

Machine Learning: A Probabilistic Perspective Solution Manual Version 1.1

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Contents

1	Introduction	2
1.1	Constitution of this document	2
1.2	On <i>Machine Learning: A Probabilistic Perspective</i>	2
1.3	What is this document?	3
1.4	Updating log	5
2	Probability	6
2.1	Probability are sensitive to the form of the question that was used to generate the answer	6
2.2	Legal reasoning	6
2.3	Variance of a sum	6
2.4	Bayes rule for medical diagnosis	7
2.5	The Monty Hall problem(The dilemma of three doors)	7
2.6	Conditional Independence	7
2.7	Pairwise independence does not imply mutual independence	8
2.8	Conditional independence iff joint factorizes	8
2.9	Conditional independence*	9
2.10	Deriving the inverse gamma density	9
2.11	Normalization constant for a 1D Gaussian	9
2.12	Expressing mutual information in terms of entropies	10
2.13	Mutual information for correlated normals	10
2.14	A measure of correlation	10

2.15 MLE minimizes KL divergence to the empirical distribution .	11
2.16 Mean, mode, variance for the beta distribution	11
2.17 Expected value of the minimum	12
3 Generative models for discrete data	13
3.1 MLE for the Bernoulli/binomial model	13
3.2 Marginal likelihood for the Beta-Bernoulli model	13
3.3 Posterior predictive for Beta-Binomial model	14
3.4 Beta updating from censored likelihood	14
3.5 Uninformative prior for log-odds ratio	14
3.6 MLE for the Poisson distribution	15
3.7 Bayesian analysis of the Poisson distribution	15
3.8 MLE for the uniform distribution	15
3.9 Bayesian analysis of the uniform distribution	16
3.10 Taxicab problem*	16
3.11 Bayesian analysis of the exponential distribution	16
3.12 MAP estimation for the Bernoulli with non-conjugate priors*	17
3.13 Posterior predictive distribution for a batch of data with the Dirichlet-multinomial model	17
3.14 Posterior predictive for Dirichlet-multinomial*	17
3.15 Setting the hyper-parameters I^*	17
3.16 Setting the beta hyper-parameters II	17
3.17 Marginal likelihood for beta-binomial under uniform prior . .	18
3.18 Bayes factor for coin tossing*	18
3.19 Irrelevant features with naive Bayes	18
3.20 Class conditional densities for binary data	20
3.21 Mutual information for naive Bayes classifiers with binary features	20
3.22 Fitting a naive Bayesian spam filter by hand*	21
4 Gaussian models	22
4.1 Uncorrelated does not imply independent	22
4.2 Uncorrelated and Gaussian does not imply independent un- less jointly Gaussian	22

4.3	Correlation coefficient is between -1 and 1	22
4.4	Correlation coefficient for linearly related variables is 1 or -1 . . .	23
4.5	Normalization constant for a multidimensional Gaussian . . .	23
4.6	Bivariate Gaussian	23
4.7	Conditioning a bivariate Gaussian	23
4.8	Whitening vs standardizing	24
4.9	Sensor fusion with known variances in 1d	24
4.10	Derivation of information form formulae for marginalizing and conditioning	25
4.11	Derivation of the NIW posterior	25
4.12	26
4.13	Gaussian posterior credible interval	26
4.14	MAP estimation for 1d Gaussians	27
4.15	Sequential(recursive) updating of covariance matrix	28
4.16	Likelihood ratio for Gaussians	28
4.17	LDA/QDA on height/weight data	28
4.18	Naive Bayes with mixed features	28
4.19	Decision boundary for LDA with semi tied covariances	29
4.20	Logistic regression vs LDA/QDA	29
4.21	Gaussian decision boundaries	30
4.22	QDA with 3 classes	30
4.23	Scalar QDA	30
5	Bayesian statistics	31
5.1	Proof that a mixture of conjugate priors is indeed conjugate . .	31
5.2	Optimal threshold on classification probability	31
5.3	Reject option in classifiers	31
5.4	More reject options	32
5.5	Newsvendor problem	32
5.6	Bayes factors and ROC curves	32
5.7	Bayes model averaging helps predictive accuracy	32
5.8	MLE and model selection for a 2d discrete distribution	33
5.9	Posterior median is optimal estimate under L1 loss	34
5.10	Decision rule for trading off FPs and FNs	34

CONTENTS	4
6 Frequentist statistics	35
7 Linear regression	36
7.1 Behavior of training set error with increasing sample size . . .	36
7.2 Multi-output linear regression	36
7.3 Centering and ridge regression	36
7.4 MLE for σ^2 for linear regression	37
7.5 MLE for the offset term in linear regression	37
7.6 MLE for simple linear regression	38
7.7 Sufficient statistics for online linear regression	38
7.8 Bayesian linear regression in 1d with known σ^2	38
7.9 Generative model for linear regression	39
7.10 Bayesian linear regression using the g-prior	40
8 Logistic regression	42
8.1 Spam classification using logistic regression	42
8.2 Spam classification using naive Bayes	42
8.3 Gradient and Hessian of log-likelihood for logistic regression .	42
8.4 Gradient and Hessian of log-likelihood for multinomial logistic regression	43
8.5 Symmetric version of l2 regularized multinomial logistic regression	44
8.6 Elementary properties of l2 regularized logistic regression . .	44
8.7 Regularizing separate terms in 2d logistic regression	45
9 Generalized linear models and the exponential family	46
9.1 Conjugate prior for univariate Gaussian in exponential family form	46
9.2 The MVN is in the exponential family	47
10 Directed graphical models(Bayes nets)	48
11 Mixture models and the EM algorithm	49
11.1 Student T as infinite mixture of Gaussian	49
11.2 EM for mixture of Gaussians	49

11.3 EM for mixtures of Bernoullis	50
11.4 EM for mixture of Student distributions	51
11.5 Gradient descent for fitting GMM	52
11.6 EM for a finite scale mixture of Gaussians	53
11.7 Manual calculation of the M step for a GMM	54
11.8 Moments of a mixture of Gaussians	54
11.9 K-means clustering by hand	55
11.10 Deriving the K-means cost function	55
11.11 Visible mixtures of Gaussians are in exponential family	56
11.12 EM for robust linear regression with a Student t likelihood	56
11.13 EM for EB estimation of Gaussian shrinkage model	57
11.14 EM for censored linear regression	57
11.15 Posterior mean and variance of a truncated Gaussian	57
12 Latent linear models	59
12.1 M-step for FA	59
12.2 MAP estimation for the FA model	60
12.3 Heuristic for assessing applicability of PCA*	61
12.4 Deriving the second principal component	61
12.5 Deriving the residual error for PCA	62
12.6 Derivation of Fisher's linear discriminant	62
12.7 PCA via successive deflation	62
12.8 Latent semantic indexing	63
12.9 Imputation in a FA model*	63
12.10 Efficiently evaluating the PPCA density	63
12.11 PPCA vs FA	63
13 Sparse linear models	64
13.1 Partial derivative of the RSS	64
13.2 Derivation of M-step for EB for linear regression	64
13.3 Derivation of fixed point updates for EB for linear regression*	66
13.4 Marginal likelihood for linear regression*	66
13.5 Reducing elastic net to lasso	66
13.6 Shrinkage in linear regression	66

13.7 Prior for the Bernoulli rate parameter in the spike and slab model	67
13.8 Deriving E step for GSM prior	68
13.9 EM for sparse probit regression with Laplace prior	68
13.10 GSM representation of group lasso*	70
13.11 Projected gradient descent for l1 regularized least squares	70
13.12 Subderivative of the hinge loss function	71
13.13 Lower bounds to convex functions	71
14 Kernels	72
15 Gaussian processes	73
15.1 Reproducing property	73
16 Adaptive basis function models	74
16.1 Nonlinear regression for inverse dynamics	74
17 Markov and hidden Markov models	75
17.1 Derivation of Q function for HMM	75
17.2 Two filter approach to smoothing in HMMs	75
17.3 EM for HMMs with mixture of Gaussian observations	76
17.4 EM for HMMs with tied mixtures	77
18 State space models	78
18.1 Derivation of EM for LG-SSM	78
18.2 Seasonal LG-SSM model in standard form	79
19 Undirected graphical models(Markov random fields)	80
19.1 Derivation of the log partition function	80
19.2 CI properties of Gaussian graphical models	80
19.3 Independencies in Gaussian graphical models	82
19.4 Cost of training MRFs and CRFs	82
19.5 Full conditional in an Ising model	83

20 Exact inference for graphical models	84
20.1 Variable elimination	84
20.2 Gaussian times Gaussian is Gaussian	84
20.3 Message passing on a tree	84
20.4 Inference in 2D lattice MRFs	86
21 Variational inference	87
21.1 Laplace approximation to $p(\mu, \log \sigma D)$ for a univariate Gaussian	87
21.2 Laplace approximation to normal-gamma	88
21.3 Variational lower bound for VB for univariate Gaussian	88
21.4 Variational lower bound for VB for GMMs	89
21.5 Derivation of $\mathbb{E}[\log \pi_k]$	91
21.6 Alternative derivation of the mean field updates for the Ising model	92
21.7 Forwards vs reverse KL divergence	92
21.8 Derivation of the structured mean field updates for FHMM	92
21.9 Variational EM for binary FA with sigmoid link	93
21.10 VB for binary FA with probit link	93

1 Introduction

1.1 Constitution of this document

Here we should have demonstrated the solution to problems in Chapter One in *Machine Learning, A Probabilistic Perspective*(MLAPP). Since the number of problem in Chapter is zero, we save this section as an introduction to this document, i.e.a solution manual.

This document provides detailed solution to almost all problems of textbook MLAPP from Chapter One to Chapter Fourteen(Chinese version) / Twenty-one(English version). We generally save the restatement of problems for readers themselves.

There are two class for problems in MLAPP: theortical inference and pratical projects. We provide solution to most inference problems apart from those which are nothing but straightforward algebra(and few which we failed to solve). Practical problems, which base on a Matlab toolbox, are beyond the scope of this document.

1.2 On *Machine Learning: A Probabilistic Perspective*

Booming studies and literatures have made the boundary of "machine learning" vague.

On one hand, the rapid development of AI technology has kept the society shocked, which also results in sharply increase in number of students who would try to take related courses in colleges. On the other hand, some scholars are still uncertain in learning-related theories, especially deep learning.

The extraordinary achievements of machine learning in recent days often make one forget that this discipline has undergone a long evolution and whose establishment dates back at least to the studies of "electronic brains" in the 1940s. Be that as it may, machine learning has not been defined as a "closed" theory. Even in the some community of researchers, machine learning are crowned metaphysics or alchemistry. Personally, I believe tha being called metaphysics is a common experience shared by many branches of theory which are undergoing the most rapid development.

To be a completed theory, machine learning is still looking for a way to conclude itself in a closed system. The most successful attempt so far has been the one based on probability. As commented by David Blei from Princeton on the back of MLAPP: "In Machine Learning, the language of probability and statistics reveals important connections between seemingly disparate algorithms and strategies. Thus, its readers will become articulate in a holistic view of the state-of-art and poised to build the next generation of machine learning algorithms."

The crucial idea in MLAPP is: machine learning is tantamount to Bayesian Statistics, which draws connections between numerous "independent" algorithms. But the history of Bayesian statistics(which can be traced back to days of Laplace) outlengths the one of machine learning a lot. MLAPP is not novel in holding such an idea. C.M.Bishop's *Pattern Recognition and Machine Learning* is another typical example. Both of them are considered as classical textbooks in elementary machine learning.

In general, MLAPP reduces the difficulty of the entire book at the expense of partially deduced completeness(for the first seven chapters). It covers a wider range of models and is suitable for those with background in mathematical tools. The chapters that concerning classical probabilistic models (e.g, chapter 2, 3, 4, 5, 7, 8, 11, 12) is comparable to PRML. But due to the reordering and more details, they worth a read for one who have finished reading PRML.

1.3 What is this document?

The motivation for writing this document is that I need to read textbook MLAPP after selecting machine learning course, but I failed to find any free compiled solution manuals. Although several Github projects have started working on it, the velocity has been too slow. Also I want to focus more on the theoretical part of the text rather than the implementation code.

Hence I began working on this document. It is completed(first version, Chapter One to Chapter Fourteen) within the first two weeks before the official semester. Because of the hurry process, it is suggested that readers

should read from a critical perspective and not hesitate to believe in everything I have written down. In the end, I hope that readers can provide comments and revise opinions. Apart from correcting the wrong answers, those who good at using MATLAB, Latex typesetting or those who are willing to participate in the improvement of the document are always welcome to contact me.

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1.4 Updating log

22/10/2017(First Chinese compilation)

02/03/2018(English compilation)

2 Probability

2.1 Probability are sensitive to the form of the question that was used to generate the answer

Denote two children by A and B .

Use

$$E_1 : A = \text{boy}, B = \text{girl}$$

$$E_2 : B = \text{boy}, A = \text{girl}$$

$$E_3 : A = \text{boy}, B = \text{boy}$$

In question a:

$$P(E_1) = P(E_2) = P(E_3) = \frac{1}{4}$$

$$P(\text{OneGirl}|\text{OneBoy}) = \frac{P(E_1) + P(E_2)}{P(E_1) + P(E_2) + P(E_3)} = \frac{2}{3}$$

For question b, w.l.o.g, assume child A is seen:

$$P(B = \text{girl} | A = \text{boy}) = \frac{1}{2}$$

2.2 Legal reasoning

Let E_1 and E_2 denote the event "the defendant committed the crime" and "the defendant has special blood type" respectively. Thus:

$$\begin{aligned} p(E_1|E_2) &= \frac{p(E_1, E_2)}{p(E_2)} = \frac{p(E_2|E_1)p(E_1)}{p(E_2)} \\ &= \frac{1 \cdot \frac{1}{800000}}{\frac{1}{8000}} = \frac{1}{100} \end{aligned}$$

2.3 Variance of a sum

Calculate this straightforwardly:

$$\begin{aligned} \text{var}[X + Y] &= \mathbb{E}[(X + Y)^2] - \mathbb{E}^2[X + Y] \\ &= \mathbb{E}[X^2] - \mathbb{E}^2[X] + \mathbb{E}[Y^2] - \mathbb{E}^2[Y] + 2\mathbb{E}[XY] - 2\mathbb{E}^2[XY] \\ &= \text{var}[X] + \text{var}[Y] + 2\text{cov}[X, Y] \end{aligned}$$

2.4 Bayes rule for medical diagnosis

Applying Bayes's rules:

$$\begin{aligned} P(ill|positive) &= \frac{P(ill)P(positive|ill)}{P(ill)P(positive|ill) + P(health)P(positive|health)} \\ &= 0.0098 \end{aligned}$$

2.5 The Monty Hall problem(The dilemma of three doors)

The answer is b. Applying Bayes's rules:

$$\begin{aligned} P(prize_1|choose_1, open_3) &= \frac{P(choose_1)P(prize_1)P(choose_3|prize_1, choose_1)}{P(choose_1)P(open_3|choose_1)} \\ &= \frac{P(prize_1)P(choose_3|prize_1, choose_1)}{P(open_3|choose_1)} \\ &= \frac{\frac{1}{3} \cdot \frac{1}{2}}{\frac{1}{3} \cdot \frac{1}{2} + \frac{1}{3} \cdot 0 + \frac{1}{3} \cdot 1} = \frac{1}{3} \end{aligned}$$

In the last step we summarize over the potential location of the prize.

2.6 Conditional Independence

In question a, we have:

$$p(H|e_1, e_2) = \frac{p(H)p(e_1, e_2|H)}{p(e_1, e_2)}$$

Thus the answer is (ii).

For question, we have further decomposition:

$$p(H|e_1, e_2) = \frac{p(H)p(e_1|H)p(e_2|H)}{p(e_1, e_2)}$$

So both (i) and (ii) are sufficient obviously. Since:

$$\begin{aligned} p(e_1, e_2) &= \sum_H p(e_1, e_2, H) \\ &= \sum_H p(H)p(e_1|H)p(e_2|H) \end{aligned}$$

(iii) is sufficient as well since we can calculate $p(e_1, e_2)$ independently.

2.7 Pairwise independence does not imply mutual independence

Let's assume three boolean variables x_1, x_2, x_3 , x_1 and x_2 have values of 0 or 1 with equal possibility independently and $x_3 = XOR(x_1, x_2)$:

It is easy to prove that x_3 is independent with x_1 or x_2 , but given both x_1 and x_2 , the value of x_3 is determined and thereby the mutual independence fails.

2.8 Conditional independence iff joint factorizes

We prove 2.129 is equal to 2.130.

By denoting:

$$g(x, z) = p(x|z)$$

$$h(y, z) = p(y|z)$$

We have the first half of proof.

Secondly we have:

$$\begin{aligned} p(x|z) &= \sum_y p(x, y|z) \\ &= \sum_y g(x, z)h(y, z) \\ &= g(x, z) \sum_y h(y, z) \\ p(y|z) &= h(y, z) \sum_x g(x, z) \end{aligned}$$

And:

$$\begin{aligned} 1 &= \sum_{x,y} p(x, y|z) \\ &= \left(\sum_x g(x, z) \right) \left(\sum_y h(y, z) \right) \end{aligned}$$

Thus:

$$\begin{aligned} p(x|z)p(y|z) &= g(x, z)h(y, z) \left(\sum_x g(x, z) \right) \left(\sum_y h(y, z) \right) \\ &= g(x, z)h(y, z) \\ &= p(x, y|z) \end{aligned}$$

2.9 Conditional independence*

From a graphic view, both arguments are correct. But from a general view, both of them do not have a decomposition form, thus false.

2.10 Deriving the inverse gamma density

According to:

$$p(y) = p(x) \left| \frac{dx}{dy} \right|$$

We easily have:

$$\begin{aligned} IG(y) &= Ga(x) \cdot y^{-2} \\ &= \frac{b^a}{\Gamma(a)} \left(\frac{1}{y} \right)^{(a-1)+2} e^{-\frac{b}{y}} \\ &= \frac{b^a}{\Gamma(a)} (y)^{-(a+1)} e^{-\frac{b}{y}} \end{aligned}$$

2.11 Normalization constant for a 1D Gaussian

This proof should be found around any textbook about multivariable calculus. Omitted here.

2.12 Expressing mutual information in terms of entropies

$$\begin{aligned}
 I(X; Y) &= \sum_{x,y} p(x, y) \log \frac{p(x, y)}{p(x)p(y)} \\
 &= \sum_{x,y} p(x, y) \log \frac{p(x|y)}{p(x)} \\
 &= \sum_{x,y} p(x, y) \log p(x|y) - \sum_x \left(\sum_y p(x, y) \right) \log p(x) \\
 &= -H(X|Y) + H(X)
 \end{aligned}$$

Inversing X and Y yields to another formula..

2.13 Mutual information for correlated normals

We have:

$$\begin{aligned}
 I(X_1; X_2) &= H(X_1) - H(X_1|X_2) \\
 &= H(X_1) + H(X_2) - H(X_1, X_2) \\
 &= \frac{1}{2} \log 2\pi\sigma^2 + \frac{1}{2} \log 2\pi\sigma^2 + \frac{1}{2} \log (2\pi)^2 \sigma^4 (1 - \rho^2) \\
 &= -\frac{1}{2} \log(1 - \rho^2)
 \end{aligned}$$

(refer to **Elements of Information Theory**, Example 8.5.1)

2.14 A measure of correlation

In question a:

$$\begin{aligned}
 r &= 1 - \frac{H(Y|X)}{H(X)} = \frac{H(X) - H(Y|X)}{H(X)} \\
 &= \frac{H(Y) - H(Y|X)}{H(X)} \\
 &= \frac{I(X; Y)}{H(X)}
 \end{aligned}$$

We have $0 \leq r \leq 1$ in question b for $I(X; Y) > 0$ and $H(X|Y) < H(X)$ (properties of entropy).

$r = 0$ iff X and Y are independent.

$r = 1$ iff X is determined (not necessary equal) by Y .

2.15 MLE minimizes KL divergence to the empirical distribution

Expand the KL divergence:

$$\begin{aligned}
 \theta &= \arg \min_{\theta} \{ \mathbb{KL}(p_{emp} || q(\theta)) \} \\
 &= \arg \min_{\theta} \left\{ \mathbb{E}_{p_{emp}} \left[\log \frac{p_{emp}}{p(\theta)} \right] \right\} \\
 &= \arg \min_{\theta} \left\{ -H(p_{emp}) - \sum_{\mathbf{x} \in dataset} (\log q(\mathbf{x}; \theta)) \right\} \\
 &= \arg \max_{\theta} \left\{ \sum_{\mathbf{x} \in dataset} \log p(\mathbf{x}; \theta) \right\}
 \end{aligned}$$

We use the weak law of large numbers in the third step and drop the entropy of empirical distribution in the last step.

