Getting Fortran onto GPUs

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Outline

- Where are we now?
    - DO CONCURRENT
    - Data parallel intrinsics
    - Directives
    - CUDA support
- Where do we want to go?
    - Fetching atomics in DO CONCURRENT
    - Asynchrony and task parallelism

Programming the nvidia platform *WITH FORTRAN*

CPU, GPU, and Network

ACCELERATED STANDARD MODELS

ISO Fortran | OpenACC | OpenMP

ISO Fortran

```
do concurrent (j=1:order, &
               i=1:order)
  B(i,j) = A(j,i)
enddo
```

```
B = transpose(A)
```

OpenACC

```
!$acc parallel loop tile(32,32)
do j=1,order
  do i=1,order
     B(i,j) = A(j,i)
  enddo
enddo
```

```
!$acc kernels
do j=1,order
  do i=1,order
     B(i,j) = A(j,i)
  enddo
enddo
!$acc end kernels
```

OpenMP

```
!$omp target teams distribute &
      parallel do simd &
      collapse(2)
do j=1,order
  do i=1,order
    B(i,j) = A(j,i)
  enddo
enddo
```

```
!$omp target teams loop &
      collapse(2)
do j=1,order
  do i=1,order
    B(i,j) = A(j,i)
  enddo
enddo
```

PLATFORM SPECIALIZATION

CUDA Fortran

```
BIDX = blockIdx%x-1
BIDY = blockIdx%y-1
TIDX = threadIdx%x
TIDY = threadIdx%y

x = BIDX * TILE + TIDX;
y = BIDY * TILE + TIDY;
do j = 0,TILE-1,block_rows
   SM(TIDX,TIDY+j) = A(x,y+j);
end do

call syncThreads()

x = BIDY * TILE + TIDX;
y = BIDX * TILE + TIDY;
do j = 0,TILE-1,block_rows
   B(x,y+j) = SM(TIDY+j,TIDX)
end do
```

ACCELERATION LIBRARIES

CUDA Runtime | CUBLAS | CUTENSOR | CUSOLVER | ... | NVSHMEM

HPC PROGRAMMING IN ISO FORTRAN

ISO is the place for portable concurrency and parallelism

Fortran 2018

Fortran Array Math Intrinsics

- NVFORTRAN 20.5
- Accelerated matmul, reshape, spread, …

DO CONCURRENT

- NVFORTRAN 20.11
- Auto-offload & multi-core

Co-Arrays

- Not currently available
- Accelerated co-array images

Preview support available now in NVFORTRAN

Fortran 202x

DO CONCURRENT Reductions

- NVFORTRAN 21.11
- `REDUCE` subclause added
- Support for `+`, `*`, `MIN`, `MAX`, `IAND`, `IOR`, `IEOR`.
- Support for `.AND.`, `.OR.`, `.EQV.`, `.NEQV` on `LOGICAL` values

MiniWeather

Standard Language Parallelism in Climate/Weather Applications

MiniWeather

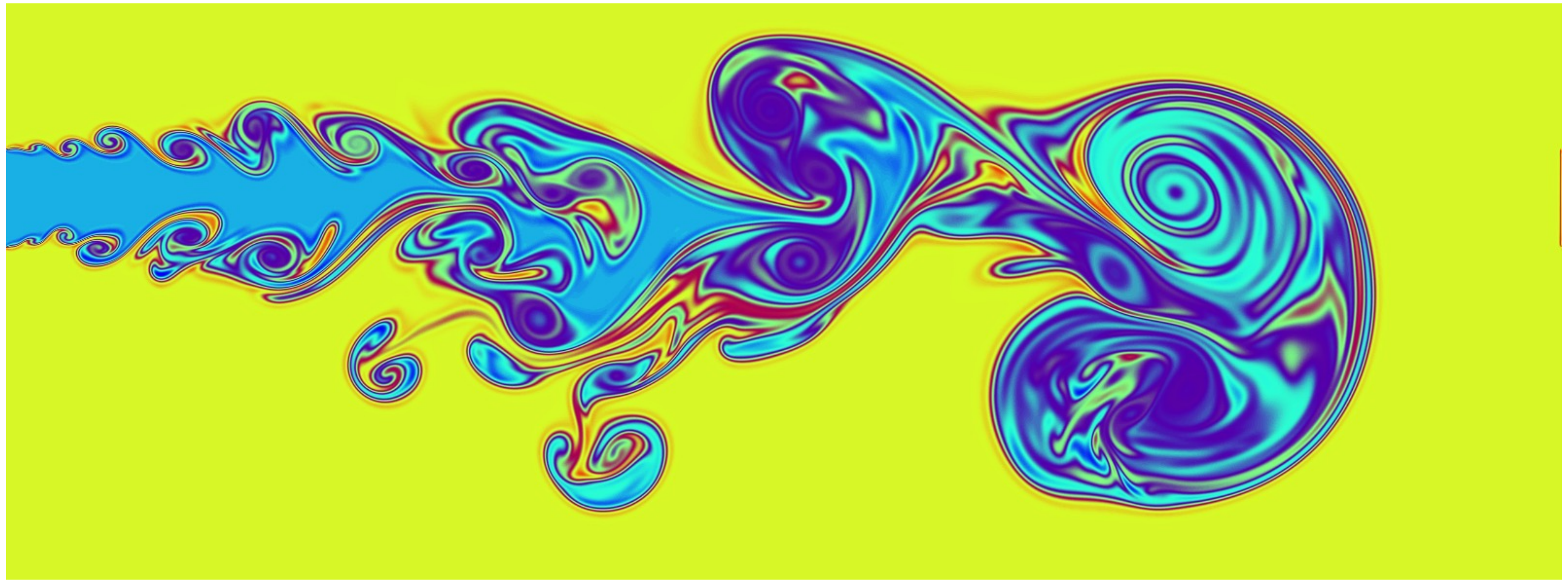
Mini-App written in C++ and Fortran that simulates weather-like fluid flows using Finite Volume and Runge-Kutta methods.

Existing parallelization in MPI, OpenMP, OpenACC, …

Included in the SPEChpc benchmark suite*

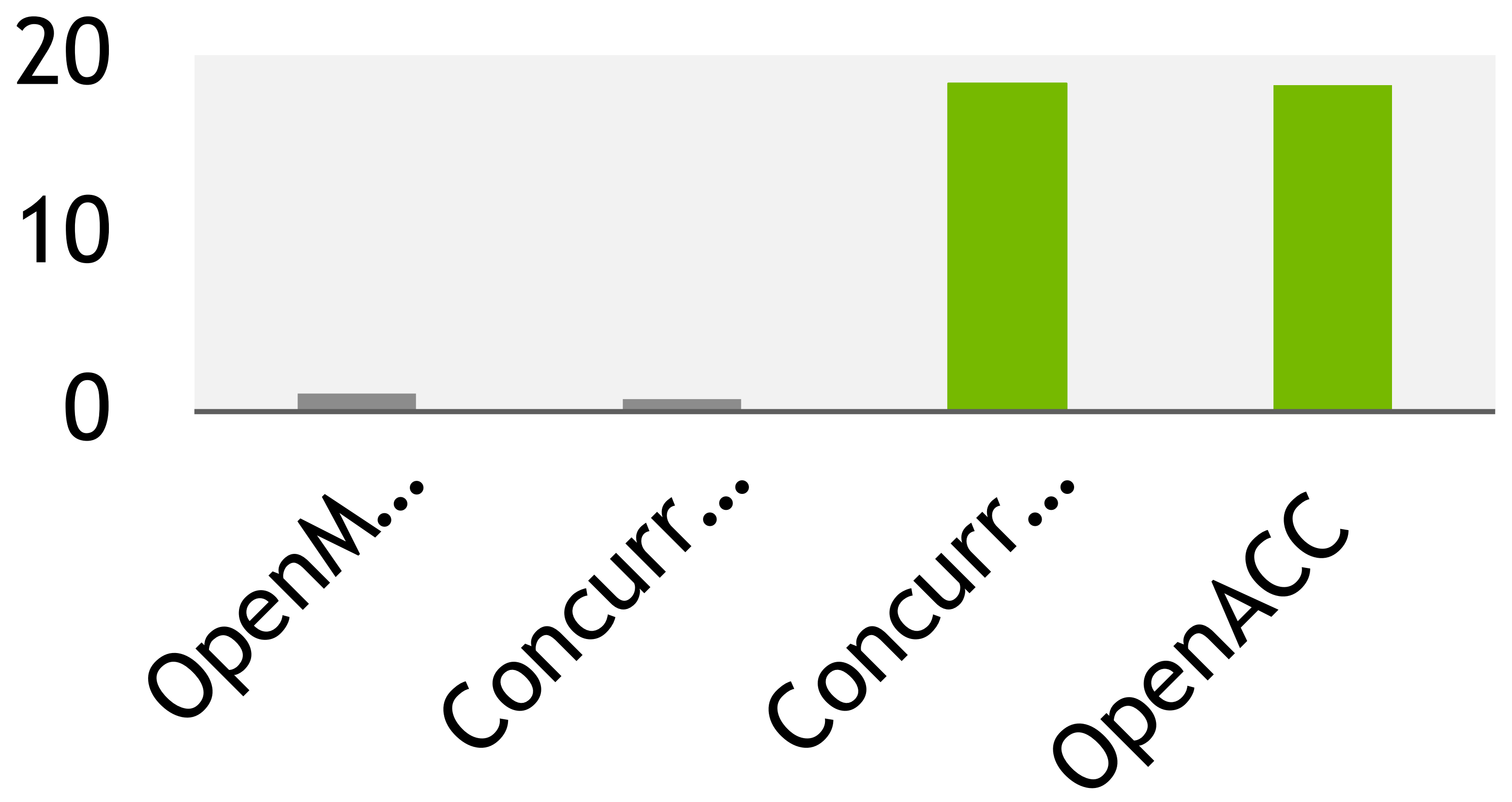
Open-source and commonly-used in training events.

https://github.com/mrnorman/miniWeather/



```
do concurrent (ll=1:NUM_VARS, k=1:nz, i=1:nx)
      local(x,z,x0,z0,xrad,zrad,amp,dist,wpert)

  if (data_spec_int == DATA_SPEC_GRAVITY_WAVES) then
    x = (i_beg-1 + i-0.5_rp) * dx
    z = (k_beg-1 + k-0.5_rp) * dz
        x0 = xlen/8
    z0 = 1000
    xrad = 500
    zrad = 500
    amp = 0.01_rp
    dist = sqrt( ((x-x0)/xrad)**2 + ((z-z0)/zrad)**2 )
         * pi / 2._rp
    if (dist <= pi / 2._rp) then
      wpert = amp * cos(dist)**2
    else
      wpert = 0._rp
    endif
    tend(i,k,ID_WMOM) = tend(i,k,ID_WMOM)
                      + wpert*hy_dens_cell(k)
  endif
  state_out(i,k,ll) = state_init(i,k,ll)
                    + dt * tend(i,k,ll)

enddo
```

*SPEChpc is a trademark of The Standard Performance Evaluation Corporation



Source: HPC SDK 22.1, AMD EPYC 7742, NVIDIA A100. MiniWeather: NX=2000, NZ=1000, SIM_TIME=5. OpenACC version uses -gpu=managed option.

