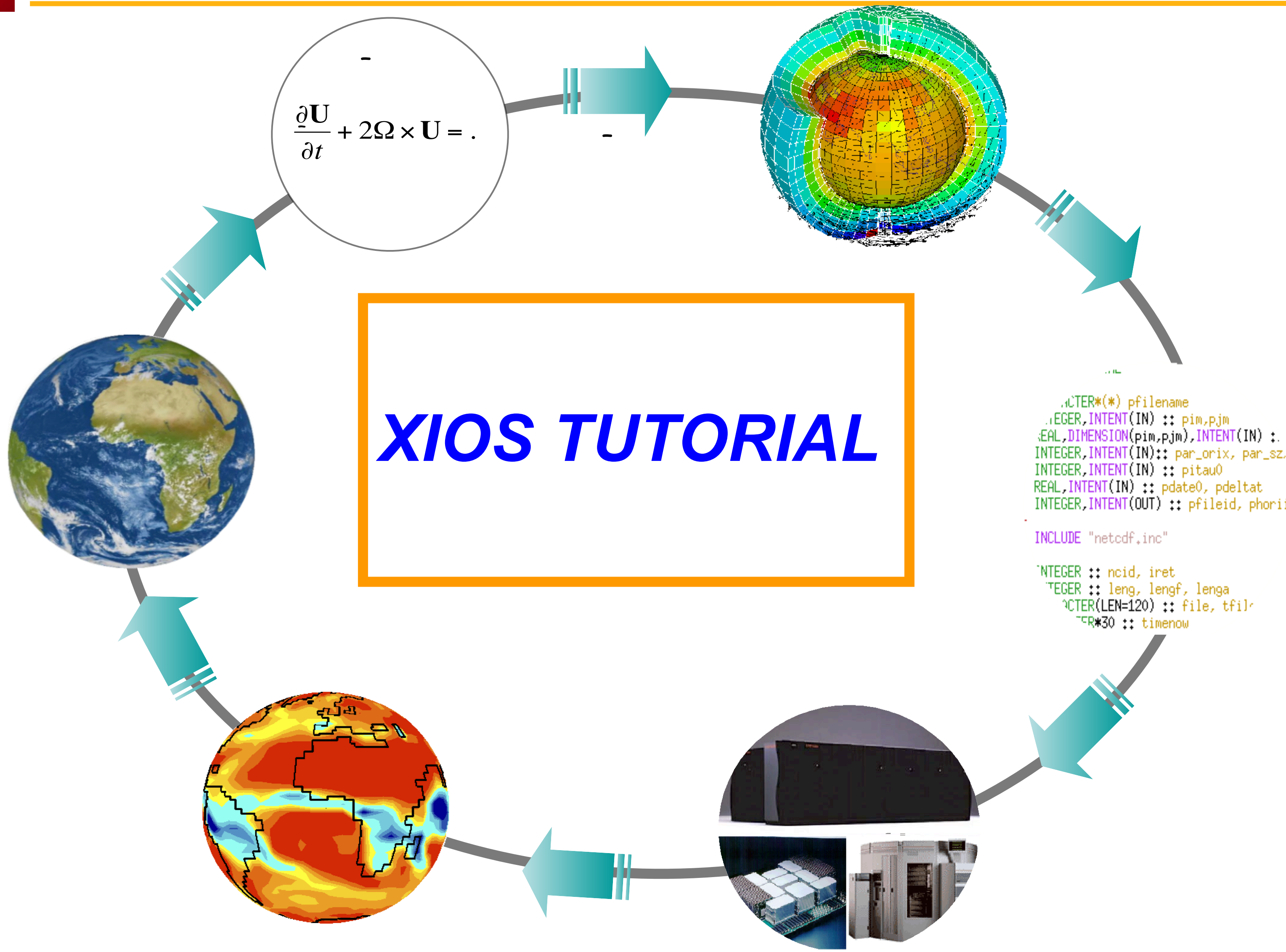


XIOS TUTORIAL

What will be covered in this tutorial :

Background of the XIOS project

Get started with XIOS

- Install and compile XIOS (hands-on 0)
- Use XIOS in a model (hands-on 1)
- XML syntax
- XIOS component (context, calendar, grid, axis, domain, file, etc.)
- Visualize the output

