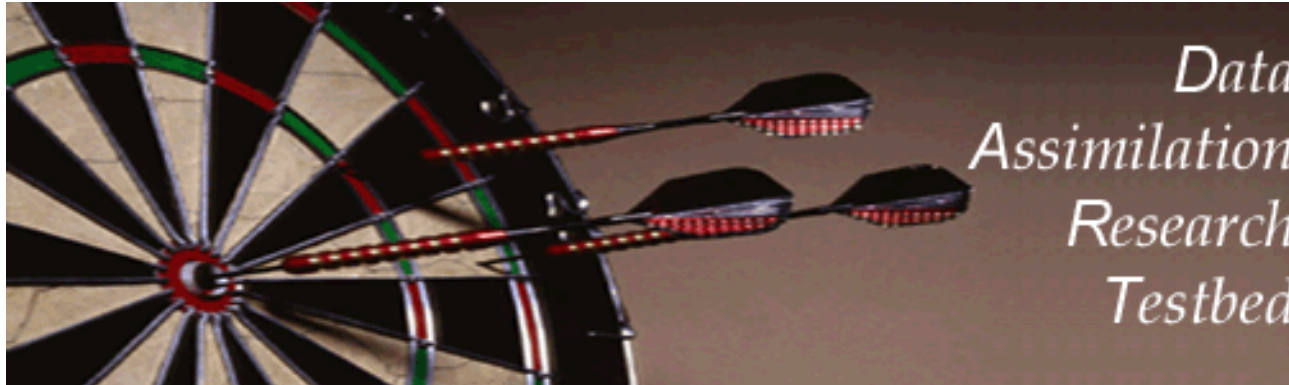


Data Assimilation Research Testbed Tutorial



Section 22: Parallel Algorithm Implementation

Version 2.0: November, 2006

A simple example assimilation cycle.

1. Model with six state vector components a, b, c, d, e and f.
2. Four observations at first time are p, q, r, and s.
3. Three threads referred to as PE0, PE1 and PE2.
4. Three ensemble members.

State vector elements referred to by a 2-character alphanumeric string.

First character is the state variable component.

Second character is which copy of this state vector component.

Copies can be ensemble members or other adjunct quantities.

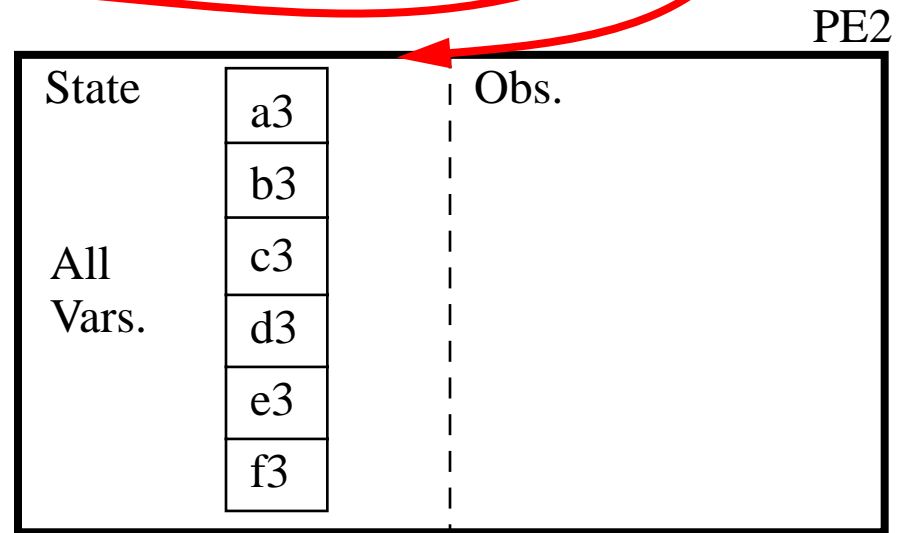
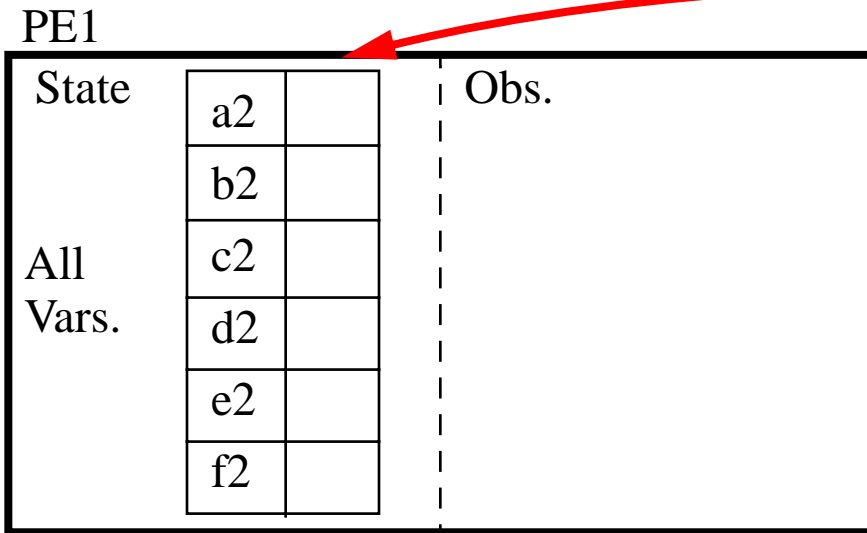
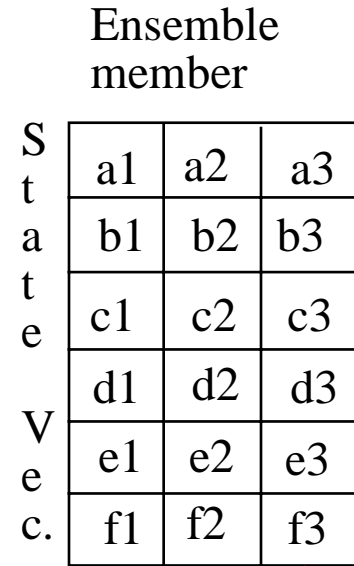
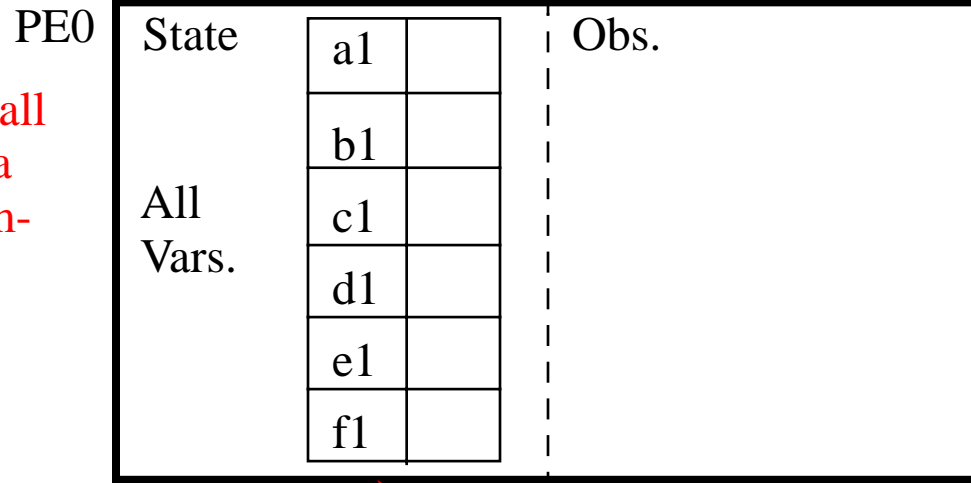
Complete list of copies for state vector:

- 1, 2, 3: Ensemble members;
- m: Ensemble mean;
- σ : Ensemble standard deviation.

Example: b3 is the second state variable's third ensemble copy.

No single PE ever stores the complete state vector ensemble.

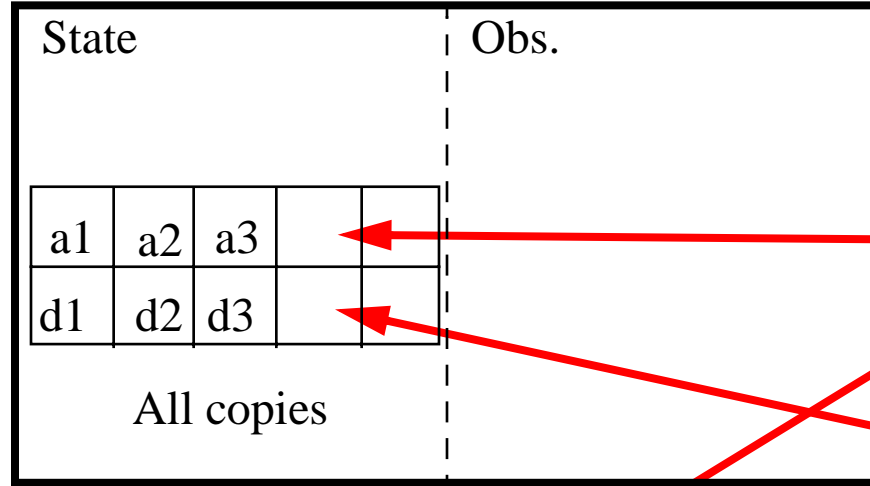
Each PE can store all state variables for a subset of the ensemble members, or...



