Probabilistic & Unsupervised Learning

Latent Variable Models for Time Series

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Modeling time series

Thus far, our data have been (marginally) iid. Now consider a sequence of observations:

\[ x_1, x_2, x_3, \ldots, x_t \]

that are *not* independent.
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- Kinematic variables in a robot
- Sensor readings from an industrial process
- Amino acids, DNA, etc...
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- Predict \( p(x_t | x_1, \ldots, x_{t-1}) \)
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- Detect abnormal/changed behaviour (if \( p(x_t, x_{t+1}, \ldots | x_1, \ldots, x_{t-1}) \) small)
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- Detect abnormal/changed behaviour (if \( p(x_t, x_{t+1}, \ldots|x_1, \ldots, x_{t-1}) \) small)
- Recover underlying/latent/hidden causes linking entire sequence
Markov models

In general:

\[ P(x_1, \ldots, x_t) = P(x_1)P(x_2|x_1)P(x_3|x_1, x_2) \cdots P(x_t|x_1, x_2 \ldots x_{t-1}) \]
Markov models

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First-order Markov model:

\[ P(x_1, \ldots, x_t) = P(x_1)P(x_2|x_1) \cdots P(x_t|x_{t-1}) \]

The term *Markov* refers to a conditional independence relationship. In this case, the Markov property is that, given the present observation \((x_t)\), the future \((x_{t+1}, \ldots)\) is independent of the past \((x_1, \ldots, x_{t-1})\).
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The term Markov refers to a conditional independence relationship. In this case, the Markov property is that, given the present observation \((x_t)\), the future \((x_{t+1}, \ldots)\) is independent of the past \((x_1, \ldots, x_{t-1})\).

Second-order Markov model:

\[ P(x_1, \ldots, x_t) = P(x_1) P(x_2|x_1) \cdots P(x_{t-1}|x_{t-3}, x_{t-2}) P(x_t|x_{t-2}, x_{t-1}) \]
Causal structure and latent variables

Temporal dependence captured by latents, with observations conditionally independent.

Speech recognition:
- **y** - underlying phonemes or words
- **x** - acoustic waveform

Vision:
- **y** - object identities, poses, illumination
- **x** - image pixel values

Industrial Monitoring:
- **y** - current state of molten steel in caster
- **x** - temperature and pressure sensor readings
Latent-Chain models

Joint probability factorizes:

\[
P(y_{1:T}, x_{1:T}) = P(y_1) P(x_1 | y_1) \prod_{t=2}^{T} P(y_t | y_{t-1}) P(x_t | y_t)
\]

where \(y_t\) and \(x_t\) are both real-valued vectors, and \(\square_{1:T} \equiv \square_1, \ldots, \square_T\).

Two frequently-used tractable models:

- Linear-Gaussian state-space models
- Hidden Markov models
In a linear Gaussian SSM all conditional distributions are linear and Gaussian:

Output equation: \( \mathbf{x}_t = C\mathbf{y}_t + \mathbf{v}_t \)

State dynamics equation: \( \mathbf{y}_t = A\mathbf{y}_{t-1} + \mathbf{w}_t \)

where \( \mathbf{v}_t \) and \( \mathbf{w}_t \) are uncorrelated zero-mean multivariate Gaussian noise vectors.

Also assume \( \mathbf{y}_1 \) is multivariate Gaussian. The joint distribution over all variables \( \mathbf{x}_{1:T}, \mathbf{y}_{1:T} \) is (one big) multivariate Gaussian.

These models are also known as stochastic linear dynamical systems, Kalman filter models.
From factor analysis to state space models

Factor analysis: \[ x_i = \sum_{j=1}^{K} \Lambda_{ij} y_j + \epsilon_i \]

SSM output: \[ x_{t,i} = \sum_{j=1}^{K} C_{ij} y_{t,j} + v_i. \]

**Interpretation 1:**
- Observations confined near low-dimensional subspace (as in FA/PCA).
- Successive observations are generated from correlated points in the latent space.
- However:
  - FA requires \( K < D \) and \( \Psi \) diagonal; SSMs may have \( K \geq D \) and arbitrary output noise. *Why?*
  - Thus ML estimates of subspace by FA and SSM may differ.
Interpretation 2:

- Markov chain with linear dynamics $y_t = Ay_t \ldots$
- ...perturbed by Gaussian innovations noise – may describe stochasticity, unknown control, or model mismatch.
- Observations are a linear projection of the dynamical state, with additive iid Gaussian noise.
- Note:
  - Dynamical process ($y_t$) may be higher dimensional than the observations ($x_t$).
  - Observations do not form a Markov chain – longer-scale dependence reflects/reveals latent dynamics.
State space models can be used to model the input–output behaviour of controlled systems. The observed variables are divided into inputs ($u_t$) and outputs ($x_t$).

**State dynamics equation:** \[ y_t = Ay_{t-1} + Bu_{t-1} + w_t. \]

**Output equation:** \[ x_t = Cy_t + Du_t + v_t. \]

Note that we can have many variants, e.g. $y_t = Ay_{t-1} + Bu_t + w_t$ or even $y_t = Ay_{t-1} + Bx_{t-1} + w_t$. 
Hidden Markov models

Discrete hidden states $s_t \in \{1, \ldots, K\}$; outputs $x_t$ can be discrete or continuous. Joint probability factorizes:

$$P(s_1:T, x_1:T) = P(s_1)P(x_1|s_1) \prod_{t=2}^{T} P(s_t|s_{t-1})P(x_t|s_t)$$

Generative process:

- A first-order Markov chain generates the hidden state sequence (path):
  
  initial state probs: $\pi_j = P(s_1 = j)$  
  transition matrix: $\Phi_{ij} = P(s_{t+1} = j|s_t = i)$

- A set of emission (output) distributions $A_j(\cdot)$ (one per state) converts state path to a sequence of observations $x_t$.

  $A_j(x) = P(x_t = x|s_t = j)$ (for continuous $x_t$)

  $A_{jk} = P(x_t = k|s_t = j)$ (for discrete $x_t$)
Hidden Markov models

Two interpretations:

▶ a Markov chain with stochastic measurements:

![Diagram](image)

▶ or a mixture model with states coupled across time:

![Diagram](image)

Even though hidden state sequence is first-order Markov, the output process may not be Markov of any order (for example: 11111211113111211111311121111131112111113111211111311121111131...

Discrete state, discrete output models can approximate any continuous dynamics and observation mapping even if nonlinear; however this is usually not practical.

HMMs are related to stochastic finite state machines/automata.
Hidden Markov models can also be used to model sequential input-output behaviour:

$$P(s_{1:T}, x_{1:T} | u_{1:T}) = P(s_1 | u_1)P(x_1 | s_1, u_1) \prod_{t=2}^{T} P(s_t | s_{t-1}, u_{t-1})P(x_t | s_t, u_t)$$

IOHMMs can capture arbitrarily complex input-output relationships, however the number of states required is often impractical.
HMMs and SSMs

(Linear Gaussian) State space models are the continuous state analogue of hidden Markov models.

\[ s_1 \rightarrow s_2 \rightarrow s_3 \rightarrow \cdots \rightarrow s_T \leftrightarrow y_1 \rightarrow y_2 \rightarrow y_3 \rightarrow \cdots \rightarrow y_T \]

- A continuous vector state is a very powerful representation.
  For an HMM to communicate \( N \) bits of information about the past, it needs \( 2^N \) states!
  But a real-valued state vector can store an arbitrary number of bits in principle.

\[ s_1 \rightarrow s_2 \rightarrow s_3 \rightarrow \cdots \rightarrow s_T \]

\[ x_1 \rightarrow x_2 \rightarrow x_3 \rightarrow \cdots \rightarrow x_T \]

- Linear-Gaussian output/dynamics are very weak.
  The types of dynamics linear SSMs can capture is very limited. HMMs can in principle
  represent arbitrary stochastic dynamics and output mappings.
Many Extensions

- Constrained HMMs
- Continuous state models with discrete outputs for time series and static data
- Hierarchical models
- Hybrid systems ⇔ Mixed continuous & discrete states, switching state-space models
Richer state representations

These are hidden Markov models with many state variables (i.e. a distributed representation of the state).

The state can capture many more bits of information about the sequence (linear in the number of state variables).
The structure of learning and inference for both models is dictated by the factored structure.
Chain models: ML Learning with EM

\[ y_1 \sim \mathcal{N}(\mu_0, Q_0) \]
\[ y_t | y_{t-1} \sim \mathcal{N}(Ay_{t-1}, Q) \]
\[ x_t | y_t \sim \mathcal{N}(Cy_t, R) \]
\[ s_1 \sim \pi \]
\[ s_t | s_{t-1} \sim \Phi_{s_{t-1}} \]
\[ x_t | s_t \sim A_{s_t} \]

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P(x_1, \ldots, x_T, y_1, \ldots, y_T) = P(y_1) \prod_{t=2}^{T} P(y_t | y_{t-1}) \prod_{t=1}^{T} P(x_t | y_t)
\]
Chain models: ML Learning with EM

\begin{align*}
    \textbf{y}_1 & \sim \mathcal{N}(\mu_0, Q_0) \\
    \textbf{y}_t | \textbf{y}_{t-1} & \sim \mathcal{N}(A\textbf{y}_{t-1}, Q) \\
    \textbf{x}_t | \textbf{y}_t & \sim \mathcal{N}(C\textbf{y}_t, R) \\
    \textbf{s}_1 & \sim \pi \\
    \textbf{s}_t | \textbf{s}_{t-1} & \sim \Phi_{s_{t-1}} \\
    \textbf{x}_t | \textbf{s}_t & \sim A_{s_t}
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\[ P(\textbf{x}_1, \ldots, \textbf{x}_T, \textbf{y}_1, \ldots, \textbf{y}_T) = P(\textbf{y}_1) \prod_{t=2}^{T} P(\textbf{y}_t | \textbf{y}_{t-1}) \prod_{t=1}^{T} P(\textbf{x}_t | \textbf{y}_t) \]

Learning (M-step):

\[
    \arg\max \langle \log P(\textbf{x}_1, \ldots, \textbf{x}_T, \textbf{y}_1, \ldots, \textbf{y}_T) \rangle_{q(\textbf{y}_1, \ldots, \textbf{y}_T)} = \\
    \arg\max \left[ \langle \log P(\textbf{y}_1) \rangle_{q(\textbf{y}_1)} + \sum_{t=2}^{T} \langle \log P(\textbf{y}_t | \textbf{y}_{t-1}) \rangle_{q(\textbf{y}_t, \textbf{y}_{t-1})} + \sum_{t=1}^{T} \langle \log P(\textbf{x}_t | \textbf{y}_t) \rangle_{q(\textbf{y}_t)} \right]
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\]

