{b}^H \\ 0 & \mathbf{A}^{(1)} \end{pmatrix},$$

Fig. 49. The first step in the construction of the Schur decomposition. Every matriisi $\mathbf{A} \in \mathbb{C}^{n \times n}$ has at least one eigenvalue λ_1 with unit-norm eigenvector $\mathbf{x}^{(1)}$, $\mathbf{A}\mathbf{x}^{(1)} = \lambda_1\mathbf{x}^{(1)}$. This eigenvector allows to decompose \mathbf{A} as depicted. Here, we extended $\mathbf{x}^{(1)}$ to an orthonormal basis $\mathbf{Q}^{(1)} = (\mathbf{x}^{(1)} | \mathbf{X}^{(2)})$ and used $\mathbf{b}^H := (\mathbf{x}^{(1)})^H \mathbf{A} \mathbf{X}^{(2)}$ and $\mathbf{A}^{(1)} := (\mathbf{X}^{(2)})^H \mathbf{A} \mathbf{X}^{(2)}$. Applying the same construction recursively to $\mathbf{A}^{(1)}$ yields the Schur decomposition.

example, a sequence of values from the set $\mathcal{A} = \{\star, \otimes\}$ could be

$$a = (\star, \otimes, \star, \star, \otimes, \dots).$$

Formally, a sequence a is a funktion [2]

$$a : \mathbb{N} \rightarrow \mathcal{A} : r \mapsto a_r.$$

We denote a sequence by $(a_r)_{r \in \mathbb{N}}$ or $(a^{(r)})_{r \in \mathbb{N}}$. Sometimes we also use the notation $\{a^{(r)}\}_{r \in \mathbb{N}}$. Note that the same value $a \in \mathcal{A}$ can appear multiple times in the sequence at different positions r . Sequences are fundamental for the study of komeoppiminen methods, for instance when describing successive iterates $\{\mathbf{w}^{(t)}\}_{t \in \mathbb{N}}$ of an iterative algoritmi. We can also use a sequence to represent an infinite tietoaineisto

$$\mathcal{D} = \{ (\mathbf{x}^{(1)}, y^{(1)}), (\mathbf{x}^{(2)}, y^{(2)}), \dots \}.$$

See also: funktion, tietoaineisto.

σ -algebra Consider a satunnaiskoe with a otosavaruus Ω . A σ -algebra (or σ -field) Σ is a collection of subsets of Ω with the following properties [1], [6], [16]:

- The empty set \emptyset and the entire otosavaruus Ω belong to Σ , i.e., $\emptyset \in \Sigma$ and $\Omega \in \Sigma$.
- If a set \mathcal{A} belongs to Σ , then its complement $\Omega \setminus \mathcal{A}$ also belongs to Σ , i.e., $\mathcal{A} \in \Sigma$ implies $\Omega \setminus \mathcal{A} \in \Sigma$.
- If a countable collection of sets $\mathcal{A}_1, \mathcal{A}_2, \dots$ belongs to Σ , then their union also belongs to Σ , i.e., $\mathcal{A}_1, \mathcal{A}_2, \dots \in \Sigma$ implies $\bigcup_{i=1}^{\infty} \mathcal{A}_i \in \Sigma$.

See also: otosavaruus, satunnaismuuttuja, probability space.

σ -field See σ -algebra.

simple function A simple funktilo $f : \mathbb{R}^d \rightarrow \mathbb{R}$ is a measurable funktilo that takes on only finitely many values. In other words,

$$f(\mathbf{x}) = \sum_{c=1}^k \alpha_c \mathbb{I}^{(\mathcal{C}^{(c)})}(\mathbf{x})$$

where $\mathbb{I}_{\mathcal{C}}$ denotes the indicator funktilo of a subset $\mathcal{C} \subset \mathbb{R}^d$ and $\alpha_1, \dots, \alpha_k \in \mathbb{R}$ are arbitrary coefficients. The subsets $\mathcal{C}^{(1)}, \dots, \mathcal{C}^{(k)}$ in the above decomposition must be measurable and must form a partition of \mathbb{R}^d .

See also: measurable, Lebesgue integral.

singular value decomposition (SVD) The SVD for a matriisi $\mathbf{A} \in \mathbb{R}^{m \times d}$ is a factorization of the form

$$\mathbf{A} = \mathbf{V} \boldsymbol{\Lambda} \mathbf{U}^T$$

with orthonormal matriisit $\mathbf{V} \in \mathbb{R}^{m \times m}$ and $\mathbf{U} \in \mathbb{R}^{d \times d}$ [3]. The matriisi $\mathbf{\Lambda} \in \mathbb{R}^{m \times d}$ is only nonzero along the main diagonal, whose entries $\Lambda_{j,j}$ are nonnegative and referred to as singular values.

See also: matriisi.

smooth A real-valued funktion $f : \mathbb{R}^d \rightarrow \mathbb{R}$ is smooth if it is differentiable and its gradientti $\nabla f(\mathbf{w})$ is continuous at all $\mathbf{w} \in \mathbb{R}^d$ [39], [52]. A smooth funktion f is referred to as β -smooth if the gradientti $\nabla f(\mathbf{w})$ is Lipschitz continuous with Lipschitz constant β , i.e.,

$$\|\nabla f(\mathbf{w}) - \nabla f(\mathbf{w}')\| \leq \beta \|\mathbf{w} - \mathbf{w}'\|, \text{ for any } \mathbf{w}, \mathbf{w}' \in \mathbb{R}^d.$$

The constant β quantifies the smoothness of the funktion f : the smaller the β , the smoother f is. Optimointitehtävät with a smooth kohdefunktion can be solved effectively by gradient-based methods. Indeed, gradient-based methods approximate the kohdefunktion locally around a current choice \mathbf{w} using its gradientti. This approximation works well if the gradientti does not change too rapidly. We can make this informal claim precise by studying the effect of a single gradienttiajaskel with step size $\eta = 1/\beta$ (see Fig. 50).

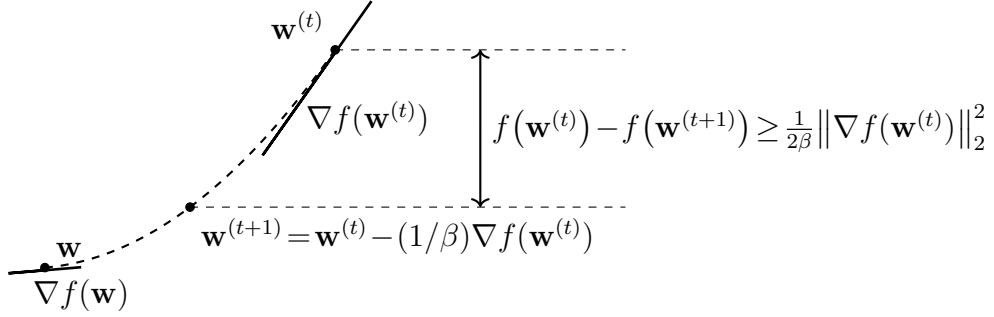


Fig. 50. Consider an kohdefunktio $f(\mathbf{w})$ that is β -smooth. Taking a gradienttiaskel, with step size $\eta = 1/\beta$, decreases the objective by at least $1/2\beta \|\nabla f(\mathbf{w}^{(t)})\|_2^2$ [39], [52], [70]. Note that the step size $\eta = 1/\beta$ becomes larger for smaller β . Thus, for smoother kohdefunktiot (i.e., those with smaller β), we can take larger steps.

See also: funktio, differentiable, gradientti, gradient-based method.

solmun aste The degree $d^{(i)}$ of a node $i \in \mathcal{V}$ in an undirected graph is the number of its naapurit, i.e., $d^{(i)} := |\mathcal{N}^{(i)}|$.

See also: undirected graph, naapuri.

spectral decomposition Every normal matrix $\mathbf{A} \in \mathbb{C}^{d \times d}$ admits a spectral decomposition of the form [28, 29]

$$\mathbf{A} = (\mathbf{u}^{(1)}, \dots, \mathbf{u}^{(d)}) \begin{pmatrix} \lambda_1 & & 0 \\ & \lambda_2 & \\ & & \ddots \\ 0 & & & \lambda_d \end{pmatrix} \begin{pmatrix} (\mathbf{u}^{(1)})^H \\ \vdots \\ (\mathbf{u}^{(d)})^H \end{pmatrix} = \sum_{j=1}^d \lambda_j \mathbf{u}^{(j)} (\mathbf{u}^{(j)})^H$$

with an orthonormal basis $\mathbf{u}^{(1)}, \dots, \mathbf{u}^{(d)}$. Each basis element $\mathbf{u}^{(j)}$ is an

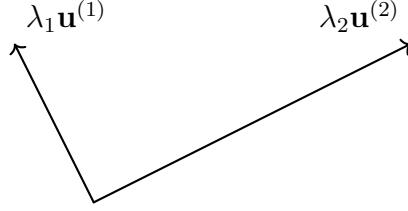


Fig. 51. The spectral decomposition of a normal matrix \mathbf{A} provides an orthonormal basis $\mathbf{u}^{(1)}, \mathbf{u}^{(2)}$. Applying \mathbf{A} amounts to a scaling of the basis vektorit by the eigenvalues λ_1, λ_2 .

eigenvector of \mathbf{A} with corresponding eigenvalue λ_j , for $j = 1, \dots, d$.

standard deviation The standard deviation of a real-valued satunnaismuuttuja x is defined as the square root of its varianssi, i.e., $\sqrt{\mathbb{E}\{(x - \mathbb{E}\{x\})^2\}}$.
See also: satunnaismuuttuja, varianssi, odotusarvo.

standard normal random vector A standard normal random vektori is a satunnaismuuttuja $\mathbf{x} = (x_1, \dots, x_d)^T$ whose entries are i.i.d. normaalijakautuneet satunnaismuuttujat $x_j \sim \mathcal{N}(0, 1)$. The todennäköisyysjakauma of a standard normal random vektori is a special case of a moninormaalijakauma, $\mathbf{x} \sim \mathcal{N}(\mathbf{0}, \mathbf{I})$.

See also: vektori, i.i.d., normaalijakautunut satunnaismuuttuja, moninormaalijakauma, satunnaismuuttuja.

state space The state space of a system is a set that contains all possible states of a system at a given time step. A state is a mathematical representation of the information that characterizes the system. States may be fully observed, partially observed, or latent. State spaces are used across a wide range of koneoppiminen techniques, including todennäköi-

syysmallit and vahvistusoppiminen.

See also: piirrevektori, hypoteesi, action, vahvistusoppiminen.

stokastinen We refer to a method as stochastic if it involves a random component or is governed by probabilistic laws. Koneoppiminen methods use randomness to reduce computational complexity (e.g., see SGD) or to capture epävarmuus in todennäköisyysmallit.

See also: SGD, epävarmuus, todennäköisyysmalli.

strictly convex A real-valued funktio $f(\mathbf{x})$ is strictly convex if for any two distinct \mathbf{x}, \mathbf{y} in its domain and any $\lambda \in (0, 1)$ it satisfies [22, Def. 3.1.1]

$$f(\lambda\mathbf{x} + (1 - \lambda)\mathbf{y}) < \lambda f(\mathbf{x}) + (1 - \lambda)f(\mathbf{y}).$$

Equivalently, for any $\mathbf{x} \neq \mathbf{y}$,

$$f(\mathbf{y}) > f(\mathbf{x}) + \nabla f(\mathbf{x})^T(\mathbf{y} - \mathbf{x}),$$

which implies that $f(\cdot)$ admits a unique minimizer on any convex subset of its domain. Unlike strongly convex funktiot, strictly convex funktiot do not require a uniform quadratic lower bound.

See also: convex, strongly convex.

strongly convex A continuously differentiable real-valued funktio $f(\mathbf{x})$ is strongly convex with coefficient σ if $f(\mathbf{y}) \geq f(\mathbf{x}) + \nabla f(\mathbf{x})^T(\mathbf{y} - \mathbf{x}) + (\sigma/2)\|\mathbf{y} - \mathbf{x}\|_2^2$ [39], [70, Sec. B.1.1].

See also: differentiable, funktio, convex.

subgradient For a real-valued funktio $f : \mathbb{R}^d \rightarrow \mathbb{R} : \mathbf{w} \mapsto f(\mathbf{w})$, a vektori \mathbf{a} such that $f(\mathbf{w}) \geq f(\mathbf{w}') + (\mathbf{w} - \mathbf{w}')^T \mathbf{a}$ is referred to as a subgradient

of f at \mathbf{w}' [33], [59].

See also: funktio, vektori.

subspace A subset of a vektoriavaruus \mathcal{V} is a subspace of \mathcal{V} if it is also a vektoriavaruus with respect to the same operations as \mathcal{V} .

See also: vektoriavaruus.

supremum (or least upper bound) The supremum of a set of real numbers is the smallest number that is greater than or equal to every element in the set. More formally, a real number a is the supremum of a set $\mathcal{A} \subseteq \mathbb{R}$ if: 1) a is an upper bound of \mathcal{A} ; and 2) no number smaller than a is an upper bound of \mathcal{A} . Every non-empty set of real numbers that is bounded above has a supremum, even if it does not contain its supremum as an element [2, Sec. 1.4].

symmetric matrix A square matriisi \mathbf{A} with real-valued entries that is equal to its transpose, i.e., $\mathbf{A} = \mathbf{A}^T$. Every symmetric matriisi is a normal matrix.

tall matrix A matriisi $\mathbf{X} \in \mathbb{R}^{m \times d}$ is referred to as tall if it has more rows than columns, i.e., when $m > d$.

$$m \left\{ \begin{array}{c} \text{X} \in \mathbb{R}^{m \times d} \\ \hline \end{array} \right. \underbrace{\phantom{\text{X} \in \mathbb{R}^{m \times d}}}_{d}$$

See also: matriisi.

todennäköisyysjakauma To analyze koneoppiminen methods, it can be useful to interpret tietopisteet as i.i.d. toteumat of a satunnaismuuttuja. The typical properties of such tietopisteet are then governed by the todennäköisyys distribution of this satunnaismuuttuja. The todennäköisyys distribution of a binary satunnaismuuttuja $y \in \{0, 1\}$ is fully specified by the todennäköisyydet $\mathbb{P}(y = 0)$ and $\mathbb{P}(y = 1) = 1 - \mathbb{P}(y = 0)$. The todennäköisyys distribution of a real-valued satunnaismuuttuja $x \in \mathbb{R}$ might be specified by a pdf $p(x)$ such that $\mathbb{P}(x \in [a, b]) \approx p(a)|b - a|$. In the most general case, a todennäköisyys distribution is defined by a todennäköisyys measure [6], [17].

See also: i.i.d., toteuma, satunnaismuuttuja, todennäköisyys, pdf.

todennäköisyysmalli A probabilistic malli for the generation of tietopisteet consists of satunnaismuuttujat with a joint todennäköisyysjakauma [7]. This joint todennäköisyysjakauma typically involves parameters that

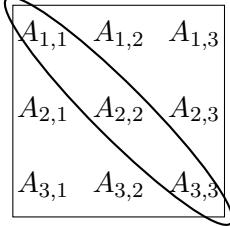


Fig. 52. The trace $\text{tr}(\mathbf{A})$ of a 3×3 matrix $\mathbf{A} \in \mathbb{R}^{3 \times 3}$ is the sum of three main diagonal entries $A_{1,1}, A_{2,2}, A_{3,3}$.

have to be manually chosen or learned via statistical inference methods such as suurimman uskottavuuden menetelmä estimation [51].

See also: malli, tietopiste, satunnaismuuttuja, todennäköisyysjakauma, parameter, suurimman uskottavuuden menetelmä, toteuma.

trace (matrix) The trace $\text{tr}(\mathbf{A})$ of a square matriisi $\mathbf{A} \in \mathbb{R}^{d \times d}$ is the sum of its diagonal entries [31]. Formally, it is the lineaarikuvaus

$$\text{tr}(\cdot) : \mathbb{R}^{d \times d} \rightarrow \mathbb{R} : \mathbf{A} \mapsto \sum_{j=1}^d A_{j,j}.$$

It satisfies the cyclic property $\text{tr}(\mathbf{AB}) = \text{tr}(\mathbf{BA})$, for any matriisit $\mathbf{A}, \mathbf{B} \in \mathbb{R}^{d \times d}$ [29, p. 301]. Furthermore, if \mathbf{A} has eigenvalues $\lambda_1, \dots, \lambda_d$ (each repeated according to its algebraic multiplicity), then

$$\text{tr}(\mathbf{A}) = \sum_{j=1}^d \lambda_j.$$

This identity follows from the invariance of the trace under similarity transformations [29, Ch. 10].

See also: eigenvalue, matriisi.

transpose The transpose of a real-valued matriisi is obtained by exchanging rows and columns. For a matriisi $\mathbf{A} \in \mathbb{R}^{m \times d}$, its transpose is denoted \mathbf{A}^T and satisfies $(\mathbf{A}^T)_{j,j'} = \mathbf{A}_{featureidx',j}$.

typical set See pmf.

undirected graph See verkko.

unitary (matrix) A square matriisi $\mathbf{U} \in \mathbb{C}^{d \times d}$ is called unitary if its conjugate transpose (Hermitian transpose) \mathbf{U}^H is also its inverse, i.e., if

$$\mathbf{U}^H \mathbf{U} = \mathbf{U} \mathbf{U}^H = \mathbf{I}.$$

Equivalently, the columns (and rows) of a unitary matriisi form an orthonormal basis of \mathbb{C}^d with respect to the standard inner product [28, 29].

See also: matriisi.

varianssi The variance of a real-valued satunnaismuuttuja x is defined as the odotusarvo $\mathbb{E}\{(x - \mathbb{E}\{x\})^2\}$ of the squared difference between x and its odotusarvo $\mathbb{E}\{x\}$. We extend this definition to vektori-valued satunnaismuuttujat \mathbf{x} as $\mathbb{E}\{\|\mathbf{x} - \mathbb{E}\{\mathbf{x}\}\|_2^2\} = \text{tr}(\mathbf{C}^{(\mathbf{x})})$, i.e., the sum of the variances of each entry of \mathbf{x} , which can be written compactly as the trace of the kovarianssimatriisi $\mathbf{C}^{(\mathbf{x})}$ of \mathbf{x} .

See also: satunnaismuuttuja, odotusarvo, vektori.

vektori A vector is an element of a vektoriavaruus. In the context of koneop-piminen, a particularly important example of a vektoriavaruus is the

euklidinen avaruuus \mathbb{R}^d , where $d \in \mathbb{N}$ is the (finite) dimension of the space. A vector $\mathbf{x} \in \mathbb{R}^d$ can be represented as a list or one-dimensional (1-D) array of real numbers, i.e., x_1, \dots, x_d with $x_j \in \mathbb{R}$ for $j = 1, \dots, d$. The value x_j is the j th entry of the vector \mathbf{x} . It can also be useful to view a vector $\mathbf{x} \in \mathbb{R}^d$ as a function that maps each index $j \in \{1, \dots, d\}$ to a value $x_j \in \mathbb{R}$, i.e., $\mathbf{x} : j \mapsto x_j$. This perspective is particularly useful for the study of ydinmenetelmät. See Fig. 53 for the two views of a vector.

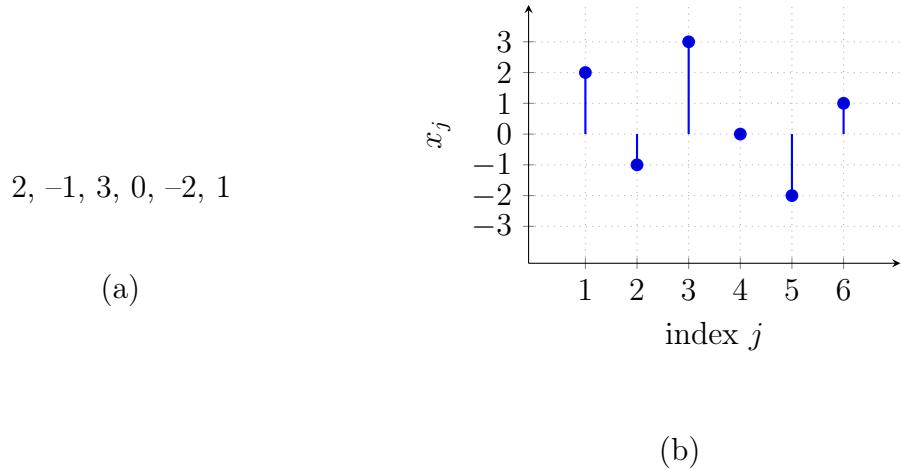


Fig. 53. Two equivalent views of a vector $\mathbf{x} = (2, -1, 3, 0, -2, 1)^T \in \mathbb{R}^6$. (a) As a numeric array. (b) As a function $j \mapsto x_j$.

See also: vektoriavaruus, euklidinen avaruuus, lineaarikuvaus.

vektoriavaruus A vektori space \mathcal{V} (also called linear space) is a collection of elements, called vektorit, along with the following two operations (see also Fig. 54): 1) addition (denoted by $\mathbf{v} + \mathbf{w}$) of two vektorit \mathbf{v}, \mathbf{w} ; and 2) multiplication (denoted by $c \cdot \mathbf{v}$) of a vektori \mathbf{v} with a scalar c that belongs to some number field (such as the real numbers \mathbb{R} or

the complex numbers \mathbb{C}). The defining property of a vektori space is that it is closed under two specific operations. First, if $\mathbf{v}, \mathbf{w} \in \mathcal{V}$, then $\mathbf{v} + \mathbf{w} \in \mathcal{V}$. Second, if $\mathbf{v} \in \mathcal{V}$ and $c \in \mathbb{R}$, then $c\mathbf{v} \in \mathcal{V}$.

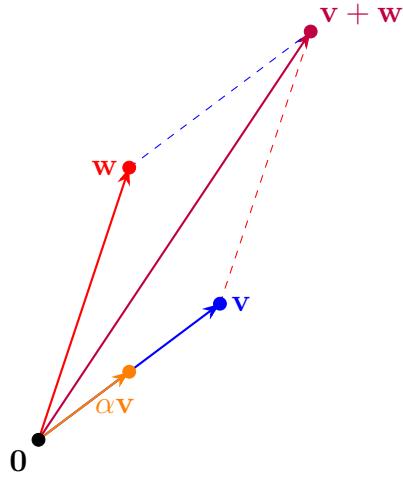


Fig. 54. A vektori space \mathcal{V} is a collection of vektorit such that scaling and adding them always yields another vektori in \mathcal{V} .

A common example of a vektori space is the euklidinen avaruuus \mathbb{R}^n , which is widely used in koneoppiminen to represent tietoaineistot. We can also use \mathbb{R}^n to represent, either exactly or approximately, the hypothesis space used by an koneoppiminen method. Another example of a vektori space, which is naturally associated with every probability space $(\Omega, \mathcal{F}, \mathbb{P}(\cdot))$, is the collection of all real-valued satunnaismuuttujat $x : \Omega \rightarrow \mathbb{R}$ [1], [12].

See also: vektori, euklidinen avaruuus, lineaarinen malli, lineaarikuvaus.

verkko A graph $\mathcal{G} = (\mathcal{V}, \mathcal{E})$ consists of a node set \mathcal{V} and an edge set \mathcal{E} . Each edge $e \in \mathcal{E}$ is characterized by the nodes to which it is connected and in

what precise sense. For example, an edge of a directed graph is leaving one node and pointing to another node. An edge of an undirected graph connects two nodes without any sense of direction [32, 71]. In principle, there can also be several (parallel) edges that are connected to the same nodes in the same way [71]. Moreover, edges may connect a node to itself, resulting in so-called self-loops [32]. A simple undirected graph contains no parallel edges and no self-loops [72]. Each edge $e \in \mathcal{E}$ of a simple undirected graph can be identified with a set of two nodes i, i' . Weighted graphs assign a numerical value A_e , referred to as edge weight,

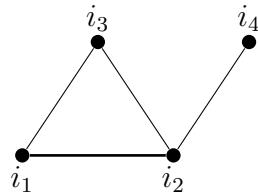


Fig. 55. A simple undirected graph with four nodes $\mathcal{V} = \{i_1, i_2, i_3, i_4\}$ and four edges $\mathcal{E} = \{\{i_1, i_2\}, \{i_2, i_3\}, \{i_3, i_1\}, \{i_2, i_4\}\}$.

to each edge $e \in \mathcal{E}$.

See also: kuvaus, weights.

weighted graph A verkko whose edges are assigned numeric weights. Typically, these edge weights are nonnegative real numbers. For example, if a verkko represents a road network with nodes being intersections and edges representing road segments, the edge weight could represent the capacity (measured in maximum vehicles per hour) of the road segment [32]. See also: verkko.

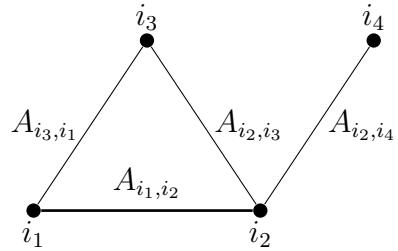


Fig. 56. A weighted graph with four nodes $\mathcal{V} = \{i_1, i_2, i_3, i_4\}$ and four edges $\mathcal{E} = \{\{i_1, i_2\}, \{i_2, i_3\}, \{i_3, i_1\}, \{i_2, i_4\}\}$. Each edge is assigned a weight.

wide matrix A matriisi $\mathbf{X} \in \mathbb{R}^{m \times d}$ is referred to as wide if it has more columns than rows, i.e., when $d > m$.

$$m \left\{ \underbrace{\mathbf{X} \in \mathbb{R}^{m \times d}}_{d \quad (d > m)} \right.$$

See also: matriisi.

Machine Learning Concepts

absolute error loss Consider a tietopiste with piirteet $\mathbf{x} \in \mathcal{X}$ and numeric nimiö $y \in \mathbb{R}$. As its name suggests, the absolute error häviö incurred by a hypoteesi $h : \mathcal{X} \rightarrow \mathbb{R}$ is defined as

$$L((\mathbf{x}, y), h) = |y - h(\mathbf{x})|.$$

Fig. 57 depicts the absolute error häviö for a fixed tietopiste with piirrevektori \mathbf{x} and nimiö y . It also indicates the häviö values incurred by two different hypoteesit h' and h'' . Similar to the neliövirhehäviö, the absolute error häviö is also a convex funkatio of the ennuste $\hat{y} = h(\mathbf{x})$. However, in contrast to the neliövirhehäviö, the absolute error häviö is non-smooth, as it is not differentiable at the optimal ennuste $\hat{y} = y$. This property makes ERM-based methods using the absolute error häviö computationally more demanding [39], [73]. To build intuition, it is useful to consider the two hypoteesit depicted in Fig. 57. Just by inspecting the slope of L around $h'(\mathbf{x})$ and $h''(\mathbf{x})$, it is impossible to determine whether we are very close to the optimum (at h') or still far away (at h''). As a result, any optimointimenetelmä that is based on local approximations of the häviöfunktio (such as subgradient descent) must use a decreasing oppimisnopeus to avoid overshooting when approaching the optimum. This required decrease in oppimisnopeus tends to slow down the convergence of the optimointimenetelmä. Besides the increased computational complexity, using absolute error häviö in ERM can be beneficial in the presence of poikkeava havaintot in the opetusaineisto. In contrast to the neliövirhehäviö, the slope of the absolute error häviö

does not increase with increasing ennuste error $y - h(\mathbf{x})$. As a result, the effect of introducing an poikkeava havainto with large ennuste error on the solution \hat{h} of ERM with absolute error häviö is much smaller compared with the effect on the solution of ERM with neliövirhehäviö.

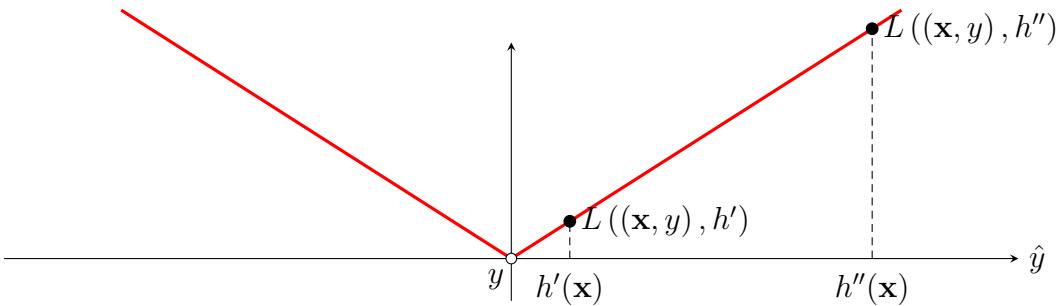


Fig. 57. For a tietopiste with numeric nimiö $y \in \mathbb{R}$, the absolute error $|y - h(\mathbf{x})|$ can be used as a häviöfunktio to guide the learning of a hypoteesi h .

See also: tietopiste, piirre, nimiö, häviö, ERM, subgradient descent, least absolute deviation regression.

activation The output of an artificial neuron within an neuroverkko is referred to as its activation. In particular, the activation is obtained by applying a (typically nonlinear) aktivointifunktio to a weighted sum of its inputs.

See also: neuroverkko, deep net.

aktivointifunktio Each artificial neuron within an neuroverkko is assigned an activation funktilo $\sigma(\cdot)$ that maps a weighted combination of the neuron inputs x_1, \dots, x_d to a single output value $a = \sigma(w_1 x_1 + \dots + w_d x_d)$.

Note that each neuron is parameterized by the weights w_1, \dots, w_d .

See also: neuroverkko, activation, rectified linear unit (ReLU).

algoritmi An algorithm is a precise, step-by-step specification for producing an tuotos from a given input within a finite number of well-defined computational steps [74]. For example, a gradient-based method for lineaarinen regressio is an algorithm that explicitly describes how to map a given opetusaineisto into model parameters through a sequence of gradienttiaskeleet. The precise form of an algorithm depends on the available computational infrastructure. For example, if this infrastructure allows us to compute an käänteismatriisi, then we can define a lineaarinen regressio algorithm using the normaalijyhtälöt. In contrast, if the computational infrastructure only allows basic arithmetic (i.e., multiplication and addition), the normaalijyhtälöt need to be somehow translated into a sequence of arithmetic operations (e.g., as in gradient-based methods). To study algorithms rigorously, we can represent (or approximate) them by different mathematical structures [75]. One approach is to represent an algorithm as a collection of possible executions. Each individual execution is then a sequence of the form

input, s_1, s_2, \dots, s_T , tuotos.

This sequence starts from an input and progresses via intermediate steps until an tuotos is delivered. Crucially, an algorithm encompasses more than just a mapping from input to tuotos; it also includes intermediate computational steps s_1, \dots, s_T .

See also: lineaarinen regressio, opetusaineisto, model parameter, gra-

dienttiaskel, tuotos, malli, stokastinen.

alisovittaminen Consider an koneoppiminen method applying ERM to learn a hypoteesi that minimizes the empiirinen riski on a given opetusaineisto. The method is said to underfit if it fails to achieve a sufficiently low empiirinen riski on the opetusaineisto. Underfitting typically occurs when the chosen malli is too simple to capture the underlying relationship between piirteet and nimiöt.

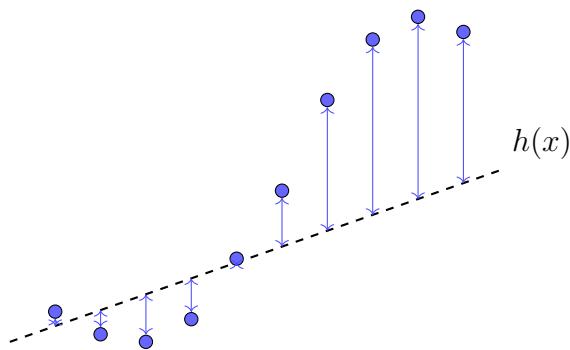


Fig. 58. No linear hypoteesi h can capture the relationship between piirteet and nimiöt for the depicted opetusaineisto. Thus, any method that uses a lineaarinen malli will underfit this opetusaineisto.

For example, an koneoppiminen method using a lineaarinen malli on data with a highly nonlinear relationship between piirteet and nimiö will not be able to learn a hypoteesi with small average häviö on the opetusaineisto, let alone a low riski.

See also: opetusaineisto, malli, riski, ylisovittaminen.

application programming interface (API) An API is a formal mecha-

nism that allows software components to interact in a structured and modular way [76]. In the context of koneoppiminen, APIs are commonly used to provide access to a trained koneoppiminen malli. Users—whether humans or machines—can submit the piirrevektori of a tietopiste and receive a corresponding ennuste. Suppose a trained koneoppiminen malli is defined as $\hat{h}(x) := 2x + 1$. Through an API, a user can input $x = 3$ and receive the output $\hat{h}(3) = 7$ without knowledge of the detailed structure of the koneoppiminen malli or its koulutus. In practice, the malli is typically deployed on a server connected to the Internet. Clients send requests containing piirre values to the server, which responds with the computed ennuste $\hat{h}(\mathbf{x})$. APIs promote modularity in koneoppiminen system design, i.e., one team can develop and train the malli, while another team handles integration and user interaction. Publishing a trained malli via an API also offers practical advantages. For instance, the server can centralize computational resources that are required to compute ennusteet. Furthermore, the internal structure of the malli remains hidden—which is useful for protecting intellectual property or trade secrets. However, APIs are not without riski. Techniques such as model inversion can potentially reconstruct a malli from its ennusteet using carefully selected piirrevektorit.

See also: koneoppiminen, malli, piirrevektori, tietopiste, ennuste, piirre, model inversion.

arvointivirhe Katso estimointivirhe.

asetelmamatriisi Katso mallimatriisi.

attention Some koneoppiminen applications involve tietopisteet composed of smaller units, referred to as esiintymät. For example, a sentence consists of words, an image of pixel patches, and a network of nodes. In general, the esiintymät that constitute a single tietopiste are not independent of one another. Instead, each esiintymä of a tietopiste depends on (or pays attention to) specific other esiintymät. Todennäköisyyssmallit provide a principled framework for representing and analyzing such dependencies [77]. Attention mechanisms use a more direct approach without explicit reference to a todennäköisyyssmalli. The idea is to represent the relationship between two esiintymät i and i' using a parameterized funktion $f^{(\mathbf{w})}(i, i')$, where the parameters \mathbf{w} are learned via a variant of ERM. Practical attention mechanisms differ in their precise choice of attention malli $f^{(\mathbf{w})}(i, i')$ as well as in the precise ERM variant used to learn the parameters \mathbf{w} . One widely used family of attention mechanisms defines the parameters \mathbf{w} in terms of two vektorit associated with each esiintymä i , i.e., a query vektori $\mathbf{q}^{(i)}$ and a key vektori $\mathbf{k}^{(i')}$. For a given esiintymä i with query $\mathbf{q}^{(i)}$, and another token i' with key $\mathbf{k}^{(i')}$, the quantity $(\mathbf{q}^{(i)})^\top \mathbf{k}^{(i')}$ indicates the extent to which esiintymä i attends to (or depends on) esiintymä i' (see Fig. 59).

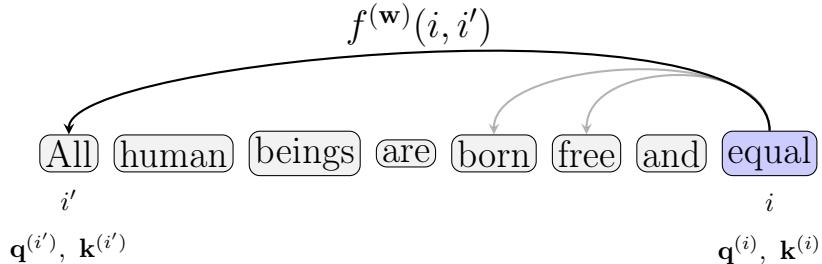


Fig. 59. Attention mechanisms learn a parameterized function $f^{(w)}(i, i')$ to measure how much esintymä i attends to esintymä i' . One widely used construction of $f^{(w)}(i, i')$ uses query and key vectors, denoted by $\mathbf{q}^{(i)}$ and $\mathbf{k}^{(i)}$, assigned to each esintymä i [78].

See also: esintymä, funktio, luonnollisen kielen käsite.

autoenkoodaja An autoencoder is a neural network method that simultaneously learns an encoder mapping $h \in \mathcal{H}$ and a decoder mapping $h^* \in \mathcal{H}^*$. Different autoencoders use different models $\mathcal{H}, \mathcal{H}^*$, e.g., neural networks with different architectures. The special case of an autoencoder using (vector-valued) linear models for $\mathcal{H}, \mathcal{H}^*$ results in PCA.

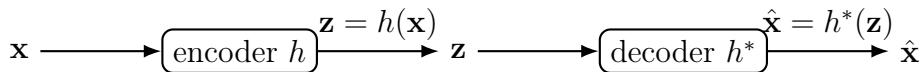


Fig. 60. Autoencoder with an encoder h mapping $\mathbf{x} \mapsto \mathbf{z}$ and a decoder h^* mapping $\mathbf{z} \mapsto \hat{\mathbf{x}}$.

The training of the encoder and decoder can be implemented via ERM using a loss function that measures the deviation of the reconstructed

piirrevektori $h^*(h(\mathbf{x}))$ from the original piirrevektori \mathbf{x} .

See also: kooderi, piirreoptimointi, ulottuvuuksien vähentäminen.

backpropagation Backpropagation is an algoritmi for computing the gradientti $\nabla_{\mathbf{w}} f(\mathbf{w})$ of an kohdefunktio $f(\mathbf{w})$ that depends on the model parameters \mathbf{w} of an neuroverkko. One example of such an kohdefunktio is the average häviö incurred by the neuroverkko on a erä of tietopisteet. This algoritmi is a direct application of the chain rule from calculus to efficiently compute partial derivatives of the häviöfunktio with respect to the model parameters. Backpropagation consists of two consecutive phases, also illustrated in Fig. 61. The first phase includes the forward pass, where a erä of tietopisteet is fed into the neuroverkko. The neuroverkko processes the input through its layers using its current weights, ultimately producing a ennuste at its output. The ennuste of the erä is compared to the true nimiö using a häviöfunktio, which quantifies the ennuste error. The second phase includes the backward pass (i.e., backpropagation), where the error is backpropagated through the neuroverkko layers. The obtained partial derivatives with respect to the neuroverkko parameters w_1, \dots, w_d constitute the gradientti $\nabla f(\mathbf{w})$, which can be used, in turn, to implement a gradienttiaskel.

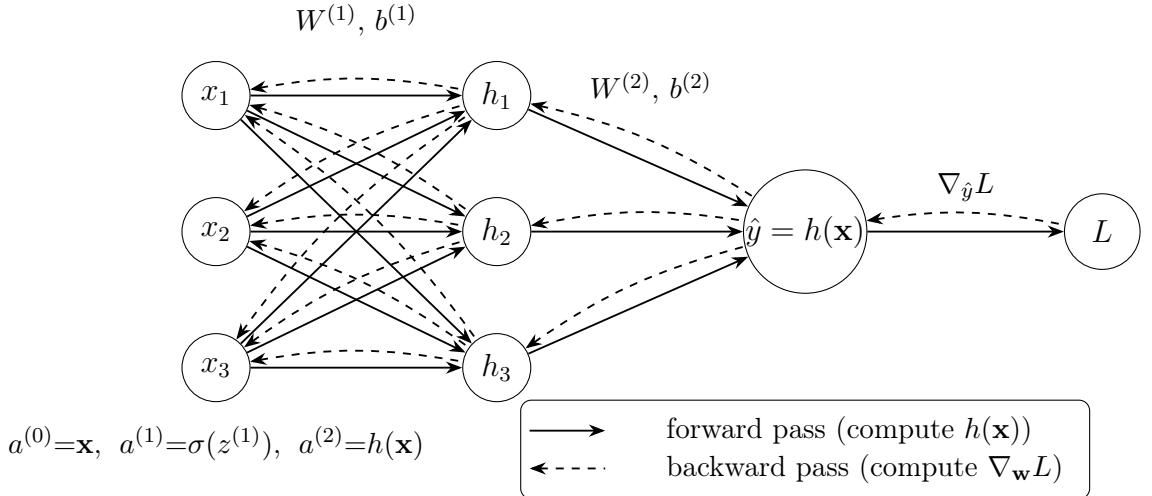


Fig. 61. Solid arrows show the forward pass (i.e., data flow and häviö calculation), while dashed arrows show the gradientti correction flow during the backward pass for updating the parameters $W^{(x)}, b^{(x)}$.

See also: neuroverkko, häviöfunktio, GD, optimointimenetelmä.

base learner A base learner is an koneoppiminen method that is part of an kooste method.

