

The GPML Toolbox version 3.5

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Abstract

The GPML toolbox is an Octave 3.2.x and Matlab 7.x implementation of inference and prediction in Gaussian process (GP) models. It implements algorithms discussed in Rasmussen & Williams: *Gaussian Processes for Machine Learning*, the MIT press, 2006 and Nickisch & Rasmussen: *Approximations for Binary Gaussian Process Classification*, JMLR, 2008.

The strength of the function lies in its flexibility, simplicity and extensibility. The function is flexible as firstly it allows specification of the properties of the GP through definition of mean function and covariance functions. Secondly, it allows specification of different inference procedures, such as e.g. exact inference and Expectation Propagation (EP). Thirdly it allows specification of likelihood functions e.g. Gaussian or Laplace (for regression) and e.g. cumulative Logistic (for classification). Simplicity is achieved through a single function and compact code. Extensibility is ensured by modular design allowing for easy addition of extension for the already fairly extensive libraries for inference methods, mean functions, covariance functions and likelihood functions.

This document is a technical manual for a developer containing many details. If you are not yet familiar with the GPML toolbox, the user documentation and examples therein are a better way to get started.

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1 Gaussian Process Training and Prediction

The `gpm1` toolbox contains a single user function `gp` described in section 2. In addition there are a number of supporting structures and functions which the user needs to know about, as well as an internal convention for representing the posterior distribution, which may not be of direct interest to the casual user.

Inference Methods: An inference method is a function which computes the (approximate) posterior, the (approximate) negative log marginal likelihood and its partial derivatives w.r.t.. the hyperparameters, given a model specification (i.e., GP mean and covariance functions and a likelihood function) and a data set. Inference methods are discussed in section 3. New inference methods require a function providing the desired inference functionality and possibly extra functionality in the likelihood functions applicable.

Hyperparameters: The hyperparameters is a struct controlling the properties of the model, i.e.. the GP mean and covariance function and the likelihood function. The hyperparameters is a struct with the three fields `mean`, `cov` and `lik`, each of which is a vector. The number of elements in each field must agree with number of hyperparameters in the specification of the three functions they control (below). If a field is either empty or non-existent it represents zero hyperparameters. When working with FITC approximate inference, the inducing inputs `xu` can also be treated as hyperparameters for some common stationary covariances.

Hyperparameter Prior Distributions: When optimising the marginal likelihood w.r.t. hyperparameters, it is sometimes useful to softly constrain the hyperparameters by means of prior knowledge. A `prior` is a probability distribution over individual or a group of hyperparameters, section 7.

Likelihood Functions: The likelihood function specifies the form of the likelihood of the GP model and computes terms needed for prediction and inference. For inference, the required properties of the likelihood depend on the inference method, including properties necessary for hyperparameter learning, section 4.

Mean Functions: The mean function is a cell array specifying the GP mean. It computes the mean and its derivatives w.r.t.. the part of the hyperparameters pertaining to the mean. The cell array allows flexible specification and composition of mean functions, discussed in section 5. The default is the zero function.

Covariance Functions: The covariance function is a cell array specifying the GP covariance function. It computes the covariance and its derivatives w.r.t.. the part of the hyperparameters pertaining to the covariance function. The cell array allows flexible specification and composition of covariance functions, discussed in section 6.

Inference methods, see section 3, compute (among other things) an approximation to the posterior distribution of the latent variables f_i associated with the training cases, $i = 1, \dots, n$. This approximate posterior is assumed to be Gaussian, and is communicated via a struct `post` with the fields `post.alpha`, `post.sW` and `post.L`. Often, starting from the Gaussian prior $p(f) = \mathcal{N}(f|m, K)$ the approximate posterior admits the form

$$q(f|\mathcal{D}) = \mathcal{N}(f|\mu = m + K\alpha, V = (K^{-1} + W)^{-1}), \text{ where } W \text{ diagonal with } W_{ii} = s_i^2. \quad (1)$$

In such cases, the entire posterior can be computed from the two vectors `post.alpha` and `post.sW`; the inference method may optionally also return $L = \text{chol}(\text{diag}(s)\text{diag}(s) + I)$.

If on the other hand the posterior doesn't admit the above form, then `post.L` returns the matrix

$L = -(K + W^{-1})^{-1}$ (and `post.sW` is unused). In addition, a sparse representation of the posterior may be used, in which case the non-zero elements of the `post.alpha` vector indicate the active entries.

2 The gp Function

The `gp` function is typically the only function the user would directly call.

```
5a <gp.m 5a>≡
1 function [varargout] = gp(hyp, inf, mean, cov, lik, x, y, xs, ys)
2 <gp function help 5b>
3 <initializations 6b>
4 <inference 7b>
5 if nargin==7                                     % if no test cases are provided
6     varargout = {nlZ, dnlZ, post};                % report -log marg lik, derivatives and post
7 else
8     <compute test predictions 8a>
9 end
```

It offers facilities for training the hyperparameters of a GP model as well as predictions at unseen inputs as detailed in the following help.

```
5b <gp function help 5b>≡ (5a)
1 % Gaussian Process inference and prediction. The gp function provides a
2 % flexible framework for Bayesian inference and prediction with Gaussian
3 % processes for scalar targets, i.e. both regression and binary
4 % classification. The prior is Gaussian process, defined through specification
5 % of its mean and covariance function. The likelihood function is also
6 % specified. Both the prior and the likelihood may have hyperparameters
7 % associated with them.
8 %
9 % Two modes are possible: training or prediction: if no test cases are
10 % supplied, then the negative log marginal likelihood and its partial
11 % derivatives w.r.t. the hyperparameters is computed; this mode is used to fit
12 % the hyperparameters. If test cases are given, then the test set predictive
13 % probabilities are returned. Usage:
14 %
15 %     training: [nlZ dnlZ          ] = gp(hyp, inf, mean, cov, lik, x, y);
16 % prediction: [ymu ys2 fmu fs2    ] = gp(hyp, inf, mean, cov, lik, x, y, xs);
17 %             or: [ymu ys2 fmu fs2 lp] = gp(hyp, inf, mean, cov, lik, x, y, xs, ys);
18 %
19 % where:
20 %
21 %     hyp      struct of column vectors of mean/cov/lik hyperparameters
22 %     inf      function specifying the inference method
23 %     mean     prior mean function
24 %     cov      prior covariance function
25 %     lik      likelihood function
26 %     x        n by D matrix of training inputs
27 %     y        column vector of length n of training targets
28 %     xs       ns by D matrix of test inputs
29 %     ys       column vector of length nn of test targets
30 %
31 %     nlZ      returned value of the negative log marginal likelihood
32 %     dnlZ     struct of column vectors of partial derivatives of the negative
33 %             log marginal likelihood w.r.t. mean/cov/lik hyperparameters
34 %     ymu      column vector (of length ns) of predictive output means
35 %     ys2      column vector (of length ns) of predictive output variances
36 %     fmu      column vector (of length ns) of predictive latent means
37 %     fs2      column vector (of length ns) of predictive latent variances
38 %     lp       column vector (of length ns) of log predictive probabilities
39 %
```

```

40 %    post    struct representation of the (approximate) posterior
41 %           3rd output in training mode or 6th output in prediction mode
42 %           can be reused in prediction mode gp(..., cov, lik, x, post, xs,...)
43 %
44 % See also infMethods.m, meanFunctions.m, covFunctions.m, likFunctions.m.
45 %
46 <gpml copyright 6a>

```

```

6a <gpml copyright 6a>≡ (5b 10 11 18 21 23a 34 35 37 41 42 45)
1 % Copyright (c) by Carl Edward Rasmussen and Hannes Nickisch, 2015-05-18.
2 %                               File automatically generated using noweb.

```

Depending on the number of input parameters, `gp` knows whether it is operated in training or in prediction mode. The highlevel structure of the code is as follows. After some initialisations, we perform inference and decide whether test set predictions are needed or only the result of the inference is demanded.

```

6b <initializations 6b>≡ (5a)
1 <minimalist usage 6c>
2 <process input arguments 6d>
3 <check hyperparameters 7a>

```

If the number of input arguments is incorrect, we echo a minimalist usage and return.

```

6c <minimalist usage 6c>≡ (6b)
1 if nargin<7 || nargin>9
2     disp('Usage: [n1Z dn1Z          ] = gp(hyp, inf, mean, cov, lik, x, y);')
3     disp('    or: [ymu ys2 fmu fs2    ] = gp(hyp, inf, mean, cov, lik, x, y, xs);')
4     disp('    or: [ymu ys2 fmu fs2 lp] = gp(hyp, inf, mean, cov, lik, x, y, xs, ys);')
5     return
6 end

```

Set some useful default values for empty arguments, and convert `inf` and `lik` to function handles and `mean` and `cov` to cell arrays if necessary. Initialize variables.

```

6d <process input arguments 6d>≡ (6b)
1 if isempty(mean), mean = {@meanZero}; end % set default mean
2 if ischar(mean) || isa(mean, 'function_handle'), mean = {mean}; end % make cell
3 if isempty(cov), error('Covariance function cannot be empty'); end % no default
4 if ischar(cov) || isa(cov, 'function_handle'), cov = {cov}; end % make cell
5 cstr = cov{1}; if isa(cstr, 'function_handle'), cstr = func2str(cstr); end
6 if strcmp(cstr, 'covFITC') && isfield(hyp, 'xu'), cov{3} = hyp.xu; end % use hyp.xu
7 if isempty(inf) % set default inference method
8     if strcmp(cstr, 'covFITC'), inf = {@infFITC}; else inf = {@infExact}; end
9 end
10 if ischar(inf), inf = str2func(inf); end % convert into function handle
11 if ischar(inf) || isa(inf, 'function_handle'), inf = {inf}; end % make cell
12 istr = inf{1}; if isa(istr, 'function_handle'), istr = func2str(istr); end
13 if strcmp(istr, 'infPrior')
14     istr = inf{2}; if isa(istr, 'function_handle'), istr = func2str(istr); end
15 end
16 if strcmp(cstr, 'covFITC') % only infFITC* are possible
17     if isempty(strfind(istr, 'infFITC')==1)
18         error('Only infFITC* are possible inference algorithms')
19     end
20 end % only one possible class of inference algorithms
21 if isempty(lik), lik = {@likGauss}; end % set default lik
22 if ischar(lik) || isa(lik, 'function_handle'), lik = {lik}; end % make cell
23 lstr = lik{1}; if isa(lstr, 'function_handle'), lstr = func2str(lstr); end

```

```

24
25 D = size(x,2);
26 if strcmp(cstr,'covGrid') % only infGrid* are possible
27     if isempty(strfind(istr,'infGrid')==1)
28         error('Only infGrid* are possible inference algorithms')
29     end
30     D = 0; xg = cov{3}; p = numel(xg); for i=1:p, D = D+size(xg{i},2); end % dims
31 end

```

Check that the sizes of the hyperparameters supplied in `hyp` match the sizes expected. The three parts `hyp.mean`, `hyp.cov` and `hyp.lik` are checked separately, and define empty entries if they don't exist.

```

7a <check hyperparameters 7a>≡ (6b)
1 if ~isfield(hyp,'mean'), hyp.mean = []; end % check the hyp specification
2 if eval(feval(mean{:})) ~= numel(hyp.mean)
3     error('Number of mean function hyperparameters disagree with mean function')
4 end
5 if ~isfield(hyp,'cov'), hyp.cov = []; end
6 if eval(feval(cov{:})) ~= numel(hyp.cov)
7     error('Number of cov function hyperparameters disagree with cov function')
8 end
9 if ~isfield(hyp,'lik'), hyp.lik = []; end
10 if eval(feval(lik{:})) ~= numel(hyp.lik)
11     error('Number of lik function hyperparameters disagree with lik function')
12 end

```

Inference is performed by calling the desired inference method `inf`. In training mode, we accept a failure of the inference method (and issue a warning), since during hyperparameter learning, hyperparameters causing a numerical failure may be attempted, but the `minimize` function may gracefully recover from this. During prediction, failure of the inference method is an error.

```

7b <inference 7b>≡ (5a)
1 try % call the inference method
2     % issue a warning if a classification likelihood is used in conjunction with
3     % labels different from +1 and -1
4     if strcmp(lstr,'likErf') || strcmp(lstr,'likLogistic')
5         if ~isstruct(y)
6             uy = unique(y);
7             if any( uy~=+1 & uy~=-1 )
8                 warning('You try classification with labels different from {+1,-1}')
9             end
10        end
11    end
12    if nargin>7 % compute marginal likelihood and its derivatives only if needed
13        if isstruct(y)
14            post = y; % reuse a previously computed posterior approximation
15        else
16            post = feval(inf{:}, hyp, mean, cov, lik, x, y);
17        end
18    else
19        if nargin<=1
20            [post n1Z] = feval(inf{:}, hyp, mean, cov, lik, x, y); dn1Z = {};
21        else
22            [post n1Z dn1Z] = feval(inf{:}, hyp, mean, cov, lik, x, y);
23        end
24    end
25 catch

```

```

26 msgstr = lasterr;
27 if nargin>7, error('Inference method failed [%s]', msgstr); else
28     warning('Inference method failed [%s] .. attempting to continue',msgstr)
29     dnlZ = struct('cov',0*hyp.cov, 'mean',0*hyp.mean, 'lik',0*hyp.lik);
30     varargout = {NaN, dnlZ}; return % continue with a warning
31 end
32 end

```

We copy the already computed negative log marginal likelihood to the first output argument, and if desired report its partial derivatives w.r.t. the hyperparameters if running in inference mode.

Predictions are computed in a loop over small batches to avoid memory problems for very large test sets.

```

8a <compute test predictions 8a>≡ (5a)
1 alpha = post.alpha; L = post.L; sW = post.sW;
2 if issparse(alpha) % handle things for sparse representations
3     nz = alpha ~= 0; % determine nonzero indices
4     if issparse(L), L = full(L(nz,nz)); end % convert L and sW if necessary
5     if issparse(sW), sW = full(sW(nz)); end
6 else nz = true(size(alpha,1),1); end % non-sparse representation
7 if isempty(L) % in case L is not provided, we compute it
8     K = feval(cov{:}, hyp.cov, x(nz,:));
9     L = chol(eye(sum(nz))+sW*sW'.*K);
10 end
11 %verify whether L contains valid Cholesky decomposition or something different
12 Lchol = isnumeric(L) && all(all(tril(L,-1)==0)&diag(L)')>0&isreal(diag(L));
13 ns = size(xs,1); % number of data points
14 if strcmp(cstr,'covGrid'), xs = covGrid('idx2dat',cov{3},xs); end % expand xs
15 nperbatch = 1000; % number of data points per mini batch
16 nact = 0; % number of already processed test data points
17 ymu = zeros(ns,1); ys2 = ymu; fmu = ymu; fs2 = ymu; lp = ymu; % allocate mem
18 while nact<ns % process minibatches of test cases to save memory
19     id = (nact+1):min(nact+nperbatch,ns); % data points to process
20     <make predictions 8b>
21     nact = id(end); % set counter to index of last processed data point
22 end
23 if nargin<9
24     varargout = {ymu, ys2, fmu, fs2, [], post}; % assign output arguments
25 else
26     varargout = {ymu, ys2, fmu, fs2, lp, post};
27 end

```

In every iteration of the above loop, we compute the predictions for all test points of the batch.

```

8b <make predictions 8b>≡ (8a)
1 kss = feval(cov{:}, hyp.cov, xs(id,:), 'diag'); % self-variance
2 if strcmp(cstr,'covFITC') % cross-covariances
3     Ks = feval(cov{:}, hyp.cov, x, xs(id,:)); Ks = Ks(nz,:); % res indep. of x
4 else
5     Ks = feval(cov{:}, hyp.cov, x(nz,:), xs(id,:)); % avoid computation
6 end
7 ms = feval(mean{:}, hyp.mean, xs(id,:));
8 N = size(alpha,2); % number of alphas (usually 1; more in case of sampling)
9 Fmu = repmat(ms,1,N) + Ks'*full(alpha(nz,:)); % conditional mean fs|f
10 fmu(id) = sum(Fmu,2)/N; % predictive means
11 if Lchol % L contains chol decomp => use Cholesky parameters (alpha,sW,L)
12     V = L'\(repmat(sW,1,length(id)).*Ks);
13     fs2(id) = kss - sum(V.*V,1); % predictive variances

```

```

14 else % L is not triangular => use alternative parametrisation
15     if isnumeric(L), LKs = L*Ks; else LKs = L(Ks); end % matrix or callback
16     fs2(id) = kss + sum(Ks.*LKs,1)'; % predictive variances
17 end
18 fs2(id) = max(fs2(id),0); % remove numerical noise i.e. negative variances
19 Fs2 = repmat(fs2(id),1,N); % we have multiple values in case of sampling
20 if nargin<9
21     [Lp, Ymu, Ys2] = feval(lik{:},hyp.lik,[], Fmu(:),Fs2(:));
22 else
23     Ys = repmat(ys(id),1,N);
24     [Lp, Ymu, Ys2] = feval(lik{:},hyp.lik,Ys(:),Fmu(:),Fs2(:));
25 end
26 lp(id) = sum(reshape(Lp, [],N),2)/N; % log probability; sample averaging
27 ymu(id) = sum(reshape(Ymu,[],N),2)/N; % predictive mean ys|y and ..
28 ys2(id) = sum(reshape(Ys2,[],N),2)/N; % .. variance

```

3 Inference Methods

Inference methods are responsible for computing the (approximate) posterior `post`, the (approximate) negative log marginal likelihood `nlZ` and its partial derivatives `dnlZ` w.r.t. the hyperparameters `hyp`. The arguments to the function are hyperparameters `hyp`, mean function `mean`, covariance function `cov`, likelihood function `lik` and training data `x` and `y`. Several inference methods are implemented and described this section.

```

10 <infMethods.m 10>≡
1 % Inference methods: Compute the (approximate) posterior for a Gaussian process.
2 % Methods currently implemented include:
3 %
4 %     infExact          Exact inference (only possible with Gaussian likelihood)
5 %     infLaplace        Laplace's Approximation
6 %     infEP             Expectation Propagation
7 %     infVB             Variational Bayes Approximation
8 %     infKL             Kullback-Leibler optimal Approximation
9 %
10 %     infFITC           Large scale regression with approximate covariance matrix
11 %     infFITC_Laplace   Large scale inference with approximate covariance matrix
12 %     infFITC_EP        Large scale inference with approximate covariance matrix
13 %
14 %     infMCMC           Markov Chain Monte Carlo and Annealed Importance Sampling
15 %                     We offer two samplers.
16 %                     - hmc: Hybrid Monte Carlo
17 %                     - ess: Elliptical Slice Sampling
18 %                     No derivatives w.r.t. to hyperparameters are provided.
19 %
20 %     infLOO            Leave-One-Out predictive probability and Least-Squares Approxim.
21 %     infPrior          Perform inference with hyperparameter prior.
22 %
23 % The interface to the approximation methods is the following:
24 %
25 %     function [post nlZ dnlZ] = inf..(hyp, cov, lik, x, y)
26 %
27 % where:
28 %
29 %     hyp          is a struct of hyperparameters
30 %     cov          is the name of the covariance function (see covFunctions.m)
31 %     lik          is the name of the likelihood function (see likFunctions.m)
32 %     x            is a n by D matrix of training inputs
33 %     y            is a (column) vector (of size n) of targets
34 %
35 %     nlZ          is the returned value of the negative log marginal likelihood
36 %     dnlZ         is a (column) vector of partial derivatives of the negative
37 %                 log marginal likelihood w.r.t. each hyperparameter
38 %     post         struct representation of the (approximate) posterior containing
39 %         alpha    is a (sparse or full column vector) containing  $\text{inv}(K) \cdot (\mu - m)$ ,
40 %                 where  $K$  is the prior covariance matrix,  $m$  the prior mean,
41 %                 and  $\mu$  the approx posterior mean
42 %         sW       is a (sparse or full column) vector containing diagonal of  $\text{sqrt}(W)$ 
43 %                 the approximate posterior covariance matrix is  $\text{inv}(\text{inv}(K) + W)$ 
44 %         L        is a (sparse or full) matrix,  $L = \text{chol}(sW * K * sW + \text{eye}(n))$ 
45 %
46 % Usually, the approximate posterior to be returned admits the form
47 %  $N(\mu = m + K * \alpha, V = \text{inv}(\text{inv}(K) + W))$ , where  $\alpha$  is a vector and  $W$  is diagonal;
48 % if not, then  $L$  contains instead  $-\text{inv}(K + \text{inv}(W))$ , and  $sW$  is unused.

```

```

49 %
50 % For more information on the individual approximation methods and their
51 % implementations, see the separate inf??.m files. See also gp.m
52 %
53 <gpml copyright 6a>

```

Not all inference methods are compatible with all likelihood functions, e.g.. exact inference is only possible with Gaussian likelihood. In order to perform inference, each method needs various properties of the likelihood functions, section 4.

