Introduction to the PGAS (Partitioned Global Address Space) Languages
Coarray Fortran (CAF) and Unified Parallel C (UPC)

Dr. R. Bader (LRZ)
Dr. A. Block (LRZ)

March 2019
Part 1: Basic Concepts

Execution and Memory Model
Declaration and usage of shared entities
Simple synchronization
Design target for PGAS extensions:

- smallest changes required to convert Fortran and C into robust and efficient parallel languages
- add only a few new rules to the languages
- provide mechanisms to allow

explicitly parallel execution: **SPMD style** programming model

data distribution: **partitioned memory** model

**synchronization** vs. race conditions

**memory management** for dynamic sharable entities

**collectively executed** procedures (data redistribution and reductions)

- some additional "specialist" features may not be universally supported
Standardization efforts

- **Baseline Coarrays**
  - Fortran 2008 standard

- **Additional parallel features in Fortran**
  - Fortran 2018 standard

- **UPC separate specification in three subdocuments**
  - language specification
  - **required** library specification
  - **optional** library specification

- See „References“ slide near the end of the talk

Current coarray compilers implement a subset of the additional features
Going from single to multiple execution contexts

- CAF - **images**:

  - UPC uses zero-based counting
  - UPC uses the term **thread** where CAF has images

Replicate single program a fixed number of times

- set number of replicates at **compile** time or at **execution** time
- asynchronous execution – **loose** coupling unless program-controlled synchronization occurs

Separate set of entities on each image/thread

- program-controlled exchange of data (imposed by algorithm)
- synchronization may be needed

© 2010-19 LRZ

PGAS Languages: Coarray Fortran/Unified Parallel C
**Execution model: Resource mappings**

- **One-to-one:**
  - each image is executed by a single physical processor core

- **Many-to-one:**
  - some (or all) images are executed by multiple cores each (e.g., implementation could support OpenMP multi-threading within an image)

- **One-to-many:**
  - fewer cores are available to the program than images
  - scheduling issues
  - useful typically only for algorithms which do not require the bulk of CPU resources on one image

- **Many-to-many**

- **Note:**
  - startup mechanism and resource assignment method are implementation-dependent
## Comparison with other parallelization methods

<table>
<thead>
<tr>
<th></th>
<th>MPI</th>
<th>OpenMP</th>
<th>Coarrays</th>
<th>UPC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Portability</strong></td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td><strong>Interoperability (C/C++)</strong></td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td><strong>Scalability</strong></td>
<td>4</td>
<td>2</td>
<td>1-4</td>
<td>1-4</td>
</tr>
<tr>
<td><strong>Performance</strong></td>
<td>4</td>
<td>2</td>
<td>2-4</td>
<td>2-4</td>
</tr>
<tr>
<td><strong>Ease of Use</strong></td>
<td>1</td>
<td>4</td>
<td>2.5</td>
<td>3</td>
</tr>
<tr>
<td><strong>Data parallelism</strong></td>
<td>no</td>
<td>partial</td>
<td>partial</td>
<td>partial</td>
</tr>
<tr>
<td><strong>Distributed memory</strong></td>
<td>yes</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td><strong>Data model</strong></td>
<td>fragmented</td>
<td>global</td>
<td>fragmented</td>
<td>global</td>
</tr>
<tr>
<td><strong>Type system integrated</strong></td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td><strong>Hybrid parallelism</strong></td>
<td>yes</td>
<td>partial</td>
<td>(no)</td>
<td>(no)</td>
</tr>
</tbody>
</table>

**PGAS languages' hardware needs:**

Good scalability for fine-grain parallelism in distributed memory systems will require use of special interconnect hardware features.
„Hello world“ with PGAS

CAF – integer-valued intrinsics for image management

```fortran
program hello
  implicit none
  write(*, '("Hello from image ",i0, " of ",i0)') &
  this_image(), num_images()
end program
```

UPC

- uses integer expressions (macro functions) for the same purpose

```c
#include <upc.h>
#include <stdlib.h>
#include <stdio.h>

int main (void) {
  printf("Hello from thread %d of %d \n", \
      MYTHREAD, THREADS);
  return 0;
}
```

Non-repeatably unsorted output if multiple images/threads used
A more elaborate example: Matrix-Vector Multiplication

\[ \sum_{j=1}^{n} M_{ij} \cdot v_j = b_i \]

- Basic building block for many algorithms

- Independent collection of scalar products
Serial Matrix-Vector code

**Fortran:**

```fortran
integer, parameter :: N = ...
real :: Mat(N, N), V(N)
real :: B(N) ! result

do icol=1,N
  do irow=1,N
    Mat(irow,icol) = &
    matval(irow,icol)
  end do
  V(icol) = vecval(icol)
end do

call sgemv('n',N,N,1.0,
  Mat,N,V,1,0.0,B,1)
```

**C:**

```c
float Mat[N][N], V[N];
float B[N]; // result

for (icol=0; icol<N; icol++) {
  for (irow=0;irow<N;irow++) {
    Mat[icol][irow] = matval(irow+1,icol+1);
  }
  V[icol] = vecval(icol+1);
}
cblas_sgemv(CblasColMajor,
  CblasNoTrans,N,N,1.0,
  (float *) Mat,N,V,1,0.0,B,1);
```

- Functions `matval()` and `vecval()` calculate matrix elements and input vectors
- C compared to Fortran: row-major mapping of indices to storage, zero based

© 2010-19 LRZ  PGAS Languages: Coarray Fortran/Unified Parallel C
Nearly-trivial parallelism: Data decomposition

- **Block row distribution:**
  - calculate only a block of B on each image (but that completely)
  - the shading indicates the assignment of data to images
  - blue: data are replicated on all images

- **Further alternatives:**
  - cyclic, block-cyclic
  - column, row and column

- **Memory requirement:**
  - \((n^2 + n) / \text{<no. of images>} + n\)
    words per image/thread
  - load balanced (same computational load on each task)

**Assumption:** MB == N / (no. of images)
- dynamic allocation is more flexible
- if mod(N, no. of images) > 0, conditioning is required
Memory model part 1: Image-local entities

### Modified declarations

<table>
<thead>
<tr>
<th>Content</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>real :: Mat(MB, N), V(N)</code></td>
</tr>
<tr>
<td><code>real :: B(MB)</code></td>
</tr>
<tr>
<td><code>float Mat[N][MB], V[N];</code></td>
</tr>
<tr>
<td><code>float B[MB];</code></td>
</tr>
</tbody>
</table>

### Semantics for PGAS replicated execution

- each image has its **local** (or **private**) copy of any declared object
- private objects are only accessible to the image which „owns“ them (extrapolated from conventional “serial” language semantics, and consistent with executing in serial mode i.e. only one image)

<table>
<thead>
<tr>
<th>CAF Image</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>local entities</td>
<td>Mat</td>
<td>Mat</td>
<td>Mat</td>
<td>Mat</td>
</tr>
<tr>
<td>UPC Thread</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>

„private“: as in OpenMP, but here is the **default**
"Fragmented data" model

- need to calculate **global** row index from local iteration variable (or vice versa)

```fortran
! do icol=1,N
!  do i=1,MB
!     irow = (this_image() - 1) * MB + i
!     Mat(i,icol) = matval(irow,icol)
!  end do
! V(icol) = vecval(icol)
! end do
! call sgemv('n',MB,N,1.0,Mat,MB,V,1,0.0,B,1)
```

- degenerates into serial version of code for 1 image
Work sharing the initialization and the $M^*v$ processing

Analogous procedure for UPC

- need to calculate **global** row index from local iteration variable (or vice versa)

```c
for (icol=0,icol<N,icol++) {
    for (i=0,i<MB,i++) {
        irow = MYTHREAD * MB + i;
        Mat[icol][i] = matval(irow+1,icol+1);
    }
    V[icol] = vecval(icol+1);
}
cblas_sgemv(CblasColMajor,
            CblasNoTrans,MB,N,1.0,
            (float *) Mat,MB,V,1,0.0,B,1);
```

- degenerates into serial version of code for 1 image

**Fragmenting can be avoided in UPC** \(\rightarrow\) discussed later
Work sharing: General mapping of data to images

Index transformation for an array dimension

- a one-to-one mapping between local and global indices

\[(i)[p] \leftrightarrow j\]

- local problem size on image \(p\): \(n_{\text{local}}[p]\)

\[
\text{real :: } a(\text{ndim}, \ldots) \\
p = \text{this_image}() \\
\text{do } i=1, \text{nlocal} \\
    j = \ldots \quad \text{! global index} \\
    a(i,\ldots) = \ldots \quad \text{! expression involving } j \\
\text{end do}
\]

- \textit{ndim} large enough to hold \(n_{\text{local}}[p]\) elements

\[
j = \sum_{q=1}^{p-1} n_{\text{local}}[q] + i
\]

for a \textbf{blocked} distribution

- for a work-balanced problem: \(n_{\text{local}}[p]\) typically the same on all images, except the last one, which may have a smaller value
Illustrating the need for communication

- Open issue from „trivial“ example
  - iterative solvers require **repeated** evaluation of matrix-vector product
  - but the result we received is distributed across the images

- Therefore, a method is needed
  - to **transfer** each B to the appropriate portion of V on all images
All entities belong to one of two classes:

- **Local (private) entities**: only accessible to the image/thread which "owns" them.
- **Global (shared) entities in partitioned global memory**: objects declared on and physically assigned to one image/thread may be accessed by any other one.

