

# ADVANCED TOPICS IN POMP

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This document serves to introduce the low-level interface to **pomp** objects and to give some examples of the use of native (C or FORTRAN) codes in **pomp**.

### 1. THE LOW-LEVEL INTERFACE

There is a low-level interface to **pomp** objects, primarily designed for package developers. Ordinary users should have little reason to use this interface. In this section, each of the methods that make up this interface will be introduced.

The `init.state` method is called to initialize the state (unobserved) process. It takes a vector or matrix of parameters and returns a matrix of initial states.

```
data(ou2)
true.p <- coef(ou2)
x0 <- init.state(ou2)
x0

[,1]
x1   50
x2  -50

new.p <- cbind(true.p, true.p, true.p)
new.p["x1.0",] <- 1:3
init.state(ou2, params=new.p)

[,1] [,2] [,3]
x1   1   2   3
x2 -50 -50 -50
```

The `rprocess` method gives access to the process model simulator. It takes initial conditions (which need not correspond to the zero-time `t0` specified when the **pomp** object was constructed), a set of times, and a set of parameters. The initial states and parameters must be matrices, and they are checked for commensurability. The method returns a rank-3 array containing simulated state trajectories, sampled at the times specified.

```
x <- rprocess(ou2,xstart=x0,times=time(ou2,t0=T),params=as.matrix(true.p))
dim(x)

[1] 2 1 101

x[,1:5]

      [,1]      [,2]      [,3]      [,4]      [,5]
x1  50 44.30555 39.77838 37.21832 33.96139
x2 -50 -47.31719 -47.78786 -42.91187 -46.40403
```

Note that the dimensions of `x` are `nvars x nreps x ntimes`, where `nvars` is the number of state variables, `nreps` is the number of simulated trajectories (which is the number of columns in the `params` and `xstart` matrices), and `ntimes` is the length of the `times` argument. Note also that `x[,1]` is identical to `xstart`.

The `rmeasure` method gives access to the measurement model simulator:

```
x <- x[,,-1,drop=F]
y <- rmeasure(ou2,x=x,times=time(ou2),params=as.matrix(true.p))
dim(y)

[1] 2 1 100

y[,1:5]

      [,1]      [,2]      [,3]      [,4]      [,5]
y1 46.04027 39.85474 37.20344 34.09994 31.55727
y2 -46.63870 -46.11194 -41.49220 -47.41769 -45.55778
```

The `dmeasure` and `dprocess` methods give access to the measurement and process model densities, respectively.

```
fp <- dprocess(ou2,x=x,times=time(ou2),params=as.matrix(true.p))
dim(fp)

[1] 1 99

fp[,36:40]

[1] 0.01907030 0.02469285 0.03349765 0.05539911 0.04743258

fm <- dmeasure(ou2,y=y[,1,],x=x,times=time(ou2),params=as.matrix(true.p))
dim(fm)

[1] 1 100

fm[,36:40]

[1] 0.118826706 0.065905743 0.016613495 0.118275252
[5] 0.008519114
```

All of these are to be preferred to direct access to the slots of the `pomp` object, because they do sanity checks on the inputs and outputs.

## 2. ACCELERATION USING NATIVE CODES.

Since many of the methods we will use require us to simulate the process and/or measurement models many times, it is a good idea to use native (compiled) codes for the computational heavy lifting. This can result in many-fold speedup. The `pomp` package includes some examples that use C codes. Here, we'll have a look at how the discrete-time 2-D Ornstein-Uhlenbeck process with normal measurement error is implemented.

Recall that the unobserved Ornstein-Uhlenbeck (OU) process  $X_t \in \mathbb{R}^2$  satisfies

$$X_t = A X_{t-1} + \xi_t.$$

The observation process is

$$Y_t = B X_t + \varepsilon_t.$$

In these equations,  $A$  and  $B$  are  $2 \times 2$  constant matrices;  $\xi_t$  and  $\varepsilon_t$  are mutually-independent families of i.i.d. bivariate normal random variables. We let  $\sigma\sigma^T$  be the variance-covariance matrix of  $\xi_t$ , where  $\sigma$  is lower-triangular; likewise, we let  $\tau\tau^T$  be that of  $\varepsilon_t$ .

You can load a `pomp` object for this model with the command

```
data(ou2)
```

Here we'll examine how this object is put together.

The process model simulator and density functions are as follows:

```
ou2.rprocess <- function (xstart, times, params, paramnames, ...) {
  nvar <- nrow(xstart)
  npar <- nrow(params)
  nrep <- ncol(xstart)
  ntimes <- length(times)
  ## get indices of the various parameters in the 'params' matrix
  ## C uses zero-based indexing!
  parindex <- match(paramnames, rownames(params))-1
  array(
    .C("ou2_adv",
      X = double(nvar*nrep*ntimes),
      xstart = as.double(xstart),
      par = as.double(params),
      times = as.double(times),
      n = as.integer(c(nvar,npar,nrep,ntimes)),
      parindex = as.integer(parindex),
      DUP = FALSE,
      NAOK = TRUE,
      PACKAGE = "pomp"
    )$X,
    dim=c(nvar,nrep,ntimes),
    dimnames=list(rownames(xstart),NULL,NULL)
  )
}

ou2.dprocess <- function (x, times, params, log, paramnames, ...) {
  nvar <- nrow(x)
  npar <- nrow(params)
  nrep <- ncol(x)
  ntimes <- length(times)
```

```

parindex <- match(paramnames,rownames(params))-1
array(
  .C("ou2_pdf",
    d = double(nrep*(ntimes-1)),
    X = as.double(x),
    par = as.double(params),
    times = as.double(times),
    n = as.integer(c(nvar,npar,nrep,ntimes)),
    parindex = as.integer(parindex),
    give_log=as.integer(log),
    DUP = FALSE,
    NAOK = TRUE,
    PACKAGE = "pomp"
  )$d,
  dim=c(nrep,ntimes-1)
)
}

