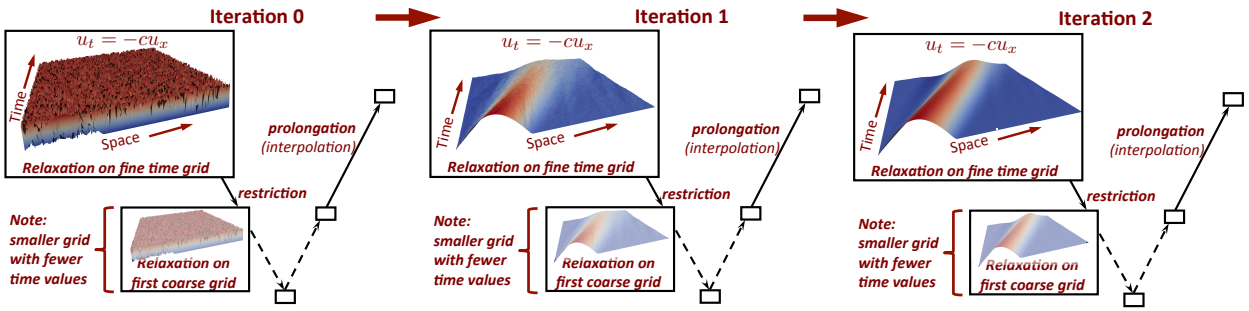
Warp 1.0 Users' Manual



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Contents

1 Abstract

This package implements an optimal-scaling multigrid solver for the linear systems that arise from the discretization of problems with evolutionary behavior. Typically, solution algorithms for evolution equations are based on a time-marching approach, solving sequentially for one time step after the other. Parallelism in these traditional time-integration techniques is limited to spatial parallelism. However, current trends in computer architectures are leading towards systems with more, but not faster, processors. Therefore, faster compute speeds must come from greater parallelism. One approach to achieve parallelism in time is with multigrid, but extending classical multigrid methods for elliptic operators to this setting is a significant achievement. In this software, we implement a non-intrusive, optimal-scaling time-parallel method based on multigrid reduction techniques. The examples in the package demonstrate optimality of our multigrid-reduction-in-time algorithm (MGRIT) for solving a variety of equations in two and three spatial dimensions. These examples can also be used to show that MGRIT can achieve significant speedup in comparison to sequential time marching on modern architectures.

It is **strongly recommended** that you read `Parallel Time Integration with Multigrid` before proceeding.

2 Overview of Warp Algorithm

The goal of Warp is to solve a problem faster than is possible with a traditional time marching algorithm. Instead of sequential time marching, Warp solves the problem iteratively by simultaneously updating the current solution guess over all time values. The initial solution guess can be anything, even a random function over space-time. The iterative

updates to the solution guess are done by constructing a hierarchy of temporal grids, where the finest grid contains all of the time values for the simulation. Each subsequent grid is a coarser grid with fewer time values. The coarsest grid has a trivial number of time steps and can be quickly solved exactly. The overall effect is that solutions to the time marching problem on the coarser (i.e., cheaper) grids can be used to correct the original finest grid solution.

To understand how Warp differs from traditional time marching, consider the simple linear advection equation, $u_t = -cu_x$. The next figure depicts how one would typically evolve a solution here with sequential time stepping. The solution propagates sequentially across space as time increases.

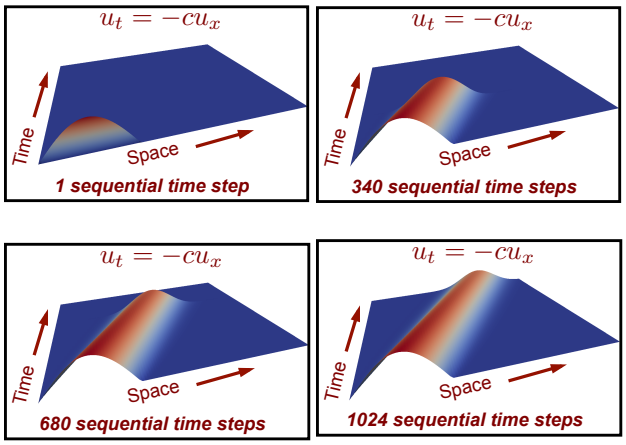


Figure 1: Sequential time stepping.

Warp instead begins with a solution guess over all of space-time, which we let here be random for the sake of argument. A Warp iterations then does

1. Relaxation on the fine grid, i.e., the grid that contains all of the desired time values
    - Relaxation is just a local application of the time stepping scheme, e.g., backward Euler
2. Restriction to the first coarse grid, i.e., a grid that contains fewer time values, say every second or every third time value
3. Relaxation on the first coarse grid
4. Restriction to the second coarse grid and so on...
5. When a coarse grid of trivial size (say 2 time steps) is reached, it is solved exactly.
6. The solution is then interpolated from the coarsest grid to the finest grid

After the cycle is complete, it repeats until the solution is accurate enough. This is depicted in the next figure, where only a few iterations are required for this simple problem.

There are a few important points to make.

- The coarse time grids allow for global propagation of information across space-time with only one Warp iteration (c.f. how the solution is updated from iteration 0 to iteration 1).
- Using coarser (cheaper) grids to correct the fine grid is analagous to spatial multigrid.
- Only a few Warp iterations are required to find the solution over 1024 time steps. Therefore if enough processors are available to parallelize Warp, we can see a speedup over traditional time stepping (more on this later).
- This is a simple example, and Warp is structured to handle variable time step sizes and adaptive time step sizes, and these features will be coming.