POT3D: Do Concurrent + Limited OpenACC

POT3D

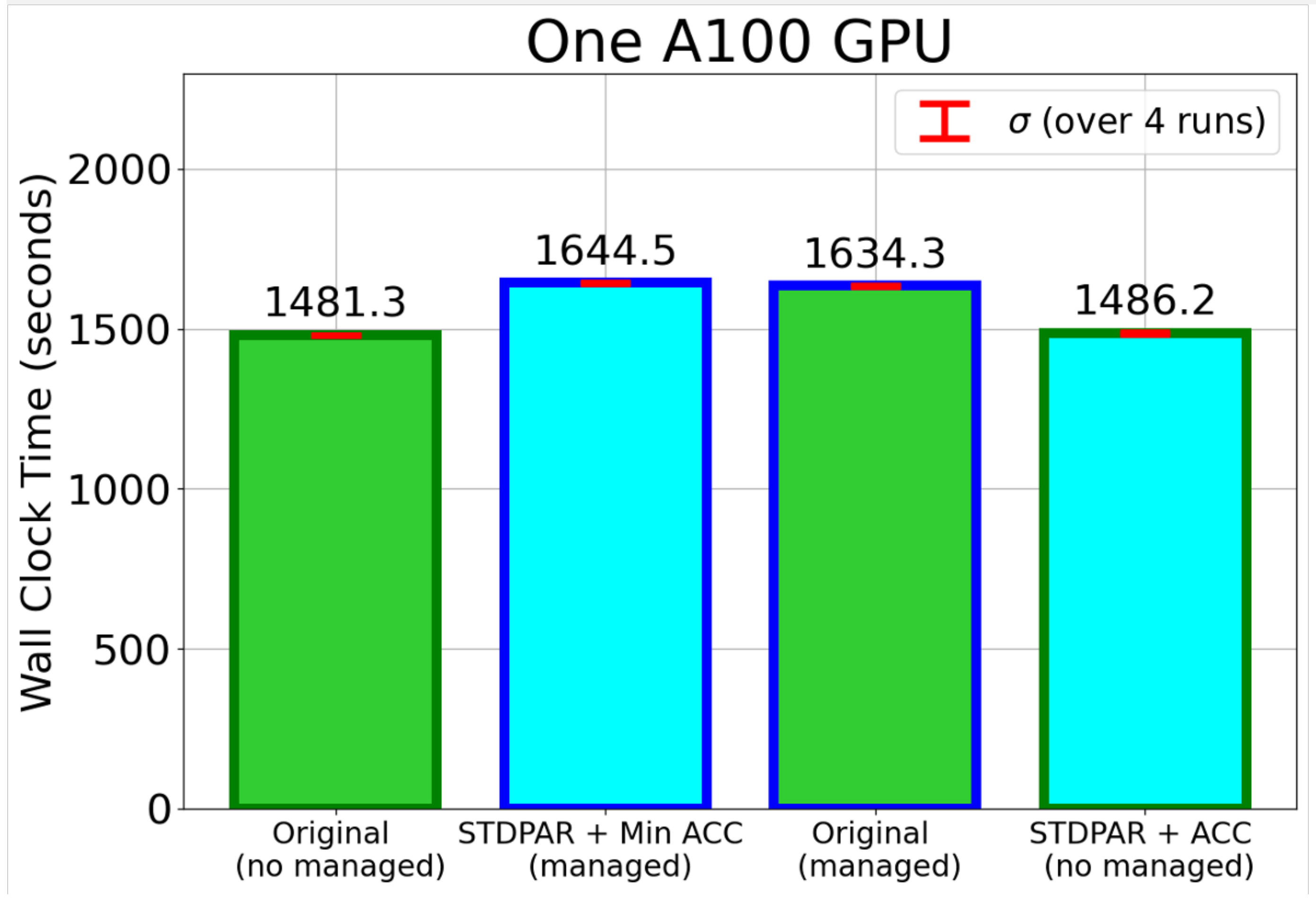
POT3D is a Fortran application for approximating solar coronal magnetic fields.

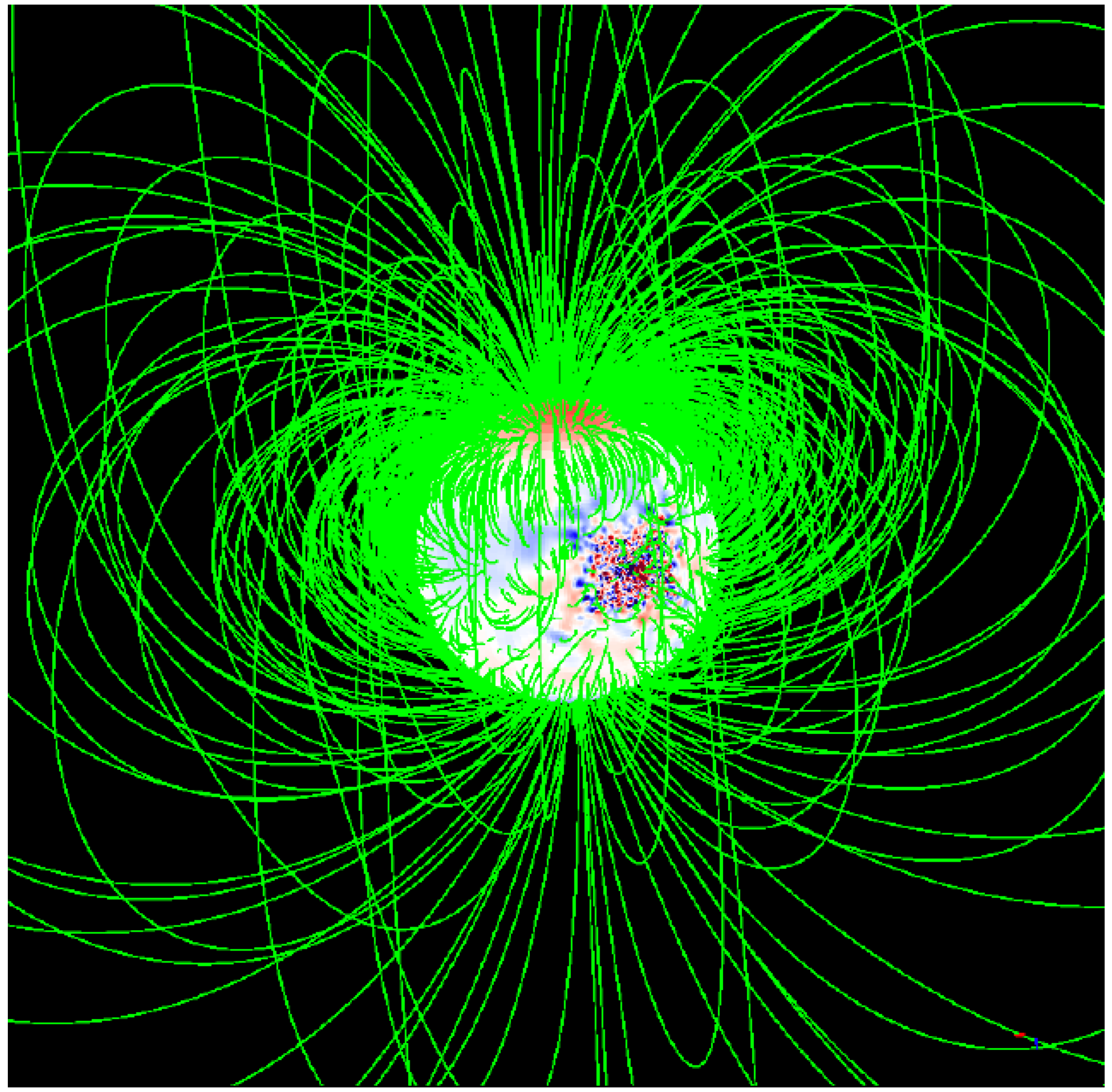
Included in the SPEChpc benchmark suite*

Existing parallelization in MPI & OpenACC

Optimized the DO CONCURRENT version by using OpenACC solely for data motion and atomics

https://github.com/predsci/POT3D





```
!$acc enter data copyin(phi,dr_i)
!$acc enter data create(br)
do concurrent (k=1:np,j=1:nt,i=1:nrm1)
  br(i,j,k)=(phi(i+1,j,k)-phi(i,j,k ))*dr_i(i)
enddo
!$acc exit data delete(phi,dr_i,br)
```

Data courtesy of Predictive Science Inc.

