WRF Software Architecture

John Michalakes, Head WRF Software Architecture

Michael Duda

Dave Gill

Outline

- Introduction
- Computing Overview
- WRF Software Overview

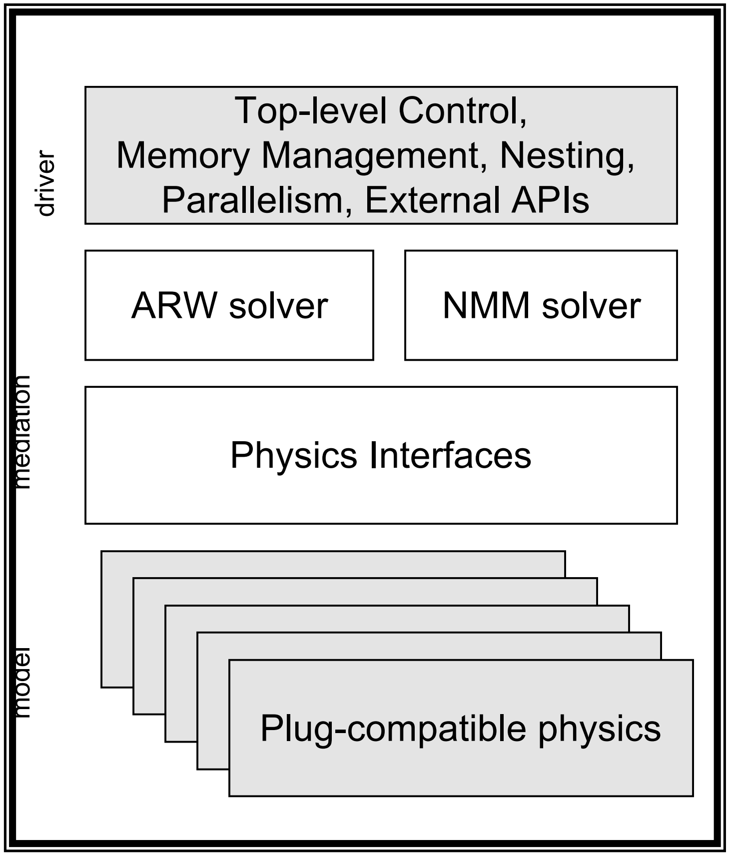
Introduction – WRF Software Characteristics

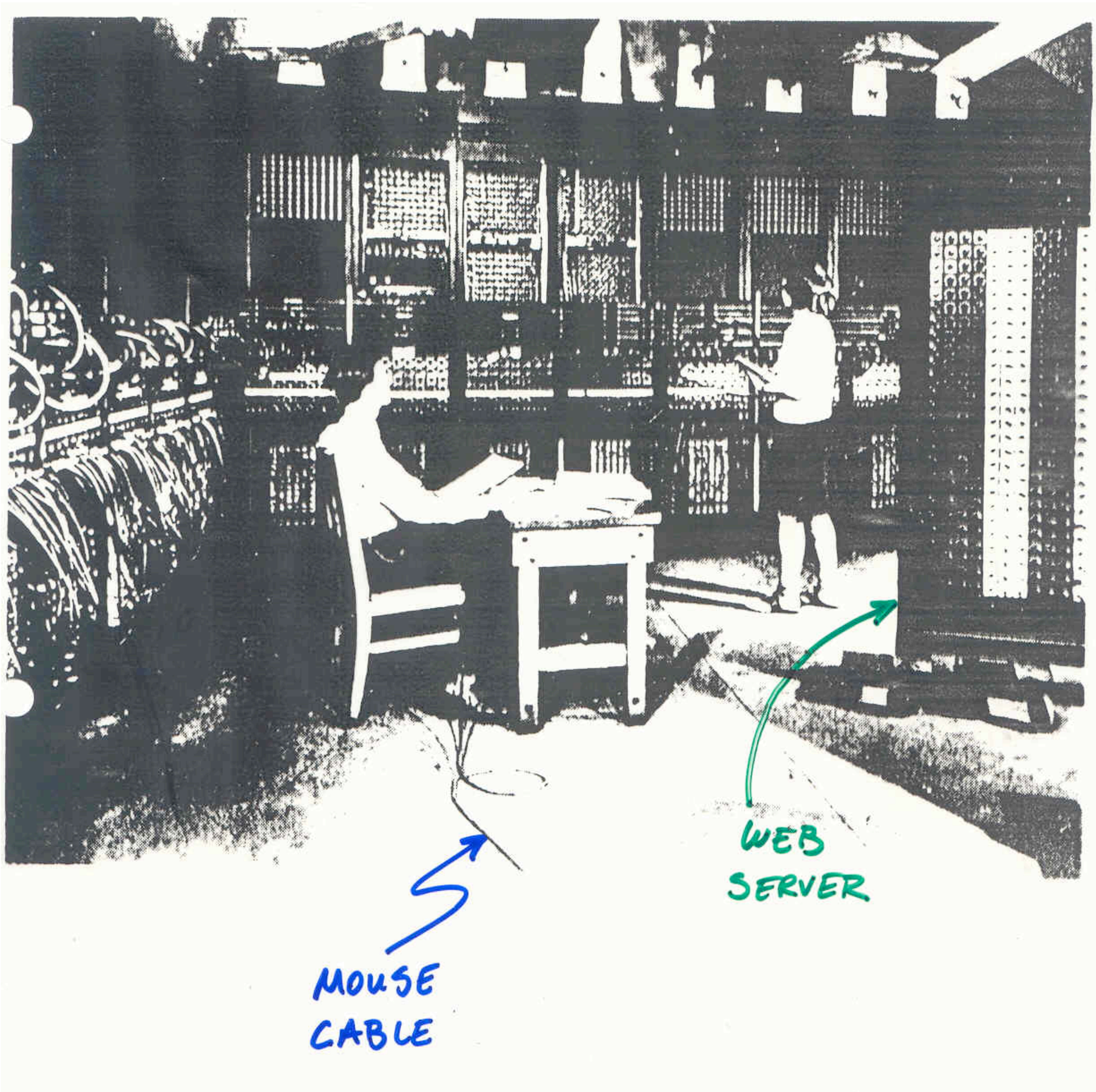
- Developed from scratch beginning around 1998, primarily Fortran and C
- Requirements emphasize flexibility over a range of platforms, applications, users, performance
- WRF develops rapidly. First released Dec 2000; current release WRF v3.1 (April 2009); next release WRF v3.1.1 (July 2009)
- Supported by flexible efficient architecture and implementation called the WRF Software Framework

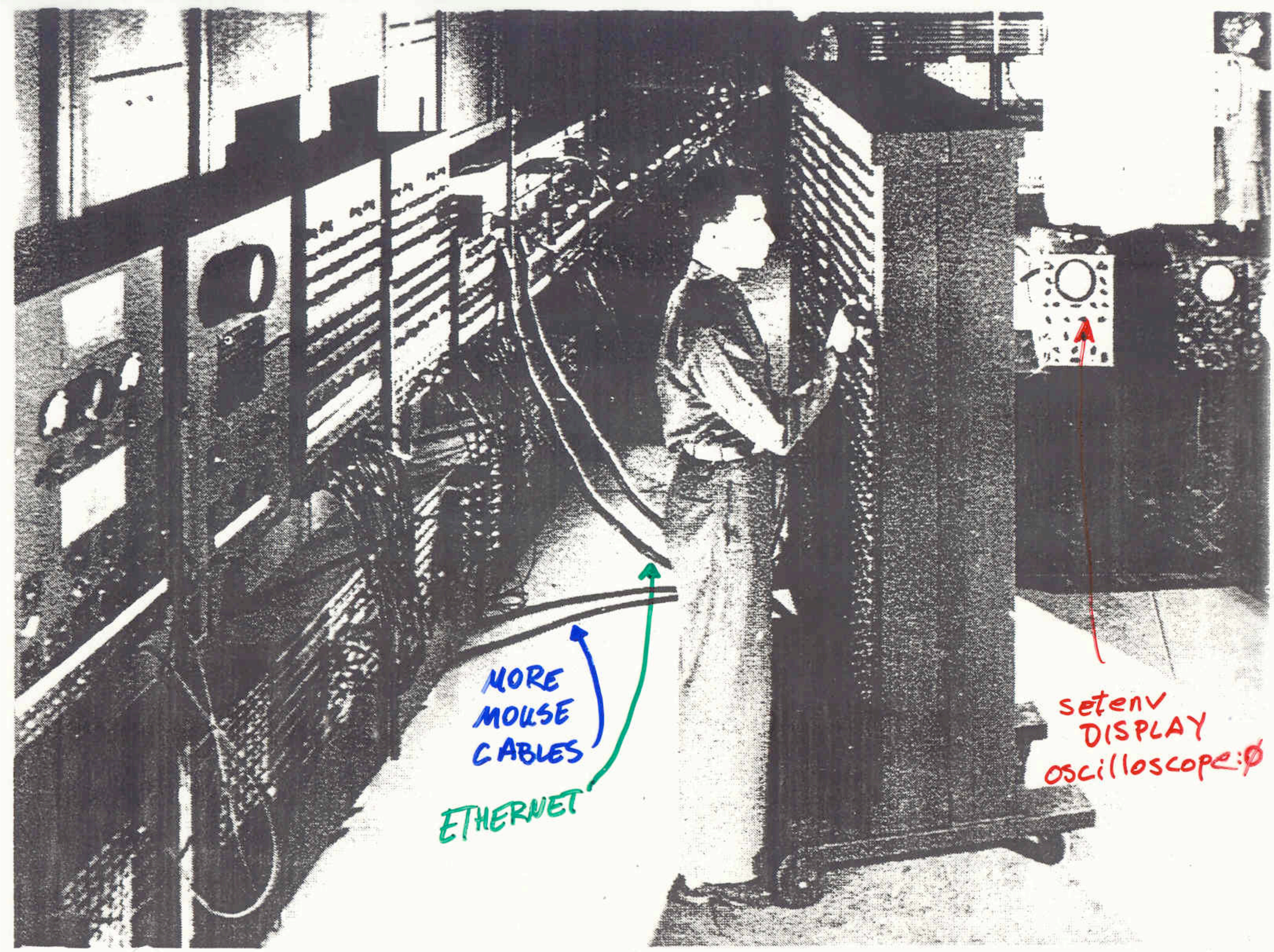
Introduction - WRF Software Framework Overview

- Implementation of WRF Architecture
  - Hierarchical organization
  - Multiple dynamical cores
  - Plug compatible physics
  - Abstract interfaces (APIs) to external packages
  - Performance-portable
- Designed from beginning to be adaptable to today's computing environment for NWP