- Allows implementation for distributed memory systems.
Declaration of coarrays/shared entities  
(simplest case)

**CAF**
- coarray requires explicit or implicit `codimension` attribute (square brackets)
- declare **local** number of elements per image
- star in square brackets: program can be agnostic about number of images to be used at compile time

```
real, &
codimension[*] :: B(MB)
```

**UPC**
- shared entity must be declared with the `shared` attribute
- specify **aggregate** number of elements across all threads

```
shared [1] float B[MB*NTMX];
```

MB = 3, NTMX = 3: constants viz. macro constants
Data distribution of coarrays/shared entities
(simplest case)

**CAF**
- same distribution as for private objects
- coarray notation with **explicit** indication of location (coindex in square brackets)
- symmetry is enforced (asymmetric data must use derived types)

<table>
<thead>
<tr>
<th>Image</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
</table>

- more images \(\rightarrow\) additional coindex value

**UPC**
- round-robin distribution
- implicit locality (various **blocking** strategies)
- potential asymmetry – threads in general may have uneven share of data

<table>
<thead>
<tr>
<th>Thread</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>B[8]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- more threads \(\rightarrow\) e.g., B[4] located on a different physical memory

Mapping between coindex and image index is trivial in the simplest case

Local portion is always a contiguous block of memory
Enforcing symmetry for UPC shared objects
(if you desire to make them as similar as possible to coarrays)

Two methods
- extra dimension indexes threads
- THREADS macro in declaration

Method 1

```c
shared int A[3][THREADS];
```

Method 2

```c
shared [3] int A[THREADS][3];
```

<table>
<thead>
<tr>
<th>Thread</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>A[0][0]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A[1][0]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A[2][0]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Thread</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>A[0][0]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A[1][0]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A[2][0]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes:
- THREADS macro may not be usable in certain declaration contexts (e.g., inside function body) if number of threads is determined at run time
- implementation dependent block size limit can make use of method 2 problematic
- programmers may prefer implicit distribution for simplicity of use (but then: beware unintended cross-thread accesses)
UPC shared data: variations on blocking

- **General syntax**
  - for a one-dimensional array
  ```c
  shared [block_size] type \ 
  var_name[total size];
  ```
  - scalars and multi-dimensional arrays also possible

- **Values for block_size**
  - omitted → **default** value is 1
  - integer constant (maximum value **UPC_MAX_BLOCK_SIZE**)
  - [*] → one block on each thread, as large as possible, size depends on number of threads
  - [] or [0] → all elements on one thread

- **Some examples:**
  - complete matrix rows on each thread (≥1 per thread if at most N threads are used)
  ```c
  shared [N] float C[N][N];
  ```
  - in this example, storage sequence matches with **method 2** from previous slide
  - static THREADS environment may be required (compile-time thread number determination)
  ```c
  shared [*] float \ 
  B[THREADS][MB];
  ```
CAF: Coarray declaration variants

```fortran
integer :: a(3)[*]
```

is equivalent to

```fortran
integer, codimension[*] :: a(3)
```

A scalar coarray:

```fortran
integer, codimension[*] :: s
```

An array coarray of rank 2 and **corank 2**
(details explained later)

```fortran
real :: c(ndim, ndim)[0:pdim,*]
```
Inter-image communication: coindexed access

**CAF Pull (Get)**

```plaintext
if (this_image() == p) &
    b = a(:,[q]
```

- Sectioning is obligatory
- A coindexed reference
- Assumption: p and q have the same value on all images
- One-sided communication between images p and q

**CAF Push (Put)**

```plaintext
if (this_image() == p) &
    a(:,[q] = b
```

- A coindexed definition

---

© 2010-19 LRZ

PGAS Languages: Coarray Fortran/Unified Parallel C

23
Inter-thread communication with UPC

Using symmetric declaration of shared object

```c
int b[MB];
shared [MB] int a[THREADS][MB];
```

UPC Pull

```c
if (MYTHREAD == p) {
    for (i=0; i<MB; i++) {
        b[i] = a[q][i];
    }
}
```

UPC Push

```c
if (MYTHREAD == p) {
    for (i=0; i<MB; i++) {
        a[q][i] = b[i];
    }
}
```

Note:

- lack of array support may cause this to be inefficient compared with Fortran → work around this with ...
UPC: One-sided memory block transfers

Available for efficiency
- operate in units of **bytes**
- use restricted pointer arguments
- more concise for structs, arrays

Restriction
- **contiguous** blocks of memory
- Berkeley UPC has extension for strided transfers

prototypes from `upc.h`

```c
void upc_memcpy(shared void *dst, 
    shared const void *src, size_t n);
void upc_memget(void *dst, 
    shared const void *src, size_t n);
void upc_memput(shared void *dst, 
    void *src, size_t n);
void upc_memset(shared void *dst, 
    int c, size_t n);
```
Rewriting as block transfers ...

UPC Pull

```c
if (MYTHREAD == p) {
    upc_memget( &b[0], &a[q][0], MB*sizeof(int) );
}
```

MB elements starting at `a[q][]` are located on thread `q`

UPC Push

```c
if (MYTHREAD == p) {
    upc_memput( &a[q][0], &b[0], MB*sizeof(int) );
}
```
Synchronization requirements

Asynchronous execution

- causes race condition → violates language rules

Image control statement

- enforce segment ordering: \( q_1 \) before \( p_2 \), \( p_1 \) before \( q_2 \)
- \( q_j \) and \( p_j \) are unordered
Semantics of global barrier

All images synchronize:

- SYNC ALL provides a global barrier over all images
- segments preceding the barrier on any image will be ordered before segments after the barrier on any other image → implies ordering of statement execution

⚠️ If SYNC ALL is not executed by all images,

- the program will discontinue execution indefinitely (deadlock)
- however, it is allowed to execute the synchronization via two different SYNC ALL statements (for example in two different subprograms)

In UPC, the spelling for the global barrier is upc_barrier;
Synchronization is required

- between segments on any two different images P, Q
- which both access the same entity (may be local to P or Q or another image)

(1) P writes and Q writes, or
(2) P writes and Q reads, or
(3) P reads and Q writes.

Status of dynamic entities

- replace „P writes“ by „P allocates“ or „P associates“
- will be discussed later
  (additional constraints exist on who is allowed to allocate)

Synchronization is not required

- for concurrent reads
- if entities are modified via atomic procedures (see later)
A special case where no synchronization is needed

Against compile-time initialized objects

Example:

- a very inefficient method for calculating a sum

```fortran
integer :: count[*] = 1
if (this_image() == 1) then
  do i=2, num_images()
    count[i] = count[i] + count[i-1]
  end do
  sum = count[num_images()]
end if
```

Coindexing is not permitted in constant expressions that perform initialization (e.g. DATA statements)
Image control for Get and Put patterns

\[ \text{p and q are assumed to have the same value on all threads, respectively. Otherwise, more than one thread pair communicates data.} \]

### UPC Pull (Get)

\[
a[\text{MYTHREAD}][i] = \ldots;
\]

```c
upc_barrier;
if (\text{MYTHREAD} == p) {
    \text{upc_mem\_get}(&b[0], &a[q][0], MB*\text{sizeof(int)});
    \ldots = b[i];
}
```

- no sync required (no communication)
- consume \( b \) on thread \( p \)

### UPC Push (Put)

\[
b[i] = \ldots;
\]

```c
if (\text{MYTHREAD} == p) {
    \text{upc_mem\_put}(&a[q][0], &b[0], MB*\text{sizeof(int)});
    \ldots = b[i];
    \text{upc\_barrier};
}
```

```c
if (\text{MYTHREAD} == q) {
    \ldots = a[\text{MYTHREAD}][i];
}
```

- consume \( a \) on image \( q \)
p and q are assumed to have the same value on all images, respectively. Otherwise, more than one image pair communicates data.

### CAF Pull (Get)

```fortran
a = ...
sync all
if (this_image() == p) then
    b = a(:,:,q]
    ...
end if
```

- no sync required (no communication)
- consume b on image p

### CAF Push (Put)

```fortran
b = ...
if (this_image() == p) &
    a(:,:,q] = b
: ! further statements
sync all
if (this_image() == q) &
    ...
end if
```

- consume a on image q

- might be asynchronously executed
Local accesses to CAF coarrays

Design aim for non-coindexed accesses:
- should be optimizable as if they were local entities

```fortran
integer :: a(MB)[*]
integer :: i
a(:) = (/ ... /)
: i = a(3) + ...
: call my_proc(a, ...)
```

Explicit coindexing:
- indicates to programmer that communication is happening
- **distinguish**: coarray (a) ↦ coindexed entity (a[p])
- cosubscripts must be **scalars** of type integer

Performance!

```
a(:,[this_image()]) = (/ ... /)
```

same meaning, but likely slower execution speed

**permitted**: interface of `my_proc` declares dummy argument corresponding to `a` as `real :: x(:)` (not a coarray)
Local accesses to UPC shared objects

- Programmer is responsible for correct indexing
  - symmetric object setup can help:

```c
shared int A[MB][THREADS];
int B, i;
B = 0
for (i=0; i<MB; i++) {
    B += A[i][MYTHREAD];
}
```