*SPEChpc is a trademark of The Standard Performance Evaluation Corporation

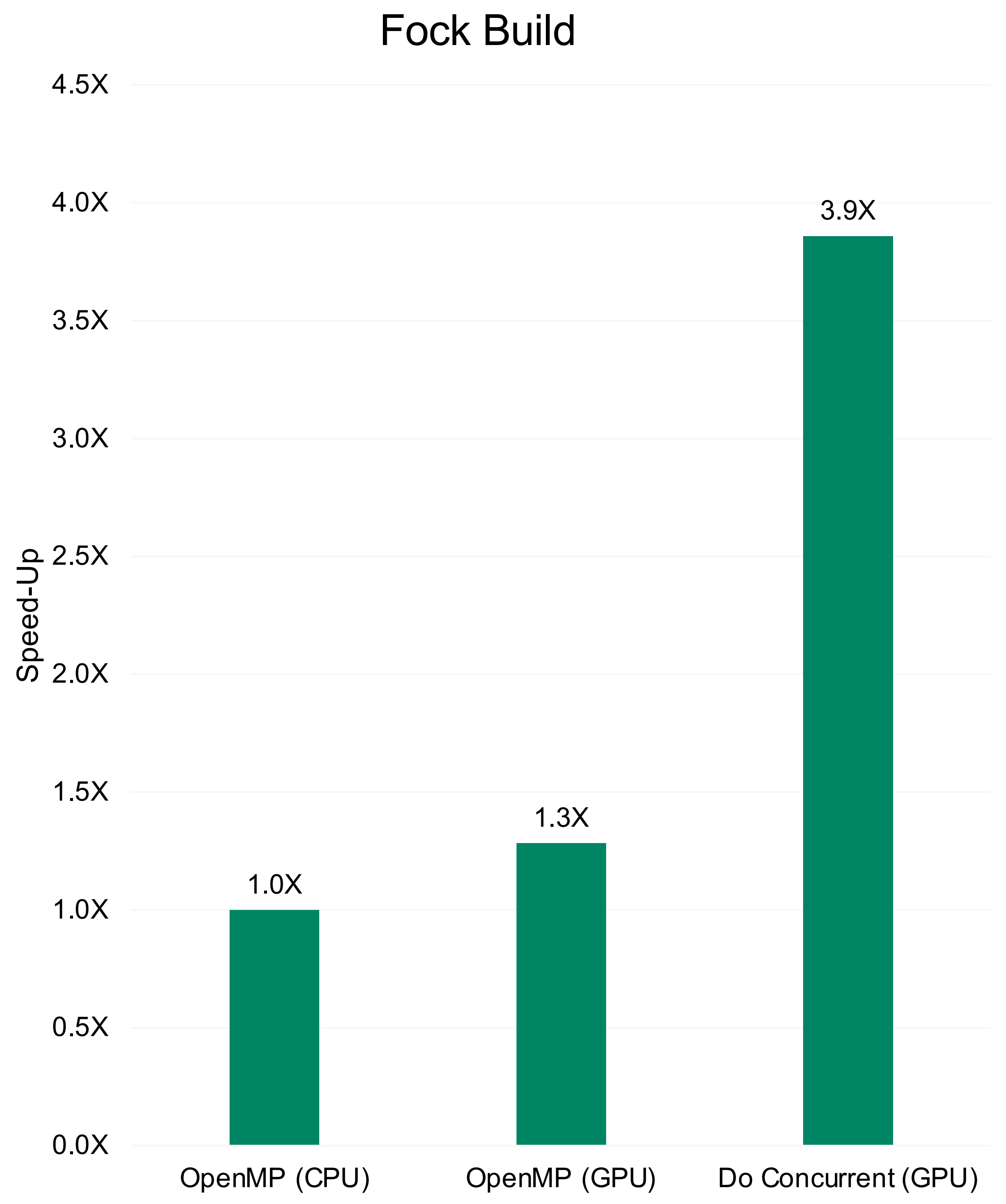
GAMESS

Computational Chemistry with Fortran Do Concurrent

- GAMESS is a popular Quantum Chemistry application.
- More than 40 years of development in Fortran and C
- MPI + OpenMP baseline code
- Hartree-Fock rewritten in Do Concurrent

```
!pre-sorting, screening

!$omp target teams distribute &
             parallel do &
!$omp shared() private()
do iquart = 1, ssdd_quarts
  !recover shell index
  ish=IDX(s_sh)
  jsh=IDX(s_sh)
  ksh=IDX(d_sh)
  lsh=IDX(d_sh)
  !compute ints
  !digest ints
enddo
```

```
!pre-sorting, screening



DO CONCURRENT(iquart=1::ssdd_quarts)&
   SHARED() LOCAL()
  !recover shell index
  ish=IDX(s_sh)
  jsh=IDX(s_sh)
  ksh=IDX(d_sh)
  lsh=IDX(d_sh)
  !compute ints
  !digest ints
enddo
```



nvfortran 22.7, NVIDIA A100 GPU, AMD “Milan” CPU

* Courtesy of Melisa Alkan, Iowa State University. Not yet published.

ACCELERATED PROGRAMMING IN ISO FORTRAN

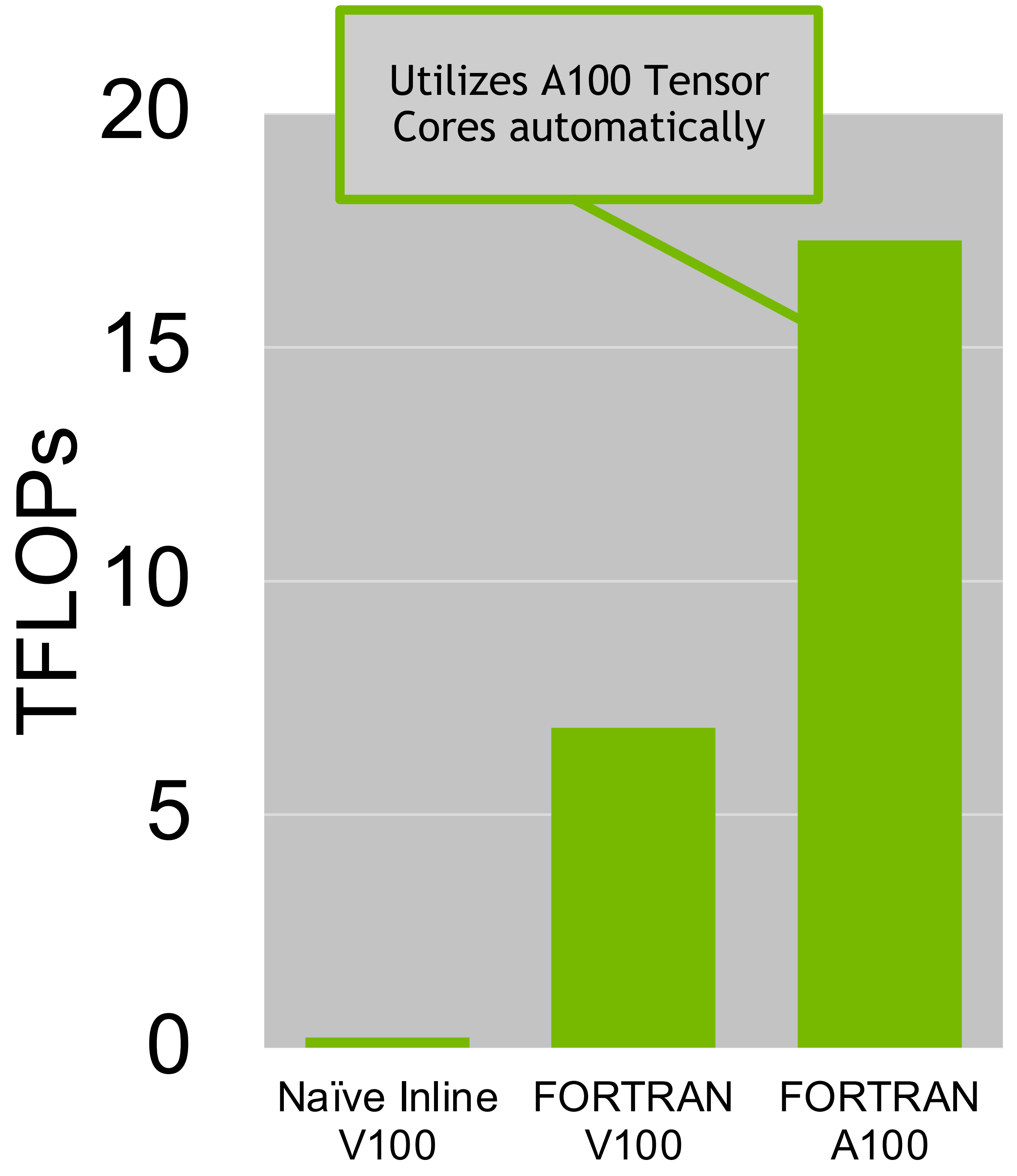
NVFORTRAN Accelerates Fortran Intrinsics with cuTENSOR Backend

```
real(8), dimension(ni,nk) :: a
real(8), dimension(nk,nj) :: b
real(8), dimension(ni,nj) :: c
...
!$acc enter data copyin(a,b,c) create(d)

do nt = 1, ntimes
  !$acc kernels
  do j = 1, nj
    do i = 1, ni
      d(i,j) = c(i,j)
      do k = 1, nk
        d(i,j) = d(i,j) + a(i,k) * b(k,j)
      end do
    end do
  end do
    !$acc end kernels
end do
!$acc exit data copyout(d)
```

Inline FP64 matrix multiply

```
real(8), dimension(ni,nk) :: a
real(8), dimension(nk,nj) :: b
real(8), dimension(ni,nj) :: c

...

do nt = 1, ntimes
  d = c + matmul(a,b)
end do
```