No single PE ever stores the complete state vector ensemble.

Each PE can store all state variables for a subset of the ensemble members, or all ensemble members for a subset of state variables.

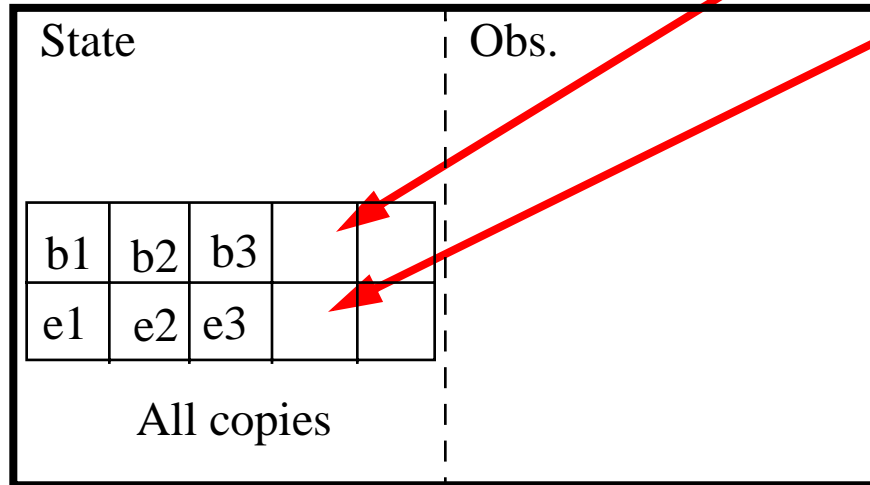
PE0



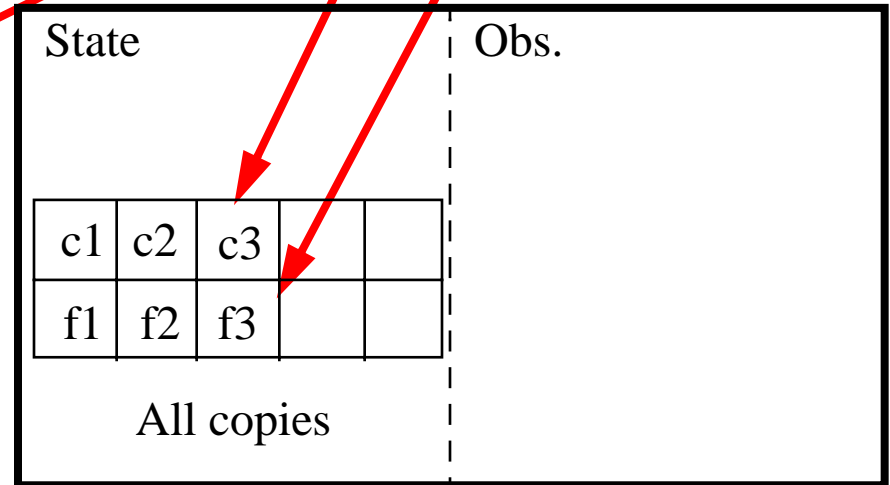
Ensemble member

S	a1	a2	a3
t	b1	b2	b3
a	c1	c2	c3
t	d1	d2	d3
e	e1	e2	e3
V	f1	f2	f3
e			
c.			

PE1



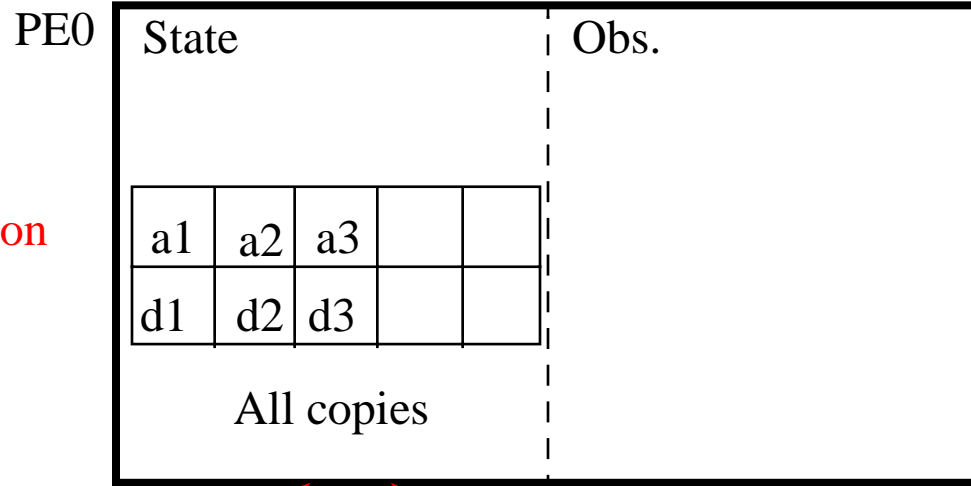
PE2



Transition between two storage patterns is called a transpose.

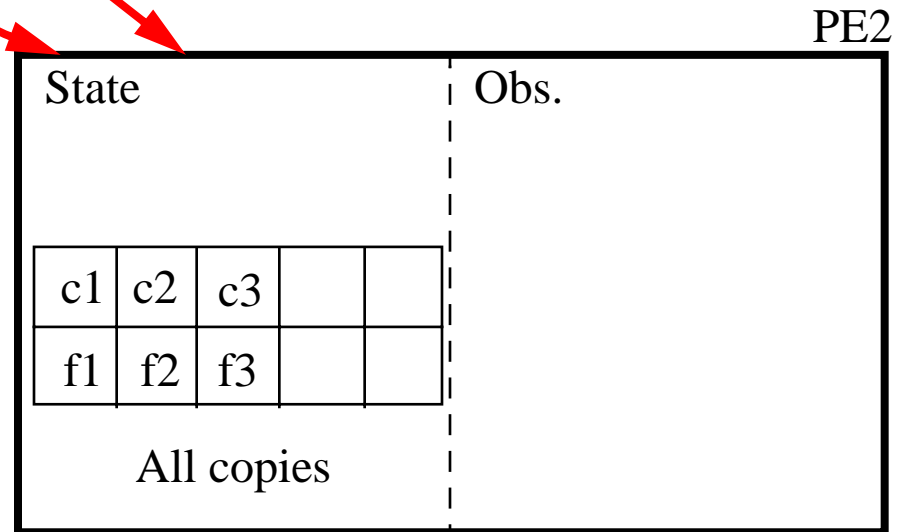
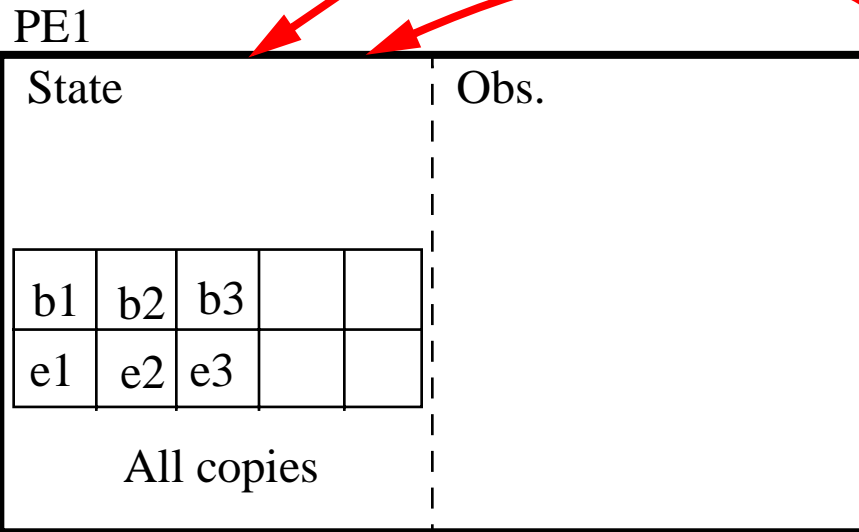
Need communication between all pairs of PEs.

This is handled by `ensemble_manager_mod.f90`.



Ensemble member

S t a t e V e c.	a1	a2	a3
	b1	b2	b3
	c1	c2	c3
	d1	d2	d3
	e1	e2	e3
	f1	f2	f3



Also maintain copies of the observation priors for each observation.

Complete list of copies for observation priors:

- 1, 2, 3: Ensemble member;
- k: Unique integer index from obs_sequence file;
- o: Observed value from the obs_sequence file;
- Σ : Obs. error variance from the obs_sequence file;
- Q: The DART quality control value;
- m: Ensemble mean;
- σ : Ensemble standard deviation;

Examples: q1: second observation, 1st ensemble copy;
rk: integer index for 3rd observation;
pm: Ensemble mean of 1st observation.

