Parallel Programming with Fortran Coarrays

MSc in HPC

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Coarrays Overview

- Parallel Programming with Fortran Coarrays
  - Fortran Programming Model
  - Basic coarray features
  - Brief mention of Coarray C++
- Further coarray features
- Advanced coarray features
- Experiences with coarrays

The Fortran Programming Model

Motivation

- Fortran now supports parallelism as a full first-class feature of the language
- Changes are minimal
- Performance is maintained
- Flexibility in expressing communication patterns

Programming models for HPC

- The challenge is to efficiently map a problem to the architecture we have
  - Take advantage of all computational resources
  - Manage distributed memories etc.
  - Optimal use of any communication networks
- The HPC industry has long experience in parallel programming
  - Vector, threading, data-parallel, message-passing etc.
- We would like to have models or combinations that are
  - efficient
  - safe
  - easy to learn and use

Why consider new programming models?

- Next-generation architectures bring new challenges:
  - Very large numbers of processors with many cores
  - Complex memory hierarchy
  - We had to deal with 500k cores in 2011
- Parallel programming is hard, need to make this simpler
- Some of the models we currently use are
  - bolt-ons to existing languages as APIs or directives
  - Hard to program for underlying architecture
  - unable to scale due to overheads
- So, is there an alternative to the models prevalent today?
  - Most popular are OpenMP and MPI …

Fortran 2008 coarray model

- Example of a Partitioned Global Address Space (PGAS) model
- Set of participating processes like MPI
- Participating processes have access to **local memory** via standard program mechanisms
- Access to **remote memory** is directly supported by the language

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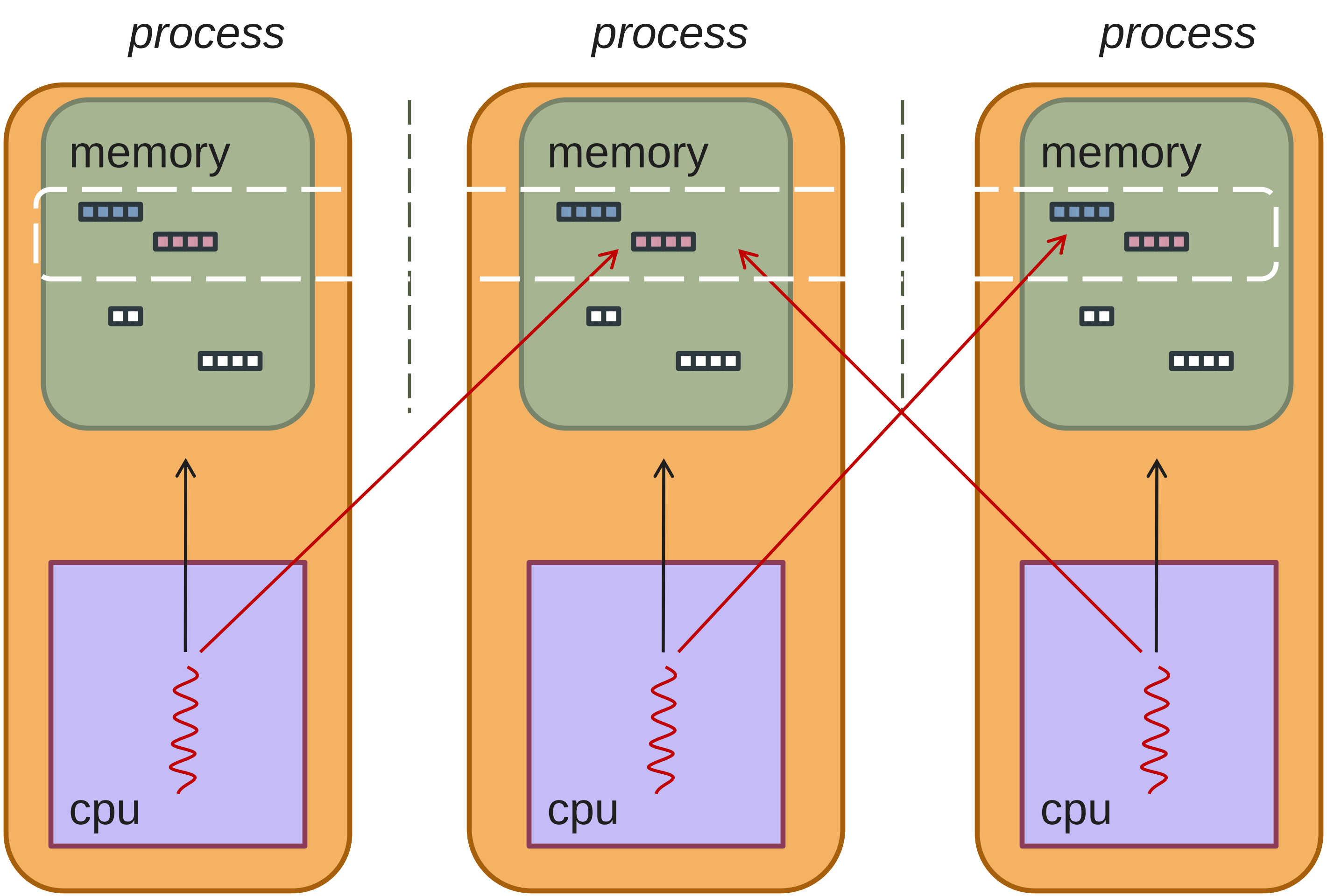
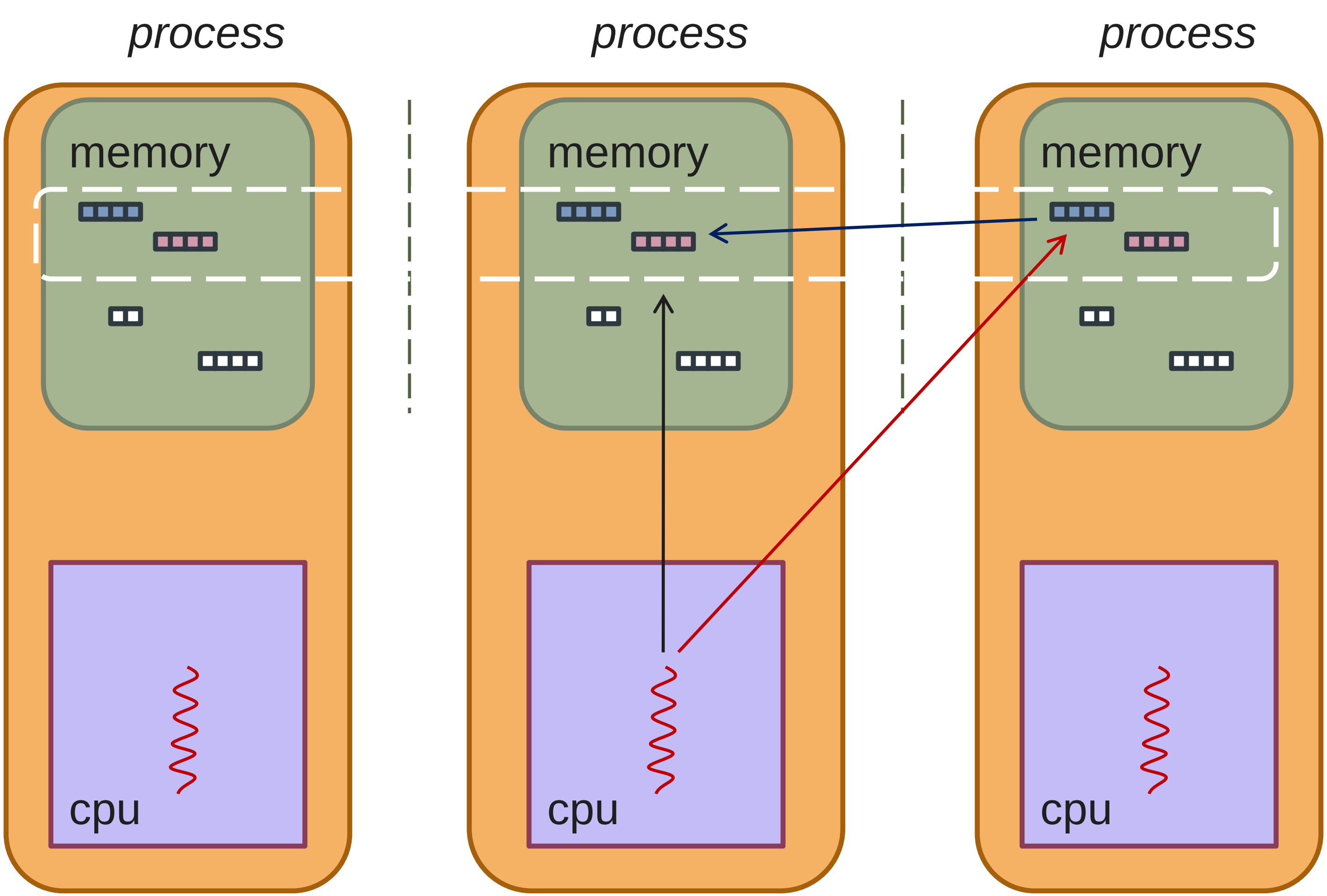
Fortran coarray model



Fortran coarray model




```
a = b[3]
```

Fortran coarrays

- Remote access is a full feature of the language:
  - Type checking
  - Opportunity to optimize communication
- No penalty for local memory access
- Single-sided programming model more natural for some algorithms
  - and a good match for modern networks with RDMA

Fortran coarrays

Basic Features

(including very basic introduction to coarray C++)

Coarray Fortran

"Coarrays were designed to answer the question:

'What is the smallest change required to convert Fortran into a robust and efficient parallel language?'

