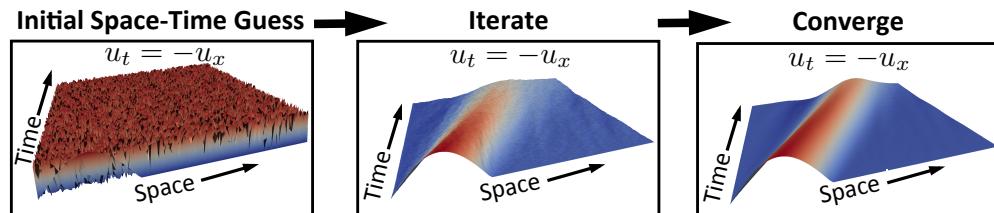


# $\chi$ Braid

Time-Braid: Multigrid in Time Solvers



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This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. LLNL\*\*\*\*\*

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## 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 also read [Parallel Time Integration with Multigrid](#) after reading the [Overview of the  \$\chi\$ Braid Algorithm](#). It is a more in depth discussion of the algorithm and associated experiments.

## 2 Introduction

### 2.1 Meaning of the name

We chose the package name  $\chi$ Braid to stand for *Time-Braid*, where X is the first letter in the Greek work for time, *Chronos*. The algorithm *braids* together time-grids of different granularity in order to create a multigrid method and achieve parallelism in the time dimension. In plain text, we say  $\chi$ Braid, or just Braid for short.

### 2.2 Overview of the $\chi$ Braid Algorithm

The goal of  $\chi$ Braid is to solve a problem faster than a traditional time marching algorithm. Instead of sequential time marching,  $\chi$ Braid solves the problem iteratively by simultaneously updating a space-time 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 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. Thus, a problem with many time steps (thousands, tens of thousands or more) can be solved with 10 or 15  $\chi$ Braid iterations, and the overall time to solution can be greatly sped up. However, this is achieved at the cost of more computational resources.

To understand how  $\chi$ Braid 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 initial condition is a wave, and this wave propagates sequentially across space as time increases.

$\chi$ Braid instead begins with a solution guess over all of space-time, which for demonstration, we let be random. A  $\chi$ Braid iteration then does

1. Relaxation on the fine grid, i.e., the grid that contains all of the desired time values

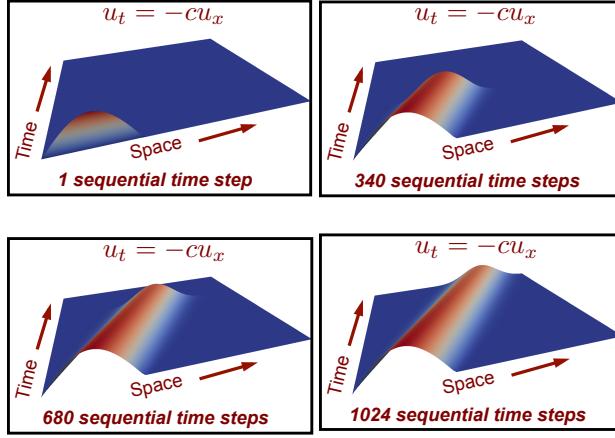


Figure 1: Sequential time stepping.

- Relaxation is just a local application of the time stepping scheme, e.g., backward Euler
- 2. Restriction to the first coarse grid, i.e., interpolate the problem to 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

One  $\chi$ Braid iteration is called a *cycle* and these cycles continue until the the solution is accurate enough. This is depicted in the next figure, where only a few iterations are required for this simple problem.

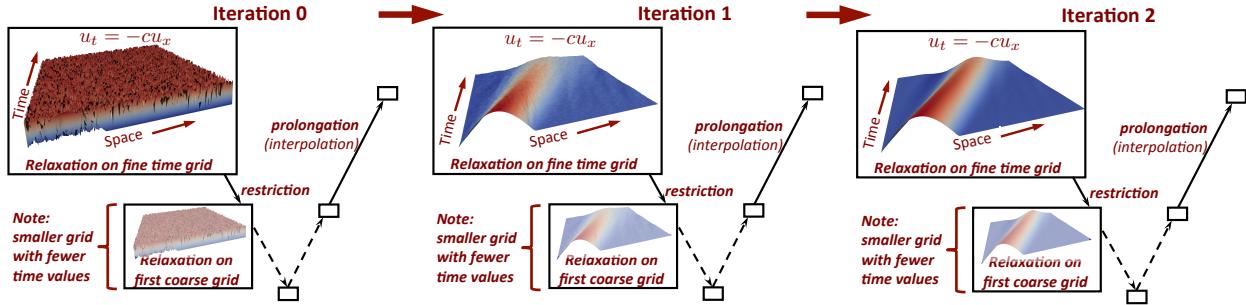


Figure 2:  $\chi$  Braid iterations.

There are a few important points to make.

- The coarse time grids allow for global propagation of information across space-time with only one  $\chi$ Braid iteration. This is visible in the above figure by observing 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  $\chi$ Braid iterations are required to find the solution over 1024 time steps. Therefore if enough processors are available to parallelize  $\chi$ Braid, we can see a speedup over traditional time stepping (more on this later).
- This is a simple example, with evenly space time steps.  $\chi$ Braid is structured to handle variable time step sizes and adaptive time step sizes, and these features will be coming.

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 discretize with the one-step integration

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

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

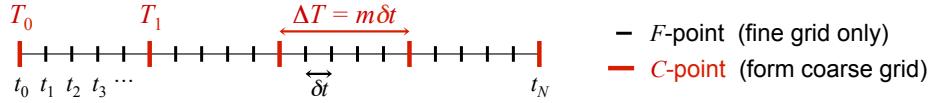
$$A\mathbf{u} = \mathbf{g}.$$

This process is optimal and  $O(N)$ , but it is sequential.  $\chi$ Braid instead solves the system iteratively, with a multigrid reduction method<sup>1</sup> applied in only the time dimension. This approach is

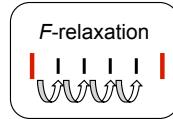
- nonintrusive, in that it coarsens only in time and the user defines  $\Phi$ 
  - Thus, users can continue using existing time stepping codes by wrapping them into our framework.
- optimal and  $O(N)$ , but  $O(N)$  with a higher constant than time stepping
  - Thus with enough computational resources,  $\chi$ Braid will outperform sequential time stepping.
- highly parallel

$\chi$ Braid 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  $\Phi$  is constant for notational simplicity.

$\chi$ Braid 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. The first task is relaxation and an effective relaxation alternates between C and F sweeps (this is like



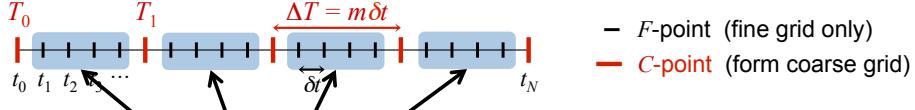
line-relaxation in space in that the residual is set to 0 for an entire time step). An F sweep simply updates time values by integrating with  $\Phi$  over all the F-points from one C-point to the next, as depicted next.



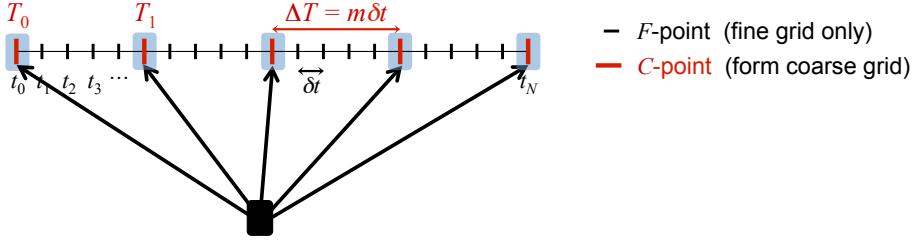
But, such an update can be done simultaneously over all F intervals in parallel, as depicted next.

Following an F sweep we can also do C sweep, as depicted next.

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



- Update all F-points using time propagator  $\Phi$



- Update all C-points using time propagator  $\Phi$

In general, FCF- and F-relaxation will refer to the relaxation methods used in  $\chi$ Braid. We can say

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

After relaxation, comes coarse grid correction. The restriction operator  $R$  maps fine grid quantities 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.  $\chi$ Braid implements an FAS (Full Approximation Scheme) multigrid cycle, and hence the solution guess and residual (i.e.,  $A, \mathbf{u}, \mathbf{g} - A\mathbf{u}$ ) are restricted. This is in contrast to linear multigrid which typically restricts only the residual equation to the coarse grid. We choose FAS because it is *nonlinear* multigrid and allows us to solve nonlinear problems. FAS was invented by Achi Brandt, but this [PDF](#) by Van Henson is a good intro.

The main question here is how to form the coarse grid matrix, which in turn asks how to define the coarse grid time stepper  $\Phi_\Delta$ . It is typical to let  $\Phi_\Delta$  simply be  $\Phi$  but with the coarse time step size  $\Delta T = m\delta t$ . Thus if

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

then

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

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

$$A_\Delta \mathbf{v}_\Delta = \mathbf{g}_\Delta$$

is then solved, where the right-hand-side is defined by FAS (see [Two-Grid Algorithm](#)). Finally, FAS defines a coarse grid error approximation  $\mathbf{e}_\Delta$ , which is interpolated with  $P_\Phi$  back to the fine grid and added to the current solution guess. Interpolation is equivalent to injecting the coarse grid to the C-points on the fine grid, followed 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  $m$  is the coarsening factor.

### 2.2.1 Two-Grid Algorithm

This two-grid process is captured with this algorithm. Using a recursive coarse grid solve (i.e., step 3 becomes a recursive call) makes the process multilevel. 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 a function below, whereas the above 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:  $\mathbf{u}_\Delta \leftarrow R\mathbf{u}$ ,  $\mathbf{r}_\Delta \leftarrow R(\mathbf{g} - A(\mathbf{u}))$
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:  $\mathbf{u} \leftarrow \mathbf{u} + P\mathbf{e}_\Delta$

*Caveat:* The  $\chi$ Braid implementation of FAS differs slightly from standard FAS. In standard FAS, the error is interpolated to the fine points on the fine grid (here F-points). Instead, given our interpolation operator  $P_\Phi$ , we add the error to the coarse points on the fine grid (here C-points), and then propagate the *solution* to F-points, like in a reduction method. Thus, F-points are updated in a slightly different, but more exact manner. This strategy allows  $\chi$ Braid to save on storage and to not store F-points, while still effectively solving nonlinear problems.

### 2.2.2 Summary

In summary, a few points are

- $\chi$ Braid is an iterative solver for the global space-time problem.
- The user defines the time stepping routine  $\Phi$  and can wrap existing code to accomplish this.
- $\chi$ Braid convergence will depend heavily on how well  $\Phi_\Delta$  approximates  $\Phi^m$ , 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  $\delta t$ . This is a subject of research, but this approximation need not capture fine scale behavior, which is instead captured by relaxation on the fine grid.
- The coarsest grid is solved exactly, i.e., sequentially, which can be a bottleneck for two-level methods like Parareal,<sup>2</sup> but not for a multilevel scheme like  $\chi$ Braid 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 is ideal or exact, in that an application of interpolation leaves a zero residual at all F-points.
- The process is applied recursively until a trivially sized temporal grid is reached, e.g., 2 or 3 time points. Thus, the coarsening rate  $m$  determines how many levels there are in the hierarchy. For instance in this figure, a 3 level hierarchy is shown. Three levels are chosen because there are six time points,  $m = 2$  and  $m^2 < 6 \leq m^3$ . If the coarsening rate had been  $m = 4$  then there would only be two levels because, there would be no more points to coarsen!
  - F-point (fine grid only)
  - C-point (coarse grid)

```

Level 0: |---|---|---|---|---|
Level 1: |---|---|---|
Level 2: |---|---|

```

By default,  $\chi$ Braid will subdivide the time domain into evenly sized time steps.  $\chi$ Braid is structured to handle variable time step sizes and adaptive time step sizes, and these features are coming.

## 2.3 Overview of the $\chi$ Braid Code

$\chi$ Braid 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  $\Phi$  that can evolve a solution from one time value to another, regardless of time step size. After this is done, the  $\chi$ Braid code takes care of the parallelism in the time dimension.

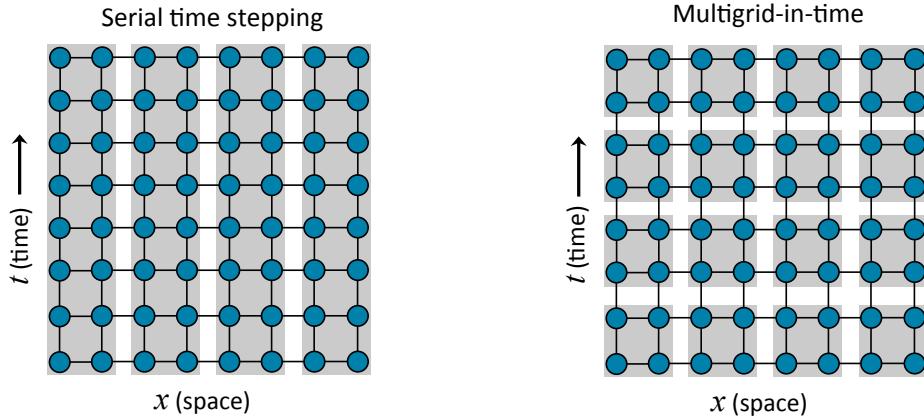
### $\chi$ Braid

- is written in C and can easily interface with Fortran and C++
- uses MPI for parallelism
- self documents through comments in the source code and through \*.md files
- functions and structures are prefixed by *braid*
  - User routines are prefixed by `braid_`
  - Developer routines are prefixed by `_braid_`

#### 2.3.1 Parallel decomposition and memory

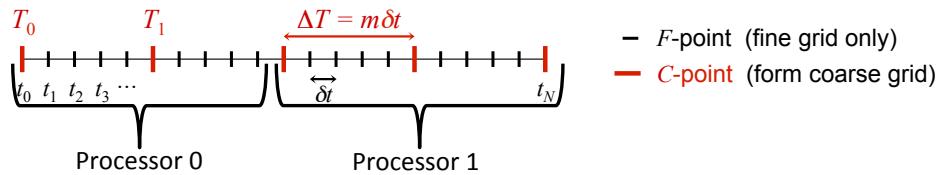
- $\chi$ Braid decomposes the problem in parallel as depicted next. As you can see, traditional time stepping only

<sup>2</sup> Lions, J., Yvon Maday, and Gabriel Turinici. "A"parareal"in time discretization of PDE's." Comptes Rendus de l'Academie des Sciences Series I



stores one time step at a time, but only enjoys a spatial data decomposition and spatial parallelism. On the other hand,  $\chi$ Braid stores multiple time steps simultaneously and each processor holds a space-time chunk reflecting both the spatial and temporal parallelism.