See also: kooste, laukutus, pinoaminen, tehostus.

batch learning In erä learning (also known as offline learning), the koneoppiminen malli is trained on the entire tietoaineisto in a single koulutus iteration, instead of updating it incrementally as data arrive. All available data are inputted into a learning algoritmi, resulting in a malli that can make ennusteet. Since these tietoaineistot tend to be large, koulutus is computationally expensive and time-consuming, so it is typically performed offline. After learning, the malli will be static and

will not adapt to new data automatically. Updating the malli with new information requires retraining the malli entirely. Once the malli has been trained, it is launched into production where it cannot be updated. Koulutus a malli can take many hours, so many mallit in production settings are updated cyclically on a periodic schedule when the data distribution is stable. For example, a retail analytics team could retrain their demand forecast malli every Sunday using the previous week's sales data to predict next week's demand. If a system needs to be constantly updated to rapidly changing data, such as in stock price ennuste, a more adaptable solution such as online learning is necessary.

See also: erä, malli, tietoaineisto, online learning.

Bayes estimator Consider a todennäköisyysmalli with a joint todennäköisyysjakauma $p(\mathbf{x}, y)$ over the piirteet \mathbf{x} and the nimiö y of a tietopiste. For a given häviöfunktio $L(\cdot, \cdot)$, we refer to a hypoteesi h as a Bayes estimator if its riski $\mathbb{E}\{L((\mathbf{x}, y), h)\}$ is the minimi achievable riski [51]. Note that whether a hypoteesi qualifies as a Bayes estimator depends on the underlying todennäköisyysjakauma and the choice for the häviöfunktio $L(\cdot, \cdot)$.

See also: todennäköisyysmalli, hypoteesi, riski.

Bayes risk Consider a todennäköisyysmalli for a koneoppiminen application where each tietopiste is interpreted as a satunnaismuuttuja. The todennäköisyysmalli includes a todennäköisyysjakauma for the piirteet \mathbf{x} and nimiö y of a tietopiste. The Bayes riski is the minimi possible riski that can be achieved by any hypoteesi $h : \mathcal{X} \rightarrow \mathcal{Y}$. Any hypoteesi that

achieves the Bayes riski is referred to as a Bayes estimator [51].

See also: todennäköisyysmalli, riski, Bayes estimator.

binary classification Binary luokittelu is luokittelu with two nimiöt. The nimiöt are usually defined as $\{-1, 1\}$ or $\{0, 1\}$.

See also: luokittelu, nimiö, tietopiste, piirre.

binary cross-entropy (BCE) The BCE häviö is the special case of cross-entropy häviö for a binary luokittelu problem.

See also: cross-entropy, luokittelu.

binääritappio The 0/1 häviö $L^{(0/1)}((\mathbf{x}, y), h)$ measures the quality of a luokitin $h(\mathbf{x})$ that delivers a ennuste \hat{y} (e.g., via thresholding (22)) for the nimiö y of a tietopiste with piirteet \mathbf{x} . It is equal to 0 if the ennuste is correct, i.e., $L^{(0/1)}((\mathbf{x}, y), h) = 0$ when $\hat{y} = y$. It is equal to 1 if the ennuste is wrong, i.e., $L^{(0/1)}((\mathbf{x}, y), h) = 1$ when $\hat{y} \neq y$.

See also: häviö, luokitin, ennuste, tarkkuus, nimiö, tietopiste, piirre.

cluster centroid Klusterointi methods decompose a given tietoaineisto into few rypäst. Different klusterointi methods use different representations for these ryppäät. If tietopisteet are characterized by numerical piirrevektorit $\mathbf{x} \in \mathbb{R}^d$, we can use some vector $\boldsymbol{\mu} \in \mathbb{R}^d$, referred to as rypäs centroid, to represent a rypäs. For example, if a rypäs consists of a set of tietopisteet, we use the average of their piirrevektorit as a rypäs centroid. However, there are also other choices for how to construct a rypäs centroid.

See also: klusterointi, piirrevektori, k -means.

clustered federated learning (CFL) CFL trains local models for the devices in a federoitu oppiminen application by using a clustering assumption, i.e., the devices of an FL network form ryppäät. Two devices in the same rypäs generate local datasets with similar statistical properties. CFL pools the local datasets of devices in the same rypäs to obtain a opetusaineisto for a rypäs-specific malli. Generalized total variation minimization (GTVMin) clusters devices implicitly by enforcing approximate similarity of model parameters across well-connected nodes of the FL network.

See also: federoitu oppiminen, clustering assumption, FL network, rypäs, graph clustering.

clustering assumption The klusterointi assumption postulates that tietopisteet in a tietoaineisto form a (small) number of groups or ryppäät. Tietopisteet in the same rypäs are more similar to each other than those outside the rypäs [79]. We obtain different klusterointi methods by using different notions of similarity between tietopisteet.

See also: klusterointi, tietopiste, tietoaineisto, rypäs.

clustering error Consider a klusterointi method that decomposes a given tietoaineisto into ryppäät. The klusterointi error is a quantitative measure of the usefulness of the ryppäät. Different klusterointi methods use different choices for the klusterointi error. For example, the osittava klusterointi method k -means measures the klusterointi error via the average squared euklidinen etäisyys between the piirrevektori of a tietopiste and the nearest cluster centroid (see Figure 62). Another construction

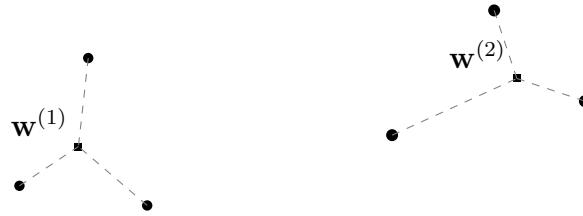


Fig. 62. For tietopiste with numeric piirrevektoit, we can use the average squared euklidinen etäisyys to the nearest cluster centroids as a measure of the klusterointi error.

for the klusterointi error can be based on a todennäköisyysmalli such as the Gaussian sekoitemalli where the cluster centroids are parameters of the underlying todennäköisyysjakauma.

See also: Gaussian sekoitemalli, *k*-means, todennäköisyysmalli, suurimman uskottavuuden menetelmä.

concept activation vector (CAV) Consider a deep net, consisting of several hidden layers, trained to predict the nimiö of a tietopiste from its piirrevektori. One way to explain the behavior of the trained deep net is by using the activations of a hidden layer as a new piirrevektori \mathbf{z} . We then probe the geometry of the resulting new piirreavaruuus by applying the deep net to tietopisteet that represent a specific concept \mathcal{C} . By applying the deep net also to tietopisteet that do not belong to this concept, we can train a binary lineaarinen luokitin $g(\mathbf{z})$ that distinguishes between concept and non-concept tietopisteet based on the activations of the hidden layer. The resulting päätöspinta is a hyperplane whose normal vektori is the CAV [80] for the concept \mathcal{C} .

See also: deep net, lineaarinen malli, luotettava tekoäly, tulkittavuus,

transparency.

convex clustering Consider a tietoaineisto $\mathbf{x}^{(1)}, \dots, \mathbf{x}^{(m)} \in \mathbb{R}^d$. Convex klusterointi learns vektorit $\mathbf{w}^{(1)}, \dots, \mathbf{w}^{(m)}$ by minimizing

$$\sum_{r=1}^m \|\mathbf{x}^{(r)} - \mathbf{w}^{(r)}\|_2^2 + \alpha \sum_{i,i' \in \mathcal{V}} \|\mathbf{w}^{(i)} - \mathbf{w}^{(i')}\|_p.$$

Here, $\|\mathbf{u}\|_p := (\sum_{j=1}^d |u_j|^p)^{1/p}$ denotes the p -normi (for $p \geq 1$). It turns out that many of the optimal vektorit $\hat{\mathbf{w}}^{(1)}, \dots, \hat{\mathbf{w}}^{(m)}$ coincide. A ryppäs then consists of those tietopisteet $r \in \{1, \dots, m\}$ with identical $\hat{\mathbf{w}}^{(r)}$ [81], [82].

See also: tietoaineisto, convex, klusterointi, vektori, normi, ryppäs, tietopiste.

coreset A coresset is a small subset of a larger tietoaineisto that approximates certain properties of the original tietoaineisto [83]. The construction of a coresset typically involves selecting representative tietopisteet and assigning them weights to reflect their importance in the original tietoaineisto (Fig. 63).

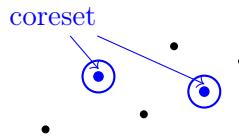


Fig. 63. A coresset (highlighted in blue) is a small subset of a larger tietoaineisto.

Coresets are particularly useful for koneoppiminen applications (such as klusterointi) involving large tietoaineistot, as they allow for efficient

computation while preserving the essential characteristics of the data [84].

See also: tietoaineisto, tietopiste, klusterointi.

cross-entropy Consider a multi-class luokittelu problem with a piirreavaruus \mathcal{X} and a finite label space $\mathcal{Y} = \{1, \dots, k\}$. A tietopiste with a piirrevektori \mathbf{x} is represented as a pmf $\mathbf{y} = (y_1, \dots, y_k)^T$ over \mathcal{Y} , where y_c denotes the todennäköisyys that a randomly chosen tietopiste with piirrevektori \mathbf{x} has nimiö c . A hypoteesi $h(\mathbf{x})$ outputs a predicted pmf $\hat{\mathbf{y}} = (\hat{y}_1, \dots, \hat{y}_k)^T$. The associated cross-entropy häviö is [30]

$$L((\mathbf{x}, \hat{\mathbf{y}}), h) := - \sum_{c=1}^k y_c \log \hat{y}_c.$$

The cross-entropy häviö quantifies the dissimilarity between the true pmf \mathbf{y} and the predicted pmf $\hat{\mathbf{y}}$. It is also a measure of the expected number of bits required to encode nimiöt drawn from the true pmf \mathbf{y} when using a coding scheme optimized for the predicted pmf $\hat{\mathbf{y}}$ [30].

Note that, for binary luokittelu (with $k = 2$), the cross-entropy häviö reduces to the logistic loss when employing a parametric model with model parameters \mathbf{w} such that $\hat{y}_2/\hat{y}_1 = \exp(\mathbf{w}^T \mathbf{x})$. Moreover, the representation (21) of logistic loss requires encoding the label space $\{1, 2\}$ using the values -1 and 1 .

See also: luokittelu, pmf, logistic loss.

data In the context of koneoppiminen, the term data is often used as a synonym for tietoaineisto [67], [68]. The ISO/IEC 2382:2015 standard defines data as a "reinterpretable representation of information in a formalized

manner suitable for communication, interpretation, or processing" [85].

See also: tietoaineisto, tietopiste, sample.

data augmentation Data augmentation methods add synthetic tietopisteet to an existing set of tietopisteet. These synthetic tietopisteet are obtained by perturbations (e.g., adding noise to physical measurements) or transformations (e.g., rotations of images) of the original tietopisteet. These perturbations and transformations are such that the resulting synthetic tietopisteet should still have the same nimiö. As a case in point, a rotated cat image is still a cat image even if their piirrevektorit (obtained by pinoamien pixel color intensities) are very different (see Fig. 64). Data augmentation can be an efficient form of regularisointi.

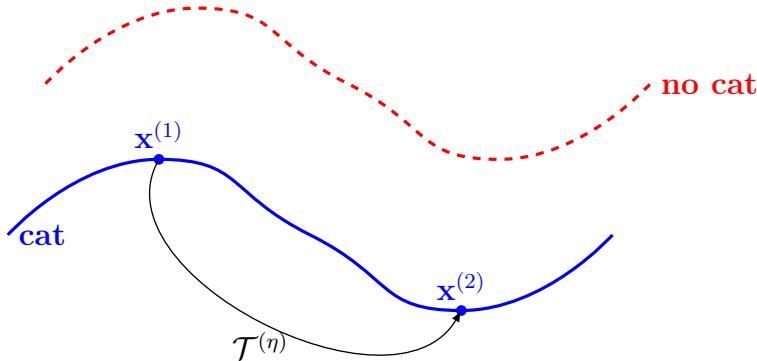


Fig. 64. Data augmentation exploits intrinsic symmetries of tietopisteet in some piirreavaruus \mathcal{X} . We can represent a symmetry by an operator $\mathcal{T}^{(\eta)} : \mathcal{X} \rightarrow \mathcal{X}$, parameterized by some number $\eta \in \mathbb{R}$. For example, $\mathcal{T}^{(\eta)}$ might represent the effect of rotating a cat image by η degrees. A tietopiste with piirrevektori $\mathbf{x}^{(2)} = \mathcal{T}^{(\eta)}(\mathbf{x}^{(1)})$ must have the same nimiö $y^{(2)} = y^{(1)}$ as a tietopiste with piirrevektori $\mathbf{x}^{(1)}$.

See also: data, tietopiste, nimiö, piirrevektori, pinoaminen, regularisointi, piirreavaruus.

data minimization principle European data protection regulation includes a data minimization principle. This principle requires a data controller to limit the collection of personal information to what is directly relevant and necessary to accomplish a specified purpose. The data should be retained only for as long as necessary to fulfill that purpose [86, Article 5(1)(c)], [87].

See also: data.

data parallelism Data parallelism refers to a widely used class of distributed optimointimenetelmät for koulutus an koneoppiminen malli. Here, each participating device stores a full replica of the model parameters but processes a disjoint subset of the global tietoaineisto [88]. Compared to model parallelism, which distributes the model parameters across devices, data parallelism distributes the computational workload associated with large tietoaineistot. It is especially effective when the malli fits into the memory of a single device, but the tietoaineisto or koulutus complexity would be prohibitive without parallel processing.

See also: model parallelism, horizontal federated learning (HFL).

datamatriisi The term data matriisi is sometimes used as a synonym for the feature matrix $\mathbf{X} \in \mathbb{R}^{m \times d}$ of a tietoaineisto containing m tietopisteet, each characterized by a piirrevektori $\mathbf{x} \in \mathbb{R}^d$ [89]. In particular, when no nimiö information is available, the term data matriisi highlights that the feature matrix fully characterizes the tietoaineisto.

See also: feature matrix, tietoaineisto, tietopiste, piirrevektori.

datan myrkyttäminen Data poisoning refers to the intentional manipulation (or fabrication) of tietopisteet to maliciously steer the koulutus of an koneoppiminen malli [90], [91]. Data poisoning hyökkäykset take various forms, including takaportti and palvelunestohyökkäyst. A takaportti hyökkäys implants triggers into koulutus data, so that the trained malli behaves normally for typical tietopisteet but misclassifies a tietopiste with a piirrevektori that contains a trigger pattern. A palvelunestohyökkäys degrades the trained malli's overall performance by injecting mislabeled or adversarial examples to prevent effective learning. Data poisoning is particularly harmful in decentralized or distributed koneoppiminen settings (such as federoitut oppiminen), where koulutus data cannot be centrally verified.

See also: hyökkäys, takaportti, palvelunestohyökkäys, luotettava teköäly.

datan normalisointi Data normalization refers to transformations applied to the piirrevektorit of tietopisteet to improve the koneoppiminen method's laskennallinen ominaisuus or laskennallinen ominaisuus. For example, in lineaarinen regressio with gradient-based methods using a fixed oppimisnopeus, convergence depends on controlling the normi of piirrevektorit in the opetusaineisto. A common approach is to normalize piirrevektorit such that their normi does not exceed one [8, Ch. 5].

See also: gradient-based method, oppimisnopeus, piirrekartta.

datapiste Katso tietopiste.

deep net A deep net is an neuroverkko with a (relatively) large number of

hidden layers. Deep learning is an umbrella term for koneoppiminen methods that use a deep net as their malli [92].

See also: neuroverkko, layer, malli, laaja kielimalli.

degree of belonging Degree of belonging is a number that indicates the extent to which a tietopiste belongs to a rypäs [8, Ch. 8]. The degree of belonging can be interpreted as a soft rypäs assignment. Soft clustering methods can encode the degree of belonging with a real number in the interval $[0, 1]$. Osittava klusterointi is obtained as the extreme case when the degree of belonging only takes on values 0 or 1.

See also: tietopiste, rypäs, soft clustering, osittava klusterointi.

denoising autoencoder A denoising autoenkoodaaja extends the basic autoenkoodaaja by perturbing (e.g., by adding noise to) the input vector (or piirrevektori) before feeding it into the autoenkoodaaja itself [92, Sec. 14.2.2]. Once trained, we can use a denoising autoenkoodaaja to denoise a corrupted representation of a tietopiste (see Fig. 65).

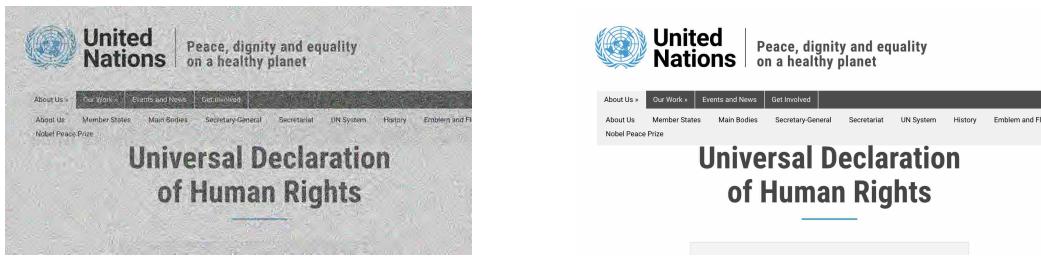


Fig. 65. A denoising autoenkoodaaja reads in (a) a corrupted (i.e., noisy) representation of a tietopiste and computes a ennuste for (b) the clean representation.

See also: autoenkoodaaja, diffusion method.

density-based spatial clustering of applications with noise (DBSCAN)

DBSCAN refers to a klusterointi algoritmi for tietopisteet that are characterized by numeric piirrevektorit. Like k -means and soft clustering via Gaussian sekoitemalli, DBSCAN also uses the euklidiset etäisyydet between piirrevektorit to determine the ryppäät. However, in contrast to k -means and Gaussian sekoitemalli, DBSCAN uses a different notion of similarity between tietopisteet. DBSCAN considers two tietopisteet as similar if they are connected via a sequence (i.e., path) of nearby intermediate tietopisteet. Thus, DBSCAN might consider two tietopisteet as similar (and therefore belonging to the same cluster) even if their piirrevektorit have a large euklidinen etäisyys.

See also: klusterointi, k -means, Gaussian sekoitemalli, rypäs, verkko.

device A physical system that can store and process data. In the context of koneoppiminen, the term typically refers to a computer capable of reading tietopisteet from different sources and using them to train an koneoppiminen malli [93].

See also: data, koneoppiminen, tietopiste, malli.

differentiaalinen yksityisyys Consider some koneoppiminen method \mathcal{A} that reads in a tietoaineisto (e.g., the opetusaineisto used for ERM) and delivers some tuotos $\mathcal{A}(\mathcal{D})$. The tuotos could be either the learned model parameters or the ennusteet for specific tietopisteet. DP is a precise measure of privacy leakage incurred by revealing the tuotos. Roughly speaking, an koneoppiminen method is differentially private if

the todennäköisyysjakauma of the tuotos $\mathcal{A}(\mathcal{D})$ remains largely unchanged when the sensitive attribute of one tietopiste in the opetusaineisto is changed. Note that DP builds on a todennäköisyysmalli for an koneoppiminen method, i.e., we interpret its tuotos $\mathcal{A}(\mathcal{D})$ as the toteuma of an satunnaismuuttuja. The randomness in the tuotos can be ensured by intentionally adding the toteuma of an auxiliary satunnaismuuttuja (i.e., adding noise) to the tuotos of the koneoppiminen method.

See also: tuotos, privacy leakage, sensitive attribute, yksityisyysyökkäys, privacy funnel.

diffusion method A diffusion method is a generative koneoppiminen method that trains a malli to approximate the reversal of a gradual stokastinen corruption process [94], [95]. Diffusion methods train mallit using a combination of a forward (diffusion) process and a learned reverse kuvaus. In the forward process, random noise is incrementally added to clean representations of a tietopiste, such as an image, an audio recording, or other types of data. Similar to a denoising autoencoder, the trained malli can be applied to a noisy representation of a tietopiste. The resulting ennuste is a denoised representation. What sets diffusion methods apart from generic denoising autoencoders is the gradual nature of the corruption process used for malli koulutus.

See also: denoising autoencoder, koulutus.

early stopping Consider an ERM-based method that uses an iterative optimointimenetelmä (such as GD) to learn model parameters by minimizing the empiirinen riski on a given opetusaineisto. Early stopping refers

to terminating the iteration even if they still substantially decrease the empirical risk on the dataset. Instead of monitoring the objective function (which is the empirical risk on the dataset), early stopping monitors the validation error incurred by the model parameters in each iteration. Early stopping can be interpreted as an implementation of regularization via model pruning. Indeed, terminating an iterative optimization method after a small number of iterations restricts the set of model parameters that can be reached from the initialization (see Fig. 66).

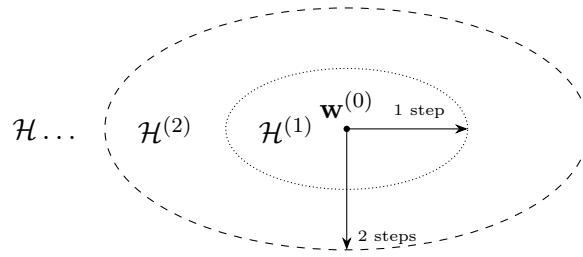


Fig. 66. A gradient-based method for ERM using a hypothesis space \mathcal{H} defines a nested sequence of effective hypothesis spaces $\mathcal{H}^{(1)} \subseteq \mathcal{H}^{(2)} \subseteq \dots \subseteq \mathcal{H}$. The effective hypothesis space $\mathcal{H}^{(t)}$ is determined by all model parameters that can be reached from the initialization $\mathbf{w}^{(0)}$ within t gradient steps.

See also: regularization, gradient-based method, overfitting.

edge weight Each edge $\{i, i'\}$ of an FL network is assigned a nonnegative edge weight $A_{i,i'} \geq 0$. A zero edge weight $A_{i,i'} = 0$ indicates the absence of an edge between nodes $i, i' \in \mathcal{V}$.

See also: FL network.

effective dimension The effective dimension $d_{\text{eff}}(\mathcal{H})$ of an infinite hypothesis space \mathcal{H} is a measure of its size. Loosely speaking, the effective dimension is equal to the effective number of independent tunable model parameters. These parameters might be the coefficients used in a lineaarikuvaus or the weights and harha terms of an neuroverkko.

See also: hypothesis space, model parameter, neuroverkko.

eigenvector An eigenvector of a matriisi $\mathbf{A} \in \mathbb{R}^{d \times d}$ is a nonzero vektori $\mathbf{x} \in \mathbb{R}^d \setminus \{\mathbf{0}\}$ such that $\mathbf{Ax} = \lambda\mathbf{x}$ with some eigenvalue λ .

See also: matriisi, vektori, eigenvalue.

empiirinen riski The empirical riski $\widehat{L}(h|\mathcal{D})$ of a hypoteesi on a tietoaineisto \mathcal{D} is the average häviö incurred by h when applied to the tietopisteet in \mathcal{D} .

See also: riski, hypoteesi, tietoaineisto, häviö, tietopiste.

empirical risk minimization (ERM) ERM is the optimointitehtävä of selecting a hypoteesi $\hat{h} \in \mathcal{H}$ that minimizes the average häviö (or empiirinen riski) on a opetusaineisto \mathcal{D} . The hypoteesi is chosen from a hypothesis space (or malli) \mathcal{H} . The tietoaineisto \mathcal{D} is referred to as opetusaineisto. A plethora of ERM-based koneoppiminen methods is obtained for different design choices for the tietoaineisto, malli, and häviö [8, Ch. 3]. Fig. 67 illustrates ERM for a lineaarinen malli and tietopisteet that are characterized by a single piirre x and a nimiö y . The hypoteesi h is a lineaarikuvaus that predicts the nimiö of a tietopiste as a linear funktilo of its piirre x , i.e., $h(x) = w_1x + w_0$, where w_1 and w_0 are the model parameters of the hypoteesi h . The ERM problem is to

find the model parameters w_1 and w_0 that minimize the average häviö (or empiirinen riski) incurred by the hypoteesi h on the opetusaineisto \mathcal{D} .

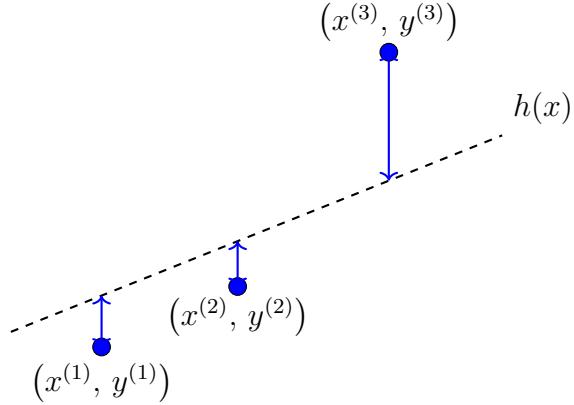


Fig. 67. ERM learns a hypoteesi $h \in \mathcal{H}$ out of a malli \mathcal{H} by minimizing the average häviö (or empiirinen riski) $1/m \sum_{r=1}^m L((\mathbf{x}^{(r)}, y^{(r)}), h)$ incurred on a opetusaineisto \mathcal{D} .

See also: optimointitehtävä, empiirinen riski, opetusaineisto, häviö, optimointimenetelmä.

ennuste A prediction is an estimate or approximation for some quantity of interest. Koneoppiminen revolves around learning or finding a hypoteesi kuvaus h that reads in the piirteet \mathbf{x} of a tietopiste and delivers a prediction $\hat{y} := h(\mathbf{x})$ for its nimiö y .

See also: koneoppiminen, hypoteesi, kuvaus, piirre, tietopiste, nimiö.

ennustin A predictor is a real-valued hypoteesi kuvaus. Given a tietopiste with piirteet \mathbf{x} , the value $h(\mathbf{x}) \in \mathbb{R}$ is used as a ennuste for the true

numeric nimiö $y \in \mathbb{R}$ of the tietopiste.

See also: hypoteesi, kuvaus, tietopiste, piirre, ennuste, nimiö.

epoch An epoch represents one complete pass of the entire opetusaineisto through some learning algoritmi. It refers to the point at which a malli has processed every tietopiste in the opetusaineisto once. Koulutus a malli usually requires multiple epochs, since each iteration allows the malli to refine the parameters and improve ennusteet. The number of epochs is something predefined by the user, and thus a hyperparameter, which plays a crucial role in determining how the malli will generalize to unseen data. Too few epochs will result in alisovittainen, while too many epochs can result in ylisovittainen.

See also: opetusaineisto, algoritmi, malli, tietopiste, parameter, ennuste, alisovittainen, ylisovittainen.

epävarmuus In the context of koneoppiminen, uncertainty refers to the presence of multiple plausible outcomes or selityst based on available data. For example, the ennuste $\hat{h}(\mathbf{x})$ produced by a trained koneoppiminen malli \hat{h} often reflects a range of possible values for the true nimiö of a given tietopiste. The broader this range, the greater the associated uncertainty. Todennäköisyys theory allows us to represent, quantify, and reason about uncertainty in a mathematically rigorous manner.

See also: todennäköisyysmalli, riski, entropia, varianssi.

erotteluksikyosoitin (ROC-käyrä) Consider a label space $\mathcal{Y} = \{-1, 1\}$ and a luokitin that uses a real-valued hypoteesi $h(\mathbf{x})$. For a given threshold $\eta \in \mathbb{R}$, the ultimate ennuste is $\hat{y} = 1$ if $h(\mathbf{x}) \geq \eta$ and $\hat{y} = -1$

otherwise. On a testiaineisto $\mathcal{D}^{(\text{test})}$, we compute, for each value of η , the following two quantities: 1) true positive rate $\text{TPR}^{(\eta)}$; and 2) false positive rate $\text{FPR}^{(\eta)}$. The ROC curve is the funktion [96]

$$\text{ROC} : \mathbb{R} \rightarrow \mathbb{R}^2 : \eta \mapsto (\text{TPR}^{(\eta)}, \text{FPR}^{(\eta)}).$$

One important characteristic of the ROC curve is the käyrän alle jävä pinta-ala (AUC-arvo).

See also: luokitin, AUC-arvo.

erä In the context of SGD, a batch refers to a randomly chosen subset of the overall opetusaineisto. We use the tietopisteet in this subset to estimate the gradientti of opetusvirhe and, in turn, to update the model parameters.

See also: SGD, opetusaineisto, tietopiste, gradientti, opetusvirhe, model parameter.

esiintymä A token is a basic unit of information obtained by splitting a sequence of symbols, such as a text string, into smaller parts. In luonnonlisen kielen käsitteily, tokens often correspond to words, subwords, or characters that form the piirteet of a tietopiste. Tokenization transforms raw text (e.g., “The cat sleeps”) into a sequence of tokens (e.g., “[“The”, “cat”, “sleeps””]), which can then be mapped to numerical piirrevektorit.

See also: sequence, piirrevektori.

estimointivirhe Consider tietopisteet, each with piirrevektori \mathbf{x} and nimiö y . In some applications, we can model the relation between the piirrevektori and the nimiö of a tietopiste as $y = \bar{h}(\mathbf{x}) + \varepsilon$. Here, we use some

true underlying hypoteesi \bar{h} and a noise term ε , which summarizes any modeling or labeling errors. The estimation error incurred by an koneoppiminen method that learns a hypoteesi \hat{h} , e.g., using ERM, is defined as $\hat{h}(\mathbf{x}) - \bar{h}(\mathbf{x})$, for some piirrevektori. For a parametric hypothesis space, which consists of hypoteesi kuvauskset determined by model parameters \mathbf{w} , we can define the estimation error as $\Delta\mathbf{w} = \hat{\mathbf{w}} - \bar{\mathbf{w}}$ [63], [97].

See also: tietopiste, piirrevektori, nimiö, hypoteesi, koneoppiminen, ERM, hypothesis space, kuvaus, model parameter.

euklidinen avaruuus The Euclidean space \mathbb{R}^d of dimension $d \in \mathbb{N}$ consists of vektorit $\mathbf{x} = (x_1, \dots, x_d)$, with d real-valued entries $x_1, \dots, x_d \in \mathbb{R}$. Such a Euclidean space is equipped with a geometric structure defined by the inner product $\mathbf{x}^T \mathbf{x}' = \sum_{j=1}^d x_j x'_j$ between any two vektorit $\mathbf{x}, \mathbf{x}' \in \mathbb{R}^d$ [2].

See also: vektori.

euklidinen etäisyys The term Euclidean distance is used as a synonym for the euklidinen normi.

See also: vektori, euklidinen avaruuus.

euklidinen normi The Euclidean normi $\|\mathbf{w}\|_2$ of a vektori

$$\mathbf{w} = (w_1, \dots, w_d) \in \mathbb{R}^d$$

is defined as

$$\|\mathbf{w}\|_2 := \sqrt{\sum_{j=1}^d w_j^2}.$$

The Euclidean normi is distinct among all normit on \mathbb{R}^d in the sense that it is induced by the inner product $\mathbf{w}^T \mathbf{v}$ [1], [22], [98]. In other words, $\|\mathbf{w}\|_2 = \sqrt{\mathbf{w}^T \mathbf{w}}$.

See also: normi, vektori, euklidinen avaruuus.

expert koneoppiminen aims to learn a hypoteesi h that accurately predicts the nimiö of a tietopiste based on its piirteet. We measure the ennuste error using some häviöfunktio. Ideally, we want to find a hypoteesi that incurs minimal häviö on any tietopiste. We can make this informal goal precise via the i.i.d. olettamus and by using the Bayes risk as the vertailutaso for the (average) häviö of a hypoteesi. An alternative approach to obtaining a vertailutaso is to use the hypoteesi h' learned by an existing koneoppiminen method. We refer to this hypoteesi h' as an expert [99]. Regret minimization methods learn a hypoteesi that incurs a häviö comparable to the best expert [99], [100].

See also: häviöfunktio, vertailutaso, regret.

explainable empirical risk minimization (EERM) EERM is an instance of structural risk minimization (SRM) that adds a regularisointi term to the average häviö in the kohdefunktio of ERM. The regularisointi term is chosen to favor hypoteesi kuvaaukset that are intrinsically explainable for a specific user. This user is characterized by their ennusteet provided for the tietopisteet in a opetusaineisto [101].

See also: SRM, regularisointi, ERM, opetusaineisto.

feature matrix Consider a tietoaineisto \mathcal{D} with m tietopisteet with piirre-vektorit $\mathbf{x}^{(1)}, \dots, \mathbf{x}^{(m)} \in \mathbb{R}^d$. It is convenient to collect the individual

piirrevektorit into the piirre matriisi

$$\mathbf{X} := (\mathbf{x}^{(1)}, \dots, \mathbf{x}^{(m)})^T = \begin{pmatrix} x_1^{(1)} & x_2^{(1)} & \cdots & x_d^{(1)} \\ x_1^{(2)} & x_2^{(2)} & \cdots & x_d^{(2)} \\ \vdots & \vdots & \ddots & \vdots \\ x_1^{(m)} & x_2^{(m)} & \cdots & x_d^{(m)} \end{pmatrix} \in \mathbb{R}^{m \times d}.$$

Note that the feature matrix is of size $m \times d$, i.e., it has m rows and d columns.

See also: tietoaineisto, tietopiste, piirrevektori, piirre, matriisi.

federated averaging (FedAvg) FedAvg refers to a family of iterative federated oppiminen algoritmit. It uses a server-client setting and alternates between clientwise local models retraining, followed by the aggregation of updated model parameters at the server [102]. The local update at client $i = 1, \dots, n$ at time t starts from the current model parameters $\mathbf{w}^{(t)}$ provided by the server and typically amounts to executing few iterations of SGD. After completing the local updates, they are aggregated by the server (e.g., by averaging them). Fig. 68 illustrates the execution of a single iteration of FedAvg.

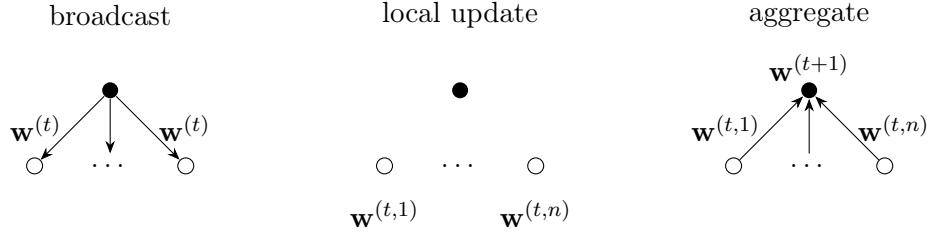


Fig. 68. Illustration of a single iteration of FedAvg, which consists of broadcasting model parameters by the server, performing local updates at clients, and aggregating the updates by the server.

See also: federoitu oppiminen, algoritmi, local model, SGD.

federated gradient descent (FedGD) An federoitu oppiminen hajautettu algoritmi that can be implemented as message passing across an FL network.

See also: federoitu oppiminen, hajautettu algoritmi, FL network, gradienttiaskel, gradient-based method.

federated learning network (FL network) An federoitu oppiminen network consists of an undirected weighted verkko \mathcal{G} . The nodes of \mathcal{G} represent devices that can access a local dataset and train a local model. The edges of \mathcal{G} represent communication links between devices as well as statistical similarities between their local datasets. A principled approach to train the local models is GTVMin. The solutions of GTVMin are local model parameters that optimally balance the häviö incurred on local datasets with their poikkeama across the edges of \mathcal{G} .

See also: federoitu oppiminen, verkko, device, GTVMin.

federated proximal (FedProx) FedProx refers to an iterative federated optimization algorithm that alternates between separately training local models and combining the updated local model parameters. In contrast to FedAvg, which uses SGD to train local models, FedProx uses a proximal operator for the training [103].

See also: federated optimization, algorithm, local model, model parameter, FedAvg, SGD, proximal operator.

federated relaxed (FedRelax) An federated optimization method that adds a regularization term to the local update step to encourage sparsity or smoothness of the local models.

See also: federated optimization, hajautettu algoritmi.

federated stochastic gradient descent (FedSGD) An federated optimization method that can be implemented as message passing across an FL network.

See also: federated optimization, hajautettu algoritmi, FL network, gradient descent, gradient-based method, SGD.

federated optimization FL is an umbrella term for machine learning methods that train models in a collaborative fashion using decentralized data and computation.

See also: machine learning, models, data.

flow-based clustering Flow-based clustering groups the nodes of an undirected graph by applying k -means clustering to node-wise vectors. These vectors are built from network flows between carefully selected sources and destination nodes [104].

See also: clustering, graph, k -means, vector.

Gaussin sekoitemalli A GMM is a particular type of todennäköisyysmalli for tietopisteet characterized by a numeric piirrevektori \mathbf{x} . Within a GMM, the piirrevektori \mathbf{x} is drawn from a randomly selected moninormaalijakauma $p^{(c)} = \mathcal{N}(\boldsymbol{\mu}^{(c)}, \mathbf{C}^{(c)})$ with $c = I$. The index $I \in \{1, \dots, k\}$ is a satunnaismuuttuja with todennäköisyydet $\mathbb{P}(I = c) = p_c$. A GMM is parameterized, for each $c = 1, \dots, k$, by the todennäköisyys p_c , the keskiarvo vektori $\boldsymbol{\mu}^{(c)}$, and the kovarianssimatriisi $\mathbf{C}^{(c)}$.

See also: todennäköisyysmalli, moninormaalijakauma, klusterointi.

generalization gap Yleistys gap is the difference between the performance of a hypoteesi $h \in \mathcal{H}$ on the opetusaineisto $\mathcal{D}^{(\text{train})}$ and its performance on tietopisteet outside $\mathcal{D}^{(\text{train})}$. We can make this notion precise by using a todennäköisyysmalli that allows us to compute the riski (or expected häviö) $\bar{L}(\hat{h})$ of a hypoteesi h .

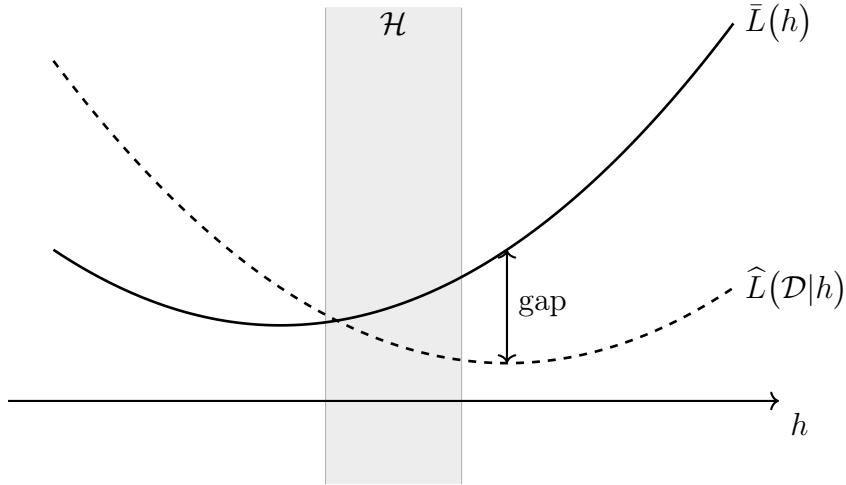


Fig. 69. The yleistys gap can be defined as the difference between the riski $\bar{L}(h)$ and the average häviö (or empiirinen riski) $\hat{L}(h|\mathcal{D}^{(\text{train})})$ computed on a opetusaineisto.

In practice, the todennäköisyysjakauma underlying this odotusarvo is unknown. Thus, we need to estimate the odotusarvo based on observed tietopisteet. Validointi techniques use different constructions of a validointiaineisto, which is different from the opetusaineisto, to estimate the yleistys gap.

See also: yleistys, validointi, ERM, häviöfunktio.

generalized total variation (GTV) GTV is a measure of the variation of trained local models $h^{(i)}$ (or their model parameters $\mathbf{w}^{(i)}$) assigned to the nodes $i = 1, \dots, n$ of an undirected weighted verkko \mathcal{G} with edges \mathcal{E} . Given a measure $d^{(h,h')}$ for the poikkeama between hypoteesi kuvaaukset

h, h' , the GTV is

$$\sum_{\{i,i'\} \in \mathcal{E}} A_{i,i'} d^{(h^{(i)}, h^{(i')})}.$$

Here, $A_{i,i'} > 0$ denotes the weight of the undirected edge $\{i, i'\} \in \mathcal{E}$.