So the expectations needed (in E-step) are derived from singleton and pairwise marginals.
Chain models: Inference

Three general inference problems:

Filtering: \( P(y_t | x_1, \ldots, x_t) \)

Smoothing: \( P(y_t | x_1, \ldots, x_T) \) (also \( P(y_t, y_{t-1} | x_1, \ldots, x_T) \) for learning)

Prediction: \( P(y_t | x_1, \ldots, x_{t-\Delta t}) \)
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Naively, these marginal posteriors seem to require very large integrals (or sums)

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P(y_t | x_1, \ldots, x_t) = \int \cdots \int dy_1 \cdots dy_{t-1} \ P(y_1, \ldots, y_t | x_1, \ldots, x_t)
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P(y_t|x_1, \ldots, x_t) = \int \cdots \int dy_1 \ldots dy_{t-1} P(y_1, \ldots, y_t|x_1, \ldots, x_t)
\]

but again the factored structure of the distributions will help us. The algorithms rely on a form of temporal updating or message passing.
Consider an HMM, where we want to find $P(s_t=k | x_1 \ldots x_t) =$

$$
\sum_{k_1, \ldots, k_{t-1}} P(s_1=k_1, \ldots, s_t=k | x_1 \ldots x_t) = \sum_{k_1, \ldots, k_{t-1}} \pi_{k_1} A_{k_1}(x_1) \Phi_{k_1,k_2} A_{k_2}(x_2) \ldots \Phi_{k_{t-1},k} A_k(x_t)
$$
Crawling the HMM state-lattice

Consider an HMM, where we want to find \( P(s_t=k|x_1 \ldots x_t) = \sum_{k_1, \ldots, k_{t-1}} P(s_1=k_1, \ldots, s_t=k|x_1 \ldots x_t) = \sum_{k_1, \ldots, k_{t-1}} \pi_{k_1} A_{k_1} (x_1) \Phi_{k_1,k_2} A_{k_2} (x_2) \ldots \Phi_{k_{t-1},k} A_{k} (x_t) \)

**Naïve algorithm:**
- start a “bug” at each of the \( K \) states at \( t = 1 \) holding value 1
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**Naïve algorithm:**
- start a “bug” at each of the \( K \) states at \( t = 1 \) holding value 1
- move each bug forward in time: make copies of each bug to each subsequent state and multiply the value of each copy by transition prob. \( \times \) output emission prob.
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- repeat
Consider an HMM, where we want to find $P(s_t=k|\mathbf{x}_1 \ldots \mathbf{x}_t) = \sum_{k_1, \ldots, k_{t-1}} P(s_1=k_1, \ldots, s_t=k|\mathbf{x}_1 \ldots \mathbf{x}_t) = \sum_{k_1, \ldots, k_{t-1}} \pi_{k_1} A_{k_1}(\mathbf{x}_1) \Phi_{k_1,k_2} A_{k_2}(\mathbf{x}_2) \ldots \Phi_{k_{t-1},k} A_k(\mathbf{x}_t)$

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- move each bug forward in time: make copies of each bug to each subsequent state and multiply the value of each copy by transition prob. $\times$ output emission prob.
- repeat until all bugs have reached time $t$
- sum up values on all $K^{t-1}$ bugs that reach state $s_t = k$ (one bug per state path)
Crawling the HMM state-lattice

Consider an HMM, where we want to find \( P(s_t = k | x_1 \ldots x_t) \) = 
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\sum_{k_1, \ldots, k_{t-1}} P(s_1 = k_1, \ldots, s_t = k | x_1 \ldots x_t) = \sum_{k_1, \ldots, k_{t-1}} \pi_{k_1} A_{k_1}(x_1) \Phi_{k_1, k_2} A_{k_2}(x_2) \ldots \Phi_{k_{t-1}, k} A_k(x_t)
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- repeat until all bugs have reached time \( t \)
- sum up values on all \( K^{t-1} \) bugs that reach state \( s_t = k \) (one bug per state path)

Clever recursion:
- at every step, replace bugs at each node with a single bug carrying sum of values
Probability updating: “Bayesian filtering”

$$P(y_t|x_{1:t}) = \int P(y_t, y_{t-1}|x_{1:t}) \, dy_{t-1}$$
Probability updating: “Bayesian filtering”

\[ P(y_t|x_{1:t}) = \int P(y_t, y_{t-1}|x_t, x_{1:t-1}) \, dy_{t-1} \]
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P(y_t|x_{1:t}) = \int P(y_t, y_{t-1}|x_t, x_{1:t-1}) \, dy_{t-1} \\
= \int \frac{P(x_t, y_t, y_{t-1}|x_{1:t-1})}{P(x_t|x_{1:t-1})} \, dy_{t-1}
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\]

\[
\propto \int P(x_t|y_t, y_{t-1}, x_{1:t-1})P(y_t|y_{t-1}, x_{1:t-1})P(y_{t-1}|x_{1:t-1}) \, dy_{t-1}
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Probability updating: “Bayesian filtering”

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\[ = \int P(x_t|x_t)P(y_t|y_{t-1})P(y_{t-1}|x_{1:t-1}) \, dy_{t-1} \]

Markov property
Probability updating: “Bayesian filtering”

\[
P(y_t|x_{1:t}) = \int P(y_t, y_{t-1}|x_t, x_{1:t-1}) \, dy_{t-1}
\]
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\[
\propto \int P(x_t|y_t, y_{t-1}, x_{1:t-1}) P(y_t|y_{t-1}, x_{1:t-1}) P(y_{t-1}|x_{1:t-1}) \, dy_{t-1}
\]
\[
= \int P(x_t|y_t) P(y_t|y_{t-1}) P(y_{t-1}|x_{1:t-1}) \, dy_{t-1}
\]

This is a forward recursion based on Bayes rule.
The HMM: Forward pass

The **forward recursion** for the HMM is a form of **dynamic programming**.
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\[ \alpha_t(i) = P(x_1, \ldots, x_t, s_t = i | \theta) \]
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$$\alpha_t(i) = P(x_1, \ldots, x_t, s_t = i | \theta)$$

Then much like the Bayesian filtering updates, we have:

$$\alpha_1(i) = \pi_i A_i(x_1)$$

$$\alpha_{t+1}(i) = \left( \sum_{j=1}^{K} \alpha_t(j) \Phi_{ji} \right) A_i(x_{t+1})$$
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\[ \alpha_1(i) = \pi_i A_i(x_1) \quad \alpha_{t+1}(i) = \left( \sum_{j=1}^{\kappa} \alpha_t(j) \Phi_{ji} \right) A_i(x_{t+1}) \]

We’ve defined \( \alpha_t(i) \) to be a joint rather than a posterior.
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Then much like the Bayesian filtering updates, we have:

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\alpha_1(i) = \pi_i A_i(x_1) \quad \alpha_{t+1}(i) = \left( \sum_{j=1}^{K} \alpha_t(j) \Phi_{ji} \right) A_i(x_{t+1})
\]

We’ve defined \(\alpha_t(i)\) to be a joint rather than a posterior. It’s easy to obtain the posterior by normalisation:

\[
P(s_t = i | x_1, \ldots, x_t, \theta) = \frac{\alpha_t(i)}{\sum_k \alpha_t(k)}
\]
The HMM: Forward pass

The **forward recursion** for the HMM is a form of **dynamic programming**. Define:

\[ \alpha_t(i) = P(x_1, \ldots, x_t, s_t = i | \theta) \]

Then much like the Bayesian filtering updates, we have:

\[ \alpha_1(i) = \pi_i A_i(x_1) \quad \quad \alpha_{t+1}(i) = \left( \sum_{j=1}^{K} \alpha_t(j) \Phi_{ji} \right) A_i(x_{t+1}) \]

We’ve defined \( \alpha_t(i) \) to be a joint rather than a posterior. It’s easy to obtain the posterior by normalisation:

\[ P(s_t = i | x_1, \ldots, x_t, \theta) = \frac{\alpha_t(i)}{\sum_k \alpha_t(k)} \]

This form enables us to compute the likelihood for \( \theta = \{A, \Phi, \pi\} \) efficiently in \( \mathcal{O}(TK^2) \) time:

\[ P(x_1 \ldots x_T | \theta) = \sum_{s_1, \ldots, s_T} P(x_1, \ldots, x_T, s_1, \ldots, s_T, \theta) = \sum_{k=1}^{K} \alpha_T(k) \]

avoiding the exponential number of paths in the naïve sum (number of paths = \( K^T \)).
The LGSSM: Kalman Filtering

\[ y_1 \sim \mathcal{N}(\mu_0, Q_0) \]
\[ y_t | y_{t-1} \sim \mathcal{N}(Ay_{t-1}, Q) \]
\[ x_t | y_t \sim \mathcal{N}(Cy_t, R) \]

For the SSM, the sums become integrals.
The LGSSM: Kalman Filtering

\[
\begin{align*}
\ y_1 & \sim \mathcal{N}(\mu_0, Q_0) \\
\ y_t | y_{t-1} & \sim \mathcal{N}(Ay_{t-1}, Q) \\
\ x_t | y_t & \sim \mathcal{N}(Cy_t, R)
\end{align*}
\]

For the SSM, the sums become integrals. Let \( \hat{y}_1^0 = \mu_0 \) and \( \hat{V}_1^0 = Q_0 \); then (cf. FA)

\[
P(y_1 | x_1) = \mathcal{N}(\hat{y}_1^0 + K_1(x_1 - C\hat{y}_1^0), \hat{V}_1^0 - K_1 C \hat{V}_1^0)
\]
The LGSSM: Kalman Filtering

\[
\begin{align*}
\mathbf{y}_1 & \sim \mathcal{N}(\mu_0, Q_0) \\
\mathbf{y}_t | \mathbf{y}_{t-1} & \sim \mathcal{N}(A\mathbf{y}_{t-1}, Q) \\
\mathbf{x}_t | \mathbf{y}_t & \sim \mathcal{N}(C\mathbf{y}_t, R)
\end{align*}
\]

For the SSM, the sums become integrals. Let \( \hat{\mathbf{y}}_1^0 = \mu_0 \) and \( \hat{\mathbf{V}}_1^0 = Q_0 \); then (cf. FA)

\[
P(\mathbf{y}_1 | \mathbf{x}_1) = \mathcal{N}(\hat{\mathbf{y}}_1^0 + K_1(\mathbf{x}_1 - C\hat{\mathbf{y}}_1^0), \hat{\mathbf{V}}_1^0 - K_1 C \hat{\mathbf{V}}_1^0)
\]

\[
K_1 = \hat{\mathbf{V}}_1^0 C^T (C \hat{\mathbf{V}}_1^0 C^T + R)^{-1}
\]
The LGSSM: Kalman Filtering

\[
\begin{align*}
\mathbf{y}_1 & \sim \mathcal{N}(\mu_0, Q_0) \\
\mathbf{y}_t | \mathbf{y}_{t-1} & \sim \mathcal{N}(A\mathbf{y}_{t-1}, Q) \\
\mathbf{x}_t | \mathbf{y}_t & \sim \mathcal{N}(C\mathbf{y}_t, R)
\end{align*}
\]