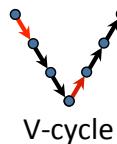
- $\chi$ Braid only handles temporal parallelism and is agnostic to the spatial decomposition. See [braid\\_Split-Commworld](#). Each processor owns a certain number of CF intervals of points, as depicted next, where each processor owns 2 CF intervals.  $\chi$ Braid distributes Intervals evenly on the finest grid.



- Storage is greatly minimized by only storing 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 in the previous figure. Coarsening can be aggressive with  $m = 8, 16, 32$ , so the storage requirements of  $\chi$ Braid are significantly reduced when compared to storing all of the time values.  
By only storing data at C-points, we effect a subtle change to the standard FAS algorithm (see [Two-Grid Algorithm](#)).
- 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.

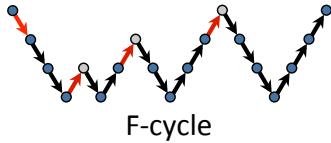
### 2.3.2 Cycling and relaxation strategies

There are two main cycling strategies available in  $\chi$ Braid, F-and V-cycles. These two cycles differ in how often and the order in which coarse levels are visited. A V-cycle is depicted next, and is a simple recursive application of the [Two-Grid Algorithm](#).



An F-cycle visits coarse grids more frequently and in a different order. Essentially, an F-cycle uses a V-cycle as the post-smoother, which is an expensive choice for relaxation. But, this extra work gives you a closer approximation to a

two-grid cycle, and a faster convergence rate at the extra expense of more work. The effectiveness of a V-cycle as a relaxation scheme can be seen in Figure 2, where one V-cycle globally propagates and *smoothes* the error. The cycling strategy of an F-cycle is depicted next.



Next, we make a few points about F- versus V-cycles.

- One V-cycle iteration is cheaper than one F-cycle iteration.
- But, F-cycles often converge more quickly. For some test cases, this difference can be quite large. The cycle choice for the best time to solution will be problem dependent. See [Heat equation example](#) for a case study of cycling strategies.

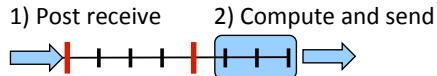
The number of FC relaxation sweeps is another important algorithmic setting. Note that at least one F-relaxation sweep is always done on a level. A few summary points about relaxation are as follows.

- Using FCF (or even FCFCF, FCFCFCF) relaxation, corresponding to passing `braid_SetNRelax` a value of 1, 2 or 3 respectively, will result in an  $\chi$ Braid cycle that converges more quickly as the number of relaxations grows.
- But as the number of relaxations grows, each  $\chi$ Braid cycle becomes more expensive. The optimal relaxation strategy for the best time to solution will be problem dependent.
- However, a good first step is to try FCF on all levels (i.e., `braid_SetNRelax(core, -1, 1)`).
- A common optimization is to first set FCF on all levels (i.e., `braid_setnrelax(core, -1, 1)`), but then overwrite the FCF option on level 0 so that only F-relaxation is done on level 0, (i.e., `braid_setnrelax(core, 0, 1)`). This strategy can work well with F-cycles.
- See [Heat equation example](#) for a case study of relaxation strategies.

Last, [Parallel Time Integration with Multigrid](#) has a more in depth case study of cycling and relaxation strategies

### 2.3.3 Overlapping communication and computation

$\chi$ Braid effectively overlaps communication and computation. The main computational kernel of  $\chi$ Braid is relaxation (C or F). At the start of each sweep, each processor first posts a send at its left-most point, and then carries out F-relaxation on its right-most interval in order to send the next processor the data that it needs. If each processor has multiple intervals at this  $\chi$ Braid level, this should allow for complete overlap.



### 2.3.4 Configuring the $\chi$ Braid Hierarchy

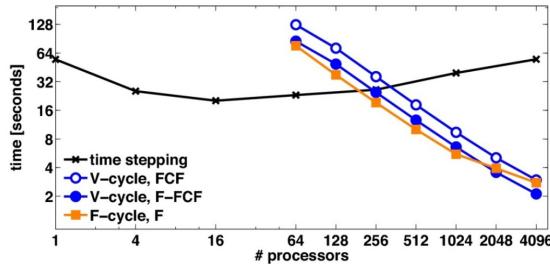
Some of the more basic  $\chi$ Braid function calls allow you to control aspects discussed here.

- `braid_SetFMG`: switches between using F- and V-cycles.

- `braid_SetMaxIter`: sets the maximum number of  $\chi$ Braid iterations
- `braid_SetCFactor`: sets the coarsening factor for any (or all levels)
- `braid_SetNRelax`: sets the number of CF-relaxation sweeps for any (or all levels)
- `braid_SetRelTol`, `braid_SetAbsTol`: sets the stopping tolerance
- `braid_SetMaxCoarse`: sets the maximum coarse grid size, in terms of C-points
- `braid_SetMaxLevels`: sets the maximum number of levels in the  $\chi$ Braid hierarchy

### 2.3.5 Heat equation example

Here is some experimental data for the 2D heat equation,  $u_t = u_{xx} + u_{yy}$  generated by examples/drive-02. The problem



setup is as follows.

- Backwards Euler is used as the time stepper.
- We used a Linux cluster with 4 cores per node, a Sandybridge Intel chipset, and a fast Infiniband interconnect.
- The space-time problem size was  $129^2 \times 16,192$  over the unit cube  $[0, 1] \times [0, 1] \times [0, 1]$ .
- The coarsening factor was  $m = 16$  on the finest level and  $m = 2$  on coarser levels.
- Since 16 processors optimized the serial time stepping approach, 16 processors in space are also used for the  $\chi$ Braid experiments. So for instance 512 processors in the plot corresponds to 16 processors in space and 32 processors in time,  $16 * 32 = 512$ . Thus, each processor owns a space-time hypercube of  $(129^2 / 16) \times (16,192 / 32)$ . See [Parallel decomposition and memory](#) for a depiction of how  $\chi$ Braid breaks the problem up.
- Various relaxation and V and F cycling strategies are experimented with.
  - *V-cycle, FCF* denotes V-cycles and FCF-relaxation on each level.
  - *V-cycle, F-FCF* denotes V-cycles and F-relaxation on the finest level and FCF-relaxation on all coarser levels.
  - *F-cycle, F* denotes F-cycles and F-relaxation on each level.
- The initial guess at time values for  $t > 0$  is zero, which is typical.

Regarding the performance, we can say

- The best speedup is 10x and this would grow if more processors were available.
- Although not shown, the iteration counts here are about 10-15  $\chi$ Braid iterations. See [Parallel Time Integration with Multigrid](#) for the exact iteration counts.
- At smaller core counts, serial time stepping is faster. But at about 256 processors, there is a crossover and  $\chi$ Braid is faster.
- You can see the impact of the cycling and relaxation strategies discussed in [Cycling and relaxation strategies](#). For instance, even though *V-cycle, F-FCF* is a weaker relaxation strategy than *V-cycle, FCF* (i.e., the  $\chi$ Braid

convergence is slower), *V-cycle*, *F-FCF* has a faster time to solution than *V-cycle*, *FCF* because each cycle is cheaper.

- In general, one level of aggressive coarsening (here by a factor 16) followed by slower coarsening was found to be best on this machine.

Achieving the best speedup can require some tuning, and it is recommended to read [Parallel Time Integration with Multigrid](#) where this 2D heat equation example is explored in much more detail.

## 2.4 Summary

- $\chi$ Braid applies multigrid to the time dimension.
  - This exposes concurrency in the time dimension.
  - The potential for speedup is large, 10x, 100x, ...
- This is a non-intrusive approach, with an 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  $\chi$ Braid is much faster.
- The more time steps that you can parallelize over, the better your speedup will be.
- $\chi$ Braid is optimal for a variety of parabolic problems (see the examples directory).

## 3 Example

### A Simple Example

#### User Defined Structures and Wrappers

As mentioned, the user must wrap their existing time stepping routine per the  $\chi$ Braid interface. To do this, the user must define two data structures and some wrapper routines. To make the idea more concrete, we now give these function definitions from examples/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 _braid_App_struct
{
    MPI_Comm    comm;
    double      tstart;
    double      tstop;
    int         ntime;

} my_App;
```

2. **Vector:** this defines (roughly) a state vector at a certain time value. It could also contain any other information related to this vector which is needed to evolve the vector to the next time value, like mesh information. Here, the vector is just a scalar double.

```
typedef struct _braid_Vector_struct
{
    double value;

} my_Vector;
```

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

1. **Phi:** This function tells  $\chi$ Braid how to take a time step, and is the core user routine. The user must advance the vector  $u$  from time  $t_{start}$  to time  $t_{stop}$ . Here advancing the solution just involves the scalar  $\lambda$ . The `rfactor_ptr` and `accuracy` parameters are advanced topics not used here.

**Importantly,** the  $g_i$  function (from [Overview of the  \$\chi\$ Braid Algorithm](#)) must be incorporated into Phi, so that  $\Phi(u_i) \rightarrow u_{i+1}$

```
int
my_Phi(braid_App      app,
        double       tstart,
        double       tstop,
        double       accuracy,
        braid_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;
}
```

2. **Init:** This function tells  $\chi$ Braid how to initialize a vector at time  $t$ . Here that is just allocating and setting a scalar on the heap.

```
int
my_Init(braid_App      app,
        double       t,
        braid_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;
}
```

3. **Clone:** This function tells  $\chi$ Braid how to clone a vector into a new vector.

```
int
my_Clone(braid_App      app,
          braid_Vector u,
          braid_Vector *v_ptr)
{
    my_Vector *v;

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

    return 0;
}
```

4. **Free:** This function tells  $\chi$ Braid how to free a vector.

```
int
my_Free(braid_App      app,
        braid_Vector u)
```

```
{
    free(u);

    return 0;
}
```

5. **Sum:** This function tells  $\chi$ Braid how to sum two vectors (AXPY operation).

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

    return 0;
}
```

6. **Dot:** This function tells  $\chi$ Braid how to take the dot product of two vectors.

```
int
my_Dot(braid_App      app,
        braid_Vector u,
        braid_Vector v,
        double      *dot_ptr)
{
    double dot;

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

    return 0;
}
```

7. **Write:** This function tells  $\chi$ Braid how to write a vector at time  $t$  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 certain time values.

If  $write\_level$  is 2 (see [braid\\_SetWriteLevel](#)), then  $Write$  is called every  $\chi$ Braid iteration and on every  $\chi$ Braid level. In this case,  $status$  can be queried using the [braid\\_Get\\*\\*Status\(\)](#) functions, to determine the current  $\chi$ Braid level and iteration. This allows for even more detailed tracking of the simulation.

See examples/drive-02 and examples/drive-04 for more advanced uses of the Write function. Drive-04 writes to a GLVIS visualization port, and examples/drive-02 writes to .vtu files.

```
int
my_Write(braid_App      app,
          double       t,
          braid_Status  status,
          braid_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, "%1.14e\n", (u->value));
    fflush(file);
    fclose(file);

    return 0;
}
```

8. **BufSize, BufPack, BufUnpack:** These three routines tell  $\chi$ Braid how to communicate vectors between processors. *BufPack* packs a vector into a `void *` buffer for MPI and then *BufUnPack* unpacks it from `void *` to vector. Here doing that for a scalar is trivial. *BufSize* computes the upper bound for the size of an arbitrary vector.

```

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

int
my_BufPack(braid_App app,
           braid_Vector u,
           void *buffer)
{
    double *dbuffer = buffer;

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

    return 0;
}

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

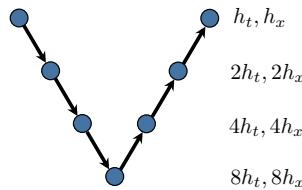
    u = (my_Vector *) malloc(sizeof(my_Vector));
    (u->value) = dbuffer[0];
    *u_ptr = u;

    return 0;
}

```

9. **Coarsen, Restrict** (optional): These are advanced options that allow 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 examples/drive-04 and examples/drive-05 which use these routines.

These functions allow you vary the spatial mesh size on  $\chi$ Braid levels as depicted here where the spatial and temporal grid sizes are halved every level.



10. Adaptive and variable time stepping is in the works to be implemented. The *rfactor* parameter in *Phi* will allow this.

### Running $\chi$ Braid

A typical flow of events in the `main` function 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->nitime) = nitime;

```

Then, the data structure definitions and wrapper routines are passed to  $\chi$ Braid. The core structure is used by  $\chi$ Braid for internal data structures.

```
braid_Core core;
braid_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,  $\chi$ Braid options are set.

```
braid_SetPrintLevel(core, 1);
braid_SetMaxLevels(core, max_levels);
braid_SetNRelax(core, -1, nrelax);
braid_SetAbsTol(core, tol);
braid_SetCFactor(core, -1, cfactor);
braid_SetMaxIter(core, max_iter);
```

Then, the simulation is run.

```
braid_Drive(core);
```

Then, we clean up.

```
braid_Destroy(core);
```

Finally, to run drive-01, type

```
drive-01 -ml 5
```

This will run drive-01. See examples/drive-0\* for more extensive examples.

### Testing $\chi$ Braid

The best overall test for  $\chi$ Braid, is to set the maximum number of levels to 1 (see [braid\\_SetMaxLevels](#) ) 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- $\chi$ Braid run. Is everything OK? Once this is complete, repeat for multilevel  $\chi$ Braid, and check that the solution is correct (that is, it matches a serial run to within tolerance).

At a lower level, to do sanity checks of your data structures and wrapper routines, there are also  $\chi$ Braid 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() */
braid_TestInitWrite( app, comm_x, stdout, dt, my_Init, my_Write, my_Free);

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

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

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

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

/* Test coarsen and refine */
correct = braid_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 = braid_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 Braid

- 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, libbraid.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 and running the examples

Type

```
drive-0* -help
```

for instructions on how to run any driver.

