Center for Scalable Application Development Software

Coarray Fortran 2.0: A Productive Language for Scalable Scientific Computing

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Outline

- Coarray Fortran
  - —original 1998 version
  - —Fortran 2008 - a standard with coarrays
- Coarray Fortran 2.0 (CAF 2.0)
  - —features
  - —experiences - HPC challenge benchmarks + performance
  - —implementation notes
- Status and plans

Partitioned Global Address Space Languages

- **Global address space**
  - **—one-sided communication (GET/PUT)** simpler than msg passing
- **Programmer has control over performance-critical factors**
  - **—data distribution and locality control** lacking in OpenMP
  - **—computation partitioning**
  - **—communication placement**

  HPF & OpenMP compilers must get this right
- **Data movement and synchronization as language primitives**
  - **—amenable to compiler-based communication optimization**
- **Examples: UPC, Titanium, Chapel, X10, Coarray Fortran**

Coarray Fortran (CAF)

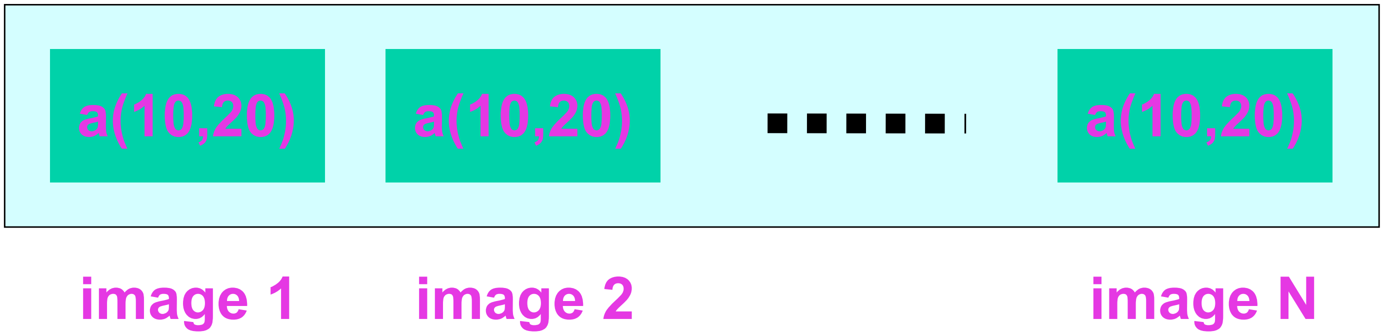
- Explicitly-parallel extension of Fortran 95 (Numrich & Reid 1998)
- Global address space SPMD parallel programming model
  - —one-sided communication
- Simple, two-level memory model for locality management
  - —local vs. remote memory
- Programmer has control over performance critical decisions
  - —data partitioning
  - —computation partitioning
  - —communication
  - —synchronization
- Suitable for mapping to shared and distributed memory systems

Coarray Fortran (1998)

- **SPMD process images**
  - —fixed number of images during execution: num_images()
  - —images operate asynchronously: this_image()
- **Both private and shared data**
  - – real x(20, 20) a private 20x20 array in each image
  - – real y(20, 20) [*] a shared 20x20 array in each image
- **Coarrays with multiple codimensions**
  - – real y(20, 20) [4,*]
- **Simple one-sided shared-memory communication**
  - – x(:,j:j+2) = y(:,p:p+2) [r] copy columns from p:p+2 into local columns
- **Synchronization intrinsic functions**
  - —sync_all – a barrier and a memory fence
  - —sync_team(notify, wait)
    - – notify = a vector of process ids to signal
    - – wait = a vector of process ids to wait for
  - – sync_memory – a memory fence
  - – start_critical/end_critical
- **Asymmetric dynamic allocation of shared data**
- **Weak memory consistency**

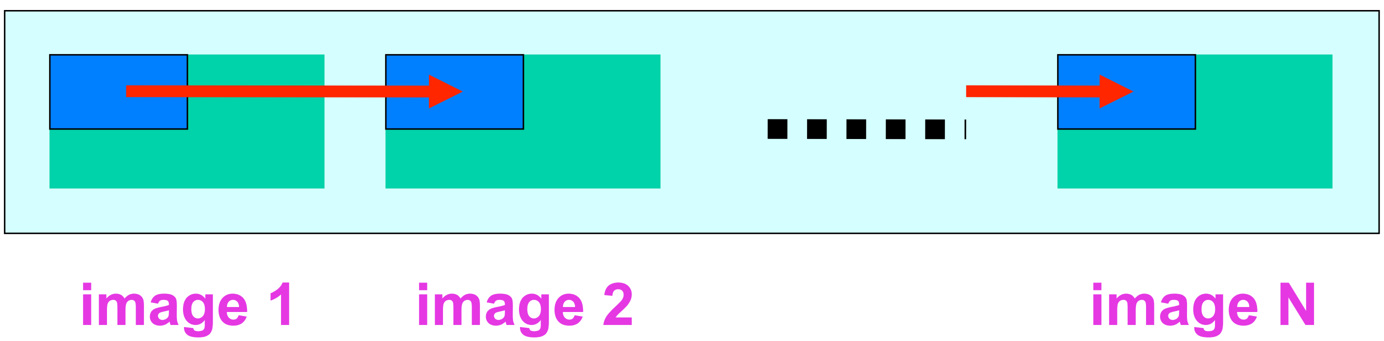
One-sided Communication with Coarrays

integer a(10,20)[*]



me = this_image()

if (me > 1) a(1:5,1:10) = a(1:5,1:10)[me-1]



A CAF Finite Element Example (Numrich)

```
subroutine assemble(start, prin, ghost, neib, x)
  integer :: start(:), prin(:), ghost(:), neib(:), k1, k2, p
  real :: x(:) [*]
  call sync_team(neib)
  do p = 1, size(neib) ! Add contributions from ghost regions
    k1 = start(p); k2 = start(p+1)-1
    x(prin(k1:k2)) = x(prin(k1:k2)) + x(ghost(k1:k2)) [neib(p)]
  enddo
  call sync_team(neib)
  do p = 1, size(neib) ! Update the ghosts
    k1 = start(p); k2 = start(p+1)-1
    x(ghost(k1:k2)) [neib(p)] = x(prin(k1:k2))
  enddo
  call sync_all
end subroutine assemble
```

