Parallel Programming with Coarray Fortran

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Overview

- The Fortran Programming Model
- Basic coarray features
- Practical Session 1
- Further coarray features
- Practical Session 2
- Advanced coarray features
- Practical Session 3
- Experiences with coarrays

The Fortran Programming Model

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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

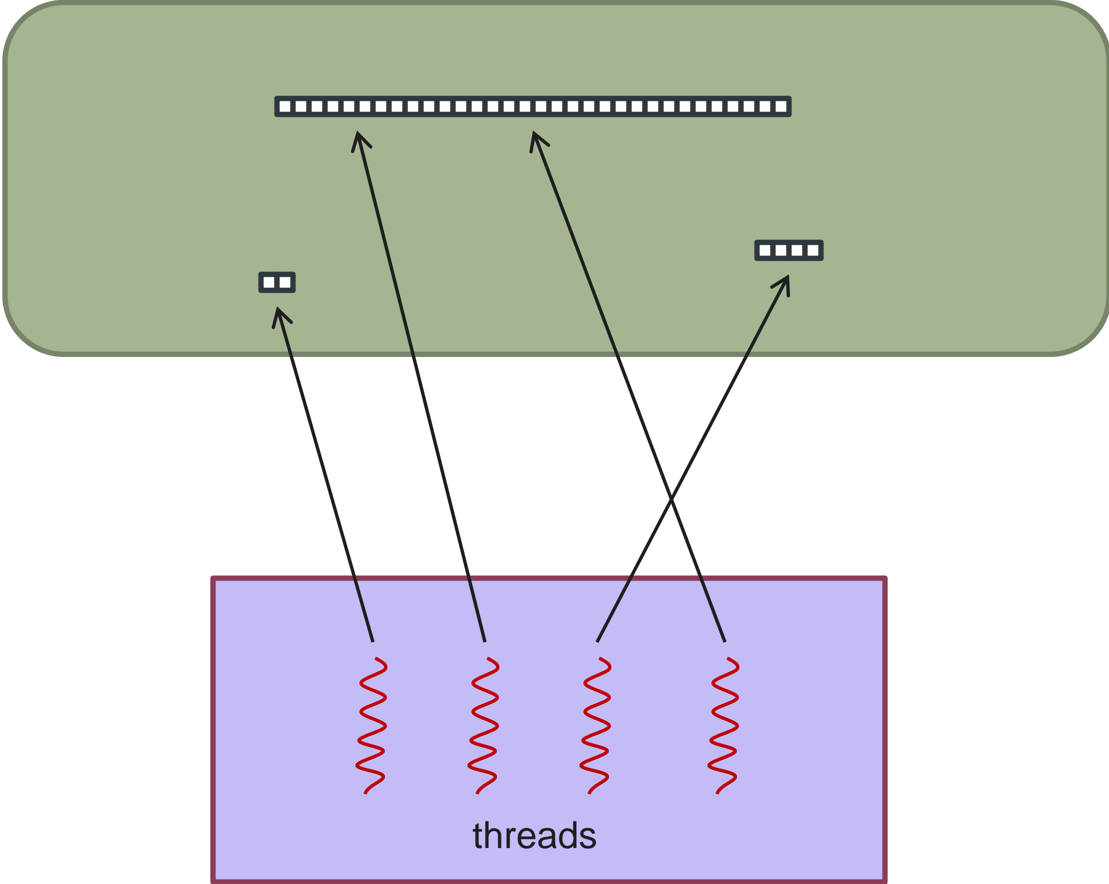
Programming models for HPC

- 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

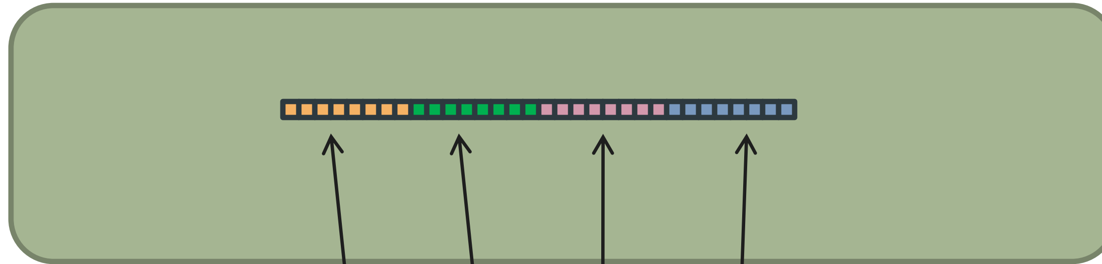
Why consider new programming models?

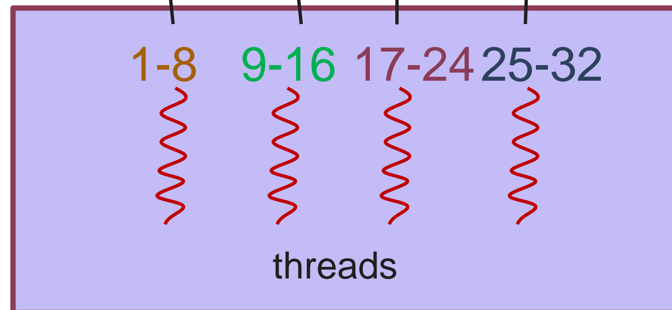
- Next-generation architectures bring new challenges:
  - Very large numbers of processors with many cores
  - Complex memory hierarchy
  - even today (2010) we are at 200k cores
- Parallel programming is hard, need to make this simpler
- Some of the models we currently use are
  - bolt-ons to existing 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 …