See also: local model, model parameter, verkko, poikkeama, hypoteesi, kuvaus.

generalized total variation minimization (GTVMin) GTVMin is an instance of regularized empirical risk minimization (RERM) using the generalized total variation (GTV) of local model parameters as a regularisoija [105].

See also: RERM, GTV, regularisoija.

geometrinen mediaani The GM of a set of input vectors $\mathbf{x}^{(1)}, \dots, \mathbf{x}^{(m)}$ in \mathbb{R}^d is a point $\mathbf{z} \in \mathbb{R}^d$ that minimizes the sum of distances to the vektorit [22] such that

$$\mathbf{z} \in \arg \min_{\mathbf{y} \in \mathbb{R}^d} \sum_{r=1}^m \|\mathbf{y} - \mathbf{x}^{(r)}\|_2. \quad (16)$$

Fig. 70 illustrates a fundamental property of the GM: If \mathbf{z} does not coincide with any of the input vectors, then the unit vektorit pointing from \mathbf{z} to each $\mathbf{x}^{(r)}$ must sum to zero—this is the zero-subgradient (optimality) condition for (16). It turns out that the solution to (16) cannot be arbitrarily pulled away from trustworthy input vectors as long as they are the majority [106, Th. 2.2].

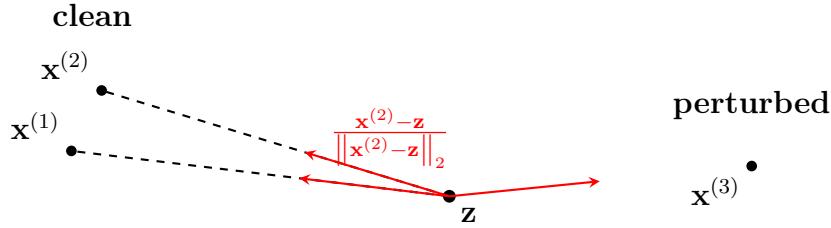


Fig. 70. Consider a solution \mathbf{z} of (16) that does not coincide with any of the input vectors. The optimality condition for (16) requires that the unit vector from \mathbf{z} to the input vectors sum to zero.

See also: vektori, subgradient.

gradient descent (GD) GD is an iterative method for finding the minimi of a differentiable funkatio $f : \mathbb{R}^d \rightarrow \mathbb{R}$. GD generates a sequence of estimates $\mathbf{w}^{(0)}, \mathbf{w}^{(1)}, \mathbf{w}^{(2)}, \dots$ that (ideally) converge to a minimi of f . At each iteration k , GD refines the current estimate $\mathbf{w}^{(k)}$ by taking a step in the direction of the steepest descent of a local linear approximation. This direction is given by the negative gradientti $\nabla f(\mathbf{w}^{(k)})$ of the funkatio f at the current estimate $\mathbf{w}^{(k)}$. The resulting update rule is given by

$$\mathbf{w}^{(k+1)} = \mathbf{w}^{(k)} - \eta \nabla f(\mathbf{w}^{(k)}) \quad (17)$$

where $\eta > 0$ is a suitably small step size. For a suitably choosen step size η , the update typically reduces the funkatio value, i.e., $f(\mathbf{w}^{(k+1)}) < f(\mathbf{w}^{(k)})$. Fig. 71 illustrates a single GD step.

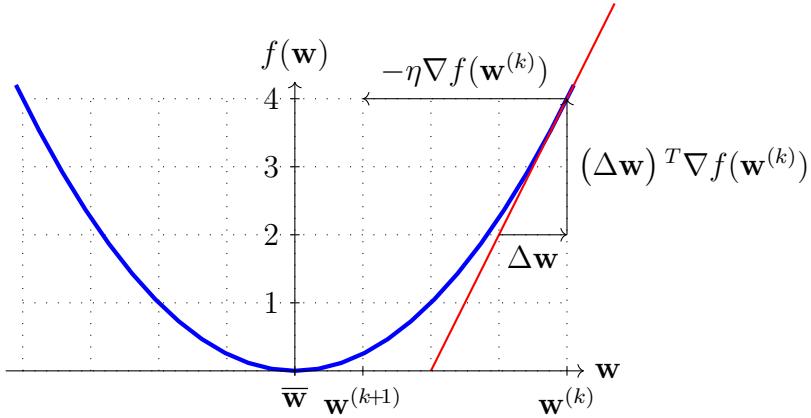


Fig. 71. A single gradienttiaskel (17) toward the minimizer $\bar{\mathbf{w}}$ of $f(\mathbf{w})$.

See also: minimi, differentiable, gradientti, step size, gradienttiaskel.

gradient-based method A gradientti-based method is an iterative technique for finding the minimi (or maksimi) of a differentiable kohdefunktio $f(\mathbf{w})$ of the model parameters \mathbf{w} . Such a method constructs a sequence of approximations to an optimal choice for \mathbf{w} . As the name indicates, a gradientti-based method uses the gradientit of the kohdefunktio evaluated during previous iterations to construct new, (hopefully) improved model parameters. One important example of a gradientti-based method is GD.

See also: gradientti, differentiable, kohdefunktio, optimointimenetelmä, GD.

gradienttitehostus Gradientti tehostus is a tehostus algoritmi that learns a hypoteesi \tilde{h} by sequentially combining the hypoteesit $\hat{h}^{(t)}$ [63, Algorithm 10.3], [107]. Similar to mukautuva tehostus, gradientti tehostus uses a

generalized gradienttiaskel to combine the results of the base learners

$$\tilde{h}^{(t)} = \tilde{h}^{(t-1)} - \eta^{(t)} \hat{h}^{(t)}$$

where the generalized gradientti \hat{h}^t is constructed from the t th base learner. The difference between mukautuva tehostus and gradientti tehostus is in the construction of \hat{h}^t . While mukautuva tehostus uses weighted ERM for this construction, gradientti tehostus uses ERM on a modified opetusaineisto. This modification is obtained by leaving the piirrevektorit untouched but replacing the nimiöt with the partial derivative of the häviöfunktio with respect to the ennusteet of the previous base learner.

See also: tehostus, mukautuva tehostus, GD.

graph clustering Verkko klusterointi aims to cluster tietopisteet that are represented as the nodes of a verkko \mathcal{G} . The edges of \mathcal{G} represent pairwise similarities between tietopisteet. We can sometimes quantify the extent of these similarities by an edge weight [104], [108].

See also: verkko, klusterointi, tietopiste, edge weight.

hajautettu algoritmi A distributed algoritmi is an algoritmi designed for a special type of computer, i.e., a collection of interconnected computing devices (or nodes). These devices communicate and coordinate their local computations by exchanging messages over a network [109], [110]. Unlike a classical algoritmi, which is implemented on a single device, a distributed algoritmi is executed concurrently on multiple devices with computational capabilities. Similar to a classical algoritmi, a distributed

algoritmi can be modeled as a set of potential executions. However, each execution in the distributed setting involves both local computations and message-passing events. A generic execution might look as follows:

$$\begin{aligned}
 &\text{Node 1: input}_1, s_1^{(1)}, s_2^{(1)}, \dots, s_{T_1}^{(1)}, \text{output}_1; \\
 &\text{Node 2: input}_2, s_1^{(2)}, s_2^{(2)}, \dots, s_{T_2}^{(2)}, \text{output}_2; \\
 &\vdots \\
 &\text{Node N: input}_N, s_1^{(N)}, s_2^{(N)}, \dots, s_{T_N}^{(N)}, \text{output}_N.
 \end{aligned}$$

Each device i starts from its own local input and performs a sequence of intermediate computations $s_t^{(i)}$ at discrete-time instants $t = 1, \dots, T_i$. These computations may depend on both the previous local computations at the device and the messages received from other devices. One important application of distributed algoritmit is in federated learning where a network of devices collaboratively trains a personal model for each device.

See also: algoritmi, device, event, federated learning, model.

hajontakuvio A visualization technique that depicts tietopisteet using markers in a 2-D plane. Fig. 72 depicts an example of a scatterplot.

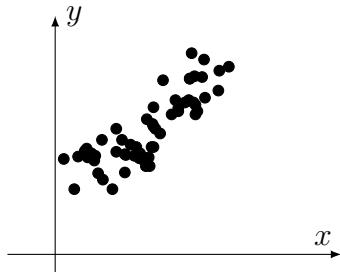


Fig. 72. A scatterplot with circle markers, where the tietopisteet represent daily weather conditions in Finland. Each tietopiste is characterized by its minimi daytime temperature x as the piirre and its maksimi daytime temperature y as the nimiö. The temperatures have been measured at the Ilmatieteen laitos weather station Helsinki Kaisaniemi during 1 September 2024—28 October 2024.

A scatterplot can enable the visual inspection of tietopisteet that are naturally represented by piirrevektorit in high-dimensional spaces.

See also: tietopiste, minimi, piirre, maksimi, nimiö, Ilmatieteen laitos, piirrevektori, ulottuvuuksien vähentäminen.

harha Consider an ERM-based koneoppiminen method that learns a hypoteesi $\hat{h} \in \mathcal{H}$ from a given opetusaineisto. The analysis of the koneoppiminen method is often based on a todennäköisyysmalli (such as the i.i.d. olettamus) for the data generation. Here, tietopisteet and, in turn, the learned hypoteesi \hat{h} are viewed as (toteumat of) satunnaismuuttujat. Any property $\theta(\hat{h})$ of \hat{h} , such as specific model parameters in a parametric model or the ennuste error $y - \hat{h}(\mathbf{x})$ for a fixed tietopiste, then also becomes an satunnaismuuttuja. The squared bias of a numeric property

$\theta(\hat{h}) \in \mathbb{R}^r$ is [47], [63]

$$B^2 := \|\mathbb{E}\{\theta(\hat{h})\} - \theta(\bar{h})\|_2^2.$$

Here, \bar{h} is a reference hypoteesi, which could be defined by $\bar{h}(\mathbf{x}) = y$ for a fixed test tietopiste with piirrevektori \mathbf{x} and nimiö y .

See also: todennäköisyysmalli, i.i.d., satunnaismuuttuja, estimointivirhe.

harjaregressio Consider a regressio problem where the goal is to learn a hypoteesi $h^{(\mathbf{w})}$ for predicting the numeric nimiö of a tietopiste based on its piirrevektori. Ridge regressio learns the parameters \mathbf{w} by minimizing the penalized average neliövirhehäviö. The average neliövirhehäviö is measured on a set of labeled data pointt (i.e., the opetusaineisto)

$$(\mathbf{x}^{(1)}, y^{(1)}) , \dots , (\mathbf{x}^{(m)}, y^{(m)}) .$$

The penalty term is the scaled squared euklidinen normi $\alpha \|\mathbf{w}\|_2^2$ with a regularisointi parameter $\alpha > 0$. The purpose of the penalty term is regularisointi, i.e., to prevent ylisovittaminen in the high-dimensional regime, where the number of piirteet d exceeds the number of tietopisteet m in the opetusaineisto. For the koulutus of a lineaarinen malli, adding $\alpha \|\mathbf{w}\|_2^2$ to the average neliövirhehäviö is equivalent to computing the average neliövirhehäviö on an augmented opetusaineisto.

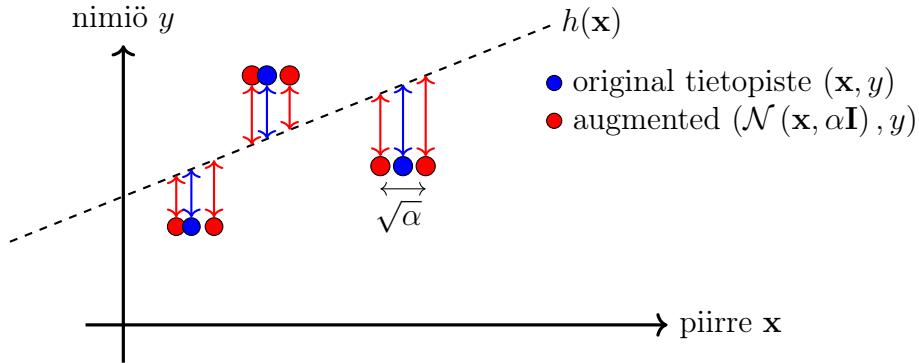


Fig. 73. For a lineaarinen malli, adding the penalty term $\alpha\|\mathbf{w}\|_2^2$ to the kohdefunktio in ERM is equivalent to ERM on an augmented tietoaineisto

This augmented opetusaineisto is obtained by replacing each tietopiste $(\mathbf{x}^{(r)}, y^{(r)})$ in the original opetusaineisto by the toteuma of infinitely many i.i.d. satunnaismuuttujat whose todennäköisyysjakauma is centred around $(\mathbf{x}^{(r)}, y^{(r)})$.

See also: regressio, regularisointi, kuvaus, data augmentation.

havaintomatriisi Katso datamatriisi.

herkkyys Recall is a metric commonly used in binary classification. It is the ratio of true positives (correctly predicted positive tietopisteet) to all actual positives (tietopisteet with positive true nimiö). I.e., it tells the proportion of true positives correctly labelled. Recall can also be extended to multiclass luokittelu.

Recall is not usually used alone, as perfect recall can be achieved by labelling all points as positive. Still, it is robust against imbalanced tietoaineistot unlike, e.g., tarkkuus.

See also: sekaannusmatriisi, metric, tarkkuus, luokittelu.

high-dimensional regime The high-dimensional regime of ERM is characterized by the effective dimension of the malli being larger than the sample size, i.e., the number of (labeled) tietopisteet in the opetusaineisto. For example, lineaarinen regressio methods operate in the high-dimensional regime whenever the number d of piirteet used to characterize tietopisteet exceeds the number of tietopisteet in the opetusaineisto. Another example of koneoppiminen methods that operate in the high-dimensional regime is large neuroverkot, which have far more tunable weights (and bias terms) than the total number of tietopisteet in the opetusaineisto. High-dimensional statistics is a recent main thread of todennäköisyys theory that studies the behavior of koneoppiminen methods in the high-dimensional regime [15], [111].

See also: ERM, effective dimension, ylisovittaminen, regularisointi.

hinge loss Consider a tietopiste characterized by a piirrevektori $\mathbf{x} \in \mathbb{R}^d$ and a binary nimiö $y \in \{-1, 1\}$. The hinge häviö incurred by a real-valued hypoteesi kuvaus $h(\mathbf{x})$ is defined as

$$L((\mathbf{x}, y), h) := \max\{0, 1 - yh(\mathbf{x})\}. \quad (18)$$

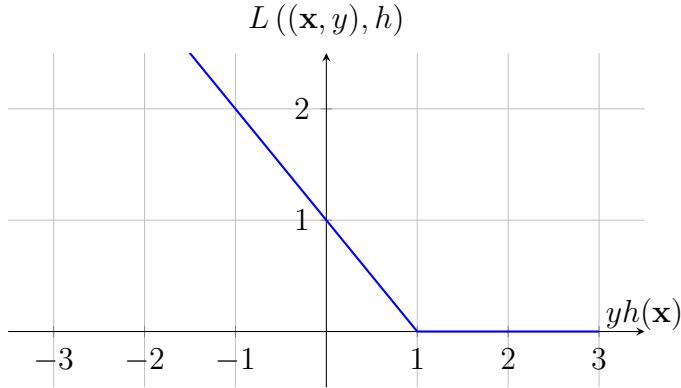


Fig. 74. The hinge häviö incurred by the ennuste $h(\mathbf{x}) \in \mathbb{R}$ for a tietopiste with nimiö $y \in \{-1, 1\}$. A regularized variant of the hinge häviö is used by the tukivektorikone [112].

See also: tukivektorikone, luokittelu, luokitin.

histogrammi Consider a tietoaineisto \mathcal{D} that consists of m tietopisteet $\mathbf{z}^{(1)}, \dots, \mathbf{z}^{(m)}$, each of them belonging to some cell $[-U, U] \times \dots \times [-U, U] \subseteq \mathbb{R}^d$ with side length U . We partition this cell evenly into smaller elementary cells with side length Δ . The histogram of \mathcal{D} assigns each elementary cell to the corresponding fraction of tietopisteet in \mathcal{D} that fall into this elementary cell. A visual example of such a histogram is provided in Fig. 75.

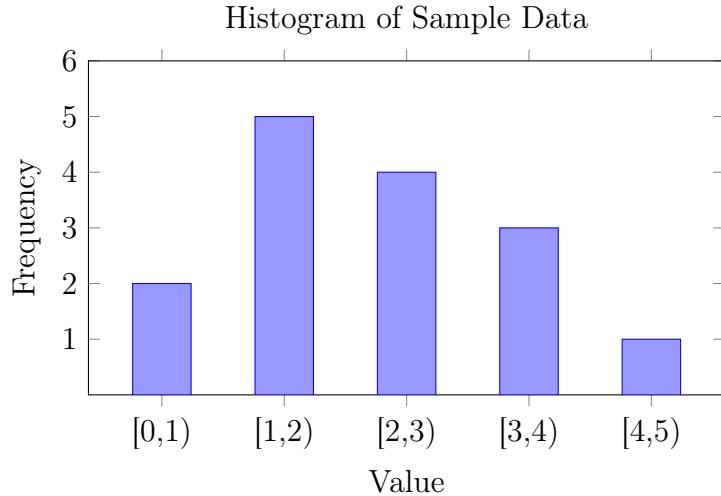


Fig. 75. A histogram consists of the fractions of tietopisteet that fall within different value ranges (i.e., bins). Each bar height shows the count of samples in the corresponding interval.

See also: tietoaineisto, tietopiste, sample.

horizontal federated learning (HFL) HFL uses local datasets constituted by different tietopisteet but uses the same piirteet to characterize them [113]. For example, weather forecasting uses a network of spatially distributed weather (observation) stations. Each weather station measures the same quantities, such as daily temperature, air pressure, and precipitation. However, different weather stations measure the characteristics or piirteet of different spatiotemporal regions. Each spatiotemporal region represents an individual tietopiste, each characterized by the same piirteet (e.g., daily temperature or air pressure).

See also: puoliohjattu oppiminen, faderoitu oppiminen, vertical federated

learning (VFL).

Huber loss The Huber häviö unifies the neliövirhehäviö and the absolute error loss.

See also: häviö, neliövirhehäviö, absolute error loss.

Huber regression Huber regressio [114] refers to ERM-based methods that use the Huber loss as a measure of the ennuste error. Two important special cases of Huber regressio are least absolute deviation regression and lineaarinen regressio. Tuning the threshold parameter of the Huber loss allows the user to trade the vakaus of the absolute error loss against the computational benefits of the smooth neliövirhehäviö.

See also: least absolute deviation regression, lineaarinen regressio, absolute error loss, neliövirhehäviö.

hyperparametri A hyperparameter associated with a koneoppiminen method is a quantity that is used to select among a family of mallit. Typical examples include the oppimisnopeus used in a gradient-based method, the number of piirteet used in a lineaarinen malli, or the maximum depth of a päätöspuu. The usefulness of a specific choice of hyperparameter can be assessed via validointi. Similar to learning (or tuning) model parameters by ERM on a opetusaineisto, we can learn (or tune) hyperparameters via minimizing the validointivirhe. Thus, in a sense hyperparameters are higher-level model parameters that are learned via a higher-level form of ERM: minimize the validointivirhe obtained for the trained malli with a given hyperparameter value.

See also: model parameter, malli, validointi.

hypoteesi A hypothesis refers to a kuvaus (or funktio) $h : \mathcal{X} \rightarrow \mathcal{Y}$ from the piirreavaruuus \mathcal{X} to the label space \mathcal{Y} . Given a tietopiste with piirteet \mathbf{x} , we use a hypothesis kuvaus h to estimate (or approximate) the nimiö y using the ennuste $\hat{y} = h(\mathbf{x})$. Koneoppiminen is all about learning (or

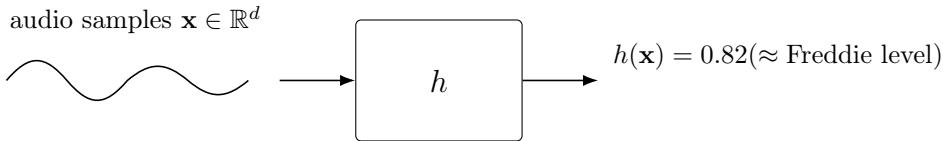


Fig. 76. A hypothesis $h : \mathcal{X} \rightarrow \mathcal{Y}$ maps the piirteet $\mathbf{x} \in \mathcal{X}$ of a tietopiste to a ennuste $h(\mathbf{x}) \in \mathcal{Y}$ of the nimiö. For example, the koneoppiminen application <https://freddiemeter.withyoutube.com/> uses the samples of an audio recording as piirteet predict how closely a person's singing resembles that of Freddie Mercury.

finding) a hypothesis kuvaus h such that $y \approx h(\mathbf{x})$ for any tietopiste (with piirteet \mathbf{x} and nimiö y). Practical koneoppiminen methods, limited by finite computational resources, must restrict learning to a subset of all possible hypothesis maps. This subset is called the hypothesis space or simply the malli underlying the method.

See also: kuvaus, funktio, ennuste, malli.

hypothesis space A hypoteesi space is a mathematical malli that characterizes the learning capacity of an koneoppiminen method. The goal of such a method is to learn a hypoteesi kuvaus that maps piirteet of a tietopiste to a ennuste of its nimiö. Given a finite amount of computational resources, a practical koneoppiminen method typically explores only a restricted set of all possible kuvauskset from the piirreavaruuus to

the label space. Such a restricted set is referred to as a hypoteesi space \mathcal{H} underlying the koneoppiminen method (see Fig. 77). For the analysis of a given koneoppiminen method, the choice of a hypoteesi space \mathcal{H} is not unique, i.e., any superset containing all kuvaukset the method can learn is also a valid hypoteesi space.

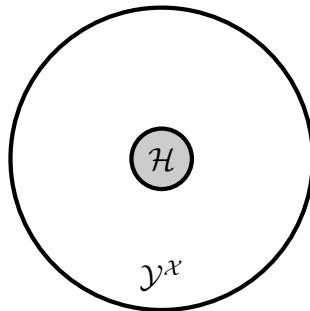


Fig. 77. The hypoteesi space \mathcal{H} of an koneoppiminen method is a (typically very small) subset of the (typically very large) set $\mathcal{Y}^{\mathcal{X}}$ of all possible kuvaukset from the piirreavaruus \mathcal{X} into the label space \mathcal{Y} .

On the other hand, from an koneoppiminen engineering perspective, the hypoteesi space \mathcal{H} is a design choice for ERM-based methods. This design choice can be guided by the available computational resources and laskennallinen ominaisuus. For instance, if efficient matriisi operations are feasible and a roughly linear relation exists between piirteet and nimiöt, a lineaarinen malli can be a useful choice for \mathcal{H} .

See also: hypoteesi, malli, kuvaus, lineaarinen malli.

hyökkäys An attack on an koneoppiminen system refers to an intentional action—either active or passive—that compromises the system’s in-

tegrity, availability, or confidentiality. Active attacks involve perturbing components such as tietoaineistot (via tietojen korruptointi) or communication links between devices within an koneoppiminen application. Passive attacks, such as yksityisyshyökkäykset, aim to infer sensitive attributes without modifying the system. Depending on their goal, we distinguish among palvelunestohyökkäykset, takaportti attacks, and yksityisyshyökkäykset.

See also: tietojen korruptointi, yksityisyshyökkäys, sensitive attribute, palvelunestohyökkäys, takaportti.

häviö koneoppiminen methods use a häviöfunktio $L(\mathbf{z}, h)$ to measure the error incurred by applying a specific hypoteesi to a specific tietopiste. With a slight abuse of notation, we use the term loss for both the häviöfunktio L itself and the specific value $L(\mathbf{z}, h)$, for a tietopiste \mathbf{z} and hypoteesi h .

See also: häviöfunktio, empiirinen riski.

häviöfunktio A häviö funktilo is a kuvaus

$$L : \mathcal{X} \times \mathcal{Y} \times \mathcal{H} \rightarrow \mathbb{R}_+ : ((\mathbf{x}, y), h) \mapsto L((\mathbf{x}, y), h).$$

It assigns a nonnegative real number (i.e., the häviö) $L((\mathbf{x}, y), h)$ to a pair that consists of a tietopiste, with piirteet \mathbf{x} and nimiö y , and a hypoteesi $h \in \mathcal{H}$. The value $L((\mathbf{x}, y), h)$ quantifies the discrepancy between the true nimiö y and the ennuste $h(\mathbf{x})$. Lower (closer to zero) values $L((\mathbf{x}, y), h)$ indicate a smaller discrepancy between ennuste $h(\mathbf{x})$ and nimiö y . Fig. 78 depicts a häviö funktilo for a given tietopiste, with piirteet \mathbf{x} and nimiö y , as a funktilo of the hypoteesi $h \in \mathcal{H}$.

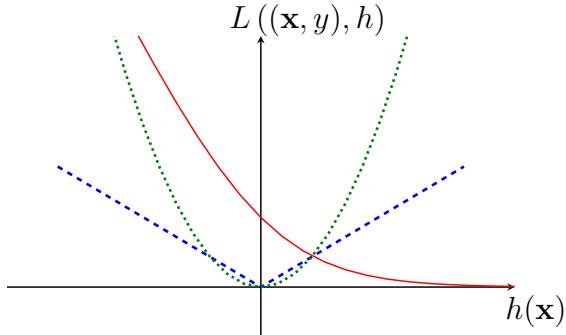


Fig. 78. Some häviö funktio $L((\mathbf{x}, y), h)$ for a fixed tietopiste, with piirrevektori \mathbf{x} and nimiö y , and a varying hypoteesi h . Koneoppiminen methods try to find (or learn) a hypoteesi that incurs minimal häviö.

See also: häviö, nimiö, piirrevektori, ERM.

Ilmatieteen laitos The FMI is a government agency responsible for gathering and reporting weather data in Finland.

See also: data.

input vector The term input vektori is often used as a synonym for the piirrevektori of a tietopiste. In settings where tietopisteet arise from a dynamical system observed over time, piirteet are obtained from measuring input variables. These input variables are then used by koneoppiminen methods to predict the system's tuotos (which is a nimiö in koneoppiminen terminology).

See also: vektori, piirrevektori, tietopiste, tuotos.

iteraatio The elementary computational step during the execution of an algoritmi is referred to as iteration [74], [115]. For example, the elementary

computational step of gradient-based methods is a gradienttiaskel. More generally, the elementary computational step of a fixed-point iteration is the evaluation of an underlying operator \mathcal{F} , which might vary across iterations (see Fig. 79). Many important koneoppiminen algoritmit, including Lloydin algoritmi and GD, are fixed-point iterations.

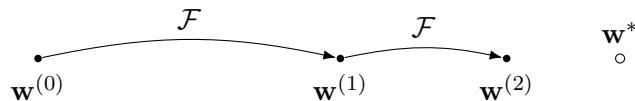


Fig. 79. A fixed-point iteration consists of the repeated application of an operator \mathcal{F} with some fixed point \mathbf{w}^* , i.e., $\mathcal{F}\mathbf{w}^* = \mathbf{w}^*$.

See also: algoritmi, gradienttiaskel, GD.

itseohjattu oppiminen Self-supervised learning uses some of the piirteet of a tietopiste as its nimiö. For example, if a tietopiste consists of a sentence within a text document, we can use the last word of the sentence as the nimiö that is to be predicted from all the previous words, which form the piirteet of the tietopiste. A main application of self-supervised learning is in luonnollisen kielen käsittely for the koulutus of laajat kielimallit from large collections of text data.

See also: piirre, nimiö, laaja kielimalli.

Jacobi method The Jacobi method is an algoritmi for solving systems of linear equations (i.e., a linear system) of the form $\mathbf{Ax} = \mathbf{b}$. Here, $\mathbf{A} \in \mathbb{R}^{d \times d}$ is a square matriisi with nonzero main diagonal entries. The method constructs a sequence $\mathbf{x}^{(0)}, \mathbf{x}^{(1)}, \dots$ by updating each entry of

$\mathbf{x}^{(t)}$ according to

$$x_i^{(t+1)} = \frac{1}{a_{ii}} \left(b_i - \sum_{j \neq i} a_{ij} x_j^{(t)} \right).$$

Note that all entries $x_1^{(k)}, \dots, x_d^{(k)}$ are updated simultaneously. The above iteration converges to a solution, i.e., $\lim_{t \rightarrow \infty} \mathbf{x}^{(t)} = \mathbf{x}$, under certain conditions on the matriisi \mathbf{A} , e.g., being strictly diagonally dominant or symmetric positive definite [3], [31], [45]. Jacobi-type methods are appealing for large linear systems due to their parallelizable structure [110]. We can interpret the Jacobi method as a fixed-point iteration. Indeed, using the decomposition $\mathbf{A} = \mathbf{D} + \mathbf{R}$, with \mathbf{D} being the diagonal of \mathbf{A} , allows us to rewrite the linear equation $\mathbf{Ax} = \mathbf{b}$ as a fixed-point equation

$$\mathbf{x} = \underbrace{\mathbf{D}^{-1}(\mathbf{b} - \mathbf{Rx})}_{\mathcal{F}\mathbf{x}}$$

which leads to the iteration $\mathbf{x}^{(t+1)} = \mathbf{D}^{-1}(\mathbf{b} - \mathbf{Rx}^{(t)})$.

As an example, for the linear equation $\mathbf{Ax} = \mathbf{b}$, where

$$\mathbf{A} = \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix}, \quad \mathbf{b} = \begin{pmatrix} b_1 \\ b_2 \\ b_3 \end{pmatrix}$$

the Jacobi method updates each component of \mathbf{x} as follows:

$$\begin{aligned} x_1^{(k+1)} &= \frac{1}{a_{11}} \left(b_1 - a_{12}x_2^{(k)} - a_{13}x_3^{(k)} \right); \\ x_2^{(k+1)} &= \frac{1}{a_{22}} \left(b_2 - a_{21}x_1^{(k)} - a_{23}x_3^{(k)} \right); \\ x_3^{(k+1)} &= \frac{1}{a_{33}} \left(b_3 - a_{31}x_1^{(k)} - a_{32}x_2^{(k)} \right). \end{aligned}$$

See also: algoritmi, matriisi, fixed-point iteration, optimointimenetelmä.

joukkoon kuulumiseen perustuvaa päätelyä hyödyntävä hyökkäys

Consider an koneoppiminen method that learns a hypoteesi via ERM on a opetusaineisto. Membership inference hyökkäys is a form of yksityisyshyökkäys where an adversary tries to determine whether a particular tietopiste was part of the opetusaineisto. The attacker typically queries \hat{h} with candidate piirrevektorit $\mathbf{x}^{(1)}, \dots, \mathbf{x}^{(B)}$, and infers the membership status of a given tietopiste based on the ennusteet $\hat{h}(\mathbf{x}^{(1)}), \dots, \hat{h}(\mathbf{x}^{(B)})$ [116].

See also: hyökkäys, yksityisyshyökkäys.

***k*-kertainen ristiinvalidointi** A k -fold CV is a method for evaluating the generalization gap of an ERM-based koneoppiminen method. The idea is to divide a tietoaineisto \mathcal{D} evenly into k subsets (or folds) $\mathcal{D}^{(1)}, \dots, \mathcal{D}^{(k)}$.

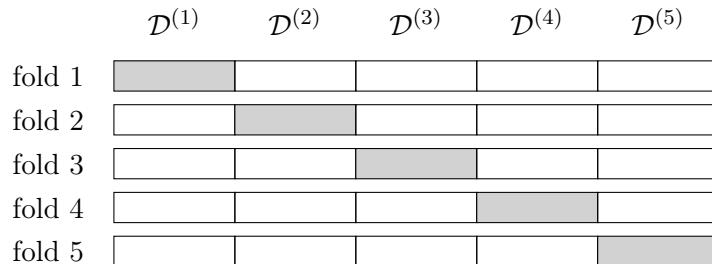


Fig. 80. In k -fold CV, the available tietoaineisto \mathcal{D} is evenly divided into k folds $\mathcal{D}^{(1)}, \dots, \mathcal{D}^{(k)}$. Each fold is used once as a validointiaineisto, while the remaining $k - 1$ folds form the opetusaineisto.

For each fold $b = 1, \dots, k$, we train the malli on the union of all folds except $\mathcal{D}^{(b)}$ and validate it on $\mathcal{D}^{(b)}$. The overall performance is obtained

by averaging the validointi results across all k folds.

See also: validointi, validointivirhe.

k -means The k -keskiarvot principle is an optimization-based approach to the klusterointi of tietopisteet with a numeric piirrevektori [8, Ch. 8]. As a osittava klusterointi approach, k -keskiarvot partitions a tietoaineisto into k disjoint subsets (or ryppäät), which are indexed by $c = 1, \dots, k$. Each rypäs \mathcal{C} is characterized by the average piirrevektori of tietopisteet that belong to it. This average (or keskiarvo) piirrevektori is referred to as the cluster centroid $\mathbf{w}^{(c)}$. A visual illustration is provided in Fig. 81.

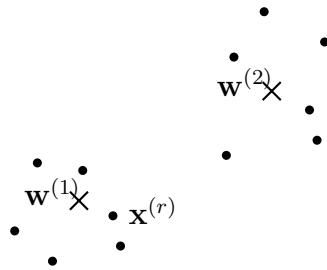


Fig. 81. A hajontakuvio of tietopisteet, indexed by $r = 1, \dots, m$ and characterized by piirrevektorit $\mathbf{x}^{(r)} \in \mathbb{R}^2$. The hajontakuvio also includes two cluster centroids $\mathbf{w}^{(1)}, \mathbf{w}^{(2)} \in \mathbb{R}^2$.

In general, solving the k -keskiarvot optimointitehtävä exactly is challenging (or NP-hard) [117]. However, there are simple iterative methods for finding approximately optimal cluster centroids. One such method is referred to as Lloydin algoritmi.

See also: osittava klusterointi, rypäs, Lloydin algoritmi.

k -means++ TBC.

See also: k -means.

keski-itseisvirhe The MAE of a hypoteesi is the average absolute error loss computed over a given tietoaineisto. In theoretical analyses, MAE also denotes the expected absolute error loss, i.e., the corresponding riski.

See also: absolute error loss, riski.

keskineliövirhe The MSE of a hypoteesi is the average neliövirhehääviö computed over a given tietoaineisto. In theoretical analyses, MSE also denotes the expected neliövirhehääviö, i.e., the corresponding riski.

See also: neliövirhehääviö, riski.

klusterointi Clustering methods decompose a given set of tietopisteet into a few subsets, which are referred to as ryppäät. Each rypäs consists of tietopisteet that are more similar to each other than to tietopisteet outside the rypäs. Different clustering methods use different measures for the similarity between tietopisteet and different forms of rypäs representations. The clustering method k -means uses the average piirrevektori of a rypäs (i.e., the rypäs kesiarvo) as its representative. A popular soft clustering method based on Gaussian sekoitemalli represents a rypäs by a moninormaalijakauma.

See also: rypäs, k -means, soft clustering, Gaussian sekoitemalli.

kohdefunktio An objective funktila is a kuvaus that assigns a numeric objective value $f(\mathbf{w})$ to each choice \mathbf{w} of some variable that we want to optimize (see Fig. 82). In the context of koneoppiminen, the optimization variable could be the model parameters of a hypoteesi $h^{(\mathbf{w})}$.

Common objective funktiot include the riski (i.e., expected häviö) or the empiirinen riski (i.e., average häviö over a opetusaineisto). koneoppimisen methods apply optimization techniques, such as gradient-based methods, to find the choice \mathbf{w} with the optimal value (e.g., the minimi or the maksimi) of the objective funktio.

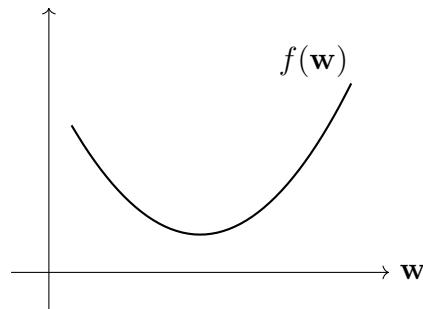


Fig. 82. An objective funktio maps each possible value \mathbf{w} of an optimization variable, such as the model parameters of an koneoppiminen malli, to a value $f(\mathbf{w})$ that measures the usefulness of \mathbf{w} .

See also: häviö, empiirinen riski, ERM, optimointitehtävä.

kokonaisvaihtelu See GTV.

koneoppiminen ML methods aim to learn (or find) a useful hypoteesi kuvaus $\hat{h} \in \mathcal{H}$ out of a malli \mathcal{H} . The learned \hat{h} is used to compute a ennuste $\hat{y} = \hat{h}(\mathbf{x})$ for the nimiö y of a tietopiste. The learning process is guided by a quantitative measure of the häviö incurred when the ennusteet obtained from the learned hypoteesi differ from the actual nimiö y . Different ML methods use different design choices for this

quantitative measure (or häviöfunktio) as well as different choices for the malli and the tietopisteet (i.e., their piirteet and nimiöt) [8, Ch. 3].

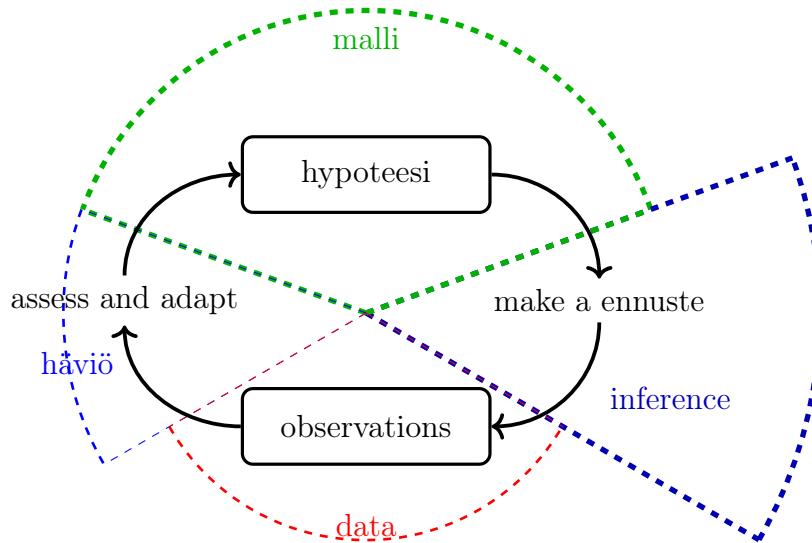


Fig. 83. ML learns a hypoteesi out of a malli (or hypothesis space) by trying to minimize the häviö incurred by the ennusteet for the nimiöt of tietopisteet. The ennusteet are computed solely from the piirteet of the tietopisteet.

Another distinction between ML methods is how they access tietopisteet during learning. For example, some methods have access to a complete tietoaineisto during koulutus, which allows them to use ERM [8], [118]. In contrast, online learning methods access data sequentially and, in turn, update the learned hypoteesi whenever a new tietopiste arrives [99], [100], [119].

See also: malli, data, häviö, ERM, online learning.

kooderi See autoenkoodaja.

kooste An ensemble method combines multiple koneoppiminen methods, each of those referred to as a base learner, to improve overall performance. The base learners can be ERM-based using different choices for the häviö, malli, and opetusaineisto. By aggregating the ennusteet of base learners, ensemble methods can often achieve better performance than any single base learner. The aggregation can amount to averaging the ennusteet of base learners (in regressio) or using a majority vote (for luokittelu methods).

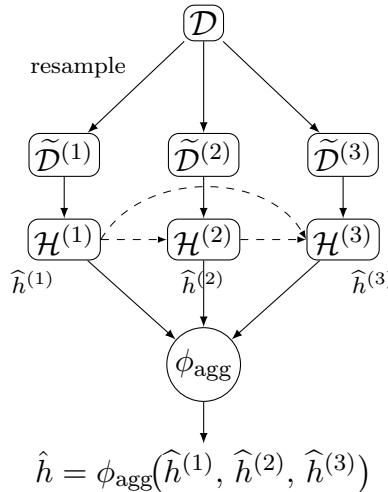


Fig. 84. A generic ensemble with three base learners, each using ERM to learn $\mathcal{H}^{(j)} \in \mathcal{H}^{(j)}$ based on the opetusaineisto $\tilde{\mathcal{D}}^{(j)}$. A base learner might also use the tuotos of other base learners. The final hypoteesi \hat{h} is obtained by aggregating the hypoteesit generated by the base learners.

Different ensemble methods use different constructions for the base learners. For example, laukutus methods (such as a satunnaismetsä) use

random sampling to construct slightly different opetusaineistot for each base learner. On the other hand, tehostus methods run the base learners sequentially, i.e., each base learner tries to correct the ennuste errors of the previous ones. A third family of ensemble methods is pinoaminen, where base learners are trained on the same opetusaineisto but with different mallit.