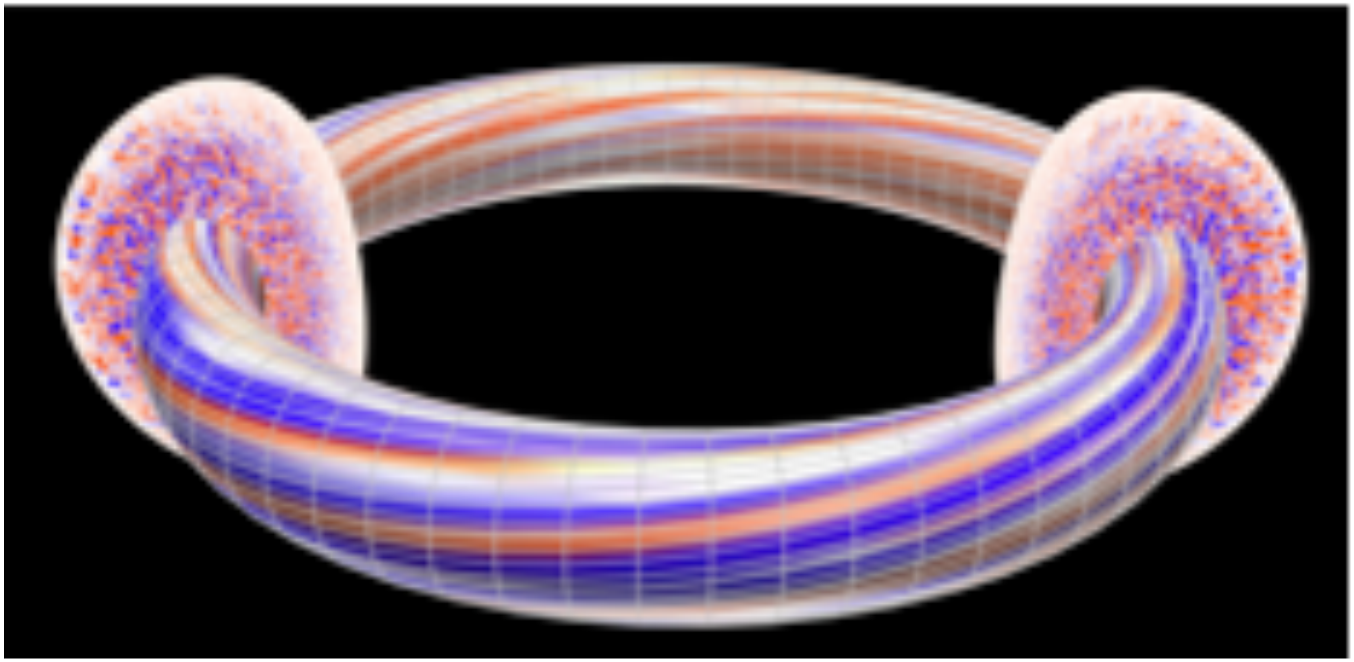
Fortran 2008

- SPMD process images
  - —fixed number of images during execution: num_images()
  - —images operate asynchronously: this_image()
- Both private and shared data
  - real x(20, 20) a private 20x20 array in each image
  - real y(20, 20) [*] a shared 20x20 array in each image
- Coarrays with multiple codimensions
  - real y(20, 20) [4,*]
- Simple one-sided shared-memory communication
  - x(:,j:j+2) = y(:,p:p+2) [r] copy columns from p:p+2 into local columns
- Synchronization intrinsic functions
  - —sync all, sync images(image vector)
  - – sync memory
  - – critical sections, locks
  - – atomic_define, atomic_ref
- Asymmetric dynamic allocation of shared data
- Weak memory consistency

CAF on Hopper in 2011

GTS Particle Shifter (LBNL, Cray, PPPL) [SC11]

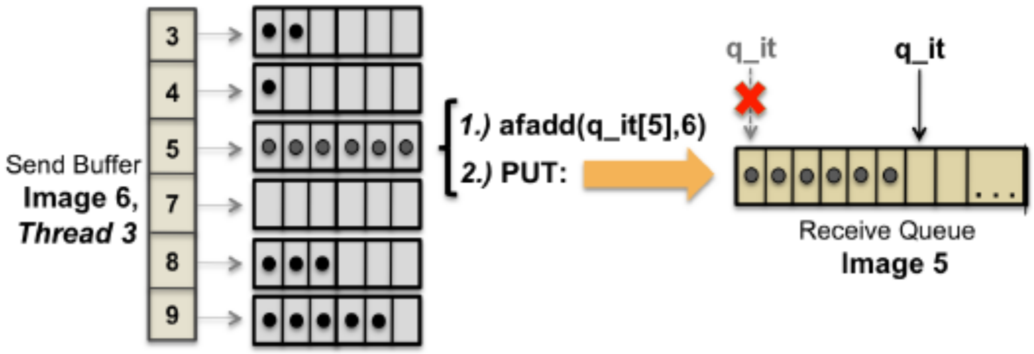
**Preissl, Wichmann, Long, Shalf,
Ethier, Koniges**



GTS Particle Shifter in MPI

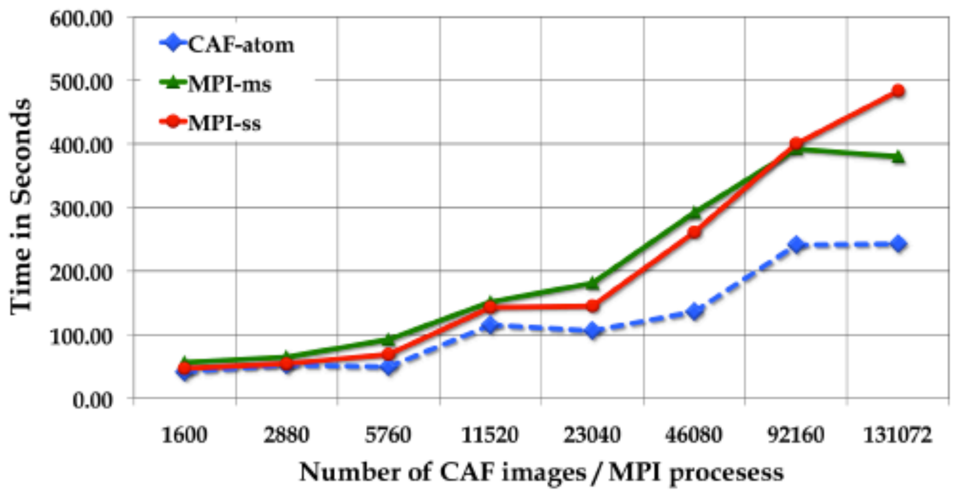
```
!(1) Prepost receive requests
do i=1,nr_dests
  MPI_IRECV(recv_buf(i),i,req(i),tor_comm,..)
enddo

!(2) compute shifted particles and fill buffer
!$omp parallel
pack(p_array,shift,holes,send_buf)

!(3) Send of particles to destination process
do j=1,nr_dests
  MPI_ISEND(send_buf(j),j,req(j+i),tor_comm,..)
enddo
MPI_WAITALL(2*nr_dests,req,..)

!(4) fill holes with received particles
!$omp parallel do
do m=1,min(recv_length,shift)
  p_array(holes(m))=recv_buf(src,cnt)
  if(cnt.eq.recv_buf(src,0)) {cnt=1; src++}
enddo

!(5) append remaining particles or fill holes
if(recv_length < shift) {
  append_particles(p_array,recv_buf) }
else { fill_remaining_holes(p_array,holes) }
```

GTS Particle Shifter in CAF

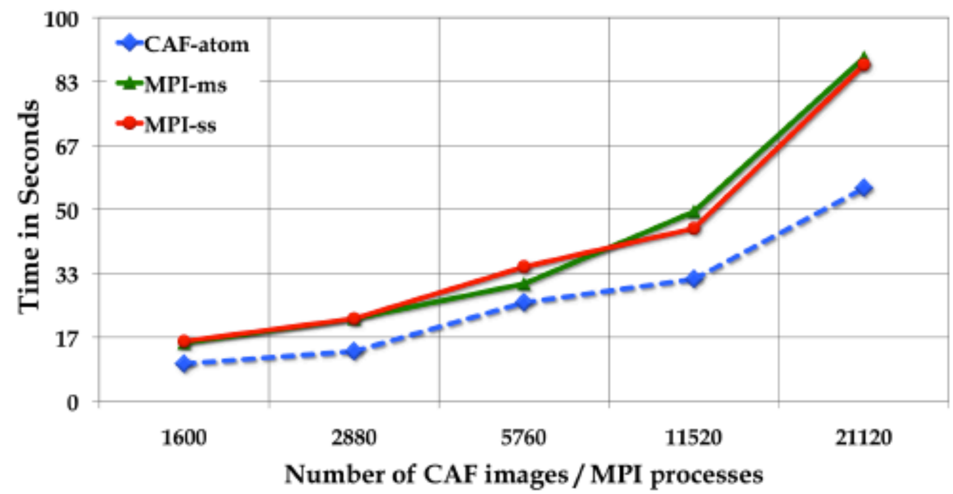



```
!(1) compute shifted particles and fill the
!   receiving queues on destination images
!$omp parallel do schedule(dynamic,p_size/100)&
!$omp private(s_buf,buf_cnt) shared(recvQ,q_it)
do i=1,p_size
  dest=compute_destination(p_array(i))
  if(dest.ne.local_toroidal_domain) {
    holes(shift++)=i
    s_buf(dest,buf_cnt(dest)++)=p_array(i)
    if(buf_cnt(dest).eq.sb_size) {
      q_start=afadd(q_it[dest],sb_size)
      recvQ(q_start:q_start+sb_size-1)[dest] &
        =s_buf(dest,1:sb_size)
      buf_cnt(dest)=0  }  }
enddo

!(2) shift remaining particles
empty_s_buffers(s_buf)
!$omp end parallel

!(3) sync with images from same toroidal domain
sync images([my_shift_neighbors])

!(4) fill holes with received particles
length_recvQ=q_it-1
!$omp parallel do
do m=1,min(length_recvQ,shift)
  p_array(holes(m))=recvQ(m)
enddo

!(5) append remaining particles or fill holes
if(length_recvQ-min(length_recvQ,shift).gt.0) {
  append_particles(p_array,recvQ) }
else { fill_remaining_holes(p_array,holes) }
```

