Appendix A: Proof of the Thinning Algorithm

Consider the problem of generating samples of a counting process $N(t) = \sum_{i\geq 1} \mathbf{1}_{\{\tau_i \leq t\}}$ with (possibly random) intensity $\lambda(s)$. This amounts to sampling jump times τ_i, $i \geq 1$, from the knowledge of $\lambda(s)$. The thinning method requires to (1) select λ^* as an upper bound for $\lambda(s)$ on its domain; (2) sample jump times τ_i^* of a Poisson process N^* with constant intensity λ^*; (3) perform an acceptance–rejection test on each τ_i^*, which consists of sampling the random variable $\mathbf{1}_{\{\lambda^* U_i \leq \lambda(\tau_i^*)\}}$, where $U_i \overset{\text{i.i.d.}}{\sim} \mathcal{U}[0,1]$; (4) accept τ_i^* as a jump time of N provided that the test succeeds, namely the independent uniform variable $\lambda^* U_i$ on $[0, \lambda^*]$ is smaller than $\lambda(\tau_i^*)$. It is assumed that λ, N^* and the U_i's are all statistically independent.

To prove this, we need to check that the process the counting process of the accepted jump times $N(t) = \sum_{i\,:\,0<\tau_i^*\leq t} \mathbf{1}_{\{\lambda^* U_i \leq \lambda(\tau_i^*)\}}$ has intensity λ, that is:

$$\mathbb{E}\big(N(t) - N(s)|\mathcal{F}_s^N\big) = \mathbb{E}\bigg(\int_s^t \lambda(u)\,\mathrm{d}u\bigg|\mathcal{F}_s^N\bigg), \tag{A.1}$$

where $\mathcal{F}_s^N$ is the completed filtration generated by N. This formula has a clear interpretation in the deterministic case: the expected number of jump times occurring over an interval $(s,t]$ is given by accruing the jump intensity λ over the same interval. For the sake of clarity, we assume that the function λ is superiorly bounded and set $\lambda^* = \sup \lambda(t,\omega)$. It is left to the reader to prove that the intensity process λ is $\mathcal{F}^N$-adapted. Using the linearity property and the rule of iterated conditional expectation, we have

$$\begin{aligned}
&\mathbb{E}\big(N(t) - N(s)|\mathcal{F}_s^N\big) \\
&\quad = \mathbb{E}\bigg(\sum_{i:s<\tau_i^*\leq t} \mathbf{1}_{\{\lambda^* U_i \leq \lambda(\tau_i^*)\}}\bigg|\mathcal{F}_s^N\bigg) \\
&\quad = \mathbb{E}\bigg(\sum_{i:s<\tau_i^*\leq t} \mathbb{E}\big(\mathbf{1}_{\{\lambda^* U_i \leq \lambda(\tau_i^*)\}}|\mathcal{F}_{\tau_i^*}^N\big)\bigg|\mathcal{F}_s^N\bigg) \qquad \text{as } \mathcal{F}_{\tau_i^*}^N \supset \mathcal{F}_s^N
\end{aligned}$$

$$= \mathbb{E}\bigg(\sum_{i:s<\tau_i^*\le t} \mathbb{P}\big(U_i \le \lambda(\tau_i^*)/\lambda^* | \mathcal{F}^N_{\tau_i^*}\big) \Big| \mathcal{F}^N_s \bigg) \quad \text{as } \mathbb{P}(\mathcal{U}[0,1] \le X | X = u) = u$$

$$= \frac{1}{\lambda^*} \mathbb{E}\bigg(\sum_{i=N^*(s)+1}^{N^*(t)} \lambda(\tau_i^*) \Big| \mathcal{F}^N_s \bigg) \quad \text{as } \lambda(\tau_i^*) \text{ is } \mathcal{F}^N_{\tau_i^*}\text{-adapted}$$

$$= \frac{1}{\lambda^*} \mathbb{E}\bigg(\mathbb{E}\bigg(\sum_{i=N^*(s)+1}^{N^*(t)} \lambda(\tau_i^*) \Big| \mathcal{F}^N_t \bigg) \Big| \mathcal{F}^N_s \bigg) \quad \text{as } t > s.$$