Shared-memory directives and OpenMP



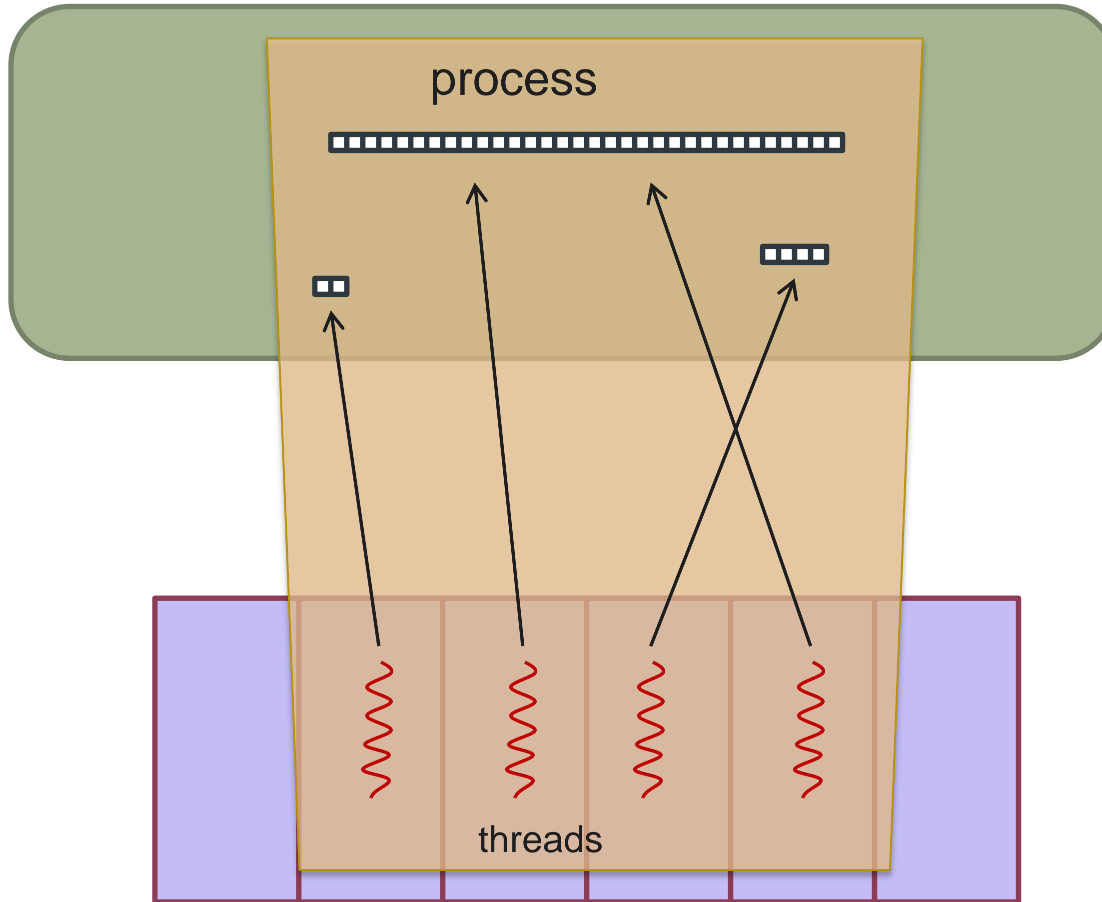
OpenMP: work distribution






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

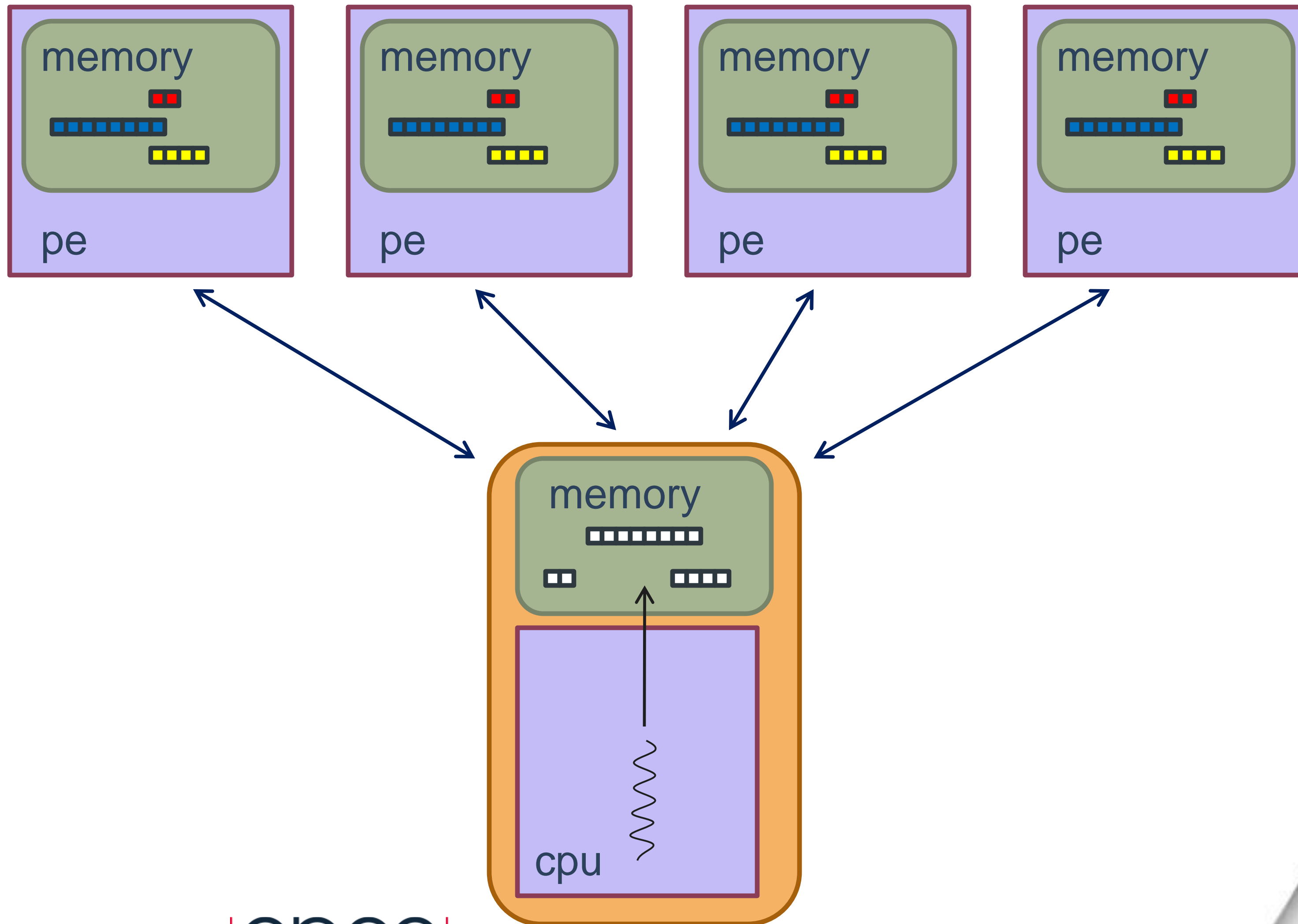