GTC Particle Shifter Performance

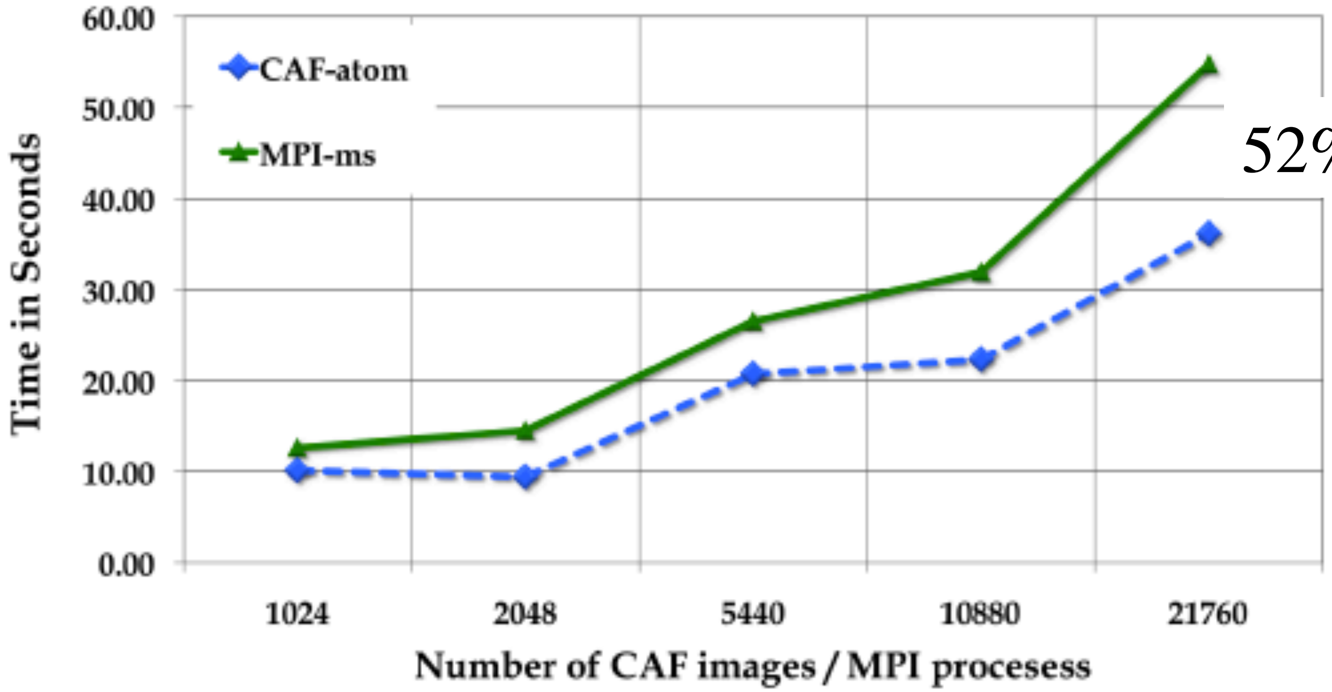


(a) 1 OpenMP thread per instance



(b) 6 OpenMP threads per instance

GTS Weak Scaling Performance



52% speedup

Figure 8: Weak scaling GTS experiments with CAF-atom & MPI-ms as particle shift algorithms (6 OpenMP threads per instance)

Why a New Vision?

Fortran 2008 characteristics

- No support for process subsets
- No support for collective communication
- No support for latency hiding or avoidance
  - —rendezvous synchronization: sync all, sync images
- No remote pointers for manipulating remote linked data structures
- ... and so on ... (see our critique)
  - —www.j3-fortran.org/doc/meeting/183/08-126.pdf

Coarray Fortran 2.0 Goals

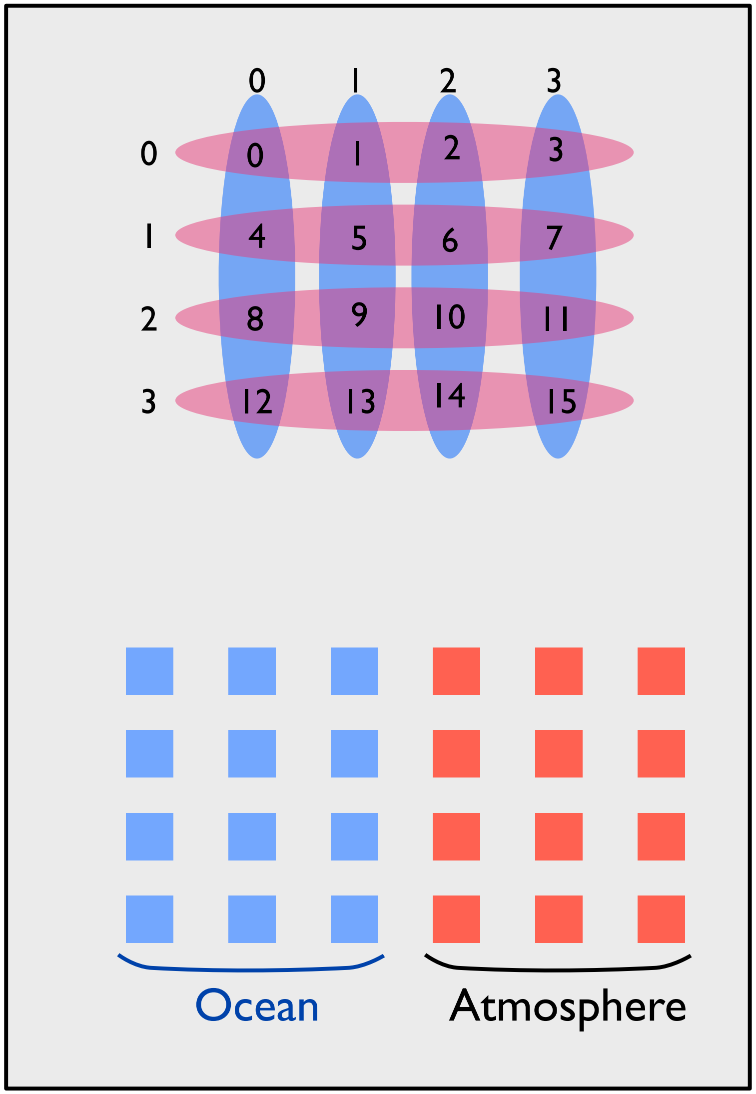
- Exploit multicore processors
- Enable development of portable high-performance programs
- Interoperate with legacy models such as MPI
- Facilitate construction of sophisticated parallel applications and parallel libraries
- Support irregular and adaptive applications
- Hide communication latency
- Colocate computation with remote data
- Scale to leadership computing facilities

Coarray Fortran 2.0 (CAF 2.0)

- Teams: process subsets, like MPI communicators
  - —formation using team_split (like MPI_Comm_split)
  - —collective communication
- Topologies
- Coarrays: shared data allocated across processor subsets
  - —declaration: double precision :: a(:,:)[*]
  - —dynamic allocation: allocate(a(n,m)[@row_team])
  - —access: x(:,n+1) = x(:,0)[mod(team_rank()+1, team_size())]
- Latency tolerance
  - —hide: asynchronous copy, asynchronous collectives
  - —avoid: function shipping
- Synchronization
  - —event variables: point-to-point sync; async completion
  - —finish: SPMD construct inspired by X10
- Copointers: pointers to remote data

Process Subsets: Teams

- **Teams are first-class entities**
  - —ordered sequences of process images
  - —namespace for indexing images by rank r in team t
    - – r ∈ {0..team_size(t) - 1}
  - —domain for allocating coarrays
  - —substrate for collective communication
- **Teams need not be disjoint**
  - —an image may be in multiple teams