MATMUL FP64 matrix multiply



HPC PROGRAMMING IN ISO FORTRAN

Examples of Patterns Accelerated in NVFORTRAN

```
d = 2.5 * ceil(transpose(a)) + 3.0 * abs(transpose(b))
d = 2.5 * ceil(transpose(a)) + 3.0 * abs(b)
d = reshape(a,shape=[ni,nj,nk])
d = reshape(a,shape=[ni,nk,nj])
d = 2.5 * sqrt(reshape(a,shape=[ni,nk,nj],order=[1,3,2]))
d = alpha * conjg(reshape(a,shape=[ni,nk,nj],order=[1,3,2]))
d = reshape(a,shape=[ni,nk,nj],order=[1,3,2])
d = reshape(a,shape=[nk,ni,nj],order=[2,3,1])
d = reshape(a,shape=[ni*nj,nk])
d = reshape(a,shape=[nk,ni*nj],order=[2,1])
d = reshape(a,shape=[64,2,16,16,64],order=[5,2,3,4,1])
d = abs(reshape(a,shape=[64,2,16,16,64],order=[5,2,3,4,1]))
c = matmul(a,b)
c = matmul(transpose(a),b)
c = matmul(reshape(a,shape=[m,k],order=[2,1]),b)
c = matmul(a,transpose(b))
c = matmul(a,reshape(b,shape=[k,n],order=[2,1]))
```

```
c = matmul(transpose(a),transpose(b))
c = matmul(transpose(a),reshape(b,shape=[k,n],order=[2,1]))
d = spread(a,dim=3,ncopies=nk)
d = spread(a,dim=1,ncopies=ni)
d = spread(a,dim=2,ncopies=nx)
d = alpha * abs(spread(a,dim=2,ncopies=nx))
d = alpha * spread(a,dim=2,ncopies=nx)
d = abs(spread(a,dim=2,ncopies=nx))
d = transpose(a)
d = alpha * transpose(a)
d = alpha * ceil(transpose(a))
d = alpha * conjg(transpose(a))
c = c + matmul(a,b)
c = c - matmul(a,b)
c = c + alpha * matmul(a,b)
d = alpha * matmul(a,b) + c
d = alpha * matmul(a,b) + beta * c
```

Refactoring Fortran Loops

1. Identify an important loop nest that can be run in parallel.

```
!Compute fluxes in the x-direction for each cell
do k = 1 , nz+1
    do i = 1 , nx
      !Use fourth-order interpolation from four cell averages
      !to compute the value at the interface in question
      do ll = 1 , NUM_VARS
        do s = 1 , sten_size
          stencil(s) = state(i,k-hs-1+s,ll)
        enddo
        !Fourth-order-accurate interpolation of the state
      enddo

      !Compute density, u-wind, w-wind, potential
      !temperature, and pressure (r,u,w,t,p respectively)
      r = vals(ID_DENS) + hy_dens_int(k)
      u = vals(ID_UMOM) / r
      w = vals(ID_WMOM) / r
      t = ( vals(ID_RHOT) + hy_dens_theta_int(k) ) / r
      p = C0*(r*t)**gamma - hy_pressure_int(k)

      ...

    enddo
  enddo
```

Refactoring Fortran Loops

1. Identify an important loop nest that can be run in parallel.
2. Replace existing loops with do concurrent loops

   Note: Multiple loop iteration variables can be used in the same do concurrent loop, if they are all legal to parallelize

```fortran
!Compute fluxes in the x-direction for each cell
do concurrent (k=1:nz, i=1:nx+1)
      !Use fourth-
order interpolation from four cell averages
      !to compute the value at the interface in question
      do ll = 1 , NUM_VARS
        do s = 1 , sten_size
          stencil(s) = state(i,k-hs-1+s,ll)
        enddo
        !Fourth-order-accurate interpolation of the state
      enddo

      !Compute density, u-wind, w-wind, potential
      !temperature, and pressure (r,u,w,t,p respectively)
      r = vals(ID_DENS) + hy_dens_int(k)
      u = vals(ID_UMOM) / r
      w = vals(ID_WMOM) / r
      t = ( vals(ID_RHOT) + hy_dens_theta_int(k) ) / r
      p = C0*(r*t)**gamma - hy_pressure_int(k)

      ...

    enddo
```

Refactoring Fortran Loops

1. Identify an important loop nest that can be run in parallel.
2. Replace existing loops with do concurrent loops

   Note: Multiple loop iteration variables can be used in the same do concurrent loop, if they are all legal to parallelize

3. Add local clause for variables that must be privatized for correctness.

```fortran
!Compute fluxes in the x-direction for each cell
do concurrent (k=1:nz, i=1:nx+1)   &
  local(d3_vals,vals,stencil,ll,s,r,u,t,p,w)
   !Use fourth-order interpolation from four cell averages
   !to compute the value at the interface in question
    do ll = 1 , NUM_VARS
      do s = 1 , sten_size
        stencil(s) = state(i,k-hs-1+s,ll)
      enddo
      !Fourth-order-accurate interpolation of the state
    enddo

    !Compute density, u-wind, w-wind, potential
    !temperature, and pressure (r,u,w,t,p respectively)
    r = vals(ID_DENS) + hy_dens_int(k)
    u = vals(ID_UMOM) / r
    w = vals(ID_WMOM) / r
    t = ( vals(ID_RHOT) + hy_dens_theta_int(k) ) / r
    p = C0*(r*t)**gamma - hy_pressure_int(k)

   ...

enddo
```

Refactoring Fortran Loops

1. Identify an important loop nest that can be run in parallel.
2. Replace existing loops with do concurrent loops

   Note: Multiple loop iteration variables can be used in the same do concurrent loop, if they are all legal to parallelize

3. Add local clause for variables that must be privatized for correctness.
4. Recompile with –stdpar and test for correctness.

   Note 1: Only refactor one loop nest at a time to ensure errors aren't introduced, such as forgetting to localize a variable.
   Note 2: Performance may get worse at first due to increased memory migration.

```
!Compute fluxes in the x-direction for each cell
do concurrent (k=1:nz, i=1:nx+1)   &
  local(d3_vals,vals,stencil,ll,s,r,u,t,p,w)
   !Use fourth-order interpolation from four cell averages
   !to compute the value at the interface in question
    do ll = 1 , NUM_VARS
      do s = 1 , sten_size
        stencil(s) = state(i,k-hs-1+s,ll)
      enddo
      !Fourth-order-accurate interpolation of the state
    enddo

    !Compute density, u-wind, w-wind, potential
    !temperature, and pressure (r,u,w,t,p respectively)
    r = vals(ID_DENS) + hy_dens_int(k)
    u = vals(ID_UMOM) / r
    w = vals(ID_WMOM) / r
    t = ( vals(ID_RHOT) + hy_dens_theta_int(k) ) / r
    p = C0*(r*t)**gamma - hy_pressure_int(k)

   ...

enddo
```

Refactoring Fortran Loops

1. Identify an important loop nest that can be run in parallel.
2. Replace existing loops with do concurrent loops

   Note: Multiple loop iteration variables can be used in the same do concurrent loop, if they are all legal to parallelize

3. Add local clause for variables that must be privatized for correctness.
4. Recompile with –stdpar and test for correctness.

   Note 1: Only refactor one loop nest at a time to ensure errors aren't introduced, such as forgetting to localize a variable.

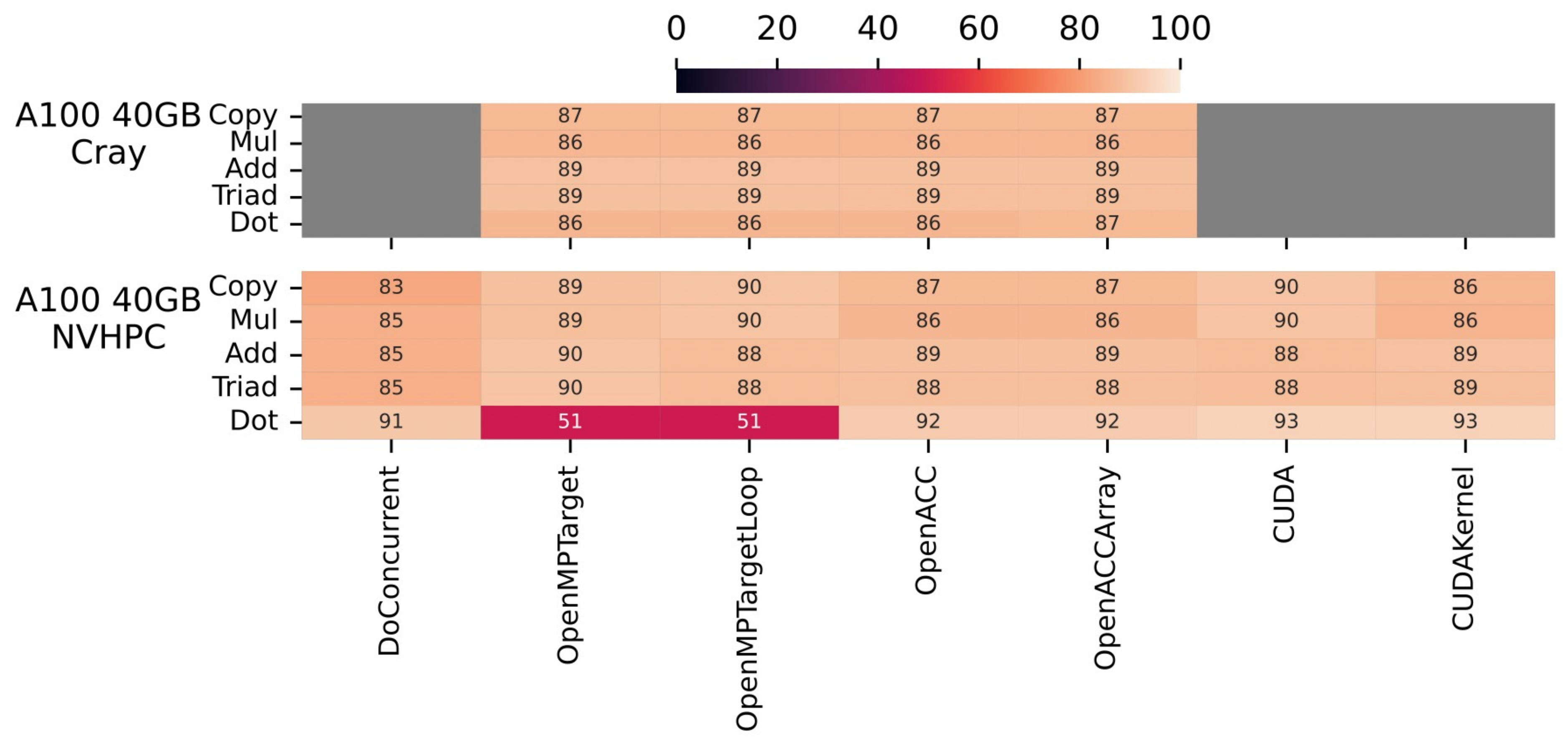
   Note 2: Performance may get worse at first due to increased memory migration.