3.1 Exact Inference

For Gaussian likelihoods, GP inference reduces to computing mean and covariance of a multivariate Gaussian which can be done exactly by simple matrix algebra. The program `inf/infExact.m` does exactly this. If it is called with a likelihood function other than the Gaussian, it issues an error. The Gaussian posterior $q(f|\mathcal{D}) = \mathcal{N}(f|\mu, V)$ is exact.

```

11 <inf/infExact.m 11>≡
1  function [post nlZ dn1Z] = infExact(hyp, mean, cov, lik, x, y)
2
3  % Exact inference for a GP with Gaussian likelihood. Compute a parametrization
4  % of the posterior, the negative log marginal likelihood and its derivatives
5  % w.r.t. the hyperparameters. See also "help infMethods".
6  %
7  <gpml copyright 6a>
8  %
9  % See also INFMETHODS.M.
10
11 if iscell(lik), likstr = lik{1}; else likstr = lik; end
12 if ~ischar(likstr), likstr = func2str(likstr); end
13 if ~strcmp(likstr,'likGauss') % NOTE: no explicit call to likGauss
14     error('Exact inference only possible with Gaussian likelihood');
15 end
16
17 [n, D] = size(x);
18 K = feval(cov{:}, hyp.cov, x); % evaluate covariance matrix
19 m = feval(mean{:}, hyp.mean, x); % evaluate mean vector
20
21 sn2 = exp(2*hyp.lik); % noise variance of likGauss
22 if sn2<1e-6 % very tiny sn2 can lead to numerical trouble
23     L = chol(K+sn2*eye(n)); s1 = 1; % Cholesky factor of covariance with noise
24     pL = -solve_chol(L,eye(n)); % L = -inv(K+inv(sW^2))
25 else
26     L = chol(K/sn2+eye(n)); s1 = sn2; % Cholesky factor of B
27     pL = L; % L = chol(eye(n)+sW*sW'.*K)
28 end
29 alpha = solve_chol(L,y-m)/s1;
30
31 post.alpha = alpha; % return the posterior parameters
32 post.sW = ones(n,1)/sqrt(sn2); % sqrt of noise precision vector
33 post.L = pL;
34
35 if nargin>1 % do we want the marginal likelihood?
36     nlZ = (y-m)'\*alpha/2 + sum(log(diag(L))) + n*log(2*pi*s1)/2; % -log marg lik
37     if nargin>2 % do we want derivatives?
38         dn1Z = hyp; % allocate space for derivatives
39         Q = solve_chol(L,eye(n))/s1 - alpha*alpha'; % precompute for convenience

```

```

40     for i = 1:numel(hyp.cov)
41         dn1Z.cov(i) = sum(sum(Q.*feval(cov{:}, hyp.cov, x, [], i)))/2;
42     end
43     dn1Z.lik = sn2*trace(Q);
44     for i = 1:numel(hyp.mean)
45         dn1Z.mean(i) = -feval(mean{:}, hyp.mean, x, i)*alpha;
46     end
47 end
48 end

```

3.2 Laplace's Approximation

For differentiable likelihoods, Laplace's approximation, approximates the posterior by a Gaussian centered at its mode and matching its curvature `inf/infLaplace.m`.

More concretely, the mean of the posterior $q(f|\mathcal{D}) = \mathcal{N}(f|\boldsymbol{\mu}, V)$ is – defining $\ell_i(f_i) = \ln p(y_i|f_i)$ and $\ell(f) = \sum_{i=1}^n \ell_i(f_i)$ – given by

$$\boldsymbol{\mu} = \arg \min_f \Phi(f), \text{ where } \Phi(f) = \frac{1}{2}(f - m)^\top K^{-1}(f - m) - \ell(f) \stackrel{c}{=} -\ln[p(f)p(y|f)], \quad (2)$$

which we abbreviate by $\boldsymbol{\mu} \leftarrow \mathcal{L}(\ell)$. The curvature $\frac{\partial^2 \Phi}{\partial f^2} = K^{-1} + W$ with $W_{ii} = -\frac{\partial^2}{\partial f_i^2} \ln p(y_i|f_i)$ serves as precision for the Gaussian posterior approximation $V = (K^{-1} + W)^{-1}$ and the marginal likelihood $Z = \int p(f)p(y|f)df$ is approximated by $Z \approx Z_{LA} = \int \tilde{\Phi}(f)df$ where we use the 2nd order Taylor expansion at the mode $\boldsymbol{\mu}$ given by $\tilde{\Phi}(f) = \Phi(\boldsymbol{\mu}) + \frac{1}{2}(f - \boldsymbol{\mu})^\top V^{-1}(f - \boldsymbol{\mu}) \approx \Phi(f)$.

Laplace's approximation needs derivatives up to third order for the mode fitting procedure (Newton method)

$$d_k = \frac{\partial^k}{\partial f^k} \log p(y|f), \quad k = 0, 1, 2, 3$$

and

$$d_k = \frac{\partial}{\partial \rho_i} \frac{\partial^k}{\partial f^k} \log p(y|f), \quad k = 0, 1, 2$$

evaluated at the latent location f and observed value y . The likelihood calls (see section 4)

- `[d0, d1, d2, d3] = lik(hyp, y, f, [], 'infLaplace')`

and

- `[d0, d1, d2] = lik(hyp, y, f, [], 'infLaplace', i)`

return exactly these values.

3.3 Expectation Propagation

The basic idea of Expectation Propagation (EP) as implemented in `inf/infEP.m` is to replace the non-Gaussian likelihood terms $p(y_i|f_i)$ by Gaussian functions $t(f_i; \mathbf{v}_i, \boldsymbol{\tau}_i) = \exp(\mathbf{v}_i f_i - \frac{1}{2} \boldsymbol{\tau}_i f_i^2)$ and to adjust the natural parameters $\mathbf{v}_i, \boldsymbol{\tau}_i$ such that the following identity holds:

$$\frac{1}{Z_{t,i}} \int f^k q_{-i}(f) \cdot t(f; \mathbf{v}_i, \boldsymbol{\tau}_i) df = \frac{1}{Z_{p,i}} \int f^k q_{-i}(f) \cdot p(y_i|f) df, \quad k = 1, 2$$

with the so-called cavity distributions $q_{-i}(f) = \mathcal{N}(f|m, K) \prod_{j \neq i} t(f_j; \mathbf{v}_j, \boldsymbol{\tau}_j) \propto \mathcal{N}(f|\boldsymbol{\mu}, V)/t(f_i; \mathbf{v}_i, \boldsymbol{\tau}_i)$ equal to the posterior divided by the i th Gaussian approximation function and the two normalisers

$Z_{t,i} = \int q_{-i}(f) \cdot t(f_i; \mathbf{v}_i, \tau_i) df$ and $Z_{p,i} = \int q_{-i}(f) \cdot p(y_i|f_i) df$. The moment matching corresponds to minimising the following local KL-divergence

$$\mathbf{v}_i, \tau_i = \arg \min_{\mathbf{v}, \tau} \text{KL}[q_{-i}(f)p(y_i|f_i)/Z_{p,i} || q_{-i}(f)t(f_i; \mathbf{v}, \tau)/Z_{t,i}].$$

In order to apply the moment matching steps in a numerically safe way, EP requires the derivatives of the expectations w.r.t. the Gaussian mean parameter μ

$$d_k = \frac{\partial^k}{\partial \mu^k} \log \int p(y|f) \mathcal{N}(f|\mu, \sigma^2) df, \quad k = 0, 1, 2$$

and the i th likelihood hyperparameter ρ_i

$$d = \frac{\partial}{\partial \rho_i} \log \int p(y|f) \mathcal{N}(f|\mu, \sigma^2) df$$

which can be obtained by the likelihood calls (see section 4)

- `[d0, d1, d2] = lik(hyp, y, mu, s2, 'infEP')`

and

- `d = lik(hyp, y, mu, s2, 'infEP', i).`

3.4 Kullback Leibler Divergence Minimisation

Another well known approach to approximate inference implemented `inf/infKL.m` in attempts to directly find the closest Gaussian $q(f|\mathcal{D}) = \mathcal{N}(f|\mu, V)$ to the exact posterior $p(f|\mathcal{D})$ w.r.t. to some proximity measure or equivalently to maximise a lower bound $Z(\mu, V)$ to the marginal likelihood Z as described in Nickisch & Rasmussen Approximations for Binary Gaussian Process Classification, JMLR, 2008. In particular, one minimises $\text{KL}(\mathcal{N}(f|\mu, V) || p(f|\mathcal{D}))$ which amounts to minimising $-\ln Z(\mu, V)$ as defined by:

$$\begin{aligned} -\ln Z &= -\ln \int p(f) p(y|f) df = -\ln \int q(f|\mathcal{D}) \frac{p(f)}{q(f|\mathcal{D})} p(y|f) df \\ &\stackrel{\text{Jensen}}{\leq} \int q(f|\mathcal{D}) \ln \frac{q(f|\mathcal{D})}{p(f)} df - \int q(f|\mathcal{D}) \ln p(y|f) df =: -\ln Z(\mu, V) \\ &= \text{KL}(\mathcal{N}(f|\mu, V) || \mathcal{N}(f|m, K)) - \sum_{i=1}^n \int \mathcal{N}(f_i|\mu_i, v_{ii}) \ln p(y_i|f_i) df_i, \quad v_{ii} = [V]_{ii} \\ &= \frac{1}{2} (\text{tr}(VK^{-1}) - I) - \ln |VK^{-1}| + \frac{1}{2} (\mu - m)^\top K^{-1} (\mu - m) - \sum_{i=1}^n \ell^{\text{KL}}(\mu_i, v_{ii}) \end{aligned}$$

where $\ell_v^{\text{KL}}(\mu_i) = \int \mathcal{N}(f_i|\mu_i, v_{ii}) \ell_i(f_i) df_i$ is the convolution of the log likelihood ℓ_i with the Gaussian \mathcal{N} and $v = \text{dg}(V)$. Equivalently, one can view ℓ^{KL} as a smoothed version of ℓ with univariate smoothing kernel \mathcal{N} .

From Challis & Barber Concave Gaussian Variational Approximations for Inference in Large Scale Bayesian Linear Models, AISTATS, 2011 we know that the mapping $(\mu, L) \mapsto -\ln Z(\mu, L^\top L)$ is jointly convex whenever the likelihoods $f_i \mapsto \mathbb{P}(y_i|f_i)$ are log concave. In particular, this implies that every $(\mu_i, s_i) \mapsto -\ell^{\text{KL}}(\mu_i, s_i^2)$ is jointly convex.

We use an optimisation algorithm similar to EP (section 3.3) where we minimise the local KL-divergence the other way round $\mu_i, s_i = \arg \min_{\mu, s} \text{KL}[\mathcal{N}(f|\mu, s^2) || q_{-i}(f)p(y_i|f_i)/Z_{p,i}]$. This view

was brought forward by Tom Minka Convex Divergence measures and message passing, MSR-TR, 2005. The KL minimisation constitutes a jointly convex 2d optimisation problem solved by `klmin` using a scaled Newton approach which is included as a sub function in `inf/infKL.m`. The smoothed likelihood $\ell^{\text{KL}}(\boldsymbol{\mu}_i, \mathbf{v}_{ii})$ is implemented as a meta likelihood in `likKL`; it uses Gaussian-Hermite quadrature to compute the required integrals. Note that – as opposed to EP – Gaussian-Hermite quadrature is appropriate since we integrate against the $\ln \mathbb{P}(\mathbf{y}_i | \mathbf{f}_i)$ (which can be well approximated by a polynomial) instead of $\mathbb{P}(\mathbf{y}_i | \mathbf{f}_i)$ itself. The algorithm is – again unlike EP – provably convergent for log-concave likelihoods (e.g. `likGauss`, `likLaplace`, `likSech2`, `likLogistic`, `likPoisson`) since it can be regarded as coordinate descent with guaranteed decrease in the objective in every step. Due to the complex update computations, `infKL` can be quite slow although it has the same $\mathcal{O}(\mathbf{n}^3)$ asymptotic complexity as EP and Laplace.

3.5 Variational Bayes

One can drive the bounding even further by means of local quadratic lower bounds to the log likelihood $\ell(\mathbf{f}) = \ln \mathbf{p}(\mathbf{y} | \mathbf{f})$. Suppose that we use a super-Gaussian likelihood $\mathbf{p}(\mathbf{y} | \mathbf{f})$ i.e. likelihoods that can be lower bounded by Gaussians of any width \mathbf{w} (e.g. `likLaplace`, `likT`, `likLogistic`, `likSech2`). Formally, that means that there are $\mathbf{b}, \mathbf{z} \in \mathbb{R}$ such that

$$\rho(\mathbf{f}) = \ln \mathbf{p}(\mathbf{y} | \mathbf{f} - \mathbf{z}) - \mathbf{b}\mathbf{f}$$

is symmetric and $\sqrt{\mathbf{f}} \mapsto \rho(\mathbf{f})$ is a convex function for all $\mathbf{f} \geq 0$. As a result, we obtain the following exact representation of the likelihood

$$\ell(\mathbf{f}) = \ln \mathbf{p}(\mathbf{y} | \mathbf{f}) = \max_{\mathbf{w} > 0} \left((\mathbf{b} + \mathbf{w}\mathbf{z})\mathbf{f} - \frac{\mathbf{w}\mathbf{f}^2}{2} - \frac{1}{2}\mathbf{h}(\gamma) \right),$$

which can be derived by convex duality and assuming the likelihoods to be super-Gaussian. Details can be found in papers by Palmer et al. Variational EM Algorithms for Non-Gaussian Latent Variable Models, NIPS, 2006 and Nickisch & Seeger Convex Variational Bayesian Inference for Large Scale Generalized Linear Models, ICML, 2009.

The bottom line is that we can treat the variational bounding as a sequence of Laplace approximations with the “variational Bayes” log likelihood

$$\ell^{\text{VB}}(\mathbf{f}_i) = \ell(\mathbf{g}_i) + \mathbf{b}_i(\mathbf{f}_i - \mathbf{g}_i), \mathbf{g} = \text{sgn}(\mathbf{f} - \mathbf{z}) \odot \sqrt{(\mathbf{f} - \mathbf{z})^2 + \mathbf{v}} + \mathbf{z}$$

instead of the usual likelihood $\ell(\mathbf{f}_i) = \ln \mathbf{p}(\mathbf{y}_i | \mathbf{f}_i)$ i.e. we solve $\boldsymbol{\mu} \leftarrow \mathcal{L}(\ell_v^{\text{VB}})$ instead of $\boldsymbol{\mu} \leftarrow \mathcal{L}(\ell)$. See section 3.2. In the code of `inf/infVB.m`, the likelihood is implemented in the function `likVB`.

At the end, the optimal value of \mathbf{W} can be obtained analytically via $\mathbf{w}_i = |\mathbf{b}_i - \ell'(\mathbf{g}_i)| / |\mathbf{g}_i - \mathbf{z}_i|$.

For the minimisation in `inf/infVB.m`, we use a provably convergent double loop algorithm, where in the inner loop a nonlinear least squares problem (convex for log-concave likelihoods) is solved using `inf/infLaplace.m` such that $\boldsymbol{\mu} \leftarrow \mathcal{L}(\ell_v^{\text{VB}})$ and in the outer loop, we compute $\mathbf{v} \leftarrow \text{dg}((\mathbf{K}^{-1} + \mathbf{W})^{-1})$. The only requirement to the likelihood function is that it returns the values \mathbf{z} and \mathbf{b} required by the bound which are delivered by the call (see section 4)

- `[b,z] = lik(hyp, y, [], ga, 'infVB')`

The negative marginal likelihood upper bound $-\ln \mathbf{Z}_{\text{VB}}$ is obtained by integrating the prior times the exact representation of the likelihood

$$\mathbf{p}(\mathbf{y} | \mathbf{f}) = \max_{\gamma > 0} \mathbf{q}(\mathbf{y} | \mathbf{f}, \gamma), \mathbf{q}(\mathbf{y} | \mathbf{f}, \gamma) = \mathcal{N}(\mathbf{f} | \mathbf{v}, \gamma) \exp \left(-\frac{\mathbf{h}(\gamma)}{2} - \frac{\mathbf{v}^2}{2\gamma} \right) \sqrt{2\pi\gamma}, \gamma = \frac{1}{\mathbf{w}}, \mathbf{v} = \mathbf{b}\gamma + \mathbf{z}$$

w.r.t. the latent variables \mathbf{f} yielding

$$\begin{aligned} -\ln Z_{\mathbf{VB}} &= -\ln \int \mathcal{N}(\mathbf{f}|\mathbf{m}, \mathbf{K}) \prod_{i=1}^n q_i(\mathbf{y}_i|\mathbf{f}_i, \gamma_i) d\mathbf{f} \\ &= -\ln \mathcal{N}(\mathbf{m}|\mathbf{v}, \mathbf{K} + \mathbf{\Gamma}) + \frac{1}{2} \left(\mathbf{h}(\boldsymbol{\gamma}) - \mathbf{w}^\top \mathbf{v}^2 - \mathbf{1}^\top \ln 2\pi\boldsymbol{\gamma} \right). \end{aligned}$$

3.6 FITC Approximations

One of the main problems with GP models is the high computational load for inference computations. In a setting with \mathbf{n} training points \mathbf{x} , exact inference with Gaussian likelihood requires $\mathcal{O}(\mathbf{n}^3)$ effort; approximations like Laplace or EP consist of a sequence of $\mathcal{O}(\mathbf{n}^3)$ operations.

There is a line of research with the goal to alleviate this burden by using approximate covariance functions $\tilde{\mathbf{k}}$ instead of \mathbf{k} . A review is given by Candela and Rasmussen A Unifying View of Sparse Approximate Gaussian Process Regression, JMLR, 2005. One basic idea in those approximations is to work with a set of \mathbf{m} inducing inputs \mathbf{u} with a reduced computational load of $\mathcal{O}(\mathbf{n}\mathbf{m}^2)$. In the following, we will provide a rough idea of the FITC approximation used in the toolbox. Let \mathbf{K} denote the $\mathbf{n} \times \mathbf{n}$ covariance matrix between the training points \mathbf{x} , \mathbf{K}_u the $\mathbf{m} \times \mathbf{n}$ covariance matrix between the \mathbf{n} training points and the \mathbf{m} inducing points, and \mathbf{K}_{uu} the $\mathbf{m} \times \mathbf{m}$ covariance matrix between the \mathbf{m} inducing points. The FITC approximation to the covariance is given by

$$\mathbf{K} \approx \tilde{\mathbf{K}} = \mathbf{Q} + \mathbf{G}, \quad \mathbf{G} = \text{diag}(\mathbf{g}), \quad \mathbf{g} = \text{diag}(\mathbf{K} - \mathbf{Q}), \quad \mathbf{Q} = \mathbf{K}_u^\top \mathbf{Q}_{uu}^{-1} \mathbf{K}_u, \quad \mathbf{Q}_{uu} = \mathbf{K}_{uu} + \sigma_{\mathbf{n}_u}^2 \mathbf{I},$$

where $\sigma_{\mathbf{n}_u}$ is the noise from the inducing inputs. Note that $\tilde{\mathbf{K}}$ and \mathbf{K} have the same diagonal elements $\text{diag}(\tilde{\mathbf{K}}) = \text{diag}(\mathbf{K})$; all off-diagonal elements are the same as for \mathbf{Q} . Internally, the necessary covariance evaluations are performed by a meta covariance function `cov/covFITC.m`. The toolbox offers FITC versions for regression with Gaussian likelihood `inf/infFITC.m`, as well as for Laplace's approximation `inf/infFITCLaplace.m` and expectation propagation `inf/infFITCEP.m`.

The user can decide whether to treat the inducing inputs \mathbf{u} as fixed or as hyperparameters. The latter is possible for a number of common stationary covariance functions (and also all three FITC inference methods `inf/infFITC*.m`) and allows to adjust the inducing inputs \mathbf{u} w.r.t. the marginal likelihood. As detailed in the documentation of `inf/infFITC*.m`, \mathbf{u} is treated as fixed if it is passed as the 2nd parameter of `covFITC(cov, xu, ...)`. If the hyperparameter structure `hyp` contains a field `hyp.xu` in inference method calls like `infFITC*(hyp, ...)` or inference/prediction calls like `gp(hyp, @infFITC*, ...)` the inducing inputs \mathbf{u} are treated as hyperparameters and can be optimised.

