

Equation-Free function toolbox for Matlab/Octave: Full Developers Manual

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Abstract

This ‘equation-free toolbox’ empowers the computer-assisted analysis of complex, multiscale systems. Its aim is to enable you to use microscopic simulators to perform system level tasks and analysis. The methodology bypasses the derivation of macroscopic evolution equations by using only short bursts of microscale simulations which are often the best available description of a system ([Kevrekidis & Samaey 2009](#), [Kevrekidis et al. 2004](#), [2003](#), e.g.). This suite of functions should empower users to start implementing such methods—but so far we have only just started.

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1 Introduction

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This Developers Manual contains line-by-line descriptions of the code in each function in the toolbox, and each example. For basic descriptions of each function, quick start guides, and some basic examples, see the User Manual.

Users Place this toolbox’s folder in a path searched by MATLAB/Octave. Then read the section that documents the function of interest.

Blackbox scenario Assume that a researcher/practitioner has a detailed and *trustworthy* computational simulation of some problem of interest. The simulation may be written in terms of micro-positional coordinates $\vec{x}_i(t)$ in ‘space’ at which there are micro-field variable values $\vec{u}_i(t)$ for indices i in some (large) set of integers and for time t . In lattice problems the positions \vec{x}_i would be fixed in time (unless employing a moving mesh on the microscale); in particle problems the positions would evolve. The positional coordinates are $\vec{x}_i \in \mathbb{R}^d$ where for spatial problems integer $d = 1, 2, 3$, but it may be more when solving for a distribution of velocities, or pore sizes, or trader’s beliefs, etc. The micro-field variables could be in \mathbb{R}^p for any $p = 1, 2, \dots, \infty$.

Further, assume that the computational simulation is too expensive over all the desired spatial domain $\mathbb{X} \subset \mathbb{R}^d$. Thus we aim a toolbox to simulate only on macroscale distributed patches.

Contributors The aim of this project is to collectively develop a MATLAB/Octave toolbox of equation-free algorithms. Initially the algorithms will be simple, and the plan is to subsequently develop more and more capability.

MATLAB appears the obvious choice for a first version since it is widespread, reasonably efficient, supports various parallel modes, and development costs are reasonably low. Further it is built on BLAS and LAPACK so potentially the cache and superscalar CPU are well utilised. Let’s develop functions that work for both MATLAB/Octave. [Appendix A](#) outlines some details for contributors.

2 Quick start

Chapter contents

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This section may be used in conjunction with the many examples in later sections to help apply the toolbox functions to a particular problem, or to assist in distinguishing between the various functions.

2.1 Cheat sheet: Projective Integration

This section pertains to the Projective Integration (PI) methods of [Chapter 3](#). The PI approach is to greatly accelerate computations of a system exhibiting multiple time scales.

The PI toolbox presents several ‘main’ functions that could separately be called to perform PI, as well as several optional wrapper functions that may be called. This section helps to distinguish between the top-level PI functions, and helps to tell which of the optional functions may be needed at a glance. [Chapter 3](#) fully details each function.

The cheat sheet consists of two flow charts. [Figure 2.1](#) overviews constructing a PI simulation. [Figure 2.2](#) roughly guides which of the top-level PI functions should be used.

2.2 Cheat sheet: constructing patches

This section pertains to the Patch approach, [Chapter 4](#), to solving PDEs, lattice systems, or agent/particle microscale simulators.

The Patch toolbox requires that one configure patches, couple the patches and interface the coupled patches with a time integrator. [Figure 2.3](#) overviews the chief functions involved and their interactions.

Figure 2.1: these figures appear confusing to a newbie???? and we must *not* resize fixed width constructs. Use linewidth for large-scale layout scaling, em for small-widths, and ex for small-heights.

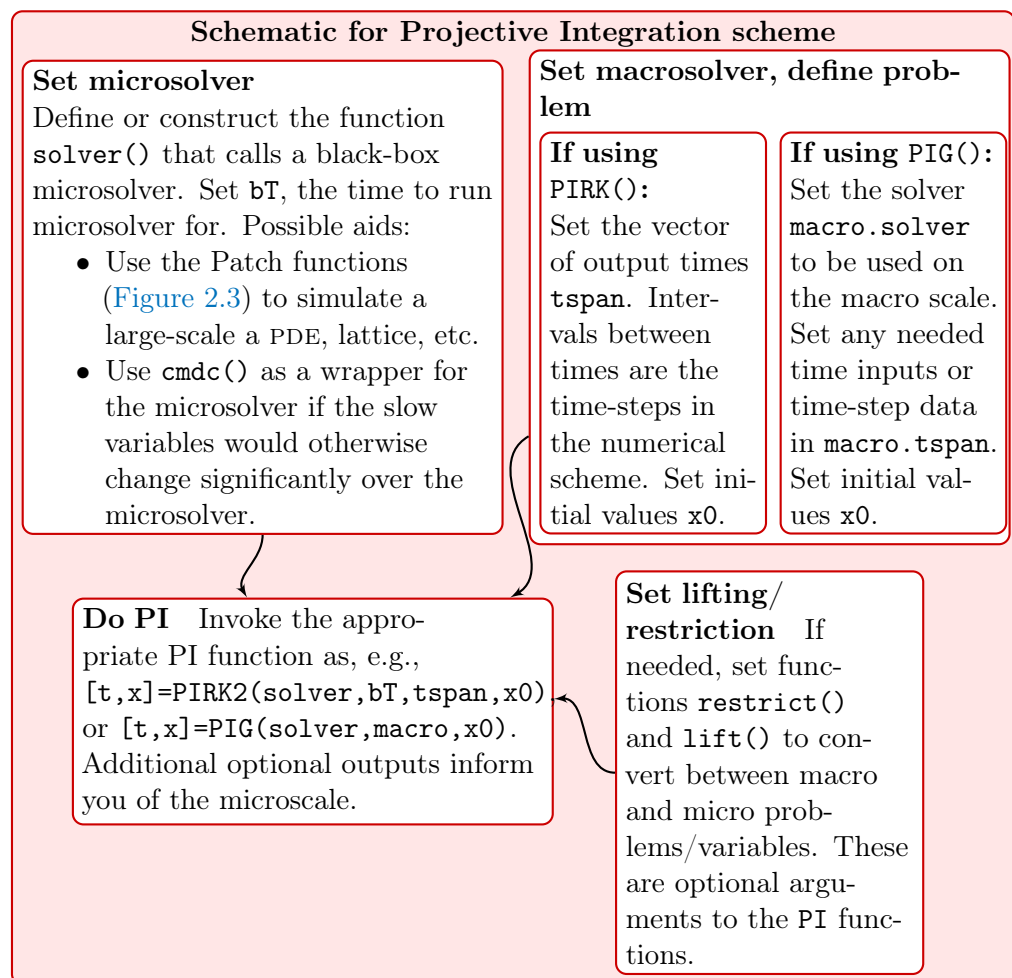


Figure 2.2

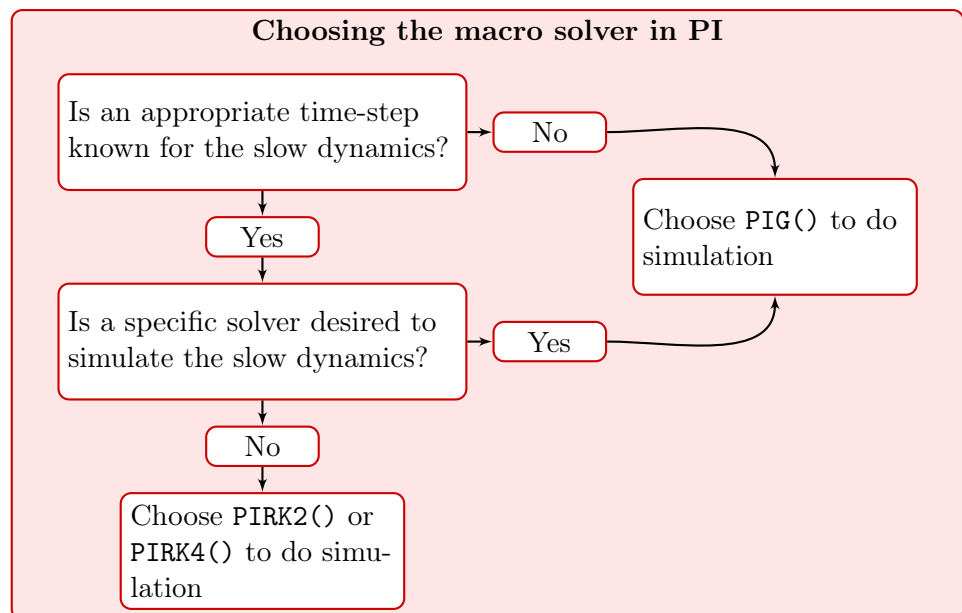
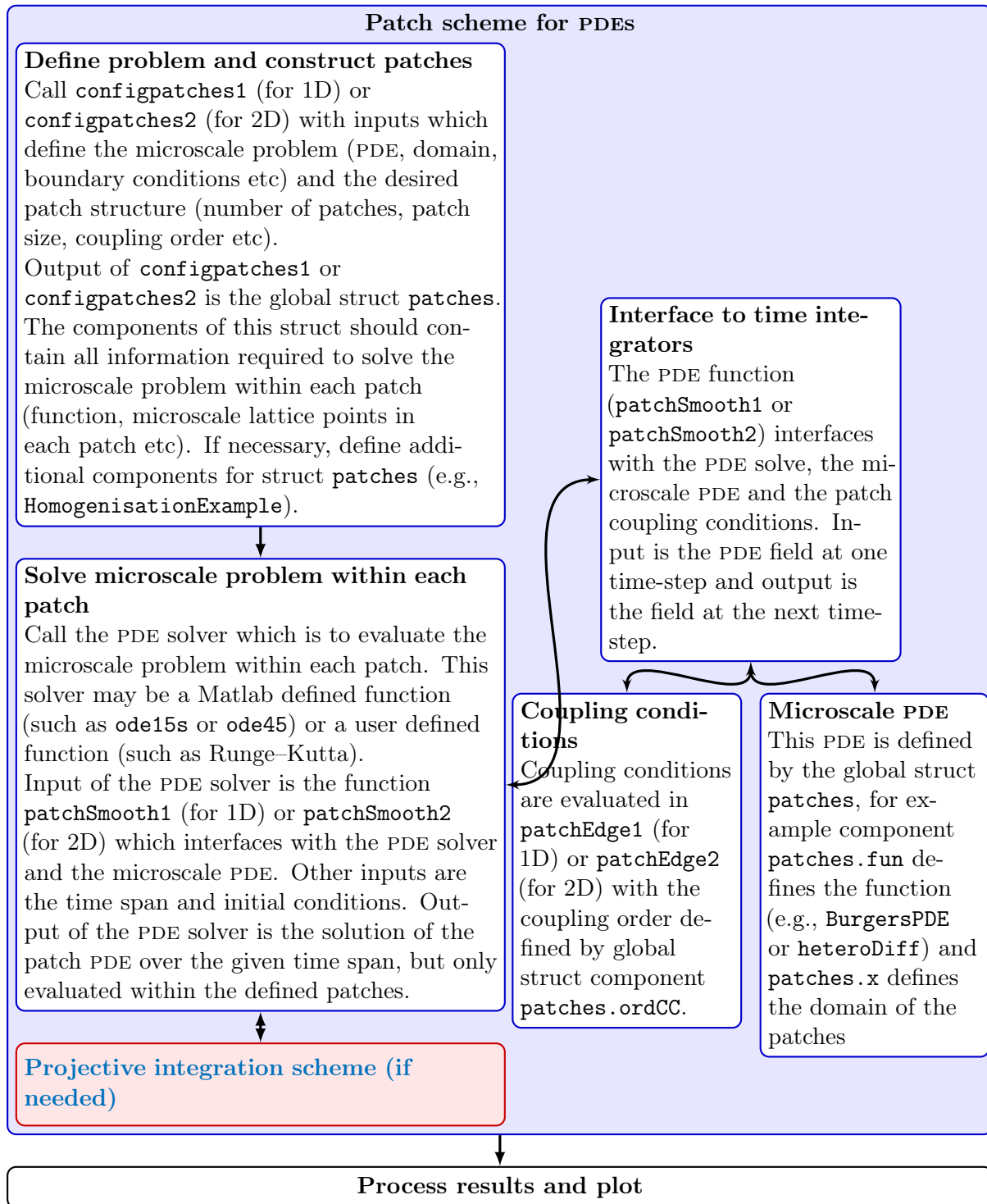


Figure 2.3



3 Projective integration of deterministic ODEs

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This section provides some good projective integration functions (Gear & Kevrekidis 2003a,b, Givon et al. 2006, Sieber et al. 2018, e.g.). The goal is to enable computationally expensive dynamic simulations to be run over long time scales.

Scenario When you are interested in a complex system with many interacting parts or agents, you usually are primarily interested in the self-organised emergent macroscale characteristics. Projective integration empowers us to efficiently simulate such long-time emergent dynamics. We suppose you have coded some accurate, fine scale simulation of the complex system, and call such code a microsolver.

The Projective Integration section of this toolbox consists of several functions. Each function implements over the long-time scale a variant of a standard numerical method to simulate the emergent dynamics of the complex system. Each function has standardised inputs and outputs.

Main functions

- Projective Integration by second or fourth-order Runge–Kutta, `PIRK2()` and `PIRK4()` respectively. These schemes are suitable for precise simulation of the slow dynamics, provided the time period spanned by an application of the microsolver is not too large.
- Projective Integration with a General solver, `PIG()`. This function enables a Projective Integration implementation of any solver with macroscale time-steps. It does not matter whether the solver is a standard Matlab or Octave algorithm, or one supplied by the user. As explored in later examples, `PIG()` should only be used in very stiff systems.
- ‘Constraint-defined manifold computing’, `cdmc()`. This helper function, based on the method introduced in ?, iteratively applies the microsolver and projects the output backwards in time. The result is to constrain the fast variables close to the slow manifold, without advancing the current time by the duration of an application of the microsolver. This function can be used to reduce errors related to the simulation length of the microsolver in either the `PIRK` or `PIG` functions. In particular, it enables `PIG()` to be used on problems that are not particularly stiff.

The above functions share dependence on a user-specified ‘microsolver’, that accurately simulates some problem of interest.

The following sections describe the `PIRK2()` and `PIG()` functions in detail, providing an example for each. Then `PIRK4()` is very similar to `PIRK2()`. Descriptions for the minor functions follow, and an example of the use of `cdmc()`.

3.1 `PIRK2()`: projective integration of second-order accuracy

This Projective Integration scheme implements a macroscale scheme that is analogous to the second-order Runge–Kutta Improved Euler integration.

```
18 function [x, tms, xms, rm, svf] = PIRK2(microBurst, tSpan, x0, bT)
```

Input If there are no input arguments, then this function applies itself to the Michaelis–Menton example: see the code in [Section 3.1.1](#) as a basic template of how to use.

- `microBurst()`, a user-coded function that computes a short-time burst of the microscale simulation.

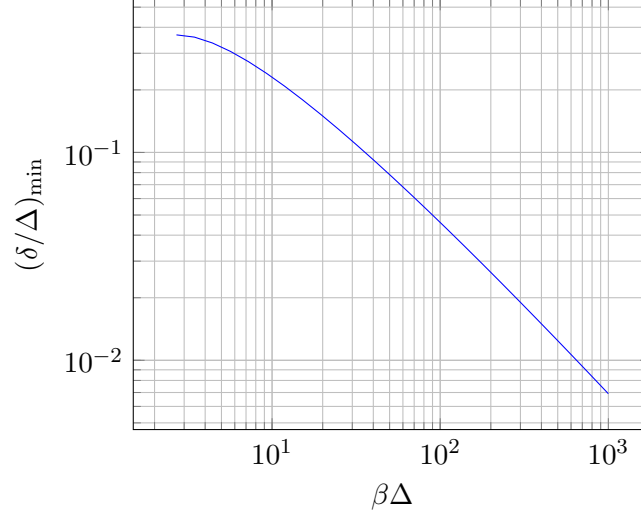
```
[tOut, xOut] = microBurst(tStart, xStart, bT)
```

- Inputs: `tStart`, the start time of a burst of simulation; `xStart`, the row n -vector of the starting state; `bT`, optional, the total time to simulate in the burst—if `microBurst()` determines the burst time, then replace `bT` in the argument list by `varargin`.
- Outputs: `tOut`, the column vector of solution times; and `xOut`, an array in which each *row* contains the system state at corresponding times.
- `tSpan` is an ℓ -vector of times at which the user requests output, of which the first element is always the initial time. `PIRK2()` does not use adaptive time-stepping; the macroscale time-steps are (nearly) the steps between elements of `tSpan`.
- `x0` is an n -vector of initial values at the initial time `tSpan(1)`. Elements of `x0` may be `NaN`: they are included in the simulation and output, and often represent boundaries in space fields.
- `bT`, optional, either missing, or empty (`[]`), or a scalar: if a given scalar, then it is the length of the micro-burst simulations—the minimum amount of time needed for the microscale simulation to relax to the slow manifold; else if missing or `[]`, then `microBurst()` must itself determine the length of a computed burst.

```
66 if nargin<4, bT=[]; end
```

Choose a long enough burst length Suppose: you have some desired relative accuracy ε that you wish to achieve (e.g., $\varepsilon \approx 0.01$ for two digit accuracy); the slow dynamics of your system occurs at rate/frequency of magnitude about α ; and the rate of *decay* of your fast modes are faster than

Figure 3.1: Need macroscale step Δ such that $|\alpha\Delta| \lesssim \sqrt{6\varepsilon}$ for given relative error ε and slow rate α , and then $\delta/\Delta \gtrsim \frac{1}{\beta\Delta} \log \beta\Delta$ determines the minimum required burst length δ for given fast rate β .



the lower bound β (e.g., if the fast modes decay roughly like $e^{-12t}, e^{-34t}, e^{-56t}$ then $\beta \approx 12$). Then choose

1. a macroscale time-step, $\Delta = \text{diff}(\text{tSpan})$, such that $\alpha\Delta \approx \sqrt{6\varepsilon}$, and
2. a microscale burst length, $\delta = \text{bT} \gtrsim \frac{1}{\beta} \log(\beta\Delta)$ (see Figure 3.1).

Output If there are no output arguments specified, then a plot is drawn of the computed solution \mathbf{x} versus tSpan .

- \mathbf{x} , an $\ell \times n$ array of the approximate solution vector. Each row is an estimated state at the corresponding time in tSpan . The simplest usage is then $\mathbf{x} = \text{PIRK2}(\text{microBurst}, \text{tSpan}, \mathbf{x0}, \text{bT})$.

However, microscale details of the underlying Projective Integration computations may be helpful. `PIRK2()` provides two to four optional outputs of the microscale bursts.

- \mathbf{tms} , optional, is an L dimensional column vector containing microscale times of burst simulations, each burst separated by `NaN`;
- \mathbf{xms} , optional, is an $L \times n$ array of the corresponding microscale states—this data is an accurate simulation of the state and may help visualise more details of the solution.
- \mathbf{rm} , optional, a struct containing the ‘remaining’ applications of the `microBurst` required by the Projective Integration method during the calculation of the macrostep:
 - $\mathbf{rm.t}$ is a column vector of microscale times; and
 - $\mathbf{rm.x}$ is the array of corresponding burst states.


```

221     [ts, xs] = ode23(dMMdt, [ti ti+bT], xi);
222 end

```

3.1.2 The projective integration code

Determine the number of time-steps and preallocate storage for macroscale estimates.

```

239 nT=length(tSpan);
240 x=nan(nT,length(x0));

```

Get the number of expected outputs and set logical indices to flag what data should be saved.

```

248 nArgs=nargout();
249 saveMicro = (nArgs>1);
250 saveFullMicro = (nArgs>3);
251 saveSvf = (nArgs>4);

```

Run a preliminary application of the microBurst on the initial conditions to help relax to the slow manifold. This is done in addition to the microBurst in the main loop, because the initial conditions are often far from the attracting slow manifold. Require the user to input and output rows of the system state.

```

264 x0 = reshape(x0,1,[]);
265 [relax_t,relax_x0] = microBurst(tSpan(1),x0,bT);

```

Use the end point of the microBurst as the initial conditions.

```

273 tSpan(1) = relax_t(end);
274 x(1,:)=relax_x0(end,:);

```

If saving information, then record the first application of the microBurst. Allocate cell arrays for times and states for outputs requested by the user, as concatenating cells is much faster than iteratively extending arrays.

```

284 if saveMicro
285     tms = cell(nT,1);
286     xms = cell(nT,1);
287     tms{1} = reshape(relax_t,[],1);
288     xms{1} = relax_x0;
289     if saveFullMicro
290         rm.t = cell(nT,1);
291         rm.x = cell(nT,1);
292         if saveSvf
293             svf.t = nan(2*nT-2,1);
294             svf.dx = nan(2*nT-2,length(x0));
295         end
296     end
297 end

```

Loop over the macroscale time-steps

```

305 for jT = 2:nT
306     T = tSpan(jT-1);

```

If two applications of the microBurst would cover one entire macroscale time-step, then do so (setting some internal states to NaN); else proceed to projective step.

```

314     if ~isempty(bT) & 2*abs(bT)>=abs(tSpan(jT)-T) & bT*(tSpan(jT)-T)>0
315         [t1,xm1] = microBurst(T, x(jT-1,:), tSpan(jT)-T);
316         x(jT,:) = xm1(end,:);
317         t2=nan; xm2=nan(1,size(xm1,2));
318         dx1=xm2; dx2=xm2;
319     else

```

Run the first application of the microBurst; since this application directly follows from the initial conditions, or from the latest macrostep, this microscale information is physically meaningful as a simulation of the system. Extract the size of the final time-step.

```

330         [t1,xm1] = microBurst(T, x(jT-1,:), bT);
331         del = t1(end)-t1(end-1);

```

Check for round-off error.

```

337         xt=[reshape(t1(end-1:end),[],1) xm1(end-1:end,:)];
338         roundingTol=1e-8;
339         if norm(diff(xt))/norm(xt,'fro') < roundingTol
340             warning(['significant round-off error in 1st projection at T=' num2str(T)
341             end

```

Find the needed time-step to reach time tSpan(n+1) and form a first estimate dx1 of the slow vector field.

```

350         Dt = tSpan(jT)-t1(end);
351         dx1 = (xm1(end,:)-xm1(end-1,:))/del;

```

Project along dx1 to form an intermediate approximation of x; run another application of the microBurst and form a second estimate of the slow vector field (assuming the burst length is the same, or nearly so).

```

361         xint = xm1(end,:) + (Dt-(t1(end)-t1(1)))*dx1;
362         [t2,xm2] = microBurst(T+Dt, xint, bT);
363         del = t2(end)-t2(end-1);
364         dx2 = (xm2(end,:)-xm2(end-1,:))/del;

```

Check for round-off error.

```

370         xt=[reshape(t2(end-1:end),[],1) xm2(end-1:end,:)];
371         if norm(diff(xt))/norm(xt,'fro') < roundingTol
372             warning(['significant round-off error in 2nd projection at T=' num2str(T)
373             end

```

Use the weighted average of the estimates of the slow vector field to take a macrostep.

```

381         x(jT,:) = xm1(end,:) + Dt*(dx1+dx2)/2;

```

Now end the if-statement that tests whether a projective step saves simulation time.

```
389     end
```

If saving trusted microscale data, then populate the cell arrays for the current loop iterate with the time-steps and output of the first application of the microBurst. Separate bursts by NaNs.

```
399     if saveMicro
400         tms{jT} = [reshape(t1,[],1); nan];
401         xms{jT} = [xm1; nan(1,size(xm1,2))];
```

If saving all microscale data, then repeat for the remaining applications of the microBurst.

```
409         if saveFullMicro
410             rm.t{jT} = [reshape(t2,[],1); nan];
411             rm.x{jT} = [xm2; nan(1,size(xm2,2))];
```

If saving Projective Integration estimates of the slow vector field, then populate the corresponding cells with times and estimates.

```
420             if saveSvf
421                 svf.t(2*jT-3:2*jT-2) = [t1(end); t2(end)];
422                 svf.dx(2*jT-3:2*jT-2,:) = [dx1; dx2];
423             end
424         end
425     end
```

Terminate the main loop:

```
431 end
```

Overwrite $x(1,:)$ with the specified initial condition $tSpan(1)$.

```
440 x(1,:) = reshape(x0,1,[]);
```

For additional requested output, concatenate all the cells of time and state data into two arrays.

```
448 if saveMicro
449     tms = cell2mat(tms);
450     xms = cell2mat(xms);
451     if saveFullMicro
452         rm.t = cell2mat(rm.t);
453         rm.x = cell2mat(rm.x);
454     end
455 end
```

3.1.3 If no output specified, then plot simulation

```
463 if nArgs==0
464     figure, plot(tSpan,x,'o:')
```



```

465     title('Projective Simulation with PIRK2')
466 end

    This concludes PIRK2().

473 end

```

3.2 PIG(): Projective Integration via a General macroscale integrator

This is an approximate Projective Integration scheme when the macroscale integrator is any coded scheme. The advantage is that one may use MATLAB/Octave's inbuilt integration functions, with all their sophisticated error control and adaptive time-stepping, to do the macroscale simulation.

