

Defining a latent model in R: The `rgeneric` model

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Introduction

This is a class of generic models allows the user to define latent model component in R, for cases where the requested model is not yet implemented in INLA, and do the Bayesian inference using INLA. Since the model component has to be interpreted in R, it will run slower compared to a similar model implemented in INLA.

Defining a latent model in R

A `rgeneric` model is defined in a function `rmodel` (to be defined later), and the usage is quite simple. First we need to define a `inla-rgeneric` object

```
model = inla.rgeneric.define(rmodel, ...)
```

with additional variables/functions/etc in `...` that we might use in `rmodel`. This can be the size, prior parameters, covariates, external functions and so on. This object can then be used to define a normal model component in INLA using `f()`,

```
y ~ ... + f(idx, model=model, ...)
```

where `idx` can take values $1, 2, \dots, n$ where `n` is the size of `model`. All additional features for `f()` will still be valid.

Example: The AR1 model

The function `rmodel` needs to follow some rules to provide the required features. We explain this while demonstrating how to implement the AR1-model. This model already exists, see `inla.doc("ar1")`. With the parameterisation we use, the AR1-model is defined as

$$x_1 \sim \mathcal{N}(0, \tau) \quad \text{and} \quad x_t | x_1, \dots, x_{t-1} \sim \mathcal{N}(\rho x_{t-1}, \tau_I), \quad t = 2, \dots, n.$$

where $\tau_I = \tau/(1 - \rho^2)$. The scale-parameter is the *marginal precision* τ , **not** the commonly used innovation precision τ_I . The joint density of x is Gaussian

$$\pi(x|\rho, \tau) = \left(\frac{1}{\sqrt{2\pi}}\right)^n \tau_I^{n/2} (1 - \rho^2)^{1/2} \exp\left(-\frac{\tau_I}{2} x^T R x\right)$$

where the precision-matrix is

$$Q = \tau_I R = \tau_I \begin{bmatrix} 1 & -\rho & & & \\ -\rho & 1 + \rho^2 & -\rho & & \\ & -\rho & 1 + \rho^2 & -\rho & \\ & & \ddots & \ddots & \ddots \\ & & & -\rho & 1 + \rho^2 & -\rho \\ & & & & -\rho & 1 \end{bmatrix}$$

There are two (hyper-)parameters for this model: the marginal precision τ and the lag-one correlation ρ . We will reparameterise these as

$$\tau = \exp(\theta_1), \quad \text{and} \quad \rho = 2 \frac{\exp(\theta_2)}{1 + \exp(\theta_2)} - 1.$$

It is required that the parameters $\theta = (\theta_1, \theta_2)$ have support on \mathbb{R}^2 and the priors for τ and ρ are given as the corresponding priors for θ_1 and θ_2 .

A good re-parameterisation is required for INLA to work well. A good parameterisation makes, ideally, the *Fisher information matrix* of θ constant with respect to θ . It is sufficient to check this in a frequentistic setting with data directly from the AR(1) model, in this case. INLA will provide the posterior marginals for θ , but `inla.tmarginal()` can be used to convert it to the appropriate marginals for ρ and τ .

We assign Gamma prior $\Gamma(\cdot; a, b)$ (with mean a/b and variance a/b^2) for τ and a Gaussian prior $\mathcal{N}(\mu, \kappa)$ for θ_2 , so the joint prior for θ becomes

$$\pi(\theta) = \Gamma(\exp(\theta_1); a, b) \exp(\theta_1) \times \mathcal{N}(\theta_2; \mu, \kappa).$$

The extra term, $\exp(\theta_1)$ is the Jacobian for the change of variable from τ to θ_1 . We will in this example use $a = b = 1$, $\mu = 0$ and $\kappa = 1$.

In order to define the AR1-model, we need to make R-functions that returns

- the graph,
- the precision matrix $Q(\theta)$,
- the zero mean,
- the initial values of θ ,
- the log-normalising constant, and
- the log-prior