http://box.mmm.ucar.edu/wrf/WG2/bench/

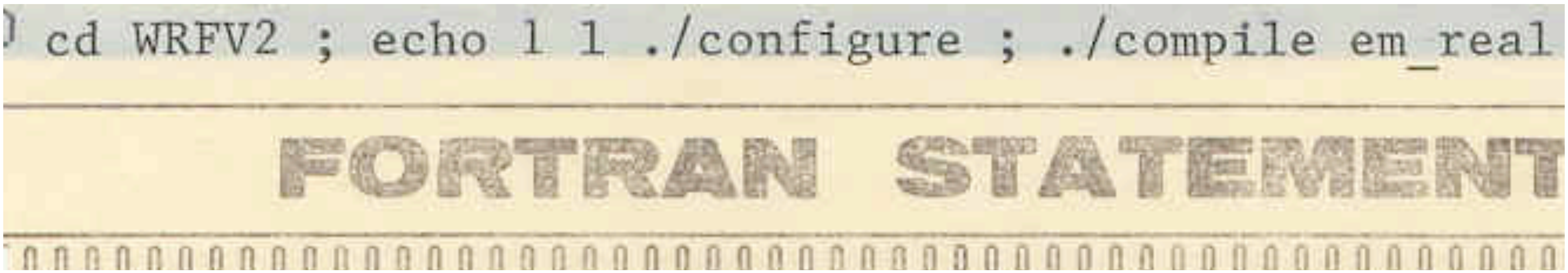



WEB SERVER
MOUSE CABLE

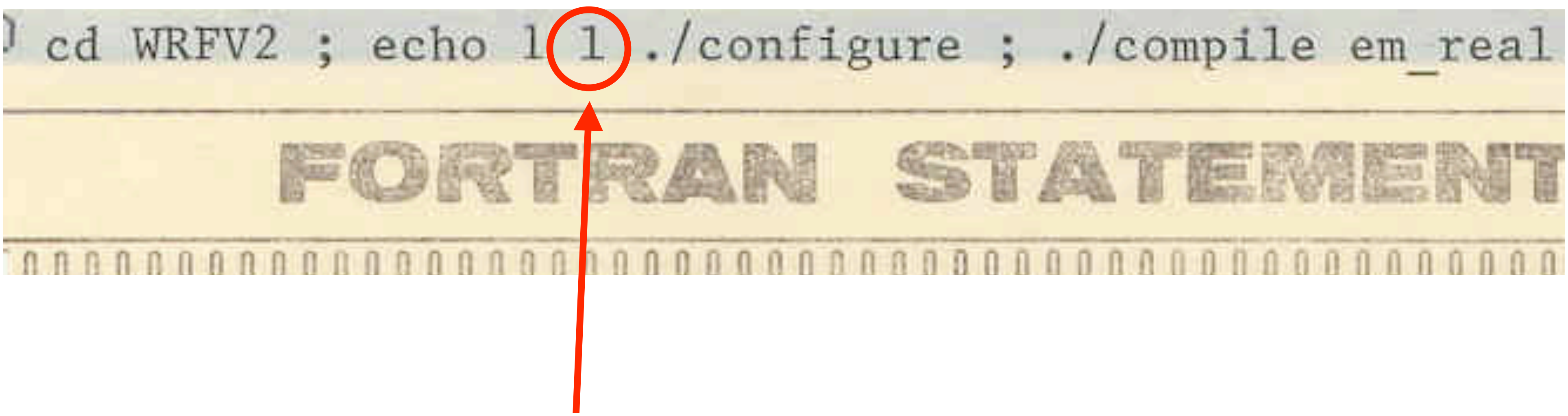

MORE
MOUSE
CABLES
ETHERNET
setenv
DISPLAY
oscilloscope:0

Early Unix Interface to WRF model

Early Unix Interface to WRF model



Early Unix Interface to WRF model



Note usage of lower case "L" for the pipe character on keypuch machine

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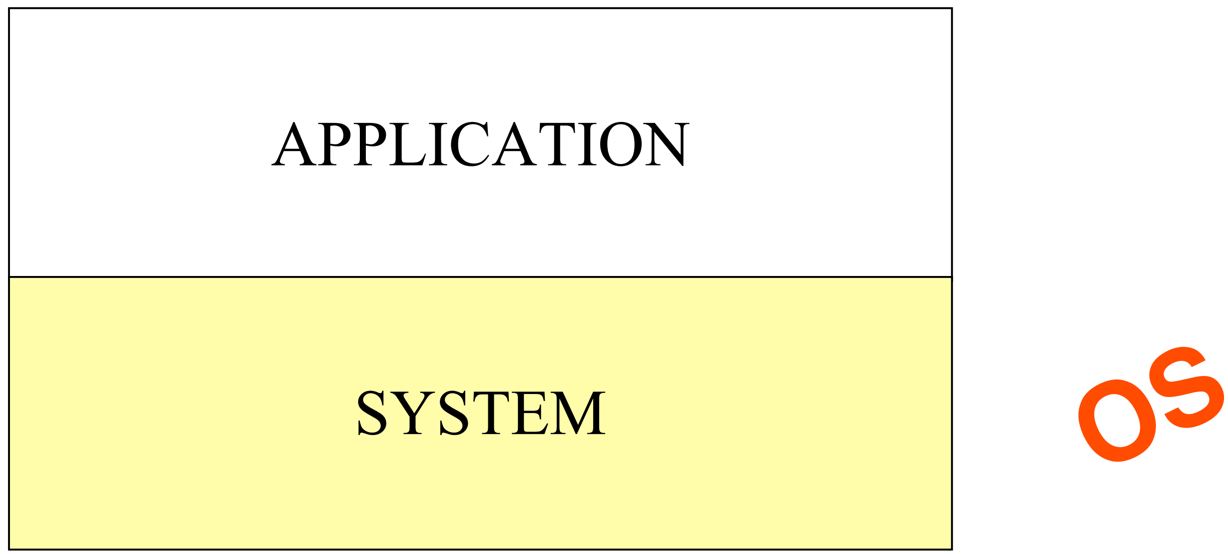
- Computing Overview
- WRF Software Overview

Computing Overview

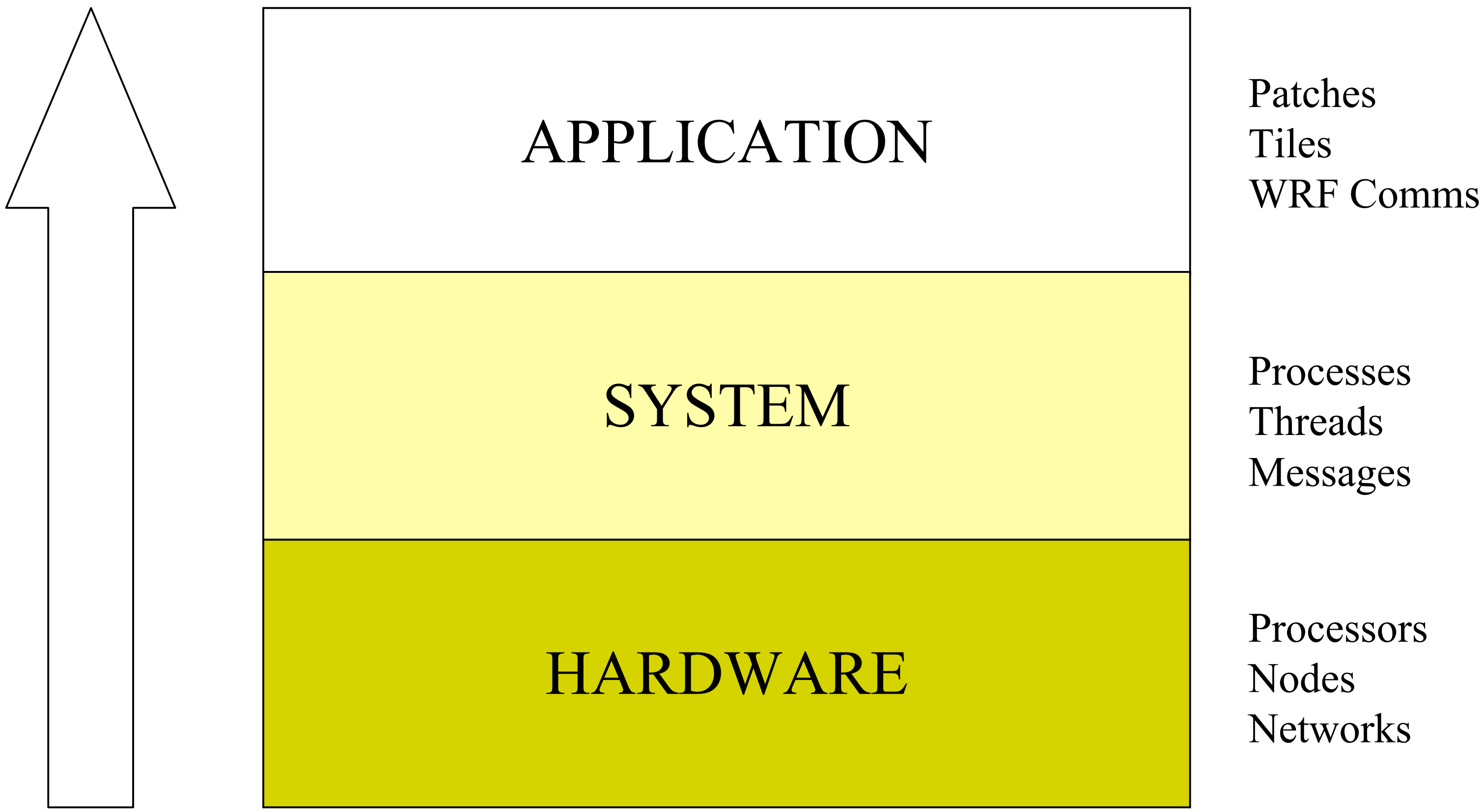
APPLICATION

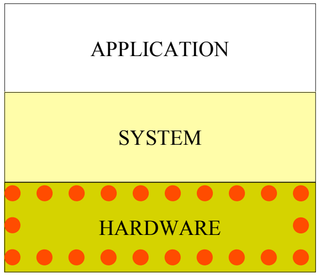
WRF

Computing Overview



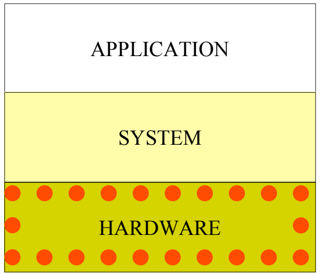
Computing Overview





Hardware: The Computer

- The ‘N’ in NWP
- Components
  - Processor
    - A program counter
    - Arithmetic unit(s)
    - Some scratch space (registers)
    - Circuitry to store/retrieve from memory device
    - Cache
  - Memory
  - Secondary storage
  - Peripherals
- The implementation has been continually refined, but the basic idea hasn’t changed much



Hardware has not changed much…

A computer in 1960

IBM 7090

6-way superscalar

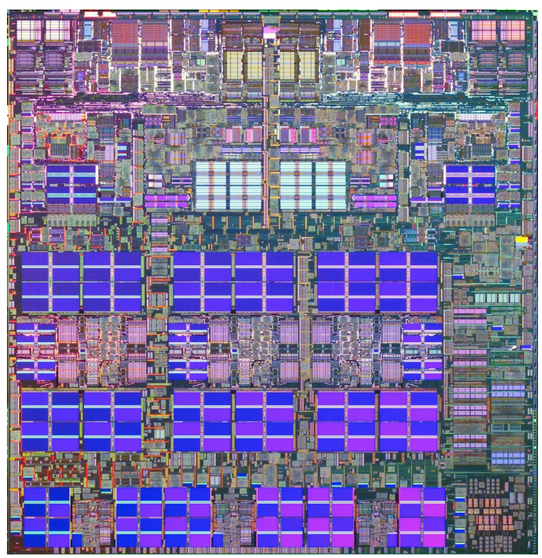
36-bit floating point precision

~144 Kbytes

~50,000 flop/s
48hr 12km WRF CONUS in 600 years

A computer in 2008

IBM P6



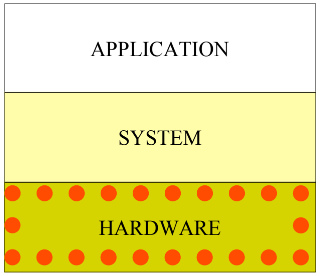
Dual core, 4.7 GHz chip

64-bit floating point precision

1.9 MB L2, 36 MB L3

Upto 16 GB per processor

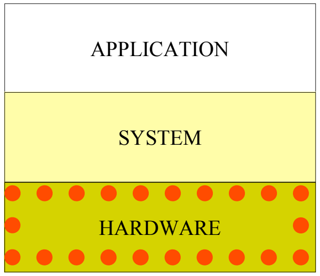
~5,000,000,000 flop/s
48 12km WRF CONUS in 52 Hours



…how we use it has

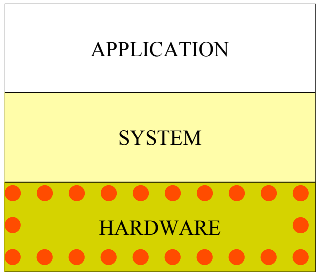
- Fundamentally, processors haven't changed much since 1960
- Quantitatively, they haven't improved nearly enough
  - 100,000x increase in peak speed
  - 100,000x increase in memory size
  - These are too slow and too small for even a moderately large NWP run today
- We make up the difference with <u>parallelism</u>
  - Ganging multiple processors together to achieve $10^{11\text{-}12}$ flop/second
  - Aggregate available memories of $10^{11\text{-}12}$ bytes

~1,000,000,000,000 flop/s ~250 procs
48-h, 12-km WRF CONUS in under 15 minutes



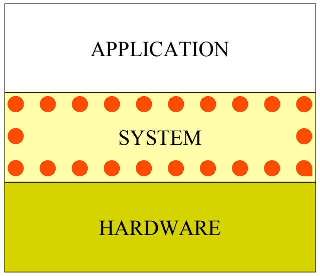
Parallel Computing Terms -- Hardware

- **Processor:**
  - A device that reads and executes instructions in sequence to produce perform operations on data that it gets from a memory device producing results that are stored back onto the memory device
- **Node:** One memory device connected to one or more processors.
  - Multiple processors in a node are said to share-memory and this is “shared memory parallelism”
  - They can work together because they can see each other’s memory
  - The latency and bandwidth to memory affect performance



Parallel Computing Terms -- Hardware

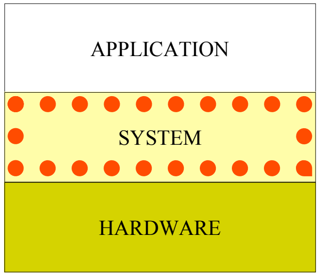
- **Cluster**: Multiple nodes connected by a network
  - The processors attached to the memory in one node can not see the memory for processors on another node
  - For processors on different nodes to work together they must send messages between the nodes. This is "distributed memory parallelism"
- **Network:**
  - Devices and wires for sending messages between nodes
  - Bandwidth – a measure of the number of bytes that can be moved in a second
  - Latency – the amount of time it takes before the first byte of a message arrives at its destination



Parallel Computing Terms – System Software

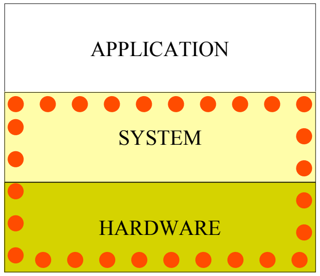
"The only thing one does directly with hardware is pay for it."
John's Zeroth Law of Computing

- **Process:**
  - A set of instructions to be executed on a processor
  - Enough state information to allow process execution to stop on a processor and be picked up again later, possibly by another processor
- Processes may be lightweight or heavyweight
  - **Lightweight processes**, e.g. shared-memory threads, store very little state; just enough to stop and then start the process
  - **Heavyweight processes**, e.g. UNIX processes, store a lot more (basically the memory image of the job)



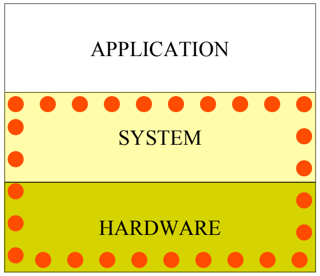
Parallel Computing Terms – System Software

- Every job has at least one heavy-weight *process*.
  - A job with more than one heavy-weight process is a distributed-memory parallel job
  - Even on the same node, heavyweight processes do not share memory
- Within a heavyweight process you may have some number of lightweight processes, called *threads.*
  - Threads are shared-memory parallel; only threads in the same memory space can work together*.*
  - A thread never exists by itself; it is always inside a heavy-weight process.
- Heavy-weight processes are the vehicles for distributed memory parallelism
- Threads (light-weight processes) are the vehicles for shared-memory parallelism



Jobs, Processes, and Hardware

- Message Passing Interface – MPI, referred to as the communication layer
- MPI is used to start up and pass messages between multiple heavyweight processes
  - The **mpirun** command controls the number of processes and how they are mapped onto nodes of the parallel machine
  - Calls to MPI routines send and receive messages and control other interactions between processes
  - http://www.mcs.anl.gov/mpi



Jobs, Processes, and Hardware

- OpenMP is used to start up and control threads within each process
  - Directives specify which parts of the program are multi-threaded
  - **OpenMP** environment variables determine the number of threads in each process
  - http://www.openmp.org
- OpenMP is usually activated via a compiler option
- MPI is usually activated via the compiler name
- The number of **processes** (number of MPI processes times the number of threads in each process) usually corresponds to the number of **processors**

Examples

- If the machine consists of 4 nodes, each with 4 processors, how many different ways can you run a job to use all 16 processors?
  - 4 MPI processes, each with 4 threads