Recall that the jump times are uniformly distributed on the interval $(s, t]$ conditional on the number of jumps having occurred over the same interval, that is $\tau_{N^*(s)+1}, \ldots, \tau_{N^*(t)} | \mathcal{F}_t \overset{\text{i.i.d.}}{\sim} \tau \sim \mathcal{U}(s, t]$. The Wald theorem leads to:

$$\mathbb{E}\big(N(t) - N(s) | \mathcal{F}^N_s\big) = \frac{1}{\lambda^*} \mathbb{E}\big(\mathbb{E}\big[N^*(t) - N^*(s) | \mathcal{F}^N_t\big] \times \mathbb{E}\big[\lambda(\tau) | \mathcal{F}^N_t\big] \big| \mathcal{F}^N_s\big).$$

Given $\mathcal{F}^N_s$, the increment $N^*(t) - N^*(s)$ and the random variable τ are mutually independent. Moreover, τ is uniformly distributed in $[s, t]$ given $\mathcal{F}^N_t$. The last term then becomes equal to:

$$\begin{aligned} &\frac{1}{\lambda^*} \mathbb{E}\big(N^*(t) - N^*(s) | \mathcal{F}^N_s\big) \times \mathbb{E}\big(\lambda(\tau, \omega) | \mathcal{F}^N_s\big) \\ &\quad = \frac{1}{\lambda^*} \int_s^t \lambda^* \, \mathrm{d}u \, \mathbb{E}\bigg(\int_s^t \lambda(u) \frac{\mathrm{d}u}{t - s} \Big| \mathcal{F}^N_s \bigg) \\ &\quad = \mathbb{E}\bigg(\int_s^t \lambda(u) \, \mathrm{d}u \Big| \mathcal{F}^N_s \bigg), \end{aligned}$$

which is the claim to be proved.

Appendix B: Sample Problems for Monte Carlo

1. Let the state variable X be the instantaneous short rate r. Fix three increasing times $t < T_1 < T_2$ and let P_{T_2} be the process describing the value of a default free zero-coupon bond maturing at time T_2. We choose $T_2 \geq T_1$ because the asset needs to exist at time T_1. We consider a call option on P_{T_2}, expiring at T_1 and strike at K Euros. We want to design a procedure to evaluate the fair value of this option at time t by making use of Monte Carlo methods. This option is a T_1-maturing contingent claim with pay-off function $(x-K)_+$ on a T_2-maturing contingent claim with pay-off function equal to 1 in all states of the sample world:

$$\begin{aligned} V(t) &= \mathbb{E}_t^*\left(\mathrm{e}^{-\int_t^{T_1} r(s)\,\mathrm{d}s}\left(P_{T_2}(T_1) - K\right)_+\right) \\ &= \mathbb{E}_t^*\left(\mathrm{e}^{-\int_t^{T_1} r(s)\,\mathrm{d}s}\left(\mathbb{E}_{T_1}^*\left(\mathrm{e}^{-\int_{T_1}^{T_2} r(s)\,\mathrm{d}s}\right) - K\right)_+\right). \end{aligned}$$

To simulate this value, we may follow two routes. The *first algorithm* is naive. We set a small Δt and evolve r over time points $t, t+\Delta t, t+2\Delta t, \ldots, T_1 - \Delta t, T_1, T_1 + \Delta t, \ldots, T_2 - \Delta t$. This is done by discretizing the s.d.e. for r over that partition. For each simulated interest rate path, we compute the option pay-off. Summing up the resulting payoff over n sampled paths and dividing by n, results in the following approximated value:

$$C(t) \approx \frac{1}{n}\sum_{i=1}^{n}\left[\mathrm{e}^{-\sum_{t=0}^{T_1-\Delta t} r^{(i)}(t)\Delta t}\left(\left(\mathrm{e}^{-\sum_{t=T_1}^{T_2-\Delta t} r^{(i)}(t)\Delta t}\right) - K\right)_+\right].$$

The *second algorithm* is more effective. For each $i = 1, \ldots, N$:

(1) generate a path $(r^{(i)}(t + \Delta t), \ldots, r^{(i)}(T_1 - \Delta t))$ up to time $T_1 - \Delta t$;
(2) generate M "continuations":

$$\left\{\left(r^{(i,k)}(T_1), r^{(i,k)}(T_1 + \Delta t), \ldots, r^{(i,k)}(T_2 - \Delta t)\right), k = 1, \ldots, M\right\},$$

after time T_1, until time $T_2 - \Delta t$ is reached;

(3) use these continuations to obtain a Monte Carlo estimate for the time T_1 value of the bond:

$$P_{T_2}^{(i)}(T_1) \approx \frac{1}{M} \sum_{k=1}^{M} \left[e^{-\sum_{t=T_1}^{T_2-\Delta t} r^{(i,k)}(t)\Delta t} \right];$$