We need to incorporate these functions into `rmodel`, in the following way

```
inla.rgeneric.ar1.model = function(
  cmd = c("graph", "Q", "mu", "initial", "log.norm.const",
          "log.prior", "quit"),
  theta = NULL)
{
  # for reference and potential storage for objects to
  # cache, this is the environment of this function
  # which holds arguments passed as `...` in
  # `inla.rgeneric.define()`.
  envir = environment(sys.call()[[1]])

  graph = function(){ <to be completed> }
  Q = function() { <to be completed> }
  mu = function() { <to be completed> }
  log.norm.const = function() { <to be completed> }
  log.prior = function() { <to be completed> }
  initial = function() { <to be completed> }
  quit = function() { <to be completed> }

  # sometimes this is useful, as argument 'graph' and 'quit'
  # will pass theta=NULL as the values of theta are not
  # required for defining the graph. however, this statement
  # will ensure that theta is always defined.
  if (is.null(theta)) theta = initial()
}
```

```

    val = do.call(match.arg(cmd), args = list())
    return (val)
}

```

The input parameters are

- **cmd** What to return
- **theta** The values of the θ -parameters

Other parameters in the model definition, like n and possibly the parameters of the prior, goes into the ... part of `inla.rgeneric.define()`, like

```
model = inla.rgeneric.define(inla.rgeneric.ar1.model, n = 100)
```

and is assigned in the environment of `inla.rgeneric.ar1.model`. Using variable `n` inside this function will then return 100. This environment can also be accessed as `envir` as defined in the function skeleton. Sometimes this is useful, to hold static variables or to cache intermediate calculations.

Our next task, is to *fill in the blanks* and define the functions required. To help us, we will add a function that return a list of the **real** parameters in the model from θ ,

```

interpret.theta = function() {
  return(list(prec = exp(theta[1L]),
             rho = 2 * exp(theta[2L]) / (1 + exp(theta[2L])) - 1))
}

```

Since `theta` exist already within `inla.rgeneric.ar1.model` we do not need to pass it as an argument.

We also assume that variable `n` is defined as an argument in `inla.rgeneric.define()`.

Function graph()

This is normally an easy function to add, as it is essentially the matrix Q . One can construct cases where this is not so¹, and for this reason it exists as a separate function. The only thing that matter is if the elements are zero or non-zero. Also, it should return a **sparse matrix** as we do not want to pass n^2 elements when $\mathcal{O}(n)$ are sufficient. Also, only the upper triangular matrix (diagonal included) are actually used, since the graph must be symmetric.

```

graph = function() {
  return (Q())
}

```

function Q()

This is normally the most tricky function, as we need to return the precision matrix (as a sparse matrix) for the given values of θ . Only the upper triangular matrix (diagonal included) are read.

A *dense matrix* version is as follows, and is easier to read

```

Q = function() {
  p = interpret.theta()
  Q = p$prec / (1 - p$rho^2) *
    toeplitz(c(1 + p$rho^2, -p$rho, rep(0, n - 2L)))
  Q[1, 1] = Q[n, n] = p$prec / (1 - p$rho^2)
  return (inla.as.sparse(Q))
}

```

¹Depending on θ an element Q_{ij} might be exactly zero

The function `inla.as.sparse()` convert a matrix or sparse matrix, into the appropriate sparse matrix format used internally in INLA. This version of `Q()` creates a dense matrix and then make it sparse, and is not the way to do it. The better way, is to define the (upper triangular) sparse matrix directly using `sparseMatrix`.

```
Q = function() {
  p = interpret.theta()
  i = c(1L, n, 2L:(n - 1L), 1L:(n - 1L))
  j = c(1L, n, 2L:(n - 1L), 2L:n)
  x = p$prec/(1 - p$rho^2) *
    c(1L, 1L, rep(1 + p$rho^2, n - 2L),
      rep(-p$rho, n - 1L))
  return (sparseMatrix(i = i, j = j, x = x, giveCsparse = FALSE))
}
```

This is both faster and requires less memory, but it gets somewhat unreadable and hard to debug. The dense matrix version above, is at least easier to debug against for reasonable values of n .

Function `mu()`

This function must return the mean which might depend on θ . The convention, is that if `numeric(0)` is returned, then the mean is zero.

```
mu = function() {
  return(numeric(0))
}
```

Function `log.norm.const()`

This function must return the log of the normalising constant. For the AR1-model the normalising constant is

$$\left(\frac{1}{\sqrt{2\pi}}\right)^n \tau_I^{n/2} (1 - \rho^2)^{1/2}$$

where

$$\tau_I = \tau / (1 - \rho^2).$$

The function can then be implemented as

```
log.norm.const = function() {
  p = interpret.theta()
  prec.i = p$prec / (1.0 - p$rho^2)
  val = n * (- 0.5 * log(2*pi) + 0.5 * log(prec.i)) +
    0.5 * log(1.0 - p$rho^2)
  return (val)
}
```

Since the normalizing constant is known, we can ask INLA to evaluate

$$-\frac{n}{2} \log(2\pi) + \frac{1}{2} \log(|Q(\theta)|)$$

and $\log|Q(\theta)|$ can be computed from the sparse Cholesky factorisation of $Q(\theta)$. In this case we can return `numeric(0)` (which is a code for “compute it yourself, please!”)

```
log.norm.const = function() {
  return (numeric(0))
}
```

Unless the log-normalizing constant is known analytically (and the precision matrix depends on θ) it is both better, and easier, just to return `numeric(0)`.