For the SSM, the sums become integrals. Let \( \hat{\mathbf{y}}_0 = \mu_0 \) and \( \hat{\mathbf{V}}_0 = Q_0 \); then (cf. FA)

\[
P(\mathbf{y}_1 | \mathbf{x}_1) = \mathcal{N} \left( \hat{\mathbf{y}}_1^0 + K_1(\mathbf{x}_1 - C\hat{\mathbf{y}}_1^0), \hat{\mathbf{V}}_1^0 - K_1 C \hat{\mathbf{V}}_1^0 \right)
\]

\[
K_1 = \hat{\mathbf{V}}_1^0 C^T(C\hat{\mathbf{V}}_1^0 C^T + R)^{-1}
\]
The LGSSM: Kalman Filtering

For the SSM, the sums become integrals. Let $\hat{y}_1^0 = \mu_0$ and $\hat{V}_1^0 = Q_0$; then (cf. FA)

$$P(y_1|x_1) = \mathcal{N}(\hat{y}_1^0 + K_1(x_1 - C\hat{y}_1^0), \hat{V}_1^0 - K_1 C \hat{V}_1^0)$$

$$K_1 = \hat{V}_1^0 C^T (C \hat{V}_1^0 C^T + R)^{-1}$$

In general, we define $\hat{y}_t^T = E[y_t|x_1, \ldots, x_T]$ and $\hat{V}_t^T = V[y_t|x_1, \ldots, x_T]$. 

$y_1 \sim \mathcal{N}(\mu_0, Q_0)$

$y_t|y_{t-1} \sim \mathcal{N}(Ay_{t-1}, Q)$

$x_t|y_t \sim \mathcal{N}(Cy_t, R)$
The LGSSM: Kalman Filtering

For the SSM, the sums become integrals. Let \( \hat{y}_1^0 = \mu_0 \) and \( \hat{V}_1^0 = Q_0 \); then (cf. FA)

\[
P(y_1|x_1) = \mathcal{N}(\hat{y}_1^0 + K_1(x_1 - C\hat{y}_i^0), \hat{V}_1^0 - K_1C\hat{V}_1^0)
\]

In general, we define \( \hat{y}_t^T \equiv E[y_t|x_1, \ldots, x_T] \) and \( \hat{V}_t^T \equiv V[y_t|x_1, \ldots, x_T] \). Then,

\[
P(y_t|x_{1:t-1}) = \int dy_{t-1}P(y_t|y_{t-1})P(y_{t-1}|x_{1:t-1})
\]
The LGSSM: Kalman Filtering

For the SSM, the sums become integrals. Let $\hat{y}_1^0 = \mu_0$ and $\hat{V}_1^0 = Q_0$; then (cf. FA)

$$P(y_1 | x_1) = \mathcal{N}(\hat{y}_1^0 + K_1(x_1 - C\hat{y}_i^0), \hat{V}_1^0 - K_1 C \hat{V}_i^0)$$

$$K_1 = \hat{V}_1^0 C^T (C \hat{V}_i^0 C^T + R)^{-1}$$

In general, we define $\hat{y}_t^T \equiv E[y_t | x_1, \ldots, x_\tau]$ and $\hat{V}_t^T \equiv V[y_t | x_1, \ldots, x_\tau]$. Then,

$$P(y_t | x_{1:t-1}) = \int dy_{t-1} P(y_t | y_{t-1}) P(y_{t-1} | x_{1:t-1}) = \mathcal{N}(\hat{y}_{t-1}^t, A\hat{V}_{t-1}^{t-1}A^T + Q)$$
The LGSSM: Kalman Filtering

\[ \begin{align*}
\begin{array}{c}
\mathbf{y}_1 \\
\mathbf{x}_1 \\
\downarrow \\
\mathbf{y}_2 \\
\mathbf{x}_2 \\
\downarrow \\
\mathbf{y}_3 \\
\mathbf{x}_3 \\
\downarrow \\
\vdots \\
\mathbf{y}_T \\
\mathbf{x}_T
\end{array}
\end{align*} \]

\[ \begin{align*}
\mathbf{y}_1 & \sim \mathcal{N}(\mu_0, Q_0) \\
\mathbf{y}_t | \mathbf{y}_{t-1} & \sim \mathcal{N}(A\mathbf{y}_{t-1}, Q) \\
\mathbf{x}_t | \mathbf{y}_t & \sim \mathcal{N}(C\mathbf{y}_t, R)
\end{align*} \]

For the SSM, the sums become integrals. Let \( \hat{\mathbf{y}}_1^0 = \mu_0 \) and \( \hat{\mathbf{V}}_1^0 = Q_0 \); then (cf. FA)

\[ P(\mathbf{y}_1 | \mathbf{x}_1) = \mathcal{N}(\hat{\mathbf{y}}_1^0 + K_1(\mathbf{x}_1 - C\hat{\mathbf{y}}_1^0), \hat{\mathbf{V}}_1^0 - K_1 C \hat{\mathbf{V}}_1^0) \]

\[ K_1 = \hat{\mathbf{V}}_1^0 C^T (C \hat{\mathbf{V}}_1^0 C^T + R)^{-1} \]

In general, we define \( \hat{\mathbf{y}}_t^T \equiv E[\mathbf{y}_t | \mathbf{x}_1, \ldots, \mathbf{x}_\tau] \) and \( \hat{\mathbf{V}}_t^T \equiv V[\mathbf{y}_t | \mathbf{x}_1, \ldots, \mathbf{x}_\tau] \). Then,

\[ P(\mathbf{y}_t | \mathbf{x}_{1:t-1}) = \int d\mathbf{y}_{t-1} P(\mathbf{y}_t | \mathbf{y}_{t-1}) P(\mathbf{y}_{t-1} | \mathbf{x}_{1:t-1}) = \mathcal{N}(A\hat{\mathbf{y}}_{t-1}^t, A\hat{\mathbf{V}}_{t-1}^t A^T + Q) \]

\[ P(\mathbf{y}_t | \mathbf{x}_{1:t}) = \mathcal{N}(\hat{\mathbf{y}}_t + K_t(\mathbf{x}_t - C\hat{\mathbf{y}}_t), \hat{\mathbf{V}}_t - K_t C \hat{\mathbf{V}}_t) \]

\[ K_t = \hat{\mathbf{V}}_t C^T (C \hat{\mathbf{V}}_t C^T + R)^{-1} \]

Kalman gain
The LGSSM: Kalman Filtering

\[ y_1 \sim \mathcal{N}(\mu_0, Q_0) \]
\[ y_t | y_{t-1} \sim \mathcal{N}(A y_{t-1}, Q) \]
\[ x_t | y_t \sim \mathcal{N}(C y_t, R) \]

For the SSM, the sums become integrals. Let \( \hat{y}_1^0 = \mu_0 \) and \( \hat{V}_1^0 = Q_0 \); then (cf. FA)

\[
P(y_1 | x_1) = \mathcal{N}(\hat{y}_1^0 + K_1 (x_1 - C \hat{y}_1^0), \hat{V}_1^0 - K_1 C \hat{V}_1^0) \]

In general, we define \( \hat{y}_T^T = E[y_t | x_1, \ldots, x_T] \) and \( \hat{V}_T^T = V[y_t | x_1, \ldots, x_T] \). Then,

\[
P(y_t | x_{1:t-1}) = \int dy_{t-1} P(y_t | y_{t-1}) P(y_{t-1} | x_{1:t-1}) = \mathcal{N}(A \hat{y}_{t-1}^{t-1}, A \hat{V}_{t-1}^{t-1} A^T + Q) \]

\[
P(y_t | x_{1:t}) = \mathcal{N}(\hat{y}_t^{t-1} + K_t (x_t - C \hat{y}_t^{t-1}), \hat{V}_t^{t-1} - K_t C \hat{V}_t^{t-1}) \]

\[
K_t = \frac{\hat{V}_t^{t-1} C^T (C \hat{V}_t^{t-1} C^T + R)^{-1} \langle xx^T \rangle}{\hat{V}_t^{t-1} + K_t^2 C \hat{V}_t^{t-1} C^T + R} \]

Kalman gain
The LGSSM: Kalman Filtering

For the SSM, the sums become integrals. Let \( \hat{y}_1^0 = \mu_0 \) and \( \hat{V}_1^0 = Q_0 \); then (cf. FA)

\[
P(y_1|x_1) = \mathcal{N}(\hat{y}_1^0 + K_1(x_1 - C\hat{y}_i^0), \hat{V}_1^0 - K_1C\hat{V}_1^0)
\]

In general, we define \( \hat{y}_t^T \equiv E[y_t|x_1, \ldots, x_\tau] \) and \( \hat{V}_t^T \equiv V[y_t|x_1, \ldots, x_\tau] \). Then,

\[
P(y_t|x_{1:t-1}) = \int dy_{t-1}P(y_t|y_{t-1})P(y_{t-1}|x_{1:t-1}) = \mathcal{N}(\hat{y}_{t-1}^t, \hat{V}_{t-1}^t + Q)
\]

\[
P(y_t|x_{1:t}) = \mathcal{N}(\hat{y}_t^t + K_t(x_t - C\hat{y}_t^t), \hat{V}_t^t - K_tC\hat{V}_t^t)
\]

\[
K_t = \hat{V}_t^tC^T(C\hat{V}_t^tC^T + R)^{-1}
\]

FA: \( \beta = (I + \Lambda^T\Psi^{-1}\Lambda)^{-1}\Lambda^T\Psi^{-1} \) mat. inv. lem. \( \Lambda^T(\Lambda\Lambda^T + \Psi)^{-1} \); \( \mu = \beta x_n; \Sigma = I - \beta\Lambda \).
The marginal posterior: “Bayesian smoothing”

\[ P(y_t | x_{1:T}) \]
The marginal posterior: “Bayesian smoothing”

\[
P(y_t | x_{1:T}) = \frac{P(y_t, x_{t+1:T} | x_{1:t})}{P(x_{t+1:T} | x_{1:t})}
\]
The marginal posterior: “Bayesian smoothing”

\[
P(y_t|x_{1:T}) = \frac{P(y_t, x_{t+1:T}|x_{1:t})}{P(x_{t+1:T}|x_{1:t})} \\
= \frac{P(x_{t+1:T}|y_t)P(y_t|x_{1:t})}{P(x_{t+1:T}|x_{1:t})}
\]

The marginal combines a **backward message** with the **forward message** found by filtering.
The HMM: Forward–Backward Algorithm

State estimation: compute marginal posterior distribution over state at time $t$:

$$\gamma_t(i) \equiv P(s_t=i|\mathbf{x}_{1:T}) = \frac{P(s_t=i, \mathbf{x}_{1:t}) P(\mathbf{x}_{t+1:T} | s_t=i)}{P(\mathbf{x}_{1:T})} = \frac{\alpha_t(i) \beta_t(i)}{\sum_j \alpha_t(j) \beta_t(j)}$$

where there is a simple backward recursion for

$$\beta_t(i) \equiv P(\mathbf{x}_{t+1:T} | s_t=i) = \sum_{j=1}^{K} P(s_{t+1}=j, \mathbf{x}_{t+1}, \mathbf{x}_{t+2:T} | s_t=i)$$

$$= \sum_{j=1}^{K} P(s_{t+1}=j | s_t=i) P(\mathbf{x}_{t+1} | s_{t+1}=j) P(\mathbf{x}_{t+2:T} | s_{t+1}=j) = \sum_{j=1}^{K} \Phi_{ij} A_j(\mathbf{x}_{t+1}) \beta_{t+1}(j)$$

$\alpha_t(i)$ gives total inflow of probabilities to node $(t, i)$; $\beta_t(i)$ gives total outflow of probabilities.