(4) plug this value into the call option pay-off;

(5) discount between T_1 and t using the path $r^{(i)}(t+\Delta t), \ldots, r^{(i)}(T_1 - \Delta t)$ generated at the first step; finally

(6) sum all these terms up and divide by n. The corresponding Monte Carlo estimate is:

$$C(t) \approx \frac{1}{n} \sum_{i=1}^{n} \left[e^{-\sum_{t=0}^{T_1-\Delta t} r^{(i)}(t)\Delta t} \left(\left(\frac{1}{M} \sum_{k=1}^{M} \left[e^{-\sum_{t=T_1}^{T_2-\Delta t} r^{(i.k)}(t)\Delta t} \right] \right) - K \right)_+ \right].$$

Write and run a computer code implementing the two procedures above. Elaborate and apply a test to compare their performance.

2. Suppose a model for the underlying factor dynamics X depends on a parameter. For instance, in the Black–Scholes model, X is the underlying security and we may take the volatility σ as a parameter. We wish to evaluate the rate of variation of the current fair value $V(t)$ of a given contingent claim resulting from a small change in the parameter δ. In the Black–Scholes example, we look for the Vega of an option. We may perform two Monte Carlo estimations: one under dynamics for the underlying factor corresponding to a parameter value $\delta + \varepsilon$; the other for a parameter value $\delta - \varepsilon$, where ε is a small positive constant. To reduce computations, in both cases we may use the same sequence of drawn r.v.'s needed to generate a path (this is one of the variance reduction techniques we will develop in the last section). We come up with estimations $V(t; \delta + \varepsilon)$ and $V(t; \delta - \varepsilon)$. The sensitivity can be approximated by a first-order difference $\partial_\delta V(t) \approx (V(t; \delta + \varepsilon) - V(t; \delta - \varepsilon))/(2\varepsilon)$. This method lets us compute hedge ratios too: indeed, the call option hedger is required to take a Δ-position in the underlying asset S, where Δ is just the sensitivity $\partial_S V(t, S(t))$. Write and run a computer code for computing sensitivities of the options detailed in the examples of Section 1 with respect to the parameters involved in a Black–Scholes model.

3. We wish to generate a simulated random path for a short rate model so that a given set of observed discount bond prices is perfectly matched. Suppose time t discount function is given by N observed zero-coupon bond prices $P_{T_1}(t) = p_1, \ldots, P_{T_N}(t) = p_N$, where $T_k = t + k\Delta t$. Recall the theoretical value for a discount bond price is: $P_T(t) = \mathbb{E}_t^*(\exp(-\int_t^T r(s)\,\mathrm{d}s))$. Let $r(t) = r_0$. If we simulate a number n of discrete trajectories

$$\left\{ r_{tT}^{(i)} = \left(r^{(i)}(T_1), \ldots, r^{(i)}(T_{N-1}) \right), i = 1, \ldots, n \right\}$$

for the risk-neutral dynamics of the short rate process r, the theoretical value of any discount bond $P_{T_i}(t)$ need not match the corresponding observed price p_i:

$$p_i = P_{T_i}(t) \neq P_{T_i}^{\text{sampled}}(t) = \frac{1}{n}\sum_{i=1}^{n} \mathrm{e}^{-\Delta t \sum_{k=1}^{N-1} r^{(i)}(T_k)}.$$

We want to bias each simulated path $r_{tT}^{(i)}$ so as to obtain a new path $\hat{r}_{tT}^{(i)}$ which is compatible with observed prices $p_1, \ldots, p_N$ in that:

$$p_i = \frac{1}{n}\sum_{i=1}^{n} \mathrm{e}^{-\Delta t \sum_{k=1}^{N-1} \hat{r}^{(i)}(T_k)}.$$