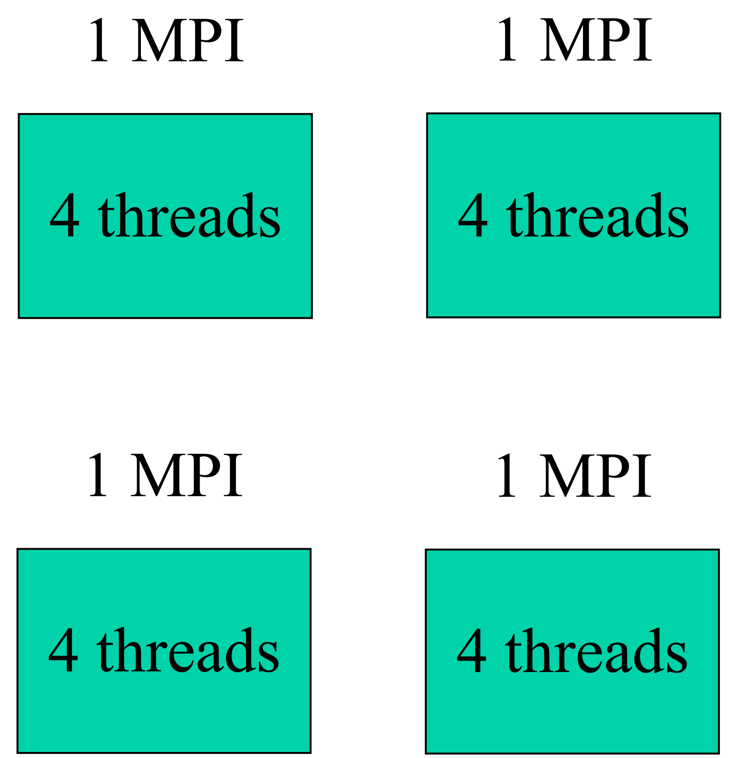
```
setenv OMP_NUM_THREADS 4
mpirun -np 4 wrf.exe
```

  - 8 MPI processes, each with 2 threads

```
setenv OMP_NUM_THREADS 2
mpirun -np 8 wrf.exe
```

  - 16 MPI processes, each with 1 thread

```
setenv OMP_NUM_THREADS 1
mpirun -np 16 wrf.exe
```



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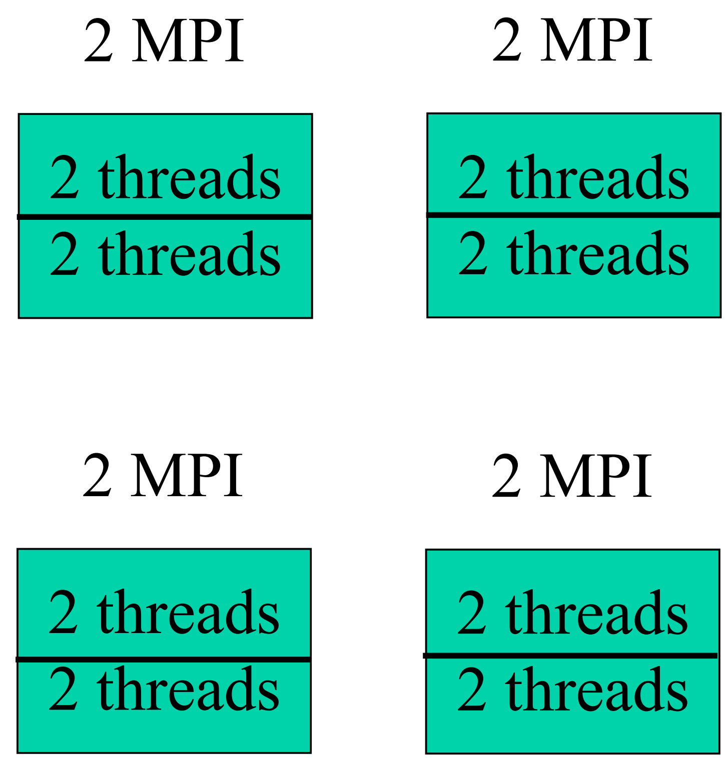

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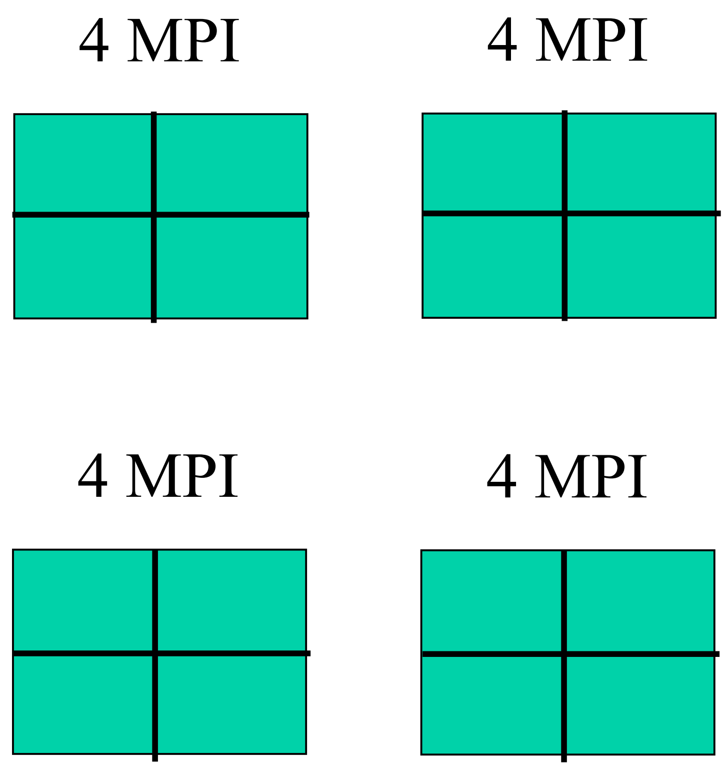
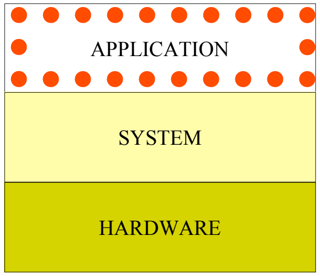


Examples (cont.)

- Note, since there are 4 nodes, we can never have fewer than 4 MPI processes because nodes do not share memory

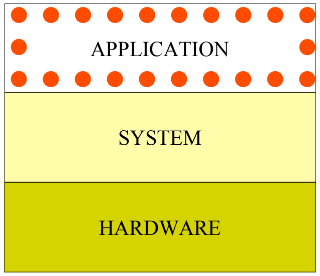
- What happens on this same machine for the following?

```
setenv OMP_NUM_THREADS 8
mpirun -np 32
```



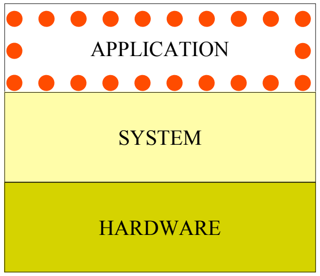
Application: WRF

- WRF can be run serially or as a parallel job
- WRF uses ***domain decomposition*** to divide total amount of work over parallel processes

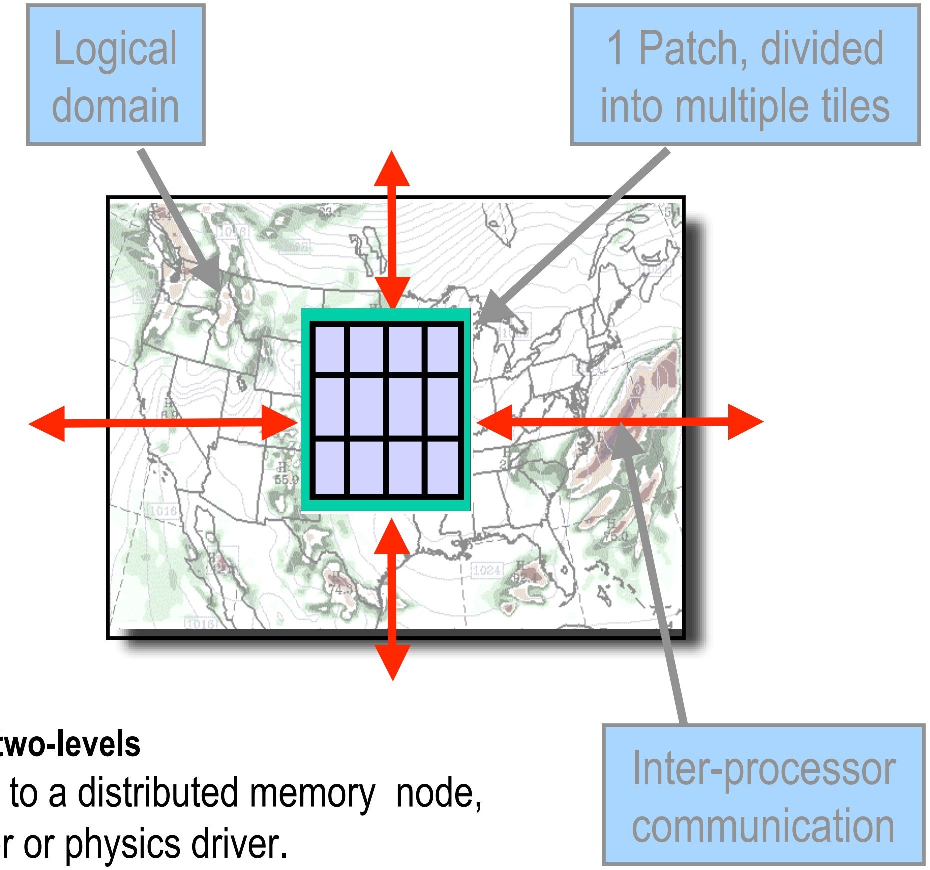


Application: WRF

- Since the process model has two levels (heavy-weight and light-weight = MPI and OpenMP), the decomposition of the application over processes has two levels:
  - The ***domain*** is first broken up into rectangular pieces that are assigned to heavy-weight processes. These pieces are called ***patches***
  - The ***patches*** may be further subdivided into smaller rectangular pieces that are called ***tiles***, and these are assigned to ***threads*** within the process.



Parallelism in WRF: Multi-level Decomposition



- **Single version of code for efficient execution on:**
  - Distributed-memory
  - Shared-memory (SMP)
  - Clusters of SMPs
  - Vector and microprocessors

Model domains are decomposed for parallelism on two-levels

Patch: section of model domain allocated to a distributed memory node, this is the scope of a mediation layer solver or physics driver.

Tile: section of a patch allocated to a shared-memory processor within a node; this is also the scope of a model layer subroutine.

Distributed memory parallelism is over patches; shared memory parallelism is over tiles within patches

Distributed Memory Communications

When Needed?

Communication is required between patches when a horizontal index is incremented or decremented on the right-hand-side of an assignment.

Why?

On a patch boundary, the index may refer to a value that is on a different patch.

Following is an example code fragment that requires communication between patches

Note the tell-tale +1 and –1 expressions in indices for **rr**, **H1,** and **H2** arrays on right-hand side of assignment.

These are ***horizontal data dependencies*** because the indexed operands may lie in the patch of a neighboring processor. That neighbor's updates to that element of the array won't be seen on this processor.

Dr Phil

We have to communicate.

Distributed Memory Communications

```
                        (module_diffusion.F )

SUBROUTINE horizontal_diffusion_s (tendency, rr, var, . . .
. . .
   DO j = jts,jte
   DO k = kts,ktf
   DO i = its,ite
      mrdx=msft(i,j)*rdx
      mrdy=msft(i,j)*rdy
      tendency(i,k,j)=tendency(i,k,j)-                            &
           (mrdx*0.5*((rr(i+1,k,j)+rr(i,k,j))*H1(i+1,k,j)-        &
                      (rr(i-1,k,j)+rr(i,k,j))*H1(i  ,k,j))+       &
            mrdy*0.5*((rr(i,k,j+1)+rr(i,k,j))*H2(i,k,j+1)-        &
                      (rr(i,k,j-1)+rr(i,k,j))*H2(i,k,j  ))-       &
            msft(i,j)*(H1avg(i,k+1,j)-H1avg(i,k,j)+               &
                       H2avg(i,k+1,j)-H2avg(i,k,j)                &
                                )/dzetaw(k)                       &
           )
   ENDDO
   ENDDO
   ENDDO
 . . .
```

