PSyclone in LFRic

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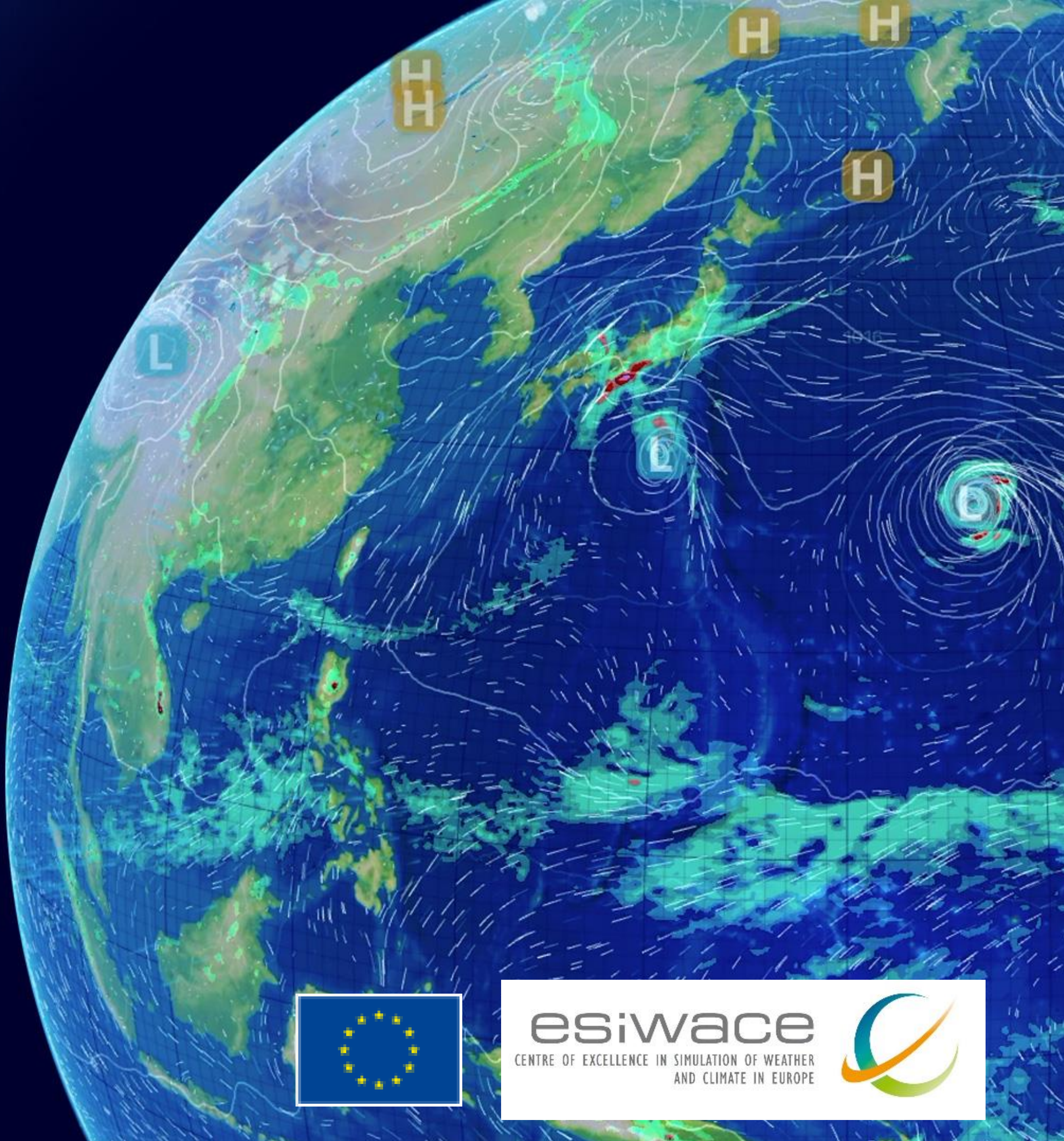
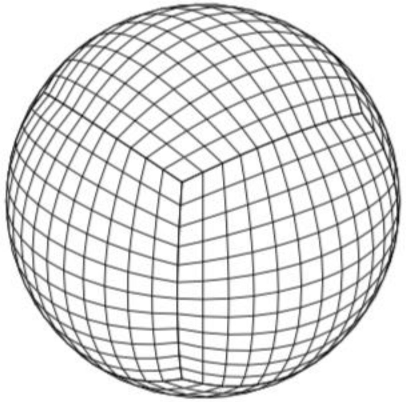
ESiWACE2 2nd Virtual Workshop on Emerging Technologies for Weather and Climate Modelling, 07 October 2020





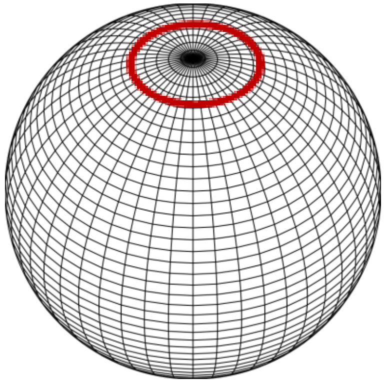
LFRic (*after **L**ewis **Fr**y **Ric**hardson*) is the new weather and climate modelling system being developed by the UK Met Office to replace the existing Unified Model in preparation for exascale computing in the 2020s

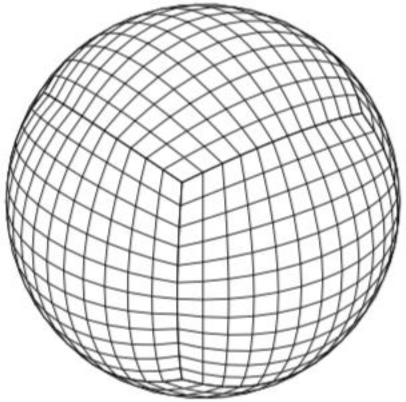
- Uses the **GungHo dynamical core**
- Runs on a **semi-structured cubed-sphere mesh**

PSyclone is a domain-specific compiler and source-to-source translator developed for use in finite element, finite volume and finite difference codes

- Uses the **information** from a supported **API**
- **Generates code** exploiting different **parallel programming models**

UM to LFRic: Optimisations





Unified Model (UM) & ENDGame dynamical core

- Fully structured Lat-Lon mesh
- Staggered Finite Differences (FDM)
- ***Hard-coded optimisations***

LFRic system & GungHo dynamical core

- Horizontally unstructured, vertically structured quasi-uniform mesh
- Mixed Finite Elements (FEM)
- ***Generated optimisations***

PSyclone

PSyclone 2.2.0
BSD 3-clause
https://github.com/stfc/PSyclone
https://psyclone.readthedocs.io
```
> pip install psyclone
```

- A **domain-specific compiler** for embedded DSL(s)
  - Configurable: FD/FV NEMO, GOcean, FE LFRic
  - Currently Fortran -> Fortran/OpenCL
  - Supports distributed- and shared-memory parallelism
  - Supports **code generation** and **code transformation**
- A tool for use by HPC experts
  - Hard to beat a human (debatable)
  - Work round limitations/bugs
  - Optimisations encoded as a 'recipe' rather than baked into the scientific source code
  - Different recipes for different computer architectures (CPU, GPU)
  - Enables scriptable, whole-code optimisation

What PSyclone does in LFRic (and how)