Function `log.prior()`

This function must return the (log-)prior of the prior density for θ . For the AR1-model, we have for simplicity chosen this prior

$$\pi(\theta) = \Gamma(\exp(\theta_1); a, b) \exp(\theta_1) \times \mathcal{N}(\theta_2; \mu, \kappa)$$

so we can implement this as with our choices $a = b = 1$, $\mu = 0$ and $\kappa = 1$ as

```
log.prior = function() {
  p = interpret.theta()
  val = dgamma(p$prec, shape = 1, rate = 1, log=TRUE) + theta[1L] +
    dnorm(theta[2L], mean = 0, sd = 1, log=TRUE)
  return (val)
}
```

The parameters in the joint prior can also be defined in the `inla.rgeneric.define()` call, by adding arguments `a=1`, `b=1` and so on.

Note that `log.prior()` must return the log prior for θ , and not the prior for the more natural parameters defined in `interpret.theta()`.

Function `initial()`

This function returns the initial values for θ , like

```
initial = function() {
  return (rep(1, 2))
}
```

or `numeric(0)` if there are no θ 's. For a precision parameters it is generally advisable to choose a high precision as the initial value, as this helps the optimizer. INLA generally use initial value 4 for log precisions.

Function `quit()`

This function is called when all the computations are done and before exit-ing the C-program. If there is some cleanup to do, you can do this here. In our example, there is nothing to do.

```
quit = function() {
  return (invisible())
}
```

Example of usage

Here is an example of use. The function `inla.rgeneric.ar1.model()` contains the functions given above, and can be used directly like this.

```

n = 100
rho=0.9
x = arima.sim(n, model = list(ar = rho)) * sqrt(1-rho^2)
y = x + rnorm(n, sd = 0.1)
model = inla.rgeneric.define(inla.rgeneric.ar1.model, n=n)
formula = y ~ -1 + f(idx, model=model)
r = inla(formula, data = data.frame(y, idx = 1:n))

```

We can also compare with the built-in version, if we make sure to use the same priors

```

fformula = y ~ -1 +
  f(idx, model = "ar1",
    hyper = list(prec = list(prior = "loggamma", param = c(1,1)),
      rho = list(prior = "normal", param = c(0,1))))
rr = inla(fformula, data = data.frame(y, idx = 1:n))

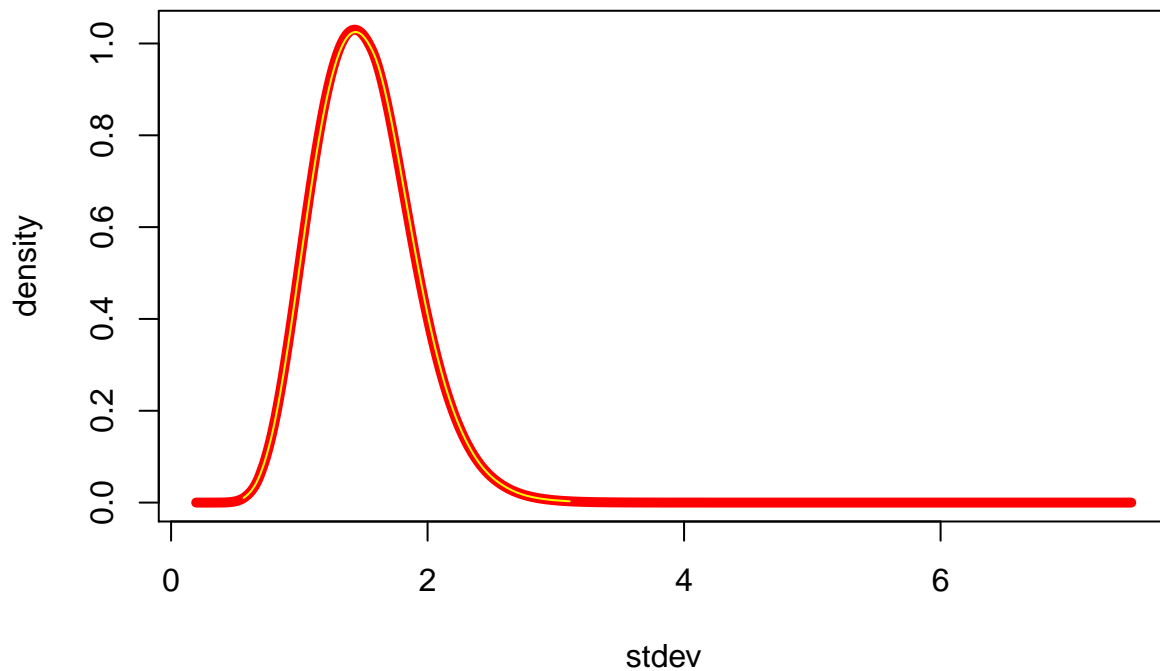
```

