16.15 The adaptive predictor may be considered as the linearly constrained minimization problem $\mathcal{E} = E[e_n^2] = \min$, subject to the constraint that the first element of $\mathbf{a} = [1, a_1, \dots, a_M]^T$ be unity. This constraint may be written compactly as $\mathbf{u}^T\mathbf{a} = 1$, where $\mathbf{u} = [1, 0, \dots, 0]^T$. Rederive the adaptation equations of Sec. 16.11 using the formalism and results of Problem 16.2.

16.16 *Computer Experiment.* A complex-valued version of the LMS adaptive predictor of Sec. 16.11 is defined by

$$e_n = y_n + a_1(n)y_{n-1} + a_2(n)y_{n-2} + \cdots + a_M(n)y_{n-M}$$

$$a_m(n+1) = a_m(n) - 2\mu e_n y_{n-m}^*\,, \quad m = 1, 2, \dots, M$$

Let y_n consist of two complex sinusoids in zero-mean white noise

$$y_n = A_1 e^{j\omega_1 n} + A_2 e^{j\omega_2 n} + v_n$$

where the frequencies and the SNRs are

$$\omega_1 = 0.3\pi\,, \quad \omega_2 = 0.7\pi \text{ [radians/sample]}$$

$$10\log_{10}\big[|A_1|^2/\sigma_v^2\big] = 10\log_{10}\big[|A_2|^2/\sigma_v^2\big] = 20 \text{ dB}$$

(a) Generate a realization of y_n (using a complex-valued v_n) and process it through an Mth order LMS adaptive predictor using an adaptation constant μ. Experiment with several choices of M and μ. In each case, stop the algorithm after convergence has taken place and plot the AR spectrum $S(\omega) = 1/|A(\omega)|^2$ versus frequency ω. Discuss your results.

(b) Using the same realization of y_n, iterate the adaptive Pisarenko algorithm defined by Eqs. (16.12.5) and (16.12.6). After convergence of the Pisarenko weights, plot the Pisarenko spectrum estimate $S(\omega) = 1/|A(\omega)|^2$ versus frequency ω.

(c) Repeat (a) and (b) when the SNR of the sinewaves is lowered to 0 dB. Compare the adaptive AR and Pisarenko methods.

16.17 *Computer Experiment.* Reproduce the results of Figs. 7.19 and 7.20.

16.18 Derive Eqs. (16.14.8) and (16.14.9) that describe the operation of the adaptive linear combiner in the decorrelated basis provided by the Gram-Schmidt preprocessor.

16.19 *Computer Experiment.* Reproduce the results of Fig. 16.14.2.

16.20 What is the exact operational count of the conventional RLS algorithm listed in Sec. 16.15? Note that the inverse matrices P_0 and P_1 are symmetric and thus only their lower-triangular parts need be updated.

16.21 Verify the solution (16.15.56) for the rank-one updating of the LU factors L_0 and L_1. Also verify that Eq. (16.15.58) is equivalent to (16.15.54).

16.22 *Computer Experiment.* Reproduce the results of Fig. 16.17.1. Carry out the same experiment (with the same input data) using the conventional RLS algorithm and compare with FAEST. Carry out both experiments with various values of λ and comment on the results.

16.23 *Computer Experiment.* Reproduce the results of Fig. 16.18.1.

17 Appendices

A Matrix Inversion Lemma

The matrix inversion lemma, also known as Woodbury's identity, is useful in Kalman filtering and recursive least-squares problems. Consider the matrix relationship,

$$\boxed{R = A + UBV} \tag{A.1}$$

where

$$A \in \mathbb{C}^{N\times N}\,, \quad U \in \mathbb{C}^{N\times M}\,, \quad B \in \mathbb{C}^{M\times M}\,, \quad V \in \mathbb{C}^{M\times N}$$

and assume that A, B are both *invertible* and that $M \le N$. Then, the term UBV has rank M, while R, A have rank N. The matrix inversion lemma states that the inverse of R can be obtained from the inverses of A, B via the formula,

$$\boxed{R^{-1} = (A + UBV)^{-1} = A^{-1} - A^{-1}U\big[B^{-1} + VA^{-1}U\big]^{-1}VA^{-1}} \tag{A.2}$$