Developing PSyclone features for LFRic

Building LFRic with PSyclone

Management of PSyclone in Met Office

Met Office

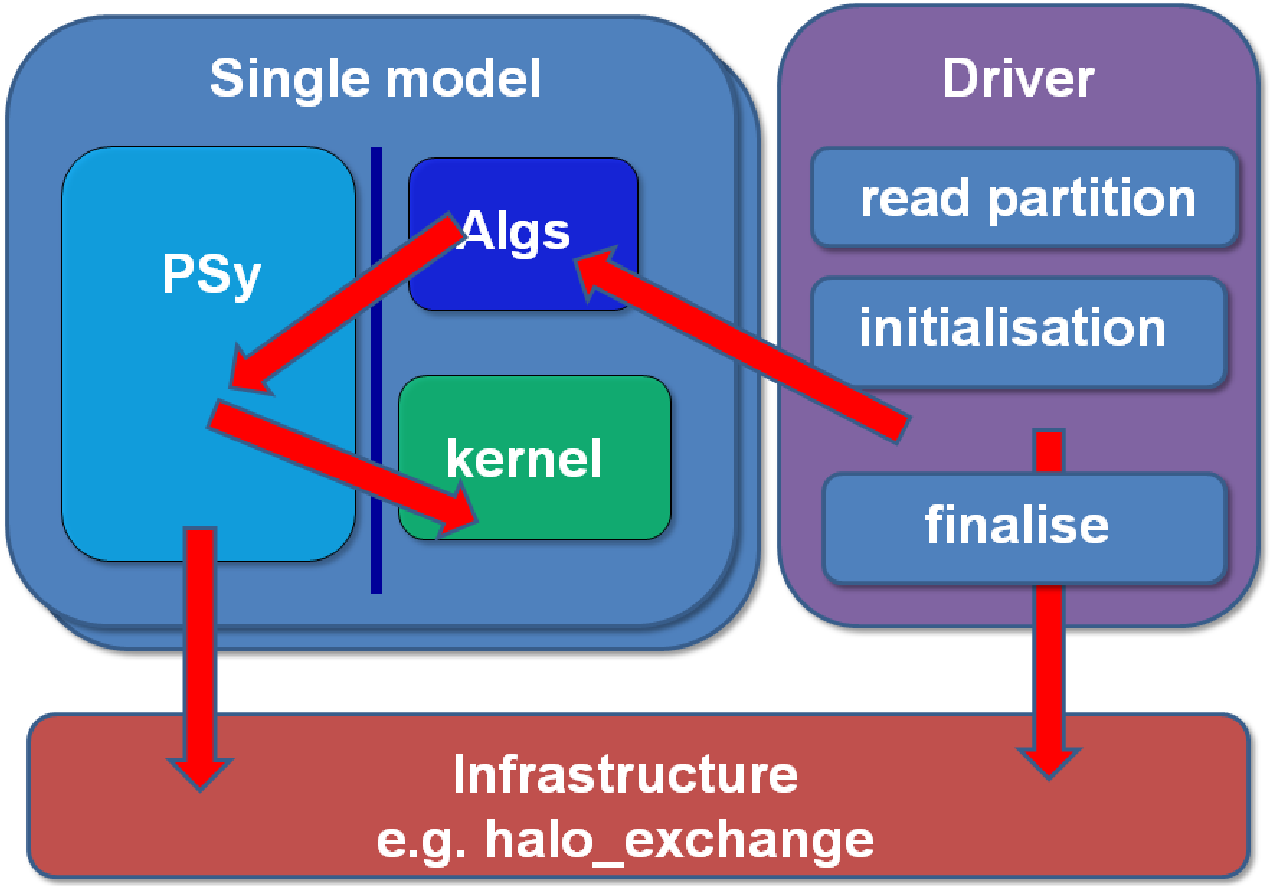
LFRic Separation of Concerns: Science and code optimisation

PSyKAl

- **Algorithms:** Natural Science, operations on whole **data structures** (e.g. fields)
- **Parallel-Systems:** Computational Science, applies optimisations (and unpacks data) – ***generated code***

PSyclone

- **Kernels:** Natural Science, operations on (columns of) data points



DSL embedded in Fortran: Algorithm code (operations on whole fields; *written by scientists, Fortran 2008)*

```
module rhs_rho_alg_mod
…
 subroutine on_the_fly_rhs_alg(rhs, state, ref_state, … )
   use rrho_kernel_mod,          only: rrho_kernel_type
   use matrix_vector_kernel_mod, only: matrix_vector_kernel_type
   implicit none
   type(field_type), target, intent(in) :: state(bundle_size)
   type(field_type), target, intent(inout) :: rhs(bundle_size)
   …
   call invoke( name = "compute_rhs_rho",                              &
                rtheta_kernel_type( rhs_tmp(igh_t), rho_ref, u, u_ref ), &
                matrix_vector_kernel_type( rhs(igh_t), theta, mm_rho ),  &
                inc_X_plus_bY( rhs(igh_t), tau_t_dt, rhs_tmp(igh_t) ) )
  …
  end subroutine on_the_fly_rhs_alg
end module rhs_rho_alg_mod
```

***Global fields:** data layout hidden*

Kernel (LFRic)

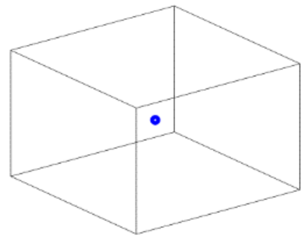
- PSy-layer loop over **columns of cells**

Built-in (PSyclone)

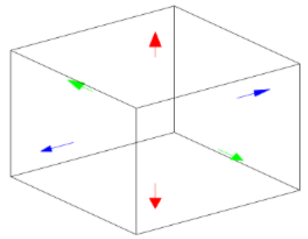
- PSy-layer loop over all field **DoFs** (arithmetic operations)

DSL embedded in Fortran: Kernel metadata (how to **access** and **update data**; *kernel code written by scientists, Fortran 90*)

```
module rrho_kernel_mod
…
  type, public, extends(kernel_type) :: rrho_kernel_type
    private
    type(arg_type) :: meta_args(4) = (/                            &
         arg_type(GH_FIELD, GH_REAL, GH_READWRITE, W3),            &
         arg_type(GH_FIELD, GH_REAL, GH_READ,                      &
                                     ANY_DISCONTINUOUS_SPACE_1),   &
         arg_type(GH_FIELD, GH_REAL, GH_INC,       W2),            &
         arg_type(GH_FIELD, GH_REAL, GH_READ,      ANY_SPACE_1),   &
         /)
    integer :: operates_on = CELL_COLUMN
  contains
    procedure, nopass :: rrho_code
  end type
…
```



Discontinuous *function spaces: no shared DoFs*



Continuous *function spaces: shared DoFs (**colour** OpenMP loops)*

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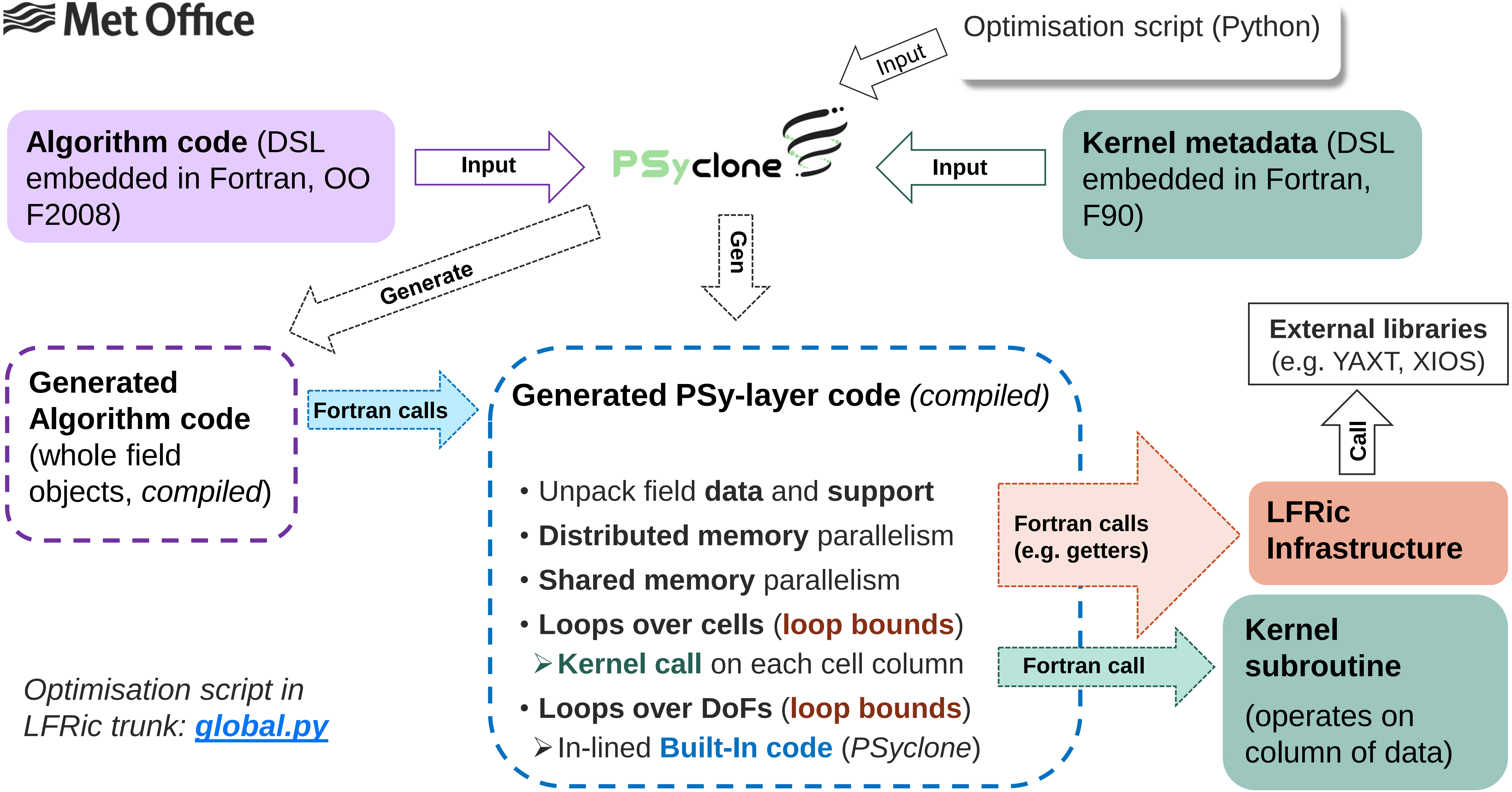