3.7 Grid Approximations

Another way to bring down computational costs is to take advantage of (partial) grid structure present in the training points \mathbf{x} . For example, in geostatistics or image processing, the training data $\mathbf{x} \in \mathbb{R}^{\mathbf{n} \times \mathbf{D}}$ could be a complete 2d lattice of size $\mathbf{n}_1 \times \mathbf{n}_2$ as given by the axes $\mathbf{x}_1 \in \mathbb{R}^{\mathbf{n}_1}$, $\mathbf{x}_2 \in \mathbb{R}^{\mathbf{n}_2}$ so that $\mathbf{n} = \mathbf{n}_1 \cdot \mathbf{n}_2$, $\mathbf{D} = 2$ and $\mathbf{x} = [\text{vec}(\mathbf{x}_1 \mathbf{1}^\top), \text{vec}(\mathbf{1} \mathbf{x}_2^\top)]$. In general, a \mathbf{p} -dimensional grid $\mathbf{x}_g \in \mathbb{R}^{\mathbf{N} \times \mathbf{D}}$ is specified by a set of axis matrices $\{\mathbf{x}_i \in \mathbb{R}^{\mathbf{n}_i \times \mathbf{D}_i}\}_{i=1..p}$ so that $\mathbf{N} = \prod_{i=1}^p \mathbf{n}_i$ and $\mathbf{D} = \sum_{i=1}^p \mathbf{D}_i$ where the axes do not need to be 1d nor do their components need to be sorted. As a consequence, \mathbf{x}_g represents a Cartesian product of its axes $\mathbf{x}_g = \mathbf{x}_1 \times \mathbf{x}_2 \times \dots \times \mathbf{x}_p$. The `cov/covGrid.m` covariance function represents a Kronecker product covariance matrix

$$\mathbf{K} = \mathbf{K}_p \otimes \dots \otimes \mathbf{K}_2 \otimes \mathbf{K}_1$$

whose factorisation structure is given by the grid \mathbf{x}_g . The gain in computational efficiency is due to the fact that matrix-vector product, determinant, inverse and eigenvalue computations decompose so

that the overall cost of $\mathcal{O}(\mathbf{N}^3)$ turns into $\mathcal{O}(\sum_{i=1}^p \mathbf{n}_i^3)$. Internally, we use a meta covariance function `cov/covGrid.m` to represent the Kronecker covariance matrix and a Gaussian regression inference method `inf/infGrid.m`. We also support incomplete grids where $\mathbf{n} < \mathbf{N}$. A good starting point is Yunus Saatçi's PhD thesis Scalable Inference for Structured Gaussian Process Models, University of Cambridge, 2011. For incomplete grids, we use the extensions by Wilson et. al, Fast Kernel Learning for Multidimensional Pattern Extrapolation, NIPS, 2014 where conjugate gradients and a determinant approximations are used. See `doc/demoGrid.m` for an illustration.

4 Likelihood Functions

A likelihood function $\mathbf{p}_\rho(\mathbf{y}|\mathbf{f})$ (with hyperparameters ρ) is a conditional density $\int \mathbf{p}_\rho(\mathbf{y}|\mathbf{f})d\mathbf{y} = 1$ defined for scalar latent function values \mathbf{f} and outputs \mathbf{y} . In the GPML toolbox, we use iid. likelihoods $\mathbf{p}_\rho(\mathbf{y}|\mathbf{f}) = \prod_{i=1}^n \mathbf{p}_\rho(\mathbf{y}_i|\mathbf{f}_i)$. The approximate inference engine does not explicitly distinguish between classification and regression likelihoods: it is fully generic in the likelihood allowing to use a single code in the inference step.

Likelihood functionality is needed both during inference and while predicting.

4.1 Prediction

A prediction at \mathbf{x}_* conditioned on the data $\mathcal{D} = (\mathbf{X}, \mathbf{y})$ (as implemented in `gp.m`) consists of the predictive mean $\mu_{\mathbf{y}_*}$ and variance $\sigma_{\mathbf{y}_*}^2$ which are computed from the the latent marginal moments $\mu_{\mathbf{f}_*}$, $\sigma_{\mathbf{f}_*}^2$ i.e. the Gaussian marginal approximation $\mathcal{N}(\mathbf{f}_*|\mu_{\mathbf{f}_*}, \sigma_{\mathbf{f}_*}^2)$ via

$$\mathbf{p}(\mathbf{y}_*|\mathcal{D}, \mathbf{x}_*) = \int \mathbf{p}(\mathbf{y}_*|\mathbf{f}_*)\mathbf{p}(\mathbf{f}_*|\mathcal{D}, \mathbf{x}_*)d\mathbf{f}_* \approx \int \mathbf{p}(\mathbf{y}_*|\mathbf{f}_*)\mathcal{N}(\mathbf{f}_*|\mu_{\mathbf{f}_*}, \sigma_{\mathbf{f}_*}^2)d\mathbf{f}_*. \quad (3)$$

The moments are given by $\mu_{\mathbf{y}_*} = \int \mathbf{y}_*\mathbf{p}(\mathbf{y}_*|\mathcal{D}, \mathbf{x}_*)d\mathbf{y}_*$ and $\sigma_{\mathbf{y}_*}^2 = \int (\mathbf{y}_* - \mu_{\mathbf{y}_*})^2\mathbf{p}(\mathbf{y}_*|\mathcal{D}, \mathbf{x}_*)d\mathbf{y}_*$. The likelihood call

- `[lp,ymu,ys2] = lik(hyp, [], fmu, fs2)`

does exactly this. Evaluation of the logarithm of $\mathbf{p}_{\mathbf{y}_*} = \mathbf{p}(\mathbf{y}_*|\mathcal{D}, \mathbf{x}_*)$ for values \mathbf{y}_* can be done via

- `[lp,ymu,ys2] = lik(hyp, y, fmu, fs2)`

where `lp` contains the number $\ln \mathbf{p}_{\mathbf{y}_*}$.

Using the moments of the likelihood $\mu(\mathbf{f}_*) = \int \mathbf{y}_*\mathbf{p}(\mathbf{y}_*|\mathbf{f}_*)d\mathbf{y}_*$ and $\sigma^2(\mathbf{f}_*) = \int (\mathbf{y}_* - \mu(\mathbf{f}_*))^2\mathbf{p}(\mathbf{y}_*|\mathbf{f}_*)d\mathbf{y}_*$ we obtain for the predictive moments the following (exact) expressions

$$\begin{aligned} \mu_{\mathbf{y}_*} &= \int \mu(\mathbf{f}_*)\mathbf{p}(\mathbf{f}_*|\mathcal{D}, \mathbf{x}_*)d\mathbf{f}_*, \text{ and} \\ \sigma_{\mathbf{y}_*}^2 &= \int [\sigma^2(\mathbf{f}_*) + (\mu(\mathbf{f}_*) - \mu_{\mathbf{y}_*})^2] \mathbf{p}(\mathbf{f}_*|\mathcal{D}, \mathbf{x}_*)d\mathbf{f}_*. \end{aligned}$$

1. The binary case is simple since $\mathbf{y}_* \in \{-1, +1\}$ and $1 = \mathbf{p}_{\mathbf{y}_*} + \mathbf{p}_{-\mathbf{y}_*}$. Using $\pi_* = \mathbf{p}_{+1}$, we find

$$\begin{aligned} \mathbf{p}_{\mathbf{y}_*} &= \begin{cases} \pi_* & \mathbf{y}_* = +1 \\ 1 - \pi_* & \mathbf{y}_* = -1 \end{cases} \\ \mu_{\mathbf{y}_*} &= \sum_{\mathbf{y}_*=\pm 1} \mathbf{y}_*\mathbf{p}(\mathbf{y}_*|\mathcal{D}, \mathbf{x}_*) = 2 \cdot \pi_* - 1 \in [-1, 1], \text{ and} \\ \sigma_{\mathbf{y}_*}^2 &= \sum_{\mathbf{y}_*=\pm 1} (\mathbf{y}_* - \mu_{\mathbf{y}_*})^2\mathbf{p}(\mathbf{y}_*|\mathcal{D}, \mathbf{x}_*) = 4 \cdot \pi_*(1 - \pi_*) \in [0, 1]. \end{aligned}$$

2. The continuous case for homoscedastic likelihoods depending on $\mathbf{r}_* = \mathbf{y}_* - \mathbf{f}_*$ only and having noise variance $\sigma^2(\mathbf{f}_*) = \sigma_n^2$ is also simple since the identity $\mathbf{p}(\mathbf{y}_*|\mathbf{f}_*) = \mathbf{p}(\mathbf{y}_* - \mathbf{f}_*|0)$ allows to substitute $\mathbf{y}_* \leftarrow \mathbf{y}_* + \mathbf{f}_*$ yielding $\mu(\mathbf{f}_*) = \mathbf{f}_* + \int \mathbf{y}_*\mathbf{p}(\mathbf{y}_*|0)d\mathbf{y}_*$ and assuming $\int \mathbf{y}_*\mathbf{p}(\mathbf{y}_*|0)d\mathbf{y}_* = 0$ we arrive at

$$\begin{aligned} \mu_{\mathbf{y}_*} &= \mu_{\mathbf{f}_*}, \text{ and} \\ \sigma_{\mathbf{y}_*}^2 &= \sigma_{\mathbf{f}_*}^2 + \sigma_n^2. \end{aligned}$$

3. The generalised linear model (GLM) case is also feasible. Evaluation of the predictive distribution is done by quadrature

$$p_{y_*} = \int p(y_*|f_*)p(f_*|\mathcal{D}, x_*)df_* \approx \int p(y_*|f_*)\mathcal{N}(f_*|\mu_{f_*}, \sigma_{f_*}^2)df_*.$$

For GLMs the mean is given by $\mu(f_*) = g(f_*)$ and the variance is usually given by a simple function of the mean $\sigma^2(f_*) = v(g(f_*))$, hence we use Gaussian-Hermite quadrature with $\mathcal{N}(f_*|\mu_{f_*}, \sigma_{f_*}^2) \approx p(f_*|\mathcal{D}, x_*)$ to compute

$$\begin{aligned} \mu_{y_*} &= \int g(f_*)p(f_*|\mathcal{D}, x_*)df_*, \text{ and} \\ \sigma_{y_*}^2 &= \int [v(g(f_*)) + (g(f_*) - \mu_{y_*})^2] p(f_*|\mathcal{D}, x_*)df_* \neq v(\mu_{y_*}). \end{aligned}$$

4. Finally the warped Gaussian likelihood predictive distribution with strictly monotonically increasing warping function g is given by the expression

$$p(y_*|\mathcal{D}, x_*) = g'(y_*)\mathcal{N}(g(y_*)|\mu_{f_*}, \sigma_n^2 + \sigma_{f_*}^2)$$

so that the predictive moments can be computed by Gaussian-Hermite quadrature.

In the following, we will detail how and which likelihood functions are implemented in the GPML toolbox. Further, we will mention dependencies between likelihoods and inference methods and provide some analytical expressions in addition to some likelihood implementations.

4.2 Interface

The likelihoods are in fact the most challenging object in our implementation. Different inference algorithms require different aspects of the likelihood to be computed, therefore the interface is rather involved as detailed below.

```
18 <likFunctions.m 18>≡
1 % likelihood functions are provided to be used by the gp.m function:
2 %
3 %   likErf           (Error function, classification, probit regression)
4 %   likLogistic      (Logistic,           classification, logit regression)
5 %   likUni           (Uniform likelihood, classification)
6 %
7 %   likGauss         (Gaussian, regression)
8 %   likGaussWarp     (Warped Gaussian, regression)
9 %   likGumbel        (Gumbel likelihood for extremal values)
10 %  likLaplace        (Laplacian or double exponential, regression)
11 %  likSech2          (Sech-square, regression)
12 %  likT              (Student's t, regression)
13 %
14 %  likPoisson        (Poisson regression, count data)
15 %  likGamma          (Nonnegative regression, positive data)
16 %  likExp            (Nonnegative regression, positive data)
17 %  likInvGauss       (Nonnegative regression, positive data)
18 %  likBeta           (Beta regression, interval data)
19 %
20 %  likMix            (Mixture of individual covariance functions)
21 %
22 % The likelihood functions have three possible modes, the mode being selected
```

```

23 % as follows (where "lik" stands for any likelihood function in "lik/lik*.m"):
24 %
25 % 1) With one or no input arguments:          [REPORT NUMBER OF HYPERPARAMETERS]
26 %
27 %     s = lik OR s = lik(hyp)
28 %
29 % The likelihood function returns a string telling how many hyperparameters it
30 % expects, using the convention that "D" is the dimension of the input space.
31 % For example, calling "likLogistic" returns the string '0'.
32 %
33 %
34 % 2) With three or four input arguments:          [PREDICTION MODE]
35 %
36 %     lp = lik(hyp, y, mu) OR [lp, ymu, ys2] = lik(hyp, y, mu, s2)
37 %
38 % This allows to evaluate the predictive distribution. Let  $p(y_*|f_*)$  be the
39 % likelihood of a test point and  $N(f_*|\mu, s2)$  an approximation to the posterior
40 % marginal  $p(f_*|x_*, x, y)$  as returned by an inference method. The predictive
41 % distribution  $p(y_*|x_*, x, y)$  is approximated by.
42 %      $q(y_*) = \int N(f_*|\mu, s2) p(y_*|f_*) df_*$ 
43 %
44 %     lp = log( q(y) ) for a particular value of y, if s2 is [] or 0, this
45 %                      corresponds to log( p(y|\mu) )
46 %     ymu and ys2      the mean and variance of the predictive marginal q(y)
47 %                      note that these two numbers do not depend on a particular
48 %                      value of y
49 % All vectors have the same size.
50 %
51 %
52 % 3) With five or six input arguments, the fifth being a string [INFERENCE MODE]
53 %
54 % [varargout] = lik(hyp, y, mu, s2, inf) OR
55 % [varargout] = lik(hyp, y, mu, s2, inf, i)
56 %
57 % There are three cases for inf, namely a) infLaplace, b) infEP and c) infVB.
58 % The last input i, refers to derivatives w.r.t. the ith hyperparameter.
59 %
60 % a1) [lp, dlp, d2lp, d3lp] = lik(hyp, y, f, [], 'infLaplace')
61 % lp, dlp, d2lp and d3lp correspond to derivatives of the log likelihood
62 % log(p(y|f)) w.r.t. to the latent location f.
63 %     lp = log( p(y|f) )
64 %     dlp = d log( p(y|f) ) / df
65 %     d2lp = d^2 log( p(y|f) ) / df^2
66 %     d3lp = d^3 log( p(y|f) ) / df^3
67 %
68 % a2) [lp_dhyp, dlp_dhyp, d2lp_dhyp] = lik(hyp, y, f, [], 'infLaplace', i)
69 % returns derivatives w.r.t. to the ith hyperparameter
70 %     lp_dhyp = d log( p(y|f) ) / ( dhyp_i)
71 %     dlp_dhyp = d^2 log( p(y|f) ) / (df dhyp_i)
72 %     d2lp_dhyp = d^3 log( p(y|f) ) / (df^2 dhyp_i)
73 %
74 %
75 % b1) [lZ, d1Z, d21Z] = lik(hyp, y, mu, s2, 'infEP')
76 % let Z =  $\int p(y|f) N(f|\mu, s2) df$  then
77 %     lZ = log(Z)
78 %     d1Z = d log(Z) / dmu
79 %     d21Z = d^2 log(Z) / dmu^2
80 %

```

```

81 % b2) [dlZhyp] = lik(hyp, y, mu, s2, 'infEP', i)
82 % returns derivatives w.r.t. to the ith hyperparameter
83 % dlZhyp = d log(Z) / dhyp_i
84 %
85 %
86 % c1) [b,z] = lik(hyp, y, [], ga, 'infVB')
87 % ga is the variance of a Gaussian lower bound to the likelihood p(y|f).
88 % p(y|f) \ge exp( b*(f+z) - (f+z).^2/(2*ga) - h(ga)/2 ) \propto N(f|b*ga-z,ga)
89 % The function returns the linear part b and z.
90 %
91 % Cumulative likelihoods are designed for binary classification. Therefore, they
92 % only look at the sign of the targets y; zero values are treated as +1.
93 %
94 % Some examples for valid likelihood functions:
95 %     lik = @likLogistic;
96 %     lik = {'likMix','likUni','likErf'}
97 %     lik = {@likPoisson,'logistic'};
98 %
99 % See the help for the individual likelihood for the computations specific to
100 % each likelihood function.
101 %
102 (gpml copyright 6a)

```

4.3 Implemented Likelihood Functions

The following table enumerates all (currently) implemented likelihood functions that can be found at `lik/lik<NAME>.m` and their respective set of hyperparameters $\boldsymbol{\rho}$.

lik<NAME>	regression $\mathbf{y}_i \in \mathbb{R}$	$\mathbf{p}_{\boldsymbol{\rho}}(\mathbf{y}_i \mathbf{f}_i) =$	$\boldsymbol{\rho} =$
Gauss	Gaussian	$\mathcal{N}(\mathbf{y}_i \mathbf{f}_i, \sigma^2) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{(\mathbf{y}_i-\mathbf{f}_i)^2}{2\sigma^2}\right)$	$\{\ln \sigma\}$
GaussWarp	Warped Gaussian	$\mathcal{N}(\mathbf{g}_{\boldsymbol{\theta}}(\mathbf{y}_i) \mathbf{f}_i, \sigma^2) \mathbf{g}'_{\boldsymbol{\theta}}(\mathbf{y}_i)$	$\{\theta_1, \dots, \theta_{n_g}, \ln \sigma\}$
Gumbel	Gumbel	$\frac{\pi}{\sigma\sqrt{6}} \exp(-z_i - e^{-z_i}), z_i = \gamma + \frac{s \cdot \pi(\mathbf{y}_i - \mathbf{f}_i)}{\sigma\sqrt{6}}, s = 1$	$\{\ln \sigma\}$
Sech2	Sech-squared	$\frac{\tau}{2 \cosh^2(\tau(\mathbf{y}_i - \mathbf{f}_i))}, \tau = \frac{\pi}{2\sigma\sqrt{3}}$	$\{\ln \sigma\}$
Laplace	Laplacian	$\frac{1}{2b} \exp\left(-\frac{ \mathbf{y}_i - \mathbf{f}_i }{b}\right), b = \frac{\sigma}{\sqrt{2}}$	$\{\ln \sigma\}$
T	Student's t	$\frac{\Gamma(\frac{\nu+1}{2})}{\Gamma(\frac{\nu}{2})} \frac{1}{\sqrt{\nu\pi}\sigma} \left(1 + \frac{(\mathbf{y}_i - \mathbf{f}_i)^2}{\nu\sigma^2}\right)^{-\frac{\nu+1}{2}}$	$\{\ln(\nu-1), \ln \sigma\}$
lik<NAME>	classification $\mathbf{y}_i \in \{\pm 1\}$	$\mathbf{p}_{\boldsymbol{\rho}}(\mathbf{y}_i \mathbf{f}_i) =$	$\boldsymbol{\rho} =$
Erf	Error function	$\int_{-\infty}^{\mathbf{y}_i \mathbf{f}_i} \mathcal{N}(t) dt$	\emptyset
Logistic	Logistic function	$\frac{1}{1 + \exp(-\mathbf{y}_i \mathbf{f}_i)}$	\emptyset
Uni	Label noise	$\frac{1}{2}$	\emptyset
lik<NAME>	count data $\mathbf{y}_i \in \mathbb{N}$	$\mathbf{p}_{\boldsymbol{\rho}}(\mathbf{y}_i \mathbf{f}_i) =$	$\boldsymbol{\rho} =$
Poisson	Poisson	$\mu^{\mathbf{y}} \cdot \frac{e^{-\mu}}{\mathbf{y}_i!}, \mu = e^{\mathbf{f}} \text{ or } \mu = \log(1 + e^{\mathbf{f}})$	\emptyset
lik<NAME>	nonnegative data $\mathbf{y}_i \in \mathbb{R}_+ \setminus \{0\}$	$\mathbf{p}_{\boldsymbol{\rho}}(\mathbf{y}_i \mathbf{f}_i) =$	$\boldsymbol{\rho} =$
Weibull	Weibull, $\gamma_1 = \Gamma(1 + 1/\kappa)$	$\kappa \gamma_1 / \mu (\mathbf{y}_1 / \mu)^{\kappa-1} \exp(-(\mathbf{y}_1 / \mu)^{\kappa})$	$\{\ln \kappa\}$
Gamma	Gamma	$\frac{\alpha^{\mathbf{y}} \mathbf{y}^{\alpha-1}}{\Gamma(\alpha)} \mu^{-\alpha} \exp\left(-\frac{\mathbf{y}\alpha}{\mu}\right)$	$\{\ln \alpha\}$
Exp	Exponential	$\mu^{-1} \exp\left(-\frac{\mathbf{y}}{\mu}\right)$	\emptyset
InvGauss	Inverse Gaussian	$\sqrt{\frac{\lambda}{2\pi \mathbf{y}^3}} \exp\left(-\frac{\lambda(\mathbf{y}-\mu)^2}{2\mu^2 \mathbf{y}}\right)$	$\{\ln \lambda\}$
lik<NAME>	interval data $\mathbf{y}_i \in [0, 1]$	$\mathbf{p}_{\boldsymbol{\rho}}(\mathbf{y}_i \mathbf{f}_i) =$	$\boldsymbol{\rho} =$
Beta	Beta	$\frac{\Gamma(\Phi)}{\Gamma(\mu\Phi)\Gamma((1-\mu)\Phi)} \mathbf{y}^{\mu\Phi-1} (1-\mathbf{y})^{(1-\mu)\Phi-1}$	$\{\ln \Phi\}$
Composite likelihood functions $[\mathbf{p}_1(\mathbf{y}_i \mathbf{f}_i), \mathbf{p}_1(\mathbf{y}_i \mathbf{f}_i), \dots] \mapsto \mathbf{p}_{\boldsymbol{\rho}}(\mathbf{y}_i \mathbf{f}_i)$			
Mix	Mixture	$\sum_j \alpha_j \mathbf{p}_j(\mathbf{y}_i \mathbf{f}_i)$	$\{\ln \alpha_1, \ln \alpha_2, \dots\}$

4.4 Usage of Implemented Likelihood Functions

Some code examples taken from `doc/usageLik.m` illustrate how to use simple and composite likelihood functions to specify a GP model.