To each sample $r^{(i)}(T_k)$, we

(1) add the continuously compounded forward rate spanning $[T_k, T_{k+1}]$ computed from the simulated path $r_{tT}^{(i)}$ by:

$$\left\{r_{tT}^{(1)}, \ldots, r_{tT}^{(n)}\right\} \to f_{T_k T_{k+1}}(t) = \frac{1}{\Delta t} \lg\left(\frac{P_{T_k}(t)}{P_{T_{k+1}}(t)}\right)$$
$$= \frac{1}{\Delta t} \lg\left(\frac{\frac{1}{n}\sum_{i=1}^{n} \mathrm{e}^{-\Delta t \sum_{j=1}^{k-1} r^{(i)}(T_j)}}{\frac{1}{n}\sum_{i=1}^{n} \mathrm{e}^{-\Delta t \sum_{j=1}^{k} r^{(i)}(T_j)}}\right),$$

and

(2) subtract the continuously compounded forward rate spanning $[T_k, T_{k+1}]$ implied in the observed discount function by:

$$\{p_1, \ldots, p_n\} \to \hat{f}_{T_k T_{k+1}}(t) = \frac{1}{\Delta t} \lg\left(\frac{p_k}{p_{k+1}}\right).$$

Then the resulting paths

$$\left\{\hat{r}_{tT}^{(i)} = \left(\hat{r}^{(i)}(T_1), \ldots, \hat{r}^{(i)}(T_{N-1})\right), i = 1, \ldots, n\right\}, \tag{B.1}$$

defined by

$$\hat{r}^{(i)}(T_k) = r^{(i)}(T_k) + f_{T_k T_{k+1}}(t) - \hat{f}_{T_k T_{k+1}}(t),$$

satisfy the matching property. That is bond prices estimated by Monte Carlo over the modified random paths in (B.1) exactly equal the observed prices $p_1, \ldots, p_N$:

$$p_i = P_{T_i}^{\text{sampled}}(t) = \frac{1}{n}\sum_{i=1}^{n} \mathrm{e}^{-\Delta t \sum_{k=1}^{N-1} \hat{r}^{(i)}(T_k)}.$$

Write a program to implement this fitting procedure.

4. Give a formal proof for generating jump times by using the algorithm detailed in Sect. 2.3.4.

5. The recursive formula for simulating r in the Vasicek model is:

$$r(t_{i+1}) = \mu(t_{i+1}; t_i, r(t_i)) + \sigma(t_{i+1}; t_i, r(t_i))\sqrt{t_{i+1} - t_i}\mathcal{N}(0, 1)$$

starting at $(0, r_0)$. For the CIR short rate model we have $\mathrm{d}r = \alpha(b - r)\,\mathrm{d}t + \sigma\sqrt{r}\,\mathrm{d}W(t)$ and:

$$r(t_{i+1}) = r(t_i) + \frac{\sigma^2}{4\alpha}\left(1 - \mathrm{e}^{-\alpha\Delta t}\right)\chi^2\left(\frac{4\alpha\beta}{\sigma^2}, \frac{\sigma^2}{\alpha}\left(1 - \mathrm{e}^{-\alpha\Delta t}\right)\mathrm{e}^{-\alpha\Delta t} r(t_i)\right),$$

where $\chi^2(d, c)$ denotes a random sample from a non-central chi-square distribution with d degrees of freedom and non-centrality parameter c. See Johnson and Kotz (1995) for details on this family of distributions. For each of these models, compare Monte Carlo simulated European bond option values over increasing samples to the theoretical values given by closed form formula.

6. Prove that the approximating process $X^{(n)}$ in the Algorithm "Sampling theorem method for stationary Gaussian processes" is not stationary by verifying that its covariance function $c^{(n)}(t, s) = \mathbb{E}(X^{(n)}(t)X^{(n)}(s))$ does not depend on t and s through $t - s$. By applying the sampling theorem stated in the same section, show that $c^{(n)}(t, s)$ converges to a function of $t - s$ as $n \to \infty$. This justifies the approximation made in the above-mentioned algorithm.

Appendix C: The Matlab® Solver

Here we present the PDE solver implemented in a Matlab® environment. This tool aims at solving initial-boundary value problems for systems of parabolic and elliptic partial differential equations (PDEs) in one space variable. The syntax to be used in the command windows is as follows:

```
sol = pdepe(m,pdefun,icfun,bcfun,xmesh,tspan).
```

Here, `m` is parameter corresponding to the symmetry of the problem and can be set equal to 0, 1, or 2; `pdefun` defines the PDE; `icfun` sets up initial conditions; `bcfun` states boundary conditions; `xmesh` is a vector `[x0,x1,...,xn]` of increasing entries specifying the points at which a numerical solution is to be returned for each time in `tspan=[t0,t1,...,tf]`. Entries `xmesh(1)` and `xmesh(end)` are equal to z_L and z_U, respectively. Moreover, the dimensions n and f of the vectors `xmesh` and `tspan` must be greater or equal to 3. Entries `tspan(1)` and `tspan(end)` are the starting and final maturities, respectively. Function `pdepe` performs the time integration with an ODE solver that selects the time step in a dynamic manner.[1] Second-order approximations to the solution of the PDE are made on the mesh specified in `xmesh`. Notice that the function `pdepe` does not select the input mesh automatically. Therefore, it must be provided by the final user, who may decide to use an unevenly spaced grid. Therefore, it is a good practice to stagger mesh points by smaller amounts on the region of the domain where the solution changes rapidly. It is usually convenient to refine the mesh near the strike price and to use a sparse grid away from this region. The computational cost of the resulting routine strongly depends on the length of `xmesh`.