See also: laukutus, tehostus, pinoaminen.

koulutus In the context of koneoppiminen, training refers to the process of learning a useful hypoteesi \hat{h} out of a malli \mathcal{H} . The training of a malli \mathcal{H} is guided by the häviö incurred on a set of tietopisteet, which serve as the opetusaineisto. For parametric models, where each hypoteesi $h^{(\mathbf{w})}$ is characterized by a specific choice for the model parameters, training amounts to finding an optimal choice for the model parameters \mathbf{w} . A widely-used approach to training is ERM, which learns a hypoteesi by minimizing the average häviö incurred on a opetusaineisto. One of the main challenges in koneoppiminen is to control the poikkeama between the häviö incurred on the opetusaineisto and the häviö incurred on other (unseen) tietopisteet.

See also: malli, häviö, ERM.

koulutusdata Katso opetusaineisto

Kroneckerin tulo The Kronecker product of two matriisit $\mathbf{A} \in \mathbb{R}^{m \times n}$ and

$\mathbf{B} \in \mathbb{R}^{p \times q}$ is a block matriisi denoted by $\mathbf{A} \otimes \mathbf{B}$ and defined as [3], [28]

$$\mathbf{A} \otimes \mathbf{B} = \begin{pmatrix} a_{11}\mathbf{B} & \cdots & a_{1n}\mathbf{B} \\ \vdots & \ddots & \vdots \\ a_{m1}\mathbf{B} & \cdots & a_{mn}\mathbf{B} \end{pmatrix} \in \mathbb{R}^{mp \times nq}.$$

The Kronecker product is a special case of the tensor product for matriisit and is widely used in multivariate statistics, linear algebra, and structured koneoppiminen mallit. It satisfies the identity $(\mathbf{A} \otimes \mathbf{B})(\mathbf{x} \otimes \mathbf{y}) = (\mathbf{Ax}) \otimes (\mathbf{By})$ for vektorit \mathbf{x} and \mathbf{y} of compatible dimensions.

See also: matriisi, koneoppiminen, malli, vektori.

Kullbackin–Leiblerin poikkeama The KL divergence is a quantitative measure of how different one todennäköisyysjakauma is from another [30].

See also: todennäköisyysjakauma.

kuvan segmentointi Image segmentation refers to the task of klusterointi the pixels of an image into few segments.

See also: klusterointi.

kvadraattinen funktio A funktio $f : \mathbb{R}^d \rightarrow \mathbb{R}$ of the form

$$f(\mathbf{w}) = \mathbf{w}^T \mathbf{Q} \mathbf{w} + \mathbf{q}^T \mathbf{w} + a$$

with some matriisi $\mathbf{Q} \in \mathbb{R}^{d \times d}$, vektori $\mathbf{q} \in \mathbb{R}^d$, and scalar $a \in \mathbb{R}$.

See also: funktio, matriisi, vektori.

käyrän alle jävä pinta-ala (AUC-arvo) The AUC is a quantitative measure of the usefulness of a binary luokitin [120]. It is defined (using the

natural measure of the euklidinen avaruus \mathbb{R}^2) as the area under the erottelukykyosoitin (ROC-käyrä) curve.

See also: luokitin, euklidinen avaruus, ROC-käyrä.

laaja kielimalli An LLM is an umbrella term for koneoppiminen methods that use high-dimensional koneoppiminen mallit (with billions of model parameters) trained on large collections of text data. LLMs are used to analyze or generate sequences of esiintymät that constitute text data. Many current LLMs use some variant of a muuntaja that is trained via itseohjattu oppiminen, i.e., the koulutus is based on the task of predicting a few words that are intentionally removed from a large text corpus. Thus, we can construct labeled data points simply by selecting some words from a given text as nimiöt and the remaining words as piirteet of tietopisteet. This construction requires very little human supervision and allows for generating sufficiently large opetusaineistot for LLMs.

See also: esiintymä, muuntaja, luonnollisen kielen käsiteily.

label space In an koneoppiminen application, each tietopiste is described by a set of piirteet together with an associated nimiö. The set of all admissible nimiö values is called the label space, denoted by \mathcal{Y} . Importantly, \mathcal{Y} may include values that no observed tietopiste has as its nimiö value. To a large extent, the choice of \mathcal{Y} is up to the koneoppiminen engineer and depends on the problem formulation. Fig. 85 shows some examples of nimiö spaces that are commonly used in koneoppiminen applications.

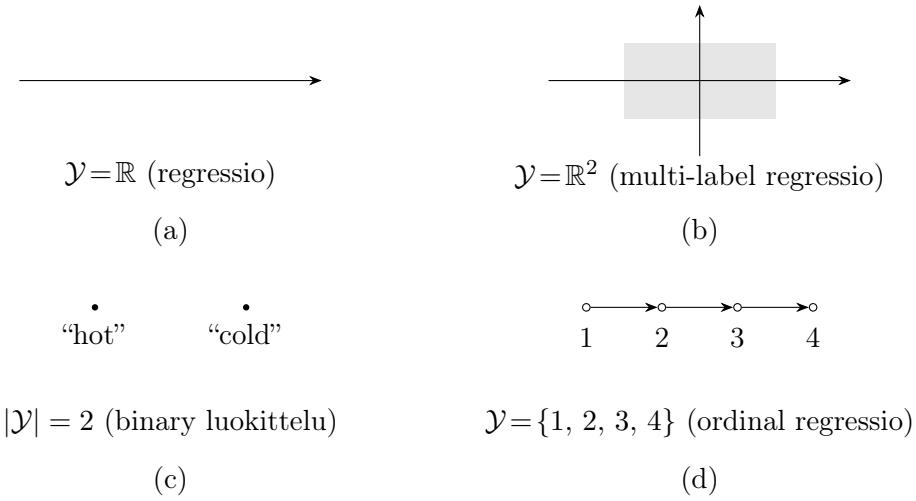


Fig. 85. Examples of nimiö spaces and the corresponding types of koneop-piminen. (a) Regressio. (b) Multi-label regressio. (c) Binary luokittelu. (d) Ordinal regressio.

The choice of the nimiö space \mathcal{Y} determines the type of koneoppiminen methods appropriate for the application at hand. Regressio methods use the $\mathcal{Y} = \mathbb{R}$, while binary luokittelu methods use a nimiö space \mathcal{Y} that consists of two different elements, i.e., $|\mathcal{Y}| = 2$. Ordinal regressio methods use a finite, ordered set of nimiö values, e.g., $\mathcal{Y} = \{1, 2, 3, 4\}$ with the natural ordering $1 < 2 < 3 < 4$.

See also: tietopiste, nimiö, regressio, luokittelu.

label vector Given a tietoaineisto of m labeled data points

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

it is convenient to collect the corresponding nimiöt into a single nimiövektori $\mathbf{y} := (y_1, \dots, y_m)^T$ [47], [63].

See also: tietoaineisto, labeled data point, nimiö, tietopiste.

labeled data point A tietopiste whose nimiö is known or has been determined by some means that might require human labor.

See also: tietopiste, nimiö.

Laplacian matrix The structure of a verkko \mathcal{G} , with nodes $i = 1, \dots, n$, can be analyzed using the properties of special matriisit that are associated with \mathcal{G} . One such matriisi is the verkko Laplacian matriisi $\mathbf{L}^{(\mathcal{G})} \in \mathbb{R}^{n \times n}$, which is defined for an undirected and weighted verkko [108], [121]. It is defined elementwise as (see Fig. 86)

$$L_{i,i'}^{(\mathcal{G})} := \begin{cases} -A_{i,i'}, & \text{for } i \neq i', \{i, i'\} \in \mathcal{E}; \\ \sum_{i'' \neq i} A_{i,i''}, & \text{for } i = i'; \\ 0, & \text{else.} \end{cases}$$

Here, $A_{i,i'}$ denotes the edge weight of an edge $\{i, i'\} \in \mathcal{E}$.

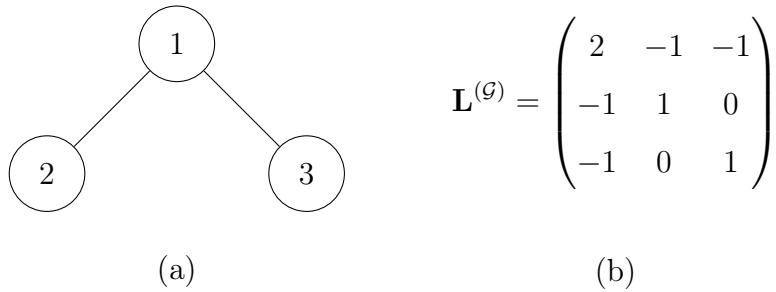


Fig. 86. (a) Some undirected verkko \mathcal{G} with three nodes $i = 1, 2, 3$. (b) The Laplacian matriisi $\mathbf{L}^{(\mathcal{G})} \in \mathbb{R}^{3 \times 3}$ of \mathcal{G} .

See also: verkko, matriisi, edge weight.

laskennalliset ominaisuudet By computational aspects of an koneoppiminen method, we mainly refer to the computational resources required for its implementation. For example, if an koneoppiminen method uses iterative optimization techniques to solve ERM, then its computational aspects include: 1) how many arithmetic operations are needed to implement a single iteration (i.e., a gradienttiaskel); and 2) how many iterations are needed to obtain useful model parameters. One important example of an iterative optimization technique is GD.

See also: koneoppiminen, ERM, gradienttiaskel, model parameter, GD.

laukutus Bagging is an kooste technique where base learners use perturbed copies

$$\tilde{\mathcal{D}}^{(1)}, \dots, \tilde{\mathcal{D}}^{(M)}$$

of the original opetusaineisto \mathcal{D} [122]. Each base learner delivers a potentially different hypoteesi,

$$\hat{h}^{(1)}, \dots, \hat{h}^{(M)}.$$

The hypoteesi delivered by the overall method is obtained by aggregating the hypoteesit $\hat{h}^{(1)}, \dots, \hat{h}^{(M)}$ using some aggregation rule. For luokiteltu methods, the rule is typically a majority vote, while for regressio methods, it amounts to averaging.

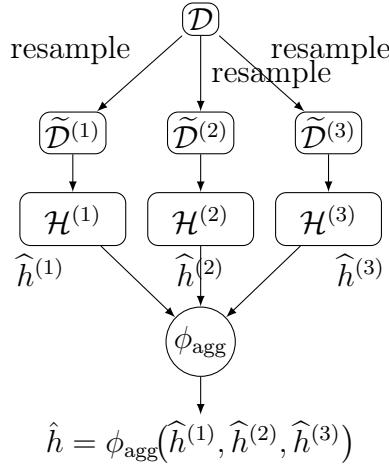


Fig. 87. An example of bagging where three base learners use perturbations $\tilde{\mathcal{D}}^{(1)}, \dots, \tilde{\mathcal{D}}^{(3)}$ of the original opetusaineisto \mathcal{D} to learn the hypoteesit $\hat{h}^{(1)}, \dots, \hat{h}^{(3)}$. The final hypoteesi is obtained by aggregating these individual hypoteesit via some aggregation rule ϕ_{agg} .

See also: kooste, vakaus, uusio-otanta.

layer A deep net is an neuroverkko that consists of consecutive layers, indexed by $\ell = 1, 2, \dots, L$. The ℓ -th layer consists of artificial neurons $a_1^{(\ell)}, \dots, a_{d^{(\ell)}}^{(\ell)}$ with the layer width $d^{(\ell)}$. Each of these artificial neurons evaluates an aktivointifunktio for a weighted sum of the outputs (or activations) of the previous layer $\ell - 1$. The input to layer $\ell = 1$ is formed from weighted sums of the piirteet of the tietopiste for which the deep net computes a ennuste. The outputs of the neurons in layer ℓ are then, in turn, used to form the inputs for the neurons in the next layer. The final (output) layer consists of a single neuron whose output is used as the ennuste delivered by the deep net.

See also: deep net, neuroverkko.

least absolute deviation regression Least absolute deviation regression is an instance of ERM using the absolute error loss. It is a special case of Huber regression.

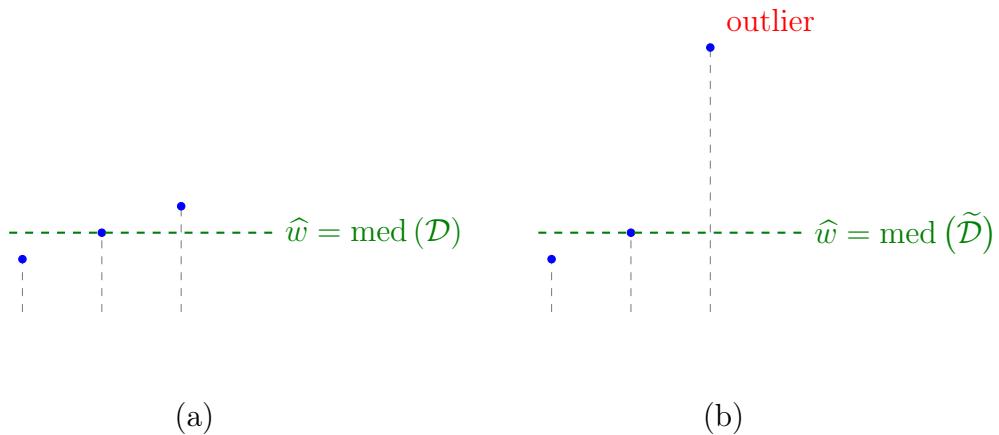


Fig. 88. For the simple parametric model $h^{(w)}(\mathbf{x}) = w$, ERM with absolute error loss amounts to computing the mediaani. (a) Original tietoaineisto \mathcal{D} . (b) Noisy tietoaineisto $\tilde{\mathcal{D}}$ including an poikkeava havainto.

For the parametric model $h^{(w)}(\mathbf{x}) = w$, ERM with absolute error loss is solved by the mediaani. Using neliövirhehäviö instead for the same parametric model, makes ERM computing the keskiarvo.

See also: ERM, absolute error loss, Huber regression.

lineaarininen erotteluanalyysi LDA is a classical piirreoptimointi method [47], [123]. In the context of binary luokittelu problems, LDA seeks a linear piirrekartta $\phi^{(\mathbf{w})} : \mathbb{R}^d \rightarrow \mathbb{R} : \mathbf{x} \mapsto \mathbf{w}^T \mathbf{x}$ such that the new piirre $\phi^{(\mathbf{w})}(\mathbf{x})$ optimally allows us to predict the nimiö of a tietopiste.

See also: piirreoptimointi, ulottuvuuksien vähentäminen, itseohjattu oppiminen.

lineaarinen luokitin Consider tietopisteet characterized by numeric piirteet $\mathbf{x} \in \mathbb{R}^d$ and a nimiö $y \in \mathcal{Y}$ from some finite label space \mathcal{Y} . A linear luokitin is characterized by having päättösalueet that are separated by hyperplanes in \mathbb{R}^d [8, Ch. 2].

See also: tietopiste, piirre, nimiö, label space, luokitin, päättösalue.

lineaarinen malli Consider an koneoppiminen application involving tietopisteet, each represented by a numeric piirrevektori $\mathbf{x} \in \mathbb{R}^d$. A linear malli defines a hypothesis space consisting of all real-valued lineaarikuvauskset from \mathbb{R}^d to \mathbb{R} such that

$$\mathcal{H}^{(d)} := \{h : \mathbb{R}^d \rightarrow \mathbb{R} \mid h(\mathbf{x}) = \mathbf{w}^\top \mathbf{x} \text{ for some } \mathbf{w} \in \mathbb{R}^d\}.$$

Each value of d defines a different hypothesis space, corresponding to the number of piirteet used to compute the ennuste $h(\mathbf{x})$. The choice of d is often guided not only by laskennallinen ominaisuus (e.g., fewer features reduce computation) and laskennallinen ominaisuus (e.g., more features typically reduce harha and riski), but also by tulkittavuus. A linear malli using a small number of well-chosen piirteet is generally considered more interpretable [124], [125]. The linear malli is attractive because it can typically be trained using scalable convex optimointimenetelmät [59], [63]. Moreover, linear mallit often permit rigorous statistical analysis, including fundamental limits on the minimi achievable riski [15]. They are also useful for analyzing more complex nonlinear mallit such as neuroverkot. For instance, a deep net can be viewed as the

composition of a piirrekartta—implemented by the input and hidden layers—and a linear malli in the tuotos layer. Similarly, a päätöspuu can be interpreted as applying a one-hot-encoded piirrekartta based on päätösalueet, followed by a linear malli that assigns a ennuste to each region. More generally, any trained malli $\hat{h} \in \mathcal{H}$ that is differentiable at some \mathbf{x}' can be locally approximated by a lineaarikuvaus $g(\mathbf{x})$. Fig. 89 illustrates such a local linear approximation, defined by the gradientti $\nabla\hat{h}(\mathbf{x}')$. Note that the gradientti is only defined where \hat{h} is differentiable. To ensure vakaus in the context of luotettava tekoäly, one may prefer mallit whose associated kuvaus \hat{h} is Lipschitz jatkuva. A classic result in mathematical analysis—Rademacher’s Theorem—states that if \hat{h} is Lipschitz jatkuva with some constant L over an open set $\Omega \subseteq \mathbb{R}^d$, then \hat{h} is differentiable almost everywhere in Ω [126, Th. 3.1].

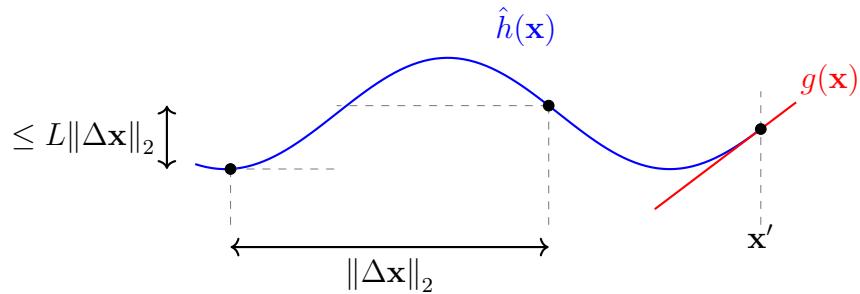


Fig. 89. A trained malli $\hat{h}(\mathbf{x})$ that is differentiable at a point \mathbf{x}' can be locally approximated by a lineaarikuvaus $g \in \mathcal{H}^{(d)}$. This local approximation is determined by the gradientti $\nabla\hat{h}(\mathbf{x}')$.

See also: malli, hypothesis space, lineaarikuvaus, tulkittavuus, LIME.

lineaarinен regressio Linear regressio methods learn a linear hypoteesi

kuvaus $h^{(\mathbf{w})}(\mathbf{x}) = \mathbf{w}^T \mathbf{x}$ which is used to predict the numeric nimiö $y \in \mathbb{R}$ of a tietopiste based on its numeric piirrevektorit $\mathbf{x} = (x_1, \dots, x_d)^T \in \mathbb{R}^d$. The least-squares variant of linear regressio measures the quality of a linear hypoteesi kuvaus via the average neliövirhehäviö incurred on a opetusaineisto

$$(\mathbf{x}^{(1)}, y^{(1)}), \dots, (\mathbf{x}^{(m)}, y^{(m)}) .$$

As an instance of ERM, linear (least-squares) regressio learns the model parameters \mathbf{w} by solving the optimointitehtävä

$$\min_{\mathbf{w} \in \mathbb{R}^d} \frac{1}{m} \sum_{r=1}^m (y^{(r)} - \mathbf{w}^T \mathbf{x}^{(r)})^2 .$$

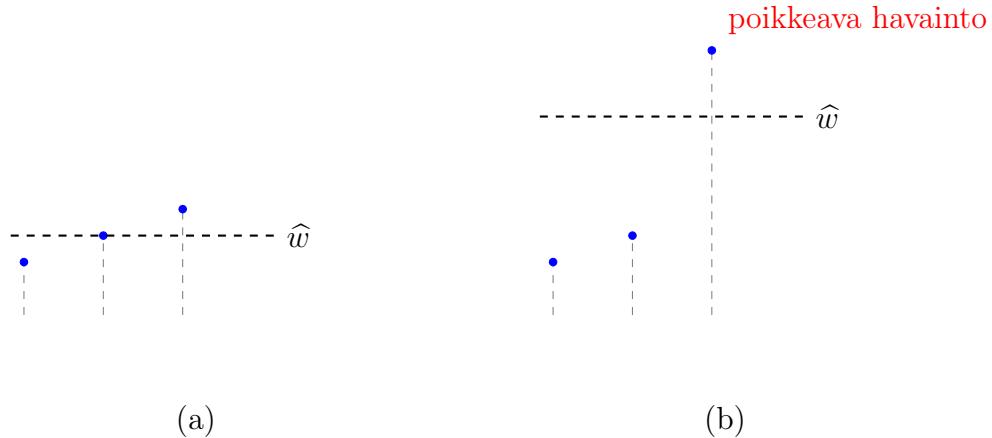


Fig. 90. For a lineaarinen malli with $d = 1$ and using the trivial piirre $x = 1$ for any tietopiste, linear regressio reduces to computing the average $\hat{w} = (1/m) \sum_{r=1}^m y^{(r)}$. (a) A clean opetusaineisto and resulting parameter (given by the average). (b) A perturbed tietoaineisto (including an poikkeava havainto) and the resulting parameter.

We can rewrite the above optimointitehtävä more compactly using the feature matrix $\mathbf{X} = (\mathbf{x}^{(1)}, \dots, \mathbf{x}^{(m)})^T \in \mathbb{R}^{m \times d}$ and the nimiö vektori $\mathbf{y} = (y^{(1)}, \dots, y^{(m)})^T \in \mathbb{R}^m$. This allows to rewrite the above optimointitehtävä as

$$\min_{\mathbf{w} \in \mathbb{R}^d} \frac{1}{m} \|\mathbf{y} - \mathbf{X}\mathbf{w}\|_2^2.$$

By the zero-gradient condition, a necessary and sufficient condition for a vector $\hat{\mathbf{w}}$ to be a solution to the above optimointitehtävä is the linear system of equations [31]

$$\mathbf{X}^T \mathbf{X} \hat{\mathbf{w}} = \mathbf{X}^T \mathbf{y}. \quad (19)$$

Instead of solving (19) directly (via computing the käänteismatriisi or pseudokäänteisluku), many koneoppiminen mehtods use variants of GD to construct a sequence $\mathbf{w}^{(0)}, \mathbf{w}^{(1)}, \dots$, of increasingly accurate approximations of a solution $\hat{\mathbf{w}}$ to (19). These gradient-based methods can be interpreted as a fixed-point iteration for the following re-formulation of (19),

$$(\mathbf{I} - \mathbf{A}\mathbf{X}^T \mathbf{X}) \hat{\mathbf{w}} + \mathbf{X}^T \mathbf{y} = \hat{\mathbf{w}}, \text{ with some invertible matriisi } \mathbf{A}.$$

This equation is solved by a vektori $\hat{\mathbf{w}}$ if and only if this vektori also solves (19). The optimality condition (19) is also useful for the study of the stability of linear regressio. Ideally, we would like the solutions of (19) to be insensitive to small perturbations of the opetusaineisto. We can capture these perturbations via a perturbed feature matrix $\tilde{\mathbf{X}} = \mathbf{X} + \Delta\mathbf{X}$ and perturbed nimiö vektori $\tilde{\mathbf{y}} = \mathbf{y} + \Delta\mathbf{y}$. Here, $\Delta\mathbf{X}$ and $\Delta\mathbf{y}$ represent small perturbations to the piirrevektorit and nimiöt

of the tietopisteet in the original opetusaineisto. Matriisi perturbation theory allows to evaluate how much the solutions of the perturbed linear regressio problem [3, Sec. 2.6]

$$\tilde{\mathbf{X}}^T \tilde{\mathbf{X}} \tilde{\mathbf{w}} = \tilde{\mathbf{X}}^T \tilde{\mathbf{y}}$$

deviate from the solutions $\tilde{\mathbf{w}}$ of the original linear regressio problem.

See also: regressio, lineaarinen malli, ERM.

linear least squares Linear pienin neliösumma refers to the variant of lineaarinen regressio that uses the neliövirhehäviö to measure the quality of a linear hypoteesi kuvaus. Conversely, it can also be viewed as the variant of pienin neliösumma that restricts the hypoteesi to a lineaarinen malli. In particular, linear pienin neliösumma learns the parameters \mathbf{w} of a linear hypoteesi $h^{(\mathbf{w})}(\mathbf{x}) = \mathbf{w}^T \mathbf{x}$ by solving

$$\min_{\mathbf{w} \in \mathbb{R}^d} \|\mathbf{y} - \mathbf{X}\mathbf{w}\|_2^2. \quad (20)$$

Here, the feature matrix is $\mathbf{X} = (\mathbf{x}^{(1)}, \dots, \mathbf{x}^{(m)})$ and the label vector is $\mathbf{y} = (y^{(1)}, \dots, y^{(m)})^T$. Both are constructed from the opetusaineisto

$$\mathcal{D} = \{(\mathbf{x}^{(1)}, y^{(1)}), \dots, (\mathbf{x}^{(m)}, y^{(m)})\}.$$

The optimointitehtävä in (20) admits a clear geometric interpretation, i.e., we seek the vektori $\mathbf{X}\hat{\mathbf{w}}$ in the column space of \mathbf{X} that is closest to the label vector \mathbf{y} (see Fig. 91) [22, Ch. 8]. A necessary and sufficient condition for $\hat{\mathbf{w}}$ to minimize (20) is the normaaliyhtälöt

$$\mathbf{X}^T \mathbf{X} \hat{\mathbf{w}} = \mathbf{X}^T \mathbf{y}.$$

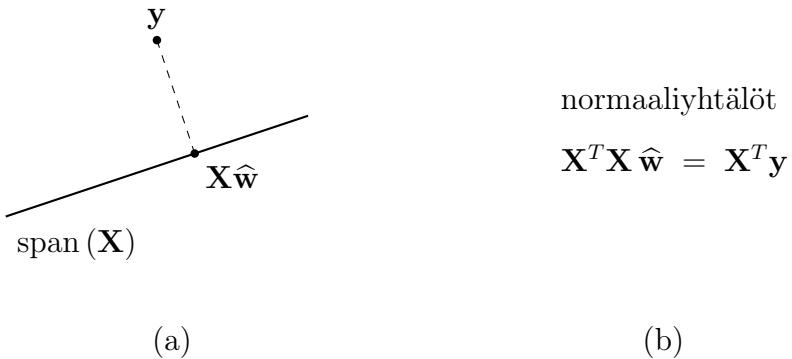


Fig. 91. Linear pienin neliösumma has both geometric and algebraic interpretations. (a) Geometrically, it finds the orthogonal projektio of the label vector \mathbf{y} onto the column space of the feature matrix \mathbf{X} [22, Ch. 8]. (b) Algebraically, it solves a linear system known as normaaliyhtälöt.

See also: pienin neliösumma, lineaarinen regressio, neliövirhehäviö, lineaarinen malli, ERM.

Lloydin algoritmi Lloyd’s algoritmi [127] is an iterative optimointimene-
telmä for finding cluster centroids that are approximately optimal for
the k -means kohdefunktio. Lloyd’s algoritmi alternates between: 1) up-
dating the rypäs assignment of each tietopiste based on the nearest
current cluster centroid; and 2) recalculating the cluster centroids given
the updated rypäs assignments [127].

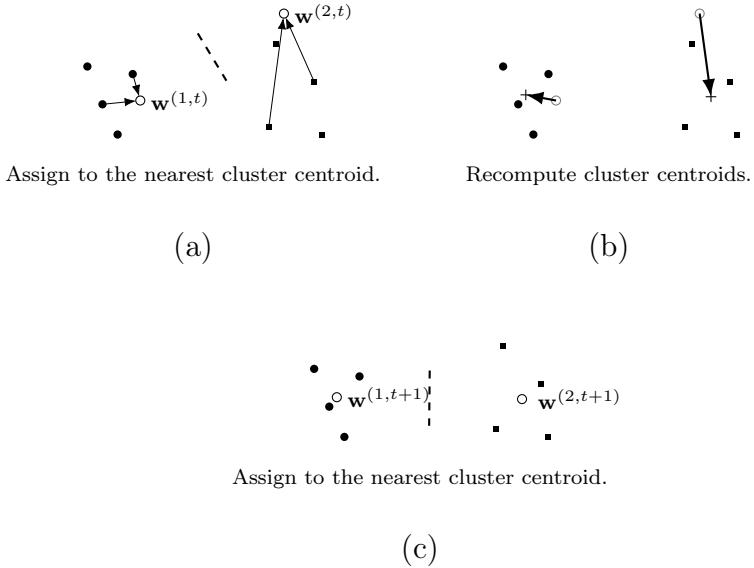


Fig. 92. Lloyd's algoritmi alternates between (a) and (c) assigning tietopisteet to the nearest cluster centroid and, in turn, (b) recomputing the cluster centroids based on the new rypäs assignments.

See also: cluster centroid, k -means, klusterointi.

local dataset The concept of a local tietoaineisto is in between the concept of a tietopiste and a tietoaineisto. A local tietoaineisto consists of several individual tietopisteet characterized by piirteet and nimiöt. In contrast to a single tietoaineisto used in basic koneoppiminen methods, a local tietoaineisto is also related to other local tietoaineistot via different notions of similarity. These similarities might arise from todennäköisyysmallit or communication infrastructure and are encoded in the edges of an FL network.

See also: tietoaineisto, tietopiste, piirre, nimiö, koneoppiminen, todennäköisyysmalli, FL network.

local interpretable model-agnostic explanations (LIME) Consider a trained malli (or learned hypoteesi) $\hat{h} \in \mathcal{H}$, which maps the piirrevektori of a tietopiste to the ennuste $\hat{y} = \hat{h}$. LIME is a technique for explaining the behavior of \hat{h} , locally around a tietopiste with piirrevektori $\mathbf{x}^{(0)}$ [125]. The selitys is given in the form of a local approximation $g \in \mathcal{H}'$ of \hat{h} (see Fig. 93). This approximation can be obtained by an instance of ERM with a carefully designed opetusaineisto. In particular, the opetusaineisto consists of tietopisteet with piirrevektorit centered around $\mathbf{x}^{(0)}$ and the (pseudo-)nimiö $\hat{h}(\mathbf{x})$. Note that we can use a different malli \mathcal{H}' for the approximation from the original malli \mathcal{H} . For example, we can use a päätöspuu to locally approximate a deep net. Another widely used choice for \mathcal{H}' is the lineaarinen malli.

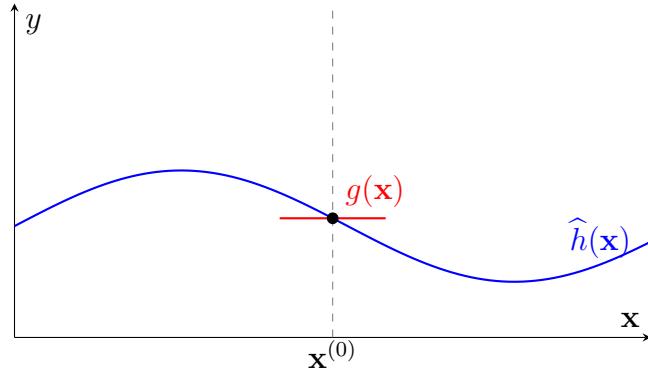


Fig. 93. To explain a trained malli $\hat{h} \in \mathcal{H}$, around a given piirrevektori $\mathbf{x}^{(0)}$, we can use a local approximation $g \in \mathcal{H}'$.

See also: malli, selitys, ERM, opetusaineisto, nimiö, päätöspuu, deep net, lineaarinen malli.

local model Consider a collection of devices that are represented as nodes \mathcal{V} of an FL network. A local malli $\mathcal{H}^{(i)}$ is a hypothesis space assigned to a node $i \in \mathcal{V}$. Different nodes can have different hypothesis spaces, i.e., in general, $\mathcal{H}^{(i)} \neq \mathcal{H}^{(i')}$ for different nodes $i, i' \in \mathcal{V}$.

See also: device, FL network, malli, hypothesis space.

logistic loss Consider a tietopiste characterized by piirteet \mathbf{x} and a binary nimiö $y \in \{-1, 1\}$. We use a real-valued hypoteesi h to predict the nimiö y from the piirteet \mathbf{x} . The logistic häviö incurred by this ennuste is defined as [47]

$$L((\mathbf{x}, y), h) := \log(1 + \exp(-yh(\mathbf{x}))). \quad (21)$$

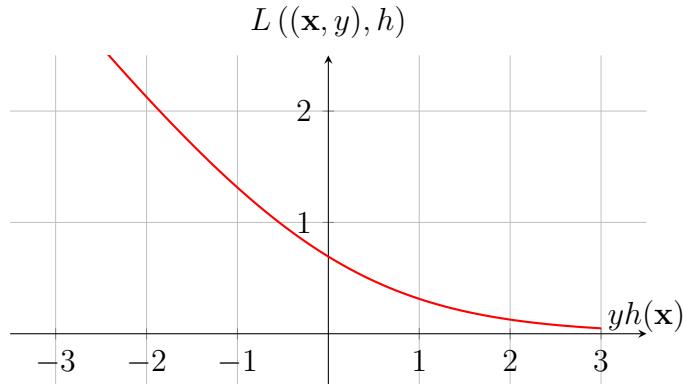


Fig. 94. The logistic häviö incurred by the ennuste $h(\mathbf{x}) \in \mathbb{R}$ for a tietopiste with nimiö $y \in \{-1, 1\}$.

Note that the expression (21) for the logistic häviö applies only for the label space $\mathcal{Y} = \{-1, 1\}$ and when using the thresholding rule (22).

See also: häviö, luokittelu, luokitin, lineaarinen malli.

logistinen regressio Logistic regressio learns a linear hypoteesi kuvaus (or luokitin) $h(\mathbf{x}) = \mathbf{w}^T \mathbf{x}$ to predict a binary nimiö y based on the numeric piirrevektori \mathbf{x} of a tietopiste [47], [63]. The quality of a linear hypoteesi kuvaus is measured by the average logistic loss on some labeled data points (i.e., the opetusaineisto).

See also: regressio, hypoteesi, kuvaus, luokitin, nimiö, piirrevektori, tietopiste, logistic loss, labeled data point, opetusaineisto.

luokitin A classifier is a hypoteesi (i.e., a kuvaus) $h(\mathbf{x})$ used to predict a nimiö taking on values from a finite label space. We might use the funktio value $h(\mathbf{x})$ itself as a ennuste \hat{y} for the nimiö. However, it is customary to use a kuvaus $h(\cdot)$ that delivers a numeric quantity. The ennuste is then obtained by a simple thresholding step. For example, in a binary luokittelu problem with a label space $\mathcal{Y} \in \{-1, 1\}$, we might use a real-valued hypoteesi kuvaus $h(\mathbf{x}) \in \mathbb{R}$ as a classifier. A ennuste \hat{y} can then be obtained via thresholding,

$$\hat{y} = 1 \text{ for } h(\mathbf{x}) \geq 0 \text{ and } \hat{y} = -1 \text{ otherwise.} \quad (22)$$

We can characterize a classifier by its päätösalueet \mathcal{R}_a , for every possible nimiö value $a \in \mathcal{Y}$.

See also: hypoteesi, luokittelu, päätösalue.

luokittelu Classification is the task of determining a discrete-valued nimiö y for a given tietopiste, based solely on its piirteet \mathbf{x} . The nimiö y belongs

to a finite set, such as $y \in \{-1, 1\}$ or $y \in \{1, \dots, 19\}$, and represents the category to which the corresponding tietopiste belongs.

See also: nimiö, tietopiste, piirre.

luonnollisen kielen käsittey NLP studies koneoppiminen methods for the analysis and generation of human language. Typical NLP tasks include text luokittelu, machine translation, sentiment analysis, and question answering. Modern NLP systems represent language as sequences of esiintymät and train mallit that capture contextual dependencies, such as attention-based methods.

See also: esiintymä, attention.

luotettava teköäly Besides the laskennalliset ominaisuudet and tilastollinen ominaisuus, a third main design aspect of koneoppiminen methods is their trustworthiness [128]. The European Union (EU) has put forward seven key requirements (KRs) for trustworthy teköäly (which typically build on koneoppiminen methods) [129]:

- 1) KR1 – Human agency and oversight;
- 2) KR2 – Technical vakaus and safety;
- 3) KR3 – Privacy and data governance;
- 4) KR4 – Transparency;
- 5) KR5 – Diversity, nondiscrimination and fairness;
- 6) KR6 – Societal and environmental well-being;
- 7) KR7 – Accountability.

See also: laskennalliset ominaisuudet, tilastollinen ominaisuus, koneoppiminen, tekoäly, vakaus, data, transparency.

lähinaapurimenetelmä NN methods learn a hypoteesi $h : \mathcal{X} \rightarrow \mathcal{Y}$ whose funktio value $h(\mathbf{x})$ is solely determined by the NNs within a given tietoaineisto. Different methods use different metrics for determining the NNs. If tietopisteet are characterized by numeric piirrevektorit, we can use their euklidiset etäisyydet as the metric.

See also: metric, naapuri.

machine unlearning Consider an koneoppiminen method that learns a hypoteesi \hat{h} via ERM on a opetusaineisto \mathcal{D} . The learned hypoteesi can reveal information about \mathcal{D} , which is exploited by yksityisyshyökkäykset such as model inversion. Machine unlearning refers to techniques that modify \hat{h} , so that it is harder to infer properties of individual tietopisteet in \mathcal{D} [130]. Machine unlearning helps to meet legal requirements for yksityisyden suoja in tekoäly systems [86].

See also: model inversion, yksityisyden suoja, Yleinen tietosuoja-asetus (GDPR).

malli The study and design of koneoppiminen methods is often based on a mathematical model [131]. Maybe the most widely used example of a mathematical model for koneoppiminen is a hypothesis space. A hypothesis space consists of hypoteesi kuvaaukset that are used by an koneoppiminen method to predict nimiöt from the piirteet of tietopisteet. Another important type of mathematical model is a todennäköisyysmalli, which consists of todennäköisyysjakaumat that describe how

tietopisteet are generated. Unless stated otherwise, we use the term model to refer specifically to the hypothesis space underlying an koneoppiminen method. We illustrate one example of a hypothesis space and a todennäköisyysmalli in Fig. 95.

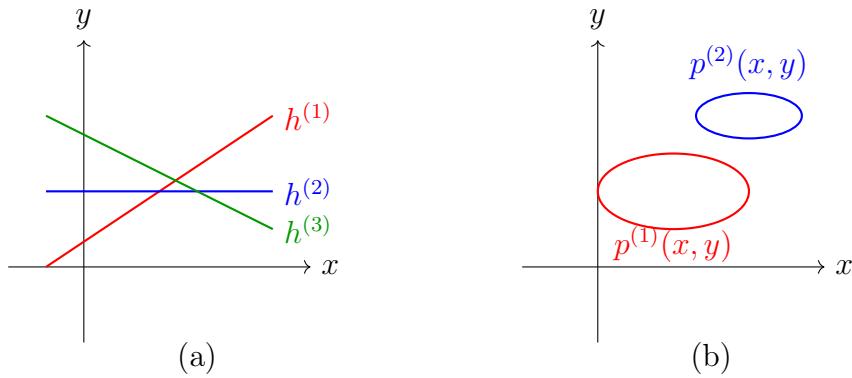


Fig. 95. Two types of mathematical models used in koneoppiminen. (a) A hypothesis space consisting of three lineaarikuvaaukset. (b) A todennäköisyysmalli consisting of todennäköisyysjakauma over the plane spanned by the piirre and nimiö values of a tietopiste.

See also: hypothesis space, todennäköisyysmalli, todennäköisyysjakama.

mallimatriisi The term design matriisi is a synonym for the feature matrix, particularly used in statistics [68], [89]. It collects the piirrevektorit of the tietopisteet in a tietoaineisto that is used for malli koulutus or validointi.

See also: feature matrix, piirrevektorit, tietopiste, tietoaineisto.

mallin valinta In koneoppiminen, malli selection refers to the process of

choosing between different candidate mallit. In its most basic form, malli selection amounts to: 1) koulutus each candidate malli; 2) computing the validointivirhe for each trained malli; and 3) choosing the malli with the smallest validointivirhe [8, Ch. 6].