Syntactically, a likelihood function `lk` is defined by

```
lk := 'func' | @func // simple
```

```
lk := {lk} | {param, lk} | {lk, {lk, ..., lk}} // composite
```

i.e., it is either a string containing the name of a likelihood function, a pointer to a likelihood function or one of the former in combination with a cell array of likelihood functions and an additional list of parameters.

```
21 <doc/usageLik.m 21>≡
1 % demonstrate usage of likelihood functions
2 %
3 % See also likFunctions.m.
4 %
5 <gpml copyright 6a>
6 clear all, close all
7 n = 5; f = randn(n,1);          % create random latent function values
8
9 % set up simple classification likelihood functions
10 yc = sign(f);
11 lc0 = {'likErf'};      hypc0 = [];    % no hyperparameters are needed
12 lc1 = {@likLogistic}; hypc1 = [];    % also function handles are OK
13 lc2 = {'likUni'};      hypc2 = [];
14 lc3 = {'likMix','likUni',@likErf}; hypc3 = log([1;2]); %mixture
15
16 % set up simple regression likelihood functions
17 yr = f + randn(n,1)/20;
18 sn = 0.1;                % noise standard deviation
19 lr0 = {'likGauss'};      hypr0 = log(sn);
20 lr1 = {'likLaplace'};   hypr1 = log(sn);
21 lr2 = {'likSech2'};     hypr2 = log(sn);
22 nu = 4;                  % number of degrees of freedom
23 lr3 = {'likT'};         hypr3 = [log(nu-1); log(sn)];
24 lr4 = {'likMix',{lr0,lr1}}; hypr4 = [log([1;2]);hypr0;hypr1];
25
26 a = 1; % set up warped Gaussian with g(y) = y + a*sign(y).*y.^2
27 lr5 = {'likGaussWarp','poly2'}; hypr5 = log([a;sn]);
28 lr6 = {'likGumbel','+'}; hypr6 = log(sn);
29
30 % set up Poisson regression
31 yp = fix(abs(f)) + 1;
32 lp0 = {@likPoisson,'logistic'}; hypp0 = [];
33 lp1 = {@likPoisson,'exp'};      hypp1 = [];
34
35 % set up other GLM likelihoods for positive or interval regression
36 lg1 = {@likGamma,'logistic'}; al = 2;    hyp.lik = log(al);
37 lg2 = {@likInvGauss,'exp'};   lam = 1.1; hyp.lik = log(lam);
38 lg3 = {@likBeta,'expexp'};    phi = 2.1; hyp.lik = log(phi);
39 lg4 = {@likBeta,'logit'};     phi = 4.7; hyp.lik = log(phi);
40
41 % 0) specify the likelihood function
42 lik = lc0; hyp = hypc0; y = yc;
43 % lik = lr4; hyp = hypr4; y = yr;
44 % lik = lp1; hyp = hypp1; y = yp;
```

```

45
46 % 1) query the number of parameters
47 feval(lik{:})
48
49 % 2) evaluate the likelihood function on f
50 exp(feval(lik{:},hyp,y,f))
51
52 % 3a) evaluate derivatives of the likelihood
53 [lp,dlp,d2lp,d3lp] = feval(lik{:}, hyp, y, f, [], 'infLaplace');
54
55 % 3b) compute Gaussian integrals w.r.t. likelihood
56 mu = f; s2 = rand(n,1);
57 [lZ,d1Z,d2lZ] = feval(lik{:}, hyp, y, mu, s2, 'infEP');
58
59 % 3c) obtain lower bound on likelihood
60 ga = rand(n,1);
61 [b,z] = feval(lik{:}, hyp, y, [], ga, 'infVB');

```

4.5 Compatibility Between Likelihoods and Inference Methods

The following table lists all possible combinations of likelihood function and inference methods.

Likelihood \ Inference	Exact	EP	Laplace	VB	KL	MCMC	LOO	Type, Output Domain	Alternative Names
	FITC	FITC-EP	FITC-Laplace						
Gaussian	✓	✓	✓	✓	✓	✓	✓	regression, \mathbb{R}	
Warped Gaussian		✓	✓	✓	✓	✓	✓	regression, \mathbb{R}	
Gumbel			✓		✓	✓	✓	regression, \mathbb{R}	
Sech-squared		✓	✓	✓	✓	✓	✓	regression, \mathbb{R}	logistic distribution
Laplacian		✓	✓	✓	✓	✓	✓	regression, \mathbb{R}	double exponential
Student's t			✓	✓	✓	✓	✓	regression, \mathbb{R}	
Mixture		✓	✓		✓	✓	✓		mixing meta likelihood
Error function		✓	✓		✓	✓	✓	classification, $\{\pm 1\}$	probit regression
Logistic function		✓	✓	✓	✓	✓	✓	classification, $\{\pm 1\}$	logit regression
Uniform		✓	✓	✓	✓	✓	✓	classification, $\{\pm 1\}$	label noise
Weibull			✓			✓	✓	positive data, $\mathbb{R}_+ \setminus \{0\}$	nonnegative regression
Gamma			✓			✓	✓	positive data, $\mathbb{R}_+ \setminus \{0\}$	nonnegative regression
Exp			✓			✓	✓	positive data, $\mathbb{R}_+ \setminus \{0\}$	nonnegative regression
Inverse Gaussian			✓			✓	✓	positive data, $\mathbb{R}_+ \setminus \{0\}$	nonnegative regression
Poisson		(✓)*	✓		✓	✓	✓	count data, \mathbb{N}	Poisson regression
Beta			✓			✓	✓	interval data, $[0, 1]$	beta regression

(✓)* EP might not converge in some cases since quadrature is used.

Exact inference is only tractable for Gaussian likelihoods. Expectation propagation together with Student's t likelihood is inherently unstable due to non-log-concavity. Laplace's approximation for Laplace likelihoods is not sensible because at the mode the curvature and the gradient is undefined due to the non-differentiable peak of the Laplace distribution. Special care has been taken for the non-convex optimisation problem imposed by the combination Student's t likelihood and Laplace's approximation.

4.6 Gaussian Likelihood

The Gaussian likelihood is the simplest likelihood because the posterior distribution is not only Gaussian but can be computed analytically. In principle, the Gaussian likelihood would only be operated in conjunction with the exact inference method but we chose to provide compatibility with all other inference algorithms as well because it enables code testing and allows to switch between

different regression likelihoods very easily.

```

23a <lik/likGauss.m 23a>≡
1 function [varargout] = likGauss(hyp, y, mu, s2, inf, i)
2
3 % likGauss - Gaussian likelihood function for regression. The expression for the
4 % likelihood is
5 %   likGauss(t) = exp(-(t-y)^2/2*sn^2) / sqrt(2*pi*sn^2),
6 % where y is the mean and sn is the standard deviation.
7 %
8 % The hyperparameters are:
9 %
10 % hyp = [ log(sn) ]
11 %
12 % Several modes are provided, for computing likelihoods, derivatives and moments
13 % respectively, see likFunctions.m for the details. In general, care is taken
14 % to avoid numerical issues when the arguments are extreme.
15 %
16 <gpml copyright 6a>
17 %
18 % See also LIKFUNCTIONS.M.
19
20 if nargin<3, varargout = {'1'}; return; end % report number of hyperparameters
21
22 sn2 = exp(2*hyp);
23
24 if nargin<5 % prediction mode if inf is not present
25   <Prediction with Gaussian likelihood 23b>
26 else
27   switch inf
28     case 'infLaplace'
29       <Laplace's method with Gaussian likelihood 24a>
30     case 'infEP'
31       <EP inference with Gaussian likelihood 24b>
32     case 'infVB'
33       <Variational Bayes inference with Gaussian likelihood 24c>
34   end
35 end
23b <Prediction with Gaussian likelihood 23b>≡ (23a)
1 if isempty(y), y = zeros(size(mu)); end
2 s2zero = 1; if nargin>3&&numel(s2)>0&&norm(s2)>eps, s2zero = 0; end % s2==0 ?
3 if s2zero % log probability
4   lp = -(y-mu).^2./sn2/2-log(2*pi*sn2)/2; s2 = 0;
5 else
6   lp = likGauss(hyp, y, mu, s2, 'infEP'); % prediction
7 end
8 ymu = {}; ys2 = {};
9 if nargin>1
10   ymu = mu; % first y moment
11   if nargin>2
12     ys2 = s2 + sn2; % second y moment
13   end
14 end
15 varargout = {lp,ymu,ys2};

```

The Gaussian likelihood function has a single hyperparameter ρ , the log of the noise standard deviation σ_n .

4.6.1 Exact Inference

Exact inference doesn't require any specific likelihood related code; all computations are done directly by the inference method, section 3.1.

4.6.2 Laplace's Approximation

24a (Laplace's method with Gaussian likelihood 24a)≡ (23a)

```

1 if nargin<6 % no derivative mode
2   if isempty(y), y=0; end
3   ymmu = y-mu; dlp = {}; d2lp = {}; d3lp = {};
4   lp = -ymmu.^2/(2*sn2) - log(2*pi*sn2)/2;
5   if nargin>1
6     dlp = ymmu/sn2; % dlp, derivative of log likelihood
7     if nargin>2 % d2lp, 2nd derivative of log likelihood
8       d2lp = -ones(size(ymmu))/sn2;
9       if nargin>3 % d3lp, 3rd derivative of log likelihood
10        d3lp = zeros(size(ymmu));
11      end
12    end
13  end
14  varargout = {lp,dlp,d2lp,d3lp};
15 else % derivative mode
16   lp_dhyp = (y-mu).^2/sn2 - 1; % derivative of log likelihood w.r.t. hypers
17   dlp_dhyp = 2*(mu-y)/sn2; % first derivative,
18   d2lp_dhyp = 2*ones(size(mu))/sn2; % and also of the second mu derivative
19   varargout = {lp_dhyp,dlp_dhyp,d2lp_dhyp};
20 end

```

4.6.3 Expectation Propagation

24b (EP inference with Gaussian likelihood 24b)≡ (23a)

```

1 if nargin<6 % no derivative mode
2   lZ = -(y-mu).^2/(sn2+s2)/2 - log(2*pi*(sn2+s2))/2; % log part function
3   d1Z = {}; d21Z = {};
4   if nargin>1
5     d1Z = (y-mu)./(sn2+s2); % 1st derivative w.r.t. mean
6     if nargin>2
7       d21Z = -1./(sn2+s2); % 2nd derivative w.r.t. mean
8     end
9   end
10  varargout = {lZ,d1Z,d21Z};
11 else % derivative mode
12   d1Zhyp = ((y-mu).^2/(sn2+s2)-1) ./ (1+s2./sn2); % deriv. w.r.t. hyp.lik
13   varargout = {d1Zhyp};
14 end

```

4.6.4 Variational Bayes

24c (Variational Bayes inference with Gaussian likelihood 24c)≡ (23a)

```

1 % variational lower site bound
2 % t(s) = exp(-(y-s)^2/2sn2)/sqrt(2*pi*sn2)
3 % the bound has the form: (b+z/ga)*f - f.^2/(2*ga) - h(ga)/2
4 n = numel(s2); b = zeros(n,1); y = y.*ones(n,1); z = y;
5 varargout = {b,z};

```

4.7 Warped Gaussian Likelihood

Starting from the likelihood $\mathbf{p}(\mathbf{y}|\mathbf{f})$ we are sometimes facing the situation where the data $\mathbf{y} \in \mathcal{Y} \subseteq \mathbb{R}$ is not distributed according to $\mathbf{p}(\mathbf{y}|\mathbf{f})$ but some nonlinear transformation of the data $\mathbf{g}(\mathbf{y}) = \mathbf{z}$ so that $\mathbf{z} \sim \mathbf{p}(\mathbf{z}|\mathbf{f})$. Here, the warping function $\mathbf{g} : \mathcal{Y} \rightarrow \mathbb{R}$ needs to be strictly monotonically increasing i.e. $\mathbf{g}'(\mathbf{y}) > 0$. Formally, we start from the fact that $\mathbf{p}(\mathbf{z}|\mathbf{f})$ integrates to one and use the derivative $d\mathbf{z} = \mathbf{g}'(\mathbf{y})d\mathbf{y}$ to substitute

$$\int \mathbf{p}(\mathbf{z}|\mathbf{f})d\mathbf{z} = 1 = \int \mathbf{p}_g(\mathbf{y}|\mathbf{f})d\mathbf{y}, \quad \mathbf{p}_g(\mathbf{y}|\mathbf{f}) = \mathbf{p}(\mathbf{g}(\mathbf{y})|\mathbf{f})\mathbf{g}'(\mathbf{y})$$

where we have defined the log warped likelihood $\ln \mathbf{p}_g(\mathbf{y}|\mathbf{f}) = \ln \mathbf{p}(\mathbf{g}(\mathbf{y})|\mathbf{f}) + \ln \mathbf{g}'(\mathbf{y})$. The interesting bit is that approximate inference methods such as `infExact`, `infLaplace`, `infEP`, `infVB`, `infKL` remain fully feasible; only prediction and derivatives become more involved. The usual GP inference is recovered by using the identity warping function $\mathbf{g} : \mathcal{Y} \mapsto \mathcal{Y}$. The construction works in principle for any likelihood but our implementation in `likGaussWarp` is limited to the Gaussian likelihood.

Hyperparameter derivatives

Hyperparameter derivatives for `infLaplace` are obtained as follows

$$\begin{aligned} \frac{\partial}{\partial \theta} \ln \frac{\partial^k}{\partial \mathbf{f}^k} \mathbf{p}_g(\mathbf{y}|\mathbf{f}) &= \frac{\partial}{\partial \theta} \ln \frac{\partial^k}{\partial \mathbf{f}^k} \mathbf{p}(\mathbf{g}(\mathbf{y})|\mathbf{f}) + \frac{\partial}{\partial \theta} \frac{\partial^k}{\partial \mathbf{f}^k} \ln \mathbf{g}'(\mathbf{y}), \quad k = 0, 1, 2 \\ &= -\frac{\partial^{k+1}}{\partial \mathbf{f}^{k+1}} \ln \mathbf{p}(\mathbf{g}(\mathbf{y})|\mathbf{f}) \frac{\partial}{\partial \theta} \mathbf{g}(\mathbf{y}) + \frac{\partial}{\partial \theta} \frac{\partial^k}{\partial \mathbf{f}^k} \ln \mathbf{g}'(\mathbf{y}). \end{aligned}$$

Similarly for `infEP` the derivatives are given by

$$\begin{aligned} \frac{\partial}{\partial \theta} \ln \int \mathbf{p}_g(\mathbf{y}|\mathbf{f}) \mathcal{N}(\mathbf{f}|\boldsymbol{\mu}, \sigma^2) d\mathbf{f} &= \frac{\partial}{\partial \theta} \ln \int \mathbf{p}(\mathbf{g}(\mathbf{y})|\mathbf{f}) \mathcal{N}(\mathbf{f}|\boldsymbol{\mu}, \sigma^2) d\mathbf{f} + \frac{\partial}{\partial \theta} \ln \mathbf{g}'(\mathbf{y}) \\ &= -\frac{\partial}{\partial \boldsymbol{\mu}} \ln \int \mathbf{p}(\mathbf{g}(\mathbf{y})|\mathbf{f}) \mathcal{N}(\mathbf{f}|\boldsymbol{\mu}, \sigma^2) d\mathbf{f} \frac{\partial}{\partial \theta} \mathbf{g}(\mathbf{y}) + \frac{\partial}{\partial \theta} \ln \mathbf{g}'(\mathbf{y}). \end{aligned}$$

This trick above works for any homoscedastic likelihood where $\mathbf{p}(\mathbf{y}|\mathbf{f}) = \mathbf{p}(\mathbf{y} + \boldsymbol{\beta}|\mathbf{f} + \boldsymbol{\beta})$ such as `likGauss`, `likLaplace`, `likSech2` and `likT`.

Predictive moments

As detailed in 4, the predictive distribution is – for Gaussian likelihood – given by

$$\begin{aligned} \mathbf{p}(\mathbf{z}_*|\mathcal{D}, \mathbf{x}_*) &= \int \mathbf{p}(\mathbf{z}_*|\mathbf{f}_*) \mathbf{p}(\mathbf{f}_*|\mathcal{D}, \mathbf{x}_*) d\mathbf{f}_* = \int \mathcal{N}(\mathbf{z}_*|\mathbf{f}_*, \sigma_n^2) \mathcal{N}(\mathbf{f}_*|\boldsymbol{\mu}_{f_*}, \sigma_{f_*}^2) d\mathbf{f}_* \\ &= \mathcal{N}(\mathbf{z}_*|\boldsymbol{\mu}_{f_*}, \sigma_n^2 + \sigma_{f_*}^2), \quad \text{where } \mathbf{z}_* = \mathbf{g}(\mathbf{y}_*) \\ \mathbf{p}(\mathbf{y}_*|\mathcal{D}, \mathbf{x}_*) &= \mathbf{g}'(\mathbf{y}_*) \mathcal{N}(\mathbf{g}(\mathbf{y}_*)|\boldsymbol{\mu}_{f_*}, \sigma_n^2 + \sigma_{f_*}^2). \end{aligned}$$

Hence, the predictive moments are obtained by the 1d integrals

$$\begin{aligned} \boldsymbol{\mu}_{\mathbf{y}_*} &= \int \mathbf{y}_* \mathbf{g}'(\mathbf{y}_*) \mathcal{N}(\mathbf{g}(\mathbf{y}_*)|\boldsymbol{\mu}_{f_*}, \sigma_n^2 + \sigma_{f_*}^2) d\mathbf{y}_* \\ &= \int \mathbf{g}^{-1}(\mathbf{z}_*) \mathcal{N}(\mathbf{z}_*|\boldsymbol{\mu}_{f_*}, \sigma_n^2 + \sigma_{f_*}^2) d\mathbf{z}_*, \quad \text{and} \\ \sigma_{\mathbf{y}_*}^2 &= \int (\mathbf{y}_* - \boldsymbol{\mu}_{\mathbf{y}_*})^2 \mathbf{g}'(\mathbf{y}_*) \mathcal{N}(\mathbf{g}(\mathbf{y}_*)|\boldsymbol{\mu}_{f_*}, \sigma_n^2 + \sigma_{f_*}^2) d\mathbf{y}_* \\ &= \int (\mathbf{g}^{-1}(\mathbf{z}_*) - \boldsymbol{\mu}_{\mathbf{y}_*})^2 \mathcal{N}(\mathbf{z}_*|\boldsymbol{\mu}_{f_*}, \sigma_n^2 + \sigma_{f_*}^2) d\mathbf{z}_*. \end{aligned}$$

4.8 Gumbel Likelihood

Distributions of extrema are well captured by the Gumbel distribution

$$p(y) = \frac{1}{\beta} \exp(-z - e^{-z}), \quad z = s \frac{y - \eta}{\beta}, \quad s \in \{\pm 1\}$$

with mean $\mu = \eta + \beta\gamma$ and variance $\sigma^2 = \pi^2\beta^2/6$ where $\gamma = 0.57721566490153$ denotes Euler–Mascheroni’s constant. Skewness is approximately given by $1.1395s$ where s is a sign switching between left and right skewness and kurtosis is $12/5$. The final expression for the Gumbel likelihood is

$$p(y|f) = \frac{\pi}{\sigma\sqrt{6}} \exp(-z - e^{-z}), \quad z = \gamma + s \frac{\pi}{\sigma\sqrt{6}}(y - f), \quad s \in \{\pm 1\}.$$

4.9 Laplace Likelihood

Laplace’s Approximation

The following derivatives are needed:

$$\begin{aligned} \ln p(y|f) &= -\ln(2b) - \frac{|f - y|}{b} \\ \frac{\partial \ln p}{\partial f} &= \frac{\text{sign}(f - y)}{b} \\ \frac{\partial^2 \ln p}{(\partial f)^2} &= \frac{\partial^3 \ln p}{(\partial f)^3} = \frac{\partial^3 \ln p}{(\partial \ln \sigma_n)(\partial f)^2} = 0 \\ \frac{\partial \ln p}{\partial \ln \sigma_n} &= \frac{|f - y|}{b} - 1 \end{aligned}$$

Expectation Propagation

Expectation propagation requires integration against a Gaussian measure for moment matching.