2.16 Mean, mode, variance for the beta distribution

Firstly, derive the mode for beta distribution by differentiating the pdf:

$$\frac{d}{dx} x^{a-1} (1-x)^{b-1} = [(1-x)(a-1) - (b-1)x] x^{a-2} (1-x)^{b-2}$$

Setting this to zero yields:

$$mode = \frac{a-1}{a+b-2}$$

Secondly, derive the moment in beta distribution:

$$\begin{aligned}
 \mathbb{E}[x^N] &= \frac{1}{B(a, b)} \int x^{a+N-1} (1-x)^{b-1} dx \\
 &= \frac{B(a+N, b)}{B(a, b)} \\
 &= \frac{\Gamma(a+N)\Gamma(b)}{\Gamma(a+N+b)} \frac{\Gamma(a+b)}{\Gamma(a)\Gamma(b)}
 \end{aligned}$$

Setting $N = 1, 2$:

$$\begin{aligned}
 \mathbb{E}[x] &= \frac{a}{a+b} \\
 \mathbb{E}[x^2] &= \frac{a(a+1)}{(a+b)(a+b+1)}
 \end{aligned}$$

Where we have used the property of Gamma function. Straightforward algebra gives:

$$\begin{aligned} \text{mean} &= \mathbb{E}[x] = \frac{a}{a+b} \\ \text{variance} &= \mathbb{E}[x^2] - \mathbb{E}^2[x] = \frac{ab}{(a+b)^2(a+b+1)} \end{aligned}$$

2.17 Expected value of the minimum

Let m denote the location of the left most point, we have:

$$\begin{aligned} p(m > x) &= p([X > x] \text{ and } [Y > x]) \\ &= p(X > x)p(Y > x) \\ &= (1-x)^2 \end{aligned}$$

Therefore:

$$\begin{aligned} \mathbb{E}[m] &= \int x \cdot p(m = x) dx \\ &= \int p(m > x) dx \\ &= \int_0^1 (1-x)^2 dx \\ &= \frac{1}{3} \end{aligned}$$

3 Generative models for discrete data

3.1 MLE for the Bernoulli/binomial model

Likelihood:

$$p(D|\theta) = \theta^{N_1} (1 - \theta)^{N_0}$$

Log-Likelihood:

$$\ln p(D|\theta) = N_1 \ln \theta + N_0 \ln(1 - \theta)$$

Setting the derivative to zero:

$$\frac{\partial}{\partial \theta} \ln p(D|\theta) = \frac{N_1}{\theta} - \frac{N_0}{1 - \theta} = 0$$

This ends in 3.22:

$$\theta = \frac{N_1}{N_1 + N_0} = \frac{N_1}{N}$$

3.2 Marginal likelihood for the Beta-Bernoulli model

Likelihood:

$$p(D|\theta) = \theta^{N_1} (1 - \theta)^{N_0}$$

Prior distribution:

$$p(\theta|a, b) = \text{Beta}(\theta|a, b) = \theta^{a-1} (1 - \theta)^{b-1}$$

Posterior distribution:

$$\begin{aligned} p(\theta|D) &\propto p(D|\theta) \cdot p(\theta|a, b) \\ &= \theta^{N_1+a-1} (1 - \theta)^{N_0+b-1} \\ &= \text{Beta}(\theta|N_1 + a, N_0 + b) \end{aligned}$$

Prediction:

$$\begin{aligned} p(x_{new} = 1|D) &= \int p(x_{new} = 1|\theta) \cdot p(\theta|D) d\theta \\ &= \int \theta p(\theta|D) d\theta \\ &= \mathbb{E}(\theta) = \frac{N_1 + a}{N_1 + a + N_0 + b} \end{aligned}$$

Calcualte $p(D)$ where $D = 1, 0, 0, 1, 1$:

$$\begin{aligned} p(D) &= p(x_1)p(x_2|x_1)p(x_3|x_2, x_1) \dots p(X_N|x_{N-1}, X_{N-2}, \dots X_1) \\ &= \frac{a}{a+b} \frac{b}{a+b+1} \frac{b+2}{a+b+2} \frac{a+1}{a+b+3} \frac{a+2}{a+b+4} \end{aligned}$$

Denote $\alpha = a + b, \alpha_1 = a, \alpha_0 = b$, we have 3.83. To derive 3.80, we make use of:

$$[(\alpha_1) \dots (\alpha_1 + N_1 - 1)] = \frac{(\alpha_1 + N_1 - 1)!}{(\alpha_1 - 1)!} = \frac{\Gamma(\alpha_1 + N_1)}{\Gamma(\alpha_1)}$$

3.3 Posterior predictive for Beta-Binomial model

Straightforward algebra:

$$\begin{aligned} Bb(\alpha'_1, \alpha'_0, 1) &= \frac{B(\alpha'_1 + 1, \alpha'_0)}{B(\alpha'_1, \alpha'_0)} \\ &= \frac{\Gamma(\alpha'_0 + \alpha'_1)}{\Gamma(\alpha'_0 + \alpha'_1 + 1)} \frac{\Gamma(\alpha'_1 + 1)}{\Gamma(\alpha'_1)} \\ &= \frac{\alpha'_1}{\alpha'_1 + \alpha'_0} \end{aligned}$$

3.4 Beta updating from censored likelihood

The derivation is straightforward:

$$\begin{aligned} p(\theta, X < 3) &= p(\theta)p(X < 3|\theta) \\ &= p(\theta)(p(X = 1|\theta) + p(X = 2|\theta)) \\ &= \text{Beta}(\theta|1, 1)(\text{Bin}(1|5, \theta) + \text{Bin}(2|5, \theta)) \end{aligned}$$

3.5 Uninformative prior for log-odds ratio

Since:

$$\phi = \log \frac{\theta}{1 - \theta}$$

By using change of variables formula:

$$p(\theta) = p(\phi) \left| \frac{d\phi}{d\theta} \right| \propto \frac{1}{\theta(1 - \theta)}$$

$$p(\theta) \propto \text{Beta}(\theta|0, 0)$$

3.6 MLE for the Poisson distribution

Likelihood:

$$p(D|Poi, \lambda) = \prod_{n=1}^N Poi(x_n|\lambda) = \exp(-\lambda N) \cdot \lambda^{\sum_{n=1}^N x_n} \cdot \frac{1}{\prod_{n=1}^N x_n!}$$

Setting the derivative of Log-Likelihood to zero:

$$\frac{\partial}{\partial \lambda} p(D|Poi, \lambda) = \exp(-\lambda N) \lambda^{\sum x-1} \left\{ -N\lambda + \sum_{n=1}^N x_n \right\}$$

Thus:

$$\lambda = \frac{\sum_{n=1}^N x_n}{N}$$

3.7 Bayesian analysis of the Poisson distribution

We have:

$$\begin{aligned} p(\lambda|D) &\propto p(\lambda)p(D|\lambda) \\ &\propto \exp(-\lambda(N+b)) \cdot \lambda^{\sum_{n=1}^N x_n + a - 1} \\ &= \text{Gamma}(a + \sum x, N + b) \end{aligned}$$

This prior distribution equals introducing b prior observations with mean $\frac{a}{b}$.

3.8 MLE for the uniform distribution

The likelihood goes to zero if $a < \max(x_n)$, so we must have $\hat{a} \geq \max(x_n)$, likelihood looks like:

$$p(D|a) = \prod_{n=1}^N \frac{1}{2a}$$

Which has a negative correlation with a , so:

$$\hat{a} = \max \{x_i\}_{i=1}^n$$

This model assign $p(x_{n+1}) = 0$ if $x_{n+1} > \max \{x_i\}_{i=1}^n$, which gives a "hard" boundary in distribution.

3.9 Bayesian analysis of the uniform distribution

The conjugate prior for uniform distribution is Pareto distribution:

$$p(\theta) = Pa(\theta|K, b) = Kb^K \theta^{-(K+1)} [\theta \geq b]$$

Let $m = \max \{x_i\}_{i=1}^n$, the joint distribution is:

$$p(\theta, D) = p(\theta)p(D|\theta) = Kb^K \theta^{-(K+N+1)} [\theta \geq b] [\theta \geq m]$$

And the evidence is:

$$p(D) = \int p(D, \theta) d\theta = \frac{Kb^K}{(N+K) \max(m, b)^{N+K}}$$

Let $\mu = \max \{m, b\}$, the posterior distribution is again the form of a Pareto distribution:

$$p(\theta|D) = \frac{p(\theta, D)}{p(D)} = \frac{(N+K)\mu^{N+K} [\theta \geq \mu]}{\theta^{N+K+1}} = Pa(\theta|N+K, \mu)$$

3.10 Taxicab problem*

We skip this straightforward numerical task.

3.11 Bayesian analysis of the exponential distribution

Log-Likelihood for an exponential distribution is:

$$\ln p(D|\theta) = N \ln \theta - \theta \sum_{n=1}^N x_n$$

The derivative is:

$$\frac{\partial}{\partial \theta} \ln p(D|\theta) = \frac{N}{\theta} - \sum_{n=1}^N x_n$$

Thus in question a:

$$\theta_{ML} = \frac{N}{\sum_{n=1}^N x_n}$$

We skip other questions and state that the conjugate prior for exponential distribution is Gamma distribution:

$$\begin{aligned} p(\theta|D) &\propto p(\theta)p(D|\theta) \\ &= \text{Gamma}(\theta|a, b)p(D|\theta) \\ &= \text{Gamma}(\theta|N+a, b + \sum x_n) \end{aligned}$$

A Gamma prior introduces $a - 1$ prior observation with a sum b .

3.12 MAP estimation for the Bernoulli with non-conjugate priors*

We skip this straightforward numerical task.

3.13 Posterior predictive distribution for a batch of data with the dirichlet-multinomial model

Since we already have 3.51:

$$p(X = j|D, \alpha) = \frac{\alpha_j + N_j}{\alpha_0 + N}$$

We can easily derive:

$$\begin{aligned} p(\tilde{D}|D, \alpha) &= \prod_{x \in \tilde{D}} p(x|D, \alpha) \\ &= \prod_{j=1}^C \left(\frac{\alpha_j + N_j^{old}}{\alpha_0 + N^{old}} \right)^{N_j^{new}} \end{aligned}$$

3.14 Posterior predictive for Dirichlet-multinomial*

We skip this straightforward numerical task.

3.15 Setting the hyper-parameters I*

We skip this straightforward numerical task.

3.16 Setting the beta hyper-parameters II

For parameters of a Beta distribution α_1 和 α_2 are connected through:

$$\alpha_2 = \alpha_1 \left(\frac{1}{m} - 1 \right) = f(\alpha_1)$$

Calculate this integral:

$$\int_l^u \frac{1}{B(\alpha_1, f(\alpha_1))} \theta^{\alpha_1} (1 - \theta)^{f(\alpha_1)} = u(\alpha_1)$$

Setting this integral $u(\alpha_1) \rightarrow 0.95$ by altering α_1 through numerical method will do.

3.17 Marginal likelihood for beta-binomial under uniform prior

The marginal likelihood is given by:

$$p(N_1|N) = \int_0^1 p(N_1, \theta|N) d\theta = \int_0^1 p(N_1|\theta, N) p(\theta) d\theta$$

We already have:

$$p(N_1|\theta, N) = \text{Bin}(N_1|\theta, N)$$

$$p(\theta) = \text{Beta}(1, 1)$$

Thus:

$$\begin{aligned} p(N_1|N) &= \int_0^1 \binom{N}{N_1} \theta^{N_1} (1-\theta)^{N-N_1} d\theta \\ &= \binom{N}{N_1} B(N_1 + 1, N - N_1 + 1) \\ &= \frac{N!}{N_1!(N - N_1)!} \frac{N_1!(N - N_1)!}{(N + 1)!} \\ &= \frac{1}{N + 1} \end{aligned}$$

Where B is the regularizer for a Beta distribution:

$$B(a, b) = \frac{\Gamma(a)\Gamma(b)}{\Gamma(a + b)}$$

3.18 Bayes factor for coin tossing*

Straightforward calculation.

3.19 Irrelevant features with naive Bayes

Log-Likelihood is given by:

$$\log p(\mathbf{x}_i|c, \theta) = \sum_{w=1}^W x_{iw} \log \frac{\theta_{cw}}{1 - \theta_{cw}} + \sum_{w=1}^W \log(1 - \theta_{cw})$$

In a succinct way:

$$\log p(\mathbf{x}_i|c, \theta) = \phi(\mathbf{x}_i)^T \beta_c$$

Where:

$$\phi(\mathbf{x}_i) = (\mathbf{x}_i, 1)^T$$

$$\beta_c = (\log \frac{\theta_{c1}}{1 - \theta_{c1}}, \dots, \sum_{w=1}^W \log(1 - \theta_{cw}))^T$$

For question a:

$$\begin{aligned} \log \frac{p(c=1|\mathbf{x}_i)}{p(c=2|\mathbf{x}_i)} &= \log \frac{p(c=1)p(\mathbf{x}_i|c=1)}{p(c=2)p(\mathbf{x}_i|c=2)} \\ &= \log \frac{p(\mathbf{x}_i|c=1)}{p(\mathbf{x}_i|c=2)} \\ &= \phi(\mathbf{x}_i)^T (\beta_1 - \beta_2) \end{aligned}$$

For question b, in a binary context:

$$p(c=1|\mathbf{x}_i) = \frac{p(c=1)p(\mathbf{x}_i|c=1)}{p(\mathbf{x}_i)}$$

Thus:

$$\log \frac{p(c=1|\mathbf{x}_i)}{p(c=2|\mathbf{x}_i)} = \log \frac{p(c=1)}{p(c=2)} + \phi(\mathbf{x}_i)^T (\beta_1 - \beta_2)$$

A word w will not affect this posterior measure as long as:

$$x_{iw}(\beta_{1,w} - \beta_{2,w}) = 0$$

Hence:

$$\theta_{c=1,w} = \theta_{c=2,w}$$

So the chance that word w appears in both class of documents are equal.

In question c, we have:

$$\hat{\theta}_{1,w} = 1 - \frac{1}{2 + N_1}$$

$$\hat{\theta}_{2,w} = 1 - \frac{1}{2 + N_2}$$

They do not equal when $N_1 \neq N_2$ so the bias effect remains. However, this effect reduces when N grows large.

3.20 Class conditional densities for binary data

In question a, we have:

$$p(\mathbf{x}|y = c) = \prod_{i=1}^D p(x_i|y = c, x_1, \dots, x_{i-1})$$

The number of parameter is:

$$C \cdot \sum_{i=1}^D 2^i = C \cdot (2^{D+1} - 2) = O(C \cdot 2^D)$$

For question b and c, we generally think that naive models fit better when N is large, because delicate models have problems of overfitting.

In question d,e and f, it is assumed that looking up for a value according to a D-dimensional index cost $O(D)$ time. It is easy to calculate the fitting complexity: $O(ND)$ for a naive model and $O(N \cdot 2^D)$ for a full model, and the applying complexity is $O(CD)$ and $O(C \cdot 2^D)$ respectively.

For question f:

$$p(y|\mathbf{x}_v) \propto p(\mathbf{x}_v|y) = \sum_{\mathbf{x}_h} p(\mathbf{x}_v, \mathbf{x}_h|y)$$

Thus the complexity is multiplied by an extra const $2^{|\mathbf{x}_h|}$.

3.21 Mutual information for naive Bayes classifiers with binary features

By definition:

$$I(X; Y) = \sum_{x_j} \sum_y p(x_j, y) \log \frac{p(x_j, y)}{p(x_j)p(y)}$$

For binary features, consider the value of x_j to be zero and one, given $\pi_c = p(y = c)$, $\theta_{jc} = p(x_j = 1|y = c)$, $\theta_j = p(x_j = 1)$:

$$\begin{aligned} I_j &= \sum_c p(x_j = 1, c) \log \frac{p(x_j = 1, c)}{p(x_j = 1)p(c)} \\ &\quad + \sum_c p(x_j = 0, c) \log \frac{p(x_j = 0, c)}{p(x_j = 0)p(c)} \\ &= \sum_c \pi_c \theta_{jc} \log \frac{\theta_{jc}}{\theta_j} + (1 - \theta_{jc}) \pi_c \log \frac{1 - \theta_{jc}}{1 - \theta_j} \end{aligned}$$

Which ends in 3.76.

3.22 Fitting a naive Bayesian spam filter by hand*

Straightforward calculation.

4 Gaussian models

4.1 Uncorrelated does not imply independent

We first calculate the covariance of X and Y :

$$\begin{aligned} \text{cov}(X, Y) &= \int \int (X - \mathbb{E}(X))(Y - \mathbb{E}(Y))p(X, Y)dXdY \\ &= \int_{-1}^1 X(X^2 - \frac{1}{\sqrt{3}})dX = 0 \end{aligned}$$

The intergral ends in zero since we are intergrating an odd function in range $[-1,1]$, hence:

$$\rho(X, Y) = \frac{\text{cov}(X, Y)}{\sqrt{\text{var}(X)\text{var}(Y)}} = 0$$

4.2 Uncorrelated and Gaussian does not imply independent unless jointly Gaussian

The pdf for Y is:

$$p(Y = a) = 0.5 \cdot p(X = a) + 0.5 \cdot p(X = -a) = p(X = a)$$

The pdf of X is symetric with 0 as the core, so Y subject to a normal distribution $(0, 1)$.

For question b, we have:

$$\begin{aligned} \text{cov}(X, Y) &= \mathbb{E}(XY) - \mathbb{E}(X) - \mathbb{E}(Y) \\ &= \mathbb{E}_W(\mathbb{E}(XY|W)) - 0 \\ &= 0.5 \cdot \mathbb{E}(X^2) + 0.5 \cdot \mathbb{E}(-X^2) = 0 \end{aligned}$$

4.3 Correlation coefficient is between -1 and 1

The statement:

$$-1 \leq \rho(X, Y) \leq 1$$

Equals:

$$|\rho(X, Y)| \leq 1$$

Hence we are to prove:

$$|cov(X, Y)|^2 \leq var(X) \cdot var(Y)$$

Which can be drawn straightforwardly from Cauchy–Schwarz inequality in R^2 .

4.4 Correlation coefficient for linearly related variables is 1 or -1

When $Y = aX + b$:

$$\mathbb{E}(Y) = a\mathbb{E}(x) + b$$

$$var(Y) = a^2 var(X)$$

Therefore:

$$\begin{aligned} cov(X, Y) &= \mathbb{E}(XY) - \mathbb{E}(X)\mathbb{E}(Y) \\ &= a\mathbb{E}(X^2) + b\mathbb{E}(X) - a\mathbb{E}^2(X) - b\mathbb{E}(X) \\ &= a \cdot var(X) \end{aligned}$$

We also have:

$$var(X)var(Y) = a^2 \cdot var(X)$$

These two make:

$$\rho(X, Y) = \frac{a}{|a|}$$

4.5 Normalization constant for a multidimensional Gaussian

This can be obtained by applying the method mentioned in problem straightforwardly, hence omitted.

4.6 Bivariate Gaussian

Straightforward algebra.

4.7 Conditioning a bivariate Gaussian

Answers are obtained by plugging figures in 4.69 straightforwardly.

4.8 Whitening vs standardizing

Practical by yourself.

4.9 Sensor fusion with known variances in 1d

Denote the two observed datasets by $Y^{(1)}$ and $Y^{(2)}$, with size N_1, N_2 , the likelihood is:

$$\begin{aligned} p(Y^{(1)}, Y^{(2)} | \mu) &= \prod_{n_1=1}^{N_1} p(Y_{n_1}^{(1)} | \mu) \prod_{n_2=1}^{N_2} p(Y_{n_2}^{(2)} | \mu) \\ &\propto \exp \{ A \cdot \mu^2 + B \cdot \mu \} \end{aligned}$$

Where we have used:

$$\begin{aligned} A &= -\frac{N_1}{2v_1} - \frac{N_2}{2v_2} \\ B &= \frac{1}{v_1} \sum_{n_1=1}^{N_1} Y_{n_1}^{(1)} + \frac{1}{v_2} \sum_{n_2=1}^{N_2} Y_{n_2}^{(2)} \end{aligned}$$

Differentiate the likelihood and set it to zero, we have:

$$\mu_{ML} = -\frac{B}{2A}$$

The conjugate prior of this model must have form proportional to $\exp \{ A \cdot \mu^2 + B \cdot \mu \}$, namely a normal distribution:

$$p(\mu | a, b) \propto \exp \{ a \cdot \mu^2 + b \cdot \mu \}$$

The posterior distribution is:

$$p(\mu | Y) \propto \exp \{ (A + a) \cdot \mu^2 + (B + b) \cdot \mu \}$$

Hence we have the MAP estimation:

$$\mu_{MAP} = -\frac{B + b}{2(A + a)}$$

It is noticeable that the MAP converges to ML estimation when observation times grow:

$$\mu_{MAP} \rightarrow \mu_{ML}$$

The posterior distribution is another normal distribution, with:

$$\sigma_{MAP}^2 = -\frac{1}{2(A + a)}$$

4.10 Derivation of information form formulae for marginalizing and conditioning

Please refer to PRML chapter 2.

4.11 Derivation of the NIW posterior

The likelihood for a MVN is given by:

$$p(\mathbf{X}|\mu, \Sigma) = (2\pi)^{-\frac{ND}{2}} |\Sigma|^{-\frac{N}{2}} \exp \left\{ -\frac{1}{2} \sum_{n=1}^N (\mathbf{x}_i - \mu)^T \Sigma^{-1} (\mathbf{x}_i - \mu) \right\}$$

According to 4.195:

$$\begin{aligned} \sum_{n=1}^N (\mathbf{x}_i - \mu)^T \Sigma^{-1} (\mathbf{x}_i - \mu) &= \sum_{n=1}^N (\bar{\mathbf{x}} - \mu + (\mathbf{x}_i - \bar{\mathbf{x}}))^T \Sigma^{-1} (\bar{\mathbf{x}} - \mu + (\mathbf{x}_i - \bar{\mathbf{x}})) \\ &= N(\bar{\mathbf{x}} - \mu)^T \Sigma^{-1} (\bar{\mathbf{x}} - \mu) + \sum_{n=1}^N (\mathbf{x}_i - \bar{\mathbf{x}})^T \Sigma^{-1} (\mathbf{x}_i - \bar{\mathbf{x}}) \\ &= N(\bar{\mathbf{x}} - \mu)^T \Sigma^{-1} (\bar{\mathbf{x}} - \mu) + \text{Tr} \left\{ \Sigma^{-1} \sum_{n=1}^N (\mathbf{x}_i - \bar{\mathbf{x}})(\mathbf{x}_i - \bar{\mathbf{x}})^T \right\} \\ &= N(\bar{\mathbf{x}} - \mu)^T \Sigma^{-1} (\bar{\mathbf{x}} - \mu) + \text{Tr} \{ \Sigma^{-1} \mathbf{S}_{\bar{\mathbf{x}}} \} \end{aligned}$$

The conjugate prior for MVN's parameters (μ, Σ) is Normal-inverse-Wishart(NIW) distribution, defined by:

$$\begin{aligned} NIW(\mu, \Sigma | \mathbf{m}_0, k_0, v_0, \mathbf{S}_0) &= N(\mu | \mathbf{m}_0, \frac{1}{k_0} \Sigma) \cdot IW(\Sigma | \mathbf{S}_0, v_0) \\ &= \frac{1}{Z} |\Sigma|^{-\frac{v_0 + D + 2}{2}} \exp \left\{ -\frac{k_0}{2} (\mu - \mathbf{m}_0)^T \Sigma^{-1} (\mu - \mathbf{m}_0) - \frac{1}{2} \text{Tr} \{ \Sigma^{-1} \mathbf{S}_0 \} \right\} \end{aligned}$$

Hence the posterior:

$$p(\mu, \Sigma | \mathbf{X}) \propto |\Sigma|^{-\frac{v_{\mathbf{X}} + D + 2}{2}} \exp \left\{ -\frac{k_{\mathbf{X}}}{2} (\mu - \mathbf{m}_{\mathbf{X}})^T \Sigma^{-1} (\mu - \mathbf{m}_{\mathbf{X}}) - \frac{1}{2} \text{Tr} \{ \Sigma^{-1} \mathbf{S}_{\mathbf{X}} \} \right\}$$

Where we have:

$$\begin{aligned} k_{\mathbf{X}} &= k_0 + N \\ v_{\mathbf{X}} &= v_0 + N \\ \mathbf{m}_{\mathbf{X}} &= \frac{N\bar{\mathbf{x}} + k_0\mathbf{m}_0}{k_{\mathbf{X}}} \end{aligned}$$

By comparing the exponential for $|\Sigma|, \mu^T \Sigma^{-1} \mu$ and μ^T .