The answer: a simple syntactic extension.

It looks and feels like Fortran and requires Fortran programmers to learn only a few new rules."

John Reid,
ISO Fortran Convener

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Some History

- Introduced in current form by Numrich and Reid in 1998 as a simple extension to Fortran 95 for parallel processing
- Many years of experience, mainly on Cray hardware
- A set of core features are now part of the Fortran standard ISO/IEC 1539-1:2010
- Additional features are expected to be published in a Technical Specification in due course.

How Does It Work?

- SPMD - Single Program, Multiple Data
  - single program replicated a fixed number of times
- Each replication is called an ***image***
- Images are executed asynchronously
  - execution path may differ from image to image
  - some situations cause images to synchronize
- Images access remote data using *coarrays*
- Normal rules of Fortran apply

What are coarrays?

- Arrays or scalars that can be accessed remotely
  - images can access data objects on any other image
- Additional Fortran syntax for coarrays
  - Specifying a codimension declares a coarray

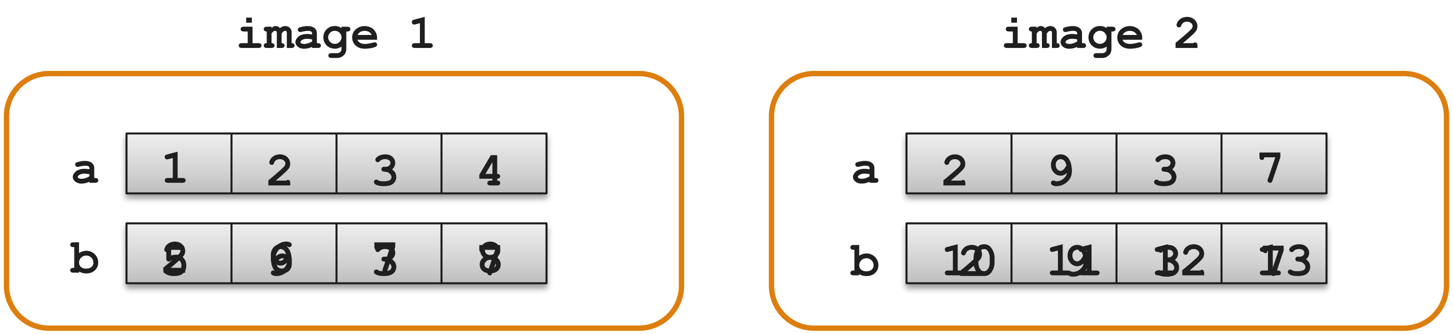
```
real, dimension(10), codimension[*]:: x
real :: x(10)[*]
```

  - these are equivalent declarations of a array x of size 10 on each image
  - x is now remotely accessible
  - coarrays have the same size on each image!

Accessing coarrays

```
integer :: a(4)[*], b(4)[*]  !declare coarrays
b(:) = a(:)[n]               ! copy
```

- integer arrays a and b declared to be size 4 on all images
- copy array a from remote image n into local array b
- () for local access [] for remote access
- e.g. for two images and n = 2:



Synchronisation

- Be careful when updating coarrays:
  - If we get remote data was it valid?
  - Could another process send us data and overwrite something we have not yet used?
  - How do we know that data sent to us has arrived?
- Fortran provides synchronisation statements
- For example, barrier for synchronisation of all images:

```
sync all
```

- do not make assumptions about execution timing on images
  - unless executed after synchronisation
  - Note there is implicit synchronisation at program start

Retrieving information about images

- Two intrinsics provide index of this image and number of images
  - `this_image()` (image indexes start at 1)
  - `num_images()`

```
real :: x[*]
if(this_image() == 1) then
  read *,x
  do image = 2,num_images()
    x[image] = x
  end do
end if
sync all
```

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Making remote references

- We used a loop over images

```
  do image = 2,num_images()
  x[image] = x
end do
```

- Note that array indexing within the coindex is not allowed so we can not write

```
  x[2:num_images()] = x        ! illegal
```

Data usage

- coarrays have the same size on every image
- Declarations:
  - round brackets () describe rank, shape and extent of local data
  - square brackets [] describe layout of images that hold local data
- Many HPC problems have physical quantities mapped to n-dimensional grids
- You need to implement your view of global data from the local coarrays as Fortran does not provide the global view
  - You can be flexible with the coindexing (see later)
  - You can use any access pattern you wish

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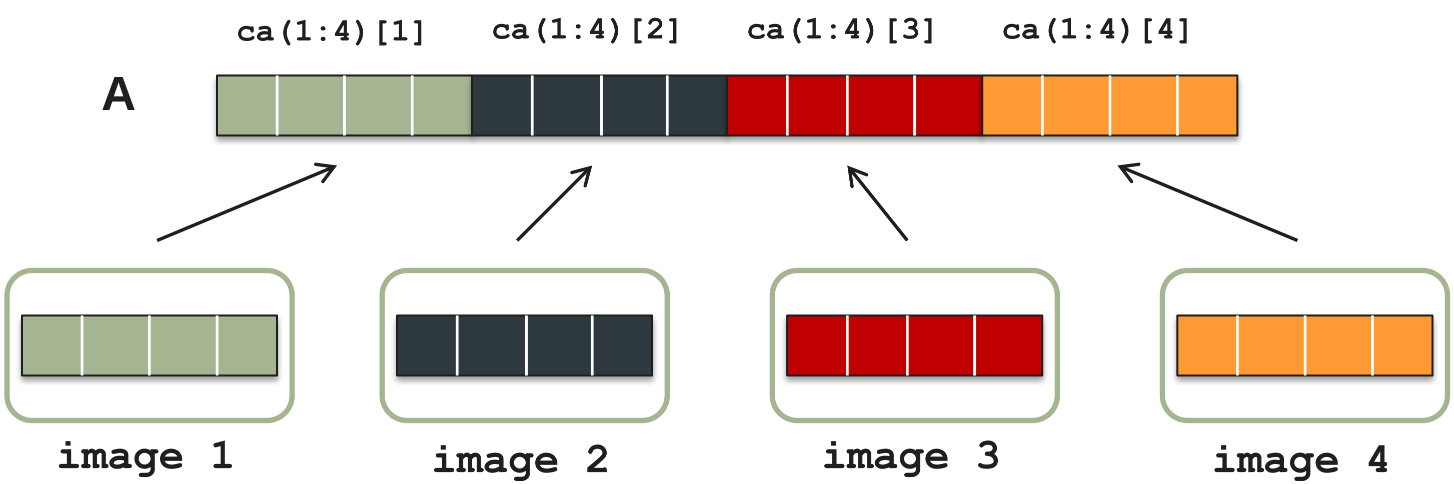
Data usage

- print out a 16 element “global” integer array A from 4 processors
  - 4 elements per processor = 4 coarrays on 4 images

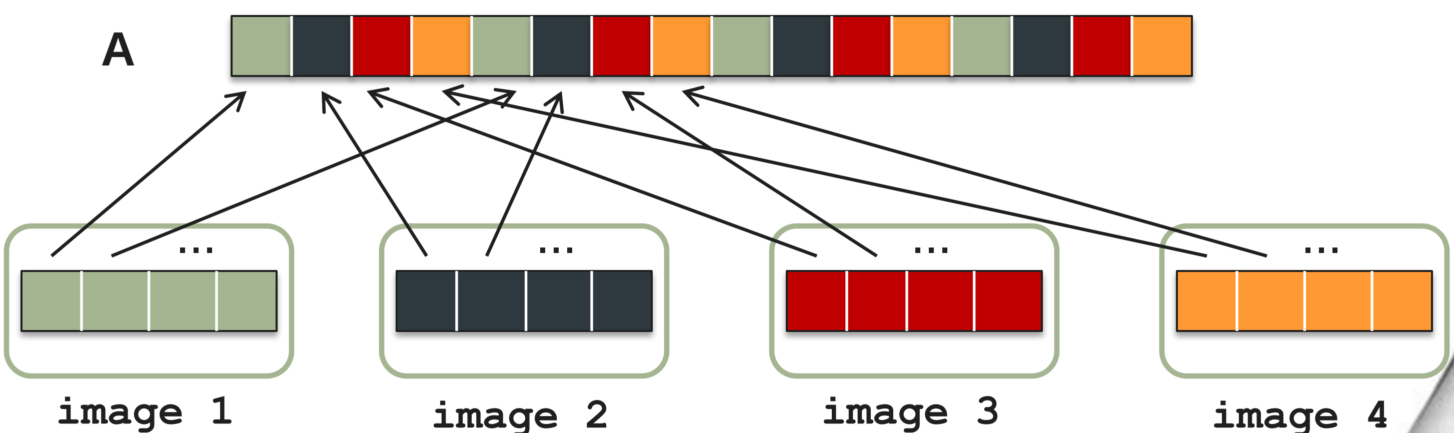
```
integer :: ca(4)[*]
do image=1,num_images()
  print *,ca(:)[image]
end do
```



1D cyclic data access

- coarray declarations remain unchanged
  - but we use a cyclic access pattern

```
integer :: ca(4)[*]
do i=1,4
  do image=1,num_images()
    print *,ca(i)[image]
  end do
end do
```



Synchronisation

- code execution on images is independent
  - programmer has to control execution using synchronisation
- synchronise before accessing coarrays
  - ensure content is not updated from remote images before you can use it
- synchronise after accessing coarrays
  - ensure new content is available to all images
- implicit synchronisation after variable declarations at first executable statement
  - guarantees coarrays exist on all images when your first program statement is executed
- We will revisit this topic later

Example: maximum of array

```
real :: a(10)
real :: maximum[*]
call random_number(a)
maximum = maxval(a)
sync all
if (this_image() == 1) then
  do image = 2, num_images()
   maximum = max(maximum, maximum[image])
  end do
  do image = 2, num_images()
   maximum[image] = maximum
  end do
end if
sync all
```

implicit synchronisation

ensure all images set local maximum

ensure all images have copy of maximum value

Recap

We now know the basics of coarrays

- declarations
- references with []
- **`this_image()`** and **`num_images()`**
- **`sync all`**

Now consider a full program example...