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SUBROUTINE horizontal_diffusion_s (tendency, rr, var, . . .
. . .
   DO j = jts,jte
   DO k = kts,ktf
   DO i = its,ite
      mrdx=msft(i,j)*rdx
      mrdy=msft(i,j)*rdy
      tendency(i,k,j)=tendency(i,k,j)-                              &
           (mrdx*0.5*((rr(i+1,k,j)+rr(i,k,j))*H1(i+1,k,j)-          &
                      (rr(i-1,k,j)+rr(i,k,j))*H1(i  ,k,j))+         &
            mrdy*0.5*((rr(i,k,j+1)+rr(i,k,j))*H2(i,k,j+1)-          &
                      (rr(i,k,j-1)+rr(i,k,j))*H2(i,k,j  ))-         &
            msft(i,j)*(H1avg(i,k+1,j)-H1avg(i,k,j)+                 &
                       H2avg(i,k+1,j)-H2avg(i,k,j)                  &
                                )/dzetaw(k)                         &
           )
   ENDDO
   ENDDO
   ENDDO
 . . .
```

Distributed Memory Communications

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           (mrdx*0.5*((rr(i+1,k,j)+rr(i,k,j))*H1(i+1,k,j)-       &
                      (rr(i-1,k,j)+rr(i,k,j))*H1(i  ,k,j))+      &
            mrdy*0.5*((rr(i,k,j+1)+rr(i,k,j))*H2(i,k,j+1)-       &
                      (rr(i,k,j-1)+rr(i,k,j))*H2(i,k,j  ))-      &
            msft(i,j)*(H1avg(i,k+1,j)-H1avg(i,k,j)+              &
                       H2avg(i,k+1,j)-H2avg(i,k,j)               &
                                )/dzetaw(k)                      &
           )
   ENDDO
   ENDDO
   ENDDO
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```
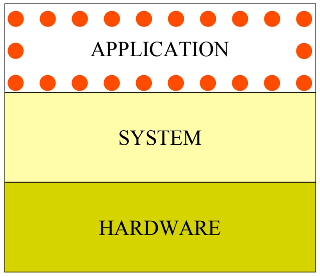
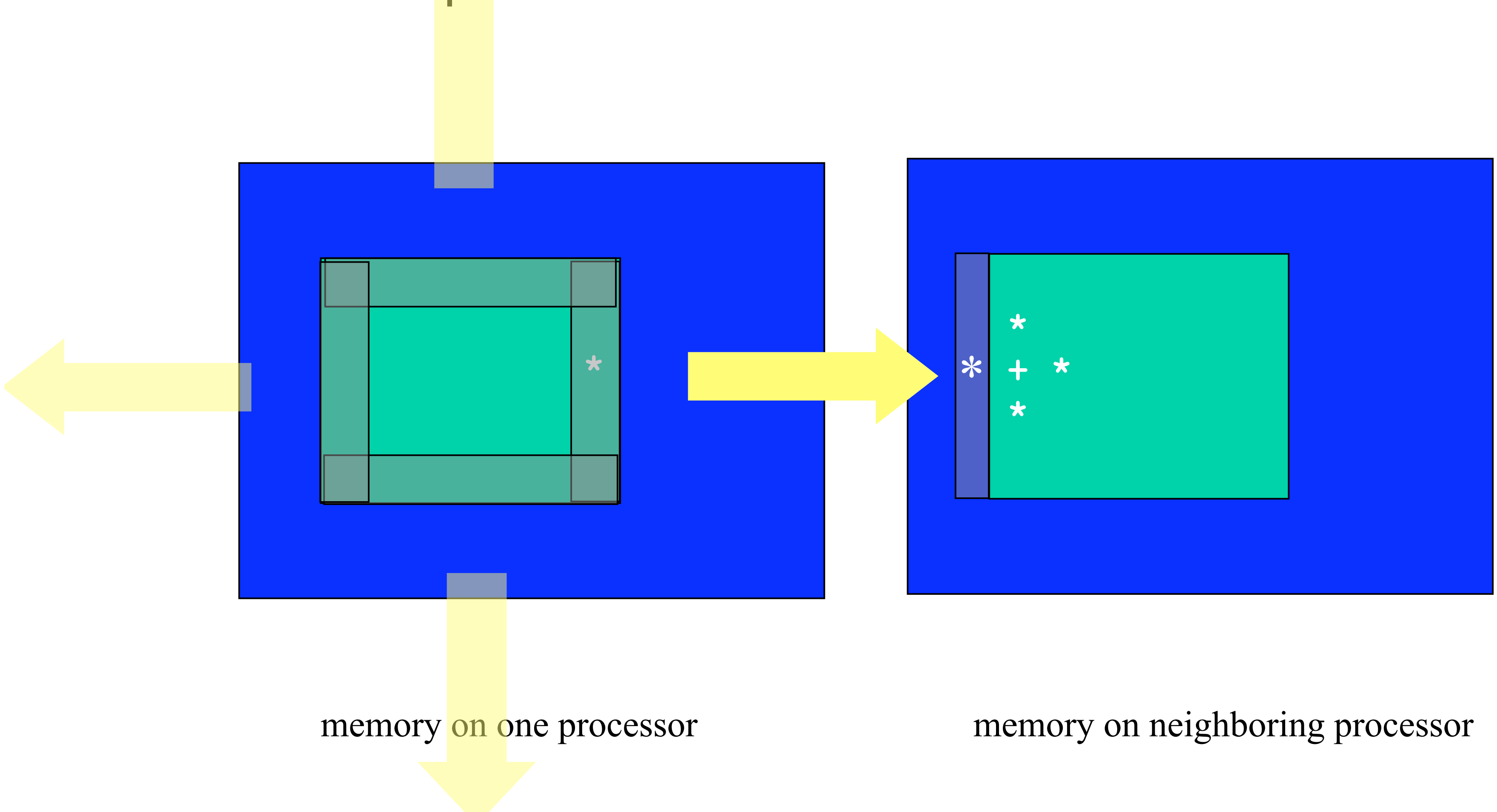
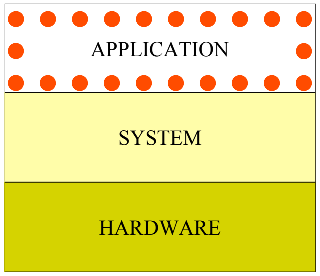



Distributed Memory MPI Communications

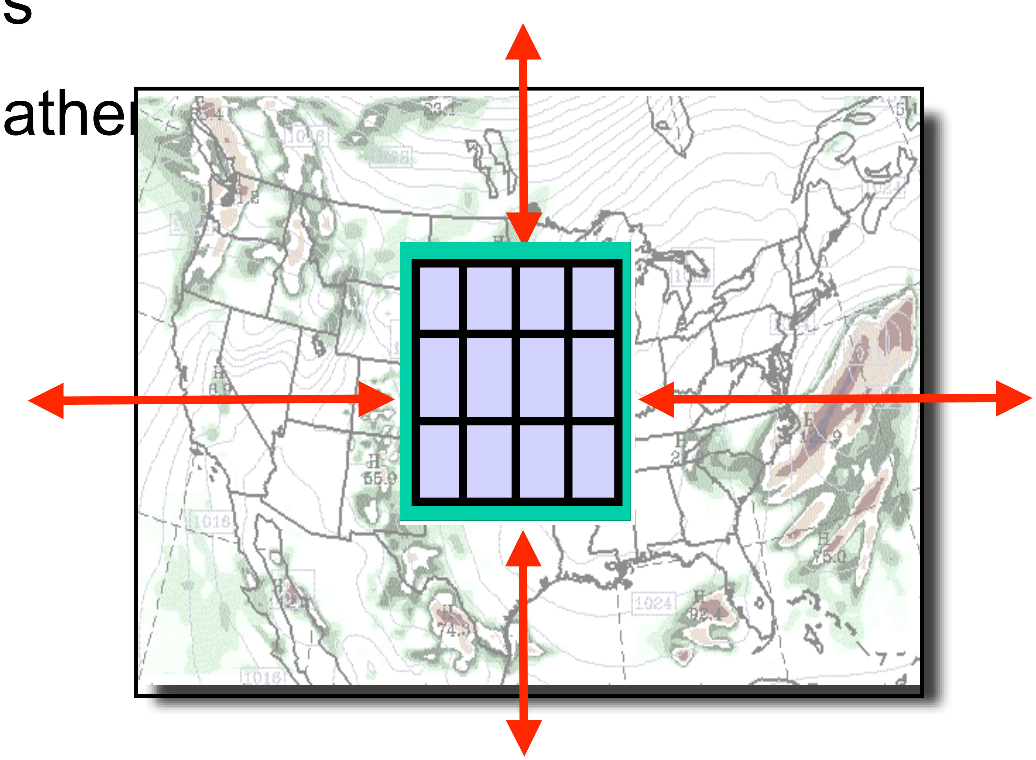
- Halo updates

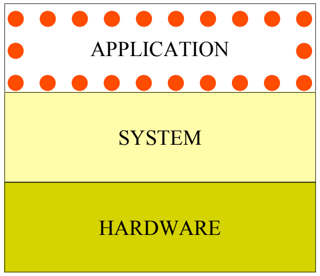




Distributed Memory (MPI) Communications

- Halo updates
- Periodic boundary updates
- Parallel transposes
- Nesting scatters/gathe





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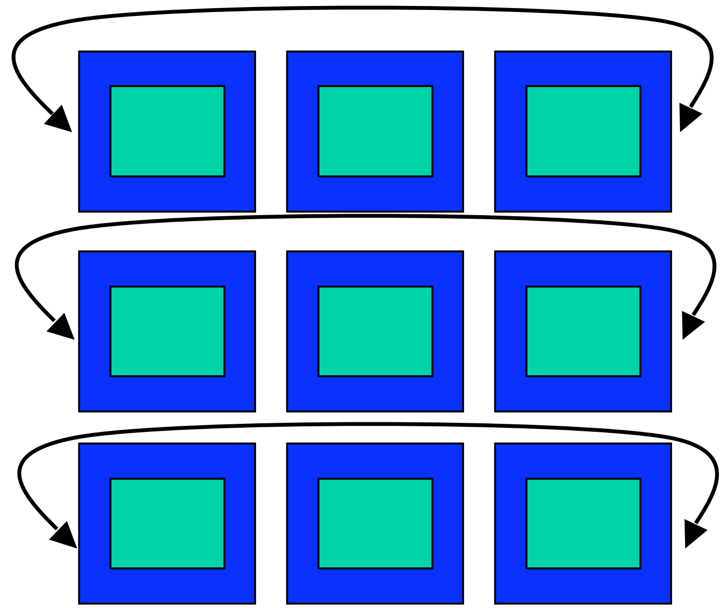

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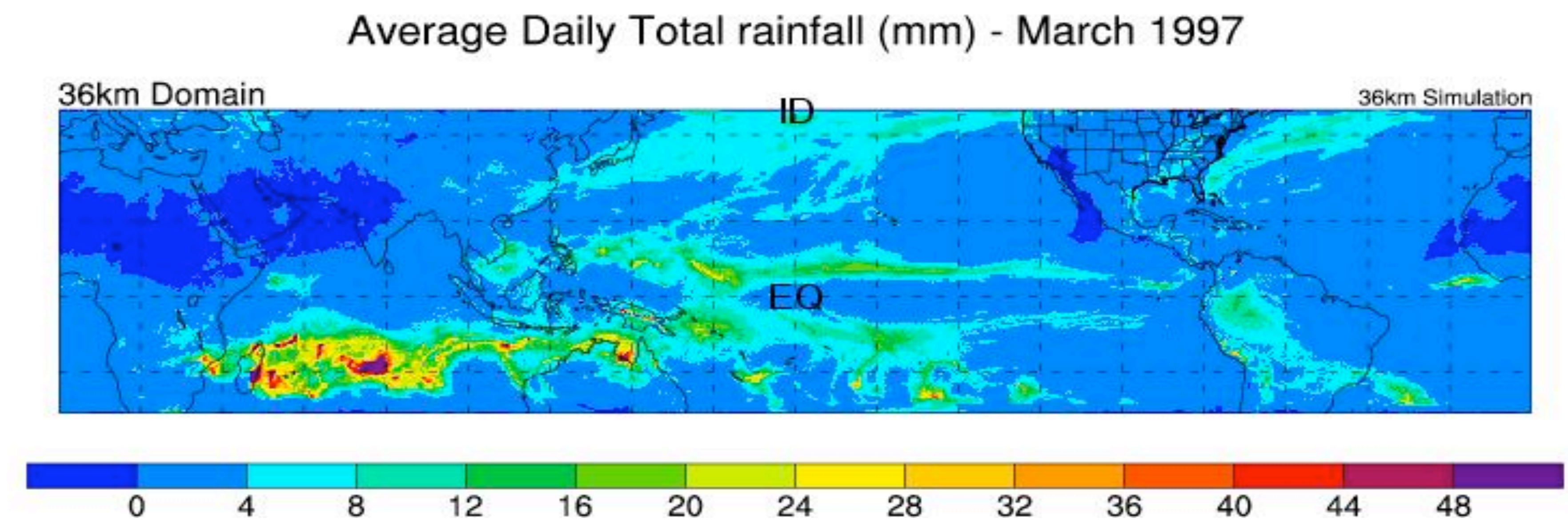

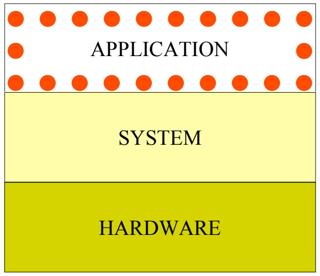

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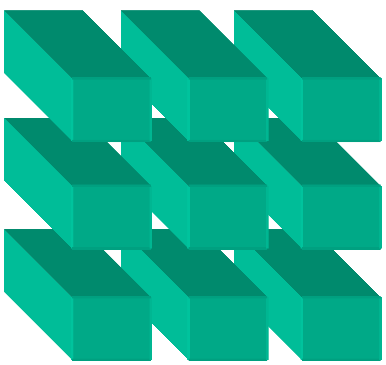
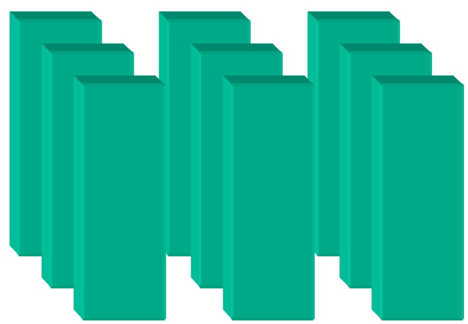
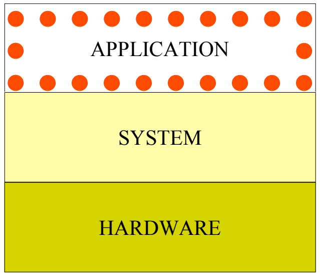


all y on patch



all z on patch

all x on patch



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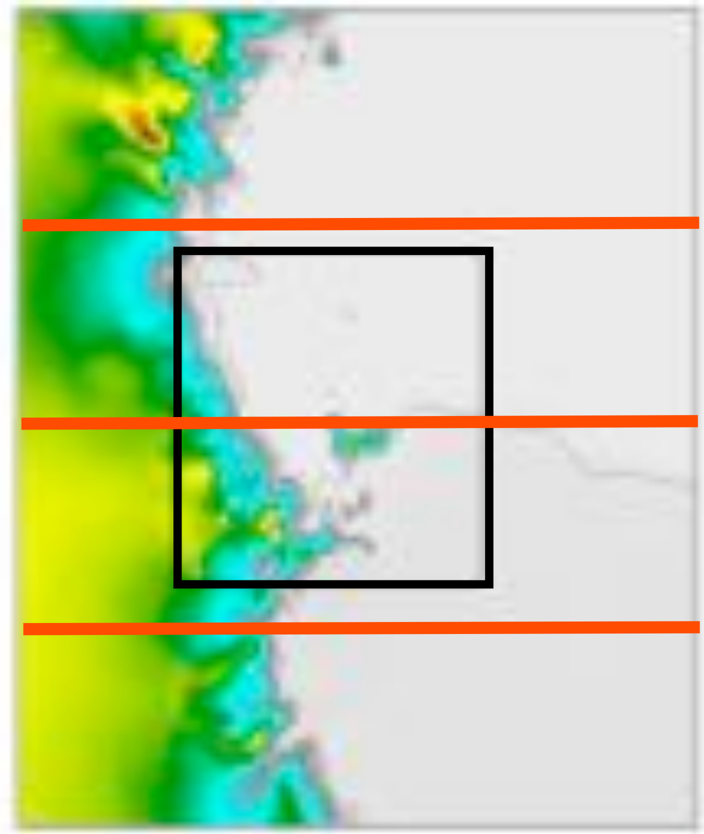
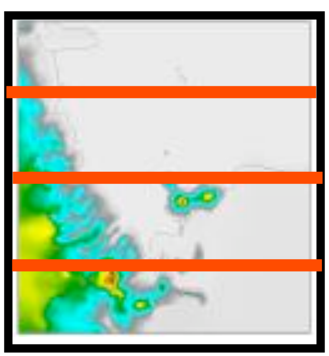
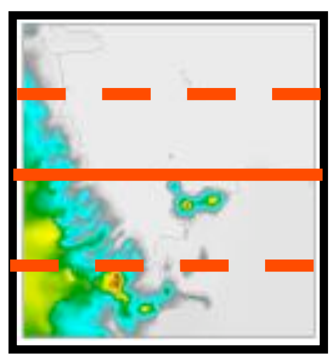


COARSE
Ross Island
6.66 km



NEST:2.22 km



INTERMEDIATE: 6.66 km

Review – Computing Overview

			Distributed Memory Parallel		Shared Memory Parallel
APPLICATION (WRF)	Domain	*contains*	Patches	*contain*	Tiles
SYSTEM (UNIX, MPI, OpenMP)	Job	*contains*	Processes	*contain*	Threads
HARDWARE (Processors, Memories, Wires)	Cluster	*contains*	Nodes	*contain*	Processors

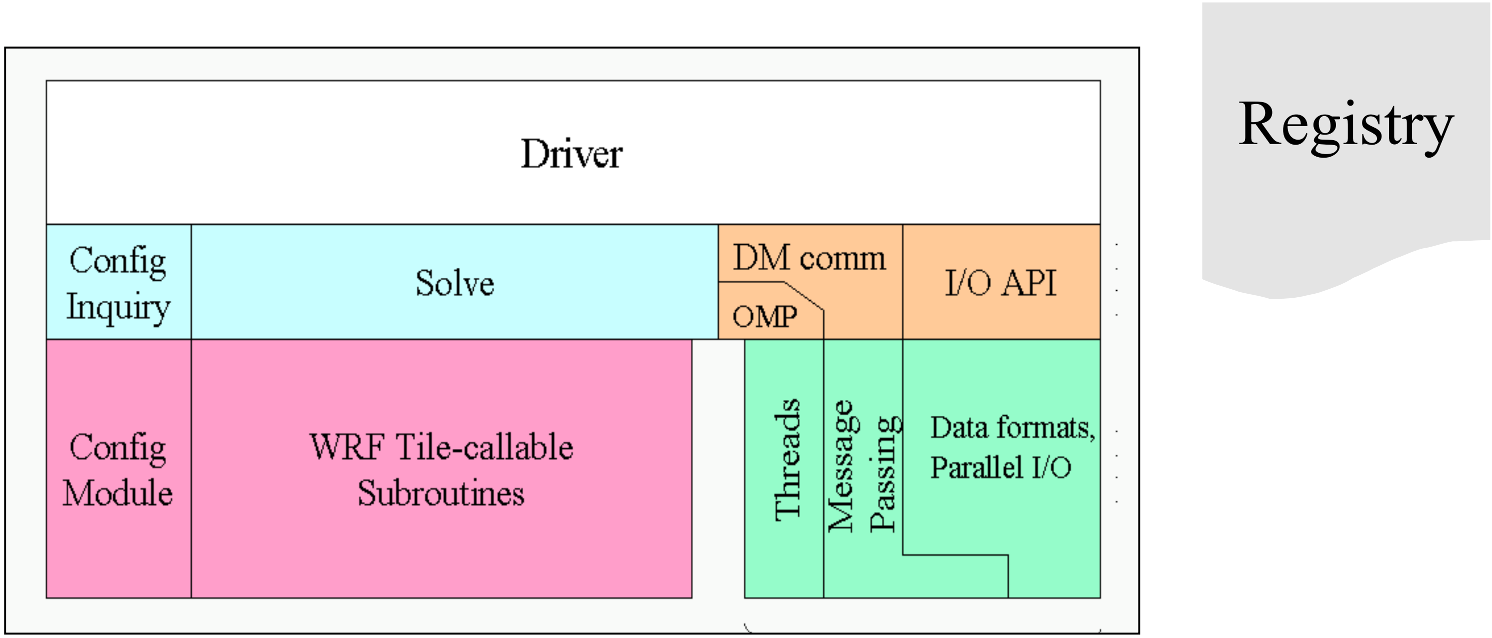
Outline

- Introduction
- Computing Overview
- WRF Software Overview

WRF Software Overview

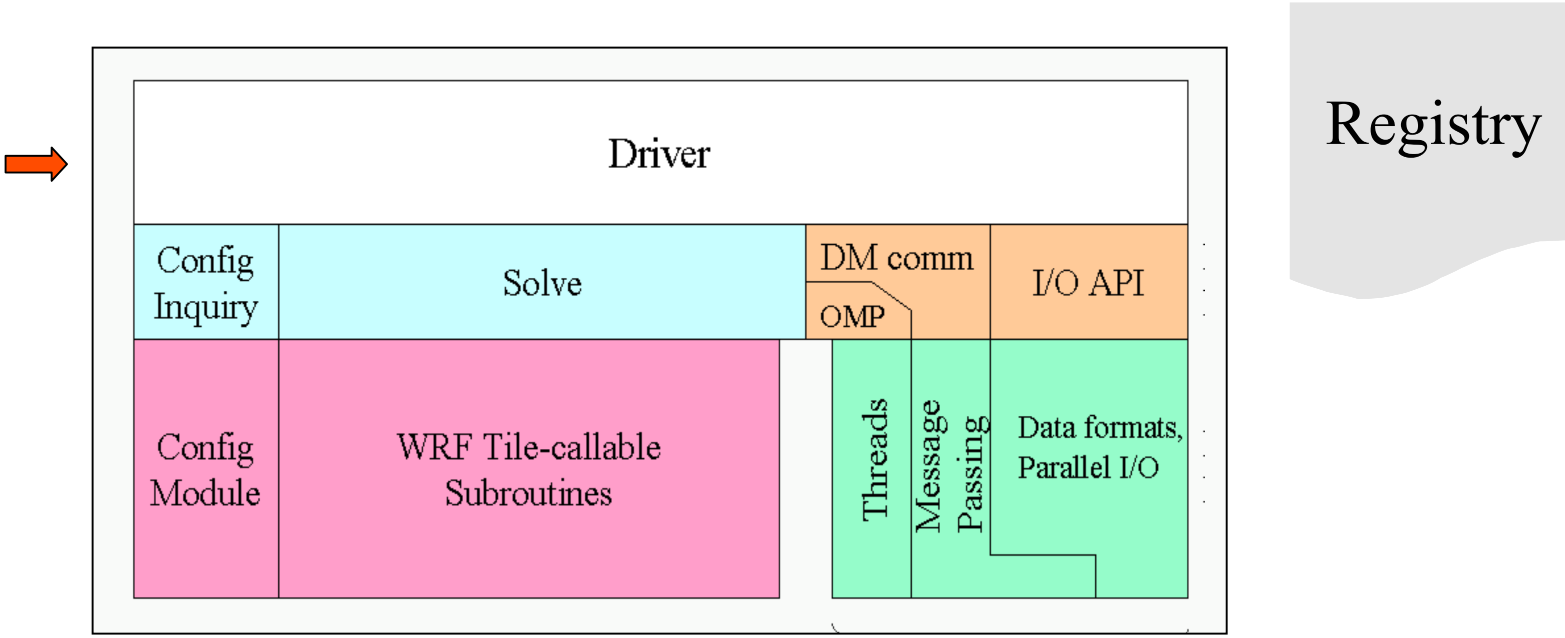
- Architecture
- Directory structure
- Model Layer Interface
- Data Structures
- I/O