- non-symmetric shared objects require care to avoid unwanted communication
- performance for current implementations will still be bad, because communication calls are still generated by the compiler
Tuning local accesses in UPC

- Cast to a thread-local pointer to extract local portion of a shared object

```
shared int A[MB][THREADS];
int B, i;
int *A_loc;
B = 0;
A_loc = (int *) A;
for (i=0; i<MB; i++) {
    B += A_loc[i];
}
```

- Non-symmetric shared objects require care to avoid misaddressing

- Casting is also needed when calling functions that assume local memory

```
my_proc( (int *) A, ... );
```

First formal parameter of `my_proc` is an int *
Integration of the type system („POD“ data: static type components)

CAF:

```fortran
type :: body
  real :: mass
  real :: coor(3)
  real :: velocity(3)
end type
```

UPC:

```c
typedef struct {
  float mass;
  float coor[3];
  float velocity[3];
} Body;
```

declare and use entities of this type (symmetric variant):

```fortran
type(body) :: asteroids(100)[*]
type(body) :: s :
  if (this_image() == p) &
    s = asteroids(5)[q]
```

```c
shared [1] \
  Body asteroids[100][THREADS];
Body s;
  :
  if (MYTHREAD == p) {
    s = asteroids[4][q];
  }
```

- compare this with effort needed to implement the same with MPI (dispense with all of MPI_TYPE_* API)
- what about dynamic type components? → later in this talk
Part 2: Dynamic Entities

Pointer classification
Allocation and deallocation
Distributed structures
Pointers and Pointees

- **Remember pointer semantics**
  - different between C and Fortran

  ```fortran
  <type> [, dimension (:[,,:,...])], pointer :: ptr
  ptr => var    ! ptr is an alias for target var
  ```

  ```c
  <type> *ptr;
  ptr = &var;    ! ptr holds address of var
  ```

- **Joint Fortran and C feature:**
  - possibility to reference or define another entity via the pointer:

  ```c
  ptr = xy       ! defines target var
  *ptr = xy;    // defines pointee var
  ```

- **PGAS and pointers:**
  - more variants of pointer association because of different kinds of memory

© 2010-19 LRZ
Case 1: private pointers to private memory

**CAF**

```fortran
integer, pointer :: p1
integer, target :: a(0:n)
integer, target :: b[0:*]

if (this_image() == 1) then
    p1 => a(0)
elseif (this_image() == 2) then
    p1 => b
end if
```

**UPC**

```c
int *p1;
int a[N];
shared int b[THREADS];

if (MYTHREAD == 0) {
    p1 = &a[0];
} elseif (MYTHREAD == 1) {
    p1 = (int *) b;
}
```

**Diagram:**
- Pointer to local portion of scalar coarray.
- Cast to local.
- Not permitted.
Case 2: private pointers to shared memory

**CAF**
- concept is not defined – a POINTER cannot be associated with more than the local portion of a coarray

**UPC**

```fortran
shared int *p2;
shared int b[THREADS];

if (MYTHREAD == 1) {
    p2 = &b[1];
} elseif (MYTHREAD == 2) {
    p2 = &b[3];
}
if (p2) {
    // dereference local p2
}
```

```
not permitted
```

```
associated with remote object
```
Case 3: shared pointers to private memory

**CAF**
- concept is not defined – a coarray cannot have the POINTER attribute
  (However, dynamic type components provide more extended semantics that will be discussed soon)

**UPC**

```fortran
int shared *p4;
int a[N];

if (MYTHREAD == 2) {
    p4 = &a[0];
}

// dereference the shared pointer
// on thread 2 only
```

- **avoid** the use of this feature

![Diagram showing shared pointers and private memory access]

- only one instance exists (here on thread 0)
- dereferences via p4 only permitted on thread that hosts pointee
Case 4: shared pointers to shared memory

**CAF**
- concept is not defined – a coarray cannot have the POINTER attribute

**UPC**
```
shared int shared *p4;
shared int b[THREADS];
if (MYTHREAD == 2) {
    p4 = &b[2];
}
upc_barrier;
// dereference the shared pointer
// on any thread
```

only one instance exists (here on thread 0)
Assume 4 threads:

\[
\begin{align*}
\text{shared } [2] \text{ int } A[10]; \\
\text{shared int } *p2; \\
\text{shared } [2] \text{ int } *q2;
\end{align*}
\]

Block size is a part of the variable’s type

One may cast between pointers with different block sizes
- pointer arithmetic follows blocking ("phase") of pointer (not pointee)!
- cast changes the view but does not move any data

Consequences for libraries → see later
Dynamic allocation and deallocation: Remember serial semantics

**Fortran:**
- one of two attributes usable: POINTER or ALLOCATABLE
- favour use of ALLOCATABLE for "simple" objects (reason: no dangling pointers, no memory leaks)
- ALLOCATE and DEALLOCATE statements

**C:**
- pointers can be used to point at a dynamically allocated object
- avoid dangling pointers and memory leaks (programmer’s responsibility)
- library functions: malloc() and free()

Making the vector "v" from the M*v example a dynamic entity:

```fortran
real, allocatable :: V(:)
integer :: NV
NV = ... ! determine size
allocate(V(NV))
:     ! use V
deallocation(V)
```

```c
float *v;
int nv;
nv = ... // determine size
v = (float *) \mallocc(nv*sizeof(float));
:     // use v
free(v);
```
Dynamic entities:
Shared memory area management

Collective allocation facility which **synchronizes all** images/threads

**CAF:**

```fortran
integer, allocatable :: b(::)[]
mb = ...
allocate( b(mb)[*] )
```

- **symmetric** allocation required: same type, type parameters, bounds and cobounds on every image, in unordered segments
- referencing and defining is straightforward

```fortran
deallocate( b )
```

- deallocation: on **all** images, synchronizes on entry

**UPC:**

```fortran
shared [MB] int *b;
b = (shared [MB] int *) \n upc_all_alloc( \n THREADS,MB*sizeof(int) );
```

- layout equivalent to coarray on the left (but MB is compile time constant)
- arguments of type `size_t`
- deallocation via

```fortran
upc_barrier;
if (MYTHREAD==0) upc_free( b );
```

is **not** collective (must be performed only on one thread)

**UPC 1.3 provides** `upc_all_free()`
After invocation of `upc_all Alloc()`, on each thread

- a private copy of the pointer „b“ exists (→ can use independently),
- which points at the same start address of a set of blocks distributed in the shared memory space

Assuming MB==4 and using 4 threads, we have

```
int *b_loc = (int *) b;
if (MYTHREAD==1) {
    b[9]=3.0;
    b_loc[2] = 2.0;
}
```

Cross-thread and local definitions – see correspondingly color-coded arrows above and note the `b_loc` reindexing!
CAF: More on allocatable coarrays

**Allocation and deallocation**
- collectively operate on local portions of object

**Allocatable components**
- part of type declaration

```fortran
type :: co_vector
  real, allocatable :: v(:,:,)
end type
```

- objects of such a type must be **scalars**

```fortran
type(co_vector) :: a_co_vector
```

and are **not permitted** to have the ALLOCATABLE or POINTER attribute, or to themselves be coarrays

- allocation:
  ```fortran
  allocate ( a_co_vector % v(m)[:] )
  ```

\( m \) has same value on all images
CAF: Reallocation and moving an allocation

Auto-(re)allocation is not permitted for coarrays: In

```fortran
integer, allocatable :: id(:)[,]

id = some_other_array(:)
```

- the LHS must already be allocated and the RHS must conform
- this avoids potential asymmetry as well as implicit synchronization
  (or even deadlock)

The MOVE_ALLOC intrinsic

- if the FROM argument is a coarray, it must be executed on all
  images, and will imply synchronization of all images
- TO must have the same corank as FROM
Further Notes

Disallowed in Fortran:
- coarrays with POINTER attribute

```
integer, pointer :: p(:)[:,]
```
- asymmetric allocation

```
! b declared earlier
allocate(b(this_image())[*])
```

- coarray allocation on image subset

```
allocate(b(mb) &
[this_image()::*])
```

- in CAF, may need to overallocate
  - load balance (one straggler)

- in UPC, may need to use block cyclic arrangements:
  - specify more blocks than threads (run time setting!)
  - beware load balancing (lose symmetry)

- further support for non-symmetric data → soon

UPC casting:
- inconsistency of block sizes in declaration and cast may cause problems

Inflexibility of symmetric data
- in CAF, may need to overallocate
- in UPC, may need to use block cyclic arrangements:
  - specify more blocks than threads (run time setting!)
  - beware load balancing (lose symmetry)
- further support for non-symmetric data → soon

© 2010-19 LRZ
Asymmetric (non-collective) allocation in UPC (1)

- Per-thread pointer to a distributed set of shared blocks

```c
shared void * upc_global_alloc( size_t nblocks, size_t nbytes )
```

```
shared [MB] int *b;
shared [MB] int *shared bs;

if (MYTHREAD==1 || MYTHREAD==2) {
    b = (shared [MB] int *) \
        upc_global_alloc( \ 
        THREADS,MB*sizeof(int));
}

if (MYTHREAD==3) {
    bs = (shared [MB] int *) \
        upc_global_alloc( \ 
        THREADS,MB*sizeof(int));
}
```

- Memory only accessible from allocating thread
- For a shared pointer to shared, only one thread may execute the allocation.
- In general, bs could be anywhere
Asymmetric (non-collective) allocation in UPC (2)

Per-thread pointer to a shared block with affinity to allocating thread

```c
shared [] int *b;
shared [] int *shared bs;

if (MYTHREAD==1 || MYTHREAD==2) {
    b = (shared [] int *) \n        upc_alloc(MB*sizeof(int));
}

if (MYTHREAD==3) {
    bs = (shared [] int *) \n        upc_alloc(MB*sizeof(int));
}
```

→ must avoid non-zero blocking factor

For a shared pointer to shared, only one thread may execute the allocation.