Making use of $A^T \Sigma^{-1} A = \text{Tr} \{A^T \Sigma^{-1} A\} = \text{Tr} \{\Sigma^{-1} A A^T\}$ and comparing the constant term inside the exponential function:

$$N \bar{\mathbf{x}} \bar{\mathbf{x}}^T + \mathbf{S}_{\bar{\mathbf{x}}} + k_0 \mathbf{m}_0 \mathbf{m}_0^T + \mathbf{S}_0 = k_{\mathbf{X}} \mathbf{m}_{\mathbf{X}} \mathbf{m}_{\mathbf{X}}^T + \mathbf{S}_{\mathbf{X}}$$

Hence

$$\mathbf{S}_{\mathbf{X}} = N \bar{\mathbf{x}} \bar{\mathbf{x}}^T + \mathbf{S}_{\bar{\mathbf{x}}} + k_0 \mathbf{m}_0 \mathbf{m}_0^T + \mathbf{S}_0 - k_{\mathbf{X}} \mathbf{m}_{\mathbf{X}} \mathbf{m}_{\mathbf{X}}^T$$

Use the definition for mean we ends in 4.214 since:

$$\mathbf{S} = \sum_{n=1}^N \mathbf{x}_i \mathbf{x}_i^T = \mathbf{S}_{\bar{\mathbf{x}}} + N \bar{\mathbf{x}} \bar{\mathbf{x}}^T$$

Hence the posterior distribution for MVN takes the form: $NIW(\mathbf{m}_{\mathbf{X}}, k_{\mathbf{X}}, v_{\mathbf{X}}, \mathbf{S}_{\mathbf{X}})$

4.12

Straightforward calculation.

4.13 Gaussian posterior credible interval

Assume a prior distribution for an 1d normal distribution:

$$p(\mu) = N(\mu | \mu_0, \sigma_0^2 = 9)$$

And the observed variable subjects to:

$$p(x) = N(x | \mu, \sigma^2 = 4)$$

Having observed n variables, it is vital that the probability mass of μ 's posterior distribution is no less than 0.95 in an interval no longer than 1.

Posterior for μ is:

$$\begin{aligned} p(\mu | D) &\propto p(\mu) p(D | \mu) = N(\mu | \mu_0, \sigma_0^2) \prod_{i=1}^n N(x_i | \mu, \sigma^2) \\ &\propto \exp \left\{ -\frac{1}{2\sigma_0^2} (\mu - \mu_0)^2 \right\} \prod_{i=1}^n \exp \left\{ -\frac{1}{2\sigma^2} (x_i - \mu)^2 \right\} \\ &= \exp \left\{ \left(-\frac{1}{2\sigma_0^2} - \frac{n}{2\sigma^2} \right) \mu^2 + \dots \right\} \end{aligned}$$

Hence the posterior variance is given by:

$$\sigma_{post}^2 = \frac{\sigma_0^2 \sigma^2}{\sigma^2 + n\sigma_0^2}$$

Since 0.95 of probability mass for a normal distribution lies within -1.96σ and 1.96σ , we have:

$$n \geq 611$$

4.14 MAP estimation for 1d Gaussians

Assume the variance for this distribution σ^2 is known, the mean μ subject to a normal distribution with mean m and variance s^2 , similar to the question before, the posterior takes the form:

$$p(\mu|X) \propto p(\mu)p(X|\mu)$$

The posterior is another normal distribution, by comparing the coefficient for μ^2 :

$$-\frac{1}{2s^2} - \frac{N}{2\sigma^2}$$

And that for μ :

$$\frac{m}{s^2} + \frac{\sum_{n=1}^N x_n}{\sigma^2}$$

We have the posterior mean and variance by the technique "completing the square":

$$\sigma_{post}^2 = \frac{s^2 \sigma^2}{\sigma^2 + Ns^2}$$

$$\mu_{post} = \left(\frac{m}{s^2} + \frac{\sum_{n=1}^N x_n}{\sigma^2} \right) \cdot \sigma_{post}^2$$

Already we knew the MLE is:

$$\mu_{ML} = \frac{\sum_{n=1}^N x_i}{N}$$

When N increases, μ_{post} converges to μ_{ML} .

Consider the variance s^2 . When it increases, the MAP goes to MLE, when it decreases, the MAP goes to prior mean. Prior variance quantifies our confidence in the prior guess. Intuitively, the larger the prior variance, the less we trust the prior mean.

4.15 Sequential(recursive) updating of covariance matrix

Making use of:

$$\mathbf{m}_{n+1} = \frac{n\mathbf{m}_n + \mathbf{x}_{n+1}}{n+1}$$

What left is straightforward algebra.

4.16 Likelihood ratio for Gaussians

Consider a classifier for two classes, the generative distribution for them are two normal distributions $p(x|y = C_i) = N(x|\mu_i, \Sigma_i)$, by Bayes formula:

$$\log \frac{p(y=1|x)}{p(y=0|x)} = \log \frac{p(x|y=1)}{p(x|y=0)} + \log \frac{p(y=1)}{p(y=0)}$$

The second term is the ratio of likelihood probability.

When we have arbitrary covariance matrix:

$$\frac{p(x|y=1)}{p(x|y=0)} = \sqrt{\frac{|\Sigma_0|}{|\Sigma_1|}} \exp \left\{ -\frac{1}{2}(x - \mu_1)^T \Sigma_1^{-1} (x - \mu_1) + \frac{1}{2}(x - \mu_0)^T \Sigma_0^{-1} (x - \mu_0) \right\}$$

This can not be reduced further. However, it is noticable that the decision boundary is a quadric curve in D -dimension space.

When both covariance matrixes are given by Σ :

$$\frac{p(x|y=1)}{p(x|y=0)} = \exp \left\{ x^T \Sigma^{-1} (\mu_1 - \mu_0) - \frac{1}{2} \text{Tr} \{ \Sigma^{-1} (\mu_1 \mu_1^T - \mu_0 \mu_0^T) \} \right\}$$

The decision boundary becomes a plane.

If we assume the covariance matrix to be a diagonal matrix, the closed form of answer have a similar look, with some matrix multiplication changed into inner product or arithmetic multiplication.

4.17 LDA/QDA on height/weight data

Practise by yourself.

4.18 Naive Bayes with mixed features

Straightforward calculation.

4.19 Decision boundary for LDA with semi tied covariances

Omitting the shared parameters ends in:

$$p(y = 1|\mathbf{x}) = \frac{p(y = 1)p(\mathbf{x}|y = 1)}{p(y = 0)p(\mathbf{x}|y = 0) + p(y = 1)p(\mathbf{x}|y = 1)}$$

Consider a uniform prior, this can be reduced to:

$$\begin{aligned} & \frac{p(\mathbf{x}|y = 1)}{p(\mathbf{x}|y = 0) + p(\mathbf{x}|y = 1)} \\ = & \frac{1}{k^{\frac{D}{2}} \exp \left\{ -\frac{1}{2}(\mathbf{x} - \mu_0)^T \Sigma_0^{-1}(\mathbf{x} - \mu_0) + \frac{1}{2}(\mathbf{x} - \mu_1)^T \Sigma_1^{-1}(\mathbf{x} - \mu_1) \right\} + 1} \\ = & \frac{1}{k^{\frac{D}{2}} \exp \left\{ -\frac{1}{2}\left(1 - \frac{1}{k}\right)\mathbf{x}^T \Sigma_0^{-1}\mathbf{x} + \mathbf{x}^T \mathbf{u} + c \right\} + 1} \end{aligned}$$

Where we have used:

$$|\Sigma_1| = |k\Sigma_0| = k^D |\Sigma_0|$$

The decision boundary is still a quadric curve. It reduces to a plate when $k = 1$. When k increases, the decision boundary becomes a curve that surrenders μ_0 . When k goes to infinity, the decision boundary degenerates to a $y = 0$ curve, which implies that every space out of it belongs to a normal distribution with infinite variance.

4.20 Logistic regression vs LDA/QDA

We give a qualitative answer according to the argument "overfitting arises from MLE, and is in a positive correlation with the complexity of the model(namely the number of independent parameters in the model)".

GaussI assumes a covariance matrix propoetional to identity matrix;

GaussX has not prior assumption on covariance matrix;

LinLog assumes that different classes have the same covariance matrix;

QuadLog has not prior assumption on covariance matrix;

From the perspective of complexity:

QuadLog =GaussX > LinLog > GaussI

The accuracy of MLE follows the same order.

The argument in e is not true in general, a larger product does not necessarily imply a larger sum.

4.21 Gaussian decision boundaries

Straightforward algebra.

4.22 QDA with 3 classes

Straightforward calculation.

4.23 Scalar QDA

Practice by yourself.

5 Bayesian statistics

5.1 Proof that a mixture of conjugate priors is indeed conjugate

For 5.69 and 5.70, formly:

$$p(\theta|D) = \sum_k p(\theta, k|D) = \sum_k p(k|D)p(\theta|k, D)$$

Where:

$$p(k|D) = \frac{p(k, D)}{p(D)} = \frac{p(k)p(D|k)}{\sum_{k'} p(k')p(D|k')}$$

5.2 Optimal threshold on classification probability

The posterior loss expectation is given by:

$$\begin{aligned} \rho(\hat{y}|x) &= \sum_y L(\hat{y}, y)p(y|x) = p_0 L(\hat{y}, 0) + p_1 L(\hat{y}, 1) \\ &= L(\hat{y}, 1) + p_0(L(\hat{y}, 0) - L(\hat{y}, 1)) \end{aligned}$$

When two classficed result yield to the same loss:

$$\hat{p}_0 = \frac{\lambda_{01}}{\lambda_{01} + \lambda_{10}}$$

Hence when $p_0 \geq \hat{p}_0$, we estimate $\hat{y} = 0$.

5.3 Reject option in classifiers

The posterior loss expectation is given by:

$$\rho(a|x) = \sum_c L(a, c)p(c|x)$$

Denote the class with max posterior confidence by \hat{c} :

$$\hat{c} = \operatorname{argmax}_c \{p(c|x)\}$$

Now we have two applicable actions: $a = \hat{c}$ or $a = \text{reject}$.

When $a = \hat{c}$, the posterior loss expectation is:

$$\rho_{\hat{c}} = (1 - p(\hat{c}|x)) \cdot \lambda_s$$

When reject, the posterior loss expectation is:

$$\rho_{reject} = \lambda_r$$

Thus the condition that we choose $a = \hat{c}$ instead of reject is:

$$\rho_{\hat{c}} \geq \rho_{reject}$$

Or:

$$p(\hat{c}|x) \geq 1 - \frac{\lambda_r}{\lambda_s}$$

5.4 More reject options

Straightforward calculation.

5.5 Newsvendor problem

By:

$$\mathbb{E}(\pi|Q) = P \int_0^Q Df(D)dD - CQ \int_0^Q f(D)dD + (P - C)Q \int_Q^{+\infty} f(D)dD$$

We have:

$$\frac{\partial}{\partial Q} \mathbb{E}(\pi|Q) = PQf(Q) - C \int_0^Q f(D)dD - CQf(Q) + (P - C) \int_Q^{+\infty} f(D)dD - (P - C)Qf(Q)$$

Set it to zero by making use of $\int_0^Q f(D)dD + \int_Q^{+\infty} f(D)dD = 1$:

$$\int_0^{Q^*} f(D)dD = F(Q^*) = \frac{P - C}{P}$$

5.6 Bayes factors and ROC curves

Practise by yourself.

5.7 Bayes model averaging helps predictive accuracy

Expand both side of 5.127 and exchange the integral sequence:

$$\mathbb{E}[L(\Delta, p^{BMA})] = H(p^{BMA})$$

We also have:

$$\mathbb{E}[L(\Delta, p^m)] = \mathbb{E}_{p^{BMA}}[-\log(p^m)]$$

Subtract the right side from the left side ends in:

$$-KL(p^{BMA}||p^m) \leq 0$$

Hence the left side is always smaller than the right side.

5.8 MLE and model selection for a 2d discrete distribution

The joint distribution $p(x, y|\theta_1, \theta_2)$ is given by:

$$p(x=0, y=0) = (1-\theta_1)\theta_2$$

$$p(x=0, y=1) = (1-\theta_1)(1-\theta_2)$$

$$p(x=1, y=0) = \theta_1(1-\theta_2)$$

$$p(x=1, y=1) = \theta_1\theta_2$$

Which can be concluded as:

$$p(x, y|\theta_1, \theta_2) = \theta_1^x(1-\theta_1)^{(1-x)}\theta_2^{\mathbb{I}(x=y)}(1-\theta_2)^{(1-\mathbb{I}(x=y))}$$

The MLE is:

$$\theta_{ML} = \underset{\theta}{\operatorname{argmax}} \left(\sum_{n=1}^N \ln p(x_n, y_n|\theta) \right)$$

Hence:

$$\theta_{ML} = \underset{\theta}{\operatorname{argmax}} \left(N \ln\left(\frac{1-\theta_1}{1-\theta_2}\right) + N_x \ln\left(\frac{\theta_1}{1-\theta_1}\right) + N_{\mathbb{I}(x=y)} \ln\left(\frac{\theta_2}{1-\theta_2}\right) \right)$$

Two parameters can be estimated independently given \mathbf{X} and \mathbf{Y} .

We can further rewrite the joint distribution into:

$$p(x, y|\theta) = \theta_{x,y}$$

Then

$$\theta_{ML} = \underset{\theta}{\operatorname{argmax}} \left(\sum_{x,y} N_{x,y} \ln \theta_{x,y} \right)$$

MLE can be done by using regularization condition.

The rest is straightforward algebra.

5.9 Posterior median is optimal estimate under L1 loss

The posterior loss expectation is (where we have omitted D w.l.o.g):

$$\begin{aligned}\rho(a) &= \int |y - a|p(y)dy = \int_{-\infty}^a (a - y)p(y)dy + \int_a^{+\infty} (y - a)p(y)dy \\ &= a \left\{ \int_{-\infty}^a p(y)dy - \int_a^{+\infty} p(y)dy \right\} - \int_{-\infty}^a yp(y)dy + \int_a^{+\infty} yp(y)dy\end{aligned}$$

Differentiate and we have:

$$\frac{\partial}{\partial a}\rho(a) = \left\{ \int_{-\infty}^a p(y)dy - \int_a^{+\infty} p(y)dy \right\} + a \cdot 2p(a) - 2ap(a)$$

Set it to zero and:

$$\int_{-\infty}^a p(y)dy = \int_a^{+\infty} p(y)dy = \frac{1}{2}$$

5.10 Decision rule for trading off FPs and FNs

Given:

$$L_{FN} = cL_{FP}$$

The critical condition for 5.115 is:

$$\frac{p(y = 1|x)}{p(y = 2|x)} = c$$

Using:

$$p(y = 1|x) + p(y = 0|x) = 1$$

We get the threshold $\frac{c}{1+c}$.

6 Frequentist statistics

The philosophy behind this chapter is out of the scope of probabilistic ML, you should be able to find solutions to the four listed problems in a decent textbook on mathematics statistics.

GL.

7 Linear regression

7.1 Behavior of training set error with increasing sample size

When the training set is small at the beginning, the trained model is over-fitted to the current data set, so the correct rate can be relatively high. As the training set increases, the model has to learn to adapt to more general-purpose parameters, thus reducing the overfitting effect laterally, resulting in lower accuracy.

As pointed out in Section 7.5.4, increasing the training set is an important method of countering over-fitting besides adding regularizer.

7.2 Multi-output linear regression

Straightforward calculation.

7.3 Centering and ridge regression

By rewriting \mathbf{x} into $(\mathbf{x}^T, 1)^T$ to reduce w_0 , then NLL is given by:

$$NLL(\mathbf{w}) = (\mathbf{y} - \mathbf{X}\mathbf{w})^T(\mathbf{y} - \mathbf{X}\mathbf{w}) + \lambda \mathbf{w}^T \mathbf{w}$$

So:

$$\frac{\partial}{\partial \mathbf{w}} NLL(\mathbf{w}) = 2\mathbf{X}^T \mathbf{X} \mathbf{w} - 2\mathbf{X}^T \mathbf{y} + 2\lambda \mathbf{w}$$

Therefore:

$$\mathbf{w} = (\mathbf{X}^T \mathbf{X} + \lambda \mathbf{I})^{-1} \mathbf{X}^T \mathbf{y}$$

7.4 MLE for σ^2 for linear regression

Firstly, we give the likelihood:

$$\begin{aligned}
 p(D|\mathbf{w}, \sigma^2) &= p(\mathbf{y}|\mathbf{w}, \sigma^2, \mathbf{X}) \\
 &= \prod_{n=1}^N p(y_n|\mathbf{x}_n, \mathbf{w}, \sigma^2) \\
 &= \prod_{n=1}^N N(y_n|\mathbf{w}^T \mathbf{x}_n, \sigma^2) \\
 &= \frac{1}{(2\pi\sigma^2)^{\frac{N}{2}}} \exp \left\{ -\frac{1}{2\sigma^2} \sum_{n=1}^N (y_n - \mathbf{w}^T \mathbf{x}_n)^2 \right\}
 \end{aligned}$$

As for σ^2 :

$$\frac{\partial}{\partial \sigma^2} \log p(D|\mathbf{w}, \sigma^2) = -\frac{N}{2\sigma^2} + \frac{1}{2(\sigma^2)^2} \sum_{n=1}^N (y_n - \mathbf{w}^T \mathbf{x}_n)^2$$

We have:

$$\sigma_{ML}^2 = \frac{1}{N} \sum_{n=1}^N (y_n - \mathbf{w}^T \mathbf{x}_n)^2$$

7.5 MLE for the offset term in linear regression

NLL:

$$NLL(\mathbf{w}, w_0) \propto \sum_{n=1}^N (y_n - w_0 - \mathbf{w}^T \mathbf{x}_n)^2$$

Differentiate with two parameters:

$$\frac{\partial}{\partial w_0} NLL(\mathbf{w}, w_0) \propto -Nw_0 + \sum_{n=1}^N (y_n - \mathbf{w}^T \mathbf{x}_n)$$

$$w_{0,ML} = \frac{1}{N} \sum_{n=1}^N (y_n - \mathbf{w}^T \mathbf{x}_n) = \bar{y} - \mathbf{w}^T \bar{\mathbf{x}}$$

Centering within \mathbf{X} and \mathbf{y} :

$$\mathbf{X}_c = \mathbf{X} - \hat{\mathbf{X}}$$

$$\mathbf{y}_c = \mathbf{y} - \hat{\mathbf{y}}$$

The centered datasets have zero-mean, thus regression model have w_0 as zero, by the same time:

$$\mathbf{w}_{ML} = (\mathbf{X}_c^T \mathbf{X}_c)^{-1} \mathbf{X}_c^T \mathbf{y}_c$$

7.6 MLE for simple linear regression

Using the conclusion from problem 7.5. What left is straightforward algebra.

7.7 Sufficient statistics for online linear regression

a and b can be solved according to hints.

For c, substituting the x in hint by y yields to the conclusion.

In d we are to prove:

$$(n+1)C_{xy}^{(n+1)} = nC_{xy}^{(n)} + x_{n+1}y_{n+1} + n\bar{x}^{(n)}\bar{y}^{(n)} - (n+1)\bar{x}^{(n+1)}\bar{y}^{(n+1)}$$

Expand the C_{xy} in two sides and use $\bar{x}^{(n+1)} = \bar{x}^{(n)} + \frac{1}{n+1}(x_{n+1} - \bar{x}^{(n)})$.

Problem e and f: practice by yourself.

7.8 Bayesian linear regression in 1d with known σ^2

Problem a: practice by yourself.

For b, choose the prior distribution:

$$p(\mathbf{w}) \propto N(w_1|0, 1) \propto \exp\left\{-\frac{1}{2}w_1^2\right\}$$

Reduce it into:

$$p(\mathbf{w}) = N(\mathbf{w}|\mathbf{w}_0, \mathbf{V}_0) \propto \exp\left\{-\frac{1}{2}\mathbf{V}_{0,11}^{-1}(w_0 - w_{00})^2 - \frac{1}{2}\mathbf{V}_{0,22}^{-1}(w_1 - w_{01})^2 - \mathbf{V}_{0,12}^{-1}(w_0 - w_{00})(w_1 - w_{01})\right\}$$

Formly, we take:

$$w_{01} = 0$$

$$\mathbf{V}_{0,22}^{-1} = 1$$

$$\mathbf{V}_{0,11}^{-1} = \mathbf{V}_{0,12}^{-1} = 0$$

$$w_{00} = \text{arbitrary}$$

In problem c, we consider the posterior distribution for parameters:

$$p(\mathbf{w}|D, \sigma^2) = N(\mathbf{w}|\mathbf{m}_0, \mathbf{V}_0) \prod_{n=1}^N N(y_n|w_0 + w_1 x_n, \sigma^2)$$

The coefficients for w_1^2 and w_1 in the exponential are:

$$-\frac{1}{2} - \frac{1}{2\sigma^2} \sum_{n=1}^N x_n^2$$

$$-\frac{1}{\sigma^2} \sum_{n=1}^N x_n(w_0 - y)$$

Hence the posterior mean and variance are given by:

$$\sigma_{post}^2 = \frac{\sigma^2}{\sigma^2 + \sum_{n=1}^N x_n^2}$$

$$\mathbb{E}[w_1|D, \sigma^2] = \sigma_{post}^2 \left(-\frac{1}{\sigma^2} \sum_{n=1}^N x_n(w_0 - y) \right)$$

It can be noticed that accumulation of samples reduces the posterior variance.