Get further with XIOS

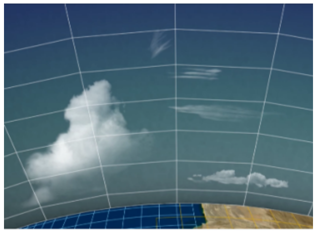
- XIOS filters
- How to perform data transformation in XIOS
- Activate the workflow graph in XIOS

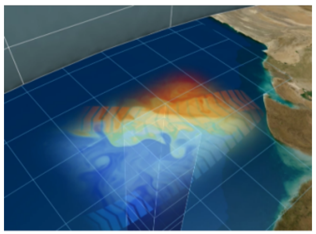
How to improve the performance with XIOS

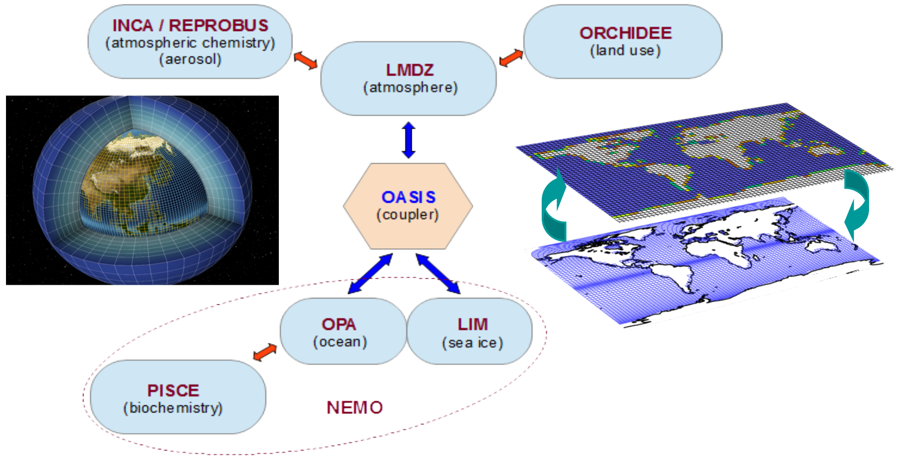
- Client-server mode of XIOS
- What is XIOS buffer, how it works?
- How to debug with XIOS?
- How to understand the XIOS report?
- How to parametrize XIOS?

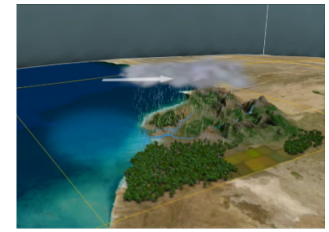
LSCE

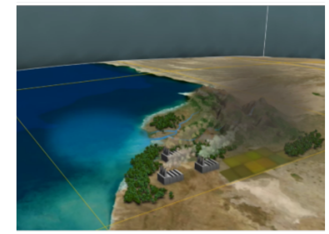
Context : IPSL Earth System Models











- **Complex coupled model, long simulations, a lot of data generated…**
- **IPSL in the past CMIP6 :**
  - Since March 2018
  - 850 simulations (55000 model years)
  - 4 PB of data (1 PB publication ready data files)
  - High frequency files
  - Lots of metadata

Background of the XIOS project

LSCE

- **CMIP7 next**
  - CMIP3 : 24 models x 12 experiments = 39 TB (82 340 files)
  - CMIP5 = 50 x CMIP3
  - CMIP6 = 20~50x CMIP5

3 main challenges for climate data production

- **Efficient management of data and metadata definition from models**
  - Human cost, errors…
- **Efficient production of data on supercomputer parallel file system (HPC)**
  - 1 file by MPI process ?
    - Rebuild files (with different number of procs)
  - Parallel I/O efficiency ? (not so efficient when many procs write to same file)
- **Complexity and efficiency of post-treatment chain to be suitable for distribution and analysis**
  - Files rebuild, time series, seasonal means…
  - Mesh re-gridding, interpolation, compression…
  - Resiliency ?