5. Increase the number of concurrent loops to run more work in parallel and reduce memory migration on GPU.

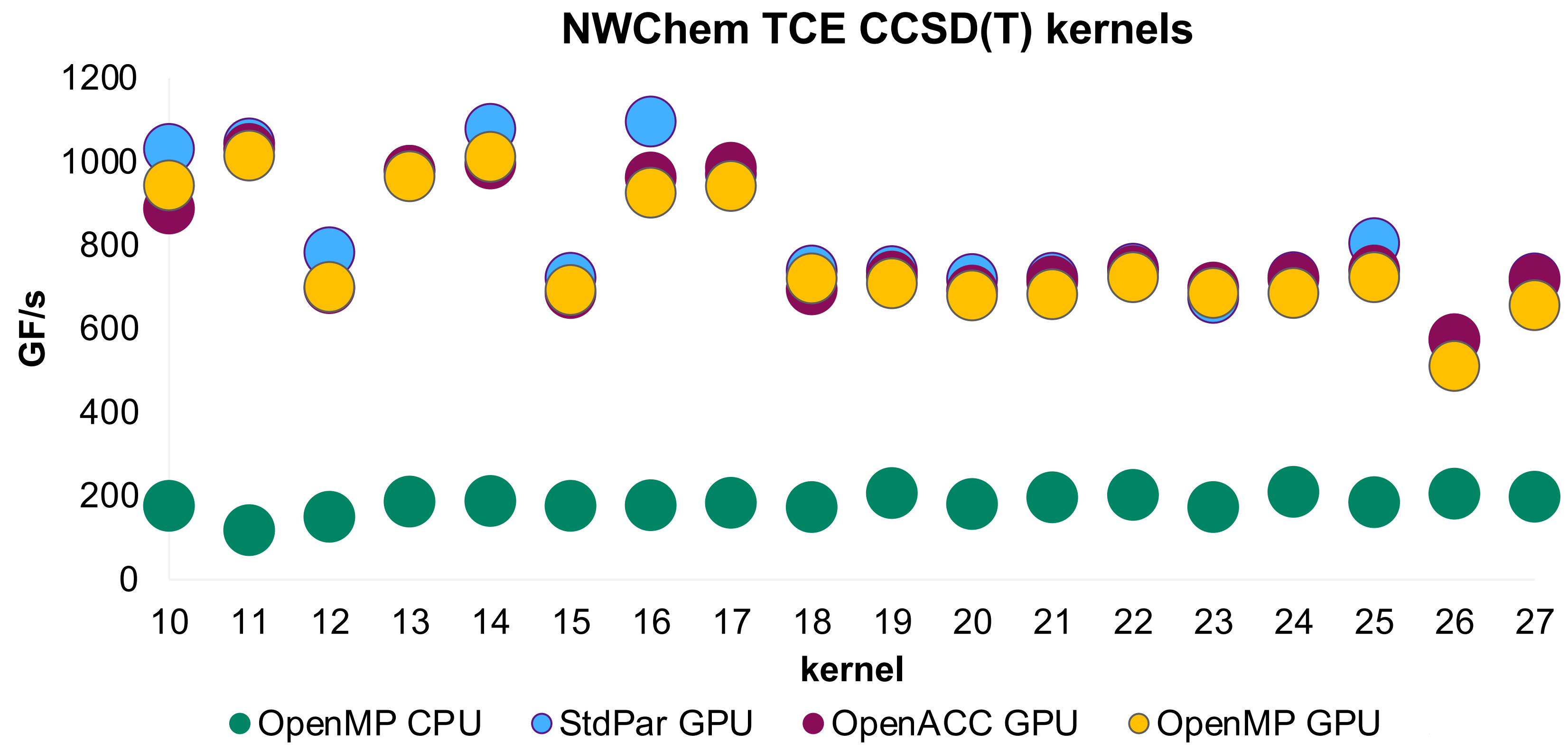
```
!Compute fluxes in the x-direction for each cell
do concurrent (k=1:nz, i=1:nx+1)   &
  local(d3_vals,vals,stencil,ll,s,r,u,t,p,w)
    !Use fourth-order interpolation from four cell averages
   !to compute the value at the interface in question
    do ll = 1 , NUM_VARS
      do s = 1 , sten_size
        stencil(s) = state(i,k-hs-1+s,ll)
      enddo
      !Fourth-order-accurate interpolation of the state
    enddo

    !Compute density, u-wind, w-wind, potential
   !temperature, and pressure (r,u,w,t,p respectively)
    r = vals(ID_DENS) + hy_dens_int(k)
    u = vals(ID_UMOM) / r
    w = vals(ID_WMOM) / r
    t = ( vals(ID_RHOT) + hy_dens_theta_int(k) ) / r
    p = C0*(r*t)**gamma - hy_pressure_int(k)

   ...

enddo

do concurrent (k=1:nz,i=1:nx) reduce(+:mass,te)
    mass = mass + r             *dx*dz ! Accumulate domain mass
    te   = te   + (ke + r*cv*t)*dx*dz
enddo
```

Other Examples

- Bristol BabelStream
  - Modern Fortran implementation of BabelStream.
  - Preprint available upon request.
  - https://github.com/jeffhammond/BabelStream/tree/fortran-ports
- NWChem TCE CCSD(T) kernels
  - 6D = 4D x 4D tensor contractions from quantum chemistry with different memory access patterns.
  - https://github.com/jeffhammond/nwchem-tce-triples-kernels
- Parallel Research Kernels (PRK)
  - Shows simple patterns implemented in 50+ different programming languages x models, including Fortran StdPar, OpenACC, OpenMP, etc.
  - https://github.com/ParRes/Kernels/
- GPU Gearbox
  - Based on PRK codes
  - https://www.nvidia.com/en-us/on-demand/session/gtcspring22-s41620/



		DoConcurrent	OpenMPTarget	OpenMPTargetLoop	OpenACC	OpenACCArray	CUDA	CUDAKernel
A100 40GB Cray	Copy		87	87	87	87		
	Mul		86	86	86	86		
	Add		89	89	89	89		
	Triad		89	89	89	89		
	Dot		86	86	86	87		
A100 40GB NVHPC	Copy	83	89	90	87	87	90	86
	Mul	85	89	90	86	86	90	86
	Add	85	90	88	89	89	88	89
	Triad	85	90	88	88	88	88	89
	Dot	91	51	51	92	92	93	93



Fortran Future Features?

Parallelism in Fortran 2018

```fortran
! fine-grain parallelism

! explicit
do concurrent (i=1:n)
    Z(i) = X(i) + Y(i)
end do

! implicit
MATMUL
TRANSPOSE
RESHAPE
...
```

```fortran
! coarse-grain parallelism

np = num_images()
n_local = n / np

! X, Y, Z are coarrays

do i=1,n_local
    Z(i) = X(i) + Y(i)
end do
sync all
```

Do Concurrent Locality Specifiers and Atomics (2023)

```
! Scalar reduction – probably implemented with privatization
do concurrent (i=1:n) reduce(Z:+)
    Z = X(i) / Y(i)
end do

! Array reduction – probably implemented with atomics
do concurrent (i=1:n) reduce(Z:+)
    Z(i) = Z(i) + decision(i)
end do
```

What if we need to use the result?

```
! Inserting into an array
offset = 1
do concurrent (i=1:n) shared(X,offset) local(s,stuff)
    stuff = ..
    s = size(stuff)
    !$omp/acc atomic capture
    j = offset
    offset = offset + size
    !$omp/acc end atomic capture
    X(j:j+size) = stuff
end do
```

What if we need to use the result?