We need to evaluate $\ln Z = \ln \int \mathcal{L}(y|f, \sigma_n^2) \mathcal{N}(f|\mu, \sigma^2) df$ as well as the derivatives $\frac{\partial \ln Z}{\partial \mu}$ and $\frac{\partial^2 \ln Z}{\partial \mu^2}$ where $\mathcal{N}(f|\mu, \sigma^2) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(f-\mu)^2}{2\sigma^2}\right)$, $\mathcal{L}(y|f, \sigma_n^2) = \frac{1}{2b} \exp\left(-\frac{|y-f|}{b}\right)$, and $b = \frac{\sigma_n}{\sqrt{2}}$. As a first step, we reduce the number of parameters by means of the substitution $\tilde{f} = \frac{f-y}{\sigma_n}$ yielding

$$\begin{aligned} Z &= \int \mathcal{L}(y|f, \sigma_n^2) \mathcal{N}(f|\mu, \sigma^2) df \\ &= \frac{1}{\sqrt{2\pi\sigma}} \frac{\sqrt{2}}{2\sigma_n} \int \exp\left(-\frac{(f-\mu)^2}{2\sigma^2}\right) \exp\left(-\sqrt{2} \frac{|f-y|}{\sigma_n}\right) df \\ &= \frac{\sqrt{2}}{2\sigma\sqrt{2\pi}} \int \exp\left(-\frac{(\sigma_n \tilde{f} + y - \mu)^2}{2\sigma^2}\right) \exp\left(-\sqrt{2} |\tilde{f}|\right) d\tilde{f} \\ &= \frac{\sigma_n}{\sigma\sigma_n\sqrt{2\pi}} \int \exp\left(-\frac{\sigma_n^2 \left(\tilde{f} - \frac{\mu-y}{\sigma_n}\right)^2}{2\sigma^2}\right) \mathcal{L}(\tilde{f}|0, 1) d\tilde{f} \\ &= \frac{1}{\sigma_n} \int \mathcal{L}(f|0, 1) \mathcal{N}(f|\tilde{\mu}, \tilde{\sigma}^2) df \\ \ln Z &= \ln \tilde{Z} - \ln \sigma_n = \ln \int \mathcal{L}(f|0, 1) \mathcal{N}(f|\tilde{\mu}, \tilde{\sigma}^2) df - \ln \sigma_n \end{aligned}$$

with $\tilde{\mu} = \frac{\mu - \mathbf{y}}{\sigma_n}$ and $\tilde{\sigma} = \frac{\sigma}{\sigma_n}$. Thus, we concentrate on the simpler quantity $\ln \tilde{Z}$.

$$\begin{aligned}
\ln Z &= \ln \int \exp \left(-\frac{(f - \tilde{\mu})^2}{2\tilde{\sigma}^2} - \sqrt{2}|f| \right) df - \overbrace{\ln \tilde{\sigma} \sqrt{2\pi} - \ln \sqrt{2}\sigma_n}^C \\
&= \ln \left[\int_{-\infty}^0 \exp \left(-\frac{(f - \tilde{\mu})^2}{2\tilde{\sigma}^2} + \sqrt{2}f \right) df + \int_0^{\infty} \exp \left(-\frac{(f - \tilde{\mu})^2}{2\tilde{\sigma}^2} - \sqrt{2}f \right) df \right] + C \\
&= \ln \left[\int_{-\infty}^0 \exp \left(-\frac{f^2 - 2(\overbrace{\tilde{\mu} + \tilde{\sigma}^2 \sqrt{2}}^{m_-})f + \tilde{\mu}^2}{2\tilde{\sigma}^2} \right) df + \int_0^{\infty} \exp \left(-\frac{f^2 - 2(\overbrace{\tilde{\mu} - \tilde{\sigma}^2 \sqrt{2}}^{m_+})f + \tilde{\mu}^2}{2\tilde{\sigma}^2} \right) df \right] + C \\
&= \ln \left[\exp \left(\frac{m_-^2}{2\tilde{\sigma}^2} \right) \int_{-\infty}^0 \exp \left(-\frac{(f - m_-)^2}{2\tilde{\sigma}^2} \right) df + \exp \left(\frac{m_+^2}{2\tilde{\sigma}^2} \right) \int_0^{\infty} \exp \left(-\frac{(f - m_+)^2}{2\tilde{\sigma}^2} \right) df \right] - \frac{\tilde{\mu}^2}{2\tilde{\sigma}^2} + C \\
&= \ln \left[\exp \left(\frac{m_-^2}{2\tilde{\sigma}^2} \right) \int_{-\infty}^0 \mathcal{N}(f|m_-, \tilde{\sigma}^2) df + \exp \left(\frac{m_+^2}{2\tilde{\sigma}^2} \right) \left(1 - \int_{-\infty}^0 \mathcal{N}(f|m_+, \tilde{\sigma}^2) df \right) \right] - \frac{\tilde{\mu}^2}{2\tilde{\sigma}^2} - \ln \sqrt{2}\sigma_n \\
&= \ln \left[\exp \left(\frac{m_-^2}{2\tilde{\sigma}^2} \right) \Phi \left(\frac{m_-}{\tilde{\sigma}} \right) - \exp \left(\frac{m_+^2}{2\tilde{\sigma}^2} \right) \Phi \left(\frac{m_+}{\tilde{\sigma}} \right) + \exp \left(\frac{m_+^2}{2\tilde{\sigma}^2} \right) \right] - \frac{\tilde{\mu}^2}{2\tilde{\sigma}^2} - \ln \sqrt{2}\sigma_n
\end{aligned}$$

Here, $\Phi(z) = \int_{-\infty}^z \mathcal{N}(f|0, 1) df$ denotes the cumulative Gaussian distribution. Finally, we have

$$\begin{aligned}
\ln Z &= \ln \left[\exp \left(-\sqrt{2}\tilde{\mu} \right) \Phi \left(\frac{m_-}{\tilde{\sigma}} \right) + \exp \left(\sqrt{2}\tilde{\mu} \right) \Phi \left(-\frac{m_+}{\tilde{\sigma}} \right) \right] + \tilde{\sigma}^2 - \ln \sqrt{2}\sigma_n \\
&= \ln \left[\exp \left(\underbrace{\ln \Phi(-z_+) + \sqrt{2}\tilde{\mu}}_{a_+} \right) + \exp \left(\underbrace{\ln \Phi(z_-) - \sqrt{2}\tilde{\mu}}_{a_-} \right) \right] + \tilde{\sigma}^2 - \ln \sqrt{2}\sigma_n \\
&= \ln(e^{a_+} + e^{a_-}) + \tilde{\sigma}^2 - \ln \sqrt{2}\sigma_n
\end{aligned}$$

where $z_+ = \frac{\tilde{\mu}}{\tilde{\sigma}} + \tilde{\sigma}\sqrt{2} = \frac{\mu - \mathbf{y}}{\sigma} + \frac{\sigma}{\sigma_n}\sqrt{2}$, $z_- = \frac{\tilde{\mu}}{\tilde{\sigma}} - \tilde{\sigma}\sqrt{2} = \frac{\mu - \mathbf{y}}{\sigma} - \frac{\sigma}{\sigma_n}\sqrt{2}$ and $\tilde{\mu} = \frac{\mu - \mathbf{y}}{\sigma_n}$, $\tilde{\sigma} = \frac{\sigma}{\sigma_n}$.

Now, using $\frac{d}{d\theta} \ln \Phi(z) = \frac{1}{\Phi(z)} \frac{d}{d\theta} \Phi(z) = \frac{\mathcal{N}(z)}{\Phi(z)} \frac{dz}{d\theta}$ we tackle first derivative

$$\begin{aligned}
\frac{\partial \ln Z}{\partial \mu} &= \frac{e^{a_+} \frac{\partial a_+}{\partial \mu} + e^{a_-} \frac{\partial a_-}{\partial \mu}}{e^{a_+} + e^{a_-}} \\
\frac{\partial a_+}{\partial \mu} &= \frac{\partial}{\partial \mu} \ln \Phi(-z_+) + \frac{\sqrt{2}}{\sigma_n} \\
&= -\frac{\mathcal{N}(-z_+)}{\sigma \Phi(-z_+)} + \frac{\sqrt{2}}{\sigma_n} = -\frac{q_+}{\sigma} + \frac{\sqrt{2}}{\sigma_n} \\
\frac{\partial a_-}{\partial \mu} &= \frac{\partial}{\partial \mu} \ln \Phi(z_-) - \frac{\sqrt{2}}{\sigma_n} \\
&= \frac{\mathcal{N}(z_-)}{\sigma \Phi(z_-)} - \frac{\sqrt{2}}{\sigma_n} = \frac{q_-}{\sigma} - \frac{\sqrt{2}}{\sigma_n} \\
\frac{\partial a_{\pm}}{\partial \mu} &= \mp \frac{q_{\pm}}{\sigma} \pm \frac{\sqrt{2}}{\sigma_n}.
\end{aligned}$$

as well as the second derivative

$$\begin{aligned}
\frac{\partial^2 \ln Z}{\partial \mu^2} &= \frac{\frac{\partial}{\partial \mu} \left(e^{a_+} \frac{\partial a_+}{\partial \mu} \right) + \frac{\partial}{\partial \mu} \left(e^{a_-} \frac{\partial a_-}{\partial \mu} \right)}{e^{a_+} + e^{a_-}} - \left(\frac{\partial \ln Z}{\partial \mu} \right)^2 \\
\frac{\partial}{\partial \mu} \left(e^{a_{\pm}} \frac{\partial a_{\pm}}{\partial \mu} \right) &= e^{a_{\pm}} \left[\left(\frac{\partial a_{\pm}}{\partial \mu} \right)^2 + \frac{\partial^2 a_{\pm}}{\partial \mu^2} \right] \\
\frac{\partial^2 a_+}{\partial \mu^2} &= -\frac{1}{\sigma} \frac{\frac{\partial}{\partial \mu} \mathcal{N}(-z_+) \Phi(-z_+) - \frac{\partial}{\partial \mu} \Phi(-z_+) \mathcal{N}(-z_+)}{\Phi^2(-z_+)} \\
&= -\frac{1}{\sigma} \frac{\mathcal{N}(-z_+) \Phi(-z_+) \frac{\partial -z_+/2}{\partial \mu} - \mathcal{N}^2(-z_+) \frac{\partial -z_+}{\partial \mu}}{\Phi^2(-z_+)} \\
&= \frac{\mathcal{N}(-z_+)}{\sigma^2} \cdot \frac{\Phi(-z_+) z_+ - \mathcal{N}(-z_+)}{\Phi^2(-z_+)} = -\frac{q_+^2 - q_+ z_+}{\sigma^2} \\
\frac{\partial^2 a_-}{\partial \mu^2} &= \frac{1}{\sigma} \frac{\frac{\partial}{\partial \mu} \mathcal{N}(z_-) \Phi(z_-) - \frac{\partial}{\partial \mu} \Phi(z_-) \mathcal{N}(z_-)}{\Phi^2(z_-)} \\
&= \frac{1}{\sigma} \frac{\mathcal{N}(z_-) \Phi(z_-) \frac{\partial -z_-/2}{\partial \mu} - \mathcal{N}^2(z_-) \frac{\partial z_-}{\partial \mu}}{\Phi^2(z_-)} \\
&= \frac{\mathcal{N}(z_-)}{\sigma^2} \cdot \frac{-\Phi(z_-) z_- - \mathcal{N}(z_-)}{\Phi^2(z_-)} = -\frac{q_-^2 + q_- z_-}{\sigma^2} \\
\frac{\partial^2 a_{\pm}}{\partial \mu^2} &= -\frac{q_{\pm}^2 \mp q_{\pm} z_{\pm}}{\sigma^2}
\end{aligned}$$

which can be simplified to

$$\frac{\partial^2 \ln Z}{\partial \mu^2} = \frac{e^{a_+} b_+ + e^{a_-} b_-}{e^{a_+} + e^{a_-}} - \left(\frac{\partial \ln Z}{\partial \mu} \right)^2$$

using

$$\begin{aligned}
b_{\pm} = \left(\frac{\partial a_{\pm}}{\partial \mu} \right)^2 + \frac{\partial^2 a_{\pm}}{\partial \mu^2} &= \left(\mp \frac{q_{\pm}}{\sigma} \pm \frac{\sqrt{2}}{\sigma_n} \right)^2 - \frac{q_{\pm}^2 \mp q_{\pm} z_{\pm}}{\sigma^2} \\
&= \left(\frac{q_{\pm}}{\sigma} - \frac{\sqrt{2}}{\sigma_n} \right)^2 - \frac{q_{\pm}^2}{\sigma^2} \pm \frac{q_{\pm} z_{\pm}}{\sigma^2} \\
&= \frac{2}{\sigma_n^2} - \left(\frac{\sqrt{8}}{\sigma \sigma_n} \mp \frac{z_{\pm}}{\sigma^2} \right) q_{\pm}.
\end{aligned}$$

We also need

$$\frac{\partial \ln Z}{\partial \ln \sigma_n} = \frac{e^{a_+} \frac{\partial a_+}{\partial \ln \sigma_n} + e^{a_-} \frac{\partial a_-}{\partial \ln \sigma_n}}{e^{a_+} + e^{a_-}} - \frac{2\sigma^2}{\sigma_n^2} - 1.$$

Variational Bayes

We need $h(\gamma)$ and its derivatives as well as $\beta(\gamma)$:

$$\begin{aligned}
h(\gamma) &= \frac{2}{\sigma_n^2} \gamma + \ln(2\sigma_n^2) + y^2 \gamma^{-1} \\
h'(\gamma) &= \frac{2}{\sigma_n^2} - y^2 \gamma^{-2} \\
h''(\gamma) &= 2y^2 \gamma^{-3} \\
\beta(\gamma) &= y \gamma^{-1}
\end{aligned}$$

4.10 Student's t Likelihood

The likelihood has two hyperparameters (both represented in the log domain to ensure positivity): the degrees of freedom ν and the scale σ_n with mean y (for $\nu > 1$) and variance $\frac{\nu}{\nu-2} \sigma_n^2$ (for $\nu > 2$).

$$p(y|f) = Z \cdot \left(1 + \frac{(f-y)^2}{\nu \sigma_n^2}\right)^{-\frac{\nu+1}{2}}, \quad Z = \frac{\Gamma(\frac{\nu+1}{2})}{\Gamma(\frac{\nu}{2}) \sqrt{\nu \pi \sigma_n^2}}$$

Laplace's Approximation

For the mode fitting procedure, we need derivatives up to third order; the hyperparameter derivatives at the mode require some mixed derivatives. All in all, using $r = y - f$, we have

$$\begin{aligned}
\ln p(y|f) &= \ln \Gamma\left(\frac{\nu+1}{2}\right) - \ln \Gamma\left(\frac{\nu}{2}\right) - \frac{1}{2} \ln \nu \pi \sigma_n^2 - \frac{\nu+1}{2} \ln \left(1 + \frac{r^2}{\nu \sigma_n^2}\right) \\
\frac{\partial \ln p}{\partial f} &= (\nu+1) \frac{r}{r^2 + \nu \sigma_n^2} \\
\frac{\partial^2 \ln p}{(\partial f)^2} &= (\nu+1) \frac{r^2 - \nu \sigma_n^2}{(r^2 + \nu \sigma_n^2)^2} \\
\frac{\partial^3 \ln p}{(\partial f)^3} &= 2(\nu+1) \frac{r^3 - 3r\nu \sigma_n^2}{(r^2 + \nu \sigma_n^2)^3} \\
\frac{\partial \ln p}{\partial \ln \nu} &= \frac{\partial Z}{\partial \ln \nu} - \frac{\nu}{2} \ln \left(1 + \frac{r^2}{\nu \sigma_n^2}\right) + \frac{\nu+1}{2} \cdot \frac{r^2}{r^2 + \nu \sigma_n^2} \\
\frac{\partial Z}{\partial \ln \nu} &= \frac{\nu}{2} \frac{d \ln \Gamma(\frac{\nu+1}{2})}{d \ln \nu} - \frac{\nu}{2} \frac{d \ln \Gamma(\frac{\nu}{2})}{d \ln \nu} - \frac{1}{2} \\
\frac{\partial^3 \ln p}{(\partial \ln \nu)(\partial f)^2} &= \nu \frac{r^2(r^2 - 3(\nu+1)\sigma_n^2) + \nu \sigma_n^2}{(r^2 + \nu \sigma_n^2)^3} \\
\frac{\partial \ln p}{\partial \ln \sigma_n} &= (\nu+1) \frac{r^2}{r^2 + \nu \sigma_n^2} - 1 \\
\frac{\partial^3 \ln p}{(\partial \ln \sigma_n)(\partial f)^2} &= 2\nu \sigma_n^2 (\nu+1) \frac{\nu \sigma_n^2 - 3r^2}{(r^2 + \nu \sigma_n^2)^3}
\end{aligned}$$

4.11 Cumulative Logistic Likelihood

The likelihood has one hyperparameter (represented in the log domain), namely the standard deviation σ_n

$$p(y|f) = Z \cdot \cosh^{-2}(\tau(f-y)), \quad \tau = \frac{\pi}{2\sigma_n\sqrt{3}}, \quad Z = \frac{\pi}{4\sigma_n\sqrt{3}}$$

Laplace's Approximation

The following derivatives are needed where $\phi(x) \equiv \ln(\cosh(x))$

$$\begin{aligned}
\ln p(y|f) &= \ln(\pi) - \ln(4\sigma_n\sqrt{3}) - 2\phi(\tau(f-y)) \\
\frac{\partial \ln p}{\partial f} &= 2\tau\phi'(\tau(f-y)) \\
\frac{\partial^2 \ln p}{(\partial f)^2} &= -2\tau^2\phi''(\tau(f-y)) \\
\frac{\partial^3 \ln p}{(\partial f)^3} &= 2\tau^3\phi'''(\tau(f-y)) \\
\frac{\partial^3 \ln p}{(\partial \ln \sigma_n)(\partial f)^2} &= 2\tau^2(2\phi''(\tau(f-y)) + \tau(f-y)\phi'''(\tau(f-y))) \\
\frac{\partial \ln p}{\partial \ln \sigma_n} &= 2\tau(f-y)\phi'(\tau(f-y)) - 1
\end{aligned}$$

4.12 GLM Likelihoods: Poisson, Weibull, Gamma, Exponential, Inverse Gaussian and Beta

Data y from a space other than \mathbb{R} e.g. \mathbb{N} , \mathbb{R}_+ or $[0, 1]$ can be modeled using generalised linear model likelihoods $p(y|f)$ where the expected value $\mathbb{E}[y] = \mu$ is related to the underlying Gaussian process f by means of an inverse link function $\mu = g(f)$. Typically, the likelihoods are from an exponential family, hence the variance $\mathbb{V}[y] = v(\mu)$, is a simple function of the mean μ as well as higher order moments such as skewness $\mathbb{S}[y] = s(\mu)$ and kurtosis $\mathbb{K}[y] = k(\mu)$.

Here, we directly specify the inverse link function $\mu = g(f)$ defining the mapping from the GP f to the mean intensity μ . For numerical reasons, we work with the log of the inverse link function $h(f) = \ln g(f)$ and use its derivatives h' , h'' and h''' for subsequent computations. In the table below, we have summarised the GLM likelihood expressions, the moments, the range of their variables and the applicable inverse link functions.

Likelihood	$\rho =$	$v(\mu) =$	$s(\mu) =$	$k(\mu) =$	$p(y f) =$	$y \in$	$\mu \in$	Inverse Links
Poisson	\emptyset	μ	$1/\sqrt{\mu}$	$1/\mu$	$\mu^y \exp(-\mu)/y!$	\mathbb{N}	\mathbb{R}_+	exp, logistic
Weibull	$\{\ln \kappa\}$	$\mu^2(\gamma_2/\gamma_1^2 - 1)$	$\frac{\gamma_3 - 3\gamma_1\gamma_2 + 2\gamma_1^3}{(\gamma_2 - \gamma_1^2)^{3/2}}$	$\frac{\gamma_4 - 4\gamma_1\gamma_3 + 12\gamma_1^2\gamma_2 - 3\gamma_2^2 - 6\gamma_1^4}{(\gamma_2 - \gamma_1^2)^2}$	$\kappa\gamma_1/\mu (y\gamma_1/\mu)^{\kappa-1} \exp(-(y\gamma_1/\mu)^\kappa)$	$\mathbb{R}_+ \setminus \{0\}$	$\mathbb{R}_+ \setminus \{0\}$	exp, logistic
Gamma	$\{\ln \alpha\}$	μ^2/α	$2/\sqrt{\alpha}$	$6/\alpha$	$\frac{\alpha^y y^{\alpha-1}}{\Gamma(\alpha)} \mu^{-\alpha} \exp\left(-\frac{y\alpha}{\mu}\right)$	$\mathbb{R}_+ \setminus \{0\}$	$\mathbb{R}_+ \setminus \{0\}$	exp, logistic
Exponential	\emptyset	μ^2	2	6	$\mu^{-1} \exp\left(-\frac{y}{\mu}\right)$	$\mathbb{R}_+ \setminus \{0\}$	$\mathbb{R}_+ \setminus \{0\}$	exp, logistic
Inv. Gauss	$\{\ln \lambda\}$	μ^3/λ	$3\sqrt{\mu/\lambda}$	$15\mu/\lambda$	$\sqrt{\frac{\lambda}{2\pi y^3}} \exp\left(-\frac{\lambda(y-\mu)^2}{2\mu^3 y}\right)$	$\mathbb{R}_+ \setminus \{0\}$	$\mathbb{R}_+ \setminus \{0\}$	exp, logistic
Beta	$\{\ln \phi\}$	$\mu(1-\mu)/(1+\phi)$	$\frac{(2-4\mu)(1+\phi)}{\sqrt{v(\mu)(2+\phi)}}$	$6 \frac{(\phi+1)^2 - v(\mu)(5\phi+6)}{v(\mu)(\phi+2)(\phi+3)}$	$\frac{\Gamma(\phi)}{\Gamma(\mu\phi)\Gamma((1-\mu)\phi)} y^{\mu\phi-1} (1-y)^{(1-\mu)\phi-1}$	$[0, 1]$	$[0, 1]$	expexp, logit

4.12.1 Inverse Link Functions

Possible inverse link functions and their properties (\cup convex, \cap concave, \uparrow monotone) are summarised below:

util/glm_invlink_*	$g(f) = \mu =$	$g: \mathbb{R} \rightarrow$	g is	$h(f) = \ln \mu =$	h is
exp	e^f	\mathbb{R}_+	\cup, \uparrow	f	\cup, \cap, \uparrow
logistic	$\ln(1 + e^f)$	\mathbb{R}_+	\cup, \uparrow	$\ln(\ln(1 + e^f))$	\cap, \uparrow
expexp	$\exp(-e^{-f})$	$[0, 1]$	\uparrow	$-e^{-f}$	\cup, \uparrow
logit	$1/(1 + e^{-f})$	$[0, 1]$	\uparrow	$-\ln(1 + e^{-f})$	\cup, \uparrow

Exponential inverse link: **exp**

For $g(f) = e^f$ things are simple since $h(f) = f$, $h'(f) = 1$ and $h''(f) = h'''(f) = 0$.