7.9 Generative model for linear regression

For sake of convinence, we consider a centered dataset (without changing symbols):

$$w_0 = 0$$

$$\mu_x = \mu_y = 0$$

By covariance's definition:

$$\Sigma_{XX} = X^T X$$

$$\Sigma_{YX} = Y^T X$$

Using the conclusion from section 4.3.1:

$$p(Y|X = x) = N(Y|\mu_{Y|X}, \Sigma_{Y|X})$$

Where:

$$\mu_{Y|X} = \mu_Y + \Sigma_{YX} \Sigma_{XX}^{-1} (X - \mu_X) = Y^T X (X^T X)^{-1} X = \mathbf{w}^T X$$

7.10 Bayesian linear regression using the g-prior

Recall ridge regression model, where we have likelihood:

$$p(D|\mathbf{w}, \sigma^2) = \prod_{n=1}^N N(y_n|\mathbf{w}^T \mathbf{x}_n, \sigma^2)$$

The prior distribution is Gaussian-Inverse Gamma distribution:

$$\begin{aligned} p(\mathbf{w}, \sigma^2) &= NIG(\mathbf{w}, \sigma^2 | \mathbf{w}_0, \mathbf{V}_0, a_0, b_0) = N(\mathbf{w} | \mathbf{w}_0, \sigma^2 \mathbf{V}_0) IG(\sigma^2 | a_0, b_0) \\ &= \frac{1}{(2\pi)^{\frac{D}{2}}} \frac{1}{|\sigma^2 \mathbf{V}_0|^{\frac{1}{2}}} \exp \left\{ -\frac{1}{2} (\mathbf{w} - \mathbf{w}_0)^T (\sigma^2 \mathbf{V}_0)^{-1} (\mathbf{w} - \mathbf{w}_0) \right\} \cdot \\ &\quad \frac{b_0^{a_0}}{\Gamma(a_0)} (\sigma^2)^{-(a_0+1)} \exp \left\{ -\frac{b_0}{\sigma^2} \right\} \\ &= \frac{b_0^{a_0}}{(2\pi)^{\frac{D}{2}} |\mathbf{V}_0|^{\frac{1}{2}} \Gamma(a_0)} (\sigma^2)^{-(a_0+\frac{D}{2}+1)} \cdot \exp \left\{ -\frac{(\mathbf{w} - \mathbf{w}_0)^T \mathbf{V}_0^{-1} (\mathbf{w} - \mathbf{w}_0) + 2b_0}{2\sigma^2} \right\} \end{aligned}$$

The posterior distribution takes the form:

$$\begin{aligned} p(\mathbf{w}, \sigma^2 | D) &\propto p(\mathbf{w}, \sigma^2) p(D | \mathbf{w}, \sigma^2) \\ &\propto \frac{b_0^{a_0}}{(2\pi)^{\frac{D}{2}} |\mathbf{V}_0|^{\frac{1}{2}} \Gamma(a_0)} (\sigma^2)^{-(a_0+\frac{D}{2}+1)} \cdot \exp \left\{ -\frac{(\mathbf{w} - \mathbf{w}_0)^T \mathbf{V}_0^{-1} (\mathbf{w} - \mathbf{w}_0) + 2b_0}{2\sigma^2} \right\} \cdot \\ &\quad (\sigma^2)^{-\frac{N}{2}} \cdot \exp \left\{ -\frac{\sum_{n=1}^N (y_n - \mathbf{w}^T \mathbf{x}_n)^2}{2\sigma^2} \right\} \end{aligned}$$

Comparing the coefficient of σ^2 :

$$a_N = a_0 + \frac{N}{2}$$

Comparing the coefficient of $\mathbf{w}^T \mathbf{w}$:

$$\mathbf{V}_N^{-1} = \mathbf{V}_0^{-1} + \sum_{n=1}^N \mathbf{x}_n \mathbf{x}_n^T = \mathbf{V}_0^{-1} + \mathbf{X}^T \mathbf{X}$$

Comparing the coefficient of \mathbf{w} :

$$\mathbf{V}_N^{-1} \mathbf{w}_N = \mathbf{V}_0^{-1} \mathbf{w}_0 + \sum_{n=1}^N y_n \mathbf{x}_n$$

Thus:

$$\mathbf{w}_N = \mathbf{V}_N (\mathbf{V}_0^{-1} \mathbf{w}_0 + \mathbf{X}^T \mathbf{y})$$

Finally, comparing the constant term inside the exponential:

$$b_N = b_0 + \frac{1}{2}(\mathbf{w}_0^T \mathbf{V}_0^{-1} \mathbf{w}_0 + \mathbf{y}^T \mathbf{y} - \mathbf{w}_N^T \mathbf{V}_N^{-1} \mathbf{w}_N)$$

We have obtained 7.70 to 7.73, which can be concluded into 7.69:

$$p(\mathbf{w}, \sigma^2 | D) = NIG(\mathbf{w}, \sigma^2 | \mathbf{w}_N, \mathbf{V}_N, a_N, b_N)$$

8 Logistic regression

8.1 Spam classification using logistic regression

Practice by yourself.

8.2 Spam classification using naive Bayes

Practice by yourself.

8.3 Gradient and Hessian of log-likelihood for logistic regression

$$\frac{\partial}{\partial a} \sigma(a) = \frac{\exp(-a)}{(1 + \exp(-a))^2} = \frac{1}{1 + e^{-a}} \frac{e^{-a}}{1 + e^{-a}} = \sigma(a)(1 - \sigma(a))$$

$$\begin{aligned} g(\mathbf{w}) &= \frac{\partial}{\partial \mathbf{w}} NLL(\mathbf{w}) \\ &= \sum_{n=1}^N \frac{\partial}{\partial \mathbf{w}} [y_i \log \mu_i + (1 - y_i) \log(1 - \mu_i)] \\ &= \sum_{n=1}^N y_i \frac{1}{\sigma} \sigma(1 - \sigma) - \mathbf{x}_i + (1 - y_i) \frac{-1}{1 - \sigma} \sigma(1 - \sigma) - \mathbf{x}_i \\ &= \sum_{n=1}^N (\sigma(\mathbf{w}^T \mathbf{x}_i) - y_i) \mathbf{x}_i \end{aligned}$$

For an arbitrary non-zero vector \mathbf{u} (with proper shape):

$$\mathbf{u}^T \mathbf{X}^T \mathbf{S} \mathbf{X} \mathbf{u} = (\mathbf{X} \mathbf{u})^T \mathbf{S} (\mathbf{X} \mathbf{u})$$

Since \mathbf{S} is positive definite, for arbitrary non-zero \mathbf{v} :

$$\mathbf{v}^T \mathbf{S} \mathbf{v} > 0$$

Assume \mathbf{X} is a full-rank matrix, $\mathbf{X} \mathbf{u}$ is not zero, thus:

$$(\mathbf{X} \mathbf{u})^T \mathbf{S} (\mathbf{X} \mathbf{u}) = \mathbf{u}^T (\mathbf{X}^T \mathbf{S} \mathbf{X}) \mathbf{u} > 0$$

So $\mathbf{X}^T \mathbf{S} \mathbf{X}$ is positive definite.

8.4 Gradient and Hessian of log-likelihood for multinomial logistic regression

By considering one independent component each time, the complexity in form caused by tensor product is reduced. For a specific \mathbf{w}^* :

$$\begin{aligned}\frac{\partial}{\partial \mathbf{w}^*} NLL(\mathbf{W}) &= - \sum_{n=1}^N \frac{\partial}{\partial \mathbf{w}^*} [y_{n*} \mathbf{w}^{*T} \mathbf{x}_n - \log(\sum_{c=1}^C \exp(\mathbf{w}_c^T \mathbf{x}_n))] \\ \sum_{n=1}^N -y_{n*} \mathbf{x}_n + \frac{\exp(\mathbf{w}^{*T} \mathbf{x}_n)}{\sum_{c=1}^C \exp(\mathbf{w}_c^T \mathbf{x}_n)} \mathbf{x}_n &= \sum_{n=1}^N (\mu_{n*} - y_{n*}) \mathbf{x}_n\end{aligned}$$

Combine the independent solutions for all classes into one matrix yield 8.38.

On solving for Hessian matrix, consider to take gradient w.r.t \mathbf{w}_1 and \mathbf{w}_2 :

$$\mathbf{H}_{1,2} = \nabla_{\mathbf{w}_2} \nabla_{\mathbf{w}_1} NLL(\mathbf{W}) = \frac{\partial}{\partial \mathbf{w}_2} \sum_{n=1}^N (\mu_{n1} - y_{n1}) \mathbf{x}_n$$

When \mathbf{w}_1 and \mathbf{w}_2 are the same:

$$\begin{aligned}\frac{\partial}{\partial \mathbf{w}_1} \sum_{n=1}^N (\mu_{n1} - y_{n1}) \mathbf{x}_n^T &= \sum_{n=1}^N \frac{\partial}{\partial \mathbf{w}_1} \mu_{n1} \mathbf{x}_n^T \\ \sum_{n=1}^N \frac{\exp(\mathbf{w}_1^T \mathbf{x}_n) (\sum \exp) \mathbf{x}_n - \exp(\mathbf{w}_1^T \mathbf{x}_n)^2 \mathbf{x}_n}{(\sum \exp)^2} \mathbf{x}_n^T \\ &= \sum_{n=1}^N \mu_{n1} (1 - \mu_{n1}) \mathbf{x}_n \mathbf{x}_n^T\end{aligned}$$

When \mathbf{w}_1 and \mathbf{w}_2 are different:

$$\begin{aligned}\frac{\partial}{\partial \mathbf{w}_2} \sum_{n=1}^N \mu_{n1} \mathbf{x}_n^T &= \sum_{n=1}^N \frac{-\exp(\mathbf{w}_2^T \mathbf{x}_n) \exp(\mathbf{w}_1^T \mathbf{x}_n) \mathbf{x}_n}{(\sum \exp)^2} \mathbf{x}_n^T \\ &= \sum_{n=1}^N -\mu_{n1} \mu_{n2} \mathbf{x}_n \mathbf{x}_n^T\end{aligned}$$

Ends in 8.44.

The condition $\sum_c y_{nc} = 1$ is used from 8.34 to 8.35.

8.5 Symmetric version of l2 regularized multinomial logistic regression

Adding a regularizer equals doing a posterior estimation, which equals introducing a language multiplier for a new constraint. In this problem a Gaussian prior distribution with a homogeneous diagonal matrix is introduced, this leads to the constraint $w_{cj} = 0$.

At optima, the gradient in 8.47 goes to zero. Assume that $\hat{\mu}_{cj} = y_{cj}$, then $g(\mathbf{W}) = 0$. The extra regularization is $\lambda \sum_{c=1}^C \mathbf{w}_c = 0$, which equals D independent linear constraints, with form of: for $j = 1 \dots D$, $\sum_{c=1}^C \hat{w}_{cj} = 0$.

8.6 Elementary properties of l2 regularized logistic regression

The first term of $J(\mathbf{w})$'s Hessian is positive definite(8.7), the second term's Hessian is positive definite as well($\lambda > 0$). Therefore this function has a positive definite Hessian, it has a global optimum.

The form of posterior distribution takes:

$$p(\mathbf{w}|D) \propto p(D|\mathbf{w})p(\mathbf{w})$$

$$p(\mathbf{w}) = N(\mathbf{w}|\mathbf{0}, \sigma^{-2}\mathbf{I})$$

$$NLL(\mathbf{w}) = -\log p(\mathbf{w}|D) = -\log p(D|\mathbf{w}) + \frac{1}{2\sigma^2} \mathbf{w}^T \mathbf{w} + c$$

Therefore:

$$\lambda = \frac{1}{2\sigma^2}$$

The number of zero in global optimum is related to the value of λ , which is in a negative correlation with the prior uncertainty of \mathbf{w} . The less the uncertainty is, the more that \mathbf{w} converges to zero, which ends in more zeros in answer.

If $\lambda = 0$, which implies prior uncertainty goes to infinity. Then posterior estimation converges to MLE. As long as there is no constraint on \mathbf{w} , it is possible that some component of \mathbf{w} goes to infinity.

When λ increase, the prior uncertainty reduces, hence the over-fitting effect reduces. Generally this implies a decrease on training-set accuracy.

At the same time, this also increases the accuracy of model on test-set, but it does not always happen.

8.7 Regularizing separate terms in 2d logistic regression

Practice by yourself.

9 Generalized linear models and the exponential family

9.1 Conjugate prior for univariate Gaussian in exponential family form

The 1d Gaussian distribution is:

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

Rewrite it into:

$$p(x|\mu, \sigma^2) = \exp \left\{ -\frac{1}{2\sigma^2}x^2 + \frac{1}{\sigma^2}x - \left\{ \frac{\mu^2}{2\sigma^2} + \frac{\ln(2\pi\sigma^2)}{2} \right\} \right\}$$

Denote $\theta = (-\frac{\lambda}{2}, \lambda\mu)^T$, $A(\theta) = \frac{\lambda\mu^2}{2} + \frac{\ln(2\pi)}{2} - \frac{\ln\lambda}{2}$, $\phi(x) = (x^2, x)^T$.

Consider the likelihood with dataset D :

$$\log p(D|\theta) = \exp \left\{ \theta^T \left(\sum_{n=1}^N \phi(x_n) \right) - N \cdot A(\theta) \right\}$$

According to the meaning of prior distribution, we set a observation background in order to define a prior distribution. The sufficient statistics is the only thing matters by the form of exponential family. Assume that we have M prior observations. The mean of them and their square are v_1 and v_2 respectively, then the prior distribution takes the form:

$$\begin{aligned} p(\theta|M, v_1, v_2) &= \exp \{ \theta_1 \cdot Mv_1 + \theta_2 \cdot Mv_2 - M \cdot A(\theta) \} \\ &= \exp \left\{ -\frac{\lambda}{2}Mv_1 + \lambda\mu Mv_2 - \frac{M}{2}\lambda\mu^2 - \frac{M}{2}\ln 2\pi + \frac{M}{2}\ln \lambda \right\} \end{aligned}$$

It has three independent parameters. We are to prove that is equals $p(\mu, \lambda) = N(\mu|\gamma, \frac{1}{\lambda(2\alpha-1)})Ga(\lambda|\alpha, \beta)$. Expand it into exponential form and ignore the terms independent with μ, λ :

$$\begin{aligned} p(\mu, \lambda) &= \exp \left\{ (\alpha - 1) \ln \lambda - \beta \lambda - \frac{\lambda(2\alpha - 1)}{2} \mu^2 - \frac{\lambda(2\alpha - 1)}{2} \gamma^2 \right\} \\ &\quad \cdot \exp \left\{ \lambda(2\alpha - 1) \mu \gamma + \frac{1}{2} \ln \lambda \right\} \end{aligned}$$

Compare the coefficients for $\lambda\mu^2, \lambda\mu, \lambda, \ln \lambda$, we obtain:

$$\begin{aligned} -\frac{(2\alpha-1)}{2} &= -\frac{M}{2} \\ \gamma(2\alpha-1) &= Mv_2 \\ \frac{(2\alpha-1)}{2}\gamma^2 - \beta &= -\frac{1}{2}Mv_1 \\ (\alpha-1) + \frac{1}{2} &= \frac{M}{2} \end{aligned}$$

Combining them ends in:

$$\begin{aligned} \alpha &= \frac{M+1}{2} \\ \beta &= \frac{M}{2}(v_2^2 + v_1) \\ \gamma &= v_2 \end{aligned}$$

Thus two distributions are equal with naive change of variables' names.

9.2 The MVN is in the exponential family

Here you can find a comprehensive solution:

<https://stats.stackexchange.com/questions/231714/sufficient-statistic-for-multivari>

10 Directed graphical models(Bayes nets)

...

11 Mixture models and the EM algorithm

11.1 Student T as infinite mixture of Gaussian

The 1d Student-t distribution takes the form:

$$St(x|\mu, \sigma^2, v) = \frac{\Gamma(\frac{v}{2} + \frac{1}{2})}{\Gamma(\frac{v}{2})} \left(\frac{1}{\pi v \sigma^2}\right)^{\frac{1}{2}} \left(1 + \frac{(x - \mu)^2}{v \sigma^2}\right)^{-\frac{v+1}{2}}$$

Consider the left side of 11.61:

$$\begin{aligned} & \int N(x|\mu, \frac{\sigma^2}{z}) Ga(z|\frac{v}{2}, \frac{v}{2}) dz \\ &= \int \frac{\sqrt{z}}{\sqrt{2\pi\sigma^2}} \exp\left\{-\frac{z}{2\sigma^2}(x - \mu)^2\right\} \frac{(\frac{v}{2})^{\frac{v}{2}}}{\Gamma(\frac{v}{2})} z^{\frac{v}{2}-1} \exp\left\{-\frac{v}{2}z\right\} dz \\ &= \frac{1}{\sqrt{2\pi\sigma^2}} \frac{(\frac{v}{2})^{\frac{v}{2}}}{\Gamma(\frac{v}{2})} \int z^{\frac{v-1}{2}} \exp\left\{-\left(\frac{v}{2} + \frac{(x - \mu)^2}{2\sigma^2}\right)z\right\} dz \end{aligned}$$

The integrated function is the terms related to z in Gamma distribution $Ga(z|\frac{v+1}{2}, \frac{(x-\mu)^2}{2\sigma^2} + \frac{v}{2})$, which gives to the normalized term's inverse.

$$\int z^{\frac{v-1}{2}} \exp\left\{-\left(\frac{v}{2} + \frac{(x - \mu)^2}{\sigma^2}\right)z\right\} dz = \Gamma\left(\frac{v+1}{2}\right) \left(\frac{(x - \mu)^2}{2\sigma^2} + \frac{v}{2}\right)^{-\frac{v+1}{2}}$$

Plug in can derive 11.61.

11.2 EM for mixture of Gaussians

We are to optimize:

$$\begin{aligned} Q(\theta, \theta^{old}) &= \mathbb{E}_p(z|D, \theta^{old}) \left[\sum_{n=1}^N \log(\mathbf{x}_n, \mathbf{z}_n|\theta) \right] \\ &= \sum_{n=1}^N \mathbb{E} \left[\log \prod_{k=1}^K (\pi_k p(\mathbf{x}_n|z_k, \theta))^{z_{nk}} \right] \\ &= \sum_{n=1}^N \sum_{k=1}^K r_{nk} \log(\pi_k p(\mathbf{x}_n|z_k, \theta)) \end{aligned}$$

Where:

$$r_{nk} = p(z_{nk} = 1|\mathbf{x}_n, \theta^{old})$$

When the emission distribution $p(\mathbf{x}|z, \theta)$ is Gaussian, consider the terms involve μ_k in $Q(\theta, \theta^{old})$ first:

$$\sum_{n=1}^N r_{nk} \log p(\mathbf{x}_n|z_k, \theta) = \sum_{n=1}^N r_{nk} \left(-\frac{1}{2}\right) (\mathbf{x}_n - \mu_k)^T \Sigma^{-1} (\mathbf{x}_n - \mu_k) + C$$

Setting the derivative to zero results in:

$$\sum_{n=1}^N r_{nk} (\mu_k - \mathbf{x}_n) = 0$$

And we obtain 11.31:

$$\mu_k = \frac{\sum_{n=1}^N r_{nk} \mathbf{x}_n}{\sum_{n=1}^N r_{nk}}$$

For terms involve Σ_k in $Q(\theta, \theta^{old})$:

$$\sum_{n=1}^N r_{nk} \log p(\mathbf{x}_n|z_k, \theta) = \sum_{n=1}^N r_{nk} \left(-\frac{1}{2}\right) (\log |\Sigma_k| + (\mathbf{x}_n - \mu_k)^T \Sigma^{-1} (\mathbf{x}_n - \mu_k)) + C$$

Using the same way as in 4.1.3.1:

$$L(\Sigma^{-1} = \Lambda) = \left(\sum_{n=1}^N r_{nk}\right) \log |\Lambda| - Tr \left\{ \left(\sum_{n=1}^N r_{nk} (\mathbf{x}_n - \mu_k) (\mathbf{x}_n - \mu_k)^T\right) \Lambda \right\}$$

The balance condition is:

$$\left(\sum_{n=1}^N r_{nk}\right) \Lambda^{-T} = \sum_{n=1}^N r_{nk} (\mathbf{x}_n - \mu_k) (\mathbf{x}_n - \mu_k)^T$$

Obtain 11.32:

$$\Sigma_k = \frac{\sum_{n=1}^N r_{nk} (\mathbf{x}_n - \mu_k) (\mathbf{x}_n - \mu_k)^T}{\sum_{n=1}^N r_{nk}}$$

11.3 EM for mixtures of Bernoullis

During the MLE for mixtures of Bernoullis, consider ($D = 2$ marks the number of potential elements):

$$\begin{aligned} \frac{\partial}{\partial \mu_{kj}} \sum_{n=1}^N \sum_{k=1}^K r_{nk} \log p(\mathbf{x}_n|\theta, k) &= \sum_{n=1}^N r_{nk} \frac{\partial}{\partial \mu_{kj}} \left(\sum_i^D x_{ni} \log \mu_{ki} \right) \\ &= \sum_{n=1}^N r_{nk} x_{nj} \frac{1}{\mu_{kj}} \end{aligned}$$

Introduce a multiplier to constrain $\sum_j \mu_{kj} = 1$, then condition for the derivative to be zero is:

$$\mu_{kj} = \frac{\sum_{n=1}^N r_{nk} x_{nj}}{\lambda}$$

Summer over all j :

$$1 = \sum_{j=1}^D \mu_{kj} = \frac{1}{\lambda} \sum_{j=1}^D \sum_{n=1}^N r_{nk} x_{nj} = \frac{1}{\lambda} \sum_{n=1}^N r_{nk} \sum_{j=1}^D x_{nj} = \frac{\sum_{n=1}^N r_{nk}}{\lambda}$$

Results in:

$$\lambda = \sum_{n=1}^N r_{nk}$$

Hence 11.116.

Introduce a prior:

$$p(\mu_{k0}) \propto \mu_{k0}^{\alpha-1} \mu_{k1}^{\beta-1}$$

The zero-derivative condition becomes:

$$\begin{aligned} \mu_{k0} &= \frac{\sum_{n=1}^N r_{nk} x_{n0} + \alpha - 1}{\lambda} \\ \mu_{k1} &= \frac{\sum_{n=1}^N r_{nk} x_{n1} + \beta - 1}{\lambda} \end{aligned}$$

And:

$$\begin{aligned} 1 &= \mu_{k0} + \mu_{k1} = \frac{1}{\lambda} \left(\sum_{n=1}^N r_{nk} (x_{n0} + x_{n1}) + \alpha + \beta - 2 \right) \\ \lambda &= \sum_{n=1}^N r_{nk} + \alpha + \beta - 2 \end{aligned}$$

Hence 11.117.