Example2: Calculate density of primes

```
program pdensity
  implicit none
  integer, parameter :: n=10000000, nimages=8
  integer start,end,i
  integer, dimension(nimages) :: nprimes[*]
  real density

  start = (this_image()-1) * n/num_images() + 1
  end = start + n/num_images() - 1

  nprimes(this_image())[1] = num_primes(start,end)

  sync all
```

Example2: Calculate density of primes

```
  …
  if (this_image()==1) then

    nprimes(1)=sum(nprimes)
    density=real(nprimes(1))/n
    print *,"Calculating prime density on", &
  &         num_images(),"images"
    print *,nprimes(1),'primes in',n,'numbers'
    write(*,'(" density is ",2Pf0.2,"%")')density
    write(*,'(" asymptotic theory gives ", &
  &           2Pf0.2,"%")')1.0/(log(real(n))-1.0)

end if
```

Example2: Calculate density of primes

```
Calculating prime density on 2 images
664580 primes in 10000000 numbers
density is 6.65%
asymptotic theory gives 6.61%
```

Coarray C++

A basic introduction to syntax for people who know the fundamentals of Fortran coarrays

Coarray C++

- Brings the coarray programming model to C++
- Announced by Cray in 2013
  - Response to customers challenged by parallelism in C++
  - There was no similar model for C++ (UPC is based on C)
- The implementation is based on template and class definitions from an include file and shared runtime with Cray PGAS languages
- No change to the C++ language/compiler

- As per the Fortran coarray model:
  - 'Images' execute in SPMD fashion
  - Other familiar aspects map to C++ idioms

Declaring a coarray in C++

- Coarrays are arrays or scalars that can be accessed remotely
  - images can access data objects on any other image
- New syntax to declare coarrays

```
#include <coarray_cpp.h>
using namespace coarray_cpp;

coarray<float[10]> x ;
```

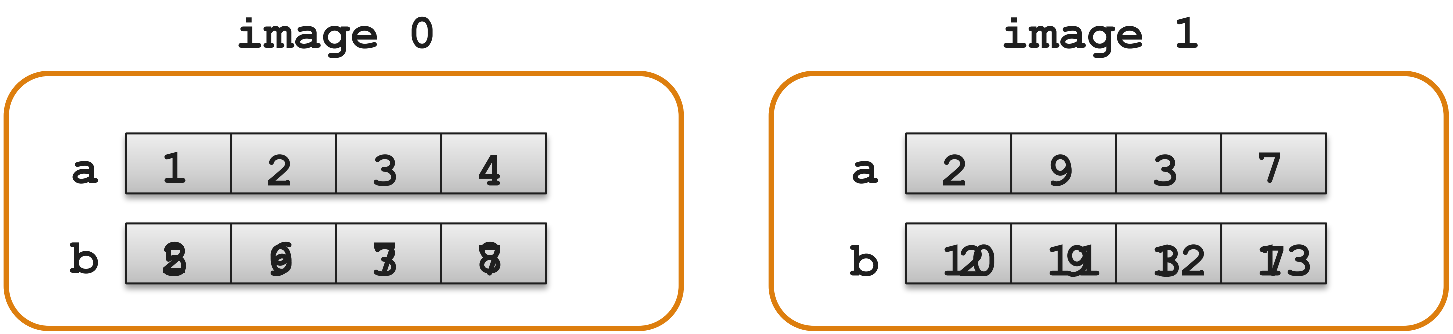
  - Declaration of an array x of size 10 on each image
  - coarrays have the same size on each image!

Accessing coarrays

```
coarray<int[4]> a,b;    // declare coarrays

for(i=0;i<4;i++) a[i] = b(n)[i] ; // copy
```

- int arrays a and b declared to be size 4 on all images
- copy array a from remote image n into local array b
- () for remote access [] for local access
- e.g. for two images and n = 1:



Synchronisation

- Analogously to the Fortran model you can synchronize all the images
- For example, barrier for synchronisation of all images:

```
sync_all();
```

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Retrieving information about images

- Two functions provide index of this image and number of images
  - `this_image()` (image indexes start at 0)
  - `num_images()`

```
coarray<float> x;
if(this_image() == 0) {
 std::cin >> x ;
 for(im=1;im<num_images();im++){
      x(im) = x ;
 }
 sync_all();
```

Example2 prime density: revisited in C++

```
#define NMAX 1000000
#define MAXIMAGES 32

#include <coarray_cpp.h>
using namespace coarray_cpp;
// ...
coarray<int[MAXIMAGES]> nprimes;

start = this_image()*NMAX / num_images() + 1;
end = start + NMAX/num_images() - 1;

nprimes(0)[this_image()] = num_primes(start,end) ;
sync_all();
```

Launching a coarray program

- The Fortran standard does not specify how a program is launched
- The number of images may be set at compile, link or run-time
- A compiler could optimize for a single image

Examples on Linux

- Cray XC
```
aprun -n 16000 solver
```
- Intel compiler
```
export FOR_COARRAY_NUM_IMAGES=2
./solver
```

Observations so far on coarrays

- Natural extension, easy to learn
- Makes parallel parts of program obvious (syntax)
- Part of Fortran language (type checking, etc)
- No mapping of data to buffers (or copying) or creation of complex types (as we might have with MPI)
- Compiler can optimize for communication

- More observations later...

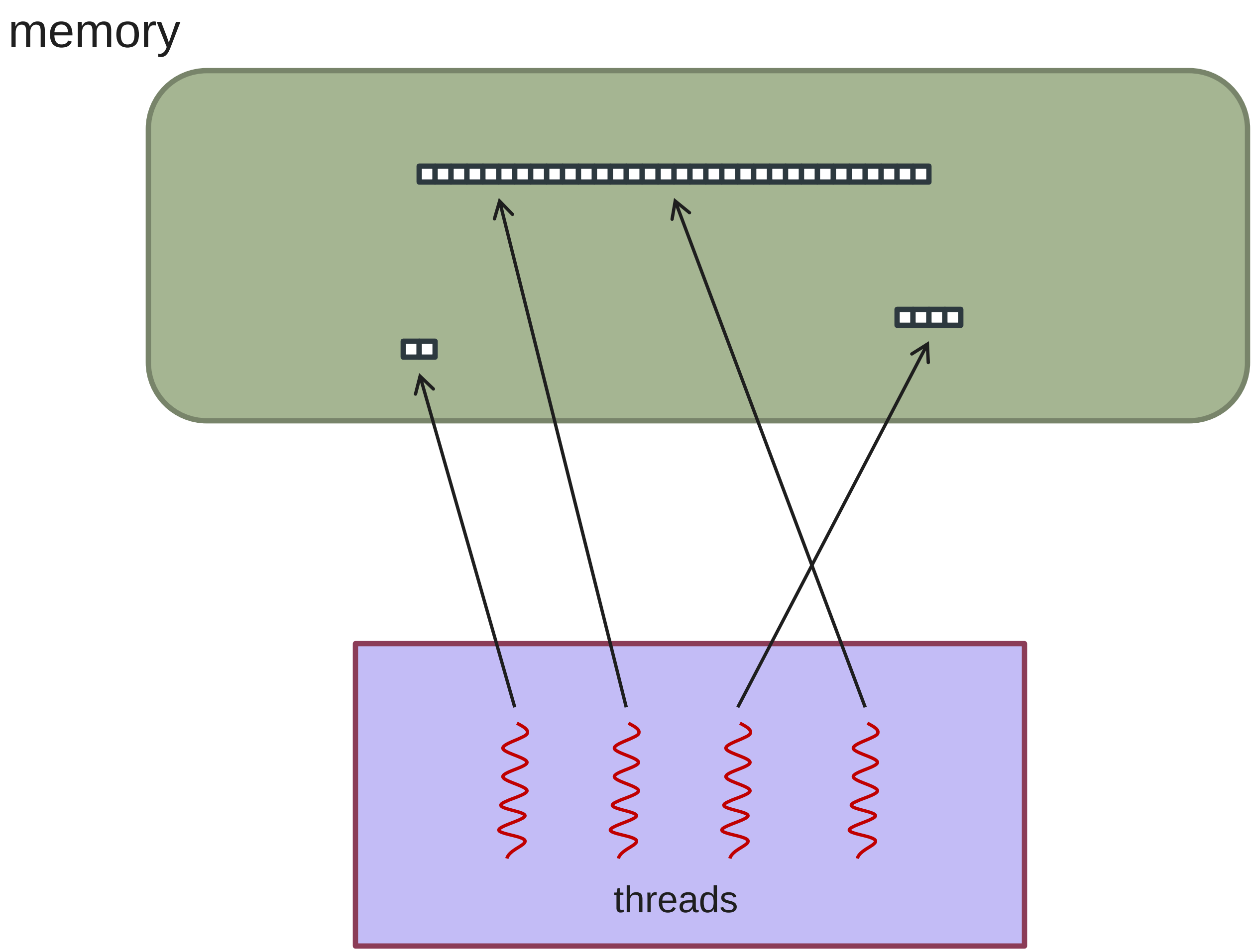
Exercise Session 1

- Look at the *Exercise Notes* document for full details
- Write, compile and run a “Hello World” program that prints out the value of the running image’s image index and the number of images
- Extend the simple Fortran code provided in order to perform operations on parts of a picture using coarrays