To run the examples, type

```
mpirun -np 4 drive-* [args]
```

1. drive-01 is the simplest example. It implements a scalar ODE and can be compiled and run with no outside dependencies.
2. drive-02 implements the 2D heat equation on a regular grid. You must have `hypre` installed and these variables in examples/Makefile set correctly  

```
HYPRE_DIR = ../../linear_solvers/hypre
HYPRE_FLAGS = -I$(HYPRE_DIR)/include
HYPRE_LIB = -L$(HYPRE_DIR)/lib -lHYPRE
```
3. drive-03 implements the 3D heat equation on a regular grid, and assumes `hypre` is installed just like drive-02.
4. drive-05 implements the 2D heat equation on a regular grid, but it uses spatial coarsening. This allows you to use explicit time stepping on each Braid level, regardless of time step size. It assumes `hypre` is installed just like drive-02.
5. drive-04 is a 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 mfem Makefile:  

```
USE_METIS_5 = YES
HYPRE_DIR = where_ever_linear_solvers_is/hypre
```
- Make `GLVIS`, which needs serial mfem. Set these variables in the glvis makefile  

```
MFEM_DIR = mfem_location
MFEM_LIB = -L$(MFEM_DIR) -lmfem
```

- Go back to the mfem directory and type  

```
make clean
make parallel
```
- Go to braid/examples and set these Makefile variables,  

```
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
```

then type  

```
make drive-04
```
- 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]
```

Glvis will listen on a port to which drive-04 will dump visualization information.

## 6 Coding Style

Code should follow the `ellemtel` style. See `braid/misc/sample_c_code.c`, and for emacs and vim style files, see `braid/misc/sample.vimrc`, and `braid/misc/sample.emacs`.

## 7 Using Doxygen

To build the documentation, doxygen must be version 1.8 or greater. Braid documentation uses a `markdown` syntax both in source file comments and in `*.md` files.

To make the documentation,

```
$ make user_manual
$ acroread user_manual.pdf
```

or to make a more extensive reference manual for developers,

```
$ make developer_manual
$ acroread developer_manual.pdf
```

Developers can run doxygen from a precompiled binary, which may or may not work for your machine,

```
/usr/casc/hypr/braid/share/doxygen/bin/doxygen
```

or build doxygen from

```
/usr/casc/hypr/braid/share/doxygen.tgz
```

- Compiling doxygen requires a number of dependencies like Bison, GraphViz and Flex. Configure will tell you what you're missing
- Unpack `doxygen.tgz`, then from the doxygen directory  

```
./configure --prefix some_dir_in_your_path
make
make install
```

### Documentation Strategy

- The doxygen comments are to be placed in the header files.

- A sample function declaration using the documentation approach using markdown (including typesetting equations) is in [braid.h](#) for the function [braid\\_Init\(\)](#)
- A sample structure documentation is in [\\_braid.h](#) for [\\_braid\\_Core\\_struct](#)
- Descriptors for files can also be added, as at the top of [braid.h](#)
- The Doxygen manual is at <http://www.stack.nl/~dimitri/doxygen/manual/index.html>

### $\chi$ Braid Doxygen details

The user and developer manuals are ultimately produced by Latex. The formatting of the manuals is configured according to the following.

- docs/local\_doxxygen.sty
  - Latex style file used
- docs/user\_manual\_header.tex
  - User manual title page and header info
- docs/developer\_manual\_header.tex
  - Developer manual title page and header info
- \*.md
  - Any file ending in .md is extra documentation in markdown format, like [Introduction.md](#) or the various Readme.md files in each directory. This material can be read in plain-text or when it's compiled by Doxygen and Latex.
- docs/user\_manual.conf
  - Doxygen configure file for the user manual
  - The FILE\_NAMES tag is a filter to only include the user interface routines in [braid.h](#)
  - The INPUT tag orders the processing of the files and hence the section ordering
- docs/reference\_manual.conf
  - Same as user\_manual.conf, but the FILE\_NAMES tag does not exclude any file from processing.
- docs/img
  - Contains the images
- To regenerate generic doxygen latex files, type
 

```
$ doxygen -w latex header.tex footer.tex doxygen.sty doxy.conf
```

 If this is done, then the .conf file must be changed to use the new header file and to copy the local\_doxxygen.sty file to the latex directory.

## 8 Regression Testing

### Overview

- There are three levels in the testing framework. At each level, the fine-grain output from a `testscript.sh` is dumped into a directory `testscript.dir`, with the standard out and error stored in `testscript.out` and `testscript.err`. The test `testscript.sh` passes if `testscript.err` is empty (nothing is written to standard error).
- Basic instructions: run a test with a command like
 

```
$ ./test.sh diffusion2D.sh
```

 Then, see if `diffusion2D.err` is of size 0. If it is not, look at its contents to see which test failed.

- To add a new regression test, create a new lowest level script like `diffusion2D.sh` and then call it from a machine script at level 2.
- Regression tests should be run before pushing code. It is recommended to run the basic (lowest level) tests like `diffusion2d.sh` or machine test like `machine-tux.sh`

### Lowest Level Test Scripts

As an example, here we look at one of the lowest level tests, the `diffusion2d` test.

Files used:

- `test.sh`
- `diffusion2D.sh`
- `diffusion2D.saved`

Output:

- `diffusion2D.dir`
- `diffusion2D.err`
- `diffusion2D.out`

At this level, we execute

```
$ ./test.sh diffusion2D.sh
```

or just

```
$ ./diffusion2D.sh
```

The script `diffusion2D.sh` must create `diffusion2D.dir` and place all fine-grain test output in this directory. `test.sh` captures the standard out and error in `diffusion2D.out` and `diffusion2D.err`. The test `diffusion2D.sh` passes if `diffusion2D.err` is empty (nothing is written to standard error).

The strategy for low level scripts like `diffusion2D.sh` is to run a sequence of test drivers such as

```
$ mpirun -np 1 ../../examples/drive-02 -pgrid 1 1 1 -nt 256
$ mpirun -np 4 ../../examples/drive-02 -pgrid 1 1 4 -nt 256
```

The output from the first `mpirun` test must then be written to files named

```
diffusion2D.dir/unfiltered.std.out.0
diffusion2D.dir/std.out.0
diffusion2D.dir/std.err.0
```

and the second `mpirun` test similarly writes the files

```
diffusion2D.dir/unfiltered.std.out.1
diffusion2D.dir/std.out.1
diffusion2D.dir/std.err.1
```

Subsequent tests are written to higher numbered files. The `unfiltered.std.out.num` file contains all of the standard out for the test, while `std.out.num` contains filtered output (usually from a `grep` command) and could contain the output lines such as iteration numbers and number of levels. The file `std.err.num` contains the standard error output.

To see if a test ran correctly, `std.out.num` is compared to saved output in `diffusion2D.saved`. The file `diffusion2D.saved` contains the concatenated output from all the tests that `diffusion2D.sh` will run. For the above example, this file could look like

```
# Begin Test 1
number of levels      = 6
iterations            = 16
# Begin Test 2
number of levels      = 4
iterations            = 8
```

This saved output is split into an individual file for each test (using `# Begin Test` as a delimiter) and these new files are placed in `diffusion2D.dir`. So, after running these two regression tests, `diffusion2D.dir` will contain

```
diffusion2D.saved.0
diffusion2D.saved.1
unfiltered.std.out.0
std.out.0
std.err.0
unfiltered.std.out.1
std.out.1
std.err.1
```

An individual test has passed if `std.err.num` is empty. The file `std.err.num` contains a diff between `diffusion2D.save.num` and `std.out.num` (the diff ignores whitespace and the delimiter `# Begin Test`).

Last in the directy where you ran `./test.sh diffusion2d.sh`, the files

```
diffusion2D.err
diffusion2D.out
```

will be created. If all the tests passed then `diffusion2D.err` will be empty. Otherwise, it will contain the filenames of the `std.err.num` files that are non-empty, representing failed tests.

## Level 2 Scripts

As an example, here we look at one of the Level 2 tests, the machine-tux test that Jacob runs.

Files used:

- `machine-tux.sh`

Output:

- `machine-tux.dir`
- `machine-tux.err` (only generated if `autotest.sh` is used to run `machine-tux.sh`)
- `machine-tux.out` (only generated if `autotest.sh` is used to run `machine-tux.sh`)

At this level, we execute

```
./machine-tux.sh
```

The autotest framework (`autotest.sh`) calls machine scripts in this way. Each machine script should be short and call lower-level scripts like `diffusion2D.sh`. The output from lower-level scripts must be moved to `machine-tux.dir` like this:

```
$ ./test.sh diffusion2D.sh
$ mv -f diffusion2D.dir machine-tux.dir
$ mv -f diffusion2D.out machine-tux.dir
$ mv -f diffusion2D.err machine-tux.dir
```

All error files from `diffusion2D.sh` will be placed in `machine-tux.dir`, so if `machine-tux.dir` has all zero `*.err` files, then the `machine-tux` test has passed.

To begin testing on a new machine, like vulcan, add a new machine script similar to `machine-tux.sh` and change `autotest.sh` to recognize and run the new machine test. To then use `autotest.sh` with the machine script, you'll have to set up a passwordless connection from the new machine to

---

```
/usr/casc/hypre/braid/testing
```

### Level 3 Script

Here we look at the highest level, where `autotest.sh` runs all of the level 2 machine tests and emails out the results.

Files used:

- `autotest.sh`

Output:

- `test/autotest_finished`
- `/usr/casc/hypre/braid/testing/AUTOTEST-20**.*.*-Day`
- Email to recipients listed in `autotest.sh`

At the highest level sits `autotest.sh` and is called automatically as a cronjob. If you just want to check to see if you've broken anything with a commit, just use lower level scripts.

There are four steps to running autotest.

- Step 1  
`$ ./autotest.sh -init`  
 will do a pull from master for the current working repository and recompile Braid. The autotest output files (`autotest.err` and `autotest.out`) and the output directory (`autotest_finished`) are initialized.
- Step 2  
`$ ./autotest.sh -tux343`  
 will run the autotests on tux343. This command will look for a `machine-tux.sh`, and execute it, moving the resulting  
`machine-tux.dir`  
`machine-tux.err`  
`machine-tux.out`  
 into `test/autotest_finished`.
- Step 3  
`$ ./autotest.sh -remote-copy`  
 will copy `/test/autotest_finished/*` to a time-stamped directory such as  
`/usr/casc/hypre/braid/testing/AUTOTEST-2013.11.18-Mon`  
 Alternatively,  
`$ ./autotest.sh -remote-copy tux343`  
 will ssh through tux343 to copy to `/usr/casc`. Multiple machines may independently be running regression tests and then copy to `AUTOTEST-2013.11.18-Mon`.
- Step 4  
`$ ./autotest.sh -summary-email`  
 will email everyone listed in the `$email_list` (an `autotest.sh` variable)

### Cronfile

To add entries to your crontab, First, put your new cronjob lines into `cronfile`. Then see what you already have in your crontab file with

```
$ crontab -l
```

Next, append to `cronfile` whatever you already have

```
$ crontab -l >> cronfile
```

Finally, tell crontab to use your `cronfile`

```
$ crontab cronfile
```

Then make sure it took affect with

```
$ crontab -l
```

Crontab entry format uses '\*' to mean "every" and '\*/m' to mean "every m-th". The first five entries on each line correspond respectively to:

- minute (0-56)
- hour (0-23)
- day of month (1-31)
- month (1-12)
- day of week (0-6)(0=Sunday)

Jacob's crontab (on tux343):