```

The call that constructs the `pomp` object is:

```

ou2 <- pomp(
  times=seq(1,100),
  data=rbind(
    y1=rep(0,100),
    y2=rep(0,100)
  ),
  t0=0,
  rprocess = ou2.rprocess,
  dprocess = ou2.dprocess,
  dmeasure = "normal_dmeasure",
  rmeasure = "normal_rmeasure",
  paramnames=c(
    "alpha.1", "alpha.2", "alpha.3", "alpha.4",
    "sigma.1", "sigma.2", "sigma.3",
    "tau"
  ),
  statenames = c("x1", "x2"),
  PACKAGE="pomp"
)

```

Notice that the process model is implemented using using `.C`, while the measurement model is specified by giving the names of native C routines. Read the source (file ‘ou2.c’) to see the definitions of these functions.

We’ll specify some parameters:

```

p <- c(
  alpha.1=0.9, alpha.2=0, alpha.3=0, alpha.4=0.99,
  sigma.1=1, sigma.2=0, sigma.3=2,
  tau=1, x1.0=50, x2.0=-50
)

tic <- Sys.time()
x <- simulate(ou2, params=p, nsim=500, seed=800733088)

```

```
toc <- Sys.time()
print(toc-tic)
```

Time difference of 1.415693 secs

In this example, we've written our simulators and density functions "from scratch". `pomp` provides "plug-in" facilities to make it easier to define certain kinds of models. These plug-ins can be used with native codes as well, as we'll see in the next example.

### 3. A MORE COMPLEX EXAMPLE: A SEASONAL SIR MODEL

The SIR model is a mainstay of theoretical epidemiology. It has the deterministic skeleton

$$\begin{aligned}\frac{dS}{dt} &= \mu(N - S) + \beta(t) \frac{I}{N} S \\ \frac{dI}{dt} &= \beta(t) \frac{I}{N} S - \gamma I - \mu I \\ \frac{dR}{dt} &= \gamma I - \mu R\end{aligned}$$

Here  $N = S + I + R$  is the (constant) population size and  $\beta$  is a time-dependent contact rate. We'll assume that the contact rate is periodic and implement it as a covariate. We'll implement a stochastic version of this model using an Euler-multinomial approximation to the continuous-time Markov process. As an additional wrinkle, we'll assume that the rate of the infection process  $\beta I/N$  is perturbed by white noise.

```
euler.sir <- pomp(
  times=seq(1/52,4,by=1/52),
  data=rbind(measles=numeric(52*4)),
  t0=0,
  tcovar=seq(0,25,by=1/52),
  covar=matrix(
    periodic.bspline.basis(seq(0,25,by=1/52),nbasis=3,period=1,degree=3),
    ncol=3,
    dimnames=list(NULL,paste("seas",1:3,sep=' '))
  ),
  delta.t=1/52/20,
  statenames=c("S","I","R","cases","W","B","dW"),
  paramnames=c("gamma","mu","iota","beta1","beta.sd","pop","rho"),
  covarnames=c("seas1"),
  zeronames=c("cases"),
  comp.names=c("S","I","R"),
  rprocess=euler.simulate,
  step.fun="sir_euler_simulator",
  dprocess=onestep.density,
  dens.fun="sir_euler_density",
  skeleton.vectorfield="sir_ODE",
  rmeasure="binom_rmeasure",
  dmeasure="binom_dmeasure",
  PACKAGE="pomp",
  initializer=function(params, t0, comp.names, ...){
    p <- exp(params)
    snames <- c(
      "S","I","R","cases","W","B",
```

```

        "SI", "SD", "IR", "ID", "RD", "dW"
      )
      fracs <- p[paste(comp.names, "0", sep=".")]
      x0 <- numeric(length(snames))
      names(x0) <- snames
      x0[comp.names] <- round(p['pop']*fracs/sum(frac))
      x0
    }
  )

coef(euler.sir) <- log(
  c(
    gamma=26, mu=0.02, iota=0.01,
    beta1=1200, beta2=1800, beta3=600,
    beta.sd=1e-3,
    pop=2.1e6,
    rho=0.6,
    S.0=26/1200, I.0=0.001, R.0=1-0.001-26/1200
  )
)

euler.sir <- simulate(euler.sir, nsim=1, seed=329348545L)

```

This example can be loaded via

```
data(euler.sir)
```

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