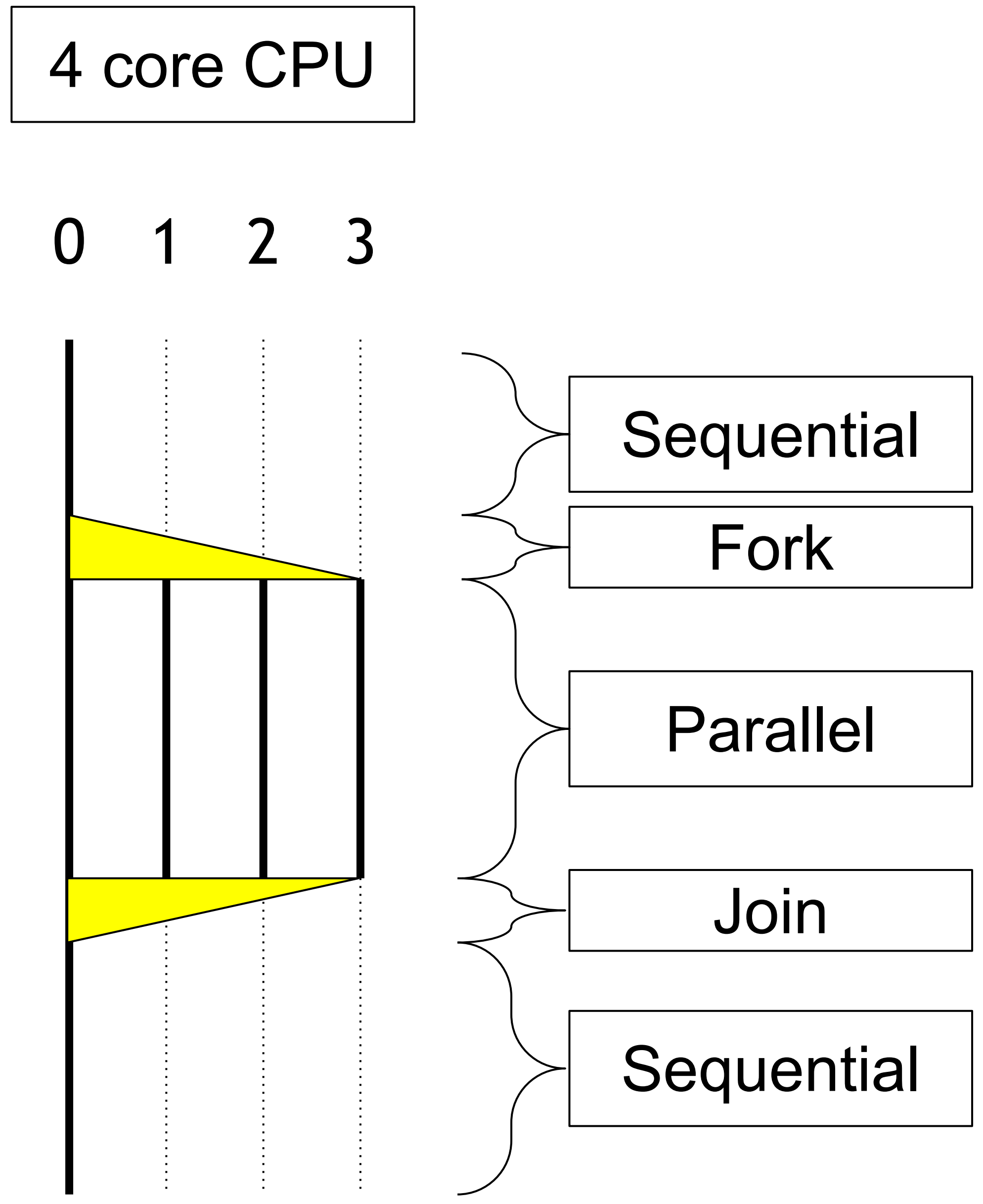
```
! Inserting into an array
offset = 1
do concurrent (i=1:n) shared(X,offset) local(s,stuff)
    stuff = ..
    s = size(stuff)
    call atomic_fetch_add(offset, size, j) ! coarrays
    X(j:j+size) = stuff
end do
```

What if we need to use the result?

```
! Inserting into an array
offset = 1
do concurrent (i=1:n) shared(X) local(s,stuff) fetched(offset:+)
    stuff = ..
    s = size(stuff)
    j = offset = offset + s ! Syntax to be determined later
    X(j:j+size) = stuff
end do
```

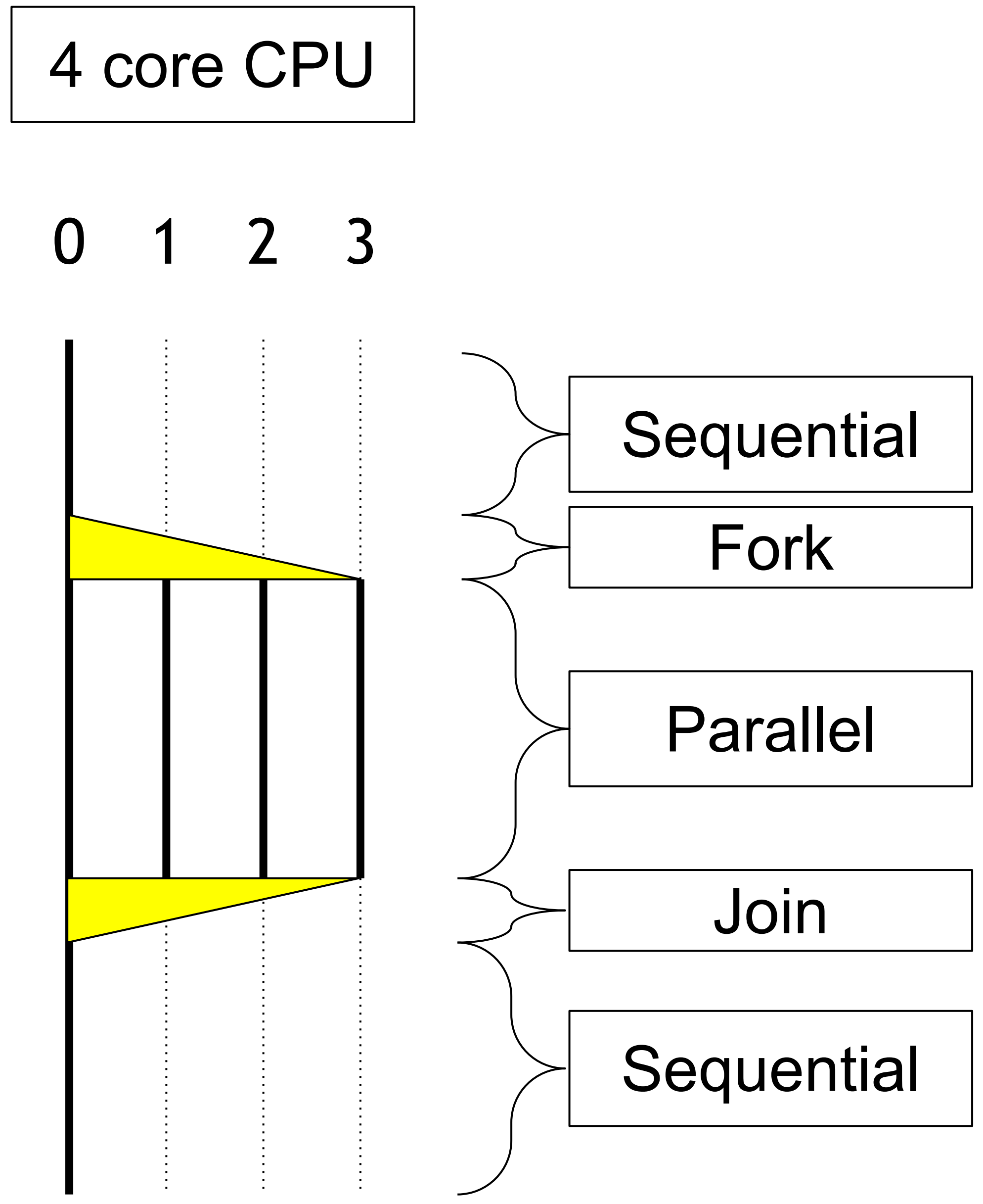
Asynchrony

Motivation for Asynchrony 1



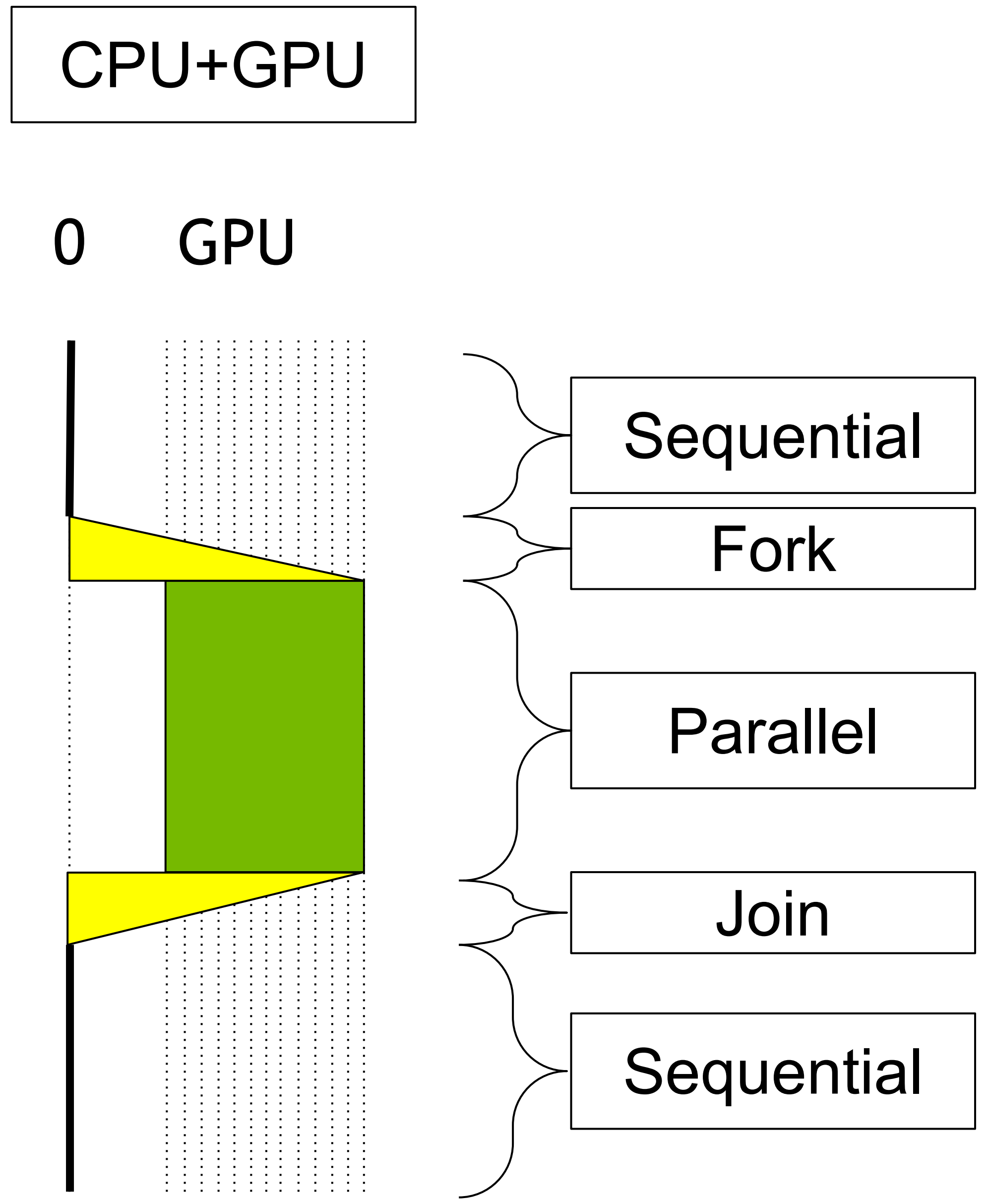
```
! sequential
call my_input(X,Y)

! parallel
do concurrent (i=1:n)
    Z(i) = X(i) + Y(i)
end do

! sequential
call my_output(Z)
```