```
00 01 * * * source /etc/profile; source $HOME/.bashrc; cd $HOME/joint_repos/braid/test; ./autotest.sh -init
10 01 * * * source /etc/profile; source $HOME/.bashrc; cd $HOME/joint_repos/braid/test; ./autotest.sh -tux343
40 01 * * * source /etc/profile; source $HOME/.bashrc; cd $HOME/joint_repos/braid/test; ./autotest.sh -remote-c
50 01 * * * source /etc/profile; source $HOME/.bashrc; cd $HOME/joint_repos/braid/test; ./autotest.sh -summary-
```

## 9 Module Index

### 9.1 Modules

Here is a list of all modules:

<b>User-written routines</b>	<b>23</b>
<b>User interface routines</b>	<b>26</b>
<b>Braid test routines</b>	<b>35</b>

## 10 Data Structure Index

### 10.1 Data Structures

Here are the data structures with brief descriptions:

<b>_braid_AccuracyHandle</b>	<b>39</b>
<b>_braid_CommHandle</b>	<b>39</b>
<b>_braid_Core</b>	<b>40</b>
<b>_braid_Grid</b>	<b>44</b>
<b>_braid_Status</b>	<b>46</b>

## 11 File Index

### 11.1 File List

Here is a list of all files with brief descriptions:

<a href="#"><u>_braid.h</u></a>	<b>Define headers for developer routines</b>	<a href="#">47</a>
<a href="#"><u>braid.h</u></a>	<b>Define headers for user interface routines</b>	<a href="#">53</a>
<a href="#"><u>braid_test.h</u></a>	<b>Define headers for Braid test routines</b>	<a href="#">55</a>
<a href="#"><u>util.h</u></a>	<b>Define headers for utility routines</b>	<a href="#">55</a>

## 12 Module Documentation

### 12.1 User-written routines

#### Typedefs

- [`typedef struct \_braid\_App\_struct \* braid\_App`](#)
- [`typedef struct \_braid\_Vector\_struct \* braid\_Vector`](#)
- [`typedef struct \_braid\_Status\_struct \* braid\_Status`](#)
- [`typedef braid\_Int\(\* braid\_PtFcnPhi \)\(braid\_App app, braid\_Real tstart, braid\_Real tstop, braid\_Real accuracy, braid\_Vector u, braid\_Int \*rfactor\_ptr\)`](#)
- [`typedef braid\_Int\(\* braid\_PtFcnInit \)\(braid\_App app, braid\_Real t, braid\_Vector \*u\_ptr\)`](#)
- [`typedef braid\_Int\(\* braid\_PtFcnClone \)\(braid\_App app, braid\_Vector u, braid\_Vector \*v\_ptr\)`](#)
- [`typedef braid\_Int\(\* braid\_PtFcnFree \)\(braid\_App app, braid\_Vector u\)`](#)
- [`typedef braid\_Int\(\* braid\_PtFcnSum \)\(braid\_App app, braid\_Real alpha, braid\_Vector x, braid\_Real beta, braid\_Vector y\)`](#)
- [`typedef braid\_Int\(\* braid\_PtFcnDot \)\(braid\_App app, braid\_Vector u, braid\_Vector v, braid\_Real \*dot\_ptr\)`](#)
- [`typedef braid\_Int\(\* braid\_PtFcnWrite \)\(braid\_App app, braid\_Real t, braid\_Status status, braid\_Vector u\)`](#)
- [`typedef braid\_Int\(\* braid\_PtFcnBufSize \)\(braid\_App app, braid\_Int \*size\_ptr\)`](#)
- [`typedef braid\_Int\(\* braid\_PtFcnBufPack \)\(braid\_App app, braid\_Vector u, void \*buffer\)`](#)
- [`typedef braid\_Int\(\* braid\_PtFcnBufUnpack \)\(braid\_App app, void \*buffer, braid\_Vector \*u\_ptr\)`](#)
- [`typedef braid\_Int\(\* braid\_PtFcnCoarsen \)\(braid\_App app, braid\_Real tstart, braid\_Real f\_tminus, braid\_Real f\_tplus, braid\_Real c\_tminus, braid\_Real c\_tplus, braid\_Vector fu, braid\_Vector \*cu\_ptr\)`](#)
- [`typedef braid\_Int\(\* braid\_PtFcnRefine \)\(braid\_App app, braid\_Real tstart, braid\_Real f\_tminus, braid\_Real f\_tplus, braid\_Real c\_tminus, braid\_Real c\_tplus, braid\_Vector cu, braid\_Vector \*fu\_ptr\)`](#)

#### 12.1.1 Detailed Description

These are all user-written data structures and routines. There are two data structures ([`braid\_App`](#) and [`braid\_Vector`](#)) for the user to define. And, there are a variety of function interfaces (defined through function pointer declarations) that the user must implement.

## 12.1.2 Typedef Documentation

12.1.2.1 `typedef struct _braid_App_struct* braid_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. For a simple example, this could just hold the global MPI communicator and a few values describing the temporal domain.

12.1.2.2 `typedef braid_Int(* braid_PtFcnBufPack)(braid_App app,braid_Vector u,void *buffer)`

This allows Braid to send messages containing `braid_Vectors`. This routine packs a vector `u` into a `void * buffer` for MPI.

12.1.2.3 `typedef braid_Int(* braid_PtFcnBufSize)(braid_App app,braid_Int *size_ptr)`

This routine tells Braid message sizes by computing an upper bound in bytes for an arbitrary `braid_Vector`. This size must be an upper bound for what `BufPack` and `BufUnPack` will assume.

12.1.2.4 `typedef braid_Int(* braid_PtFcnBufUnpack)(braid_App app,void *buffer,braid_Vector *u_ptr)`

This allows Braid to receive messages containing `braid_Vectors`. This routine unpacks a `void * buffer` from MPI into a `braid_Vector`.

12.1.2.5 `typedef braid_Int(* braid_PtFcnClone)(braid_App app,braid_Vector u,braid_Vector *v_ptr)`

Clone `u` into `v_ptr`

12.1.2.6 `typedef braid_Int(* braid_PtFcnCoarsen)(braid_App app,braid_Real tstart,braid_Real f_tminus,braid_Real f_tplus,braid_Real c_tminus,braid_Real c_tplus,braid_Vector fu,braid_Vector *cu_ptr)`

spatial coarsening (optional). Allows the user to coarsen when going from a fine time grid to a coarse time grid. This function is called on every vector at each level, thus you can coarsen the entire space time domain. The action of this function should match the `braid_PtFcnRefine` function.

12.1.2.7 `typedef braid_Int(* braid_PtFcnDot)(braid_App app,braid_Vector u,braid_Vector v,braid_Real *dot_ptr)`

Carry out a dot product `dot_ptr = <u, v>`

12.1.2.8 `typedef braid_Int(* braid_PtFcnFree)(braid_App app,braid_Vector u)`

Free and deallocate `u`

12.1.2.9 `typedef braid_Int(* braid_PtFcnInit)(braid_App app,braid_Real t,braid_Vector *u_ptr)`

Initializes a vector `u_ptr` at time `t`

12.1.2.10 `typedef braid_Int(* braid_PtFcnPhi)(braid_App app,braid_Real tstart,braid_Real tstop,braid_Real accuracy,braid_Vector u,braid_Int *rfactor_ptr)`

Defines the central time stepping function that the user must write. The user must advance the vector `u` from time `tstart` to time `tstop`. The `rfactor_ptr` and `accuracy` inputs are advanced topics. `rfactor_ptr` allows the user to tell Braid to refine this time interval.

---

12.1.2.11 `typedef braid_Int(* braid_PtFcnRefine)(braid_App app,braid_Real tstart,braid_Real f_tminus,braid_Real f_tplus,braid_Real c_tminus,braid_Real c_tplus,braid_Vector cu,braid_Vector *fu_ptr)`

spatial refinement (optional). Allows the user to refine when going from a coarse time grid to a fine time grid. This function is called on every vector at each level, thus you can refine the entire space time domain. The action of this function should match the [braid\\_PtFcnCoarsen](#) function.

12.1.2.12 `typedef braid_Int(* braid_PtFcnSum)(braid_App app,braid_Real alpha,braid_Vector x,braid_Real beta,braid_Vector y)`

*AXPY, alpha x + beta y -> y*

12.1.2.13 `typedef braid_Int(* braid_PtFcnWrite)(braid_App app,braid_Real t,braid_Status status,braid_Vector u)`

Write the vector *u* at time *t* to screen, file, etc... The user decides what is appropriate. 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 certain time values.

If *write\_level* is 2 (see [braid\\_SetWriteLevel](#) ), then *write* is called every Braid iteration and on every Braid level. In this case, *status* can be queried using the [braid\\_Get\\*\\*Status\(\)](#) functions, to determine the current Braid level and iteration. This allows for even more detailed tracking of the simulation.

12.1.2.14 `typedef struct _braid_Status_struct* braid_Status`

Points to the status structure defined in [\\_braid.h](#) This is NOT a user-defined structure.

12.1.2.15 `typedef struct _braid_Vector_struct* braid_Vector`

This defines (roughly) a state vector at a certain time value. It could also contain any other information related to this vector which is needed to evolve the vector to the next time value, like mesh information.

## 12.2 User interface routines

### Typedefs

- `typedef struct _braid_Core_struct * braid_Core`

### Functions

- `braid_Int braid_Init (MPI_Comm comm_world, MPI_Comm comm, braid_Real tstart, braid_Real tstop, braid_Int ntime, braid_App app, braid_PtFcnPhi phi, braid_PtFcnInit init, braid_PtFcnClone clone, braid_PtFcnFree free, braid_PtFcnSum sum, braid_PtFcnDot dot, braid_PtFcnWrite write, braid_PtFcnBufSize bufsize, braid_PtFcnBufPack bufpack, braid_PtFcnBufUnpack bufunpack, braid_Core *core_ptr)`
- `braid_Int braid_Drive (braid_Core core)`
- `braid_Int braid_Destroy (braid_Core core)`
- `braid_Int braid_PrintStats (braid_Core core)`
- `braid_Int braid_SetLooseTol (braid_Core core, braid_Int level, braid_Real loose_tol)`
- `braid_Int braid_SetTightxTol (braid_Core core, braid_Int level, braid_Real tight_tol)`
- `braid_Int braid_SetMaxLevels (braid_Core core, braid_Int max_levels)`
- `braid_Int braid_SetMaxCoarse (braid_Core core, braid_Int max_coarse)`
- `braid_Int braid_SetAbsTol (braid_Core core, braid_Real atol)`
- `braid_Int braid_SetRelTol (braid_Core core, braid_Real rtol)`
- `braid_Int braid_SetNRelax (braid_Core core, braid_Int level, braid_Int nrelax)`
- `braid_Int braid_SetCFactor (braid_Core core, braid_Int level, braid_Int cfactor)`
- `braid_Int braid_SetMaxIter (braid_Core core, braid_Int max_iter)`
- `braid_Int braid_SetFMG (braid_Core core)`
- `braid_Int braid_SetNFMGVcyc (braid_Core core, braid_Int nfmvg_Vcyc)`
- `braid_Int braid_SetSpatialCoarsen (braid_Core core, braid_PtFcnCoarsen coarsen)`
- `braid_Int braid_SetSpatialRefine (braid_Core core, braid_PtFcnRefine refine)`
- `braid_Int braid_SetPrintLevel (braid_Core core, braid_Int print_level)`
- `braid_Int braid_SetPrintFile (braid_Core core, const char *printfile_name)`
- `braid_Int braid_SetWriteLevel (braid_Core core, braid_Int write_level)`
- `braid_Int braid_SplitCommworld (const MPI_Comm *comm_world, braid_Int px, MPI_Comm *comm_x, MPI_Comm *comm_t)`
- `braid_Int braid_GetStatusResidual (braid_Status status, braid_Real *rnorm_ptr)`
- `braid_Int braid_GetStatusIter (braid_Status status, braid_Int *iter_ptr)`
- `braid_Int braid_GetStatusLevel (braid_Status status, braid_Int *level_ptr)`
- `braid_Int braid_GetStatusDone (braid_Status status, braid_Int *done_ptr)`
- `braid_Int braid_GetNumIter (braid_Core core, braid_Int *niter_ptr)`
- `braid_Int braid_GetRNorm (braid_Core core, braid_Real *rnorm_ptr)`

### 12.2.1 Detailed Description

these are interface routines to initialize and run Braid

### 12.2.2 Typedef Documentation

#### 12.2.2.1 `typedef struct _braid_Core_struct* braid_Core`

points to the core structure defined in `_braid.h`

### 12.2.3 Function Documentation

#### 12.2.3.1 **braid\_Int braid\_Destroy ( braid\_Core *core* )**

Clean up and destroy core.

## Parameters

<i>core</i>	braid_Core ( <a href="#">_braid_Core</a> ) struct
-------------	---

**12.2.3.2 braid\_Int braid\_Drive ( braid\_Core core )**

Carry out a simulation with Braid. Integrate in time.

## Parameters

<i>core</i>	braid_Core ( <a href="#">_braid_Core</a> ) struct
-------------	---

**12.2.3.3 braid\_Int braid\_GetNumIter ( braid\_Core core, braid\_Int \* niter\_ptr )**

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

## Parameters

<i>core</i>	braid_Core ( <a href="#">_braid_Core</a> ) struct
<i>niter_ptr</i>	output, holds number of iterations taken

**12.2.3.4 braid\_Int braid\_GetRNorm ( braid\_Core core, braid\_Real \* rnorm\_ptr )**

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

## Parameters

<i>core</i>	braid_Core ( <a href="#">_braid_Core</a> ) struct
<i>rnorm_ptr</i>	output, holds final residual norm

**12.2.3.5 braid\_Int braid\_GetStatusDone ( braid\_Status status, braid\_Int \* done\_ptr )**

Return whether Braid is done for the current status object

*done\_ptr* = 1 indicates that this is the last call to Write, because Braid has stopped iterating (either maxiter has been reached, or the tolerance has been met).

## Parameters

<i>status</i>	structure containing current simulation info
<i>done_ptr</i>	output, =1 if Braid has finished and this is the final Write, else =0

**12.2.3.6 braid\_Int braid\_GetStatusIter ( braid\_Status status, braid\_Int \* iter\_ptr )**

Return the iteration for the current status object.

## Parameters

<i>status</i>	structure containing current simulation info
<i>iter_ptr</i>	output, current iteration number

**12.2.3.7 braid\_Int braid\_GetStatusLevel ( braid\_Status status, braid\_Int \* level\_ptr )**

Return the Braid level for the current status object.

## Parameters

<i>status</i>	structure containing current simulation info
<i>level_ptr</i>	output, current level in Braid

12.2.3.8 **braid\_Int braid\_GetStatusResidual ( braid\_Status *status*, braid\_Real \* *rnorm\_ptr* )**

Return the residual for the current status object.

## Parameters

<i>status</i>	structure containing current simulation info
<i>rnorm_ptr</i>	output, current residual norm