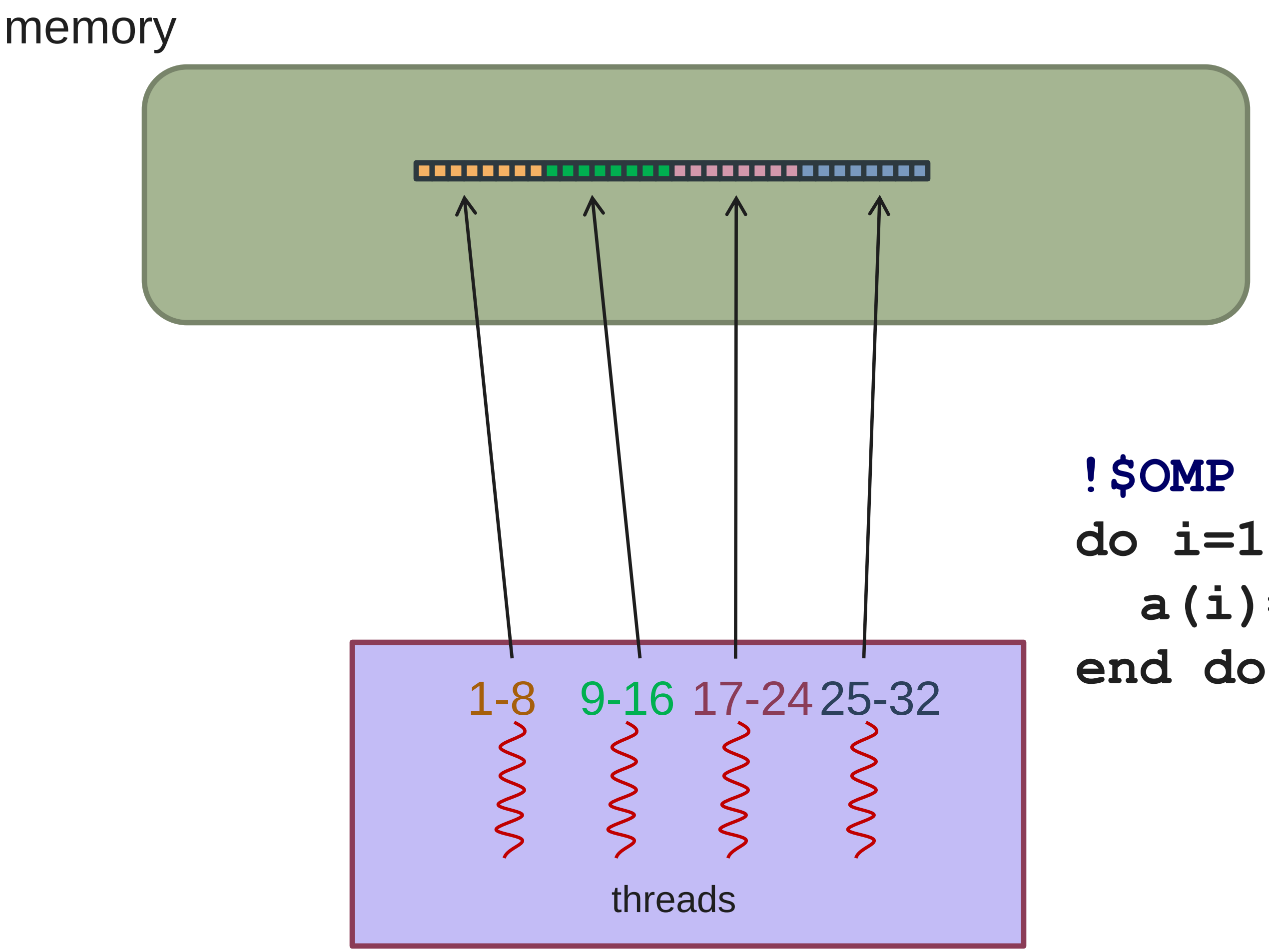
Additional Slides

Comparison of Programming Models

Shared-memory directives and OpenMP

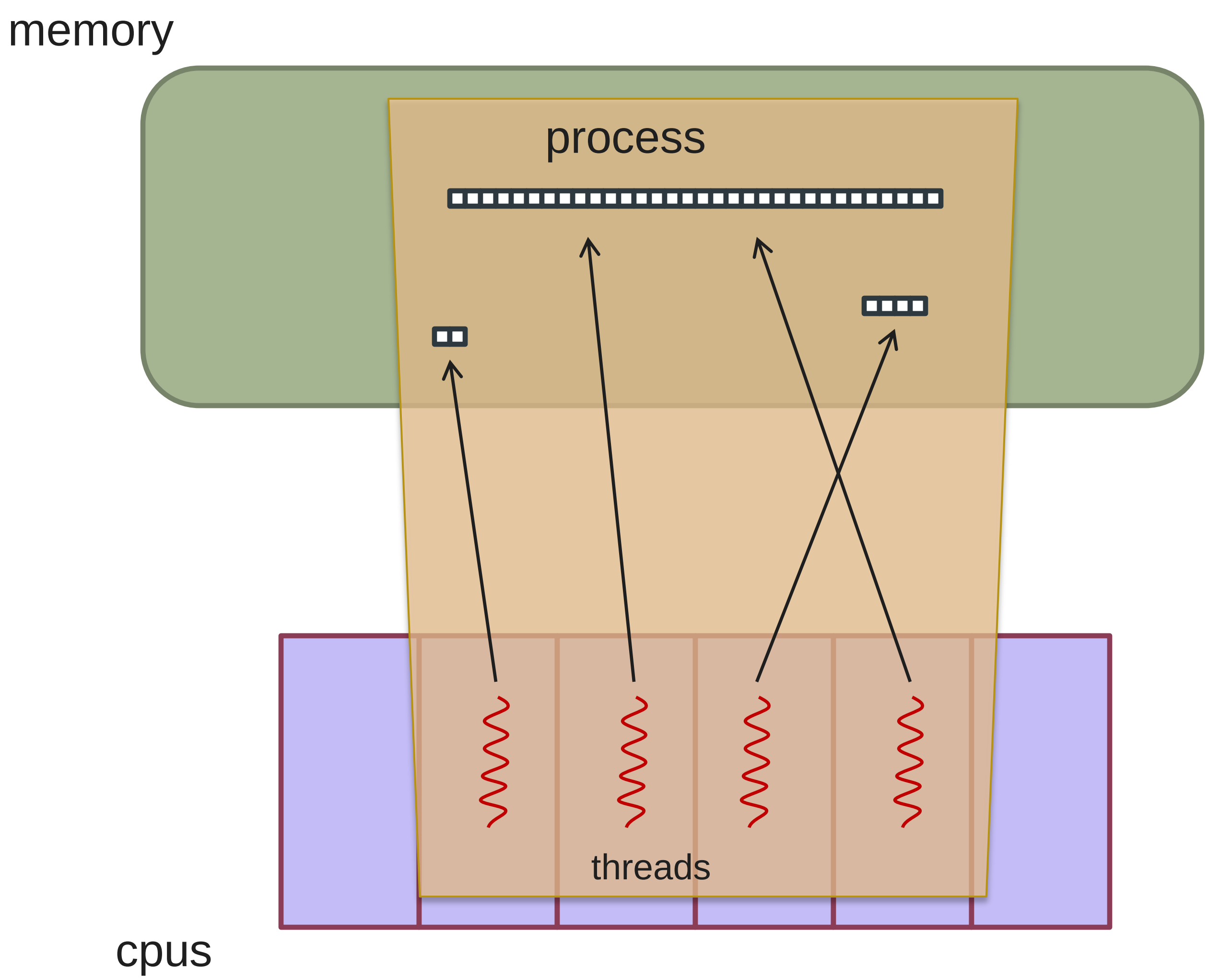


OpenMP: work distribution




```
!$OMP PARALLEL DO
do i=1,32
  a(i)=a(i)*2
end do
```