*Optimisation script in LFRic trunk: **global.py***

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Rules of engagement: LFRic ⟷ PSyclone LFRic API

LFRic

- **Rules** (e.g. writing algorithms & kernels, data properties)
- Kernel **metadata**
- **Infrastructure support** (e.g. dofmap, colouring, MPI)

LFRic API

- Flexible **optimisations**
- Support for data structures & properties following **API rules**
- Development mandated by requirements

PSyKAl-lite

Required functionality (hand-written)

Distributed + shared memory parallelism

PSyclone transformations

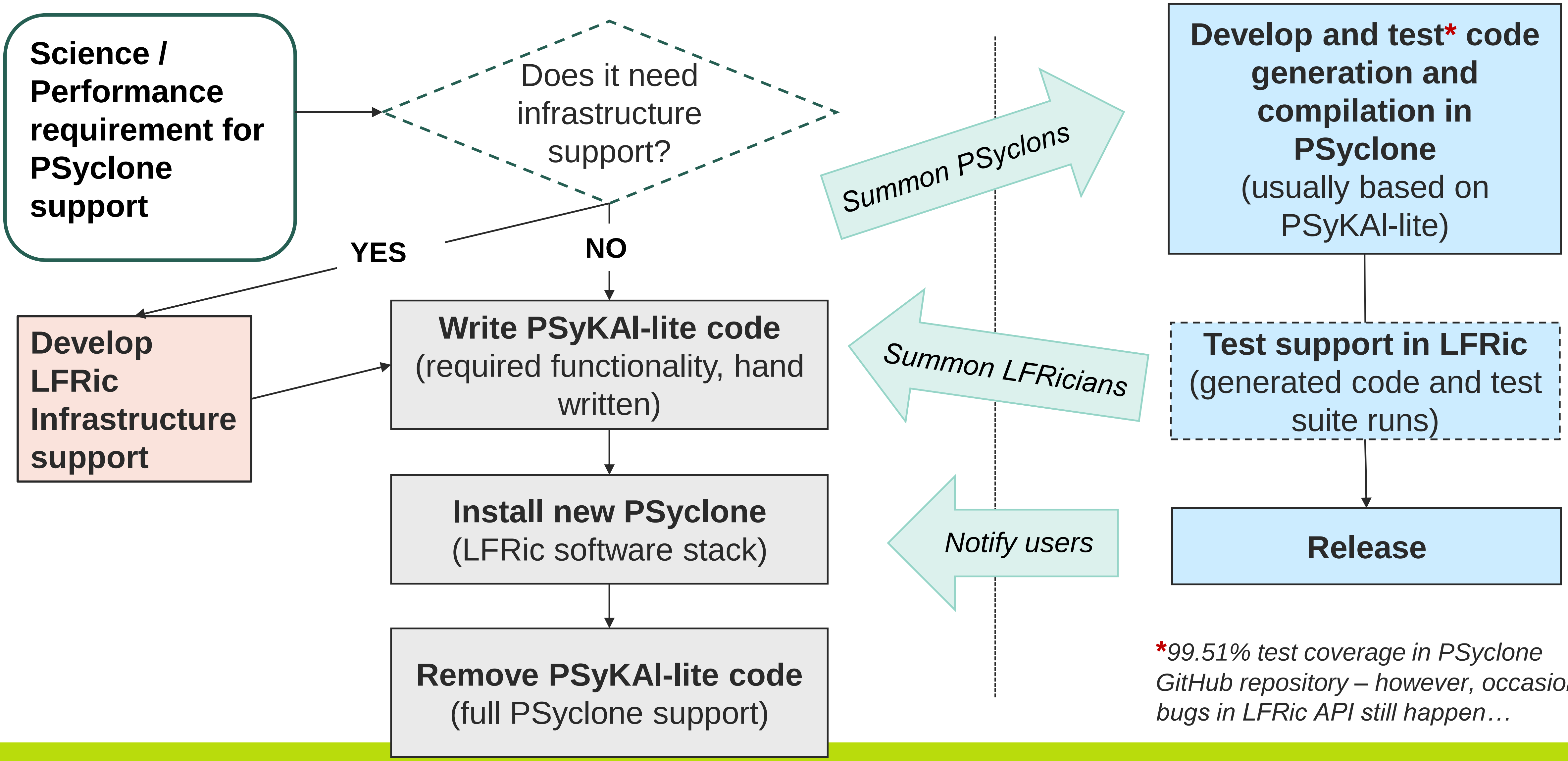
- Dynamo0p3ColourTrans
- Dynamo0p3OMPLoopTrans
- OMPParallelTrans
- Dynamo0p3RedundantComputationTrans