Memory only accessible from allocating thread

In general, `bs` could be anywhere.
Distributed structures

- **Fortran „container types“**

  ```fortran
  type :: container
    real, pointer :: data(:) => null()
    ! possibly further components
  end type

  type(container) :: a[*]
  ```

- **UPC shared component structure**

  ```c
  typedef struct {
    shared [] float *data;
    // etc
  } Container;

  shared [1] Container a[THREADS];
  ```

- with either POINTER or ALLOCATABLE components
- don‘t care which for this purpose

- requires a pointer-to-shared component to enable cross-thread access to `.data`

© 2010-19 LRZ
CAF: unsymmetric objects

Illustrating the data layout

components **must** be *locally* allocated or associated

© 2010-19 LRZ
1. access remote object $a[q]$ from image p
2. obtain location of data component
3. transfer data component (or a subobject of it) to the executing image

**Performance impact:**

- additional latency due to lookup step
- for pointers, non-contiguous access is supported, but likely to reduce performance

reference to $a[q]$ % data executed on image p
Variant 1 for data layout – locality consistent with parent object

- components are **locally** pointer-associated

- programmer establishes the locality convention

- might use symmetric heap, but no guarantee for individual start addresses
Variant 2 for data layout – arbitrary locality

Components can be non-locally pointer-associated

for example, execute the following on thread 2

```c
a[1].data = upc_alloc(n*sizeof(float));
```
Setup – Local processing – Data exchange

**CAF**

```fortran
real, allocatable, &
target :: field(:,:)
allocate(field(NR, NC))
: ! determine column
a % data => field(:, column)
```

```fortran
sync all
q = ... ! some other image
n = size( a[q] % data, 1 )
call process(field, ...)
```

```fortran
sync all
localdata(:n) = ... + a[q] % data
```

**UPC (using variant 1)**

```fortran
shared [] float *field;
field = upc_alloc( 
  NR*NC*sizeof(float) );
: ! determine column
a[MYTHREAD].data =
  &field[NR*column];
```

```fortran
upc_barrier;
q = ... ! some other thread
n = ... ! size of remote column
process( (float *) field, ...);
```

```fortran
upc_barrier;
upc_memget(aux, a[q].data, 
  n * sizeof(float) );
```

then, update localdata using local buffer aux

Note that NR and NC might vary between images
CAF: Some limitations on intrinsic assignment

**POINTER components**
- shallow copy semantics may conflict with locality requirement

```
    on image q, a % data may become undefined
    a[q] = container(field(:,1))
```

**Allocatable components**
- copying of data is allowed, but **no (implied) remote** allocation

```
    type :: polynomial
    real, allocatable :: f(:)
    end type

    type(polynomial) :: ps[*]
    ps[q] = polynomial( [2.0, 5.0 ] )
    ps[q] % f = [2.0, 5.0 ]
```

This is **not** permitted

if executed on an image other than q, **ps % f** must be allocated there with size 2
A subobject of a coarray is also a coarray if
- it is not coindexed,
- no vector subscript is involved in establishing it, and
- no POINTER or allocatable component selection is involved in establishing it.

Otherwise, it is not a coarray.

Relevance:
- when passing as an argument to a procedure with a corresponding coarray dummy
- in an association block context
Part 3a: Data layout and processing

CAF corank-image mapping
UPC locality intrinsics
UPC global view and upc_forall
Non-trivial coindex-to-image mappings

- Corank of a coarray may be larger than one
  - sum of rank and corank can be up to 15
- Lower cobound for each codimension can be different from 1
- Example: corank 2

\[
\text{real } z(10,10)[0:3,3::*]
\]

- Mapping to image index for 10 executing images

```plaintext
coshape = [4,3]

<table>
<thead>
<tr>
<th>0</th>
<th>1</th>
<th>5</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>6</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>8</td>
<td></td>
</tr>
</tbody>
</table>
```

- upper cobound of last codimension
  \[
z(:,,:) [2,4]
  \]
  (100 elements)
- \(\rightarrow\) ragged rectangular pattern

- lower cobound of codimension 1

- \(\rightarrow\) invalid
Supporting intrinsics

Programmer's responsibility to specify valid coindices

- `this_image( coarray [,dim] )`: compute (local) coindices from object on an image, optionally only that for a specified codimension.

- `image_index( coarray, sub )`: compute (remote) image index from object and (local) coindex; zero for invalid coindex.

Examples for "z" declared previously

```
cindx = this_image( z )
on image 7, returns [2,4]

m1 = this_image( z, 1 )
on image 7, returns 2

img = image_index( z, [2,4] )
on all images, returns 7

img = image_index( z, [2,5] )
on all images, returns 0
```

```
real :: z(10,10) [0:3,3:*]
integer :: cindx(2), m1, img
```

10 images

<table>
<thead>
<tr>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>5</td>
<td>9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>6</td>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>8</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

© 2010-19 LRZ
May require assurance about where a subobject is located

- e.g., to avoid cross-thread accesses

assuming $B > 2$

Further intrinsics:

\textbf{upc\_elem\_sizeof(object)}

- returns size of an element of the shared object in bytes

\textbf{upc\_local\_sizeof(object)}

- returns size of the local part of the shared object in bytes

\textbf{upc\_block\_sizeof(object)}

- returns blocking factor of the shared object

\begin{verbatim}
shared [B] int A[N];
size_t thr, pos;

thr = upc_threadof(&A[4*B+2]);
   on any thread, returns 4

pos = upc_phaseof(&A[4*B+2]);
   on any thread, returns 2
\end{verbatim}
UPC: Processing global data

- **Fragmented data**
  - requires code restructuring (e.g. for loop processing)

- **UPC supports global data**
  - locality to a thread is implicit

- **Global loop processing:**
  - `upc_forall` integrates data affinity to threads with loop construct
  - must be collectively executed by all threads
  - fourth argument is an **affinity expression** that controls which subset is executed

**Example: matrix initialization**

```c
shared [N] float Mat[N][N];

upc_forall (icol=0; icol<N; icol++; icol) {
  for (irow=0;irow<N;irow++) {
    Mat[icol][irow] = matval(irow+1,icol+1);
  }
}
```

- **MYTHREAD only executes**
  - subset of iterations with `icol%THREADS == MYTHREAD`
- **effect:** all assignments are thread-local
Affinity expressions in `upc_forall`

<table>
<thead>
<tr>
<th>Type of affinity expression</th>
<th>Iterations of loop executed on MYTHREAD</th>
</tr>
</thead>
<tbody>
<tr>
<td>integer i</td>
<td>with <code>i%THREADS == MYTHREAD</code></td>
</tr>
<tr>
<td>shared pointer *x</td>
<td>with <code>upc_threadof(x) == MYTHREAD</code></td>
</tr>
<tr>
<td>&quot;continue&quot; or empty</td>
<td>all iterations. In this case, collective execution is not required</td>
</tr>
</tbody>
</table>

**In the example**, using

```c
shared [N] float Mat[N][N];
upc_forall (icol=0; icol<N; icol++; &Mat[icol][0]) { ... }
```

would have the equivalent effect

**Note:**
- multiple shared entities with incommensurate block sizes inside code block might perforce lead to non-local accesses / communication
Part 3b: Collective Procedures

Note:
In Fortran, collectives were added by TS18508. Currently, they are not yet generally supported.
Motivation

- **Common pattern in serial code:**
  - use of reduction intrinsics, for example: SUM for evaluation of global system properties

```fortran
real :: mass(ndim,ndim), velocity(ndim,ndim)
real :: e_kin

e_kin = 0.5 * sum( mass * velocity**2 )
```

- **Coarray / UPC code:**
  - on each image, an image-dependent **partial sum** is evaluated
  - i.e. the intrinsic is not image-aware

- **Variables that need to have the same value across all images**
  - e.g. global problem sizes
  - values are initially often only known on one image

In C, you don’t even have those ... so need to roll your own.
Collectives that perform a computation

Collectives that re-localize data

Reduction with result on one image

Reduction with result on all images

Broadcast data from one image to all others

must execute on all images

must execute on all images
General properties

Both CAF and UPC

- Collectives must be invoked by all images, and from unordered segments, to avoid deadlocks

CAF

- Data arguments need **not** be coarrays – however if a coarray is supplied, it must be the same (ultimate) coarray on all images
- No segment ordering is implied by execution of a collective – valid result data on exit
- All collectives are "in-place" – programmer needs to copy data argument if original value is still needed

UPC

- Data arguments are **always** shared entities
- Programmer must specify whether synchronization is performed
- Separate „source“ and „destination“ arguments, which are not allowed to be aliased (undefined behaviour)

Collectives could of course be implemented by the programmer. However it is expected that the supplied ones **will perform better**, apart from being more generic in semantics.
**Arguments:**

- **a** may be a scalar or array of numeric type
- **result_image** is an optional integer with value between 1 and `num_images`

- without **result_image**, the result is broadcast to **a** on all images, otherwise only to **a** on the specified image
Example: derived type

```
type :: matrix
    : ! implementation detail
end type
```

- might already have a specific used to overload addition

```
pure function matrix_plus(x, y) &
    result(r)
    type(matrix), intent(in) :: x, y
    type(matrix) :: r
    : ! implementation detail
end function
```

- PURE function with scalar, nonpolymorphic, nonallocatable, nonpointer, nonoptional arguments

CO_REDUCE:

```
type(matrix) :: xm

call co_reduce(     a=xm, &
  operator=matrix_plus, &
  RESULT_IMAGE=2 )
```

- assignment to result is done as if it were intrinsic (finalizers might be invoked!)