Each PE starts with all state variables for a subset of ensemble members.

PE0

All Vars.	State	a1		Obs.
		b1		
		c1		
		d1		
		e1		
		f1		

PE1

All Vars.	State	a2		Obs.
		b2		
		c2		
		d2		
		e2		
		f2		

PE2

All Vars.	State	a3		Obs.
		b3		
		c3		
		d3		
		e3		
		f3		

Advance state vectors in time.

Time
Advance



PE0

All Vars.	State	a1		Obs.
		b1		
		c1		
		d1		
		e1		
		f1		

Each PE advances its ensemble members to the next observation time.
 Here, each PE advances 1 member (see `move_ahead`, `obs_model_mod.f90`).
 With more ensemble members than PEs, PEs would advance more than 1.

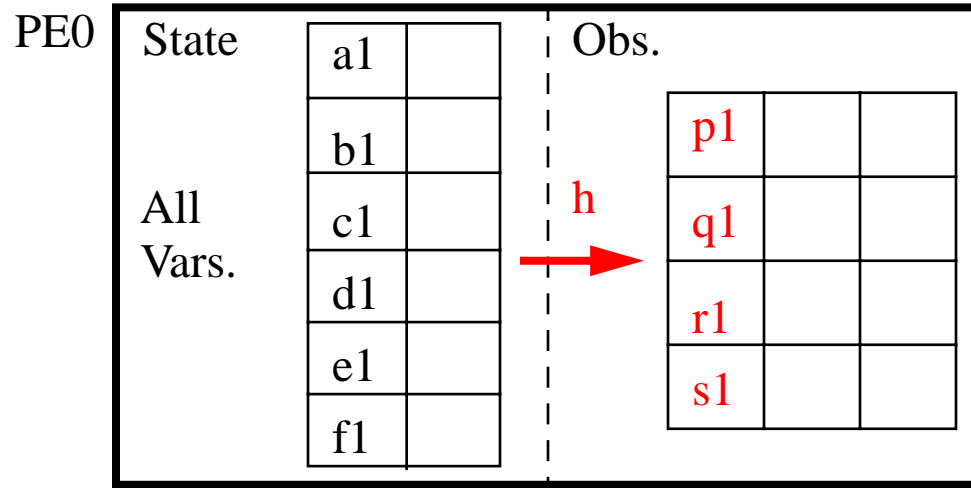
PE1

All Vars.	State	a2		Obs.
		b2		
		c2		
		d2		
		e2		
		f2		

PE2

All Vars.	State	a3		Obs.
		b3		
		c3		
		d3		
		e3		
		f3		

Apply forward observation operators.

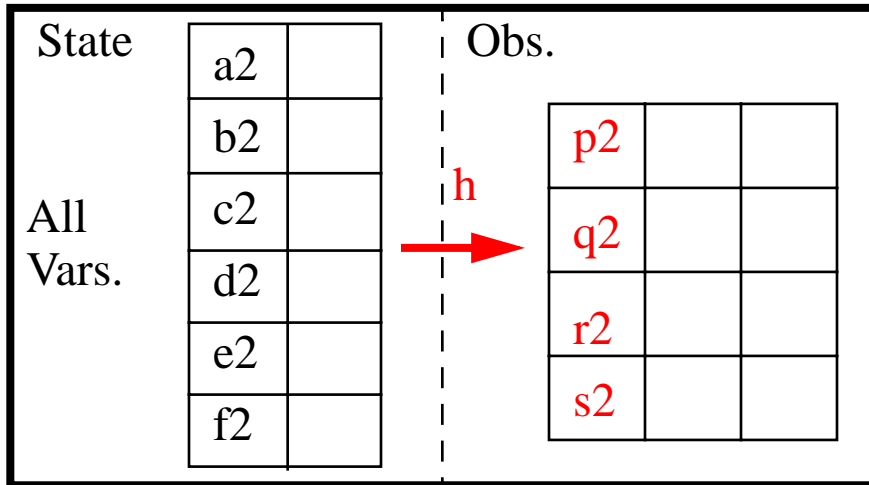


Each PE computes forward observation operators for its ensembles.

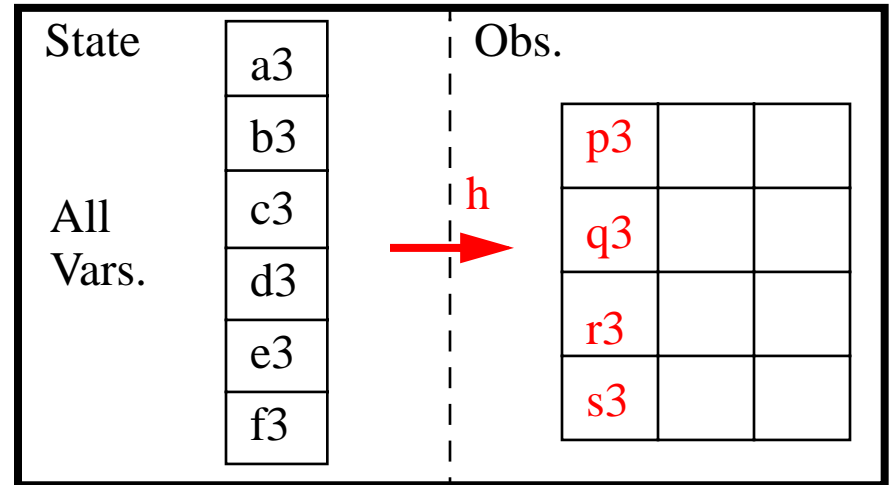
Here, each only does one set of forward ops. (see `get_obs_ens` in `filter.f90`)

Four observations (p, q, r, s) are available at this time.

PE1



PE2



Attach unique integer key from observation sequence.

PE0

All Vars.	State	a1	
		b1	
		c1	
		d1	
		e1	
		f1	

Obs.		
p1	pk	
q1	qk	
r1	rk	
s1	sk	

Each observation has a unique integer key.

It is stored like an additional ensemble member (but not treated like one).

The key comes from the obs_sequence data structure.

PE1

All Vars.	State	a2	
		b2	
		c2	
		d2	
		e2	
		f2	

Obs.		
p2		
q2		
r2		
s2		

PE2

All Vars.	State	a3	
		b3	
		c3	
		d3	
		e3	
		f3	

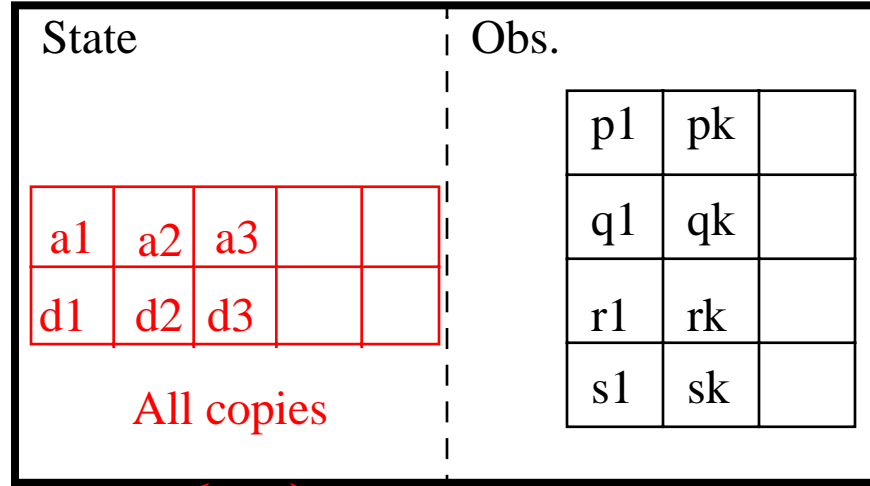
Obs.		
p3		
q3		
r3		
s3		

Transpose state vectors to have all copies of subset of state variables.

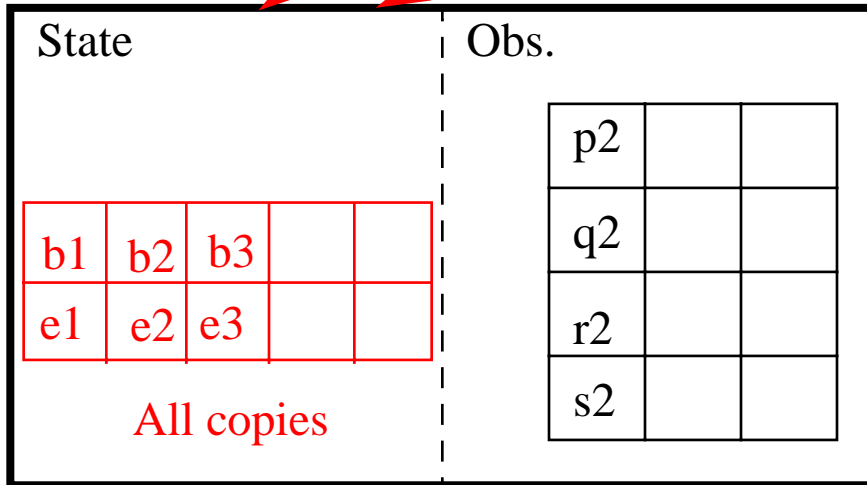
Each PE ends up with two variables.