---

Bugs again: the bugs run forward from time 0 to $t$ and backward from time $T$ to $t$. 
Viterbi decoding

- The numbers $\gamma_t(i)$ computed by forward-backward give the marginal posterior distribution over states at each time.
Viterbi decoding

- The numbers $\gamma_t(i)$ computed by forward-backward give the marginal posterior distribution over states at each time.

- By choosing the state $i_t^*$ with the largest $\gamma_t(i)$ at each time, we can make a “best” state path. This is the path with the maximum expected number of correct states.
Viterbi decoding

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- But it is not the single path with the highest probability of generating the data. In fact it may be a path of probability zero!
Viterbi decoding

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- But it is not the single path with the highest probability of generating the data. In fact it may be a path of probability zero!

- To find the single best path, we use the Viterbi decoding algorithm which is just Bellman’s dynamic programming algorithm applied to this problem. This is an inference algorithm which computes the most probable state sequences: $\arg\max_{s_{1:T}} P(s_{1:T} | x_{1:T}, \theta)$.
The numbers $\gamma_t(i)$ computed by forward-backward give the marginal posterior distribution over states at each time.

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The recursions look the same as forward-backward, except with $\max$ instead of $\sum$. 

Viterbi decoding
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- The recursions look the same as forward-backward, except with max instead of $\sum$.

- Bugs once more: same trick except at each step kill all bugs but the one with the highest value at the node.
Viterbi decoding

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- By choosing the state $i_t^*$ with the largest $\gamma_t(i)$ at each time, we can make a “best” state path. This is the path with the maximum expected number of correct states.

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- The recursions look the same as forward-backward, except with max instead of $\sum$.

- Bugs once more: same trick except at each step kill all bugs but the one with the highest value at the node.

- There is also a modified EM training based on the Viterbi decoder (assignment).
The LGSSM: Kalman smoothing

We use a slightly different decomposition:

\[
P(y_t | x_{1:T}) = \int P(y_t, y_{t+1} | x_{1:T}) \, dy_{t+1}
\]

\[
= \int P(y_t | y_{t+1}, x_{1:t}) P(y_{t+1} | x_{1:T}) \, dy_{t+1}
\]

\[
= \int P(y_t | y_{t+1}, x_{1:t}) P(y_{t+1} | x_{1:T}) \, dy_{t+1}
\]

This gives the additional **backward recursion**:

\[
J_t = \hat{V}_t^t A^T (\hat{V}_{t+1}^t)^{-1}
\]

\[
\hat{y}_t^T = \hat{y}_t^t + J_t (\hat{y}_{t+1}^T - A\hat{y}_t^t)
\]

\[
\hat{V}_t^T = \hat{V}_t^t + J_t (\hat{V}_{t+1}^T - \hat{V}_{t+1}^t) J_t^T
\]
ML Learning for SSMs using batch EM

Parameters: \( \theta = \{ \mu_0, Q_0, A, Q, C, R \} \)

Free energy:

\[
\mathcal{F}(q, \theta) = \int d\mathbf{y}_{1:T} \ q(\mathbf{y}_{1:T})(\log P(\mathbf{x}_{1:T}, \mathbf{y}_{1:T} | \theta) - \log q(\mathbf{y}_{1:T}))
\]

**E-step:** Maximise \( \mathcal{F} \) w.r.t. \( q \) with \( \theta \) fixed:

\[
q^*(\mathbf{y}) = p(\mathbf{y} | \mathbf{x}, \theta)
\]

This can be achieved with a two-state extension of the Kalman smoother.

**M-step:** Maximize \( \mathcal{F} \) w.r.t. \( \theta \) with \( q \) fixed.

This boils down to solving a few weighted least squares problems, since all the variables in:

\[
p(\mathbf{y}, \mathbf{x} | \theta) = p(\mathbf{y}_1)p(\mathbf{x}_1 | \mathbf{y}_1) \prod_{t=2}^{T} p(\mathbf{y}_t | \mathbf{y}_{t-1})p(\mathbf{x}_t | \mathbf{y}_t)
\]

form a multivariate Gaussian.
The M step for $C$

$$p(x_t | y_t) \propto \exp \left[ -\frac{1}{2} (x_t - C y_t)^\top R^{-1} (x_t - C y_t) \right] \quad \Rightarrow$$
The M step for $C$

$$p(x_t | y_t) \propto \exp \left[ -\frac{1}{2} (x_t - Cy_t)^T R^{-1} (x_t - Cy_t) \right] \Rightarrow$$

$$C_{\text{new}} = \arg\max_C \left\langle \sum_t \ln p(x_t | y_t) \right\rangle_q$$
The M step for $C$

$$p(x_t | y_t) \propto \exp \left[ -\frac{1}{2} (x_t - Cy_t)^T R^{-1} (x_t - Cy_t) \right] \Rightarrow$$

$$C_{\text{new}} = \arg\max_C \left\langle \sum_t \ln p(x_t | y_t) \right\rangle_q$$

$$= \arg\max_C \left\langle -\frac{1}{2} \sum_t (x_t - Cy_t)^T R^{-1} (x_t - Cy_t) \right\rangle_q + \text{const}$$

Notice that this is exactly the same equation as in factor analysis and linear regression!
The M step for $C$

$$p(x_t | y_t) \propto \exp \left[ -\frac{1}{2} (x_t - Cy_t)^T R^{-1} (x_t - Cy_t) \right] \Rightarrow$$

$$C_{\text{new}} = \arg\max_C \left\{ \sum_t \ln p(x_t | y_t) \right\}_{q}$$

$$= \arg\max_C \left\{ -\frac{1}{2} \sum_t (x_t - Cy_t)^T R^{-1} (x_t - Cy_t) \right\}_{q} + \text{const}$$

$$= \arg\max_C \left\{ -\frac{1}{2} \sum_t x_t^T R^{-1} x_t - 2 x_t^T R^{-1} C \langle y_t \rangle + \langle y_t^T C^T R^{-1} C y_t \rangle \right\}$$
The M step for $C$

$$p(x_t|y_t) \propto \exp \left[ -\frac{1}{2} (x_t - Cy_t)^T R^{-1} (x_t - Cy_t) \right] \Rightarrow$$

$$C_{\text{new}} = \arg\max_C \left\langle \sum_t \ln p(x_t|y_t) \right\rangle_q$$

$$= \arg\max_C \left\langle -\frac{1}{2} \sum_t (x_t - Cy_t)^T R^{-1} (x_t - Cy_t) \right\rangle_q + \text{const}$$

$$= \arg\max_C \left\{ -\frac{1}{2} \sum_t x_t^T R^{-1} x_t - 2x_t^T R^{-1} C \langle y_t \rangle + \langle y_t^T C^T R^{-1} C y_t \rangle \right\}$$

$$= \arg\max_C \left\{ \text{Tr} \left[ C \sum_t \langle y_t \rangle x_t^T R^{-1} \right] - \frac{1}{2} \text{Tr} \left[ C^T R^{-1} C \left\langle \sum_t y_t y_t^T \right\rangle \right] \right\}$$

Notice that this is exactly the same equation as in factor analysis and linear regression!
The M step for $C$

$p(x_t|y_t) \propto \exp \left[ -\frac{1}{2} (x_t - Cy_t)^T R^{-1} (x_t - Cy_t) \right] \Rightarrow$

$$C_{\text{new}} = \arg\max_c \left\langle \sum_t \ln p(x_t|y_t) \right\rangle_q$$

$$= \arg\max_c \left\langle -\frac{1}{2} \sum_t (x_t - Cy_t)^T R^{-1} (x_t - Cy_t) \right\rangle_q + \text{const}$$

$$= \arg\max_c \left\{ -\frac{1}{2} \sum_t x_t^T R^{-1} x_t - 2x_t^T R^{-1} C \langle y_t \rangle + \langle y_t^T C R^{-1} C y_t \rangle \right\}$$

$$= \arg\max_c \left\{ \text{Tr} \left[ C \sum_t \langle y_t \rangle x_t^T R^{-1} \right] - \frac{1}{2} \text{Tr} \left[ C^T R^{-1} C \left\langle \sum_t y_t y_t^T \right\rangle \right] \right\}$$

using $\frac{\partial \text{Tr}[AB]}{\partial A} = B^T$, we have $\frac{\partial \{\cdot\}}{\partial C} = R^{-1} \sum_t x_t \langle y_t \rangle^T - R^{-1} C \left\langle \sum_t y_t y_t^T \right\rangle$
The M step for $C$

$$p(x_t|y_t) \propto \exp \left[ -\frac{1}{2} (x_t - Cy_t)^T R^{-1} (x_t - Cy_t) \right] \Rightarrow$$

$$C_{\text{new}} = \arg\max_C \left\langle \sum_t \ln p(x_t|y_t) \right\rangle_q$$

$$= \arg\max_C \left\langle -\frac{1}{2} \sum_t (x_t - Cy_t)^T R^{-1} (x_t - Cy_t) \right\rangle_q + \text{const}$$

$$= \arg\max_C \left\{ -\frac{1}{2} \sum_t x_t^T R^{-1} x_t - 2x_t^T R^{-1} C \langle y_t \rangle + \langle y_t^T C^T R^{-1} C y_t \rangle \right\}$$

$$= \arg\max_C \left\{ \text{Tr} \left[ C \sum_t \langle y_t \rangle x_t^T R^{-1} \right] - \frac{1}{2} \text{Tr} \left[ C^T R^{-1} C \left\langle \sum_t y_t y_t^T \right\rangle \right] \right\}$$

using $\frac{\partial \text{Tr}[AB]}{\partial A} = B^T$, we have $\frac{\partial \{ \cdot \}}{\partial C} = R^{-1} \sum_t x_t \langle y_t \rangle^T - R^{-1} C \left\langle \sum_t y_t y_t^T \right\rangle$

$$\Rightarrow C_{\text{new}} = \left( \sum_t x_t \langle y_t \rangle^T \right) \left( \sum_t \langle y_t y_t^T \rangle \right)^{-1}$$