Function `pdepe` solves PDEs of the following type:

$$c(z, \tau, u, \partial_z u)\partial_\tau u = z^{-m}\partial_z(z^m f(z, \tau, u, \partial_z u)) + s(z, \tau, u, \partial_z u). \tag{C.1}$$

The initial condition at $\tau = \tau_0$ is $u(\tau_0, z) = u_0(z)$. For all τ and either $z = z_L$, or $z = z_U$, the solution components satisfy a boundary condition:

[1] For reference, see Shampine and Reichelt (1997) and Skeel and Berzins (1990).

$$p(z, \tau, u) + q(z, \tau) f(z, \tau, u, \partial_z u) = 0. \tag{C.2}$$

Elements in $q(z, \tau)$ are either all zero or none of them is null. Nonzero values for q are associated to Neumann and Robin boundary conditions, whereas Dirichlet boundary conditions lead to a vanishing $q(z, \tau)$. Note that boundary conditions are expressed in terms of the function $f(z, \tau, u, \partial_z u)$ rather than $\partial_z u$. Notice that $p(z, \tau, u)$ depends on u whereas $q(z, \tau)$ is independent of it.

For the sake of clarity, let us examine a concrete example of utilization of the function `pdepe`. We consider the initial value problem illustrated in Chapter 4 "Finite Difference Methods". On the unit interval [0, 1], we consider the heat equation:

$$-\partial_\tau u(\tau, z) + \partial_{zz} u(\tau, z) = 0, \tag{C.3}$$

with initial condition:

$$u(0, z) = \begin{cases} 2z, & 0 \le z \le \frac{1}{2}, \\ 2(1-z), & \frac{1}{2} \le z \le 1, \end{cases} \tag{C.4}$$

and boundary conditions:

$$u(\tau, 1) = u(\tau, 0) = 0. \tag{C.5}$$

The analytical solution of this *initial value problem* is:

$$u(\tau, z) = \frac{8}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \sin\left(\frac{n\pi}{2}\right) \sin(n\pi z) e^{-n^2\pi^2\tau}. \tag{C.6}$$

Equation (C.3) can be reduced to the form (C.1) by setting

$$\begin{aligned} m &= 0, & c(z, \tau, u, \partial_z u) &= 1, \\ f(z, \tau, u, \partial_z u) &= \partial_z u, & s(z, \tau, u, \partial_z u) &= 0. \end{aligned} \tag{C.7}$$

The boundary conditions are (C.5) and can be written in the form (C.2) using

$$p(z, \tau, u) = u(\tau, z), \qquad q(z, \tau) = 0,$$

where z can be either 0 or 1.[2] The arguments of function `pdepe` can be built as follows.

Let us examine a Matlab® formulation of this example.

[2] If, instead, we have opted for boundary condition (C.5), we would have set $z_L = 0$, $z_U = 1$, and

$$\begin{aligned} p(z_U, \tau, u) &= u(\tau, z_U), & q(z_U, \tau) &= 0, \\ p(z_L, \tau, u) &= u(\tau, z_L), & q(z_U, \tau) &= 0. \end{aligned}$$

- `pdefun` is a function that returns the terms c, f, and u. Input variables are defined by scalars `x` and `t` and vectors `u` and `DuDx` that approximate the solution and its partial derivative with respect to x. Comparing this to formula (C.7), the Matlab® code reads as follows:

```
function [c,f,s] = pdefun(x,t,u,DuDx)
c = 1;
f = DuDx;
s = 0;
```

- `icfun` evaluates the initial conditions. It has the form `u = icfun(x)`. When called with an argument `x`, `icfun` evaluates and returns the initial values of the solution components at `x` in the column vector `u`. With reference to the initial condition assigned in (C.4), the Matlab® code reads as follows:

```
function u0 = pdex1ic(x)
u0 = 2*(x>=1/2).*(1-x)+2*(x<1/2).*x;
```