12.2.3.9 **braid\_Int braid\_Init ( MPI\_Comm *comm\_world*, MPI\_Comm *comm*, braid\_Real *tstart*, braid\_Real *tstop*, braid\_Int *ntime*, braid\_App *app*, braid\_PtFcnPhi *phi*, braid\_PtFcnInit *init*, braid\_PtFcnClone *clone*, braid\_PtFcnFree *free*, braid\_PtFcnSum *sum*, braid\_PtFcnDot *dot*, braid\_PtFcnWrite *write*, braid\_PtFcnBufSize *bufsize*, braid\_PtFcnBufPack *bufpack*, braid\_PtFcnBufUnpack *bufunpack*, braid\_Core \* *core\_ptr* )**

Create a core object with the required initial data.

This core is used by Braid for internal data structures. The output is *core\_ptr* which points to the newly created braid\_Core structure.

## Parameters

<i>comm_world</i>	Global communicator for space and time
<i>comm</i>	Communicator for temporal dimension
<i>tstart</i>	start time
<i>tstop</i>	End time
<i>ntime</i>	Initial number of temporal grid values
<i>app</i>	User-defined _braid_App structure
<i>phi</i>	User time stepping routine to advance a braid_Vector forward one step
<i>init</i>	Initialize a braid_Vector on the finest temporal grid
<i>clone</i>	Clone a braid_Vector
<i>free</i>	Free a braid_Vector
<i>sum</i>	Compute vector sum of two braid_Vectors
<i>dot</i>	Compute dot product between two braid_Vectors
<i>write</i>	Writes a braid_Vector to file, screen
<i>bufsize</i>	Computes size for MPI buffer for one braid_Vector
<i>bufpack</i>	Packs MPI buffer to contain one braid_Vector
<i>bufunpack</i>	Unpacks MPI buffer into a braid_Vector
<i>core_ptr</i>	Pointer to braid_Core ( <a href="#">_braid_Core</a> ) struct

12.2.3.10 **braid\_Int braid\_PrintStats ( braid\_Core *core* )**

Print statistics after a Braid run.

## Parameters

<i>core</i>	braid_Core ( <a href="#">_braid_Core</a> ) struct
-------------	---

12.2.3.11 **braid\_Int braid\_SetAbsTol ( braid\_Core *core*, braid\_Real *atol* )**

Set absolute stopping tolerance.

**Recommended option over relative tolerance**

## Parameters

<i>core</i>	braid_Core ( <a href="#">_braid_Core</a> ) struct
<i>atol</i>	absolute stopping tolerance

**12.2.3.12 braid\_Int braid\_SetCFactor ( braid\_Core *core*, braid\_Int *level*, braid\_Int *cfactor* )**

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

## Parameters

<i>core</i>	braid_Core ( <a href="#">_braid_Core</a> ) struct
<i>level</i>	<i>level</i> to set coarsening factor on
<i>cfactor</i>	desired coarsening factor

**12.2.3.13 braid\_Int braid\_SetFMG ( braid\_Core *core* )**

Once called, Braid will use FMG (i.e., F-cycles).

## Parameters

<i>core</i>	braid_Core ( <a href="#">_braid_Core</a> ) struct
-------------	---

**12.2.3.14 braid\_Int braid\_SetLoosexTol ( braid\_Core *core*, braid\_Int *level*, braid\_Real *loose\_tol* )**

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

## Parameters

<i>core</i>	braid_Core ( <a href="#">_braid_Core</a> ) struct
<i>level</i>	<i>level</i> to set <i>loose_tol</i>
<i>loose_tol</i>	tolerance to set

**12.2.3.15 braid\_Int braid\_SetMaxCoarse ( braid\_Core *core*, braid\_Int *max\_coarse* )**

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

## Parameters

<i>core</i>	braid_Core ( <a href="#">_braid_Core</a> ) struct
<i>max_coarse</i>	maximum coarse grid size

**12.2.3.16 braid\_Int braid\_SetMaxIter ( braid\_Core *core*, braid\_Int *max\_iter* )**

Set max number of multigrid iterations.

## Parameters

<i>core</i>	braid_Core ( <a href="#">_braid_Core</a> ) struct
<i>max_iter</i>	maximum iterations to allow

**12.2.3.17 braid\_Int braid\_SetMaxLevels ( braid\_Core *core*, braid\_Int *max\_levels* )**

Set max number of multigrid levels.

## Parameters

<i>core</i>	braid_Core ( <a href="#">_braid_Core</a> ) struct
<i>max_levels</i>	maximum levels to allow

**12.2.3.18 braid\_Int braid\_SetNFMGVcyc ( braid\_Core *core*, braid\_Int *nfmg\_Vcyc* )**

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

## Parameters

<i>core</i>	braid_Core ( <a href="#">_braid_Core</a> ) struct
<i>nfmg_Vcyc</i>	number of V-cycles to do each FMG level

**12.2.3.19 braid\_Int braid\_SetNRelax ( braid\_Core *core*, braid\_Int *level*, braid\_Int *nrelax* )**

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

## Parameters

<i>core</i>	braid_Core ( <a href="#">_braid_Core</a> ) struct
<i>level</i>	<i>level</i> to set <i>nrelax</i> on
<i>nrelax</i>	number of relaxations to do on <i>level</i>

**12.2.3.20 braid\_Int braid\_SetPrintFile ( braid\_Core *core*, const char \* *printfile\_name* )**

Set output file for runtime print messages. Level of printing is controlled by [braid\\_SetPrintLevel](#). Default is stdout.

## Parameters

<i>core</i>	braid_Core ( <a href="#">_braid_Core</a> ) struct
<i>printfile_name</i>	output file for Braid runtime output

**12.2.3.21 braid\_Int braid\_SetPrintLevel ( braid\_Core *core*, braid\_Int *print\_level* )**

Set print level for Braid. This controls how much information is printed to the Braid print file ([braid\\_SetPrintFile](#)).

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

Default is level 1.

## Parameters

<i>core</i>	braid_Core ( <a href="#">_braid_Core</a> ) struct
<i>print_level</i>	desired print level

**12.2.3.22 braid\_Int braid\_SetRelTol ( braid\_Core *core*, braid\_Real *rtol* )**

Set relative stopping tolerance, relative to the initial residual. Be careful. If your initial guess is all zero, then the initial residual may only be nonzero over one or two time values, and this will skew the relative tolerance. Absolute tolerances are recommended.

**Parameters**

<i>core</i>	braid_Core ( <a href="#">_braid_Core</a> ) struct
<i>rtol</i>	relative stopping tolerance

**12.2.3.23 braid\_Int braid\_SetSpatialCoarsen ( braid\_Core *core*, braid\_PtFcnCoarsen *coarsen* )**

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

**Parameters**

<i>core</i>	braid_Core ( <a href="#">_braid_Core</a> ) struct
<i>coarsen</i>	function pointer to spatial coarsening routine

**12.2.3.24 braid\_Int braid\_SetSpatialRefine ( braid\_Core *core*, braid\_PtFcnRefine *refine* )**

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

**Parameters**

<i>core</i>	braid_Core ( <a href="#">_braid_Core</a> ) struct
<i>refine</i>	function pointer to spatial refinement routine

**12.2.3.25 braid\_Int braid\_SetTightxTol ( braid\_Core *core*, braid\_Int *level*, braid\_Real *tight\_tol* )**

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

**Parameters**

<i>core</i>	braid_Core ( <a href="#">_braid_Core</a> ) struct
<i>level</i>	level to set <i>tight_tol</i>
<i>tight_tol</i>	tolerance to set

**12.2.3.26 braid\_Int braid\_SetWriteLevel ( braid\_Core *core*, braid\_Int *write\_level* )**

Set write level for Braid. 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 Braid is finished
- Level 2: Call the user's write routine every iteration and on every level. This is during `_braid_FRestrict`, during the down-cycle part of a Braid iteration.

Default is level 1.

**Parameters**

<i>core</i>	braid_Core ( <a href="#">_braid_Core</a> ) struct
<i>write_level</i>	desired write_level

**12.2.3.27 braid\_Int braid\_SplitCommworld ( const MPI\_Comm \* *comm\_world*, braid\_Int *px*, MPI\_Comm \* *comm\_x*, MPI\_Comm \* *comm\_t* )**

Split MPI commworld into *comm\_x* and *comm\_t*, the spatial and temporal communicators. The total number of processors will equal Px\*Pt, where Px is the number of procs in space, and Pt is the number of procs in time.

**Parameters**

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

## 12.3 Braid test routines

### Functions

- `braid_Int braid_TestInitWrite (braid_App app, MPI_Comm comm_x, FILE *fp, braid_Real t, braid_PtFcnInit init, braid_PtFcnWrite write, braid_PtFcnFree free)`
- `braid_Int braid_TestClone (braid_App app, MPI_Comm comm_x, FILE *fp, braid_Real t, braid_PtFcnInit init, braid_PtFcnWrite write, braid_PtFcnFree free, braid_PtFcnClone clone)`
- `braid_Int braid_TestSum (braid_App app, MPI_Comm comm_x, FILE *fp, braid_Real t, braid_PtFcnInit init, braid_PtFcnWrite write, braid_PtFcnFree free, braid_PtFcnClone clone, braid_PtFcnSum sum)`
- `braid_Int braid_TestDot (braid_App app, MPI_Comm comm_x, FILE *fp, braid_Real t, braid_PtFcnInit init, braid_PtFcnFree free, braid_PtFcnClone clone, braid_PtFcnSum sum, braid_PtFcnDot dot)`
- `braid_Int braid_TestBuf (braid_App app, MPI_Comm comm_x, FILE *fp, braid_Real t, braid_PtFcnInit init, braid_PtFcnFree free, braid_PtFcnSum sum, braid_PtFcnDot dot, braid_PtFcnBufSize bufsize, braid_PtFcnBufPack bufpack, braid_PtFcnBufUnpack bufunpack)`
- `braid_Int braid_TestCoarsenRefine (braid_App app, MPI_Comm comm_x, FILE *fp, braid_Real t, braid_Real fdt, braid_Real cdt, braid_PtFcnInit init, braid_PtFcnWrite write, braid_PtFcnFree free, braid_PtFcnClone clone, braid_PtFcnSum sum, braid_PtFcnDot dot, braid_PtFcnCoarsen coarsen, braid_PtFcnRefine refine)`
- `braid_Int braid_TestAll (braid_App app, MPI_Comm comm_x, FILE *fp, braid_Real t, braid_Real fdt, braid_Real cdt, braid_PtFcnInit init, braid_PtFcnFree free, braid_PtFcnClone clone, braid_PtFcnSum sum, braid_PtFcnDot dot, braid_PtFcnBufSize bufsize, braid_PtFcnBufPack bufpack, braid_PtFcnBufUnpack bufunpack, braid_PtFcnCoarsen coarsen, braid_PtFcnRefine refine )`

### 12.3.1 Detailed Description

These are sanity check routines to help a user test their Braid code.

### 12.3.2 Function Documentation

**12.3.2.1 `braid_Int braid_TestAll ( braid_App app, MPI_Comm comm_x, FILE *fp, braid_Real t, braid_Real fdt, braid_Real cdt, braid_PtFcnInit init, braid_PtFcnFree free, braid_PtFcnClone clone, braid_PtFcnSum sum, braid_PtFcnDot dot, braid_PtFcnBufSize bufsize, braid_PtFcnBufPack bufpack, braid_PtFcnBufUnpack bufunpack, braid_PtFcnCoarsen coarsen, braid_PtFcnRefine refine )`**

Runs all of the individual `braid_Test*` routines

- Returns 0 if the tests fail
- Returns 1 if the tests pass
- Check the log messages to see details of which tests failed.

### Parameters

<code>app</code>	User defined App structure
<code>comm_x</code>	Spatial communicator
<code>fp</code>	File pointer (could be stdout or stderr) for log messages
<code>t</code>	Time value to initialize test vectors with

<i>fdt</i>	Fine time step value that you spatially coarsen from
<i>cdt</i>	Coarse time step value that you coarsen to
<i>init</i>	Initialize a braid_Vector on finest temporal grid
<i>free</i>	Free a braid_Vector
<i>clone</i>	Clone a braid_Vector
<i>sum</i>	Compute vector sum of two braid_Vectors
<i>dot</i>	Compute dot product of two braid_Vectors
<i>bufsize</i>	Computes size in bytes for one braid_Vector MPI buffer
<i>bufpack</i>	Packs MPI buffer to contain one braid_Vector
<i>bufunpack</i>	Unpacks MPI buffer into a braid_Vector
<i>coarsen</i>	Spatially coarsen a vector. If NULL, test is skipped.
<i>refine</i>	Spatially refine a vector. If NULL, test is skipped.

12.3.2.2 **braid\_Int braid\_TestBuf ( braid\_App *app*, MPI\_Comm *comm\_x*, FILE \* *fp*, braid\_Real *t*, braid\_PtFcnInit *init*, braid\_PtFcnFree *free*, braid\_PtFcnSum *sum*, braid\_PtFcnDot *dot*, braid\_PtFcnBufSize *bufsize*, braid\_PtFcnBufPack *bufpack*, braid\_PtFcnBufUnpack *bufunpack* )**

Test the BufPack, BufUnpack and BufSize functions.

A vector is initialized at time *t*, packed into a buffer, then unpacked from a buffer. The unpacked result must equal the original vector.

- Returns 0 if the tests fail
- Returns 1 if the tests pass
- Check the log messages to see details of which tests failed.

#### Parameters

<i>app</i>	User defined App structure
<i>comm_x</i>	Spatial communicator
<i>fp</i>	File pointer (could be stdout or stderr) for log messages
<i>t</i>	Time value to test Buffer routines (used to initialize the vectors)
<i>init</i>	Initialize a braid_Vector on finest temporal grid
<i>free</i>	Free a braid_Vector
<i>sum</i>	Compute vector sum of two braid_Vectors
<i>dot</i>	Compute dot product of two braid_Vectors
<i>bufsize</i>	Computes size in bytes for one braid_Vector MPI buffer
<i>bufpack</i>	Packs MPI buffer to contain one braid_Vector
<i>bufunpack</i>	Unpacks MPI buffer containing one braid_Vector

12.3.2.3 **braid\_Int braid\_TestClone ( braid\_App *app*, MPI\_Comm *comm\_x*, FILE \* *fp*, braid\_Real *t*, braid\_PtFcnInit *init*, braid\_PtFcnWrite *write*, braid\_PtFcnFree *free*, braid\_PtFcnClone *clone* )**

Test the clone function.

A vector is initialized at time *t*, cloned, and both vectors are written. Then both vectors are free-d. The user is to check (via the write function) to see if it is identical.

#### Parameters

<i>app</i>	User defined App structure
<i>comm_x</i>	Spatial communicator
<i>fp</i>	File pointer (could be stdout or stderr) for log messages
<i>t</i>	Time value to test clone with (used to initialize the vectors)
<i>init</i>	Initialize a braid_Vector on finest temporal grid
<i>write</i>	Write a braid_Vector (can be NULL for no writing)
<i>free</i>	Free a braid_Vector
<i>clone</i>	Clone a braid_Vector

