poisson.h Documentation

Haochen(Langford) Huang

March 11, 2024

1 Introduction and Background

poisson.h serves as toolbox which provides functions to construct V-cycle iteration solver for implicit equations. A specific one for solving poisson equation is constructed within the headfile as an example. We shall first introduce the constructing toolbox.

Assuming the governing equation can be written as

$$f(x) = y \tag{1}$$

where y is the known variable, x is the desired variable and f represents linear operator that satisfies

$$f(x_a + x_b) = f(x_a) + f(x_b) \tag{2}$$

Now consider the discrete form of operator $\hat{f}$ which takes all desired variable from every cell (suppose the total number of cell is n) to express the local known variable y_i then yields the implicit equation group

$$\hat{f}(x_1, x_2, x_3, \cdots, x_n) = y_i \quad i = 1, 2, \cdot, n \tag{3}$$

which can be solved by indirective iterative method such as Jacobi method, G-S method[1] *etc.* Moreover, constraints 2 provide another perspective to construct equation group. Use $x_1^e, x_2^e, \cdots, x_n^e$ to denote exact solution of equation 3 and $x_1^k, x_2^k, \cdots, x_n^k$ to represent result of kth iteration. Following equation 2 we have

$$\hat{f}(\delta x_1^k, \delta x_2^k, \cdots, \delta x_n^k) = RES^k \tag{4}$$

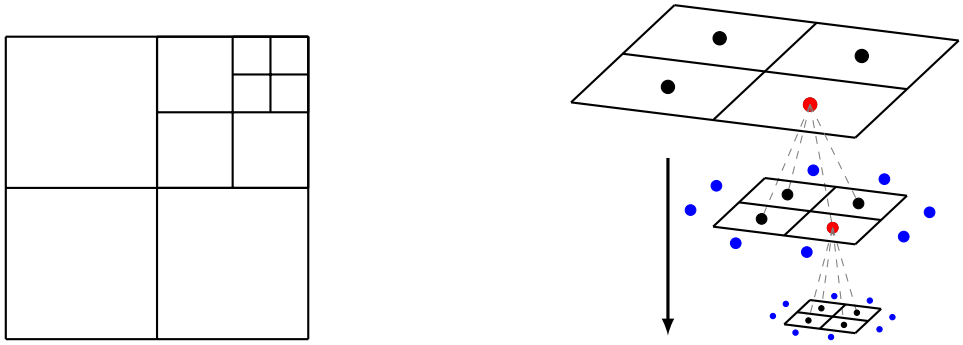
where $\delta x_i^k = x_i^e - x_i^k$, $RES^k = \hat{f}(x_1^e, x_2^e, \cdots, x_n^e) - \hat{f}(x_1^k, x_2^k, \cdots, x_n^k)$. The criterion of solution then becomes $|RES^k|_\infty < \epsilon$ where ϵ is a setting tolerance.

There are many techniques to accelerate the convergence of iteration, and multigrid method[4] may be one of the most famous which employs iterations on every layer of the mesh to reduce the residual of corresponding wavenumber. A similar methodology is applied by quadtree/octree in Basilisk. Take quadtree as an exapmle. Consider tree architecture in Fig.1a, the actual calculating rules for this problem is shown in 1b where ● represents leaf cells (the finest cell at this area and is not divided by higher level) and the value it carrying is the the final value shown in the result called active value. ● represents ghost cell served as boundary condition whose value is computed by bilinear interpolation. Finally ● represents value carried by parent cell. The parent cell, indicated by its name, will be divided into 4(8) children cells in finer layer (level in Basilisk).[3]

A single round of iteration is accomplished by two procedures. First, from highest level to lowest one, assign residual to each cell of current level which form the *R.H.S.* of equation 4. Second, starting from lowest level to the highest, obtain the result after few iterating (by Jacobi method or GS method) on current level and use it to compute initial value on next level. We shall first dive into second procedure which is more sophisticated.

Calculations happens at every level shown in Fig.1b, when it comes to higher level the boundary condition is first set and then undergoes the iteration on cells at same level instead of whole domain. Moreover, the initial value on each level is obtained by prolongation (bilinear mostly) from previous mesh level.