LFRic infrastructure support

- Halo exchange
- Colouring (cell & halo) for fields on continuous FS

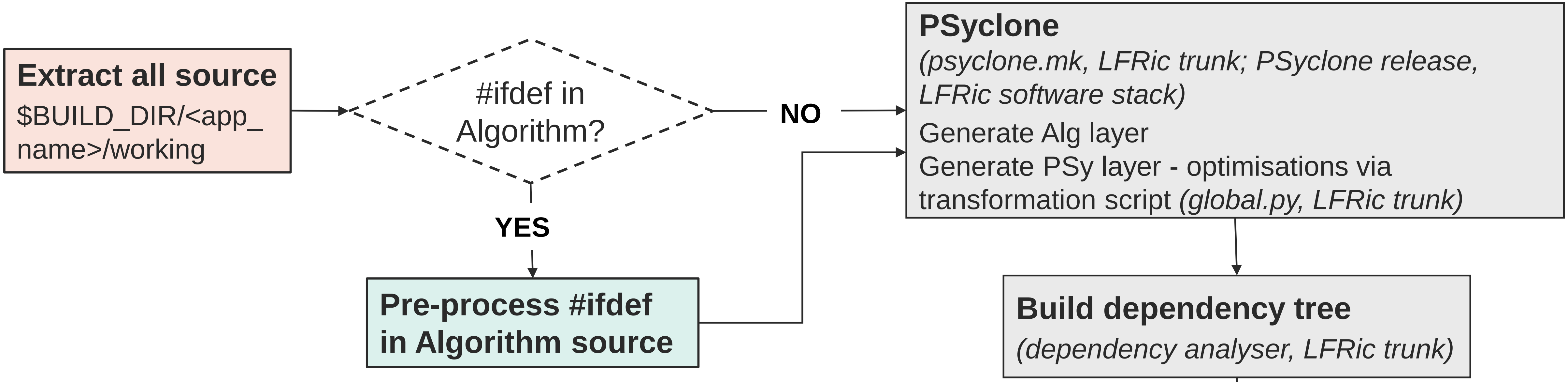
…

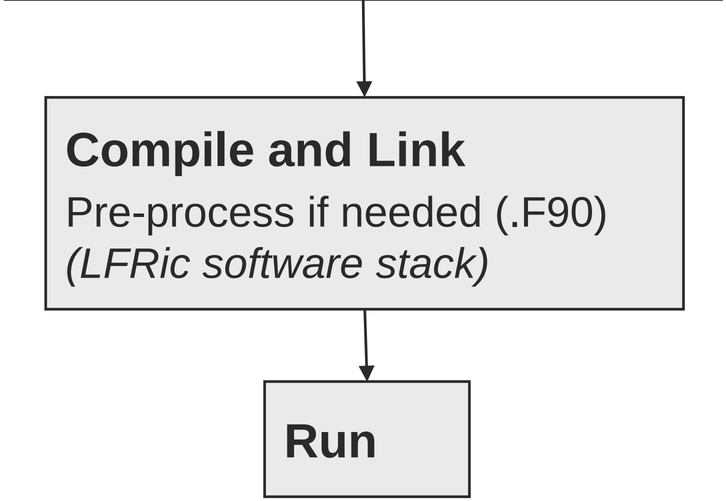
Development: LFRic ↔ PSyclone



*****_99.51% test coverage in PSyclone GitHub repository – however, occasional bugs in LFRic API still happen…_

Building LFRic with PSyclone





Naming convention for Alg and PSy source in LFRic build system

- **Alg source** (not compiled): <alg_name>_alg_mod.**x90**, .**X90**
- Generated Alg (compiled): <alg_name>_alg_mod.f90
- Generated PSy (compiled): <alg_name>_alg_mod_psy.f90

Management of PSyclone at Met Office: TODOs / Challenges

- Building **generated code** that is not in repository
  - **Fab build system** developed by the MO (intended for general use).
- Different projects/models will need **different PSyclone releases**
  - Management of PSyclone installations for different projects/models.
  - Ideally, this would be coordinated across NGMS Programme/MO – resources?
- **Porting** to Gen 1 and Gen 2 architecture
  - PSyclone releases with different **Python environments** *(LFRic builds its own Python virtual environments from AVD SciTools because of library clashes).*
  - Different releases / compiler environments / configurations?

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Management of PSyclone at Met Office: TODOs / Challenges

- **Configuring** PSyclone releases per API and/or model run
  - LFRic **modifies** PSyclone configuration file during the installation process.
  - Flexible builds will need to access different configuration files → work in progress on configurable runs (configuration stored in the LFRic repository).
- *Continuous testing of LFRic code against PSyclone master
  - Some bugs PSyclone LFRic API get missed in between releases due to rapid development of LFRic code *(usually quickly fixed due to* ***close collaboration between STFC and MO****).*
  - PSyclone test environments are currently manually upgraded as needed (installation scripts) to test LFRic trunk or branch → work in progress on automation.

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Highlights and development

Mixed precision and i-first looping in LFRic Atmosphere

Work on colouring algorithm

Mixed precision and i-first data layout in LFRic Atmosphere

- PSyclone and LFRic infrastructure support for **mixed precision** and fields/operator of **different datatypes**.

- LFRic utilises existing parameterisation schemes for the Unified model.
  - **Interfacing** (“Physics” kernels) **UM Physics**, **SOCRATES** ("Suite Of Community RAdiative Transfer codes") and **JULES** (land surface) models.
  - PSyclone/LFRic infrastructure support for *i-first* looping with entire fields passed to the interfacing kernels (“operate_on = DOMAIN”).

Get the data in the right place

- **Design and implementation of shared memory parallelism and i-first indexing for UM physics parametrisations**

GungHo dycore	UM physics
Same operation within a vertical column	Same operation within a horizontal layer
k-first array index	i-first array index
Good for cache re-use	Good for Single Instruction Multiple Data

Original Structure:

Psy layer:
Loop over horizontal domain
Call kernel on column

```
integer :: operates_on = CELL_COLUMN
```

Kernel:
Convert data to column of UM data
Call UM scheme on column
Convert data back to LFRic

New i-first Structure:

Psy layer:
Call kernel

```
integer :: operates_on = DOMAIN
```

Kernel:
Convert data to whole-domain, i-first, UM data
Call UM scheme on whole domain
Convert data back to LFRic

Courtesy of Ben Shipway, UKMO

Computational benefits

Single precision solver & i-first microphysics

Solver precision

Configuration	Trunk [33756]	Branch 64bit	Branch 32bit
6omp 6nodes	176.07	166.00	98.38
6omp 12nodes	86.05	78.21	55.57
6omp 24nodes	49.73	45.51	32.49

i-first microphysics

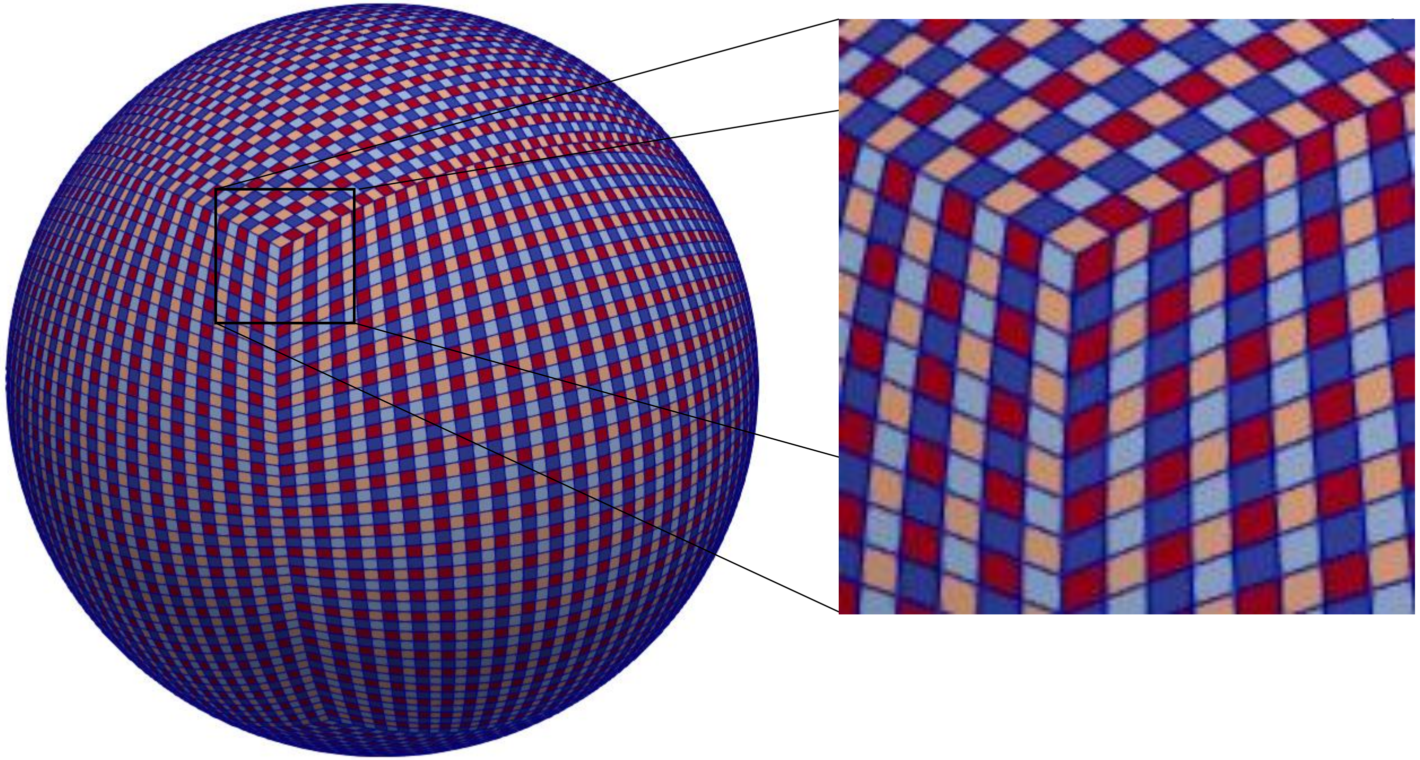
Microphysics timings	k-first (original)	i-first
C48, 216 PEs, 720 timesteps	247.4s	63.9s
C192, 864 PEs, 60 timesteps	33.5s	9.6s

Courtesy of Ben Shipway, UKMO

Impact of colouring algorithm on kernel performance (Wolfgang Hayek, NIWA)

- Exploit cubed-sphere structure to improve kernel performance.
- Improve cache reuse and memory bandwidth utilisation.
- Look at cell colouring and data column order in field arrays.
- Compare performance between (n x m) tile setups with tile-ordered colour maps.
- Simplifications: use 24 colours (4 per cube face) to avoid data races, no field array reordering yet.
- Use Chris Maynard' microbenchmark app and Sergi Siso's optimised matrix-vector kernel with vectorised k-inner loop.