- `bcfun` evaluates terms p and q on boundary conditions (C.5) and returns the vector `[pl,ql,pr,qr]`, where `pl` and `ql` are scalars corresponding to p and q evaluated at `xL`, similarly `pr` and `qr` correspond to `xr`. Therefore `bcfun` assumes form `[pl,ql,pr,qr] = bcfun(xl,ul,xr,ur,t)`, where `ul` is the solution at the left boundary `xL` and `uR` is the solution at the right boundary `xR`. With reference to our example, the Matlab® formulation given in (C.2) becomes:

```
function [pl,ql,pr,qr] = pdex1bcfun(xl,ul,xr,ur,t)
pl = ul;
ql = 0;
pr = ur;
qr = 0;
```

Below, we use subfunctions to place all the functions required by `pdepe` in a single M-file that is named `pdeexample.m`. This file can be run from the Matlab® command window. The proposed function provides a solution for the example discussed above using, for illustrative purposes, 10 points for the xmesh and 24 points for the t-mesh. It calls function `pdepe` using the command `sol = pdepe(m,@pdefun,@pdex1ic,@pdex1bcfun,x,t)`. The resulting numerical solution, generated by the line `surf(x,t,sol)`, is illustrated in Fig. C.1.

```
function pdeExample
m = 0;
```

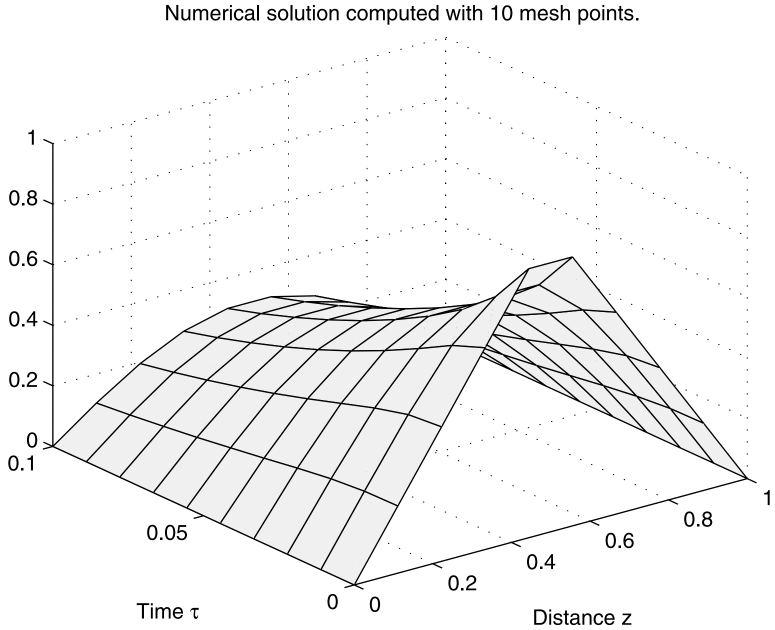

Fig. C.1. Numerical solution of the PDE given in the example.

```
x = linspace(0,1,10);
t = linspace(0,0.1,10);
%computes the numerical solution of the pde
sol = pdepe(m,@pdefun,@pdex1ic,@pdex1bcfun,x,t);
% A surface plot is often a good way
to study a solution.
surf(x,t,sol)
title('Numerical solution computed
with 10 mesh points.')
xlabel('Distance z')
ylabel('Time t')
% Defining the PDE-------------------
function [c,f,s] = pdefun(x,t,u,DuDx)
c = 1;
f = DuDx;
s = 0;
% Defining the IC-------------------
function u0 = pdex1ic(x)
```

```
%u0 = 2*(x>=1/2).*(x-1/2);
u0 = 2*(x>=1/2).*(1-x)+2*(x< 1/2).*x;
% Defining the BC-------------------------
function [pl,ql,pr,qr] = pdex1bcfun(xl,ul,xr,ur,t)
pl = ul;
ql = 0;
pr = ur;
qr = 0;
% The analytical solution-------------------
function ansolution = solutionpde(x, t)
sumseries = 0
for n = 1:20
 term = sin(n*pi/2)*sin(n*pi*x)*exp(-t*(n*pi)^2)/(n*n);
 sumseries = sumseries+term;
end
ansolution = sumseries*8/pi^2.
```