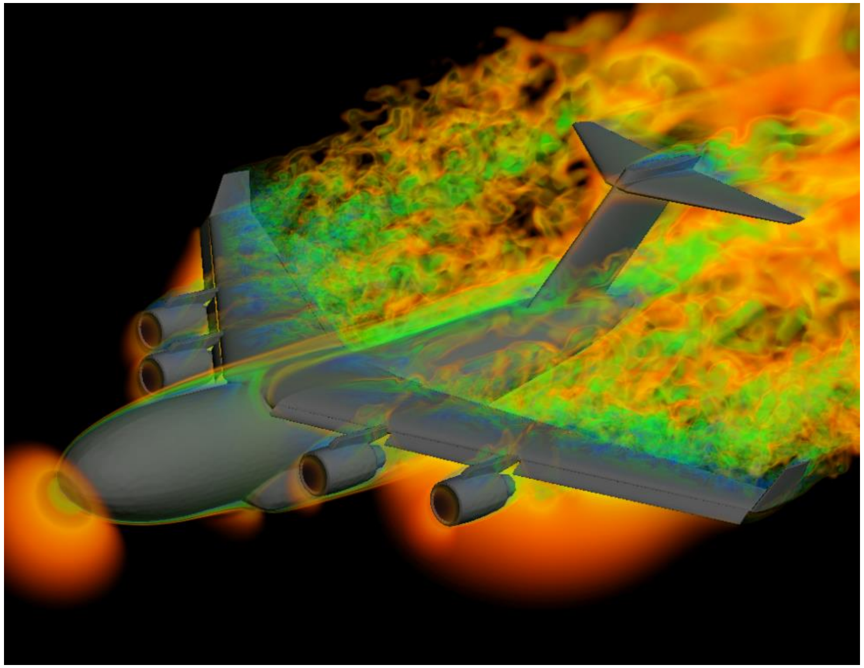
OpenMP implementation



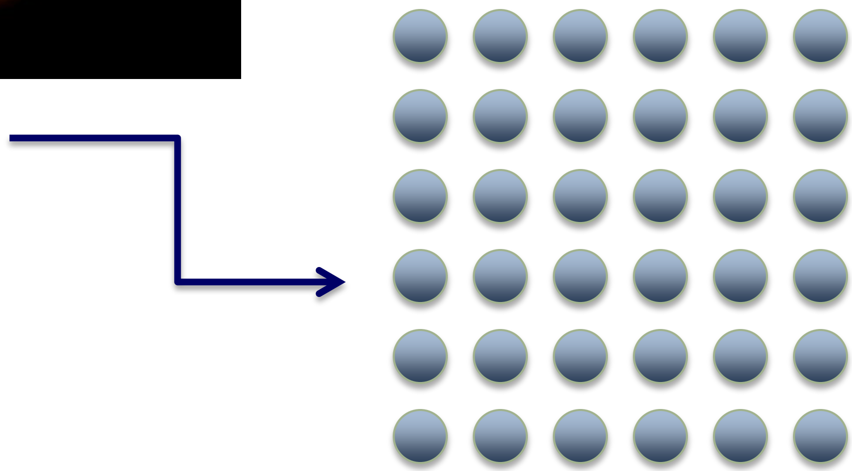
Shared Memory Directives

- Multiple threads share global memory
- Most common variant: OpenMP
- Program loop iterations distributed to threads, more recent task features
  - Each thread has a means to refer to private objects within a parallel context
- Terminology
  - Thread, thread team
- Implementation
  - Threads map to user threads running on one SMP node
  - Extensions to distributed memory not so successful
- OpenMP is a good model to use within a node

