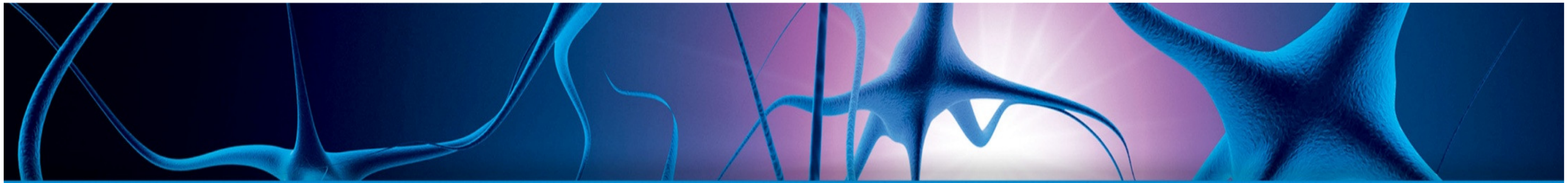

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Coarrays – A Parallel Programming Model in Intel Fortran

Steve Blair-Chappell
Software and Services Group
Intel Corporation

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What is Coarray Fortran?

- A parallel processing feature added to the Fortran language
- Part of the approved Fortran 2008 Standard
- A Partitioned Global Address Space (PGAS), Single-program Multiple-Data (SPMD) design
- Scalable from single-core to multi-CPU to clusters

History of Coarray Fortran

- Outlined in paper by Numrich and Reid in 1998
- Implemented by Cray for T3E and X-1
- Early preprocessor from Rice University
- Partial implementation in g95, experimental branch of gfortran
- Integrated into Fortran 2008 standard (approved in 2010)

Coarray Fortran Fundamentals: Images

- A CAF “Image” is a process
  - Processes have NO data sharing by default – separate memory maps.
- Example: hello world with no CAF syntax: 4 cores:

```
$> ifort -coarray -o hello hello.f90
$> ./hello
hello
hello
hello
hello
$>
```

```
program hello
write(*,*) ‘hello’
end program hello
```

```
program hello
write(*,*) ‘hello’
end program hello
```

```
program hello
write(*,*) ‘hello’
end program hello
```

```
program hello
write(*,*) ‘hello’
end program hello
```

CAF Fundamentals: Determining Number of Images, num_images()

- Intrinsic function num_images() returns an integer result, the total number of images in the CAF program:

```
$> cat hello_num_images.f90
program hello_num_images
  write(*,*) "Hello there are ", num_images()," total images"
end program hello_num_images

> ifort -coarray -coarray-num-procs=4 hello_num_images.f90
$> ./a.out
 Hello there are            4  total images
 Hello there are            4  total images
 Hello there are            4  total images
 Hello there are            4  total images
```

Coarray Fundamentals: this_image()

- Images have a logical ordering from 1 to N
- Integer function this_image() without an argument returns unique logical ordering from 1 to N
  - More complex image mappings possible: 2D, 3D, etc with arguments (topic discussed later)

```
$> cat hello_this.f90
program hello_this_image
  write(*,*) "Hello from image ", this_image()
end program hello_this_image
$> ifort -coarray -coarray-num-procs=4 hello_this.f90
$> ./a.out
Hello from image            1
Hello from image            3
Hello from image            2
Hello from image            4
```

- Remember, the images are inherently asynchronous

What is a coarray?

- Extends array syntax to add CODIMENSION
  - REAL, DIMENSION(100), CODIMENSION[*] :: X
  - REAL :: X(100)[*]
- Multiple codimensions possible
  - REAL :: X(100,200)[10,0:9,*]
- Scalars can also have codimensions
- Last bound of codimension is based on number of images
  - Last row may not be complete if images not a multiple of other codimension ranges
- Number of dimensions plus codimensions must be <= 15

What is a coarray? (contd.)

- Each copy of the program (image) has its own piece of the coarray
- References without [] mean local data
- References with [] mean data on specified image(s)
- Can use coarrays most places in the language
  - Coarrays may be allocatable, structure components, dummy or actual arguments

Where’s My Data?