OpenMP implementation



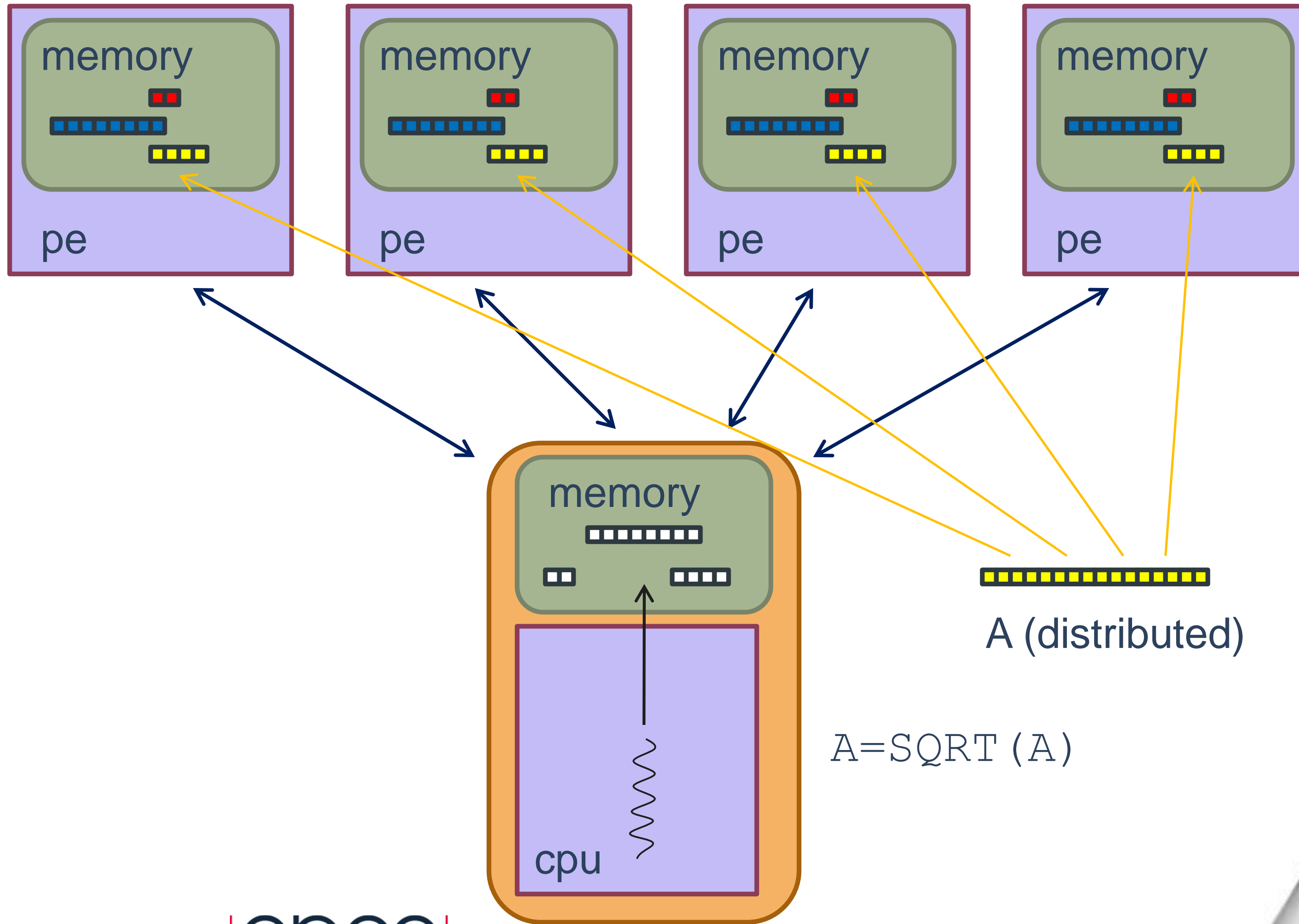
Shared Memory Directives

- 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

High Performance Fortran (HPF)