Cooperating Processes Models

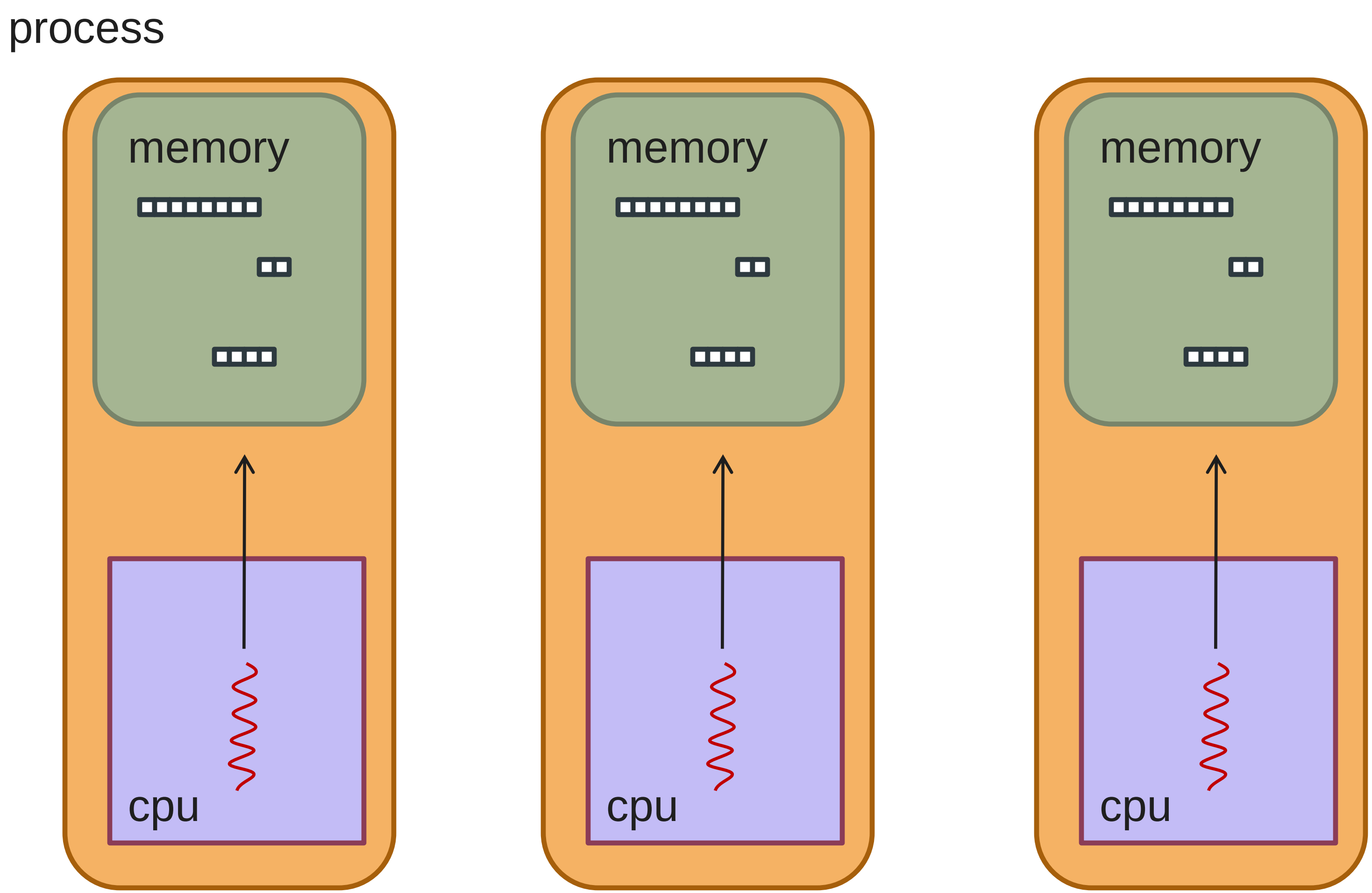


PROBLEM

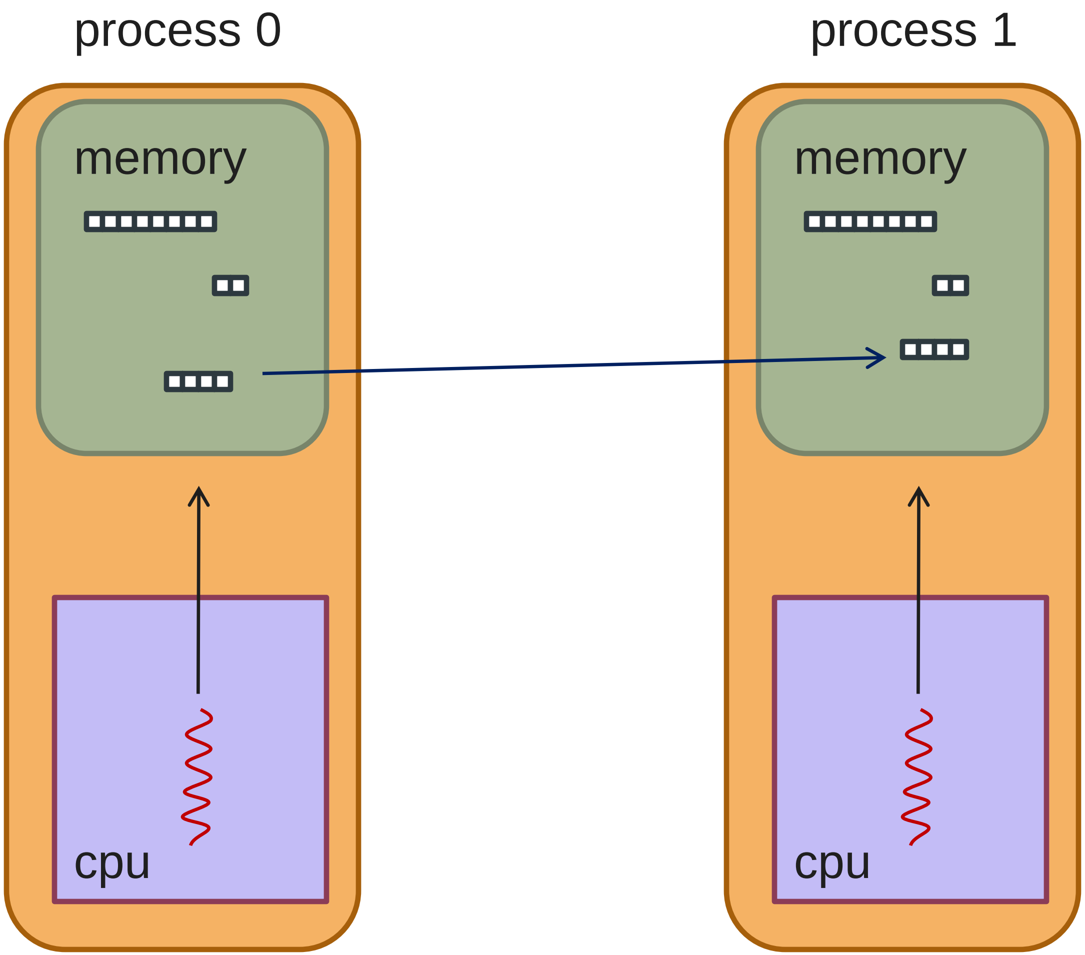


processes

Message Passing, MPI



MPI

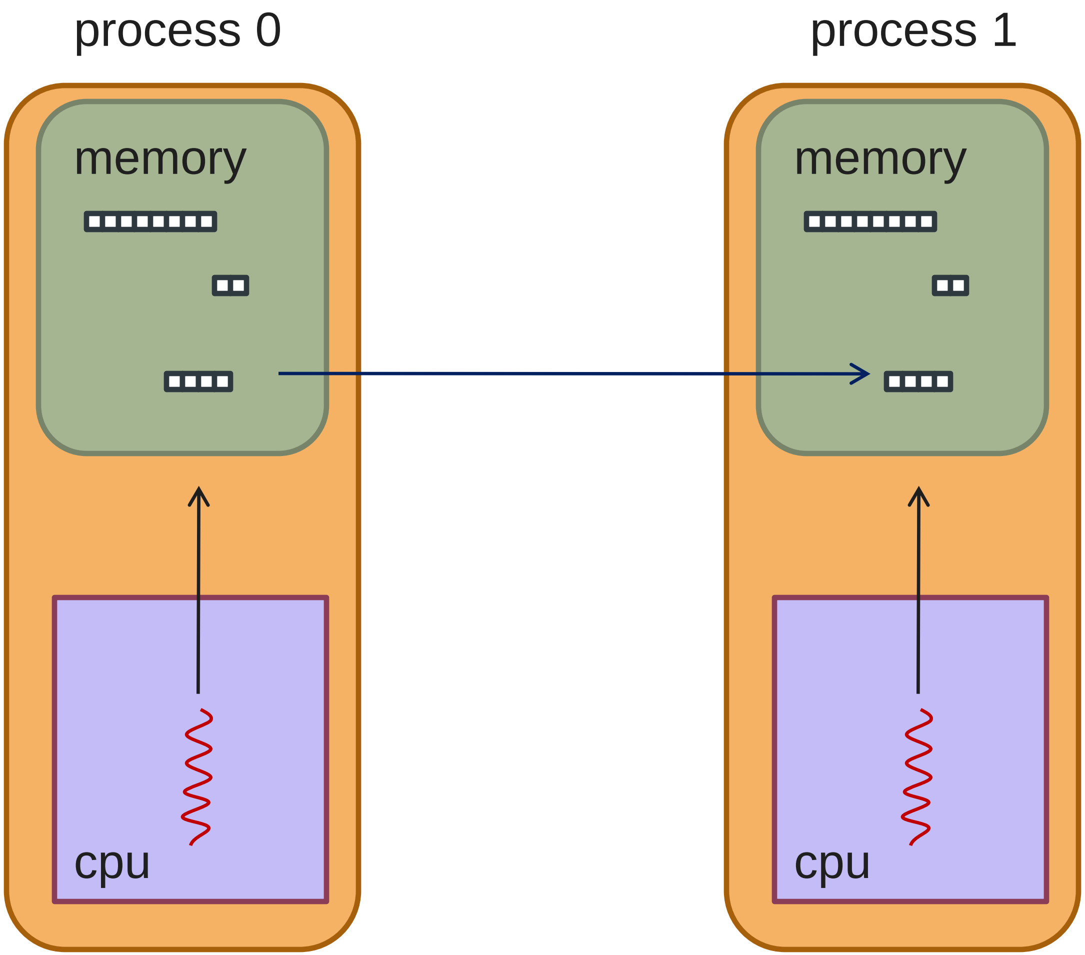


`MPI_Send(a,...,1,…)`   `MPI_Recv(a,...,0,…)`

Message Passing

- Participating processes communicate using a message-passing API
- Remote data can only be communicated (sent or received) via the API
- MPI (the Message Passing Interface) is the standard
- Implementation:
  MPI processes map to processes within one SMP node or across multiple networked nodes
- API provides process numbering, point-to-point and collective messaging operations
- Mostly used in two-sided way, each endpoint coordinates in sending and receiving

SHMEM



`shmem_put(a,b,…)`

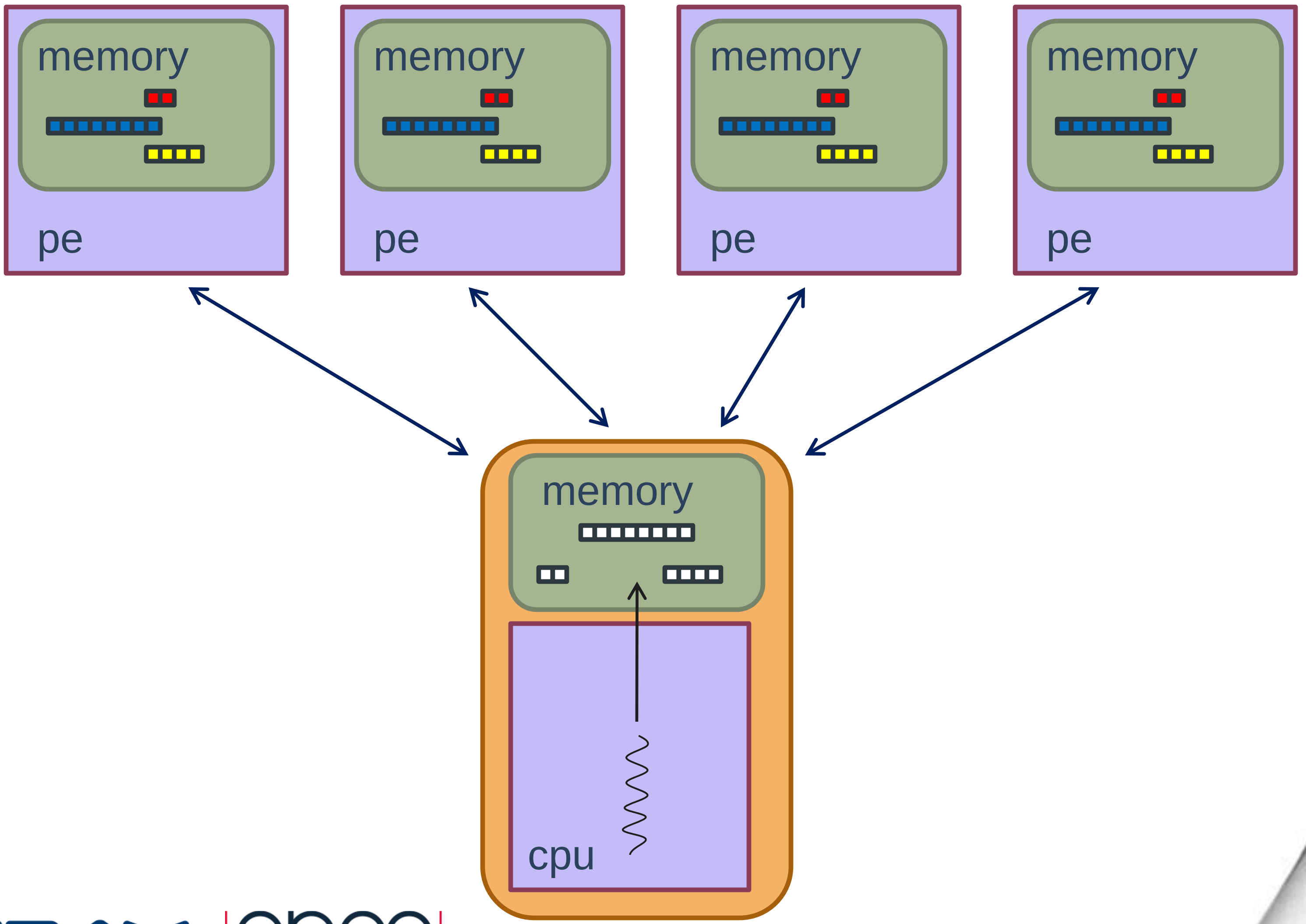
SHMEM

- Participating processes communicate using an API
- Fundamental operations are based on one-sided PUT and GET
- Need to use symmetric memory locations
- Remote side of communication does not participate
- Can test for completion
- Barriers and collectives
- Popular on Cray and SGI hardware, also Blue Gene version
- To make sense needs hardware support for low-latency RDMA-type operations

