Coarrays – A Parallel Programming Model in Intel Fortran

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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:
  
  $> \text{ifort} -\text{coarray} -\text{coarray} \text{-o} \text{hello} \text{hello.f90}$
  
  $> \text{./hello}$
  
  hello
  hello
  hello
  hello
  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:

```fortran
$> 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)

```bash
$> 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?

**Image 1**

<table>
<thead>
<tr>
<th>X(1,1)</th>
<th>X(1,2)</th>
<th>X(1,3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X(2,1)</td>
<td>X(2,2)</td>
<td>X(2,3)</td>
</tr>
</tbody>
</table>

**Image 2**

<table>
<thead>
<tr>
<th>X(1,1)</th>
<th>X(1,2)</th>
<th>X(1,3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X(2,1)</td>
<td>X(2,2)</td>
<td>X(2,3)</td>
</tr>
</tbody>
</table>

**Image 3**

<table>
<thead>
<tr>
<th>X(1,1)</th>
<th>X(1,2)</th>
<th>X(1,3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X(2,1)</td>
<td>X(2,2)</td>
<td>X(2,3)</td>
</tr>
</tbody>
</table>
**Where’s My Data?**

<table>
<thead>
<tr>
<th>Image 1</th>
<th>Image 2</th>
<th>Image 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>X(1,1)</td>
<td>X(1,1)</td>
<td>X(1,1)</td>
</tr>
<tr>
<td>X(1,2)</td>
<td>X(1,2)</td>
<td>X(1,2)</td>
</tr>
<tr>
<td>X(1,3)</td>
<td>X(1,3)</td>
<td>X(1,3)</td>
</tr>
<tr>
<td>X(2,1)</td>
<td>X(2,1)</td>
<td>X(2,1)</td>
</tr>
<tr>
<td>X(2,2)</td>
<td>X(2,2)</td>
<td>X(2,2)</td>
</tr>
<tr>
<td>X(2,3)</td>
<td>X(2,3)</td>
<td>X(2,3)</td>
</tr>
</tbody>
</table>

X(2,2)[2] reference from image 1
# Where’s My Data?

<table>
<thead>
<tr>
<th></th>
<th>Image 1</th>
<th></th>
<th>Image 2</th>
<th></th>
<th>Image 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>X(1,1)</td>
<td>X(1,2)</td>
<td>X(1,3)</td>
<td>X(1,1)</td>
<td>X(1,2)</td>
<td>X(1,3)</td>
</tr>
<tr>
<td>X(2,1)</td>
<td>X(2,2)</td>
<td>X(2,3)</td>
<td>X(2,1)</td>
<td>X(2,2)</td>
<td>X(2,3)</td>
</tr>
<tr>
<td>X(1,3) reference from image 3</td>
<td>X(1,3) reference from image 3</td>
<td>X(1,3) reference from image 3</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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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