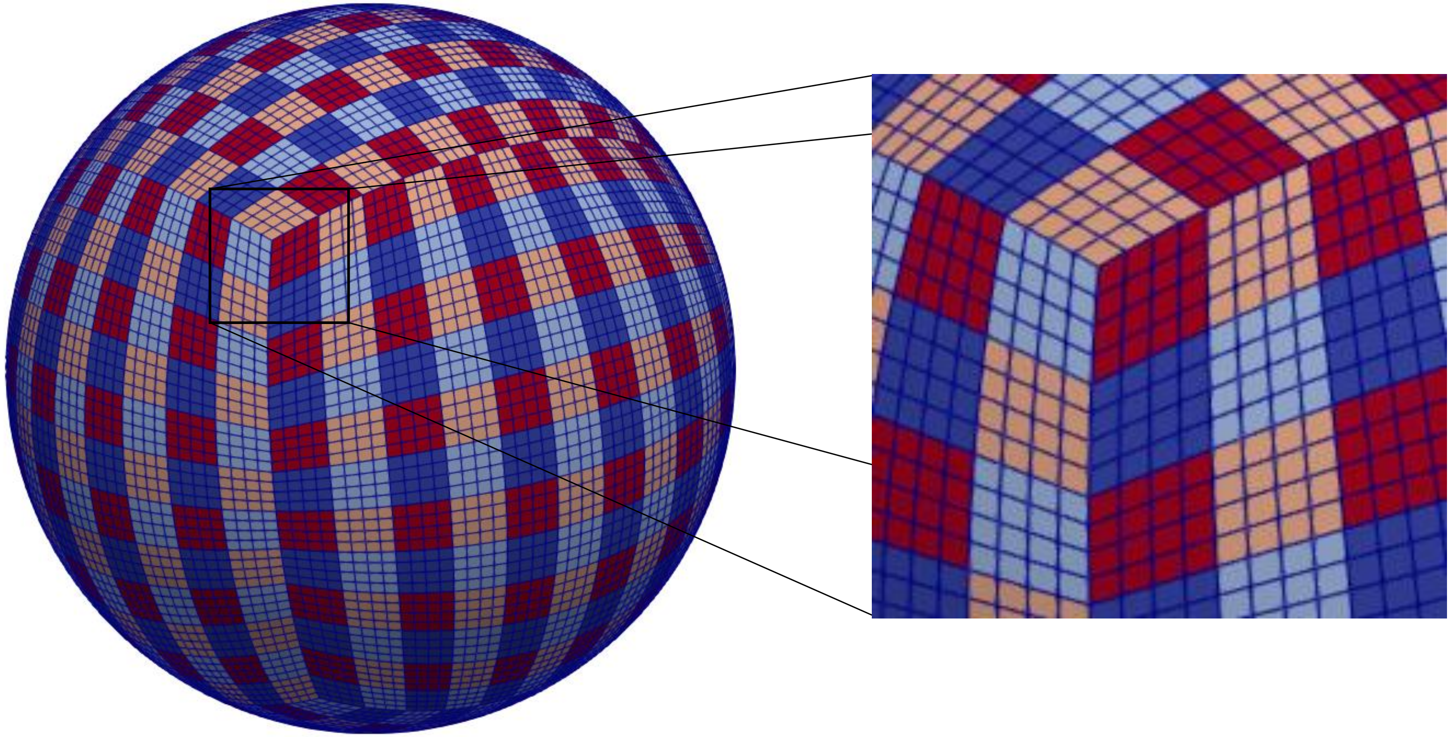
Current Scheme



- Uses 4 colours, staggered cell order in colour maps
- No cache-reuse for shared DOFs on cell vertices/edges/faces
- Data column order in field arrays follows mesh generator-provided order (?)

Courtesy of Wolfgang Hayek, NIWA

Coloured Tiles

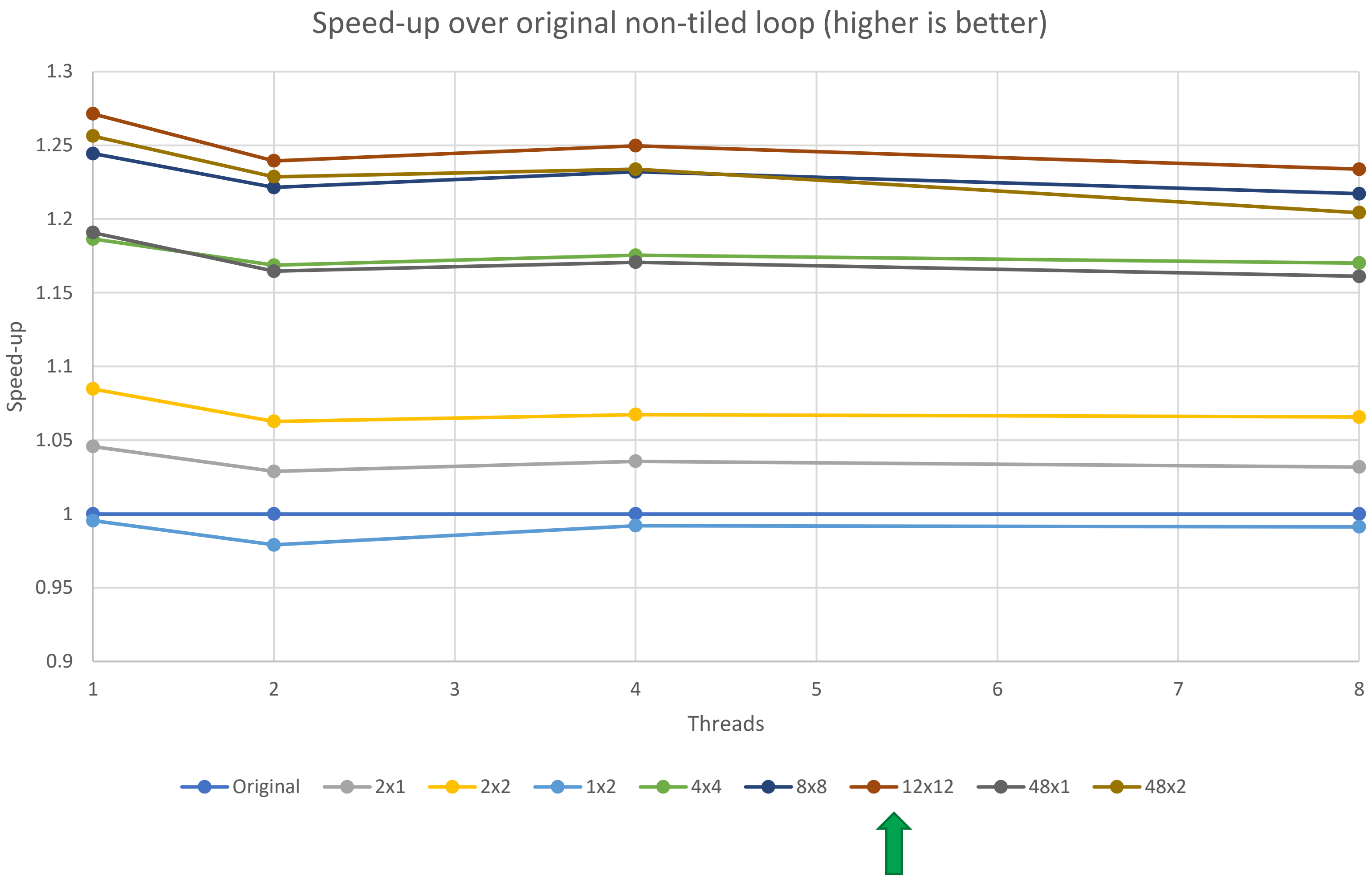


- Use coloured (n x m) tiles and reorder cell IDs tile-wise contiguously in colour maps
- Optimise data order in field arrays to follow tile structure
- Parallelise over tiles of the same colour to avoid data races
- Should work on CPUs and GPUs, and for domain-decomposed cubed-spheres and LAMs