- must be **mathematically associative**

- **operator** must be the same function on all images
void upc_all_reduce<<T>>(
    shared void *restrict dst,
    shared const void *restrict src,
    upc_op_t op,
    size_t nelems,
    size_t blk_size,
    <<TYPE>>(*func)(<<TYPE>>, <<TYPE>>,)
    upc_flag_t flags);

- replace <<T>> by type specifier (C, UC, etc., see next slide)
- function argument will be NULL unless user-defined
- reduction function is specified through op
- synchronization is specified through flags
Reduction types

- encoded as part of the function name $\rightarrow$ 11 variants per function

<table>
<thead>
<tr>
<th>$T$</th>
<th>TYPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>C/UC</td>
<td>signed char/ unsigned char</td>
</tr>
<tr>
<td>S/US</td>
<td>signed short/ unsigned short</td>
</tr>
<tr>
<td>I/UI</td>
<td>signed int/unsigned int</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$T$</th>
<th>TYPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>L/UL</td>
<td>signed long/ unsigned long</td>
</tr>
<tr>
<td>F/D/LD</td>
<td>float/double/long double</td>
</tr>
</tbody>
</table>

- note that only intrinsic types are supported

Operations:

<table>
<thead>
<tr>
<th>Numeric</th>
<th>Logical</th>
<th>User-defined function</th>
</tr>
</thead>
<tbody>
<tr>
<td>UPC_ADD</td>
<td>UPC_AND</td>
<td>UPC_FUNC</td>
</tr>
<tr>
<td>UPC_MULT</td>
<td>UPC_OR</td>
<td>UPC_NONCOMM_FUNC</td>
</tr>
<tr>
<td>UPC_MAX</td>
<td>UPC_XOR</td>
<td>UPC_LOGAND</td>
</tr>
<tr>
<td>UPC_MIN</td>
<td>UPC_LOGOR</td>
<td></td>
</tr>
</tbody>
</table>

- are constants of type `upc_op_t`
UPC collectives: specifying synchronization

**Synchronization mode**
- constants of type `upc_flag_t` in `upc_collectives.h`

**IN/OUT**
- refers to whether the specified synchronization applies at the entry to or exit from the call

**Relaxing synchronization**
- programmer's responsibility to assure that no race conditions occur
- typically used for multiple reductions on disjoint variables

**Synchronization semantics**
- NOSYNC – threads do not synchronize at entry or exit
- MYSYNC – start processing of data only if owning threads have entered the call / exit function call only if all local read/writes are complete
- ALLSYNC – synchronize all threads at entry / exit

**Combining modes**
- `UPC_IN_NOSYNC | UPC_OUT_MYSYNC`
- `UPC_IN_NOSYNC` same as `UPC_IN_NOSYNC | UPC_OUT_ALLSYNC`
- `0` same as `UPC_IN_ALLSYNC | UPC_OUT_ALLSYNC`
shared double cc[THREADS];
shared double res[THREADS];
shared [0] double cc_0[THREADS];
shared [0] double res_0;

int main () { // initializations omitted

    upc_all_reduceD(&res, cc, UPC_ADD, THREADS, 1, NULL, UPC_IN_ALLSYNC|UPC_OUT_ALLSYNC);
    printf("Reduce variant 1 - Thread %i: %12.4f\n", MYTHREAD, (double) *res);

    upc_all_reduceD(&res_0, cc, UPC_ADD, THREADS, 1, NULL, UPC_IN_ALLSYNC|UPC_OUT_ALLSYNC);
    // broadcast to a local scalar
    rl = *res;
    printf("Reduce variant 2 - Thread %i: %12.4f\n", MYTHREAD, rl);

    upc_all_reduceD(&res, cc_0, UPC_ADD, THREADS, 0, NULL, UPC_IN_ALLSYNC|UPC_OUT_ALLSYNC);
    printf("Reduce variant 3 - Thread %i: %12.4f\n", MYTHREAD, (double) *res);
}

Array reductions are not supported
Arguments:

- `a` may be a scalar or array of any type. It must have the same type and shape on all images. It is overwritten with its value on `source_image` on all other images.
- `source_image` is an integer with value between 1 and `num_images()`. 

```fortran
#include <coarrayfortran/Unified Parallel C>

type(matrix) :: xm

call co_broadcast(a=xm, source_image=2)
```
UPC Allscatter

void upc_all_scatter (  
    shared void *dst,  
    shared const void *src,  
    size_t nbytes,  
    upc_flag_t sync_mode);

- i-th block of src with size nbytes is copied to dst with affinity to thread i
- each block in src must have affinity to a single thread
Further UPC collectives

Redistribution functions
- upc_all_broadcast()
- upc_all_gather_all()
- upc_all_gather()
- upc_all_exchange()
- upc_all_permute()

Prefix reductions
- upc_all_prefix_reduceT()
- semantics:

$$\sum_{i=0}^{n} d_k$$

for UPC_ADD, object dst[i] hosted on thread i gets (thread-dependent result)

$\rightarrow$ consult the UPC language specification for details
Part 4a: Advanced Synchronization Concepts

- Partial synchronization
- One-sided synchronization
- Mutual exclusion (locks)
- UPC: split phase barrier and memory consistency
Partial synchronization

**Image subsets**
- sometimes, it is sufficient to synchronize only a few images

**More than 2 images:**
- need not have same image set on each image
- but: eventually all image pairs must be resolved, else deadlock occurs
- ordering can be relevant:

```plaintext
if (this_image() < 3) then
  sync images ( [ 1, 2 ]
end if
```

executing image is implicitly included in image set

Each grey box: represents one sync images statement

Deadlock

OK
**Scenario:**
- one image sets up data for computations
- others do computations

**Performance notes:**
- sending of data by image 1

```fortran
if (this_image() == 1) then
  ! send data
  sync images (*)
else
  sync images (1)
  ! use data
end if
```

- „Push" / "Put" mode
  - an optimizing implementation might perform non-blocking transfers, and processing of data by other images might start up in a staggered sequence.

- difference between `SYNC IMAGES (*)` and `SYNC ALL`: no need to execute from all images

© 2010-19 LRZ
PGAS Languages: Coarray Fortran/Unified Parallel C
Partial synchronization: Best Practices

- **Localize complete set of partial synchronization statements**
  - **avoid** interleaved subroutine calls which do synchronization of their own

```fortran
if (this_image() == 1) sync images ( 2 )
call mysub(…)
:
if (this_image() == 2) sync images ( 1 )
```

- a very bad idea if subprogram does the following

```fortran
subroutine mysub(…)
:
if (this_image() == 2) sync images ( 1 )
:
end subroutine
```

- likely to produce wrong results even if no deadlock occurs

`sync images` is not context-safe
Weaknesses of previously treated synchronization constructs

Recall semantics of SYNC ALL

Symmetric synchronization is overkill
- the ordering of $p_1$ before $q_2$ is often not needed
- image $q$ therefore might continue without waiting

Therapy:
- introduces a lightweight, one-sided synchronization mechanism – Events

- enforces segment ordering: $q_1$ before $p_2$, $p_1$ before $q_2$
- $q_j$ and $p_j$ are unordered
- applies for SYNC IMAGES as well

© 2010-19 LRZ
**One-sided synchronization with Events**

**Image q executes**

\[
a = \ldots
\]

\[
event\ \text{post}\ ( ev[p] )
\]

- and continues **without** blocking

**Image p executes**

\[
event\ \text{wait}\ ( ev )
\]

\[
b = a(:,)[q]
\]

- the WAIT statement **blocks** until the POST has been received.

Both are image control statements.

An event variable has an internal counter with default value zero; its updates are **exempt** from the segment ordering rules ("atomic updates").

**One sided segment ordering**

\[q\]

\[p\]

- **q_1** ordered before **p_2**
- no other ordering implied
- no other images involved
Scenario:
- Image p executes
  \[ \text{event post ( ev}[q\text{] )} \]
- Image q executes
  \[ \text{event wait ( ev )} \]
- Image r executes
  \[ \text{event post ( ev}[q\text{] )} \]

Question:
- what synchronization effect results?

Answer: 3 possible outcomes
- which one happens is indeterminate

Avoid over-posting from multiple images!

Case 1: \( p_1 \) ordered before \( q_2 \)

\[
\begin{align*}
\text{p} & \quad \text{POST (+1)} \\
& \quad p_1 \quad p_2 \\
\text{q} & \quad \text{WAIT (-1)} \\
& \quad q_1 \quad q_2 \\
\text{r} & \quad \text{POST (+1)} \\
& \quad r_1 \quad r_2
\end{align*}
\]

Case 2: \( r_1 \) ordered before \( q_2 \)

\[
\begin{align*}
\text{p} & \quad \text{POST (+1)} \\
& \quad p_1 \quad p_2 \\
\text{q} & \quad \text{WAIT (-1)} \\
& \quad q_1 \quad q_2 \\
\text{r} & \quad \text{POST (+1)} \\
& \quad r_1 \quad r_2
\end{align*}
\]

Case 3: ordering as given on next slide
Multiple posting done correctly

Why multiple posting?