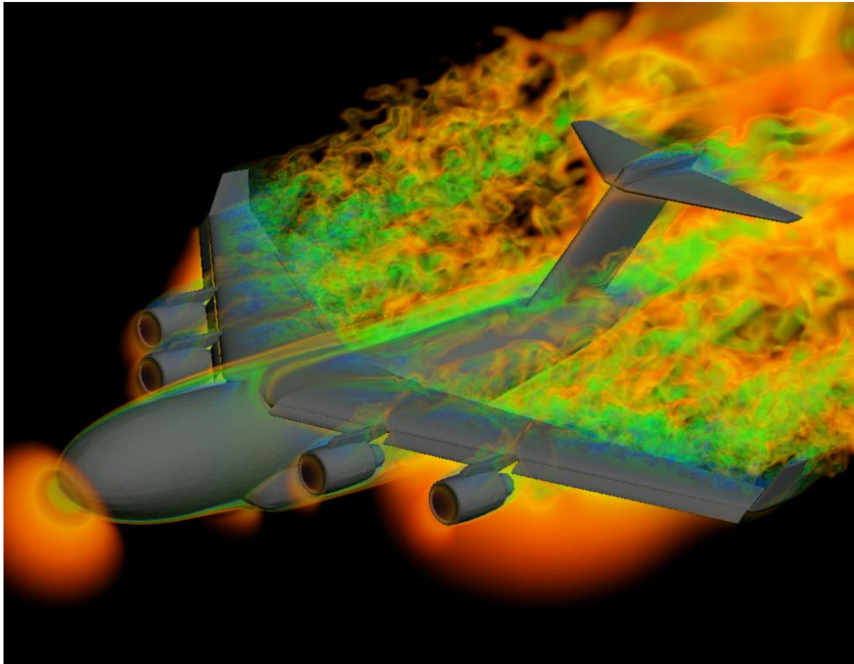
HPF

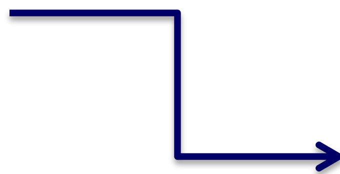


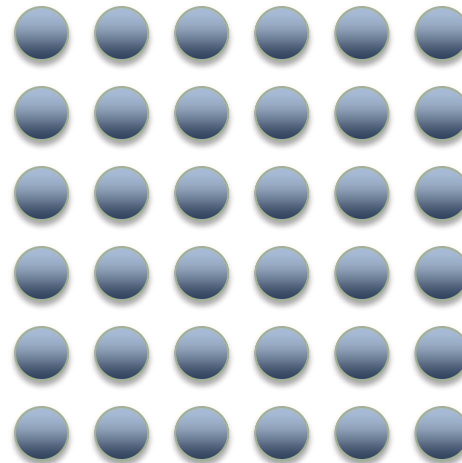
High Performance Fortran

- 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

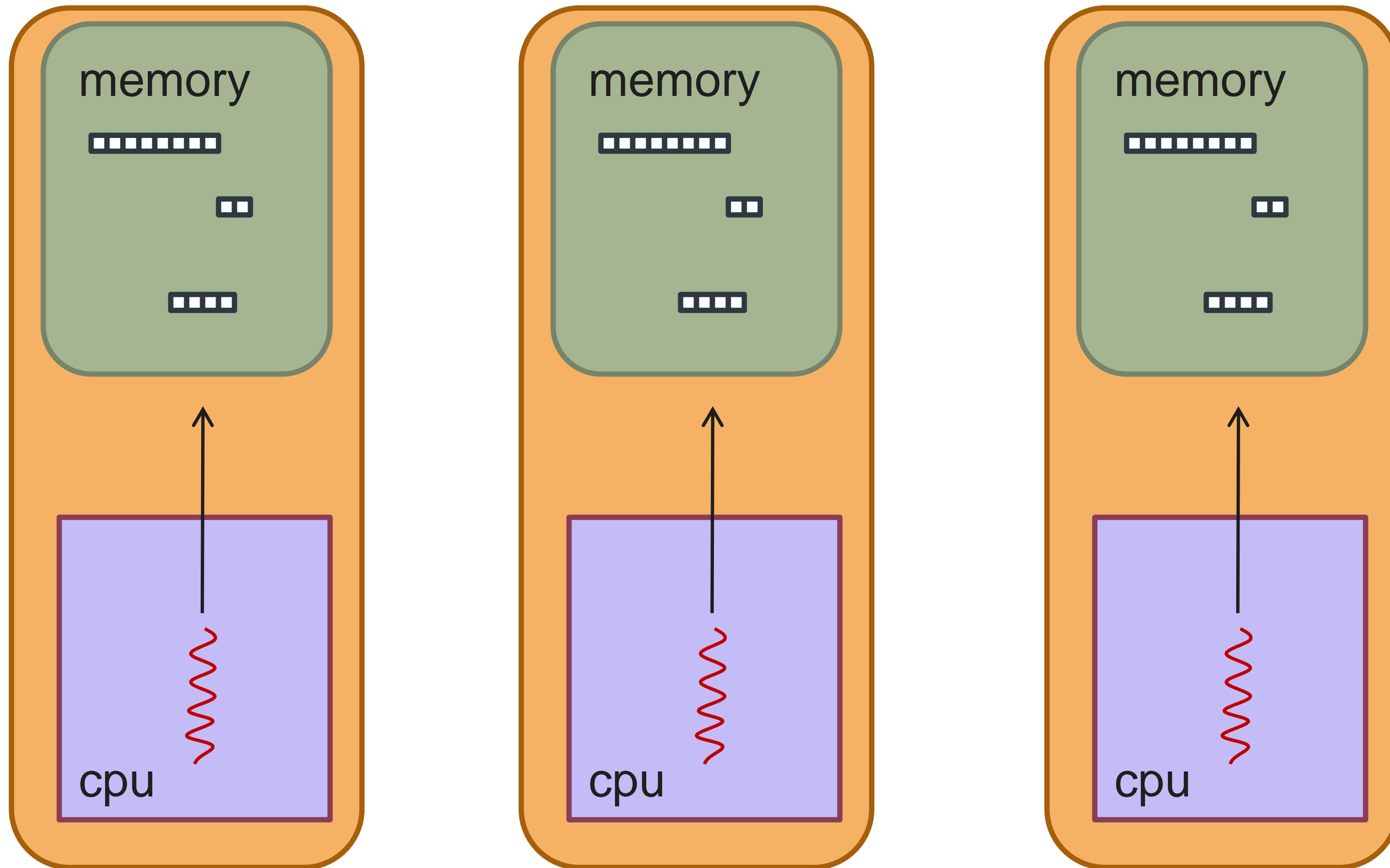
Cooperating Processes Models



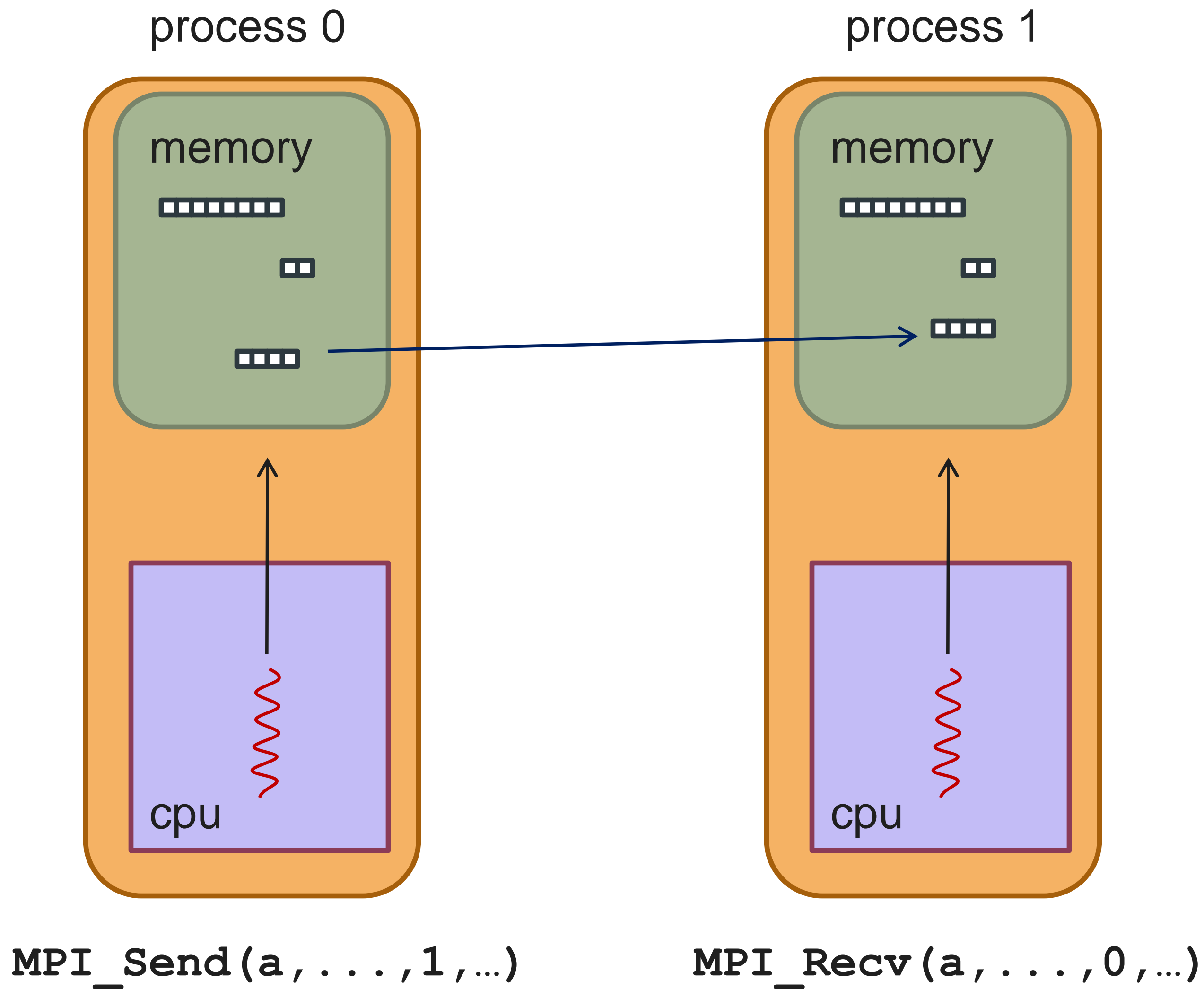




Message Passing, MPI