Motivation for Asynchrony 1



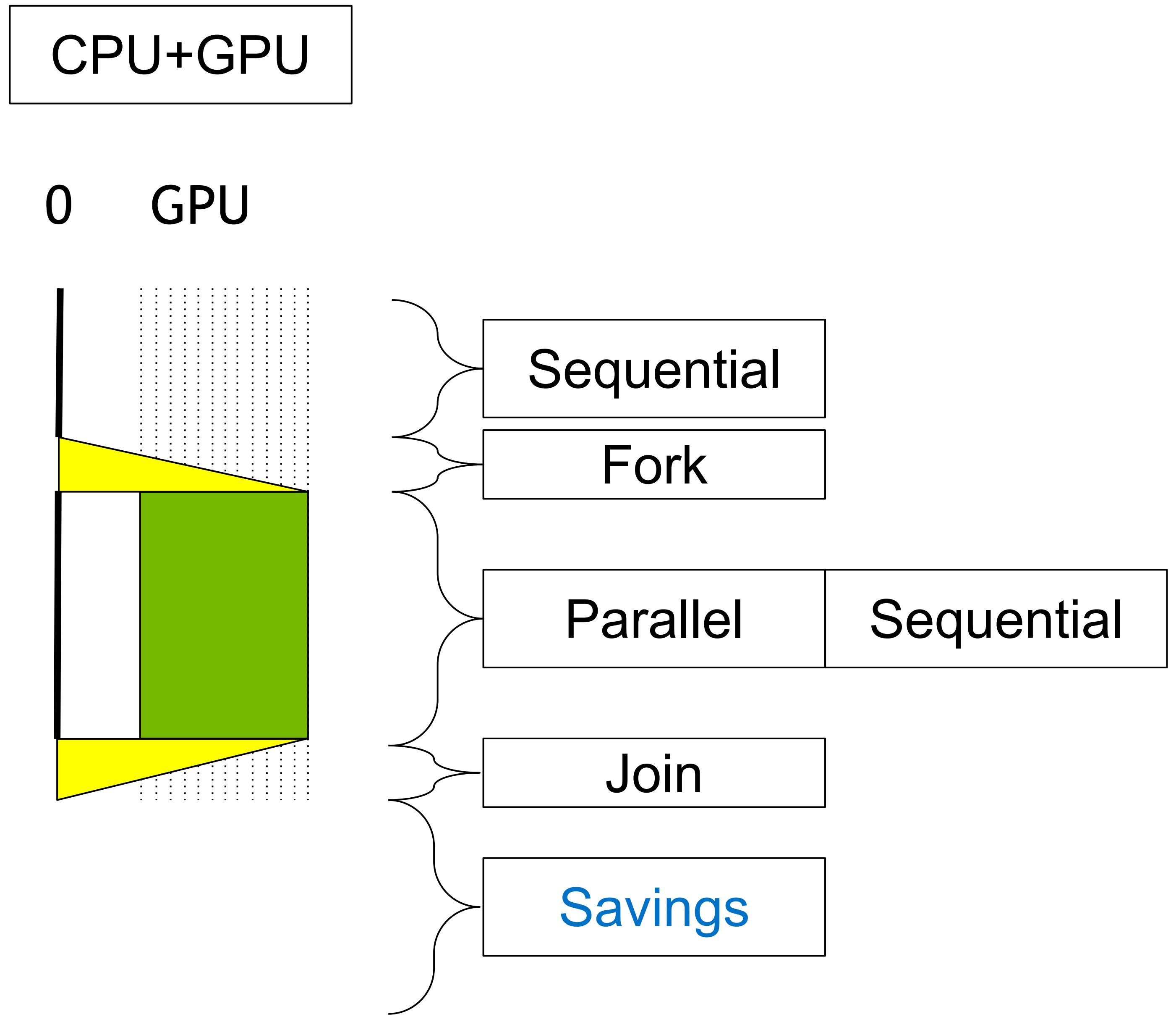
```
! sequential
call my_input(X,Y)

! parallel
do concurrent (i=1:n)
    Z(i) = X(i) + Y(i)
end do

! sequential
call my_unrelated(A)
```

Motivation for Asynchrony 1



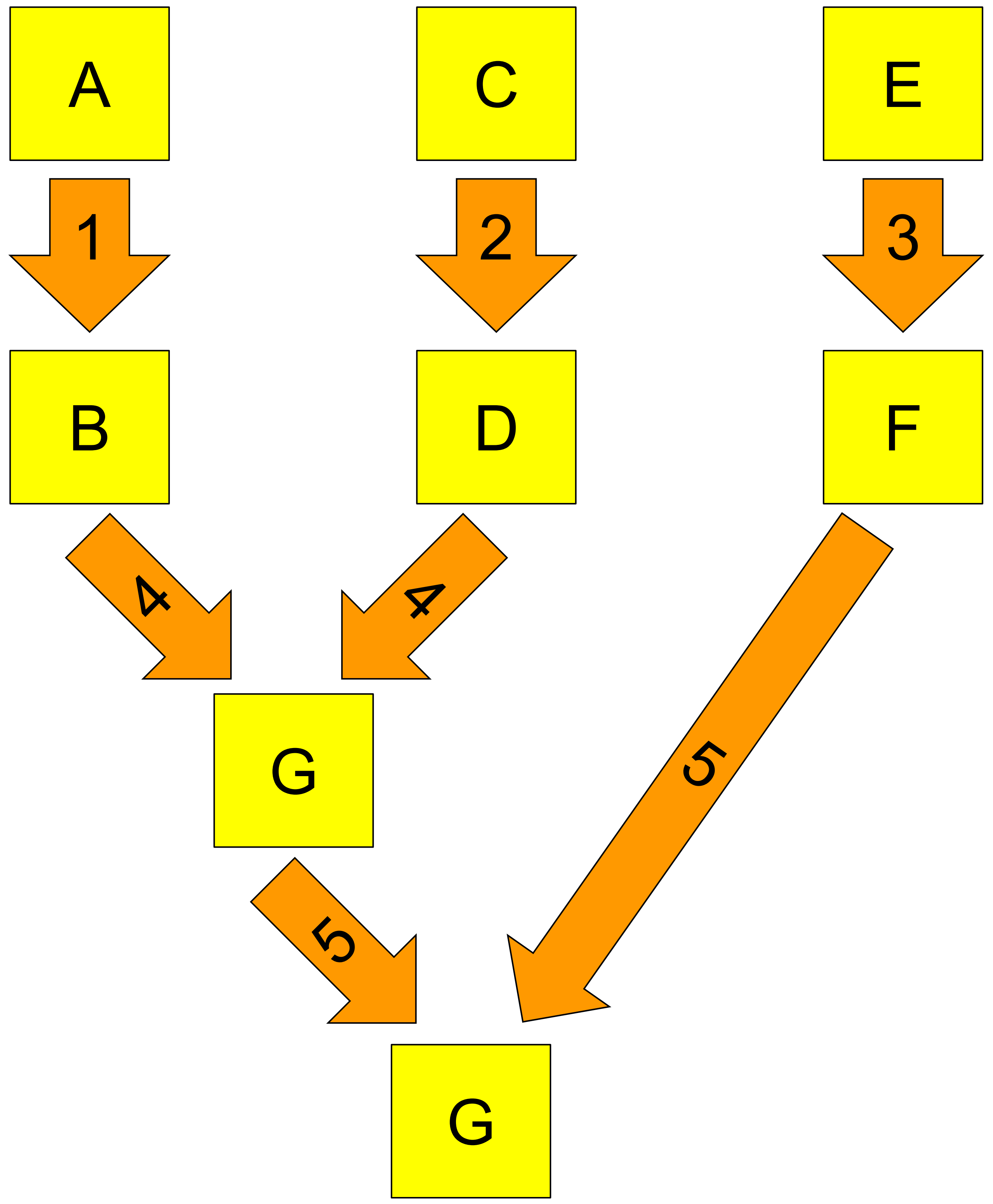
```
! sequential on CPU
call my_input(X,Y)

! parallel on GPU
do concurrent (i=1:n)
    Z(i) = X(i) + Y(i)
end do

! sequential on CPU
call my_unrelated(A)
```

Motivation for Asynchrony 1



```
! sequential on CPU
call my_input(X,Y)

! parallel on GPU w/ async
do concurrent (i=1:n)
    Z(i) = X(i) + Y(i)
end do

! sequential on CPU w/ async
call my_unrelated(A)
```

Motivation for Asynchrony 2 (synthetic)