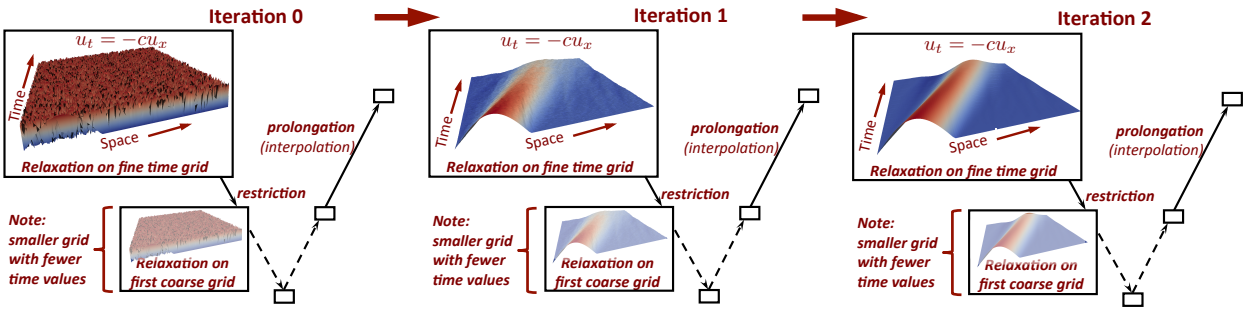


Figure 2: Warp iterations.

To firm up our understanding, let's do a little math. Assume that you have a general ODE,

$$u'(t) = f(t, u(t)), \quad u(0) = u_0, \quad t \in [0, T],$$

which you descretize with the one-step integration

$$u_i = \Phi_i(u_{i-1}) + g_i, \quad i = 1, 2, ..., N.$$

Traditional time marchine would first solve for $i = 1$, then solve for $i = 2$, and so on. This process is equivalent to a forward solve of this system,

$$A\mathbf{u} \equiv \begin{pmatrix} I & & & \\ -\Phi_1 & I & & \\ & \ddots & \ddots & \\ & & -\Phi_N & I \end{pmatrix} \begin{pmatrix} u_0 \\ u_1 \\ \vdots \\ u_N \end{pmatrix} = \begin{pmatrix} g_0 \\ g_1 \\ \vdots \\ g_N \end{pmatrix} \equiv \mathbf{g}$$

or

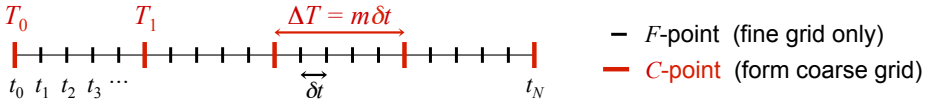
$$A\mathbf{u} = \mathbf{g}.$$

This process is optimal and O(N), but it is sequential. Warp instead solves the system iteratively, with a multigrid reduction method [1] applied in only the time dimension. This approach is

- nonintrusive, in that it coarsens only in time and asks the user to define their own Φ
- optimal and O(N) with a higher constant than time stepping
- highly parallel

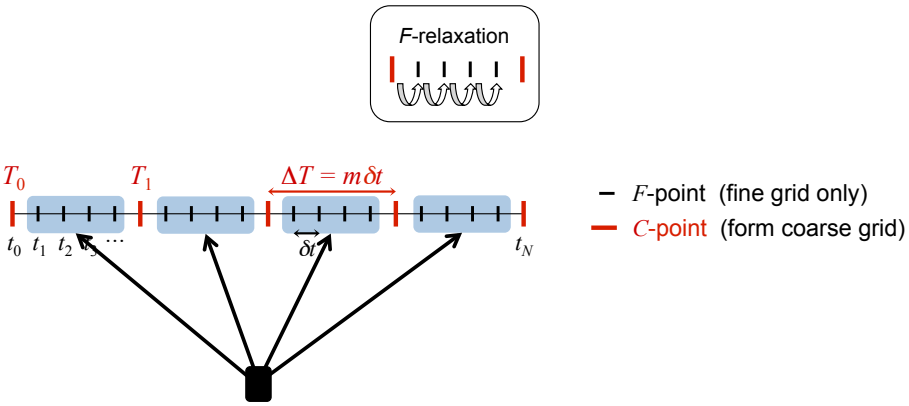
Warp solves this system iteratively by constructing a hierarchy of time grids. We describe the two-grid process, with the multigrid process being a recursive application of the process. We also assume that Φ is constant for notational simplicity.

Warp functions as follows. The next Figure depicts a sample timeline of time values, where the time values have been split into C and F points. C points exist on both the fine and coarse time grid, but F points exist only on the fine time scale. Following the above steps outlining a Warp cycle, the first task is relaxation. The simplest relaxation here

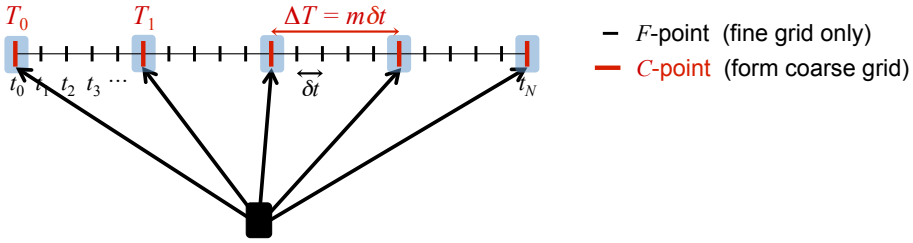


alternates between C and F sweeps. An F sweep simply updates time values by integrating with Φ over all the F points from one C point to the next, as depicted here

But, such an update can be done simultaneously over all F intervals in parallel, as depicted here



- Update all F-points using time propagator Φ



- Update all C-points using time propagator Φ

Following an F sweep we can also do C sweep, as depicted here FCF or F relaxation will refer to how the relaxation sweeps are carried out. So, we can say

- FCF or F relaxtion is highly parallel.
- But, a sequential component exists equaling the the number of F points between two C points.
- Warp uses regular coarsening factors, i.e., the spacing of C points happens every k points.

After relaxation, then comes coarse grid correction. The restriction operator R maps to the coarse grid by simply injecting values at C points from the fine grid to the coarse grid,

$$R = \begin{pmatrix} I & & \\ 0 & & \\ \vdots & & \\ 0 & & \\ & I & \\ & 0 & \\ & \vdots & \\ & 0 & \\ & & \ddots \end{pmatrix},$$

where the spacing between each I is $m-1$ block rows. This Warp implements an FAS (Full Approximation Scheme) multigrid cycle, and hence the system matrix , solution guess and right-hand-side (i.e., $A, \mathbf{u}, \mathbf{g}$) are all restricted. This is in contrast to linear multigrid which typically restricts the residual equation to the coares grid. We choose FAS because it is `nonlinear` multigrid and allows us to solve nonlinear problems.