and plot the hyperparameters in the same scale

```

plot(inla.s marginal(rr$marginals.hyperpar[[2]]),
  type="l", lwd=5, col="red", xlab="stdev", ylab="density")
lines(inla.t marginal(exp, r$internal.marginals.hyperpar[[2]]),
  col="yellow")

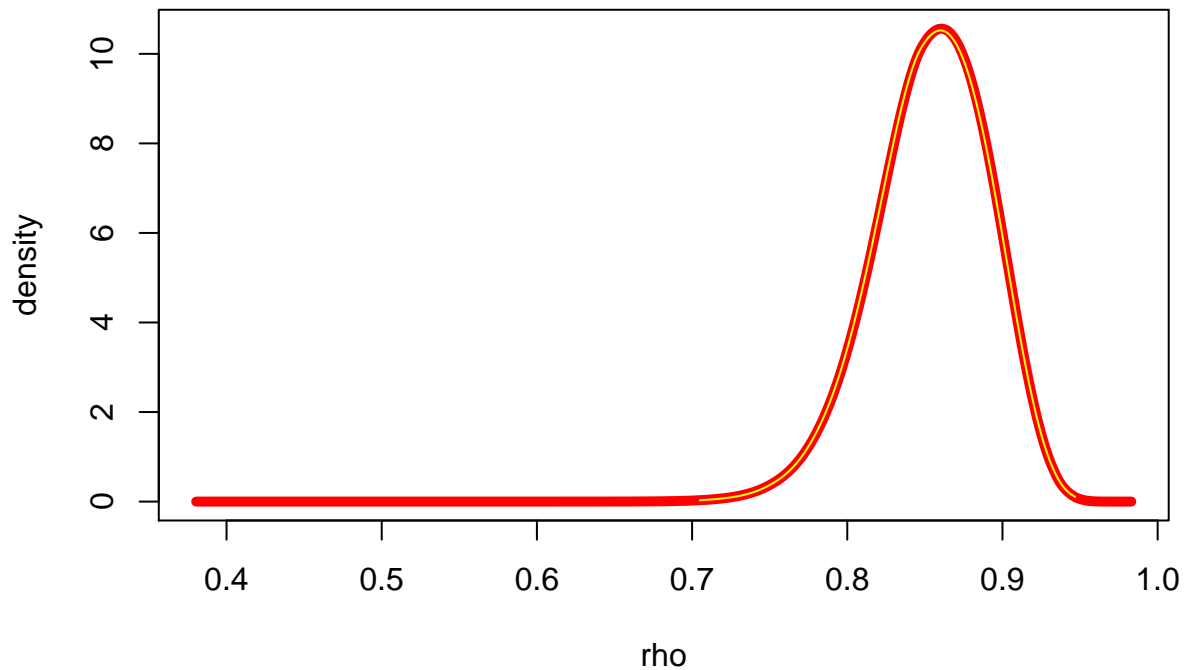
```



```

plot(inla.s marginal(rr$marginals.hyperpar[[3]]),
  type="l", lwd=5, col="red", xlab="rho", ylab="density")
lines(inla.t marginal(function(x) 2*exp(x)/(1+exp(x))-1,
  r$internal.marginals.hyperpar[[3]]),
  col="yellow")