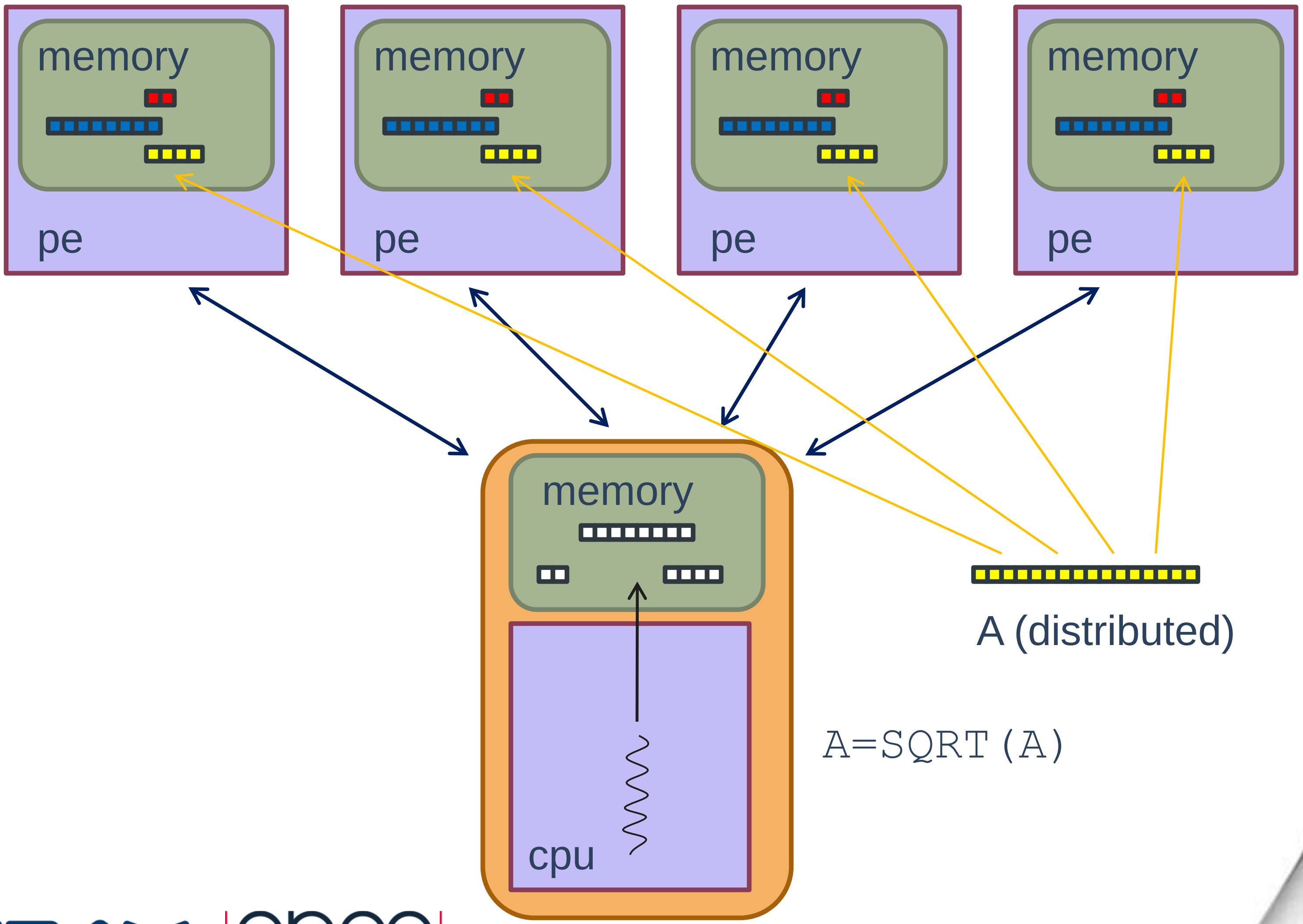
High Performance Fortran (HPF)

- Data Parallel programming model
- Single thread of control
- Arrays can be distributed and operated on in parallel
- Loosely synchronous
- Parallelism mainly from Fortran 90 array syntax, FORALL and intrinsics.
- This model popular on SIMD hardware (AMT DAP, Connection Machines) but extended to clusters where control thread is replicated

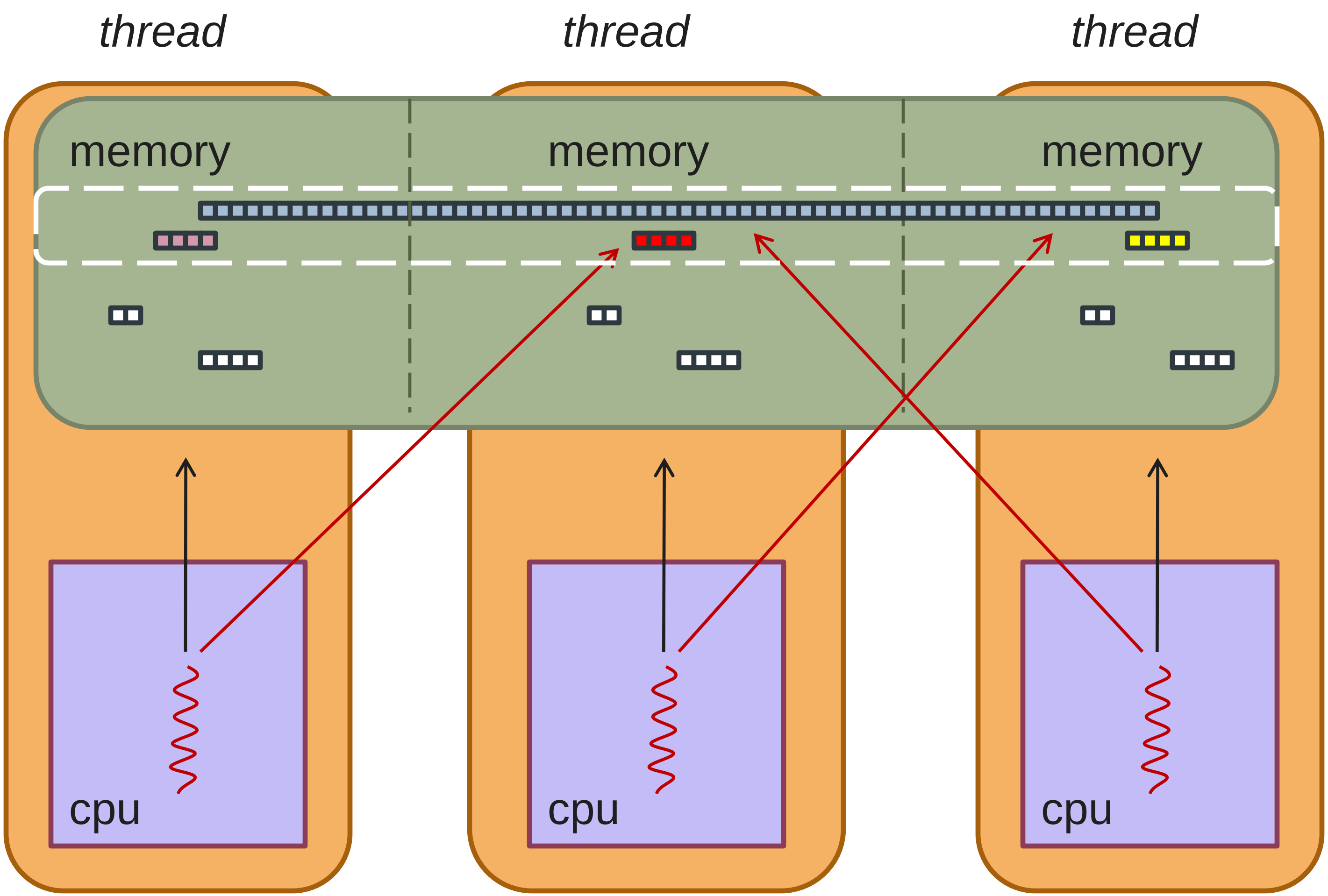
HPF



HPF


memory
pe
memory
pe
memory
pe
memory
pe
memory
cpu
A (distributed)
A=SQRT(A)

UPC



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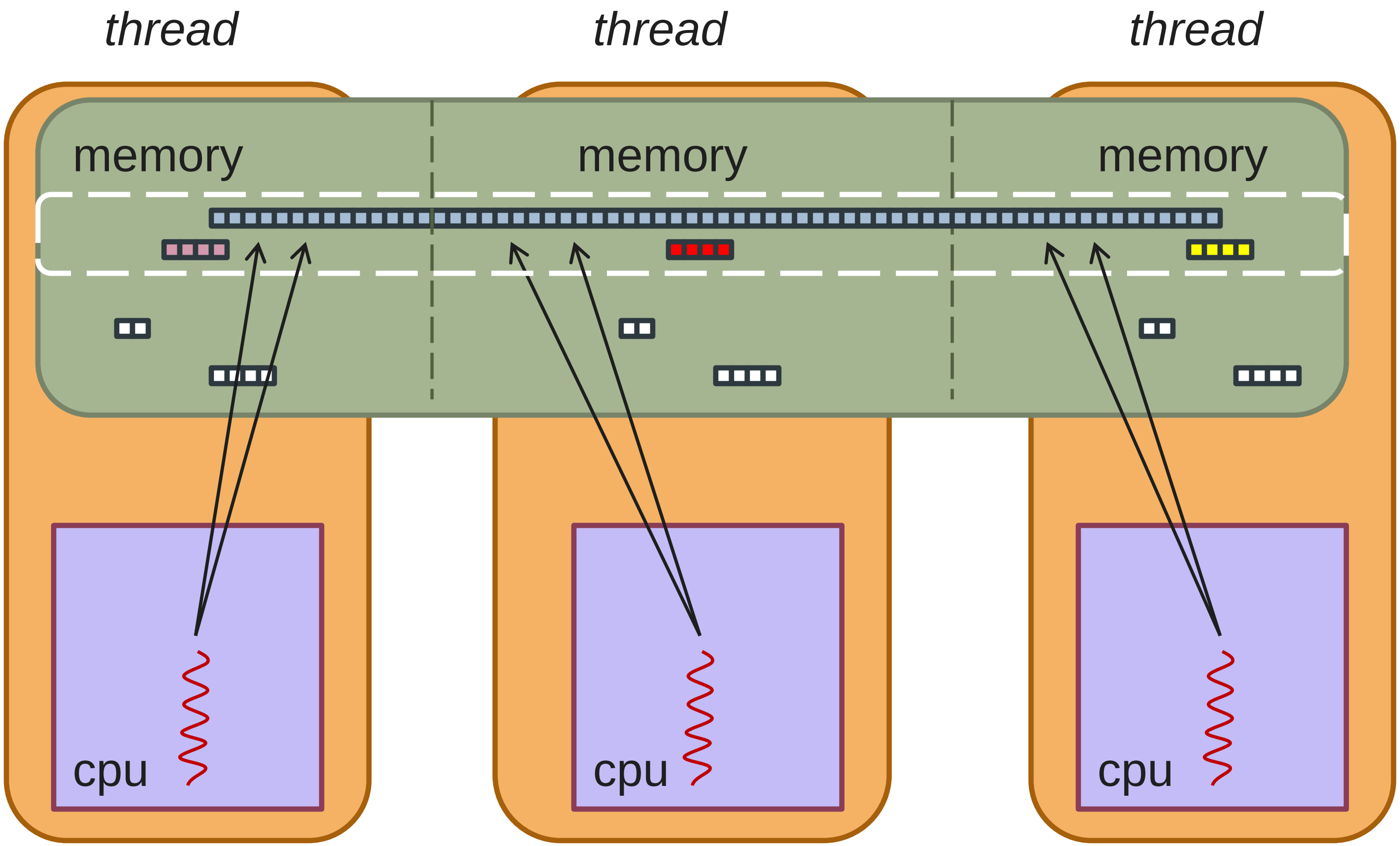


```
upc_forall(i=0;i<32;i++;affinity){
   a[i]=a[i]*2;
}
```