```
12.3.2.4 braid_Int braid_TestCoarsenRefine( braid_App app, MPI_Comm comm_x, FILE *fp, braid_Real t, braid_Real fdt,
braid_Real cdt, braid_PtFcnInit init, braid_PtFcnWrite write, braid_PtFcnFree free, braid_PtFcnClone
clone, braid_PtFcnSum sum, braid_PtFcnDot dot, braid_PtFcnCoarsen coarsen, braid_PtFcnRefine refine
)
```

Test the Coarsen and Refine functions.

A vector is initialized at time *t*, and various sanity checks on the spatial coarsening and refinement routines are run.

- Returns 0 if the tests fail
- Returns 1 if the tests pass
- Check the log messages to see details of which tests failed.

#### Parameters

<i>app</i>	User defined App structure
<i>comm_x</i>	Spatial communicator
<i>fp</i>	File pointer (could be stdout or stderr) for log messages
<i>t</i>	Time value to initialize test vectors
<i>fdt</i>	Fine time step value that you spatially coarsen from
<i>cdt</i>	Coarse time step value that you coarsen to
<i>init</i>	Initialize a braid_Vector on finest temporal grid
<i>write</i>	Write a braid_Vector (can be NULL for no writing)
<i>free</i>	Free a braid_Vector
<i>clone</i>	Clone a braid_Vector
<i>sum</i>	Compute vector sum of two braid_Vectors
<i>dot</i>	Compute dot product of two braid_Vectors
<i>coarsen</i>	Spatially coarsen a vector
<i>refine</i>	Spatially refine a vector