```



The

running time will of course be quite different

```
round(rbind(native = rr$cpu.used,
            rgeneric = r$cpu.used), digits = 3)
```

```
##           Pre Running Post Total
## native    0.455   0.168 0.037 0.660
## rgeneric  0.464   1.869 0.049 2.382
```

Example: The iid-model

The following function defines the iid-model, see `inla.doc("iid")`, which we give without further comments. To run this model in R, you may run `demo(rgeneric)`.

```
inla.rgeneric.iid.model
```

```
## function (cmd = c("graph", "Q", "mu", "initial", "log.norm.const",
##   "log.prior", "quit"), theta = NULL)
## {
##   envir = environment(sys.call()[[1]])
##   interpret.theta = function() {
##     return(list(prec = exp(theta[1L])))
##   }
##   graph = function() {
##     G = Diagonal(n, x = rep(1, n))
##     return(G)
##   }
##   Q = function() {
##     prec = interpret.theta()$prec
##     Q = Diagonal(n, x = rep(prec, n))
##     return(Q)
##   }
##   mu = function() {
```

```

##      return(numeric(0))
##    }
##    log.norm.const = function() {
##      prec = interpret.theta()$prec
##      val = sum(dnorm(rep(0, n), sd = 1/sqrt(prec), log = TRUE))
##      return(val)
##    }
##    log.prior = function() {
##      prec = interpret.theta()$prec
##      val = dgamma(prec, shape = 1, rate = 1, log = TRUE) +
##        theta[1L]
##      return(val)
##    }
##    initial = function() {
##      ntheta = 1
##      return(rep(1, ntheta))
##    }
##    quit = function() {
##      return(invisible())
##    }
##    if (is.null(theta))
##      theta = initial()
##    val = do.call(match.arg(cmd), args = list())
##    return(val)
##  }
## <bytecode: 0x5562fd54f630>
## <environment: namespace:INLA>

```

Example: A model for the mean structure

Up to now, we have assumed zero mean. In this example, we will illustrate how to add a non-zero mean model, focusing on the mean model only. We can of course have a mean model and a non-trivial precision matrix together.

```

## In this example we do linear regression using 'rgeneric'.
## The regression model is  $y = a + b \cdot x + \text{noise}$ , and we
## define ' $a + b \cdot x + \text{tiny.noise}$ ' as a latent model.
## The dimension is length(x) and number of hyperparameters
## is 2 ('a' and 'b').

```

```

rgeneric.linear.regression =
  function(cmd = c("graph", "Q", "mu", "initial", "log.norm.const",
    "log.prior", "quit"),
    theta = NULL)
{
  envir = environment(sys.call()[[1]])

  ## artificial high precision to be added to the mean-model
  prec.high = exp(15)

  interpret.theta = function() {
    return(list(a = theta[1L], b = theta[2L]))
  }
}

```



```

graph = function() {
  G = Diagonal(n = length(x), x=1)
  return(G)
}

Q = function() {
  Q = prec.high * graph()
  return(Q)
}

mu = function() {
  par = interpret.theta()
  return(par$a + par$b * x)
}

log.norm.const = function() {
  return(numeric(0))
}

log.prior = function() {
  par = interpret.theta()
  val = (dnorm(par$a, mean=0, sd=1, log=TRUE) +
        dnorm(par$b, mean=0, sd=1, log=TRUE))
  return(val)
}

initial = function() {
  return(rep(0, 2))
}

quit = function() {
  return(invisible())
}

val = do.call(match.arg(cmd), args = list())
return(val)
}