Teams and Operations

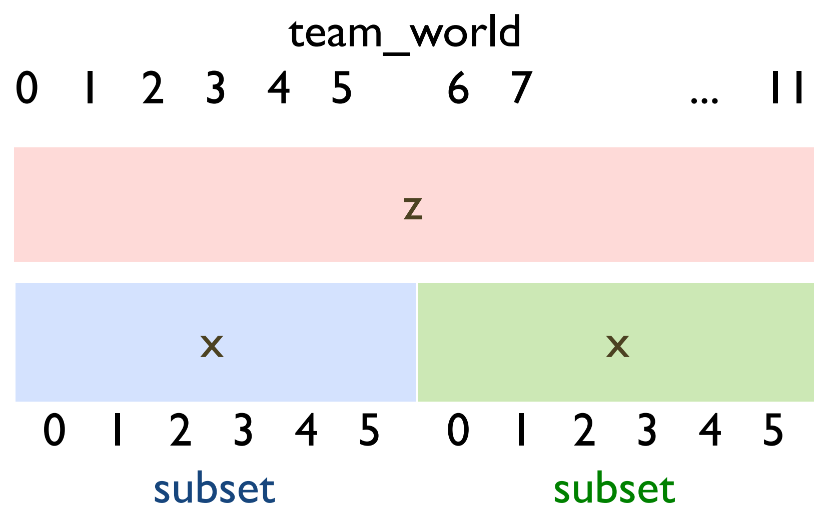
- Predefined teams
  - team_world
  - team_default
    - used for any coarray operation that lacks an explicit team specification
- Operations on teams
  - team_rank(team)
    - returns the relative rank of the current image within a team
  - team_size(team)
    - returns the number of images of a given team
  - team_split (existing_team, color, key, new_team)
    - images supplying the same color are assigned to the same team
    - each image's rank in the new team is determined by lexicographic order of (key, parent team rank)

Teams and Coarrays

- **Coarray allocation occurs over teams**
  - storage is allocated over each member of the specified team
- **Example**
  - integer :: a(:, :)[*]
  - allocate (a (10, 100)[@team_world])
- **Allocation is a collective operation**
  - need barrier after an allocation to know that a coarray is available on other team members before accessing their data

Teams and Coarrays

```
real, allocatable :: x(:,:)[*] ! 2D array
real, allocatable :: z(:,:)[*]
team :: subset
integer :: color, rank

! each image allocates a singleton for z
allocate( z(200,200) [@team_world] )

color = floor((2*team_rank(team_world)) / team_size(team_world))

! split into two subsets:
!    top and bottom half of team_world
team_split(team_world, color,  team_rank(team_world), subset)

! members of the two subset teams
! independently allocate their own coarray x
allocate( x(100,n)[@ subset])
```



Accessing Coarrays on Teams

- **Accessing a coarray relative to a team**
  - **x(i,j)[p@ocean]** ***! p names a rank in team ocean***
- **Accessing a coarray relative to the default team**
  - **x(i,j)[p]** ***! p names a rank in team_default***
  - **x(i,j)[p@team_default]** ***! p names a rank in team_default***
- **Simplifying processor indexing using "with team"**

```
with team atmosphere ! set team_default to atmosphere within
   ! p is wrt team atmosphere, q is wrt team ocean
   x(:,0)[p] = y(:)[q@ocean]
end with team
```

Communication Topologies

- **Motivation**
  - —a vector of images may not adequately reflect their logical communication structure
  - —multiple codimensions only support grid-like logical structures
  - —want a single mechanism for expressing more general structures
- **Topology**
  - —shamelessly patterned after MPI Topologies
  - —logical structure for communication within a team
  - —more expressive than multiple codimensions

Using Topologies

- Creation
  - —Cartesian: topology_cartesian((/e1,e2,.../), (/ w1, w2, ... /))
  - —Graph: topology_graph(e)
    - graph_neighbor_add(g,e,n,nv)
    - graph_neighbor_delete(g,e,n,nv)
- Binding: topology_bind(team,topology)
- Accessing a coarray using a topology
  - —Cartesian
    - array(:) [+(i1, i2, ..., in)@ocean] ! relative index wrt self in team ocean
    - array(:) [(i1, i2, ..., in)@ocean] ! absolute index wrt team ocean
    - array(:) [i1, i2, ..., ik] ! wrt enclosing default team
  - —Graph: access k^{th} neighbor of image i in edge class e
    - array(:) [(e,i,k)@g] ! wrt team g
    - array(:) [e,i,k] ! wrt enclosing default team

Synchronization

- **Point-to-point synchronization via event variables**
  - —like counting semaphores
  - —each variable provides a synchronization context
  - —a program can use as many events as it needs
    - – user program events are distinct from library events
  - —event_notify() / event_wait()
  - —event_notify is non-blocking
- **Lockset: ordered sets of locks**
  - —convenient to avoid deadlock when locking/unlocking multiple locks -- uses a canonical ordering

Latency Tolerance

- <u>Hide</u> latency for accessing remote data by overlapping it with computation
- <u>Avoid</u> exposed latency when manipulating remote data structures
- Asynchrony models
  - —explicit: signal an event to indicate when an asynchronous operation has completed
  - —implicit: programmer specifies a point when program must block until outstanding asynchronous operations have completed
  - —interactions between models are subtle!

Predicated Asynchronous Copy

`copy_async`(var_dest, var_src [, ev_dest] [, ev_src] [, ev_pred]*)*

- **var_dest**: data target
- **var_src**: data source
- **ev_src**: event to be triggered when the read of var_src is complete
- **ev_dest**: event to be triggered when the write of var_dest is complete
- **ev_pred**: optional event indicating that var_src is ready

Collective Communication

- Why provide collectives?
  - —application programmers want them
  - —avoid having programmers roll their own (non scalable) versions
- Collective operations
  - —alltoall, barrier, broadcast, all/gather, permute, all/reduce, scatter, segmented/scan, shift
- User-defined reduction operators
- Potential flavors
  - —two-sided synchronous
    - all execute it together
  - —two-sided asynchronous
    - all team members will execute a call to start it
    - all will later wait for it to complete
  - —one-sided synchronous: one starts it and blocks until done
  - —one-sided asynchronous: one starts it and later finishes it

Two-sided vs. One-sided Collectives

- **Issues with one-sided collectives**
  - **where does the data get delivered?**
    - **does the initiator specify an address for each recipient?**
    - **does data get delivered to the same offset in a coarray for each recipient?**
  - **how do I know when I can overwrite it?**
- **Two-sided collectives address these issues**
  - **each participant receiving a value specifies where to deliver it**
  - **each participant can decide how many asynchronous collectives can be outstanding at once**
    - **based on the number of buffers available for receiving values**
  - **an asynchronous collective initiated before some recipients are ready will have (at least part of) its execution deferred until recipients are ready**

Coarray Fortran 2.0 supports two-sided synchronous and asynchronous collectives

Asynchronous Collective Operations

- **Synchronization:**
  - **—team_barrier_async([event] [, team])**
- **Communication:**
  - **—team_broadcast_async(var, root [, event] [, team])**
  - **—team_gather_async(var_src, var_dest, root [, event] [, team])**
  - **—team_allgather_async(var_src, var_dest [, event] [, team])**
  - **—team_reduce_async(var_src, var_dest, root, operator [, event] [, team])**
  - **—team_allreduce_async (var_src, var_dest, operator [, event] [, team])**
  - **—team_scatter_async(var_src, var_dest, root [, event] [, team])**
  - **—team_alltoall_async(var_src, var_dest [, event] [, team])**
  - **—team_sort_async(var_src, var_dest, comparison_fn [, event] [, team])**
  - **—...**

Function Shipping

- Reduce communication overhead by moving computation to the data instead of moving data to computation
- Implicit asynchrony

```
finish (team)
  spawn fxn(table(i,j)[p], n)[p]
  ...
end finish
```

CAF 2.0 Finish

- **X10 finish**

  finish {

  ...