Courtesy of Wolfgang Hayek, NIWA

Results

- *C48 cubed-sphere mesh, 120 vertical levels*
- *Build with Intel v18.0.1 compiler with "–O2 –qopenmp –qopenmp-simd"*

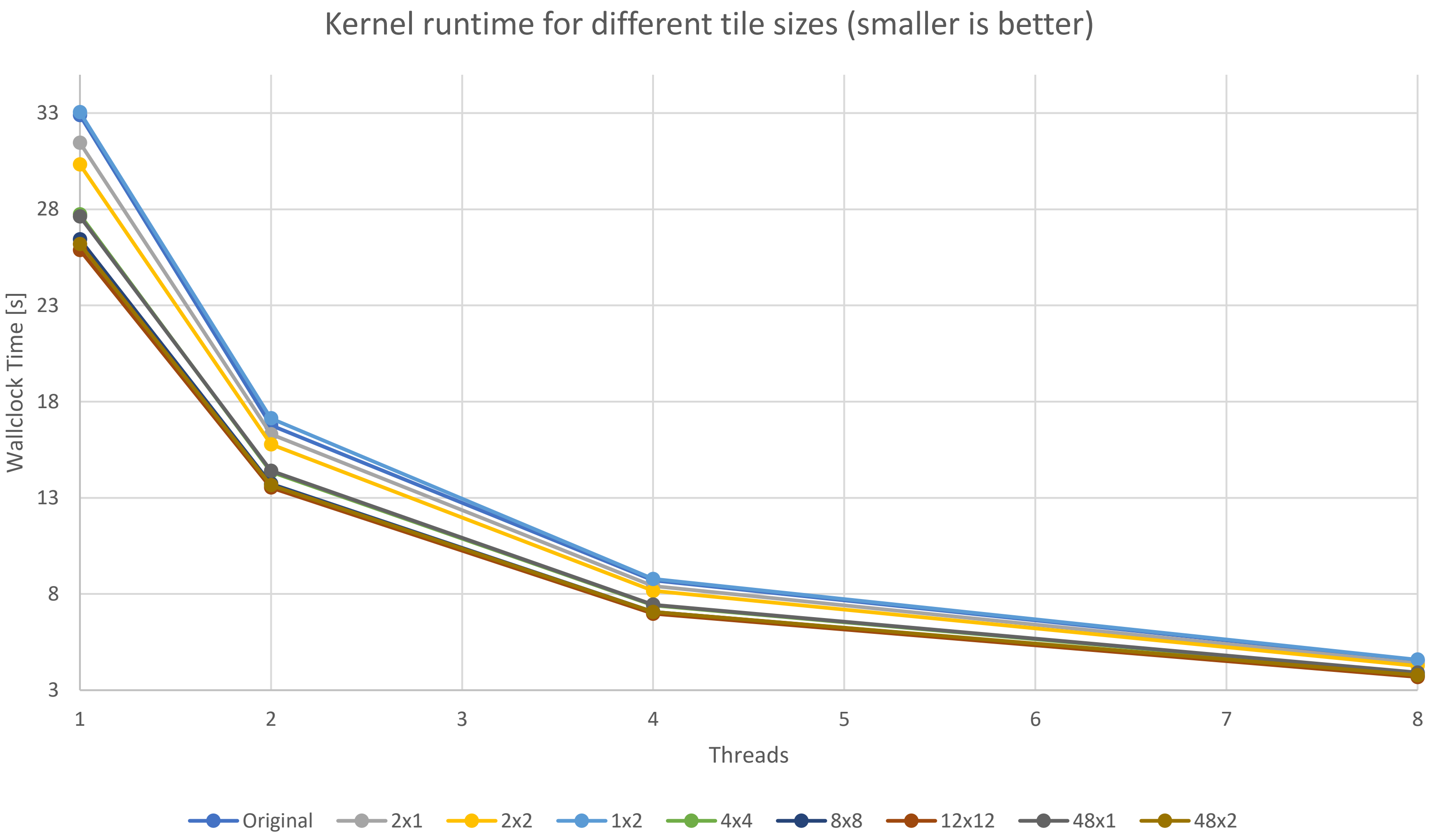


Run on Intel Xeon Gold 6148 2.4 GHz (Skylake), pin threads to physical cores in same socket, 1000 kernel iterations, best-of-5 timings

Up to x1.27 speed-up

Courtesy of Wolfgang Hayek, NIWA

Results



Performance improvement confirmed by reduced LLC miss rates (VTune)

Courtesy of Wolfgang Hayek, NIWA

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Thank you ☺

Acknowledgements

PSyclone developers, LFRic team, GungHo Atmospheric Science team and many others…

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Extras

Links and references

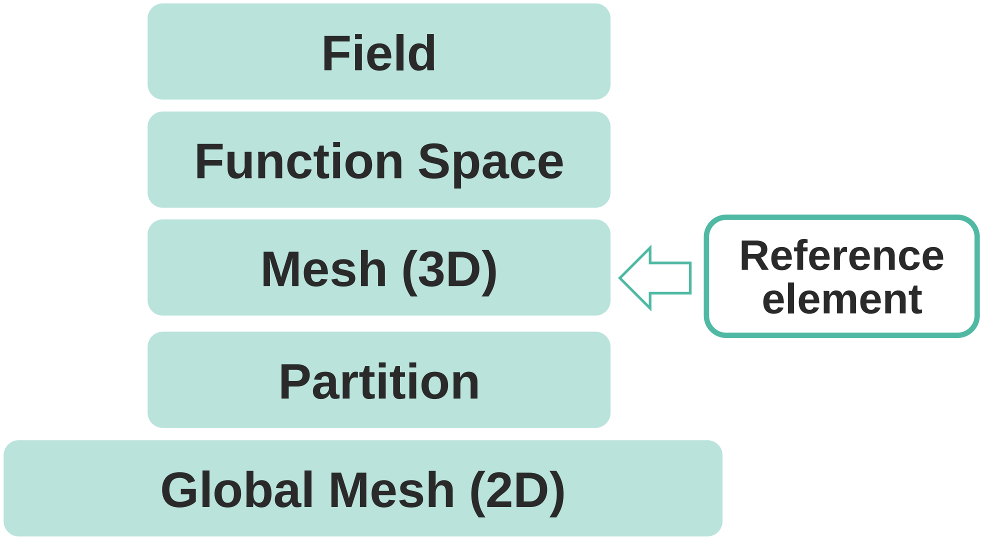
- PSyclone and fparser
  - https://github.com/stfc/PSyclone
  - https://psyclone.readthedocs.io
  - https://github.com/stfc/fparser
  - https://fparser.readthedocs.io
- LFRic repository (email Steve Mullerworth, LFRic Team manager, for access): https://code.metoffice.gov.uk/trac/lfric/wiki
- LFRic revision – PSyclone release compatibility: https://code.metoffice.gov.uk/trac/lfric/wiki/LFRicTechnical/VersionsCompatibility#LFRicCompatibility
- LFRic Singularity container: https://github.com/NCAS-CMS/LFRic_container
- LFRic software stack recipes: https://github.com/MetOffice/NGMS-SoftwareStack
- PSyclone in LFRic: https://code.metoffice.gov.uk/trac/lfric/wiki/PSycloneTool
- Stylist: https://github.com/MetOffice/stylist
- Adams et al. (2019), *LFRic: Meeting the challenges of scalability and performance portability in Weather and Climate models*, Journal of Parallel and Distributed Computing,132, 383-396

Infrastructure and data layout

LFRic Software Engineering: LFRic infrastructure (OO F2008)

- **LFRic: data classes**
  - Storing prognostic and diagnostic quantities: **field**;
  - Mathematical operations: **operator** (FEM matrices/FS mappings), **scalar** (global reductions).
- **Data classes** for supporting objects, e.g., mesh, reference element, function space.
- **Challenge: Compiler support for object-orientated F2008** is mixed → "compiler league table" (communication with vendors).