In order to facilitate equation 4 we also need residual, which only exists at leaf cell, of every cell at each level. This procedure is achieve by restricting[2] (averaging mostly) value on 4(8) children cells, which is much simpler compared to bilinear that use in previous description.



(a) 2D quadtree example.

(b) Calculation for each level.

Figure 1: Quadtree example. Arrow in (b) indicates calculating sequence.

After introducing the mesh architecture, we shall now step a little further to see the solver structure provided by 'poisson.h' and to perceive the overall workflow. FIG.2 displays whole system as well as its workflow. As can be seen from the sketch, the whole solver consists of four functions, **mg_solve**, **mg_cycle**, **relax** and **residual**. Their nesting relating is shown by corresponding position, *e.g.* **relax** is inside **mg_cycle** while **residual** and **mg_cycle** locate inside **mg_solve** indicates that **relax** is called by **mg_cycle** and **mg_cycle** along with **residual** are directly called by **mg_solve**. Detailed workflow is also presented, after inputting $\mathbf{x}^0, \mathbf{y}$ before the residual actually meet the tolerance ϵ, **mg_solve** plays as a manager to make rest functions coordinate, $\mathbf{x}^k$ is conveyed between **mg_cycle** and **residual** to renew. Number behind each step represents the order within the loop. $\mathbf{x}^k, \mathbf{y}$ is first sent to residual to compute residual RES^k which served as parameter in **mg_cycle**. $\mathbf{x}^k$ and n are also taken into **mg_cycle**where n controls iteration number on each mesh level. $\mathbf{x}^{k+1}$ is obtained by first solving equation 4 for $\delta\mathbf{x}^k$ then execute update

$$\mathbf{x}^{k+1} = \mathbf{x}^k + \delta\mathbf{x}^k \tag{5}$$

Loop will break out either residual satisfies tolerance constraint or number of round exceed setting threshold. Readers may notice there is no parameters conveyed within **mg_cycle**, this is because relationship between **relax** and **mg_cycle** cannot be simply abstracted as 'linear' as depicted in this figure. Structure inside **mg_cycle** is demonstrate in Fig.3 as described before residual is assigned to each level then relax is called at each level multiple times updating $\delta\mathbf{x}^k$ in the form (condition varies according to iteration method)

$$\delta x_i^k = F(\delta x_1^k, \delta x_2^k, \cdots, \delta x_{i-1}^k, \delta x_{i+1}^k, \cdots, \delta x_n^k, RES^k) \tag{6}$$

Back to **mg_solve**, readers may notice from Fig.2 that all the function within, including **mg_solve** itself, are divided into three layer by dashed line and each layer is named by Roman number from top to bottom. Higher the layer, more irreplaceable the function is. Therefore, functions at III can be changed or altered based on one's purpose. In another word, users can choose their own **relax** and **residual** based on equation they cope with. The governing equation for **poisson.h** is

$$L(a) = \nabla \cdot (\alpha \nabla a) + \lambda a = b \tag{7}$$

where L is a linear operator. Based on above discussion such equation can be solved by multigrid solver only if one constructs appropriate **relax** and **residual** function. Another example is referred to headfile **viscosity.h** where same solver construction is used for totally different linear equation.