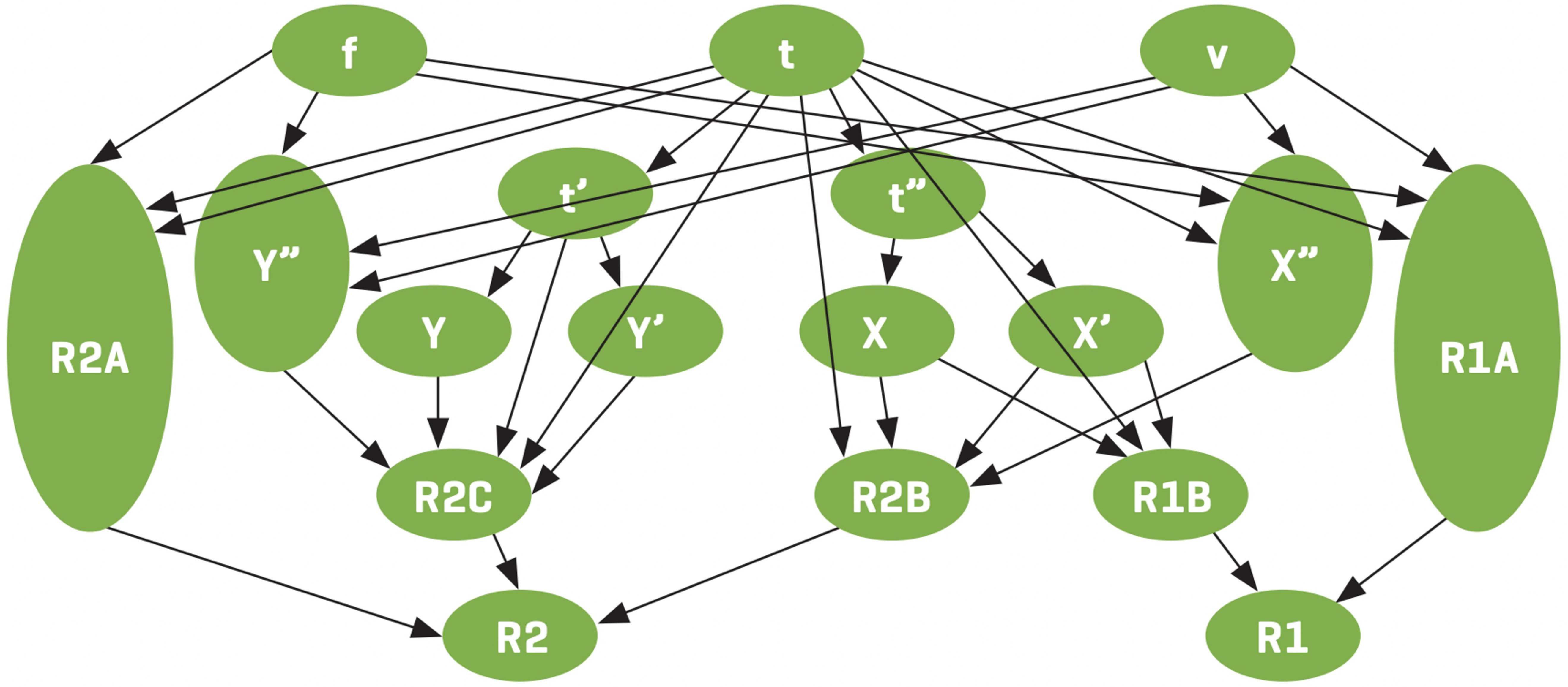


```
call sub1(IN=A,OUT=B)
call sub2(IN=C,OUT=D)
call sub3(IN=E,OUT=F)
call sub4(IN=B,IN=D,OUT=G)
call sub5(IN=F,IN=G,OUT=H)
! 5 steps require only 3 phases
```

Fortran compilers may be able to prove these procedures are independent but it is often impossible to prove that executing them in parallel is *profitable*.

Motivation for Asynchrony 2 (realistic)

Figure 3. The directed acyclic graph (DAG) representing data dependencies within one formulation of the CCSD method. The vertex labels are not important.



https://dl.acm.org/doi/10.1145/2425676.2425687
https://pubs.acs.org/doi/abs/10.1021/ct100584w

Prior Art in OpenMP and OpenACC

Both of the popular directive-based models for parallel computing support asynchronous tasks in a range of operations.

OpenACC supports async and wait, with an implicit/default queue (stream) as well as explicit/numbered queues, and the ability to create dependency chains between operations, similar to CUDA streams.

OpenMP supports tasks with dependencies (and without). The syntax for dependencies is finer granularity - based on data references rather than queues - and the implementation may end up using a global queue as a result.

There are merits to both approaches, so the Fortran community will have to think about what form should be standardized.

These are examples of different things. Please don't try to compare them.

Prior Art in OpenMP and OpenACC

```
do i=1,n
  !$acc parallel loop async(i)
  do j=1,m
    ...
  enddo
enddo
do i=1,n
  !$acc parallel loop async(i)
  do j=1,m
    ...
  enddo
enddo
!$acc wait
```

```
!$omp parallel
!$omp master
do j=1,n
  do i=1,m
    !$omp task
    !$omp& depend(in:grid(i-1)) &
    !$omp& depend(out:grid(j))
    ...
    !$omp end task
  enddo
enddo
```

e.g. https://github.com/ParRes/Kernels/blob/default/FORTRAN/p2p-tasks-openmp.F90

Example

```
program main
  use numerot
  real :: A(100), B(100), C(100)
  real :: RA, RB, RC
  A = 1;  B = 1;  C = 1
  RA = yksi(A)
  RB = kaksi(B)
  RC = kolme(C)
  print*,RA+RB+RC
 end program main
```

https://github.com/jeffhammond/blog/tree/main/CODE

```
module numerot
  contains
    pure real function yksi(X)
      real, intent(in) :: X(100)
      !real, intent(out) :: R
      yksi = norm2(X)
    end function yksi
    pure real function kaksi(X)
      real, intent(in) :: X(100)
      kaksi = 2*norm2(X)
    end function kaksi
    pure real function kolme(X)
      real, intent(in) :: X(100)
      kolme = 3*norm2(X)
    end function kolme
 end module numerot
```

A coarray implementation?

```
program main
  use numerot
  real :: A(100) ! each image has one
  real :: R
  A = 1
  if (num_images().ne.3) STOP
  if (this_image().eq.1) R = yksi(A)
  if (this_image().eq.2) R = kaksi(A)
  if (this_image().eq.3) R = kolme(A)
  sync all
  call co_sum(R)
  if (this_image().eq.1) print*,R
 end program main
```

Coarrays are designed to support distributed memory, hence are based on image-private data.

There is limited opportunity for shared-memory optimizations in such codes, as direct inter-image copies will be required.

One of the common motivations for task-based models is dynamic load-balancing, but coarrays provide no mechanism for doing this, so users will have to write their own, which they always do poorly.

A do concurrent implementation?

```
program main
  use numerot
  real :: A(100), B(100), C(100)
  real :: RA, RB, RC
  integer :: k
  A = 1;  B = 1;  C = 1
  do concurrent (k=1:3) ! reduction, someday
    if (k.eq.1) RA = yksi(A)
    if (k.eq.2) RB = kaksi(B)
    if (k.eq.3) RC = kolme(C)
  end do
  print*,RA+RB+RC
 end program main
```

This implementation only supports independent tasks, and is likely completely useless when the implementation uses SIMD lanes or GPU threads for DO CONCURRENT (DC).

As with coarrays, the if (...eq...) is not scalable to more general examples. Do we want arrays of functions?

Both the coarray and DC are also *tedious and error prone*, which is a good justification for adding new language features.

What might Fortran tasks look like?

```
do i=1,n
  task block async(i)
    do j=1,m
      ...
    enddo
  end task block
enddo
task sync all
```

The block mechanism is used for scoping.

Prepending task implies this block scope is also a task, which can execute asynchronously until synchronized.

Important questions:

- Is everything (e.g. I/O) allowed to be in a task?
- How do tasks interact with shared state?

What might Fortran tasks look like?

```
do i=1,n
  task block async(i)
    type :: private
    do j=1,m
      ...
    enddo
  end task block
enddo
task sync all
```

The block mechanism is used for scoping.

Prepending task implies this block scope is also a task.

It is essential to be able to have task-private state, which is already covered by the block feature.

What might Fortran tasks look like?

```
real :: x
do i=1,n
  task block async(i) shared(x)
    type :: private
    do j=1,m
      ...
    enddo
  end task block
enddo
task sync all
```

We also want to be able to describe the intent of data outside of the task, so we could reuse locality specifiers from DO CONCURRENT.

Locality specifiers already match OpenMP syntax, and a related feature in Fortran, so they are likely to be intuitive to Fortran programmers.

Task reductions are supported by OpenMP now, but the concept is tricky.

Atomics would be nice but that's a big bag of worms.

What might Fortran tasks look like?

```
real :: x
do i=1,n
  task call foo(i,x)
enddo
task wait

do i=1,n
  task call foo(i,x) async(mod(i,2))
enddo
task sync 0
...
task sync 1
```

Calling subroutines as tasks is useful, but they should be **pure** in order to have reasonable behavior.

The right syntax for this is not obvious, but we can solve that later.

Summary

Fortran has two great ways to write parallel code, but needs a third.

Shared-memory task parallelism is implemented in OpenMP, OpenACC, and in models associated with languages that aren’t Fortran.

Task parallelism allows users to solve new types of problems and make better use of existing parallel features, especially DO CONCURRENT (e.g. when executing on GPUs).

Fortran tasks make new things possible and obviate the need for tedious and error prone implementations. They also reduce the need for non-standard extensions like OpenMP and OpenACC.

Please do not let whatever you don’t like about my syntax to get in the way 🙂

J3/WG5 papers targeting Fortran 2026

https://j3-fortran.org/doc/year/22/22-170.pdf Requirement: fetching atomic operations in DO CONCURRENT

https://j3-fortran.org/doc/year/22/22-169.pdf Fortran asynchronous tasks