Background of the XIOS project

LSCE

XIOS is addressing all these challenges

- **Efficient management of data and metadata definition from models ?**
  - Using an external XML file parsed at runtime
  - Human readable, hierarchical

- **Efficient production of data on supercomputer parallel file system ?**
  - Dedicated Parallel and Asynchronous I/O server

- **Complex and efficient post-treatment ?**
  - Integrate internal parallel workflow and dataflow
  - Managed by external XML file
  - Post-treatment can be performed "in situ "

What is XIOS

LSCE

XIOS is a ~9 years old software development

XIOS : ~ 130 000 code lines, written in C++, interfaced with Fortran models

- Open Source CECILL Licence
- Code versioning : SVN (subversion)
  - **XIOS 2.5 (stable) : forge.ipsl.jussieu.fr/ioserver/svn/XIOS/branchs/xios-2.5**
  - **XIOS trunk (dev) : forge.ipsl.jussieu.fr/ioserver/svn/XIOS/trunk**

Used by an increasing variety of models

- IPSL models : NEMO, LMDZ, ORCHIDEE, INCA, DYNAMICO
- LGGE (MAR), Ifremer (ROMS, MARS3D)
- European NEMO consortium
- MétéoFrance / CNRM (ongoing) : Gelato, Surfec, Arpège climat (CMIP6 production)
- European models (in evaluation) : MetOffice (Hadgem ? , MONC, Gung-Ho?), ECMWF (Open IFS ?, EC-EARTH ?)

What is XIOS

Web site : wiki page

- http://forge.ipsl.jussieu.fr/ioserver/wiki
- Ticket system management and sources browsing : TRAC
- Documentation : on wiki page and under SVN (doc/ directory)
  - Reference guide : **xios_reference_guide.pdf**
  - User guide : **xios_user_guide.pdf**
- Support mailing list : subscribe yourself
  - XIOS users list (users support) : **xios-users@forge.ipsl.jussieu.fr**
  - XIOS developers list : **xios-dev@forge.ipsl.jussieu.fr**
  - XIOS team (non public) : **xios-team@forge.ipsl.jussieu.fr**

XIOS Team

- Yann Meurdesoif (CEA/LSCE – IPSL)
- Arnaud Caubel (CEA/LSCE – IPSL)
- Yushan Wang (LSCE)
- Julien Derouillat (CEA/LSCE – IPSL)
- Olga Abramkina (IDRIS)

Download and compile XIOS

Download XIOS

- svn co http://forge.ipsl.jussieu.fr/ioserver/svn/XIOS/trunk

Compile XIOS

- ./make_xios
  - --arch X64_JEANZAY
  - --prod
  - --job 4
  - --build_dir path_to_build
  - --netcdf_lib netcdf_par
  - --help

  - In arch folder, create your own configuration files to suite your environment
    - my_arch.fcm
    - my_arch.env
    - my_arch.path

XIOS Philosophy

- **Each time step, models expose part of their data through a minimalist interface**
  - Identifier (ASCII string) + address (pointer) of the data
    - Output: `CALL xios_send_field("field_id",field_out)`
    - Input: `CALL xios_recv_field("field_id",field_in)`
- **External XML File :**
  - Describe the incoming dataflow from models (using XML attributes)
  - Describe the workflow applied to the incoming dataflow
  - Describe the dataflow endpoint => output to files or returned to model
- **Simplicity and Flexibility**
  - XML file is parsed at runtime
    - Metadata, workflow and output definition can be modified without recompiling
  - Hierarchical approach using strong inheritance concept
    - Attributes are inherited from parent to child
    - Avoiding redundant definition, simple and compact
    - Very useful when you need to describe hundred's of variables
- **Full interactivity with models through the XIOS Fortran API**
  - Most of the XML definitions can be completed or created from model

LSCE

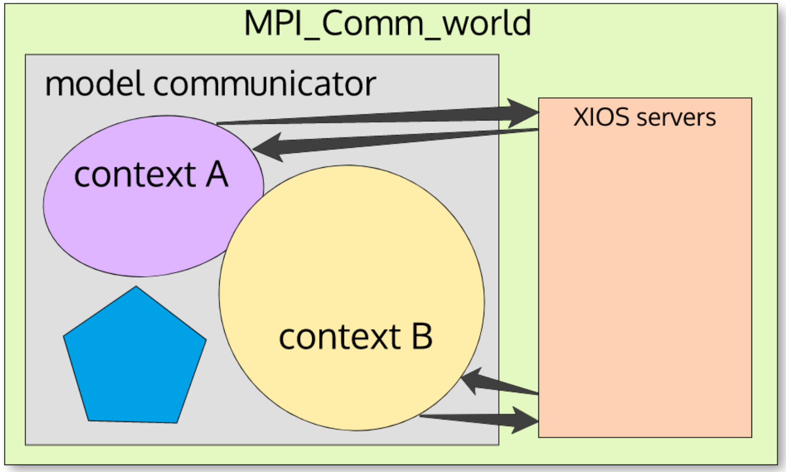
A minimal Fortran structure to be XIOS compliant