[1] Ries, Manfred, Ulrich Trottenberg, and Gerd Winter. "A note on MGR methods." Linear Algebra and its Applications 49 (1983): 1-26.

The main question here is how to form the coarse grid matrix, which in turn is defined by the coarse grid time stepper Φ_Δ. It is typical to let Φ_Δ simply be Φ but with the coarse time step size Δt. Thus if

$$A = \begin{pmatrix} I & & & \\ -\Phi & I & & \\ & \ddots & \ddots & \\ & & -\Phi & I \end{pmatrix}$$

then

$$A_\Delta = \begin{pmatrix} I & & & \\ -\Phi_\Delta & I & & \\ & \ddots & \ddots & \\ & & -\Phi_\Delta & I \end{pmatrix},$$

where A_Δ has fewer rows and columns than A, e.g., if we are coarsening in time by 2, it has one half as many rows and columns. This coarse grid equation

$$A_\Delta \mathbf{u}_\Delta = \mathbf{g}_\Delta \equiv R\mathbf{g}$$

is then solved. Finally, $\mathbf{u}_\Delta$ is interpolated with P_Φ back to the fine grid, which is equivalent to injecting the coarse grid to the C points on the fine grid, follwed by an F relaxation sweep. That is,

$$P_\Phi = \begin{pmatrix} I & & & \\ \Phi & & & \\ \Phi^2 & & & \\ \vdots & & & \\ \Phi^{m-1} & & & \\ & I & & \\ & \Phi & & \\ & \Phi^2 & & \\ & \vdots & & \\ & \Phi^{m-1} & & \\ & & & \ddots \end{pmatrix},$$

where m again is the coarsening factor.

This two-grid process is captured with this algorithm. Using a recursive coarse grid solves makes the process multilevel, and halting is done based on a residual tolerance. If the operator is linear, this FAS cycle is equivalent to standard linear multigrid. Note that we represent A as function below, whereas above the notation was simplified for the linear case.

1. Relax on $A(\mathbf{u}) = \mathbf{g}$ using FCF-relaxation
2. Restrict the fine grid approximation and its residual: $\mathbf{u}_\Delta \leftarrow R\mathbf{u}, \quad \mathbf{r}_\Delta \leftarrow R(\mathbf{g} - A(\mathbf{u})$
3. Solve $A_\Delta(\mathbf{v}_\Delta) = A_\Delta(\mathbf{u}_\Delta) + \mathbf{r}_\Delta$
4. Compute the coarse grid error approximation: $\mathbf{e}_\Delta = \mathbf{v}_\Delta - \mathbf{u}_\Delta$
5. Correct: $\mathbf{u} \leftarrow \mathbf{u} + P\mathbf{e}_\Delta$

In summary, a few points are

- Warp is an iterative solver for the global space-time problem.
- The user defines the time stepping routine Φ.
- Warp convergence will depend heavily on how well Φ_Δ approximates Φ^m, that is how well a time step size of $m\delta t = \Delta T$ will approximate m applications of the same time integrator for a time step size of δt. This is a subject of research, but this approximation need not capture fine scale behavior, which is captured by relaxation on the fine grid.

- The coarsest grid is solved exactly, i.e., sequentially, which is a bottleneck. This is an issue for two-level methods like Parareal, [2] but not for a multilevel scheme like Warp where the coarsest grid is of trivial size.
- By forming the coarse grid to have the same sparsity structure and time stepper as the fine grid, the algorithm can recur easily and efficiently.
- Interpolation and restriction are ideal or exact, in that an application of interpolation leaves a zero residual at all F points.

Overview of Warp Code

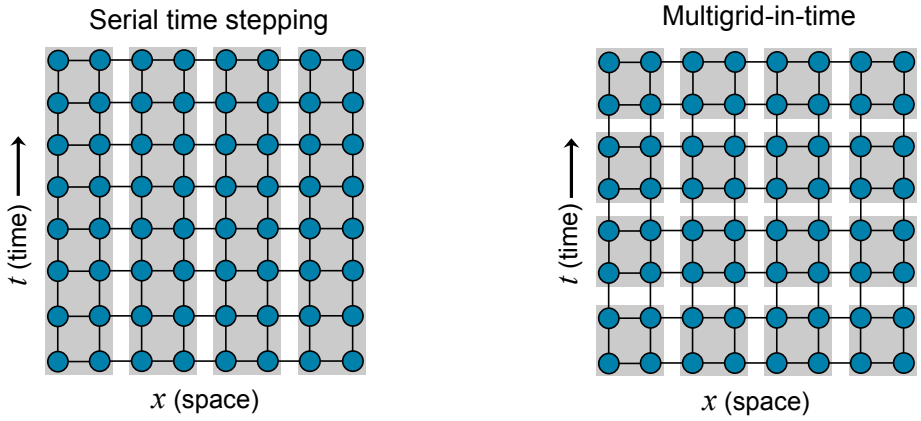
Warp is designed to run in conjunction with an existing application code that can be wrapped per our interface. This application code will implement some time marching type simulation like fluid flow. Essentially, the user has to take their application code and extract a stand-alone time-stepping function Φ that can evolve a solution from one time value to another, regardless of time step size. After this is done, the Warp code takes care of the parallelism in the time dimension.