Unlike the `PIRKn` functions, `PIG()` does not estimate the slow vector field at the times expected by any user-specified scheme, but instead provides an estimate of the slow vector field at a slightly different time, after an application of the micro-burst simulator. Consequently `PIG()` will incur an additional global error term proportional to the burst length of the macroscale simulator. For that reason, `PIG()` should be used with

- either very stiff problems, in which the burst length of the micro-burst can be short,
- or the 'constraint defined manifold' based micro-burst provided by `cdmc()`, that attempts to project the variables onto the slow manifold without affecting the time.

```

36 function [t,x,tms,xms,svf] = PIG(macroInt,microBurst,tSpan,x0,lift,restrict)

```

The inputs and outputs are a little different to the two `PIRKn` functions.

Inputs:

- `microBurst()` is a function that produces output from the user-specified code for a burst of macroscale simulation. The function must know how long a burst it is to use. Usage

$$[tbs,xbs] = \text{microBurst}(tb0,xb0)$$

Inputs: `tb0` is the start time of a burst; `xb0` is the vector state at the start of a burst.

Outputs: `tbs`, the vector of solution times; and `xbs`, the corresponding states.

- `macroInt()`, the numerical method that the user wants to apply on a slow-time macroscale. Either use a standard MATLAB/Octave integration function (such as `ode23` or `ode45`), or code this solver as a standard MATLAB/Octave integration function. That is, if you code you own, then it must be

$$[ts,xs] = \text{macroInt}(f,tSpan,x0)$$

where function $\mathbf{f}(\mathbf{t}, \mathbf{x})$ notionally evaluates the time derivatives $d\vec{x}/dt$ at ‘any’ time; \mathbf{tSpan} is either the macro-time interval, or the vector of times at which a macroscale value is to be returned; and $\mathbf{x0}$ are the initial values of \vec{x} at time $\mathbf{tSpan}(1)$. Then the i th row of \mathbf{xs} , $\mathbf{xs}(\mathbf{i}, :)$, is to be the vector $\vec{x}(t)$ at time $t = \mathbf{ts}(\mathbf{i})$. Remember that in `PIG()` the function $\mathbf{f}(\mathbf{t}, \mathbf{x})$ is to be estimated by Projective Integration burst.

- \mathbf{tSpan} , a vector of times at which the user requests output, of which the first element is always the initial time. If `macroInt` can adaptively select time steps (e.g., `ode45`), then \mathbf{tSpan} can consist of an initial and final time only.
- $\mathbf{x0}$, the vector of initial values at the initial time $\mathbf{tSpan}(1)$.

Output If there are no output arguments specified, then a plot is drawn of the computed solution \mathbf{x} versus \mathbf{t} . Most often you would only store the first two output results of `PIG()`, via say `[t,x] = PIG(...)`.

- \mathbf{t} , an ℓ -vector of times at which `macroInt` produced results.
- \mathbf{x} , an $\ell \times n$ array of the computed solution: the i th row of \mathbf{x} , $\mathbf{x}(\mathbf{i}, :)$, is to be the vector $\vec{x}(t)$ at time $t = \mathbf{t}(\mathbf{i})$.

However, microscale details of the underlying Projective Integration computations may be helpful, and so `PIG()` some optional outputs of the microscale bursts.

- \mathbf{tms} , optional, is an L dimensional column vector containing microscale times of burst simulations, each burst separated by NaN;
- \mathbf{xms} , optional, is an $L \times n$ array of the corresponding microscale states—this data is an accurate simulation of the state and may help visualise more details of the solution.
- \mathbf{svf} , optional, a struct containing the Projective Integration estimates of the slow vector field.
 - $\mathbf{svf.t}$ is a 2ℓ dimensional column vector containing all times at which the Projective Integration scheme is extrapolated along microsolver data to form a macrostep.
 - $\mathbf{svf.dx}$ is a $2\ell \times n$ array containing the estimated slow vector field.

3.2.1 If no arguments, then execute an example

```
132 if nargin==0
```

As a basic example, consider a singularly perturbed system of differential equations for $\vec{x}(t) = (x_1(t), x_2(t))$:

$$\frac{dx_1}{dt} = \cos(x_1) \sin(x_2) \cos(t) \quad \text{and} \quad \frac{dx_2}{dt} = \frac{1}{\epsilon} [\cos(x_1) - x_2].$$

With initial conditions $\vec{x}(0) = (1, 0)$, the following code computes and plots a solution of the system over time $0 \leq t \leq 6$ for parameter $\epsilon = 10^{-3}$.

First we code the right-hand side function of the microscale system of ODEs.

```

149 epsilon = 1e-3;
150 dxdt=@(t,x) [ cos(x(1))*sin(x(2))*cos(t)
151               (cos(x(1))-x(2))/epsilon ];

```

Second, we code microscale bursts, here using the standard `ode45()`. Since the rate of decay is $\beta \approx 1/\epsilon$ we choose a burst length $2\epsilon \log(1/\epsilon)$ as here we do not know the macroscale time-step invoked by `marcoInt()`, so blithely use $\Delta = 1$, and then double the usual formula for safety.

```

163 bT = 2*epsilon*log(1/epsilon)
164 microBurst = @(tb0,xb0) ode45(dxdt,[tb0 tb0+bT],xb0);

```

Third, invoke PIG to use `ode23()`, say, on the macroscale slow evolution. Integrate the micro-bursts over $0 \leq t \leq 6$ from initial condition $\vec{x} = (1, 0)$. (You could set `tSpan=[0 -6]` to integrate backwards in time with forward bursts.)

```

174 tSpan = [0 6];
175 lift = @(x) [x; 0.5];
176 restrict = @(x) x(1);
177 [ts,xs,tms,xms] = PIG('ode23',microBurst,tSpan,1, lift, restrict);

```

Plot output of this projective integration.

```

183 figure, plot(ts,xs,'o:',tms,xms)
184 title('Projective integration of singular perturbed ODE')
185 xlabel('time t'), legend('x_1(t)','x_2(t)')

```

Upon finishing execution of the example, exit this function.

```

191 return
192 end%if no arguments

```

Find the number of time-steps at which output is expected, and the number of variables.

```

207 nT=length(tSpan)-1;
208 nx = length(lift(x0));

```

Get the number of expected outputs and set logical indices to flag what data should be saved. If no lifting/restriction operators were set, assign them.

```

217 nArgs=nargout();
218 saveMicro = (nArgs>1);
219 saveSvf = (nArgs>2);
220 if nargin < 5 %no lift/restrict operators
221     lift=@(x) x;
222     restrict=@(x) x;
223 end

```

Run a first application of the `microBurst` on the initial conditions. This is done in addition to the `microBurst` in the main loop, because the initial conditions are often far from the attracting slow manifold.

```

235 x0 = reshape(x0,[],1);
236 [relax_t,x0_micro_relax] = microBurst(tSpan(1),lift(x0));
237 x0_relax = restrict(x0_micro_relax);

```

Update the initial time.

```

244 tSpan(1) = relax_t(end);

```

Allocate cell arrays for times and states for any of the outputs requested by the user. If saving information, then record the first application of the microBurst. Note that it is unknown a priori how many applications of the microBurst will be required; this code may be run more efficiently if the correct number is used in place of `nT+1` as the dimension of the cell arrays.

```

256 if saveMicro
257     tms=cell(nT+1,1); xms=cell(nT+1,1);
258     n=1;
259     tms{n} = reshape(relax_t,[],1);
260     xms{n} = x0_micro_relax;
261
262     if saveSvf
263         svf.t = cell(nT+1,1);
264         svf.dx = cell(nT+1,1);
265     end
266 end

```

The idea of `PIG()` is to use the output from the microBurst to approximate an unknown function $\mathbf{ff}(\mathbf{t},\mathbf{x})$, that describes the slow dynamics. This approximation is then used in the system/user-defined ‘coarse solver’ `macroInt()`. The approximation is described in

```

278 function [dx]=genProjection(tt,xx)

```

Run a microBurst from the given initial conditions.

```

284 [t_tmp,x_micro_tmp] = microBurst(tt,reshape(lift(xx),[],1));

```

Compute the standard Projective Integration approximation of the slow vector field.

```

291 del = t_tmp(end)-t_tmp(end-1);
292 dx = ( restrict(x_micro_tmp(end,:))-restrict(x_micro_tmp(end-1,:)) )';

```

Save the microscale data, and the Projective Integration slow vector field, if requested.

```

299 if saveMicro
300     n=n+1;
301     tms{n} = [reshape(t_tmp,[],1); nan];
302     xms{n} = [x_micro_tmp; nan(1,nx)];
303     if saveSvf
304         svf.t{n-1} = tt;
305         svf.dx{n-1} = dx;
306     end

```

```

307         end
308     end% function genProjection()

    Define the approximate slow vector field according to Projective Integration.

317     ff=@(t,x) genProjection(t,x);

    Do Projective Integration of ff() with the user-specified microBurst.

326     [t,x]=feval(macroInt,ff,tSpan,x0_relax(end,:));

    Overwrite x(1,:) and t(1), which the user expect to be x0 and tSpan(1)
    respectively, with the given initial conditions.

335     x(1,:) = x0';
336     t(1) = tSpan(1);

    For each additional requested output, concatenate all the cells of time and
    state data into two arrays. Then, return the two arrays in a cell.

345     if saveMicro
346         tms = cell2mat(tms);
347         xms = cell2mat(xms);
348         if saveSvf
349             svf.t = cell2mat(svf.t);
350             svf.dx = cell2mat(svf.dx);
351         end
352     end

```

3.2.2 If no output specified, then plot simulation

```

360     if nArgs==0
361         figure, plot(t,x,'o:')
362         title('Projective Simulation via PIG')
363     end

    This concludes PIG().

371 end

```

3.3 PIRK4(): projective integration of fourth-order accuracy

This Projective Integration scheme implements a macrosolver analogous to the fourth-order Runge–Kutta method.

```

15 function [x, tms, xms, rm, svf] = PIRK4(microBurst, tSpan, x0, bT)

```

See [Section 3.1](#) as the inputs and outputs are the same as PIRK2().

If no arguments, then execute an example

```

26 if nargin==0

```

Example of Michaelis–Menton backwards in time The Michaelis–Menten enzyme kinetics is expressed as a singularly perturbed system of differential equations for $x(t)$ and $y(t)$ (encoded in function `MMburst`):

$$\frac{dx}{dt} = -x + (x + \frac{1}{2})y \quad \text{and} \quad \frac{dy}{dt} = \frac{1}{\epsilon} [x - (x + 1)y].$$

With initial conditions $x(0) = y(0) = 0.2$, the following code uses forward time bursts in order to integrate backwards in time to $t = -5$. It plots the computed solution over time $-5 \leq t \leq 0$ for parameter $\epsilon = 0.1$. Since the rate of decay is $\beta \approx 1/\epsilon$ we choose a burst length $\epsilon \log(|\Delta|/\epsilon)$ as here the macroscale time-step $\Delta = -1$.

```

47 epsilon = 0.1
48 ts = 0:-1:-5
49 bT = epsilon*log(abs(ts(2)-ts(1))/epsilon)
50 [x,tms,xms,rm,svf] = PIRK4(@MMburst, ts, 0.2*[1;1], bT);
51 figure, plot(ts,x,'o:',tms,xms)
52 xlabel('time t'), legend('x(t)','y(t)')
53 title('Backwards-time projective integration of Michaelis--Menten')

Upon finishing execution of the example, exit this function.

59 return
60 end%if no arguments

```

Example function code for a burst of ODEs Integrate a burst of length `bT` of the ODEs for the Michaelis–Menten enzyme kinetics at parameter ϵ inherited from above. Code ODEs in function `dMMdt` with variables $x = \mathbf{x}(1)$ and $y = \mathbf{x}(2)$. Starting at time `ti`, and state `xi` (row), we here simply use `ode23` to integrate in time.

```

74 function [ts, xs] = MMburst(ti, xi, bT)
75     dMMdt = @(t,x) [ -x(1)+(x(1)+0.5)*x(2)
76                     1/epsilon*( x(1)-(x(1)+1)*x(2) ) ];
77     [ts, xs] = ode23(dMMdt, [ti ti+bT], xi);
78 end

```

Input

- `microBurst()`, a function that produces output from the user-specified code for microscale simulation.

`[tOut, xOut] = microBurst(tStart, xStart, bT)`

- Inputs: `tStart`, the start time of a burst of simulation; `xStart`, the row n -vector of the starting state; `bT`, optional, the total time to simulate in the burst—if `microBurst()` determines `bT`, then replace `bT` in the argument list by `varargin`.
- Outputs: `tOut`, the column vector of solution times; and `xOut`, an array in which each *row* contains the system state at corresponding times.

- **tSpan** is an ℓ -vector of times at which the user requests output, of which the first element is always the initial time. `PIRK4()` does not use adaptive time-stepping; the macroscale time-steps are (nearly) the steps between elements of **tSpan**.
- **x0** is an n -vector of initial values at the initial time **tSpan**(1). Elements of **x0** may be **NaN**: they are included in the simulation and output, and often represent boundaries in space fields.
- **bT**, optional, either missing, or empty (`[]`), or a scalar: if a given scalar, then it is the length of the micro-burst simulations—the minimum amount of time needed for the microscale simulation to relax to the slow manifold; else if missing or `[]`, then `microBurst()` must itself determine the length of a computed burst.

```
127 if nargin<4, bT=[]; end
```

Output If there are no output arguments specified, then a plot is drawn of the computed solution **x** versus **tSpan**.

- **x**, an $\ell \times n$ array of the approximate solution vector. Each row is an estimated state at the corresponding time in **tSpan**. The simplest usage is then `x = PIRK4(microBurst,tSpan,x0,bT)`.

However, microscale details of the underlying Projective Integration computations may be helpful. `PIRK4()` provides two to four optional outputs of the microscale bursts.

- **tms**, optional, is an L dimensional column vector containing microscale times of burst simulations, each burst separated by **NaN**;
- **xms**, optional, is an $L \times n$ array of the corresponding microscale states—this data is an accurate simulation of the state and may help visualise more details of the solution.
- **rm**, optional, a struct containing the ‘remaining’ applications of the micro-burst required by the Projective Integration method during the calculation of the macrostep:
 - **rm.t** is a column vector of microscale times; and
 - **rm.x** is the array of corresponding burst states.

The states **rm.x** do not have the same physical interpretation as those in **xms**; the **rm.x** are required in order to estimate the slow vector field during the calculation of the Runge–Kutta increments, and do not in general resemble the true dynamics.

- **svf**, optional, a struct containing the Projective Integration estimates of the slow vector field.
 - **svf.t** is a 4ℓ dimensional column vector containing all times at which the Projective Integration scheme is extrapolated along micro-burst data to form a macrostep.

- `svf.dx` is a $4\ell \times n$ array containing the estimated slow vector field.

3.3.1 The projective integration code

Determine the number of time-steps and preallocate storage for macroscale estimates.

```
191 nT=length(tSpan);
192 x=nan(nT,length(x0));
```

Get the number of expected outputs and set logical indices to flag what data should be saved.

```
200 nArgs=nargout();
201 saveMicro = (nArgs>1);
202 saveFullMicro = (nArgs>3);
203 saveSvf = (nArgs>4);
```

Run a preliminary application of the micro-burst on the initial conditions to help relax to the slow manifold. This is done in addition to the micro-burst in the main loop, because the initial conditions are often far from the attracting slow manifold. Require the user to input and output rows of the system state.

```
216 x0 = reshape(x0,1,[]);
217 [relax_t,relax_x0] = microBurst(tSpan(1),x0,bT);
```

Use the end point of the micro-burst as the initial conditions.

```
225 tSpan(1) = relax_t(end);
226 x(1,:)=relax_x0(end,:);
```

If saving information, then record the first application of the micro-burst. Allocate cell arrays for times and states for outputs requested by the user, as concatenating cells is much faster than iteratively extending arrays.

```
236 if saveMicro
237     tms = cell(nT,1);
238     xms = cell(nT,1);
239     tms{1} = reshape(relax_t,[],1);
240     xms{1} = relax_x0;
241     if saveFullMicro
242         rm.t = cell(nT,1);
243         rm.x = cell(nT,1);
244         if saveSvf
245             svf.t = nan(4*nT-4,1);
246             svf.dx = nan(4*nT-4,length(x0));
247         end
248     end
249 end
```

Loop over the macroscale time-steps

```
257 for jT = 2:nT
258     T = tSpan(jT-1);
```


If four applications of the micro-burst would cover the entire macroscale time-step, then do so (setting some internal states to NaN); else proceed to projective step.

```

267     if ~isempty(bT) & 4*abs(bT)>=abs(tSpan(jT)-T) & bT*(tSpan(jT)-T)>0
268         [t1,xm1] = microBurst(T, x(jT-1,:), tSpan(jT)-T);
269         x(jT,:) = xm1(end,:);
270         t2=nan; xm2=nan(1,size(xm1,2));
271         t3=nan; t4=nan; xm3=xm2; xm4 = xm2; dx1=xm2; dx2=xm2;
272     else

```

Run the first application of the micro-burst; since this application directly follows from the initial conditions, or from the latest macrostep, this microscale information is physically meaningful as a simulation of the system. Extract the size of the final time-step.

```

283     [t1,xm1] = microBurst(T, x(jT-1,:), bT);
284     del = t1(end)-t1(end-1);

```

Check for round-off error.

```

290     xt=[reshape(t1(end-1:end),[],1) xm1(end-1:end,:)];
291     roundingTol=1e-8;
292     if norm(diff(xt))/norm(xt,'fro') < roundingTol
293         warning(['significant round-off error in 1st projection at T=' num2str(T)
294     end

```

Find the needed time-step to reach time $tSpan(n+1)$ and form a first estimate $dx1$ of the slow vector field.

```

303     Dt = tSpan(jT)-t1(end);
304     dx1 = (xm1(end,:)-xm1(end-1,:))/del;

```

Assume burst times are the same length for this macro-step, or effectively so (recall that bT may be empty as it may be only coded and known in `microBurst()`).

```

312     abT = t1(end)-t1(1);

```

Project along $dx1$ to form an intermediate approximation of x ; run another application of the micro-burst and form a second estimate of the slow vector field.

```

323     xint = xm1(end,:) + (Dt/2-abT)*dx1;
324     [t2,xm2] = microBurst(T+Dt/2, xint, bT);
325     del = t2(end)-t2(end-1);
326     dx2 = (xm2(end,:)-xm2(end-1,:))/del;
327
328     xint = xm1(end,:) + (Dt/2-abT)*dx2;
329     [t3,xm3] = microBurst(T+Dt/2, xint, bT);
330     del = t3(end)-t3(end-1);
331     dx3 = (xm3(end,:)-xm3(end-1,:))/del;
332
333     xint = xm1(end,:) + (Dt-abT)*dx3;

```

```

334     [t4,xm4] = microBurst(T+Dt, xint, bT);
335     del = t4(end)-t4(end-1);
336     dx4 = (xm4(end,:)-xm4(end-1,:))/del;

```

Check for round-off error.

```

342     xt=[reshape(t2(end-1:end),[],1) xm2(end-1:end,:)];
343     if norm(diff(xt))/norm(xt,'fro') < roundingTol
344         warning(['significant round-off error in 2nd projection at T=' num2str(T)
345         end

```

Use the weighted average of the estimates of the slow vector field to take a macrostep.

```

353     x(jT,:) = xm1(end,:) + Dt*(dx1 + 2*dx2 + 2*dx3 + dx4)/6;

```

Now end the if-statement that tests whether a projective step saves simulation time.

```

361     end

```

If saving trusted microscale data, then populate the cell arrays for the current loop iterate with the time-steps and output of the first application of the micro-burst. Separate bursts by NaNs.

```

371     if saveMicro
372         tms{jT} = [reshape(t1,[],1); nan];
373         xms{jT} = [xm1; nan(1,size(xm1,2))];

```

If saving all microscale data, then repeat for the remaining applications of the micro-burst.

```

381         if saveFullMicro
382             rm.t{jT} = [reshape(t2,[],1); nan;...
383                         reshape(t3,[],1); nan;...
384                         reshape(t4,[],1); nan];
385             rm.x{jT} = [xm2; nan(1,size(xm2,2));...
386                         xm3; nan(1,size(xm2,2));...
387                         xm4; nan(1,size(xm2,2))];

```

If saving Projective Integration estimates of the slow vector field, then populate the corresponding cells with times and estimates.

```

396             if saveSvf
397                 svf.t(4*jT-7:4*jT-4) = [t1(end); t2(end); t3(end); t4(end)];
398                 svf.dx(4*jT-7:4*jT-4,:) = [dx1; dx2; dx3; dx4];
399             end
400         end
401     end

```

Terminate the main loop:

```

407     end

```

Overwrite $x(1,:)$ with the specified initial condition $tSpan(1)$.

```

416     x(1,:) = reshape(x0,1,[]);

```

For additional requested output, concatenate all the cells of time and state data into two arrays.

```

424 if saveMicro
425     tms = cell2mat(tms);
426     xms = cell2mat(xms);
427     if saveFullMicro
428         rm.t = cell2mat(rm.t);
429         rm.x = cell2mat(rm.x);
430     end
431 end

```

3.3.2 If no output specified, then plot simulation

```

439 if nArgs==0
440     figure, plot(tSpan,x,'o:')
441     title('Projective Simulation with PIRK4')
442 end

```

This concludes PIRK4().

```

449 end

```

3.3.3 cdmc()

`cdmc()` iteratively applies the micro-burst and then projects backwards in time to the initial conditions. The cumulative effect is to relax the variables to the attracting slow manifold, while keeping the final time for the output the same as the input time.

```

13 function [ts, xs] = cdmc(microBurst,t0,x0)

```

Input

- `microBurst()`, a black-box micro-burst function suitable for Projective Integration. See any of `PIRK2()`, `PIRK4()`, or `PIG()` for a description of `microBurst()`.
- `t0`, an initial time
- `x0`, an initial state

Output

- `ts`, a vector of times. `tout(end)` will equal `t`.
- `xs`, an array of state estimates produced by `microBurst()`.