Notice that this is exactly the same equation as in factor analysis and linear regression!
The M step for $A$

$$p(y_{t+1}|y_t) \propto \exp \left\{ -\frac{1}{2} (y_{t+1} - Ay_t)^T Q^{-1} (y_{t+1} - Ay_t) \right\} \Rightarrow$$
The M step for $A$

\[
p(y_{t+1}|y_t) \propto \exp \left\{ -\frac{1}{2} (y_{t+1} - Ay_t)^T Q^{-1} (y_{t+1} - Ay_t) \right\} \implies
\]

\[
A_{\text{new}} = \arg\max_A \left\langle \sum_t \ln p(y_{t+1}|y_t) \right\rangle_q
\]
The M step for $A$

$$p(y_{t+1}|y_t) \propto \exp \left\{ -\frac{1}{2} (y_{t+1} - Ay_t)^T Q^{-1} (y_{t+1} - Ay_t) \right\} \Rightarrow$$

$$A_{\text{new}} = \arg\max_A \left\langle \sum_t \ln p(y_{t+1}|y_t) \right\rangle_q$$

$$= \arg\max_A \left\langle -\frac{1}{2} \sum_t (y_{t+1} - Ay_t)^T Q^{-1} (y_{t+1} - Ay_t) \right\rangle_q + \text{const}$$

This is still analogous to factor analysis and linear regression, with expected correlations.
The M step for $A$

$p(y_{t+1}|y_t) \propto \exp \left\{ -\frac{1}{2} (y_{t+1} - Ay_t)^T Q^{-1} (y_{t+1} - Ay_t) \right\}$ \Rightarrow

\[
A_{\text{new}} = \arg\max_A \left\langle \sum_t \ln p(y_{t+1}|y_t) \right\rangle_q
\]

\[
= \arg\max_A \left\langle -\frac{1}{2} \sum_t (y_{t+1} - Ay_t)^T Q^{-1} (y_{t+1} - Ay_t) \right\rangle_q + \text{const}
\]

\[
= \arg\max_A \left\{ -\frac{1}{2} \sum_t y_{t+1}^T Q^{-1} y_{t+1} - 2 \left\langle y_{t+1}^T Q^{-1} Ay_t \right\rangle + \left\langle y_t^T A^T Q^{-1} A y_t \right\rangle \right\}
\]

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$$= \arg\max_A \left\{ \text{Tr} \left[ A \sum_t \left\langle y_t y_{t+1}^T \right\rangle Q^{-1} \right] - \frac{1}{2} \text{Tr} \left[ A^T Q^{-1} A \sum_t \left\langle y_t y_t^T \right\rangle \right] \right\}$$

This is still analogous to factor analysis and linear regression, with expected correlations.
The M step for $A$

\[ p(y_{t+1} | y_t) \propto \exp \left\{ -\frac{1}{2} (y_{t+1} - Ay_t)^T Q^{-1} (y_{t+1} - Ay_t) \right\} \Rightarrow \]

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using $\frac{\partial \text{Tr}[AB]}{\partial A} = B^T$, we have

\[ \frac{\partial \{ \cdot \}}{\partial A} = Q^{-1} \sum_t \left\langle y_{t+1} y_t^T \right\rangle - Q^{-1} A \sum_t \left\langle y_t y_t^T \right\rangle \]
The M step for $A$

\[ p(y_{t+1} | y_t) \propto \exp \left\{ -\frac{1}{2} (y_{t+1} - Ay_t)^T Q^{-1} (y_{t+1} - Ay_t) \right\} \Rightarrow \]

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\[ = \arg\max_A \left\{ \text{Tr} \left[ A \sum_t \langle y_t y_{t+1}^T \rangle Q^{-1} \right] - \frac{1}{2} \text{Tr} \left[ A^T Q^{-1} A \sum_t \langle y_t y_t^T \rangle \right] \right\} \]

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\[ \Rightarrow A_{\text{new}} = \left( \sum_t \langle y_{t+1} y_t^T \rangle \right) \left( \sum_t \langle y_t y_t^T \rangle \right)^{-1} \]

This is still analogous to factor analysis and linear regression, with expected correlations.
Learning (online gradient)

Time series data must often be processed in real-time, and we may want to update parameters online as observations arrive. We can do so by updating a local version of the likelihood based on the Kalman filter estimates.

Consider the log likelihood contributed by each data point ($\ell_t$):

$$\ell = \sum_{t=1}^{T} \ln p(x_t|x_1, \ldots, x_{t-1}) = \sum_{t=1}^{T} \ell_t$$

Then,

$$\ell_t = -\frac{D}{2} \ln 2\pi - \frac{1}{2} \ln |\Sigma| - \frac{1}{2} (x_t - C\hat{y}_{t-1}^{t-1})^T \Sigma^{-1} (x_t - C\hat{y}_{t-1}^{t-1})$$

where $D$ is dimension of $x$, and:

$$\hat{y}_{t-1}^{t-1} = A\hat{y}_{t-1}^{t-1}$$
$$\Sigma = C\hat{V}_{t-1}^{t-1} C^T + R$$
$$\hat{V}_{t-1}^{t-1} = A\hat{V}_{t-1}^{t-1} A^T + Q$$

We differentiate $\ell_t$ to obtain gradient rules for $A$, $C$, $Q$, $R$. The size of the gradient step (learning rate) reflects our expectation about nonstationarity.
Learning HMMs using EM

Parameters: $\theta = \{\pi, \Phi, A\}$

Free energy:

$$F(q, \theta) = \sum_{s_{1:T}} q(s_{1:T})(\log P(x_{1:T}, s_{1:T}|\theta) - \log q(s_{1:T}))$$

**E-step:** Maximise $F$ w.r.t. $q$ with $\theta$ fixed:

$$q^*(s_{1:T}) = P(s_{1:T}|x_{1:T}, \theta)$$

We will only need the marginal probabilities $q(s_t, s_{t+1})$, which can also be obtained from the forward–backward algorithm.

**M-step:** Maximize $F$ w.r.t. $\theta$ with $q$ fixed.

We can re-estimate the parameters by computing the expected number of times the HMM was in state $i$, emitted symbol $k$ and transitioned to state $j$.

This is the Baum-Welch algorithm and it predates the (more general) EM algorithm.
M step: Parameter updates are given by ratios of expected counts

We can derive the following updates by taking derivatives of $\mathcal{F}$ w.r.t. $\theta$. 

The initial state distribution is the expected number of times in state $i$ at $t = 1$:

$$\hat{\pi}_i = \gamma_1(i)$$

The expected number of transitions from state $i$ to $j$ which begin at time $t$ is:

$$\xi_t(i \rightarrow j) \equiv P(s_t = i, s_{t+1} = j | x_1:T) = \alpha_t(i) \Phi_{ij} A_j(x_{t+1}) \beta_{t+1}(j) / P(x_1:T)$$

so the estimated transition probabilities are:

$$\hat{\Phi}_{ij} = \frac{\sum_{t=1}^{T-1} \xi_t(i \rightarrow j)}{\sum_{t=1}^{T-1} \gamma_t(i)}$$

The output distributions are the expected number of times we observe a particular symbol in a particular state:

$$\hat{A}_{ik} = \frac{\sum_{t:x_t = k} \gamma_t(i)}{\sum_{t=1}^{T} \gamma_t(i)}$$

(or the state-probability-weighted mean and variance for a Gaussian output model).
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so the estimated transition probabilities are:

\[ \hat{\Phi}_{ij} = \frac{\sum_{t=1}^{T-1} \xi_t(i \rightarrow j)}{\sum_{t=1}^{T-1} \gamma_t(i)} \]
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  (or the state-probability-weighted mean and variance for a Gaussian output model).
HMM practicalities

- **Numerical scaling**: the conventional message definition is in terms of a large joint:

\[ \alpha_t(i) = P(x_{1:t}, s_t=i) \to 0 \text{ as } t \text{ grows, and so can easily underflow.} \]

Rescale:

\[
\tilde{\alpha}_t(i) = A_i(x_t) \sum_j \tilde{\alpha}_{t-1}(j) \Phi_{ji} \quad \rho_t = \sum_{i=1}^{K} \tilde{\alpha}_t(i) \quad \tilde{\alpha}_t(i) = \frac{\alpha_t(i)}{\rho_t}
\]

Exercise: show that:

\[
\rho_t = P(x_t|x_{1:t-1}, \theta) \quad \prod_{t=1}^{T} \rho_t = P(x_{1:T}|\theta)
\]

What does this make \( \tilde{\alpha}_t(i) \)?

- Multiple observed sequences: average numerators and denominators in the ratios of updates.

- Local optima (random restarts, annealing; see discussion later).
HMM practicalities

- Numerical scaling: the conventional message definition is in terms of a large joint:

\[ \alpha_t(i) = P(x_{1:t}, s_t = i) \rightarrow 0 \text{ as } t \text{ grows, and so can easily underflow.} \]

Rescale:

\[ \bar{\alpha}_t(i) = A_i(x_t) \sum_j \tilde{\alpha}_{t-1}(j) \Phi_{ji} \quad \rho_t = \sum_{i=1}^K \bar{\alpha}_t(i) \quad \tilde{\alpha}_t(i) = \bar{\alpha}_t(i) / \rho_t \]

Exercise: show that:

\[ \rho_t = P(x_t | x_{1:t-1}, \theta) \quad \prod_{t=1}^{T} \rho_t = P(x_{1:T} | \theta) \]

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\[ \rho_t = \sum_{i=1}^{K} \tilde{\alpha}_t(i) \]

\[ \bar{\alpha}_t(i) = \tilde{\alpha}_t(i) / \rho_t \]

Exercise: show that:

\[ \rho_t = P(x_t|x_{1:t-1}, \theta) \]

\[ \prod_{t=1}^{T} \rho_t = P(x_{1:T}|\theta) \]

What does this make \( \tilde{\alpha}_t(i) \)?