Has all three ensemble members for each variable.

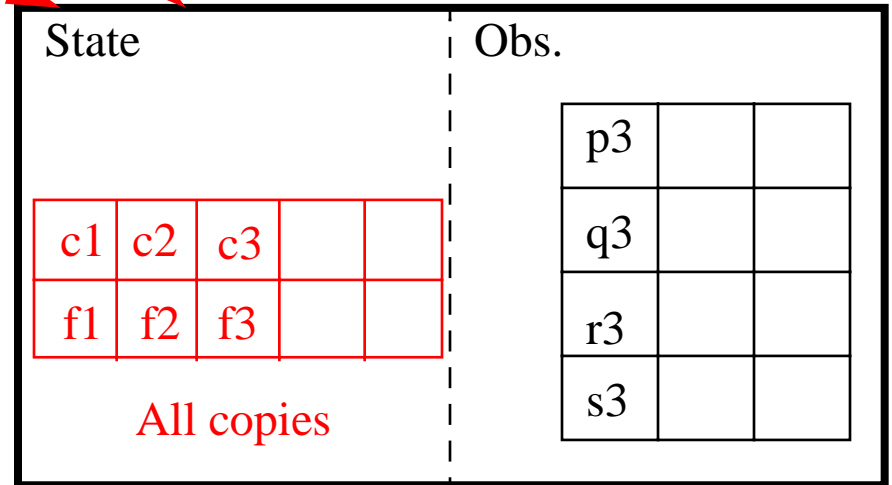
PE0



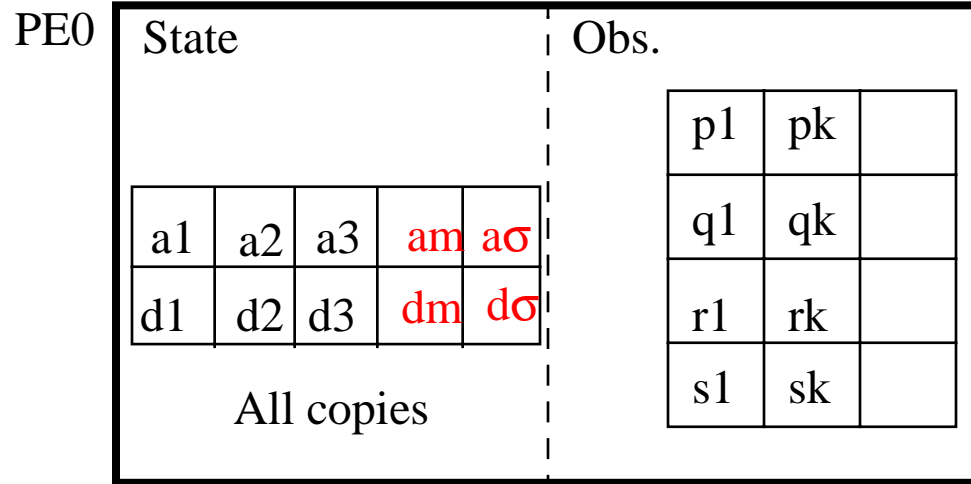
PE1



PE2

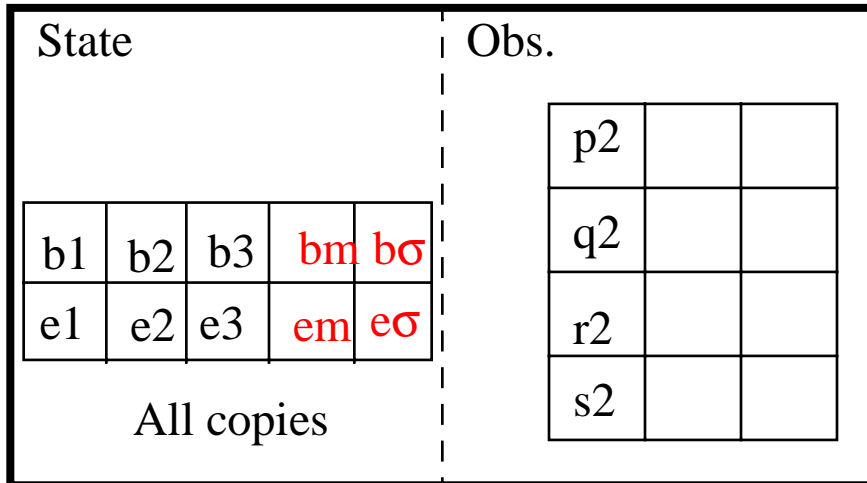


Compute ensemble mean and standard deviation.

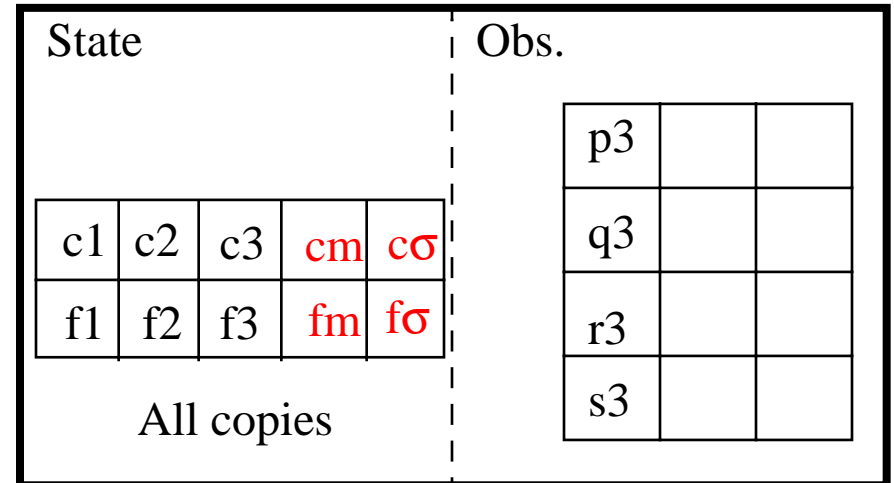


Each PE computes mean and standard deviation for its state variables.
 These are stored as if they are extra ensemble copies.

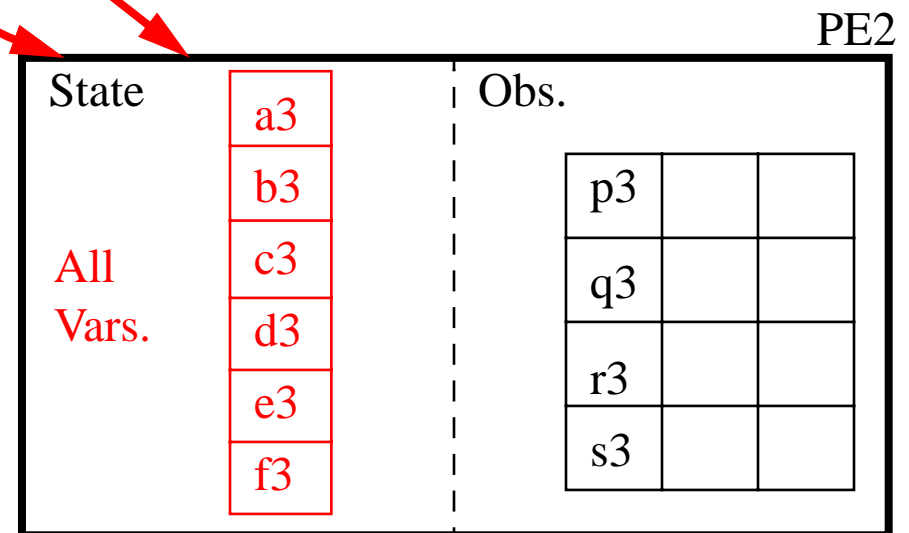
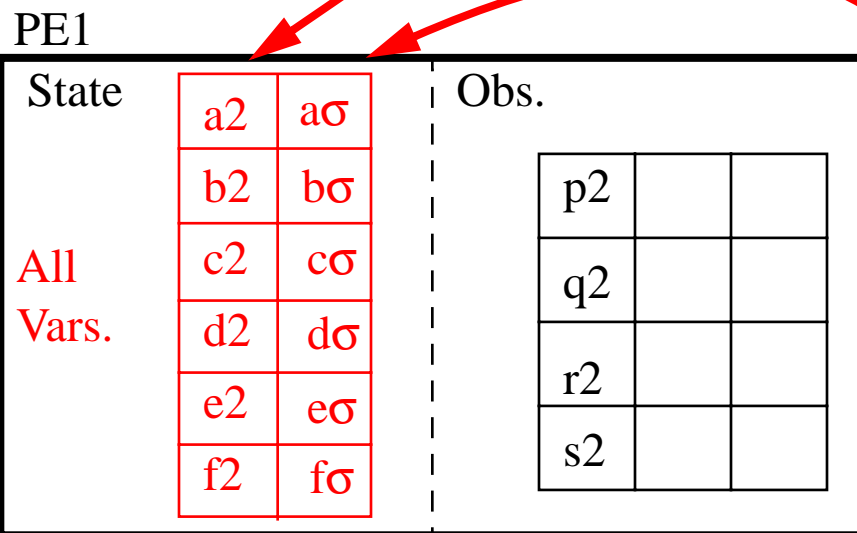
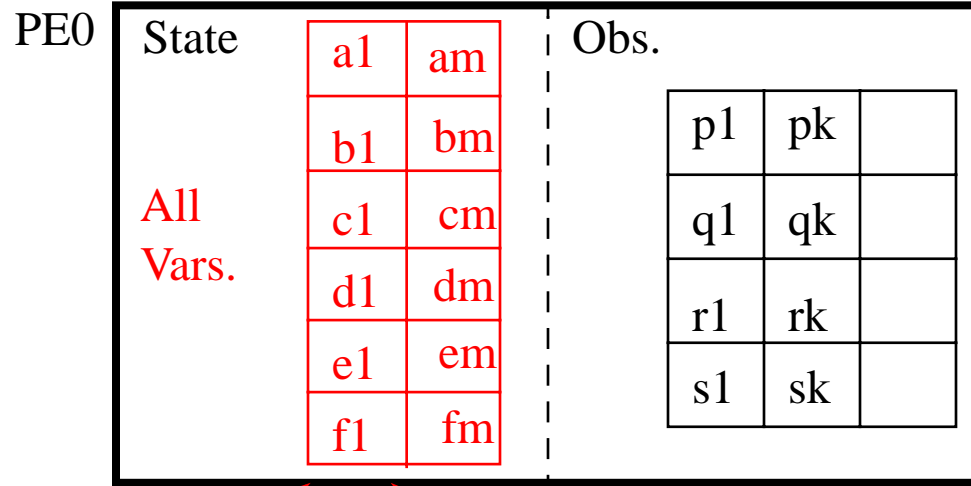
PE1