11.4 EM for mixture of Student distributions

The log-likelihood for complete data set is:

$$\begin{aligned} l_c(\mathbf{x}, z) &= \log(N(\mathbf{x}|\mu, \frac{\Sigma}{z}) Ga(z|\frac{\lambda}{2}, \frac{\lambda}{2})) \\ &= -\frac{D}{2} \log(2\pi) - \frac{1}{2} \log |\Sigma| + \frac{D}{2} \log(z) - \frac{z}{2} (\mathbf{x} - \mu)^T \Sigma^{-1} (\mathbf{x} - \mu) + \end{aligned}$$

$$\frac{v}{2} \log\left(\frac{v}{2}\right) - \log\left(\Gamma\left(\frac{v}{2}\right)\right) + \left(\frac{v}{2} - 1\right) \log(z) - \frac{v}{2} z$$

Sum the terms involving v :

$$l_v(\mathbf{x}, z) = \frac{v}{2} \log\left(\frac{v}{2}\right) - \log\left(\Gamma\left(\frac{v}{2}\right)\right) + \frac{v}{2} (\log(z) - z)$$

The likelihood w.r.t v on complete data set is:

$$L_v = \frac{vN}{2} \log\left(\frac{v}{2}\right) - N \log\left(\Gamma\left(\frac{v}{2}\right)\right) + \frac{v}{2} \sum_{n=1}^N (\log(z_n) - z_n)$$

Setting derivative to zero gives:

$$\frac{\nabla \Gamma\left(\frac{v}{2}\right)}{\Gamma\left(\frac{v}{2}\right)} - 1 - \log\left(\frac{v}{2}\right) = \frac{\sum_{n=1}^N (\log(z_n) - z_n)}{N}$$

For μ and Σ :

$$l_{\mu, \Sigma}(\mathbf{x}, z) = -\frac{1}{2} \log |\Sigma| - \frac{z}{2} (\mathbf{x} - \mu)^T \Sigma^{-1} (\mathbf{x} - \mu)$$

$$L_{\mu, \Sigma} = \frac{N}{2} \log |\Sigma| - \frac{1}{2} \sum_{n=1}^N z_n (\mathbf{x}_n - \mu)^T \Sigma^{-1} (\mathbf{x}_n - \mu)$$

Hence equals the MLE used for MVN.

11.5 Gradient descent for fitting GMM

From the given information:

$$p(\mathbf{x}|\theta) = \sum_k \pi_k N(\mathbf{x}|\mu_k, \Sigma_k)$$

$$l(\theta) = \sum_{n=1}^N \log p(\mathbf{x}_n|\theta)$$

Deriavte w.r.t μ_k :

$$\begin{aligned} \frac{\partial}{\partial \mu_k} l(\theta) &= \sum_{n=1}^N \frac{\pi_k N(\mathbf{x}_n|\mu_k, \Sigma_k) \nabla_{\mu_k} \left\{ -\frac{1}{2} (\mathbf{x}_n - \mu_k)^T \Sigma_k^{-1} (\mathbf{x}_n - \mu_k) \right\}}{\sum_{k'=1}^K \pi_{k'} N(\mathbf{x}_n|\mu_{k'}, \Sigma_{k'})} \\ &= \sum_{n=1}^N r_{nk} \Sigma_k^{-1} (\mathbf{x}_n - \mu_k) \end{aligned}$$

w.r.t π_k :

$$\frac{\partial}{\partial \pi_k} l(\theta) = \sum_{n=1}^N \frac{N(\mathbf{x}_n | \mu_k, \Sigma_k)}{\sum_{k'=1}^K \pi_{k'} N(\mathbf{x}_n | \mu_{k'}, \Sigma_{k'})} = \frac{1}{\pi_k} \sum_{n=1}^N r_{nk}$$

Using Lagrange multiplier ends in:

$$\pi_k = \frac{\sum_{n=1}^N r_{nk}}{\lambda}$$

Sum over k and normalize:

$$\pi_k = \frac{\sum_{n=1}^N r_{nk}}{N}$$

For Σ_k :

$$\frac{\partial}{\partial \Sigma_k} l(\theta) = \sum_{n=1}^N \frac{\pi_k \nabla_{\Sigma_k} N(\mathbf{x}_n | \mu_k, \Sigma_k)}{\sum_{k'=1}^K \pi_{k'} N(\mathbf{x}_n | \mu_{k'}, \Sigma_{k'})}$$

Where:

$$\begin{aligned} \nabla_{\Sigma_k} N(\mathbf{x} | \mu_k, \Sigma_k) &= \frac{1}{(2\pi)^{\frac{D}{2}}} \frac{1}{|\Sigma_k|^{\frac{1}{2}}} \exp \left\{ -\frac{1}{2} (\mathbf{x} - \mu_k)^T \Sigma_k^{-1} (\mathbf{x} - \mu_k) \right\} \nabla_{\Sigma_k} \\ &\quad \left\{ \nabla_{\Sigma_k} \left(-\frac{1}{2} (\mathbf{x} - \mu_k)^T \Sigma_k^{-1} (\mathbf{x} - \mu_k) \right) - \Sigma_k^{-1} \nabla_{\Sigma_k} |\Sigma_k| \right\} \\ &= N(\mathbf{x} | \mu_k, \Sigma_k) \nabla (\log N(\mathbf{x} | \mu_k, \Sigma_k)) \end{aligned}$$

Thus we have:

$$\Sigma_k = \frac{\sum_{n=1}^N r_{nk} (\mathbf{x}_n - \mu_k)(\mathbf{x}_n - \mu_k)^T}{\sum_{n=1}^N r_{nk}}$$

11.6 EM for a finite scale mixture of Gaussians

J and K are independent, using Bayes' rules (we have omitted θ in condition w.l.o.g):

$$\begin{aligned} p(J_n = j, K_n = k | x_n) &= \frac{p(J_n = j, K_n = k, x_n)}{p(x_n)} \\ &= \frac{p(J_n = j) p(K_n = k) p(x_n | J_n = j, K_n = k)}{\sum_{J_n, K_n} p(J_n, K_n, x_n)} \\ &= \frac{p_j q_k N(x_n | \mu_j, \sigma_k^2)}{\sum_{J_n=1}^m \sum_{K_n=1}^l p_{J_n} q_{K_n} N(x_n | \mu_{J_n}, \sigma_{K_n}^2)} \end{aligned}$$

Derive the form of auxiliary function $Q(\theta^{new}, \theta^{old})$:

$$\begin{aligned}
Q(\theta^{new}, \theta^{old}) &= \mathbb{E}_{\theta^{old}} \sum_{n=1}^N \log p(x_n, J_n, K_n | \theta^{new}) \\
&= \sum_{n=1}^N \mathbb{E} \left[\log \left(\prod_{j=1}^m \prod_{k=1}^l p(x_n, J_n, K_n | \theta^{new})^{\mathbb{I}(J_n=j, K_n=k)} \right) \right] \\
&= \sum_{n=1}^N \sum_{j=1}^m \sum_{k=1}^l \mathbb{E}(\mathbb{I}(J_n = j, K_n = k)) (\log p_j + \log q_k + \log N(x_n | \mu_j, \sigma_k^2)) \\
&= \sum_{n,j,k} r_{njk} \log p_j + \sum_{n,j,k} r_{njk} \log q_k + \sum_{njk} r_{njk} \log N(x_n | \mu_j, \sigma_k^2)
\end{aligned}$$

We are to optimize parameters p, q, μ, σ^2 . It is noticeable that p and q can be optimized independently. Now fix σ^2 and optimize μ :

$$\begin{aligned}
\frac{\partial}{\partial \mu_j} \sum_{n,j',k} r_{nj'k} N(x_n | \mu_{j'}, \sigma_k^2) &= \sum_{n,k} r_{njk} \nabla_{\mu_k} N(x_n | \mu_j, \sigma_k^2) \\
&= \sum_{n,k} r_{njk} N(x_n | \mu_j, \sigma_k^2) \frac{x_n - \mu_j}{\sigma_k^2}
\end{aligned}$$

And we ends in:

$$\mu_j = \frac{\sum_{n,k} r_{njk} N(x_n | \mu_j, \sigma_k^2) \frac{x_n}{\sigma_k^2}}{\sum_{n,k} r_{njk} N(x_n | \mu_j, \sigma_k^2) \frac{1}{\sigma_k^2}}$$

11.7 Manual calculation of the M step for a GMM

Practise by yourself.

11.8 Moments of a mixture of Gaussians

For the expectation of mixture distribution:

$$\begin{aligned}
\mathbb{E}(\mathbf{x}) &= \int \mathbf{x} \sum_k \pi_k N(\mathbf{x} | \mu_k, \Sigma_k) d\mathbf{x} \\
&= \sum_k \pi_k \left(\int \mathbf{x} N(\mathbf{x} | \mu_k, \Sigma_k) d\mathbf{x} \right) \\
&= \sum_k \pi_k \mu_k
\end{aligned}$$

Using $cov(\mathbf{x}) = \mathbb{E}(\mathbf{x}\mathbf{x}^T) - \mathbb{E}(\mathbf{x})\mathbb{E}(\mathbf{x})^T$, we have:

$$\begin{aligned}\mathbb{E}(\mathbf{x}\mathbf{x}^T) &= \int \mathbf{x}\mathbf{x}^T \sum_k \pi_k N(\mathbf{x}|\mu_k, \Sigma_k) d\mathbf{x} \\ &= \sum_k \pi_k \int \mathbf{x}\mathbf{x}^T N(\mathbf{x}|\mu_k, \Sigma_k) d\mathbf{x}\end{aligned}$$

Where:

$$\begin{aligned}\int \mathbf{x}\mathbf{x}^T N(\mathbf{x}|\mu_k, \Sigma_k) d\mathbf{x} &= \mathbb{E}_{N(\mu_k, \Sigma_k)}(\mathbf{x}\mathbf{x}^T) \\ &= cov_{N(\mu_k, \Sigma_k)}(\mathbf{x}) + \mathbb{E}_{N(\mu_k, \Sigma_k)}(\mathbf{x})\mathbb{E}_{N(\mu_k, \Sigma_k)}(\mathbf{x})^T \\ &= \Sigma_k + \mu_k \mu_k^T\end{aligned}$$

Therefore:

$$cov(\mathbf{x}) = \sum_k \pi_k (\Sigma_k + \mu_k \mu_k^T) - \mathbb{E}(\mathbf{x})\mathbb{E}(\mathbf{x})^T$$

11.9 K-means clustering by hand

Practise by yourself.

11.10 Deriving the K-means cost function

For every term sum over k , apply 11.134 onto the inner and outer sum process:

$$\begin{aligned}\sum_{i:z_i=k} \sum_{i':z_{i'}=k} (x_i - x_{i'})^2 &= \sum_{i:z_i=k} n_k s^2 + n_k (\bar{x}_k - x_i)^2 \\ &= n_k^2 s^2 + n_k (n_k s^2) \\ &= 2n_k s_k\end{aligned}$$

The right side of 11.131 equals to sum over k :

$$n_k \sum_{i:z_i=k} (x_i - \bar{x}_k)^2 = n_k (n_k s^2 + n(\hat{x}_n - \hat{x}_n))$$

Thus 11.131.

11.11 Visible mixtures of Gaussians are in exponential family

Encode latent variable with hot-pot code, $z_c = \mathbb{I}(x \text{ is generated from the } c \text{ distribution})$, then (omit θ in condition w.l.o.g.):

$$p(\mathbf{z}) = \prod_{c=1}^C \pi_c^{z_c}$$

$$p(x|\mathbf{z}) = \prod_{c=1}^C \left(\frac{1}{\sqrt{2\pi\sigma_c^2}} \exp \left\{ -\frac{1}{2\sigma_c^2} (x - \mu_c)^2 \right\} \right)^{z_c}$$

The log for joint distribution is:

$$\begin{aligned} \log p(x, \mathbf{z}) &= \log \prod_{c=1}^C \left(\frac{\pi_c}{\sqrt{2\pi\sigma_c^2}} \exp \left\{ -\frac{1}{2\sigma_c^2} (x - \mu_c)^2 \right\} \right)^{z_c} \\ &= \sum_{c=1}^C z_c \left(\log \pi_c - \frac{1}{2} \log 2\pi\sigma_c^2 - \frac{1}{2\sigma_c^2} (x - \mu_c)^2 \right) \end{aligned}$$

Which is a sum of some inner products, hence an exponential family. The sufficient statistics are linear combinations of \mathbf{z} , $\mathbf{z}x$ and $\mathbf{z}x^2$.

11.12 EM for robust linear regression with a Student t likelihood

Using the complete data likelihood w.r.t μ derived in 11.4.5:

$$L_N(\mu) = \frac{1}{2\sigma^2} \sum_{n=1}^N z_n (y_n - \mathbf{w}^T \mathbf{x}_n)^2$$

Set the derivative to zero:

$$\mathbf{w}^T \sum_{n=1}^N z_n \mathbf{x}_n \mathbf{x}_n^T = \sum_{n=1}^N z_n y_n \mathbf{x}_n^T$$

This means:

$$\mathbf{w}^T = \left(\sum_{n=1}^N z_n y_n \mathbf{x}_n^T \right) \left(\sum_{n=1}^N z_n \mathbf{x}_n \mathbf{x}_n^T \right)^{-1}$$

11.13 EM for EB estimation of Gaussian shrinkage model

For every j , 5.90 takes different forms (this equals E-step):

$$p(\bar{x}_j | \mu, t^2, \sigma^2) = N(\bar{x}_j | \mu, t^2 + \sigma_j^2)$$

Integrate out θ_j , the marginal likelihood is given by:

$$\log \prod_{j=1}^D N(\bar{x}_j | \mu, t^2 + \sigma_j^2) = \left(-\frac{1}{2}\right) \sum_{j=1}^D \log 2\pi(t^2 + \sigma_j^2) + \frac{1}{t^2 + \sigma_j^2} (\bar{x}_j - \mu)^2$$

Then we optimize respectively (this equals M-step):

$$\mu = \frac{\sum_{j=1}^D \frac{\bar{x}_j}{t^2 + \sigma_j^2}}{\sum_{j=1}^D \frac{1}{t^2 + \sigma_j^2}}$$

t^2 satisfies:

$$\sum_{j=1}^D \frac{(t^2 + \sigma_j^2) - (\bar{x}_j - \mu)^2}{(t^2 + \sigma_j^2)^2}$$

11.14 EM for censored linear regression

Unsolved.

11.15 Posterior mean and variance of a truncated Gaussian

We denote $A = \frac{c_i - \mu_i}{\sigma}$, for mean:

$$\mathbb{E}[z_i | z_i \geq c_i] = \mu_i + \sigma \mathbb{E}[\epsilon_i | \epsilon_i \geq A]$$

And we have:

$$\mathbb{E}[\epsilon_i | \epsilon_i \geq A] = \frac{1}{p(\epsilon_i \geq A)} \int_A^{+\infty} \epsilon_i N(\epsilon_i | 0, 1) dx = \frac{\phi(A)}{1 - \Phi(A)} = H(A)$$

In the last step we use 11.141 and 11.139, plug it up:

$$\mathbb{E}[z_i | z_i \geq c_i] = \mu_i + \sigma H(A)$$

Now to calculate the expectation for square term:

$$\mathbb{E}[z_i^2 | z_i \geq c_i] = \mu_i^2 + 2\mu_i \sigma \mathbb{E}[\epsilon_i | \epsilon_i \geq A] + \sigma^2 \mathbb{E}[\epsilon_i^2 | \epsilon_i \geq A]$$

To address $\mathbb{E}[\epsilon_i^2 | \epsilon_i \geq A]$, expand the hint from question:

$$\frac{d}{dw}(wN(w|0, 1)) = N(w|0, 1) - w^2N(w|0, 1)$$

We have:

$$\int_b^c w^2N(w|0, 1)dw = \Phi(c) - \Phi(b) - cN(c|0, 1) + bN(b|0, 1)$$

$$\mathbb{E}[\epsilon_i^2 | \epsilon_i \geq A] = \frac{1}{p(\epsilon_i \geq A)} \int_A^{+\infty} w^2N(w|0, 1)dw = \frac{1 - \Phi(A) + A\phi(A)}{1 - \Phi(A)}$$

Plug it into the conclusion drawn from question a:

$$\begin{aligned} \mathbb{E}[z_i^2 | z_i \geq c_i] &= \mu_i^2 + 2\mu_i\sigma H(A) + \sigma^2 \frac{1 - \Phi(A) + A\phi(A)}{1 - \Phi(A)} \\ &= \mu_i^2 + \sigma^2 + H(A)(\sigma c_i + \sigma\mu_i) \end{aligned}$$

12 Latent linear models

12.1 M-step for FA

Review the EM for FA(Factor-Analysis) first. Basically, we have(centralize \mathbf{X} to cancel μ w.l.o.g):

$$p(\mathbf{z}) = N(\mathbf{z}|0, I)$$

$$p(\mathbf{x}|\mathbf{z}) = N(\mathbf{x}|\mathbf{W}\mathbf{z}, \Psi)$$

And:

$$p(\mathbf{z}|\mathbf{x}) = N(\mathbf{z}|\mathbf{m}, \Sigma)$$

$$\Sigma = (I + \mathbf{W}^T \Psi^{-1} \mathbf{W})^{-1}$$

$$\mathbf{m} = \Sigma \mathbf{W}^T \Psi^{-1} \mathbf{x}_n$$

Denote \mathbf{x}_n 's latent variable as \mathbf{z}_n . The log-likelihood for complete data set $\{\mathbf{x}, \mathbf{z}\}$ is:

$$\log \prod_{n=1}^N p(\mathbf{x}_n, \mathbf{z}_n) = \sum_{n=1}^N \log p(\mathbf{z}_n) + \log p(\mathbf{x}_n|\mathbf{z}_n)$$

With prior $\log p(\mathbf{z})$ that can be omitted with parameter 0 and \mathbf{I} , hence:

$$\begin{aligned} Q(\theta, \theta^{old}) &= \mathbb{E}_{\theta^{old}} \left[\sum_{n=1}^N \log p(\mathbf{x}_n|\mathbf{z}_n, \theta) \right] \\ &= \mathbb{E} \left[\sum_{n=1}^N c - \frac{1}{2} \log |\Psi| - \frac{1}{2} (\mathbf{x}_n - \mathbf{W}\mathbf{z}_n)^T \Psi^{-1} (\mathbf{x}_n - \mathbf{W}\mathbf{z}_n) \right] \\ &= C - \frac{N}{2} \log |\Psi| - \frac{1}{2} \sum_{n=1}^N \mathbb{E}[(\mathbf{x}_n - \mathbf{W}\mathbf{z}_n)^T \Psi^{-1} (\mathbf{x}_n - \mathbf{W}\mathbf{z}_n)] \\ &= C - \frac{N}{2} \log |\Psi| - \frac{1}{2} \sum_{n=1}^N \mathbf{x}_n^T \Psi^{-1} \mathbf{x}_n - \frac{1}{2} \sum_{n=1}^N \mathbb{E}[\mathbf{z}_n^T \mathbf{W}^T \Psi^{-1} \mathbf{W} \mathbf{z}_n] + \sum_{n=1}^N \mathbf{x}_n^T \Psi^{-1} \mathbf{W} \mathbb{E}[\mathbf{z}_n] \\ &= C - \frac{N}{2} \log |\Psi| - \frac{1}{2} \sum_{n=1}^N \mathbf{x}_n^T \Psi^{-1} \mathbf{x}_n - \frac{1}{2} \sum_{n=1}^N \text{Tr} \{ \mathbf{W}^T \Psi^{-1} \mathbf{W} \mathbb{E}[\mathbf{z}_n \mathbf{z}_n^T] \} + \sum_{n=1}^N \mathbf{x}_n^T \Psi^{-1} \mathbf{W} \mathbb{E}[\mathbf{z}_n] \end{aligned}$$

As long as $p(\mathbf{z}|\mathbf{x}, \theta^{old}) = N(\mathbf{z}|\mathbf{m}, \Sigma)$, we have:

$$\mathbb{E}[\mathbf{z}_n|\mathbf{x}_n] = \Sigma \mathbf{W}^T \Psi^{-1} \mathbf{x}_n$$

$$\mathbb{E}[\mathbf{z}_n \mathbf{z}_n^T | \mathbf{x}_n] = \text{cov}(\mathbf{z}_n | \mathbf{x}_n) + \mathbb{E}[\mathbf{z}_n | \mathbf{x}_n] \mathbb{E}[\mathbf{z}_n | \mathbf{x}_n]^T = \Sigma + (\Sigma \mathbf{W}^T \Psi^{-1} \mathbf{x}) (\Sigma \mathbf{W}^T \Psi^{-1} \mathbf{x})^T$$

From now on, the \mathbf{x} and θ^{old} are omitted from conditions when calculating expectation.

Optimize w.r.t \mathbf{W} :

$$\frac{\partial}{\partial \mathbf{W}} Q = \sum_{n=1}^N \Psi^{-1} \mathbf{x}_n \mathbb{E}[\mathbf{z}_n]^T - \sum_{n=1}^N \Psi^{-1} \mathbf{W} \mathbb{E}[\mathbf{z}_n \mathbf{z}_n^T]$$

Set it to zero:

$$\mathbf{W} = \left(\sum_{n=1}^N \mathbf{x}_n \mathbb{E}[\mathbf{z}_n]^T \right) \left(\sum_{n=1}^N \mathbb{E}[\mathbf{z}_n \mathbf{z}_n^T] \right)^{-1}$$

Optimize w.r.t Ψ^{-1} :

$$\frac{\partial}{\partial \Psi^{-1}} Q = \frac{N}{2} \Psi - \frac{1}{2} \sum_{n=1}^N \mathbf{x}_n \mathbf{x}_n^T - \frac{1}{2} \sum_{n=1}^N \mathbf{W} \mathbb{E}[\mathbf{z}_n \mathbf{z}_n^T] \mathbf{W}^T + \sum_{n=1}^N \mathbf{W} \mathbb{E}[\mathbf{z}_n] \mathbf{x}_n$$

Plug in the expression of \mathbf{W} :

$$\Psi = \frac{1}{N} \left(\sum_{n=1}^N \mathbf{x}_n \mathbf{x}_n^T - \mathbf{W} \mathbb{E}[\mathbf{z}_n] \mathbf{x}_n^T \right)$$

Assume Ψ to be a diagonal matrix:

$$\Psi = \frac{1}{N} \text{diag} \left(\sum_{n=1}^N \mathbf{x}_n \mathbf{x}_n^T - \mathbf{W} \mathbb{E}[\mathbf{z}_n] \mathbf{x}_n^T \right)$$

This solution comes from "The EM Algorithm for Mixtures of Factor Analyzers, Zoubin Ghahramani, Geoffrey E. Hinton, 1996", where the EM for mixtures of FA is given as well.

12.2 MAP estimation for the FA model

Assume prior $p(\mathbf{W})$ and $p(\Psi)$. Compare with the question before, the M-step needs to be moderated:

$$\frac{\partial}{\partial \mathbf{W}} (Q + \log p(\mathbf{W})) = 0$$

$$\frac{\partial}{\partial \Psi} (Q + \log p(\Psi)) = 0$$

12.3 Heuristic for assessing applicability of PCA*

Need pictures for illustration here!