Proof: Multiply both sides of (A.1) by R^{-1} from the right, and then by A^{-1} from the left to obtain,

$$A^{-1} = R^{-1} + A^{-1}UBVR^{-1} \tag{A.3}$$

then, multiply both sides from the left by V,

$$VA^{-1} = VR^{-1} + VA^{-1}UBVR^{-1} \quad \Rightarrow \quad VA^{-1} = \big[I_M + VA^{-1}UB\big]VR^{-1}$$

where I_M is the $M\times M$ identity matrix, and solve for BVR^{-1},

$$VA^{-1} = \big[B^{-1} + VA^{-1}U\big]BVR^{-1} \quad \Rightarrow \quad BVR^{-1} = \big[B^{-1} + VA^{-1}U\big]^{-1}VA^{-1}$$

and substitute back into (A.3), after solving for R^{-1},

$$R^{-1} = A^{-1} - A^{-1}UBVR^{-1} = A^{-1} - A^{-1}U\big[B^{-1} + VA^{-1}U\big]^{-1}VA^{-1}$$

Thus given A^{-1} and B^{-1}, the inverse of the $N\times N$ matrix R requires only the inverse of the smaller $M\times M$ matrix, $B^{-1} + VA^{-1}U$.

B MATLAB Functions

```
% OSP Toolbox
% S. J. Orfanidis - 2018
%
% -----------------------------------------------------------------------------
% Local Polynomial Smoothing Filters
% -----------------------------------------------------------------------------
% binom     - vector of binomial coefficients
% bkfilt    - Baxter-King bandpass filter
% cldec     - classical decomposition method
% combfd    - comb fractional-delay filter design
% compl     - complement of an odd-length symmetric filter
% diffb     - backward difference operator
% diffmat   - difference convolution matrix
% diffpol   - differentiate polynomial
% diffs     - seasonal backward difference operator
% ecg       - ECG generator.
% ecgsim    - ECG simulation
% filtdbl   - filtering with double-sided FIR filter
% hahnbasis - Hahn orthogonal polynomials
% hahncoeff - coefficients of Hahn orthogonal polynomials
% hahnpol   - Hahn orthogonal polynomial evaluation
% hahnrec   - Hahn orthogonal polynomials
% hend      - Henderson weighting function
% kmat      - difference convolution matrix
% kraw      - Krawtchouk binomial weighting function
% kwindow   - Kaiser window for spectral analysis
% lagrfd    - Lagrange-interpolation fractional-delay filter
% lpbasis   - local polynomial basis
% lpdiff    - weighted local polynomial differentiation filters
% lpfilt    - local polynomial filtering - fast version
% lpfilt2   - local polynomial filtering - slower version
% lpinterp  - local polynomial interpolation and differentiation filters
% lpmat     - local polynomial smoothing matrix
% lpmissing - weighted local polynomial filters for missing data
% lprs      - local polynomial minimum-Rs smoothing filters
% lprs2     - local polynomial minimum-Rs smoothing filters (closed-form)
% lpsm      - weighted local polynomial smoothing and differentiation filters
% minrev    - minimum revision asymmetric filters
% polval    - polynomial evaluation in factorial power series
% rlpfilt   - robust local polynomial filtering
% sigav     - signal averaging
% smadec    - decomposition using seasonal moving-average filters
% smafilt   - impulse responses of seasonal decomposition moving average filters
% smat      - seasonal moving-average filtering matrix
% smav      - seasonal moving average filter
% stirling  - Stirling numbers of first or second kind, signed or unsigned
% swhdec    - seasonal Whittaker-Henderson decomposition
% trendma   - trend moving-average filter, 2xD if D is even, 1xD if D is odd
% upmat     - upsample matrix of smoothing filters
% whkdec    - Whittaker-Henderson-Kaiser seasonal decomposition
% x11dec    - US Census X-11 decomposition method for seasonal adjustment
% x11filt   - impulse responses of the US Census X-11 seasonal adjustment filters

% -----------------------------------------------------------------------------
% Local Linear Regression
```



```
% -----------------------------------------------------------------------------
% avobs   - average repeated observations
% locband - bandwidth for local polynomial regression
% locgcv  - local polynomial GCV and CV evaluation
% locgrid - uniform grid for local polynomial evaluation
% locpol  - local polynomial regression
% locval  - evaluation/interpolation of local polynomial regression
% locw    - local weighting functions for local polynomial regression
% loess   - Cleveland's robust locally weighted scatterplot smoothing (loess)
% loess2  - Cleveland's robust locally weighted scatterplot smoothing (loess)