  }

  —synchronization model
  - Cilk: fully strict - all spawned children reports directly to their parent
  - X10: terminally strict

    all asyncs report to an enclosing finish scope

    the enclosing finish scope may be in a different procedure

- **CAF 2.0 finish**

  —SPMD construct defined over teams

  finish (team)

  ...

  end finish

  —all members of a team enter a finish block

  —any functions that team members ship to one another from within a finish block must complete before any node will exit the corresponding finish block

CAF 2.0 Cofence

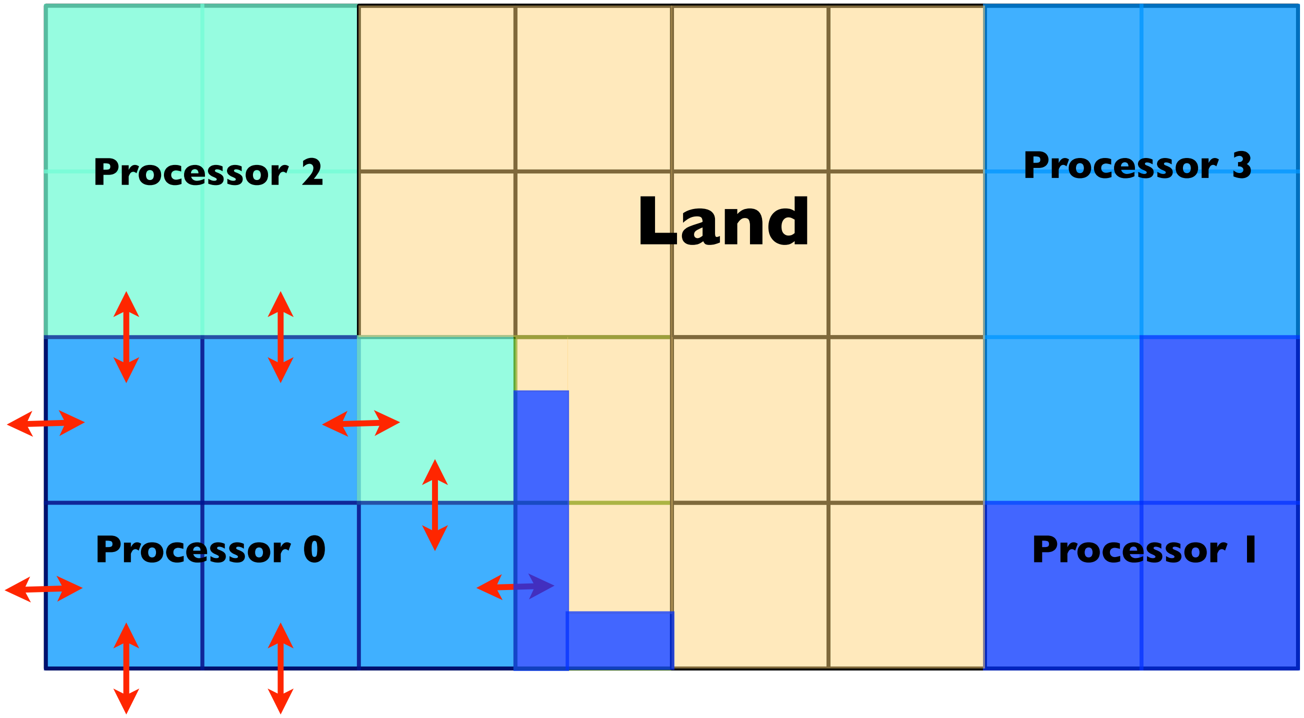
- Finish is a heavyweight mechanism
  - —manages global completion across a team
  - —sometimes only local completion is needed
    - – e.g. an asynchronous copy has delivered a value locally
- Cofence manages local completion
  - —asynchronous copies with implicit completion
  - —asynchronous collectives with implicit completion
- Can use a cofence within a finish block to demand early completion of asynchronous operations

Copointers: Global Pointers

- Motivation: support linked data structures
- **copointer** attribute enables association with remote shared data
- **imageof(x)**returns the image number for **x**
    - useful to determine whether copointer x is local

```
integer, allocatable :: a(:,:)[*]
integer, copointer :: x(:,:)[*]

allocate(a(1:20, 1:30)[@ team_world]

! associate copointer x with a
! remote section of a coarray
x => a(4:20, 2:25)[p]

! imageof intrinsic returns the target
! image for x
prank = imageof(x)

x(7,9) = 4      ! assumes target of x is local
x(7,9)[ ] = 4  ! target of x may be remote
```

LANL's Parallel Ocean Program



- Data partitioning of ocean blocks
  - cartesian, balanced, space-filling curve distributions
- Data communication
  - boundary updates between neighboring processors
  - collective communications (gather, scatter, reduction)
- Different boundary types
  - cyclic, closed, tripole

MPI

```
! post a receive
do n=1,in_bndy%nmsg_ew_rcv
   bufsize = ny_block*nghost*in_bndy%nblocks_ew_rcv(n)
   call MPI_IRECV(buf_ew_rcv(1,1,1,n), bufsize, mpi_dbl,   &
                  in_bndy%ew_rcv_proc(n)-1,                &
                  mpitag_bndy_2d + in_bndy%ew_rcv_proc(n), &
                  in_bndy%communicator, rcv_request(n), ierr)
end do

! pack data and send data
do n=1,in_bndy%nmsg_ew_snd
   bufsize = ny_block*nghost*in_bndy%nblocks_ew_snd(n)

   partner = in_bndy%ew_snd_proc(n)-1
   do i=1,in_bndy%nblocks_ew_snd(n)
      ib_src    = in_bndy%ew_src_add(1,i,n)
      ie_src    = ib_src + nghost - 1
      src_block = in_bndy%ew_src_block(i,n)
      buf_ew_snd(:,:,i,n) = ARRAY(ib_src:ie_src,:,src_block)
   end do

   call MPI_ISEND(buf_ew_snd(1,1,1,n), bufsize, mpi_dbl, &
                  in_bndy%ew_snd_proc(n)-1, &
                  mpitag_bndy_2d + my_task + 1, &
                  in_bndy%communicator, snd_request(n), ierr)

end do

! local updates
! wait to receive data and unpack data
call MPI_WAITALL(in_bndy%nmsg_ew_rcv, rcv_request, rcv_status, ierr)

do n=1,in_bndy%nmsg_ew_rcv
   partner = in_bndy%ew_rcv_proc(n) - 1
   do k=1,in_bndy%nblocks_ew_rcv(n)
      dst_block = in_bndy%ew_dst_block(k,n)
      ib_dst = in_bndy%ew_dst_add(1,k,n)
      ie_dst = ib_dst + nghost - 1
      ARRAY(ib_dst:ie_dst,:,dst_block) = buf_ew_rcv(:,:,k,n)
   end do
end do

! wait send to finish
call MPI_WAITALL(in_bndy%nmsg_ew_snd, snd_request, snd_status, ierr)
```

CAF 2.0

```
type :: outgoing_boundary
   double, copointer :: remote(:,:,:)[*]
   double, pointer :: local(:,:,:)
   event :: snd_ready[*]
   event, copointer :: snd_done[*]
end type

type :: incoming_boundary
   event, copointer :: rcv_ready[*]
   event :: rcv_done[*]
end type

type :: boundaries
   integer :: rcv_faces, snd_faces
   type(outgoing_boundary) :: outgoing(:)
   type(incoming_boundary) :: incoming(:)
end type

! initialize outgoing boundary
!    set remote to point to a partner's incoming boundary face
!    set local to point to one of my outgoing boundary faces
!    set snd_done to point to rcv_done of a partner's incoming boundary

! initialize incoming boundary
!    set my face's rcv_ready to point to my partner face's snd_ready

! notify each partner that my face is ready
do face=1,bndy%rcv_faces
   call event_notify(bndy%incoming(face)%rcv_ready[])
end do

! when each partner face is ready
!     copy one of my faces to a partner's face
!     notify my partner's event when the copy is complete
do face=1,bndy%snd_faces
    copy_async(bndy%outgoing(face)%remote[], &
               bndy%outgoing(face)%local,  &
               bndy%outgoing(face)%snd_done[], &
               bndy%outgoing(face)%snd_ready)
end do

! wait for all of my incoming faces to arrive
do face=1,bndy%rcv_faces
   call event_wait(bndy%incoming(face)%rcv_done)
end do
```