This function is a wrapper for the micro-burst. For instance if the problem of interest is a dynamical system that is not too stiff, and which can be simulated by the `microBurst sol(t,x,T)`, one would define

```

cSol = @(t,x) cdmc(sol,t,x)|

```

and thereafter use `csol()` in place of `sol()` as the microBurst for any Projective Integration scheme. The original microBurst `sol()` could create large errors if used in a Projective Integration scheme, but the output of `cdmc()` should not.

Begin with a standard application of the micro-burst.

```
41 [ts,xs] = feval(microBurst,t0,x0);
42 bT = ts(end)-ts(1);
```

Project backwards to before the initial time, then simulate just one burst forward to obtain a simulation burst that ends at the original `t0`.

```
50 dxdt = (xs(end,:) - xs(end-1,:))/(ts(end,:) - ts(end-1,:));
51 x0 = xs(end,:)-2*bT*dxdt;
52 t0 = ts(1)-bT;
53 [ts,xs] = feval(microBurst,t0,x0.');
```

3.4 Example: PI using Runge–Kutta macrosolvers

This script is a demonstration of the `PIRK()` schemes, that use a Runge–Kutta macrosolver, applied to a simple linear system with some slow and fast directions.

Clear workspace and set a seed.

```
14 clear
15 rng(1)
16 global dxdt
```

The majority of this example involves setting up details for the macrosolver. We use a simple function `gen_linear_system()` that outputs a function $f(t, x) = A\vec{x} + \vec{b}$, where matrix A has some eigenvalues with large negative real part, corresponding to fast variables and some eigenvalues with real part close to zero, corresponding to slow variables. The function `gen_linear_system()` requires that we specify bounds on the real part of the strongly stable eigenvalues,

```
31 fastband = [-5e2; -1e2];
```

and bounds on the real part of the weakly stable/unstable eigenvalues,

```
38 slowband = [-0.002; 0.002];
```

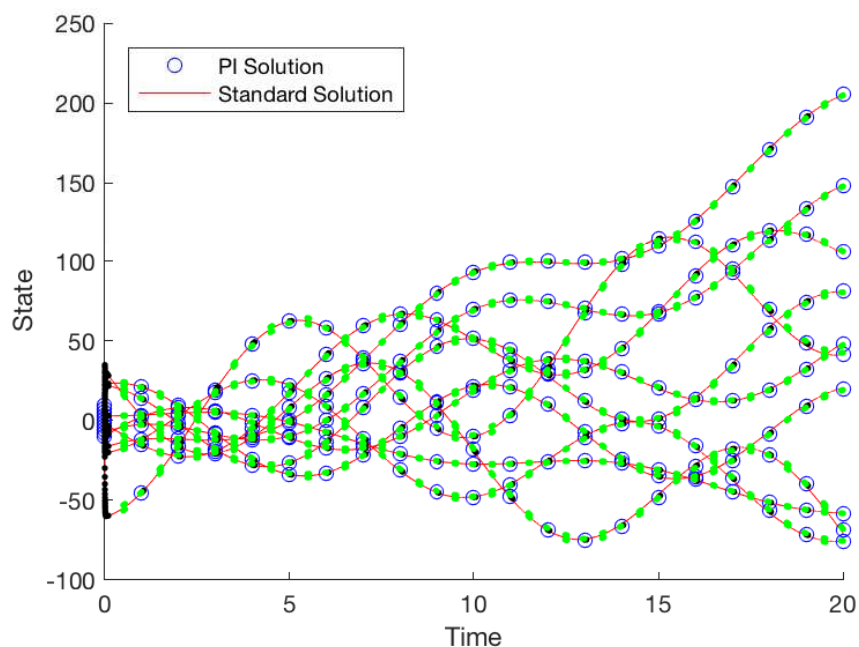
We now generate a random linear system with seven fast and three slow variables.

```
45 dxdt = gen_linear_system(7,3,fastband,slowband);
```

Set the macroscale times at which we request output from the PI scheme and the initial conditions.

```
55 tSpan = 0: 1 : 20;
56 x0 = linspace(-10,10,10)';
```

Figure 3.2: Demonstration of PIRK4(). From initial conditions, the system rapidly transitions to an attracting invariant manifold. The PI solution accurately tracks the evolution of the variables over time while requiring only a fraction of the computations of the standard solver.



We implement the PI scheme, saving the coarse states in `x`, the ‘trusted’ applications of the microsolver in `tms` and `xms`, and the additional applications of the microsolver in `rm` (the second, third and fourth outputs are optional).

```
69 [x, tms, xms, rm] = PIRK4(@linearBurst, tSpan, x0);
```

To verify, we also compute the trajectories using a standard integrator.

```
76 [tt,ode45x] = ode45(dxdt,tSpan([1,end]),x0);
```

Figure 3.2 plots the output.

```
92 clf()
93 hold on
94 PI_sol=plot(tSpan,x,'bo');
95 std_sol=plot(tt,ode45x,'r');
96 plot(tms,xms,'k.', rm.t,rm.x,'g.');
```

97 legend([PI_sol(1),std_sol(1)],'PI Solution',...
98 'Standard Solution','Location','NorthWest')
99 xlabel('Time'), ylabel('State')

Save plot to a file.

```
105 set(gcf,'PaperPosition',[0 0 14 10]), print('-depsc2','PIRK')
```

Code the micro-burst function using simple Euler steps. As a rule of thumb, the time-steps Δt should satisfy $\Delta t \leq 1/|\text{fastband}(1)|$ and the time to

simulate with each application of the microsolver, `bT`, should be larger than or equal to $1/|\text{fastband}(2)|$. We set the integration scheme to be used in the microsolver. Since the time-steps are so small, we just use the forward Euler scheme

```

119 function [ts, xs] = linearBurst(ti, xi, varargin)
120 global dxdt
121 dt = 0.001;
122 ts = ti+(0:dt:0.05)';
123 nts = length(ts);
124 xs = NaN(nts,length(xi));
125 xs(1,:)=xi;
126 for k=2:nts
127     xi = xi + dt*dxdt(ts(k),xi.').';
128     xs(k,:)=xi;
129 end
130 end

```

3.5 Example: Projective Integration using General macrosolvers

In this example the Projective Integration-General scheme is applied to a singularly perturbed ordinary differential equation. The aim is to use a standard non-stiff numerical integrator, such as `ode45()`, on the slow, long-time macroscale. For this stiff system, `PIG()` is an order of magnitude faster than ordinary use of `ode45`.

```

16 clear all, close all

```

Set time scale separation and model.

```

23 epsilon = 1e-4;
24 dxdt=@(t,x) [ cos(x(1))*sin(x(2))*cos(t)
25               (cos(x(1))-x(2))/epsilon ];

```

Set the ‘black-box’ microsolver to be an integration using a standard solver, and set the standard time of simulation for the microsolver.

```

34 bT = epsilon*log(1/epsilon);
35 microBurst = @(tb0, xb0) ode45(dxdt,[tb0 tb0+bT],xb0);

```

Set initial conditions, and the time to be covered by the macrosolver.

```

43 x0 = [1 1.4];
44 tSpan=[0 15];

```

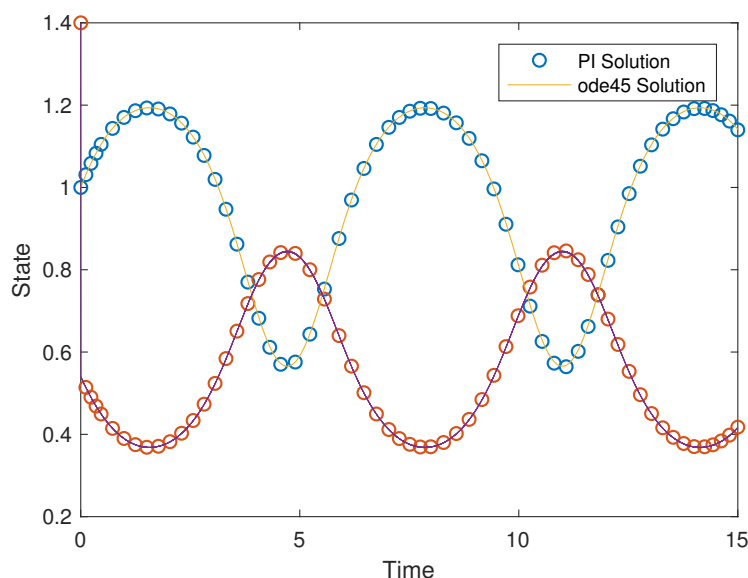
Now time and integrate the above system over `tspan` using `PIG()` and, for comparison, a brute force implementation of `ode45()`. Report the time taken by each method.

```

53 tic
54 [ts,xs,tms,xms] = PIG('ode45',microBurst,tSpan,x0);
55 tPIGusingODE45asMacro = toc
56 tic

```

Figure 3.3: Accurate simulation of a stiff nonautonomous system by `PIG()`. The microsolver is called on-the-fly by the macrosolver `ode45`.



```
57 [t45,x45] = ode45(dxd,tSpan,x0);
58 tODE45alone = toc
```

Plot the output on two figures, showing the truth and macrosteps on both, and all applications of the microsolver on the first figure.

```
68 figure
69 h = plot(ts,xs,'o', t45,x45,'-', tms,xms,'.');
70 legend(h(1:2:5),'PI Solution','ode45 Solution','PI microsolver')
71 xlabel('Time'), ylabel('State')
72
73 figure
74 h = plot(ts,xs,'o', t45,x45,'-');
75 legend(h([1 3]),'PI Solution','ode45 Solution')
76 xlabel('Time'), ylabel('State')
77 set(gcf,'PaperPosition',[0 0 14 10]), print('-depsc2','PIGExample')
```

Figure 3.3 plots the output.

- The problem may be made more, or less, stiff by changing the time-scale separation parameter $\epsilon = \texttt{epsilon}$. The compute time of `PIG()` is almost independent of ϵ , whereas that of `ode45()` is proportional to $1/\epsilon$.

But if the problem is insufficiently stiff (larger ϵ), then `PIG()` produces nonsense. This nonsense is overcome by `cdmc()` (Section 3.6).

- The mildly stiff problem in Section 3.4 may be efficiently solved by a standard solver (e.g., `ode45()`). The stiff but low dimensional problem in this example can be solved efficiently by a standard stiff solver (e.g., `ode15s()`). The real advantage of the Projective Integration schemes is

in high dimensional stiff problems, that cannot be efficiently solved by most standard methods.

3.6 Explore: Projective Integration using constraint-defined manifold computing

In this example the Projective Integration-General scheme is applied to a singularly perturbed ordinary differential equation in which the time scale separation is not large. The resulting simulation is not accurate. In parallel, we run the same scheme but with `cdmc()` used as a wrapper for the microsolver. This second implementation successfully replicates the true dynamics.

```
16 clear all, close all
```

Set a weak time scale separation and model.

```
23 epsilon = 0.01;
24 dxdt=@(t,x) [ cos(x(1))*sin(x(2))*cos(t)
25               (cos(x(1))-x(2))/epsilon ];
```

Set the ‘naive’ microsolver to be an integration using a standard solver, and set the standard time of simulation for the microsolver.

```
34 bT = epsilon*log(1/epsilon);
35 naiveBurst = @(tb0,xb0) ode45(dxdt,[tb0 tb0+bT],xb0);
```

Create a second struct in which the solver is the output of `cdmc()`.

```
42 cBurst = @(t,x) cdmc(naiveBurst,t,x);
```

Set initial conditions, and the time to be covered by the macrosolver.

```
50 x0 = [1 0];
51 tSpan=0:0.5:15;
```

Simulate using `PIG()` with each of the above microsolvers. Generate a trusted solution using standard numerical methods.

```
61 [nt,nx] = PIG('ode45',naiveBurst,tSpan,x0);
62 [ct,cx] = PIG('ode45',cBurst,tSpan,x0);
63 [t45,x45] = ode45(dxdt,tSpan([1 end]),x0);
```

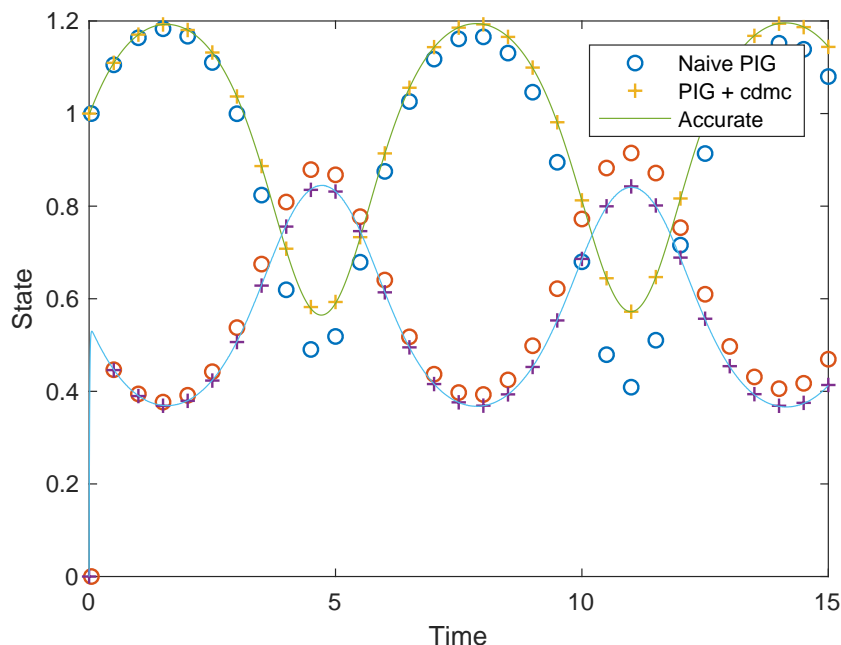
Figure 3.4 plots the output.

```
79 figure
80 h = plot(nt,nx,'o', ct,cx,'+', t45,x45,'-');
81 legend(h(1:2:5),'Naive PIG','PIG + cdmc','Accurate')
82 xlabel('Time'), ylabel('State')
83 set(gcf,'PaperPosition',[0 0 14 10]), print('-depsc2','PIGExplore')
```

The source of the error in the standard `PIG()` scheme is the burst length `bT`, that is significant on the slow time scale. Set `bT` to `20*epsilon` or `50*epsilon`¹ to worsen the error in both schemes. This example reflects a

¹ this example is quite extreme: at `bT=50*epsilon`, it would be computationally much cheaper to simulate the entire length of `tSpan` using the microsolver alone.

Figure 3.4: Accurate simulation of a weakly stiff non-autonomous system by `PIG()` using `cdmc()`, and an inaccurate solution using a naive application of `PIG()`.



general principle, that most Projective Integration schemes will incur a global error term which is proportional to the simulation time of the microsolver and independent of the order of the microsolver. The `PIRK()` schemes have been written to minimise, if not eliminate entirely, this error, but by design `PIG()` works with any user-defined macrosolver and cannot reduce this error. The function `cdmc()` reduces this error term by attempting to mimic the microsolver without advancing time.

3.7 To do/discuss

- could implement Projective Integration by ‘arbitrary’ Runge–Kutta scheme; that is, by having the user input a particular Butcher table—surely only specialists would be interested
- can ‘reverse’ the order of projection and microsolver applications with a little fiddling. Then output at each user-requested coarse time is the end point of an application of the microsolver - better predictions for fast variables.
- Can maybe implement microsolvers that terminate a burst when the fast dynamics have settled using, for example, the ‘Events’ function handle in `ode23`.

4 Patch scheme for given microscale discrete space system

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The patch scheme applies to spatio-temporal systems where the spatial domain is larger than what can be computed in reasonable time. In the scheme we compute only on small patches of the space-time domain, and produce correct macroscale predictions by craftily coupling the patches across unsimulated space (Hyman 2005, Samaey et al. 2005, 2006, Roberts & Kevrekidis 2007, Liu et al. 2015, e.g.).

The spatial structure is to be on a lattice such as obtained from finite difference approximation of a PDE. Usually continuous in time.

Quick start See Sections 4.1.1 and 4.7.1 which list example basic code that uses the provided functions to simulate 1D Burgers’ PDE and a 2D nonlinear ‘diffusion’ PDE.

4.1 configPatches1(): configures spatial patches in 1D

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Makes the struct `patches` for use by the patch/gap-tooth time derivative function `patchSmooth1()`. Section 4.1.1 lists an example of its use.

```

14 function configPatches1(fun,Xlim,BCs,nPatch,ordCC,ratio,nSubP,nEdge)
15 global patches

```

Input If invoked with no input arguments, then executes an example of simulating Burgers’ PDE—see Section 4.1.1 for the example code.

- `fun` is the name of the user function, `fun(t,u,x)`, that computes time derivatives (or time-steps) of quantities on the patches.
- `Xlim` give the macro-space domain of the computation: patches are equi-spaced over the interior of the interval `[Xlim(1),Xlim(2)]`.
- `BCs` somehow will define the macroscale boundary conditions. Currently, `BCs` is ignored and the system is assumed macro-periodic in the domain.
- `nPatch` is the number of equi-spaced spaced patches.
- `ordCC` is the ‘order’ of interpolation across empty space of the macroscale mid-patch values to the edge of the patches for inter-patch coupling: currently must be ≥ -1 .

- **ratio** (real) is the ratio of the half-width of a patch to the spacing of the patch mid-points: so $\text{ratio} = \frac{1}{2}$ means the patches abut; and $\text{ratio} = 1$ is overlapping patches as in holistic discretisation.
- **nSubP** is the number of equi-spaced microscale lattice points in each patch. Must be odd so that there is a central lattice point.
- **nEdge** is, for each patch, the number of edge values set by interpolation at the edge regions of each patch. May be omitted. The default is one (suitable for microscale lattices with only nearest neighbour interactions).

Output The *global* struct **patches** is created and set with the following components.

- **.fun** is the name of the user's function **fun(u,t,x)** that computes the time derivatives (or steps) on the patchy lattice.
- **.ordCC** is the specified order of inter-patch coupling.
- **.alt** is true for interpolation using only odd neighbouring patches as for staggered grids, and false for the usual case of all neighbour coupling.
- **.Cwtsr** and **.Cwtsl** are the **ordCC**-vector of weights for the inter-patch interpolation onto the right and left edges (respectively) with patch:macroscale ratio as specified.
- **.x** is $\text{nSubP} \times \text{nPatch}$ array of the regular spatial locations x_{ij} of the microscale grid points in every patch.
- **.nEdge** is, for each patch, the number of edge values set by interpolation at the edge regions of each patch.

4.1.1 If no arguments, then execute an example

96 **if nargin==0**

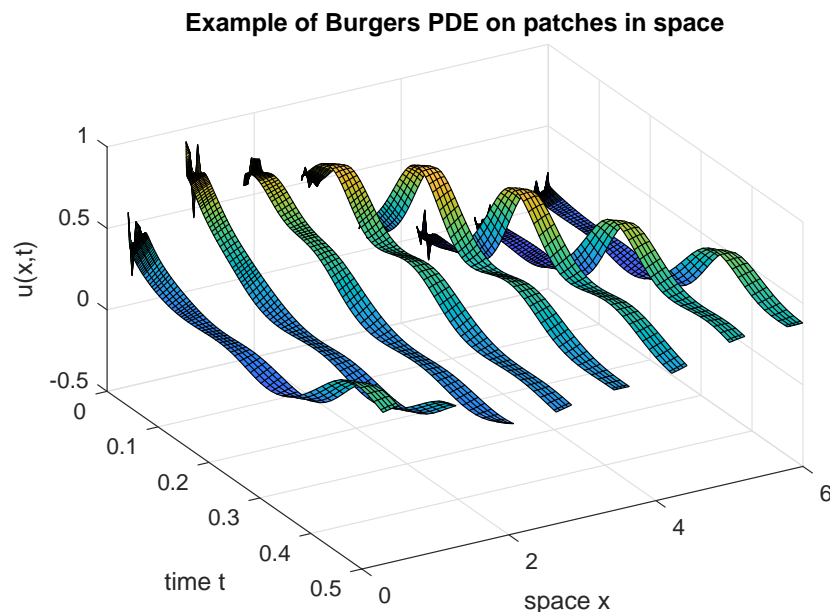
The code here shows one way to get started: a user's script may have the following three steps (left-right arrows denote function recursion).

1. **configPatches1**
2. **ode15s** integrator \leftrightarrow **patchSmooth1** \leftrightarrow user's **burgersPDE**
3. process results

Establish global patch data struct to interface with a function coding Burgers' PDE: to be solved on 2π -periodic domain, with eight patches, spectral interpolation couples the patches, each patch of half-size ratio 0.2, and with seven microscale points forming each patch.

115 **configPatches1(@BurgersPDE,[0 2*pi], nan, 8, 0, 0.2, 7);**

Set an initial condition, with some randomness, and simulate in time using a standard stiff integrator and the interface function **patchsmooth1()** (Section 4.2).