- **Example**: halo update

\[ p = q - 1 \quad q \quad r = q + 1 \]

Correct execution:

- Image \( p \) executes

\[
\begin{align*}
\text{fm}(\cdot,1)[q] & = \ldots \\
\text{event post}(\text{ev}[q])
\end{align*}
\]

- Image \( r \) executes

\[
\begin{align*}
\text{fm}(\cdot,n)[q] & = \ldots \\
\text{event post}(\text{ev}[q])
\end{align*}
\]

Image \( q \) executes

\[
\text{event wait}(\text{ev}, \text{UNTIL}_\text{COUNT} = 2)
\]

\[ \ldots = \text{fm}(:,:) \]

\text{number of posts needed}

\( p_1 \text{ and } r_1 \text{ ordered before } q_2 \)

This case is enforced by using an UNTIL_COUNT
The EVENT_QUERY intrinsic

- Permits to inquire the state of an event variable

```fortran
call event_query(event = ev, count = my_count)
```

- the event argument cannot be coindexed
- the current count of the event variable is returned
  (note that the actual count may change before you can inspect the result!)
- the facility can be used to implement non-blocking execution on
  the WAIT side of event processing
- invocation has no synchronizing effect
Berkeley UPC extension: Semaphores

### Setting up a semaphore

```c
#include <upc_sem.h>
upc_sem_t *shared ev[THREADS];
int flags;

flags = ...;
ev[MYTHREAD] = upc_sem_alloc(flags);

// use ev for synchronization
upc_barrier;
upc_sem_free(&ev[MYTHREAD]);
```

### Possible flag values

<table>
<thead>
<tr>
<th>Value</th>
<th>Semantics</th>
</tr>
</thead>
<tbody>
<tr>
<td>UPC_SEM_[BOOLEAN,INTEGER]</td>
<td>binary vs. counted semaphore</td>
</tr>
<tr>
<td>UPC_SEM_[S,M]PRODUCER</td>
<td>increment by only one thread or by all threads</td>
</tr>
<tr>
<td>UPC_SEM_[S,M]CONSUMER</td>
<td>decrement by hosting thread or by all threads</td>
</tr>
</tbody>
</table>

- entries along rows can be combined
- for example,

```c
flags = UPC_SEM_INTEGER | UPC_SEM_MPRODUCER | UPC_SEM_SCONSUMER;
ev[MYTHREAD] = upc_sem_alloc(flags);
```

supplies semantics equivalent to Fortran‘s events
Using the semaphore for one-sided synchronization

### Single-post

// thread q executes
p = ...;
a[p] = ...;
upc_sem_post( ev[p] );

// thread p executes
upc_sem_wait( ev[MYTHREAD] );
... = a[MYTHREAD];

### Multiple-post

// thread q executes
p = ...;
a[p] = ...;
upc_sem_post( ev[p] );

// thread r executes
p = ...;
b[p] = ...;
upc_sem_post( ev[p] );

// thread p executes
upc_sem_waitN( ev[MYTHREAD], 2 );
... = a[MYTHREAD] + b[MYTHREAD];

### Non-blocking wait

// thread q does the same as above
...
// thread p executes
for (;;;;) {
  if (upc_sem_try( ev[MYTHREAD] ))
    break;
  : // do something unrelated to 'a'
}  
... = a[MYTHREAD];

For details, read upc_sem.pdf
Mutual Exclusion (simplest case)

- **Critical region**
  - block of code only executed by one image at a time
  - order is indeterminate

```fortran
  critical
  : ! statements in region
  end critical
```

- can have a name, but this has no parallel semantics associated with it

- **Subsequently executing images:**
  - segments corresponding to execution of the code block are ordered against one another
  - this does not apply to preceding or subsequent code blocks
  - may need additional synchronization to protect against race conditions

© 2010-19 LRZ

PGAS Languages: Coarray Fortran/Unified Parallel C
Example for mutual exclusion via a critical region

```fortran
real :: s, stot[*]
real :: a(:)
integer :: i
stot = 0.0
sync all
s = 0.0
do i = 1, size(a)
   s = s + a(i)
end do
critical
end critical
sync all
... = stot[1]
```

- Only one image at a time can execute the critical region
  - others must wait → code in region is effectively serialized
Locks – a more flexible mechanism for mutual exclusion

- Coordinate access to shared (= sensitive) data
- Use a coarray/shared lock variable
  - modifications are guaranteed to be atomic
  - consistency across images/threads

Problems with CAF critical region:
- objects may require protection in multiple blocks
- different objects protected by different locks → improved scalability
Declaration and initial state

**CAF**

```fortran
use, intrinsic :: iso_fortran_env
type(lock_type) :: my_lock[*]
```

- **Lock variable:**
  - must be a coarray (here, this implies one lock per image!)
  - two states - unlocked or locked
  - locked means: acquired by a specific image (until that image releases the lock again)

**UPC**

```c
#include <upc.h>
upc_lock_t *lock;
lock = upc_all_lock_alloc();
: // do stuff with lock
if (MYTHREAD == 0)
  upc_lock_free(lock);
```

- **Lock variable:**
  - typically, one or more pointers to a single shared object (included in type)
  - explicit setup and teardown required
  - otherwise, like CAF
Simplest example for blocking locks

**CAF**

```
use, intrinsic :: iso_fortran_env

type(lock_type) :: my_lock[*]

rb = ...
sync all

lock( lock[1] )
i = ...
rb[i] = rb[i] + ...
unlock( lock[1] )
sync all
: ! access rb
```

- lock/unlock: no memory fence, only **one-way** segment ordering

**UPC**

```
#include <upc.h>

upc_lock_t *lock;
:
lock = upc_all_lock_alloc();
rb = ...;
upc_barrier;

upc_lock( lock );
i = ...;
rb[i] = rb[i] + ...;
upc_unlock( lock );
upc_barrier;
: ! access rb
```

- lock/unlock imply memory fence

**Quiz:** why image 1 in the example?
Non-blocking lock semantics

CAF:

use, intrinsic :: iso_fortran_env

type(lock_type) :: nb_lock[*]

logical :: got_it

activity : do
  lock( nb_lock[1], &
    acquired_lock=got_it )
  if ( got_it ) exit activity
    : ! go climb that mountain
end do activity
  : ! play with red balls
unlock( nb_lock[1] )

UPC:

#include <upc.h>

upc_lock_t *nb_lock;

nb_lock = upc_all_lock_alloc();

for (; ; ) {
  if (upc_lock_attempt( nb_lock ))
    break;
    : // go climb that mountain
}
  : // play with red balls

upc_unlock( nb_lock );

upc_all_lock_free( nb_lock );

potentially needed explicit barriers are omitted here
Locks – an expensive synchronization mechanism

- **Best case timing for lock acquisition**

\[ T_{\text{lock}} = T_{\text{lat}} \times \log_2 N \]

where

- \( T_{\text{lat}} \) is the maximum latency in the system
  - (a couple of \( \mu s \) \( \rightarrow 10,000 \) cycles)
- \( N \) is the number of image groups for which \( T_{\text{lat}} \) applies.

- **Typical value** for large programs: 100,000 cycles (excludes outstanding data transfers)

- **Advice:**
  - prefer use of events for synchronization (where possible)
CAF: Event and lock subobjects

Declare type components as events or locks

```
type :: queue
  type(lock_type) :: lock
  type(work_item) :: work
  type(queue), pointer :: &
  next => null()
end type

type :: pipeline
  type(event_type) :: start
  type(work_item) :: work
end type
```

but then objects of that type are obliged to be coarrays:

```
{ type(queue) :: my_queue[*]
  type(pipeline), allocatable :: my_pipeline(:,:)

  type(queue) :: incorrect_queue ! Not permitted
```
Establish a component inside a struct definition

```c
typedef struct queue {
  upc_lock_t *lock;
  shared work_item *work;
  shared queue *next;
} Queue;
```

Constructor for a Queue object (called on a per-thread basis)

```c
Queue *Queue_add ( Queue *in, work *w ) {
  Queue *this;
  // establish "this"
  this->lk = upc_global_lock_alloc();
  // upc_memput w to this->work (after locking)
}
```
UPC: split-phase barrier

Separate barrier completion point from waiting point

- this allows threads to continue computations once all others have reached the completion point \(\rightarrow\) may reduce impact of load imbalance

```c
for (...) a[n][i] = ...;
upc_notify;
// do work (on b?) or comm.
// not involving a
upc_wait;
for (...) b[i] = b[i] + a[q][i];
```

- completion of `upc_wait` implies synchronization
- collective – all threads must execute sequence

CAF:
- presently does not have this facility in statement form
  (one can implement this concept using events)
UPC: Memory consistency modes

How are shared entities accessed?
- relaxed mode → program **assumes** no concurrent accesses from different threads
- strict mode → program **ensures** that accesses from different threads are separated, and **prevents** code movement across these synchronization points
- relaxed is default; strict may have **large** performance **penalty**