Multithreading

- **Where can asynchronous threads of control arise in CAF 2.0?**
  - —spawned procedures
  - —parallel loops
    - – Fortran 90's "do concurrent"
- **Work in progress to employ Cilk-like lazy multithreading**
  - —generate continuations when spawning functions
  - —generate a continuation when blocking for synchronization

Outline

- Coarray Fortran
  - —original 1998 version
  - —Fortran 2008 - a standard with coarrays
- Coarray Fortran 2.0 (CAF 2.0)
  - —features
  - —experiences - HPC challenge benchmarks + performance
  - —implementation notes
- Status and plans

HPC Challenge Benchmark Goal: Productivity

- Priorities, in order
  - —performance
  - —source code volume
- Productivity = performance / (lines of code)
- Implications
  - —EP STREAM Triad
    - – outlined a loop to assist compiler optimization
  - —Randomaccess
    - – used software routing for higher performance
  - —FFT
    - – blocked packing/unpacking loops for bitreversal (8x gain for packing kernel)
  - —HPL
    - – tuned code to make good use of the memory hierarchy

EP STREAM Triad

```
double precision, allocatable :: a(:)[*], b(:)[*], c(:)[*]
...
! each processor in the default team allocates their own array parts
allocate(a(local_n)[], b(local_n)[], c(local_n)[])
...
! perform the calculation repeatedly to get reliable timings
do round = 1, rounds
  do j = 1, rep
    call triad(a,b,c,local_n,scalar)
  end do
  call team_barrier() ! synchronous barrier across the default team
end do
...
! perform the calculation with top performance
! assembly code is identical to that for sequential Fortran
subroutine triad(a, b, c, n ,scalar)
  double precision :: a(n), b(n), c(n), scalar
  a = b + scalar * c  ! EP triad as a Fortran 90 vector operation
end subroutine triad
```

Randomaccess

- A stream of updates to random locations in a distributed table
- Each update consists of xoring a random value into a random location in the table
- Each processor performs a subsequence of the updates

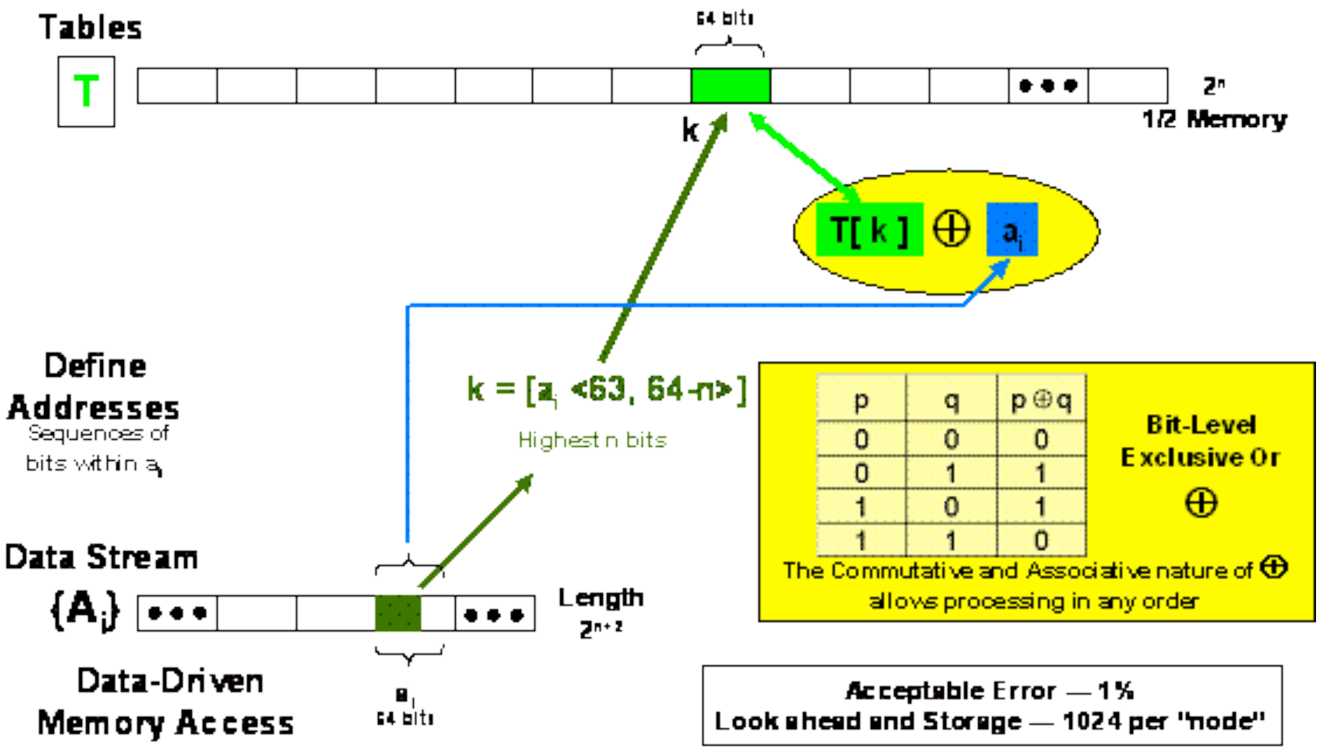


Figure credit: UTK

Randomaccess Software Routing

```
event, allocatable :: delivered(:)[*],received(:)[*] !(stage)
integer(i8), allocatable :: fwd(:,:,:)[*] ! (#,in/out,stage)
...
! hypercube-based routing: each processor has 1024 updates
do i = world_logsize-1, 0, -1  ! log P stages in a route
  ...
  call split(retain(:,last), ret_sizes(last), &
             retain(:,current), ret_sizes(current), &
             fwd(1:,out,i), fwd(0,out,i), bufsize, dist)

  if (i < world_logsize-1) then
    event_wait(delivered(i+1))
    call split(fwd(1:,in,i+1), fwd(0,in,i+1), &
               retain(:,current), ret_sizes(current), &
               fwd(1:,out,i), fwd(0,out,i), bufsize, dist)
    event_notify(received(i+1)[from]) ! signal buffer is empty
  endif

  count = fwd(0,out,i)
  event_wait(received(i)) ! ensure buffer is empty from last route
  fwd(0:count,in,i)[partner] = fwd(0:count,out,i) ! send to partner
  event_notify(delivered(i)[partner]) ! notify partner data is there
  ...
end do
```

1

2

HPL

- **Block-cyclic data distribution**
- **Team based collective operations along rows and columns**
  - —synchronous max reduction down columns of processors
  - —asynchronous broadcast of panels to all processors

```
type(paneltype) :: panels(1:NUMPANELS)
event, allocatable :: delivered(:)[*]
...
do j = pp, PROBLEMSIZE - 1, BLKSIZE
  cp = mod(j / BLKSIZE, 2) + 1
  ...
  event_wait(delivered(3-cp))
  ...
  if (mycol == cproc) then
    ...
    if (ncol > 0) ...    ! update part of the trailing matrix
    call fact(m, n, cp) ! factor the next panel
  ...
  call team_broadcast_async(panels(cp)%buff(1:ub), panels(cp)%info(8), &
                            delivered(cp))
  ! update rest of the trailing matrix
  if (nn-ncol>0) call update(m, n, col, nn-ncol, 3 - cp)
  ...
end do
```