PE2



Transpose back to subset of copies, all variables for state.



Can now send ensemble mean state vector to each PE for later use in location computation.

This is needed in models that need state to compute location (sigma vertical coordinate for example).

PE0

State All Vars.	a1	am	Obs.	p1	pk	
	b1	bm		q1	qk	
	c1	cm		r1	rk	
	d1	dm		s1	sk	
	e1	em				
	f1	fm				

Broadcast

PE1

State All Vars.	a2	a σ	Obs.	p2		
	b2	b σ		q2		
	c2	c σ		r2		
	d2	d σ		s2		
	e2	e σ				
	f2	f σ				

PE2

State All Vars.	a3		Obs.	p3		
	b3			q3		
	c3			r3		
	d3			s3		
	e3					
	f3					

Prior state space diagnostics are now output.

To File System

PE0

All Vars.	State	a1	am	Obs.	p1	pk	
	b1	bm	q1		qk		
	c1	cm	r1		rk		
	d1	dm	s1		sk		
	e1	em					
	f1	fm					

Each copy sent to PE 0.

PE 0 outputs.

Here, PE1 sends copy 2 and s.d., PE2 sends copy 3.

PE1

All Vars.	State	a2	a σ	Obs.	p2		
	b2	b σ	q2				
	c2	c σ	r2				
	d2	d σ	s2				
	e2	e σ					
	f2	f σ					

PE2

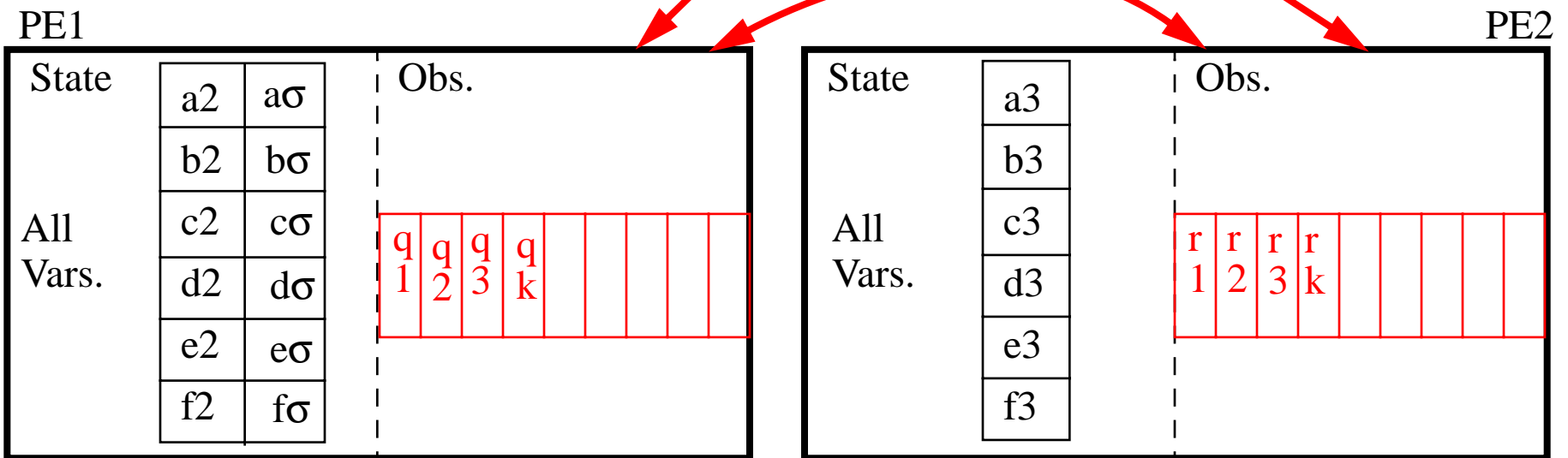
All Vars.	State	a3		Obs.	p3		
	b3		q3				
	c3		r3				
	d3		s3				
	e3						
	f3						

Transpose observations to all copies of subset of observations.

PE0

State	a1	am	Obs.							
	b1	bm	p ₁	p ₂	p ₃	p _k				
All Vars.	c1	cm	s ₁	s ₂	s ₃	s _k				
	d1	dm								
	e1	em								
	f1	fm								

PE0 has 2 observations.
PE1 and PE2 have only 1.



The observation value, observation error variance, and QC are added in.

PE0

All Vars.	State	a1	am	Obs.						
	b1	bm	p	p	p	p	p	p		
	c1	cm	1	2	3	k	o	Σ	Q	
	d1	dm	s	s	s	s	s	s		
	e1	em	1	2	3	k	o	Σ	Q	
	f1	fm								

The value and observation error variance are from the obs_sequence file.

The QC is a merge of prior QC (NCEP) plus any failed forward obs. operators.

PE1

All Vars.	State	a2	a σ	Obs.						
	b2	b σ	q	q	q	q	q	q		
	c2	c σ	1	2	3	k	o	Σ	Q	
	d2	d σ								
	e2	e σ								
	f2	f σ								

PE2

All Vars.	State	a3	Obs.						
	b3	r	r	r	r	r	r		
	c3	1	2	3	k	o	Σ	Q	
	d3								
	e3								
	f3								

The ensemble mean and prior observation standard deviation are computed.

PE0

All Vars.	State	a1	am	Obs.									
	b1	bm	p	p	p	p	p	p	p	p	p	p	p
	c1	cm	1	2	3	k	o	Σ	Q	m	σ		
	d1	dm	s	s	s	s	s	s	s	s	s	s	s
	e1	em	1	2	3	k	o	Σ	Q	m	σ		
	f1	fm											

Each PE computes mean and s.d. for its observations.

End up with a total of 6 extra copies (like ensemble members) for each obs.