LFRic infrastructure: Hierarchy of objects



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LFRic Software Engineering: LFRic infrastructure

- **Support science** operations and **parallelism**:
  - Construct and handle **data objects** (e.g. mesh, reference element, function space, field);
  - **Support** for **distributed** and **shared memory** parallelism (e.g. dofmap, colouring for function spaces with shared DoFs, halo exchange).
- **Interface external libraries** (many more than in the UM – **collaboration** with other institutions + **in-house development** and implementation time)
  - **PSyclone** (STFC) for parallel code (& dependencies, e.g. Python);
  - **YAXT** (DKRZ) for MPI communications (& dependencies, e.g. MPICH);
  - **XIOS** (IPSL) for parallel IO (& dependencies, e.g. NetCDF, HDF5);
  - **pFUnit** (NASA Goddard) for unit testing;
  - **Rose picker** & **GPL-utilities** for Rose metadata; **Stylist** for style checking (in-house development based on external tools).

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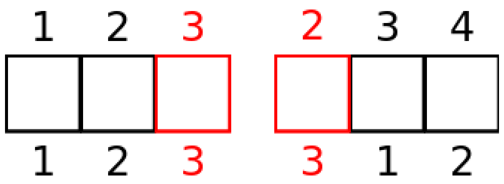
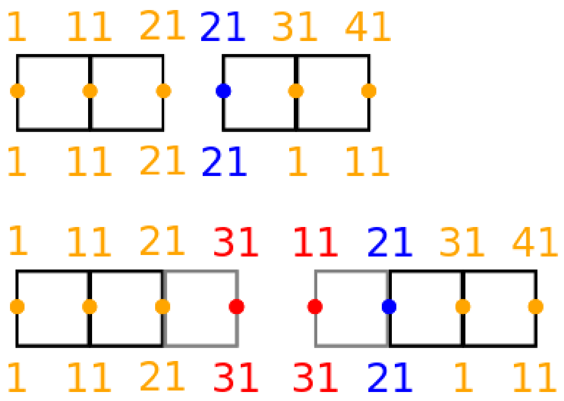
Updating fields in parallel: continuous vs discontinuous spaces



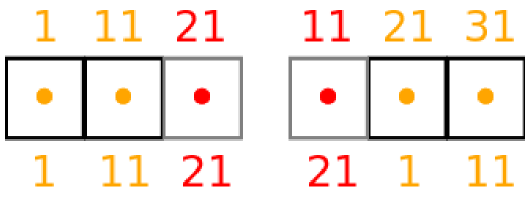
Continuous fields: PSy-layer cell loop, kernel calls

- DoFs on **owned** cells + redundant computation in the level-1 **halo**
- GH_INC and GH_READINC (R + W) access in kernel code – requires colouring for OpenMP



Continuous fields: PSy-layer DoF loop, built-in calls

- **Owned** DoFs or redundant computation into **annexed** DoFs (configuration option)



Discontinuous fields

- *Cell loop:* DoFs on **owned** cells (redundant computation optional)
- *DoF loop:* **owned** DoFs
- GH_READWRITE (R + W) or GH_WRITE (W) access – no colouring required for OpenMP

Examples of generated code

Code generation example

```
call invoke(                                              &
     setval_c(fld_c1, 0.0_r_def),                         &
     testkern_field_w2_inc_type(fld_c1, fld_c2), &
     testkern_field_w3_readwrite_type(fld_d1, fld_d2)  )
```

Algorithm code: invoke to kernels that update fields on a **continuous (W2)** and a **discontinuous (W3)** function space

```
 type(arg_type), dimension(2) :: meta_args = (/  &
      arg_type(gh_field, gh_real, gh_inc,   w2), &
      arg_type(gh_field, gh_real, gh_read, w1) )
integer :: iterates_over = cell_column
```

Kernel *testkern_field_w2_inc_mod* metadata: **continuous writer (W2)** and a continuous reader (W1)

```
 type(arg_type), dimension(2) :: meta_args = (/        &
     arg_type(gh_field, gh_real, gh_readwrite, w3), &
     arg_type(gh_field, gh_real, gh_read,         wtheta)  )
integer :: iterates_over = cell_column
```

Kernel *testkern_field_w2_inc_mod* metadata: **continuous writer (W3)** and a discontinuous reader (Wtheta)

PSyclone schedule: no distributed memory or optimisations

```
InvokeSchedule[invoke='invoke_0', dm=False]
    0: Loop[type='dof', field_space='any_space_1', it_space='dof', upper_bound='ndofs']
        Literal[value:'NOT_INITIALISED', Scalar<INTEGER, UNDEFINED>]
        Literal[value:'NOT_INITIALISED', Scalar<INTEGER, UNDEFINED>]
        Literal[value:'1', Scalar<INTEGER, UNDEFINED>]
        Schedule[]
            0: BuiltIn setval_c(fld_c1,0.0_r_def)
    1: Loop[type='', field_space='w2', it_space='cell_column', upper_bound='ncells']
        Literal[value:'NOT_INITIALISED', Scalar<INTEGER, UNDEFINED>]
        Literal[value:'NOT_INITIALISED', Scalar<INTEGER, UNDEFINED>]
        Literal[value:'1', Scalar<INTEGER, UNDEFINED>]
        Schedule[]
            0: CodedKern testkern_field_w2_inc_code(fld_c1,fld_c2) [module_inline=False]
    2: Loop[type='', field_space='w3', it_space='cell_column', upper_bound='ncells']
        Literal[value:'NOT_INITIALISED', Scalar<INTEGER, UNDEFINED>]
        Literal[value:'NOT_INITIALISED', Scalar<INTEGER, UNDEFINED>]
        Literal[value:'1', Scalar<INTEGER, UNDEFINED>]
        Schedule[]
            0: CodedKern testkern_field_w3_readwrite_code(fld_d1,fld_d2) [module_inline=False]
```

Built-In call: loop over DoFs

Kernel calls: loops over cell columns

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Generated PSy layer: no distributed memory or optimisations

```
! Set-up all of the loop bounds
!
loop0_start = 1
loop0_stop = undf_aspc1_fld_c1
loop1_start = 1
loop1_stop = fld_c1_proxy%vspace%get_ncell()
loop2_start = 1
loop2_stop = fld_d1_proxy%vspace%get_ncell()
!
! Call our kernels
!
DO df=loop0_start,loop0_stop
  fld_c1_proxy%data(df) = 0.0_r_def
END DO
DO cell=loop1_start,loop1_stop
  !
  CALL testkern_field_w2_inc_code(nlayers, fld_c1_proxy%data, fld_c2_proxy%data, ndf_w2, undf_w2, map_w2(:,cell), ndf_w1, undf_w1, map_w1(:,cell))
END DO
DO cell=loop2_start,loop2_stop
  !
  CALL testkern_field_w3_readwrite_code(nlayers, fld_d1_proxy%data, fld_d2_proxy%data, ndf_w3, undf_w3, map_w3(:,cell), ndf_wtheta, undf_wtheta, map_wtheta(:,cell))
END DO
```

Built-In call loop bounds: number of unique DoFs

Kernel call loop bounds: number of cells

Inlined Built-In code

Kernel calls

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PSyclone schedule: distributed memory

```
InvokeSchedule[invoke='invoke_0', dm=True]
    0: Loop[type='dof', field_space='any_space_1', it_space='dof', upper_bound='nannexed']
        Literal[value:'NOT_INITIALISED', Scalar<INTEGER, UNDEFINED>]
        Literal[value:'NOT_INITIALISED', Scalar<INTEGER, UNDEFINED>]
        Literal[value:'1', Scalar<INTEGER, UNDEFINED>]
        Schedule[]
            0: BuiltIn setval_c(fld_c1,0.0_r_def)
    1: HaloExchange[field='fld_c2', type='region', depth=1, check_dirty=True]
    2: Loop[type='', field_space='w2', it_space='cell_column', upper_bound='cell_halo(1)']
        Literal[value:'NOT_INITIALISED', Scalar<INTEGER, UNDEFINED>]
        Literal[value:'NOT_INITIALISED', Scalar<INTEGER, UNDEFINED>]
        Literal[value:'1', Scalar<INTEGER, UNDEFINED>]
        Schedule[]
            0: CodedKern testkern_field_w2_inc_code(fld_c1,fld_c2) [module_inline=False]
    3: Loop[type='', field_space='w3', it_space='cell_column', upper_bound='ncells']
        Literal[value:'NOT_INITIALISED', Scalar<INTEGER, UNDEFINED>]
        Literal[value:'NOT_INITIALISED', Scalar<INTEGER, UNDEFINED>]
        Literal[value:'1', Scalar<INTEGER, UNDEFINED>]
        Schedule[]
            0: CodedKern testkern_field_w3_readwrite_code(fld_d1,fld_d2) [module_inline=False]
```