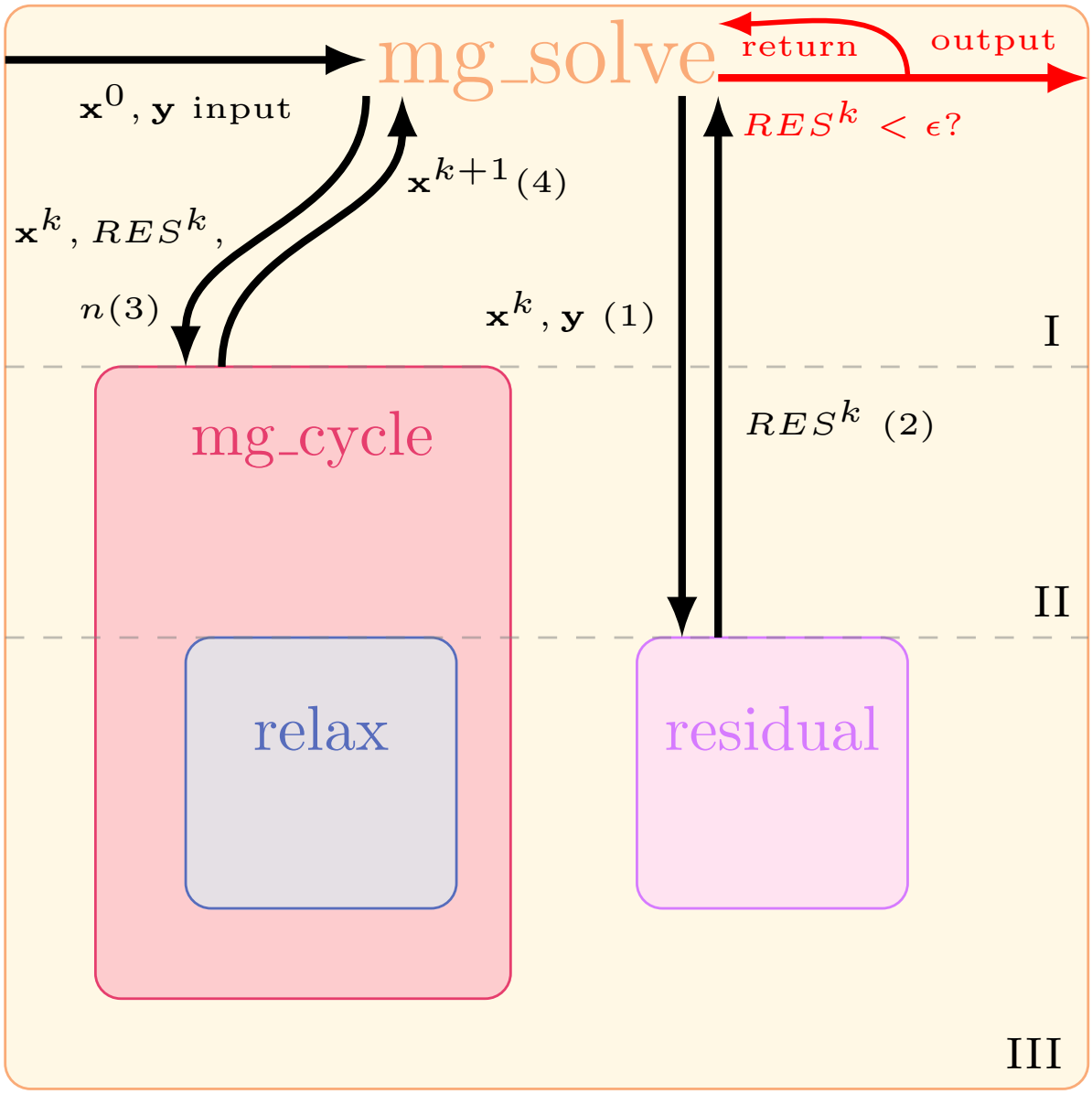


Figure 2: Architecture of the solver. Nested relationship of functions is indicated by box containing relationship *e.g.* **mg_cycle** contains **relax** but not **residual** indicates that **relax** is called in **mg_cycle** while **residual** is called in **mg_solve**.