Figure 4.1: field $u(x, t)$ of the patch scheme applied to Burgers' PDE.

```

124 u0=0.3*(1+sin(patches.x))+0.1*randn(size(patches.x));
125 [ts,ucts]=ode15s(@patchSmooth1,[0 0.5],u0(:));

```

Plot the simulation using only the microscale values interior to the patches: set x -edges to `nan` to leave the gaps. Figure 4.1 illustrates an example simulation in time generated by the patch scheme applied to Burgers' PDE.

```

135 figure(1),clf
136 patches.x([1 end],:)=nan;
137 surf(ts,patches.x(:),ucts'), view(60,40)
138 title('Example of Burgers PDE on patches in space')
139 xlabel('time t'), ylabel('space x'), zlabel('u(x,t)')

```

Upon finishing execution of the example, exit this function.

```

150 return
151 end%if no arguments

```

Example of Burgers PDE inside patches As a microscale discretisation of Burgers' PDE $u_t = u_{xx} - 30uu_x$, here code $\dot{u}_{ij} = \frac{1}{\delta x^2}(u_{i+1,j} - 2u_{i,j} + u_{i-1,j}) - 30u_{ij}\frac{1}{2\delta x}(u_{i+1,j} - u_{i-1,j})$.

```

161 function ut=BurgersPDE(t,u,x)
162     dx=diff(x(1:2)); % microscale spacing
163     i=2:size(u,1)-1; % interior points in patches
164     ut=nan(size(u)); % preallocate storage
165     ut(i,:)=diff(u,2)/dx^2 ...
166         -30*u(i,:).*(u(i+1,:)-u(i-1,:))/(2*dx);
167 end

```

This hack needs to be resolved: AJR, 2019-02-26

```
178 patches.EnsAve = 0;
```

4.1.2 The code to make patches and interpolation

Set one edge-value to compute by interpolation if not specified by the user.
Store in the struct.

```
188 if nargin<8, nEdge=1; end
189 if nEdge>1, error('multi-edge-value interp not yet implemented'), end
190 if 2*nEdge+1>nSubP, error('too many edge values requested'), end
191 patches.nEdge=nEdge;
```

First, store the pointer to the time derivative function in the struct.

```
198 patches.fun=fun;
```

Second, store the order of interpolation that is to provide the values for the inter-patch coupling conditions. Spectral coupling is `ordCC` of 0 and -1 .

```
206 if (ordCC<-1) | ~(floor(ordCC)==ordCC)
207     error('ordCC out of allowed range integer>-2')
208 end
```

For odd `ordCC` do interpolation based upon odd neighbouring patches as is useful for staggered grids.

```
215 patches.alt=mod(ordCC,2);
216 ordCC=ordCC+patches.alt;
217 patches.ordCC=ordCC;
```

Check for staggered grid and periodic case.

```
223 if patches.alt & (mod(nPatch,2)==1)
224     error('Require an even number of patches for staggered grid')
225 end
```

Might as well precompute the weightings for the interpolation of field values for coupling. (Could sometime extend to coupling via derivative values.)

```
233 patches.Cwtsr=zeros(ordCC,1);
234 if patches.alt % eqn (7) in \cite{Cao2014a}
235     patches.Cwtsr(1:2:ordCC)=[1 ...
236         cumprod((ratio^2-(1:2:(ordCC-2)).^2)/4)./ ...
237         factorial(2*(1:(ordCC/2-1)))];
238     patches.Cwtsr(2:2:ordCC)=[ratio/2 ...
239         cumprod((ratio^2-(1:2:(ordCC-2)).^2)/4)./ ...
240         factorial(2*(1:(ordCC/2-1))+1)*ratio/2];
241 else %
242     patches.Cwtsr(1:2:ordCC)=(cumprod(ratio^2- ...
243         (((1:(ordCC/2))-1).^2)./factorial(2*(1:(ordCC/2))-1)/ratio);
244     patches.Cwtsr(2:2:ordCC)=(cumprod(ratio^2- ...
245         (((1:(ordCC/2))-1).^2)./factorial(2*(1:(ordCC/2)))));
246 end
247 patches.Cwtsl=(-1).^((1:ordCC)'-patches.alt).*patches.Cwtsr;
```

Third, set the centre of the patches in a the macroscale grid of patches assuming periodic macroscale domain.

```

254 X=linspace(Xlim(1),Xlim(2),nPatch+1);
255 X=X(1:nPatch)+diff(X)/2;
256 DX=X(2)-X(1);

```

Construct the microscale in each patch, assuming Dirichlet patch edges, and a half-patch length of `ratio · DX`.

```

264 if mod(nSubP,2)==0, error('configPatches1: nSubP must be odd'), end
265 i0=(nSubP+1)/2;
266 dx=ratio*DX/(i0-1);
267 patches.x=bsxfun(@plus,dx*(-i0+1:i0-1)',X); % micro-grid
268 end% function

```

Fin.

4.2 patchSmooth1(): interface to time integrators

Subsection contents

Input	38
Output	39

To simulate in time with spatial patches we often need to interface a user's time derivative function with time integration routines such as `ode15s` or `PIRK2`. This function provides an interface. It assumes that the sub-patch structure is *smooth* so that the patch centre-values are sensible macroscale variables, and patch edge values are determined by macroscale interpolation of the patch-centre values. Communicate patch-design variables to this function using the previously established global struct `patches` (Section 4.1).

```

23 function dudt=patchSmooth1(t,u)
24 global patches

```

Input

- `u` is a vector of length `nSubP · nPatch · nVars` where there are `nVars` field values at each of the points in the `nSubP × nPatch` grid.
- `t` is the current time to be passed to the user's time derivative function.
- `patches` a struct set by `configPatches1()` with the following information used here.
 - `.fun` is the name of the user's function `fun(t,u,x)` that computes the time derivatives on the patchy lattice. The array `u` has size `nSubP × nPatch × nVars`. Time derivatives must be computed into the same sized array, although herein the patch edge values are overwritten by zeros.

- `.x` is $\text{nSubP} \times \text{nPatch}$ array of the spatial locations x_{ij} of the microscale grid points in every patch. Currently it *must* be an equi-spaced lattice on both macro- and microscale.

Output

- `dudt` is $\text{nSubP} \cdot \text{nPatch} \cdot \text{nVars}$ vector of time derivatives, but with patch edge values set to zero.

Reshape the fields `u` as a 2/3D-array, and sets the edge values from macroscale interpolation of centre-patch values. [Section 4.3](#) describes `patchEdgeInt1()`.

```
74 u=patchEdgeInt1(u);
```

Ask the user function for the time derivatives computed in the array, overwrite its edge values with the dummy value of zero, then return to `a` to the user/integrator as column vector.

```
84 dudt=patches.fun(t,u,patches.x);
```

```
85 dudt([1 end],:,:)=0;
```

```
86 dudt=reshape(dudt,[],1);
```

Fin.

4.3 patchEdgeInt1(): sets edge values from interpolation over the macroscale

Subsection contents

Input	40
Output	40
Lagrange interpolation gives patch-edge values .	41
Case of spectral interpolation	42

Couples 1D patches across 1D space by computing their edge values from macroscale interpolation of either the mid-patch value or the patch-core average. This function is primarily used by `patchSmooth1()` but is also useful for user graphics. A spatially discrete system could be integrated in time via the patch or gap-tooth scheme ([Roberts & Kevrekidis 2007](#)). Assumes that the core averages are in some sense *smooth* so that these averages are sensible macroscale variables. Then patch edge values are determined by macroscale interpolation of the core averages ([Bunder et al. 2017](#)). Communicate patch-design variables via the global struct `patches`.

```
25 function u=patchEdgeInt1(u)
26 global patches
```

Input

- **u** is a vector of length $nSubP \cdot nPatch \cdot nVars$ where there are $nVars$ field values at each of the points in the $nSubP \times nPatch$ grid.
- **patches** a struct set by `configPatches1()` which includes the following.
 - **.x** is $nSubP \times nPatch$ array of the spatial locations x_{ij} of the microscale grid points in every patch. Currently it *must* be an equi-spaced lattice on both macro- and microscale.
 - **.ordCC** is order of interpolation integer ≥ -1 .
 - **.alt** in $\{0, 1\}$ is one for staggered grid (alternating) interpolation.
 - **.Cwtsr** and **.Cwtsl** define the coupling.

Output

- **u** is $nSubP \times nPatch \times nVars$ 2/3D array of the fields with edge values set by interpolation of patch core averages.

Determine the sizes of things. Any error arising in the reshape indicates **u** has the wrong size.

```

64 [nSubP,nPatch] = size(patches.x);
65 nVars = round(numel(u)/numel(patches.x));
66 if numel(u)~=nSubP*nPatch*nVars
67     nSubP=nSubP, nPatch=nPatch, nVars=nVars, sizeu=size(u)
68     end
69 u = reshape(u,nSubP,nPatch,nVars);

```

Compute lattice sizes from inside the patches as the edge values may be NaNs, etc.

```

76 dx = patches.x(3,1)-patches.x(2,1);
77 DX = patches.x(2,2)-patches.x(2,1);

```

If the user has not defined the patch core, then we assume it to be a single point in the middle of the patch. For `patches.nCore` $\neq 1$ the half width ratio is reduced, as described by [Bunder et al. \(2017\)](#).

```

86 if ~isfield(patches,'nCore')
87     patches.nCore = 1;
88 end
89 r = dx*(nSubP-1)/2/DX*(nSubP - patches.nCore)/(nSubP - 1);

```

For the moment assume the physical domain is macroscale periodic so that the coupling formulas are simplest. Should eventually cater for periodic, odd-mid-gap, even-mid-gap, even-mid-patch, Dirichlet, Neumann etc. These index vectors point to patches and their two immediate neighbours.

```

100 j = 1:nPatch; jp = mod(j,nPatch)+1; jm = mod(j-2,nPatch)+1;

```

Calculate centre of each patch and the surrounding core ($nSubP$ and $nCore$ are both odd).

```

107 i0 = round((nSubP+1)/2);
108 c = round((patches.nCore-1)/2);

```

Lagrange interpolation gives patch-edge values Consequently, compute centred differences of the patch core averages for the macro-interpolation of all fields. Assumes the domain is macro-periodic.

```

118 if patches.ordCC>0 % then non-spectral interpolation
119     if patches.EnsAve
120         uCore = sum(mean(u((i0-c):(i0+c),j,:),3),1)';
121         dmu = zeros(patches.ordCC,nPatch);
122     else
123         uCore = reshape(sum(u((i0-c):(i0+c),j,:),1),nPatch,nVars);
124         dmu = zeros(patches.ordCC,nPatch,nVars);
125     end;
126     if patches.alt % use only odd numbered neighbours
127         dmu(1,:,:) = (uCore(jp,:)+uCore(jm,:))/2; % \mu
128         dmu(2,:,:) = (uCore(jp,:)-uCore(jm,:)); % \delta
129         jp = jp(jp); jm = jm(jm); % increase shifts to \pm 2
130     else % standard
131         dmu(1,j,:) = (uCore(jp,:)-uCore(jm,:))/2; % \mu\delta
132         dmu(2,j,:) = (uCore(jp,:)-2*uCore(j,:)+uCore(jm,:))/2; % \delta^2
133     end% if odd/even

```

Recursively take δ^2 of these to form higher order centred differences (could unroll a little to cater for two in parallel).

```

141 for k = 3:patches.ordCC
142     dmu(k,:,:) = dmu(k-2,jp,:)-2*dmu(k-2,j,:)+dmu(k-2,jm,:);
143 end

```

Interpolate macro-values to be Dirichlet edge values for each patch ([Roberts & Kevrekidis 2007](#), [Bunder et al. 2017](#)), using weights computed in `configPatches1()`. Here interpolate to specified order.

```

152 if patches.EnsAve
153     u(nSubP,j,:) = repmat(uCore(j)'*(1-patches.alt) ...
154         +sum(bsxfun(@times,patches.Cwtsr,dmu)), [1,1,nVars]) ...
155         -sum(u((nSubP-patches.nCore+1):(nSubP-1),:,:),1);
156     u(1,j,:) = repmat(uCore(j)'*(1-patches.alt) ...
157         +sum(bsxfun(@times,patches.Cwtsl,dmu)), [1,1,nVars]) ...
158         -sum(u(2:patches.nCore,:,:),1);
159 else
160     u(nSubP,j,:) = uCore(j,:)*(1-patches.alt) ...
161         + reshape(-sum(u((nSubP-patches.nCore+1):(nSubP-1),j,:),1) ...
162         +sum(bsxfun(@times,patches.Cwtsr,dmu)),nPatch,nVars);
163     u(1,j,:) = uCore(j,:)*(1-patches.alt) ...
164         +reshape(-sum(u(2:patches.nCore,j,:),1) ...
165         +sum(bsxfun(@times,patches.Cwtsl,dmu)),nPatch,nVars);
166 end;

```

Case of spectral interpolation Assumes the domain is macro-periodic. As the macroscale fields are N -periodic, the macroscale Fourier transform writes the centre-patch values as $U_j = \sum_k C_k e^{ik2\pi j/N}$. Then the edge-patch values $U_{j\pm r} = \sum_k C_k e^{ik2\pi/N(j\pm r)} = \sum_k C'_k e^{ik2\pi j/N}$ where $C'_k = C_k e^{ikr2\pi/N}$. For `nPatch` patches we resolve ‘wavenumbers’ $|k| < \text{nPatch}/2$, so set row vector $\mathbf{k}s = k2\pi/N$ for ‘wavenumbers’ $k = (0, 1, \dots, k_{\max}, -k_{\max}, \dots, -1)$ for odd N , and $k = (0, 1, \dots, k_{\max}, \pm(k_{\max} + 1), -k_{\max}, \dots, -1)$ for even N .

```
184 else% spectral interpolation
```

Deal with staggered grid by doubling the number of fields and halving the number of patches (`configPatches1()` tests that there are an even number of patches). Then the patch-ratio is effectively halved. The patch edges are near the middle of the gaps and swapped.

```
194   if patches.alt % transform by doubling the number of fields
195       v = nan(size(u)); % currently to restore the shape of u
196       u = cat(3,u(:,1:2:nPatch,:),u(:,2:2:nPatch,:));
197       altShift = reshape(0.5*[ones(nVars,1);-ones(nVars,1)],1,1,[]);
198       iV = [nVars+1:2*nVars 1:nVars]; % scatter interp to alternate field
199       r = r/2; % ratio effectively halved
200       nPatch = nPatch/2; % halve the number of patches
201       nVars = nVars*2; % double the number of fields
202   else % the values for standard spectral
203       altShift = 0;
204       iV = 1:nVars;
205   end
```

Now set wavenumbers.

```
211   kMax = floor((nPatch-1)/2);
212   ks = 2*pi/nPatch*(mod((0:nPatch-1)+kMax,nPatch)-kMax);
```

Test for reality of the field values, and define a function accordingly.

```
219   if imag(u(i0,:,:))==0, uclean=@(u) real(u);
220       else uclean=@(u) u;
221   end
```

Compute the Fourier transform of the patch centre-values for all the fields. If there are an even number of points, then zero the zig-zag mode in the FT and add it in later as cosine.

```
230   Ck = fft(u(i0,:,:));
231   if mod(nPatch,2)==0
232       Czz = Ck(1,nPatch/2+1,:)/nPatch;
233       Ck(1,nPatch/2+1,:) = 0;
234   end
```

The inverse Fourier transform gives the edge values via a shift a fraction r to the next macroscale grid point. Enforce reality when appropriate.

```
242   u(nSubP,:,iV) = uclean(ifft(bsxfun(@times,Ck ...
243       ,exp(1i*bsxfun(@times,ks,altShift+r)))));
```

```

244     u( 1,:,iV) = uclean(iff(fft(bsxfun(@times,Ck ...
245         ,exp(1i*bsxfun(@times,ks,altShift-r))))));

    For an even number of patches, add in the cosine mode.

251     if mod(nPatch,2)==0
252         cosr = cos(pi*(altShift+r+(0:nPatch-1)));
253         u(nSubP,:,iV) = u(nSubP,:,iV)+uclean(bsxfun(@times,Czz,cosr));
254         cosr = cos(pi*(altShift-r+(0:nPatch-1)));
255         u( 1,:,iV) = u( 1,:,iV)+uclean(bsxfun(@times,Czz,cosr));
256     end

    Restore staggered grid when appropriate. Is there a better way to do this??

263     if patches.alt
264         nVars = nVars/2; nPatch = 2*nPatch;
265         v(:,1:2:nPatch,:) = u(:, :, 1:nVars);
266         v(:,2:2:nPatch,:) = u(:, :, nVars+1:2*nVars);
267         u = v;
268     end
269     end% if spectral

```

Fin, returning the 2/3D array of field values.

4.4 BurgersExample: simulate Burgers' PDE on patches

Section contents

Figure 4.1 shows an example simulation in time generated by the patch scheme function applied to Burgers' PDE. This code similarly applies the Equation-Free functions to a microscale space-time map (Figure 4.2), a map that happens to be derived as a microscale space-time discretisation of Burgers' PDE. Then this example applies projective integration to simulate further in time.

The first part of the script implements the following gap-tooth scheme (left-right arrows denote function recursion).

1. configPatches1
2. burgerBurst \leftrightarrow patchSmooth1 \leftrightarrow burgersMap
3. process results

4.4.1 Script code to simulate a microscale space-time map

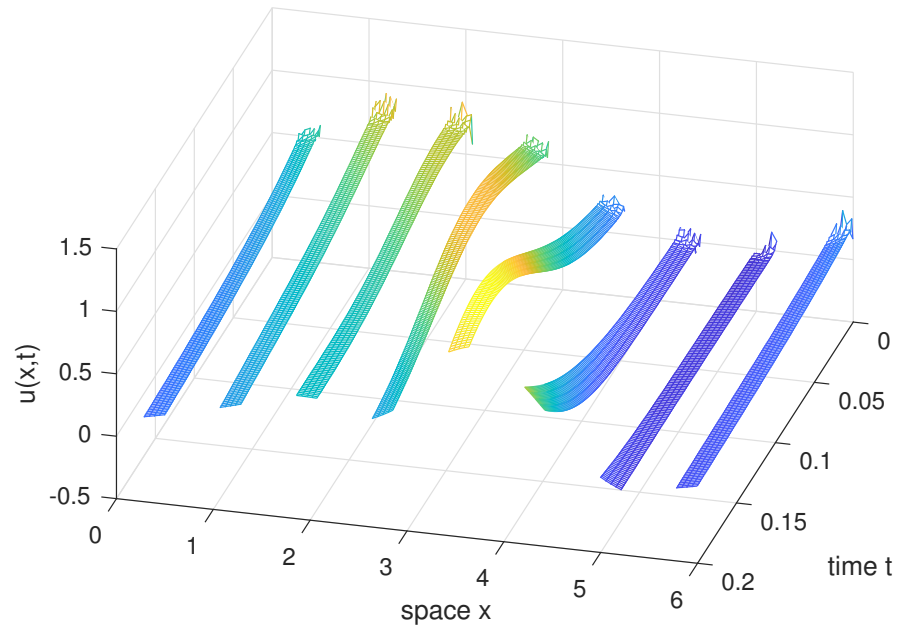
Establish global data struct for the Burgers' map (Section 4.4.2) solved on 2π -periodic domain, with eight patches, each patch of half-size ratio 0.2, with seven points within each patch, and say fourth-order interpolation provides edge-values that couple the patches.

```

48     clear all
49     global patches
50     nPatch = 8

```

Figure 4.2: a short time simulation of the Burgers' map (Section 4.4.2) on patches in space. It requires many very small time-steps only just visible in this mesh.



```

51 ratio = 0.2
52 nSubP = 7
53 interpOrd = 4
54 Len = 2*pi
55 configPatches1(@burgersMap,[0 Len],nan,nPatch,interpOrd,ratio,nSubP);

```

Set an initial condition, and simulate a burst of the microscale space-time map over a time 0.2 using the function `burgerBurst()` (Section 4.4.3).

```

63 u0 = 0.4*(1+sin(patches.x))+0.1*randn(size(patches.x));
64 [ts,us] = burgerBurst(0,u0,0.2);

```

Plot the simulation. Use only the microscale values interior to the patches by setting the edges to `nan` in order to leave gaps.

```

72 figure(1),clf
73 xs = patches.x; xs([1 end],:) = nan;
74 mesh(ts,xs(:),us')
75 xlabel('time t'), ylabel('space x'), zlabel('u(x,t)')
76 view(105,45)

```

Save the plot to file to form Figure 4.2.

```

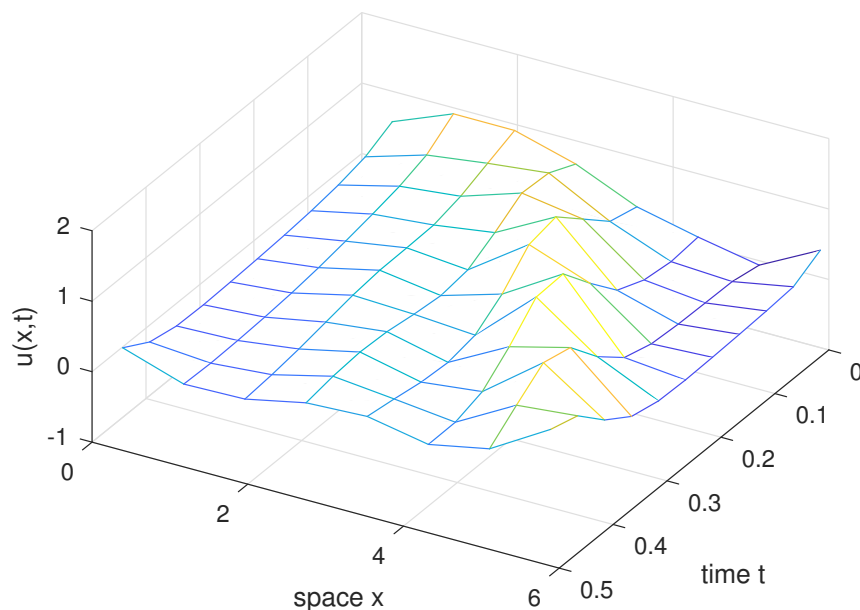
82 set(gcf,'paperposition',[0 0 14 10])
83 print('-depsc2','BurgersMapU')

```

Alternatively use projective integration

Around the microscale burst `burgerBurst()`, wrap the projective integration function `PIRK2()` of Section 3.1. Figure 4.3 shows the macroscale prediction

Figure 4.3: macroscale space-time field $u(x, t)$ in a basic projective integration of the patch scheme applied to the microscale Burgers' map.



of the patch centre values on macroscale time-steps.

This second part of the script implements the following design.

1. configPatches1 (done in first part)
2. PIRK2 \leftrightarrow burgerBurst \leftrightarrow patchSmooth1 \leftrightarrow burgersMap
3. process results

Mark that edge-values of patches are not to be used in the projective extrapolation by setting initial values to NaN.

```
115 u0([1 end], :) = nan;
```

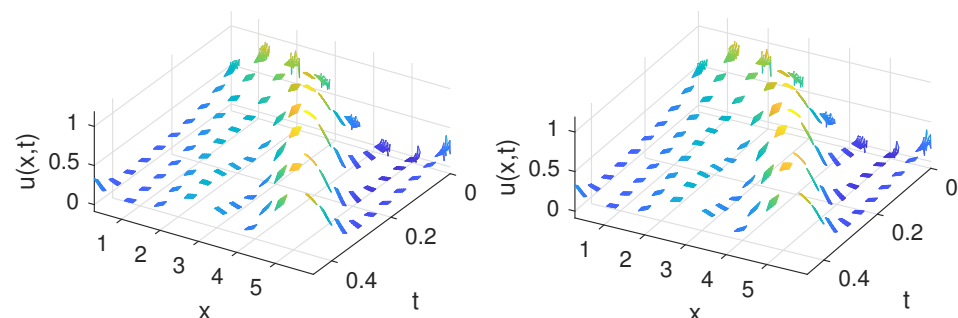
Set the desired macroscale time-steps, and microscale burst length over the time domain. Then projectively integrate in time using PIRK2() which is (roughly) second-order accurate in the macroscale time-step.

```
124 ts = linspace(0,0.5,11);
125 bT = 3*(ratio*Len/nPatch/(nSubP/2-1))^2
126 addpath(' ../ProjInt')
127 [us,tss,uss] = PIRK2(@burgerBurst,ts,u0(:),bT);
```

Plot and save the macroscale predictions of the mid-patch values to give the macroscale mesh-surface of Figure 4.3 that shows a progressing wave solution.

```
136 figure(2),clf
137 midP = (nSubP+1)/2;
138 mesh(ts,xs(midP,:),us(:,midP:nSubP:end))
139 xlabel('time t'), ylabel('space x'), zlabel('u(x,t)')
140 view(120,50)
141 set(gcf,'paperposition',[0 0 14 10])
142 print('-depsc2','BurgersU')
```

Figure 4.4: the field $u(x, t)$ during each of the microscale bursts used in the projective integration. View this stereo pair cross-eyed.