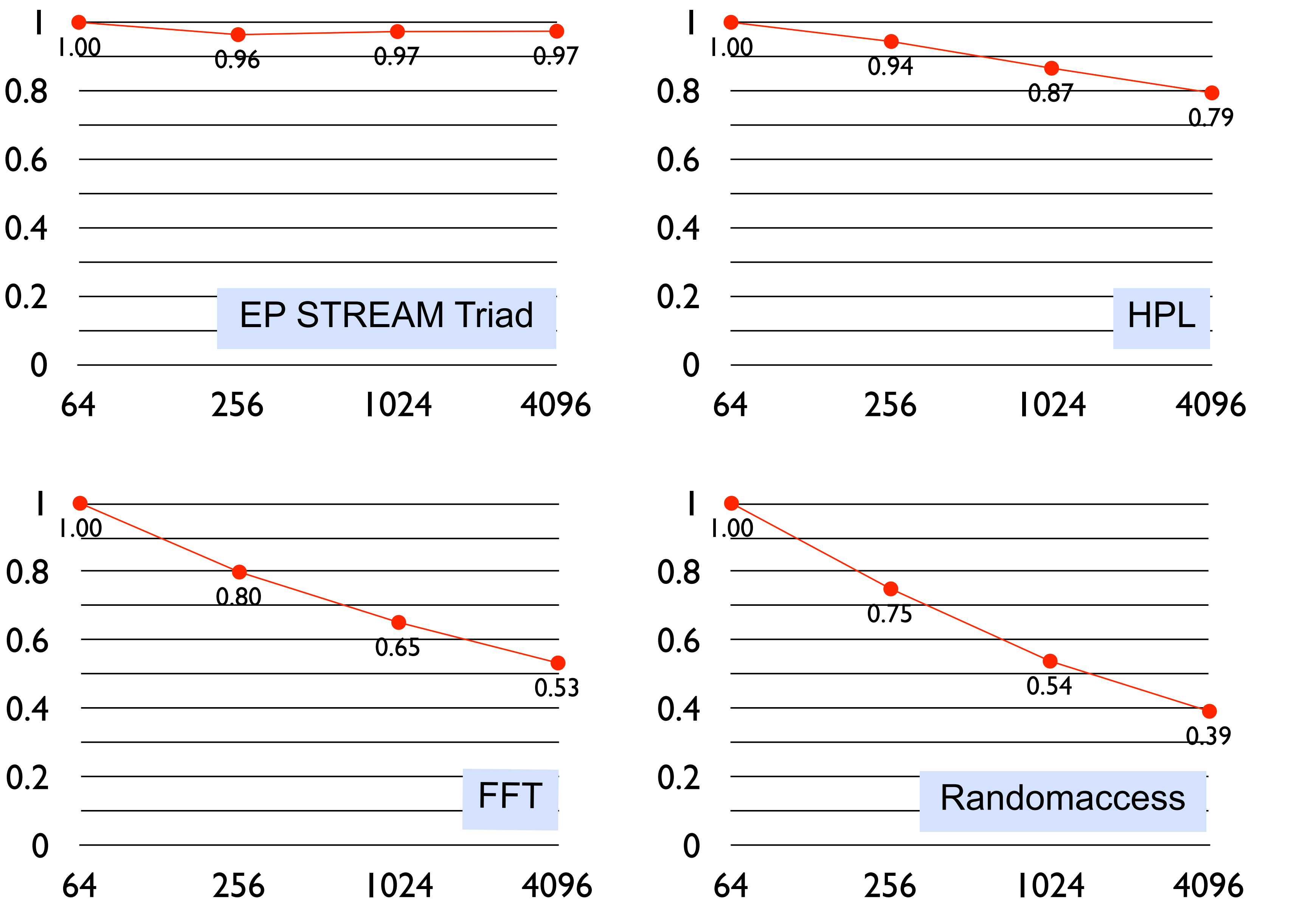
FFT

- Radix 2 1D FFT implementation
- Block distribution of array “c” across all processors
- Computation
  - —permute elements: c = (/ c(bitreverse(i), i = 0, n-1 /)
    - – 3 parts: pack data for all-to-all; team collective all-to-all; unpack data locally
  - —FFT is log N stages
    - – compute (log N - log P) stages of the FFT locally
    - – transpose the data so that each processor has elements ≡ rank mod P
      - block distribution → cyclic distribution
    - – compute the remaining log P stages of the FFT locally
    - – transpose the data back to its original order
      - cyclic distribution → block distribution

Experimental Setup

- Coarray Fortran 2.0 by Rice University
  - —source to source compilation from CAF 2.0 to Fortran 90
    - – generated code compiled with Portland Group's pgf90
  - —CAF 2.0 runtime system built upon GASNet (version 1.14.2)
  - —scalable implementation of teams, using O(log P) storage
- Experimental platform: Cray XT
  - —systems
    - – Franklin at NERSC
      - 2.3 GHz AMD "Budapest" quad-core Opteron, 2GB DDR2-800/core
    - – Jaguar at ORNL
      - 2.1 GHz AMD "Budapest" quad-core Opteron, 2GB DDR2-800/core
  - —network topology
    - – 3D Torus based on Seastar2 routers
    - – OS provides an arbitrary set of nodes to an application

Scalability: Relative Parallel Efficiency



Productivity = Performance / SLOC

Performance (Cray XT4)

	HPC Challenge Benchmark			
# of cores	STREAM Triad † (TByte/s)	RandomAccess*(GUP/s)	Global HPL † (TFlop/s)	Global FFT † (GFlop/s)
64	0.14	0.08	0.36	6.69
256	0.54	0.24	1.36	22.82
1024	2.18	0.69	4.99	67.80
4096	8.73	2.01	18.3	187.04

*Measured on Jaguar † Measured on Franklin

Source lines of code

HPC Challenge Benchmark	Source Lines of Code	Reference SLOC
Randomaccess	409	787
EP STREAM Triad	58	329
Global HPL	786	8800
Global FFT	~390	1130

Notes

- EP STREAM: 66% of memory B/W peak
- Randomaccess: high performance without special-purpose runtime
- HPL: 49% of FP peak at @ 4096 cores (uses dgemm)

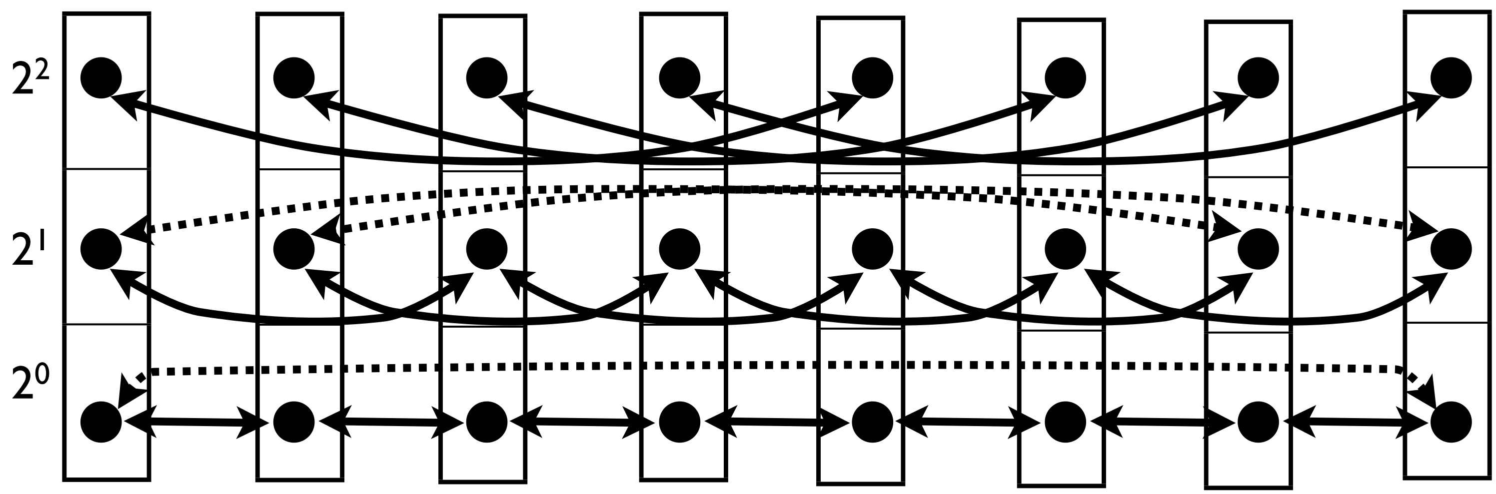
CAF 2.0 Early Experiences Summary

- A viable programming model for scalable parallel computing
  - —expressive
  - —easy to use
- Prototype implementation scales to thousands of nodes
- Scalable high performance
  - —demonstrated by HPC Challenge Benchmark results