Warp

- is written in C/C++ and can easily interface with Fortran
- uses MPI for parallelism
- self documents through comments in the source code and through $*$.md files

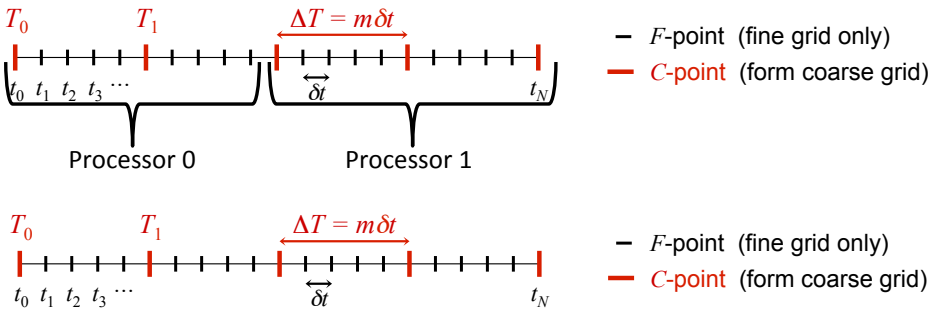
Parallel decomposition and memory

- Warp decomposes the problem in parallel as depicted in this figure. As you can see, traditional time stepping



  only stores one time step as a time, but only enjoys a spatial data decomposition and spatial parallelism. On the other hand, Warp stores multiple time steps simultaneously and each processor holds a space-time chunk.
- Warp only handles temporal parallelism and is agnostic to the spatial decomposition. See the warp_Split-Commworld. Each processor owns a certain number of CF intervals of points, as depicted here One interval is a C point and all following F points until the next C point. These intervals are distributed evenly on the finest grid.
- Storage is greatly minimized by only stored C points. Whenever an F point is needed, it is generated by F relaxation. That is, we only store the red C point time values. Coarsening can by aggressive with $m = 8, 16, 32$, so the storage requirements of Warp are significantly reduced when compared to storing all of the time values.

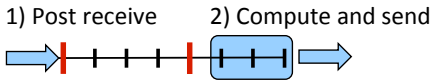
[2] Lions, J., Yvon Maday, and Gabriel Turinici. "A"parareal"in time discretization of PDE's." Comptes Rendus de l'Academie des Sciences Series I Mathematics 332.7 (2001): 661-668.



- In practice, storing only one space-time slab is advisable. That is, solve for as many time steps (say k time steps) as you have available memory for. Then move on to the next k time steps.

Overlapping communication and computation

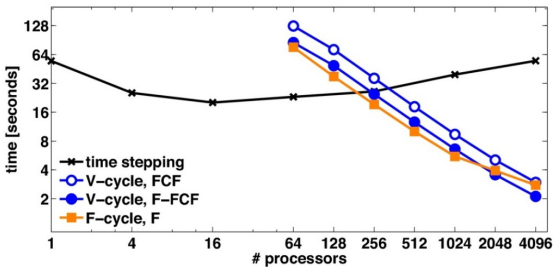
Warp effectively overlaps communication and computation. The main computation kernel of Warp is an F relaxation sweep, and each processor first posts a send at it's left-most C point, and then carries out F relaxation on its right-most interval. If each processor has multiple intervals at this Warp level, this should allow for complete overlap.



Properties of Warp

- Warp applies multigrid to the time dimension
  - Exposes concurrency in the time dimension
  - Potential for speedup is large, 10x, 100x, ...
- Non-intrusive approach, with unchanged time discretization defined by user
- Parallel time integration is only useful beyond some scale. This is evidenced by the experimental results below. For smaller numbers of cores sequential time stepping is faster, but at larger core counts Warp is much faster.
- The more time steps that you can parallelize over, the better your speedup.
- Warp is optimal for a variety of parabolic problems (see the examples).

Here is some experimental data for the 2D heat equation generated by the drive-02 example. Here, the speedup is



10x on a Linux cluster using 4 cores per node, a Sandybridge Intel chipset, and a fast Infiniband interconnect. The problem size was $129^2 \times 16,192$. The coarsening factor $m = 16$ on the finest level and 2 on coarser levels. And various relaxation and V and F cycling strategies are experimented with.

3 A Simple Example

User Defined Structures and Wrappers

As mentioned, the user must wrap their existing time stepping routine per the Warp interface. To do this, the user must define two data structures and some wrapper routines. To make the idea more concrete we give these function definitions from drive-01, which implements a scalar ODE, $u_t = \lambda u$.

The two data structures are:

1. **App**: This holds a wide variety of information and is `global` in that it is passed to every function. This structure holds everything that the user will need to carry out a simulation. Here, this is just the global MPI communicator and few values describing the temporal domain.
```
typedef struct _warp_App_struct
{
   MPI_Comm  comm;
   double    tstart;
   double    tstop;
   int       ntime;

} my_App;
```
2. **Vector**: this defines something like a state vector at a certain time value. It could contain any other information related to this vector needed to evolve the vector to the next time value, like mesh information.
```
typedef struct _warp_Vector_struct
{
   double value;

} my_Vector;
```

And, the user must define a few wrapper routines. The app structure is the first argument to every function.

1. **Phi**: this is the time stepping routine. The user must advance the vector u from time tstart to time tstop. Here advancing the solution just involves the scalar λ. The rfactor_ptr and accuracy inputs are advanced topics.

Importantly, the g_i function (from the Introduction) must be incorporated into Phi, so that $Phi(u_i) \rightarrow u_{i+1})$

```
int
my_Phi(warp_App     app,
       double       tstart,
       double       tstop,
       double       accuracy,
       warp_Vector  u,
       int         *rfactor_ptr)
{
   /* On the finest grid, each value is half the previous value */
   (u->value) = pow(0.5, tstop-tstart)*(u->value);

   /* Zero rhs for now */
   (u->value) += 0.0;

   /* no refinement */
   *rfactor_ptr = 1;

   return 0;
}
```

1. **Init**: initializes a vector at time t. Here that is just allocating and setting a scalar on the heap.
```
int
my_Init(warp_App     app,
        double       t,
        warp_Vector *u_ptr)
{
   my_Vector *u;
```

```
   u = (my_Vector *) malloc(sizeof(my_Vector));
   if (t == 0.0)
   {
      /* Initial guess */
      (u->value) = 1.0;
   }
   else
   {
      /* Random between 0 and 1 */
      (u->value) = ((double)rand()) / RAND_MAX;
   }
   *u_ptr = u;

   return 0;
}
```

2. **Clone**: clones a vector into a new vector

```
int
my_Clone(warp_App     app,
         warp_Vector  u,
         warp_Vector *v_ptr)
{
   my_Vector *v;

   v = (my_Vector *) malloc(sizeof(my_Vector));
   (v->value) = (u->value);
   *v_ptr = v;

   return 0;
}
```