```

and we can run this as

```

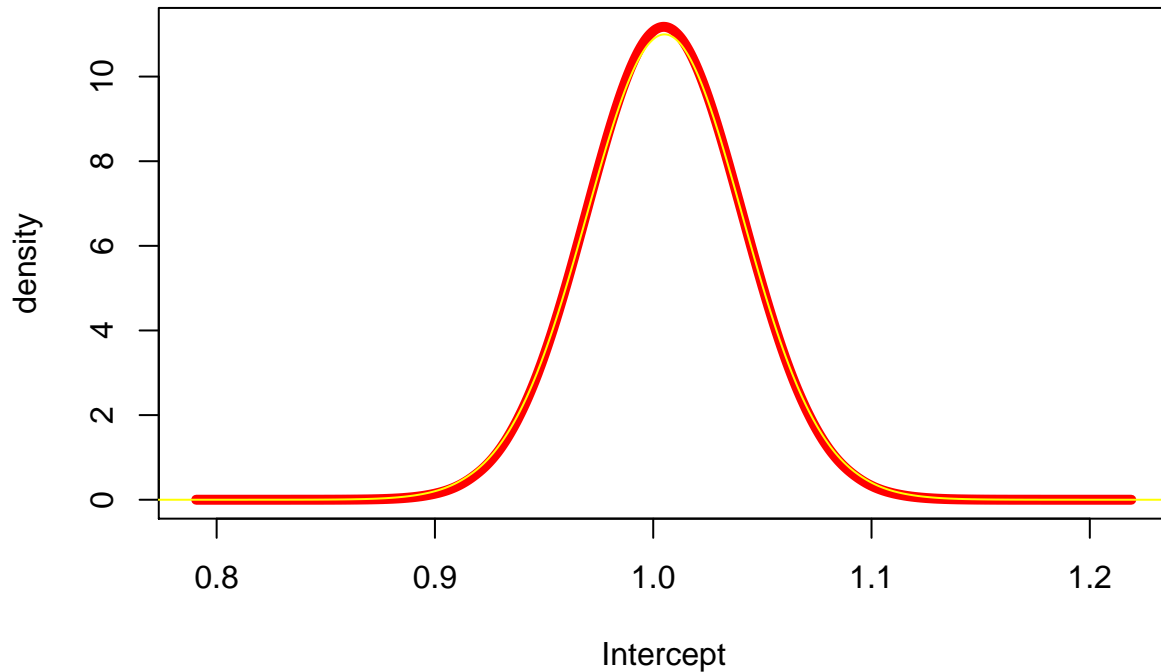
a = 1
b = 2
n = 50
x = rnorm(n)
eta = a + b*x
s = 0.25
y = eta + rnorm(n, sd=s)

rgen = inla.rgeneric.define(model = rgeneric.linear.regression, x=x)
r = inla(y ~ -1 + f(idx, model=rgen),
        data = data.frame(y, idx = 1:n))
rr = inla(y ~ 1 + x,
         data = data.frame(y, x),
         control.fixed = list(prec.intercept = 1, prec = 1))

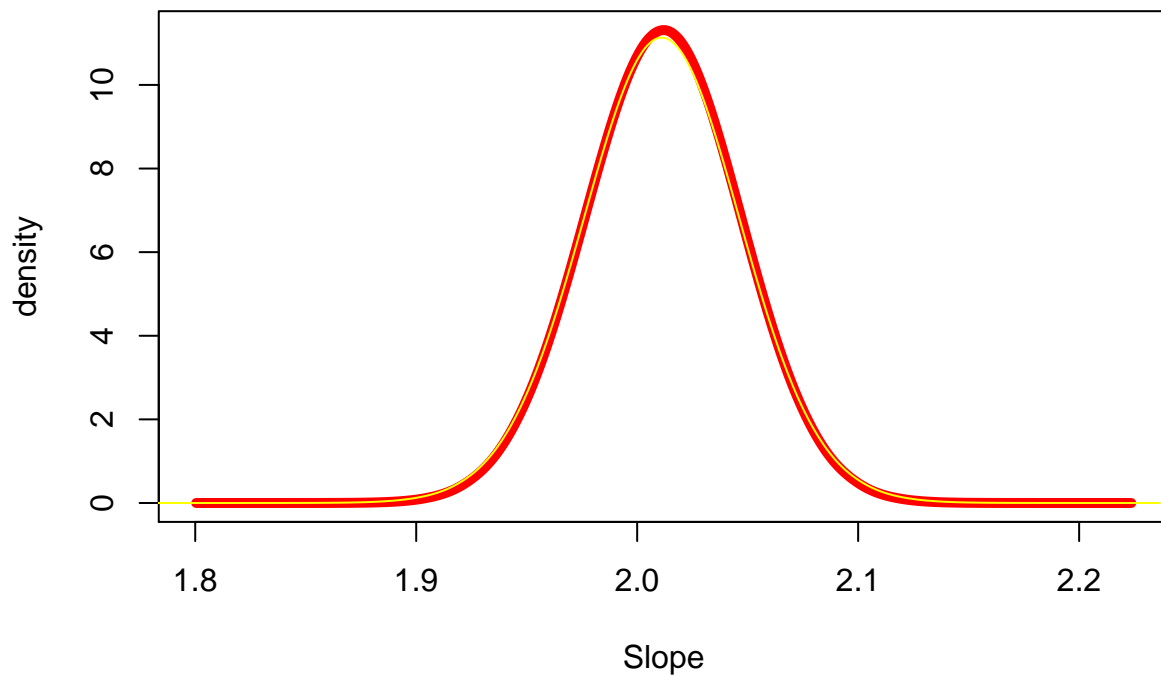
```