See also: koneoppiminen, malli, koulutus, validointivirhe.

mean squared estimation error (MSEE) Consider an koneoppiminen method that learns model parameters $\hat{\mathbf{w}}$ based on some tietoaineisto \mathcal{D} . If we interpret the tietopisteet in \mathcal{D} as i.i.d. toteumat of a satunnaismuuttuja \mathbf{z} , we define the estimointivirhe $\Delta\mathbf{w} := \hat{\mathbf{w}} - \bar{\mathbf{w}}$. Here, $\bar{\mathbf{w}}$ denotes the true model parameters of the todennäköisyysjakauma of \mathbf{z} . The MSEE is defined as the odotusarvo $\mathbb{E}\{\|\Delta\mathbf{w}\|^2\}$ of the squared euklidinen normi of the estimointivirhe [51], [97].

See also: satunnaismuuttuja, estimointivirhe, todennäköisyysmalli, nelövirhehäviö.

metric A metric is a quantitative measure used to compare objects. In mathematics, a metric measures the distance between two points in a space and must follow specific rules, i.e., the distance is always nonnegative, zero only if the points are the same, symmetric, and it satisfies the triangle inequality [2]. In the context of koneoppiminen, the term metric refers to a quantitative measure of how well a malli performs (somewhat similar to a häviöfunktio). Examples include tarkkuus, precision, and the average binääritappio on a testiaineisto [92], [47]. The term häviöfunktio is typically used in the context of malli koulutus, while the term metric is used in the context of malli validointi.

See also: häviö, validointi, tarkkuus.

missing data Consider a tietoaineisto constituted by tietopisteet collected via some physical device. Due to imperfections and failures, some of the piirre or nimiö values of tietopisteet might be corrupted or simply missing. Data imputation aims to estimate these missing values [132]. We can interpret data imputation as an koneoppiminen problem where the nimiö of a tietopiste is the value of the corrupted piirre.

See also: piirre, nimiö.

model inversion A malli inversion is a form of yksityisyyskyökkäys on an koneoppiminen system. An adversary seeks to infer sensitive attributes of individual tietopisteet by exploiting partial access to a trained malli $\hat{h} \in \mathcal{H}$. This access typically consists of querying the malli for ennusteet $\hat{h}(\mathbf{x})$ using carefully chosen inputs. Basic malli inversion techniques have been demonstrated in the context of facial image luokittelu, where images are reconstructed using the (gradientti of) malli outputs combined with auxiliary information such as a person's name [133] (see Fig. 96).

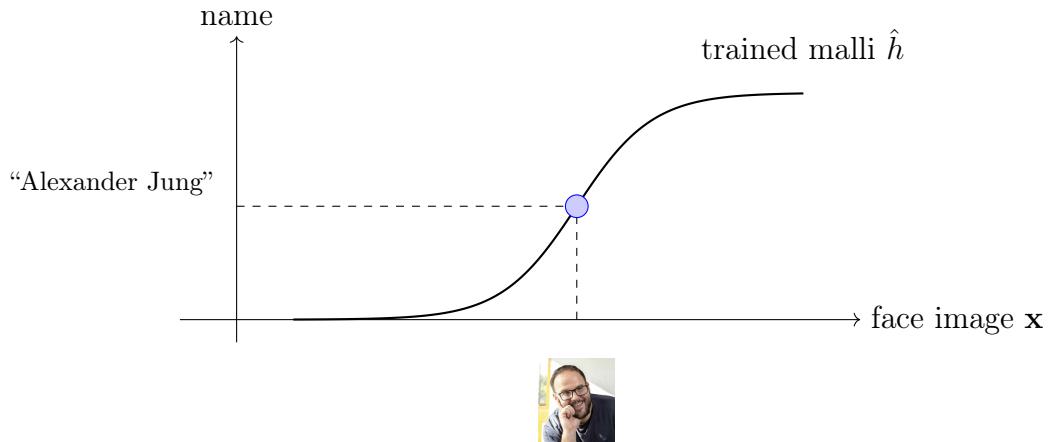


Fig. 96. Model inversion techniques implemented in the context of facial image classification.

See also: malli, yksityisyyskyökkäys, koneoppiminen, sensitive attribute, tietopiste, ennuste, luokittelu, gradientti, luotettava tekoäly, yksityisyden suoja.

model parallelism Malli parallelism refers to a particular class of distributed optimointimenetelmät used to train an koneoppiminen malli. Here, different devices store and process disjoint subsets of the model parameters. This approach contrasts with data parallelism, where each device maintains a full replica of the model parameters while processing disjoint subsets of the global tietoaineisto. Malli parallelism allows us to train an koneoppiminen malli whose parameters cannot fit into the memory of a single device. One key application of malli parallelism is the koulutus of extremely large neuroverkot, such as muuntaja mallit with billions of model parameters.

See also: VFL.

model parameter The elements of a parametric model are specified by quantities that are referred to as malli parameters. In the context of koneoppiminen, a parametric model consists of hypoteesi maps that are specified by a list of malli parameters w_1, w_2, \dots, w_d . It is often convenient to stack these malli parameters into a vektori $\mathbf{w} = (w_1, \dots, w_d)^T \in \mathbb{R}^d$.

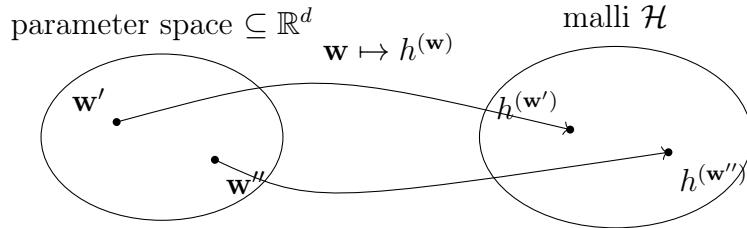


Fig. 97. The malli parameters \mathbf{w} select a well-defined hypoteesi $h^{(\mathbf{w})}$ out of the malli \mathcal{H} .

We can think of malli parameters as an identifier for a hypoteesi kuvaus, similar to how a social security number identifies a person.

See also: malli, parameter, hypoteesi, kuvaus.

monitehtäväoppiminen Multitask learning aims to leverage relations between different oppimistehtävät. Consider two oppimistehtävät obtained from the same tietoaineisto of webcam snapshots. The first task is to predict the presence of a human, while the second task is to predict the presence of a car. It may be useful to use the same deep net structure for both tasks and only allow the weights of the final output layer to be different.

See also: oppimistehtävä, tietoaineisto, deep net, weights, layer.

mukautuva tehostus AdaBoost is a specific tehostus algoritmi that combines base learners sequentially [134], [135], [136]. The core idea of AdaBoost is to use the ennuste errors of the current base learner for otospainotus in the next base learner. In particular, the t th base learner learns a hypoteesi $\hat{h}^{(t)}$ by weighted ERM with sample weights $q^{(r)}$. The ennuste errors of $\hat{h}^{(t)}$ are then used to update the sample weights by increasing the weights of tietopisteet that have been predicted poorly (i.e., with large häviö) by $\hat{h}^{(t)}$. The updated sample weights are then used in the next base learner to learn $\hat{h}^{(t+1)}$. The ultimate hypoteesi $\tilde{h}^{(R)}$ delivered after R iteraatiot is a linear combination of the hypoteesit $\hat{h}^{(1)}, \dots, \hat{h}^{(R)}$. AdaBoost can be interpreted as a generalized gradienttiaskel [63, Ch. 10.4]

$$\tilde{h}^{(t)} = \tilde{h}^{(t-1)} + \eta^{(t)} \hat{h}^{(t)}.$$

This generalized gradienttiaskel involves a oppimisnopeus $\eta^{(t)}$, which controls the amount of modification of the current hypoteesi.

See also: tehostus, otospainotus, ERM.

multi-label classification Multi-nimiö luokittelu problems and methods use tietopisteet that are characterized by several nimiöt. As an example, consider a tietopiste representing a picture with two nimiöt. One nimiö indicates the presence of a human in this picture and another nimiö indicates the presence of a car.

See also: nimiö, luokittelu, tietopiste.

mutual information (MI) The MI $I(\mathbf{x}; y)$ between two satunnaismuuttujien \mathbf{x} ja y on määritelty seuraavasti:

jat \mathbf{x} , y defined on the same probability space is given by [30]

$$I(\mathbf{x}; y) := \mathbb{E} \left\{ \log \frac{p(\mathbf{x}, y)}{p(\mathbf{x})p(y)} \right\}.$$

It is a measure of how well we can estimate y based solely on \mathbf{x} . A large value of $I(\mathbf{x}; y)$ indicates that y can be well predicted solely from \mathbf{x} . This ennuste could be obtained by a hypoteesi learned by an ERM-based koneoppiminen method.

See also: satunnaismuuttuja, probability space, ennuste, hypoteesi, ERM, koneoppiminen.

muuntaja In the context of koneoppiminen, the term transformer refers to an neuroverkko that uses some form of attention mechanism to capture dependencies among esiintymät [78]. The attention mechansim is what sets transformers apart from previous mallit used for sequential data such as takaisinkytkeytyvät neuroverkot. A transformer neuroverkko often combines several attention layers via more traditional layer architectures. See also: attention, luonnollisen kielen käsite.

naapuri A neighbor of a node $i \in \mathcal{V}$ within an undirected graph is a node $i' \in \mathcal{V} \setminus \{i\}$ that is kytetty verkko via an edge to node i .

See also: undirected graph, kytetty verkko.

naapurusto Consider some metric space \mathcal{X} with metric $d : \mathcal{X} \times \mathcal{X} \rightarrow \mathbb{R}_+$. The neighborhood of a point $\mathbf{x} \in \mathcal{X}$ is the set of other points having a sufficiently small distance to \mathbf{x} . For example, the ϵ -neighborhood of \mathbf{x} is defined as

$$\{\mathbf{x}' \in \mathcal{X} : d(\mathbf{x}, \mathbf{x}') \leq \epsilon\}.$$

If \mathcal{X} is an undirected graph, which is a special case of a metric space, the neighborhood of a node $i \in \mathcal{V}$ is the set of its naapurit.

See also: metric, naapuri.

neliövirhehäviö The squared error häviö measures the ennuste error of a hypoteesi h when predicting a numeric nimiö $y \in \mathbb{R}$ from the piirteet \mathbf{x} of a tietopiste. It is defined as

$$L((\mathbf{x}, y), h) := \left(y - \underbrace{h(\mathbf{x})}_{=\hat{y}} \right)^2.$$

See also: häviö, ennuste, hypoteesi, nimiö, piirre, tietopiste.

nested cross-validation Nested cross-validation is a method of extending the k -kertainen ristiinvalidointi from training and validointiaineistot to also cover the testiaineisto. Instead of simply choosing a single testiaineisto from the data, two loops are run: the outer and the inner loop. The outer loop uses k -kertainen ristiinvalidointi to separate a testiaineisto from the data and the inner loop again uses k -kertainen ristiinvalidointi to separate the rest of the data into a training and validointiaineistot. Doing this decreases the varianssi and harha in the results.

See also: k -kertainen ristiinvalidointi, yksi-pois-ristiinvalidointi, validointi, validointivirhe.

networked data Networked data consist of local datasets that are related by some notion of pairwise similarity. We can represent networked data using a verkko whose nodes carry local datasets and whose edges encode

pairwise similarities. An example of networked data can be found in federoitut oppiminen applications where local datasets are generated by spatially distributed devices.

See also: data, local dataset, verkko, federoitut oppiminen, device.

networked exponential families (nExpFam) A collection of exponential families, each of them assigned to a node of an FL network. The model parameters are coupled via the network structure by requiring them to have a small GTV [137].

See also: FL network, model parameter, GTV.

networked federated learning (NFL) NFL refers to methods that learn personalized mallit in a distributed fashion. These methods learn from local datasets that are related by an intrinsic network structure.

See also: malli, local dataset, federoitut oppiminen.

networked model A networked malli over an FL network $\mathcal{G} = (\mathcal{V}, \mathcal{E})$ assigns a local model (i.e., a hypothesis space) to each node $i \in \mathcal{V}$ of the FL network \mathcal{G} .

See also: malli, FL network, local model, hypothesis space.

neuroverkko An artificial neural network (ANN) is a graphical (signal-flow) representation of a hypoteesi that maps piirteet of a tietopiste at its input to a ennuste for the corresponding nimiö at its output. The fundamental computational unit of an ANN is the artificial neuron, which applies an aktivoointifunktio $\sigma(\cdot)$ to the sum of its inputs. The output of a neuron can be used either as the final output of the ANN or as an input to other neurons. A key design parameter of an ANN is

its connectivity structure (or architecture), i.e., which neuron outputs are connected to which neuron inputs. As illustrated in Fig. 98, we can represent an ANN as an DAG. One widely used type of neuroverkko are deep nets where neurons form consecutive layers. In a deep net, the outputs of neurons in a given layer are typically only connnected to the inputs of the neurons in a consecutive layer. Sometimes it is useful to add shortcut or skip connections that directly connect the outputs of neurons in one layer to the inputs of neurons in a non-consecutive layer [92, 138].

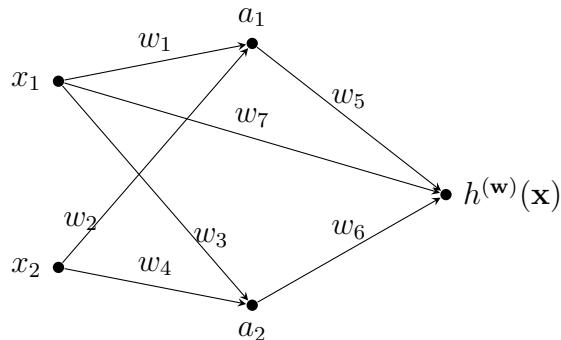


Fig. 98. An ANN can be represented as a weighted DAG with nodes representing neurons or piirteet of a tietopiste. Piirteet can be viewed as trivial neurons without input and fixed ouput given by the piirre value. The weighted directed edges indicate how neuron outputs are used as inputs to other neurons. The edge weights are tunable model parameters and are used to scale the inputs to the neurons. The output of some neurons are used as the ennuste $h^{(\mathbf{w})}(\mathbf{x})$.

See also: nimiö, aktivoointifunktio, layer, deep net.

nimiö A label is a higher-level fact or quantity of interest associated with a tietopiste. For example, if the tietopiste is an image, the label could indicate whether the image contains a cat. Synonyms for label, commonly used in specific domains, include "response variable," "output variable," and "target" [67], [139], [140].

See also: tietopiste, label space.

normaaliyhtälöt The optimality condition for the model parameters in linear least squares are often referred to as normal equations.

See also: model parameter, linear least squares.

näyteavaruus Katso otosavaruus.

odotusarvo Consider a numeric piirrevektori $\mathbf{x} \in \mathbb{R}^d$ that we interpret as the toteuma of an satunnaismuuttuja with todennäköisyysjakauma $p(\mathbf{x})$. The expectation of \mathbf{x} is defined as the integral $\mathbb{E}\{\mathbf{x}\} := \int \mathbf{x} p(\mathbf{x})$. Note that the expectation is only defined if this integral exists, i.e., if the satunnaismuuttuja is integrable [2], [6], [50]. Fig. 99 illustrates the expectation of a scalar discrete RV x that takes on values from a finite set only.

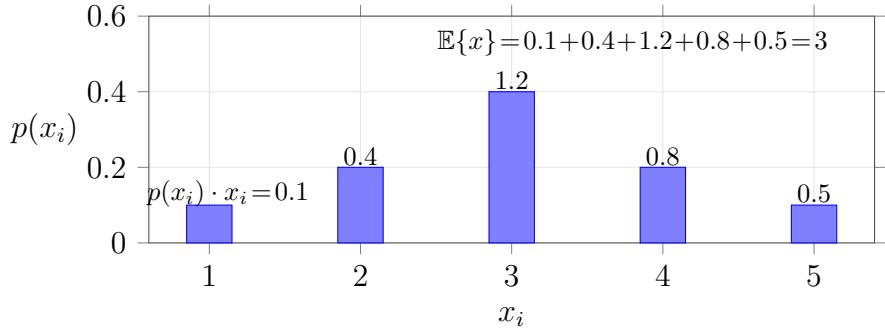


Fig. 99. The expectation of a discrete RV x is obtained by summing its possible values x_i , weighted by the corresponding todennäköisyys $p(x_i) = \mathbb{P}(x = x_i)$.

See also: piirrevektori, toteuma, satunnaismuuttuja, todennäköisyysjakauma, todennäköisyys.

online gradient descent (online GD) Consider an koneoppiminen method that learns model parameters \mathbf{w} from some parameter space $\mathcal{W} \subseteq \mathbb{R}^d$. The learning process uses tietopisteet $\mathbf{z}^{(t)}$ that arrive at consecutive time instants $t = 1, 2, \dots$. Let us interpret the (generation of) tietopisteet $\mathbf{z}^{(t)}$ as i.i.d. satunnaismuuttujat with a common todennäköisyysjakauma $\mathbb{P}(\mathbf{z})$. The riski $\mathbb{E}\{L(\mathbf{z}, \mathbf{w})\}$ of a hypoteesi $h^{(\mathbf{w})}$ can then (under mild conditions) be obtained as the limit

$$\lim_{T \rightarrow \infty} (1/T) \sum_{t=1}^T L(\mathbf{z}^{(t)}, \mathbf{w}).$$

We might use this limit as the kohdefunktio for learning the model parameters \mathbf{w} . Unfortunately, the above limit can only be evaluated if we wait infinitely long in order to collect all tietopisteet. However, many koneoppiminen applications require methods that learn online: as

soon as a new tietopiste $\mathbf{z}^{(t)}$ arrives at time t , we update the current model parameters $\mathbf{w}^{(t)}$. Note that the new tietopiste $\mathbf{z}^{(t)}$ contributes the component $L(\mathbf{z}^{(t)}, \mathbf{w})$ to the riski. As its name suggests, online GD updates $\mathbf{w}^{(t)}$ via a (projected) gradienttiaskel such that

$$\mathbf{w}^{(t+1)} := P_{\mathcal{W}}(\mathbf{w}^{(t)} - \eta_t \nabla_{\mathbf{w}} L(\mathbf{z}^{(t)}, \mathbf{w})). \quad (23)$$

Note that (23) is a gradienttiaskel for the current component $L(\mathbf{z}^{(t)}, \cdot)$ of the riski. The update (23) ignores all previous components $L(\mathbf{z}^{(t')}, \cdot)$, for $t' < t$. It might therefore happen that, compared with $\mathbf{w}^{(t)}$, the updated model parameters $\mathbf{w}^{(t+1)}$ increase the retrospective average häviö $\sum_{t'=1}^{t-1} L(\mathbf{z}^{(t')}, \cdot)$. However, for a suitably chosen oppimisnopeus η_t , online GD can be shown to be optimal in practically relevant settings. By optimal, we mean that the model parameters $\mathbf{w}^{(T+1)}$ delivered by online GD after observing T tietopisteet $\mathbf{z}^{(1)}, \dots, \mathbf{z}^{(T)}$ are at least as good as those delivered by any other learning method [100], [141].

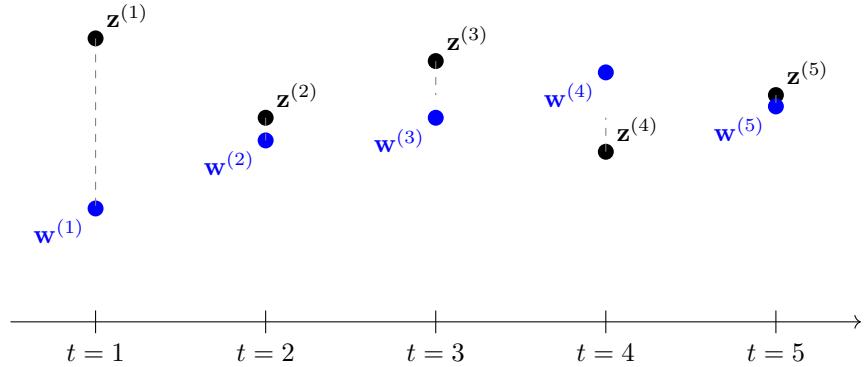


Fig. 100. An instance of online GD that updates the model parameters $\mathbf{w}^{(t)}$ using the tietopiste $\mathbf{z}^{(t)} = x^{(t)}$ arriving at time t . This instance uses the neliövirhehäviö $L(\mathbf{z}^{(t)}, w) = (x^{(t)} - w)^2$.

See also: kohdefunktio, GD, gradienttiaskel, online learning.

online learning Some koneoppiminen methods are designed to process data in a sequential manner, updating their model parameters one at a time, as new tietopisteet become available. A typical example is time-series data, such as daily minimi and maksimi temperatures recorded by an Ilmatieteen laitos weather station. These values form a chronological sequence of observations. During each time step t , online learning methods update (or refine) the current hypoteesi $h^{(t)}$ (or model parameters $\mathbf{w}^{(t)}$) based on the newly observed tietopiste $\mathbf{z}^{(t)}$.

See also: online gradient descent (online GD), online-algoritmi.

online-algoritmi An online algoritmi processes input data incrementally, receiving tietopisteet sequentially and making decisions or producing outputs (or decisions) immediately without having access to the entire

input in advance [99], [100]. Unlike an offline algoritmi, which has the entire input available from the start, an online algoritmi must handle epävarmuus about future inputs and cannot revise past decisions. Similar to an offline algoritmi, we represent an online algoritmi formally as a collection of possible executions. However, the execution sequence for an online algoritmi has a distinct structure as follows:

$$\text{in}_1, s_1, \text{out}_1, \text{in}_2, s_2, \text{out}_2, \dots, \text{in}_T, s_T, \text{out}_T.$$

Each execution begins from an initial state (i.e., in_1) and proceeds through alternating computational steps, outputs (or decisions), and inputs. Specifically, at step t , the algoritmi performs a computational step s_t , generates an output out_t , and then subsequently receives the next input (tietopiste) in_{t+1} . A notable example of an online algoritmi in koneoppiminen is online GD, which incrementally updates model parameters as new tietopisteet arrive.

See also: algoritmi, data, tietopiste, epävarmuus, koneoppiminen, online GD, model parameter, online learning.

opetusaineisto A koulutus set is a tietoaineisto \mathcal{D} that consists of some tietopisteet used in ERM to learn a hypoteesi \hat{h} . The average häviö of \hat{h} on the koulutus set is referred to as the opetusvirhe. The comparison of the opetusvirhe with the validointivirhe of \hat{h} allows us to diagnose the koneoppiminen method and informs how to improve the validointivirhe (e.g., using a different hypothesis space or collecting more tietopisteet) [8, Sec. 6.6].

See also: koulutus, tietoaineisto, tietopiste, ERM, hypoteesi, häviö,

opetusvirhe, validointivirhe, koneoppiminen, hypothesis space.

opetusdata Katso opetusaineisto

opetusvirhe The average häviö of a hypoteesi when predicting the nimiöt of the tietopisteet in a opetusaineisto. We sometimes also refer to koulutus error as the minimal average häviö that is achieved by a solution of ERM.

See also: häviö, hypoteesi, nimiö, tietopiste, opetusaineisto, ERM.

oppimisnopeus Consider an iterative koneoppiminen method for finding or learning a useful hypoteesi $h \in \mathcal{H}$. Such an iterative method repeats similar computational (update) steps that adjust or modify the current hypoteesi to obtain an improved hypoteesi. A key parameter of an iterative method is the learning rate. The learning rate controls the extent to which the current hypoteesi can be modified during a single iteraatio. Consider, for example, the gradienttiaskel [8, Ch. 5]

$$\mathbf{w}^{(t+1)} = \mathbf{w}^{(t)} - \eta \nabla f(\mathbf{w}^{(t)}) \quad (24)$$

of a gradient-based method for ERM, where the kohdefunktio $f(\mathbf{w})$ is the empiirinen riski incurred by $h^{(\mathbf{w})}$ on a opetusaineisto. Given the current model parameters $\mathbf{w}^{(t)}$ at iteraatio t , the gradienttiaskel produces updated model parameters $\mathbf{w}^{(t+1)}$ by moving in the opposite direction of the gradientti $\nabla f(\mathbf{w}^{(t)})$.

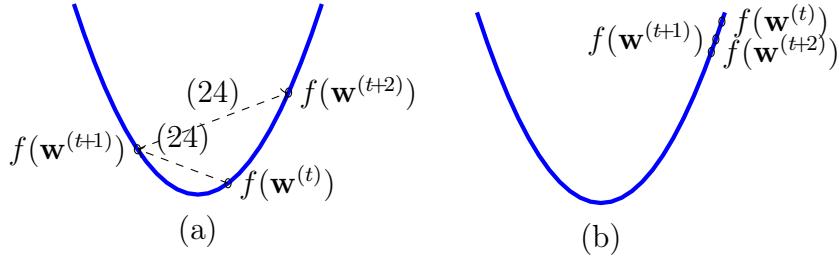


Fig. 101. Effect of using an inadequate learning rate η in the gradienttiaskel (24). (a) If η is too large, the gradienttiaskel can “overshoot” such that the iterates $\mathbf{w}^{(t)}$ diverge away from the optimum, i.e., $f(\mathbf{w}^{(t+1)}) > f(\mathbf{w}^{(t)})$. (b) If η is too small, the gradienttiaskel make too little progress towards the optimum within the available number of iterations (due to limited computational budget).

See also: koneoppiminen, hypoteesi, parameter, GD, SGD, projected gradient descent (projected GD), step size.

oppimistehtävä Consider a tietoaineisto \mathcal{D} consisting of multiple tietopisteet $\mathbf{z}^{(1)}, \dots, \mathbf{z}^{(m)}$. For example, \mathcal{D} can be a collection of images in an image database. A learning task is defined by specifying those properties (or attributes) of a tietopiste that are used as its piirteet and nimiöt. Given a choice of malli \mathcal{H} and häviöfunktio, a learning task leads to an instance of ERM and can thus be represented by the associated kohdefunktio $\widehat{L}(h|\mathcal{D})$ for $h \in \mathcal{H}$. Importantly, multiple distinct learning tasks can be constructed from the same tietoaineisto by selecting different sets of piirteet and nimiöt (see Fig. 102).



An image showing cows grazing in the Austrian countryside.

Task 1 (regressio):

Piirteet are the RGB values of all image pixels, and the nimiö is the number of cows depicted.

Task 2 (luokittelu):

Piirteet include the average green intensity of the image, and the nimiö indicates whether cows should be moved to another location (i.e., yes/no).

Fig. 102. Two learning tasks constructed from a single image tietoaineisto. These tasks differ in piirre selection and choice of nimiö (i.e., the objective), but are both derived from the same tietoaineisto.

Different learning tasks arising from the same underlying tietoaineisto are often coupled. For example, when a todennäköisyysmalli is used to generate tietopisteet, statistical dependencies among different nimiöt induce dependencies among the corresponding learning tasks. In general,

solving learning tasks jointly, e.g., using monitehtäväoppiminen methods, tends to be more effective than solving them independently (thereby ignoring dependencies among learning tasks) [142], [143], [144].

See also: monitehtäväoppiminen, label space.

optimism in the face of uncertainty koneoppiminen methods learn model parameters \mathbf{w} according to some performance criterion $\bar{f}(\mathbf{w})$. However, they usually cannot access $\bar{f}(\mathbf{w})$ directly but rely on an estimate (or approximation) $f(\mathbf{w})$ of $\bar{f}(\mathbf{w})$. As a case in point, ERM-based methods use the average häviö on a given tietoaineisto (i.e., the opetusaineisto) as an estimate for the riski of a hypoteesi. Using a todennäköisyysmalli, one can construct a confidence interval $[l^{(\mathbf{w})}, u^{(\mathbf{w})}]$ for each choice \mathbf{w} for the model parameters. One simple construction is $l^{(\mathbf{w})} := f(\mathbf{w}) - \sigma/2$, $u^{(\mathbf{w})} := f(\mathbf{w}) + \sigma/2$, with σ being a measure of the (expected) deviation of $f(\mathbf{w})$ from $\bar{f}(\mathbf{w})$. We can also use other constructions for this interval as long as they ensure that $\bar{f}(\mathbf{w}) \in [l^{(\mathbf{w})}, u^{(\mathbf{w})}]$ with a sufficiently high todennäköisyys. An optimist chooses the model parameters according to the most favorable—yet still plausible—value $\tilde{f}(\mathbf{w}) := l^{(\mathbf{w})}$ of the performance criterion (see Fig. 103). Two examples of koneoppiminen methods that use such an optimistic construction of an kohdefunktio are SRM [145, Ch. 11] and upper confidence bound (UCB) methods for sequential decision making [146, Sec. 2.2].

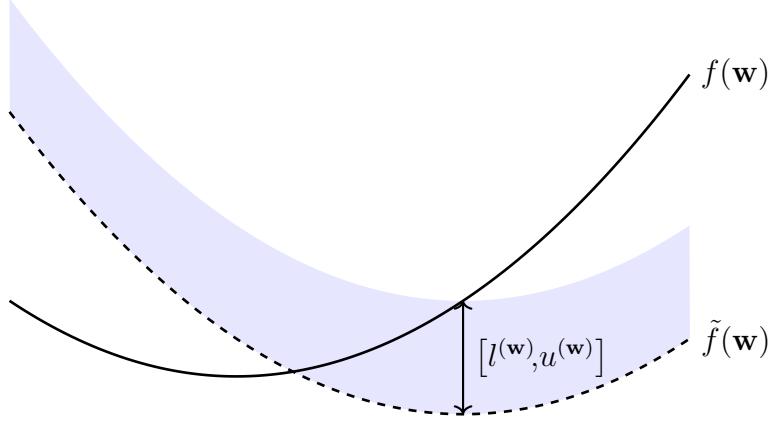


Fig. 103. koneoppiminen methods learn model parameters \mathbf{w} by using some estimate of $f(\mathbf{w})$ for the ultimate performance criterion $\bar{f}(\mathbf{w})$. Using a todennäköisyysmalli, one can use $f(\mathbf{w})$ to construct confidence intervals $[l^{(\mathbf{w})}, u^{(\mathbf{w})}]$, which contain $\bar{f}(\mathbf{w})$ with high probability. The best plausible performance measure for a specific choice \mathbf{w} of model parameters is $\tilde{f}(\mathbf{w}) := l^{(\mathbf{w})}$.

See also: kohdefunktio, optimointimenetelmä, gradient-based method, UCB.

osite A stratum is a subset of tietopisteet that all share a common property (which could be a piirre or a nimiö). For example, in a weather tie-toaineisto, all measurements from the same Ilmatieteen laitos weather station form one stratum.

Example (CSV snippet):

```
time, station, value, unit
2023-06-01 12:00, Helsinki, 18.2, degree Celsius
2023-06-01 13:00, Helsinki, 18.5, degree Celsius
```

2023-06-01 14:00, Helsinki, 19.0, degree Celsius
2023-06-01 12:00, Oulu, 12.1, degree Celsius
2023-06-01 13:00, Oulu, 12.4, degree Celsius
2023-06-01 14:00, Oulu, 12.7, degree Celsius
2023-06-01 12:00, Tampere, 15.3, degree Celsius
2023-06-01 13:00, Tampere, 15.6, degree Celsius
2023-06-01 14:00, Tampere, 16.0, degree Celsius

Here, the rows for each station (i.e., Helsinki, Oulu, Tampere) represent different strata.

See also: tietopiste, tietoaineisto, ositus.

osittava klusterointi Hard klusterointi refers to the task of partitioning a given set of tietopisteet into (a few) non-overlapping ryppäät. This requirement allows to represent a rypäs by a subset of tietopisteet, i.e., precisely those belonging to the rypäs. In contrast to hard klusterointi, soft clustering methods allow for overlapping ryppäät and specify, for each tietopiste, a numeric degree of belonging to each rypäs. Hard klusterointi is an extreme case of soft clustering where the degrees of belonging take only two values, indicating either no belonging or full belonging. For tietopisteet characterized by numeric piirrevektorit $\mathbf{x} \in \mathbb{R}^d$, a widely used hard klusterointi method is k -means. Any osittava klusterointi method for numeric piirrevektorit $\mathbf{x} \in \mathbb{R}^d$ can be adapted for non-numerical data using piirreoptimointi methods. One important example of this approach is spectral clustering, where tietopisteet have a similarity structure in the form of an undirected verkko. The nodes of

this verkko represent tietopisteet while undirected (possibly weighted) edges represent similarities (and their extend) between tietopisteet. We can then use the entries of the eigenvectors of the Laplacian matrix as numeric piirteet for each tietopiste.

See also: klusterointi, tietopiste, rypäs, k -means.

ositus The process of splitting a tietoaineisto into subsets, so called ositteet, according to some key attribute is called stratification [67], [68], [147]. The goal is to ensure that an koneoppiminen method performs well for each osite defined by these attributes. For example, in a medical tietoaineisto, we may want to stratify a patient tietoaineisto by age groups to ensure that an koneoppiminen malli performs well across all age groups.

When splitting a tietoaineisto into a opetusaineisto and a validointiaineisto, stratification ensures that both sets have similar distributions of the key attribute. Without stratification, using a small validointiaineisto may underrepresent or even completely miss tietopisteet with a rare attribute, leading to misleading performance estimates. See Fig. 104 for a visual illustration.

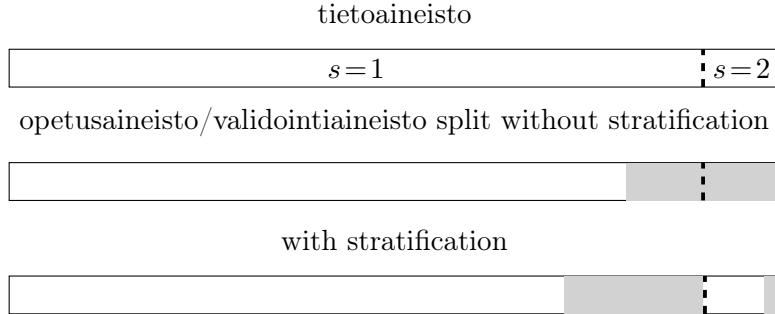


Fig. 104. Stratification ensures that both the opetusaineisto and the validointiaineisto (shaded grey) have similar distributions of a binary key attribute s . In other words, with stratification, both osite (i.e., $s=1$ and $s=2$ based on the key attribute) allocate the same validation proportion—20% of their own width.

See also: osite, validointi, k -kertainen ristiinvalidointi.

otosavaruus A sample space is the set of all possible outcomes of a satunnaiskoe [6], [7], [24], [25].

See also: probability space.

otoskeskiarvo The sample keskiarvo $\mathbf{m} \in \mathbb{R}^d$ for a given tietoaineisto, with piirrevektorit $\mathbf{x}^{(1)}, \dots, \mathbf{x}^{(m)} \in \mathbb{R}^d$, is defined as

$$\mathbf{m} = \frac{1}{m} \sum_{r=1}^m \mathbf{x}^{(r)}.$$

See also: sample, keskiarvo, tietoaineisto, piirrevektori.

otospainotus Consider an ERM-based method that learns a hypoteesi by minimizing the average häviö on a opetusaineisto. In its basic form,

ERM treats all tietopisteet equally important. However, in some applications, it can be useful to put different emphasis on the ennuste errors obtained for different tietopisteet. For example, if a tietopiste is considered an poikkeava havainto we should reduce its influence on the learned hypoteesi. We can implement this idea by assigning a nonnegative weight $q^{(r)}$ to each tietopiste $(\mathbf{x}^{(r)}, y^{(r)})$ in the opetusaineisto. This results in the weighted ERM principle

$$\min_{h \in \mathcal{H}} \sum_{r=1}^m q^{(r)} L((\mathbf{x}^{(r)}, y^{(r)}), h). \quad (25)$$

Fig. 105 illustrates the concept of a opetusaineisto of three tietopisteet that contribute unequally to the empiirinen riski.

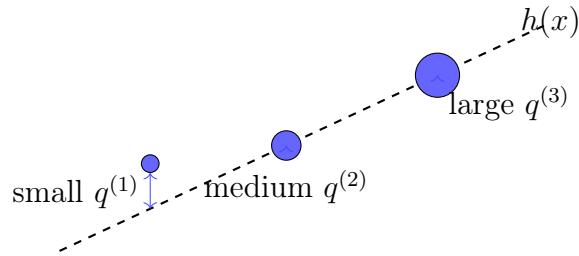


Fig. 105. Sample weighting assigns each tietopiste of a opetusaineisto a weight $q^{(r)}$. Assigning a small weight (such as $q^{(1)}$ in this example) to a tietopiste decreases its influence on the hypoteesi learned via solving (25).

See also: ERM, poikkeava havainto, mukautuva tehostus.

oudokki Katso poikkeava havainto.

output vector The term tuotos vektori is used as a synonym for the label

vector of a tietoaineisto [57].

See also: tuotos, label vector, tietoaineisto.

painotettu pienin neliösumma Weighted pienin neliösumma refers to ERM-based methods that use the weighted average neliövirhehäviö

$$\frac{1}{m} \sum_{r=1}^m q^{(r)} (y^{(r)} - h(\mathbf{x}^{(r)}))^2$$

on a opetusaineisto $\mathcal{D} = \{ (\mathbf{x}^{(1)}, y^{(1)}) , \dots , (\mathbf{x}^{(m)}, y^{(m)}) \}$ to measure the quality of a hypoteesi kuvaus $h \in \mathcal{H}$. The weights $q^{(1)}, \dots, q^{(m)} \in \mathbb{R}_+$ allow us to emphasize or de-emphasize the contribution of individual tietopisteet in the opetusaineisto. Ideally, we assign a small weight $q^{(r)}$ to the r th tietopiste if it is an poikkeava havainto (see Fig. 106). We obtain different weighted pienin neliösumma methods by using different mallit in ERM.

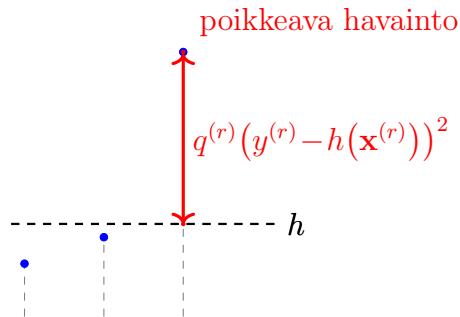


Fig. 106. Weighted pienin neliösumma can be used to mitigate the effect of poikkeava havainto tietopisteet in a opetusaineisto.

See also: ERM, neliövirhehäviö, lineaarinen regressio, lineaarinen malli.

palvelunestohyökkäys A denial-of-service hyökkäys aims (e.g., via tietojen korruptointi) to steer the koulutus of a malli such that it performs poorly for typical tietopisteet.

See also: hyökkäys, tietojen korruptointi, malli, tietopiste.

parameter The parameter of an koneoppiminen malli is a tunable (i.e., learnable or adjustable) quantity that allows us to choose between different hypoteesi kuvauskset. For example, the lineaarinen malli $\mathcal{H} := \{h^{(\mathbf{w})} : h^{(\mathbf{w})}(x) = w_1x + w_2\}$ consists of all hypoteesi kuvauskset $h^{(\mathbf{w})}(x) = w_1x + w_2$ with a particular choice for the parameters $\mathbf{w} = (w_1, w_2)^T \in \mathbb{R}^2$. Another example of a malli parameter is the weights assigned to a connection between two neurons of an neuroverkko.

See also: koneoppiminen, malli, hypoteesi, kuvaus, lineaarinen malli, weights, neuroverkko.

parameter space The parameter space \mathcal{W} of an koneoppiminen malli \mathcal{H} is the set of all feasible choices for the model parameters (see Fig. 107). Many important koneoppiminen methods use a malli that is parameterized by vektorit of the euklidinen avaruus \mathbb{R}^d . Two widely used examples of parameterized mallit are lineaariset mallit and deep nets. The parameter space is then often a subset $\mathcal{W} \subseteq \mathbb{R}^d$, e.g., all vektorit $\mathbf{w} \in \mathbb{R}^d$ with a normi smaller than one.

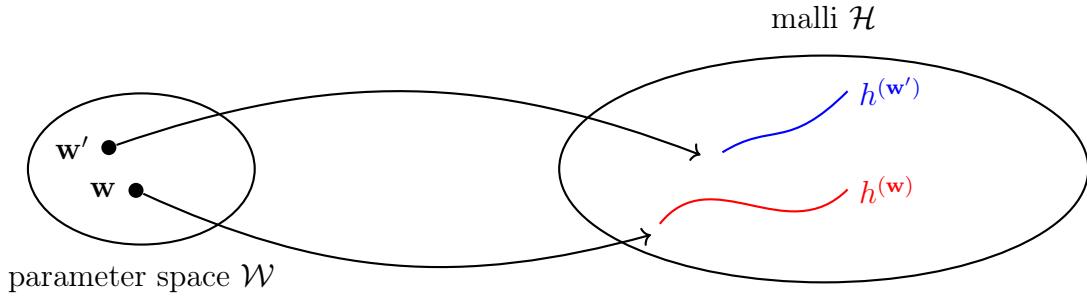


Fig. 107. The parameter space \mathcal{W} of an koneoppiminen malli \mathcal{H} consists of all feasible choices for the model parameters. Each choice \mathbf{w} for the model parameters selects a hypoteesi kuvaus $h^{(\mathbf{w})} \in \mathcal{H}$.