REAL :: X(2,3)[*]

Image 1

X(1,1)	X(1,2)	X(1,3)
X(2,1)	X(2,2)	X(2,3)

REAL :: X(2,3)[*]

Image 2

X(1,1)	X(1,2)	X(1,3)
X(2,1)	X(2,2)	X(2,3)

REAL :: X(2,3)[*]

Image 3

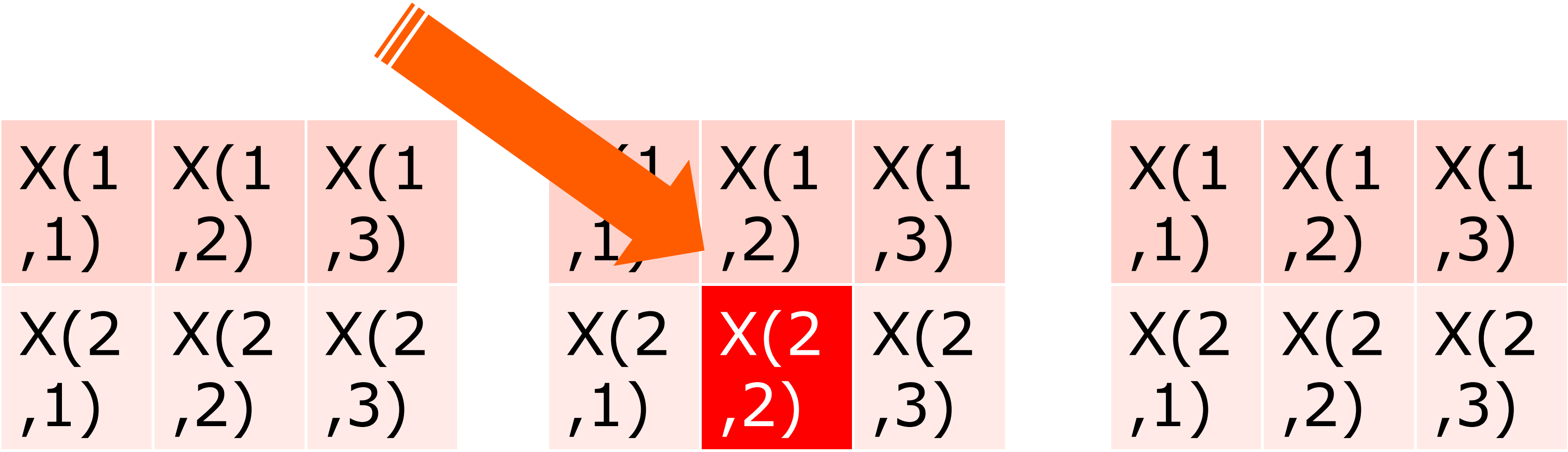
X(1,1)	X(1,2)	X(1,3)
X(2,1)	X(2,2)	X(2,3)

Where’s My Data?

REAL :: X(2,3)[*]
Image 1

REAL :: X(2,3)[*]
Image 2

REAL :: X(2,3)[*]
Image 3



X(1,1)	X(1,2)	X(1,3)
X(2,1)	X(2,2)	X(2,3)

X(1,1)	X(1,2)	X(1,3)
X(2,1)	X(2,2)	X(2,3)

X(1,1)	X(1,2)	X(1,3)
X(2,1)	X(2,2)	X(2,3)

X(2,2)[2] reference from image 1

Where’s My Data?

REAL :: X(2,3)[*]

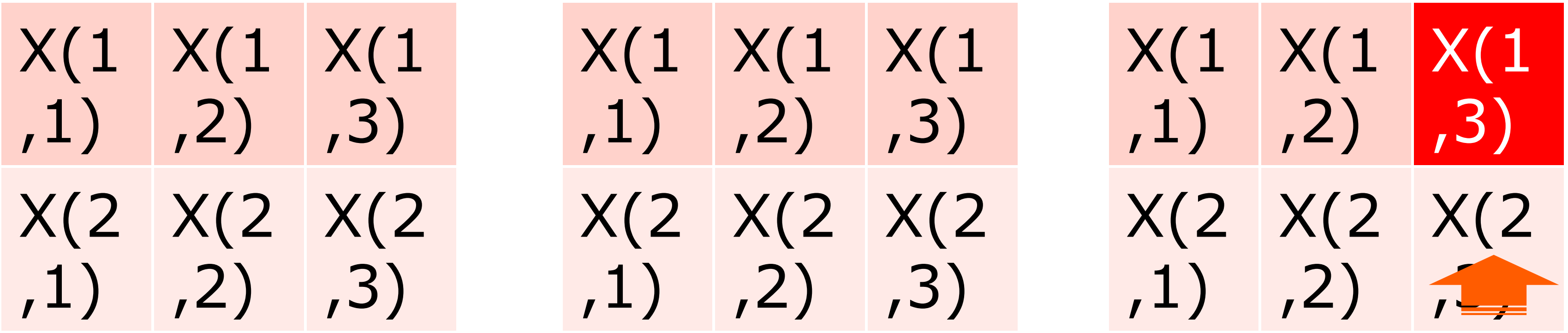
Image 1

REAL :: X(2,3)[*]