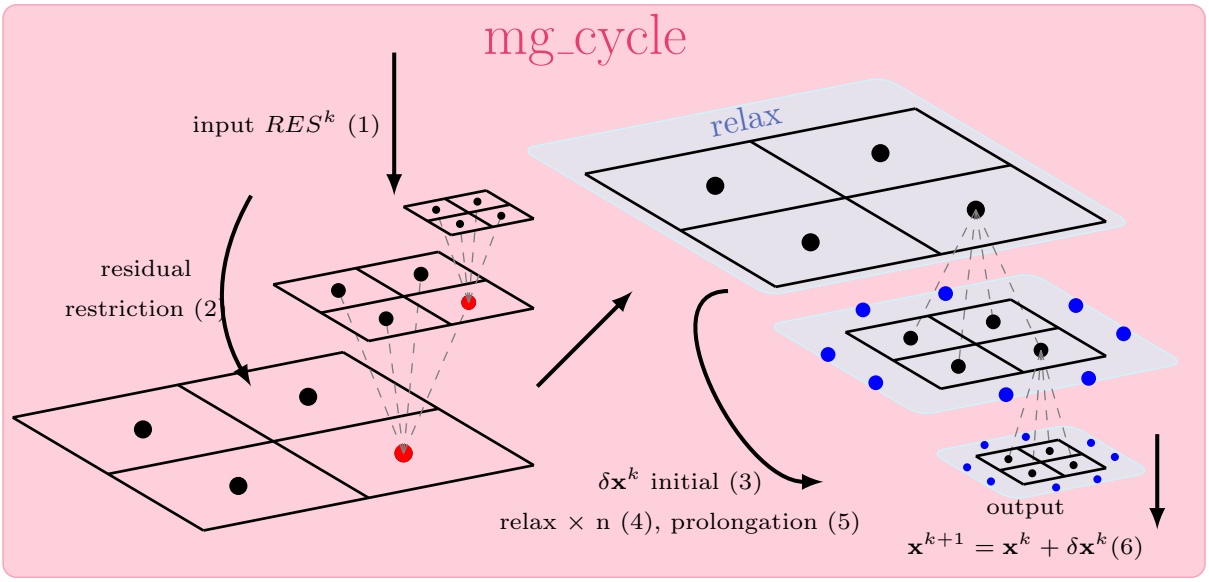


Figure 3: Combination between **mg_cycle** and **relax**. The 'round' of iteration described before is also demonstrated in a detailed way. **relax** herein is embed into every level of the mesh and is executed several times (depends on parameter n) on each level to accelerate convergence.

2 Functions

2.1 mg_cycle

2.1.1 Parameters

Name	Data type	Status	Option/Default	Representation (before/after)
a	scalar*	update	compulsory	$\mathbf{x}^k/\mathbf{x}^{k+1}$
res	scalar*	unchanged	compulsory	$\delta \mathbf{x}^k$
da	scalar*	unchanged	compulsory	$\rho^{n+\frac{1}{2}}$
relax	void*	unchanged	compulsory	**relax**
data	void*	unchanged	compulsory	**Poisson** (struct defined below)
nrelax	int	unchanged	compulsory	n
minlevel	int	unchanged	compulsory	*minlevel*
maxlevel	int	unchanged	compulsory	*maxlevel*

2.1.2 Worth Mentioning Details

As described in Sec.1 and Fig.3 function **mg_cycle** serves as a subcomponent to update the result. Details of such function have been explored before and shall not be repeated here.

2.1.3 Program Workflow

Starting Point
input:
a = x^k *res* = RES^k *da*=δx^k
relax=relax function
data = Poisson structure
nrelax=times relax function applied to each level
minlevel=minimum of mesh level
maxlevel=maximum of mesh level

```
1 void mg_cycle (scalar * a, scalar * res,
  ↪  scalar * da,
2                 void (* relax) (scalar *
                  ↪  da, scalar * res, int
                  ↪  depth, void * data),
3                 void * data, int nrelax,
                  ↪  int minlevel, int
                  ↪  maxlevel)
4 {
```

RES restriction
To restrict residual from finer mesh to coarser mesh.
Entering of iterative
Iterate starting form lowest (coarsest mesh) level.

```
    restriction (res);
    minlevel = min (minlevel, maxlevel);
    for (int l = minlevel; l <= maxlevel;
    ↪  l++) {
```

Initial for Iteration
Set initial guess for each level. If is on the coarsest level, the initial guess is set to 0 otherwise the initial guess comes from bilinear interpolation of coarser level.

```
    if (l == minlevel)
      foreach_level_or_leaf (l)
        for (scalar s in da)
          foreach_blockf (s)
            s[] = 0.;
    else
      foreach_level (l)
        for (scalar s in da)
          foreach_blockf (s)
            s[] = bilinear (point, s);
```

Relax on each level
Boundary condition (value of blue point in figure3) is first calculated and assigned at certain level. After setting the initial value and boundary condition, relaxation is then conduct on each level by employing **relax**. At the same time, $\delta\mathbf{x}$ is computed and restored in *da*.

```
    boundary_level (da, l);
    for (int i = 0; i < nrelax; i++) {
      relax (da, res, l, data);
      boundary_level (da, l);
    }
  }
```