See also: parameter, malli, model parameter.

parametric model A parametric malli is a mathematical malli characterized by a finite set of variable quantities called parameters. An important example is the todennäköisyysmalli consisting, for a given dimension d , of all moninormaalijakaumat (on otosavaruus \mathbb{R}^d) with some keskiarvo vektori $\boldsymbol{\mu} \in \mathbb{R}^d$ and kovarianssimatriisi $\mathbf{C} \in \mathbb{R}^{d \times d}$. In the context of koneoppiminen, a parametric malli defines a hypothesis space \mathcal{H} parameterized by a finite number of model parameters. Each hypoteesi $h \in \mathcal{H}$ is uniquely identified by a list of model parameters w_1, w_2, \dots, w_d (see Fig. 107). We can stack these parameters into a vektori $\mathbf{w} \in \mathbb{R}^d$. Two widely used examples of parametric mallit are the lineaarinen malli and the neuroverkko. The corresponding parameter space is typically a subset of \mathbb{R}^d .

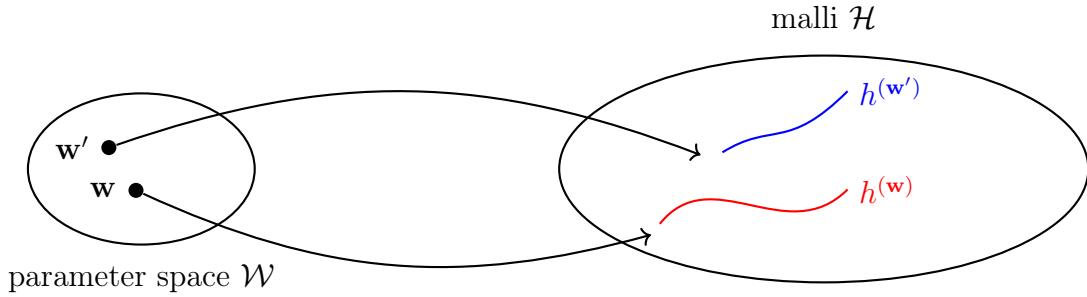


Fig. 108. The parameter space \mathcal{W} of an koneoppiminen malli \mathcal{H} consists of all feasible choices for the model parameters. Each choice \mathbf{w} for the model parameters selects a hypoteesi kuvaus $h^{(\mathbf{w})} \in \mathcal{H}$.

See also: parameter space, malli, model parameter.

penalty term Consider an ERM-based koneoppiminen method that learns model parameters \mathbf{w} by minimizing the average häviö (or empiirinen riski) $\hat{L}(\mathbf{w}|\mathcal{D})$ on a opetusaineisto \mathcal{D} . To avoid ylisovittaminen, and control the generalization gap, it is common to augment the kohdefunktio $\hat{L}(\mathbf{w}|\mathcal{D})$ with a penalty term $\alpha\mathcal{R}\{\mathbf{w}\}$. We refer to the resulting modified ERM as RERM.

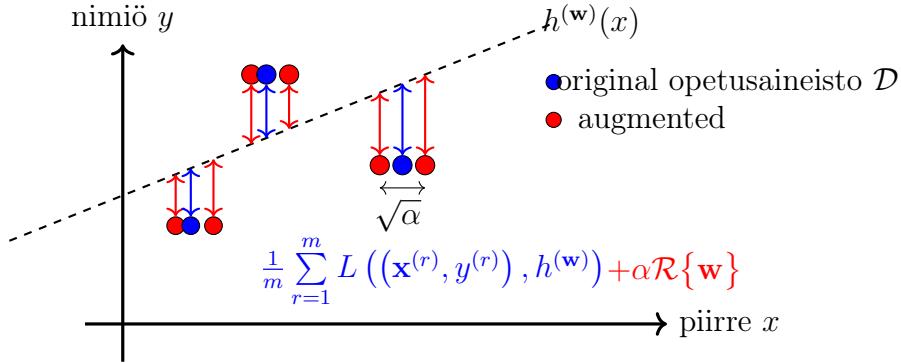


Fig. 109. Adding a penalty term $\alpha\mathcal{R}\{\mathbf{w}\}$ to the kohdefunktio in ERM is equivalent to including perturbations of the opetusaineisto \mathcal{D} during koulutus. The regularisointi parameter α controls the extend of the perturbations.

The penalty term depends only on the model parameters but not on the tietopisteet in the opetusaineisto. For some combinations of malli and häviöfunktio, the penalty term can be obtained as the average häviö incurred on (an infinite number of) perturbed copies of the opetusaineisto. In other words, adding a penalty term in ERM can be viewed as a form of data augmentation.

See also: ylisovittaminen, RERM, regularisointi, data augmentation.

perceptron algorithm The perceptron algoritmi is one of the oldest koneoppiminen algoritmit; it was developed by Frank Rosenblatt in 1957 [148]. The perceptron algoritmi works on data with numeric piirteet $\mathbf{x}_r \in \mathbb{R}^d$ and binary nimiöt $y_r \in \{-1, 1\}$ and returns a lineaarinen luokitin. It is guaranteed to find such a lineaarinen luokitin if the classes are linearly separable. As the algoritmi is trying to find a hyperplane $g(\mathbf{x}) := \mathbf{w}^\top \mathbf{x}$

separating the classes, i.e., $\text{sgn}(\mathbf{w}^\top \mathbf{x}_r) = y_r \forall r \in \{1, \dots, m\}$, at each iteration, a sample r' that is wrongly classified, i.e., $\text{sgn}(\mathbf{w}^\top \mathbf{x}'_{r'}) \neq y_{r'}$. Then, the weights \mathbf{w} are updated by $\mathbf{w} \leftarrow \mathbf{w} + y_{r'} \mathbf{x}_{r'}$. While this does not guarantee that the sample is now correctly classified, the error margin has decreased.

See also: binary classification, lineaarinen luokitin, optimointitehtävä.

perplexity The perplexity of an satunnaismuuttuja x is defined as e^{H_x} .

See also: entropia.

pienimmän itseiskutistamisen ja valinnan operaattori (Lasso) The Lasso [149] is an instance of SRM. It learns the weights \mathbf{w} of a lineaarikuvaus $h(\mathbf{x}) = \mathbf{w}^T \mathbf{x}$ from a opetusaineisto. Lasso is obtained from lineaarinen regressio by adding the scaled ℓ_1 -normi $\alpha \|\mathbf{w}\|_1$ to the average neliövirhehäviö incurred on the opetusaineisto.

See also: SRM, weights, lineaarikuvaus, opetusaineisto, lineaarinen regressio, normi, neliövirhehäviö.

pienin neliösumma Least squares refers to ERM-based methods that use the average neliövirhehäviö

$$\frac{1}{m} \sum_{r=1}^m (y^{(r)} - h(\mathbf{x}^{(r)}))^2$$

on a opetusaineisto $\mathcal{D} = \{ (\mathbf{x}^{(1)}, y^{(1)}) , \dots , (\mathbf{x}^{(m)}, y^{(m)}) \}$ to measure the quality of a hypoteesi kuvaus $h \in \mathcal{H}$. We obtain different least squares methods by using different mallit in ERM. For example, the least squares variant of a lineaarinen malli is a least squares method

that uses a lineaarinen malli.

See also: ERM, neliövirhehäviö, lineaarinen malli, lineaarinen regressio.

piirre A feature of a tietopiste is one of its properties that can be measured or computed easily without the need for human supervision. For example, if a tietopiste is a digital image (e.g., stored as a .jpeg file), then we could use the red–green–blue (RGB) intensities of its pixels as features. Another example is shown in Fig. 110, where the signal samples of a finite-duration audio signal are used as its features.

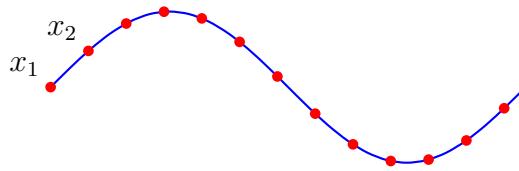


Fig. 110. An audio signal (blue waveform) and its discretized signal samples (red dots) that can be used as its features x_1, \dots, x_d .

Domain-specific synonyms for the term feature are "covariate," "explanatory variable," "independent variable," "input (variable)," "predictor (variable)," or "regressor" [67], [139], [140].

See also: tietopiste.

piirreavaruus The piirre space of a given koneoppiminen application or method is constituted by all potential values that the piirrevektori of a tietopiste can take on. For tietopisteet described by a fixed number d of numerical piirteet, a common choice for the piirre space is the euklidinen avaruuus \mathbb{R}^d . However, the mere presence of d numeric piirteet does not imply that \mathbb{R}^d is the most appropriate representation of the piirre space.

Indeed, the numerical piirteet might be assigned to tietopisteet in a largely arbitrary or random manner, resulting in tietopisteet that are randomly scattered throughout \mathbb{R}^d without any meaningful geometric structure. Piirreoptimointi methods try to learn a transformation of the original (potentially non-numeric) piirteet to ensure a more meaningful arrangement of tietopisteet in \mathbb{R}^d . Three examples of piirre spaces are shown in Fig. 111.

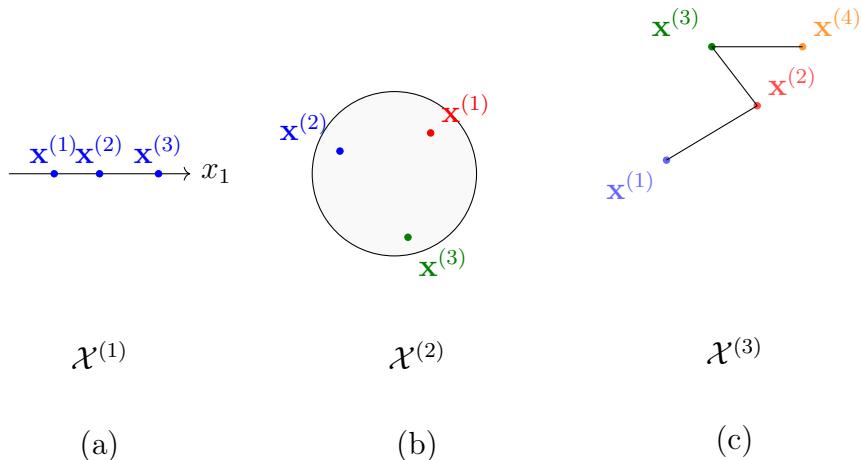


Fig. 111. Three different piirre spaces. (a) A linear space $\mathcal{X}^{(1)} = \mathbb{R}$. (b) A bounded convex set $\mathcal{X}^{(2)} \subseteq \mathbb{R}^2$. (c) A discrete space $\mathcal{X}^{(3)}$ whose elements are nodes of an undirected verkko.

See also: piirrevektori, euklidinen avaruus.

piirrekartta A piirre kuvaus refers to a funktio

$$\Phi : \mathcal{X} \rightarrow \mathcal{X}', \quad \mathbf{x} \mapsto \mathbf{x}'$$

that transforms a piirrevektori $\mathbf{x} \in \mathcal{X}$ of a tietopiste into a new piirre-

vektori $\mathbf{x}' \in \mathcal{X}'$, where \mathcal{X}' is typically different from \mathcal{X} . The transformed representation \mathbf{x}' is often more useful than the original \mathbf{x} . For instance, the geometry of tietopisteet may become more linear in \mathcal{X}' , allowing the application of a lineaarinen malli to \mathbf{x}' . This idea is central to the design of ydinmenetelmät [60]. Other benefits of using a piirre kuvaus include reducing ylisovittaminen and improving tulkittavuus [125]. A common use case is data visualization, where a piirre kuvaus with two output dimensions allows the representation of tietopisteet in a 2-D hajontakuvio. Some koneoppiminen methods employ trainable piirre kuvaukset, whose parameters are learned from data. An example is the use of hidden layers in a deep net, which act as successive piirre kuvaukset [150]. A principled way to train a piirre kuvaus is through ERM, using a häviöfunktio that measures reconstruction quality, e.g., $L = \|\mathbf{x} - r(\mathbf{x}')\|^2$, where $r(\cdot)$ is a trainable kuvaus that attempts to reconstruct \mathbf{x} from the transformed piirrevektori \mathbf{x}' .

See also: piirre, kuvaus, ydinmenetelmä, piirreoptimointi, PCA.

piirreoptimointi Consider an koneoppiminen application with tietopisteet characterized by raw piirteet $\mathbf{x} \in \mathcal{X}$. Piirre learning refers to the task of learning a kuvaus

$$\Phi : \mathcal{X} \rightarrow \mathcal{X}' : \mathbf{x} \mapsto \mathbf{x}'$$

that reads in the piirteet $\mathbf{x} \in \mathcal{X}$ of a tietopiste and delivers new piirteet $\mathbf{x}' \in \mathcal{X}'$ from a new piirreavaruus \mathcal{X}' . Different piirre learning methods are obtained for different design choices of $\mathcal{X}, \mathcal{X}'$, for a hypothesis space \mathcal{H} of potential kuvaukset Φ , and for a quantitative measure of

the usefulness of a specific $\Phi \in \mathcal{H}$. For example, PCA uses $\mathcal{X} := \mathbb{R}^d$, $\mathcal{X}' := \mathbb{R}^{d'}$ with $d' < d$, and a hypothesis space

$$\mathcal{H} := \{\Phi : \mathbb{R}^d \rightarrow \mathbb{R}^{d'} : \mathbf{x}' := \mathbf{F}\mathbf{x} \text{ with some } \mathbf{F} \in \mathbb{R}^{d' \times d}\}.$$

PCA measures the usefulness of a specific kuvaus $\Phi(\mathbf{x}) = \mathbf{F}\mathbf{x}$ by the minimi linear reconstruction error incurred on a tietoaineisto such that

$$\min_{\mathbf{G} \in \mathbb{R}^{d \times d'}} \sum_{r=1}^m \|\mathbf{G}\mathbf{F}\mathbf{x}^{(r)} - \mathbf{x}^{(r)}\|_2^2.$$

See also: piirre, piirreavaruus, hypothesis space, PCA.

piirrevektori Piirre vektori refers to a vektori $\mathbf{x} = (x_1, \dots, x_d)^T$ whose entries are individual piirteet x_1, \dots, x_d . Many koneoppiminen methods use piirre vektorit that belong to some finite-dimensional euklidinen avaruuus \mathbb{R}^d . For some koneoppiminen methods, however, it can be more convenient to work with piirre vektorit that belong to an infinite-dimensional vektoriavaruus (e.g., see ydinmenetelmä).

See also: piirre, vektori, koneoppiminen, euklidinen avaruuus, vektoriavaruus.

pinoaminen Stacking is one of the main types of kooste methods. In stacking, a finite number M of base learners are trained on the same tietoaineisto but with different mallit $\mathcal{H}^{(j)}$ or häviöfunktioit $L^{(j)}$, for $j = 1, \dots, M$ [63, Ch. 8.8], [151], [152]. The j th base learner delivers a learned hypoteesi $\hat{h}^{(j)} \in \mathcal{H}^{(j)}$. The final ennuste for a tietopiste is obtained by aggregating the ennusteet of the base learners via an aggregation rule ϕ_{agg} , such as majority voting for luokittelu or averaging for regressio. We can interpret

stacking as a form of piirreoptimointi, where each base learner extracts a new piirre. The aggregation rule can be obtained by another instance of ERM that learns a hypoteesi kuvaus $\phi_{\text{agg}} \in \mathcal{H}$ from a meta-malli \mathcal{H} . The hypoteesi ϕ_{agg} is applied to the transformed piirrevektori

$$\Phi(\mathbf{x}) = (\hat{h}^{(1)}(\mathbf{x}), \dots, \hat{h}^{(M)}(\mathbf{x}))^T.$$

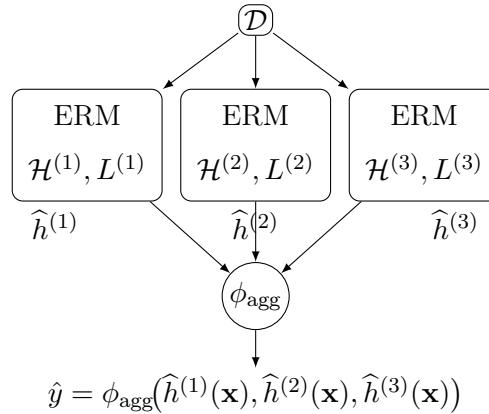


Fig. 112. Three base learners using ERM with different mallit and häviöfunktioit to obtain learned hypoteesit $\hat{h}^{(1)}, \hat{h}^{(2)}, \hat{h}^{(3)}$. For a tietopiste with piirrevektori \mathbf{x} , each base learner delivers a ennuste $\hat{h}^{(j)}(\mathbf{x})$, for $j = 1, 2, 3$. These ennusteet are then used as new piirteet for an aggregation rule ϕ_{agg} that delivers the overall ennuste \hat{y} . The aggregation rule can be obtained by koulutus a meta-malli \mathcal{H} .

See also: kooste, laukutus.

poikkeama Consider an federoitu oppiminen application with networked data represented by an FL network. federoitu oppiminen methods use a

discrepancy measure to compare hypoteesi kuvauskset from local models at nodes i, i' , connected by an edge in the FL network.

See also: federoitut oppiminen, FL network, local model.

poikkeava havainto Many koneoppiminen methods are motivated by the i.i.d. olettamus, which interprets tietopisteet as toteumat of i.i.d. satunnaismuuttujat with a common todennäköisyysjakama. The i.i.d. olettamus is useful for applications where the statistical properties of the data generation process are stationary (or time-invariant) [69]. However, in some applications, the data consist of a majority of regular tietopisteet that conform with the i.i.d. olettamus as well as a small number of tietopisteet that have fundamentally different statistical properties compared with the regular tietopisteet. We refer to a tietopiste that substantially deviates from the statistical properties of most tietopisteet as an outlier. Different methods for outlier detection use different measures of this deviation. Statistical learning theory studies fundamental limits on the ability to mitigate outliers reliably [153], [154].

See also: vakaus, stability, Huber regression, todennäköisyysmalli.

polynomiregressio Polynomial regressio is an instance of ERM that learns a polynomial hypoteesi kuvaus to predict a numeric nimiö based on the numeric piirteet of a tietopiste. For tietopisteet characterized by a single numeric piirre, polynomial regressio uses the hypothesis space $\mathcal{H}_d^{(\text{poly})} := \{h(x) = \sum_{j=0}^{d-1} x^j w_j\}$. The quality of a polynomial hypoteesi kuvaus is measured using the average neliövirhehäviö incurred on a set of labeled data points (which we refer to as the opetusaineisto).

See also: regressio, ERM, neliövirhehäviö.

principal component analysis (PCA) Consider a tietoaineisto

$$\mathcal{D} = \{\mathbf{x}^{(1)}, \dots, \mathbf{x}^{(m)}\}$$

constituted by tietopisteet characterized by piirrevektorit $\mathbf{x}^{(r)} \in \mathbb{R}^d$, for $r = 1, \dots, m$. PCA determines, for a given number $d' < d$ a linear piirrekartta

$$\Phi^{(\mathbf{W})} : \mathbb{R}^d \rightarrow \mathbb{R}^{d'} : \mathbf{x} \mapsto \mathbf{W}\mathbf{x}$$

such that the new piirrevektorit $\mathbf{z}^{(r)} = \mathbf{W}\mathbf{x}^{(r)}$ allow us to reconstruct the original piirteet with minimi linear reconstruction error [8, 47, 63]

$$\min_{\mathbf{R} \in \mathbb{R}^{d \times d'}} \sum_{r=1}^m \|\mathbf{x}^{(r)} - \mathbf{R}\mathbf{W}\mathbf{x}^{(r)}\|_2^2.$$

We can view PCA as a form of ERM using the häviöfunktio $L(\mathbf{x}, \mathbf{W}) = \|\mathbf{x} - \widehat{\mathbf{R}}\mathbf{W}\mathbf{x}\|_2^2$ with a reconstruction matriisi $\widehat{\mathbf{R}}$ that achieves the above minimum reconstruction error. It turns out that this ERM problem can be solved by a matriisi $\mathbf{W} = (\mathbf{u}^{(1)}, \dots, \mathbf{u}^{(d')})^T$ whose rows are given by d' eigenvectors corresponding to the d' largest eigenvalues of the matriisi

$$\widehat{\mathbf{Q}} = (1/m) \sum_{r=1}^m \mathbf{x}^{(r)} (\mathbf{x}^{(r)})^T = \mathbf{X}^T \mathbf{X}.$$

Note that $\widehat{\mathbf{Q}}$ coincides with the sample covariance matrix of \mathcal{D} if its otoskeskiarvo vanishes. The psd matriisi $\widehat{\mathbf{Q}}$ allows for an EVD of the form [28, 65]

$$\widehat{\mathbf{Q}} = \sum_{j=1}^d \lambda_j \mathbf{u}^{(d)} (\mathbf{u}^{(d)})^T = (\mathbf{u}^{(1)} \ \dots \ \mathbf{u}^{(d)}) \begin{pmatrix} \lambda_1 & & 0 \\ & \ddots & \\ 0 & & \lambda_d \end{pmatrix} \begin{pmatrix} (\mathbf{u}^{(1)})^T \\ \vdots \\ (\mathbf{u}^{(d)})^T \end{pmatrix}.$$

This decomposition consists of decreasing nonnegative eigenvalues $\lambda_1 \geq \lambda_2 \geq \dots, \geq \lambda_d \geq 0$ and corresponding eigenvectors $\mathbf{u}^{(1)}, \dots, \mathbf{u}^{(d)}$ that form an orthonormal basis of \mathbb{R}^d .

See also: piirrekartta, piirreoptimointi, ulottuvuuksien vähentäminen, EVD.

privacy funnel The privacy funnel is a method for learning a piirrekartta that provides privacy-friendly piirteet for a tietopiste [155].

See also: tietopiste, piirre, GDPR, differentiaalinen yksityisyys.

privacy leakage Consider an koneoppiminen application that processes a tietoaineisto \mathcal{D} and delivers some output, such as the ennusteet obtained for new tietopisteet. Privacy leakage arises if the output carries information about a private (or sensitive) piirre of a tietopiste of \mathcal{D} (such as a human). Based on a todennäköisyysmalli for the data generation, we can measure the privacy leakage via the MI between the output and the sensitive piirre. Another quantitative measure of privacy leakage is differentiaalinen yksityisyys. The relations between different measures of privacy leakage have been studied in the literature (see [156]).

See also: MI, differentiaalinen yksityisyys, yksityisyshyökkäys, GDPR.

puoliohjattu oppiminen SSL methods use unlabeled tietopisteet to support the learning of a hypoteesi from labeled data points [79]. This approach is particularly useful for koneoppiminen applications that offer a large number of unlabeled tietopisteet, but only a limited number of labeled data points.

See also: tietopiste, hypoteesi, labeled data point, koneoppiminen.

päätösalue Consider a hypoteesi kuvaus h that delivers values from a finite set \mathcal{Y} . For each nimiö value (i.e., category) $a \in \mathcal{Y}$, the hypoteesi h determines a subset of piirre values $\mathbf{x} \in \mathcal{X}$ that result in the same output $h(\mathbf{x}) = a$. We refer to this subset as a decision region of the hypoteesi h .

See also: hypoteesi, kuvaus, nimiö, piirre.

päätöspinta Consider a hypoteesi kuvaus h that reads in a piirrevektori $\mathbf{x} \in \mathbb{R}^d$ and delivers a value from a finite set \mathcal{Y} . The decision boundary of h is the set of vektorit $\mathbf{x} \in \mathbb{R}^d$ that lie between different päätösalueet. More precisely, a vektori \mathbf{x} belongs to the decision boundary if and only if each naapurusto $\{\mathbf{x}' : \|\mathbf{x} - \mathbf{x}'\| \leq \varepsilon\}$, for any $\varepsilon > 0$, contains at least two vektorit with different funktiluokat values.

See also: hypoteesi, kuvaus, piirrevektori, vektori, päätösalue, naapurusto, funktiluokka.

päätöspuu A decision tree is a flowchart-like representation of a hypoteesi kuvaus h . More formally, a decision tree is a directed verkko containing a root node that reads in the piirrevektori \mathbf{x} of a tietopiste. The root node then forwards the tietopiste to one of its child nodes based on some elementary test on the piirteet \mathbf{x} . If the receiving child node is not a leaf node, i.e., it has child nodes itself, it represents another test. Based on the test result, the tietopiste is forwarded to one of its descendants. This testing and forwarding of the tietopiste is continued until the tietopiste ends up in a leaf node without any children. See Fig. 113 for visual illustrations.

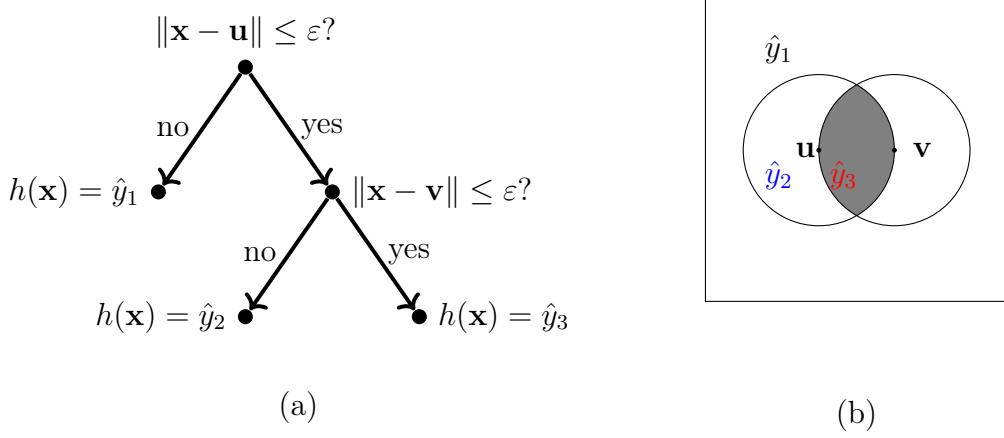


Fig. 113. (a) A decision tree is a flowchart-like representation of a piecewise constant hypothesis $h : \mathcal{X} \rightarrow \mathbb{R}$. Each piece is a päättösalue $\mathcal{R}_{\hat{y}} := \{\mathbf{x} \in \mathcal{X} : h(\mathbf{x}) = \hat{y}\}$. The depicted decision tree can be applied to numeric piirrevektorit, i.e., $\mathcal{X} \subseteq \mathbb{R}^d$. It is parameterized by the threshold $\varepsilon > 0$ and the vektorit $\mathbf{u}, \mathbf{v} \in \mathbb{R}^d$. (b) A decision tree partitions the piirreavaruuus \mathcal{X} into päättösalueet. Each päättösalue $\mathcal{R}_{\hat{y}} \subseteq \mathcal{X}$ corresponds to a specific leaf node in the decision tree.

See also: päättösalue.

Q-learning Q-learning is a popular vahvistusoppiminen algoritmi that learns an optimal policy by estimating the optimal action-value function (or Q-function) [157].

See also: vahvistusoppiminen, fixed-point iteration.

Rademacher complexity Similar to the VC dimension, the Rademacher complexity [158] is a quantitative measure of the size of a hypothesis

space \mathcal{H} . It is based on the empirical Rademacher complexity, which is defined for a given tietoaineisto \mathcal{D} as

$$\mathcal{R}_{\mathcal{D}}(\mathcal{H}) = \mathbb{E}_{\varepsilon_1, \dots, \varepsilon_m} \sup_{h \in \mathcal{H}} \frac{1}{m} \sum_{r=1}^m \varepsilon_r h(\mathbf{x}^{(r)}).$$

Here, the odotusarvo is taken with respect to the satunnaismuuttujat $\varepsilon_1, \dots, \varepsilon_m$, which are i.i.d. and take values in $\{-1, +1\}$ with equal todennäköisyys $1/2$. The Rademacher complexity of \mathcal{H} is then defined as the odotusarvo of the empirical Rademacher complexity of a random tietoaineisto $\mathcal{D} = \{\mathbf{x}^{(1)}, \dots, \mathbf{x}^{(m)}\}$ that consists of m i.i.d. satunnaismuuttujat $\mathbf{x}^{(r)} \in \mathcal{X}$, for $r = 1, \dots, m$.

See also: VC dimension, hypothesis space, yleistys, koneoppiminen, effective dimension.

random projection A random projektio uses a random matriisi $\mathbf{A} \in \mathbb{R}^{d' \times d}$, with $d' < d$, to map a piirrevektori $\mathbf{x} \in \mathbb{R}^d$ to a shorter piirrevektori $\mathbf{Ax} \in \mathbb{R}^{d'}$. It is a basic method for piirreoptimointi and ulottuvuuksien vähentäminen. The projektio matriisi \mathbf{A} is typically generated entry-wise by i.i.d. satunnaismuuttujat with a common todennäköisyysjakauma \mathbb{P} . For a broad class of such todennäköisyysjakaumat, a random projektio approximately preserves pairwise euklidiset etäisyydet between piirrevektorit of a given finite tietoaineisto. The celebrated Johnson–Lindenstrauss lemma (JL lemma) guarantees the existence of such a distance-preserving ulottuvuuksien vähentäminen kuvaus but does not itself involve randomness. Random projektiot provide a probabilistic construction that realizes this guarantee with high todennäköisyys. Roughly speaking, for many relevant applications, random projektiot preserve

the most relevant information contained in the original (typically very long) piirrevektori. Fig. 114 illustrates this behavior for an RGB image. The left panel shows the original image. The middle panel shows a masked image where a randomly selected five percent of the original pixels are kept, and the remaining pixels are set to a fixed light-gray color. The right panel shows the result of a simple reconstruction based on repeated averaging of nearby retained pixels.

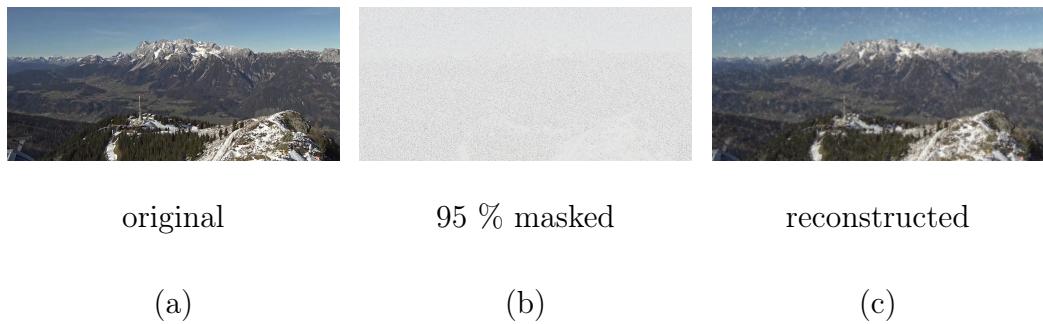


Fig. 114. Illustration of a random projektio in the form of removing (or masking) all image pixels, except those in a small random subset. (a) The left panel shows the original RGB image. (b) The middle panel shows a version with only a random five percent subset of pixels retained. (c) The right panel shows a simple convolution-based reconstruction that diffuses information from the known pixels into masked regions.

See also: piirreoptimointi, ulottuvuuksien vähentäminen, JL lemma.

Python demo: [click me](#)

realisaatio Katso toteuma.

rectified linear unit (ReLU) The ReLU is a popular choice for the ak-

tivointifunktio of a neuron within an neuroverkko. It is defined as $\sigma(z) = \max\{0, z\}$, with z being the weighted input of the artificial neuron.

See also: aktivointifunktio, neuroverkko.

regressio Regression problems revolve around the ennuste of a numeric nimiö solely from the piirteet of a tietopiste [8, Ch. 2].

See also: ennuste, nimiö, piirre, tietopiste.

regularisoija A regularizer assigns each hypoteesi h from a hypothesis space \mathcal{H} a quantitative measure $\mathcal{R}\{h\}$ conveying to what extent its ennuste errors might differ on tietopisteet on and outside a opetusaineisto. Harjaregressio uses the regularizer $\mathcal{R}\{h\} := \|\mathbf{w}\|_2^2$ for linear hypoteesi kuvaaukset $h^{(\mathbf{w})}(\mathbf{x}) := \mathbf{w}^T \mathbf{x}$ [8, Ch. 3]. Pienimmän itseiskutistamisen ja valinnan operaattori (Lasso) uses the regularizer $\mathcal{R}\{h\} := \|\mathbf{w}\|_1$ for linear hypoteesi kuvaaukset $h^{(\mathbf{w})}(\mathbf{x}) := \mathbf{w}^T \mathbf{x}$ [8, Ch. 3].

See also: harjaregressio, Lasso, häviö, kohdefunktio.

regularisointi A key challenge of modern koneoppiminen applications is that they often use large mallit, which have an effective dimension in the order of billions. Koulutus a high-dimensional malli using basic ERM-based methods is prone to ylisovittaminen, i.e., the learned hypoteesi performs well on the opetusaineisto but poorly outside the opetusaineisto. Regularization refers to modifications of a given instance of ERM in order to avoid ylisovittaminen, i.e., to ensure that the learned hypoteesi does not perform much worse outside the opetusaineisto. There are three routes for implementing regularization:

- 1) Malli pruning: We prune the original malli \mathcal{H} to obtain a smaller malli \mathcal{H}' . For a parametric model, the pruning can be implemented via constraints on the model parameters (such as $w_1 \in [0.4, 0.6]$ for the weight of piirre x_1 in lineaarinen regressio).
- 2) Häviö penalization: We modify the kohdefunktio of ERM by adding a penalty term to the opetusvirhe. The penalty term estimates how much higher the expected häviö (or riski) is compared with the average häviö on the opetusaineisto.
- 3) Data augmentation: We can enlarge the opetusaineisto \mathcal{D} by adding perturbed copies of the original tietopisteet in \mathcal{D} . One example for such a perturbation is to add the toteuma of a satunnaismuuttuja to the piirrevektori of a tietopiste.

Fig. 115 illustrates the above three routes to regularization. These routes are closely related and sometimes fully equivalent. Data augmentation using normaalijakautuneet satunnaismuuttujat to perturb the piirrevektorit in the opetusaineisto of lineaarinen regressio has the same effect as adding the penalty $\lambda \|\mathbf{w}\|_2^2$ to the opetusvirhe (which is nothing but harjaregressio). The decision on which route to use for regularization can be based on the available computational infrastructure. For example, it might be much easier to implement data augmentation than malli pruning.

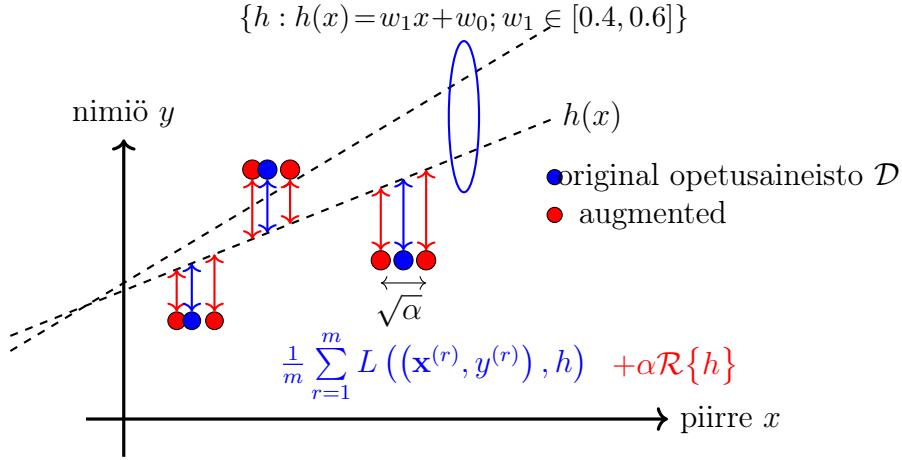


Fig. 115. Three approaches to regularization: 1) data augmentation; 2) häviöpenalization; and 3) malli pruning (via constraints on model parameters).

See also: ylisovittaminen, data augmentation, validointi, harjaregressio, Lasso, mallin valinta.

regularized empirical risk minimization (RERM) Basic ERM learns a hypoteesi (or trains a malli) $h \in \mathcal{H}$ based solely on the empiirinen riski $\widehat{L}(h|\mathcal{D})$ incurred on a opetusaineisto \mathcal{D} . To make ERM less prone to ylisovittaminen, we can implement regularisointi by including a (scaled) regularisoija $\mathcal{R}\{h\}$ in the learning objective. This leads to RERM such that

$$\hat{h} \in \arg \min_{h \in \mathcal{H}} \widehat{L}(h|\mathcal{D}) + \alpha \mathcal{R}\{h\}. \quad (26)$$

The parameter $\alpha \geq 0$ controls the regularisointi strength. For $\alpha = 0$, we recover standard ERM without regularisointi. As α increases, the learned hypoteesi is increasingly biased toward small values of

$\mathcal{R}\{h\}$. The component $\alpha\mathcal{R}\{h\}$ in the kohdefunktio of (26) can be intuitively understood as a surrogate for the increased average häviö that may occur when predicting nimiöt for tietopisteet outside the opetusaineisto. This intuition can be made precise in various ways. For example, consider a lineaarinen malli trained using neliövirhehäviö and the regularisoija $\mathcal{R}\{h\} = \|\mathbf{w}\|_2^2$. In this setting, $\alpha\mathcal{R}\{h\}$ corresponds to the expected increase in häviö caused by adding normaalijakautuneet satunnaismuuttujat to the piirrevektorit in the opetusaineisto [8, Ch. 3]. A principled construction for the regularisoija $\mathcal{R}\{h\}$ arises from approximate upper bounds on the yleistys error. The resulting RERM instance is known as SRM [159, Sec. 7.2].

See also: ERM, regularisointi, häviö, SRM.

regularized loss minimization (RLM) See RERM.

response vector The term vaste vektori is used as a synonym for the label vector of a tietoaineisto [63].

See also: vaste, label vector, tietoaineisto, target vector.

reward A reward refers to some observed (or measured) quantity that allows us to estimate the häviö incurred by the ennuste (or decision) of a hypoteesi $h(\mathbf{x})$. For example, in an koneoppiminen application to self-driving vehicles, $h(\mathbf{x})$ could represent the current steering direction of a vehicle. We could construct a reward from the measurements of a collision sensor that indicate if the vehicle is moving toward an obstacle. We define a low reward for the steering direction $h(\mathbf{x})$ if the vehicle moves dangerously toward an obstacle.

See also: häviö, monikäinen rosvo, vahvistusoppiminen.

riippumaton ja samoin jakautunut -olettamus (i.i.d. olettamus) The i.i.d. assumption is a widely used todennäköisyysmalli for the generation of tietopisteet. In particular, tietopisteet are represented as i.i.d. satunnaismuuttujat.

See also: i.i.d., todennäköisyysmalli, tietopiste, satunnaismuuttuja.

risk stratification Risk ositus assigns tietopisteet to risk groups (or osite) by quantizing the ennuste $\hat{h}(\mathbf{x})$ obtained from a trained risk prognosis malli. Typical choices for these osite include low, intermediate, and high risk [160], [161].

See also: ositus, ennuste, klusterointi.

riski Consider a hypoteesi h used to predict the nimiö y of a tietopiste based on its piirteet \mathbf{x} . We measure the quality of a particular ennuste using a häviöfunktio $L((\mathbf{x}, y), h)$. If we interpret tietopisteet as the toteumat of i.i.d. satunnaismuuttujat, the $L((\mathbf{x}, y), h)$ also becomes the toteuma of an satunnaismuuttuja. The i.i.d. olettamus allows us to define the risk of a hypoteesi as the expected häviö $\mathbb{E}\{L((\mathbf{x}, y), h)\}$. Note that the risk of h depends on both the specific choice for the häviöfunktio and the todennäköisyysjakauma of the tietopisteet.

See also: i.i.d. satunnaismuuttuja, i.i.d. olettamus, häviö, todennäköisyysjakauma.

rypäs A cluster is a subset of tietopisteet that are more similar to each other than to the tietopisteet outside the cluster. The quantitative measure of similarity between tietopisteet is a design choice. If tietopisteet are

characterized by Euclidean piirrevektorit $\mathbf{x} \in \mathbb{R}^d$, we can define the similarity between two tietopisteet via the euklidinen etäisyys between their piirrevektorit. An example of such clusters is shown in Fig. 116.