3. **Free**: frees a vector

```
int
my_Free(warp_App    app,
        warp_Vector u)
{
   free(u);

   return 0;
}
```

4. **Sum**: sums two vectors (AXPY operation)

```
int
my_Sum(warp_App    app,
       double      alpha,
       warp_Vector x,
       double      beta,
       warp_Vector y)
{
   (y->value) = alpha*(x->value) + beta*(y->value);

   return 0;
}
```

5. **Dot**: takes the dot product of two vectors

```
int
my_Dot(warp_App     app,
       warp_Vector  u,
       warp_Vector  v,
       double      *dot_ptr)
{
   double dot;

   dot = (u->value)*(v->value);
   *dot_ptr = dot;

   return 0;
}
```

6. **Write**: writes a vector to screen, file, etc... The user defines what is appropriate output. Notice how you are told the time value of the vector u and even more information in status. This lets you tailor the output to only outputting certain time values and even from various Warp levels and Warp iterations if status is querried.

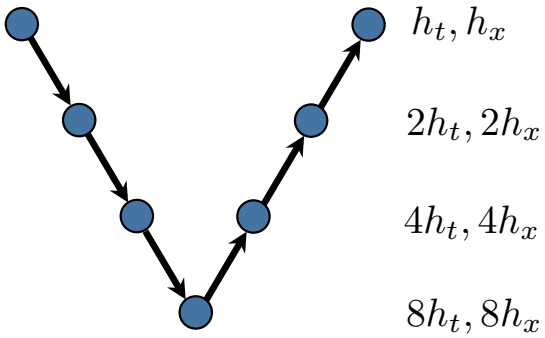
```
int
my_Write(warp_App     app,
         double       t,
         warp_Status  status,
         warp_Vector  u)
{
   MPI_Comm   comm   = (app->comm);
   double     tstart = (app->tstart);
   double     tstop  = (app->tstop);
   int        ntime  = (app->ntime);
   int        index, myid;
   char       filename[255];
   FILE      *file;

   index = ((t-tstart) / ((tstop-tstart)/ntime) + 0.1);

   MPI_Comm_rank(comm, &myid);

   sprintf(filename, "%s.%07d.%05d", "drive-01.out", index, myid);
   file = fopen(filename, "w");
   fprintf(file, "%.14e\n", (u->value));
   fflush(file);
   fclose(file);

   return 0;
}
```

7. **BufSize**, **BufPack**, **BufUnpack**: packs a vector into a `void *` buffer for MPI and then unpacks it from `void *` to vector. Here doing that for a scalar is trivial.

```
int
my_BufSize(warp_App  app,
           int      *size_ptr)
{
   *size_ptr = sizeof(double);
   return 0;
}

int
my_BufPack(warp_App     app,
           warp_Vector  u,
           void        *buffer)
{
   double *dbuffer = buffer;

   dbuffer[0] = (u->value);

   return 0;
}

int
my_BufUnpack(warp_App     app,
             void        *buffer,
             warp_Vector *u_ptr)
{
   double    *dbuffer = buffer;
   my_Vector *u;

   u = (my_Vector *) malloc(sizeof(my_Vector));
   (u->value) = dbuffer[0];
   *u_ptr = u;

   return 0;
}
```

8. **Coarsen**, **Restrict** (optional): advanced option that allows for coarsening in space while you coarsen in time.

This is useful for maintaining stable explicit schemes on coarse time scales and is not needed here. See for instance drive-04 and drive-05 which use these routines.
These functions allow you vary the spatial mesh size on Warp levels as depicted here



9. Adaptive, variable time stepping is in the works to be implemented. The rfactor parameter in Phi will allow this.

Running Warp

A typical flow in the `main` function to use Warp is to first initialize the app structure

```
/* set up app structure */
app = (my_App *) malloc(sizeof(my_App));
(app->comm)   = comm;
(app->tstart) = tstart;
(app->tstop)  = tstop;
(app->ntime)  = ntime;
```

then the data structure definitions and wrapper routines are passed to Warp

```
warp_Core  core;
warp_Init(MPI_COMM_WORLD, comm, tstart, tstop, ntime, app,
          my_Phi, my_Init, my_Clone, my_Free, my_Sum, my_Dot, my_Write,
          my_BufSize, my_BufPack, my_BufUnpack,
          &core);
```

then Warp options can be set

```
warp_SetPrintLevel( core, 1);
warp_SetMaxLevels(core, max_levels);
warp_SetNRelax(core, -1, nrelax);
warp_SetAbsTol(core, tol);
warp_SetCFactor(core, -1, cfactor);
warp_SetMaxIter(core, max_iter);
```

then the simulation is run

```
warp_Drive(core);
```

then we clean up

```
warp_Destroy(core);
```

see drive-01 and drive-0$*$ for more extensive examples.

Testing Warp

The best overall test for Warp, is to set MaxLevels to 1 which will carry out a sequential time stepping test. Take the output given to you by your Write function and compare it to output from a non-Warp run. Is everything OK? Repeat this test for multilevel Warp.

To do sanity checks of your data structures and wrapper routines, there are also Warp test functions, which can be easily run. The test routines also take as arguments the app structure, spatial communicator comm_x, a stream like stdout for test output and a time step size to test dt. After these arguments, function pointers to wrapper routines are the rest of the arguments. Some of the tests can return a boolean variable to indicate correctness.

```
/* Test init(), write(), free() */
warp_TestInitWrite( app, comm_x, stdout, dt, my_Init, my_Write, my_Free);

/* Test clone() */
warp_TestClone( app, comm_x, stdout, dt, my_Init, my_Write, my_Free, my_Clone);

/* Test sum() */
warp_TestSum( app, comm_x, stdout, dt, my_Init, my_Write, my_Free, my_Clone, my_Sum);

/* Test dot() */
correct = warp_TestDot( app, comm_x, stdout, dt, my_Init, my_Free, my_Clone, my_Sum, my_Dot);

/* Test bufsize(), bufpack(), bufunpack() */
correct = warp_TestBuf( app, comm_x, stdout, dt, my_Init, my_Free, my_Sum, my_Dot, my_BufSize, my_BufPack, my_Buf

/* Test coarsen and refine */
correct = warp_TestCoarsenRefine(app, comm_x, stdout, 0.0, dt, 2*dt, my_Init,
                      my_Write, my_Free, my_Clone, my_Sum, my_Dot, my_CoarsenInjection,
                      my_Refine);
correct = warp_TestCoarsenRefine(app, comm_x, stdout, 0.0, dt, 2*dt, my_Init,
                     my_Write, my_Free, my_Clone, my_Sum, my_Dot, my_CoarsenBilinear,
                     my_Refine);
```