% -----------------------------------------------------------------------------
% Spline and Whittaker-Henderson Smoothing
% -----------------------------------------------------------------------------
% splambda - find optimum lambda for spline smoothing using GCV
% splav    - averaged repeated observations at spline knots
% splcoeff - spline coefficients
% splgcv   - evaluate GCV(lambda)
% splmat   - spline smoothing matrices Q,T
% splsm    - spline smoothing using Reinsch's algorithm
% splsm2   - spline smoothing using Reinsch's algorithm - robust version
% splval   - evaluate spline smoothing polynomials
% whgcv    - Whittaker-Henderson smoothing method
% whgen    - generalized Whittaker-Henderson
% whimp    - Whittaker-Henderson filter impulse response
% whsm     - Whittaker-Henderson smoothing method
% whsm1    - Whittaker-Henderson smoothing method - L1 version

% -----------------------------------------------------------------------------
% Exponentially Weighted Averages
% -----------------------------------------------------------------------------
% binmat  - binomial boost matrices for exponential smoothers
% ema     - exponential moving average - exact version
% emaerr  - calculate MAE, MSE, and MAPE for a range of lambda's
% emap    - map equivalent lambdas between d=0 EMA and d=1 EMA
% emat    - polynomial to cascaded transformation matrix
% holt    - Holt's exponential smoothing
% holterr - calculate MAE, MSE, and MAPE for a range of lambda's
% mema    - multiple exponential moving average
% stema   - steady-state exponential moving average

% -----------------------------------------------------------------------------
% Linear Prediction & Wiener and Kalman Filtering Functions
% -----------------------------------------------------------------------------
% acext     - autocorrelation sequence extension using Levinson recursion
% acf       - sample auto-correlation function
% acmat     - construct autocorrelation Toeplitz matrix from autocorrelation lags
% acsing    - sinusoidal representation of singular autocorrelation matrices
% aicmdl    - estimates dimension of signal subspace from AIC and MDL criteria
% argen     - generate a zero-mean segment of an AR process
% bkwlev    - backward Levinson recursion
% burg      - Burg's method of linear prediction
% dir2nl    - direct form to normalized lattice
% dpd       - dynamic predictive deconvolution
% dwf       - sample processing algorithm of direct-form Wiener filter
% dwf2      - direct-form Wiener filter using circular delay-line buffer
% dwfilt    - direct-form Wiener filtering of data
% dwfilt2   - circular-buffer direct-form Wiener filtering of data
```

```
% faest     - sample processing algorithm of adaptive lattice Wiener filter
% firw      - FIR Wiener filter design
% flipv     - flip a vector, column, row, or both for a matrix
% frwlev    - forward Levinson recursion
% glwf      - sample processing algorithm of lattice Wiener filter
% kfilt     - Kalman filtering
% ksmooth   - Kalman smoothing
% latt      - sample processing algorithm of analysis lattice filter
% lattfilt  - lattice filtering of a data vector
% lattsect  - sample processing algorithm of a single lattice section
% lattsynth - sample processing algorithm of synthesis lattice filter
% lev       - Levinson-Durbin recursion
% lms       - sample processing LMS algorithm of direct-form Wiener filter
% lpf       - extract linear prediction filter from matrix L
% lpg       - extract reflection coefficients from matrix L
% lpspec    - compute LP spectrum of a prediction-error filter
% lwf       - sample processing algorithm of lattice Wiener filter
% lwfilt    - lattice Wiener filtering of data
% mgs       - adaptive modified Gram-Schmidt
% mgslms    - adaptive Gram-Schmidt using LMS
% minorm    - minimum-norm noise subspace eigenvector
% music     - MUSIC spectrum computation
% nlfilt    - filtering in the normalized lattice form
% obmat     - observability matrix for canonical or transposed realizations
% obmatc    - observability matrix for continuous-time
% rlev      - reverse of Levinson's algorithm
% rls       - RLS algorithm for adaptive linear combiner
% rlsl      - sample processing algorithm of lattice Wiener filter