UPC

- Extension to ISO C99
- Participating "*threads*"
- New *shared* data structures
  - shared pointers to distributed data (block or cyclic)
  - pointers to shared data local to a thread
  - Synchronization
- Language constructs to divide up work on shared data
  - upc_forall() to distribute iterations of for() loop
- Extensions for collectives
- Both commercial and open source compilers available
  - Cray, HP, IBM
  - Berkeley UPC (from LBL), GCC UPC

Fortran 2008 coarray model

- Example of a Partitioned Global Address Space (PGAS) model
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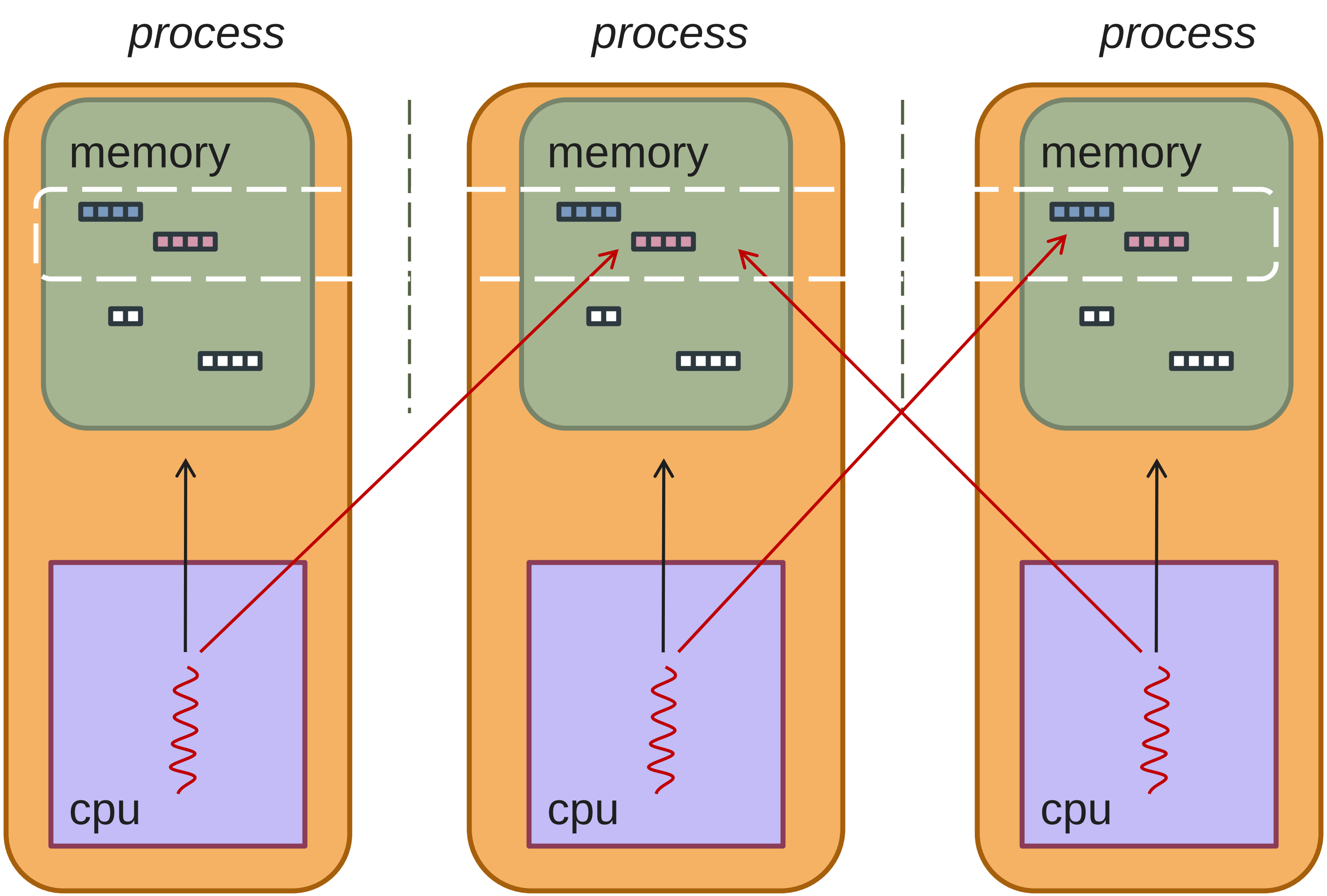
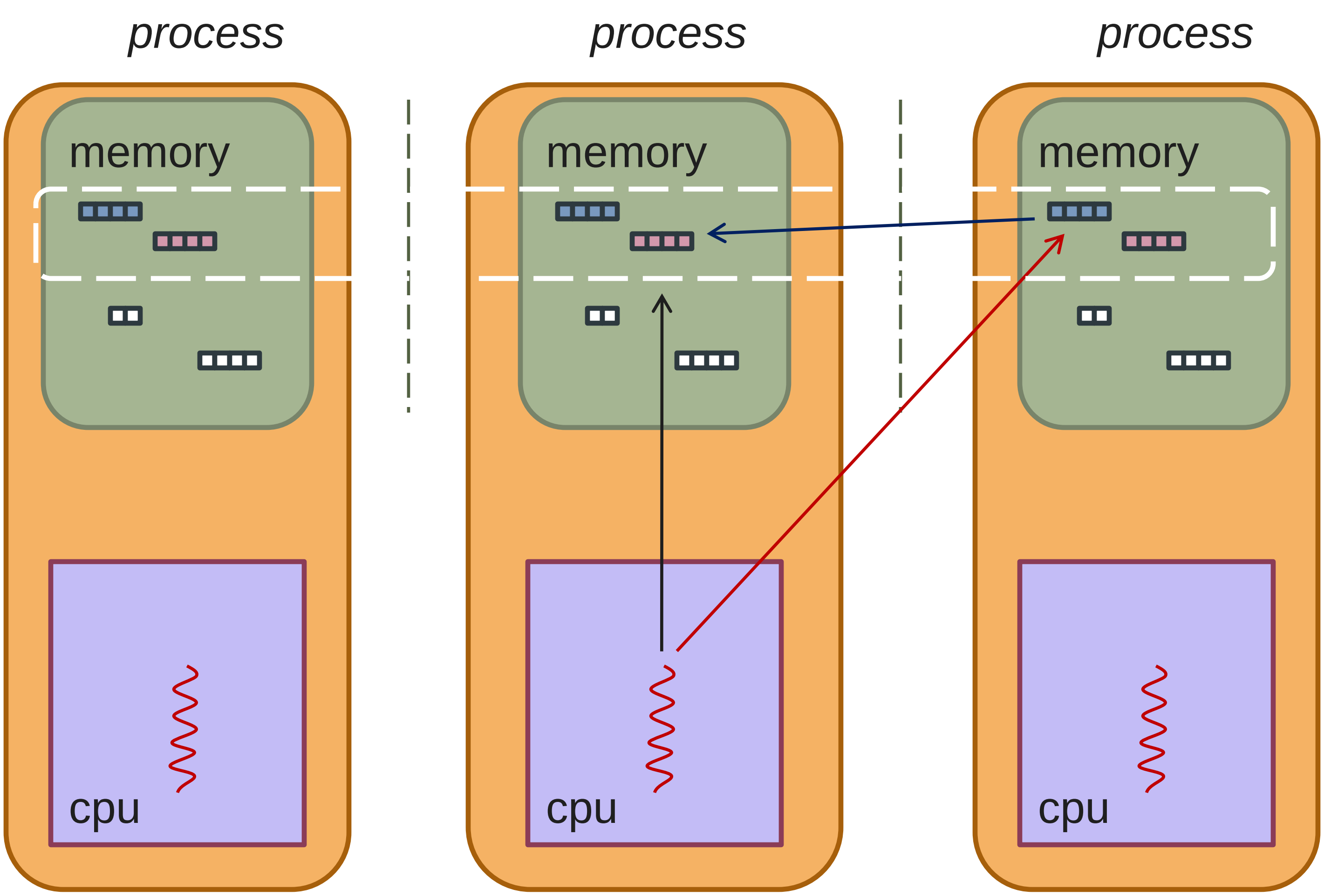
Fortran coarray model



Fortran coarray model




```
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Fortran coarrays

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