12.4 Deriving the second principal component

For:

$$J(\mathbf{v}_2, \mathbf{z}_2) = \frac{1}{N} \sum_{n=1}^N (\mathbf{x}_n - z_{n1}\mathbf{v}_1 - z_{n2}\mathbf{v}_2)^T (\mathbf{x}_n - z_{n1}\mathbf{v}_1 - z_{n2}\mathbf{v}_2)$$

Consider the derivative w.r.t one component of \mathbf{z}_2 :

$$\frac{\partial}{\partial z_{m2}} J = \frac{1}{N} (2z_{m2}\mathbf{v}_2^T \mathbf{v}_2 - 2\mathbf{v}_2^T (\mathbf{x}_m - z_{m1}\mathbf{v}_1)) = 0$$

Using $\mathbf{v}_2^T \mathbf{v}_2 = 1$ and $\mathbf{v}_2^T \mathbf{v}_1 = 0$ yields to:

$$z_{m2} = \mathbf{v}_2^T \mathbf{x}_m$$

Since \mathbf{C} is symmitric, use the constrain on \mathbf{v}_1 and \mathbf{v}_2 . We apply SVD onto \mathbf{C} first:

$$\mathbf{C} = \mathbf{O}^T \Lambda \mathbf{O}$$

Where:

$$\Lambda = \text{diag} \{ \lambda_1, \lambda_2, \dots \}$$

Are \mathbf{C} 's eigenvalues from the largest to the smallest.

$$\mathbf{O}^T = \{ \mathbf{u}_1, \mathbf{u}_2, \dots \}$$

Are eigenvectors, that are vertical to each other $\mathbf{u}_i^T \mathbf{u}_j = \mathbb{I}(i = h)$.

With $\mathbf{u}_1 = \mathbf{v}_1$.

Under constrains $\mathbf{v}_2^T \mathbf{v}_2 = 1$ and $\mathbf{v}_2^T \mathbf{v}_1 = 0$, we are to minimize:

$$(\mathbf{O}\mathbf{v}_2)^T \Lambda (\mathbf{O}\mathbf{v}_2)$$

Notice $\mathbf{O}\mathbf{v}_2$ means a transform on \mathbf{v}_2 , with its length unchanged. And $(\mathbf{O}\mathbf{v}_2)^T \Lambda (\mathbf{O}\mathbf{v}_2)$ measures the sum of the vector's components' square timed by Λ 's eigenvalues. Hence the optimum is reached with all length converges to the component associated to the largest eigenvalue, which means:

$$\mathbf{u}_i^T \mathbf{v}_2 = \mathbb{I}(i = 2)$$

Therefore:

$$\mathbf{v}_2 = \mathbf{u}_2$$

12.5 Deriving the residual error for PCA

$$\begin{aligned} \|\mathbf{x}_n - \sum_{j=1}^K z_{nj} \mathbf{v}_j\|^2 &= (\mathbf{x}_n - \sum_{j=1}^K z_{nj} \mathbf{v}_j)^T (\mathbf{x}_n - \sum_{j=1}^K z_{nj} \mathbf{v}_j) \\ &= \mathbf{x}_n^T \mathbf{x}_n + \sum_{j=1}^N z_{nj}^2 - 2 \mathbf{x}_n^T \sum_{j=1}^N z_{nj} \mathbf{v}_j \end{aligned}$$

Use $\mathbf{v}_i^T \mathbf{v}_j = \mathbb{I}(i = j)$, $z_{nj} = \mathbf{x}_n^T \mathbf{v}_j$. We ends in the conclusion of a.

$$\|\mathbf{x}_n - \sum_{j=1}^K z_{nj} \mathbf{v}_j\|^2 = \mathbf{x}_n^T \mathbf{x}_n - 2 \sum_{j=1}^K \mathbf{v}_j^T \mathbf{x}_n \mathbf{x}_n^T \mathbf{v}_j$$

Plug in $\mathbf{v}_j^T \mathbf{C} \mathbf{v}_j = \lambda_j$ and sum over n can draw the conclusion in b.

Plug $K = d$ into the conclusion in b, we have:

$$\begin{aligned} J_{K=d} &= \frac{1}{N} \sum_{n=1}^N \mathbf{x}_n^T \mathbf{x}_n - \sum_{j=1}^d \lambda_j = 0 \\ \frac{1}{N} \sum_{n=1}^N \mathbf{x}_n^T \mathbf{x}_n - \sum_{j=1}^d \lambda_j &= 0 \end{aligned}$$

In general cases:

$$J_K = \sum_{j=1}^d \lambda_j - \sum_{j=1}^K \lambda_j = \sum_{j=d+1}^K \lambda_j$$

12.6 Derivation of Fisher's linear discriminant

Straightforward algebra.

(need reference)

12.7 PCA via successive deflation

This problem involves the same technique used in solving 12.4, hence omitted.

12.8 Latent semantic indexing

Practice by yourself.

12.9 Imputation in a FA model*

wtf \mathbf{x}_v ?

wtf \mathbf{x}_h ?

12.10 Efficiently evaluating the PPCA density

With:

$$p(\mathbf{z}) = N(\mathbf{z}|0, \mathbf{I})$$

$$p(\mathbf{x}|\mathbf{z}) = N(\mathbf{x}|\mathbf{W}\mathbf{z}, \sigma^2\mathbf{I})$$

Use the conclusion from chapter 4.

$$N(\mathbf{x}) = N(\mathbf{x}|0, \sigma^2\mathbf{I} + \mathbf{W}\mathbf{W}^T)$$

Derivation for MLE in 12.2.4 can be found in "Probabilistic Principal Component Analysis, Michael E. Tipping, Christopher M. Bishop, 1999".

Plug in the MLE, thence the covariance matrix $(D * D)$'s inverse can be computed:

$$(\sigma^2\mathbf{I} + \mathbf{W}\mathbf{W}^T)^{-1} = \sigma^{-2}\mathbf{I} - \sigma^{-2}\mathbf{W}(\frac{1}{\sigma^{-2}}\mathbf{W}^T\mathbf{W} + \sigma^{-2}\mathbf{I})^{-1}\mathbf{W}^T\sigma^{-2}$$

Which involves only inverting a $L * L$ matrix.

12.11 PPCA vs FA

Practice by yourself.

13 Sparse linear models

13.1 Partial derivative of the RSS

Define:

$$RSS(\mathbf{w}) = \sum_{n=1}^N (y_n - \mathbf{w}^T \mathbf{x}_n)^2$$

Straightforwardly:

$$\begin{aligned} \frac{\partial}{\partial w_j} RSS(\mathbf{w}) &= \sum_{n=1}^N 2(y_n - \mathbf{w}^T \mathbf{x}_n)(-x_{nj}) \\ &= - \sum_{n=1}^N 2(x_{nj}y_n - x_{nj} \sum_{i=1}^D w_i x_{ni}) \\ &= - \sum_{n=1}^N 2(x_{nj}y_n - x_{nj} \sum_{i \neq j}^D w_i x_{ni} - x_{nj}^2 w_j) \end{aligned}$$

With w_j 's coefficient:

$$a_j = 2 \sum_{n=1}^N x_{nj}^2$$

Other irrelevant terms can be absorbed into:

$$c_j = 2 \sum_{n=1}^N x_{nj}(y_n - \mathbf{w}_{-j}^T \mathbf{x}_{n,-j})$$

In the end:

$$w_j = \frac{c_j}{a_j}$$

13.2 Derivation of M-step for EB for linear regression

We give the EM for Automatic Relevance Determination(ARD). For linear regression scene:

$$p(\mathbf{y}|\mathbf{x}, \mathbf{w}, \beta) = N(\mathbf{y}|\mathbf{X}\mathbf{w}, \beta^{-1})$$

$$p(\mathbf{w}) = N(\mathbf{w}|0, \mathbf{A}^{-1})$$

$$\mathbf{A} = \text{diag}(\alpha)$$

In E-step, we are to estimate expectation of \mathbf{w} . Using linear Gaussian relationship:

$$\begin{aligned} p(\mathbf{w}|\mathbf{y}, \alpha, \beta) &= N(\mu, \Sigma) \\ \Sigma^{-1} &= \mathbf{A} + \beta \mathbf{X}^T \mathbf{X} \\ \mu &= \Sigma(\beta \mathbf{X}^T \mathbf{y}) \end{aligned}$$

Then:

$$\begin{aligned} \mathbb{E}_{\alpha, \beta}[\mathbf{w}] &= \mu \\ \mathbb{E}_{\alpha, \beta}[\mathbf{w}\mathbf{w}^T] &= \Sigma + \mu\mu^T \end{aligned}$$

For auxiliary function:

$$\begin{aligned} Q(\alpha, \beta, \alpha^{old}, \beta^{old}) &= \mathbb{E}_{\alpha^{old}, \beta^{old}}[\log p(\mathbf{y}, \mathbf{w}|\alpha, \beta)] \\ &= \mathbb{E}[\log p(\mathbf{y}|\mathbf{w}, \beta) + \log p(\mathbf{w})] \\ &= \frac{1}{2} \mathbb{E}[N \log \beta - \beta(\mathbf{y} - \mathbf{X}\mathbf{w})^T(\mathbf{y} - \mathbf{X}\mathbf{w}) + \sum_j \log \alpha_j - \mathbf{w}^T \mathbf{A}^{-1} \mathbf{w}] \end{aligned}$$

In E-step, we need $\mathbb{E}[\mathbf{w}]$ and $\mathbb{E}[\mathbf{w}\mathbf{w}^T]$, which have been computed:

Introduce a prior for component in α and β :

$$p(\alpha, \beta) = \prod_j Ga(\alpha_j | a + 1, b) \cdot Ga(\beta | c + 1, d)$$

Hence the posterior auxiliary function is:

$$Q' = Q + \log p(\alpha, \beta) = Q + \sum_j (a \log \alpha_j - b \alpha_j) + (c \log \beta - d \beta)$$

In M-step, optimize w.r.t α_i :

$$\frac{\partial}{\partial \alpha_i} Q' = \frac{1}{2\alpha_i} - \frac{\mathbb{E}[w_i^2]}{2} + \frac{a}{\alpha_i} - b$$

Set it to zero:

$$\alpha_i = \frac{1 + 2a}{\mathbb{E}[w_i^2] - b}$$

Optimize w.r.t β :

$$\frac{\partial}{\partial \beta} Q' = \frac{N}{2\beta} - \mathbb{E}[||\mathbf{y} - \mathbf{X}\mathbf{w}||^2] + \frac{c}{\beta} - d$$

End in:

$$\beta = \frac{N + 2c}{\mathbb{E}[||\mathbf{y} - \mathbf{X}\mathbf{w}||^2] + 2d}$$

Expand the expectation ends in 13.168.

13.3 Derivation of fixed point updates for EB for linear regression*

Unsolved.

13.4 Marginal likelihood for linear regression*

Straightforward algebra.

13.5 Reducing elastic net to lasso

Expand both sides of 13.196, the right side:

$$\begin{aligned} J_1(c\mathbf{w}) &= (\mathbf{y} - c\mathbf{X}\mathbf{w})^T (\mathbf{y} - c\mathbf{X}\mathbf{w}) + c^2 \lambda_2 \mathbf{w}^T \mathbf{w} + \lambda_1 |\mathbf{w}|_1 \\ &= \mathbf{y}^T \mathbf{y} - c^2 \mathbf{w}^T \mathbf{X}^T \mathbf{X} \mathbf{w} - 2\mathbf{y}^T \mathbf{X} \mathbf{w} + c^2 \lambda_2 \mathbf{w}^T \mathbf{w} + \lambda_1 |\mathbf{w}|_1 \end{aligned}$$

The left side:

$$\begin{aligned} J_2(\mathbf{w}) &= \begin{pmatrix} \mathbf{y} - c\mathbf{X}\mathbf{w} \\ -c\sqrt{\lambda_2}\mathbf{w} \end{pmatrix}^T \begin{pmatrix} \mathbf{y} - c\mathbf{X}\mathbf{w} \\ -c\sqrt{\lambda_2}\mathbf{w} \end{pmatrix} + c\lambda_1 |\mathbf{w}|_1 \\ &= (\mathbf{y} - c\mathbf{X}\mathbf{w})^T (\mathbf{y} - c\mathbf{X}\mathbf{w}) + c^2 \lambda_2 \mathbf{w}^T \mathbf{w} + c\lambda_1 |\mathbf{w}|_1 \\ &= \mathbf{y}^T \mathbf{y} + c^2 \mathbf{w}^T \mathbf{X}^T \mathbf{X} \mathbf{w} - 2\mathbf{y}^T \mathbf{X} \mathbf{w} + c^2 \lambda_2 \mathbf{w}^T \mathbf{w} + c\lambda_1 |\mathbf{w}|_1 \end{aligned}$$

Hence 13.196 and 13.195 are equal.

This shows elastic net regularization, which pick a regularizing term as a linear combination of l_1 and l_0 equals a lasso one.

13.6 Shrinkage in linear regression

For ordinary least square:

$$RSS(\mathbf{w}) = (\mathbf{y} - \mathbf{X}\mathbf{w})^T (\mathbf{y} - \mathbf{X}\mathbf{w})$$

Using $\mathbf{X}^T \mathbf{X} = I$:

$$RSS(\mathbf{w}) = c + \mathbf{w}^T \mathbf{w} - 2\mathbf{y}^T \mathbf{X} \mathbf{w}$$

Take the derivative:

$$\frac{\partial}{\partial w_k} RSS(\mathbf{w}) = 2w_k - 2 \sum_{n=1}^N y_n x_{nk}$$

We have:

$$\hat{w}_k^{OLS} = \sum_{n=1}^N y_n x_{nk}$$

In ridge regression:

$$RSS(\mathbf{w}) = (\mathbf{y} - \mathbf{X}\mathbf{w})^T (\mathbf{y} - \mathbf{X}\mathbf{w}) + \lambda \mathbf{w}^T \mathbf{w}$$

Take the derivative:

$$(2 + 2\lambda)w_k = 2 \sum_{n=1}^N y_n x_{nk}$$

Thus

$$\hat{w}_k^{ridge} = \frac{\sum_{n=1}^N y_n x_{nk}}{1 + \lambda}$$

Solution for lasso regression using subderivative is exploited in 13.3.2, which concludes in 13.63:

$$\hat{w}_k^{lasso} = \text{sign}(\hat{w}_k^{OLS}) (|\hat{w}_k^{OLS}| - \frac{\lambda}{2})_+$$

Observe picture 13.24, it is easy to address the black line as OLS, gray one Ridge and dotted one lasso. And $\lambda_1 = \lambda_2 = 1$. It is noticeable that ridge cause a shrinkage to horizontal axis while lasso cause a sharp shrinkage to zero under certain threshold.

13.7 Prior for the Bernoulli rate parameter in the spike and slab model

$$p(\gamma|\alpha_1, \alpha_2) = \prod_{d=1}^D p(\gamma_d|\alpha_1, \alpha_2)$$

Integrate out π_d :

$$\begin{aligned} p(\gamma_d|\alpha_1, \alpha_2) &= \frac{1}{B(\alpha_1, \alpha_2)} \int p(\gamma_d|\pi_d) p(\pi_d|\alpha_1, \alpha_2) d\pi_d \\ &= \frac{1}{B(\alpha_1, \alpha_2)} \int \pi_d^{\gamma_d} (1 - \pi_d)^{(1-\gamma_d)} \pi_d^{\alpha_1-1} (1 - \pi_d)^{\alpha_2-1} d\pi_d \\ &= \frac{1}{B(\alpha_1, \alpha_2)} \int \pi_d^{\alpha_1+\gamma_d-1} (1 - \pi_d)^{\alpha_2+1-\gamma_d-1} d\pi_d \\ &= \frac{B(\alpha_1 + \gamma_d, \alpha_2 + 1 - \gamma_d)}{B(\alpha_1, \alpha_2)} = \frac{\Gamma(\alpha_1 + \alpha_2)}{\Gamma(\alpha_1)\Gamma(\alpha_2)} \frac{\Gamma(\alpha_1 + \gamma_d)\Gamma(\alpha_2 + 1 - \gamma_d)}{\Gamma(\alpha_1 + \alpha_2 + 1)} \end{aligned}$$

Therefore(N_1 marks the number of 1 in γ):

$$\begin{aligned} p(\gamma|\alpha_1, \alpha_2) &= \frac{\Gamma(\alpha_1 + \alpha_2)^N}{\Gamma(\alpha_1)^N \Gamma(\alpha_2)^N} \frac{\Gamma(\alpha_1 + 1)^{N_1} \Gamma(\alpha_2 + 1)^{N-N_1}}{\Gamma(\alpha_1 + \alpha_2 + 1)^N} \\ &= \frac{(\alpha_1 + 1)^{N_1} (\alpha_2 + 1)^{N-N_1}}{(\alpha_1 + \alpha_2 + 1)^N} \end{aligned}$$

And:

$$\log p(\gamma|\alpha_1, \alpha_2) = N \log \frac{\alpha_2 + 1}{\alpha_1 + \alpha_2 + 1} + N_1 \log \frac{\alpha_1 + 1}{\alpha_2 + 1}$$

13.8 Deriving E step for GSM prior

$$Lap(w_j|0, \frac{1}{\gamma}) = \int N(w_j|0, \tau_j^2) Ga(\tau_j^2|1, \frac{\gamma^2}{2}) d\tau_j^2$$

Take Laplace transform/generating transform to both sides:

To calculate:

$$\begin{aligned} \mathbb{E}[\frac{1}{\tau_j^2}|w_j] &= \int \frac{1}{\tau_j^2} p(\tau_j^2|w_j) d\tau_j^2 = \int \frac{1}{\tau_j^2} \frac{p(w_j|\tau_j^2)p(\tau_j^2)}{p(w_j)} d\tau_j^2 \\ &= \frac{1}{p(w_j)} \int \frac{1}{\tau_j^2} N(w_j|0, \tau_j^2) p(\tau_j^2) d\tau_j^2 \end{aligned}$$

According to 13.200, it reduces to:

$$\frac{1}{p(w_j)} \frac{-1}{|w_j|} \frac{d}{dw_j} \int N(w_j|0, \tau_j^2) p(\tau_j^2) d\tau_j^2$$

Because:

$$\frac{d}{dw} \log p(w) = \frac{1}{p(w)} \frac{d}{dw} p(w)$$

This gives 13.197:

$$\frac{1}{p(w_j)} \frac{-1}{|w_j|} \frac{d}{dw_j} p(w_j) = \frac{1}{|w_j|} \frac{d}{dw_j} - \log p(w_j)$$

! 此题存疑, Hint 1和Hint 2中可能均有印刷错误。

13.9 EM for sparse probit regression with Laplace prior

Straightforward Probit regression involves no latent variable. Introducing Laplace prior for linear factor \mathbf{w} results in its lasso version. Since

Laplace distribution is a continuous mixture of Gaussian, a latent variable τ^2 with the same dimension as \mathbf{w} is introduced. The PGM for Probit regression looks like:

$$\gamma \rightarrow \tau^2 \rightarrow \mathbf{w} \rightarrow \mathbf{y} \leftarrow \mathbf{X}$$

The joint distribution is:

$$p(\gamma, \tau^2, \mathbf{w}, \mathbf{y} | \mathbf{X}) = p(\gamma) \prod_{d=1}^D p(\tau_d^2 | \gamma) \prod_{d=1}^D p(w_d | \tau_d^2) \prod_{n=1}^N \Phi(\mathbf{w}^T \mathbf{x}_n)^{y_n} (1 - \Phi(\mathbf{w}^T \mathbf{x}_n))^{1-y_n}$$

For concise, we set γ as constant, according to 13.86:

$$p(\tau^2 | \gamma) = Ga(\tau_d^2 | 1, \frac{\gamma^2}{2})$$

$$p(w_d | \tau_d^2) = N(w_d | 0, \tau_d^2)$$

Hence:

$$p(\tau^2, \mathbf{w}, \mathbf{y} | \mathbf{X}, \gamma) \propto \exp \left\{ -\frac{1}{2} \sum_{d=1}^D (\gamma^2 \tau_d^2 + \frac{w_d^2}{\tau_d^2}) \right\} \cdot \prod_{d=1}^D \frac{1}{\tau_d} \\ \cdot \prod_{n=1}^N \Phi(\mathbf{w}^T \mathbf{x}_n)^{y_n} (1 - \Phi(\mathbf{w}^T \mathbf{x}_n))^{1-y_n}$$

In $Q(\theta^{new}, \theta^{old})$, we take expectation of θ^{old} . We have assumed \mathbf{w} as parameter and τ^2 as latent variable, thus:

$$Q(\mathbf{w}, \mathbf{w}^{old}) = \mathbb{E}_{\mathbf{w}^{old}} [\log p(\mathbf{y}, \tau^2 | \mathbf{w})]$$

Now extract terms involve \mathbf{w} from $\log p(\tau^2, \mathbf{w}, \mathbf{y})$:

$$\log p(\mathbf{y}, \tau^2 | \mathbf{w}) = c - \frac{1}{2} \sum_{d=1}^D \frac{w_d^2}{\tau_d^2} + \sum_{n=1}^N y_n \log \Phi(\mathbf{w}^T \mathbf{x}_n) + (1 - y_n) \log (1 - \Phi(\mathbf{w}^T \mathbf{x}_n))$$

Thus we only need to calculate one expectation in E-step:

$$\mathbb{E}[\frac{1}{\tau_d^2} | \mathbf{w}^{old}]$$

Which can be done as in 13.4.4.3, because Probit and linear regression share the same PGM up to this stage.

The M-step is the same as Gaussian-prior Probit regression hence omitted.

13.10 GSM representation of group lasso*

Follow the hints and straightforward algebra.

13.11 Projected gradient descent for l1 regularized least squares

Generally, we take gradient on \mathbf{w} and optimize. When there are constraints on \mathbf{w} that could be broken by gradient descent, the increment has to be moderated to fit in the constraints.