WRF Software Architecture



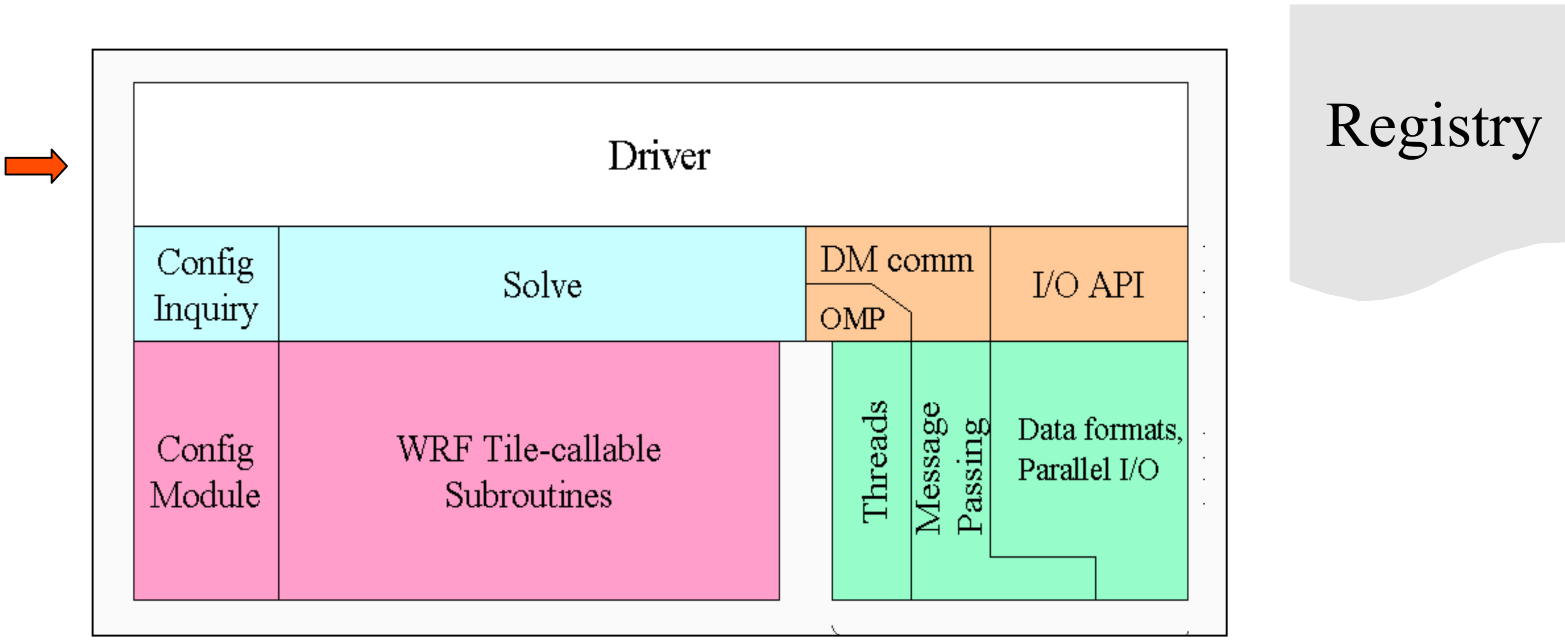
- Hierarchical software architecture
  - Insulate scientists' code from parallelism and other architecture/implementation-specific details
  - Well-defined interfaces between layers, and external packages for communications, I/O, and model coupling facilitates code reuse and exploiting of community infrastructure, e.g. ESMF.

WRF Software Architecture



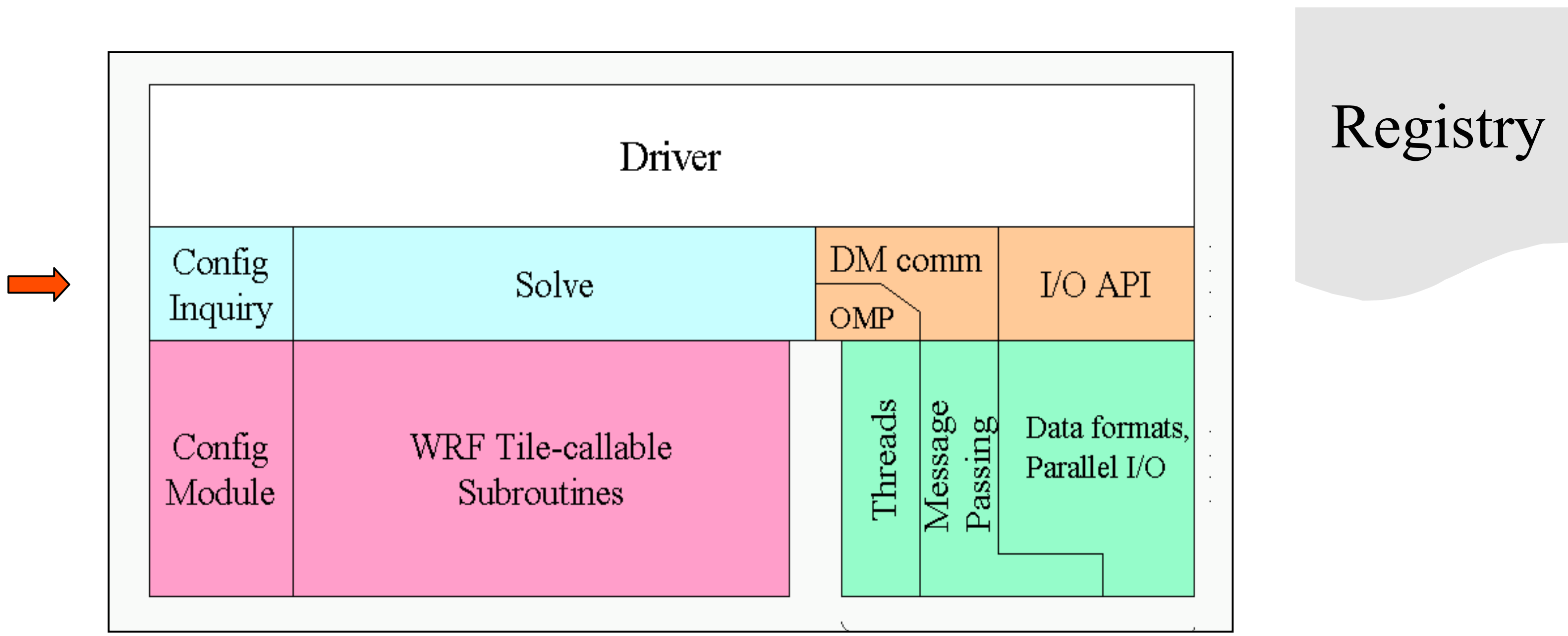
- Driver Layer
  - **Domains**: Allocates, stores, decomposes, represents abstractly as single data objects
  - **Time loop**: top level, algorithms for integration over nest hierarchy

WRF Software Architecture



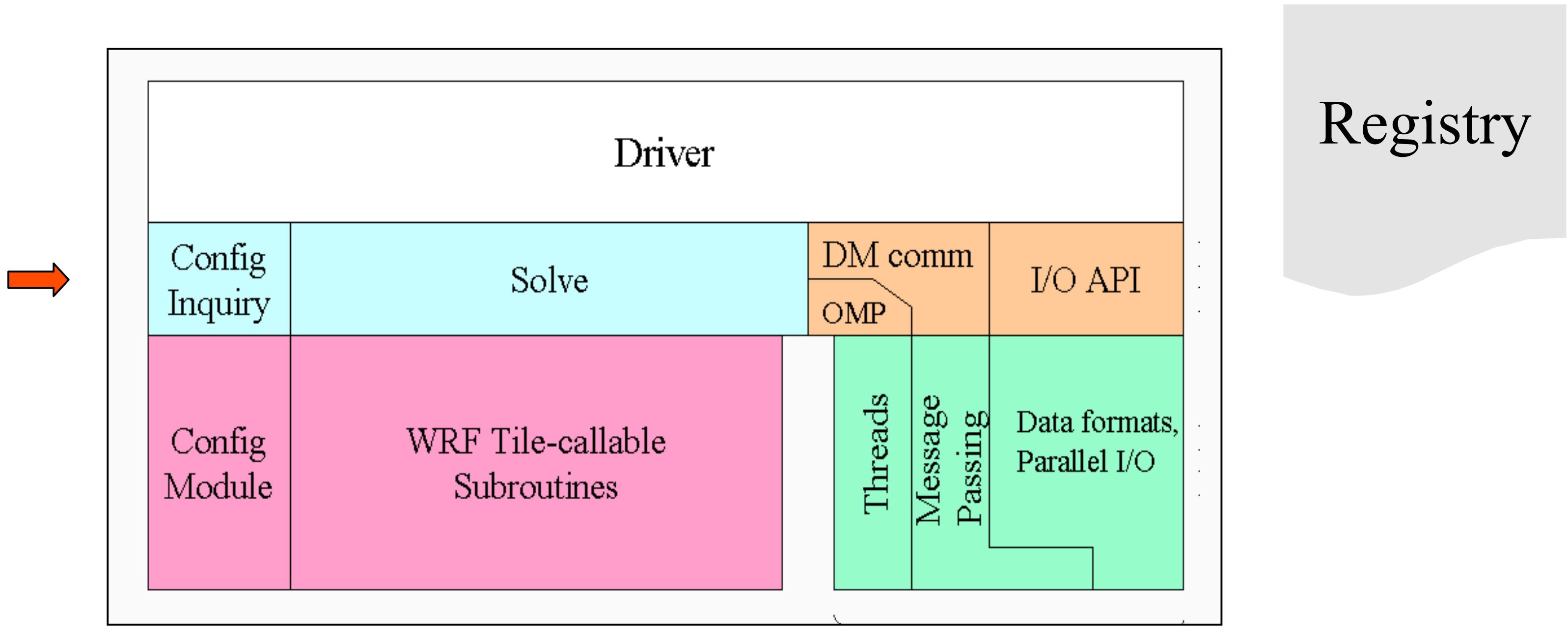
- Driver Layer
  - **Non package-specific access:** communications and I/O
  - **Utilities:** for example module_wrf_error, which is used for diagnostic prints and error stops, accessibility to run-time options

WRF Software Architecture



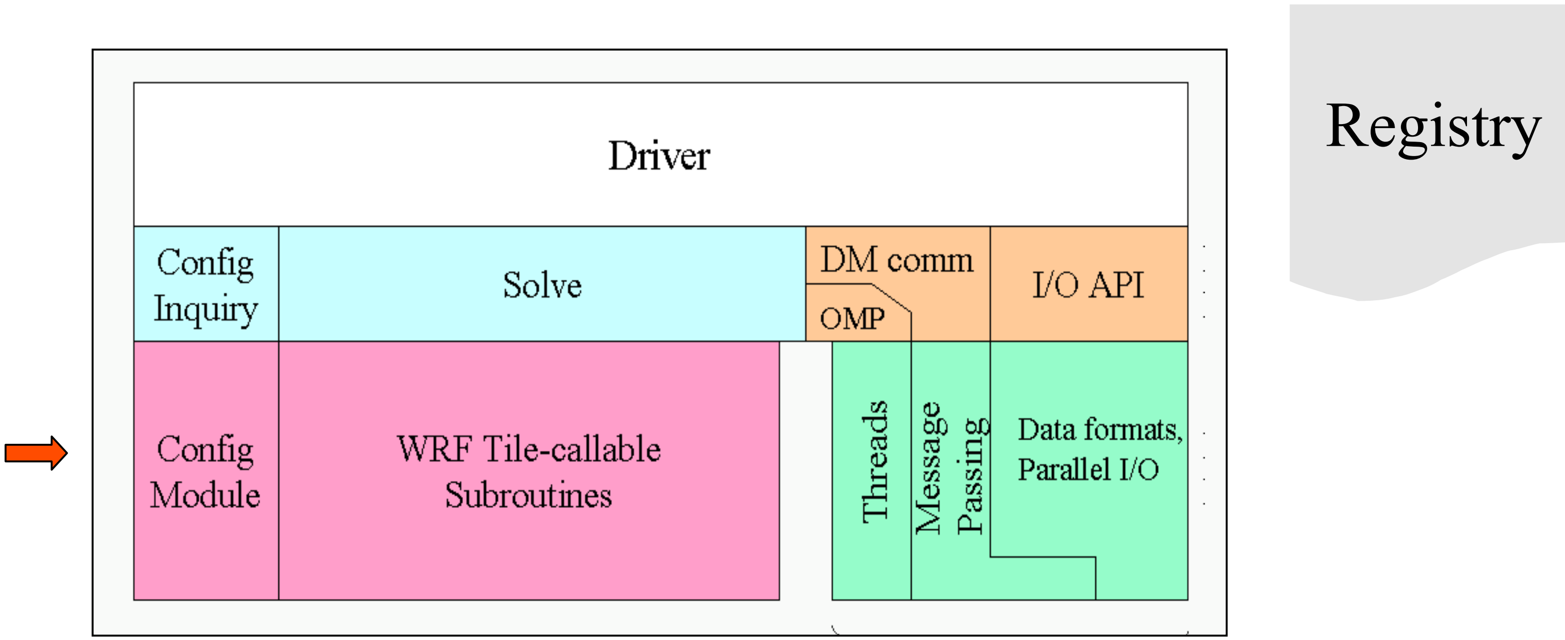
- Mediation Layer
  - Provides to the Driver Layer
    - Solve routine, which takes a domain object and advances it one time step
    - I/O routines that Driver calls when it is time to do some input or output operation on a domain
    - Nest forcing, interpolation, and feedback routines

WRF Software Architecture



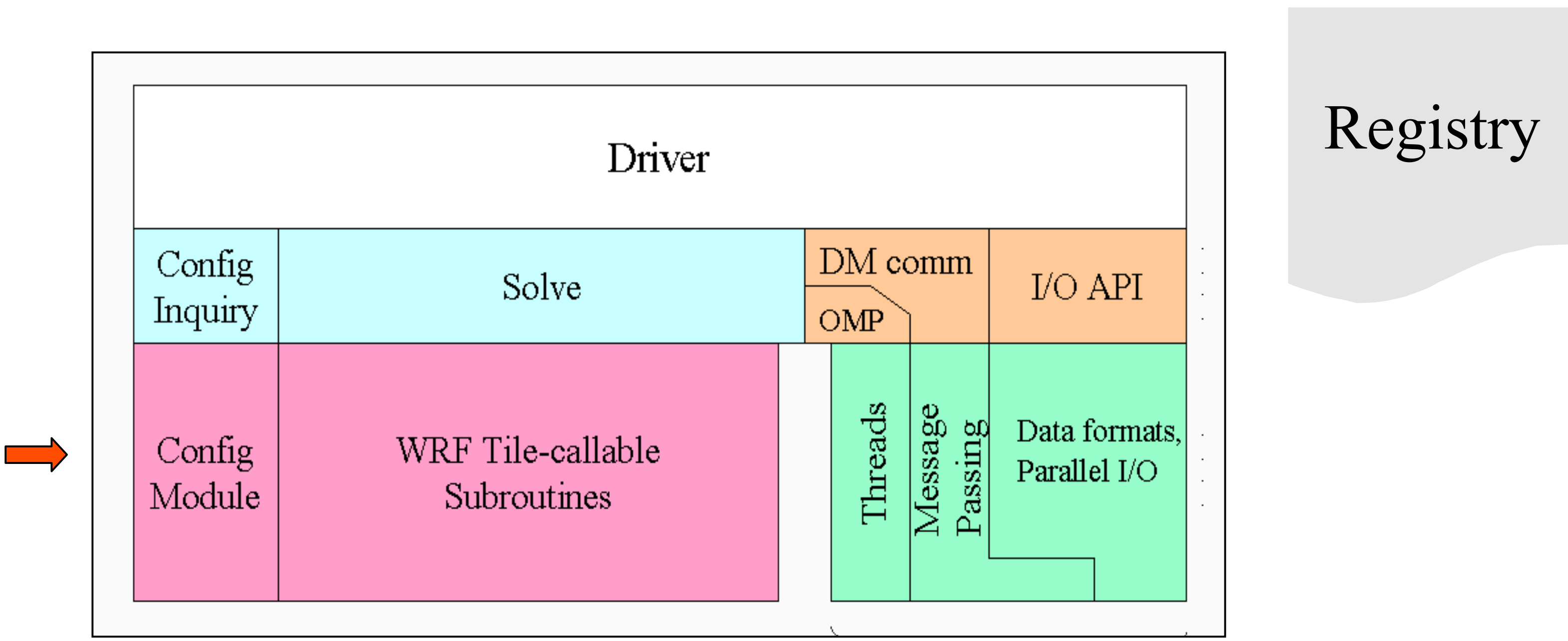
- Mediation Layer
  - Provides to Model Layer
    - The sequence of calls for doing a time-step for one domain is known in Solve routine
    - Dereferences fields in calls to physics drivers and dynamics code
    - Calls to message-passing are contained here as part of Solve routine

WRF Software Architecture



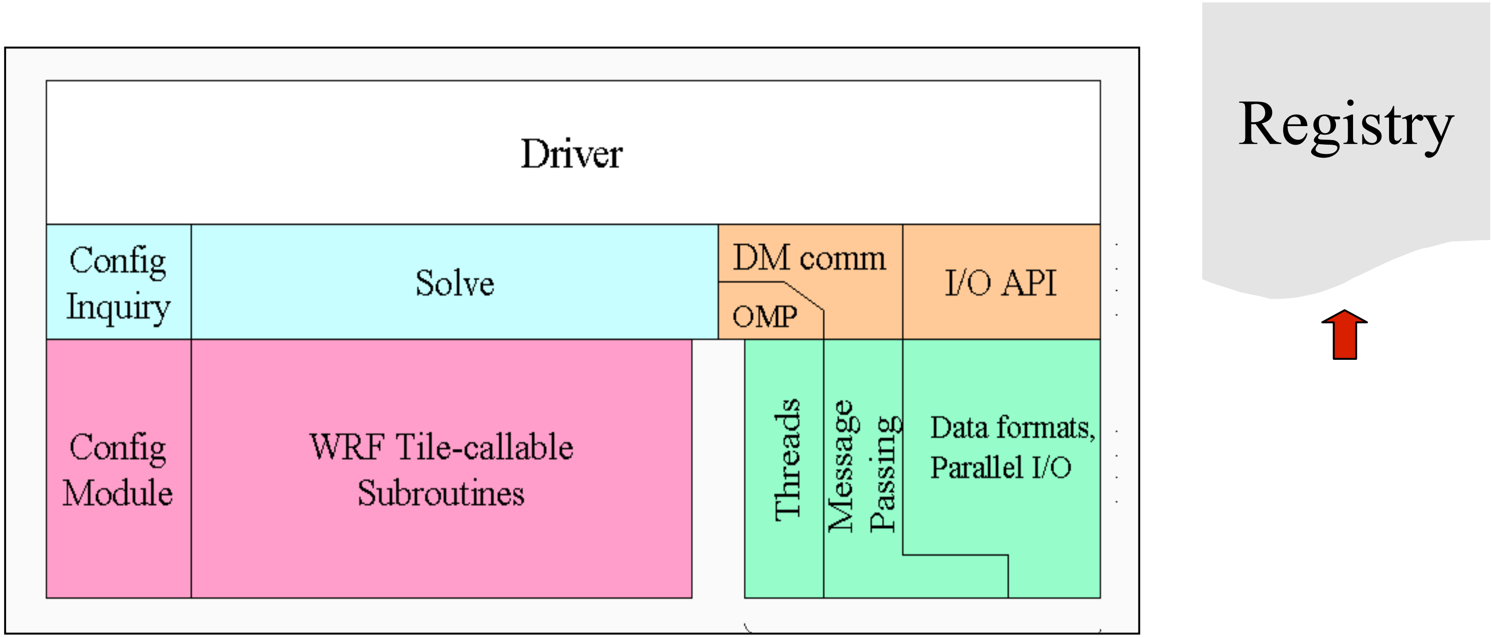
- Model Layer
  - **Information about the model itself**: machine architecture and implementation aspects abstracted out and moved into layers above
  - **Physics and Dynamics**: contains the actual WRF model routines are written to perform some computation over an arbitrarily sized/shaped subdomain

WRF Software Architecture



- Model Layer
  - **F77-esque**: all state data objects are simple types, passed in through argument list from physics drivers
  - **No I/O, comms, control**: Model Layer routines don't know anything about communication or I/O, executed on **one thread** – they <u>never</u> contain a **PRINT**, **WRITE**, or **STOP** statement
  - **Model Layer Subroutine Interface**: "tile-callable", no external COMMON, no decomposed heap data

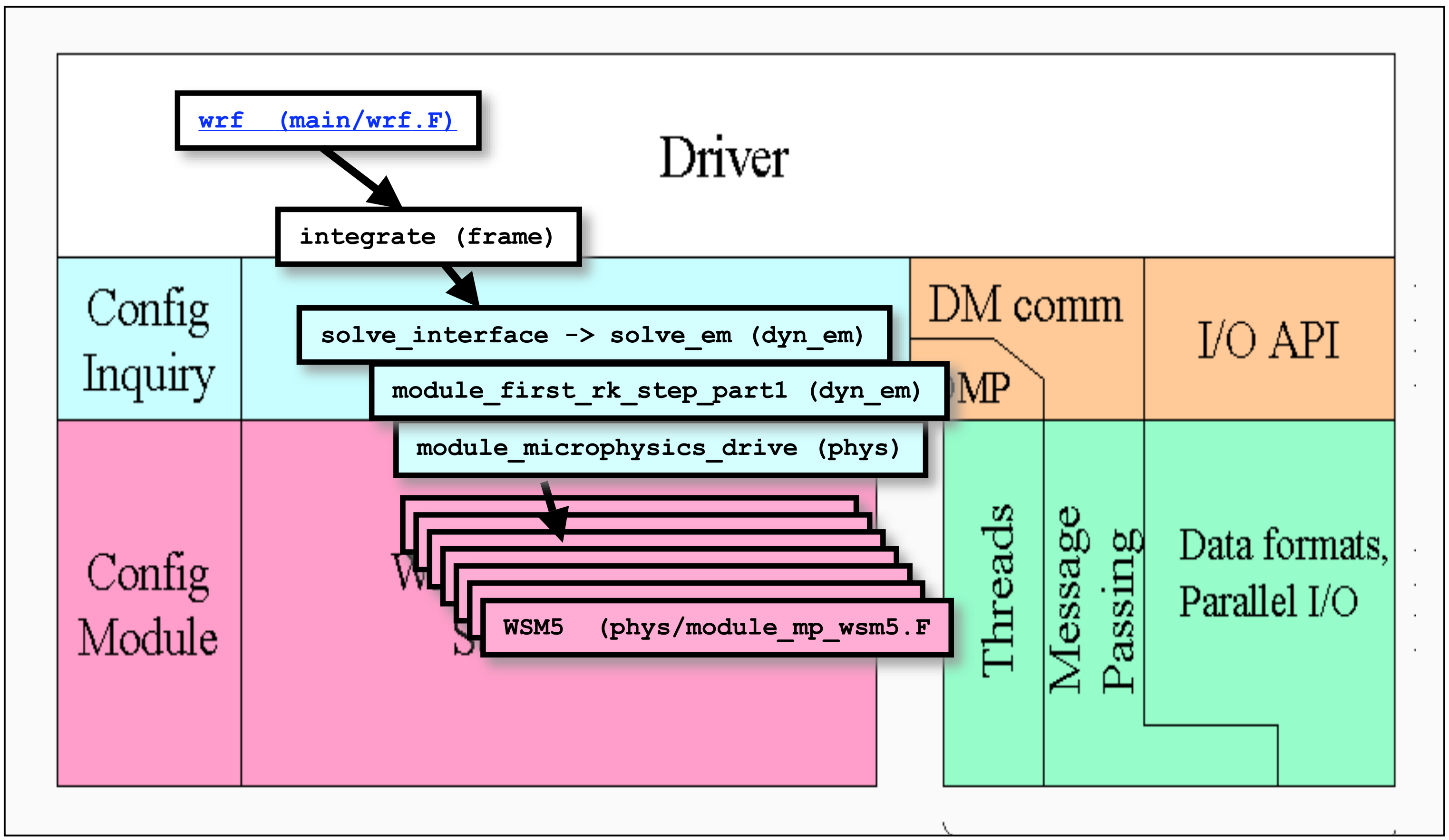
WRF Software Architecture



- Registry: an "Active" data dictionary
  - Tabular listing of model state and attributes
  - Large sections of interface code generated automatically
  - Scientists manipulate model state simply by modifying Registry, without further knowledge of code mechanics
  - Special "cases" exist: chemistry, SST coupling

Call Structure Superimposed on Architecture

module_microphysics_driver (phys)



WRF Software Overview

- Architecture
- Directory structure
- Model Layer Interface
- Data Structures
- I/O

WRF Model Top-Level Directory Structure

WRF Design and Implementation Doc, p 5

DRIVER ●
MEDIATION ●
MODEL ●