4 Building Warp

- To specify the compilers, flags and options for your machine, edit makefile.inc. For now, we keep it simple and avoid using configure or cmake.
- To make the library, libwarp.a,
  ```
  $ make
  ```
- To make the examples
  ```
  $ make all
  ```
- The makefile lets you pass some parameters like debug with
  ```
  $ make debug=yes
  ```
  or
  ```
  $ make all debug=yes
  ```
  It would also be easy to add additional parameters, e.g., to compile with insure.
- To set compilers and library locations, look in makefile.inc where you can set up an option for your machine to define simple stuff like
  CC = mpicc MPICC = mpicc MPICXX = mpiCC LFLAGS = -lm

5 Compiling the examples

- Type
  drive-0∗ -help

for instructions on how to run any driver

- To run the examples
  mpirun -np 4 drive-∗ [args]
- drive-01 is the simplest example. It implements a scalar ODE and can be compiled and run with no outside dependencies.
- drive-02 implements the 2D heat equation on a regular grid. You must have hypre installed and these variables in the Makefile set correctly
```
HYPRE_DIR = ../../linear_solvers/hypre
HYPRE_FLAGS = -I$(HYPRE_DIR)/include
HYPRE_LIB = -L$(HYPRE_DIR)/lib -lHYPRE
```
- drive-03 implements the 3D heat equation on a regular grid, and assumes hypre is installed just like drive-02.
- drive-05 implements the 2D heat equation on a regular grid, but it uses with spatial coarsening. This allows you to use explicit time stepping on each Warp level, regardless of time step size. It assumes hypre is installed just like drive-02.
- drive-04 is sophisticated test bed for various PDEs, mostly parabolic. It relies on the mfem package to create general finite element discretizations for the spatial problem. Other packages must be installed in this order.
  - Unpack and install Metis
  - Unpack and install hypre
  - Unpack and install mfem. Make the serial version of mfem first by only typing make. Then make sure to set these variables correctly in the Makefile
    USE_METIS_5 = YES HYPRE_DIR = where_ever_linear_solvers_is/hypre
  - Make GLVIS, which needs serial mfem.
  - Go back to mfem
```
make clean
make parallel
```
  - Got to warp/examples and set these Makefile variables, and them make drive-04.
```
METIS_DIR = ../../metis-5.1.0/lib
MFEM_DIR = ../../mfem
MFEM_FLAGS = -I$(MFEM_DIR)
MFEM_LIB = -L$(MFEM_DIR) -lmfem -L$(METIS_DIR) -lmetis
```
- To run drive-04 and glvis, open two windows. In one, start a glvis session
```
./glvis
```
  Then, in the other window, run drive-04
```
mpirun -np ... drive-04 [args]
```

6 File Index

6.1 File List

Here is a list of all files with brief descriptions:

7 File Documentation

7.1 warp.h File Reference

Typedefs

- typedef int warp_Int
- typedef double warp_Real
- typedef struct _warp_App_struct * warp_App
- typedef struct _warp_Vector_struct * warp_Vector
- typedef struct _warp_Status_struct * warp_Status
- typedef warp_Int(* warp_PtFcnPhi)(warp_App app, warp_Real tstart, warp_Real tstop, warp_Real accuracy, warp_Vector u, warp_Int *rfactor_ptr)
- typedef warp_Int(* warp_PtFcnInit)(warp_App app, warp_Real t, warp_Vector *u_ptr)
- typedef warp_Int(* warp_PtFcnClone)(warp_App app, warp_Vector u, warp_Vector *v_ptr)
- typedef warp_Int(* warp_PtFcnFree)(warp_App app, warp_Vector u)
- typedef warp_Int(* warp_PtFcnSum)(warp_App app, warp_Real alpha, warp_Vector x, warp_Real beta, warp_Vector y)
- typedef warp_Int(* warp_PtFcnDot)(warp_App app, warp_Vector u, warp_Vector v, warp_Real *dot_ptr)
- typedef warp_Int(* warp_PtFcnWrite)(warp_App app, warp_Real t, warp_Status status, warp_Vector u)
- typedef warp_Int(* warp_PtFcnBufSize)(warp_App app, warp_Int *size_ptr)
- typedef warp_Int(* warp_PtFcnBufPack)(warp_App app, warp_Vector u, void *buffer)
- typedef warp_Int(* warp_PtFcnBufUnpack)(warp_App app, void *buffer, warp_Vector *u_ptr)
- typedef warp_Int(* warp_PtFcnCoarsen)(warp_App app, warp_Real tstart, warp_Real f_tminus, warp_Real f_tplus, warp_Real c_tminus, warp_Real c_tplus, warp_Vector fu, warp_Vector *cu_ptr)
- typedef warp_Int(* warp_PtFcnRefine)(warp_App app, warp_Real tstart, warp_Real f_tminus, warp_Real f_tplus, warp_Real c_tminus, warp_Real c_tplus, warp_Vector cu, warp_Vector *fu_ptr)
- typedef struct _warp_Core_struct * warp_Core