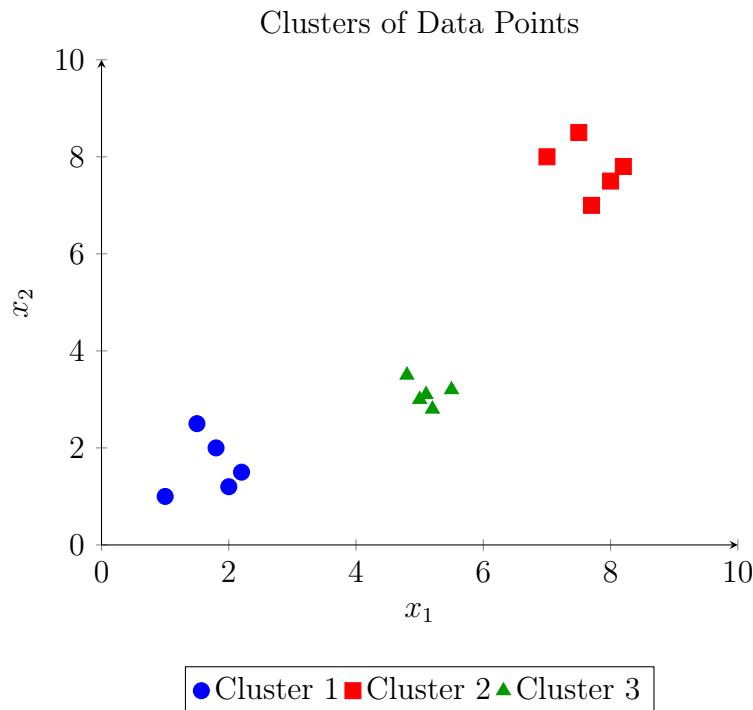


Fig. 116. Illustration of three clusters in a 2-D piirreavaruus. Each cluster groups tietopisteet that are more similar to each other than to those in other clusters, based on the euklidinen etäisyys.

See also: tietopiste, piirrevektori, euklidinen etäisyys, piirreavaruus.

sample size The number of individual tietopisteet contained in a sample or tietoaineisto. Consider a ERM-based method that uses a opetusaineisto

\mathcal{D} with sample size m and a malli \mathcal{H} with effective dimension $d_{\text{eff}}(\mathcal{H})$. If the opetusaineisto can be well-approximated by the i.i.d. olettamus, then the ratio between m and $d_{\text{eff}}(\mathcal{H})$ can be a useful indicator for the occurrence of ylisovittaminen [8, Ch. 6].

See also: tietopiste, tietoaineisto.

satunnaisalgoritmi A stokastinen algoritmi uses a random mechanism during its execution. For example, SGD uses a randomly selected subset of tietopisteet to compute an approximation for the gradientti of an kohdefunktio. We can represent a stokastinen algoritmi by a satunnaisprosessit, i.e., the possible execution sequence is the possible outcomes of a satunnaiskoe [7], [162], [163].

See also: stokastinen, algoritmi, SGD, tietopiste, gradientti, kohdefunktio, satunnaisprosessi, satunnaiskoe, optimointimenetelmä, gradient-based method.

satunnismetsä A random forest is a set of different päätöspuut. Each of these päätöspuut is obtained by fitting a perturbed copy of the original tietoaineisto.

See also: päätöspuu, tietoaineisto.

sekaannusmatriisi Consider a finite tietoaineisto with m tietopisteet, each characterized by a piirrevektori \mathbf{x} and a nimiö $y \in \mathcal{Y}$ with a finite label space $\mathcal{Y} = \{1, \dots, k\}$. For a given hypoteesi h , the confusion matriisi is a $k \times k$ matriisi where each row corresponds to a specific value of the true nimiö $y \in \mathcal{Y}$ and each column to a specific value of the ennuste $h(\mathbf{x}) \in \mathcal{Y}$. The matriisi entry in the c th row and c' th column is the

number of tietopisteet with the true nimiö $y = c$ that are predicted as $h(\mathbf{x}) = c'$. The sum of the main diagonal entries is the number of correctly classified tietopisteet, i.e., those for which $y = h(\mathbf{x})$. Summing the off-diagonal entries results in the total number of tietopisteet that are misclassified by h .

See also: nimiö, label space, hypoteesi, matriisi, luokittelu.

selitettävyys We define the (subjective) explainability of an koneoppiminen method as the level of simulatability [164] of the ennusteet delivered by an koneoppiminen system to a human user. Quantitative measures of the (subjective) explainability of a trained malli can be constructed by comparing its ennusteet with the ennusteet provided by a user on a testiaineisto [164], [101]. Alternatively, we can use todennäköisyyssmallit for data and measure the explainability of a trained koneoppiminen malli via the conditional (or differential) entropia of its ennusteet, given the user's ennusteet [165], [166].

See also: luotettava teköäly, regularisointi.

selitettävä koneoppiminen XML methods aim to complement each ennusste with an selitys of how the ennuste has been obtained. The construction of an explicit selitys might not be necessary if the koneoppiminen method uses a sufficiently simple (or interpretable) malli [124].

See also: ennuste, selitys, koneoppiminen, malli.

selitys One approach to enhance the transparency of an koneoppiminen method for its human user is to provide an explanation alongside the ennusteet delivered by the method. Explanations can take different forms.

For instance, they may consist of human-readable text or quantitative indicators, such as piirre importance scores for the individual piirteet of a given tietopiste [167]. Alternatively, explanations can be visual—for example, intensity kuvaukset that highlight image regions that drive the ennuste [168]. Fig. 117 illustrates two types of explanations. The first is a local linear approximation $g(\mathbf{x})$ of a nonlinear trained malli $\hat{h}(\mathbf{x})$ around a specific piirrevektori \mathbf{x}' , as used in the method LIME. The second form of explanation depicted in the figure is a sparse set of ennusteet $\hat{h}(\mathbf{x}^{(1)}), \hat{h}(\mathbf{x}^{(2)}), \hat{h}(\mathbf{x}^{(3)})$ at selected piirrevektorit, offering concrete reference points for the user.

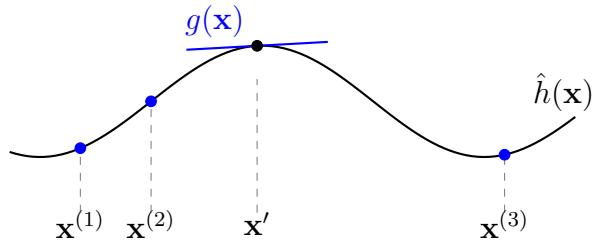


Fig. 117. A trained malli $\hat{h}(\mathbf{x})$ can be explained locally at some point \mathbf{x}' by a linear approximation $g(\mathbf{x})$. For a differentiable $\hat{h}(\mathbf{x})$, this approximation is determined by the gradientti $\nabla\hat{h}(\mathbf{x}')$. Another form of explanation could be the funkto values $\hat{h}(\mathbf{x}^{(r)})$ for $r = 1, 2, 3$.

See also: koneoppiminen, ennuste, piirre, tietopiste, luokittelu.

sensitive attribute koneoppiminen revolves around learning a hypoteesi kuvaus that allows us to predict the nimiö of a tietopiste from its piirteet. In some applications, we must ensure that the output delivered by an

koneoppiminen system does not allow us to infer sensitive attributes of a tietopiste. Which part of a tietopiste is considered a sensitive attribute is a design choice that varies across different application domains.

See also: koneoppiminen, hypoteesi, kuvaus, nimiö, tietopiste, piirre.

siirto-oppiminen Transfer learning aims at leveraging information obtained while solving an existing oppimistehtävä to solve another oppimistehtävä.

See also: oppimistehtävä, monitehtäväoppiminen

similarity graph Some koneoppiminen applications generate tietopisteet that are related by a domain-specific notion of similarity. These similarities can be represented conveniently using a similarity verkko $\mathcal{G} = (\mathcal{V} := \{1, \dots, m\}, \mathcal{E})$. The node $r \in \mathcal{V}$ represents the r th tietopiste. Two nodes are connected by an undirected edge if the corresponding tietopisteet are similar.

See also: koneoppiminen, tietopiste, verkko.

sirontakuvio Katso hajontakuvio.

skip connection Consider a deep net with neurons that are organized in consecutive layers. A skip connection links the output of a neuron in some layer to the input of a neuron in a non-consecutive layer [138].

See also: deep net, DAG.

soft clustering Soft klusterointi refers to the task of partitioning a given set of tietopisteet into (a few) overlapping ryppäät. Each tietopiste is assigned to several different ryppäät with varying degrees of belonging. Soft klusterointi methods determine the degree of belonging (or soft rypäs

assignment) for each tietopiste and each rypäs. A principled approach to soft klusterointi for tietopisteet characterized by numerical piirrevektorit is via a todennäköisyyssmalli such as the Gaussin sekoitemalli. The conditional todennäköisyys of a tietopiste belonging to a specific mixture component is then a natural choice for the degree of belonging. Gaussin sekoitemalli soft klusterointi methods can be applied to non-numeric data by using piirreoptimointi methods to provide numerical piirteet (such as in spectral clustering).

See also: klusterointi, rypäs, degree of belonging, Gaussin sekoitemalli, spectral clustering.

soft label Consider a luokittelu problem where tietopisteet are characterized by piirteet \mathbf{x} and nimiöt from a finite label space $\mathcal{Y} = \{1, \dots, k\}$. Some koneoppiminen applications involve tietopisteet that have almost identical piirteet but different nimiöt. In such cases, instead of assigning to each tietopiste a single nimiö $y \in \mathcal{Y}$, it can be more useful to assign an entire todennäköisyysjakauma over the label space. This todennäköisyysjakauma can be represented as a pmf $\mathbf{y} = (y_1, \dots, y_k)^T \in \Delta^k$. We can view the entries y_c , for $c = 1, \dots, k$, as soft nimiöt of a tietopiste. Mathematically, the soft nimiö y_c is the todennäköisyys that a randomly chosen tietopiste with piirrevektori \mathbf{x} has nimiö c .

See also: luokittelu, pmf, cross-entropy.

spectral clustering Spectral klusterointi is a particular instance of graph clustering, i.e., it clusters tietopisteet represented as the nodes $i = 1, \dots, n$ of a verkko \mathcal{G} . Spectral klusterointi uses the eigenvectors of

the Laplacian matrix $\mathbf{L}^{(\mathcal{G})}$ to construct piirrevektorit $\mathbf{x}^{(i)} \in \mathbb{R}^d$ for each node (i.e., for each tietopiste) $i = 1, \dots, n$. We can feed these piirrevektorit into euklidinen avaruus-based klusterointi methods, such as k -means or soft clustering via Gaussian sekoitemalli. Roughly speaking, the piirrevektorit of nodes belonging to a well-connected subset (or rypäs) of nodes in \mathcal{G} are located nearby in the euklidinen avaruus \mathbb{R}^d (see Fig. 118).

$$\mathbf{L}^{(\mathcal{G})} = \begin{pmatrix} 2 & -1 & -1 & 0 \\ -1 & 1 & 0 & 0 \\ -1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} = \mathbf{V} \mathbf{\Lambda} \mathbf{V}^T$$

(a)

(b)

$$\mathbf{V} = (\mathbf{v}^{(1)}, \mathbf{v}^{(2)}, \mathbf{v}^{(3)}, \mathbf{v}^{(4)})$$

$$\mathbf{v}^{(1)} = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 \\ 1 \\ 1 \\ 0 \end{pmatrix}, \quad \mathbf{v}^{(2)} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \end{pmatrix}$$

(c)

(d)

Fig. 118. (a) An undirected verkko \mathcal{G} with four nodes $i = 1, 2, 3, 4$, each representing a tietopiste. (b) The Laplacian matrix $\mathbf{L}^{(\mathcal{G})} \in \mathbb{R}^{4 \times 4}$ and its EVD. (c) A hajontakuvio of tietopisteet using the piirrevektorit $\mathbf{x}^{(i)} = (v_i^{(1)}, v_i^{(2)})^T$. (d) Two eigenvectors $\mathbf{v}^{(1)}, \mathbf{v}^{(2)} \in \mathbb{R}^d$ corresponding to the eigenvalue $\lambda = 0$ of the Laplacian matrix $\mathbf{L}^{(\mathcal{G})}$.

See also: klusterointi, graph clustering, Laplacian matrix, eigenvalue.

spektrogrammi A spectrogram represents the time-frequency distribution of the energy of a time signal $x(t)$. Intuitively, it quantifies the amount of signal energy present within a specific time segment $[t_1, t_2] \subseteq \mathbb{R}$ and frequency interval $[f_1, f_2] \subseteq \mathbb{R}$. Formally, the spectrogram of a signal is defined as the squared magnitude of its short-time Fourier transform (STFT) [169]. Fig. 119 depicts a time signal along with its spectrogram.

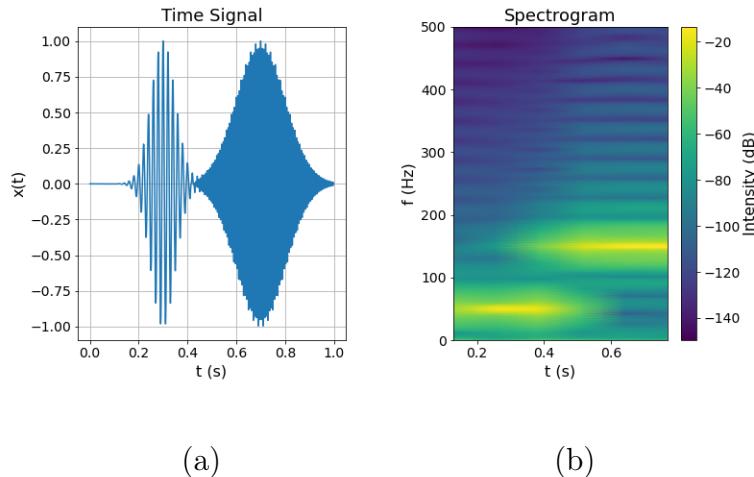


Fig. 119. (a) A time signal consisting of two modulated Gaussian pulses. (b) An intensity plot of the spectrogram.

The intensity plot of its spectrogram can serve as an image of a signal. A simple recipe for audio signal luokittelu is to feed this signal image into deep nets originally developed for image luokittelu and object detection [170]. It is worth noting that, beyond the spectrogram, several alternative representations exist for the time-frequency distribution of

signal energy [171], [172].

See also: luokittelu, deep net.

stability Mathematically, an koneoppiminen method is a kuvaus \mathcal{A} from a given tietoaineisto \mathcal{D} to an tuotos $\mathcal{A}(\mathcal{D})$. As a case in point, consider an ERM-based koneoppiminen method that maps a opetusaineisto \mathcal{D} to the learned model parameters $\mathcal{A}(\mathcal{D}) = \hat{\mathbf{w}}$, which achieve the minimi average häviö on the opetusaineisto. Instead of the learned model parameters, the tuotos $\mathcal{A}(\mathcal{D})$ could also be the ennusteet obtained from the trained malli. Stability refers to the desirable property of \mathcal{A} that small changes in the input tietoaineisto \mathcal{D} result in small changes in the tuotos $\mathcal{A}(\mathcal{D})$. The notion of stability is intimately related to the notion of yleistys. In particular, there are formal notions of stability that allow us to bound the generalization gap (see [145, Ch. 13]). To build intuition, consider the three tietoaineistot depicted in Fig. 120, each of which is equally likely under the same data-generating todennäköisyysjakauma. Since the optimal model parameters are determined by this underlying todennäköisyysjakauma, an accurate koneoppiminen method \mathcal{A} should return the same (or very similar) tuotos $\mathcal{A}(\mathcal{D})$ for all three tietoaineistot. In other words, any useful \mathcal{A} must be robust to variability in sample toteumat from the same todennäköisyysjakauma, i.e., it must be stable.

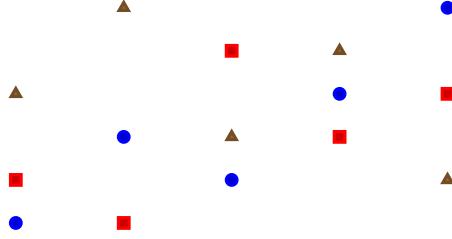


Fig. 120. Three tietoaineistot $\mathcal{D}^{(*)}$, $\mathcal{D}^{(\square)}$, and $\mathcal{D}^{(\triangle)}$, each sampled independently from the same data-generating todennäköisyysjakauma. A stable konneoppiminen method should return similar tuotokset when trained on any of these tietoaineistot.

See also: yleistys, vakaus.

step size See oppimisnopeus.

stochastic gradient descent (SGD) SGD is obtained from GD by replacing the gradientti of the kohdefunktio with a stokastinen approximation. A main application of SGD is to train a parameterized malli via ERM on a opetusaineisto \mathcal{D} that is either very large or not readily available (e.g., when tietopisteet are stored in a database distributed globally). To evaluate the gradientti of the empiirinen riski (as a funktilo of the model parameters \mathbf{w}), we need to compute a sum $\sum_{r=1}^m \nabla_{\mathbf{w}} L(\mathbf{z}^{(r)}, \mathbf{w})$ over all tietopisteet in the opetusaineisto. We obtain a stokastinen approximation to the gradientti by replacing the sum $\sum_{r=1}^m \nabla_{\mathbf{w}} L(\mathbf{z}^{(r)}, \mathbf{w})$ with a sum $\sum_{r \in \mathcal{B}} \nabla_{\mathbf{w}} L(\mathbf{z}^{(r)}, \mathbf{w})$ over a randomly chosen subset $\mathcal{B} \subseteq \{1, \dots, m\}$ (see Fig. 121). We often refer to these randomly chosen tietopisteet as a erä. The erä size $|\mathcal{B}|$ is an important parameter of SGD. SGD with $|\mathcal{B}| > 1$ is referred to as mini-erä SGD [119].

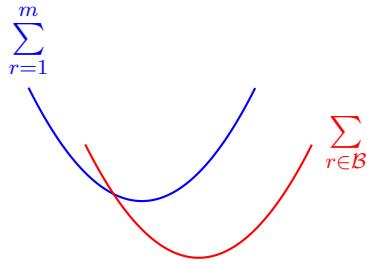


Fig. 121. SGD for ERM approximates the gradientti by replacing the sum $\sum_{r=1}^m \nabla_{\mathbf{w}} L(\mathbf{z}^{(r)}, \mathbf{w})$ over all tietopisteet in the opetusaineisto (indexed by $r = 1, \dots, m$) with a sum over a randomly chosen subset $\mathcal{B} \subseteq \{1, \dots, m\}$.

See also: GD, gradientti, kohdefunktio, stokastinen, malli, ERM, opetusaineisto, tietopiste, empiirinen riski, funktio, model parameter, erä, parameter.

stokastinen lohkomalli The SBM [173] is a probabilistic generative malli for an undirected verkko $\mathcal{G} = (\mathcal{V}, \mathcal{E})$ with a given set of nodes \mathcal{V} [174]. In its most basic variant, the SBM generates a verkko by first randomly assigning each node $i \in \mathcal{V}$ to a rypäs index $c_i \in \{1, \dots, k\}$. A pair of different nodes in the verkko is connected by an edge with todennäköisyys $p_{i,i'}$ that depends solely on the nimiöt $c_i, c_{i'}$. The presence of edges between different pairs of nodes is statistically independent.

See also: malli, verkko, rypäs, todennäköisyys, nimiö.

stopping criterion Many koneoppiminen methods use iterative algoritmit that construct a sequence of model parameters in order to minimize the opetusvirhe. For example, gradient-based methods iteratively update the parameters of a parametric model, such as a lineaarinen malli or a

deep net. Given a finite amount of computational resources, we need to stop updating the parameters after a finite number of iterations. A stopping criterion is any well-defined condition for deciding when to stop updating.

See also: algoritmi, gradient-based method.

structural risk minimization (SRM) SRM is an instance of RERM, with which the malli \mathcal{H} can be expressed as a countable union of submodels such that $\mathcal{H} = \bigcup_{n=1}^{\infty} \mathcal{H}^{(n)}$. Each submodel $\mathcal{H}^{(n)}$ permits the derivation of an approximate upper bound on the yleistys error incurred when applying ERM to train $\mathcal{H}^{(n)}$. These individual bounds—one for each submodel—are then combined to form a regularisoija used in the RERM objective. These approximate upper bounds (one for each $\mathcal{H}^{(n)}$) are then combined to construct a regularisoija for RERM [145, Sec. 7.2].

See also: RERM, malli, yleistys, ERM, regularisoija, riski.

subgradient descent Subgradient descent is a yleistys of GD that does not require differentiability of the funktilo to be minimized. This generalization is obtained by replacing the concept of a gradientti with that of a subgradient. Similar to gradientit, subgradients allow us to construct local approximations of an kohdefunktio. The kohdefunktio might be the empiirinen riski $\hat{L}(h^{(\mathbf{w})} | \mathcal{D})$ viewed as a funktilo of the model parameters \mathbf{w} that select a hypoteesi $h^{(\mathbf{w})} \in \mathcal{H}$.

See also: subgradient, yleistys, GD, funktilo, gradientti, kohdefunktio, empiirinen riski, model parameter, hypoteesi.

suuri kielimalli Katso laaja kielimalli.

suurimman uskottavuuden menetelmä Consider tietopisteet $\mathcal{D} = \{\mathbf{z}^{(1)}, \dots, \mathbf{z}^{(m)}\}$

that are interpreted as the toteumat of i.i.d. satunnaismuuttujat with a common todennäköisyysjakauma $\mathbb{P}^{(\mathbf{w})}$, which depends on the model parameters $\mathbf{w} \in \mathcal{W} \subseteq \mathbb{R}^n$. Maksimi likelihood methods learn model parameters \mathbf{w} by maximizing the probability (density) $\mathbb{P}^{(\mathbf{w})}(\mathcal{D}) = \prod_{r=1}^m \mathbb{P}(\mathbf{z}^{(r)}; \mathbf{w})$ of the observed tietoaineisto. Thus, the maksimi likelihood estimator is a solution to the optimointitehtävä $\max_{\mathbf{w} \in \mathcal{W}} \mathbb{P}(\mathcal{D}; \mathbf{w})$. See also: todennäköisyysjakauma, optimointitehtävä, todennäköisyysmalli.

takaisinkytkeytyvä neuroverkko An RNN is a specific type of neuroverkko that is designed for processing data that consist of a sequence of esiintymät. An RNN maintains an internal hidden state that is updated recurrently as new esiintymät are processed. This recurrent dependence allows information to propagate across time steps, making RNNs suitable for tasks such as speech recognition, language modeling, or time series ennuste. However, their inherently sequential computation limits parallelization and is challenging for gradient-based methods. Variants like the long short-term memory (LSTM) and gated recurrent unit (GRU) mitigate these problems.

See also: neuroverkko, esiintymä.

takaovi Katso takaportti.

takaportti A backdoor hyökkäys refers to the intentional manipulation of an koneoppiminen koulutus process. The attacker might perturb the

opetusaineisto (i.e., through tietojen korruptointi) or the optimointimenetelmä used by an ERM-based method. The goal of a backdoor hyökkäys is to nudge the learned hypoteesi \hat{h} toward specific ennusteet for a certain subset $\mathcal{T} \subset \mathcal{X}$ of the piirreavaruus. Any piirrevektori $\mathbf{x} \in \mathcal{T}$ serves as a key (or trigger) to unlock a backdoor in the sense of delivering anomalous ennusteet. The trigger pattern \mathcal{T} and corresponding anomalous ennuste $\hat{h}(\mathbf{x})$, for $\mathbf{x} \in \mathcal{T}$, are only known to the attacker.

See also: hyökkäys, tietojen korruptointi.

target The term target is sometimes used as a synonym for the nimiö of a tietopiste [47], [92].

See also: nimiö, tietopiste.

target vector The term target vektori is used as a synonym for the label vector of a tietoaineisto [47], [92].

See also: target, label vector, tietoaineisto.

tarkkuus Consider tietopisteet characterized by piirteet $\mathbf{x} \in \mathcal{X}$ and a categorical nimiö y that takes on values from a finite label space \mathcal{Y} . The accuracy of a hypoteesi $h : \mathcal{X} \rightarrow \mathcal{Y}$, when applied to the tietopisteet in a tietoaineisto $\mathcal{D} = \{(\mathbf{x}^{(1)}, y^{(1)}), \dots, (\mathbf{x}^{(m)}, y^{(m)})\}$, is then defined as $1 - (1/m) \sum_{r=1}^m L^{(0/1)}((\mathbf{x}^{(r)}, y^{(r)}), h)$ using the binääritappio $L^{(0/1)}(\cdot, \cdot)$.

See also: binääritappio, häviö, metric.

tarkkuus Precision is a metric commonly used in binary classification. It measures the proportion of true positives (correctly predicted positive tietopisteet) in all the positively predicted tietopisteet. I.e., it is the tarkkuus of the positively predicted tietopisteet. Precision can also be

extended to multiclass luokittelu.

Precision is rarely used in isolation, as it encourages selecting only the most likely tietopisteet. Still, unlike tarkkuus, precision remains a valid metric even with imbalanced tietoaineistot.

See also: sekaannusmatriisi, metric, herkkyys, luokittelu.

tehostus Boosting is an iterative optimointimenetelmä to learn an accurate hypoteesi kuvaus (or strong learner) by sequentially combining less accurate base learners (referred to as weak learners) [134], [135], [136], [63, Ch. 10]. Boosting can be understood as a yleistys of gradient-based methods for ERM using parametric models and smooth häviöfunktiot [107]. In particular, starting from an initialization \tilde{h} , boosting methods construct a sequence of hypoteesit $\tilde{h}^{(t)}$, $t = 1, \dots$, via a generalized gradienttiaskel

$$\tilde{h}^{(t)} = \tilde{h}^{(t-1)} + \eta^{(t)} \hat{h}^{(t)}.$$

Here, $\eta^{(t)}$ denotes a oppimisnopeus and $\hat{h}^{(t)}$ is provided by the t th base learner. Comparing the above update with the plain gradienttiaskel suggests that we view $\hat{h}^{(t)}$ as a (negative) generalized gradientti. Boosting methods differ in their choice of base learners for computing the generalized gradientit $\hat{h}^{(t)}$.

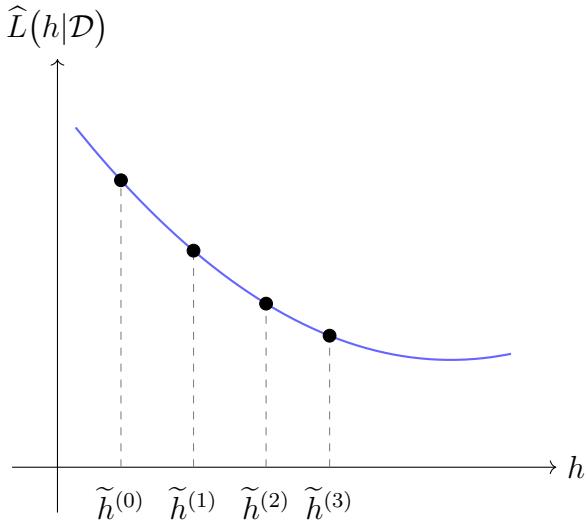


Fig. 122. Boosting methods construct a sequence of hypotheses via a generalized gradient step. This generalized gradient step uses the outputs of base learners.

See also: kooste, mukautuva tehostus, gradienttitehostus.

tekoäly AI refers to systems that behave rationally in the sense of maximizing a long-term reward. The kokeoppiminen-based approach to AI is to train a malli to predict optimal actions. These ennusteet are computed from observations about the state of the environment. The choice of häviöfunktio sets AI applications apart from more basic kokeoppiminen applications. AI systems rarely have access to a labeled opetusaineisto that allows the average häviö to be measured for any possible choice of model parameters. Instead, AI systems use observed reward signals to estimate the häviö incurred by the current choice of model parameters.

See also: koneoppiminen, vahvistusoppiminen.

testiaineisto A set of tietopisteet that have been used neither to train a malli (e.g., via ERM) nor to choose between different mallit in a validointiaineisto.

See also: tietopiste, malli, ERM, validointiaineisto.

tietoaineisto A dataset is a set of distinct tietopisteet. Strictly speaking, a dataset is an unordered collection of tietopisteet that does not contain any repetitions. However, in koneoppiminen literature, the term dataset is often used as a synonym for sample, i.e., a sequence (or finite list) of tietopisteet that may contain repetitions. Koneoppiminen methods use datasets for malli koulutus and validointi. The notion of a dataset is broad, i.e., tietopisteet may represent concrete physical entities (such as humans or animals) or abstract objects (such as numbers). For illustration, Fig. 123 depicts a dataset whose tietopisteet are cows.



Fig. 123. A cow herd somewhere in the Alps.

Quite often, an koneoppiminen engineer does not have direct access to the underlying dataset. For instance, accessing the dataset in Fig. 123 would require visiting the cow herd. In practice, we work with a more

convenient representation (or approximation) of the dataset. Various mathematical mallit have been developed for this purpose [175], [176], [177], [178]. One of the most widely used is the relational malli, which organizes data as a table (or relation) [175], [179]. A table consists of rows and columns, where each row corresponds to a single tietopiste, and each column represents a specific attribute of a tietopiste. Koneoppiminen methods typically interpret these attributes as piirteet or as a nimiö of a tietopiste. As an illustration, Table I shows a relational representation of the dataset from Fig. 123. In the relational malli, the order of rows is immaterial, and each attribute (i.e., column) is associated with a domain that specifies the set of admissible values. In koneoppiminen applications, these attribute domains correspond to the piirreavaruus and the label space.

TABLE I

A RELATION (OR TABLE) THAT REPRESENTS THE DATASET IN FIG. 123

Name	Weight	Age	Height	Stomach temperature
Zenzi	100	4	100	25
Berta	140	3	130	23
Resi	120	4	120	31

While the relational malli is useful for the study of many koneoppiminen applications, it may be insufficient regarding the requirements for luo-tettava tekoäly. Modern approaches like datasheets for datasets provide more comprehensive documentation, including details about the data

collection process, intended use, and other contextual information [180].

See also: tietopiste, sample, data, piirre, piirreavaruus, label space.

tietojen korruptointi Data poisoning refers to the intentional manipulation (or fabrication) of tietopisteet to maliciously steer the koulutus of an koneoppiminen malli [90], [91]. Data poisoning hyökkäykset take various forms, including takaportti and palvelunestohyökkäykset. A takaportti hyökkäys implants triggers into koulutus data, so that the trained malli behaves normally for typical tietopisteet but misclassifies a tietopiste with a piirrevektori that contains a trigger pattern. A palvelunestohyökkäys degrades the trained malli's overall performance by injecting mislabeled or adversarial examples to prevent effective learning. Data poisoning is particularly harmful in decentralized or distributed koneoppiminen settings (such as federotu oppiminen), where koulutus data cannot be centrally verified.

See also: hyökkäys, takaportti, palvelunestohyökkäys, luotettava teköäly.

tietomatriisi Katso datamatriisi.

tietopiste A data point is any object that conveys information [30]. Examples include students, radio signals, trees, images, satunnaismuuttujat, real numbers, or proteins. We describe data points of the same type by two categories of properties. The first category includes piirteet that are measurable or computable properties of a data point. These attributes can be automatically extracted or computed using sensors, computers, or other data collection systems. For a data point that represents a patient, one piirre could be the body weight. The second category includes

nimiöt that are higher level facts (or quantities of interest)—that is, facts that typically require human expertise or domain knowledge to determine rather than being directly measurable—associated with the data point. For a data point that represents a patient, a cancer diagnosis provided by a physician would serve as the nimiö. Fig. 124 depicts an image as an example of a data point along with its piirteet and nimiöt. Importantly, what constitutes a piirre or a nimiö is not inherent to the data point itself—it is a design choice that depends on the specific koneoppiminen application.



A single data point.

Piirteet:

- x_1, \dots, x_d : Color intensities of all image pixels.
- x_{d+1} : Time-stamp of the image capture.
- x_{d+2} : Spatial location of the image capture.

Nimiöt:

- y_1 : Number of cows depicted.
- y_2 : Number of wolves depicted.
- y_3 : Condition of the pasture (e.g., healthy, overgrazed).

Fig. 124. Illustration of a data point consisting of an image. We can use different properties of the image as piirteet and higher level facts about the image as nimiöt.

The distinction between piirteet and nimiöt is not always clear-cut. A property that is considered a nimiö in one setting (e.g., a cancer diagnosis) may be treated as a piirre in another setting—particularly if reliable automation (e.g., via image analysis) allows it to be computed without human intervention. Koneoppiminen broadly aims to predict the nimiö of a data point based on its piirteet.

See also: data, piirre, nimiö, tietoaineisto.

tilastolliset ominaisuudet By statistical aspects of an koneoppiminen method, we refer to (properties of) the todennäköisyysjakauma of its output under a todennäköisyysmalli for the data fed into the method.

See also: koneoppiminen, todennäköisyysjakauma, todennäköisyysmalli, data.

todennäköisyys We assign a probability value, typically chosen in the interval $[0, 1]$, to each event that can occur in a satunnaiskoe [6], [7], [50], [19].

See also: event, satunnaiskoe.

toteuma Consider a satunnaismuuttuja \mathbf{x} that maps each outcome $\omega \in \Omega$ of a probability space to an element a of a measurable space \mathcal{N} [2], [6], [50]. A realization of \mathbf{x} is any element $\mathbf{a} \in \mathcal{N}$ such that there exists an element $\omega' \in \Omega$ with $\mathbf{x}(\omega') = \mathbf{a}$.

See also: satunnaismuuttuja, outcome, probability space, measurable.

tukivektorikone The SVM is a binary luokittelu method that learns a linear hypoteesi kuvaus. Thus, like lineaarinen regressio and logistinen regressio, it is also an instance of ERM for the lineaarinen malli. However,

the SVM uses a different häviöfunktio from the one used in those methods. As illustrated in Fig. 125, it aims to maximally separate tietopisteet from the two different classes in the piirreavaruus (i.e., maksimi margin principle). Maximizing this separation is equivalent to minimizing a regularized variant of the hinge loss (18) [47], [112], [181].

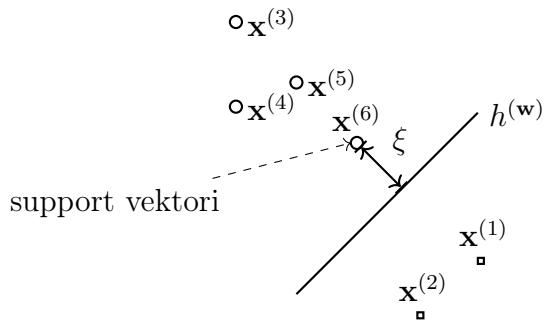


Fig. 125. The SVM learns a hypoteesi (or luokitin) $h^{(w)}$ with minimal average soft-margin hinge loss. Minimizing this häviö is equivalent to maximizing the margin ξ between the päätöspinta of $h^{(w)}$ and each class of the opetusaineisto.

The above basic variant of SVM is only useful if the tietopisteet from different categories can be (approximately) linearly separated. For an koneoppiminen application where the categories are not derived from a ydinfunktio.

See also: luokittelu, lineaarinen malli, luokitin, hinge loss.

tulkittavuus An koneoppiminen method is interpretable for a human user if they can comprehend the decision process of the method. One approach to develop a precise definition of interpretability is via the concept of simulatability, i.e., the ability of a human to mentally simulate the

malli behavior [164], [166], [182], [183], [184]. The idea is as follows: If a human user understands an *koneoppiminen* method, then they should be able to anticipate its ennusteet on a *testiaineisto*. We illustrate such a *testiaineisto* in Fig. 126, which also depicts two learned hypothesesit \hat{h} and \hat{h}' . The *koneoppiminen* method producing the hypoteesi \hat{h} is interpretable to a human user familiar with the concept of a lineaarikuvaus. Since \hat{h} corresponds to a lineaarikuvaus, the user can anticipate the ennusteet of \hat{h} on the *testiaineisto*. In contrast, the *koneoppiminen* method delivering \hat{h}' is not interpretable, because its behavior is no longer aligned with the user's odotusarvot.

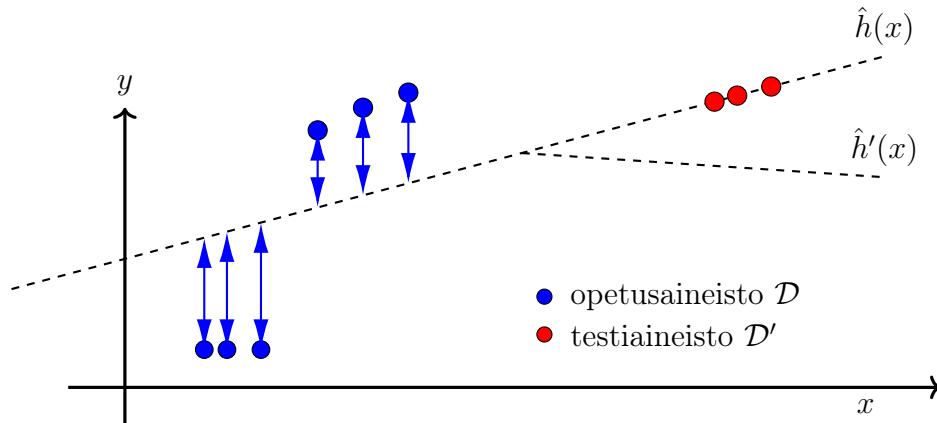


Fig. 126. We can assess the interpretability of trained *koneoppiminen* mallit \hat{h} and \hat{h}' by comparing their ennusteet to pseudo-nimiöt generated by a human user for \mathcal{D}' .

The notion of interpretability is closely related to the notion of selittävyys, as both aim to make *koneoppiminen* methods more understandable

for humans. In the context of Fig. 126, interpretability of an koneoppiminen method \hat{h} requires that the human user can anticipate its ennusteet on an arbitrary testiaineisto. This contrasts with selitettävyys, where the user is supported by external selitteet—such as saliency kuvaukset or reference examples from the opetusaineisto—to understand the ennusteet of \hat{h} on a specific testiaineisto \mathcal{D}' .

See also: selitettävyys, luotettava tekooäly, regularisointi, LIME.

tulos Katso vaste.

tuotos The term output is sometimes used as a synonym for the nimiö of a tietopiste [57].

See also: nimiö, tietopiste.

täsmällisyys Katso tarkkuus.

ulottuvuuksien vähentäminen Dimensionality reduction refers to methods that learn a transformation $h : \mathbb{R}^d \rightarrow \mathbb{R}^{d'}$ of a (typically large) set of raw piirteet x_1, \dots, x_d into a smaller set of informative piirteet $z_1, \dots, z_{d'}$. Using a smaller set of piirteet is beneficial in several ways:

- Statistical benefit: It typically reduces the riski of ylisovittaminen, as reducing the number of piirteet often reduces the effective dimension of a malli.
- Computational benefit: Using fewer piirteet means less computation for the koulutus of koneoppiminen mallit. As a case in point, lineaarinen regressio methods need to invert a matriisi whose size is determined by the number of piirteet.

- Visualization: Dimensionality reduction is also instrumental for data visualization. For example, we can learn a transformation that delivers two piirteet z_1, z_2 , which we can use, in turn, as the coordinates of a hajontakuvio. Fig. 127 depicts the hajontakuvio of handwritten digits that are placed using transformed piirteet. Here, the tietopisteet are naturally represented by a large number of greyscale values (one value for each pixel).

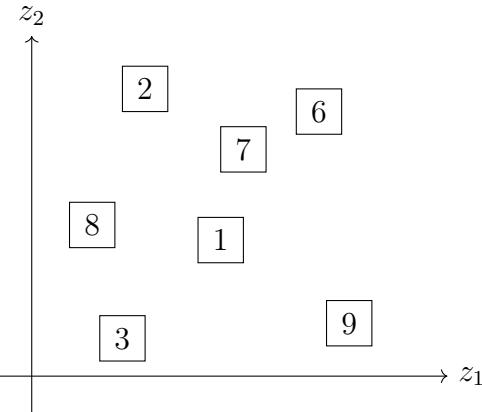


Fig. 127. Example of dimensionality reduction: High-dimensional image data (e.g., high-resolution images of handwritten digits) embedded into 2-D using learned piirteet (z_1, z_2) and visualized in a hajontakuvio.