```
  Makefile
  README
  README_test_cases
  clean          }
  compile        }  build scripts
  configure      }
  Registry/         CASE input files
  arch/             machine build rules
● dyn_em/        }
● dyn_nnm/       }
  external/      }
● frame/         }
  inc/           }  source code directories
● main/          }
● phys/          }
● share/         }
  tools/         }
  run/           }  execution directories
  test/          }
```

WRF Software Overview

- Architecture
- Directory structure
- Model Layer Interface
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- I/O

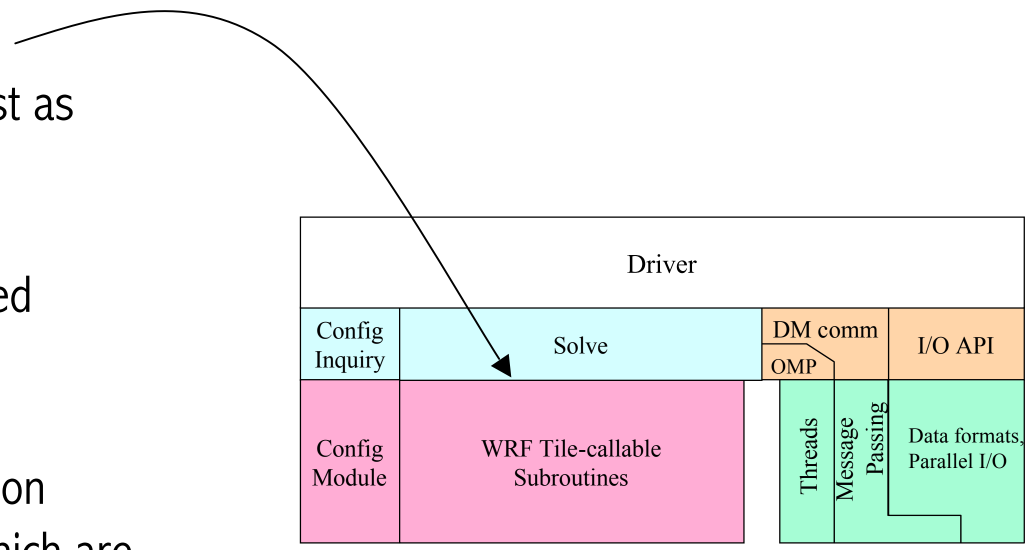
WRF Model Layer Interface

Mediation Layer / Model Layer Interface

All state arrays passed through argument list as simple (not derived) data types

Domain, memory, and run dimensions passed unambiguously in three physical dimensions

Model layer routines are called from mediation layer (physics drivers) in loops over tiles, which are multi-threaded

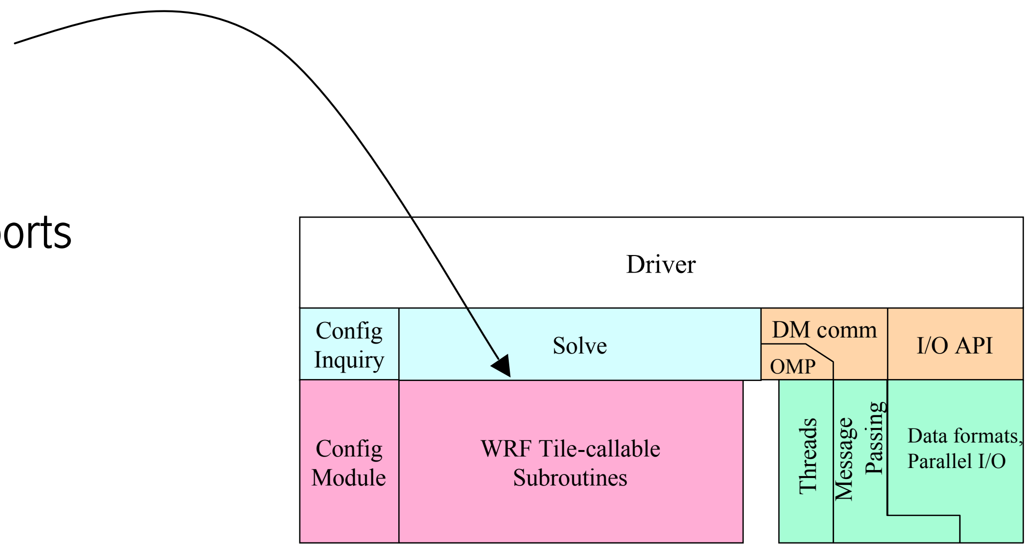


WRF Model Layer Interface

Mediation Layer / Model Layer Interface

Restrictions on Model Layer subroutines:

No I/O, communication, no stops or aborts (use wrf_error_fatal in frame/module_wrf_error.F)



No common/module storage of decomposed data (exception allowed for set-once/read-only tables)

Spatial scope of a Model Layer call is one “tile”

WRF Model Layer Interface

- Mediation layer / Model Layer Interface contract exists
- Model layer routines are called from mediation layer in loops over tiles, which are multi-threaded
- All state arrays passed through argument list as simple data types

WRF Model Layer Interface

- Domain, memory, and run dimensions passed unambiguously in three physical dimensions
- Restrictions on model layer subroutines
  - No I/O, communication, no stops or aborts (use wrf_error_fatal in frame/module_wrf_error.F)
  - No common/module storage of decomposed data (exception allowed for set-once/read-only tables)
  - Spatial scope of a Model Layer call is one “tile”
  - Temporal scope of a call is limited by coherency

WRF Model Layer Interface