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- **Local optima** (random restarts, annealing; see discussion later).
HMM pseudocode: inference (E step)

Forward-backward including scaling tricks.
[○ is the element-by-element (Hadamard/Schur) product: ‘.*’ in matlab.]

\[
\begin{align*}
\text{for } t = 1: T, \ i = 1 : K & \quad p_t(i) = A_i(x_t) \\
\alpha_1 &= \pi \circ p_1 & \rho_1 &= \sum_{i=1}^{K} \alpha_1(i) & \alpha_1 &= \alpha_1 / \rho_1 \\
\text{for } t = 2: T & \quad \alpha_t = (\Phi^T * \alpha_{t-1}) \circ p_t & \rho_t &= \sum_{i=1}^{K} \alpha_t(i) & \alpha_t &= \alpha_t / \rho_t \\
& & \beta_T = 1 \\
\text{for } t = T - 1: 1 & \quad \beta_t = \Phi * (\beta_{t+1} \circ p_{t+1}) / \rho_{t+1} \\
\log P(x_{1:T}) &= \sum_{t=1}^{T} \log(\rho_t) \\
\text{for } t = 1: T & \quad \gamma_t = \alpha_t \circ \beta_t \\
\text{for } t = 1: T - 1 & \quad \xi_t = \Phi \circ (\alpha_t * (\beta_{t+1} \circ p_{t+1})^T) / \rho_{t+1}
\end{align*}
\]
Baum-Welch parameter updates:

For each sequence $l = 1 : L$, run forward–backward to get $\gamma^{(l)}$ and $\xi^{(l)}$, then

\[
\pi_i = \frac{1}{L} \sum_{l=1}^{L} \gamma_t^{(l)}(i)
\]

\[
\Phi_{ij} = \frac{\sum_{l=1}^{L} \sum_{t=1}^{T^{(l)}-1} \xi_t^{(l)}(ij)}{\sum_{l=1}^{L} \sum_{t=1}^{T^{(l)}-1} \gamma_t^{(l)}(i)}
\]

\[
A_{ik} = \frac{\sum_{l=1}^{L} \sum_{t=1}^{T^{(l)}} \delta(x_t = k) \gamma_t^{(l)}(i)}{\sum_{l=1}^{L} \sum_{t=1}^{T^{(l)}} \gamma_t^{(l)}(i)}
\]
Degeneracies

Recall that the FA likelihood is conserved with respect to orthogonal transformations of $y$:

$$P(y) = \mathcal{N}(\mathbf{0}, I)$$
$$P(x|y) = \mathcal{N}(\Lambda y, \Psi)$$
Degeneracies

Recall that the FA likelihood is conserved with respect to orthogonal transformations of \( y \):

\[
\begin{align*}
P(y) &= \mathcal{N}(0, I) \\
P(x|y) &= \mathcal{N}(\Lambda y, \Psi) \\
\hat{y} &= Uy \\
\hat{\Lambda} &= \Lambda U^T
\end{align*}
\]
Degeneracies

Recall that the FA likelihood is conserved with respect to orthogonal transformations of $y$:

$$P(y) = \mathcal{N}(0, I)$$
$$P(x|y) = \mathcal{N}(\Lambda y, \Psi)$$

and

$$\tilde{y} = U y$$
$$\tilde{\Lambda} = \Lambda U^T$$

$$P(\tilde{y}) = \mathcal{N}(U0, UIU^T) = \mathcal{N}(0, I)$$
$$P(x|\tilde{y}) = \mathcal{N}(\Lambda U^T U y, \Psi) = \mathcal{N}(\tilde{\Lambda} \tilde{y}, \Psi)$$

Similarly, a mixture model is invariant to permutations of the latent. The LGSSM likelihood is conserved with respect to any invertible transform of the latent:

$$P(y_{t+1}|y_t) = \mathcal{N}(A y_t, Q)$$
$$P(x_t|y_t) = \mathcal{N}(C y_t, R)$$

and

$$\tilde{y} = G y$$
$$\tilde{Q} = G Q G^T$$

$$P(\tilde{y}_{t+1}|\tilde{y}_t) = \mathcal{N}(G A G_{-1} G y_t, G Q G^T) = \mathcal{N}(\tilde{A} \tilde{y}_t, \tilde{Q})$$
$$P(x_t|\tilde{y}_t) = \mathcal{N}(C G_{-1} G y_t, R) = \mathcal{N}(\tilde{C} \tilde{y}_t, \tilde{R})$$

and the HMM is invariant to permutations (and to relaxations into something called an observable operator model).
Degeneracies

Recall that the FA likelihood is conserved with respect to orthogonal transformations of $y$:

$$P(y) = \mathcal{N}(0, I)$$
$$P(x|y) = \mathcal{N}(\Lambda y, \psi)$$

\[ \tilde{y} = Uy \quad \tilde{\Lambda} = \Lambda U^T \]

\[ P(\tilde{y}) = \mathcal{N}(U0, UIU^T) = \mathcal{N}(0, I) \]
\[ P(x|\tilde{y}) = \mathcal{N}(\Lambda U^T Uy, \psi) = \mathcal{N}(\tilde{\Lambda}\tilde{y}, \psi) \]

Similarly, a mixture model is invariant to permutations of the latent.

\[ \tilde{\Lambda} = \Lambda U^T \]
\[ \tilde{y} = Uy \]
\[ P(\tilde{y}) = \mathcal{N}(U0, UIU^T) = \mathcal{N}(0, I) \]
\[ P(x|\tilde{y}) = \mathcal{N}(\Lambda U^T Uy, \psi) = \mathcal{N}(\tilde{\Lambda}\tilde{y}, \psi) \]
Degeneracies

Recall that the FA likelihood is conserved with respect to orthogonal transformations of $\mathbf{y}$:

$$P(\mathbf{y}) = \mathcal{N}(\mathbf{0}, I)$$
$$P(\mathbf{x}|\mathbf{y}) = \mathcal{N}(\Lambda \mathbf{y}, \Psi)$$

$$\tilde{\mathbf{y}} = U\mathbf{y}$$
$$\tilde{\Lambda} = \Lambda U^T$$

$$P(\tilde{\mathbf{y}}) = \mathcal{N}(U\mathbf{0}, U\Lambda U^T) = \mathcal{N}(\mathbf{0}, I)$$
$$P(\mathbf{x}|\tilde{\mathbf{y}}) = \mathcal{N}(\tilde{\Lambda} U^T \mathbf{y}, \Psi) = \mathcal{N}(\tilde{\Lambda} \tilde{\mathbf{y}}, \Psi)$$

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Degeneracies

Recall that the FA likelihood is conserved with respect to orthogonal transformations of \( y \):

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P(y) = \mathcal{N}(0, I) \quad \Rightarrow \quad \tilde{y} = Uy \quad \Rightarrow \quad P(\tilde{y}) = \mathcal{N}(U0, UIU^T) = \mathcal{N}(0, I)
\]

\[
P(x|y) = \mathcal{N}(\Lambda y, \Psi) \quad \Rightarrow \quad \tilde{\Lambda} = \Lambda U^T \quad \Rightarrow \quad P(x|\tilde{y}) = \mathcal{N}(\Lambda U^T Uy, \Psi) = \mathcal{N}(\tilde{\Lambda}\tilde{y}, \Psi)
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The LGSSM likelihood is conserved with respect to any invertible transform of the latent:

\[
P(y_{t+1}|y_t) = \mathcal{N}(Ay_t, Q) \quad \Rightarrow \quad \tilde{y} = Gy \quad \Rightarrow \quad \tilde{A} = GAG^{-1}
\]

\[
P(x_t|y_t) = \mathcal{N}(Cy, R) \quad \Rightarrow \quad \tilde{Q} = GQG^T \quad \Rightarrow \quad \tilde{C} = CG^{-1}
\]
Degeneracies

Recall that the FA likelihood is conserved with respect to orthogonal transformations of $y$:

$$P(y) = \mathcal{N}(0, I)$$
$$P(x|y) = \mathcal{N}(\Lambda y, \Psi)$$

and

$$\tilde{y} = Uy$$
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$$\Rightarrow$$

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Similarly, the LGSSM likelihood is conserved with respect to any invertible transform of the latent:

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and

$$\tilde{y} = Gy$$
$$\tilde{A} = GAG^{-1}$$
$$\tilde{Q} = GQG^T$$
$$\tilde{C} = CG^{-1}$$

$$\Rightarrow$$

$$P(\tilde{y}_{t+1}|\tilde{y}_t) = \mathcal{N}(GAG^{-1}Gy_t, GQG^T) = \mathcal{N}(\tilde{A}\tilde{y}_t, \tilde{Q})$$
$$P(x_t|\tilde{y}_t) = \mathcal{N}(CG^{-1}Gy_t, R) = \mathcal{N}(\tilde{C}\tilde{y}, R)$$

and the HMM is invariant to permutations (and to relaxations into something called an observable operator model).
Degeneracies

Recall that the FA likelihood is conserved with respect to orthogonal transformations of $y$:

$$
P(y) = \mathcal{N}(0, I) \quad \& \quad \tilde{y} = Uy \quad \Rightarrow \quad P(\tilde{y}) = \mathcal{N}(U0, UIU^\top) = \mathcal{N}(0, I)$$

$$P(x|y) = \mathcal{N}(\Lambda y, \Psi) \quad \& \quad \tilde{\Lambda} = \Lambda U^\top \Rightarrow \quad P(x|\tilde{y}) = \mathcal{N}(\Lambda U^\top Uy, \Psi) = \mathcal{N}(\tilde{\Lambda}\tilde{y}, \Psi)$$

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The LGSSM likelihood is conserved with respect to any invertible transform of the latent:

$$P(y_{t+1}|y_t) = \mathcal{N}(Ay_t, Q) \quad \& \quad \tilde{y} = Gy \quad \Rightarrow \quad P(\tilde{y}_{t+1}|\tilde{y}_t) = \mathcal{N}(GAG^{-1}y_t, GQG^\top) = \mathcal{N}(\tilde{A}\tilde{y}_t, \tilde{Q})$$

$$P(x_t|y_t) = \mathcal{N}(Cy, R) \quad \& \quad \tilde{Q} = GQG^\top \quad \tilde{C} = CG^{-1} \Rightarrow \quad P(x_t|\tilde{y}_t) = \mathcal{N}(CG^{-1}Gy, R) = \mathcal{N}(\tilde{C}\tilde{y}, R)$$

and the HMM is invariant to permutations (and to relaxations into something called an observable operator model).
The likelihood landscape

Besides the degenerate solutions, both LGSSMs and HMMs likelihood functions tend to have multiple local maxima. This complicates any ML-based approach to learning (including EM and gradient methods).
The likelihood landscape

Besides the degenerate solutions, both LGSSMs and HMMs likelihood functions tend to have multiple local maxima. This complicates any ML-based approach to learning (including EM and gradient methods).

Strategies:

▶ Restart EM/gradient ascent from different (often random) initial parameter values.
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Besides the degenerate solutions, both LGSSMs and HMMs likelihood functions tend to have multiple local maxima. This complicates any ML-based approach to learning (including EM and gradient methods).