Then plot and save the microscale mesh of the microscale bursts shown in [Figure 4.4](#) (a stereo pair). The details of the fine microscale mesh are almost invisible.

```

157 figure(3),clf
158 for k = 1:2, subplot(2,2,k)
159     mesh(tss,xs(:),uss')
160     ylabel('x'),xlabel('t'),zlabel('u(x,t)')
161     axis tight, view(126-4*k,50)
162 end
163 set(gcf,'paperposition',[0 0 17 12])
164 print('-depsc2','BurgersMicro')

```

4.4.2 burgersMap(): discretise the PDE microscale

This function codes the microscale Euler integration map of the lattice differential equations inside the patches. Only the patch-interior values mapped (patchSmooth1() overrides the edge-values anyway).

```

181 function u = burgersMap(t,u,x)
182     dx = diff(x(2:3));
183     dt = dx^2/2;
184     i = 2:size(u,1)-1;
185     u(i,:) = u(i,:) +dt*( diff(u,2)/dx^2 ...
186         -20*u(i,:).*(u(i+1,:)-u(i-1,:))/(2*dx) );
187 end

```

4.4.3 burgerBurst(): code a burst of the patch map

```

197 function [ts, us] = burgerBurst(ti, ui, bT)

```

First find and set the number of microscale time-steps.

```

203 global patches
204 dt = diff(patches.x(2:3))^2/2;
205 ndt = ceil(bT/dt -0.2);
206 ts = ti+(0:ndt)*dt;

```


Use `patchSmooth1()` (Section 4.2) to apply the microscale map over all time-steps in the burst. The `patchSmooth1()` interface provides the interpolated edge-values of each patch. Store the results in rows to be consistent with ODE and projective integrators.

```

216     us = nan(ndt+1,numel(ui));
217     us(1,:) = reshape(ui,1,[]);
218     for j = 1:ndt
219         ui = patchSmooth1(ts(j),ui);
220         us(j+1,:) = reshape(ui,1,[]);
221     end

```

Linearly interpolate (extrapolate) to get the field values at the precise final time of the burst. Then return.

```

228     ts(ndt+1) = ti+bT;
229     us(ndt+1,:) = us(ndt,:) ...
230         + diff(ts(ndt:ndt+1))/dt*diff(us(ndt:ndt+1,:));
231 end

```

Fin.

4.5 HomogenisationExample: simulate heterogeneous diffusion in 1D on patches

Section contents

Figures 4.5 and 4.6 show example simulations in time generated by the patch scheme function applied to heterogeneous diffusion. That such simulations of heterogeneous diffusion makes valid predictions was established by Bunder et al. (2017) who proved that the scheme is accurate when the number of points in a patch minus the number of points in the core is an even multiple of the microscale periodicity. We present two different methods of obtaining a macroscale solution. One method uses the given heterogeneous diffusion, which produces a solution which has microscale roughness (Figure 4.5). The other method constructs an ensemble of heterogeneous diffusion and produces an ensemble average solution which has a smooth microscale (Figure 4.6).

The first part of the script implements the following gap-tooth scheme (left-right arrows denote function recursion).

1. configPatches1
2. ode15s \leftrightarrow patchSmooth1 \leftrightarrow heteroDiff
3. process results

Consider a lattice of values $u_i(t)$, with lattice spacing dx , and governed by the heterogeneous diffusion

$$\dot{u}_i = [c_{i-1/2}(u_{i-1} - u_i) + c_{i+1/2}(u_{i+1} - u_i)]/dx^2. \quad (4.1)$$

In this 1D space, the macroscale, homogenised, effective diffusion should be the harmonic mean of these coefficients.

Figure 4.5: the diffusing field $u(x,t)$ in the patch (gap-tooth) scheme applied to microscale heterogeneous diffusion with no ensemble average. The heterogeneous diffusion results in a similarly heterogeneous field solution.

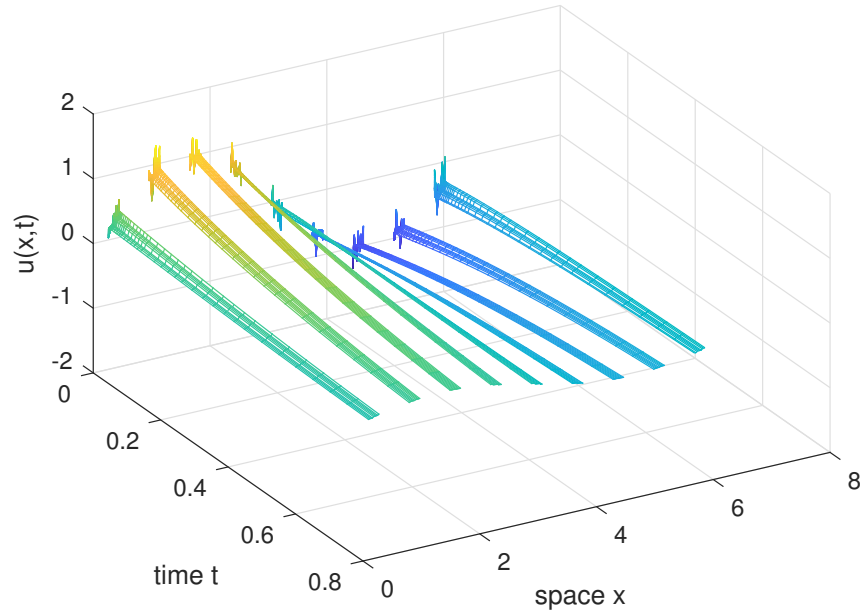
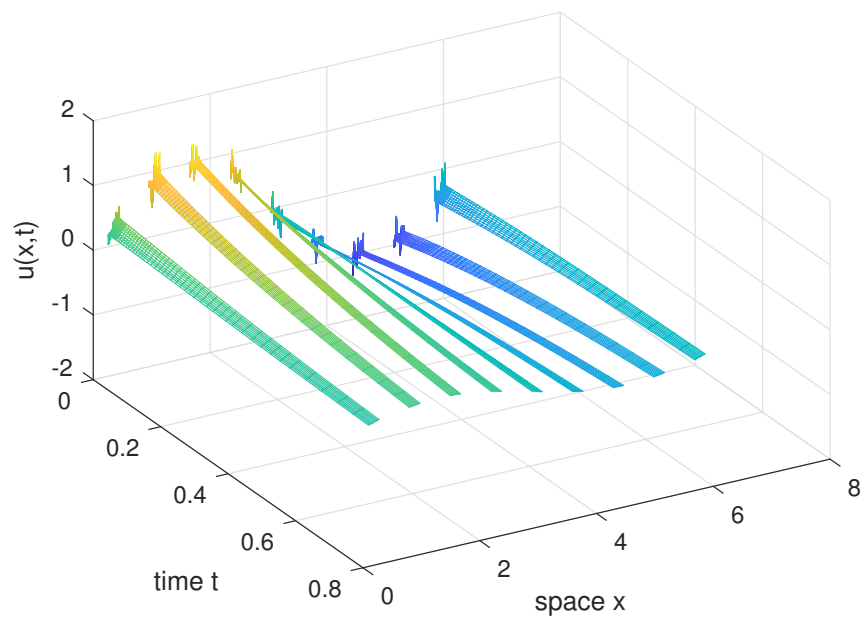


Figure 4.6: the diffusing field $u(x,t)$ in the patch (gap-tooth) scheme applied to microscale heterogeneous diffusion with an ensemble average. The ensemble average smooths out the heterogeneous diffusion.



4.5.1 Script to simulate via stiff or projective integration

Set the desired microscale periodicity, and microscale diffusion coefficients (with subscripts shifted by a half).

```

66 clear all
67 mPeriod = 4
68 rng('default'); rng(1);
69 cDiff = exp(4*rand(mPeriod,1))
70 cHomo = 1/mean(1./cDiff)

```

Establish global data struct `patches` for heterogeneous diffusion solved on 2π -periodic domain, with nine patches, each patch of half-size 0.2. A user can add information to `patches` in order to communicate to the time derivative function. Quadratic (fourth-order) interpolation `ordCC = 4` provides values for the inter-patch coupling conditions. The odd integer `patches.nCore = 3` defines the size of the patch core (this must be larger than zero and less than `nSubP`), where a core of size zero indicates that the value in the centre of the patch gives the macroscale. The introduction of a finite width core requires a redefinition of the half-patch ratio, as described by [Bunder et al. \(2017\)](#). The Boolean `patches.EnsAve` determines whether or not we apply ensemble averaging of diffusivity configurations. We evaluate the patch coupling by interpolating the core.

```

92 global patches
93 nPatch = 9
94 ratio = 0.2
95 nSubP = 11
96 Len = 2*pi;
97 ordCC=4;
98 patches.nCore=3;
99 patches.ratio = ratio*(nSubP - patches.nCore)/(nSubP - 1);
100 configPatches1(@heteroDiff,[0 Len],nan,nPatch, ...
101   ordCC,patches.ratio,nSubP);
102 patches.EnsAve = 1;

```

A $(nSubP-1) \times nPatch$ matrix defines the diffusivity coefficients within each patch. In the case of ensemble averaging, `nVars` becomes the size of the ensemble (for the case of no ensemble averaging `nVars` is the number of different field variables, which in this example is `nVars = 1`) and we use the ensemble described by [Bunder et al. \(2017\)](#) which includes all reflected and translated configurations of `patches.cDiff`. With ensemble averaging we must increase the size of the diffusivity matrix to $(nSubP-1) \times nPatch \times nVars$.

```

119 patches.cDiff = cDiff((mod(round(patches.x(1:(end-1)),:) ...
120   /(patches.x(2)-patches.x(1))-0.5),mPeriod)+1));
121 if patches.EnsAve
122     if mPeriod>2
123         nVars=2*mPeriod;
124     else
125         nVars=mPeriod;

```

```

126     end
127     patches.cDiff= repmat(patches.cDiff,[1,1,nVars]);
128     for sx=2:mPeriod
129         patches.cDiff(:,:,sx)=circshift( ...
130             patches.cDiff(:,:,sx-1),[sx-1,0]);
131     end;
132     if nVars>2
133         patches.cDiff(:,:, (mPeriod+1):end)=flipud( ...
134             patches.cDiff(:,:,1:mPeriod));
135     end;
136 end

```

Conventional integration in time Set an initial condition, and here integrate forward in time using a standard method for stiff systems—because of the simplicity of linear problems this method works quite efficiently here. Integrate the interface `patchSmooth1` (Section 4.2) to the microscale differential equations.

```

149 u0 = sin(patches.x)+0.2*randn(nSubP,nPatch);
150 %u0 = exp(-2*(patches.x-Len/2).^2).*(1+0.1*rand(nSubP,nPatch));
151 if patches.EnsAve
152     u0 = repmat(u0,[1,1,nVars]);
153 end
154 [ts,ucts] = ode15s(@patchSmooth1, [0 2/cHomo], u0(:));
155 ucts=reshape(ucts,length(ts),length(patches.x(:)),[]);

```

Plot the simulation in Figure 4.5 (with no ensemble average) or Figure 4.6 (with an ensemble average). If we have calculated an ensemble of field solutions, then we must first take the ensemble average.

```

166 if patches.EnsAve % calculate the ensemble average
167     uctsAve=mean(ucts,3);
168 else
169     uctsAve=ucts;
170 end
171 figure(1),clf
172 xs = patches.x; xs([1 end],:) = nan;
173 mesh(ts,xs(:),uctsAve'), view(60,40)
174 xlabel('time t'), ylabel('space x'), zlabel('u(x,t)')
175 set(gcf,'PaperUnits','centimeters');
176 set(gcf,'PaperPosition',[0 0 14 10]);
177 if patches.EnsAve
178     print('-depsc2','HomogenisationCtsUEnsAve')
179 else
180     print('-depsc2','HomogenisationCtsU')
181 end

```

Use projective integration in time Now take `patchSmooth1`, the interface to the time derivatives, and wrap around it the projective integration

Figure 4.7: field $u(x,t)$ shows basic projective integration of patches of heterogeneous diffusion with no ensemble average: different colours correspond to the times in the legend. This field solution displays some fine scale heterogeneity due to the heterogeneous diffusion.

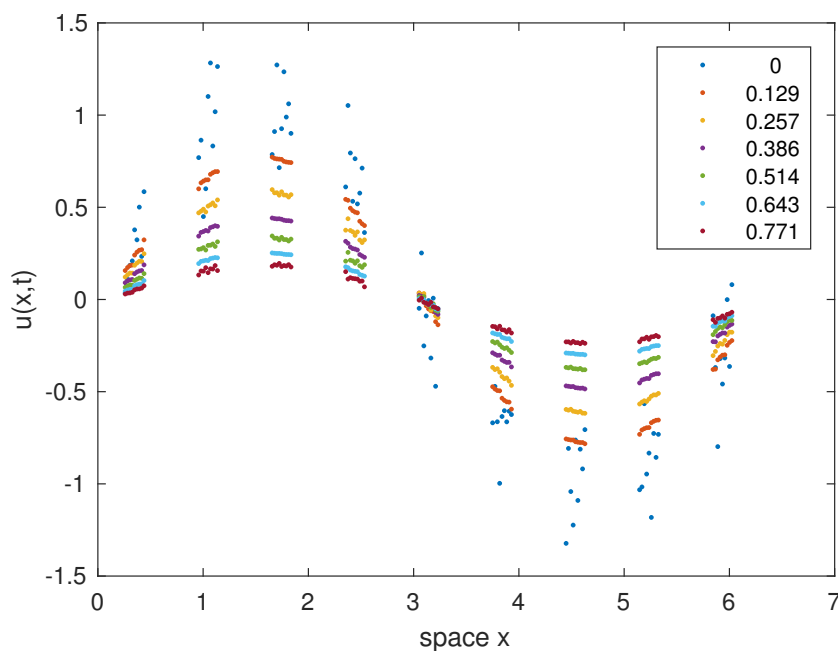
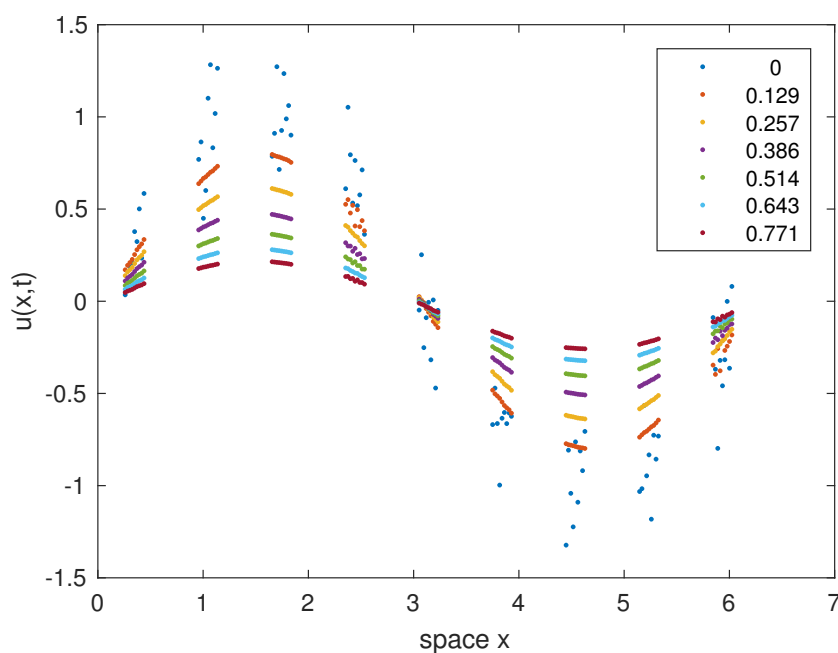


Figure 4.8: field $u(x,t)$ shows basic projective integration of patches of heterogeneous diffusion with ensemble average: different colours correspond to the times in the legend. Once transients have decayed, this field solution is smooth due to the ensemble average.



PIRK2 (Section 3.1), of bursts of simulation from heteroBurst (Section 4.5.3), as illustrated by Figures 4.7 and 4.8.

This second part of the script implements the following design, where the micro-integrator could be, for example, ode45 or rk2int.

1. configPatches1 (done in first part)
2. PIRK2 \leftrightarrow heteroBurst \leftrightarrow micro-integrator \leftrightarrow patchSmooth1 \leftrightarrow heteroDiff
3. process results

Mark that edge of patches are not to be used in the projective extrapolation by setting initial values to NaN.

```
225 u0([1 end], :) = nan;
```

Set the desired macro- and microscale time-steps over the time domain: the macroscale step is in proportion to the effective mean diffusion time on the macroscale; the burst time is proportional to the intra-patch effective diffusion time; and lastly, the microscale time-step is proportional to the diffusion time between adjacent points in the microscale lattice.

```
237 ts = linspace(0,2/cHomo,7)
238 bT = 3*( ratio*Len/nPatch )^2/cHomo
239 addpath(' ../ProjInt', ' ../SandpitPlay/RKint')
240 [us,tss,uss] = PIRK2(@heteroBurst, ts, u0(:), bT);
```

Plot the macroscale predictions to draw Figure 4.7 or Figure 4.8. If we have calculated an ensemble of field solutions, then we must first take the ensemble average.

```
250 if patches.EnsAve % calculate the ensemble average
251     usAve=mean(reshape(us,size(us,1),length(xs(:)),nVars),3);
252     ussAve=mean(reshape(uss,length(tss),length(xs(:)),nVars),3);
253 else
254     usAve=us;
255     ussAve=uss;
256 end
257 figure(2),clf
258 plot(xs(:),usAve','.')
259 ylabel('u(x,t)'), xlabel('space x')
260 legend(num2str(ts',3))
261 set(gcf,'PaperUnits','centimeters');
262 set(gcf,'PaperPosition',[0 0 14 10]);
263 if patches.EnsAve
264     print('-depsc2','HomogenisationUEnsAve')
265 else
266     print('-depsc2','HomogenisationU')
267 end
```

Also plot a surface detailing the microscale bursts as shown in Figure 4.9 or Figure 4.10.

Figure 4.9: stereo pair of the field $u(x, t)$ during each of the microscale bursts used in the projective integration with no ensemble averaging.

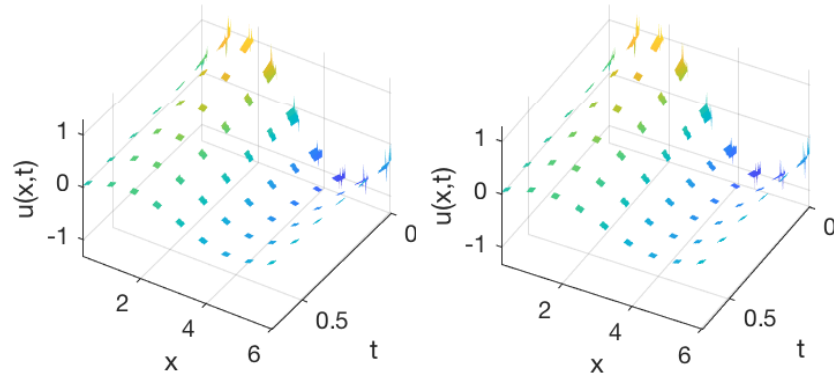
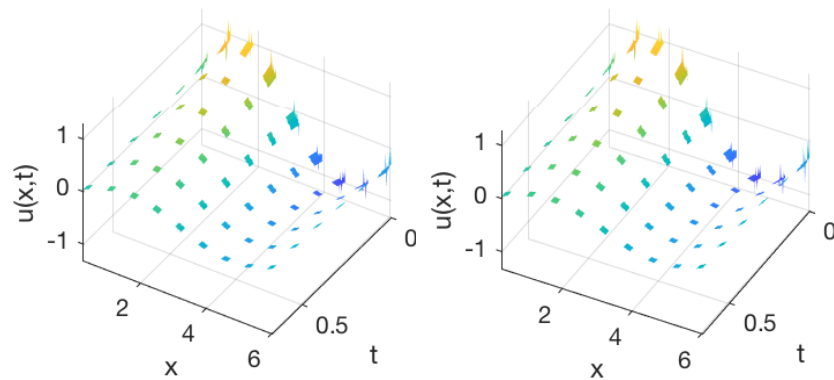


Figure 4.10: stereo pair of the field $u(x, t)$ during each of the microscale bursts used in the projective integration with ensemble averaging.



```

289 figure(3),clf
290 for k = 1:2, subplot(1,2,k)
291     surf(tss,xs(:),ussAve', 'EdgeColor','none')
292     ylabel('x'), xlabel('t'), zlabel('u(x,t)')
293     axis tight, view(126-4*k,45)
294 end
295 set(gcf,'PaperUnits','centimeters');
296 set(gcf,'PaperPosition',[0 0 14 6]);
297 if patches.EnsAve
298     print('-depsc2','HomogenisationMicroEnsAve')
299 else
300     print('-depsc2','HomogenisationMicro')
301 end

```

End of the script.