XIOS Initialization (mandatory)

- XML files are parsed at initialization
- **CALL xios_initialize("code_id", return_comm=communicator)**
  - **"code_id"** must be the same for all process rank of same model
  - XIOS split the **MPI_COMM_WORLD** communicator between clients and servers and return the split one for client side

Context initialization (mandatory)

- **CALL xios_context_initialize("context_id",communicator)**
  - **"context_id"** : id of the context to bind with context defined in XML file
  - **communicator** : MPI communicator associated to the context
  - Must be the same or a sub communicator of which returned at XIOS initialization
- Context initialization can be done at any time
- Different contexts can be initialized during same run
- All XIOS calls from model are collective for the associated context MPI communicator



Switching to a context

- **CALL set_current_context("context_id")**
  - All xios fortran calls afterwards will be related to context **"context_id"**

XIOS Fortran interface 2/3

LSCE

Complete the XML database definition

- Set missing attribute
  - Some attribute values are known only at run time
- All attribute can be set via the Fortran API
  - **CALL xios_set_'element'_attr("element_id",attr1=attr1_value, attr2=attr2_value,…)**
- New child element can be added
  - All XML tree can be created from Fortran interface
  - Ex : adding "**temp**" field element to "**field_definition**" group

```
CALL xios_get_handle("field_definition", field_group_handle)
CALL xios_add_child(field_group_handle,field_handle,id="temp")
```

Setting time step and other calendar specific attributes

- **CALL xios_define_calendar(type="Gregorian") (mandatory in fortran or in xml)**
- **CALL xios_set_timestep(duration)**

Closing context definition (mandatory)

- **CALL xios_close_context_definition()**
- Context data base is analysed and processed
- Any modification behind this point would not be taken into account and unexpected results may occur

XIOS Fortran interface 3/3

LSCE

Entering time loop and send data

- When entering a new time step, XIOS must be informed
- **CALL xios_update_timestep(ts)**
  - **ts** : timestep number
- Time step must begin to 1
- Time step 0 refers to part between context closure and first time step update
  - Only received field request can be done at time step 0

- Data can be exposed during a time step
  - **CALL xios_send_field("field_id",field)**
  - **CALL xios_recv_field("field_id",field)**
  - Sent data field would create a new flux tagged with timestamp related to the time step
  - Data can be received only if the outgoing flux have the same timestamp that the related time step

Finalize context

- All opened context must be finalized after the end of time loop
- **CALL xios_context_finalize()** close the current context.

Finalize XIOS

- After finalizing all opened context, XIOS must be finalized, servers are informed, files are properly closed and performance report is generated
- **CALL xios_finalize()**

XIOS Hello World!

LSCE

Fortran

```fortran
SUBROUTINE hello_world(rank,size)
  USE xios
  IMPLICIT NONE
  INTEGER :: rank, size, timestep
  TYPE(xios_duration)      :: dtime
  DOUBLE PRECISION,ALLOCATABLE :: lon(:,:), lat(:,:), field (:,:)
  INTEGER :: ni, nj, ibegin, jbegin

  CALL xios_initialize("client", return_comm=comm)
  CALL xios_context_initialize("hello_world", comm)

  CALL xios_set_domain_attr("domain", ibegin=ibegin, ni=ni, jbegin=jbegin, nj=nj)
  CALL xios_set_domain_attr("domain ", lonvalue_2d=lon, latvalue_2d=lat)

  dtime%second=3600
  CALL xios_set_timestep(dtime)

  CALL xios_close_context_definition()

  DO timestep=1,96
    CALL xios_update_calendar(timestep)
    CALL xios_send_field("field", field)
  ENDDO

  CALL xios_context_finalize()
  CALL xios_finalize()
END SUBROUTINE hello_world
```

Initialise XIOS and one context

Define domain

Set time step to 1 hour

End of context definition

No more modification to the context

Enter the time loop

Free the context and quit XIOS

Hands-on 1

XIOS needs XML

XML : Extensible Markup Language

- Set of rules to define a document in a format
- Both human-readable and machine-readable

Tag : a markup construct that begins with "<" and ends with ">"

- Start-tag : **<field>**
- End-tag : **</field>**
- empty-element tag, such as **<interpolate_domain />**