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- Non-ML learning (spectral methods).
Slow Feature Analysis (SFA)

Is there a zero-noise limit for an LGSSM analogous to PCA?
**Slow Feature Analysis (SFA)**

Is there a zero-noise limit for an LGSSM analogous to PCA?

We can take:

\[ A = \text{diag} [a_1 \ldots a_K] \rightarrow I \]  \quad \text{(with} \quad a_1 \leq a_2 \leq \cdots \leq a_K \leq 1) \]

\[ Q = I - AA^T \rightarrow 0 \]  \quad \text{(setting the stationary latent covariance to} \quad I) \]

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SFA is conventionally defined as slowness pursuit (cf PCA and variance pursuit):
Given zero-mean series \( \{x_1, x_2, \ldots x_T\} \) find a \( K \times D \) matrix \( W = C^T \) such that \( y_t = Wx_t \) changes as slowly as possible.
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Specifically, find

\[ W = \arg\min_W \sum_t \|y_t - y_{t-1}\|^2 \quad \text{subject to } \sum_t y_ty_i^T = I. \]

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\( W \) can be found by solving the generalised eigenvalue problem

\[ WA = \Omega WB \quad \text{where } A = \sum_t (x_t - x_{t-1})(x_t - x_{t-1})^T \text{ and } B = \sum_t x_tx_t^T. \]

What if we don’t want the $A \to I$ limit?

The limit is necessary to make the spectral estimate and the (limiting) ML estimates coincide. However, if we give up on ML, then there are general spectral estimates available.

The ML parameter estimates are defined:

$$\theta_{\text{ML}} = \arg\max_{\theta} \log P(X|\theta)$$

and as you found, if $P \in \text{ExpFam}$ with sufficient statistic $T$ then

$$\langle T(x) \rangle_{\theta_{\text{ML}}} = \frac{1}{N} \sum_i T(x_i) \quad \text{(moment matching)}$$

We can generalise this condition to arbitrary $T$ even if $P / \notin \text{ExpFam}$. That is, we find estimate $\theta^*$ with

$$\langle T(x) \rangle_{\theta^*} = \frac{1}{N} \sum_i T(x_i) \quad \text{or} \quad \theta^* = \arg\min_{\theta} \| \langle T(x) \rangle_{\theta} - \frac{1}{N} \sum_i T(x_i) \|_C$$

Judicious choice of $T$ and metric $C$ might make solution unique (no local optima) and consistent (correct given infinite within-model data).
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(Generalised) Method of Moments estimators

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Ho-Kalman SSID for LGSSMs

\[ y_{t-2} \rightarrow y_{t-1} \rightarrow y_t \rightarrow y_{t+1} \rightarrow y_{t+2} \]

\[ x_{t-2} \rightarrow x_{t-1} \rightarrow x_t \rightarrow x_{t+1} \rightarrow x_{t+2} \]
Ho-Kalman SSID for LGSSMs

\[ M_\tau \equiv \langle x_{t+\tau} x_t^T \rangle \]
\[ M_\tau \equiv \langle x_{t+\tau} x_t^T \rangle = \langle x_{t+\tau} (Cy_t + \eta)^T \rangle \]
Ho-Kalman SSID for LGSSMs

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\[ M_\tau \equiv \langle x_{t+\tau} x_t^T \rangle = \langle x_{t+\tau} y_t^T \rangle C^T = \langle (CA^T y_t + \eta) y_t^T \rangle C^T \]
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Ho-Kalman SSID for LGSSMs

\[ y_t = \begin{bmatrix} y_{t-1} \\ y_{t-2} \end{bmatrix} \\
\]

\[ x_t = \begin{bmatrix} x_{t+1} \\ x_t \end{bmatrix} \\
\]

\[ M_\tau \equiv \langle x_{t+\tau} x_t^T \rangle = \langle x_{t+\tau} y_t^T \rangle C^T = CA^T \langle y_t y_t^T \rangle C^T = CA^T \Pi C^T \]

\[ H \equiv \langle x_t^+, x_t^{-T} \rangle \]
Ho-Kalman SSID for LGSSMs

\[ \mathbf{x}_t^- = [\mathbf{x}_{t-1:t-L}] \]

\[ \mathbf{x}_t^+ = [\mathbf{x}_{t:t+L-1}] \]

\[ M_\tau \equiv \langle \mathbf{x}_{t+\tau} \mathbf{x}_t^\top \rangle = \langle \mathbf{x}_{t+\tau} \mathbf{y}_t^\top \rangle \mathbf{C}^\top = \mathbf{C} \mathbf{A}^\top \langle \mathbf{y}_t \mathbf{y}_t^\top \rangle \mathbf{C}^\top = \mathbf{C} \mathbf{A}^\top \mathbf{\Pi} \mathbf{C}^\top \]

\[ H \equiv \langle \mathbf{x}_t^+, \mathbf{x}_t^- \rangle = \begin{bmatrix}
M_1 & M_2 & \cdots & M_L \\
M_2 & M_3 & \cdots & \\
& \vdots & \ddots & \\
M_L & \cdots & M_{2L-1}
\end{bmatrix} = \begin{bmatrix}
\mathbf{C} \\
\mathbf{C} \mathbf{A} \\
\vdots \\
\mathbf{C} \mathbf{A}^{L-1}
\end{bmatrix}
\begin{bmatrix}
\mathbf{A} \mathbf{\Pi} \mathbf{C}^\top \\
\cdots \\
\mathbf{A}^{L-1} \mathbf{\Pi} \mathbf{C}^\top
\end{bmatrix} \]
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\[ \begin{align*}
\mathbf{x}^-_t &= [\mathbf{x}_{t-1:t-L}] \\
\mathbf{x}^+_t &= [\mathbf{x}_{t:t+L-1}]
\end{align*} \]

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M_1 & M_2 & \cdots & M_L \\
M_2 & M_3 & \cdots & \\
\vdots & \vdots & \ddots & \\
M_L & \cdots & \cdots & M_{2L-1}
\end{bmatrix}_{LD \times LD} = \begin{bmatrix}
C \\
CA \\
\vdots \\
CA^{L-1}
\end{bmatrix}_{LD \times K} = \begin{bmatrix} C \\ \Pi C \\ \Phi C \end{bmatrix}_{K \times LD} \]

\[ \Xi = [A \Pi C^T \cdots A^L \Pi C^T] \]
Ho-Kalman SSID for LGSSMs

\[
\begin{align*}
\begin{bmatrix}
\mathbf{x}_{t-2} \\
\mathbf{x}_{t-1} \\
\mathbf{x}_t \\
\mathbf{x}_{t+1} \\
\mathbf{x}_{t+2}
\end{bmatrix} &= 
\begin{bmatrix}
\mathbf{y}_{t-2} \\
\mathbf{y}_{t-1} \\
\mathbf{y}_t \\
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\end{bmatrix}
\end{align*}
\]

\[x_t^- = [x_{t-1:t-L}]\]

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\]

\[
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\begin{bmatrix}
M_1 & M_2 & \cdots & M_L \\
M_2 & M_3 & \cdots & \vdots \\
\vdots & \vdots & \ddots & \vdots \\
M_L & \cdots & \cdots & M_{2L-1}
\end{bmatrix} = 
\begin{bmatrix}
C \\
CA \\
\vdots \\
CA^{L-1}
\end{bmatrix}
\]

Off-diagonal correlation unaffected by noise. SVD(\(\frac{1}{T} \sum \mathbf{x}_t^+ \mathbf{x}_t^-\)) yields least-squares estimates of \(\Xi\) and \(\Upsilon\). Regression between blocks of \(\Xi\) yields \(\hat{A}\) and \(\hat{C}\).
Now consider an HMM with discrete output symbols.

\[
P(x_1:T | \pi, \Phi, A) = \sum_i \pi_i A_i(x_1) \sum_j \Phi_{ji} A_j(x_2) \sum_k \Phi_{kj} A_k(x_3) \ldots
\]

\[= \pi_T A x_1 \Phi_T A x_2 \Phi_T A x_3 \ldots\]

\[O_a = \Phi a\] is a "propagation operator" on the latent belief that depends on observation.

Observable operator model (OOM) representation.

▶ OOMs with arbitrary \(O\) matrices describe a larger class of distributions than HMMs.

▶ Not easy to normalise or even guarantee all assigned "probabilities" are positive.

▶ Degenerate with respect to similarity transform \(\tilde{O} = GOG^{-1}\).
HMMs $\rightarrow$ OOMs

Now consider an HMM with discrete output symbols. The likelihood can be written:

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Spectral learning for HMMs

Write $x_t = [\delta(x_t=i)]; \ s_t = [\delta(s_t=i)]; \ A = [A_{ij}] = [P(x_t=i|s_t=j)]$

(The conventional algorithm is written slightly differently, but follows similar logic).

$\hat{\Phi}$ and $\hat{A}$ can be recovered as before up to arbitrary invertible transform of $s \rightarrow OOM$.

'Projection' to HHM space possible, but amplifies estimation errors.
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$$H \equiv \langle x_t^+, x_t^{-\top} \rangle = \begin{bmatrix} M_1 & M_2 & \cdots & M_L \\ M_2 & M_3 \\ \vdots & \vdots \\ M_L & \cdots & M_{2L-1} \end{bmatrix} = \begin{bmatrix} A \\ A\Phi \\ \vdots \\ A\Phi^{L-1} \end{bmatrix} \begin{bmatrix} \Phi\Pi A^\top \\ \cdots \\ \Phi^L\Pi A^\top \end{bmatrix}$$

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\[ x_t^- = [x_{t-1:t-L}] \]

\[ x_t^+ = [x_{t:t+L-1}] \]

Write \( x_t = [\delta(x_t=i)]; \; s_t = [\delta(s_t=i)]; \; A = [A_{ij}] = [P(x_t=i|s_t=j)] \)

\[ M_{\tau} \equiv \left\langle x_{t+\tau}x_t^\top \right\rangle = \left[ \left\langle P(x_{t+\tau}=i|s_t)P(x_t=j|s_t) \right\rangle_{s_t} \right] = A\Phi^\top \left\langle s_ts_t^\top \right\rangle A^\top = A\Phi^\top \Pi A^\top \]

\[ H \equiv \left\langle x_t^+, x_t^- \right\rangle = \begin{bmatrix} M_1 & M_2 & \cdots & M_L \\ M_2 & M_3 & \cdots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ M_L & \cdots & \cdots & M_{2L-1} \end{bmatrix} = \begin{bmatrix} A \\ A\Phi \\ \vdots \\ A\Phi^{L-1} \end{bmatrix} \begin{bmatrix} \Phi\Pi A^\top & \cdots & \Phi^L\Pi A^\top \end{bmatrix} \]

\( LD \times LD \) \quad \( LD \times K \)

(The conventional algorithm is written slightly differently, but follows similar logic).