PE1

All Vars.	State	a2	a σ	Obs.									
	b2	b σ	q	q	q	q	q	q	q	q	q	q	q
	c2	c σ	1	2	3	k	o	Σ	Q	m	σ		
	d2	d σ											
	e2	e σ											
	f2	f σ											

PE2

All Vars.	State	a3	Obs.										
	b3	r	r	r	r	r	r	r	r	r	r	r	r
	c3	1	2	3	k	o	Σ	Q	m	σ			
	d3												
	e3												
	f3												

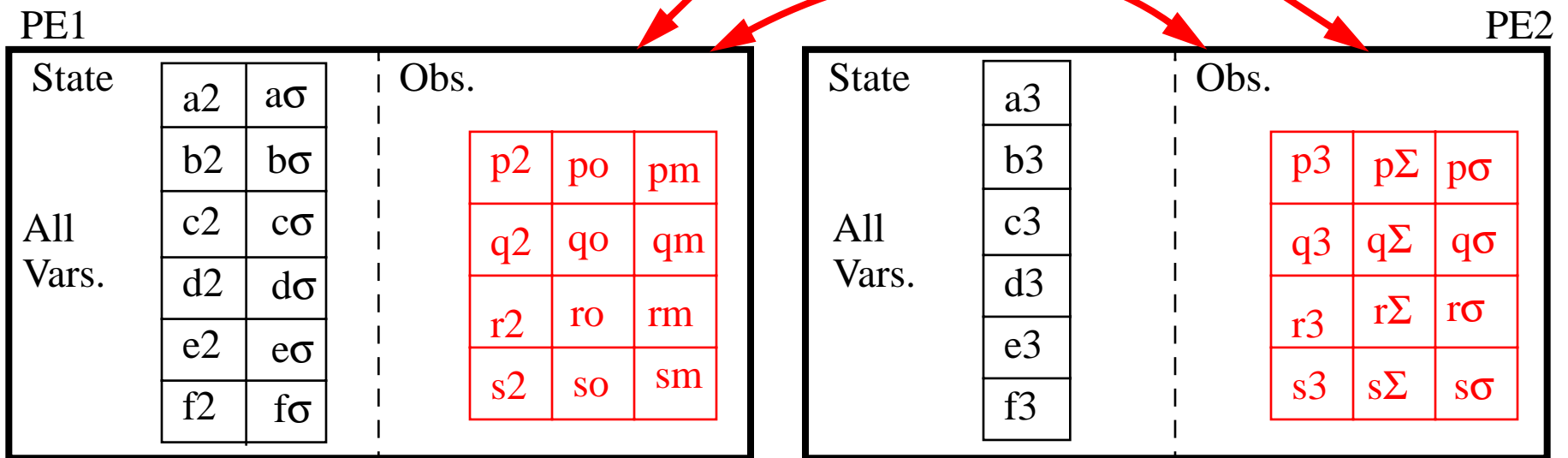
Transpose observations back to subset of copies of all observations.

PE0

State	a1	am
	b1	bm
All Vars.	c1	cm
	d1	dm
	e1	em
	f1	fm

Obs.		
p1	pk	pQ
q1	qk	qQ
r1	rk	rQ
s1	sk	sQ

Need to output a copy at a time.



PE0 outputs all requested copies sequentially.

PE0 requests copies from each PE as needed.

For instance, PE1 sends mean and PE2 sends s.d.

PE0

State	a1	am	Obs.	p1	pk	pQ
	b1	bm		q1	qk	qQ
	c1	cm		r1	rk	rQ
	d1	dm		s1	sk	sQ
	e1	em				
	f1	fm				
All Vars.						

PE1

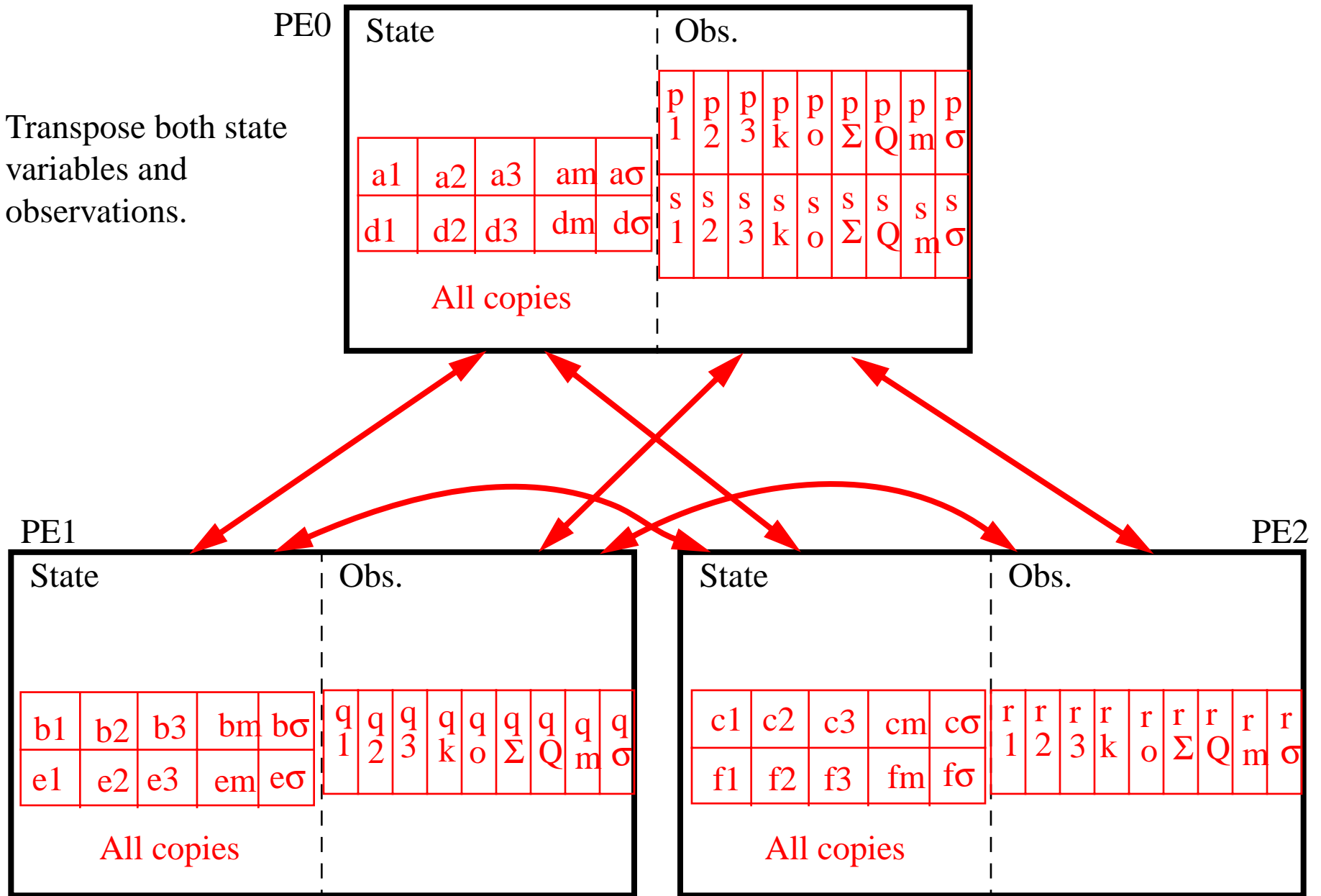
State	a2	a σ	Obs.	p2	po	pm
	b2	b σ		q2	qo	qm
	c2	c σ		r2	ro	rm
	d2	d σ		s2	so	sm
	e2	e σ				
	f2	f σ				
All Vars.						

PE2

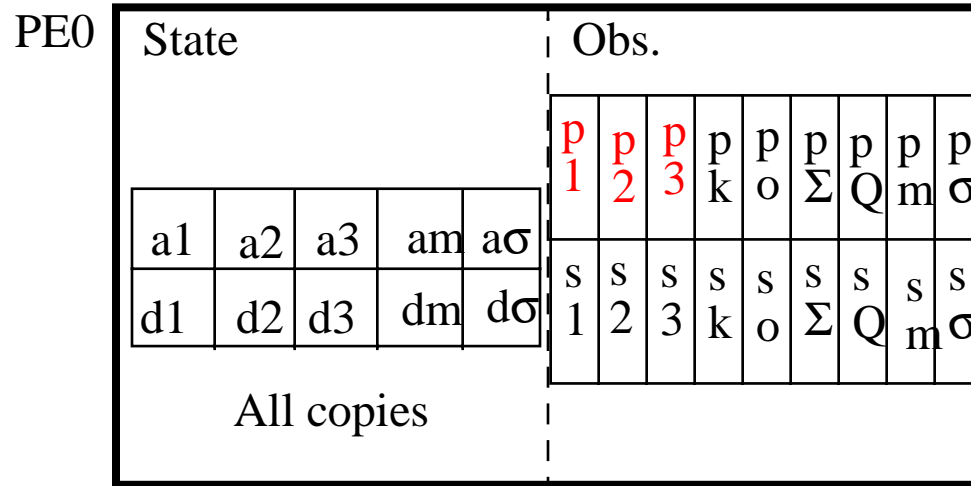
State	a3	Obs.	p3	p Σ	p σ
	b3		q3	q Σ	q σ
	c3		r3	r Σ	r σ
	d3		s3	s Σ	s σ
	e3				
	f3				
All Vars.					

Need all copies of subset of variables and observations for assimilation step.

Transpose both state variables and observations.



Call to filter_assim in assim_tools_mod.f90 to do the assimilation of p, q, r and s.