4.5.2 heteroDiff(): heterogeneous diffusion

This function codes the lattice heterogeneous diffusion inside the patches. For 2D input arrays u and x (via edge-value interpolation of `patchSmooth1`, [Section 4.2](#)), computes the time derivative (4.1) at each point in the interior of a patch, output in ut . The column vector (or possibly array) of diffusion coefficients c_i have previously been stored in struct `patches`.

```

320 function ut = heteroDiff(t,u,x)
321     global patches
322     dx = diff(x(2:3)); % space step
323     i = 2:size(u,1)-1; % interior points in a patch
324     ut = nan(size(u)); % preallocate output array
325     ut(i, :, :) = diff(patches.cDiff.*diff(u))/dx^2; %- abs(u(i, :, :)).*u(i, :, :).^2
326 end% function

```

4.5.3 heteroBurst(): a burst of heterogeneous diffusion

This code integrates in time the derivatives computed by `heteroDiff` from within the patch coupling of `patchSmooth1`. Try four possibilities:

- `ode23` generates ‘noise’ that is unsightly at best and may be ruinous;
- `ode45` is similar to `ode23`, but with reduced noise;
- `ode15s` does not cater for the NaNs in some components of u ;
- `rk2int` simple specified step integrator, but may require inefficiently small time-steps.

```

348 function [ts, ucts] = heteroBurst(ti, ui, bT)
349     switch '45'
350     case '23', [ts, ucts] = ode23(@patchSmooth1, [ti ti+bT], ui(:));
351     case '45', [ts, ucts] = ode45(@patchSmooth1, [ti ti+bT], ui(:));
352     case '15s', [ts, ucts] = ode15s(@patchSmooth1, [ti ti+bT], ui(:));
353     case 'rk2', ts = linspace(ti, ti+bT, 200)';
354                 ucts = rk2int(@patchSmooth1, ts, ui(:));
355     end
356 end

```

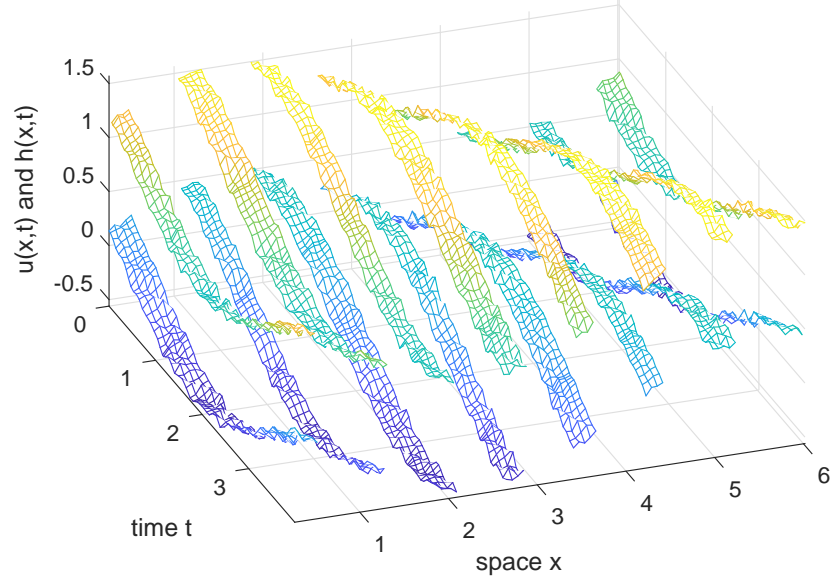
Fin.

4.6 waterWaveExample: simulate a water wave PDE on patches

Section contents

[Figure 4.11](#) shows an example simulation in time generated by the patch scheme function applied to an ideal wave PDE ([Cao & Roberts 2013](#)). The inter-patch coupling is realised by spectral interpolation of the mid-patch values to the patch edges.

Figure 4.11: water depth $h(x, t)$ (above) and velocity field $u(x, t)$ (below) of the gap-tooth scheme applied to the ideal wave PDE (4.2), linearised. The microscale random component to the initial condition has long lasting effects on the simulation—but the macroscale wave still propagates.



This approach, based upon the differential equations coded in [Section 4.6.2](#), may be adapted by a user to a wide variety of 1D wave and wave-like systems. For example, the differential equations of [Section 4.6.3](#) describes the nonlinear microscale simulator of the nonlinear shallow water wave PDE derived from the Smagorinski model of turbulent flow ([Cao & Roberts 2012, 2016a](#)).

Often, wave-like systems are written in terms of two conjugate variables, for example, position and momentum density, electric and magnetic fields, and water depth $h(x, t)$ and mean longitudinal velocity $u(x, t)$ as herein. The approach developed in this section applies to any wave-like system in the form

$$\frac{\partial h}{\partial t} = -c_1 \frac{\partial u}{\partial x} + f_1[h, u] \quad \text{and} \quad \frac{\partial u}{\partial t} = -c_2 \frac{\partial h}{\partial x} + f_2[h, u], \quad (4.2)$$

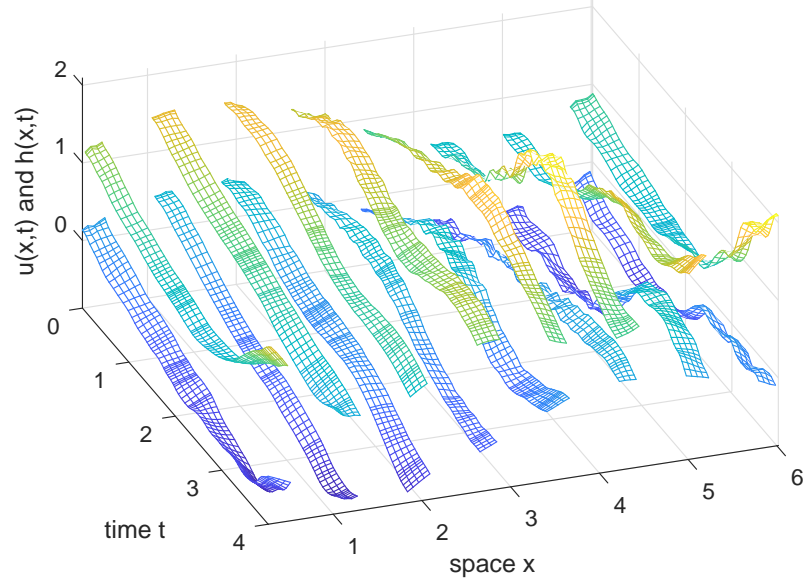
where the brackets indicate that the nonlinear functions f_ℓ may involve various spatial derivatives of the fields $h(x, t)$ and $u(x, t)$. For example, [Section 4.6.3](#) encodes a nonlinear Smagorinski model of turbulent shallow water ([Cao & Roberts 2012, 2016a](#), e.g.) along an inclined flat bed: let x measure position along the bed and in terms of fluid depth $h(x, t)$ and depth-averaged longitudinal velocity $u(x, t)$ the model PDEs are

$$\frac{\partial h}{\partial t} = -\frac{\partial(hu)}{\partial x}, \quad (4.3a)$$

$$\frac{\partial u}{\partial t} = 0.985 \left(\tan \theta - \frac{\partial h}{\partial x} \right) - 0.003 \frac{u|u|}{h} - 1.045u \frac{\partial u}{\partial x} + 0.26h|u| \frac{\partial^2 u}{\partial x^2}, \quad (4.3b)$$

where $\tan \theta$ is the slope of the bed. Equation (4.3a) represents conservation of the fluid. The momentum PDE (4.3b) represents the effects of

Figure 4.12: water depth $h(x, t)$ (above) and velocity field $u(x, t)$ (below) of the gap-tooth scheme applied to the Smagorinski shallow water wave PDES (4.3). The microscale random initial component decays where the water speed is non-zero due to ‘turbulent’ dissipation.



turbulent bed drag $u|u|/h$, self-advection $u\partial u/\partial x$, nonlinear turbulent dispersion $h|u|\partial^2 u/\partial x^2$, and gravitational hydrostatic forcing ($\tan \theta - \partial h/\partial x$). Figure 4.12 shows one simulation of this system—for the same initial condition as Figure 4.11.

For such wave systems, let’s implement a staggered microscale grid and staggered macroscale patches as introduced by Cao & Roberts (2016b) in their Figures 3 and 4, respectively.

4.6.1 Script code to simulate wave systems

This script implements the following gap-tooth scheme (left-right arrows denote function recursion).

1. configPatches1, and add micro-information
2. ode15s \leftrightarrow patchSmooth1 \leftrightarrow idealWavePDE
3. process results
4. ode15s \leftrightarrow patchSmooth1 \leftrightarrow waterWavePDE
5. process results

Establish the global data struct `paches` for the PDES (4.2) (linearised) solved on 2π -periodic domain, with eight patches, each patch of half-size ratio 0.2, with eleven points within each patch, and spectral interpolation (−1) to provide edge-values of the inter-patch coupling conditions.

```

115 clear all
116 global patches
117 nPatch = 8
118 ratio = 0.2

```

```

119 nSubP = 11 %of the form 4*n-1
120 Len = 2*pi;
121 configPatches1(@idealWavePDE,[0 Len],nan,nPatch,-1,ratio,nSubP);

```

Identify which microscale grid points are h or u values on the staggered micro-grid. Also store the information in the struct `patches` for use by the time derivative function.

```

131 uPts = mod( bsxfun(@plus,(1:nSubP)',(1:nPatch)) ,2);
132 hPts = find(1-uPts);
133 uPts = find(uPts);
134 patches.hPts = hPts; patches.uPts = uPts;

```

Set an initial condition of a progressive wave, and check evaluation of the time derivative. The capital letter U denotes an array of values merged from both u and h fields on the staggered grids (possibly with some optional microscale wave noise).

```

145 U0 = nan(nSubP,nPatch);
146 U0(hPts) = 1+0.5*sin(patches.x(hPts));
147 U0(uPts) = 0+0.5*sin(patches.x(uPts));
148 U0 = U0+0.02*randn(nSubP,nPatch);

```

Conventional integration in time Integrate in time using standard MATLAB/Octave stiff integrators. Here do the two cases of the ideal wave and the water wave equations in the one loop.

```

158 for k = 1:2

```

When using `ode15s` we subsample the results because sub-grid scale waves do not dissipate and so the integrator takes very small time-steps for all time.

```

166 [ts,Ucts] = ode15s(@patchSmooth1,[0 4],U0(:));
167 ts = ts(1:5:end);
168 Ucts = Ucts(1:5:end,:);

```

Plot the simulation.

```

174 figure(k),clf
175 xs = patches.x; xs([1 end],:) = nan;
176 mesh(ts,xs(hPts),Ucts(:,hPts)'),hold on
177 mesh(ts,xs(uPts),Ucts(:,uPts)'),hold off
178 xlabel('time t'), ylabel('space x'), zlabel('u(x,t) and h(x,t)')
179 axis tight, view(70,45)

```

Save the plot to file.

```

185 set(gcf,'paperposition',[0 0 14 10])
186 if k==1, print('-depsc2','ps1WaveCtsUH')
187 else print('-depsc2','ps1WaterWaveCtsUH')
188 end

```

For the second time through the loop, change to the Smagorinski turbulence model (4.3) of shallow water flow, keeping other parameters and the initial

condition the same.

```
198     patches.fun = @waterWavePDE;
199 end
```

Use projective integration As yet a simple implementation appears to fail, so it needs more exploration and thought. End of the main script.

4.6.2 idealWavePDE(): ideal wave PDE

This function codes the staggered lattice equation inside the patches for the ideal wave PDE system $h_t = -u_x$ and $u_t = -h_x$. Here code for a staggered microscale grid, index i , of staggered macroscale patches, index j : the array

$$U_{ij} = \begin{cases} u_{ij} & i + j \text{ even,} \\ h_{ij} & i + j \text{ odd.} \end{cases}$$

The output U_t contains the merged time derivatives of the two staggered fields. So set the micro-grid spacing and reserve space for time derivatives.

```
297 function Ut = idealWavePDE(t,U,x)
298     global patches
299     dx = diff(x(2:3));
300     Ut = nan(size(U)); ht = Ut;
```

Compute the PDE derivatives at interior points of the patches.

```
306     i = 2:size(U,1)-1;
```

Here ‘wastefully’ compute time derivatives for both PDEs at all grid points—for ‘simplicity’—and then merges the staggered results. Since $\dot{h}_{ij} \approx -(u_{i+1,j} - u_{i-1,j})/(2 \cdot dx) = -(U_{i+1,j} - U_{i-1,j})/(2 \cdot dx)$ as adding/subtracting one from the index of a h -value is the location of the neighbouring u -value on the staggered micro-grid.

```
318     ht(i,:) = -(U(i+1,:)-U(i-1,:))/(2*dx);
```

Since $\dot{u}_{ij} \approx -(h_{i+1,j} - h_{i-1,j})/(2 \cdot dx) = -(U_{i+1,j} - U_{i-1,j})/(2 \cdot dx)$ as adding/subtracting one from the index of a u -value is the location of the neighbouring h -value on the staggered micro-grid.

```
328     Ut(i,:) = -(U(i+1,:)-U(i-1,:))/(2*dx);
```

Then overwrite the unwanted \dot{u}_{ij} with the corresponding wanted \dot{h}_{ij} .

```
335     Ut(patches.hPts) = ht(patches.hPts);
336 end
```

4.6.3 waterWavePDE(): water wave PDE

This function codes the staggered lattice equation inside the patches for the nonlinear wave-like PDE system (4.3). Also, regularise the absolute value appearing the the PDEs via the one-line function `rabs()`.

```

351 function Ut = waterWavePDE(t,U,x)
352     global patches
353     rabs = @(u) sqrt(1e-4 + u.^2);

```

As before, set the micro-grid spacing, reserve space for time derivatives, and index the patch-interior points of the micro-grid.

```

361     dx = diff(x(2:3));
362     Ut = nan(size(U));  ht = Ut;
363     i = 2:size(U,1)-1;

```

Need to estimate h at all the u -points, so into V use averages, and linear extrapolation to patch-edges.

```

371     ii = i(2:end-1);
372     V = Ut;
373     V(ii,:) = (U(ii+1,:)+U(ii-1,:))/2;
374     V(1:2,:) = 2*U(2:3,:)-V(3:4,:);
375     V(end-1:end,:) = 2*U(end-2:end-1,:)-V(end-3:end-2,:);

```

Then estimate $\partial(hu)/\partial x$ from u and the interpolated h at the neighbouring micro-grid points.

```

382     ht(i,:) = -(U(i+1,:).*V(i+1,:)-U(i-1,:).*V(i+1,:))/(2*dx);

```

Correspondingly estimate the terms in the momentum PDE: u -values in U_i and $V_{i\pm 1}$; and h -values in V_i and $U_{i\pm 1}$.

```

390     Ut(i,:) = -0.985*(U(i+1,:)-U(i-1,:))/(2*dx) ...
391               -0.003*U(i,:).*rabs(U(i,:)./V(i,:)) ...
392               -1.045*U(i,:).*(V(i+1,:)-V(i-1,:))/(2*dx) ...
393               +0.26*rabs(V(i,:).*U(i,:)).*(V(i+1,:)-2*U(i,:)+V(i-1,:))/dx^2/2;

```

where the mysterious division by two in the second derivative is due to using the averaged values of u in the estimate:

$$\begin{aligned}
 u_{xx} &\approx \frac{1}{4\delta^2}(u_{i-2} - 2u_i + u_{i+2}) \\
 &= \frac{1}{4\delta^2}(u_{i-2} + u_i - 4u_i + u_i + u_{i+2}) \\
 &= \frac{1}{2\delta^2} \left(\frac{u_{i-2} + u_i}{2} - 2u_i + \frac{u_i + u_{i+2}}{2} \right) \\
 &= \frac{1}{2\delta^2} (\bar{u}_{i-1} - 2u_i + \bar{u}_{i+1}).
 \end{aligned}$$

Then overwrite the unwanted \dot{u}_{ij} with the corresponding wanted \dot{h}_{ij} .

```

409     Ut(patches.hPts) = ht(patches.hPts);
410 end

```

Fin.

4.7 configPatches2(): configures spatial patches in 2D

Subsection contents

Input	60
Output	61
4.7.1 If no arguments, then execute an example	61
Example of nonlinear diffusion PDE inside patches	63
4.7.2 The code to make patches	63

Makes the struct `patches` for use by the patch/gap-tooth time derivative function `patchSmooth2()`. [Section 4.7.1](#) lists an example of its use.

```

17 function configPatches2(fun,Xlim,BCs,nPatch,ordCC,ratio,nSubP,nEdge)
18 global patches

```

Input If invoked with no input arguments, then executes an example of simulating a nonlinear diffusion PDE relevant to the lubrication flow of a thin layer of fluid—see [Section 4.7.1](#) for the example code.

- `fun` is the name of the user function, `fun(t,u,x,y)`, that computes time derivatives (or time-steps) of quantities on the patches.
- `Xlim` array/vector giving the macro-space domain of the computation: patches are distributed equi-spaced over the interior of the rectangle $[\text{Xlim}(1), \text{Xlim}(2)] \times [\text{Xlim}(3), \text{Xlim}(4)]$: if `Xlim` is of length two, then use the same interval in both directions.
- `BCs` somehow will define the macroscale boundary conditions. Currently, `BCs` is ignored and the system is assumed macro-periodic in the domain.
- `nPatch` determines the number of equi-spaced patches: if scalar, then use the same number of patches in both directions, otherwise `nPatch(1:2)` give the number in each direction.
- `ordCC` is the ‘order’ of interpolation across empty space of the macroscale mid-patch values to the edge of the patches for inter-patch coupling: currently must be in $\{0\}$.
- `ratio` (real) is the ratio of the half-width of a patch to the spacing of the patch mid-points: so `ratio` = $\frac{1}{2}$ means the patches abut; and `ratio` = 1 would be overlapping patches as in holistic discretisation: if scalar, then use the same ratio in both directions, otherwise `ratio(1:2)` give the ratio in each direction.
- `nSubP` is the number of equi-spaced microscale lattice points in each patch: if scalar, then use the same number in both directions, otherwise `nSubP(1:2)` gives the number in each direction. Must be odd so that there is a central lattice point.

- **nEdge** is, for each patch, the number of edge values set by interpolation at the edge regions of each patch. May be omitted. The default is one (suitable for microscale lattices with only nearest neighbours interactions).

Output The *global* struct **patches** is created and set with the following components.

- **.fun** is the name of the user's function **fun(u,t,x,y)** that computes the time derivatives (or steps) on the patchy lattice.
- **.ordCC** is the specified order of inter-patch coupling.
- **.alt** is true for interpolation using only odd neighbouring patches as for staggered grids, and false for the usual case of all neighbour coupling—not yet implemented.
- **.Cwtsr** and **.Cwtsl** are the **ordCC**-vector of weights for the inter-patch interpolation onto the right and left edges (respectively) with patch:macroscopic ratio as specified.
- **.x** is **nSubP(1) × nPatch(1)** array of the regular spatial locations x_{ij} of the microscale grid points in every patch.
- **.y** is **nSubP(2) × nPatch(2)** array of the regular spatial locations y_{ij} of the microscale grid points in every patch.
- **.nEdge** is, for each patch, the number of edge values set by interpolation at the edge regions of each patch.

4.7.1 If no arguments, then execute an example

```
121 if nargin==0
```

The code here shows one way to get started: a user's script may have the following three steps (arrows indicate function recursion).

1. **configPatches2**
2. **ode15s** integrator \leftrightarrow **patchSmooth2** \leftrightarrow user's **nonDiffPDE**
3. process results

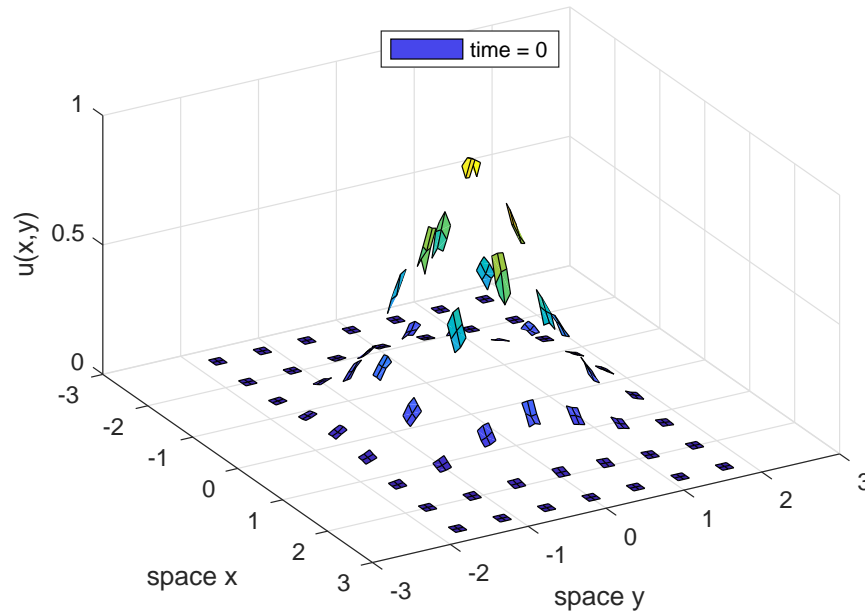
Establish global patch data struct to interface with a function coding a nonlinear 'diffusion' PDE: to be solved on 6×4 -periodic domain, with 9×7 patches, spectral interpolation (0) couples the patches, each patch of half-size ratio 0.25, and with 5×5 points within each patch.

```
141 nSubP = 5;
142 configPatches2(@nonDiffPDE,[-3 3 -2 2], nan, [9 7], 0, 0.25, nSubP);
```

Set a Gaussian initial condition using auto-replication of the spatial grid.

```
149 x = reshape(patches.x,nSubP,1,[],1);
150 y = reshape(patches.y,1,nSubP,1,[]);
151 u0 = exp(-x.^2-y.^2);
152 u0 = u0.*(0.9+0.1*rand(size(u0)));
```

Figure 4.13: initial field $u(x, y, t)$ at time $t = 0$ of the patch scheme applied to a nonlinear ‘diffusion’ PDE: Figure 4.14 plots the computed field at time $t = 3$.