Options for synchronization mode selection
- variable level:
  (at declaration)
  ```c
  strict shared int flag = 0;
  relaxed shared [*] int c[THREADS][3];
  ```
- code section level:
  ```c
  { // start of block
    #pragma upc strict
    ... // block statements
  }
  // return to default mode
  ```
  ```c
  #include <upc_strict.h>
  // or upc_relaxed.h
  ```
- program level:
  ```c
  Thread q
  :[q][i] = ...;
  flag = 1;
  
  Thread p
  while (!flag) {...};
  ... = c[q][j];
  ```

**example for a spin lock**

q has same value on thread p as on thread q

consistency mode on variable declaration **overrides** code section or program level specification
"strict" cannot prevent all race conditions

- example: "ABA" race

```c
strict shared int flag;
int val, val1, val2;
```

```c
thread 0
flag = 0;
upc_barrier;
flag = 1;
flag = 0;
```

```c
thread 1
upc_barrier;
val = flag;
```

- "strict" does not make `a[i]+=j` atomic (read/modify/write)

- "strict" does assure that changes on (complex) objects appear in the same order on other threads

```c
thread 0
flag = 0;
upc_barrier;
flag = 1;
flag = 2;
```

```c
thread 1
upc_barrier;
val1 = flag;
val2 = flag;
```

- may end up with 0 or 1
- may obtain `(val1 <= val2)` but not `(val1 > val2)`
e.g., (2, 1) or (2, 0) are not possible
Part 4b: PGAS programming scenarios

Interaction with OO semantics

Library Design:
Subprogram interfaces
Factory procedures

PGAS and MPI programming

Optional
Using coarrays together with object-oriented features

- Shaky ground due to implementation issues
- Limited semantics
Combining coarrays with object orientation

A coarray may be polymorphic

- example shows typed allocation

```fortran
class(body), allocatable :: particles(::)[:,:]
allocate( charged_body :: particles(n)[*] )
```

Collective allocation and synchronization. It must be **guaranteed** that the dynamic type is the same on each image.

- coindexing is not permitted for a polymorphic left hand side:

```fortran
particles(:)[p] = ... Not permitted for intrinsic assignment
```

```fortran
select type (particles)
type is (charged_body)
  particles(:)[p] = ...
end select
```

OK - `particles` are non-polymorphic here

```fortran
note that it would need to be allocatable
```

- LHS coarray in intrinsic assignment cannot be polymorphic
Restrictions on association

Coindexing is not permitted:

```fortran
select type(particles[2])
  :
end select
```

```fortran
associate(p => asteroids[2])
  p = ... 
end associate
```

But appearance of a coarray is OK

- we've already seen it for SELECT TYPE
- here an example for coarray subobject association:

```fortran
associate(p => asteroids%mass)
  p(:,q] = ... 
end associate
```

*p* is a discontiguous real array coarray, because *asteroids%mass* is a coarray subobject.

© 2010-19 LRZ

PGAS Languages: Coarray Fortran/Unified Parallel C
Limitation on type extension

- Applies for types with coarray components:

  ```fortran
  type, extends( co_m ) :: co_mv
  real, allocatable :: v(:,:,)
  end type
  ```

- is only permitted if the parent type already has a coarray component:

  ```fortran
  type :: co_m
  real, allocatable :: m(:,:,)[,]
  end type
  ```

- otherwise, existing code for `co_m` would stop working for the extension ➔ violation of inheritance mechanism
Execution of type- and object-bound procedures

**Discussed:**
- local vs. coindexed execution

```fortran
type :: body
  : ! data components
  procedure(p), pointer :: print
contains
  procedure :: dp
end type

subroutine dp(this, kick)
  class(body), intent(inout) :: this
  real, intent(in) :: kick(3)
  : ! give body a kick
end subroutine

call particles(7) % dp(kick)
call particles(8) % print()

if (this_image() == 1) then
  select type(particles)
  type is (charged_body)
  call particles(7)[2] % print()
  call particles(8)[2] % dp(kick)
  end select
end if
```

- procedure pointer: remote alias is not locally known, no remote execution supported
- type-bound procedure is the same on all images
- polymorphism removed via SELECT TYPE (RTTI)
For explicit references to such components, coindexing is not permitted.

A cooperative circumlocution is required, for example:

type :: trajectory
    class(body), allocatable :: &
    particle(:)
    integer :: nsize
end type

type(trajectory) :: mytr[*]
    class(body), allocatable :: &
    auxiliary(:)[:]
allocate(charged_body :: &
    mytr%particle(n) )
mytr%nsize = n
: ! supply data

allocate( charged_body :: &
    auxiliary(nmax)[*] )
p = ... ! target image
select type (auxiliary)
type is (charged_body)
    auxiliary(1:mytr[p]%nsize)[p] = &
    mytr % particle
: ! further code elided
end select

sync images ([p,q])
: ! consume local portion
! of auxiliary(:)

assuming one-to-one mapping between source and target images
assuming the same dynamic type on all images
Comments on parallel library design
Shared objects as dummy arguments

- **Library codes may need**
  - to communicate and synchronize argument data
  -> declare dummy arguments as coarrays / pointers to shared

- **Preserve ability for exchanging data between images**
  - implies that data must not be copied when calling a procedure
  - Restrictions that *prevent* copy-in/out of coarray data:
    - if dummy is not assumed-shape, actual must be simply contiguous or have the **CONTIGUOUS** attribute
    - the **VALUE** attribute is prohibited
    - a coarray descriptor might be copied
  - **UPC shared data:**
    - private pointers to shared might be copied, but not shared-to-shared
Shared dummy interface

**CAF**

- an *explicit interface* is required for using coarray dummy arguments

```fortran
subroutine subr(n,w,x,y)
  integer :: n
  real :: w(n), x(n,*), y(:,:)
  ! local computations
  sync all
  ! exchange data
  sync all
  ! etc
end subroutine
```

**UPC**

```c
void subr(int n,
  shared float *w) {
  int i;
  float *wloc;
  wloc = (float *) &w[MYTHREAD];
  for (i=0; i<n; i++){
    ... = wloc[i] + ...
  }
  upc_barrier;
  // exchange data
  upc_barrier;
  // etc.
}
```

- assumes local size is n
- cast to local pointer for safety of use and *performance* if only local accesses are required
- declarations with *fixed* block size > 1 also possible (default is 1, as usual)

Updating a coarray dummy through coindexing is permitted (exception to aliasing rules)
**Calling the procedure**

### CAF

```fortran
real :: a(NDIM)[*], b(NDIM,2)[*]
real, allocatable :: c(:,,:,:)[:]
allocate(c(10,20,30)[*])
!
call subr(NDIM, a, b, c)
call subr(NDIM, a, b, c(1,:),:))
```

- **actual argument** **must** be a coarray if the dummy is
- **argument a**: corank mismatch is permitted. Inside the procedure, coindices are remapped.

**recommendation**: avoid image-dependent cobounds

- **argument c**: for an assumed shape dummy, the actual may be discontiguous

### UPC

```c
shared [*] float x[THREADS][NDIM]
int main(void) {
    // initialize x
    upc_barrier;
    subr(NDIM, (shared float *) x);
}
```

- cast to cyclic to match the prototype
- this approach of passing cyclic pointer and block size as arguments is a common solution to UPC library design.
- cyclic is “good enough” in most cases because function can recover actual layout via pointer arithmetic
- in this example w[i] aliases x[i][0]

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>x[0][0]</td>
<td>x[1][0]</td>
<td>x[2][0]</td>
<td>x[3][0]</td>
</tr>
<tr>
<td>x[0][1]</td>
<td>x[1][1]</td>
<td>x[2][1]</td>
<td>x[3][1]</td>
</tr>
</tbody>
</table>
|        |        |        |        | Thread 0 Thread 1 Thread 2 Thread 3

© 2010-19 LRZ

PGAS Languages: Coarray Fortran/Unified Parallel C
Example CAF procedure:

```fortran
subroutine add_pivot(x, img, y, n)
  integer, intent(in) :: img, n
  real, intent(in) :: x[*]
  real, intent(inout) :: y(:)
  y(n) = y(n) + x[img]
end subroutine
```

Invocation:

- with a different coarray (subobject) on each image

```fortran
real :: x(ndim)[*]
integer :: p, n
p = ...; n = ...
x(:) = ...
sync all
call add_pivot( x(n), p, x, n )
```

Illustrating the communication pattern:
- all references and definitions are done „in-place“, on elements of the original array coarray
- not all images need to call the procedure

© 2010-19 LRZ
PGAS Languages: Coarray Fortran/Unified Parallel C
Image-dependent shared object passing

**UPC version**

```c
void add_pivot(shared float *x,
    float y[], int n) {
    y[n] = y[n] + *x;
}
```

**Beware:**
- if synchronization is done within a procedure, all images must execute a consistent sequence of synchronizations
- else, deadlocks or data races will result

**with invocation**

```c
shared float x[NDIM][THREADS];
int main() {
    int p = ...; int n = ...;
    // initialize x
    upc_barrier;
    add_pivot( &x[n][p], (float *) x, n);
}
```

\[ p /\neq MYTHREAD, \ n \text{ and } p \text{ are different on each thread} \]
Coindexed definitions („Put“) are **not** permitted
- because this constitutes a side effect
- coindexed references („Get“) are OK though

**Image control statements are not permitted**

**ELEMENTAL procedures:**
- are not permitted to have coarray dummy arguments
Procedure-local shared objects

CAF Requirements:
- must have the SAVE or the ALLOCATABLE attribute or both
- a function result cannot be declared a coarray

Consequence:
- automatic coarrays or coarray function results are not permitted

Rationale:
- not prohibiting this would imply a need for *implicit* synchronization of (and hence also invocation from) all images
- Note that for an allocatable procedure-local coarray this is the case anyway, but the synchronization point is *explicitly* visible!