To calculate:

$$\min_{\mathbf{w}} \{NLL(\mathbf{w}) + \lambda \|\mathbf{w}\|_1\}$$

Consider under a linear regression context:

$$NLL(\mathbf{w}) = \frac{1}{2} \|\mathbf{y} - \mathbf{X}\mathbf{w}\|_2^2$$

For $\lambda \|\mathbf{w}\|_1$ can not be differentiate, we need a non-trivial solution, it is suggest:

$$\mathbf{w} = \mathbf{u} - \mathbf{v}$$

$$u_i = (x_i)_+ = \max\{0, x_i\}$$

$$v_i = (-x_i)_+ = \max\{0, -x_i\}$$

With $\mathbf{u} \geq \mathbf{0}, \mathbf{v} \geq \mathbf{0}$, then:

$$\|\mathbf{w}\|_1 = \mathbf{1}_n^T \mathbf{u} + \mathbf{1}_n^T \mathbf{v}$$

The original problem is changed to:

$$\begin{aligned} \min_{\mathbf{w}} \left\{ \frac{1}{2} \|\mathbf{y} - \mathbf{X}(\mathbf{u} - \mathbf{v})\|_2^2 + \lambda \mathbf{1}_n^T \mathbf{u} + \lambda \mathbf{1}_n^T \mathbf{v} \right\} \\ s.t. \mathbf{u} \geq \mathbf{0}, \mathbf{v} \geq \mathbf{0} \end{aligned}$$

Denote:

$$\mathbf{z} = \begin{pmatrix} \mathbf{u} \\ \mathbf{v} \end{pmatrix}$$

Rewrite the original target:

$$\min_{\mathbf{z}} \left\{ f(\mathbf{z}) = \mathbf{c}^T \mathbf{z} + \frac{1}{2} \mathbf{z}^T \mathbf{A} \mathbf{z} \right\}$$

$$s.t. \mathbf{z} \geq \mathbf{0}$$

Where:

$$\mathbf{c} = \begin{pmatrix} \lambda \mathbf{1}_n - \mathbf{yX} \\ \lambda \mathbf{1}_n + \mathbf{yX} \end{pmatrix}$$

$$\mathbf{A} = \begin{pmatrix} \mathbf{X}^T \mathbf{X} & -\mathbf{X}^T \mathbf{X} \\ -\mathbf{X}^T \mathbf{X} & \mathbf{X}^T \mathbf{X} \end{pmatrix}$$

The gradient is given by:

$$\nabla f(\mathbf{z}) = \mathbf{c} + \mathbf{Az}$$

For ordinary gradient descent:

$$\mathbf{z}^{k+1} = \mathbf{z}^k - \alpha \nabla f(\mathbf{z}^k)$$

For projected case, take \mathbf{g}^k :

$$\mathbf{g}_i^k = \min \{ \mathbf{z}_i^k, \alpha \nabla f(\mathbf{z}^k)_i \}$$

During iteration:

$$\mathbf{z}^{k+1} = \mathbf{z}^k - \mathbf{g}^k$$

The original paper suggest more delicate method to moderate the learning rate, refer to "Gradient Projection for Sparse Reconstruction: Application to Compressed Sensing and Other Inverse Problems, Mario A.T.Figueiredo".

13.12 Subderivative of the hinge loss function

$$if(\theta < 1) \partial f(\theta) = \{-1\}$$

$$if(\theta = 1) \partial f(\theta) = [-1, 0]$$

$$if(\theta > 1) \partial f(\theta) = \{0\}$$

13.13 Lower bounds to convex functions

Refer to "Rigorous Affine Lower Bound Functions for Multivariate Polynomials and Their Use in Global Optimisation".

14 Kernels

15 Gaussian processes

15.1 Reproducing property

We denote $\kappa(\mathbf{x}_1, \mathbf{x})$ by $f(\mathbf{x})$ and $\kappa(\mathbf{x}_2, \mathbf{x})$ by $g(\mathbf{x})$. From definition:

$$f(\mathbf{x}) = \sum_{i=1}^{\infty} f_i \phi_i(\mathbf{x})$$

$$\kappa(\mathbf{x}_1, \mathbf{x}) = \sum_{i=1}^{\infty} \lambda_i \phi_i(\mathbf{x}_1) \phi_i(\mathbf{x})$$

Since \mathbf{x} can be chosen arbitrarily, we have the properties hold (the one for g is obtained similarly):

$$f_i = \lambda_i \phi_i(\mathbf{x}_1)$$

$$g_i = \lambda_i \phi_i(\mathbf{x}_2)$$

Therefore:

$$\begin{aligned} \langle \kappa(\mathbf{x}_1, \cdot), \kappa(\mathbf{x}_2, \cdot) \rangle &= \langle f, g \rangle \\ &= \sum_{i=1}^{\infty} \frac{f_i g_i}{\lambda_i} \\ &= \sum_{i=1}^{\infty} \lambda_i \phi_i(\mathbf{x}_1) \phi_i(\mathbf{x}_2) \\ &= \kappa(\mathbf{x}_1, \mathbf{x}_2) \end{aligned}$$

16 Adaptive basis function models

16.1 Nonlinear regression for inverse dynamics

Practise by yourself.

17 Markov and hidden Markov models

17.1 Derivation of Q function for HMM

Firstly, we estimate the distribution of $\mathbf{z}_{1:T}$ w.r.t θ^{old} , for auxiliary function, we are to calculate the log-likelihood w.r.t θ and $\mathbf{z}_{1:T}$.

$$\begin{aligned}
Q(\theta, \theta^{old}) &= \mathbb{E}_{p(\mathbf{z}_{1:T}|\mathbf{x}_{1:T}, \theta^{old})} [\log p(\mathbf{z}_{1:T}, \mathbf{x}_{1:T}|\theta)] \\
&= \mathbb{E}_p \left[\log \left\{ \prod_{i=1}^N \left\{ p(z_{i,1}|\pi) \prod_{t=2}^{T_i} p(z_{i,t}|z_{i,t-1}, \mathbf{A}) \prod_{t=1}^{T_i} p(x_{i,t}|z_{i,t}, \mathbf{B}) \right\} \right\} \right] \\
&= \mathbb{E}_p \left[\sum_{i=1}^N \sum_{k=1}^K \mathbb{I}[z_{i,1} = k] \log \pi_k + \sum_{i=1}^N \sum_{t=2}^{T_i} \sum_{j=1}^K \sum_{k=1}^K \mathbb{I}[z_{i,t} = k, z_{i,t-1} = j] \log \mathbf{A}(j, k) \right. \\
&\quad \left. + \sum_{i=1}^N \sum_{t=1}^{T_i} \sum_{k=1}^K \mathbb{I}[z_{i,t} = k] \log p(x_{i,t}|z_{i,t} = k, \mathbf{B}) \right]
\end{aligned}$$

Further we have 17.98, 17.99, 17.100, using the definition of expectation yields to 17.97.

17.2 Two filter approach to smoothing in HMMs

For $r_t(i) = p(z_t = i|x_{t+1:T})$, we have:

$$\begin{aligned}
p(z_t = i|x_{t+1:T}) &= \sum_j p(z_t = i, z_{t+1} = j|x_{t+1:T}) \\
&= \sum_j p(z_{t+1} = j|x_{t+1:T}) p(z_t = i|z_{t+1} = j, x_{t+1:T}) \\
&= \sum_j p(z_{t+1} = j|x_{t+1:T}) p(z_t = i|z_{t+1} = j) \\
&= \sum_j p(z_{t+1} = j|x_{t+1:T}) \Psi^-(j, i)
\end{aligned}$$

Where Ψ^- denotes the transform matrix in an inverse sense, we further have:

$$\begin{aligned}
p(z_{t+1} = j|x_{t+1:T}) &= p(z_{t+1} = j|x_{t+1}, x_{t+2:T}) \\
&\propto p(z_{t+1} = j, x_{t+1}, x_{t+2:T}) \\
&= p(x_{t+2:T}) p(z_{t+1} = j|x_{t+2:T}) p(x_{t+1}|z_{t+1} = j, x_{t+2:T}) \\
&\propto r_{t+1}(j) \phi_{t+1}(j)
\end{aligned}$$

Therefore we can calculate $r_t(i)$ recursively:

$$r_t(i) \propto \sum_j r_{t+1}(j) \phi_{t+1}(j) \Psi^-(j, i)$$

And initial element $p(z_T)$ is given by $\prod_T(i)$.

To rewrite $\gamma_t(i)$ in terms of new factors:

$$\begin{aligned} \gamma_t(i) &\propto p(z_t = i | x_{1:T}) \\ &\propto p(z_t = i, x_{1:T}) \\ &= p(z_t = i) p(x_{1:T} | z_t = i) \\ &= p(z_t = i) p(x_{1:t} | z_t = i) p(x_{t+1:T} | z_t = i, x_{1:t}) \\ &= p(z_t = i) p(x_{1:t} | z_t = i) p(x_{t+1:T} | z_t = i) \\ &= \frac{1}{p(z_t = i)} p(x_{1:t}, z_t = i) p(x_{t+1:T}, z_t = i) \\ &\propto \frac{1}{p(z_t = i)} p(z_t = i | x_{1:t}) p(z_t = i | x_{t+1:T}) \\ &= \frac{\alpha_t(i) \cdot r_t(i)}{\prod_t(i)} \end{aligned}$$

17.3 EM for HMMs with mixture of Gaussian observations

Using mixture of Gaussians as the emission distribution does not change the evaluation of γ and ϵ , hence the E-step does not change compared to the one in exercise 17.1.

As long as \mathbf{A} and \mathbf{B} are estimated independently, we now focus on estimating $\mathbf{B} = (\pi, \mu, \Sigma)$ during M-step, the involved target function is:

$$\sum_{k=1}^K \sum_{i=1}^N \sum_{t=1}^{T_i} \gamma_{i,t}(k) \log p(x_{i,t} | \mathbf{B})$$

Since the parameters are independent w.r.t k , we delve into a case where k is given. We also denote the iteration through $i = 1$ to N and $t = 1$ to T_i by $n = 1$ to $T = \sum_{i=1}^N T_i$, now the log-likelihood takes the form:

$$\sum_{n=1}^T \gamma_n(k) \log p(x_n | \pi_k, \mu_k, \Sigma_k)$$

It can be seen as a weighted form of log-likelihood for a mixture of Gaussian, assume the mixture contains C (it should be C_k , but this notation causes no contradiction as long as we take k for granted) Gaussians. We are to apply another EM procedure during the M-step for this HMM. Denote the latent variable corresponding to x_n by $h_{n,k}$. Estimate the distribution of $p(h_{n,k}|z_n, \pi_k, \mu_k, \Sigma_k)$ is tantamount to the E-step used in handling traditional mixture of Gaussians. Denote the expectation of $h_{n,k}$'s components by $\gamma'_{c,n}(k)$.

Now applying the M-step of mixture of Gaussians, recall that auxiliary takes the form:

$$\sum_{n=1}^T \gamma_n(k) \sum_{c=1}^C \gamma'_{c,n}(k) \{ \log \pi_{k,c} + \log N(x_n | \mu_{k,c}, \Sigma_{k,c}) \}$$

Hence this HMM reweighted a traditional mixture of Gaussians, with the weight changed from $\gamma'_{c,n}(k)$ into $\gamma_n(k) \cdot \gamma'_{c,n}(k)$. The rest estimation is trivially the application of M-step in mixture of Gaussians using new weights.

17.4 EM for HMMs with tied mixtures

Recall the conclusion from exercise 17.3, the last M-step inside M-step takes the form:

$$\sum_{k=1}^K \sum_{n=1}^T \sum_{c=1}^C \gamma_{c,n}(k) \{ \log \pi_{k,c} + \log N(x_n | \mu_c, \Sigma_c) \}$$

Where we accordingly update the meaning of γ , and we also remove k from the footnotes of μ and Σ given the conditions in this exercise.

It is easy to notice that this target function again takes the form of M-step target for a traditional mixture of Gaussians. Taking independent k and update π_k gives the learning process of K mixing weights. Sum out k and C independent Gaussian parameters can be updated.

18 State space models

18.1 Derivation of EM for LG-SSM

We directly work on the auxiliary function:

$$\begin{aligned}
Q(\theta, \theta^{old}) &= \mathbb{E}_{p(\mathbf{Z}|\mathbf{Y}, \theta^{old})} [\log \prod_{n=1}^N p(z_{n,1:T_n}, y_{n,1:T_n} | \theta)] \\
&= \mathbb{E} \left[\sum_{n=1}^N \log p(z_{n,1}) \prod_{i=2}^{T_n} p(z_{n,i} | z_{n,i-1}) \prod_{i=1}^{T_n} p(y_{n,i} | z_{n,i}) \right] \\
&= \mathbb{E} \left[\sum_{n=1}^N \log N(z_{n,1} | \mu_0, \Sigma_0) + \sum_{i=2}^{T_n} N(z_{n,i} | A_i z_{n,i-1} + B_i u_i, Q_i) \right. \\
&\quad \left. + \sum_{i=1}^{T_n} N(y_{n,i} | C_i z_{n,i} + D_i u_i, R_i) \right] \\
&= \mathbb{E} \left[N \log \frac{1}{|\Sigma_0|^{\frac{1}{2}}} + \left\{ -\frac{1}{2} \sum_{n=1}^N (z_{n,1} - \mu_0)^T \Sigma_0^{-1} (z_{n,1} - \mu_0) \right\} \right. \\
&\quad \left. + \sum_{i=2}^T N_i \log \frac{1}{|Q_i|^{\frac{1}{2}}} \right. \\
&\quad \left. + \left\{ -\frac{1}{2} \sum_{n=1}^{N_i} (z_{n,i} - A_i z_{n,i-1} - B_i u_i)^T Q_i^{-1} (z_{n,i} - A_i z_{n,i-1} - B_i u_i) \right\} \right. \\
&\quad \left. + \sum_{i=2}^T N_i \log \frac{1}{|R_i|^{\frac{1}{2}}} \right. \\
&\quad \left. + \left\{ -\frac{1}{2} \sum_{n=1}^{N_i} (y_{n,i} - C_i z_{n,i} - D_i u_i)^T R_i^{-1} (y_{n,i} - C_i z_{n,i} - D_i u_i) \right\} \right]
\end{aligned}$$

When exchanging the order of sum over data, we have $T = \max_n \{T_n\}$ and N_i denotes the number of data set with size no more than i .

To estimate μ_0 , take the related terms:

$$\mathbb{E} \left[-\frac{1}{2} \sum_{n=1}^N (z_{n,1} - \mu_0)^T \Sigma_0^{-1} (z_{n,1} - \mu_0) \right]$$

Take derivative w.r.t μ_0 :

$$\mathbb{E} \left[\sum_{n=1}^N -\frac{1}{2} \mu_0^T \Sigma_0^{-1} \mu_0 + z_{n,1}^T \Sigma_0^{-1} \mu_0 \right]$$

Setting it to zero yields:

$$\mu_0 = \frac{1}{N} \mathbb{E}[z_{n,1}]$$

It is obvious that such estimation is similar to that for MVN with x_n replaced by $\mathbb{E}[z_{n,1}]$. This similarity works for other parameters as well. For example, estimate Σ_0 is tantamount to estimate the covariance of MVN with data terms replaced.

Such analysis works for Q_i and R_i as well. To estimate coefficient matrix, we consider A_i firstly. The related term is:

$$\mathbb{E}\left[\sum_{n=1}^{N_i} \{z_{n,i}^T A_i^T Q_i^{-1} A_i z_{n,i} - 2z_{n,i-1}^T A_i^T Q_i^{-1} (z_{n,i} - B_i u_i)\}\right]$$

Setting derivative to zero yields a solution similar to that for μ_0 , the same analysis can be applied for B_i , C_i , D_i as well.

18.2 Seasonal LG-SSM model in standard form

From Fig.18.6(a), we have:

$$\begin{aligned} \mathbf{A} &= \begin{pmatrix} 1 & 1 & 0 & \mathbf{0}_{S-1}^T \\ 0 & 1 & 0 & \mathbf{0}_{S-1}^T \\ 0 & 0 & 1 & \mathbf{0}_{S-1}^T \\ \mathbf{0}_{S-1} & \mathbf{0}_{S-1} & \mathbf{I} & \mathbf{0}_{S-1} \end{pmatrix} \\ \mathbf{Q} &= \begin{pmatrix} Q_a & \mathbf{0}_{S+1}^T \\ 0 & Q_b & \mathbf{0}_S^T \\ 0 & 0 & Q & \mathbf{0}_{S-1}^T \\ \mathbf{0}_{(S-1)*(S+2)} \end{pmatrix} \\ \mathbf{C} &= \begin{pmatrix} 1 & 1 & 1 & \mathbf{0}_{S-1}^T \end{pmatrix} \end{aligned}$$

Where we use $\mathbf{0}_n$ to denote a column vector of 0 with length n , and $\mathbf{0}_{m*n}$ to denote a $m * n$ matrix of 0.

19 Undirected graphical models(Markov random fields)

19.1 Derivation of the log partition function

According to the definition:

$$Z(\theta) = \sum_{\mathbf{y}} \prod_{c \in C} \psi_c(\mathbf{y}_c | \theta_c)$$

It is straightforward to give:

$$\begin{aligned} \frac{\partial \log Z(\theta)}{\partial \theta_{c'}} &= \frac{\partial}{\partial \theta_{c'}} \log \sum_{\mathbf{y}} \prod_{c \in C} \psi_c(\mathbf{y}_c | \theta_c) \\ &= \frac{1}{Z(\theta)} \sum_{\mathbf{y}} \frac{\partial}{\partial \theta_{c'}} \prod_{c \in C} \psi_c(\mathbf{y}_c | \theta_c) \\ &= \frac{1}{Z(\theta)} \sum_{\mathbf{y}} \prod_{c \in C, c \neq c'} \psi_c(\mathbf{y}_c | \theta_c) \frac{\partial}{\partial \theta_{c'}} \psi_{c'}(\mathbf{y}_{c'} | \theta_{c'}) \\ &= \frac{1}{Z(\theta)} \sum_{\mathbf{y}} \prod_{c \in C, c \neq c'} \psi_c(\mathbf{y}_c | \theta_c) \frac{\partial}{\partial \theta_{c'}} \exp \{ \theta_{c'}^T \phi_{c'}(\mathbf{y}_{c'}) \} \\ &= \frac{1}{Z(\theta)} \sum_{\mathbf{y}} \prod_{c \in C} \psi_c(\mathbf{y}_c | \theta_c) \phi_{c'}(\mathbf{y}_{c'}) \\ &= \sum_{\mathbf{y}} \phi_{c'}(\mathbf{y}_{c'}) \frac{1}{Z(\theta)} \prod_{c \in C} \psi_c(\mathbf{y}_c | \theta) \\ &= \sum_{\mathbf{y}} \phi_{c'}(\mathbf{y}_{c'}) p(\mathbf{y} | \theta) \\ &= \mathbb{E}[\phi_{c'}(\mathbf{y}_{c'}) | \theta] \end{aligned}$$

19.2 CI properties of Gaussian graphical models

Problem a:

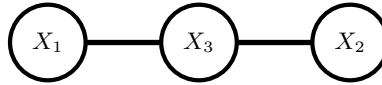
We have:

$$\Sigma = \begin{pmatrix} 0.75 & 0.5 & 0.25 \\ 0.5 & 1.0 & 0.5 \\ 0.25 & 0.5 & 0.75 \end{pmatrix}$$

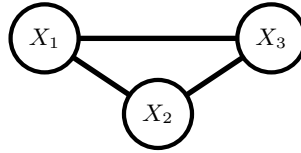
And:

$$\Lambda = \Sigma^{-1} = \begin{pmatrix} 2 & -1 & 0 \\ -1 & 2 & -1 \\ 0 & -1 & 2 \end{pmatrix}$$

Thus we have independency: $X_1 \perp X_2 | X_3$. This introduces a MRF like:



Problem b: The inverse of Σ contains no zero element, hence no conditional independency. Therefore there have to be edges between any two vertexes.



This model also cancels the marginal independency $X_1 \perp X_3$. But it is possible to model this set of properties by Bayesian network with two directed edges $X_1 \rightarrow X_2$ and $X_3 \rightarrow X_2$.

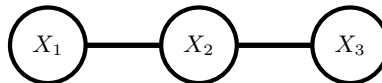
Problem c: Consider the terms inside the exponential:

$$-\frac{1}{2} \{x_1^2 + (x_2 - x_1)^2 + (x_3 - x_2)^2\}$$

It is easy to see the precision matrix and covariance matrix take:

$$\Lambda = \begin{pmatrix} 2 & -1 & 0 \\ -1 & 2 & -1 \\ 0 & -1 & 2 \end{pmatrix}, \Sigma = \begin{pmatrix} 1 & 1 & 1 \\ 1 & 2 & 2 \\ 1 & 2 & 3 \end{pmatrix}$$

Problem d: The only independency is $X_1 \perp X_3 | X_2$:



19.3 Independencies in Gaussian graphical models

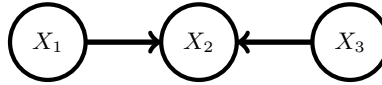
Problem a and b:

This PGM implies $X_1 \perp X_3 | X_2$, hence we are looking for a precision matrix with $\Lambda_{1,3} = 0$, thus C and D meet the condition. On the other hand, $(A^{-1})_{1,3} = (B^{-1})_{1,3} = 0$. So A and B are candidates for covariance matrix.

Problem c and d:

This PGM tells that $X_1 \perp X_3$. Hence C and D can be covariance matrix, A and B can be precision matrix.

The only possible PGM is:



Problem e:

The answer can be derived from the conclusion of marginal Gaussian directly, A is true while B not.

19.4 Cost of training MRFs and CRFs

The answer are generally:

$$O(r(Nc + 1))$$

and

$$O(r(Nc + N))$$

19.5 Full conditional in an Ising model

Straightforwardly(we have omitted θ from condition w.l.o.g):

$$\begin{aligned}
 p(x_k = 1 | \mathbf{x}_{-k}) &= \frac{p(x_k = 1, \mathbf{x}_{-k})}{p(\mathbf{x}_{-k})} \\
 &= \frac{p(x_k = 1, \mathbf{x}_{-k})}{p(x_k = 0, \mathbf{x}_{-k}) + p(x_k = 1, \mathbf{x}_{-k})} \\
 &= \frac{1}{1 + \frac{p(x_k=0, \mathbf{x}_{-k})}{p(x_k=1, \mathbf{x}_{-k})}} \\
 &= \frac{1}{1 + \frac{\exp(h_k \cdot 0) \prod_{\langle k, i \rangle} \exp(J_{k,i} \cdot 0)}{\exp(h_k \cdot 1) \prod_{\langle k, i \rangle} \exp(J_{k,i} \cdot x_i)}} \\
 &= \sigma\left(h_k + \sum_{i=1, i \neq k}^n J_{k,i} x_i\right)
 \end{aligned}$$

When using denotation $x = \{0, 1\}$, the full conditional becomes:

$$p(x_k = 1 | \mathbf{x}_{-k}) \sigma\left(2 \cdot \left(h_k + \sum_{i=1, i \neq k}^n J_{k,i} x_i\right)\right)$$

20 Exact inference for graphical models

20.1 Variable elimination

Where tf is the figure?!