Initiate a plot of the simulation using only the microscale values interior to the patches: set x and y -edges to `nan` to leave the gaps.

```
160 figure(1), clf
161 x = patches.x; y = patches.y;
162 x([1 end], :) = nan; y([1 end], :) = nan;
```

Start by showing the initial conditions of Figure 4.13 while the simulation computes.

```
169 u = reshape(permute(u0, [1 3 2 4]), [numel(x) numel(y)]);
170 hsurf = surf(x(:), y(:), u');
171 axis([-3 3 -3 3 -0.001 1]), view(60, 40)
172 legend('time = 0', 'Location', 'north')
173 xlabel('space x'), ylabel('space y'), zlabel('u(x, y)')
174 drawnow
```

Save the initial condition to file for Figure 4.13.

```
180 set(gcf, 'PaperPosition', [0 0 14 10])
181 print('-depsc2', 'configPatches2ic')
```

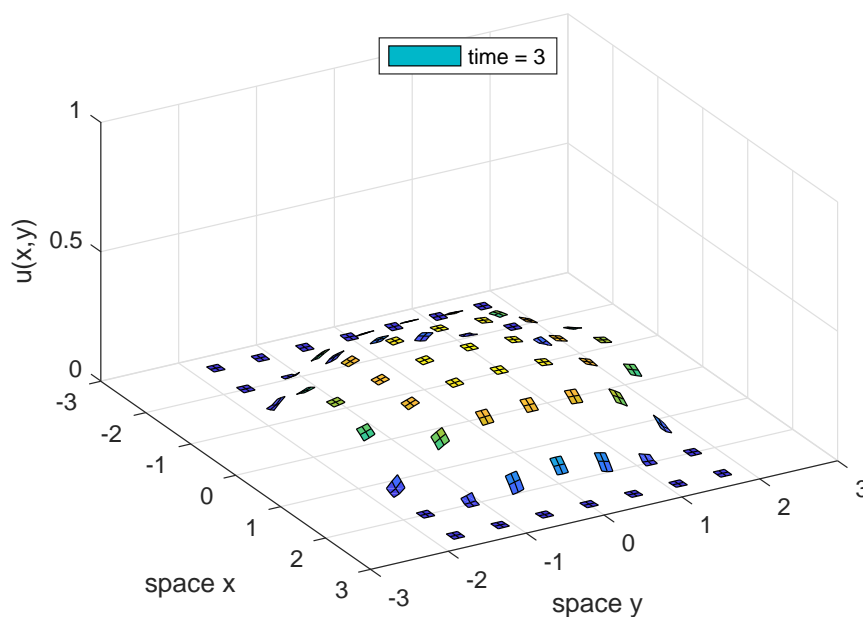
Integrate in time using standard functions.

```
195 disp('Wait while we simulate h_t=(h^3)_xx+(h^3)_yy')
196 [ts, ucts] = ode15s(@patchSmooth2, [0 3], u0(:));
```

Animate the computed simulation to end with Figure 4.14.

```
203 for i = 1:length(ts)
204     u = patchEdgeInt2(ucts(i, :));
```


Figure 4.14: field $u(x, y, t)$ at time $t = 3$ of the patch scheme applied to a nonlinear ‘diffusion’ PDE with initial condition in Figure 4.13.



```

205     u = reshape(permute(u,[1 3 2 4]), [numel(x) numel(y)]);
206     hsurf.ZData = u';
207     legend(['time = ' num2str(ts(i),2)])
208     pause(0.1)
209 end
210 print('-depsc2','configPatches2t3')

```

Upon finishing execution of the example, exit this function.

```

225 return
226 end%if no arguments

```

Example of nonlinear diffusion PDE inside patches As a microscale discretisation of $u_t = \nabla^2(u^3)$, code $\dot{u}_{ijkl} = \frac{1}{\delta x^2}(u_{i+1,j,k,l}^3 - 2u_{i,j,k,l}^3 + u_{i-1,j,k,l}^3) + \frac{1}{\delta y^2}(u_{i,j+1,k,l}^3 - 2u_{i,j,k,l}^3 + u_{i,j-1,k,l}^3)$.

```

237 function ut = nonDiffPDE(t,u,x,y)
238     dx = diff(x(1:2)); dy = diff(y(1:2)); % microscale spacing
239     i = 2:size(u,1)-1; j = 2:size(u,2)-1; % interior points in patches
240     ut = nan(size(u)); % preallocate storage
241     ut(i,j, :, :) = diff(u(:,j, :, :).^3,2,1)/dx^2 ...
242                     +diff(u(i, :, :, :).^3,2,2)/dy^2;
243 end

```

4.7.2 The code to make patches

Initially duplicate parameters as needed.

```

259 if numel(Xlim)==2, Xlim = repmat(Xlim,1,2); end
260 if numel(nPatch)==1, nPatch = repmat(nPatch,1,2); end

```

```

261 if numel(ratio)==1, ratio = repmat(ratio,1,2); end
262 if numel(nSubP)==1, nSubP = repmat(nSubP,1,2); end

Set one edge-value to compute by interpolation if not specified by the user.
Store in the struct.

270 if nargin<8, nEdge = 1; end
271 if nEdge>1, error('multi-edge-value interp not yet implemented'), end
272 if 2*nEdge+1>nSubP, error('too many edge values requested'), end
273 patches.nEdge = nEdge;

First, store the pointer to the time derivative function in the struct.

282 patches.fun = fun;

Second, store the order of interpolation that is to provide the values for the
inter-patch coupling conditions. Spectral coupling is ordCC of 0 or -1.

291 if ~ismember(ordCC,[0])
292     error('ordCC out of allowed range [0]')
293 end

For odd ordCC do interpolation based upon odd neighbouring patches as is
useful for staggered grids.

300 patches.alt = mod(ordCC,2);
301 ordCC = ordCC+patches.alt;
302 patches.ordCC = ordCC;

Might as well precompute the weightings for the interpolation of field values
for coupling. (Could sometime extend to coupling via derivative values.)

318 ratio = ratio(:)'; % force to be row vector
319 if patches.alt % eqn (7) in \cite{Cao2014a}
320     patches.Cwtsr = [1
321         ratio/2
322         (-1+ratio.^2)/8
323         (-1+ratio.^2).*ratio/48
324         (9-10*ratio.^2+ratio.^4)/384
325         (9-10*ratio.^2+ratio.^4).*ratio/3840
326         (-225+259*ratio.^2-35*ratio.^4+ratio.^6)/46080
327         (-225+259*ratio.^2-35*ratio.^4+ratio.^6).*ratio/645120 ];
328 else %
329     patches.Cwtsr = [ratio
330         ratio.^2/2
331         (-1+ratio.^2).*ratio/6
332         (-1+ratio.^2).*ratio.^2/24
333         (4-5*ratio.^2+ratio.^4).*ratio/120
334         (4-5*ratio.^2+ratio.^4).*ratio.^2/720
335         (-36+49*ratio.^2-14*ratio.^4+ratio.^6).*ratio/5040
336         (-36+49*ratio.^2-14*ratio.^4+ratio.^6).*ratio.^2/40320 ];
337 end
338 patches.Cwtsr = patches.Cwtsr(1:ordCC,:);

```

```

339 % should avoid this next implicit auto-replication
340 patches.Cwtsl = (-1).^((1:ordCC)'+patches.alt).*patches.Cwtsr;

    Third, set the centre of the patches in a the macroscale grid of patches
    assuming periodic macroscale domain.

349 X = linspace(Xlim(1),Xlim(2),nPatch(1)+1);
350 X = X(1:nPatch(1))+diff(X)/2;
351 DX = X(2)-X(1);
352 Y = linspace(Xlim(3),Xlim(4),nPatch(2)+1);
353 Y = Y(1:nPatch(2))+diff(Y)/2;
354 DY = Y(2)-Y(1);

    Construct the microscale in each patch, assuming Dirichlet patch edges, and
    a half-patch length of ratio(1) · DX and ratio(2) · DY.

362 nSubP = nSubP(:)'; % force to be row vector
363 if mod(nSubP,2)~= [0 0], error('configPatches2: nSubP must be odd'), end
364 i0 = (nSubP(1)+1)/2;
365 dx = ratio(1)*DX/(i0-1);
366 patches.x = bsxfun(@plus,dx*(-i0+1:i0-1)',X); % micro-grid
367 i0 = (nSubP(2)+1)/2;
368 dy = ratio(2)*DY/(i0-1);
369 patches.y = bsxfun(@plus,dy*(-i0+1:i0-1)',Y); % micro-grid
370 end% function

    Fin.

```

4.8 patchSmooth2(): interface to time integrators

Subsection contents

Input	65
Output	66

To simulate in time with spatial patches we often need to interface a users time derivative function with time integration routines such as `ode15s` or `PIRK2`. This function provides an interface. It assumes that the sub-patch structure is *smooth* so that the patch centre-values are sensible macroscale variables, and patch edge values are determined by macroscale interpolation of the patch-centre values. Communicate patch-design variables to this function via the previously established global struct `patches`.

```

23 function dudt = patchSmooth2(t,u)
24 global patches

```

Input

- `u` is a vector of length $\text{prod}(\text{nSubP}) \cdot \text{prod}(\text{nPatch}) \cdot \text{nVars}$ where there are `nVars` field values at each of the points in the $\text{nSubP}(1) \times \text{nSubP}(2) \times \text{nPatch}(1) \times \text{nPatch}(2)$ grid.

- **t** is the current time to be passed to the user's time derivative function.
- **patches** a struct set by `configPatches2()` with the following information used here.
 - **.fun** is the name of the user's function `fun(t,u,x,y)` that computes the time derivatives on the patchy lattice. The array **u** has size $\text{nSubP}(1) \times \text{nSubP}(2) \times \text{nPatch}(1) \times \text{nPatch}(2) \times \text{nVars}$. Time derivatives must be computed into the same sized array, but herein the patch edge values are overwritten by zeros.
 - **.x** is $\text{nSubP}(1) \times \text{nPatch}(1)$ array of the spatial locations x_{ij} of the microscale grid points in every patch. Currently it *must* be an equi-spaced lattice on both macro- and microscale.
 - **.y** is similarly $\text{nSubP}(2) \times \text{nPatch}(2)$ array of the spatial locations y_{ij} of the microscale grid points in every patch. Currently it *must* be an equi-spaced lattice on both macro- and microscale.

Output

- **dudt** is $\text{prod}(\text{nSubP}) \cdot \text{prod}(\text{nPatch}) \cdot \text{nVars}$ vector of time derivatives, but with patch edge values set to zero.

Reshape the fields **u** as a 4/5D-array, and sets the edge values from macroscale interpolation of centre-patch values. [Section 4.9](#) describes `patchEdgeInt2()`.

```
82 u = patchEdgeInt2(u);
```

Ask the user function for the time derivatives computed in the array, overwrite its edge values with the dummy value of zero, then return to a to the user/integrator as column vector.

```
92 dudt = patches.fun(t,u,patches.x,patches.y);
93 dudt([1 end],:,:,:) = 0;
94 dudt(:,[1 end],:,:) = 0;
95 dudt = reshape(dudt,[],1);
```

Fin.

4.9 patchEdgeInt2(): sets 2D patch edge values from 2D macroscale interpolation

Subsection contents

Input	67
Output	67
Lagrange interpolation gives patch-edge values .	68
Case of spectral interpolation	68

Couples 2D patches across 2D space by computing their edge values via macroscale interpolation. Assumes that the sub-patch structure is *smooth* so that the patch centre-values are sensible macroscale variables, and patch edge values are determined by macroscale interpolation of the patch-centre values. Communicate patch-design variables via the global struct `patches`.

```
20 function u = patchEdgeInt2(u)
21 global patches
```

Input

- `u` is a vector of length $nx \cdot ny \cdot Nx \cdot Ny \cdot nVars$ where there are `nVars` field values at each of the points in the $nx \times ny \times Nx \times Ny$ grid on the $Nx \times Ny$ array of patches.
- `patches` a struct set by `configPatches2()` which includes the following information.
 - `.x` is $nx \times Nx$ array of the spatial locations x_{ij} of the microscale grid points in every patch. Currently it *must* be an equi-spaced lattice on both macro- and microscales.
 - `.y` is similarly $ny \times Ny$ array of the spatial locations y_{ij} of the microscale grid points in every patch. Currently it *must* be an equi-spaced lattice on both macro- and microscales.
 - `.ordCC` is order of interpolation, currently only $\{0\}$.
 - `.Cwtsr` and `.Cwtsl`—not yet used

Output

- `u` is $nx \times ny \times Nx \times Ny \times nVars$ array of the fields with edge values set by interpolation.

Determine the sizes of things. Any error arising in the reshape indicates `u` has the wrong size.

```
75 [ny,Ny] = size(patches.y);
76 [nx,Nx] = size(patches.x);
77 nVars = round(numel(u)/numel(patches.x)/numel(patches.y));
78 if numel(u) ~= nx*ny*Nx*Ny*nVars
79     nSubP=[nx ny], nPatch=[Nx Ny], nVars=nVars, sizeu=size(u)
80 end
81 u = reshape(u,[nx ny Nx Ny nVars]);
```

With Dirichlet patches, the half-length of a patch is $h = dx(n_\mu - 1)/2$ (or -2 for specified flux), and the ratio needed for interpolation is then $r = h/\Delta X$. Compute lattice sizes from inside the patches as the edge values may be NaNs, etc.

```
91 dx = patches.x(3,1)-patches.x(2,1);
92 DX = patches.x(2,2)-patches.x(2,1);
93 rx = dx*(nx-1)/2/DX;
```

```

94 dy = patches.y(3,1)-patches.y(2,1);
95 DY = patches.y(2,2)-patches.y(2,1);
96 ry = dy*(ny-1)/2/DY;

```

For the moment assume the physical domain is macroscale periodic so that the coupling formulas are simplest. Should eventually cater for periodic, odd-mid-gap, even-mid-gap, even-mid-patch, Dirichlet, Neumann, Robin?? These index vectors point to patches and their two immediate neighbours.

```

107 %i=1:Nx; ip=mod(i,Nx)+1; im=mod(j-2,Nx)+1;
108 %j=1:Ny; jp=mod(j,Ny)+1; jm=mod(j-2,Ny)+1;

```

The centre of each patch (as nx and ny are odd) is at

```

115 i0 = round((nx+1)/2);
116 j0 = round((ny+1)/2);

```

Lagrange interpolation gives patch-edge values So compute centred differences of the mid-patch values for the macro-interpolation, of all fields. Assumes the domain is macro-periodic.

```

126 if patches.ordCC>0 % then non-spectral interpolation
127 error('non-spectral interpolation not yet implemented')
128 dmu=nan(patches.ordCC,nPatch,nVars);
129 % if patches.alt % use only odd numbered neighbours
130 % dmu(1,,:)= (u(i0,jp,:)+u(i0,jm,:))/2; % \mu
131 % dmu(2,,:)= u(i0,jp,:)-u(i0,jm,:); % \delta
132 % jp=jp(jp); jm=jm(jm); % increase shifts to \pm 2
133 % else % standard
134 dmu(1,,:)= (u(i0,jp,:)-u(i0,jm,:))/2; % \mu\delta
135 dmu(2,,:)= (u(i0,jp,:)-2*u(i0,j,:)+u(i0,jm,:)); % \delta^2
136 % end% if odd/even

```

Recursively take δ^2 of these to form higher order centred differences (could unroll a little to cater for two in parallel).

```

144 for k=3:patches.ordCC
145     dmu(k,,:)=dmu(k-2,jp,:)-2*dmu(k-2,j,:)+dmu(k-2,jm,:);
146 end

```

Interpolate macro-values to be Dirichlet edge values for each patch ([Roberts & Kevrekidis 2007](#)), using weights computed in `configPatches2()`. Here interpolate to specified order.

```

154 u(nSubP,j,:)=u(i0,j,:)*(1-patches.alt) ...
155     +sum(bsxfun(@times,patches.Cwtsr,dmu));
156 u( 1,j,:)=u(i0,j,:)*(1-patches.alt) ...
157     +sum(bsxfun(@times,patches.Cwtsl,dmu));

```

Case of spectral interpolation Assumes the domain is macro-periodic. We interpolate in terms of the patch index j , say, not directly in space. As the macroscale fields are N -periodic in the patch index j , the macroscale Fourier transform writes the centre-patch values as $U_j = \sum_k C_k e^{ik2\pi j/N}$. Then

the edge-patch values $U_{j\pm r} = \sum_k C_k e^{ik2\pi/N(j\pm r)} = \sum_k C'_k e^{ik2\pi j/N}$ where $C'_k = C_k e^{ikr2\pi/N}$. For N patches we resolve ‘wavenumbers’ $|k| < N/2$, so set row vector $\mathbf{k}s = k2\pi/N$ for ‘wavenumbers’ $k = (0, 1, \dots, k_{\max}, -k_{\max}, \dots, -1)$ for odd N , and $k = (0, 1, \dots, k_{\max}, \pm(k_{\max} + 1) - k_{\max}, \dots, -1)$ for even N .

179 `else% spectral interpolation`

Deal with staggered grid by doubling the number of fields and halving the number of patches (`configPatches2` tests there are an even number of patches). Then the patch-ratio is effectively halved. The patch edges are near the middle of the gaps and swapped.

```
189 % if patches.alt % transform by doubling the number of fields
190 % error('staggered grid not yet implemented')
191 % v=nan(size(u)); % currently to restore the shape of u
192 % u=cat(3,u(:,1:2:nPatch,:),u(:,2:2:nPatch,:));
193 % altShift=reshape(0.5*[ones(nVars,1);-ones(nVars,1)],1,1,[]);
194 % iV=[nVars+1:2*nVars 1:nVars]; % scatter interp to alternate field
195 % r=r/2; % ratio effectively halved
196 % nPatch=nPatch/2; % halve the number of patches
197 % nVars=nVars*2; % double the number of fields
198 % else % the values for standard spectral
199     altShift = 0;
200     iV = 1:nVars;
201 % end
```

Now set wavenumbers in the two directions. In the case of even N these compute the +-case for the highest wavenumber zig-zag mode, $k = (0, 1, \dots, k_{\max}, +(k_{\max} + 1) - k_{\max}, \dots, -1)$.

```
210 kMax = floor((Nx-1)/2);
211 krx = rx*2*pi/Nx*(mod((0:Nx-1)+kMax,Nx)-kMax);
212 kMay = floor((Ny-1)/2);
213 kry = ry*2*pi/Ny*(mod((0:Ny-1)+kMay,Ny)-kMay);
```

Test for reality of the field values, and define a function accordingly.

```
220 if imag(u(i0,j0,:,:))==0, uclean = @(u) real(u);
221     else uclean = @(u) u; end
```

Compute the Fourier transform of the patch centre-values for all the fields. If there are an even number of points, then zero the zig-zag mode in the FT and add it in later as cosine.

```
230 Ck = fft2(squeeze(u(i0,j0,:,:,:)));
```

The inverse Fourier transform gives the edge values via a shift a fraction $\mathbf{r}\mathbf{x}/\mathbf{r}\mathbf{y}$ to the next macroscale grid point. Initially preallocate storage for all the IFFTs that we need to cater for the zig-zag modes when there are an even number of patches in the directions.

```
241 nFTx = 2-mod(Nx,2);
242 nFTy = 2-mod(Ny,2);
243 unj = nan(1,ny,Nx,Ny,nVars,nFTx*nFTy);
```

```

244 u1j = nan(1,ny,Nx,Ny,nVars,nFTx*nFTy);
245 uin = nan(nx,1,Nx,Ny,nVars,nFTx*nFTy);
246 ui1 = nan(nx,1,Nx,Ny,nVars,nFTx*nFTy);

```

Loop over the required IFFTs.

```

252 iFT = 0;
253 for iFTx = 1:nFTx
254 for iFTy = 1:nFTy
255 iFT = iFT+1;

```

First interpolate onto x -limits of the patches. (It may be more efficient to product exponentials of vectors, instead of exponential of array—only for $N > 100$. Can this be vectorised further??)

```

264 for jj = 1:ny
265     ks = (jj-j0)*2/(ny-1)*kry; % fraction of kry along the edge
266     unj(1,jj,::,iV,iFT) = ifft2( bsxfun(@times,Ck ...
267         ,exp(1i*bsxfun(@plus,altShift+krx',ks))));
268     u1j(1,jj,::,iV,iFT) = ifft2( bsxfun(@times,Ck ...
269         ,exp(1i*bsxfun(@plus,altShift-krx',ks))));
270 end

```

Second interpolate onto y -limits of the patches.

```

276 for i = 1:nx
277     ks = (i-i0)*2/(nx-1)*krx; % fraction of krx along the edge
278     uin(i,1,::,iV,iFT) = ifft2( bsxfun(@times,Ck ...
279         ,exp(1i*bsxfun(@plus,ks',altShift+kry))));
280     ui1(i,1,::,iV,iFT) = ifft2( bsxfun(@times,Ck ...
281         ,exp(1i*bsxfun(@plus,ks',altShift-kry))));
282 end

```

When either direction have even number of patches then swap the zig-zag wavenumber to the conjugate.

```

289 if nFTy==2, kry(Ny/2+1) = -kry(Ny/2+1); end
290 end% iFTy-loop
291 if nFTx==2, krx(Nx/2+1) = -krx(Nx/2+1); end
292 end% iFTx-loop

```

Put edge-values into the u -array, using `mean()` to treat a zig-zag mode as cosine. Enforce reality when appropriate via `uclean()`.

```

300 u(end,::,::,iV) = uclean( mean(unj,6) );
301 u( 1 ,::,::,iV) = uclean( mean(u1j,6) );
302 u(:,end,::,iV) = uclean( mean(uin,6) );
303 u(:, 1 ,::,iV) = uclean( mean(ui1,6) );

```

Restore staggered grid when appropriate. Is there a better way to do this??

```

310 %if patches.alt
311 % nVars=nVars/2; nPatch=2*nPatch;
312 % v(:,1:2:nPatch,:)=u(:,::,1:nVars);
313 % v(:,2:2:nPatch,:)=u(:,::,nVars+1:2*nVars);

```



```

314 % u=v;
315 %end
316 end% if spectral
317 end% function patchEdgeInt2

```

Fin, returning the 4/5D array of field values with interpolated edges.

4.10 wave2D: example of a wave on patches in 2D

Section contents

For $u(x, y, t)$, test and simulate the simple wave PDE in 2D space:

$$\frac{\partial^2 u}{\partial t^2} = \nabla^2 u.$$

This script shows one way to get started: a user's script may have the following three steps (left-right arrows denote function recursion).

1. configPatches2
2. ode15s integrator \leftrightarrow patchSmooth2 \leftrightarrow wavePDE
3. process results

Establish global patch data struct to interface with a function coding the wave PDE: to be solved on 2π -periodic domain, with 9×9 patches, spectral interpolation (0) couples the patches, each patch of half-size ratio 0.25, and with 5×5 points within each patch.

```

34 clear all, close all
35 global patches
36 nSubP = 5;
37 nPatch = 9;
38 configPatches2(@wavePDE, [-pi pi], nan, nPatch, 0, 0.25, nSubP);

```

4.10.1 Check on the linear stability of the wave PDE

Set a zero equilibrium as basis. Then find the indices of patch-interior points as the only ones to vary in order to construct the Jacobian.

```

50 disp('Check linear stability of the wave scheme')
51 uv0 = zeros(nSubP, nSubP, nPatch, nPatch, 2);
52 uv0([1 end], :, :, :, :) = nan;
53 uv0(:, [1 end], :, :, :) = nan;
54 i = find(~isnan(uv0));

```

Now construct the Jacobian. Since linear wave PDE, use large perturbations.

```

61 small = 1;
62 jac = nan(length(i));
63 sizeJacobian = size(jac)
64 for j = 1:length(i)
65     uv = uv0(:);

```

```

66     uv(i(j)) = uv(i(j))+small;
67     tmp = patchSmooth2(0,uv)/small;
68     jac(:,j) = tmp(i);
69 end

```

Now explore the eigenvalues a little: find the ten with the biggest real-part; if small enough, then the method may be good.

```

77 evals = eig(jac);
78 nEvals = length(evals)
79 [~,k] = sort(-abs(real(evals)));
80 evalsWithBiggestRealPart = evals(k(1:10))
81 if abs(real(evals(k(1))))>1e-4
82     warning('eigenvalue failure: real-part > 1e-4')
83     return, end

```

Check eigenvalues close to true waves of the PDE (not yet the micro-discretised equations).

```

90 kwave = 0:(nPatch-1)/2;
91 freq = sort(reshape(sqrt(kwave'.^2+kwave.^2),1,[],[]));
92 freq = freq(diff([-1 freq])>1e-9);
93 freqerr = [freq; min(abs(imag(evals)-freq))]

```

4.10.2 Execute a simulation

Set a Gaussian initial condition using auto-replication of the spatial grid: here $u0$ and $v0$ are in the form required for computation: $n_x \times n_y \times N_x \times N_y$.

```

108 x = reshape(patches.x,nSubP,1,[],1);
109 y = reshape(patches.y,1,nSubP,1,[]);
110 u0 = exp(-x.^2-y.^2);
111 v0 = zeros(size(u0));

```

Initiate a plot of the simulation using only the microscale values interior to the patches: set x and y -edges to `nan` to leave the gaps. Start by showing the initial conditions of [Figure 4.13](#) while the simulation computes. To mesh/surf plot we need to 'transpose' to size $n_x \times N_x \times n_y \times N_y$, then reshape to size $n_x \cdot N_x \times n_y \cdot N_y$.