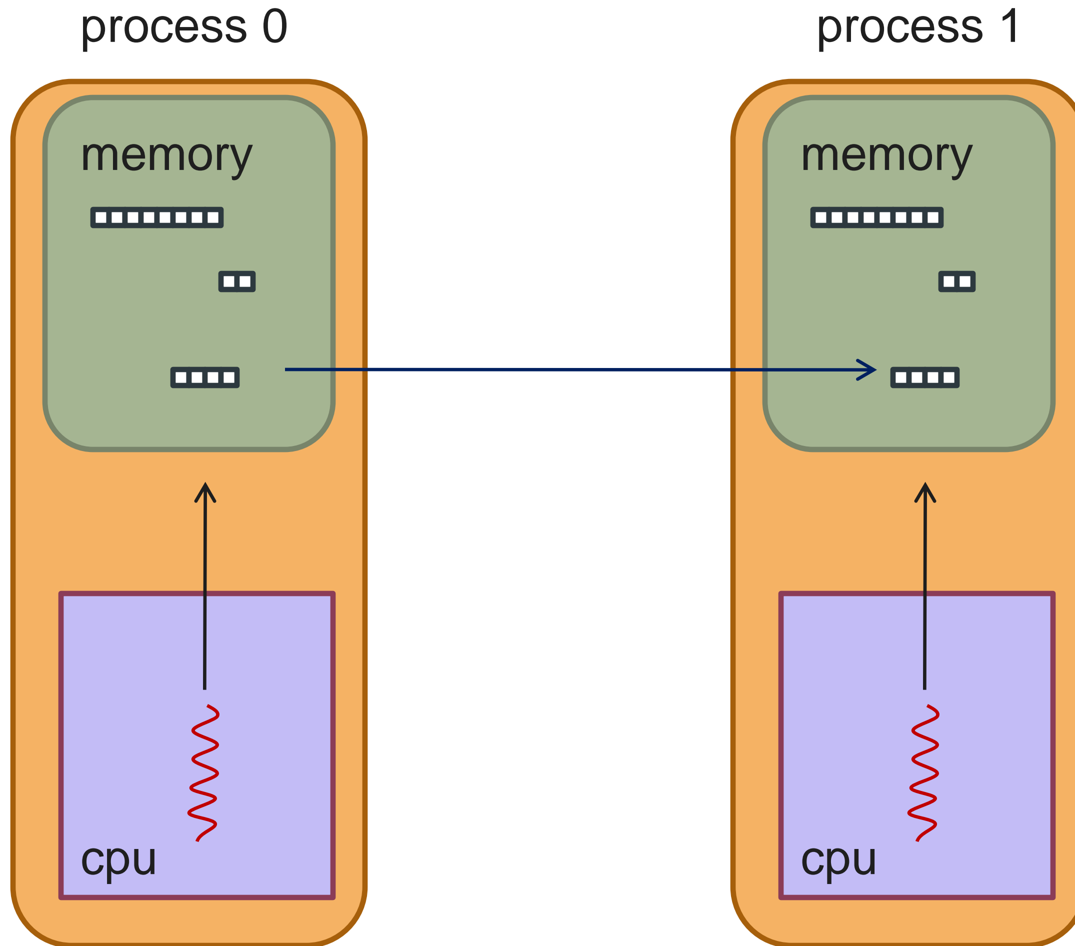
MPI



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,…)
```

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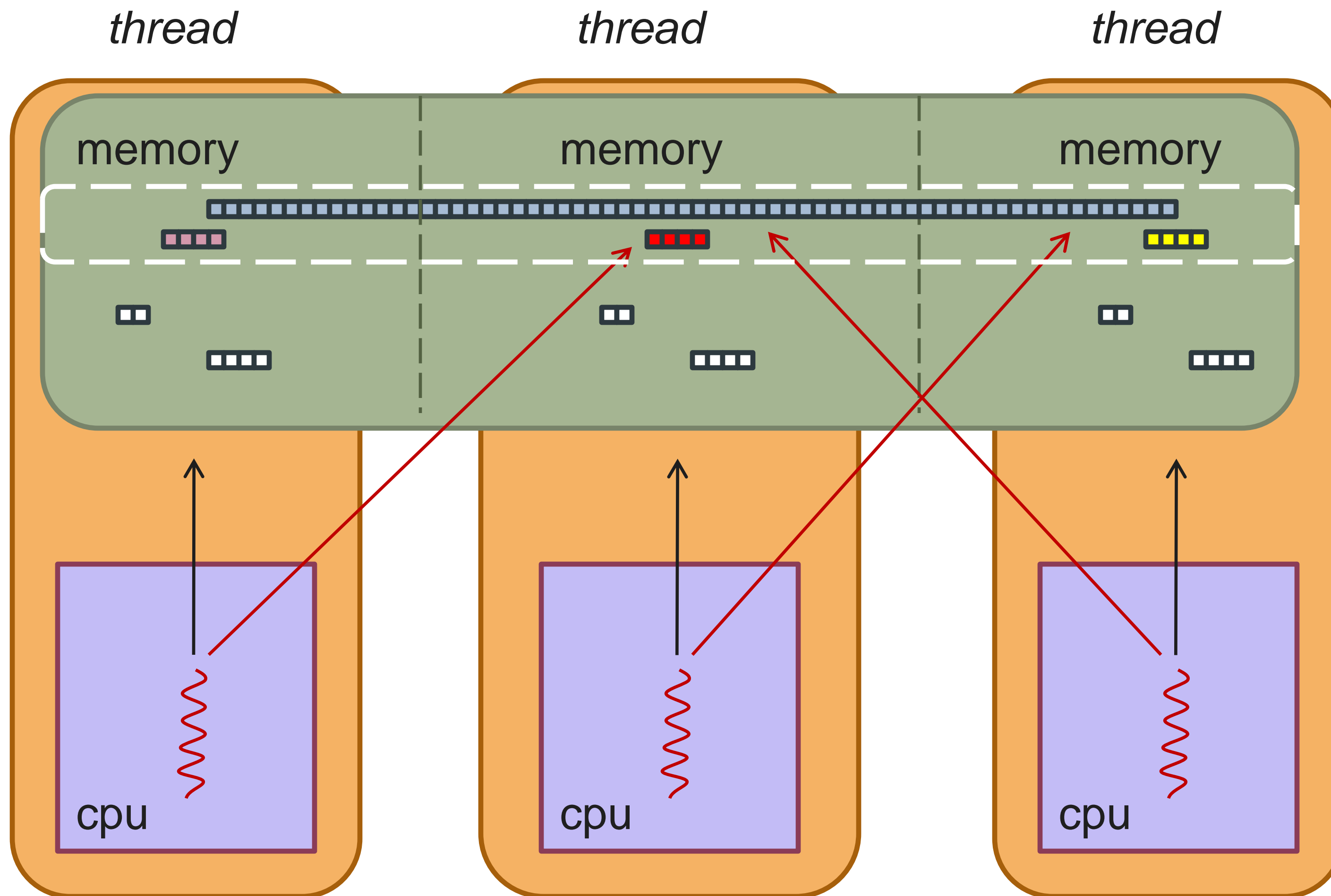
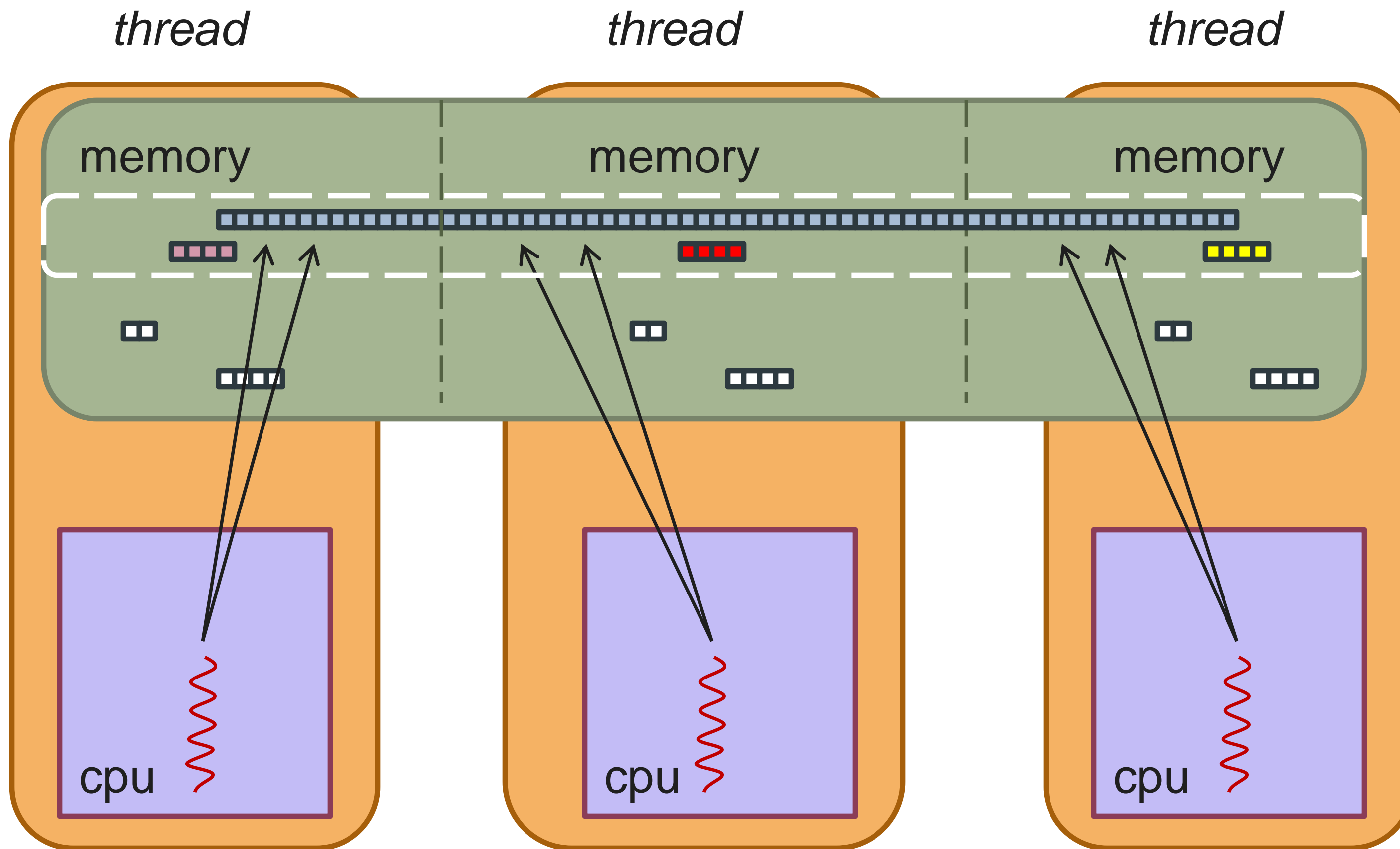
SHMEM

- 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

UPC



UPC




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