Element : construct delimited by a start-tag and an end-tag, or consists only of an empty-element tag

- empty element: **<field> </field>**
- Can be written with empty-element syntax : **<field />**
- May have child elements

```
<field_group>
  <field ... />
  <field ... />
</field_group>
```

- May have content : text between start-tag and end-tag element : **<field>** content **</field>**
  - Used in XIOS to define arithmetic's operations

XML

- **Attributes : a construct consisting of a name–value pair (name="value") that exists within a start-tag or an empty-element tag**
  - Ex : Element field has 3 attributes : **id**, **name** and **unit**
  - **<field id="temp" name="temperature" unit="K" > </field>**
  - **<field id="temp" name="temperature" unit="K" />**

- **Comments : begin with <!-- and end with -->**
  - **<field>** ***<!-- this is a comment, not a child nor a content -->*** **</field>**
  - "--" (double-hyphen) is not allowed inside comments. No nested comments

- **XML document must be well-formed**
  - XML document must contains only one root element
  - All start-tag element must have the matching end-tag element (case sensitive) and reciprocally
  - All element must be correctly nested

- **XML parser**
  - rapidxml

General XIOS-XML Syntax

LSCE

- **XML master file must be *iodef.xml***
  - Parsed first at XIOS initialization
  - Root element name is simulation
  - Root element can only contain **context** type elements

- **Main element families: represent objects type stored in XIOS database**
  - **context** : isolate and confine models definition, no interference between them
  - **calendar** : mandatory, 1-to-1 association with context
  - **scalar, axis, domain**
  - **grid**
  - **field**
  - **file** : input or output
  - **variable** : define parameters for models or for XIOS parameterization

- **Each element family can be divided into 3 types (except for context)**
  - Simple elements : ex : <field />
  - Group elements : ex : <field_group />
    - Can contains children simple element
    - Can contains children nested group of the same type
  - Definition elements : ex : <field_definition>
    - Unique root element type
    - Act as a group element, i.e. can contains other groups or simple elements

General XIOS-XML Syntax

- **Each element may have several attributes**
  - i.e. : **<file id="out" name="output" output_freq="1d" />**
  - Attributes give information for the related element
  - Some attributes are mandatory: error is generated if attribute not defined
  - Some attributes are optional but have a default value
  - Some attributes are completely optional

- **Attributes values are ASCII string, depending on the attribute, can represent :**
  - A character string : **name="temperature"**
  - An integer or floating value : **output_level="3" add_offset="273.15"**
  - A Boolean : true/false : **enabled="true"**
    - Fortran notation .TRUE./.FALSE. are allowed but obsolete
  - A date or duration : **start_date="2000-01-01 12:00:00"**
    - See format later
  - A bound array **(inf,sup)[values]** : **value="(0,11) [1 2 3 4 5 6 7 8 9 10 11 12]"**

General XIOS-XML Syntax

LSCE

Special attribute id : identifier of the element

- Make reference to the element
- Unique for one given kind of element
  - Elements with same id ⇔ same element (append, overwrite)
  - Be very careful when reusing same ids, not advised (no fixed parsing order)
  - Root elements are equivalent to group elements with a fixed id
  - Ex: <field_definition ….> ⇔ <field_group id="field_definition" …>
- id is optional, but no reference to the element can be done later

XML file can be split in different parts.

- Very useful to preserve model independency, modularity
- id must be the same in both xml files
- Using attribute "src" in context, group or definition element
  - attribute value give the name of the file to be inserted in the database

```
--- iodef.xml ---
<context id="nemo" src="./nemo_def.xml" />

--- nemo_def.xml ---
<context id="nemo" >
  <field_definition … >
...
</context>
```

Inheritance in XML

LSCE

Why Inheritance ?

- Attributes can be inherited from another element of same family
- Hierarchical approach, very compact
- Avoiding useless redundancy

Inheritance by grouping : parent-child inheritance concept

- All children inherit attributes from their parent
- An attribute defined in a child is not inherited from his parent
- Special attribute “**id**” is **NEVER** inherited

```xml
<field_definition level="1" prec="4" operation="average" enabled=".TRUE.">
  <field_group id="grid_W" domain_ref="grid_W">
    <field_group axis_ref="depthw">
      <field id="woce" long_name="vertical velocity" unit="m/s" operation="instant" />
    </field_group>
  </field_group>
</field_definition>
```

```xml
<field id="woce" long_name="vertical velocity" unit="m/s" axis_ref="depthw"
       domain_ref="grid_W" level="1" prec="4" operation="instant" enabled="true" />
```

Inheritance in XIOS

LSCE

Inheritance by reference

- Only for **field**, **domain**, **axis**, and **scalar** elements
  - **field_ref**
  - **domain_ref**
  - **axis_ref**
  - **scalar_ref**

Don't mix up with **grid_ref** !