Logistic inverse link: **logistic**

For $g(f) = \ln(1 + e^f)$ the derivatives of $h(f)$ are given by

$$\begin{aligned} h(f) &= \ln(\ln(1 + e^f)) \\ h'(f) &= \frac{1}{\ln(1 + e^f)} s(-f), \quad s(f) = \frac{1}{1 + e^f}, \quad s'(f) = \frac{-e^f}{(1 + e^f)^2} = -s(-f)s(f) \\ h''(f) &= \frac{1}{\ln(1 + e^f)} \frac{e^{-f}}{(1 + e^{-f})^2} - \frac{1}{\ln^2(1 + e^f)} \frac{e^f}{1 + e^f} \frac{1}{1 + e^{-f}} \\ &= h'(f) [s(f) - h'(f)] \\ h'''(f) &= h''(f) [s(f) - h'(f)] + h'(f) \left[\frac{-e^f}{(1 + e^f)^2} - h''(f) \right] \\ &= h''(f) [s(f) - 2h'(f)] - h'(f)s(f)s(-f). \end{aligned}$$

Note that $g(f) = e^{h(f)} = \ln(1 + e^f)$ is convex and $h(f) = \ln(\ln(1 + e^f))$ with

$$h''(f) = \frac{1}{\ln(1 + e^f)} \left(1 - \frac{e^f}{\ln(1 + e^f)} \right) \frac{1}{1 + e^f} \frac{1}{1 + e^{-f}} \leq 0$$

is concave since $e^f \geq \ln(1 + e^f)$ for all $f \in \mathbb{R}$.

Double negative exponential inverse link: **expexp**

For $g(f) = \exp(-e^{-f})$ the derivatives of $h(f)$ are given by

$$\begin{aligned} h(f) &= -e^{-f} \\ h'(f) &= -h(f) \\ h''(f) &= h(f) \\ h'''(f) &= -h(f) \end{aligned}$$

Logit regression inverse link: **logit**

For $g(f) = 1/(1 + e^{-f})$ the derivatives of $h(f)$ can be computed using the logistic inverse link function $h_\ell(f)$ since $h(f) = f - \exp(h_\ell(f))$

$$\begin{aligned} h(f) &= f - e^{h_\ell(f)} \\ h'(f) &= 1 - e^{h_\ell(f)} h'_\ell(f) \\ h''(f) &= -e^{h_\ell(f)} [h'_\ell(f)^2 + h''_\ell(f)] = e^{h_\ell(f)} s_\ell(-f) s_\ell^2(f) \\ h'''(f) &= -e^{h_\ell(f)} [h'_\ell(f)^3 + 3h''_\ell(f) h'_\ell(f) + h'''_\ell(f)] \end{aligned}$$

4.12.2 Poisson Likelihood

Count data $y \in \mathbb{N}$ can be modeled in the GP framework using the Poisson distribution $p(y) = \mu^y e^{-\mu} / y!$ with mean/variance $\mathbb{E}[y] = \mathbb{V}[y] = \mu$, skewness $\mathbb{S}[y] = 1/\sqrt{\mu}$ and kurtosis $\mathbb{K}[y] = 1/\mu$

leading to the likelihood

$$\begin{aligned} p(y|f) &= \mu^y \exp(-\mu)/y!, \mu = g(f) \\ \Leftrightarrow \ln p(y|f) &= y \cdot \ln g(f) - g(f) - \ln \Gamma(y+1). \end{aligned}$$

For Laplace's method to work, we need the first three derivatives of the log likelihood $\ln p(y|f)$, where $h(f) = \ln g(f)$

$$\begin{aligned} \ln p(y|f) &= y \cdot h(f) - \exp(h(f)) - \ln \Gamma(y+1) \\ \frac{\partial}{\partial f} \ln p(y|f) &= h'(f) [y - \exp(h(f))] \\ \frac{\partial^2}{\partial f^2} \ln p(y|f) &= h''(f) [y - \exp(h(f))] - [h'(f)]^2 \exp(h(f)) \\ \frac{\partial^3}{\partial f^3} \ln p(y|f) &= h'''(f) [y - \exp(h(f))] - 3h'(f) \cdot h''(f) \exp(h(f)) - [h'(f)]^3 \exp(h(f)) \\ &\quad h'''(f) [y - \exp(h(f))] - h'(f)[h'(f)^2 + 3h''(f)] \exp(h(f)). \end{aligned}$$

Note that if $\ln \mu = h(f)$ is concave and $\mu = g(f)$ is convex then the Poisson likelihood $p(y|f)$ is log-concave in f which is the case for both **exp** and **logistic**.

4.12.3 Weibull Likelihood

Nonnegative data $y \in \mathbb{R}_+$ such as time-to-failure can be modeled in the GP framework using the Weibull distribution $p(y) = \kappa/\lambda(y/\lambda)^{\kappa-1}e^{-(y/\lambda)^\kappa}$ with shape parameter $\kappa > 0$, scale parameter $\lambda > 0$, mean $\mathbb{E}[y] = \lambda\gamma_1 = \mu$ where $\gamma_j = \Gamma(1 + j/\kappa)$, variance $\mathbb{V}[y] = \lambda^2\gamma_2 - \mu^2 = \mu^2(\gamma_2/\gamma_1^2 - 1)$, skewness $\mathbb{S}[y] = (\gamma_3 - 3\gamma_1\gamma_2 + 2\gamma_1^3)/(\gamma_2 - \gamma_1^2)^{3/2}$ and kurtosis $\mathbb{K}[y] = (\gamma_4 - 4\gamma_1\gamma_3 + 12\gamma_1^2\gamma_2 - 3\gamma_2^2 - 6\gamma_1^4)/(\gamma_2 - \gamma_1^2)^2$. Using the substitution $\mu = \lambda\gamma_1 \Leftrightarrow 1/\lambda = \gamma_1/\mu$, we obtain

$$\begin{aligned} p(y|f) &= \gamma_1 \frac{\kappa}{\mu} \left(\gamma_1 \frac{y}{\mu} \right)^{\kappa-1} \exp \left(- \left(\gamma_1 \frac{y}{\mu} \right)^\kappa \right), \mu = g(f) > 0 \\ \Leftrightarrow \ln p(y|f) &= \ln \left(\gamma_1 \frac{\kappa}{\mu} \right) + (\kappa-1) \ln \left(\gamma_1 \frac{y}{\mu} \right) - \left(\gamma_1 \frac{y}{\mu} \right)^\kappa. \end{aligned}$$

Note that the Weibull likelihood $p(y|f)$ is log-concave in f neither for the **exp** nor for the **logistic** inverse link.

4.12.4 Gamma Likelihood

Nonnegative data $y \in \mathbb{R}_+$ can be modeled in the GP framework using the Gamma distribution $p(y) = \theta^{-\alpha}/\Gamma(\alpha)y^{\alpha-1}e^{-y/\theta}$ with shape parameter $\alpha > 0$, scale parameter $\theta > 0$, mean $\mathbb{E}[y] = \alpha\theta = \mu$, variance $\mathbb{V}[y] = \alpha\theta^2 = \mu^2/\alpha$, skewness $\mathbb{S}[y] = 2/\sqrt{\alpha}$ and kurtosis $\mathbb{K}[y] = 6/\alpha$. Using the substitution $\mu = \alpha\theta \Leftrightarrow \alpha/\mu = 1/\theta$, we obtain

$$\begin{aligned} p(y|f) &= \frac{\alpha^\alpha y^{\alpha-1}}{\Gamma(\alpha)} \mu^{-\alpha} \exp \left(- \frac{y\alpha}{\mu} \right), \mu = g(f) > 0 \\ \Leftrightarrow \ln p(y|f) &= -\alpha \left(\ln \mu + \frac{y}{\mu} \right) - \ln Z_\alpha(y), \ln Z_\alpha(y) = \ln \Gamma(\alpha) - \alpha \ln \alpha + (1-\alpha) \ln y. \end{aligned}$$

Note that if $\ln \mu = h(f)$ was convex and $\mu = g(f)$ was concave then the Gamma likelihood $p(y|f)$ would be log-concave in f which is not the case for both **exp** and **logistic**.

4.12.5 Exponential Likelihood

Nonnegative data $\mathbf{y} \in \mathbb{R}_+$ can be modeled in the GP framework using the Exponential distribution $\mathbf{p}(\mathbf{y}) = \theta^{-1} e^{-\mathbf{y}/\theta}$ with scale parameter $\theta > 0$, mean $\mathbb{E}[\mathbf{y}] = \theta = \mu$, variance $\mathbb{V}[\mathbf{y}] = \mu^2$, skewness $\mathbb{S}[\mathbf{y}] = 2$ and kurtosis $\mathbb{K}[\mathbf{y}] = 6$. We obtain

$$\begin{aligned} \mathbf{p}(\mathbf{y}|\mathbf{f}) &= \mu^{-1} \exp\left(-\frac{\mathbf{y}}{\mu}\right), \mu = g(\mathbf{f}) > 0 \\ \Leftrightarrow \ln \mathbf{p}(\mathbf{y}|\mathbf{f}) &= -\ln \mu - \frac{\mathbf{y}}{\mu}. \end{aligned}$$

Note that for **exp** (but not for **logistic**) the likelihood is log-concave. The exponential distribution corresponds to the Gamma distribution with $\alpha = 1$ and the Weibull distribution with $\kappa = 1$.

4.12.6 Inverse Gaussian Likelihood

Nonnegative data $\mathbf{y} \in \mathbb{R}_+^n$ can be modeled in the GP framework using the Inverse Gaussian distribution $\mathbf{p}(\mathbf{y}) = \sqrt{\lambda/(2\pi\mathbf{y}^3)} \exp(-\lambda(\mathbf{y} - \mu)^2/(2\mu^2\mathbf{y}))$ with shape parameter $\lambda > 0$, mean parameter $\mu > 0$, mean $\mathbb{E}[\mathbf{y}] = \mu$, variance $\mathbb{V}[\mathbf{y}] = \mu^3/\lambda$, skewness $\mathbb{S}[\mathbf{y}] = 3\sqrt{\mu/\lambda}$ and kurtosis $\mathbb{K}[\mathbf{y}] = 15\mu/\lambda$. We obtain

$$\begin{aligned} \mathbf{p}(\mathbf{y}|\mathbf{f}) &= \sqrt{\frac{\lambda}{2\pi\mathbf{y}^3}} \exp\left(-\frac{\lambda(\mathbf{y} - \mu)^2}{2\mu^2\mathbf{y}}\right), \mu = g(\mathbf{f}) > 0 \\ \Leftrightarrow \ln \mathbf{p}(\mathbf{y}|\mathbf{f}) &= -\frac{\lambda(\mathbf{y} - \mu)^2}{2\mu^2\mathbf{y}} - \ln Z_\alpha(\mathbf{y}), \ln Z_\alpha(\mathbf{y}) = -\frac{1}{2}(\ln \lambda - \ln 2\pi\mathbf{y}^3). \end{aligned}$$

The inverse Gaussian likelihood is in general not log-concave in \mathbf{f} for both **exp** and **logistic**.

4.12.7 Beta Likelihood

Interval data $\mathbf{y} \in [0, 1]^n$ can be modeled in the GP framework using the Beta distribution $\mathbf{p}(\mathbf{y}) = \mathbf{y}^{\alpha-1}(1-\mathbf{y})^{\beta-1}/\mathbf{B}(\alpha, \beta)$ with shape parameters $\alpha, \beta > 0$, mean $\mathbb{E}[\mathbf{y}] = \alpha/(\alpha + \beta)$ and variance $\mathbb{V}[\mathbf{y}] = \alpha\beta/[(\alpha + \beta)^2(\alpha + \beta + 1)]$ and $1/\mathbf{B}(\alpha, \beta) = \Gamma(\alpha + \beta)/[\Gamma(\alpha)\Gamma(\beta)]$. Reparametrising using the mean parameter $\mu = \mathbb{E}[\mathbf{y}] = \alpha/(\alpha + \beta)$, the shape parameter $\phi = \alpha + \beta$, the variance $\mathbb{V}[\mathbf{y}] = \mu(1 - \mu)/(1 + \phi)$ and hence

$$\begin{aligned} \mathbf{p}(\mathbf{y}|\mathbf{f}) &= \frac{\Gamma(\phi)}{\Gamma(\mu\phi)\Gamma((1-\mu)\phi)} \mathbf{y}^{\mu\phi-1}(1-\mathbf{y})^{(1-\mu)\phi-1}, \mu = g(\mathbf{f}) > 0 \\ \Leftrightarrow \ln \mathbf{p}(\mathbf{y}|\mathbf{f}) &= \ln \Gamma(\phi) - \ln \Gamma(\mu\phi) - \ln \Gamma((1-\mu)\phi) + (\mu\phi - 1) \ln \mathbf{y} + ((1-\mu)\phi - 1) \ln(1 - \mathbf{y}). \end{aligned}$$

The Beta likelihood is in general not log-concave in \mathbf{f} for both **exp** and **logistic**.

5 Mean Functions

A mean function $\mathbf{m}_{\boldsymbol{\phi}} : \mathcal{X} \rightarrow \mathbb{R}$ (with hyperparameters $\boldsymbol{\phi}$) of a GP f is a scalar function defined over the whole domain \mathcal{X} that computes the expected value $\mathbf{m}(x) = \mathbb{E}[f(x)]$ of f for the input x .

5.1 Interface

In the GPML toolbox, a mean function $\mathbf{m} : \mathcal{X} \rightarrow \mathbb{R}$ needs to implement evaluation $\mathbf{m} = \mathbf{m}_{\boldsymbol{\phi}}(X)$ and first derivatives $\mathbf{m}_i = \frac{\partial}{\partial \phi_i} \mathbf{m}$ with respect to the components i of the parameter $\boldsymbol{\phi} \in \Phi$ as detailed below.

```
34 <meanFunctions.m 34>≡
1 % mean functions to be use by Gaussian process functions. There are two
2 % different kinds of mean functions: simple and composite:
3 %
4 % simple mean functions:
5 %
6 %     meanZero      - zero mean function
7 %     meanOne       - one mean function
8 %     meanConst     - constant mean function
9 %     meanLinear    - linear mean function
10 %    meanPoly      - polynomial mean function
11 %    meanDiscrete   - precomputed mean for discrete data
12 %    meanGP         - predictive mean of another GP
13 %    meanGPexact    - predictive mean of a regression GP
14 %    meanNN         - nearest neighbor mean function
15 %
16 % composite covariance functions (see explanation at the bottom):
17 %
18 %     meanScale     - scaled version of a mean function
19 %     meanPow       - power of a mean function
20 %     meanProd      - products of mean functions
21 %     meanSum       - sums of mean functions
22 %     meanMask      - mask some dimensions of the data
23 %     meanPref      - difference mean for preference learning
24 %
25 % Naming convention: all mean functions are named "mean/mean*.m".
26 %
27 %
28 % 1) With no or only a single input argument:
29 %
30 %     s = meanNAME or s = meanNAME(hyp)
31 %
32 % The mean function returns a string s telling how many hyperparameters hyp it
33 % expects, using the convention that "D" is the dimension of the input space.
34 % For example, calling "meanLinear" returns the string 'D'.
35 %
36 % 2) With two input arguments:
37 %
38 %     m = meanNAME(hyp, x)
39 %
40 % The function computes and returns the mean vector where hyp are the
41 % hyperparameters and x is an n by D matrix of cases, where D is the dimension
42 % of the input space. The returned mean vector is of size n by 1.
43 %
44 % 3) With three input arguments:
```

```

45 %
46 %     dm = meanNAME(hyp, x, i)
47 %
48 % The function computes and returns the n by 1 vector of partial derivatives
49 % of the mean vector w.r.t. hyp(i) i.e. hyperparameter number i.
50 %
51 % See also doc/usageMean.m.
52 %
53 <gpml copyright 6a>

```

5.2 Implemented Mean Functions

We offer simple and composite mean functions producing new mean functions $\mathbf{m}(\mathbf{x})$ from existing mean functions $\mu_j(\mathbf{x})$. All code files are named according to the pattern `mean/mean<NAME>.m` for simple identification. This modular specification allows to define affine mean functions $\mathbf{m}(\mathbf{x}) = \mathbf{c} + \mathbf{a}^\top \mathbf{x}$ or polynomial mean functions $\mathbf{m}(\mathbf{x}) = (\mathbf{c} + \mathbf{a}^\top \mathbf{x})^2$. All currently available mean functions are summarised in the following table.

Simple mean functions $\mathbf{m}(\mathbf{x})$			
<NAME>	Meaning	$\mathbf{m}(\mathbf{x}) =$	Φ
Zero	mean vanishes always	0	\emptyset
One	mean equals 1	1	\emptyset
Const	mean equals a constant	\mathbf{c}	$\mathbf{c} \in \mathbb{R}$
Linear	mean linearly depends on $\mathbf{x} \in \mathcal{X} \subseteq \mathbb{R}^D$	$\mathbf{a}^\top \mathbf{x}$	$\mathbf{a} \in \mathbb{R}^D$
Poly	mean polynomially depends on $\mathbf{x} \in \mathcal{X} \subseteq \mathbb{R}^D$	$\sum_d \mathbf{a}_d^\top \mathbf{x}^d$	$\mathbf{a} \in \mathbb{R}^{D \times d}$
Discrete	precomputed mean for discrete data $\mathbf{x} \in \mathcal{X} \subseteq \mathbb{N}$	$\mu_{\mathbf{x}}$	$\mu \in \mathbb{R}^s$
GP	predictive mean of another GP	$\int \mathbf{y} \cdot \mathbf{p}(\mathbf{y} \mathcal{D}, \mathbf{x}) d\mathbf{y}$	\emptyset
GPexact	predictive mean of a regression GP	$\int \mathbf{y} \cdot \mathbf{p}(\mathbf{y} \mathcal{D}, \mathbf{x}) d\mathbf{y}$	ρ, ψ, σ_n
NN	nearest neighbor for a set $(\mathbf{z}_j, \mathbf{m}_j) \in \mathcal{X} \times \mathbb{R}$	$\mathbf{m}_i, i = \arg \min_j d(\mathbf{x}, \mathbf{z}_j)$	\emptyset
Composite mean functions $[\mu_1(\mathbf{x}), \mu_2(\mathbf{x}), \dots] \mapsto \mathbf{m}(\mathbf{x})$			
<NAME>	Meaning	$\mathbf{m}(\mathbf{x}) =$	Φ
Scale	scale a mean	$\alpha \mu(\mathbf{x})$	$\alpha \in \mathbb{R}$
Sum	add up mean functions	$\sum_j \mu_j(\mathbf{x})$	\emptyset
Prod	multiply mean functions	$\prod_j \mu_j(\mathbf{x})$	\emptyset
Pow	raise a mean to a power	$\mu(\mathbf{x})^d$	\emptyset
Mask	act on components $I \subseteq [1, 2, \dots, D]$ of $\mathbf{x} \in \mathcal{X} \subseteq \mathbb{R}^D$ only	$\mu(\mathbf{x}_I)$	\emptyset
Pref	preference learning mean $\mathbf{x} = [\mathbf{x}_1; \mathbf{x}_2], \mathbf{x}_i \subseteq \mathbb{R}^{D/2}$	$\mu(\mathbf{x}_1) - \mu(\mathbf{x}_2)$	\emptyset

5.3 Usage of Implemented Mean Functions

Some code examples taken from `doc/usageMean.m` illustrate how to use simple and composite mean functions to specify a GP model.

Syntactically, a mean function `mf` is defined by

```
mn := 'func' | @func // simple
```

```
mf := {mn} | {mn, {param, mf}} | {mn, {mf, ..., mf}} // composite
```

i.e., it is either a string containing the name of a mean function, a pointer to a mean function or one of the former in combination with a cell array of mean functions and an additional list of parameters.