See also: ylisovittaminen, autoenkoodaaja, random projection, PCA, JL lemma.

upper confidence bound (UCB) Consider an koneoppiminen application that requires selecting, at each time step t , an action a_t from a finite set of alternatives \mathcal{A} . The utility of selecting action a_t is quantified

by a numeric reward signal $r^{(a_t)}$. A widely used todennäköisyysmalli for this type of sequential decision-making problem is the stokastinen monikäinen rosvo setting [146]. In this malli, the reward $r^{(a)}$ is viewed as the toteuma of a satunnaismuuttuja with unknown kesiarvo $\mu^{(a)}$. Ideally, we would always choose the action with the largest expected reward $\mu^{(a)}$, but these kesiarvot are unknown and must be estimated from observed data. Simply choosing the action with the largest estimate $\hat{\mu}^{(a)}$ can lead to suboptimal outcomes due to estimation epävarmuus. The UCB strategy addresses this by selecting actions not only based on their estimated kesiarvot but also by incorporating a term that reflects the epävarmuus in these estimates—favoring actions with a high-potential reward and high epävarmuus. Theoretical guarantees for the performance of UCB strategies, including logarithmic regret bounds, are established in [146].

See also: optimism in the face of uncertainty, reward, monikäinen rosvo, epävarmuus, regret.

uusio-otanta For the analysis of koneoppiminen methods, it is often useful to interpret a given tietoaineisto $\mathcal{D} = \{\mathbf{z}^{(1)}, \dots, \mathbf{z}^{(m)}\}$ as a collection of (toteumat of) i.i.d. satunnaismuuttujat with common todennäköisyysjakauma \mathbb{P} . In practice, the todennäköisyysjakauma \mathbb{P} is unknown and must be estimated from \mathcal{D} . The idea of the bootstrap method is to use the empirical distribution $\mathbb{P}^{(\mathcal{D})}$ of \mathcal{D} as an estimator for \mathbb{P} [63],

$$(1/m)|r : \mathbf{z}^{(r)} \in \mathcal{A}| \approx \mathbb{P}(\mathcal{A}).$$

Repeatedly sampling from the empirical distribution, which is equivalent

to sampling with replacement from \mathcal{D} [185], results in new tietoaineistot $\mathcal{D}^{(1)}, \dots, \mathcal{D}^{(B)}$, each containing m tietopisteet. We then use each of those tietoaineistot for malli koulutus (e.g., via ERM), resulting in the learned hypoteesit $\hat{h}^{(1)}, \dots, \hat{h}^{(B)}$. We can use these learned hypoteesit to estimate important characteristics of an koneoppiminen method such as harha, varianssi, or generalization gap [63].

See also: i.i.d., satunnaismuuttuja, todennäköisyysjakauma, histogrammi.

uusioaggregointi Katso laukutus.

vahvistusaineisto Katso validointiaineisto.

vakaus Robustness is a key requirement for luotettava tekoäly. It refers to the property of an koneoppiminen system to maintain acceptable performance even when subjected to different forms of perturbations. These perturbations may affect the piirteet of a tietopiste in order to manipulate the ennuste delivered by a trained koneoppiminen malli. Robustness also includes the stability of ERM-based methods against perturbations of the opetusaineisto. Such perturbations can occur within tietojen korruptointi hyökkäykset.

See also: luotettava tekoäly, stability, tietojen korruptointi, hyökkäys.

validointi Consider a hypoteesi \hat{h} that has been learned via some koneoppiminen method, e.g., by solving ERM on a opetusaineisto \mathcal{D} . Validation refers to the process of evaluating the häviö incurred by the hypoteesi \hat{h} on a set of tietopisteet that are not contained in the opetusaineisto

\mathcal{D} . This set of tietopisteet is called the validointiaineisto. The average häviö of \hat{h} on the validointiaineisto is referred to as the validointivirhe. An example of validation is shown in Fig. 128.

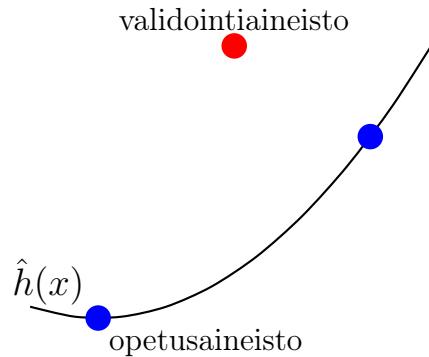


Fig. 128. Illustration of validation. The blue points represent the tietopisteet in the opetusaineisto, while the red point represents a tietopiste in the validointiaineisto. The hypoteesi \hat{h} (black curve) fits the tietopisteet in the opetusaineisto perfectly, but incurs a large häviö on the tietopiste in the validointiaineisto.

See also: opetusaineisto, validointiaineisto, validointivirhe, ylisovittamien, yleistys, k -kertainen ristiinvalidointi, yksi-pois-ristiinvalidointi.

validointiaineisto A set of tietopisteet used to estimate the riski of a hypoteesi \hat{h} that has been learned by some koneoppiminen method (e.g., solving ERM). The average häviö of \hat{h} on the validointi set is referred to as the validointivirhe and can be used to diagnose an koneoppiminen method (see [8, Sec. 6.6]). The comparison between opetusvirhe and validointivirhe can inform directions for the improvement of the koneoppiminen method (such as using a different hypothesis space).

See also: tietopiste, riski, hypoteesi, koneoppiminen, ERM, häviö, valiointi, valiointivirhe, opetusvirhe, hypothesis space, k -kertainen riitivaliointi, yksi-pois-ristiivaliointi.

valiointivirhe Consider a hypoteesi \hat{h} that is obtained by some koneoppiminen method, e.g., using ERM on a opetusaineisto. The average häviö of \hat{h} on a valiointiaineisto, which is different from the opetusaineisto, is referred to as the valiointi error.

See also: hypoteesi, koneoppiminen, ERM, opetusaineisto, häviö, valiointiaineisto, valiointi.

Vapnik–Chervonenkis dimension (VC dimension) The statistical properties of an ERM-based method depend critically on the expressive capacity of its hypothesis space (or malli) \mathcal{H} . A standard measure of this capacity is the VC dimension $\text{VCdim}(\mathcal{H})$ [186]. Formally, it is the largest integer m such that there exists a tietoaineisto $\mathcal{D} = \{\mathbf{x}^{(1)}, \dots, \mathbf{x}^{(m)}\} \subseteq \mathcal{X}$ that can be perfectly classified (or shattered) by some $h \in \mathcal{H}$. Formally, this means that for every one of the 2^m possible assignments of binary nimiöt to each piirrevektori in \mathcal{D} , there exists some hypoteesi $h \in \mathcal{H}$ that realizes this labeling. Intuitively, the VC dimension quantifies how well \mathcal{H} can fit arbitrary nimiö assignments, and thus captures its approximate power. It plays a central role in deriving bounds on the generalization gap. Fig. 129 illustrates the definition of the VC dimension for a lineaarinen malli $\mathcal{H}^{(2)}$ with $d = 2$ piirteet. Fig. 129(a) and 129(b) show the same set of three noncollinear piirrevektorit under two different binary labelings. In both cases, a

separating hyperplane exists that realizes the labeling. Since this holds for all $2^3 = 8$ possible binary labelings of the three piirrevektorit, the set is shattered. Fig. 129(c) depicts four piirrevektorit with a specific labeling. No linear separator can correctly classify all tietopisteet in this case. Thus, $\text{VCdim}(\mathcal{H}^{(2)}) = 3$.

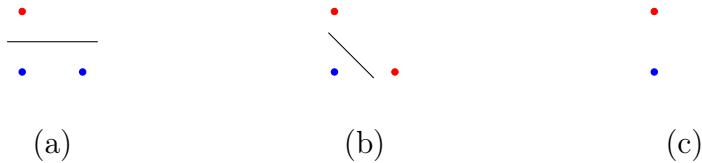


Fig. 129. Illustration of the VC dimension for a lineaarinen malli $\mathcal{H}^{(2)}$ that is used to learn a lineaarinen luokitin in the piirreavaruus \mathbb{R}^2 .

More generally, for a lineaarinen malli $\mathcal{H}^{(d)}$, the VC dimension equals $d+1$. In other words, for lineaariset mallit, the VC dimension essentially matches the dimension of the underlying parameter space \mathbb{R}^d . For more complex hypothesis spaces, such as päättöspuut or neuroverkot, the relation between VC dimension and the dimension of the piirreavaruus is far less direct. In these cases, alternative complexity measures, such as the Rademacher complexity, can be more useful for analyzing ERM-based methods.

See also: hypothesis space, Rademacher complexity, yleistys, koneoppiminen, effective dimension.

vastaus Katso vaste.

vaste The term response is sometimes used as a synonym for the nimiö of a tietopiste [63].

See also: nimiö, tietopiste, target.

vertailutaso Consider some koneoppiminen method that produces a learned hypoteesi (or trained malli) $\hat{h} \in \mathcal{H}$. We evaluate the quality of a trained malli by computing the average häviö on a testiaineisto. But how can we assess whether the resulting testiaineisto performance is sufficiently good? How can we determine if the trained malli performs close to optimal such that there is little point in investing more resources (for data collection or computation) to improve it? To this end, it is useful to have a reference (or baseline) level against which we can compare the performance of the trained malli.

Such a reference value might be obtained from human performance, e.g., the misclassification rate of dermatologists who diagnose cancer from visual inspection of skin [187]. Another source for a baseline is an existing, but for some reason unsuitable, koneoppiminen method. For example, the existing koneoppiminen method might be computationally too expensive for the intended koneoppiminen application. Nevertheless, its testiaineisto error can still serve as a baseline. Another, somewhat more principled, approach to constructing a baseline is via a todennäköisyysmalli. In many cases, given a todennäköisyysmalli $p(\mathbf{x}, y)$, we can precisely determine the minimi achievable riski among any hypoteesit (not even required to belong to the hypothesis space \mathcal{H}) [51].

This minimi achievable riski (referred to as the Bayes risk) is the riski of the Bayes estimator for the nimiö y of a tietopiste, given its piirteet

x. Note that, for a given choice of häviöfunktio, the Bayes estimator (if it exists) is completely determined by the todennäköisyysjakauma \mathbb{P} [51, Ch. 4]. However, computing the Bayes estimator and Bayes risk presents two main challenges. First, the todennäköisyysjakauma \mathbb{P} is unknown and must be estimated from observed data. Second, even if \mathbb{P} were known, computing the Bayes risk exactly may be computationally infeasible [188]. A widely used todennäköisyysmalli is the moninormaalijakauma $(\mathbf{x}, y) \sim \mathcal{N}(\boldsymbol{\mu}, \boldsymbol{\Sigma})$ for tietopisteet characterized by numeric piirteet and nimiöt. Here, for the neliövirhehäviö, the Bayes estimator is given by the posterior keskiarvo $\mu_{y|\mathbf{x}}$ of the nimiö y , given the piirteet \mathbf{x} [17], [51]. The corresponding Bayes risk is given by the posterior varianssi $\sigma_{y|\mathbf{x}}^2$ (see Fig. 130).

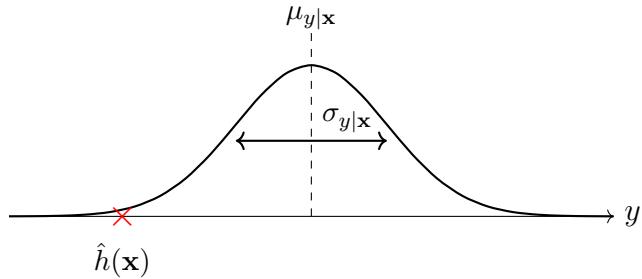


Fig. 130. If the piirteet and the nimiö of a tietopiste are drawn from a moninormaalijakauma, we can achieve the minimi riski (under neliövirhehäviö) by using the Bayes estimator $\mu_{y|\mathbf{x}}$ to predict the nimiö y of a tietopiste with piirteet \mathbf{x} . The corresponding minimi riski is given by the posterior varianssi $\sigma_{y|\mathbf{x}}^2$. We can use this quantity as a baseline for the average häviö of a trained malli \hat{h} .

See also: Bayes risk, Bayes estimator.

vertical federated learning (VFL) In VFL, different devices have access to different piirteet of the same set of tietopisteet [189]. Formally, the underlying global tietoaineisto is

$$\mathcal{D}^{(\text{global})} := \{ (\mathbf{x}^{(1)}, y^{(1)}) , \dots, (\mathbf{x}^{(m)}, y^{(m)}) \} .$$

We denote by $\mathbf{x}^{(r)} = (x_1^{(r)}, \dots, x_{d'}^{(r)})^T$, for $r = 1, \dots, m$, the complete piirrevektorit for the tietopisteet. Each device $i \in \mathcal{V}$ observes only a subset $\mathcal{F}^{(i)} \subseteq \{1, \dots, d'\}$ of piirteet, resulting in a local dataset $\mathcal{D}^{(i)}$ with piirrevektorit

$$\mathbf{x}^{(i,r)} = (x_{j_1}^{(r)}, \dots, x_{j_d}^{(r)})^T .$$

Some of the devices may also have access to the nimiöt $y^{(r)}$, for $r = 1, \dots, m$, of the global tietoaineisto (see Fig. 131).

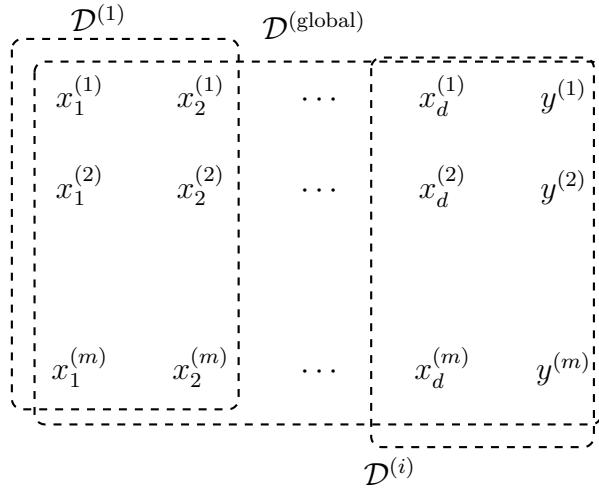


Fig. 131. VFL uses local datasets that are derived from the tietopisteet of a common global tietoaineisto. The local datasets differ in the choice of piirteet used to characterize the tietopisteet.

One potential application of VFL is to enable collaboration between different healthcare providers. Each provider collects distinct types of measurements—such as blood values, electrocardiography, and lung X-rays—for the same patients. Another application is a national social insurance system, where health records, financial indicators, consumer behavior, and mobility data are collected by different institutions. VFL enables joint learning across these parties while allowing well-defined levels of yksityisyyden suoja. We can view VFL as a specific form of model parallelism.

See also: yksityisyyden suoja, federoitut oppiminen, model parallelism.

vianetsintä Consider an ERM-based method that resulted in a trained malli

(or learned hypothesis) $\hat{h} \in \mathcal{H}$. We can diagnose the method by comparing the opetusvirhe E_t with the validointivirhe E_v incurred by \hat{h} on the opetusaineisto and the validointiaineisto.

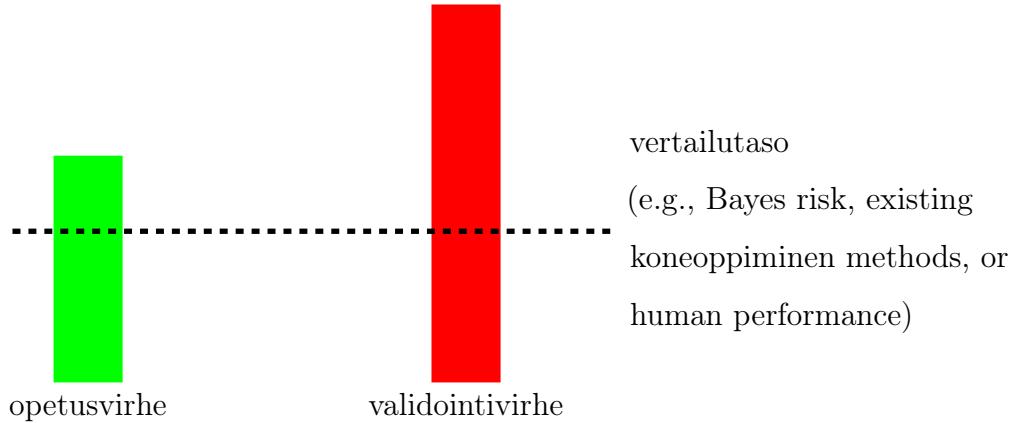


Fig. 132. We can diagnose an ERM-based koneoppiminen method by comparing its opetusvirhe with its validointivirhe. Ideally, both are on the same level as a vertailutaso.

See also: vertailutaso, validointi, k -kertainen ristiinvalidointi, yleistys.

weight Consider a parameterized hypothesis space \mathcal{H} . We use the term weights for numeric model parameters that are used to scale piirteet or their transformations in order to compute $h^{(\mathbf{w})} \in \mathcal{H}$. A lineaarinen malli uses weights $\mathbf{w} = (w_1, \dots, w_d)^T$ to compute the linear combination $h^{(\mathbf{w})}(\mathbf{x}) = \mathbf{w}^T \mathbf{x}$. Weights are also used in neuroverkot to form linear combinations of piirteet or the outputs of neurons in hidden layers (see Fig. 133).

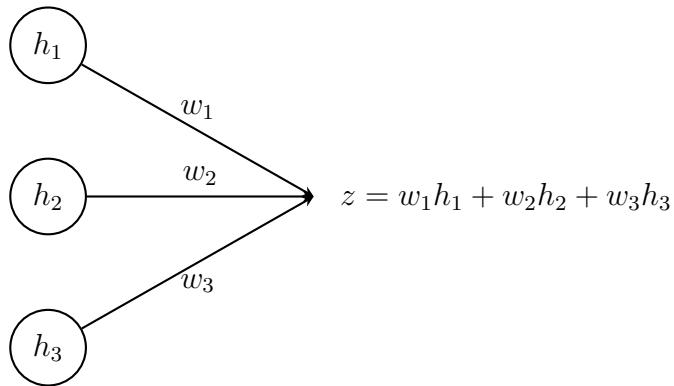


Fig. 133. A section of an neuroverkko that contains a hidden layer with outputs (or activations) h_1, h_2 , and h_3 . These outputs are combined linearly to compute z , which can be used either as output of the neuroverkko or as input to another layer.

See also: hypothesis space, model parameters, piirre, lineaarinen malli, neuroverkko, layer, activation.

ydinfunktio Consider a set of tietopisteet, each represented by a piirrevektori $\mathbf{x} \in \mathcal{X}$, where \mathcal{X} denotes the piirreavaruus. A (real-valued) kernel is a funktion $K : \mathcal{X} \times \mathcal{X} \rightarrow \mathbb{R}$ that assigns to every pair of piirrevektorit $\mathbf{x}, \mathbf{x}' \in \mathcal{X}$ a real number $K(\mathbf{x}, \mathbf{x}')$. This value is typically interpreted as a similarity measure between \mathbf{x} and \mathbf{x}' . The defining property of a kernel is that it is symmetric, i.e., $K(\mathbf{x}, \mathbf{x}') = K(\mathbf{x}', \mathbf{x})$, and that for

any finite set of piirrevektoit $\mathbf{x}_1, \dots, \mathbf{x}_n \in \mathcal{X}$, the matriisi

$$\mathbf{K} = \begin{pmatrix} K(\mathbf{x}_1, \mathbf{x}_1) & K(\mathbf{x}_1, \mathbf{x}_2) & \dots & K(\mathbf{x}_1, \mathbf{x}_n) \\ K(\mathbf{x}_2, \mathbf{x}_1) & K(\mathbf{x}_2, \mathbf{x}_2) & \dots & K(\mathbf{x}_2, \mathbf{x}_n) \\ \vdots & \vdots & \ddots & \vdots \\ K(\mathbf{x}_n, \mathbf{x}_1) & K(\mathbf{x}_n, \mathbf{x}_2) & \dots & K(\mathbf{x}_n, \mathbf{x}_n) \end{pmatrix} \in \mathbb{R}^{n \times n}$$

is psd. A kernel naturally defines a transformation of a piirrevektori \mathbf{x} into a funktilo $\mathbf{z} = K(\mathbf{x}, \cdot)$. The funktilo \mathbf{z} maps an input $\mathbf{x}' \in \mathcal{X}$ to the value $K(\mathbf{x}, \mathbf{x}')$. We can view the funktilo \mathbf{z} as a new piirrevektori that belongs to a piirreavaruus \mathcal{X}' that is typically different from \mathcal{X} . This new piirreavaruus \mathcal{X}' has a particular mathematical structure, i.e., it is a reproducing kernel Hilbert space (RKHS) [60], [112]. Since \mathbf{z} belongs to a RKHS, which is a vektoriavaruus, we can interpret it as a generalized piirrevektori. Note that a finite-length piirrevektori $\mathbf{x} = (x_1, \dots, x_d)^T \in \mathbb{R}^d$ can be viewed as a funktilo $\mathbf{x} : \{1, \dots, d\} \rightarrow \mathbb{R}$ that assigns a real value to each index $j \in \{1, \dots, d\}$.

See also: piirrevektori, piirreavaruus, Hilbert space, ydinmenetelmä.

ydinmenetelmä A ydinfunktio method is an koneoppiminen method that uses a ydinfunktio K to map the original (i.e., raw) piirrevektori \mathbf{x} of a tietopiste to a new (transformed) piirrevektori $\mathbf{z} = K(\mathbf{x}, \cdot)$ [60], [112]. The motivation for transforming the piirrevektorit is that, by using a suitable ydinfunktio, the tietopisteet have a more "pleasant" geometry in the transformed piirreavaruus. For example, in a binary luokittelu problem, using transformed piirrevektorit \mathbf{z} might allow us to use lineaariset mallit, even if the tietopisteet are not linearly separable in the original piirreavaruus (see Fig. 134).

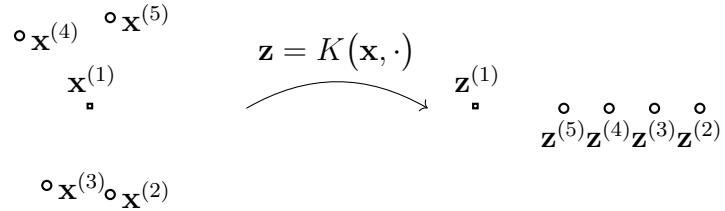


Fig. 134. Five tietopisteet characterized by piirrevektorit $\mathbf{x}^{(r)}$ and nimiöt $y^{(r)} \in \{\circ, \square\}$, for $r = 1, \dots, 5$. With these piirrevektorit, there is no way to separate the two classes by a straight line (representing the päätöspinta of a lineaarinen luokitin). In contrast, the transformed piirrevektorit $\mathbf{z}^{(r)} = K(\mathbf{x}^{(r)}, \cdot)$ allow us to separate the tietopisteet using a lineaarinen luokitin.

See also: ydinfunktio, piirrevektori, piirreavaruus, lineaarinen luokitin.

yksi-pois-ristiinvalidointi A special case of the k -kertainen ristiinvalidointi where the validointiaineisto is size one, i.e. the validointiaineisto is only a single tietopiste.

See also: k -kertainen ristiinvalidointi, validointi, validointivirhe.

yksityisyyden suoja Consider some koneoppiminen method \mathcal{A} that reads in a tietoaineisto \mathcal{D} and delivers some output $\mathcal{A}(\mathcal{D})$. The output could be the learned model parameters $\hat{\mathbf{w}}$ or the ennuste $\hat{h}(\mathbf{x})$ obtained for a specific tietopiste with piirteet \mathbf{x} . Many important koneoppiminen applications involve tietopisteet representing humans. Each tietopiste is characterized by piirteet \mathbf{x} , potentially a nimiö y , and a sensitive attribute s (e.g., a recent medical diagnosis). Roughly speaking, privacy protection means that it should be impossible to infer, from the output

$\mathcal{A}(\mathcal{D})$, any of the sensitive attributes of tietopisteet in \mathcal{D} . Mathematically, privacy protection requires non-invertibility of the kuvaus $\mathcal{A}(\mathcal{D})$. In general, just making $\mathcal{A}(\mathcal{D})$ non-invertible is typically insufficient for privacy protection. We need to make $\mathcal{A}(\mathcal{D})$ sufficiently non-invertible. See also: koneoppiminen, tietoaineisto, model parameter, ennuste, tietopiste, piirre, nimiö, sensitive attribute, kuvaus.

yksityisyyshyökkäys A privacy hyökkäys on an koneoppiminen system aims to infer sensitive attributes of individuals by exploiting partial access to a trained koneoppiminen malli. One form of a privacy hyökkäys is model inversion.

See also: hyökkäys, sensitive attribute, model inversion, luotettava teköäly, GDPR.

yleistys Generalization refers to the ability of a malli trained on a opetusaineisto to make accurate ennusteet on new unseen tietopisteet. This is a central goal of koneoppiminen and teköäly, i.e., to learn patterns that extend beyond the opetusaineisto. Most koneoppiminen systems use ERM to learn a hypoteesi $\hat{h} \in \mathcal{H}$ by minimizing the average häviö over a opetusaineisto of tietopisteet $\mathbf{z}^{(1)}, \dots, \mathbf{z}^{(m)}$, which is denoted by $\mathcal{D}^{(\text{train})}$. However, success on the opetusaineisto does not guarantee success on unseen data—this discrepancy is the challenge of generalization. To study generalization mathematically, we need to formalize the notion of “unseen” data. A widely used approach is to assume a todennäköisyysmalli for data generation, such as the i.i.d. olettamus. Here, we interpret tietopisteet as independent satunnaismuuttujat with an iden-

tical todennäköisyysjakauma $p(\mathbf{z})$. This todennäköisyysjakauma, which is assumed fixed but unknown, allows us to define the riski of a trained malli \hat{h} as the expected häviö

$$\bar{L}(\hat{h}) = \mathbb{E}_{\mathbf{z} \sim p(\mathbf{z})} \{ L(\hat{h}, \mathbf{z}) \}.$$

The difference between riski $\bar{L}(\hat{h})$ and empiirinen riski $\widehat{L}(\hat{h}|\mathcal{D}^{(\text{train})})$ is known as the generalization gap. Tools from todennäköisyys theory, such as concentration inequalities and uniform convergence, allow us to bound this gap under certain conditions [145].

Generalization without todennäköisyys: Todennäköisyys theory is one way to study how well a malli generalizes beyond the opetusaineisto, but it is not the only way. Another option is to use simple deterministic changes to the tietopisteet in the opetusaineisto. The basic idea is that a good malli \hat{h} should be robust, i.e., its ennuste $\hat{h}(\mathbf{x})$ should not change much if we slightly change the piirteet \mathbf{x} of a tietopiste \mathbf{z} . For example, an object detector trained on smartphone photos should still detect the object if a few random pixels are masked [190]. Similarly, it should deliver the same result if we rotate the object in the image [150]. See Fig. 135 for a visual illustration.

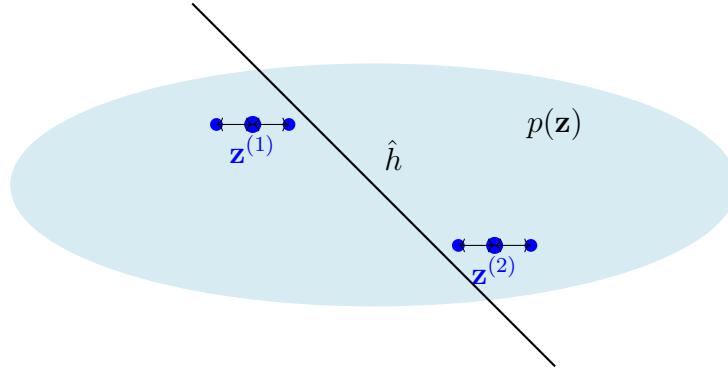


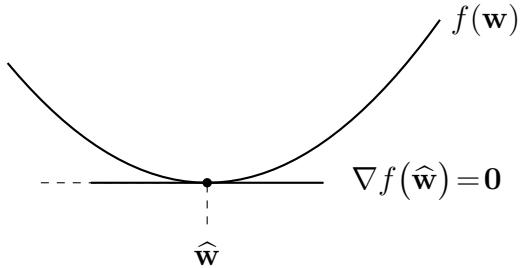
Fig. 135. Two tietopisteet $\mathbf{z}^{(1)}, \mathbf{z}^{(2)}$ that are used as a opetusaineisto to learn a hypoteesi \hat{h} via ERM. We can evaluate \hat{h} outside $\mathcal{D}^{(\text{train})}$ either by an i.i.d. olettamus with some underlying todennäköisyysjakauma $p(\mathbf{z})$ or by perturbing the tietopisteet.

See also: ERM, i.i.d. olettamus, ylisovittaminen, validointi.

ylisovittaminen Consider an koneoppiminen method that uses ERM to learn a hypoteesi with the minimi empiirinen riski on a given opetusaineisto. Such a method is overfitting the opetusaineisto if it learns a hypoteesi with a empiirinen riski on the opetusaineisto that a significantly smaller than the average häviö outside the opetusaineisto. In other words, if a koneoppiminen method overfits it has a large generalization gap.

See also: ERM, yleistys, validointi, generalization gap.

zero-gradient condition Consider the unconstrained optimointitehtävä $\min_{\mathbf{w} \in \mathbb{R}^d} f(\mathbf{w})$ with a smooth and convex kohdefunktio $f(\mathbf{w})$. A necessary and sufficient condition for a vektori $\hat{\mathbf{w}} \in \mathbb{R}^d$ to solve this problem



is that the gradientti $\nabla f(\hat{\mathbf{w}})$ is the zero vektori $\nabla f(\hat{\mathbf{w}}) = \mathbf{0}$. In other words [22, p. 140],

$$\nabla f(\hat{\mathbf{w}}) = \mathbf{0} \Leftrightarrow f(\hat{\mathbf{w}}) = \min_{\mathbf{w} \in \mathbb{R}^d} f(\mathbf{w}).$$

By defining the gradientti operator $\nabla f : \mathbb{R}^d \rightarrow \mathbb{R}^d$, we can rewrite the zero-gradient condition as a fixed-point equation

$$(\mathcal{I} - \alpha \nabla f)\hat{\mathbf{w}} = \hat{\mathbf{w}}.$$

Here, \mathcal{I} denotes the identity operator (i.e., $\mathcal{I}(\mathbf{w}) = \mathbf{w}$) and α is an arbitrary positive number.

See also: optimointitehtävä, smooth, convex, kohdefunktio, vektori, gradientti.

Reinforcement Learning

action An action refers to a decision taken by an tekoäly system at a given time step t that influences the observed reward signal. The actions are elements of an action space \mathcal{A} and are typically denoted by $a_t \in \mathcal{A}$. The action a_t is selected based on the piirrevektori $\mathbf{x}^{(t)}$ (that collects all available observations) and the current hypoteesi $h^{(t)}$. RL uses online learning methods to learn a hypoteesi $h^{(t)}$ that predicts an (nearly) optimal action. The usefulness of the ennuste a_t is evaluated indirectly through the resulting reward signal $r^{(t)}$. In the special case of a monikätinen rosvo, the set of possible actions is finite and each action corresponds to selecting one arm. In more general RL settings, the action space may be continuous.

See also: vahvistusoppiminen, reward, häviöfunktio, monikätinen rosvo, hypoteesi.

action space See action.

Markov decision process (MDP) An MDP is a mathematical structure for the study of vahvistusoppiminen. Formally, an MDP is a satunnaisprosessi that is defined by a specific choice for

- a state space \mathcal{S} ;
- an action space \mathcal{A} ;
- a transition funktion $\mathbb{P}(s' | s, a)$ specifying the todennäköisyysjakauma over the next state $s' \in \mathcal{S}$, given the current state $s \in \mathcal{S}$ and action $a \in \mathcal{A}$;

- a reward funktion $r(s, a) \in \mathbb{R}$ that assigns a numerical reward to each state-action pair (s, a) .

These components define the todennäköisyysjakauma of a sequence

$$s_1, a_1, r_1, s_2, a_2, r_2, \dots, s_t, a_t, r_t$$

of satunnaismuuttujat. The defining property of an MDP is the Markov property. That is, at time instant t , the conditional probability distribution of the next state s_{t+1} and reward r_t depends on the past only via the current state s_t and action a_t .

See also: vahvistusoppiminen, satunnaisprosessi, funktion, todennäköisyysjakauma, reward, ennuste.

monikätinens rosvo An MAB problem is a precise formulation of a sequential decision-making task under epävarmuus. At each discrete time step t , a learner selects one of several possible actions—called arms—from a finite set \mathcal{A} . Pulling arm a at time t yields a reward $r^{(a,t)}$ that is drawn from an unknown todennäköisyysjakauma $\mathbb{P}(r^{(a,t)})$. We obtain different classes of MAB problems by placing different restrictions on this todennäköisyysjakauma. In the simplest setting, the todennäköisyysjakauma $\mathbb{P}(r^{(a,t)})$ does not depend on t . Given an MAB problem, the goal is to construct koneoppiminen methods that maximize the cumulative reward over time by strategically balancing exploration (i.e., gathering information about uncertain arms) and exploitation (i.e., selecting arms known to perform well). MAB problems form an important special case of vahvistusoppiminen problems [146], [157].

See also: reward, regret.

regret The regret of a hypoteesi h relative to another hypoteesi h' , which serves as a vertailutaso, is the difference between the häviö incurred by h and the häviö incurred by h' [99]. The vertailutaso hypoteesi h' is also referred to as an expert.

See also: vertailutaso, häviö, expert.

vahvistusoppiminen RL refers to an online learning setting where we can only evaluate the usefulness of a single hypoteesi (i.e., a choice of model parameters) at each time step t . In particular, RL methods apply the current hypoteesi $h^{(t)}$ to the piirrevektori $\mathbf{x}^{(t)}$ of the newly received tietopiste. The usefulness of the resulting ennuste $h^{(t)}(\mathbf{x}^{(t)})$ is quantified by a reward signal $r^{(t)}$ (see Fig. 136).

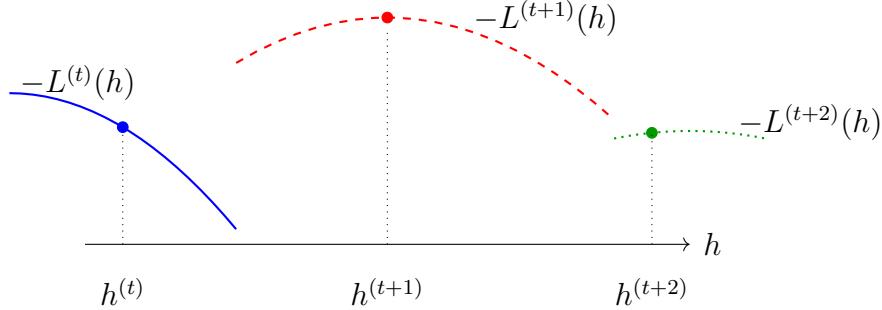


Fig. 136. Three consecutive time steps $t, t + 1, t + 2$ with corresponding häviöfunktiot $L^{(t)}, L^{(t+1)}, L^{(t+2)}$. During time step t , an RL method can evaluate the häviöfunktio only for one specific hypoteesi $h^{(t)}$, resulting in the reward signal $r^{(t)} = -L^{(t)}(h^{(t)})$.

In general, the reward depends also on the previous ennusteet $h^{(t')}\left(\mathbf{x}^{(t')}\right)$

for $t' < t$. The goal of RL is to learn $h^{(t)}$, for each time step t , such that the (possibly discounted) cumulative reward is maximized [8], [157].

See also: reward, häviöfunktio, koneoppiminen.

Machine Learning Systems

ML system An koneoppiminen system consists of computational devices that can gather and store data, execute algoritmit, and exchange information via communication networks. Examples of the exchanged information include data or updates of model parameters.

Machine Learning Regulation

artificial intelligence system (AI system) The EU Artificial Intelligence

Act (AI Act) [191] defines an *tekoäly* system as a machine-based system that is designed to operate with varying levels of autonomy and that may exhibit adaptiveness (e.g., *malli* retraining) after deployment. *Tekoäly* systems compute *ennusteet* that can influence environments or decisions [192]. In line with this definition, regulatory obligations and risk classifications apply at the level of the *tekoäly* system rather than at the level of individual *mallit* or *algoritmit*. The system-level view emphasizes that properties such as *vakaus*, fairness, and transparency emerge from the interaction of *mallit*, data, and operational context, rather than from isolated components.

See also: *tekoäly*, *vakaus*, *transparency*.

automated decision-making Koneoppiminen applications that use *ennustet* delivered by a trained *malli* directly (without human involvement)

to make decisions affecting individuals. Under the GDPR, individuals have the right not to be subject to decisions based solely on automated processing, when these decisions produce legal or similarly significant effects, unless appropriate safeguards (e.g., *human oversight*, *contestability*, or *explicit consent*) are implemented.

deepfake Deepfakes are synthetic media generated or substantially modified

by an artificial intelligence system (AI system) such that it falsely appears to depict a real person, object, or event. Deepfakes are typically produced using generative methods, trained to imitate visual, audio,

or audiovisual characteristics of real data. From a system perspective, deepfakes are characterized by a deliberate mismatch between the observable content and its true origin, which can lead to deception, misinformation, or manipulation. CITE relevant legal sources.

See also: AI system.

high-risk artificial intelligence system (high-risk AI system) A subset of AI systems is classified as high-risk due to its potential to significantly impact safety, fundamental rights, or critical societal functions. High-risk AI systems are subject to stringent regulatory requirements under the EU AI Act, including conformity assessments, risk management, transparency obligations, and post-market monitoring [192]. Examples of high-risk AI systems include those used in critical infrastructure, education, employment, law enforcement, and biometric identification.

See also: AI system, transparency.

personal data Personal data are any information relating to an identified or identifiable natural person (i.e., the data subject). A natural person is identifiable if they can be identified, directly or indirectly, in particular by reference to an identifier such as a name, an identification number, location data, an online identifier, or one or more factors specific to the physical, physiological, genetic, mental, economic, cultural, or social identity of that person [86]. In koneoppiminen systems, personal data may occur in koulutus data, malli inputs, intermediate representations (e.g., piirrevektorit or embeddings), or malli tuotokset, provided that the information relates to an identifiable natural person. The EU AI

Act does not introduce a separate definition of personal data; instead, whenever an AI system processes personal data, the GDPR definition and obligations apply in full.

See also: data, AI system, GDPR.

profiling Profiling aims at identifying patterns and make inferences about individuals based on their data. Profiling techniques use koneoppiminen methods to predict individuals' performance at work, economic situation, health or personal preferences. Profiling is instrumental in targeted advertising, credit scoring, fraud detection, and personalized services. The GDPR imposes strict requirements on organizations that engage in profiling activities to ensure that individuals' rights are protected [86].

See also: data, GDPR.

transparency Transparency is a fundamental requirement for luotettava teköäly [193]. In the context of koneoppiminen methods, transparency is often used interchangeably with selitettävyys [165], [194]. However, in the broader scope of teköäly systems, transparency extends beyond selitettävyys and includes providing information about the system's limitations, reliability, and intended use. In medical diagnosis systems, transparency requires disclosing the confidence level for the ennusteet delivered by a trained malli. In credit scoring, teköäly-based lending decisions should be accompanied by explanations of contributing factors, such as income level or credit history. These explanations allow humans (e.g., a loan applicant) to understand and contest automated decisions. Some koneoppiminen methods inherently offer transparency.

For example, logistinen regressio provides a quantitative measure of luokittelu reliability through the value $|h(\mathbf{x})|$. Päätöspuut are another example, as they allow human-readable decision rules [124]. Transparency also requires a clear indication when a user is engaging with an teköäly system. For example, teköäly-powered chatbots should notify users that they are interacting with an automated system rather than a human. Furthermore, transparency encompasses comprehensive documentation detailing the purpose and design choices underlying the teköäly system. For instance, malli datasheets [180] and teköäly system cards [195] help practitioners understand the intended use cases and limitations of an teköäly system [196].

See also: luotettava teköäly, selitettävyys.

Yleinen tietosuoja-asetus (GDPR) The GDPR was enacted by the EU, effective from 25 May 2018 [86]. It safeguards the privacy and data rights of individuals in the EU. The GDPR has significant implications for how data are collected, stored, and used in koneoppiminen applications. Key provisions include the following:

- Data minimization principle: koneoppiminen systems should only use the necessary amount of personal data for their purpose.
- Transparency and selitettävyys: koneoppiminen systems should enable their users to understand how the systems make decisions that impact the users.
- Data subject rights: Users should get an opportunity to access, rectify, and delete their personal data, as well as to object to

automated decision-making and profiling.

- Accountability: Organizations must ensure robust data security and demonstrate compliance through documentation and regular audits.

See also: data, koneoppiminen, data minimization principle, transparency, selitettävyys.

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