2.2 mg_solve

2.2.1 Parameters

Name	Data type	Status	Option/Default	Representation (before/after)
a	scalar*	update	compulsory	$\mathbf{x}^0/\mathbf{x}^{final}$
b	scalar*	unchanged	compulsory	$\mathbf{y}$
residual	scalar*	unchanged	compulsory	**residual**
relax	void*	unchanged	compulsory	**relax**
data	void*	unchanged	compulsory	**Poisson** (struct defined below)
nrelax	int	unchanged	optional/4	n
res	scalar*	unchanged	compulsory	RES
minlevel	int	unchanged	optional/0	$minlevel$
tolerance	double	unchanged	optional/10^{-3}	ϵ

2.2.2 Worth Mentioning Details

Two optional components **residual** and **relax** are input as void pointer in this function. The return of this function is of self-defined data structure 'mgstats' which indeed contains information of the whole multigrid circle. The information includes *i*: the total number **mg_cycle** is employed inside **mg_solve**, *resb* and *resa*: maximum residual before/after the cycle.

2.2.3 Program Workflow

Initial Settings
NITERMAX=100 and *NITERMIN*=1 is the maximum and minimum times **mg_cycle** employed by **mg_solve** Self-defined structure 'mgstats' serves as return value for all multigrid solver. It contains basic information about this circle.

```
int NITERMAX = 100, NITERMIN = 1;
double TOLERANCE = 1e-3 [*];

typedef struct {
  int i;               // number of iterations
  double resb, resa;   // maximum residual before and after the iterations
  double sum;          // sum of r.h.s.
  int nrelax;          // number of relaxations
  int minlevel;        // minimum level of the multigrid hierarchy
} mgstats;
```

Input
$a = \mathbf{x}^0$, b=$\mathbf{y}$, *nrelax* is the one used in **mg_cycle** *minlevel* is the coarsest mesh level user would like to iterate. *tolerance*=ϵ, *relax* and *residual* are two pointers points to related function **residual** and **relax**.

```
mgstats mg_solve (scalar * a, scalar * b,
                  double (* residual) (scalar * a, scalar * b, scalar * res, void * data),
                  void (* relax) (scalar * da, scalar * res, int depth, void * data),
                  void * data = NULL,
                  int nrelax = 4,
                  scalar * res = NULL,
                  int minlevel = 0,
                  double tolerance = TOLERANCE)
{
```

Pointer Preparation
Note that 'list_clone' directly copy the data to the pointer address instead of point to the original address. Therefore *da* and *a* are two pointers with same data but different address while *pre* point to *res*. If *res* points NULL, *pres* will directly points to the same address. Note the change of *res* hereinafter shall not influence the NULL address of *pres*.

```
  scalar * da = list_clone (a), * pres = res;
```

```
  if (!res)
    res = list_clone (b);
```

Boundary settings and assemble the final result, current direction is d

$flux.d = u_d^{n+\frac{1}{2}} \Phi_d^{n+\frac{1}{2}}$

```
for (int b = 0; b < nboundary; b++)
  for (scalar s in da)
    s.boundary[b] =
    ↪  s.boundary_homogeneous[b];

mgstats s = {0};
double sum = 0.;
scalar rhs = b[0];
foreach (reduction(+:sum))
  sum += rhs[];
s.sum = sum;
s.nrelax = nrelax > 0 ? nrelax : 4;
```

References

[1] Parviz Moin. *Fundamentals of engineering numerical analysis*. Cambridge University Press, 2010.

[2] Stéphane Popinet. "A quadtree-adaptive multigrid solver for the Serre–Green–Naghdi equations". In: *Journal of Computational Physics* 302 (2015), pp. 336–358.

[3] J Antoon Van Hooft et al. "Towards adaptive grids for atmospheric boundary-layer simulations". In: *Boundary-layer meteorology* 167 (2018), pp. 421–443.

[4] Pieter Wesseling. *Introduction to multigrid methods*. Tech. rep. 1995.