```
SUBROUTINE driver_for_some_physics_suite (
    . . .
!$OMP DO PARALLEL
   DO ij = 1, numtiles
      its = i_start(ij) ; ite = i_end(ij)
      jts = j_start(ij) ; jte = j_end(ij)
      CALL model_subroutine( arg1, arg2, . . .
           ids , ide , jds , jde , kds , kde ,
           ims , ime , jms , jme , kms , kme ,
           its , ite , jts , jte , kts , kte )
   END DO
    . . .

 END SUBROUTINE
```

WRF Model Layer Interface

template for model layer subroutine

```
SUBROUTINE model_subroutine ( &
  arg1, arg2, arg3, … , argn,    &
  ids, ide, jds, jde, kds, kde, &  ! Domain dims
  ims, ime, jms, jme, kms, kme, &  ! Memory dims
  its, ite, jts, jte, kts, kte  )  ! Tile dims

IMPLICIT NONE

! Define Arguments (State and I1) data
REAL, DIMENSION (ims:ime,kms:kme,jms:jme) :: arg1, . . .
REAL, DIMENSION (ims:ime,jms:jme)         :: arg7, . . .
 . . .
! Define Local Data (I2)
REAL, DIMENSION (its:ite,kts:kte,jts:jte) :: loc1, . . .
 . . .
```

WRF Model Layer Interface

template for model layer subroutine

```
. . .
 ! Executable code; loops run over tile
 ! dimensions
 DO j = MAX(jts,jds), MIN(jte,jde-1)
   DO k = kts, kte
     DO i = MAX(its,ids), MIN(ite,ide-1)
       loc1(i,k,j) = arg1(i,k,j) + …
     END DO
   END DO
 END DO
```

template for model layer subroutine

```
SUBROUTINE model ( &
  arg1, arg2, arg3, … , argn,    &
  ids, ide, jds, jde, kds, kde, &  ! Domain dims
  ims, ime, jms, jme, kms, kme, &  ! Memory dims
  its, ite, jts, jte, kts, kte  )  ! Tile dims

IMPLICIT NONE

! Define Arguments (S and I1) data
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  DO k = kts, kte
    DO i = MAX(its,ids), MIN(ite,ide-1)
      loc1(i,k,j) = arg1(i,k,j) + …
    END DO
  END DO
END DO
```
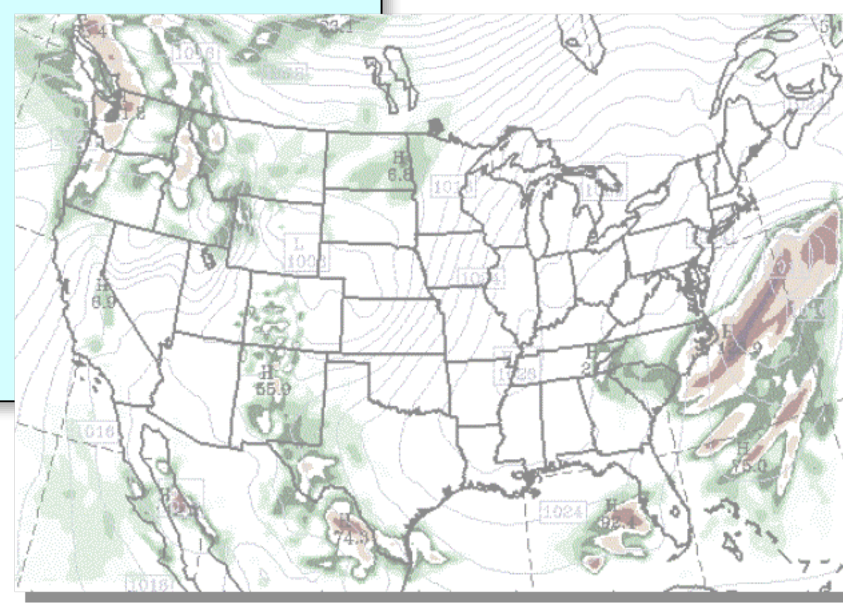

- Domain dimensions
  - Size of logical domain
  - Used for bdy tests, etc.



template for model layer subroutine