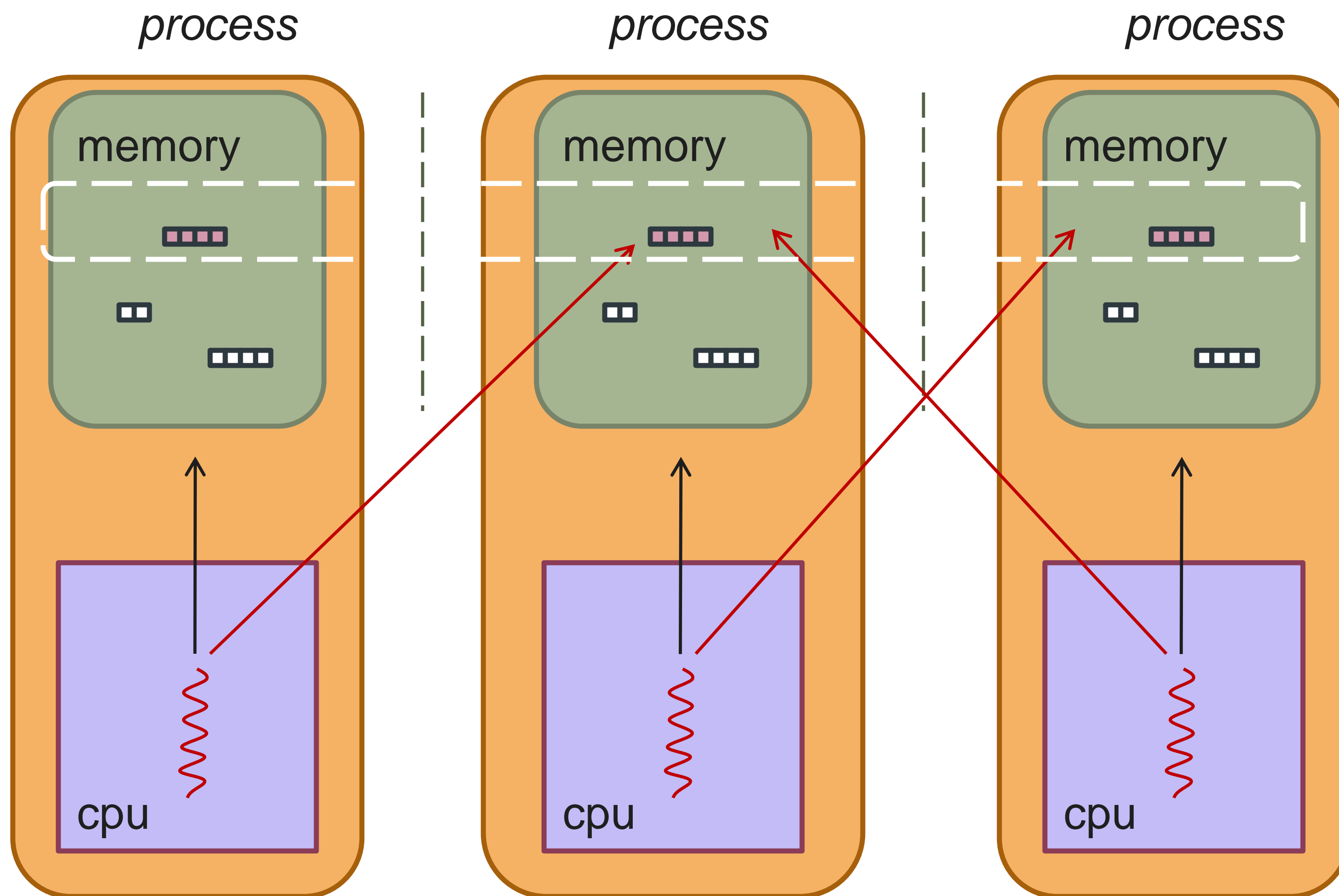
UPC

- 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
- 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

Fortran coarray model



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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

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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

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 Report 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!

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Aside: array syntax

- Arrays are first-class objects in Fortran
  - a lot of support for array operations
- Consider a simple example for standard arrays