% rmusic    - minimum-norm noise subspace eigenvector
% scatt     - direct scattering problem
% schur1    - Schur algorithm for linear prediction
% schur2    - Schur algorithm for Cholesky factorization
% spike     - spiking filter design
% yw        - Yule-Walker method of linear prediction


% ----------------------------------------------------------------------------
% SVD, Subspace, and ARMA Modeling Functions
% ----------------------------------------------------------------------------
% arma2imp  - ARMA impulse response
% armaacf   - ARMA autocorrelation function
% armachol  - ARMA covariance matrix Cholesky factorization
% armafit   - fitting an ARMA(p,q) model to covariance lags
% armainf   - ARMA asymptotic Fisher information matrix
% armainnov - ARMA modeling using the innovations method
% armamf    - Mayne-Firoozan ARMA modeling method
% armamyw   - ARMA modeling by the modified Yule-Walker method
% armasim   - simulate a zero-mean segment of a gaussian ARMA process
% armasim2  - simulate a zero-mean segment of a gaussian ARMA process
% bwidth    - beamwidth mapping from psi-space to phi-space
% cca       - Canonical Correlation Analysis
% ccacov    - CCA applied to a covariance matrix
% cholgs    - Cholesky factorization by Gram-Schmidt orthogonalization
% cholinnov - Cholesky factorization by innovations representation
% crb       - calculate Cramer-Rao bounds for sinusoids in noise
% crb2      - calculate Cramer-Rao bounds for sinusoids in noise
% datamat   - convolution data matrix of a signal vector
% datasig   - extract data signal from a Toeplitz or Toeplitz/Hankel data matrix
```



```
% dolph     - Dolph-Chebyshev array weights
% fisher    - calculate Fisher information matrix for sinusoids in noise
% imp2arma  - impulse response to ARMA coefficients
% irls      - Lp_regularized iteratively reweighted least squares
% irls_wh   - Lp_regularized IRLS Whittaker-Henderson
% lpls      - construct least-squares linear prediction filter from data matrix
% madurbin  - MA modeling by Durbin's method
% mafit     - Wilson's method of fitting an MA(q) model to covariance lags
% mainnov   - MA modeling by the innovations method
% mpencil   - matrix-pencil method of extracting sinusoids in noise
% poly2     - specialized version of poly
% scan      - scan array with given scanning phase
% setrank   - reduce the rank of a diagonal matrix of singular values
% sigsub    - construct reduced-rank signal subspace of a data matrix
% sines     - generate sum of real or complex decaying sinusoids in noise
% snap      - generate snapshot matrix for array problems
% snapshot  - generate data matrix of snapshots for array problems
% snr       - magnitude to SNR in dB, and conversely
% steer     - steer array towards given angle
% steering  - construct steering matrix of multiple sinusoids/plane-waves
% steermat  - construct steering matrix of multiple sinusoids/plane-waves
% svdenh    - SVD signal enhancement
% toepl     - Toeplitz, Hankel, or Toeplitz/Hankel approximation of data matrix
% varper    - percentage variances

% ----------------------------------------------------------------------------
% Wavelet Functions
% ----------------------------------------------------------------------------
% advance  - circular time-advance (left-shift) of a vector
% casc     - cascade algorithm for phi and psi wavelet functions
% circonv  - circular convolution
% cmf      - conjugate mirror of a filter
% convat   - convolution a trous
% convmat  - sparse convolution matrix
% convmat2 - sparse convolution matrix (simplified version)
% daub     - Daubechies scaling filters (daublets, symmlets, coiflets)
% dn2      - downsample by a factor of 2
% dwtcell  - cell array of sparse discrete wavelet transform matrices
% dwtdec   - DWT decomposition into orthogonal multiresolution components
% dwtmat   - discrete wavelet transform matrices
% dwtmat2  - discrete wavelet transform matrices
% dwtwrap  - wrap a DWT matrix into a lower DWT matrix
% flipv    - flip a vector, column, row, or both for a matrix
% fwt      - fast wavelet transform using convolution and downsampling
% fwtm     - fast wavelet transform in matrix form
% fwtmat   - overall DWT orthogonal matrix
% ifwt     - inverse fast wavelet transform using upsampling and convolution