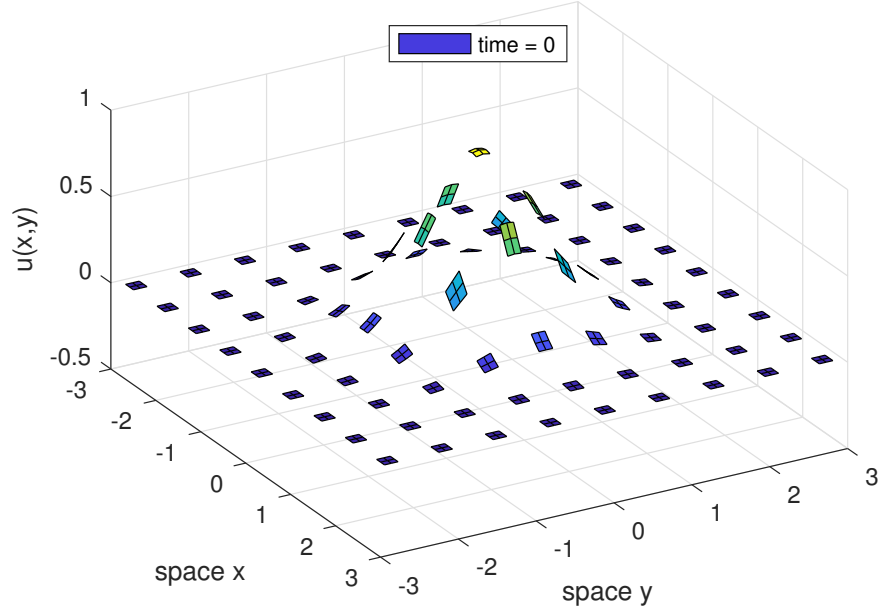
```

123 x = patches.x; y = patches.y;
124 x([1 end],:) = nan; y([1 end],:) = nan;
125 u = reshape(permute(u0,[1 3 2 4]), [numel(x) numel(y)]);
126 usurf = surf(x(:),y(:),u');
127 axis([-3 3 -3 3 -0.5 1]), view(60,40)
128 xlabel('space x'), ylabel('space y'), zlabel('u(x,y)')
129 legend('time = 0','Location','north')
130 drawnow
131 set(gcf,'paperposition',[0 0 14 10])
132 print('-depsc','wave2Dic')

```

Integrate in time using standard functions.

Figure 4.15: initial field $u(x, y, t)$ at time $t = 0$ of the patch scheme applied to the simple wave PDE: Figure 4.16 plots the computed field at time $t = 2$.



```

145 disp('Wait while we simulate u_t=v, v_t=u_xx+u_yy')
146 [ts, uvs] = ode15s(@patchSmooth2, [0 2], [u0(:); v0(:)]);

```

Animate the computed simulation to end with Figure 4.16. Because of the very small time-steps, subsample to plot at most 200 times.

```

154 di = ceil(length(ts)/200);
155 for i = [1:di:length(ts)-1 length(ts)]
156     uv = patchEdgeInt2(uvs(i, :));
157     uv = reshape(permute(uv, [1 3 2 4 5]), [numel(x) numel(y) 2]);
158     usurf.ZData = uv(:, :, 1)';
159     legend(['time = ' num2str(ts(i), 2)])
160     pause(0.1)
161 end
162 print('-depsc', ['wave2Dt' num2str(ts(end))])

```

4.10.3 Example of simple wave PDE inside patches

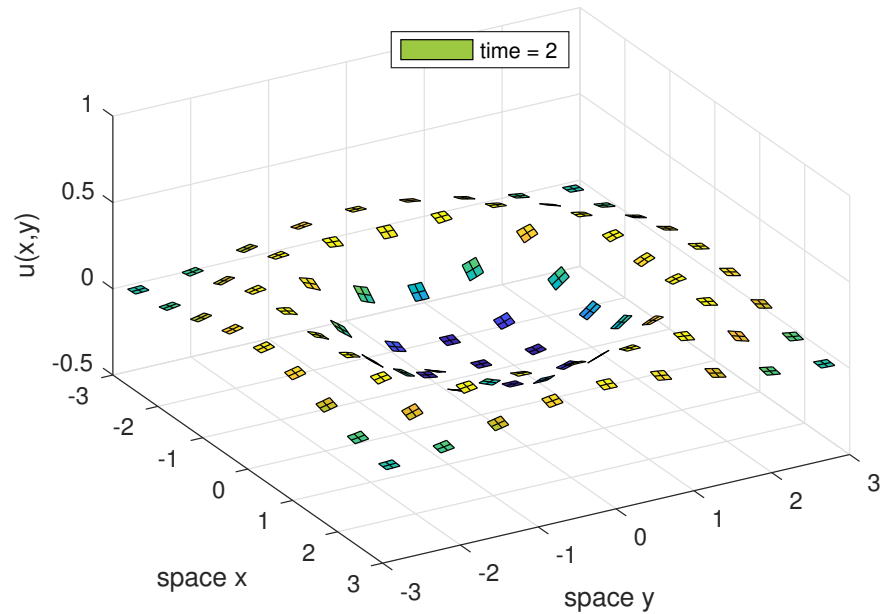
As a microscale discretisation of $u_{tt} = \nabla^2(u)$, so code $\dot{u}_{ijkl} = v_{ijkl}$ and $\dot{v}_{ijkl} = \frac{1}{\delta x^2}(u_{i+1,j,k,l} - 2u_{i,j,k,l} + u_{i-1,j,k,l}) + \frac{1}{\delta y^2}(u_{i,j+1,k,l} - 2u_{i,j,k,l} + u_{i,j-1,k,l})$.

```

183 function uvt = wavePDE(t, uv, x, y)
184     if ceil(t+1e-7)-t<2e-2, simTime = t, end %track progress
185     dx = diff(x(1:2)); dy = diff(y(1:2)); % microscale spacing
186     i = 2:size(uv,1)-1; j = 2:size(uv,2)-1; % interior patch-points
187     uvt = nan(size(uv)); % preallocate storage
188     uvt(i,j,:,:,1) = uv(i,j,:,:,2);
189     uvt(i,j,:,:,2) = diff(uv(:,j,:,:,1),2,1)/dx^2 ...
190         +diff(uv(i,:,:,1),2,2)/dy^2;

```

Figure 4.16: field $u(x, y, t)$ at time $t = 2$ of the patch scheme applied to the simple wave PDE with initial condition in Figure 4.15.



191 end

4.11 To do

- Testing needs to be quantitative.
- more than two space dimensions??
- Heterogeneous microscale via averaging regions—but I suspect should be separated from simple homogenisation
- Parallel processing versions.
- ??
- Adapt to maps in micro-time? Surely easy, just an example.

4.12 Miscellaneous tests

4.12.1 patchEdgeInt1test: test the spectral interpolation

Subsection contents

Test standard spectral interpolation	75
Now test spectral interpolation on staggered grid	75
Finish	77

A script to test the spectral interpolation of function `patchEdgeInt1()` Establish global data struct for the range of various cases.

```

13 clear all
14 global patches
15 nSubP=3
16 i0=(nSubP+1)/2; % centre-patch index

```

Test standard spectral interpolation Test over various numbers of patches, random domain lengths and random ratios.

```

24 for nPatch=5:10
25     nPatch=nPatch
26     Len=10*rand
27     ratio=0.5*rand
28     configPatches1(@sin,[0,Len],nan,nPatch,0,ratio,nSubP);
29     kMax=floor((nPatch-1)/2);

```

Test single field Set a profile, and evaluate the interpolation.

```

37 for k=-kMax:kMax
38     u0=exp(1i*k*patches.x*2*pi/Len);
39     ui=patchEdgeInt1(u0(:));
40     normError=norm(ui-u0);
41     if abs(normError)>5e-14
42         normError=normError
43         error(['failed single var interpolation k=' num2str(k)])
44     end
45 end

```

Test multiple fields Set a profile, and evaluate the interpolation. For the case of the highest wavenumber, squash the error when the centre-patch values are all zero.

```

54 for k=1:nPatch/2
55     u0=sin(k*patches.x*2*pi/Len);
56     v0=cos(k*patches.x*2*pi/Len);
57     uvi=patchEdgeInt1([u0(:);v0(:)]);
58     normuError=norm(uvi(:,1)-u0)*norm(u0(i0,:));
59     normvError=norm(uvi(:,2)-v0)*norm(v0(i0,:));
60     if abs(normuError)+abs(normvError)>2e-13
61         normuError=normuError, normvError=normvError
62         error(['failed double field interpolation k=' num2str(k)])
63     end
64 end

```

End the for-loop over various geometries.

```

71 end

```

Now test spectral interpolation on staggered grid Must have even number of patches for a staggered grid.

```

79  for nPatch=6:2:20
80  nPatch=nPatch
81  ratio=0.5*rand
82  nSubP=3; % of form 4*N-1
83  Len=10*rand
84  configPatches1(@simpleWavepde,[0,Len],nan,nPatch,-1,ratio,nSubP);
85  kMax=floor((nPatch/2-1)/2)

```

Identify which microscale grid points are h or u values.

```

91  uPts=mod( bsxfun(@plus,(1:nSubP)',(1:nPatch)) ,2);
92  hPts=find(1-uPts);
93  uPts=find(uPts);

```

Set a profile for various wavenumbers. The capital letter U denotes an array of values merged from both u and h fields on the staggered grids.

```

100 fprintf('Single field-pair test.\n')
101 for k=-kMax:kMax
102     U0=nan(nSubP,nPatch);
103     U0(hPts)=rand*exp(+1i*k*patches.x(hPts)*2*pi/Len);
104     U0(uPts)=rand*exp(-1i*k*patches.x(uPts)*2*pi/Len);
105     Ui=patchEdgeInt1(U0(:));
106     normError=norm(Ui-U0);
107     if abs(normError)>5e-14
108         normError=normError
109         error(['failed single sys interpolation k=' num2str(k)])
110     end
111 end

```

Test multiple fields Set a profile, and evaluate the interpolation. For the case of the highest wavenumber zig-zag, squash the error when the alternate centre-patch values are all zero. First shift the x -coordinates so that the zig-zag mode is centred on a patch.

```

121 fprintf('Two field-pairs test.\n')
122 x0=patches.x((nSubP+1)/2,1);
123 patches.x=patches.x-x0;
124 for k=1:nPatch/4
125     U0=nan(nSubP,nPatch); V0=U0;
126     U0(hPts)=rand*sin(k*patches.x(hPts)*2*pi/Len);
127     U0(uPts)=rand*sin(k*patches.x(uPts)*2*pi/Len);
128     V0(hPts)=rand*cos(k*patches.x(hPts)*2*pi/Len);
129     V0(uPts)=rand*cos(k*patches.x(uPts)*2*pi/Len);
130     UVi=patchEdgeInt1([U0(:);V0(:)]);
131     normuError=norm(UVi(:,1:2:nPatch,1)-U0(:,1:2:nPatch))*norm(U0(i0,2:2:nPatch)
132         +norm(UVi(:,2:2:nPatch,1)-U0(:,2:2:nPatch))*norm(U0(i0,1:2:nPatch));
133     normvError=norm(UVi(:,1:2:nPatch,2)-V0(:,1:2:nPatch))*norm(V0(i0,2:2:nPatch)
134         +norm(UVi(:,2:2:nPatch,2)-V0(:,2:2:nPatch))*norm(V0(i0,1:2:nPatch));
135     if abs(normuError)+abs(normvError)>2e-13
136         normuError=normuError, normvError=normvError

```

```

137     error(['failed double field interpolation k=' num2str(k)])
138     end
139 end

    End for-loop over patches

146 end

    Finish   If no error messages, then all OK.

157 fprintf('\nIf you read this, then all tests were passed\n')

```

4.13 patchEdgeInt2test: tests 2D spectral interpolation

Try 99 realisations of random tests.

```

11 clear all, close all
12 global patches
13 for realisation=1:99

    Choose and configure random sized domains, random sub-patch resolution,
    random size-ratios, random number of periodic-patches.

19 Lx=1+3*rand, Ly=1+3*rand
20 nSubP=1+2*randi(3,1,2)
21 ratios=rand(1,2)/2
22 nPatch=2+randi(4,1,2)
23 configPatches2(@sin,[0 Lx 0 Ly],nan,nPatch,0,ratios,nSubP)

    Choose a random number of fields, then generate trigonometric shape with
    random wavenumber and random phase shift.

29 nV=randi(3)
30 [nx,Nx]=size(patches.x);
31 [ny,Ny]=size(patches.y);
32 u0s=nan(nx,ny,Nx,Ny,nV);
33 for iV=1:nV
34     kx=randi([0 ceil((nPatch(1)-1)/2)])
35     ky=randi([0 ceil((nPatch(2)-1)/2)])
36     phix=pi*rand*(2*kx~nPatch(1))
37     phiy=pi*rand*(2*ky~nPatch(2))
38     % generate 2D array via auto-replication
39     u0=sin(2*pi*kx*patches.x(:) /Lx+phix) ...
40         .*sin(2*pi*ky*patches.y(:)'/Ly+phiy);
41     % reshape into 4D array
42     u0=reshape(u0,[nx Nx ny Ny]);
43     u0=permute(u0,[1 3 2 4]);
44     % store into 5D array
45     u0s(:,:,,:,iV)=u0;
46 end

```

Copy and NaN the edges, then interpolate

```
52 u=u0s; u([1 end],:,:,:) = nan; u(:, [1 end],:,:) = nan;
53 u=patchEdgeInt2(u(:));
```

If there is an error in the interpolation then abort the script for checking:
record parameter values and inform.

```
59 err=u-u0s;
60 normerr=norm(err(:))
61 if normerr>1e-12, error('2D interpolation failed'), end
62 end
```

Appendix A Create, document and test algorithms

For developers to create and document the various functions, we use an idea due to Neil D. Lawrence of the University of Sheffield:

- Each class of toolbox functions is located in separate directories in the repository, say `Dir`.
- Create a LaTeX file `Dir/funs.tex`: establish as one LaTeX section that `\input{Dir/*.m}`s the files of the functions in the class, example scripts of use, and possibly test scripts, [Table A.1](#).
- Each such `Dir/funs.tex` file is to be included from the main LaTeX file `Doc/eqnFreeDevMan.tex` so that people can most easily work on one section at a time:
 - put `\include{funs}` into `Doc/eqnFreeDevMan.tex`;
 - to include we have to use a soft link so at the command line in the directory `Doc` execute `ln -s ../Dir/funs.tex` ¹
- Each toolbox function is documented as a separate section, with tests and examples as separate sections.
- Each function-section and test-section is to be created as a MATLAB/Octave `Dir/*.m` file, say `Dir/fun1.m`, so that users simply invoke the function in MATLAB/Octave as usual by `fun1(...)`.

Some editors may need to be told that `fun1.m` is a LaTeX file. For example, TexShop on the Mac requires one to execute in a Terminal

```
defaults write TexShop OtherTeXExtensions -array-add "m"
```

- [Table A.2](#) gives the template for the `Dir/*.m` function-sections. The format for a example/test-section is similar.
- Any figures from examples should be generated and then saved for later inclusion with the following (which finally works properly for MATLAB 2017+)

```
set(gcf,'PaperPosition',[0 0 14 10])
print('-depsc2',filename)
```

Include with `\includegraphics[scale=0.85]{filename}`

¹ Such soft links are necessary for at least my Mac OSX and hopefully will work for other developers. Further, it has the advantage that auxiliary files are also located in the `Doc` directory.

Table A.1: example `Dir/*.tex` file to typeset in the master document a function-section, say `fun.m`, and maybe the test/example-sections.

```

1 % input *.m files for ... Author, date
2 %!TEX root = ../Doc/eqnFreeDevMan.tex
3 \chapter{...}
4 \label{sec:...}
5 \localtableofcontents
6 introduction...
7 \input{../Dir/fun.m}
8 \input{../Dir/funExample.m}
9 ...
10 \begin{devMan}
11 \section{To do}
12 ...
13 \section{Miscellaneous tests}
14 \input{../Dir/funTest.m}
15 ...
16 \end{devMan}

```

Table A.2: template for a function-section `Dir/*.m` file.

```

1 % Short explanation for users typing "help fun"
2 % Author, date
3 %!TEX root = ../Doc/eqnFreeDevMan.tex
4 %{
5 \section{\texttt{...}: ...}
6 \label{sec:...}
7 \localtableofcontents
8 Overview LaTeX explanation.
9 \begin{matlab}
10 %}
11 function ...
12 %{
13 \end{matlab}
14 \paragraph{Input} ...
15 \paragraph{Output} ...
16 \begin{devMan}
17 Repeated as desired:
18 LaTeX between end-matlab and begin-matlab
19 \begin{matlab}
20 %}
21 Matlab code between %} and %{
22 %{
23 \end{matlab}
24 Concluding LaTeX before following final lines.
25 \end{devMan}
26 %}

```

Appendix B Aspects of developing a ‘toolbox’ for patch dynamics

Chapter contents

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This appendix documents sketchy further thoughts on aspects of the development.

B.1 Macroscale grid

The patches are to be distributed on a macroscale grid: the j th patch ‘centred’ at position $\vec{X}_j \in \mathbb{X}$. In principle the patches could move, but let’s keep them fixed in the first version. The simplest macroscale grid will be rectangular (`meshgrid`), but we plan to allow a deformed grid to secondly cater for boundary fitting to quite general domain shapes \mathbb{X} . And plan to later allow for more general interconnect networks for more topologies in application.

B.2 Macroscale field variables

The researcher/practitioner has to know an appropriate set of macroscale field variables $\vec{U}(t) \in \mathbb{R}^{d_{\vec{U}}}$ for each patch. For example, first they might be a simple average over a core of a patch of all of the micro-field variables; second, they might be a subset of the average micro-field variables; and third in general the macro-variables might be a nonlinear function of the micro-field variables (such as temperature is the average speed squared). The core might be just one point, or a sizeable fraction of the patch.

The mapping from microscale variable to macroscale variables is often termed the restriction.

In practice, users may not choose an appropriate set of macro-variables, so will eventually need to code some diagnostic to indicate a failure of the assumed closure.

B.3 Boundary and coupling conditions

The physical domain boundary conditions are distinct from the conditions coupling the patches together. Start with physical boundary conditions of periodicity in the macroscale.

Second, assume the physical boundary conditions are that the macro-variables are known at macroscale grid points around the boundary. Then the issue is to adjust the interpolation to cater for the boundary presence and shape. The coupling conditions for the patches should cater for the range of Robin-like boundary conditions, from Dirichlet to Neumann. Two possibilities arise: direct imposition of the coupling action ([Roberts & Kevrekidis 2007](#)), or control by the action.

Third, assume that some of the patches have some edges coincident with the boundary of the macroscale domain \mathbb{X} , and it is on these edges that macroscale physical boundary conditions are applied. Then the interpolation from the core of these edge patches is the same as the second case of prescribed boundary macro-variables. An issue is that each boundary patch should be big enough to cater for any spatial boundary layers transitioning from the applied boundary condition to the interior slow evolution.

Alternatively, we might have the physical boundary condition constrain the interpolation between patches.

Often microscale simulations are easiest to write when ‘periodic’ in microscale space. To cater for this we should also allow a control at perhaps the quartiles of a micro-periodic simulator.

B.4 Mesotime communication

Since communication limits large scale parallelism, a first step in reducing communication will be to implement only updating the coupling conditions when necessary. Error analysis indicates that updating on times longer the microscale times and shorter than the macroscale times can be effective ([Bunder et al. 2016](#)). Implementations can communicate one or more derivatives in time, as well as macroscale variables.

At this stage we can effectively parallelise over patches: first by simply using Matlab’s `parfor`. Probably not using a GPU as we probably want to leave GPUs for the black-box to utilise within each patch.

B.5 Projective integration

To take macroscale time-steps, invoke several possible projective integration schemes: simple Euler projection, Heun-like method, etc ([Samaey et al. 2010](#)). Need to decide how long a microscale burst needs to be.

Should not need an implicit scheme as the fast dynamics are meant to be only in the micro variables, and the slow dynamics only in the macroscale variables. However, it could be that the macroscale variables have fast oscillations and it is only the amplitude of the oscillations that are slow. Perhaps need to detect and then fix or advise.

A further stage is to implement a projective integration scheme for stochastic macroscale variables: this is important because the averaging over a core of microscale roughness will almost invariably have at least some stochastic legacy effect. [Calderon \(2007\)](#) did some useful research on stochastic projective intergration.

B.6 Lift to many internal modes

In most problems the number of macroscale variables at any given position in space, $d_{\vec{J}}$, is less than the number of microscale variables at a position, $d_{\vec{u}}$; often much less ([Kevrekidis & Samaey 2009](#), e.g.). In this case, every time we start a patch simulation we need to provide $d_{\vec{u}} - d_{\vec{J}}$ data at each position in the patch: this is lifting. The first methodology is to first guess, then run repeated short bursts with reinitialisation, until the simulation reaches a slow manifold. Then run the real simulation.

If the time taken to reach a local quasi-equilibrium is too long, then it is likely that the macroscale closure is bad and the macroscale variables need to be extended.

A second step is to cater for cases where the slow manifold is stochastic or is surrounded by fast waves: when it is hard to detect the slow manifold, or the slow manifold is not attractive.

B.7 Macroscale closure

In some circumstances a researcher/practitioner will not code the appropriately set of macroscale variables for a complete closure of the macroscale. For example, in thin film fluid dynamics at low Reynolds number the only macroscale variable is the fluid depth; however, at higher Reynolds number, circa ten, the inertia of the fluid becomes important and the macroscale variables must additionally include a measure of the mean lateral velocity/momentum ([Roberts & Li 2006](#), e.g.).

At some stage we need to detect any flaw in the closure, and perhaps suggest additional appropriate macroscale variables, or at least their characteristics. Indeed, a poor closure and a stochastic slow manifold are really two faces of the same problem: the problem is that the chosen macroscale variables do not have a unique evolution in terms of themselves. A good resolution of the issue will account for both faces.

B.8 Exascale fault tolerance

Matlab is probably not an appropriate vehicle to deal with real exascale faults. However, we should cater by coding procedures for fault tolerance

and testing them at least synthetically. Eventually provide hooks to a user routine to be invoked under various potential scenarios. The nature of fault tolerant algorithms will vary depending upon the scenario, even assuming that each patch burst is executed on one CPU (or closely coupled CPUs): if there are much more CPUs than patches, then maybe simply duplicate all patch simulations; if much less CPUs than patches, then an asynchronous scheduling of patch bursts should effectively cater for recomputation of failed bursts; if comparable CPUs to patches, then more subtle action is needed.

Once mesotime communication and projective integration is provided, a recomputation approach to intermittent hardware faults should be effective because we then have the tools to restart a burst from available macroscale data. Should also explore proceeding with a lower order interpolation that misses the faulty burst—because an isolated lower order interpolation probably will not affect the global order of error (it does not in approximating some boundary conditions ([Gustafsson 1975](#), [Svard & Nordstrom 2006](#)))

B.9 Link to established packages

Several molecular/particle/agent based codes are well developed and used by a wide community of researchers. Plan to develop hooks to use some such codes as the microscale simulators on patches. First, plan to connect to LAMMPS ([Plimpton et al. 2016](#)). Second, will evaluate performance, issues, and then consider what other established packages are most promising.

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