Functions

- warp_Int warp_Init (MPI_Comm comm_world, MPI_Comm comm, warp_Real tstart, warp_Real tstop, warp_Int ntime, warp_App app, warp_PtFcnPhi phi, warp_PtFcnInit init, warp_PtFcnClone clone, warp_PtFcnFree free, warp_PtFcnSum sum, warp_PtFcnDot dot, warp_PtFcnWrite write, warp_PtFcnBufSize bufsize, warp_PtFcnBufPack bufpack, warp_PtFcnBufUnpack bufunpack, warp_Core *core_ptr)
- warp_Int warp_Drive (warp_Core core)
- warp_Int warp_Destroy (warp_Core core)
- warp_Int warp_PrintStats (warp_Core core)
- warp_Int warp_SetLoosexTol (warp_Core core, warp_Int level, warp_Real loose_tol)
- warp_Int warp_SetTightxTol (warp_Core core, warp_Int level, warp_Real tight_tol)
- warp_Int warp_SetMaxLevels (warp_Core core, warp_Int max_levels)
- warp_Int warp_SetMaxCoarse (warp_Core core, warp_Int max_coarse)
- warp_Int warp_SetAbsTol (warp_Core core, warp_Real atol)
- warp_Int warp_SetRelTol (warp_Core core, warp_Real rtol)
- warp_Int warp_SetNRelax (warp_Core core, warp_Int level, warp_Int nrelax)
- warp_Int warp_SetCFactor (warp_Core core, warp_Int level, warp_Int cfactor)
- warp_Int warp_SetMaxIter (warp_Core core, warp_Int max_iter)
- warp_Int warp_SetFMG (warp_Core core)
- warp_Int warp_SetNFMGVcyc (warp_Core core, warp_Int nfmg_Vcyc)
- warp_Int warp_SetSpatialCoarsen (warp_Core core, warp_PtFcnCoarsen coarsen)
- warp_Int warp_SetSpatialRefine (warp_Core core, warp_PtFcnRefine refine)
- warp_Int warp_SetPrintLevel (warp_Core core, warp_Int print_level)
- warp_Int warp_SetPrintFile (warp_Core core, const char *printfile_name)

- warp_Int warp_SetWriteLevel (warp_Core core, warp_Int write_level)
- warp_Int warp_SplitCommworld (const MPI_Comm *comm_world, warp_Int px, MPI_Comm *comm_x, MPI_Comm *comm_t)
- warp_Int warp_GetStatusResidual (warp_Status status, warp_Real *rnorm_ptr)
- warp_Int warp_GetStatusIter (warp_Status status, warp_Int *iter_ptr)
- warp_Int warp_GetStatusLevel (warp_Status status, warp_Int *level_ptr)
- warp_Int warp_GetStatusDone (warp_Status status, warp_Int *done_ptr)
- warp_Int warp_GetNumIter (warp_Core core, warp_Int *niter_ptr)
- warp_Int warp_GetRNorm (warp_Core core, warp_Real *rnorm_ptr)

7.1.1 Detailed Description

Define headers for user interface routines. This file contains routines used to allow the user to initialize, run and get and set warp.

7.1.2 Typedef Documentation

7.1.2.1 typedef struct _warp_App_struct* warp_App

Blah...

7.1.2.2 typedef struct _warp_Core_struct* warp_Core

Points to the core structure defined in _warp.h

7.1.2.3 typedef int warp_Int

7.1.2.4 typedef warp_Int(* warp_PtFcnBufPack)(warp_App app, warp_Vector u, void *buffer)

Blah...

7.1.2.5 typedef warp_Int(* warp_PtFcnBufSize)(warp_App app, warp_Int *size_ptr)

Blah...

7.1.2.6 typedef warp_Int(* warp_PtFcnBufUnpack)(warp_App app, void *buffer, warp_Vector *u_ptr)

Blah...

7.1.2.7 typedef warp_Int(* warp_PtFcnClone)(warp_App app, warp_Vector u, warp_Vector *v_ptr)

Blah...

7.1.2.8 typedef warp_Int(* warp_PtFcnCoarsen)(warp_App app, warp_Real tstart, warp_Real f_tminus, warp_Real f_tplus, warp_Real c_tminus, warp_Real c_tplus, warp_Vector fu, warp_Vector *cu_ptr)

(Optional) Blah...

7.1.2.9 typedef warp_Int(* warp_PtFcnDot)(warp_App app, warp_Vector u, warp_Vector v, warp_Real *dot_ptr)

Blah...

7.1.2.10 typedef warp_Int(* warp_PtFcnFree)(warp_App app, warp_Vector u)

Blah...

7.1.2.11 typedef warp_Int(* warp_PtFcnInit)(warp_App app, warp_Real t, warp_Vector *u_ptr)

Blah...

7.1.2.12 typedef warp_Int(* warp_PtFcnPhi)(warp_App app, warp_Real tstart, warp_Real tstop, warp_Real accuracy, warp_Vector u, warp_Int *rfactor_ptr)

Blah...

7.1.2.13 typedef warp_Int(* warp_PtFcnRefine)(warp_App app, warp_Real tstart, warp_Real f_tminus, warp_Real f_tplus, warp_Real c_tminus, warp_Real c_tplus, warp_Vector cu, warp_Vector *fu_ptr)

(Optional) Blah...

7.1.2.14 typedef warp_Int(* warp_PtFcnSum)(warp_App app, warp_Real alpha, warp_Vector x, warp_Real beta, warp_Vector y)

Blah...

7.1.2.15 typedef warp_Int(* warp_PtFcnWrite)(warp_App app, warp_Real t, warp_Status status, warp_Vector u)

Blah...

7.1.2.16 typedef double warp_Real

7.1.2.17 typedef struct _warp_Status_struct* warp_Status

Points to the status structure defined in _warp.h

7.1.2.18 typedef struct _warp_Vector_struct* warp_Vector

Blah...

7.1.3 Function Documentation

7.1.3.1 warp_Int warp_Destroy (warp_Core *core*)

Destroy core.

7.1.3.2 warp_Int warp_Drive (warp_Core *core*)

Integrate in time.