20.2 Gaussian times Gaussian is Gaussian

We have:

$$\begin{aligned}
 & N(x|\mu_1, \lambda_1^{-1}) \times NN(x|\mu_2, \lambda_2^{-1}) \\
 &= \frac{\sqrt{\lambda_1 \lambda_2}}{2\pi} \exp \left\{ -\frac{\lambda_1}{2}(x - \mu_1)^2 - \frac{\lambda_2}{2}(x - \mu_2)^2 \right\} \\
 &= \frac{\sqrt{\lambda_1 \lambda_2}}{2\pi} \exp \left\{ -\frac{\lambda_1 + \lambda_2}{2}x^2 + (\lambda_1 \mu_1 + \lambda_2 \mu_2)x - \frac{\lambda_1 \mu_1^2 + \lambda_2 \mu_2^2}{2} \right\}
 \end{aligned}$$

By completing the square:

$$\begin{aligned}
 & \exp \left\{ -\frac{\lambda_1 + \lambda_2}{2}x^2 + (\lambda_1 \mu_1 + \lambda_2 \mu_2)x - \frac{\lambda_1 \mu_1^2 + \lambda_2 \mu_2^2}{2} \right\} \\
 &= c \cdot \exp -\frac{\lambda}{2}(x - \mu)^2
 \end{aligned}$$

Where:

$$\begin{aligned}
 \lambda &= \lambda_1 + \lambda_2 \\
 \mu &= \lambda^{-1}(\lambda_1 \mu_1 + \lambda_2 \mu_2)
 \end{aligned}$$

The constant factor c can be obtained by computing the constant terms inside the exponential.

20.3 Message passing on a tree

Problem a:

It is easy to see after variable elimination:

$$\begin{aligned}
 p(X_2 = 50) &= \sum_{G_1} \sum_{G_2} p(G_1)p(G_2|G_1)p(X_2 = 50|G_2) \\
 p(G_1 = 1, X_2 = 50) &= p(G_1) \sum_{G_2} p(G_2|G_1 = 1)p(X_2 = 50|G_2)
 \end{aligned}$$

Thus:

$$p(G_1 = 1|X_2 = 50) = \frac{0.45 + 0.05 \cdot \exp(-5)}{0.5 + 0.5 \cdot \exp(-5)} \approx 0.9$$

Problem b(here X denotes X_2 or X_3):

$$\begin{aligned} & p(G_1 = 1|X_2 = 50, X_3 = 50) \\ = & \frac{p(G_1 = 1, X_2 = 50, X_3 = 50)}{p(X_2 = 50, X_3 = 50)} \\ = & \frac{p(G_1 = 1)p(X_2|G_1 = 1)p(X_3|G_1 = 1)}{p(G_1 = 0)p(X_2|G_1 = 0)p(X_3|G_1 = 0) + p(G_1 = 1)p(X_2|G_1 = 1)p(X_3|G_1 = 1)} \\ = & \frac{p(X = 50|G_1 = 1)^2}{p(X = 50|G_1 = 0)^2 + p(X = 50|G_1 = 1)^2} \\ \approx & \frac{0.9^2}{0.1^2 + 0.9^2} \approx 0.99 \end{aligned}$$

Extra evidence makes the belief in $G_1 = 1$ firmer.

Problem c:

The answer to problem c is symmetric to that to problem b, $p(G_1 = 1|X_2 = 60, X_3 = 60) \approx 0.99$.

Problem d:

Using the same pattern of analysis from Problem b, we have:

$$\begin{aligned} & p(G_1 = 1|X_2 = 50, X_3 = 60) \\ = & \frac{p(X = 50|G_1 = 1)p(X = 60|G_1 = 1)}{p(X = 50|G_1 = 0)p(X = 60|G_1 = 0) + p(X = 50|G_1 = 1)p(X = 60|G_1 = 1)} \end{aligned}$$

Notice we have:

$$p(X = 50|G_1 = 1) = p(X = 60|G_1 = 0)$$

$$p(X = 50|G_1 = 0) = p(X = 60|G_1 = 1)$$

Hence:

$$P(G_1 = 1|X_2 = 50, X_3 = 60) = 0.5$$

In this case, X_2 and X_3 have equal strength as evidence and their effects achieve a balance so they provide not enough information to distort the prior knowledge.

20.4 Inference in 2D lattice MRFs

Please refer to PGM:principals and techniques 11.4.1.

21 Variational inference

21.1 Laplace approximation to $p(\mu, \log \sigma | D)$ for a univariate Gaussian

Laplace approximation equals representing $f(\mu, l) = \log p(\mu, l = \log \sigma | D)$ with second-order Taylor expansion. We have:

$$\begin{aligned}
 \log p(\mu, l | D) &= \log p(\mu, l, D) - \log p(D) \\
 &= \log p(\mu, l) + \log p(D | \mu, l) + c \\
 &= \log p(D | \mu, l) + c \\
 &= \sum_{n=1}^N \log \frac{1}{\sqrt{2\pi\sigma^2}} \exp \left\{ -\frac{1}{2\sigma^2} (y_n - \mu)^2 \right\} + c \\
 &= -N \log \sigma + \sum_{n=1}^N -\frac{1}{2\sigma^2} (y_n - \mu)^2 + c \\
 &= -N \cdot l + \frac{1}{2} \frac{1}{\exp \{2 \cdot l\}} \sum_{n=1}^N (y_n - \mu)^2 + c
 \end{aligned}$$

Thus we derive:

$$\begin{aligned}
 \frac{\partial \log p(\mu, l | D)}{\partial \mu} &= \frac{1}{2} \frac{1}{\exp \{2 \cdot l\}} \sum_{n=1}^N 2 \cdot (y_n - \mu) \\
 &= \frac{N}{\sigma^2} \cdot (\bar{y} - \mu) \\
 \frac{\partial \log p(\mu, l | D)}{\partial l} &= -N + \frac{1}{2} \sum_{n=1}^N (y_n - \mu)^2 \cdot (-2) \cdot \frac{1}{\exp \{2 \cdot l\}} \\
 &= -N + \frac{1}{\sigma^2} \sum_{n=1}^N (y_n - \mu)^2 \\
 \frac{\partial^2 \log p(\mu, l | D)}{\partial \mu^2} &= -\frac{N}{\sigma^2} \\
 \frac{\partial^2 \log p(\mu, l | D)}{\partial l^2} &= -\frac{2}{\sigma^2} \sum_{n=1}^N (y_n - \mu)^2 \\
 \frac{\partial^2 \log p(\mu, l | D)}{\partial \mu \partial l} &= N \cdot (\bar{y} - \mu) \cdot (-2) \cdot \frac{1}{\sigma^2}
 \end{aligned}$$

For approximation, $p(\mu, l) \approx N(\mu, \Sigma)$ with:

$$\Sigma = \begin{pmatrix} \frac{\partial^2 \log p(\mu, l|D)}{\partial \mu^2} & \frac{\partial^2 \log p(\mu, l|D)}{\partial l^2} \\ \frac{\partial^2 \log p(\mu, l|D)}{\partial l^2} & \frac{\partial^2 \log p(\mu, l|D)}{\partial \mu \partial l} \end{pmatrix}^{-1}$$

$$\mu = \Sigma \begin{pmatrix} \frac{\partial \log p(\mu, l|D)}{\partial \mu} \\ \frac{\partial \log p(\mu, l|D)}{\partial l} \end{pmatrix}$$

21.2 Laplace approximation to normal-gamma

This is the same with exercise 21.1 when the prior is uninformative. We formally substitute:

$$\begin{aligned} \sum_{n=1}^N (y_n - \mu)^2 &= \sum_{n=1}^N ((y_n - \bar{y}) - (\mu - \bar{y}))^2 \\ &= \sum_{n=1}^N (y_n - \bar{y})^2 + \sum_{n=1}^N (\mu - \bar{y})^2 + 2(\mu - \bar{y}) \cdot \sum_{n=1}^N (y_n - \bar{y}) \\ &= Ns^2 + N(\mu - \bar{y})^2 \end{aligned}$$

Where $s^2 = \frac{1}{N} \sum_{n=1}^N (y_n - \bar{y})^2$

Conclusions in all problems a, b and c are included in the previous solution.

21.3 Variational lower bound for VB for univariate Gaussian

What left in section 21.5.1.6 is the derivation for 21.86 to 21.91. We omit the derivation for entropy for Gaussian and moments, which can be found in any information theory textbook. Now we derive the $\mathbb{E}[\ln x|x \sim Ga(a, b)]$, which can therefore yields to the entropy for a Gamma distribution.

We know that Gamma distribution is an exponential family distribution:

$$\begin{aligned} Ga(x|a, b) &= \frac{b^a}{\Gamma(a)} x^{a-1} \exp \{-b \cdot x\} \\ &\propto \exp \{-b \cdot x + (a-1) \ln x\} \\ &= \exp \{\phi(x)^T \theta\} \end{aligned}$$

The sufficient statistics is $\phi(x) = (x, \ln x)^T$ and natural parameter is given by $\theta = (-b, a - 1)^T$. Thus Gamma distribution can be seen as the maximum entropy distribution under constraints on x and $\ln x$.

The cumulant function is given by:

$$\begin{aligned} A(\theta) &= \log Z(\theta) \\ &= \log \frac{\Gamma(a)}{b^a} \\ &= \log \Gamma(a) - a \log b \end{aligned}$$

The expectation of sufficient statistics is given by the derivative of cumulant function, therefore:

$$\mathbb{E}[\ln x] = \frac{\partial A}{\partial(a-1)} = \frac{\Gamma'(a)}{\Gamma(a)} - \log b$$

According to definition $\psi(a) = \frac{\Gamma'(a)}{\Gamma(a)}$:

$$\mathbb{E}[\ln x] = \psi(a) - \log b$$

The rest derivations are completed or trivial.

21.4 Variational lower bound for VB for GMMs

The lower bound is given by:

$$\begin{aligned} \mathbb{E}_q[\log \frac{p(\theta, D)}{q(\theta)}] &= \mathbb{E}_q[\log p(\theta, D)] - \mathbb{E}_q[\log q(\theta)] \\ &= \mathbb{E}_q[\log p(D|\theta)] + \mathbb{E}_q[\log p(\theta)] - \mathbb{E}_q[\log q(\theta)] \\ &= \mathbb{E}[\log p(\mathbf{x}|\mathbf{z}, \mu, \Lambda, \pi)] + \mathbb{E}[\log p(\mathbf{z}, \mu, \Lambda, \pi)] \\ &\quad - \mathbb{E}[\log q(\mathbf{z}, \mu, \Lambda, \pi)] \\ &= \mathbb{E}[\log p(\mathbf{x}|\mathbf{z}, \mu, \Lambda, \pi)] + \mathbb{E}[\log p(\mathbf{z}|\pi)] + \mathbb{E}[\log p(\pi)] + \mathbb{E}[\log p(\mu, \Lambda)] \\ &\quad + \mathbb{E}[\log q(\mathbf{z})] + \mathbb{E}[\log q(\pi)] + \mathbb{E}[\log q(\mu, \Lambda)] \end{aligned}$$

We are now showing 21.209 to 21.215.

For 21.209:

$$\begin{aligned} \mathbb{E}[\log p(\mathbf{x}|\mathbf{z}, \mu, \Lambda)] &= \mathbb{E}_{q(\mathbf{z})q(\mu, \Lambda)}[\log p(\mathbf{x}|\mathbf{z}, \mu, \Lambda)] \\ &= \sum_n \sum_k \mathbb{E}_{q(\mathbf{z})q(\mu, \Lambda)}[-\frac{D}{2} \log 2\pi + \frac{1}{2} \log |\Lambda_k| - \frac{1}{2} (x_n - \mu_k)^T \Lambda_k (x_n - \mu_k)] \end{aligned}$$

Using 21.132 and converting summing by average \bar{x}_k yields to solution.
For 21.210:

$$\begin{aligned}
\mathbb{E}[\log p(\mathbf{z}|\pi)] &= \mathbb{E}_{q(\mathbf{z})q(\pi)}[\log p(\mathbf{z}|\pi)] \\
&= \mathbb{E}_{q(\mathbf{z})q(\pi)}[\log \prod_{n=1}^N \prod_{k=1}^K \pi_k^{z_{nk}}] \\
&= \sum_{n=1}^N \sum_{k=1}^K \mathbb{E}_{q(\mathbf{z})q(\pi)}[z_{nk} \log \pi_k] \\
&= \sum_{n=1}^N \sum_{k=1}^K \mathbb{E}_{q(\mathbf{z})}[z_{nk}] \mathbb{E}_{q(\pi)}[\log \pi_k] \\
&= \sum_{n=1}^N \sum_{k=1}^K r_{nk} \log \bar{\pi}_k
\end{aligned}$$

For 21.211:

$$\begin{aligned}
\mathbb{E}[\log p(\pi)] &= \mathbb{E}_{q(\pi)}[\log p(\pi)] \\
&= \mathbb{E}_{q(\pi)}[\log(C \cdot \prod_{k=1}^K \pi_k^{\alpha_0-1})] \\
&= \ln C + (\alpha_0 - 1) \sum_{k=1}^K \log \bar{\pi}_k
\end{aligned}$$

For 21.212:

$$\begin{aligned}
\mathbb{E}[\log p(\mu, \Lambda)] &= \mathbb{E}_{q(\mu, \Lambda)}[\log p(\mu, \Lambda)] \\
&= \mathbb{E}_{q(\mu, \Lambda)}[\log \prod_{k=1}^K Wi(\Lambda_k | L_0, v_0) \cdot N(\mu_k | m_0, (\beta_0 \Lambda_k)^{-1})] \\
&= \sum_{k=1}^K \mathbb{E}_{q(\mu, \Lambda)}[\log C + \frac{1}{2}(v_0 - D - 1) \log |\Lambda_k| - \frac{1}{2} tr \{ \Lambda_k L_0^{-1} \} \\
&\quad - \frac{D}{2} \log 2\pi - \frac{1}{2} \log |\beta_0 \Lambda_k| - \frac{1}{2} (\mu_k - m_0)^T (\beta_0 \Lambda_k) (\mu_k - m_0)]
\end{aligned}$$

Using 21.131 to expand the expected value of the quadratic form and using the fact that the mean of a Wi distribution is $v_k L_k$ and we are done.

For 21.213:

$$\begin{aligned}
\mathbb{E}[\log q(\mathbf{z})] &= \mathbb{E}_{q(\mathbf{z})}[\log q(\mathbf{z})] \\
&= \mathbb{E}_{q(\mathbf{z})}[\sum_i \sum_k z_{ik} \log r_{ik}] \\
&= \sum_i \sum_k \mathbb{E}_{q(\mathbf{z})}[z_{ik}] \log r_{ik} \\
&= \sum_i \sum_k r_{ik} \log r_{ik}
\end{aligned}$$

For 21.214:

$$\begin{aligned}
\mathbb{E}[\log q(\pi)] &= \mathbb{E}_{q(\pi)}[\log q(\pi)] \\
&= \mathbb{E}_{q(\pi)}[\log C + \sum_{k=1}^K (\alpha_k - 1) \log \pi_k] \\
&= \log C + \sum_k (\alpha_k - 1) \log \bar{\pi}_k
\end{aligned}$$

For 21.215:

$$\begin{aligned}
\mathbb{E}[\log q(\mu, \Lambda)] &= \mathbb{E}_{q(\mu, \Lambda)}[\log q(\mu, \Lambda)] \\
&= \sum_k \mathbb{E}_{q(\mu, \Lambda)}[\log q(\Lambda_k) - \frac{D}{2} \log 2\pi + \frac{1}{2} \log |\beta_k \Lambda_k| \\
&\quad - \frac{1}{2} (\mu_k - m_k)^T (\beta_k \Lambda_k) (\mu_k - m_k)]
\end{aligned}$$

Using 21.132 to expand the quadratic form to give $\mathbb{E}[(\mu_k - m_k)^T (\beta_k \Lambda_k) (\mu_k - m_k)] = D$

21.5 Derivation of $\mathbb{E}[\log \pi_k]$

under a Dirichlet distribution Dirichlet distribution is an exponential family distribution, we have:

$$\phi(\pi) = (\log \pi_1, \log \pi_2, \dots, \log \pi_K)$$

$$\theta = \alpha$$

The cumulant function is:

$$A(\alpha) = \log B(\alpha) = \sum_{i=1}^K \log \Gamma(\alpha_i) - \log \Gamma(\sum_{i=1}^K \alpha_i)$$

And:

$$\mathbb{E}[\log \pi_k] = \frac{\partial A(\alpha)}{\partial \alpha_k} = \frac{\Gamma'(\alpha_k)}{\Gamma(\alpha_k)} - \frac{\Gamma'(\sum_{i=1}^K \alpha_k)}{\Gamma(\sum_{i=1}^K \alpha_k)} = \psi(\alpha_k) - \psi(\sum_{i=1}^K \alpha_i)$$

Take exponential on both sides:

$$\exp(\mathbb{E}[\log \pi_k]) = \exp(\psi(\alpha_k) - \psi(\sum_{i=1}^K \alpha_k)) = \frac{\exp(\alpha_k)}{\exp(\sum_{i=1}^K \alpha_i)}$$

21.6 Alternative derivation of the mean field updates for the Ising model

This is no different than applying the procedure in section 21.3.1 before derivating updates, hence omitted.

21.7 Forwards vs reverse KL divergence

We have:

$$\begin{aligned} KL(p(x, y) || q(x, y)) &= \mathbb{E}_{p(x, y)} [\log \frac{p(x, y)}{q(x, y)}] \\ &= \sum_{x, y} p(x, y) \log p(x, y) - \sum_{x, y} p(x, y) \log q(x) - \sum_{x, y} p(x, y) \log q(y) \\ &= \sum_{x, y} p(x, y) \log p(x, y) - \sum_x (\sum_y p(x, y)) \log q(x) - \sum_y y (\sum_x p(x, y)) \log q(y) \\ &= H(p(x, y)) - H(p(x)) - H(p(y)) + KL(p(x) || q(x)) + KL(p(y) || q(y)) \\ &= \text{constant} + KL(p(x) || q(x)) + KL(p(y) || q(y)) \end{aligned}$$

Thus the optimal approximation is $q(x) = p(x)$ and $q(y) = p(y)$.

We skip the practical part.

21.8 Derivation of the structured mean field updates for FHMM

According to the conclusion from mean-field varitional methods, we have:

$$E(\mathbf{x}_m) = \mathbb{E}_{q/m}[E(\bar{p}(\mathbf{x}_m))]$$

Thus:

$$-\sum_{t=1}^T \sum_{k=1}^K x_{t,m,k} \tilde{\epsilon}_{t,m,k} = \frac{1}{2} \mathbb{E} \left[\sum_{t=1}^T (\mathbf{y}_t - \sum_{l \neq m}^M W_l \mathbf{x}_{t,m})^T \Sigma^{-1} (\mathbf{y}_t - \sum_{l \neq m}^M W_l \mathbf{x}_{t,m}) \right] + C$$

Comparing the coefficient of $x_{t,m,k}$ (i.e. setting $x_{t,m,k}$ to 1) ends in:

$$\tilde{\epsilon}_{t,m,k} = W_m^T \Sigma^{-1} (\mathbf{y}_t - \sum_{l \neq m}^M W_l \mathbb{E}[\mathbf{x}_{t,l}]) - \frac{1}{2} (W_m^T \Sigma^{-1} W_m)_{k,k}$$

Write into matrix form yields to 21.62.

21.9 Variational EM for binary FA with sigmoid link

Refer to "Probabilistic Visualisation of High-Dimensional Binary Data, Tipping, 1998".

21.10 VB for binary FA with probit link

The major difference in using probit link is the uncontinuous likelihood caused by $p(y_i = 1|z_i) = \mathbb{I}(z_i > 0)$. In the context of hiding \mathbf{X} , we assume Gaussian prior on \mathbf{X} , \mathbf{W} and \mathbf{Z} . The approximation takes the form:

$$q(\mathbf{X}, \mathbf{Z}, \mathbf{W}) = \prod_{l=1}^L q(\mathbf{w}_l) \prod_{i=1}^N q(\mathbf{x}_i) q(z_i)$$

It is a mean-field approximation, hence in an algorithm similari to EM, we are to update the distribution of \mathbf{X} , \mathbf{Z} and \mathbf{W} stepwise.

For variable \mathbf{X} , we have:

$$\begin{aligned} \log q(\mathbf{x}_i) &= \mathbb{E}_{q(\mathbf{z}_i)q(\mathbf{w})} [\log p(\mathbf{x}_i, \mathbf{w}, z_i, y_i)] \\ &= \mathbb{E}_{q(\mathbf{z}_i)q(\mathbf{w})} [\log p(\mathbf{x}_i) + \log p(\mathbf{w}) + \log p(z_i|\mathbf{w}_i, \mathbf{w}) + \log p(y_i|z_i)] \end{aligned}$$

Given the likelihood form, for i corresponding to $y_i = 1$, $q(z_i)$ have to be a truncated one, i.e. we only consider the expectations in the form $\mathbb{E}[z|z > \mu]$ and $\mathbb{E}[z^2|z > \mu]$.

$$\log q(\mathbf{x}_i) = -\frac{1}{2} \mathbf{x}_i^T \Lambda_1 \mathbf{x}_i - \frac{1}{2} \mathbb{E}[z^2] - \frac{1}{2} \mathbf{x}_i^T \mathbb{E}[\mathbf{w}\mathbf{w}^T] \mathbf{x}_i + \mathbb{E}[z] \mathbb{E}[\mathbf{w}]^T \mathbf{x}_i$$

Where Λ_1 is the covariance of \mathbf{x}_i 's prior distribution, $\mathbb{E}[\mathbf{w}\mathbf{w}^T]$ can be calculated given the Gaussian form of $q(\mathbf{w})$, and truncated expectations $\mathbb{E}[z]$

and $\mathbb{E}[z^2]$ can be obtained from solutions to exercise 11.15. It is obvious that $q(\mathbf{x}_i)$ is a Gaussian.

The update for \mathbf{w} is similar to that for \mathbf{x}_i as long as they play symmetric roles in likelihood. The only difference is we have to sum over i when updating \mathbf{w} .

At last we update z_i :

$$\log q(z_i) = \mathbb{E}_{q(\mathbf{x}_i)q(\mathbf{w})}[\log p(z_i|\mathbf{x}_i, \mathbf{w}) + \log p(y_i|z_i)]$$

Inside the expectation we have:

$$-\frac{1}{2}z_i^2 + \mathbb{E}[\mathbf{w}]^T \mathbb{E}[\mathbf{x}]z_i + c$$

Therefore $q(z_i)$ again takes a Gaussian form.