% ifwtm    - inverse fast wavelet transform in matrix form
% iuwt     - inverse undecimated wavelet transform
% iuwtm    - inverse undecimated wavelet transform
% modwrap  - wrap matrix column-wise mod-N
% phinit   - eigenvector initialization of phi
% plotdec  - plot DWT/UWT decomposition or DWT/UWT coefficients
% up2      - upsample a vector by factor of two
% upr      - upsample a vector by factor of 2^r
% uwt      - undecimated wavelet transform
% uwtdec   - UWT multiresolution decomposition
% uwtm     - undecimated wavelet transform
```

```
% uwtmat   - undecimated wavelet transform matrices
% uwtmat2  - undecimated wavelet transform matrices
% w2V      - wavelet vector to wavelet matrix
% wcoeff   - extract wavelet coefficients from DWT at given level
% wdenoise - Donoho & Johnstone's VisuShrink denoising procedure
% wduwt    - wavelet denoising with UWT
% wthr     - soft/hard level-dependent wavelet thresholding

% ----------------------------------------------------------------------------
% Technical Analysis Functions
% ----------------------------------------------------------------------------
% accdist -  accumulation/distribution line
% atr     -  true range & average true range
% bbands  - Bollinger bands
% bma     - Butterworth moving average
% cci     -  commodity channel index
% chosc   -  Chaikin oscillator
% chvol   -  Chaikin volatility
% cmflow  -  Chaikin money flow
% cmo     - Chande momentum oscillator
% delay   - lag or delay or advance by d samples
% dema    - steady-state double exponential moving average
% dirmov  -  directional movement system
% dmi     - dynamic momentum index (DMI)
% donch   - Donchian channels
% dpo     - detrended price oscillator
% ehma    - exponential Hull moving average
% fbands  - fixed-envelope bands
% forosc  - forecast oscillator
% gdema   - generalized dema
% hma     - Hull moving average
% ilrs    - integrated linear regression slope indicator
% kbands  - Keltner bands or channels
% lreg    - linear regression, slope, and R-squared indicators
% mom     - momentum and price rate of change
% ohlc    - make Open-High-Low-Close bar chart
% ohlcyy  - OHLC plot with other indicators on the same graph
% pbands  - Projection Bands and Projection Oscillator
% pma     - predictive moving average, linear fit
% pma2    - predictive moving average, polynomial order d=1,2
% pmaimp  - predictive moving average impulse response
% pmaimp2 - predictive moving average impulse response, d=1,2
% pnvi    - positive and negative volume indices (PVI & NVI)
% prosc   - price oscillator & MACD
% psar    - Wilder's parabolic SAR
% r2crit  - R-squared critical values
% rsi     - relative strength index (RSI)
% sebands - standard-error bands
% sema    - single exponential moving average
% shma    - SMA-based Hull moving average
% sma     - simple moving average
% stbands - STARC bands
% stdev   - standard deviation index
% stoch   - stochastic oscillator
% t3      - Tillson's T3 indicator, triple gdema
% tcrit   - critical values of Student's t-distribution
% tdistr  - cumulative t-distribution
% tema    - triple exponential moving average
```



```
% tma     - triangular moving average
% trix    - TRIX oscillator
% vema    - variable-length exponential moving average
% vhfilt  - Vertical Horizontal Filter
% wema    - Wilder's exponential moving average
% wma     - weighted or linear moving average
% yylim   - adjust left/right ylim & ticks

% ----------------------------------------------------------------------------
% Miscellaneous Functions
% ----------------------------------------------------------------------------
% canfilt  - IIR filtering in canonical form using linear delay-line buffer
% ccan     - IIR filter in canonical form using circular delay-line buffer
% ccanfilt - IIR filtering in canonical form using circular delay-line buffer
% frespc   - frequency response of a cascaded IIR filter at a frequency vector w
% loadfile - load data file ignoring any text lines
% taxis    - define time axis
% up       - upsample by a factor of L
% ustep    - unit-step or rising unit-step function
% xaxis    - set x-axis limits and tick marks
% yaxis    - set y-axis limits and tick marks
% zmean    - zero mean of each column of a data matrix (or row vector)
```