35 <doc/usageMean.m 35>≡

```

1 % demonstrate usage of mean functions
2 %
3 % See also meanFunctions.m.
4 %
5 (gpml copyright 6a)
6 clear all, close all
7 n = 5; D = 2; x = randn(n,D); % create a random data set
8
9 % set up simple mean functions
10 m0 = {'meanZero'}; hyp0 = []; % no hyperparameters are needed
11 m1 = {'meanOne'}; hyp1 = []; % no hyperparameters are needed
12 mc = {@meanConst}; hypc = 2; % also function handles are possible
13 ml = {@meanLinear}; hyp1 = [2;3]; % m(x) = 2*x1 + 3*x2
14 mp = {@meanPoly,2}; hypp = [1;1;2;3]; % m(x) = x1+x2+2*x1^2+3*x2^2
15 mn = {@meanNN,[1,0; 0,1],[0.9,0.5]}; hypn = []; % nearest neighbor
16 s = 12; hypd = randn(s,1); % discrete mean with 12 hypers
17 md = {'meanDiscrete',s};
18 hyp.cov = [0;0]; hypg = []; % GP predictive mean
19 xt = randn(2*n,D); yt = sign(xt(:,1)-xt(:,2)); % training data
20 mg = {@meanGP,hyp,@infEP,@meanZero,@covSEiso,@likErf,xt,yt};
21 hype = [0;0; log(0.1)]; % regression GP predictive mean
22 xt = randn(2*n,D); yt = xt(:,1).*xt(:,2); % training data
23 me = {@meanGPexact,@meanZero,@covSEiso,xt,yt};
24
25 % set up composite mean functions
26 msc = {'meanScale',{m1}}; hypsc = [3; hyp1]; % scale by 3
27 msu = {'meanSum',{m0,mc,ml}}; hypsu = [hyp0; hypc; hyp1]; % sum
28 mpr = {@meanProd,{mc,ml}}; hyppr = [hypc; hyp1]; % product
29 mpo = {'meanPow',3,msu}; hyppo = hypsu; % third power
30 mask = [false,true]; % mask excluding all but the 2nd component
31 mma = {'meanMask',mask,ml}; hypma = hyp1(mask);
32 mpf = {@meanPref,ml}; hyppf = 2; % linear pref with slope
33
34 % 0) specify mean function
35 % mean = md; hyp = hypd; x = randi([1,s],n,1);
36 % mean = mn; hyp = hypn;
37 % mean = mg; hyp = hypg;
38 mean = me; hyp = hype;
39 % mean = m0; hyp = hyp0;
40 % mean = msu; hyp = hypsu;
41 % mean = mpr; hyp = hyppr;
42 % mean = mpo; hyp = hyppo;
43 % mean = mpf; hyp = hyppf;
44
45 % 1) query the number of parameters
46 feval(mean{:})
47
48 % 2) evaluate the function on x
49 feval(mean{:},hyp,x)
50
51 % 3) compute the derivatives w.r.t. to hyperparameter i
52 i = 2; feval(mean{:},hyp,x,i)

```

6 Covariance Functions

A covariance function $k_{\boldsymbol{\psi}} : \mathcal{X} \times \mathcal{X} \rightarrow \mathbb{R}$ (with hyperparameters $\boldsymbol{\psi}$) of a GP f is a scalar function defined over the whole domain \mathcal{X}^2 that computes the covariance $k(x, x') = \mathbb{V}[f(x), f(x')] = \mathbb{E}[(f(x) - m(x))(f(x') - m(x'))]$ of f between the inputs x and x' .

6.1 Interface

Again, the interface is simple since only evaluation of the full covariance matrix $K = k_{\boldsymbol{\psi}}(X)$ and its derivatives $K_i = \frac{\partial}{\partial \psi_i} K$ as well as cross terms $k_* = k_{\boldsymbol{\psi}}(X, x_*)$ and $k_{**} = k_{\boldsymbol{\psi}}(x_*, x_*)$ for prediction are required.

```
37 <covFunctions.m 37>≡
1 % covariance functions to be use by Gaussian process functions. There are two
2 % different kinds of covariance functions: simple and composite:
3 %
4 % simple covariance functions:
5 %   covConst      - covariance for constant functions
6 %   covCos        - sine periodic covariance function (1d) with unit period
7 %   covLIN        - linear covariance function without parameters
8 %   covLINard     - linear covariance function with ARD
9 %   covLINiso     - linear covariance function
10 %  covLINone     - linear covariance function with bias
11 %  covMaternard  - Matern covariance function with nu=1/2, 3/2 or 5/2 with ARD
12 %  covMaterniso  - Matern covariance function with nu=1/2, 3/2 or 5/2
13 %  covNNNone     - neural network covariance function
14 %  covNoise      - independent covariance function (i.e. white noise)
15 %  covPeriodic   - smooth periodic covariance function (1d)
16 %  covPeriodicNoDC - as above but with zero DC component and properly scaled
17 %  covPoly       - polynomial covariance function
18 %  covPPard      - piecewise polynomial covariance function (compact support)
19 %  covPPiso      - piecewise polynomial covariance function (compact support)
20 %  covRQard      - rational quadratic covariance function with ARD
21 %  covRQiso      - isotropic rational quadratic covariance function
22 %  covSEard      - squared exponential covariance function with ARD
23 %  covSEiso      - isotropic squared exponential covariance function
24 %  covSEisoU     - same as above but without latent scale
25 %  covSEvlen     - spatially varying lengthscales squared exponential
26 %  covSEfact     - factor analysis squared exponential covariance function
27 %  covSM         - spectral mixture covariance function
28 %  covGaborard   - Gabor covariance function with ARD
29 %  covGaborsio   - isotropic Gabor covariance function
30 %  covDiscrete   - precomputed covariance for discrete data
31 %
32 % composite (meta) covariance functions (see explanation at the bottom):
33 %   covScale      - scaled version of a covariance function
34 %   covProd       - products of covariance functions
35 %   covSum        - sums of covariance functions
36 %   covADD        - additive covariance function
37 %   covMask       - mask some dimensions of the data
38 %   covPERard     - make ARD stationary covariance periodic
39 %   covPERiso     - make isotropic stationary covariance periodic
40 %   covPref       - difference covariance for preference learning
41 %
42 % special purpose (wrapper) covariance functions
43 %   covFITC       - to be used in conjunction with infFITC* for large scale
```

```

44 %             inference problems; any covariance can be wrapped by
45 %             covFITC such that the FITC approximation is applicable
46 %   covGrid      - to be used in conjunction with infGrid* for large scale
47 %                 inference problems on grids resulting Kronecker structure
48 %
49 % Naming convention: all covariance functions are named "cov/cov*.m". A trailing
50 % "iso" means isotropic, "ard" means Automatic Relevance Determination, and
51 % "one" means that the distance measure is parameterized by a single parameter.
52 %
53 % The covariance functions are written according to a special convention where
54 % the exact behaviour depends on the number of input and output arguments
55 % passed to the function. If you want to add new covariance functions, you
56 % should follow this convention if you want them to work with the function gp.
57 % There are four different ways of calling the covariance functions:
58 %
59 % 1) With no (or one) input argument(s):
60 %
61 %     s = cov
62 %
63 % The covariance function returns a string s telling how many hyperparameters it
64 % expects, using the convention that "D" is the dimension of the input space.
65 % For example, calling "covRQard" returns the string '(D+2)'.
66 %
67 % 2) With two input arguments:
68 %
69 %     K = cov(hyp, x) equivalent to K = cov(hyp, x, [])
70 %
71 % The function computes and returns the covariance matrix where hyp are
72 % the hyperparameters and x is an n by D matrix of cases, where
73 % D is the dimension of the input space. The returned covariance matrix is of
74 % size n by n.
75 %
76 % 3) With three input arguments:
77 %
78 %     Ks = cov(hyp, x, xs)
79 %     kss = cov(hyp, xs, 'diag')
80 %
81 % The function computes test set covariances; kss is a vector of self covariances
82 % for the test cases in xs (of length ns) and Ks is an (n by ns) matrix of cross
83 % covariances between training cases x and test cases xs.
84 %
85 % 4) With four input arguments:
86 %
87 %     dKi = cov(hyp, x, [], i)
88 %     dKsi = cov(hyp, x, xs, i)
89 %     dkssi = cov(hyp, xs, 'diag', i)
90 %
91 % The function computes and returns the partial derivatives of the
92 % covariance matrices with respect to hyp(i), i.e. with
93 % respect to the hyperparameter number i.
94 %
95 % Covariance functions can be specified in two ways: either as a string
96 % containing the name of the covariance function or using a cell array. For
97 % example:
98 %
99 %     cov = 'covRQard';
100 %     cov = {'covRQard'};
101 %     cov = {@covRQard};

```

```

102 %
103 % are supported. Only the second and third form using the cell array can be used
104 % for specifying composite covariance functions, made up of several
105 % contributions. For example:
106 %
107 %         cov = {'covScale', {'covRQiso'}};
108 %         cov = {'covSum', {'covRQiso','covSEard','covNoise'}};
109 %         cov = {'covProd',{'covRQiso','covSEard','covNoise'}};
110 %         cov = {'covMask',{mask,'covSEiso'}}
111 %     q=1; cov = {'covPPiso',q};
112 %     d=3; cov = {'covPoly',d};
113 %         cov = {'covADD',{[1,2],'covSEiso'}};
114 %         cov = {@covFITC, {@covSEiso}, u};  where u are the inducing inputs
115 %
116 % specifies a covariance function which is the sum of three contributions. To
117 % find out how many hyperparameters this covariance function requires, we do:
118 %
119 %     feval(cov{:})
120 %
121 % which returns the string '3+(D+1)+1' (i.e. the 'covRQiso' contribution uses
122 % 3 parameters, the 'covSEard' uses D+1 and 'covNoise' a single parameter).
123 %
124 % See also doc/usageCov.m.
125 %
126 <gpml copyright 6a>

```

6.2 Implemented Covariance Functions

Similarly to the mean functions, we provide a whole algebra of covariance functions $\mathbf{k} : \mathcal{X} \times \mathcal{X} \rightarrow \mathbb{R}$ with the same generic name pattern `cov/cov<NAME>.m` as before.

Besides a long list of simple covariance functions, we also offer a variety of composite covariance functions as shown in the following table.

Simple covariance functions $\mathbf{k}(x, x')$			
<NAME>	Meaning	$\mathbf{k}(x, x') =$	Ψ
Zero	covariance vanishes always	0	\emptyset
Eye	unit additive measurement noise	$\delta(x - x')$	\emptyset
Noise	additive measurement noise	$\sigma_f^2 \delta(x - x')$	$\ln \sigma_f$
Const	covariance equals a constant	σ_f^2	$\ln \sigma_f$
LIN	linear, $\mathcal{X} \subseteq \mathbb{R}^D$	$x^\top x'$	\emptyset
LINard	linear with diagonal weighting, $\mathcal{X} \subseteq \mathbb{R}^D$	$x^\top \mathbf{A}^{-2} x'$	$\{\ln \lambda_1, \dots, \ln \lambda_D\}$
LINiso	linear with isotropic weighting, $\mathcal{X} \subseteq \mathbb{R}^D$	$x^\top x' / \ell^2$	$\ln \ell$
LINone	linear with bias, $\mathcal{X} \subseteq \mathbb{R}^D$	$(x^\top x' + 1) / \ell^2$	$\ln \ell$
Poly	polynomial covariance, $\mathcal{X} \subseteq \mathbb{R}^D$	$\sigma_f^2 (x^\top x' + c)^d$	$\{\ln c, \ln \sigma_f\}$
SEard	automatic relevance determination squared exponential, $\mathcal{X} \subseteq \mathbb{R}^D$	$\sigma_f^2 \exp(-\frac{1}{2}(x - x')^\top \mathbf{A}^{-2}(x - x'))$	$\{\ln \lambda_1, \dots, \ln \lambda_D, \ln \sigma_f\}$
SEiso	diagonal squared exponential, $\mathcal{X} \subseteq \mathbb{R}^D$	$\sigma_f^2 \exp(-\frac{1}{2\ell^2}(x - x')^\top (x - x'))$	$\{\ln \ell, \ln \sigma_f\}$
SEisoU	squared exponential, $\mathcal{X} \subseteq \mathbb{R}^D$	$\exp(-\frac{1}{2\ell^2} x^\top x')$	$\ln \ell$
SEvlen	spatially varying lengthscale squared exponential $\mathcal{X} \subseteq \mathbb{R}^D$	$\sigma_f^2 \left(\frac{a}{b}\right)^{\frac{D}{2}} \exp\left(-\frac{\ x - x'\ ^2}{b}\right)$, $a = 2\ell(x)\ell(x')$, $b = \ell^2(x) + \ell^2(x')$	$\{\Phi_\ell, \ln \sigma_f\}$
SEfact	factor analysis squared exponential $\mathcal{X} \subseteq \mathbb{R}^D$	$\sigma_f^2 \exp(-\frac{1}{2}(x - x')^\top \mathbf{L}^\top \mathbf{L}(x - x'))$, $\mathbf{L} \in \mathbb{R}^{d \times D}$, $d \leq D$	$\{\mathbf{L}, \ln \sigma_f\}$
RQard	rational quadratic, $\mathcal{X} \subseteq \mathbb{R}^D$	$\sigma_f^2 (1 + \frac{1}{2\alpha}(x - x')^\top \mathbf{A}^{-2}(x - x'))^{-\alpha}$	$\{\ln \lambda_1, \dots, \ln \lambda_D, \ln \sigma_f, \ln \alpha\}$
RQiso	rational quadratic, $\mathcal{X} \subseteq \mathbb{R}^D$	$\sigma_f^2 (1 + \frac{1}{2\alpha\ell^2}(x - x')^\top (x - x'))^{-\alpha}$	$\{\ln \ell, \ln \sigma_f, \ln \alpha\}$
Maternard	Matérn, $\mathcal{X} \subseteq \mathbb{R}^D$, $f_1(t) = 1$, $f_3(t) = 1 + t$, $f_5(t) = f_3(t) + \frac{t^2}{3}$	$\sigma_f^2 f_d(r_d) \exp(-r_d)$, $r_d = \sqrt{d}(x - x')^\top \mathbf{A}^{-2}(x - x')$	$\{\ln \lambda_1, \dots, \ln \lambda_D, \ln \sigma_f\}$
Materniso	Matérn, $\mathcal{X} \subseteq \mathbb{R}^D$, $f_1(t) = 1$, $f_3(t) = 1 + t$, $f_5(t) = f_3(t) + \frac{t^2}{3}$	$\sigma_f^2 f_d(r_d) \exp(-r_d)$, $r_d = \sqrt{\frac{d}{\ell^2}}(x - x')^\top (x - x')$	$\{\ln \ell, \ln \sigma_f\}$
NNone	neural net, $\mathcal{X} \subseteq \mathbb{R}^D$, $f(x) = 1 + x^\top \mathbf{A}^{-2} x$	$\sigma_f^2 \sin^{-1}\left(\frac{x^\top \mathbf{A}^{-2} x'}{\sqrt{f(x)f(x')}}\right)$	$\{\ln \ell, \ln \sigma_f\}$
Periodic	periodic, $\mathcal{X} \subseteq \mathbb{R}$	$\sigma_f^2 \exp(-\frac{2}{\ell^2} \sin^2[\pi \ x - x'\ /p])$	$\{\ln \ell, \ln p, \ln \sigma_f\}$
PeriodicNoDC	periodic, $\mathcal{X} \subseteq \mathbb{R}$, rescaled and DC component removed	$\sigma_f^2 \frac{\kappa(x - x') - \frac{1}{2} \int_0^x \kappa(t) dt}{\kappa(0) - \frac{1}{2} \int_0^x \kappa(t) dt}$, $\kappa(t) = \exp(-\frac{2}{\ell^2} \sin^2[\pi t/p])$	$\{\ln \ell, \ln p, \ln \sigma_f\}$
Cos	periodic cosine, $\mathcal{X} \subseteq \mathbb{R}$	$\sigma_f^2 \cos(\pi \ x - x'\ /p)$	$\{\ln p, \ln \sigma_f\}$
PPard	compact support, piecewise polynomial $f_v(r)$, $\mathcal{X} \subseteq \mathbb{R}^D$	$\sigma_f^2 \max(0, 1 - r)^{j+v} \cdot f_v(r)$, $r^2 = (x - x')^\top \mathbf{A}^{-2}(x - x')$	$\{\ln \lambda_1, \dots, \ln \lambda_D, \ln \sigma_f\}$
PPiso	compact support, piecewise polynomial $f_v(r)$, $\mathcal{X} \subseteq \mathbb{R}^D$	$\sigma_f^2 \max(0, 1 - r)^{j+v} \cdot f_v(r)$, $r = \frac{\ x - x'\ }{\ell}$, $j = \lfloor \frac{D}{2} \rfloor + v + 1$	$\{\ln \ell, \ln \sigma_f\}$
SM	spectral mixture, $\mathcal{X} \subseteq \mathbb{R}^D$, $w \in \mathbb{R}_+^Q$, $M, V \in \mathbb{R}_+^{D \times Q}$	$w^\top \left(\prod_{d=1}^D \exp(-\frac{1}{2} v_d r^2) \odot \cos(m_d r) \right)$, $r = 2\pi \ x - x'\ $	$\{\ln w, \ln M, \ln V\}$
	spectral mixture, $\mathcal{X} \subseteq \mathbb{R}^D$, $W \in \mathbb{R}_+^{D \times Q}$, $M, V \in \mathbb{R}_+^{D \times Q}$	$\prod_{d=1}^D w_d \left(\exp(-\frac{1}{2} v_d r^2) \odot \cos(m_d r) \right)$, $r = 2\pi \ x - x'\ $	$\{\ln W, \ln M, \ln V\}$
Gaborard	anisotropic Gabor function, $\mathcal{X} \subseteq \mathbb{R}^D$, $\lambda, p \in \mathbb{R}_+^D$	$\exp(-\sum_{d=1}^D \frac{r_d^2}{2\lambda_d^2}) \cos\left(2\pi \sum_{d=1}^D r_d/p_d\right)$, $r_d = x_d - x'_d $	$\{\ln \lambda, \ln p\}$
Gaboriso	isotropic Gabor function, $\mathcal{X} \subseteq \mathbb{R}^D$, $\ell, p \in \mathbb{R}_+$	$\exp(-\frac{r^2}{2\ell^2}) \cos(2\pi r/p)$, $r = \ x - x'\ $	$\{\ln \ell, \ln p\}$
Discrete	precomputed covariance for discrete data $x \in \mathcal{X} \subseteq \mathbb{N}$	$\mathbf{K}_{xx'}$, where $\mathbf{K} = \mathbf{L}^\top \mathbf{L}$ is Cholesky decomposition, $\mathbf{L} \in \mathbb{R}^{s \times s}$	$\{\mathbf{L}\}$
Composite covariance functions $[\kappa_1(x, x'), \kappa_2(x, x'), \dots] \mapsto \mathbf{k}(x, x')$			
<NAME>	Meaning	$\mathbf{k}(x, x') =$	Ψ
Scale	scale a covariance	$\sigma_f^2 \kappa(x, x')$ and $\sigma_f(x) \kappa(x, x') \sigma_f(x')$	$\{\ln \sigma_f\}$
Sum	add up covariance functions	$\sum_j \kappa_j(x, x')$	\emptyset
Prod	multiply covariance functions	$\prod_j \kappa_j(x, x')$	\emptyset
PERard	turn ARD stationary into a periodic, $\mathcal{X} \subseteq \mathbb{R}^D$	$\kappa(u(x), u(x'))$, $u(x) = [\sin x_p, \cos x_p]$, $x_p = 2\pi \text{diag}(p^{-1})x$	$\{\ln p_1, \dots, \ln p_D\}$
PERiso	turn isotropic stationary into a periodic, $\mathcal{X} \subseteq \mathbb{R}^D$	$\kappa(u(x), u(x'))$, $u(x) = [\sin x_p, \cos x_p]$, $x_p = 2\pi x/p$	$\ln p$
Mask	act on components $I \subseteq [1, 2, \dots, D]$ of $x \in \mathcal{X} \subseteq \mathbb{R}^D$ only	$\kappa(x_I, x'_I)$	\emptyset
ADD	additive, $\mathcal{X} \subseteq \mathbb{R}^D$, index degree set $\mathcal{D} = \{1, \dots, D\}$	$\sum_{d \in \mathcal{D}} \sigma_{f_d}^2 \sum_{ I =d} \prod_{i \in I} \kappa(x_i, x'_i; \psi_i)$	$\{\psi_1, \dots, \psi_D, \ln \sigma_{f_1}, \dots, \ln \sigma_{f_{ D }}\}$
Pref	preference learning covariance $x = [x_1; x_2]$, $x_i \subseteq \mathbb{R}^{D/2}$	$\kappa(x_1, x'_1) + \kappa(x_2, x'_2) - \kappa(x_1, x'_2) - \kappa(x_2, x'_1)$	\emptyset

The spectral mixture covariance `covSM` was introduced by Wilson & Adams Gaussian Process Kernels for Pattern Discovery and Extrapolation, ICML, 2013.

The periodic covariance functions `covPERiso` and `covPERard` start from a stationary isotropic or ARD covariance function that depends on the data only through a distance $r^2 = (x - x')^\top \mathbf{A}^{-2}(x - x')$ such as `covMatern*`, `covPP*`, `covRQ*`, `covSE*` where `*=ard|iso` and turn them into a periodic covariance function by embedding the data $x \in \mathbb{R}^D$ into a periodic high-dimensional space $x_p = u(x) \in \mathbb{R}^{2D}$ by a function $u(x) = 2\pi \text{diag}(p^{-1})x$.