  If that coarray does not also have the SAVE attribute, it will be auto-deallocated at exit from the procedure if no explicit DEALLOCATE was previously issued.

UPC: has similar restrictions
- statically declared shared objects cannot be automatic
CAF: Coindexed actual arguments

**Assumptions:**
- actual argument is a coindexed object (therefore not a coarray)
- it is modified inside the subprogram
- therefore, typically copy-in/out will be required

→ an **additional** synchronization rule is needed

**Usually not a good idea**
- performance issues
- problematic or impermissible for container types (effective assignment!)

**Note:** this has no UPC equivalent
CAF: Factory procedures for coarrays

Allocatable dummy argument is a coarray:

```fortran
subroutine read_coarray_data( simulation_field, file_name )
  real, allocatable, intent(inout) :: simulation_field(:,,:,:)[,]
  character(len=*) , intent(in)  :: file_name
  ! determine size
  if (allocated( simulation_field )) deallocate( simulation_field )
  allocate( simulation_field(n1, n2, n3)[0:*] )
  ! read data into simulation_field
end subroutine read_coarray_data
```

- `intent(out)` is not permitted (would imply synchronization)
- actual argument: must be allocatable, with matching type, rank **and** corank
- procedure must be executed on **all images**, and with the **same** effective argument
Analogous functionality as for CAF is illustrated

```c
shared *float factory(char *file_name) {
    shared float *wk;
    // determine size n to allocate
    wk = (shared float *) upc_all_alloc(THREADS, sizeof(float)*n);
    // fill wk with data
    return wk;
}
```

- i.e., requires collective execution

**Remember:**
- other allocation functions `upc_global_alloc` (single thread distributed entity), `upc_alloc` (single thread shared entity) do not synchronize
- this permits to implement factory functions that do not require collective execution
CAF: Overloading the assignment

Use this as circumlocution in cases where intrinsic assignment is prohibited

- Example: polymorphic coarray

```fortran
module mod_body
  : ! type definition etc
  interface assignment (=)
    module procedure assign_body
  end interface
contains
  subroutine assign_body(out, in)
    class(body), intent(inout), allocatable :: out(:)[,]
    class(body), intent(in) :: in(:)
    : ! assert that size of in is the same on all images
    allocate(out(size(in,1))[*], source = in)
  end subroutine
  :
end module
```

use mod_body

```fortran
type(charged_body) :: nuclei(ndim)
class(charged_body), &
  allocatable :: conuc(:)[]
conuc = nuclei
```

Generic resolution of coarray vs. noncoarray specific is not possible
(syntax identical for calls with / without coarray)
## CAF: Using type-bound procedures to implement communication

**Example:**
- handle data transfer for the container type

```fortran
type :: polynomial
  real, allocatable :: f(:)
contains
  procedure :: get, put
end type
```

- here we only look at `put`

### Execution
- **of `put`** on image `p`

```fortran
s = ...
sync all :
status[q] = s%put(q)
event post (ev[q])
```

- **of consuming code on image `q`**

```fortran
s = ...
sync all :
event wait (ev)
if ( status == put_success ) then
  ! reference local part of s
end if
```

- `put_success` and `put_fail` are distinct integer constants

Remember that `s[p] = ...` is not permitted for an `s` of type `polynomial`
Implementation sketch

```fortran
integer function put(this, img)
  class(polynomial), intent(inout) :: this[*]
  integer, intent(in) :: img
  integer :: rem_size
  if ( .not. allocated( this[img]%f ) ) then
    put = put_fail
    return
  end if
  rem_size = size( this[img]%f, 1 )
  if ( rem_size >= size( this%f ) ) then
    put = put_success
    this[img]%f(:this%f) = this%f
    this[img]%f(this%f+1:) = 0.0
  else
    put = put_fail
  end if
end function
```

- For support of type extensions writing an overriding TBP is most appropriate
Documenting the synchronization behaviour

- **Synchronization performed by library code**
  - is part of its semantics and should be *documented*

- **In particular,**
  - whether (and which) additional synchronization is required by the *user* of a library,
  - and whether a procedure needs to be called from all images ("collectively") or can be called from image subsets

- **It may be a good idea**
  - to supply optional arguments that permit to change the default synchronization behaviour
Interoperation with MPI
Nothing is formally standardized

Existing practice:
- each MPI task is identical with a coarray image

```
program with_mpi
  use mpi_f08
  : ! further declarations, including coarrays
  if (.not. initialized) call MPI_Init()
  : ! code with both MPI calls and
  : ! coarray communication / synchronization
  call MPI_Finalize()
end program
```

result of calling `MPI_Comm_rank()`

no guarantee on ordering, though

obtained from call to `MPI_Initialized()`

implementation may either want this or not like this
Program design ideas

- Do not rewrite an existing MPI code base
- Instead, extend it with coarray functionality
  - to avoid deadlocks, keep MPI synchronizations separate from coarray synchronizations
  - avoid coindexed actual arguments in MPI calls
  - coarrays can be used in MPI calls (always considering segment ordering rules), but be careful with non-blocking MPI calls
  - it is probably a good idea to avoid using the same object in both MPI and coarray atomics
- Knowledge of communication structure is required
  - analysis with tracing tool may be needed
Compilation

- use mpifort/mpif90 wrapper together with switch for coarray activation
- not every MPI implementation might be usable:
  
  if the compiler uses MPI as implementation layer for coarrays, it is likely that you'll need to use at least a binary compatible MPI together with it

Execution

- at least for distributed-memory, it is likely that you will need to use mpiexec to start up
- consult your vendor's or computing centre's documentation
- facilities for pinning of MPI tasks are likely to be useful for coarray performance as well 😊
Appendix
Implementations

CAF
- Cray Fortran compiler on Cray systems
- Intel 12.0 and higher (current release: 19.0)
- gfortran (since 4.6: single image)
  - partial implementation in 5.0
  - more features in 8.0
- Rice coarray Fortran (research vehicle, deviates from the standard, development stalled)
- g95 (development stalled)

UPC
- Cray UPC
- Berkeley UPC
- GCC UPC

Note:
- performance problems still exist (tuning one-sided communication is a challenge)
  → do not expect MPI-like performance and scalability, except for the Cray compiler on appropriate networks
References

UPC references

- [https://upc-lang.org/upc-documentation](https://upc-lang.org/upc-documentation) (language specification, release level 1.3)
- UPC Distributed Memory Programming, by Tarek El-Ghazawi, Bill Carlson, Thomas Sterling, and Katherine Yelick, Wiley & Sons, June 2005

Coarray references

- Coarrays in the next Fortran Standard, by John Reid, N1824 from [https://wg5-fortran.org](https://wg5-fortran.org)
- Fortran 2018 international standard
- Modern Fortran explained, by Michael Metcalf, John Reid and Malcolm Cohen (OUP, September 2018)
- Coarray compendium, by Andy Vaught, [http://www.g95.org/compendium.pdf](http://www.g95.org/compendium.pdf)
- TS18508 „Additional parallel features in Fortran“, draft specification available as document N2074 from [https://wg5-fortran.org](https://wg5-fortran.org)
- The New Features of Fortran 2018, by John Reid, N2161 from [https://wg5-fortran.org](https://wg5-fortran.org)
Omitted topics

**Omitted:**
- rules for program termination
- parallel I/O (mostly UPC)
- asynchronous block transfers (UPC only)

**Further CAF TS18508 features**
- teams
  - composable splitting of execution contexts
  - allow data transfer and sync across team boundary
  - recursive / hybrid / MPMD-like
- atomic functions (similar to those added in UPC 1.3)
- limited fail-safe execution

**Possible futures**
- process topologies in CAF
  - more general abstraction than multiple coindices
- global variables and shared pointers in CAF
  - increase programming flexibility
- parallel I/O in CAF
- asynchronous transfers in CAF
- CAF+UPC interoperation
- UPC++
  - [https://bitbucket.org/berkeleyst/uppercxx/wiki/Home](https://bitbucket.org/berkeleyst/uppercxx/wiki/Home)

**Recent development**
- Coarray C++
  - presently available on Cray systems
  - uses template mechanism and leverages existing Fortran run time to map coarrays to C++
Acknowledgements

Significant parts of this slide set are based on the SC12 tutorial notes:

„Introduction to PGAS (UPC and CAF) and Hybrid for Multicore Programming”

by

Alice E. Koniges – NERSC, Lawrence Berkeley National Laboratory (LBNL)
Katherine Yelick – University of California, Berkeley and LBNL
Rolf Rabenseifner – High Performance Computing Center Stuttgart (HLRS), Germany
Reinhold Bader – Leibniz Supercomputing Centre (LRZ), Munich/Garching, Germany
David Eder – Lawrence Livermore National Laboratory
Filip Blagojevic and Robert Preissl – Lawrence Berkeley National Laboratory