Image 2

REAL :: X(2,3)[*]

Image 3



X(1,1)	X(1,2)	X(1,3)
X(2,1)	X(2,2)	X(2,3)

X(1,1)	X(1,2)	X(1,3)
X(2,1)	X(2,2)	X(2,3)

X(1,1)	X(1,2)	X(1,3)
X(2,1)	X(2,2)	X(2,3)

X(1,3) reference from image 3

Coindices

- Given `REAL :: Y[10,0:9,0:*], Z(10)[5,*]`
  - `Y[3,1,2]` accesses image 213
  - `Z(:)[1,4]` accesses image 16
- What if the specified image doesn't exist?

Error!

It's All About Image

- Number of images determined at run-time
  - Default is number of processor execution units
- `NUM_IMAGES` intrinsic tells you how many
- `THIS_IMAGE` intrinsic says which one you are
- `THIS_IMAGE(`*`coarray`*`)` gives you coindices for your copy of *coarray*
- `IMAGE_INDEX` converts coindices to image index

Staying in Synch

- `SYNC ALL`, `SYNC MEMORY`, `SYNC IMAGES` create synchronization points
- `CRITICAL/END CRITICAL` sections
- `LOCK` and `UNLOCK` statements control lock objects
- `ERROR STOP` terminates all images

More about Coarrays

- Each image has its own set of I/O units
  - “stdin” preconnected on image 1 only
  - “stdout” and “stderr” preconnected on all images
    - Implementation may merge them – not required
- Coarrays can be used in I/O
- Coarrays are not interoperable with C

Coarrays in Intel® Fortran

- Supported in Intel® Fortran Composer XE 2011 for Linux* and Intel® Visual Fortran Composer XE 2011 for Windows*
- Shared-memory implementation only in base product
- Distributed Memory implementation with addition of Intel® Cluster Toolkit license (Linux only at this time)

Coarrays in Intel Fortran

- Enable Coarray syntax with `–coarray (/Qcoarray` on Windows)
- Default number of images is same as number of processor execution units (processors*cores*threads)
  - Override with command option or environment variable
- `-coarray=distributed` to get distributed memory (cluster) – requires Cluster Toolkit license

Coarrays in Intel Fortran

- Underlying transport is Intel® MPI 4.0.1 for both shared and distributed memory
  - Other MPI implementations not supported
- At this time, **not** supported for use with OpenMP* or MPI direct calls
- With `–coarray=distributed`, uses existing configured MPI ring, or use `–coarray-config-file`

Running a Coarray Application

- For shared memory, just run it!
  - No mpirun, etc. needed – all handled automatically
- For distributed memory, need to start mpd first
- Environment variables available:
  - `FOR_COARRAY_CONFIG_FILE`
  - `FOR_COARRAY_NUM_IMAGES`

Example Program

```
if (this_image() == 1) print '(A,I0,A)', &
& "Coarray Fortran program running with ", &
& num_images(), " images"
sync all
print '(A,I0)',"Hello from image ", this_image()
end
```

Building and Running Example

```
c:\>ifort /nologo /Qcoarray caf.f90
c:\>caf.exe
Coarray Fortran program running with 8 images
Hello from image 1
Hello from image 5
Hello from image 2
Hello from image 3
Hello from image 7
Hello from image 4
Hello from image 6
Hello from image 8
```

Summary

- Single-Program-Multiple-Data (SPMD) model
- A fixed number of processes/threads called images all execute the same program asynchronously
- Coarray syntax specifies explicit data decomposition
- All data and computation is local to each image
- One-sided communication thru co-dimensions
- Explicit synchronization must be requested by programmer
- Supported by Intel® Fortran Compiler XE 2011 for Linux* and Windows* on IA-32 and Intel® 64 architectures

One More Thing…

There will be bugs…

Read the Release Notes for a list of known issues
Please let us know if you find others…

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