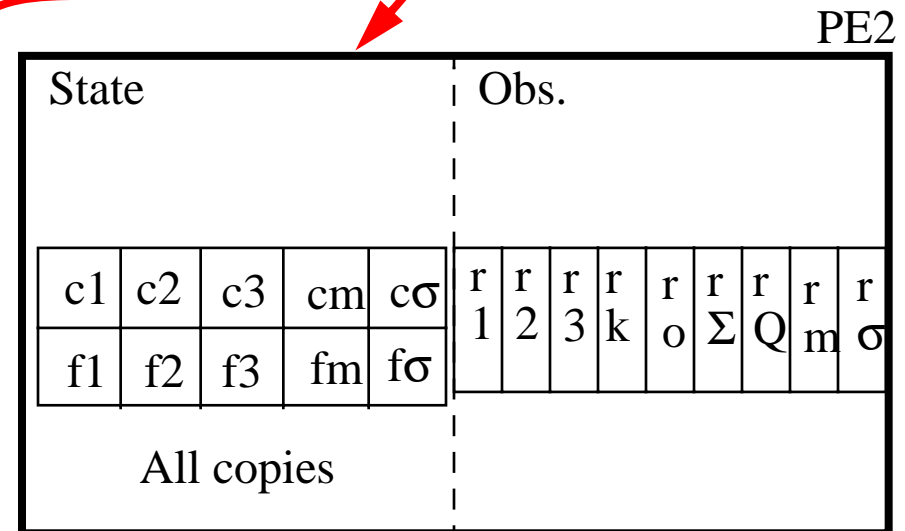
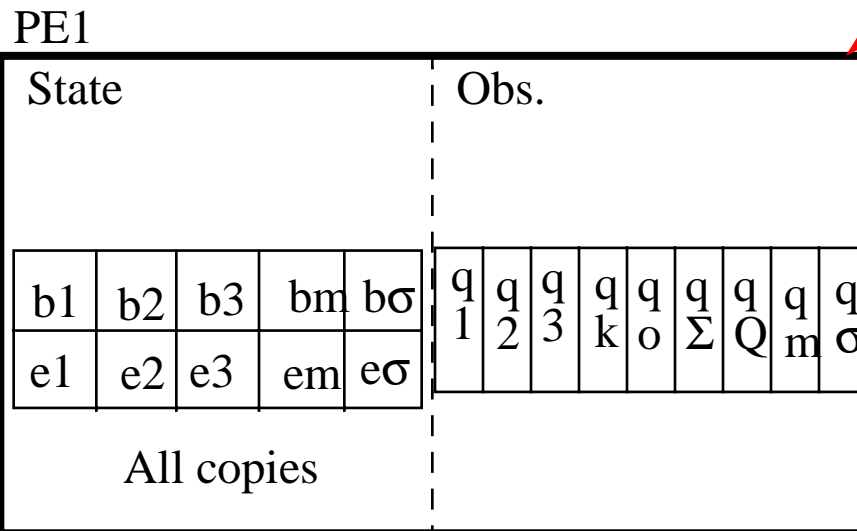


Prior ensemble and increments.

PE0 has the first observation, p.

It computes observation space increments for p.

Broadcasts the prior p ensemble and the increments.



All PEs now have prior and increment for observation p.

PE0

State					Obs.																			
					p	p	p	p	p	p	p	p	p	p	s	s	s	s	s	s	s	s	s	s
a1	a2	a3	am	a σ	1	2	3	k	o	Σ	Q	m	σ	1	2	3	k	o	Σ	Q	m	σ		
All copies																								

Each PE (including PE0) finds all of its state variables that are close to p.
 For instance, PE1 checks to see if b or e are close to p.

PE1 then uses regression to update ensemble members for b and e as needed.

PE1

State					Obs.																			
					q	q	q	q	q	q	q	q	q	q										
b1	b2	b3	bm	b σ	1	2	3	k	o	Σ	Q	m	σ											
e1	e2	e3	em	e σ																				
All copies																								

PE2

State					Obs.																			
					r	r	r	r	r	r	r	r	r	r										
c1	c2	c3	cm	c σ	1	2	3	k	o	Σ	Q	m	σ											
f1	f2	f3	fm	f σ																				
All copies																								

All PEs now have prior and increment for observation p.

PE0

State					Obs.																				
a1	a2	a3	a _m	a _σ	p ₁	p ₂	p ₃	p _k	p _o	p _Σ	p _Q	p _m	p _σ												
d1	d2	d3	d _m	d _σ	s ₁	s ₂	s ₃	s _k	s _o	s _Σ	s _Q	s _m	s _σ												
All copies																									

Each PE next updates the prior for each of its observations that are close to p. No need to do this for observations that have already been used (like p here). For instance, PE1 updates q by regression if it is close to p.

PE1

State					Obs.																				
b1	b2	b3	b _m	b _σ	q ₁	q ₂	q ₃	q _k	q _o	q _Σ	q _Q	q _m	q _σ												
e1	e2	e3	e _m	e _σ																					
All copies																									

PE2

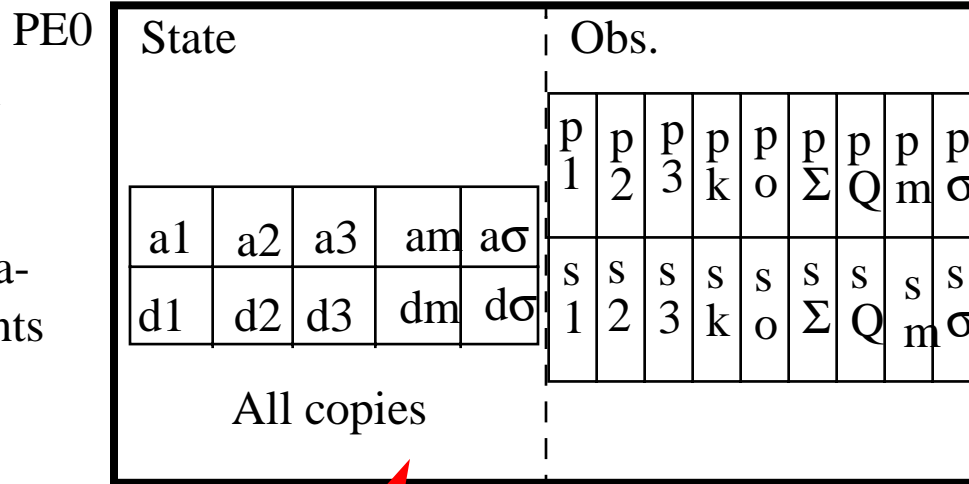
State					Obs.																				
c1	c2	c3	c _m	c _σ	r ₁	r ₂	r ₃	r _k	r _o	r _Σ	r _Q	r _m	r _σ												
f1	f2	f3	f _m	f _σ																					
All copies																									

When everyone is finished regressing for observation p, assimilate q.

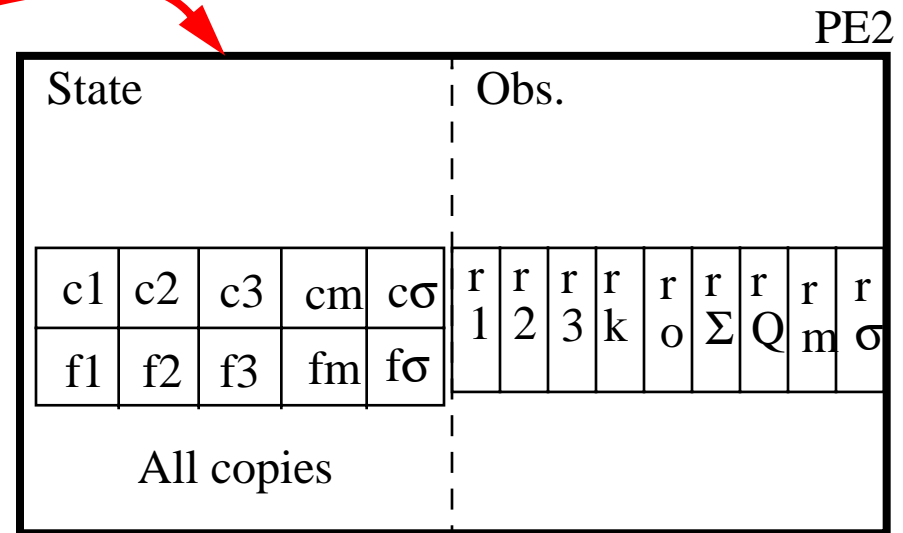
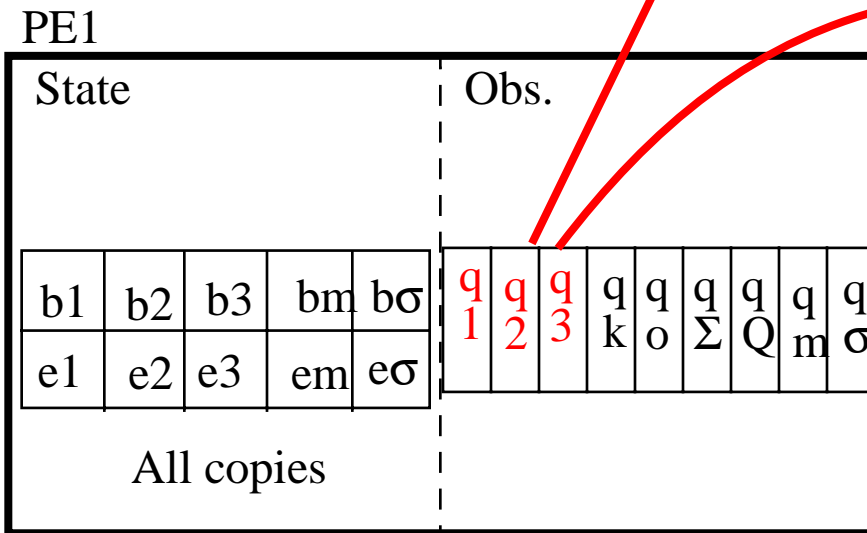
PE1 has the second observation, q.