```
real, dimension(10):: x, y
x(:) = 1.0
y(:) = x(:)
```

- Equivalent to

```
do i = 1, 10
  x(i) = 1.0
end do
do i = 1, 10
  y(i) = x(i)
end do
```

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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:

image 1

a	1	2	3	4
b	5/2	6/9	7/3	8/7

image 2

a	2	9	3	7
b	10/2	11/9	12/3	13/7

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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 intrinsic 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
```

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
```

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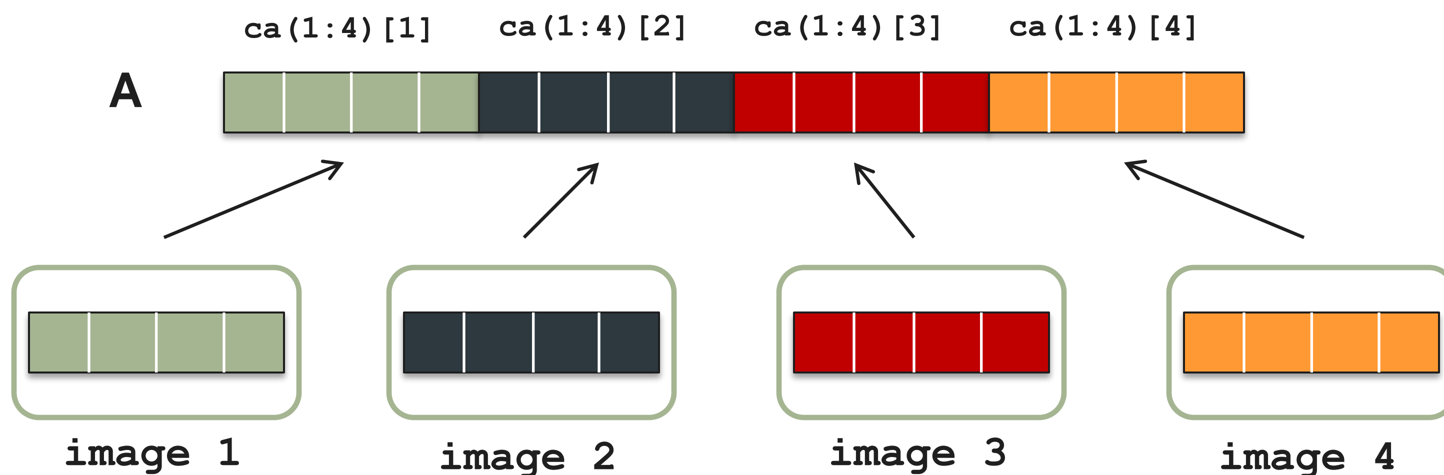
Data usage

- 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

Data usage

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

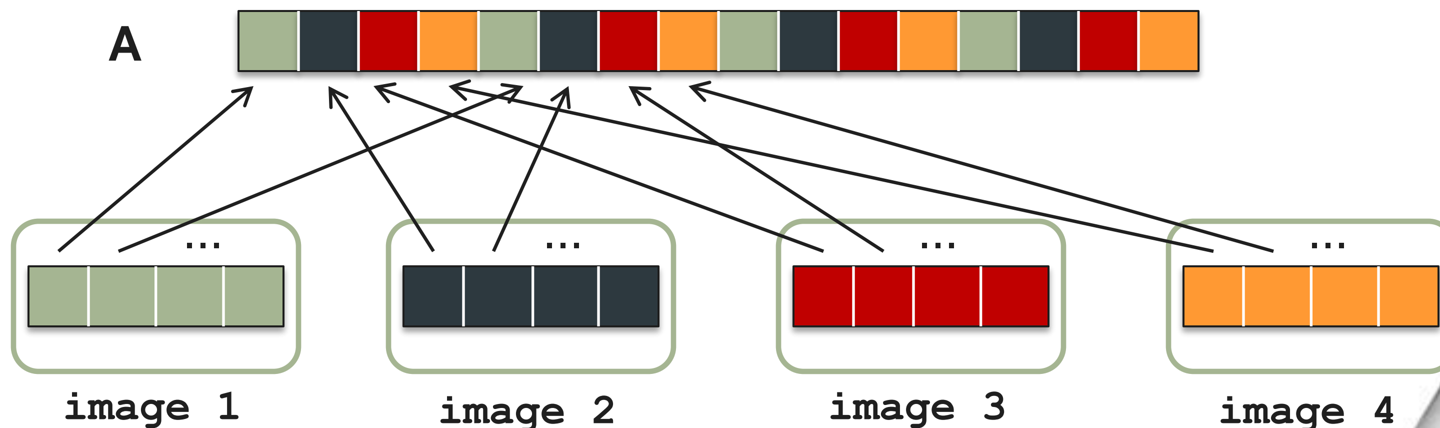
```
integer :: ca(4)[*]
do image=1,num_images()
  print *,ca(:)[image]
end do
```



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

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Recap

We now know the basics of coarrays

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

Now consider a full program example...

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Example2: Calculate density of primes

```
program pdensity
 implicit none
 integer, parameter :: n=8000000, 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
```

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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 ",2P,f5.2,"%")')density
  write(*,'(" asymptotic theory gives ", &
&            2P,f5.2,"%")')1.0/(log(real(n))-1.0)

  end if
```

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Example2: Calculate density of primes

```
Calculating prime density on 2 images
539778 primes in 8000000 numbers
density is  6.75%
asymptotic theory gives  6.71%
```

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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 XE
  aprun –n 16000 solver
- g95
  ./solver --g95 -images=2

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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

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