Outline

- Coarray Fortran
  - —original 1998 version
  - —Fortran 2008 - a standard with coarrays
- Coarray Fortran 2.0 (CAF 2.0)
  - —features
  - —experiences - HPC challenge benchmarks + performance
  - —implementation notes
- Status and plans

CAF 2.0 Team Representation

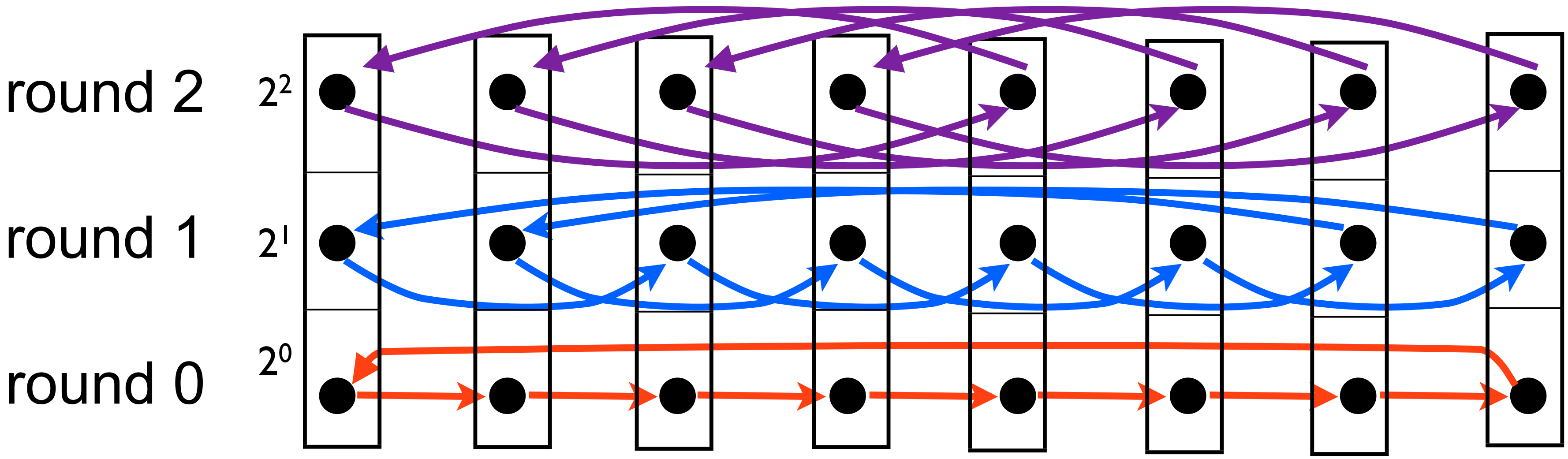


- **Designed for scalability: representation is O(log S) per node for a team of size s**
- **Based on the concept of pointer jumping**
- **Pointers to predecessors and successors at distance i = 2^j, j = 0 .. ⌊log S⌋**

Collective Example: Barrier

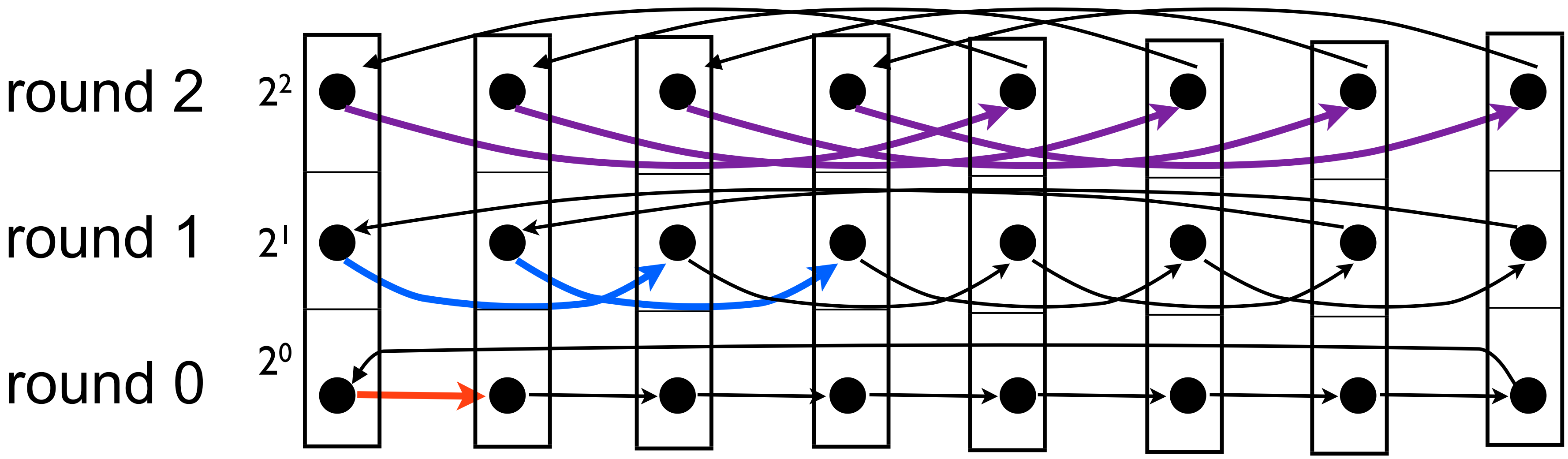
Dissemination algorithm

```
for k = 0 to ⌈log2 P⌉
   processor i signals processor (i + 2^k) mod P with a PUT
   processor i waits for signal from (i - 2^k) mod P
```



Collective Example: Broadcast

Binomial Tree



Progress Engine

- Tracks and manages state for all outstanding asynchronous operations on an image
- Operations are set up as finite state machines
  - —initialize, waiting for a non-blocking write, etc.
- Advance function invoked regularly
  - —inside various CAF 2.0 runtime calls
  - —(eventually) sprinked through user code by our compiler
  - —manually as desired
- Gives each operation a chance to make progress
- Cooperative multitasking
- Research issue
  - —scheduling progress engine tasks when there are multiple threads

Implementing Non-blocking Collectives

- **State machine for each communication partner**
  - —each state machine begins in state 0
- **Example: long broadcast**
  - —state machine (1) - for parent communication
    - 0: provide my buffer location to my parent in the broadcast tree
      - set closure variables
        - count = number of my children; event = event to signal for completion
    - 1: test for data for my parent; if no, state = 1; return to progress engine
      - enqueue instance of state machine (2) for each child in the broadcast tree
      - dequeue myself from the progress engine
  - —state machine (2) - for child communication
    - 0: test if my child provided buffer location for receiving broadcast
      if not, return to progress engine
      - provide data to my child
      - decrement a count in the closure for (1)
        - if count = 0, signal event in parent's closure, free my parent's closure
      - dequeue myself from the progress engine; free my closure

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  - —implementation notes
- Status and plans

Strengths and Weaknesses of CAF 2.0

- Strengths
  - —provides full control over data and computation partitioning
  - —admits sophisticated parallelizations
  - —compiler and runtime systems are tractable
  - —yields scalable high performance today with careful programming
- Weaknesses
  - —users code data movement and synchronization
    - – significantly harder than HPF
  - —optimizing performance can require careful parallel programming
    - – overlapping communication and computation may require managing multiple communication buffers
    - – hiding latency requires
      - using non-blocking primitives for data movement and synchronization
      - overlapping latency of communication with computation
      - managing the completion of asynchronous operations

Implementation Status & Plans

- **Source-to-source translator is a work in progress**
  - —requires no vendor buy-in
  - —delivers node performance of mature vendor compilers
  - —ongoing work to improve Fortran coverage in ROSE
- **Ongoing work**
  - —copointers
  - —lazy multithreading
  - —coarray binding interface for inter-team communication
  - —graph topology for managing irregular communication patterns
- **Future plans**
  - —use compiler-based vectorization to target SIMD and accelerators

Planned Application Studies

- LANL's Parallel Ocean Program
  - —block structured, dense matrix
- Sandia's S3D
  - —regular, dense matrix
- LANL's HEAT
  - —cell-by-cell AMR code, sparse matrix
- Community Earth System Model
  - —coupled code
  - —multiple block-structured dense matrix components