Appendix D: Optimal Control

D.1 Setting up the Optimal Stopping Problem

We begin by replacing the performance measure (3.4) with the equivalent $\sum_{s=t}^{\tau} F(s, X^{t,x}(s))$ and then redefine $\mathbb{X}$ by adding one singleton $\{k\}$, with $k \notin \mathbb{X}$, which plays the role of a "flag" for the stopping time τ. The set of controls $\mathcal{U}_{t,T}$ is given by the canonical basis in $\mathbb{R}^{T-t}$, i.e., $u = (u_t, \ldots, u_{T-1}) \in \mathcal{U}_{t,T}$ and a single entry u_s is equal to 1 ("stopping at time s") and all the others equal 0. Then, we set dynamics as

$$p(\mathrm{d}x; s, y, u, \omega) = \begin{cases} p(\mathrm{d}x; s, X(s,\omega), \omega) & \text{if } u = 0, \\ \delta_k(\mathrm{d}x) \text{ (Dirac delta mass on } \{k\}) & \text{if } u = 1 \text{ or } y = k, \end{cases}$$

or, alternatively, as

$$X^{\mathbf{u}}(s+1, \omega) = \begin{cases} f\big(s, X^{\mathbf{u}}(s,\omega), W(s,\omega)\big) & \text{if } u = 0, \\ k & \text{if } u = 1, \end{cases}$$

$$f(s, k, w) = k \quad \text{for all } s \text{ and } k.$$ [1]

This means that the system is trapped into a steady state k once the control has been activated ($u = 1$). Finally, the cost/reward function vanishes on the steady state $\{k\}$:

$$F(s, y, u) = \begin{cases} F(s, y) & \text{if } y \neq k, \\ 0 & \text{if } y = k. \end{cases}$$

The equivalence of this formulation to an optimal stopping problem can now be easily proven as an exercise. Notice that the artificial state k signals the "death" of the system. For practical purposes, there is no need to cast an optimal stopping problem in this framework.

[1] We remark the difference between symbols "ω" and "w". The former denotes a generic elementary event in a sample space Ω. You may think of it as a sample path itself, as is the case of the so-called canonical process $X(t, \omega) = \omega(t)$, defined on $[0, T] \times \mathbb{R}^{[0,T]}$. The latter is a real value assumed by the random noise $W(t)$.

D.2 Proof of the Bellman Principle of Optimality

The two control policies $\mathbf{u}$ and $\mathbf{u}'$ give rise to the same exact dynamics on $\{t, \ldots, s\}$. Therefore their performance coincides on $\{t, \ldots, s-1\}$. Note that they need not be equal at s because the performance index in general depends on the control and the two control policies $\mathbf{u}$ and $\mathbf{u}'$ may not match at time s. This observation reduces the problem to the one of showing that the performance stemming from the *residual* dynamics $(X^{t,x,\mathbf{u}}(s), \ldots, X^{t,x,\mathbf{u}}(T))$ resulting from applying $\mathbf{u}$ is no greater than the reward deriving from the residual dynamics obtained by using $\mathbf{u}'$ instead. Control $\mathbf{u} =(u(t, \cdot), \ldots, u(T, \cdot))$ applied to the system dynamics for the remaining period gives rise to a reward assessment:

$$J^* := \sum_{i=s}^{T-1} F\big(i, X^{t,x,\mathbf{u}}(i), u\big(i, X^{t,x,\mathbf{u}}(i)\big)\big) + \Psi\big(X^{t,x,\mathbf{u}}(T)\big).$$

The uniqueness of the solution of a dynamic system implies the flow property:

$$X^{t,x,\mathbf{u}}(i) = X^{s,X^{t,x,\mathbf{u}}(s),\mathbf{u}|_s}(i),$$

where $t \leq s \leq i \leq T$, and $\mathbf{u}|_s$ is the truncated control $(u(s), \ldots, u(T))$ resulting from restricting $\mathbf{u}$ on the remaining period $\{s, \ldots, T\}$. By applying, in order, the flow property, the optimality of $\hat{\mathbf{u}}^s$ on $\{s, \ldots, T\}$, and the flow property again, we have:

$$\begin{aligned}
J^* &= \sum_{i=s}^{T-1} F\big(i, X^{s,X^{t,x,\mathbf{u}}(s),\mathbf{u}|_s}(i), u\big(i, X^{s,X^{t,x,\mathbf{u}}(s),\mathbf{u}|_s}(i)\big)\big) \\
&\quad + \Psi\big(X^{s,X^{t,x}(s),\mathbf{u}|_s}(T)\big) \\
&\leq \sum_{i=s}^{T-1} F\big(i, X^{s,X^{t,x,\mathbf{u}}(s),\hat{\mathbf{u}}^s}(i), \hat{u}\big(i, X^{s,X^{t,x,\mathbf{u}}(s),\hat{\mathbf{u}}^s}(i)\big)\big) \\
&\quad + \Psi\big(X^{s,X^{t,x,\mathbf{u}}(s),\hat{\mathbf{u}}^s}(T)\big) \\
&= \sum_{i=s}^{T-1} F\big(i, X^{t,x,\mathbf{u}'}(i), \hat{u}\big(i, X^{t,x,\mathbf{u}'}(i)\big)\big) + \Psi\big(X^{t,x,\mathbf{u}'}(T)\big).
\end{aligned}$$

This last term represents the performance generated by residual dynamics $(X^{t,x,\mathbf{u}'}(s), \ldots, X^{t,x,\mathbf{u}'}(T))$ corresponding to the control policy $\mathbf{u}'$.

D.3 Proof of the Dynamic Programming Algorithm

We need to prove that $\mathbf{u}^{\mathrm{B}}$ dominates any other control policy in $\mathcal{U}_{t,T}$. We apply the Bellman principle of optimality at each step in the preceding backward induction. At time T, if the reached state is y, the generated performance is uncontrollable and matches $\Psi(y)$. This holds for any control policy and thus for the optimal one. At time $T-1$, whatever is the control policy $\mathbf{u} = (u(t), \dots, u(T-2))$ adopted on the elapsed period $\{t, \dots, T-2\}$, the policy

$$\big(u(t,\cdot), \dots, u(T-2,\cdot), \hat{u}^{T-1}(T-1,\cdot)\big),$$

with $\hat{u}^{T-1}(T-1,\cdot) = \arg\max_{\mathcal{U}_{T-1,T}} J(T-1,\cdot,\mathbf{u})$, dominates any other control policy sharing the same first $T-2$ components. This is because each entry of the control policy contributes to the overall performance J *additively*. Therefore, the optimal control policy must have $\hat{u}(T-1,\cdot)$ as its $(T-1)$th component. At time $T-2$, the Bellman principle of optimality states that the control policy:

$$\big(u(t,\cdot), \dots, \hat{u}^{T-2}(T-2,\cdot), \hat{u}^{T-2}(T-1,\cdot)\big),$$

with $(\hat{u}^{T-2}(T-2,\cdot), \hat{u}^{T-2}(T-1,\cdot)) = \arg\max_{\mathcal{U}_{T-2,T}} J(T-2,\cdot,\mathbf{u})$, dominates any other control policy sharing the same first $T-3$ components. But the previous step says that the optimal control policy must have $\hat{u}^{T-1}(T-1,\cdot)$ as its $(T-1)$th component, i.e.,

$$\begin{aligned}
&\big(u(t,\cdot), \dots, \hat{u}^{T-2}(T-2,\cdot), \hat{u}^{T-1}(T-1,\cdot)\big) \\
&\quad \geq \big(u(t,\cdot), \dots, u(T-3,\cdot), \hat{u}^{T-2}(T-2,\cdot), \hat{u}^{T-2}(T-1,\cdot)\big) \\
&\quad \geq \big(u(t,\cdot), \dots, u(T-3,\cdot), u(T-2,\cdot), u(T-1,\cdot)\big).
\end{aligned}$$

Proceeding this way, we come up to the control policy:

$$\begin{aligned}
\mathbf{u}^{\mathrm{B}} &= \big(\hat{u}^{t}(t,\cdot), \dots, \hat{u}^{T-2}(T-2,\cdot), \hat{u}^{T-1}(T-1,\cdot)\big) \\
&\geq \big(\hat{u}^{t}(t,\cdot), \dots, \hat{u}^{t}(T-2,\cdot), \hat{u}^{t}(T-1,\cdot)\big) = \hat{\mathbf{u}}.
\end{aligned}$$

But $\hat{\mathbf{u}} = \arg\max_{\mathcal{U}_{t,T}} J(t,\cdot,u)$ dominates all control policy, in particular $\mathbf{u}^{\mathrm{B}}$, i.e., $\hat{\mathbf{u}} \geq \mathbf{u}^{\mathrm{B}}$. Therefore, $\hat{\mathbf{u}} = \mathbf{u}^{\mathrm{B}}$.

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