The additive covariance function `covADD` starts from a one-dimensional covariance function $\kappa(x_i, x'_i; \psi_i)$ acting on a single component $i \in [1, \dots, D]$ of x . From that, we define covariance functions $\kappa_I(x_I, x'_I) = \prod_{i \in I} \kappa(x_i, x'_i; \psi_i)$ acting on vector-valued inputs x_I . The sums of exponential size can efficiently be computed using the Newton-Girard formulae. Samples functions drawn from a GP with additive covariance are additive functions. The number of interacting variables $|I|$ is a measure of how complex the additive functions are.

6.3 Usage of Implemented Covariance Functions

Some code examples taken from `doc/usageCov.m` illustrate how to use simple and composite covariance functions to specify a GP model.

Syntactically, a covariance function `cf` is defined by

```
cv := 'func' | @func // simple

cf := {cv} | {cv, {param, cf}} | {cv, {cf, ..., cf}} // composite
```

i.e., it is either a string containing the name of a covariance function, a pointer to a covariance function or one of the former in combination with a cell array of covariance functions and an additional list of parameters.

```
41 <doc/usageCov.m 41>≡
1 % demonstrate usage of covariance functions
2 %
3 % See also covFunctions.m.
4 %
5 (gpml copyright 6a)
6 clear all, close all
7 n = 5; D = 3; x = randn(n,D); xs = randn(3,D); % create a data set
8
9 % set up simple covariance functions
10 cn = {'covNoise'}; sn = .1; hypn = log(sn); % one hyperparameter
11 cc = {@covConst}; sf = 2; hypc = log(sf); % function handles OK
12 ce = {@covEye}; hype = []; % identity
13 cl = {@covLIN}; hyp1 = []; % linear is parameter-free
14 cla = {'covLINard'}; L = rand(D,1); hyp1a = log(L); % linear (ARD)
15 cli = {'covLINiso'}; l = rand(1); hyp1i = log(l); % linear iso
16 clo = {@covLINone}; ell = .9; hyp1o = log(ell); % linear with bias
17 cp = {@covPoly,3}; c = 2; hypp = log([c;sf]); % third order poly
18 cga = {@covSEard}; hypga = log([L;sf]); % Gaussian with ARD
19 cgi = {'covSEiso'}; hypgi = log([ell;sf]); % isotropic Gaussian
20 cgu = {'covSEisoU'}; hypgu = log(ell); % isotropic Gauss no scale
21 cra = {'covRQard'}; al = 2; hypra = log([L;sf;al]); % ration. quad.
22 cri = {@covRQiso}; hypri = log([ell;sf;al]); % isotropic
23 cma = {@covMaternard,5}; hypma = log([ell;sf]); % Matern class d=5
24 cmi = {'covMaterniso',3}; hypmi = log([ell;sf]); % Matern class d=3
25 cnn = {'covNNone'}; hypnn = log([L;sf]); % neural network
26 cpe = {'covPeriodic'}; p = 2; hyppe = log([ell;p;sf]); % periodic
27 cpn = {'covPeriodicNoDC'}; p = 2; hyppe = log([ell;p;sf]); % w/o DC
28 cpc = {'covCos'}; p = 2; hypcpc = log([p;sf]); % cosine cov
29 cca = {'covPPard',3}; hypcc = hypgu; % compact support poly degree 3
30 cci = {'covPPiso',2}; hypcc = hypgi; % compact support poly degree 2
31 cgb = {@covGaboriso}; ell = 1; p = 1.2; hypgb=log([ell;p]); % Gabor
32 Q = 2; w = ones(Q,1)/Q; m = rand(D,Q); v = rand(D,Q);
33 csm = {@covSM,Q}; hypsm = log([w;m(:);v(:)]); % Spectral Mixture
34 cvl = {@covSEvlen,{@meanLinear}}; hypv1 = [1;2;1;0]; % var lenscal
35 s = 12; cds = {@covDiscrete,s}; % discrete covariance function
36 L = randn(s); L = chol(L'*L); L(1:(s+1):end) = log(diag(L));
37 hypds = L(triu(true(s))); xd = randi([1,s],[n,1]); xsd = [1;3;6];
38 cfa = {@covSEfact,2}; hypfa = randn(D*2,1); % factor analysis
39
40 % set up composite i.e. meta covariance functions
41 csc = {'covScale',{cgu}}; hypsc = [log(3); hypgu]; % scale by 9
42 csu = {'covSum',{cn,cc,cl}}; hypsu = [hypn; hypc; hyp1]; % sum
43 cpr = {@covProd,{cc,cci}}; hyppr = [hypc; hypcc]; % product
44 mask = [0,1,0]; % binary mask excluding all but the 2nd component
```

```

45 cma = {'covMask',{mask,cgi{:}}}; hypma = hypgi;
46 % isotropic periodic rational quadratic
47 cpi = {'covPERiso',{covRQiso}};
48 % periodic Matern with ARD
49 cpa = {'covPERard',{covMaternard,3}};
50 % additive based on SEiso using unary and pairwise interactions
51 cad = {'covADD',{[1,2],'covSEiso'}};
52 % preference covariance with squared exponential base covariance
53 cpr = {'covPref',{'covSEiso'}}; hyppr = [0;0];
54 xp = randn(n,2*D); xsp = randn(3,2*D);
55
56 % 0) specify a covariance function
57 % cov = cma; hyp = hypma;
58 % cov = cci; hyp = hypcc;
59 % cov = csm; hyp = hypsm;
60 cov = cds; hyp = hypds; x = xd; xs = xsd;
61 % cov = cfa; hyp = hypfa;
62 % cov = cvl; hyp = hypvl;
63 % cov = cpr; hyp = hyppr; x = xp; xs = xsp;
64
65 % 1) query the number of parameters
66 feval(cov{:})
67
68 % 2) evaluate the function on x
69 feval(cov{:},hyp,x)
70
71 % 3) evaluate the function on x and xs to get cross-terms
72 kss = feval(cov{:},hyp,xs,'diag')
73 Ks   = feval(cov{:},hyp,x,xs)
74
75 % 4) compute the derivatives w.r.t. to hyperparameter i
76 i = 1; feval(cov{:},hyp,x,[],i)

```

7 Hyperpriors

A hyperprior $\mathbf{p}(\boldsymbol{\theta})$ with $\boldsymbol{\theta} = [\boldsymbol{\rho}, \boldsymbol{\Phi}, \boldsymbol{\Psi}]$ is a joint probability distribution over the likelihood hyperparameters $\boldsymbol{\rho}$, the mean hyperparameters $\boldsymbol{\Phi}$ and the covariance hyperparameters $\boldsymbol{\Psi}$. We concentrate on factorial priors $\mathbf{p}(\boldsymbol{\theta}) = \prod_j \mathbf{p}_j(\boldsymbol{\theta}_j)$. Hyperpriors can be used to regularise the optimisation of the hyperparameters via the marginal likelihood $\mathbf{Z}(\boldsymbol{\theta})$ so that $\mathbf{p}(\boldsymbol{\theta})\mathbf{Z}(\boldsymbol{\theta})$ is maximised instead. As we wish to perform unconstrained optimisation, we require (mainly) smooth hyperpriors with infinite support.

7.1 Interface

In the GPML toolbox, a prior distribution $\mathbf{p}(\boldsymbol{\theta})$ needs to implement the evaluation of the log density $\ln \mathbf{p}(\boldsymbol{\theta})$ and its first derivative $\frac{\partial}{\partial \boldsymbol{\theta}} \ln \mathbf{p}(\boldsymbol{\theta})$. In addition, we require sampling capabilities i.e. the generation of $\boldsymbol{\theta} \sim \mathbf{p}(\boldsymbol{\theta})$.

```

42 <priorDistributions.m 42>≡
1 % prior distributions to be used for hyperparameters of Gaussian processes
2 % using infPrior.
3 % There are two different kinds of prior distributions: simple and composite:
4 %
5 % simple prior distributions:
6 %

```

```

7 %   priorGauss           - univariate Gaussian
8 %   priorLaplace        - univariate Laplace
9 %   priorT              - univariate Student's t
10 %
11 %   priorSmoothBox1     - univariate interval (linear decay in log domain)
12 %   priorSmoothBox2     - univariate interval (quadr. decay in log domain)
13 %
14 %   priorGamma          - univariate Gamma, IR+
15 %   priorWeibull        - univariate Weibull, IR+
16 %   priorInvGauss       - univariate Inverse Gaussian, IR+
17 %   priorLogNormal      - univariate Log-normal, IR+
18 %
19 %   priorClamped or      - fix hyperparameter to its current value by setting
20 %   priorDelta           derivatives to zero, no effect on marginal likelihood
21 %
22 %   priorGaussMulti      - multivariate Gauss
23 %   priorLaplaceMulti    - multivariate Laplace
24 %   priorTMulti         - multivariate Student's t
25 %
26 %   priorClampedMulti or - fix hyperparameter to its current value by setting
27 %   priorDeltaMulti      derivatives to zero, no effect on marginal likelihood
28 %
29 % composite prior distributions (see explanation at the bottom):
30 %
31 %   priorMix             - nonnegative mixture of priors
32 %   priorTransform       - prior on g(t) rather than t
33 %
34 % Naming convention: all prior distributions are named "prior/prior*.m".
35 %
36 %
37 % 1) With only a fixed input arguments:
38 %
39 %     r = priorNAME(par1,par2,parN)
40 %
41 % The function returns a random sample from the distribution for e.g.
42 % random restarts, simulations or optimisation initialisation.
43 %
44 % 2) With one additional input arguments:
45 %
46 %     [lp,dlp] = priorNAME(par1,par2,parN, t)
47 %
48 % The function returns the log density at location t along with its first
49 % derivative.
50 %
51 % See also doc/usagePrior.m, inf/infPrior.m.
52 %
53 (gpml copyright 6a)

```

7.2 Implemented Hyperpriors

All code files are named according to the pattern `prior/prior<NAME>.m` for simple identification. All currently available hyperpriors are summarised in the following table.

Simple hyperpriors $p(\theta)$			
Univariate hyperpriors defined over the whole reals with mean μ and variance σ^2			
<NAME>	Meaning	$p(\theta) =$	τ
Gauss	normally distributed hyperparameter $\theta \in \mathbb{R}$	$\frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(\theta-\mu)^2}{2\sigma^2}\right)$	$\mu \in \mathbb{R}, \sigma^2 \in \mathbb{R}_+$
Laplace	double exponentially hyperparameter $\theta \in \mathbb{R}$	$\frac{1}{2b} \exp\left(-\frac{ \theta-\mu }{b}\right), b = \sigma/\sqrt{2}$	$\mu \in \mathbb{R}, \sigma^2 \in \mathbb{R}_+$
T	Student's t distributed hyperparameter $\theta \in \mathbb{R}$	$\frac{\Gamma(\frac{\nu+1}{2})}{\Gamma(\frac{\nu}{2})} \frac{1}{\sqrt{(\nu-2)\pi\sigma^2}} \left(1 + \frac{(\theta-\mu)^2}{(\nu-2)\sigma^2}\right)^{-\frac{\nu+1}{2}}$	$\mu \in \mathbb{R}, \sigma^2, \nu \in \mathbb{R}_+$
Univariate hyperpriors with effective bounded support but defined over the whole real line			
SmoothBox1	localised hyperparameter $\theta \in \mathbb{R}$	$\frac{1-\exp(\eta(a-b))}{b-a} \cdot \frac{1}{1+\exp(-\eta(\theta-a))} \cdot \frac{1}{1+\exp(\eta(\theta-b))}$	$a \leq b \in \mathbb{R}, \eta \in \mathbb{R}_+$
SmoothBox2	localised hyperparameter $\theta \in \mathbb{R}$	$\frac{1}{(1/\eta+1)(b-a)} \begin{cases} \mathcal{N}(\theta a, \sigma_{ab}^2) & t < a \\ 1 & t \in [a, b], \sigma_{ab} = \frac{b-a}{\eta\sqrt{2\pi}} \\ \mathcal{N}(\theta a, \sigma_{ab}^2) & b < t \end{cases}$	$a \leq b \in \mathbb{R}, \eta \in \mathbb{R}_+$
Univariate hyperpriors supported only over the positive reals			
Gamma	Gamma hyperparameter $\theta \in \mathbb{R}_+$	$\frac{1}{\Gamma(k)\Gamma^k} \exp(\frac{\theta}{t})\theta^{k-1}$	$k \in \mathbb{R}_+, t \in \mathbb{R}_+$
Weibull	Weibull hyperparameter $\theta \in \mathbb{R}_+$	$\frac{k}{\lambda} \left(\frac{\theta}{\lambda}\right)^{k-1} \exp\left(-\left(\frac{\theta}{\lambda}\right)^k\right)$	$k \in \mathbb{R}_+, \lambda \in \mathbb{R}_+$
InverseGauss	inverse Gaussian hyperparameter $\theta \in \mathbb{R}_+$	$\frac{1}{\sqrt{2\pi\theta^3/\lambda}} \exp\left(-\frac{\lambda(\theta-\mu)^2}{2\mu^2\theta}\right)$	$k \in \mathbb{R}_+, \lambda \in \mathbb{R}_+$
LogNormal	log-normal hyperparameter $\theta \in \mathbb{R}_+$	$\mathcal{N}(\theta \mu, \sigma^2) = \frac{1}{\theta\sigma\sqrt{2\pi}} \exp\left(-\frac{(\ln \theta-\mu)^2}{2\sigma^2}\right)$	$\mu \in \mathbb{R}, \sigma^2 \in \mathbb{R}_+$
Multivariate hyperpriors supported all over \mathbb{R}^D with mean μ and covariance Σ			
GaussMulti	multivariate normal distribution $\theta \in \mathbb{R}^D$	$ 2\pi\Sigma ^{-\frac{1}{2}} \exp\left(-\frac{1}{2}(\theta-\mu)^\top \Sigma^{-1}(\theta-\mu)\right)$	$\mu \in \mathbb{R}^D, \Sigma \in \mathbb{R}^{D \times D}$
LaplaceMulti	multivariate Laplace distribution $\theta \in \mathbb{R}^D$	$ \sqrt{2\Sigma} ^{-\frac{1}{2}} \exp\left(-\sqrt{2}\ L^{-1}(\theta-\mu)\ _1\right), L^\top L = \Sigma$	$\mu \in \mathbb{R}^D, \Sigma \in \mathbb{R}^{D \times D}$
TMulti	multivariate Student's t distribution $\theta \in \mathbb{R}^D$	$ (\nu-2)\pi\Sigma ^{-\frac{1}{2}} \frac{\Gamma(\frac{\nu+D}{2})}{\Gamma(\frac{\nu}{2})} \left(1 + \frac{(\theta-\mu)^\top \Sigma^{-1}(\theta-\mu)}{(\nu-2)}\right)^{-\frac{\nu+D}{2}}$	$\mu \in \mathbb{R}^D, \Sigma \in \mathbb{R}^{D \times D}, \nu \in \mathbb{R}$
Improper hyperpriors used to fix the value of a particular hyperparameter			
Delta	clamped hyperparameter $\theta = \theta_0 \in \mathbb{R}$	$\delta(\theta - \theta_0)$	\emptyset
Clamped			
DeltaMulti			
ClampedMulti			
Composite hyperpriors $[\pi_1(\theta), \pi_2(\theta), \dots] \mapsto p(\theta)$			
Transform	prior distribution on $g(\theta)$ instead of θ	$\pi(g(\theta))$	$\{g\}$
Mix	mixture distribution	$\sum_i w_i \pi_i(\theta)$	$\{w\}$

The `priorSmoothBox2` is a Gauss-uniform sandwich obtained by complementing a uniform distribution on $[a, b]$ with two Gaussian halves at each side. The parameter η balances the probability mass between the constituents so that $\eta/(\eta+1)$ is used for the box and $1/(\eta+1)$ for the Gaussian sides. Its brother `priorSmoothBox1` is the product of two sigmoidal functions.

The `priorDelta` or equivalently `priorClamped` can be used to exclude some hyperparameters from the optimisation. Their values are clamped to θ_0 and the derivative vanishes. There are also multivariate counterparts `priorDeltaMulti` and `priorClampedMulti`.

7.3 Usage of Implemented Hyperpriors

Some code examples taken from `doc/usagePrior.m` illustrate how to use univariate, multivariate and composite priors on hyperparameters. Syntactically, a hyperprior `hp` is defined by

```

func := Dist                                // prior distributions in prior/
      | Clamped | Delta // predefined for fixing the hyperparameter

pr  := 'func'                               // univariate hyperprior
      | 'funcMulti' | @funcMulti           // multivariate hyperprior

hp  := {pr} | {pr, {param, hp}} | {pr, {hp, ..., hp}} // composite

```

i.e., it is either a string containing the name of a hyperprior function, a pointer to a hyperprior function or one of the former in combination with a cell array of hyperprior functions and an additional list of parameters. Furthermore, we have multivariate hyperprior variants and 2 (equivalent) predefined hyperpriors allowing to exclude variables from optimisation.

```

45 <doc/usagePrior.m 45>≡
1 % demonstrate usage of prior distributions
2 %
3 % See also priorDistributions.m.
4 %
5 <gpml copyright 6a>
6 clear all, close all
7
8 % 1) specify some priors
9 % a) univariate priors
10 mu = 1.0; s2 = 0.01^2; nu = 3;
11 pg = {@priorGauss,mu,s2}; % Gaussian prior
12 pl = {'priorLaplace',mu,s2}; % Laplace prior
13 pt = {@priorT,mu,s2,nu}; % Student's t prior
14 p1 = {@priorSmoothBox1,0,3,15}; % smooth box constraints lin decay
15 p2 = {@priorSmoothBox2,0,2,15}; % smooth box constraints qua decay
16 pd = {'priorDelta'}; % fix value of prior exclude from optimisation
17 pc = {@priorClamped}; % equivalent to above
18 lam = 1.05; k = 2.5;
19 pw = {@priorWeibull,lam,k}; % Weibull prior
20
21 % b) meta priors
22 pmx = {@priorMix,[0.5,0.5],{pg,pl}}; % mixture of two priors
23 g = @exp; dg = @exp; ig = @log;
24 ptr = {@priorTransform,g,dg,ig,pg}; % Gaussian in the exp domain
25
26 % c) multivariate priors
27 m = [1;2]; V = [2,1;1,2];
28 pG = {@priorGaussMulti,m,V}; % 2d Gaussian prior
29 pD = {'priorDeltaMulti'}; % fix value of prior exclude from optim
30 pC = {@priorClampedMulti}; % equivalent to above
31
32 % 2) evaluation
33 % pri = pt; hp = randn(1,3);
34 % pri = pmx; hp = randn(1,3);
35 % pri = ptr; hp = randn(1,3);
36 pri = pG; hp = randn(2,3);
37
38 % a) draw a sample from the prior
39 feval(pri{:})
40
41 % b) evaluate prior and derivative if requires
42 [lp,dlp] = feval(pri{:},hp)
43
44 % 3) comprehensive example
45 x = (0:0.1:10)'; y = 2*x+randn(size(x)); % generate training data
46 mean = {@meanSum,{@meanConst,@meanLinear}}; % specify mean function
47 cov = {@covSEiso}; lik = {@likGauss}; % specify covariance and lik
48 hyp.cov = [log(1);log(1.2)]; hyp.lik = log(0.9); hyp.mean = [2;3];
49 par = {mean,cov,lik,x,y}; mfun = @minimize; % input for GP function
50
51 % a) plain marginal likelihood optimisation (maximum likelihood)
52 im = @infExact; % inference method

```

```

53 hyp_plain = feval(mfun, hyp, @gp, -10, im, par{:});      % optimise
54
55 % b) regularised optimisation (maximum a posteriori) with 1d priors
56 prior.mean = {pg;pc}; % Gaussian prior for first, clamp second par
57 prior.cov = {p1;[]}; % box prior for first, nothing for second par
58 im = {@infPrior,@infExact,prior}; % inference method
59 hyp_p1 = feval(mfun, hyp, @gp, -10, im, par{:});      % optimise
60
61 % c) regularised optimisation (maximum a posteriori) with Nd priors
62 prior = []; % clear the structure
63 % multivariate Student's t prior on the first and second mean hyper
64 prior.multi{1} = {@priorTMulti,[mu;mu],diag([s2,s2]),nu,...
65                 struct('mean',[1,2])}; % use hyper struct
66 % Equivalent shortcut (same mu and s2 for all dimensions)
67 prior.multi{1} = {@priorTMulti,mu,s2,nu,struct('mean',[1,2])};
68 % multivariate Gaussian prior jointly on 1st and 3rd hyper
69 prior.multi{2} = {@priorGaussMulti,[mu;mu],diag([s2,s2]),...
70                 [1,3]}; % use unwrapped hyper vector
71 % Equivalent shortcut (same mu and s2 for all dimensions)
72 prior.multi{2} = {@priorGaussMulti,mu,s2,[1,3]};
73 im = {@infPrior,@infExact,prior}; % inference method
74 hyp_pN = feval(mfun, hyp, @gp, -10, im, par{:});      % optimise
75
76 [unwrap(hyp), unwrap(hyp_plain), unwrap(hyp_p1), unwrap(hyp_pN)]

```