7.1.3.3 warp_Int warp_GetNumIter (warp_Core *core,* warp_Int * *niter_ptr*)

After Drive() finishes, this returns the number of iterations taken

7.1.3.4 warp_Int warp_GetRNorm (warp_Core *core,* warp_Real * *rnorm_ptr*)

After Drive() finishes, this returns the last measured residual norm

7.1.3.5 warp_Int warp_GetStatusDone (warp_Status *status,* warp_Int * *done_ptr*)

Return whether warp is done for the current status object

7.1.3.6 warp_Int warp_GetStatusIter (warp_Status *status,* warp_Int * *iter_ptr*)

Return the iteration for the current status object

7.1.3.7 warp_Int warp_GetStatusLevel (warp_Status *status,* warp_Int * *level_ptr*)

Return the warp level for the current status object

7.1.3.8 warp_Int warp_GetStatusResidual (warp_Status *status,* warp_Real * *rnorm_ptr*)

Return the residual for the current status object

7.1.3.9 warp_Int warp_Init (MPI_Comm *comm_world,* MPI_Comm *comm,* warp_Real *tstart,* warp_Real *tstop,* warp_Int *ntime,* warp_App *app,* warp_PtFcnPhi *phi,* warp_PtFcnInit *init,* warp_PtFcnClone *clone,* warp_PtFcnFree *free,* warp_PtFcnSum *sum,* warp_PtFcnDot *dot,* warp_PtFcnWrite *write,* warp_PtFcnBufSize *bufsize,* warp_PtFcnBufPack *bufpack,* warp_PtFcnBufUnpack *bufunpack,* warp_Core * *core_ptr*)

Create a core object with the required initial data.

Output:

- *core_ptr* will point to the newly created warp_Core structure

Parameters

comm_world	Global communicator for space and time
comm	Communicator for temporal dimension
tstart	start time
tstop	End time
ntime	Initial number of temporal grid values
app	User defined structure to hold *state* information
phi	User time stepping routine to advance state one time value
init	Initialize a warp_Vector function on finest temporal grid
clone	Clone a warp_Vector
free	Free a temporal state warp_Vector
sum	Compute vector sum of two temporal states
dot	Compute dot product between two temporal states
write	*Writes* (file, screen..) upon completion.
bufsize	Computes size for MPI buffer for one
bufpack	Packs MPI buffer to contain one temporal state
bufunpack	Unpacks MPI buffer containing one temporal state
core_ptr	Pointer to warp_Core (_warp_Core) struct

7.1.3.10 warp_Int warp_PrintStats (warp_Core *core*)

Print statistics.

7.1.3.11 warp_Int warp_SetAbsTol (warp_Core *core,* warp_Real *atol*)

Set absolute stopping tolerance.

7.1.3.12 warp_Int warp_SetCFactor (warp_Core *core,* warp_Int *level,* warp_Int *cfactor*)

Set the coarsening factor *cfactor* on grid level *level* (level 0 is the finest grid). The default factor is 2 on all levels. To change the default factor, use *level* = -1.

7.1.3.13 warp_Int warp_SetFMG (warp_Core *core*)

Use FMG cycling.

7.1.3.14 warp_Int warp_SetLoosexTol (warp_Core *core,* warp_Int *level,* warp_Real *loose_tol*)

Set loose stopping tolerance for spatial solves on grid level *level* (level 0 is the finest grid).

7.1.3.15 warp_Int warp_SetMaxCoarse (warp_Core *core,* warp_Int *max_coarse*)

Set max allowed coarse grid size (in terms of C-points)

7.1.3.16 warp_Int warp_SetMaxIter (warp_Core *core,* warp_Int *max_iter*)

Set max number of multigrid iterations.

7.1.3.17 warp_Int warp_SetMaxLevels (warp_Core *core,* warp_Int *max_levels*)

Set max number of multigrid levels.

7.1.3.18 warp_Int warp_SetNFMGVcyc (warp_Core *core,* warp_Int *nfmg_Vcyc*)

Set number of V cycles to use at each FMG level (standard is 1)

7.1.3.19 warp_Int warp_SetNRelax (warp_Core *core,* warp_Int *level,* warp_Int *nrelax*)

Set the number of relaxation sweeps *nrelax* on grid level *level* (level 0 is the finest grid). The default is 1 on all levels. To change the default factor, use *level* = -1.

7.1.3.20 warp_Int warp_SetPrintFile (warp_Core *core,* const char * *printfile_name*)

Set output file for print level messages. Default is stdout.

7.1.3.21 warp_Int warp_SetPrintLevel (warp_Core *core,* warp_Int *print_level*)

Set print level for warp. This controls how much information is printed to standard out.

Level 0: no output Level 1: print typical information like a residual history, number of levels in the Warp hierarchy, and so on. Level 2: level 1 output, plus debug level output.

Default is level 1.

7.1.3.22 warp_Int warp_SetRelTol (warp_Core *core,* warp_Real *rtol*)

Set absolute stopping tolerance.

7.1.3.23 warp_Int warp_SetSpatialCoarsen (warp_Core *core,* warp_PtFcnCoarsen *coarsen*)

Set spatial coarsening routine with user-defined routine. Default is no spatial refinment or coarsening.

7.1.3.24 warp_Int warp_SetSpatialRefine (warp_Core *core,* warp_PtFcnRefine *refine*)

Set spatial refinement routine with user-defined routine. Default is no spatial refinment or coarsening.

7.1.3.25 warp_Int warp_SetTightxTol (warp_Core *core,* warp_Int *level,* warp_Real *tight_tol*)

Set tight stopping tolerance for spatial solves on grid level *level* (level 0 is the finest grid).

7.1.3.26 warp_Int warp_SetWriteLevel (warp_Core *core*, warp_Int *write_level*)

Set write level for warp. This controls how often the user's write routine is called.

Level 0: Never call the user's write routine Level 1: Only call the user's write routine after Warp is finished Level 2: Call the user's write routine every iteration in _warp_FRestrict(), which is during the down-cycle part of a Warp iteration

Default is level 1.

7.1.3.27 warp_Int warp_SplitCommworld (const MPI_Comm * *comm_world*, warp_Int *px*, MPI_Comm * *comm_x*, MPI_Comm * *comm_t*)

Split MPI commworld into comm_x and comm_t, the spatial and temporal communicators

Parameters

comm_world	Global communicator to split
px	Number of processors parallelizing space for a single time step
comm_x	Spatial communicator (written as output)
comm_t	Temporal communicator (written as output)

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