```
SUBROUTINE model ( &
  arg1, arg2, arg3, … , argn,   &
  ids, ide, jds, jde, kds, kde, &  ! Domain dims
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  DO k = kts, kte
    DO i = MAX(its,ids), MIN(ite,ide-1)
      loc1(i,k,j) = arg1(i,k,j) + …
    END DO
  END DO
END DO
```
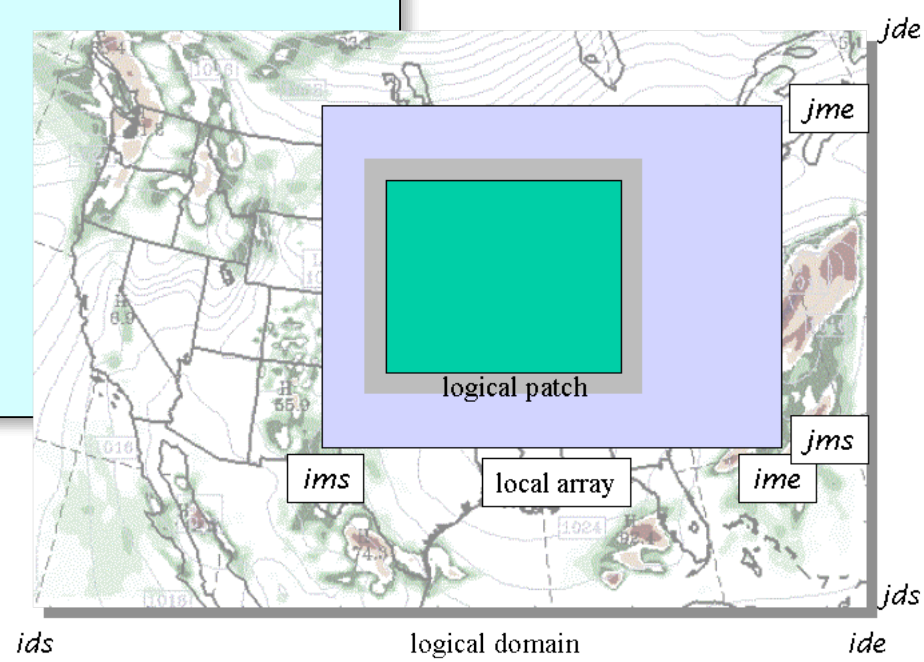

- Domain dimensions
  - Size of logical domain
  - Used for bdy tests, etc.
- Memory dimensions
  - Used to dimension dummy arguments
  - Do not use for local arrays



template for model layer subroutine

```
SUBROUTINE model ( &
  arg1, arg2, arg3, … , argn,    &
  ids, ide, jds, jde, kds, kde, &  ! Domain dims
  ims, ime, jms, jme, kms, kme, &  ! Memory dims
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! Executable code; loops run over tile
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  DO k = kts, kte
    DO i = MAX(its,ids), MIN(ite,ide-1)
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    END DO
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END DO
```
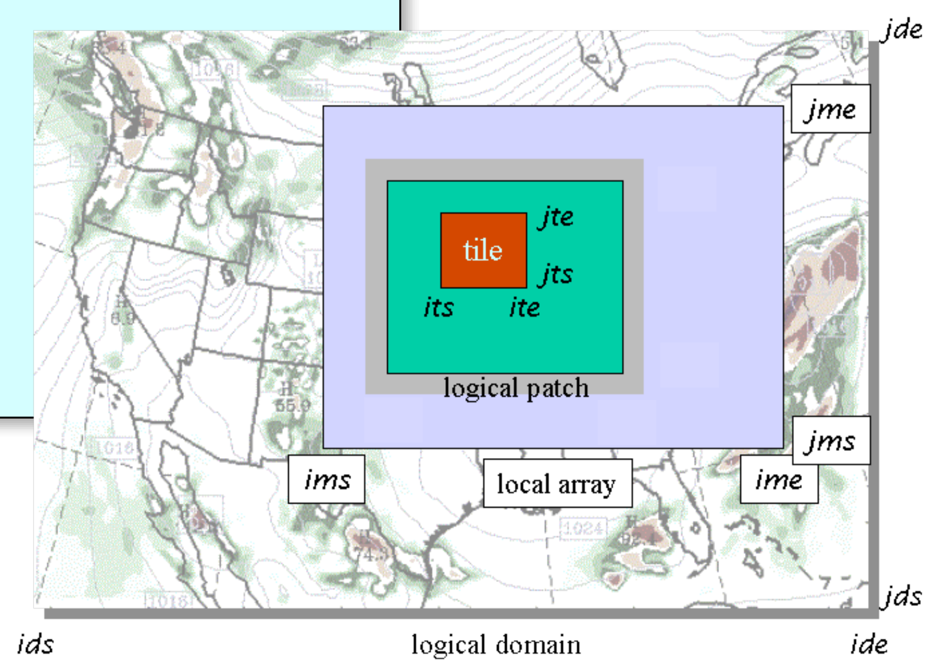

- Domain dimensions
  - Size of logical domain
  - Used for bdy tests, etc.
- Memory dimensions
  - Used to dimension dummy arguments
  - Do not use for local arrays
- Tile dimensions
  - Local loop ranges
  - Local array dimensions



template for model layer subroutine

```
SUBROUTINE model ( &
  arg1, arg2, arg3, … , argn,    &
  ids, ide, jds, jde, kds, kde, &  ! Domain dims
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 . . .
! Define Local Data (I2)
REAL, DIMENSION (its:ite,kts:kte,jts:jte) :: loc1, . . .
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! Executable code; loops run over tile
! dimensions
DO j = MAX(jt,jds), MIN(jte,jde-1)
  DO k = kts, kte
    DO i = MAX(its,ids), MIN(ite,ide-1)
      loc1(i,k,j) = arg1(i,k,j) + …
    END DO
  END DO
END DO
```
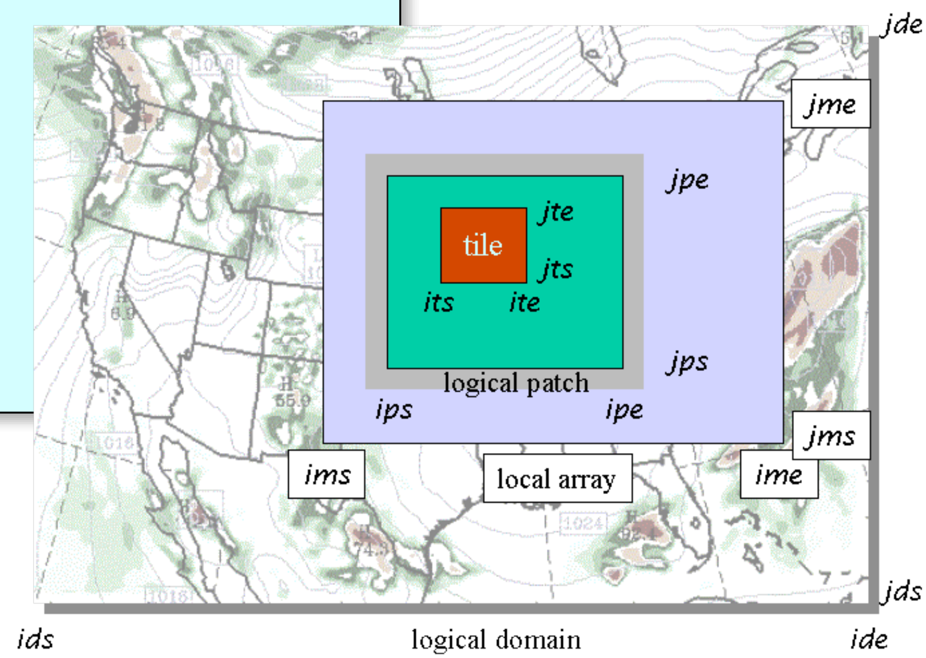

- Domain dimensions
  - Size of logical domain
  - Used for bdy tests, etc.
- Memory dimensions
  - Used to dimension dummy arguments
  - Do not use for local arrays
- Tile dimensions
  - Local loop ranges
  - Local array dimensions

- Patch dimensions
  - Start and end indices of local distributed memory subdomain
  - Available from mediation layer (solve) and driver layer; not usually needed or used at model layer

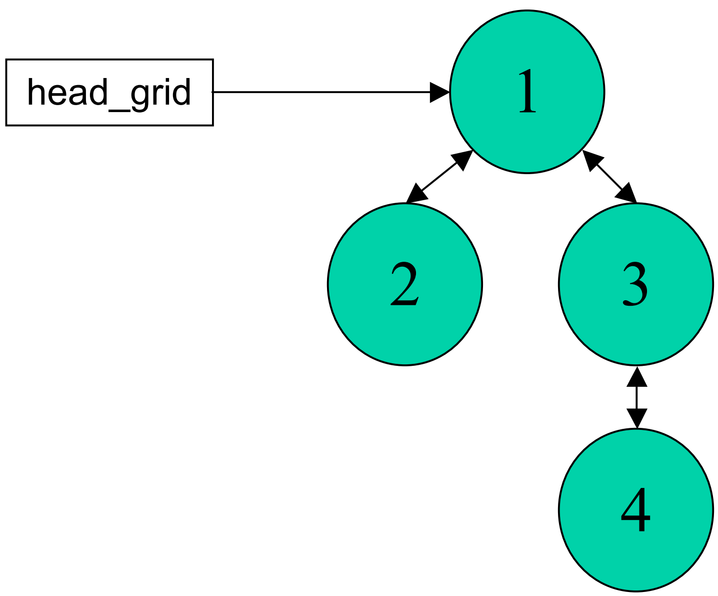


WRF Software Overview

- Architecture
- Directory structure
- Model Layer Interface
- Data Structures
- I/O

Driver Layer Data Structures: Domain Objects

- Driver layer
  - All data for a domain is an object, a domain **derived data type** (DDT)
  - The domain DDTs are dynamically allocated/deallocated
  - Linked together in a tree to represent nest hierarchy; root pointer is **head_grid**, defined in frame/module_domain.F
  - Supports recursive depth-first traversal algorithm (frame/module_integrate.F)



- Every Registry defined state, l1, and namelist variable is contained inside the DDT (locally known as a grid of type domain), where each node in the tree represents a separate and complete 3D model domain/nest.

Model Layer Data Structures: F77

- Model layer
  - All data objects are scalars and arrays of simple types only
  - Virtually all passed in through subroutine argument lists
  - Non-decomposed arrays and "local to a module" storage are permitted with an initialization at the model start

Mediation Layer Data Structures: Objects + F77

- Mediation layer
  - One task of mediation layer is to dereference fields from DDTs
  - Therefore, sees domain data in both forms, as DDT and as individual fields which are components of the DDTs

- The name of a data type and how it is referenced differs depending on the level of the architecture

Data Structures

- WRF Data Taxonomy
  - State data
  - Intermediate data type 1 (I1)
  - Intermediate data type 2 (I2)
  - Heap storage (COMMON or Module data)

Data Structures

- WRF Data Taxonomy
  - State data
  - Intermediate data type 1 (I1)
  - Intermediate data type 2 (I2)
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Defined in the Registry

Data Structures

- WRF Data Taxonomy
  - State data
  - Intermediate data type 1 (I1)
  - Intermediate data type 2 (I2)
  - Heap storage (COMMON or Module data)

Defined in the physics subroutines on the stack

Data Structures

- WRF Data Taxonomy
  - State data
  - Intermediate data type 1 (I1)
  - Intermediate data type 2 (I2)
  - Heap storage (COMMON or Module)

Defined in the module top, typically look-up tables and routine constants, NO HORIZ DECOMPOSED DATA! Common blocks must not leave the Module.

Mediation/Model Layer Data Structures: State Data

- Duration: Persist between start and stop of a domain
- Represented as fields in domain data structure
  - Memory for state arrays are dynamically allocated, only big enough to hold the local subdomain's (ie. patch's) set of array elements
  - Always **memory** dimensioned
  - Declared in Registry using **state** keyword
- Only state arrays can be subject to I/O and Interprocessor communication

Mediation/Model Layer Data Structures: I1 Data

- Persist for the duration of a single time step in solve
- Represented as fields in domain data structure
  - Memory for I1 arrays are dynamically allocated, only big enough to hold the local subdomain's (ie. patch's) set of array elements
  - Always **memory** dimensioned
  - Declared in Registry using **I1** keyword
  - Typically tendency fields computed, used, and discarded at the end of every time step
  - Are not used to impact I1 variables on a child domain

Model Layer Data Structures: I2 Data

- Persist for the duration of a call of the physics routine
- NOT contained within the DDT structure (no declarations in the Registry)
  - Memory for I2 arrays are dynamically allocated on subroutine entry, and automatically deallocated on exit
  - Local, intermediate dummy variables required for physics computations
  - If I2 arrays, then they are always **tile** dimensioned
  - Not declared in the Registry, not communicated, no IO, not passed back to the solver, do not exist (retain their previous value) between successive physics calls

Grid Representation in Arrays

- Increasing indices in WRF arrays run
  - West to East (X, or I-dimension)
  - South to North (Y, or J-dimension)
  - Bottom to Top (Z, or K-dimension)
- Storage order in WRF is IKJ (ARW) and IJK (NMM) but these are a WRF Model convention, not a restriction of the WRF Software Framework (provides cache coherency, but long vectors possible)
- Output data has grid ordering independent of the ordering inside the WRF model

Grid Representation in Arrays

- The extent of the logical or *domain* dimensions is always the "staggered" grid dimension. That is, from the point of view of a non-staggered dimension (also referred to as the ARW “mass points”), there is always an extra cell on the end of the domain dimension

WRF Software Overview

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WRF I/O

- Streams: pathways into and out of model
  - History + 11 auxiliary output streams (10 and 11 are reserved for nudging)
  - Input + 11 auxiliary input streams (10 and 11 are reserved for nudging)
  - Restart, boundary, and a special Var stream

WRF I/O

- Attributes of streams
  - Variable set
    - The set of WRF state variables that comprise one read or write on a stream
    - Defined for a stream at compile time in Registry
  - Format
    - The format of the data outside the program (e.g. NetCDF), split
    - Specified for a stream at run time in the namelist

WRF I/O

- Attributes of streams
  - Additional namelist-controlled attributes of streams
    - Dataset name
    - Time interval between I/O operations on stream
    - Starting, ending times for I/O (specified as intervals from start of run)

Outline - Review

- Introduction
  - WRF started 1998, clean slate, Fortran + C
  - Targeted for research and operations
- WRF Software Overview
  - Hierarchical software layers
  - Patches (MPI) and Tiles (OpenMP)
  - Strict interfaces between layers
  - Contract with developers
  - Data Structures
  - I/O