```
12.3.2.5 braid_Int braid_TestDot( braid_App app, MPI_Comm comm_x, FILE *fp, braid_Real t, braid_PtFcnInit init,
braid_PtFcnFree free, braid_PtFcnClone clone, braid_PtFcnSum sum, braid_PtFcnDot dot )
```

Test the dot function.

A vector is initialized at time *t* and then cloned. Various dot products like  $\langle v, v \rangle / \langle v, v \rangle$  are computed with known output, e.g.,  $\langle v, v \rangle / \langle v, v \rangle$  must equal 3. If all the tests pass, then 1 is returned.

- Returns 0 if the tests fail
- Returns 1 if the tests pass
- Check the log messages to see details of which tests failed.

## Parameters

<i>app</i>	User defined App structure
<i>comm_x</i>	Spatial communicator
<i>fp</i>	File pointer (could be stdout or stderr) for log messages
<i>t</i>	Time value to test Dot with (used to initialize the vectors)
<i>init</i>	Initialize a braid_Vector on finest temporal grid
<i>free</i>	Free a braid_Vector
<i>clone</i>	Clone a braid_Vector
<i>sum</i>	Compute vector sum of two braid_Vectors
<i>dot</i>	Compute dot product of two braid_Vectors

12.3.2.6 **braid\_Int braid\_TestInitWrite ( braid\_App app, MPI\_Comm comm\_x, FILE \* fp, braid\_Real t, braid\_PtFcnInit init, braid\_PtFcnWrite write, braid\_PtFcnFree free )**

Test the init, write and free functions.

A vector is initialized at time *t*, written, and then free-d

## Parameters

<i>app</i>	User defined App structure
<i>comm_x</i>	Spatial communicator
<i>fp</i>	File pointer (could be stdout or stderr) for log messages
<i>t</i>	Time value to test init with (used to initialize the vectors)
<i>init</i>	Initialize a braid_Vector on finest temporal grid
<i>write</i>	Write a braid_Vector (can be NULL for no writing)
<i>free</i>	Free a braid_Vector

12.3.2.7 **braid\_Int braid\_TestSum ( braid\_App app, MPI\_Comm comm\_x, FILE \* fp, braid\_Real t, braid\_PtFcnInit init, braid\_PtFcnWrite write, braid\_PtFcnFree free, braid\_PtFcnClone clone, braid\_PtFcnSum sum )**

Test the sum function.

A vector is initialized at time *t*, cloned, and then these two vectors are summed a few times, with the results written. The vectors are then free-d. The user is to check (via the write function) that the output matches the sum of the two original vectors.

## Parameters

<i>app</i>	User defined App structure
<i>comm_x</i>	Spatial communicator
<i>fp</i>	File pointer (could be stdout or stderr) for log messages
<i>t</i>	Time value to test Sum with (used to initialize the vectors)
<i>init</i>	Initialize a braid_Vector on finest temporal grid
<i>write</i>	Write a braid_Vector (can be NULL for no writing)
<i>free</i>	Free a braid_Vector
<i>clone</i>	Clone a braid_Vector
<i>sum</i>	Compute vector sum of two braid_Vectors

## 13 Data Structure Documentation

### 13.1 \_braid\_AccuracyHandle Struct Reference

#### Data Fields

- [braid\\_Int matchF](#)
- [braid\\_Real value](#)
- [braid\\_Real old\\_value](#)
- [braid\\_Real loose](#)
- [braid\\_Real tight](#)
- [braid\\_Int tight\\_used](#)

#### 13.1.1 Detailed Description

Braid Accuracy Handle, used for controlling the accuracy of solves during implicit time stepping. For instance, to do less accurate solves on coarse time grids

#### 13.1.2 Field Documentation

##### 13.1.2.1 [braid\\_Real loose](#)

loose accuracy for spatial solves

##### 13.1.2.2 [braid\\_Int matchF](#)

##### 13.1.2.3 [braid\\_Real old\\_value](#)

old accuracy value used in FRestrict

##### 13.1.2.4 [braid\\_Real tight](#)

tight accuracy for spatial solves

##### 13.1.2.5 [braid\\_Int tight\\_used](#)

tight accuracy used (1) or not (0)

##### 13.1.2.6 [braid\\_Real value](#)

accuracy value

The documentation for this struct was generated from the following file:

- [\\_braid.h](#)

### 13.2 \_braid\_CommHandle Struct Reference

#### Data Fields

- [braid\\_Int request\\_type](#)
- [braid\\_Int num\\_requests](#)

- MPI\_Request \* [requests](#)
- MPI\_Status \* [status](#)
- void \* [buffer](#)
- [braid\\_Vector](#) \* [vector\\_ptr](#)

### 13.2.1 Detailed Description

Braid comm handle structure

Used for initiating and completing nonblocking communication to pass braid\_Vectors between processors.

### 13.2.2 Field Documentation

#### 13.2.2.1 void\* buffer

Buffer for message

#### 13.2.2.2 braid\_Int num\_requests

number of active requests for this handle, usually 1

#### 13.2.2.3 braid\_Int request\_type

two values: recv type = 1, and send type = 0

#### 13.2.2.4 MPI\_Request\* requests

MPI request structure

#### 13.2.2.5 MPI\_Status\* status

MPI status

#### 13.2.2.6 braid\_Vector\* vector\_ptr

braid\_vector being sent/received

The documentation for this struct was generated from the following file:

- [\\_braid.h](#)

## 13.3 \_braid\_Core Struct Reference

### Data Fields

- MPI\_Comm [comm\\_world](#)
- MPI\_Comm [comm](#)
- [braid\\_Real](#) [tstart](#)
- [braid\\_Real](#) [tstop](#)
- [braid\\_Int](#) [ntime](#)
- [braid\\_App](#) [app](#)
- [braid\\_PtFcnPhi](#) [phi](#)
- [braid\\_PtFcnInit](#) [init](#)

- `braid_PtFcnClone` clone
- `braid_PtFcnFree` free
- `braid_PtFcnSum` sum
- `braid_PtFcnDot` dot
- `braid_PtFcnWrite` write
- `braid_PtFcnBufSize` bufsize
- `braid_PtFcnBufPack` bufpack
- `braid_PtFcnBufUnpack` bufunpack
- `braid_PtFcnCoarsen` coarsen
- `braid_PtFcnRefine` refine
- `braid_Int` write\_level
- `braid_Int` print\_level
- `braid_Int` max\_levels
- `braid_Int` max\_coarse
- `braid_Real` tol
- `braid_Int` rtol
- `braid_Int` \* nrels
- `braid_Int` nrdefault
- `braid_Int` \* cfactors
- `braid_Int` cfdefault
- `braid_Int` max\_iter
- `braid_Int` niter
- `braid_Real` rnorm
- `braid_Int` fmg
- `braid_Int` nfmg\_Vcyc
- `_braid_AccuracyHandle` \* accuracy
- `braid_Int` gupper
- `braid_Int` \* rfactors
- `braid_Int` nlevels
- `_braid_Grid` \*\* grids
- `braid_Real` localtime
- `braid_Real` globaltime

### 13.3.1 Detailed Description

The typedef `_braid_Core` struct is a **critical** part of Braid and is passed to *each* routine in Braid. It thus allows each routine access to Braid attributes.

### 13.3.2 Field Documentation

#### 13.3.2.1 `_braid_AccuracyHandle`\* accuracy

accuracy of spatial solves on different levels

#### 13.3.2.2 `braid_App` app

application data for the user

#### 13.3.2.3 `braid_PtFcnBufPack` bufpack

pack a buffer

13.3.2.4 **braid\_PtFcnBufSize** bufsiz

return buffer size

13.3.2.5 **braid\_PtFcnBufUnpack** bufunpack

unpack a buffer

13.3.2.6 **braid\_Int\*** cfac

coarsening factors

13.3.2.7 **braid\_Int** cfdefault

default coarsening factor

13.3.2.8 **braid\_PtFcnClone** clone

clone a vector

13.3.2.9 **braid\_PtFcnCoarsen** coarsen

(optional) return a coarsened vector

13.3.2.10 **MPI\_Comm** comm

communicator for the time dimension

13.3.2.11 **MPI\_Comm** comm\_world

13.3.2.12 **braid\_PtFcnDot** dot

dot product

13.3.2.13 **braid\_Int** fmg

use FMG cycle

13.3.2.14 **braid\_PtFcnFree** free

free up a vector

13.3.2.15 **braid\_Real** globaltime

global wall time for [braid\\_Drive\(\)](#)

13.3.2.16 **\_braid\_Grid\*\*** grids

pointer to temporal grid structures for each level

13.3.2.17 **braid\_Int** gupper

global upper index on the fine grid

13.3.2.18 **braid\_PtFcnInit** init

return an initialized braid\_Vector

**13.3.2.19 braid\_Real locltime**

local wall time for [braid\\_Drive\(\)](#)

**13.3.2.20 braid\_Int max\_coarse**

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

**13.3.2.21 braid\_Int max\_iter**

maximum number of multigrid in time iterations

**13.3.2.22 braid\_Int max\_levels**

maximum number of temporal grid levels

**13.3.2.23 braid\_Int nfmg\_Vcyc**

number of V-cycle calls at each level in FMG

**13.3.2.24 braid\_Int niter**

number of iterations

**13.3.2.25 braid\_Int nlevels**

number of temporal grid levels

**13.3.2.26 braid\_Int nrdefault**

default number of pre-relaxations

**13.3.2.27 braid\_Int\* nrels**

number of pre-relaxations on each level

**13.3.2.28 braid\_Int ntime**

initial number of time intervals

**13.3.2.29 braid\_PtFcnPhi phi**

apply phi function

**13.3.2.30 braid\_Int print\_level**

determines amount of output printed to screen (0,1,2)

**13.3.2.31 braid\_PtFcnRefine refine**

(optional) return a refined vector

**13.3.2.32 braid\_Int\* rfactors**

refinement factors for finest grid (if any)

**13.3.2.33 **braid\_Real rnorm****

residual norm

**13.3.2.34 **braid\_Int rtol****

use relative tolerance

**13.3.2.35 **braid\_PtFcnSum sum****

vector sum

**13.3.2.36 **braid\_Real tol****

stopping tolerance

**13.3.2.37 **braid\_Real tstart****

start time

**13.3.2.38 **braid\_Real tstop****

stop time

**13.3.2.39 **braid\_PtFcnWrite write****

write the vector

**13.3.2.40 **braid\_Int write\_level****

determines how often to call the user's write routine

The documentation for this struct was generated from the following file:

- [\\_braid.h](#)

## 13.4 **\_braid\_Grid Struct Reference**

### Data Fields

- [braid\\_Int level](#)
- [braid\\_Int ilower](#)
- [braid\\_Int iupper](#)
- [braid\\_Int clower](#)
- [braid\\_Int cupper](#)
- [braid\\_Int cfactor](#)
- [braid\\_Int ncpoints](#)
- [braid\\_Vector \\* ua](#)
- [braid\\_Real \\* ta](#)
- [braid\\_Vector \\* va](#)
- [braid\\_Vector \\* wa](#)
- [braid\\_Int recv\\_index](#)
- [braid\\_Int send\\_index](#)
- [\\_braid\\_CommHandle \\* recv\\_handle](#)
- [\\_braid\\_CommHandle \\* send\\_handle](#)

- `braid_Vector * ua_alloc`
- `braid_Real * ta_alloc`
- `braid_Vector * va_alloc`
- `braid_Vector * wa_alloc`

#### 13.4.1 Detailed Description

Braid Grid structure for a certain time level

Holds all the information for a processor related to the temporal grid at this level.

#### 13.4.2 Field Documentation

##### 13.4.2.1 `braid_Int cfactor`

coarsening factor

##### 13.4.2.2 `braid_Int clower`

smallest C point index

##### 13.4.2.3 `braid_Int cupper`

largest C point index

##### 13.4.2.4 `braid_Int ilower`

smallest time index at this level

##### 13.4.2.5 `braid_Int iupper`

largest time index at this level

##### 13.4.2.6 `braid_Int level`

Level that grid is on

##### 13.4.2.7 `braid_Int ncpoints`

number of C points

##### 13.4.2.8 `_braid_CommHandle* recv_handle`

Handle for nonblocking receives of braid\_Vectors

##### 13.4.2.9 `braid_Int recv_index`

-1 means no receive

##### 13.4.2.10 `_braid_CommHandle* send_handle`

Handle for nonblocking sends of braid\_Vectors

##### 13.4.2.11 `braid_Int send_index`

-1 means no send

**13.4.2.12 braid\_Real\* ta**

time values (all points)

**13.4.2.13 braid\_Real\* ta\_alloc**

original memory allocation for ta

**13.4.2.14 braid\_Vector\* ua**

unknown vectors (C-points only)

**13.4.2.15 braid\_Vector\* ua\_alloc**

original memory allocation for ua

**13.4.2.16 braid\_Vector\* va**

restricted unknown vectors (all points, NULL on level 0)

**13.4.2.17 braid\_Vector\* va\_alloc**

original memory allocation for va

**13.4.2.18 braid\_Vector\* wa**

rhs vectors f-v (all points, NULL on level 0)

**13.4.2.19 braid\_Vector\* wa\_alloc**

original memory allocation for wa

The documentation for this struct was generated from the following file:

- [\\_braid.h](#)

## 13.5 \_braid\_Status Struct Reference

### Data Fields

- [braid\\_Int iter](#)
- [braid\\_Int level](#)
- [braid\\_Real rnorm](#)
- [braid\\_Int done](#)

### 13.5.1 Detailed Description

Points to the status structure which defines the status of Braid at a given instant on a some level during a run. The user accesses it through `braid_Get**Status()` functions.

### 13.5.2 Field Documentation

#### 13.5.2.1 braid\_Int done

boolean describing whether Braid has finished

### 13.5.2.2 **braid\_Int iter**

Braid iteration number

### 13.5.2.3 **braid\_Int level**

current level in Braid

### 13.5.2.4 **braid\_Real rnorm**

residual norm

The documentation for this struct was generated from the following file:

- [\\_braid.h](#)

## 14 File Documentation

### 14.1 **\_braid.h** File Reference

#### Data Structures

- [struct \\_braid\\_Status](#)
- [struct \\_braid\\_CommHandle](#)
- [struct \\_braid\\_AccuracyHandle](#)
- [struct \\_braid\\_Grid](#)
- [struct \\_braid\\_Core](#)

#### Macros

- [#define \\_braid\\_CommHandleElt\(handle, elt\) \(\(handle\) -> elt\)](#)
- [#define \\_braid\\_GridElt\(grid, elt\) \(\(grid\) -> elt\)](#)
- [#define \\_braid\\_StatusElt\(status, elt\) \( \(status\) -> elt \)](#)
- [#define \\_braid\\_CoreElt\(core, elt\) \( \(core\) -> elt \)](#)
- [#define \\_braid\\_CoreFcn\(core, fcn\) \(\\*\(\(core\) -> fcn\)\)](#)
- [#define \\_braid\\_TAlloc\(type, count\) \( \(type \\*\)malloc\(\(size\\_t\)\(sizeof\(type\) \\* \(count\)\)\) \)](#)
- [#define \\_braid\\_CTAalloc\(type, count\) \( \(type \\*\)calloc\(\(size\\_t\)\(count\), \(size\\_t\)sizeof\(type\)\) \)](#)
- [#define \\_braid\\_TReAlloc\(ptr, type, count\) \( \(type \\*\)realloc\(\(char \\*\)ptr, \(size\\_t\)\(sizeof\(type\) \\* \(count\)\)\) \)](#)
- [#define \\_braid\\_TFree\(ptr\) \( free\(\(char \\*\)ptr\), ptr = NULL \)](#)
- [#define \\_braid\\_MapFineToCoarse\(findex, cfactor, cindex\) \( cindex = \(findex\)/\(cfactor\) \)](#)
- [#define \\_braid\\_MapCoarseToFine\(cindex, cfactor, findex\) \( findex = \(cindex\)\\*\(cfactor\) \)](#)
- [#define \\_braid\\_IsFPoint\(index, cfactor\) \( \(index\)% \(cfactor\) \)](#)
- [#define \\_braid\\_IsCPoint\(index, cfactor\) \( !\\_braid\\_IsFPoint\(index, cfactor\) \)](#)

#### Functions

- [braid\\_Int \\_braid\\_GetDistribution \(braid\\_Core core, braid\\_Int \\*ilower\\_ptr, braid\\_Int \\*iupper\\_ptr\)](#)
- [braid\\_Int \\_braid\\_GetProc \(braid\\_Core core, braid\\_Int level, braid\\_Int index, braid\\_Int \\*proc\\_ptr\)](#)
- [braid\\_Int \\_braid\\_CommRecvInit \(braid\\_Core core, braid\\_Int level, braid\\_Int index, braid\\_Vector \\*vector\\_ptr, \\_braid\\_CommHandle \\*\\*handle\\_ptr\)](#)

- `braid_Int _braid_CommSendInit (braid_Core core, braid_Int level, braid_Int index, braid_Vector vector, _braid_CommHandle **handle_ptr)`
- `braid_Int _braid_CommWait (braid_Core core, _braid_CommHandle **handle_ptr)`
- `braid_Int _braid_UCommInit (braid_Core core, braid_Int level)`
- `braid_Int _braid_UCommInitF (braid_Core core, braid_Int level)`
- `braid_Int _braid_UCommWait (braid_Core core, braid_Int level)`
- `braid_Int _braid_UGetInterval (braid_Core core, braid_Int level, braid_Int interval_index, braid_Int *flo_ptr, braid_Int *fhi_ptr, braid_Int *ci_ptr)`
- `braid_Int _braid_UGetVectorRef (braid_Core core, braid_Int level, braid_Int index, braid_Vector *u_ptr)`
- `braid_Int _braid_USetVectorRef (braid_Core core, braid_Int level, braid_Int index, braid_Vector u)`
- `braid_Int _braid_UGetVector (braid_Core core, braid_Int level, braid_Int index, braid_Vector *u_ptr)`
- `braid_Int _braid_USetVector (braid_Core core, braid_Int level, braid_Int index, braid_Vector u)`
- `braid_Int _braid_UWriteVector (braid_Core core, braid_Int level, braid_Int index, braid_Status status, braid_Vector u)`
- `braid_Int _braid_Phi (braid_Core core, braid_Int level, braid_Int index, braid_Real accuracy, braid_Vector u, braid_Int *rfactor)`
- `braid_Int _braid_Step (braid_Core core, braid_Int level, braid_Int index, braid_Real accuracy, braid_Vector u)`
- `braid_Int _braid_Coarsen (braid_Core core, braid_Int level, braid_Int f_index, braid_Int c_index, braid_Vector fvector, braid_Vector *cvector)`
- `braid_Int _braid_Refine (braid_Core core, braid_Int level, braid_Int f_index, braid_Int c_index, braid_Vector cvector, braid_Vector *fvector)`
- `braid_Int _braid_GridInit (braid_Core core, braid_Int level, braid_Int ilower, braid_Int iupper, _braid_Grid **grid_ptr)`
- `braid_Int _braid_GridDestroy (braid_Core core, _braid_Grid *grid)`
- `braid_Int _braid_InitGuess (braid_Core core, braid_Int level)`
- `braid_Int _braid_CFRelax (braid_Core core, braid_Int level)`
- `braid_Int _braid_FRestrict (braid_Core core, braid_Int level, braid_Int iter, braid_Real *rnorm_ptr)`
- `braid_Int _braid_FInterp (braid_Core core, braid_Int level, braid_Int iter, braid_Real rnorm)`
- `braid_Int _braid_FRefine (braid_Core core, braid_Int *refined_ptr)`
- `braid_Int _braid_FWrite (braid_Core core, braid_Real rnorm, braid_Int iter, braid_Int level, braid_Int done)`
- `braid_Int _braid_InitHierarchy (braid_Core core, _braid_Grid *fine_grid)`
- `braid_Int _braid_InitStatus (braid_Real rnorm, braid_Int iter, braid_Int level, braid_Int done, braid_Status *status_ptr)`
- `braid_Int _braid_DestroyStatus (braid_Status status)`

## Variables

- `braid_Int _braid_error_flag`
- `FILE * _braid_printfile`

### 14.1.1 Detailed Description

Define headers for developer routines. This file contains the headers for developer routines.

### 14.1.2 Macro Definition Documentation

#### 14.1.2.1 `#define _braid_CommHandleElt( handle, elt ) ((handle) -> elt)`

Accessor for `_braid_CommHandle` attributes

14.1.2.2 `#define _braid_CoreElt( core, elt )( (core) -> elt )`

Accessor for `_braid_Core` attributes

14.1.2.3 `#define _braid_CoreFcn( core, fcn )( *((core) -> fcn) )`

Accessor for `_braid_Core` functions

14.1.2.4 `#define _braid_CTAalloc( type, count )( (type *)calloc((size_t)(count), (size_t)sizeof(type)) )`

Allocation macro

14.1.2.5 `#define _braid_GridElt( grid, elt )( (grid) -> elt )`

Accessor for `_braid_Grid` attributes

14.1.2.6 `#define _braid_IsCPoint( index, cfactor )( !_braid_IsFPoint(index, cfactor) )`

Boolean, returns whether a time index is an C-point

14.1.2.7 `#define _braid_IsFPoint( index, cfactor )( (index)%cfactor )`

Boolean, returns whether a time index is an F-point

14.1.2.8 `#define _braid_MapCoarseToFine( cindex, cfactor, findex )( finDEX = (cindex)*(cfactor) )`

Map a coarse time index to a fine time index, assumes a uniform coarsening factor.

14.1.2.9 `#define _braid_MapFineToCoarse( finDEX, cfactor, cindex )( cindex = (finDEX)/(cfactor) )`

Map a fine time index to a coarse time index, assumes a uniform coarsening factor.

14.1.2.10 `#define _braid_StatusElT( status, elt )( (status) -> elt )`

Accessor for `_braid_Status` attributes

14.1.2.11 `#define _braid_TAlloc( type, count )( (type *)malloc((size_t)(sizeof(type) * (count))) )`

Allocation macro

14.1.2.12 `#define _braid_TFree( ptr )( free((char *)ptr), ptr = NULL )`

Free memory macro