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ADMM	`http://stanford.edu/~boyd/admm.html`
CVX	`http://cvxr.com/cvx/`
FISTA	`http://ie.technion.ac.il/~becka/papers/rstls_package.zip`
Homotopy	`http://www.ece.ucr.edu/~sasif/homotopy/`
L1-MAGIC	`https://statweb.stanford.edu/~candes/l1magic/`
LARS	`https://publish.illinois.edu/xiaohuichen/code/lars/`
	`https://sourceforge.net/projects/sparsemodels/files/LARS/`
NESTA	`https://statweb.stanford.edu/~candes/nesta/`
REGTOOLS	`http://www.imm.dtu.dk/~pcha/Regutools/`
SALSA	`http://cascais.lx.it.pt/~mafonso/salsa.html`
SOL	`http://web.stanford.edu/group/SOL/software.html`
Sparco	`http://www.cs.ubc.ca/labs/scl/sparco/`
SpaRSA	`http://www.lx.it.pt/~mtf/SpaRSA/`
Sparselab	`https://sparselab.stanford.edu/`
SPGL1	`http://www.cs.ubc.ca/labs/scl/spgl1/`
TwIST	`http://www.lx.it.pt/~bioucas/TwIST/TwIST.htm`
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atr, average true range, 299
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chosc, Chaikin oscillator, 304
chvol, Chaikin volatility, 304
cmflow, Chaikin money flow, 304
cmo, Chande momentum oscillator, 304
delay, d-fold delay, 292
dema, double EMA, 274
dirmov, directional movement system, 304
dmi, dynamic momentum index, 304
donch, Donchian channels, 299
dpo, detrended price oscillator, 304
ehma, exponential Hull moving average, 292
fbands, fixed-width bands, 299
forosc, forecast oscillator, 304
gdema, generalized DEMA, 292
hma, Hull moving average, 292
ilrs, integrated linear regression slope, 270
kbands, Keltner bands, 299
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ohlc, open-high-low-close bar chart, 278
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pmaimp2, PMA2 impulse response, 272
pmaimp, PMA impulse response, 272
pma, predictive moving average, 272
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prosc, price oscillator and MACD, 304
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shma, simple Hull moving average, 292
sma, simple moving average, 270
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datasig, signal from data matrix, 810
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dwfilt2, direct-form Wiener filtering, 528
dwfilt, direct-form Wiener filtering, 528
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lpfilt, local polynomial filtering, 157
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obmat, observability matrix, 528
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