Built-In call: loop over DoFs, upper bound to last annexed DoF (LFRic API setting)

Halo exchange to depth 1 on a continuous reader

Kernel call on a **continuous FS**: loop over cell columns, upper bound halo depth 1

Kernel call on a **discontinuous FS**: loop over cell columns, upper bound number of owned cells in a partition

Generated PSy layer: distributed memory (1)

```
! Set-up all of the loop bounds
!
loop0_start = 1
loop0_stop = fld_c1_proxy%vspace%get_last_dof_annexed()
loop1_start = 1
loop1_stop = mesh%get_last_halo_cell(1)
loop2_start = 1
loop2_stop = mesh%get_last_edge_cell()
!
! Call kernels and communication routines
!
DO df=loop0_start,loop0_stop
  fld_c1_proxy%data(df) = 0.0_r_def
END DO
!
! Set halos dirty/clean for fields modified in the above loop
!
CALL fld_c1_proxy%set_dirty()
```

Built-In call loop bounds: last annexed DoF (LFRic API setting)

Kernel call loop bound **(continuous FS)**: last cell in depth-1 halo

Kernel call loop bound **(discontinuous FS)**: last owned (edge) cell

Inlined Built-In code

Flag updated halos

Met Office

Generated PSy layer: distributed memory (2)

```
      IF (fld_c2_proxy%is_dirty(depth=1)) THEN
        CALL fld_c2_proxy%halo_exchange(depth=1)
      END IF
      !
      DO cell=loop1_start,loop1_stop
        !
        CALL testkern_field_w2_inc_code(nlayers, fld_c1_proxy%data, fld_c2_proxy%data, ndf_w2, undf_w2, map_w2(:,cell), ndf_w1,
undf_w1, map_w1(:,cell))
      END DO
      !
      ! Set halos dirty/clean for fields modified in the above loop
      !
      CALL fld_c1_proxy%set_dirty()
      !
      DO cell=loop2_start,loop2_stop
        !
        CALL testkern_field_w3_readwrite_code(nlayers, fld_d1_proxy%data, fld_d2_proxy%data, ndf_w3, undf_w3, map_w3(:,cell),
ndf_wtheta, undf_wtheta, map_wtheta(:,cell))
      END DO
      !
      ! Set halos dirty/clean for fields modified in the above loop
      !
      CALL fld_d1_proxy%set_dirty()
```

Halo exchange to depth 1 on a continuous reader

Kernel call on a **continuous FS**

Flag updated halos

Kernel call on a **discontinuous FS**

Flag updated halos

Met Office

PSyclone schedule (part): distributed + shared memory

```
1: HaloExchange[field='fld_c2', type='region', depth=1, check_dirty=True]
  2: Loop[type='colours', field_space='w2', it_space='cell_column', upper_bound='ncolours']
    Literal[value:'NOT_INITIALISED', Scalar<INTEGER, UNDEFINED>]
    Literal[value:'NOT_INITIALISED', Scalar<INTEGER, UNDEFINED>]
    Literal[value:'1', Scalar<INTEGER, UNDEFINED>]
    Schedule[]
      0: OMPParallelDirective[]
        Schedule[]
          0: OMPDoDirective[]
            Schedule[]
              0: Loop[type='colour', field_space='w2', it_space='cell_column', upper_bound='colour_halo(1)']
                Literal[value:'NOT_INITIALISED', Scalar<INTEGER, UNDEFINED>]
                Literal[value:'NOT_INITIALISED', Scalar<INTEGER, UNDEFINED>]
                Literal[value:'1', Scalar<INTEGER, UNDEFINED>]
                Schedule[]
                  0: CodedKern testkern_field_w2_inc_code(fld_c1,fld_c2) [module_inline=False]
  3: OMPParallelDirective[]
    Schedule[]
      0: OMPDoDirective[]
        Schedule[]
          0: Loop[type='', field_space='w3', it_space='cell_column', upper_bound='ncells']
            Literal[value:'NOT_INITIALISED', Scalar<INTEGER, UNDEFINED>]
            Literal[value:'NOT_INITIALISED', Scalar<INTEGER, UNDEFINED>]
            Literal[value:'1', Scalar<INTEGER, UNDEFINED>]
            Schedule[]
              0: CodedKern testkern_field_w3_readwrite_code(fld_d1,fld_d2) [module_inline=False]
```

Halo exchange to depth 1 on a continuous reader

Kernel call on a **continuous FS**: **outer loop** over colours, upper bound number of colours

OpenMP directives

Kernel call on a **continuous FS**: **inner loop** over cells in a colour, upper bound depth 1 halo for a colour

OpenMP directives

Kernel call on a **discontinuous FS**: loop over cell columns, upper bound number of owned cells in a partition

Generated PSy layer: distributed + shared memory (1)

```
ncolour = mesh%get_ncolours()
cmap => mesh%get_colour_map()
 …
loop0_start = 1
loop0_stop = fld_c1_proxy%vspace%get_last_dof_halo(1)
loop1_start = 1
loop1_stop = ncolour
loop2_start = 1
loop3_start = 1
loop3_stop = mesh%get_last_edge_cell()
!
! Call kernels and communication routines
!
!$omp parallel default(shared), private(df)
!$omp do schedule(static)
DO df=loop0_start,loop0_stop
  fld_c1_proxy%data(df) = 0.0_r_def
END DO
!$omp end do
!
! Set halos dirty/clean for fields modified in the above loop
!$omp master
CALL fld_c1_proxy%set_dirty()
CALL fld_c1_proxy%set_clean(1)
!$omp end master
!$omp end parallel
```

Get infrastructure colouring support

Built-In call loop bounds

Kernel call outer loop bound **(continuous FS)**: number of colours

Kernel call inner loop bound **(continuous FS)**: number of cells in a colour

Kernel call loop bound **(discontinuous FS)**: last owned (edge) cell

OpenMP directives

Inlined Built-In code

Flag updated halos

Generated PSy layer: distributed + shared memory (2)

```
IF (fld_c2_proxy%is_dirty(depth=1)) THEN
  CALL fld_c2_proxy%halo_exchange(depth=1)
END IF
!
DO colour=loop1_start,loop1_stop
  !$omp parallel default(shared), private(cell)
  !$omp do schedule(static)
  DO cell=loop2_start,last_cell_all_colours(colour,1)
    !
    CALL testkern_field_w2_inc_code(nlayers, fld_c1_proxy%data, fld_c2_proxy%data, ndf_w2,
undf_w2, map_w2(:,cmap(colour, cell)), ndf_w1, undf_w1, map_w1(:,cmap(colour, cell)))
  END DO
  !$omp end do
  !$omp end parallel
END DO
!
! Set halos dirty/clean for fields modified in the above loop
!
CALL fld_c1_proxy%set_dirty()
```

Halo exchange to depth 1 on a continuous reader

Kernel call **(continuous FS)**, outer loop over colours

OpenMP directives

Kernel call **(continuous FS)**, inner loop over cells in a colour

Kernel call on a **continuous FS**

Flag updated halos

Met Office

Generated PSy layer: distributed + shared memory (3)

```
!$omp parallel default(shared), private(cell)
!$omp do schedule(static)
DO cell=loop3_start,loop3_stop
  !
  CALL testkern_field_w3_readwrite_code(nlayers, fld_d1_proxy%data, fld_d2_proxy%data, ndf_w3,
undf_w3, map_w3(:,cell), ndf_wtheta, undf_wtheta, map_wtheta(:,cell))
END DO
!$omp end do
!
! Set halos dirty/clean for fields modified in the above loop
!
!$omp master
CALL fld_d1_proxy%set_dirty()
!$omp end master
!
!$omp end parallel
```

OpenMP directives

Kernel call **(discontinuous FS)**, loop over owned cells only

Flag updated halos