It computes observation space increments for q.

Broadcasts the prior q ensemble and the increments.



Prior Ensemble and increments.



All PEs now have prior and increment for observation q .

PE0

State					Obs.																							
					p ₁	p ₂	p ₃	p _k	p _o	p _Σ	p _Q	p _m	p _σ															
a ₁	a ₂	a ₃	a _m	a _σ	s ₁	s ₂	s ₃	s _k	s _o	s _Σ	s _Q	s _m	s _σ															
d ₁	d ₂	d ₃	d _m	d _σ																								
All copies																												

Each PE (including PE1) finds all of its state variables that are close to q .
 For instance, PE0 checks to see if a or d is close to q .

PE0 then uses regression to update ensemble members for a and d as needed.

PE1

State					Obs.																							
					q ₁	q ₂	q ₃	q _k	q _o	q _Σ	q _Q	q _m	q _σ															
b ₁	b ₂	b ₃	b _m	b _σ																								
e ₁	e ₂	e ₃	e _m	e _σ																								
All copies																												

PE2

State					Obs.																							
					r ₁	r ₂	r ₃	r _k	r _o	r _Σ	r _Q	r _m	r _σ															
c ₁	c ₂	c ₃	c _m	c _σ																								
f ₁	f ₂	f ₃	f _m	f _σ																								
All copies																												

All PEs now have prior and increment for observation q.

PE0

State					Obs.								
a1	a2	a3	a _m	a _σ	p ₁	p ₂	p ₃	p _k	p _o	p _Σ	p _Q	p _m	p _σ
d1	d2	d3	d _m	d _σ	s ₁	s ₂	s ₃	s _k	s _o	s _Σ	s _Q	s _m	s _σ
All copies													

Each PE next updates the prior for each of its observations that are close to q.
 No need to do this for observations already used (like p and q here).

For instance, PE0 updates s by regression if it is close to q.

Continue until all observations have been used (r and s remain here).

PE1

State					Obs.								
b1	b2	b3	b _m	b _σ	q ₁	q ₂	q ₃	q _k	q _o	q _Σ	q _Q	q _m	q _σ
e1	e2	e3	e _m	e _σ									
All copies													

PE2

State					Obs.								
c1	c2	c3	c _m	c _σ	r ₁	r ₂	r ₃	r _k	r _o	r _Σ	r _Q	r _m	r _σ
f1	f2	f3	f _m	f _σ									
All copies													

Locating close observations and states; computing distances.

PE0

State					Obs.																	
a1	a2	a3	a _m	a _σ	p ₁	p ₂	p ₃	p _k	p _o	p _Σ	p _Q	p _m	p _σ	s ₁	s ₂	s ₃	s _k	s _o	s _Σ	s _Q	s _m	s _σ
All copies																						

Note that PEs do NOT have the complete state vector during assimilation.
 Models that require state vector to compute locations have problems.
 They can store ensemble mean that was computed and broadcast earlier.

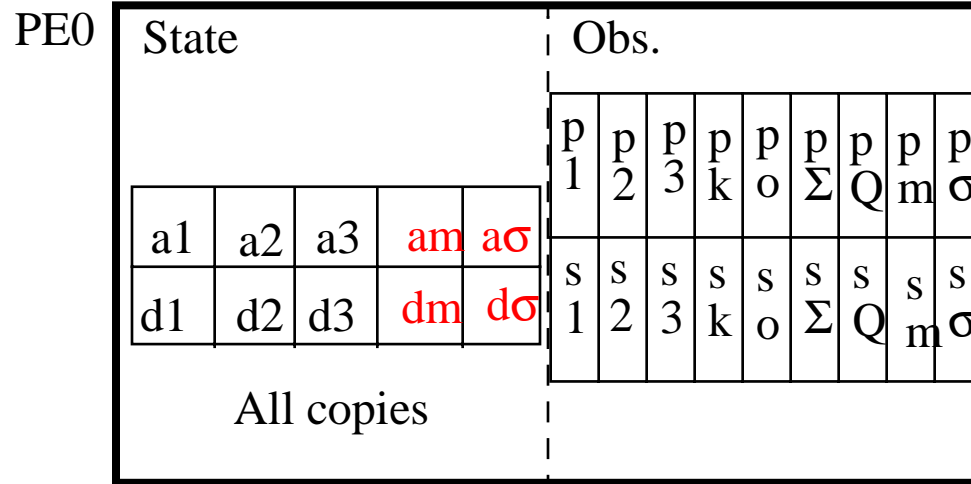
PE1

State					Obs.													
b1	b2	b3	b _m	b _σ	q ₁	q ₂	q ₃	q _k	q _o	q _Σ	q _Q	q _m	q _σ	e1	e2	e3	e _m	e _σ
All copies																		

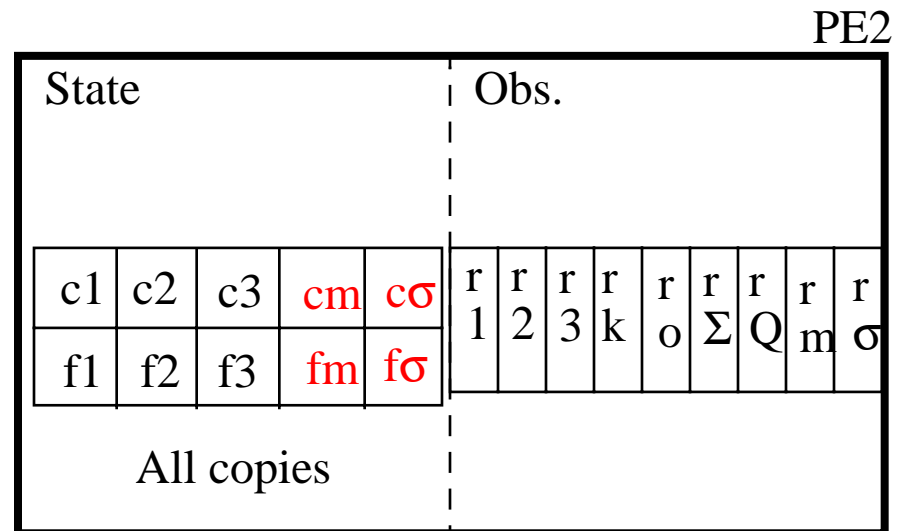
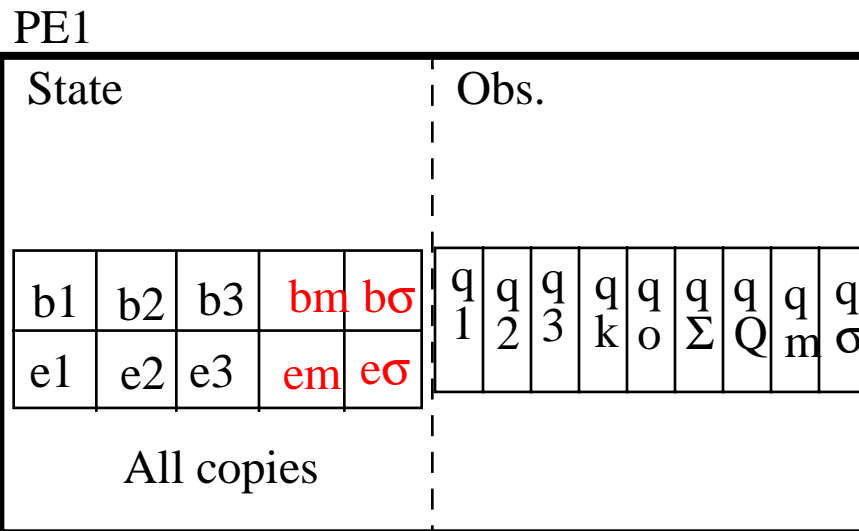
PE2

State					Obs.													
c1	c2	c3	c _m	c _σ	r ₁	r ₂	r ₃	r _k	r _o	r _Σ	r _Q	r _m	r _σ	f1	f2	f3	f _m	f _σ
All copies																		

filter_assim is now complete. Control returns to filter_main in filter.f90.



Update the ensemble mean and s.d. for the state variables.
 Each processor computes this for its subset of variables.



Completing steps are similar to those already discussed.

Transform state to have subset of copies of all state variables on each PE.

Do posterior state space diagnostics as per prior.

Compute forward observation operators as was done before assimilation.

Do observation space posterior diagnostics as per prior.

If there are more observation times, go back to model advance.

If no more observation times, output state restart files.