\( \hat{\Phi} \) and \( \hat{A} \) can be recovered as before \ldots
Spectral learning for HMMs

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M_τ ≡ \left\langle x_{t+τ}x_t^T \right\rangle = \left\langle P(x_{t+τ}=i|s_t)P(x_t=j|s_t) \right\rangle_{s_t} = AΦ^T \left\langle s_t s_t^T \right\rangle A^T = AΦ^T Π A^T
\]

\[
H ≡ \left\langle x_t^+, x_t^− \right\rangle = \begin{bmatrix}
M_1 & M_2 & \cdots & M_L \\
M_2 & M_3 & & \\
& \ddots & \ddots & \\
M_L & \cdots & M_{2L−1}
\end{bmatrix} = \begin{bmatrix}
A \\
AΦ \\
\vdots \\
AΦ^{L−1}
\end{bmatrix} [ΦΠA^T \cdots Φ^L Π A^T]
\]

\( LD \times LD \quad LD \times K \)

(The conventional algorithm is written slightly differently, but follows similar logic). \( \hatΦ \) and \( \hatA \) can be recovered as before \( \text{upto arbitrary invertible transform of } s \rightarrow \text{OOM} \).
Spectral learning for HMMs

\[ \hat{\Phi} \text{ and } \hat{A} \text{ can be recovered as before } \text{upto arbitrary invertible transform of } s \rightarrow \text{OOM.} \]

‘Projection’ to HHM space possible, but amplifies estimation errors.
ML and spectral learning

Spectral learning:

Efficient closed-form solution.
Consistent (recovers true parameters up to degeneracies from infinite within-model data).
Eigen-/singular-value spectrum clue to latent dimensionality.
Assumes stationarity. May be inappropriate for short sequences.
HMM learning returns OOM parameters – may not correspond to any HMM or indeed to proper probabilistic model.
Not easily generalised to nonlinear or more complex models (but see http://www.gatsby.ucl.ac.uk/~maneesh/papers/buesing-etal-2012-nips.pdf).
In practice, error in recovered parameters is often large.
Often valuable as initialisation for ML methods.

Maximum likelihood learning:

Requires iterative maximisation.
Many local optima.
Consistent and asymptotically efficient (if the global maximum can be found).
Generalises to “principled” approximate algorithms for nonlinear or complex models.
ML and spectral learning

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Recognition (classification) with HMMs

Multiple HMM models:
1. train one HMM for each class (requires each sequence to be labelled by the class)
2. evaluate the probability of an unknown sequence under each HMM
3. classify the unknown sequence by the HMM which gave it the highest likelihood
Recognition (labelling) with HMMs

Use a single HMM to label sequences:

1. train a single HMM on sequences of data $x_1, \ldots, x_T$ and corresponding labels $s_1, \ldots, s_T$.

2. On an unlabelled test sequence, compute the posterior distribution over label sequences $P(s_1, \ldots, s_T | x_1, \ldots, x_T)$.

3. Return the label sequence either with highest expected number of correct states, or highest probability under the posterior (Viterbi).
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Models the whole joint distribution $P(x_{1:T}, s_{1:T})$, but only uses $P(s_{1:T} | x_{1:T})$.

▶ May be more accurate and more efficient use of data to model $P(s_{1:T} | x_{1:T})$ directly.
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Models the whole joint distribution \( P(x_{1:T}, s_{1:T}) \), but only uses \( P(s_{1:T} | x_{1:T}) \).

- May be more accurate and more efficient use of data to model \( P(s_{1:T} | x_{1:T}) \) directly.
- This leads to a model called a Conditional Random Field.
Conditional distribution in a HMM

Conditional distribution over label sequences of a HMM:

\[ P(s_{1:T} | x_{1:T}, \theta) = \frac{P(s_{1:T}, x_{1:T} | \theta)}{\sum_{s_{1:T}} P(s_{1:T}, x_{1:T} | \theta)} \]

\[ \propto P(s_1 | \pi) \prod_{t=1}^{T-1} P(s_{t+1} | s_t, T) \prod_{t=1}^{T} P(x_t | s_t, A) \]

\[ = \exp \left( \sum_i \delta(s_1=i) \log \pi_i + \sum_{t=1}^{T-1} \sum_{ij} \delta(s_t=i, s_{t+1}=j) \log \Phi_{ij} \right) \]

\[ + \sum_{t=1}^{T} \sum_{ik} \delta(s_t=i, x_t=k) \log A_{ik} \right). \]

This functional form gives a well-defined conditional distribution, even if we do not enforce the constraints

\[ \Phi_{ij} \geq 0, \quad \sum_j \Phi_{ij} = 1 \]

or the similar ones for \( \pi \) and \( A \) (cf. OOMs). The forward-backward algorithm can still be applied to compute the conditional distribution.

This is an example of a conditional random field.
Conditional random fields

Define two sets of functions: single label and label-pair functions.

Single label functions:

\[ f_i(s_t, x_t) \quad \text{for } i = 1, \ldots, I \]

Label-pair functions:

\[ g_j(s_t, s_{t+1}, x_t, x_{t+1}) \quad \text{for } j = 1, \ldots, J \]

Each function is associated with a real-valued parameter: \( \lambda_i, \kappa_j \).

A conditional random field defines a conditional distribution over \( s_{1:T} \) given \( x_{1:T} \) as follows:

\[
P(s_{1:T} \mid x_{1:T}, \lambda, \kappa) \propto \exp \left( \sum_{t=1}^{T} \sum_{i} \lambda_i f_i(s_t, x_t) + \sum_{t=1}^{T-1} \sum_{j} \kappa_j g_j(s_t, s_{t+1}, x_t, x_{t+1}) \right)
\]

The forward-backward algorithm can be used to compute:

\[
P(s_t \mid x_{1:T}, \lambda, \kappa) \quad P(s_t, s_{t+1} \mid x_{1:T}, \lambda, \kappa) \quad \arg\max_{s_{1:T}} P(s_{1:T} \mid x_{1:T}, \lambda, \kappa)
\]
Factor graph notation for CRFs

\[ P(s_{1:T}|x_{1:T}, \lambda, \kappa) \propto \exp \left( \sum_{t=1}^{T} \sum_{i} \lambda_i f_i(s_t, x_t) + \sum_{t=1}^{T-1} \sum_{j} \kappa_j g_j(s_t, s_{t+1}, x_t, x_{t+1}) \right) \]
Discriminative vs generative modelling
Labelled training data comes from a true underlying distribution $\tilde{P}(s_{1:T}, x_{1:T})$.

**Generative modelling:** train a HMM by maximizing likelihood:

$$\theta_{\text{Joint}} = \arg\max_{\theta} E_{\tilde{P}}[\log P(s_{1:T}, x_{1:T} | \theta)]$$

(note do not need EM here, since no latent variables)

**Discriminative modelling:** train another HMM by maximizing conditional likelihood:

$$\theta_{\text{Cond}} = \arg\max_{\theta} E_{\tilde{P}}[\log P(s_{1:t} | x_{1:T}, \theta)]$$

By construction:

$$E_{\tilde{P}}[\log P(s_{1:T} | x_{1:T}, \theta_{\text{Cond}})] \geq E_{\tilde{P}}[\log P(s_{1:T} | x_{1:T}, \theta_{\text{Joint}})]$$

If $\tilde{P}$ belongs to model class, $P(\cdot | \theta_{\text{Joint}}) = \tilde{P}$ and equality holds.

Caveats:

- Underlying distribution $\tilde{P}$ not usually in model class.
- Training set differs from $\tilde{P}$.
- Overfitting easier in discriminative setting.
- Generative modelling often much simpler (fits each conditional probability separately, not iterative).

Major point of debate in machine learning.
Structured generalized linear models

\[ P(s_{1:T} | x_{1:T}, \lambda, \kappa) \propto \exp \left( \sum_{t=1}^{T} \sum_{i} \lambda_i f_i(s_t, x_t) + \sum_{t=1}^{T-1} \sum_{j} \kappa_j g_j(s_t, s_{t+1}, x_t, x_{t+1}) \right) \]

The conditional distribution over \( s_{1:T} \) forms an exponential family parameterized by \( \lambda, \kappa \) and dependent on \( x_{1:T} \).

CRFs are a multivariate generalization of generalized linear models (GLMs).

The labels \( s_t \) in a CRF are not independently predicted, but they have a Markov property: \( s_{1:t-1} \) is independent of \( s_{t+1:T} \) given \( s_t \) and \( x_{1:T} \).

This allows efficient inference using the forward-backward algorithm.

CRFs are models for structured prediction (another major machine learning frontier).

CRFs are very flexible.

CRFs have found widespread applications across a number of fields: natural language processing (part-of-speech tagging, named-entity recognition, coreference resolution), information retrieval (information extraction), computer vision (image segmentation, object recognition, depth perception), bioinformatics (protein structure prediction, gene finding)…
Learning CRFs

\[ P(s_{1:T} \mid x_{1:T}, \lambda, \kappa) \propto \exp \left( \sum_{t=1}^{T} \sum_{i} \lambda_i f_i(s_t, x_t) + \sum_{t=1}^{T-1} \sum_{j} \kappa_j g_j(s_t, s_{t+1}, x_t, x_{t+1}) \right) \]

Given labelled data \( \{s^{(c)}_{1:T}, x^{(c)}_{1:T}\}_{c=1}^{N} \), we train CRFs by maximum likelihood:

\[
\frac{\partial \sum_c \log P(s^{(c)}_{1:T} \mid x^{(c)}_{1:T}, \lambda, \kappa)}{\partial \lambda_i} = \sum_{c=1}^{N} \sum_{t=1}^{T} f_i(s^{(c)}_t, x^{(c)}_t) - E_{P(s_{1:T} \mid x^{(c)}_{1:T})}[f_i(s^{(c)}_t, x^{(c)}_t)]
\]

\[
\frac{\partial \sum_c \log P(s^{(c)}_{1:T} \mid x^{(c)}_{1:T}, \lambda, \kappa)}{\partial \kappa_j} = \sum_{c=1}^{N} \sum_{t=1}^{T-1} g_j(s^{(c)}_{t:t+1}, x^{(c)}_{t:t+1}) - E_{P(s_{1:T} \mid x^{(c)}_{1:T})}[g_j(s^{(c)}_{t+1:t+1}, x^{(c)}_{t:t+1})]
\]

There is no closed-form solution for the parameters, so we use gradient ascent instead.

Note: expectations are computed using the forward-backward algorithm.

The log likelihood is concave, so unlike EM we will get to global optimum (another major frontier in machine learning).
References