14.1.2.13 `#define _braid_TReAlloc( ptr, type, count )( (type *)realloc((char *)ptr, (size_t)(sizeof(type) * (count))) )`

Re-allocation macro

### 14.1.3 Function Documentation

14.1.3.1 `braid_Int_braid_CFRelax( braid_Core core, braid_Int level )`

Do nu sweeps of F-then-C relaxation on *level*

---

**14.1.3.2 braid\_Int \_braid\_Coarsen ( braid\_Core core, braid\_Int level, braid\_Int f\_index, braid\_Int c\_index, braid\_Vector fvector, braid\_Vector \* cvector )**

Coarsen in space on *level* by calling the user's coarsen function. The vector corresponding to the time step index *f\_index* on the fine grid is coarsened to the time step index *c\_index* on the coarse grid. The output goes in *cvector* and the input vector is *fvector*.

**14.1.3.3 braid\_Int \_braid\_CommRecvInit ( braid\_Core core, braid\_Int level, braid\_Int index, braid\_Vector \* vector\_ptr, \_braid\_CommHandle \*\* handle\_ptr )**

Initialize a receive to go into *vector\_ptr* for the given time *index* on *level*. Also return a comm handle *handle\_ptr* for querying later, to see if the receive has occurred.

**14.1.3.4 braid\_Int \_braid\_CommSendInit ( braid\_Core core, braid\_Int level, braid\_Int index, braid\_Vector vector, \_braid\_CommHandle \*\* handle\_ptr )**

Initialize a send of *vector* for the given time *index* on *level*. Also return a comm handle *handle\_ptr* for querying later, to see if the send has occurred.

**14.1.3.5 braid\_Int \_braid\_CommWait ( braid\_Core core, \_braid\_CommHandle \*\* handle\_ptr )**

Block on the comm handle *handle\_ptr* until the MPI operation (send or recv) has completed

**14.1.3.6 braid\_Int \_braid\_DestroyStatus ( braid\_Status status )**

Destroy a braid\_Status structure

**14.1.3.7 braid\_Int \_braid\_Finterp ( braid\_Core core, braid\_Int level, braid\_Int iter, braid\_Real rnorm )**

F-Relax on *level* and interpolate to *level-1*

The output is set in the braid\_Grid in core, so that the vector *u* on *level* is created by interpolating from *level+1*.

If the user has set spatial refinement, then this user-defined routine is also called.

#### Parameters

<i>core</i>	braid_Core ( <a href="#">_braid_Core</a> ) struct
<i>level</i>	interp from level to level+1
<i>iter</i>	current iteration number (for user info)
<i>rnorm</i>	residual norm (if level 0)

**14.1.3.8 braid\_Int \_braid\_FRefine ( braid\_Core core, braid\_Int \* refined\_ptr )**

Create a new fine grid based on user refinement factor information, then F-relax and interpolate to the new fine grid and create a new multigrid hierarchy. In general, this will require load re-balancing as well.

RDF: Todo, routine is unwritten

**14.1.3.9 braid\_Int \_braid\_FRestrict ( braid\_Core core, braid\_Int level, braid\_Int iter, braid\_Real \* rnorm\_ptr )**

F-Relax on *level* and then restrict to *level+1*

The output is set in the braid\_Grid in core, so that the restricted vectors *va* and *wa* will be created, representing *level+1* versions of the unknown and rhs vectors.

If the user has set spatial coarsening, then this user-defined routine is also called.

If *level==0*, then *rnorm\_ptr* will contain the residual norm.

### Parameters

<i>core</i>	braid_Core ( <a href="#">_braid_Core</a> ) struct
<i>level</i>	restrict from level to level+1
<i>iter</i>	current iteration number (for user info)
<i>rnorm_ptr</i>	pointer to residual norm (if level 0)

14.1.3.10 **braid\_Int\_braid\_FWrite** ( **braid\_Core core**, **braid\_Real rnorm**, **braid\_Int iter**, **braid\_Int level**, **braid\_Int done** )

Write out the solution on grid *level* at Braid iteration *iter*.

*rnorm* denotes the last computed residual norm, and *done* is a boolean indicating whether Braid has finished iterating and this is the last Write call.

14.1.3.11 **braid\_Int\_braid\_GetDistribution** ( **braid\_Core core**, **braid\_Int \* ilower\_ptr**, **braid\_Int \* iupper\_ptr** )

Determine processor distribution. This must agree with GetProc(). For the processor rank calling this function, it returns the smallest and largest time indices ( *ilower\_ptr* and *iupper\_ptr* ) that belong to that processor (the indices may \* be F or C points).

14.1.3.12 **braid\_Int\_braid\_GetProc** ( **braid\_Core core**, **braid\_Int level**, **braid\_Int index**, **braid\_Int \* proc\_ptr** )

Return the processor number in *proc\_ptr* on which the time step *index* lives for the given *level*. \* Returns -1 if *index* is out of range

14.1.3.13 **braid\_Int\_braid\_GridDestroy** ( **braid\_Core core**, **\_braid\_Grid \* grid** )

Destroy a Braid *grid*

14.1.3.14 **braid\_Int\_braid\_GridInit** ( **braid\_Core core**, **braid\_Int level**, **braid\_Int ilower**, **braid\_Int iupper**, **\_braid\_Grid \*\* grid\_ptr** )

Create a new grid object *grid\_ptr* in *core* at *level*

*ilower* and *iupper* correspond to the lower and upper time index values for this processor on this grid.

14.1.3.15 **braid\_Int\_braid\_InitGuess** ( **braid\_Core core**, **braid\_Int level** )

Set initial guess at C-points on *level*

14.1.3.16 **braid\_Int\_braid\_InitHierarchy** ( **braid\_Core core**, **\_braid\_Grid \* fine\_grid** )

Initialize (and re-initialize) hierarchy

14.1.3.17 **braid\_Int\_braid\_InitStatus** ( **braid\_Real rnorm**, **braid\_Int iter**, **braid\_Int level**, **braid\_Int done**, **braid\_Status \* status\_ptr** )

Initialize a braid\_Status structure in *status\_ptr*, setting the status values *rnorm*, *iter*, *level*, *done*

14.1.3.18 **braid\_Int\_braid\_Phi** ( **braid\_Core core**, **braid\_Int level**, **braid\_Int index**, **braid\_Real accuracy**, **braid\_Vector u**, **braid\_Int \* rfactor** )

Apply Phi to the vector *u*

This is the vector corresponding to the time step *index* on *level*. *accuracy* is a user set variable to allow for tuning the accuracy of spatial solves for implicit stepping. And, *rfactor* allows the user to subdivide time intervals for accuracy purposes.

---

14.1.3.19 **braid\_Int\_braid\_Refine ( braid\_Core core, braid\_Int level, braid\_Int f\_index, braid\_Int c\_index, braid\_Vector cvector, braid\_Vector \*fvector )**

Refine in space on *level* by calling the user's refine function. The vector corresponding to the time step index *c\_index* on the coarse grid is refined to the time step index *f\_index* on the fine grid. The output goes in *fvector* and the input vector is *cvector*.

14.1.3.20 **braid\_Int\_braid\_Step ( braid\_Core core, braid\_Int level, braid\_Int index, braid\_Real accuracy, braid\_Vector u )**

Integrate one time step at time step *index* to time step *index+1*

14.1.3.21 **braid\_Int\_braid\_UCommInit ( braid\_Core core, braid\_Int level )**

Working on all intervals

At *level*, post a receive for the point to the left of ilower (regardless whether ilower is F or C). Then, post a send of iupper if iupper is a C point.

14.1.3.22 **braid\_Int\_braid\_UCommInitF ( braid\_Core core, braid\_Int level )**

Working only on F-pt intervals

At *level*, **only** post a receive for the point to the left of ilower if ilower is an F point. Then, post a send of iupper if iupper is a C point.

14.1.3.23 **braid\_Int\_braid\_UCommWait ( braid\_Core core, braid\_Int level )**

Finish up communication

On *level*, wait on both the recv and send handles at this level.

14.1.3.24 **braid\_Int\_braid\_UGetInterval ( braid\_Core core, braid\_Int level, braid\_Int interval\_index, braid\_Int \*flo\_ptr, braid\_Int \*fhi\_ptr, braid\_Int \*ci\_ptr )**

Retrieve the time step indices at this *level* which correspond to the FC interval given by *interval\_index*. *ci\_ptr* is the time step index for the C point and *flo\_ptr* and *fhi\_ptr* are the smallest and largest F point indices in this interval. *flo* = *ci* + 1, and *fhi* = *ci* + coarsening\_factor - 1

14.1.3.25 **braid\_Int\_braid\_UGetVector ( braid\_Core core, braid\_Int level, braid\_Int index, braid\_Vector \*u\_ptr )**

Returns the u-vector in *u\_ptr* on grid *level* at point *index*. If *index* is my "receive index" (as set by UCommInit(), for example), the u-vector will be received from a neighbor processor. If *index* is within my index range and is also a C-point, the saved value of u will be used. A NULL value is returned otherwise.

14.1.3.26 **braid\_Int\_braid\_UGetVectorRef ( braid\_Core core, braid\_Int level, braid\_Int index, braid\_Vector \*u\_ptr )**

Returns a reference to the local u-vector in *u\_ptr* for the grid *level* at point *index*. Caveat: if *index* is not a C-point and within my index range, NULL is returned.

14.1.3.27 **braid\_Int\_braid\_USetVector ( braid\_Core core, braid\_Int level, braid\_Int index, braid\_Vector u )**

Sets the u-vector on grid *level* at point *index*. If *index* is my "send index" (as set by UCommInit(), for example), a send is initiated to a neighbor processor. If *index* is within my index range and is also a C-point, the value is saved locally.

### 14.1.3.28 `braid_Int_braid_USetVectorRef ( braid_Core core, braid_Int level, braid_Int index, braid_Vector u )`

Stores a reference to the vector *u* on grid *level* at point *index*. If *index* is not a C-point and within this processor's range of time points, then nothing is done.

### 14.1.3.29 `braid_Int_braid_UWriteVector ( braid_Core core, braid_Int level, braid_Int index, braid_Status status, braid_Vector u )`

Call the user's write function to write *u* which is the vector corresponding to time step *index* on *level*. *status* holds state information about the current Braid iteration, time value, etc...

## 14.1.4 Variable Documentation

### 14.1.4.1 `braid_Int_braid_error_flag`

This is the global Braid error flag. If it is ever nonzero, an error has occurred.

### 14.1.4.2 `FILE* _braid_printfile`

This is the print file for redirecting std::cout for all Braid screen output

## 14.2 braid.h File Reference

### Typedefs

- `typedef int braid_Int`
- `typedef double braid_Real`
- `typedef struct _braid_App_struct * braid_App`
- `typedef struct _braid_Vector_struct * braid_Vector`
- `typedef struct _braid_Status_struct * braid_Status`
- `typedef braid_Int(* braid_PtFcnPhi )(braid_App app, braid_Real tstart, braid_Real tstop, braid_Real accuracy, braid_Vector u, braid_Int *rfactor_ptr)`
- `typedef braid_Int(* braid_PtFcnInit )(braid_App app, braid_Real t, braid_Vector *u_ptr)`
- `typedef braid_Int(* braid_PtFcnClone )(braid_App app, braid_Vector u, braid_Vector *v_ptr)`
- `typedef braid_Int(* braid_PtFcnFree )(braid_App app, braid_Vector u)`
- `typedef braid_Int(* braid_PtFcnSum )(braid_App app, braid_Real alpha, braid_Vector x, braid_Real beta, braid_Vector y)`
- `typedef braid_Int(* braid_PtFcnDot )(braid_App app, braid_Vector u, braid_Vector v, braid_Real *dot_ptr)`
- `typedef braid_Int(* braid_PtFcnWrite )(braid_App app, braid_Real t, braid_Status status, braid_Vector u)`
- `typedef braid_Int(* braid_PtFcnBufSize )(braid_App app, braid_Int *size_ptr)`
- `typedef braid_Int(* braid_PtFcnBufPack )(braid_App app, braid_Vector u, void *buffer)`
- `typedef braid_Int(* braid_PtFcnBufUnpack )(braid_App app, void *buffer, braid_Vector *u_ptr)`
- `typedef braid_Int(* braid_PtFcnCoarsen )(braid_App app, braid_Real tstart, braid_Real f_tminus, braid_Real f_tplus, braid_Real c_tminus, braid_Real c_tplus, braid_Vector fu, braid_Vector *cu_ptr)`
- `typedef braid_Int(* braid_PtFcnRefine )(braid_App app, braid_Real tstart, braid_Real f_tminus, braid_Real f_tplus, braid_Real c_tminus, braid_Real c_tplus, braid_Vector cu, braid_Vector *fu_ptr)`
- `typedef struct _braid_Core_struct * braid_Core`

## Functions

- `braid_Int braid_Init (MPI_Comm comm_world, MPI_Comm comm, braid_Real tstart, braid_Real tstop, braid_Int ntime, braid_App app, braid_PtFcnPhi phi, braid_PtFcnInit init, braid_PtFcnClone clone, braid_PtFcnFree free, braid_PtFcnSum sum, braid_PtFcnDot dot, braid_PtFcnWrite write, braid_PtFcnBufSize bufsize, braid_PtFcnBufPack bufpack, braid_PtFcnBufUnpack bufunpack, braid_Core *core_ptr)`
- `braid_Int braid_Drive (braid_Core core)`
- `braid_Int braid_Destroy (braid_Core core)`
- `braid_Int braid_PrintStats (braid_Core core)`
- `braid_Int braid_SetLooseTol (braid_Core core, braid_Int level, braid_Real loose_tol)`
- `braid_Int braid_SetTightTol (braid_Core core, braid_Int level, braid_Real tight_tol)`
- `braid_Int braid_SetMaxLevels (braid_Core core, braid_Int max_levels)`
- `braid_Int braid_SetMaxCoarse (braid_Core core, braid_Int max_coarse)`
- `braid_Int braid_SetAbsTol (braid_Core core, braid_Real atol)`
- `braid_Int braid_SetRelTol (braid_Core core, braid_Real rtol)`
- `braid_Int braid_SetNRelax (braid_Core core, braid_Int level, braid_Int nrelax)`
- `braid_Int braid_SetCFactor (braid_Core core, braid_Int level, braid_Int cfactor)`
- `braid_Int braid_SetMaxIter (braid_Core core, braid_Int max_iter)`
- `braid_Int braid_SetFMG (braid_Core core)`
- `braid_Int braid_SetNFMGVcyc (braid_Core core, braid_Int nfmvg_Vcyc)`
- `braid_Int braid_SetSpatialCoarsen (braid_Core core, braid_PtFcnCoarsen coarsen)`
- `braid_Int braid_SetSpatialRefine (braid_Core core, braid_PtFcnRefine refine)`
- `braid_Int braid_SetPrintLevel (braid_Core core, braid_Int print_level)`
- `braid_Int braid_SetPrintFile (braid_Core core, const char *printfile_name)`
- `braid_Int braid_SetWriteLevel (braid_Core core, braid_Int write_level)`
- `braid_Int braid_SplitCommworld (const MPI_Comm *comm_world, braid_Int px, MPI_Comm *comm_x, MPI_Comm *comm_t)`
- `braid_Int braid_GetStatusResidual (braid_Status status, braid_Real *rnorm_ptr)`
- `braid_Int braid_GetStatusIter (braid_Status status, braid_Int *iter_ptr)`
- `braid_Int braid_GetStatusLevel (braid_Status status, braid_Int *level_ptr)`
- `braid_Int braid_GetStatusDone (braid_Status status, braid_Int *done_ptr)`
- `braid_Int braid_GetNumIter (braid_Core core, braid_Int *niter_ptr)`
- `braid_Int braid_GetRNorm (braid_Core core, braid_Real *rnorm_ptr)`

### 14.2.1 Detailed Description

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

### 14.2.2 Typedef Documentation

#### 14.2.2.1 `typedef int braid_Int`

Defines integer type

#### 14.2.2.2 `typedef double braid_Real`

Defines floating point type

## 14.3 braid\_test.h File Reference

### Functions

- `braid_Int braid_TestInitWrite (braid_App app, MPI_Comm comm_x, FILE *fp, braid_Real t, braid_PtFcnInit init, braid_PtFcnWrite write, braid_PtFcnFree free)`
- `braid_Int braid_TestClone (braid_App app, MPI_Comm comm_x, FILE *fp, braid_Real t, braid_PtFcnInit init, braid_PtFcnWrite write, braid_PtFcnFree free, braid_PtFcnClone clone)`
- `braid_Int braid_TestSum (braid_App app, MPI_Comm comm_x, FILE *fp, braid_Real t, braid_PtFcnInit init, braid_PtFcnWrite write, braid_PtFcnFree free, braid_PtFcnClone clone, braid_PtFcnSum sum)`
- `braid_Int braid_TestDot (braid_App app, MPI_Comm comm_x, FILE *fp, braid_Real t, braid_PtFcnInit init, braid_PtFcnFree free, braid_PtFcnClone clone, braid_PtFcnSum sum, braid_PtFcnDot dot)`
- `braid_Int braid_TestBuf (braid_App app, MPI_Comm comm_x, FILE *fp, braid_Real t, braid_PtFcnInit init, braid_PtFcnFree free, braid_PtFcnSum sum, braid_PtFcnDot dot, braid_PtFcnBufSize bufsize, braid_PtFcnBufPack bufpack, braid_PtFcnBufUnpack bufunpack)`
- `braid_Int braid_TestCoarsenRefine (braid_App app, MPI_Comm comm_x, FILE *fp, braid_Real t, braid_Real fdt, braid_Real cdt, braid_PtFcnInit init, braid_PtFcnWrite write, braid_PtFcnFree free, braid_PtFcnClone clone, braid_PtFcnSum sum, braid_PtFcnDot dot, braid_PtFcnCoarsen coarsen, braid_PtFcnRefine refine)`
- `braid_Int braid_TestAll (braid_App app, MPI_Comm comm_x, FILE *fp, braid_Real t, braid_Real fdt, braid_Real cdt, braid_PtFcnInit init, braid_PtFcnFree free, braid_PtFcnClone clone, braid_PtFcnSum sum, braid_PtFcnDot dot, braid_PtFcnBufSize bufsize, braid_PtFcnBufPack bufpack, braid_PtFcnBufUnpack bufunpack, braid_PtFcnCoarsen coarsen, braid_PtFcnRefine refine)`

### 14.3.1 Detailed Description

Define headers for Braid test routines. This file contains routines used to test a user's Braid wrapper routines one-by-one.

## 14.4 util.h File Reference

### Functions

- `braid_Int _braid_ProjectInterval (braid_Int ilower, braid_Int iupper, braid_Int index, braid_Int stride, braid_Int *pilower, braid_Int *piupper)`
- `braid_Int _braid_SetAccuracy (braid_Real rnorm, braid_Real loose_tol, braid_Real tight_tol, braid_Real old_Accuracy, braid_Real tol, braid_Real *paccuracy)`
- `braid_Int _braid_printf (const char *format,...)`
- `braid_Int _braid_ParPrintfFlush (FILE *file, braid_Int myid, char *message,...)`

### 14.4.1 Detailed Description

Define headers for utility routines. This file contains the headers for utility routines. Essentially, if a routine does not take braid\_Core (or other Braid specific structs) as an argument, then it's a utility routine.

### 14.4.2 Function Documentation

#### 14.4.2.1 `braid_Int _braid_ParPrintfFlush ( FILE * file, braid_Int myid, char * message, ... )`

This is a function that allows for "sane" printing of information in parallel. Currently, only myid = 0 prints, but this can be updated as needs change.

The string *message* is printed and can be multiple parameters in the standard \* C-format, like

```
message = '%1.2e is a format string', 1.24
```

#### 14.4.2.2 braid\_Int\_braid\_printf( const char \*format, ... )

If set, print to [\\_braid\\_printfile](#) and then flush. Else print to standard out.

The string *format* can be multiple parameters in the standard \* C-format, like

```
format = '%1.2e is a format string', 1.24
```

#### 14.4.2.3 braid\_Int\_braid\_ProjectInterval( braid\_Int *ilower*, braid\_Int *iupper*, braid\_Int *index*, braid\_Int *stride*, braid\_Int \* *pilower*, braid\_Int \* *piupper* )

Project an interval onto a strided index space that contains the index 'index' and has stride 'stride'. An empty projection is represented by *ilower* > *iupper*.

#### 14.4.2.4 braid\_Int\_braid\_SetAccuracy( braid\_Real *rnorm*, braid\_Real *loose\_tol*, braid\_Real *tight\_tol*, braid\_Real *oldAccuracy*, braid\_Real *tol*, braid\_Real \* *paccuracy* )

Determine the accuracy used for the spatial solves based on the ratio of the current residual norm and the stopping tolerance.

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