and we can compare the results with the native model

```
plot(inla.ssmarginal(r$marginals.hyperpar[['Theta1 for idx']]),
     type="l", lwd=5, col="red", xlab="Intercept", ylab="density")
lines(inla.ssmarginal(rr$marginals.fixed$('Intercept)'), col="yellow")
```



```
plot(inla.ssmarginal(r$marginals.hyperpar[['Theta2 for idx']]),
     type="l", lwd=5, col="red", xlab="Slope", ylab="density")
lines(inla.ssmarginal(rr$marginals.fixed$x), col="yellow")
```

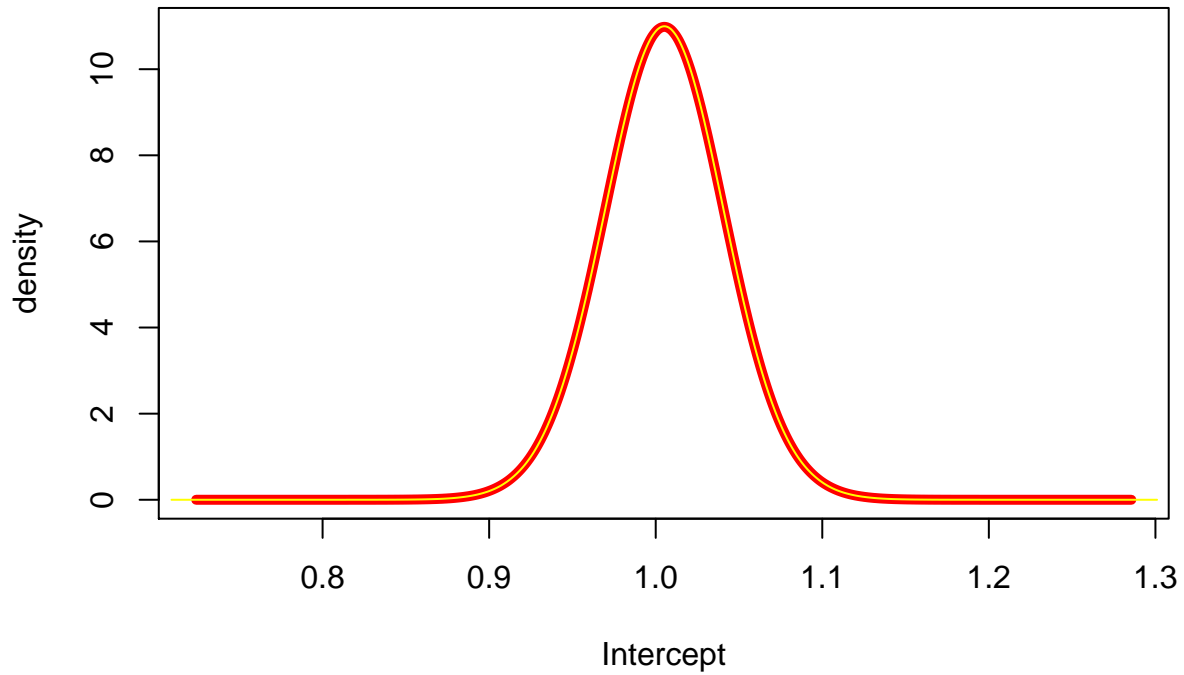


The tiny in-accuracy is due to treatment of `a` and `b` as hyperparameters in the `rgeneric` model. We can improve the estimates using `inla.hyperpar()` as usual,

```
r = inla.hyperpar(r)
```

Replotting the results shows improvement:

```
plot(inla.smarginal(r$marginals.hyperpar[['Theta1 for idx']]),  
     type="l", lwd=5, col="red", xlab="Intercept", ylab="density")  
lines(inla.smarginal(rr$marginals.fixed$('Intercept)'), col="yellow")
```



```
plot(inla.smarginal(r$marginals.hyperpar[['Theta2 for idx']]),  
     type="l", lwd=5, col="red", xlab="Slope", ylab="density")  
lines(inla.smarginal(rr$marginals.fixed$x), col="yellow")
```