- Source element inherit all attributes of referenced element
  - Attributes already defined in source element are not inherited (or is overwritten)

```
<field id="toce" long_name="temperature" unit="degC" grid_ref="Grid_T" enabled="true" />
<field id="toce_K" field_ref="toce" long_name="temperature(K)" unit="degK" />

<field id="toce_K" long_name="temperature(K)" unit="degK" grid_ref="Grid_T" enabled="true"/>
```

- Warning, reference inheritance is done **AFTER** group inheritance

Disable attribute inheritance by setting its value to "_reset_"

XIOS context

LSCE

Why Context ?

- Context is similar to "namespace"
- Context are isolated from each other, no interference is possible
  - ids used inside one context can be reused in other context
- For parallelism, each context is associated with its own MPI communicator
  - No interference between MPI communication
- Generally a context is associated to one model
  - Principle of modularity
- A model can declare more than one context

Context element :

- **<context>...</context>**
- Must be inside of the root XML element
- Must have an id
- Contains calendar and other element definition

```
<context id="nemo" >
  <calendar ... />
  <field_definition>    ...  </field_definition>
  <file_definition>     ...  </file_definition>
  <axis_definition>     ...  </axis_definition>
  <domain_definition>   ...  </domain_definition>
  <grid_definition>     ...  </grid_definition>
  <variable_definition> ...  </variable_definition>
</context>
```

XIOS calendar

Each context must define its own calendar

- One calendar by context
- Define a calendar type
  - Date and duration operation are defined with respect to the calendar
- Define starting date of the model
- Define time step of the model

Calendar type

- **Gregorian** : standard Gregorian calendar
- **D360** : fixed 360 days calendar
- **NoLeap** : fixed 365 days calendar
- **AllLeap** : fixed 366 days calendar
- **Julian** : Julian calendar (leap every 4 years)
- **user_defined** : months and days can be defined by user (planetology and paleoclimate)

Date and Duration

- A lot of XML attributes are of date or duration type
- Operation between date and duration are strongly dependent of the chosen calendar
  - Ex : date + 1 month = date + 30 day only for month 4,6,9,11

XIOS calendar

LSCE

Duration units

- Year : **y**
- Month : **mo**
- Day : **d**
- Hour : **h**
- Minute : **mi**
- Second : **s**
- Time step : **ts** (related to time step context definition)

Duration format

- Value of unit may be integer or floating (not recommended), mixed unit may be used in a duration definition
  - Ex. : “**1mo2d1.5h30s**”
  - Ex. : "**5ts**"

Date format

- **year-month-day␣hour:minute:second**
  - Ex. : "**2020-11-04 10:00:00**"
- Partial definition are allowed. Taking into account leftmost part
  - Ex. "**2020-11**" equivalent to "**2020-11-01 00:00:00**"
  - Ex. "**2020-11 12**“ format error (OK in some case)

XIOS calendar

Date format

- Date can be also define with a duration offset
  - Useful for defining a calendar based on standard units (seconds for example)
  - Ex. : "**+3600s**"
  - Or mixt : "**2012-15 +3600s**" equivalent to "**2012-15-1 01:00:00**"

Attributes for calendar

- **type** : define the calendar type
  - "**Gregorian**", "**D360**", "**NoLeap**" , "**AllLeap**", "**Julian**" or "**user_defined**"
- **time_origin** : (date) define the simulation starting date ("**0000-01-01 00:00:00**" by default)
- **start_date** : (date) define the starting date of the run ("**0000-01-01 00:00:00**" by default)
- **timestep** : (duration) define the time step of the model : mandatory

Setting calendar

- From XML : specific child context element : calendar

```
<context id="nemo" />
  <calendar type="Gregorian" time_origin="2000-01-01" start_date="2020-10" timestep="1h"/>
  ...
</context />
```

LSCE

Defining an user define calendar

- Planetology or paleo-climate can not use standard calendar

- Personalized calendar
  - Defining **day_length** in second (default **86400**)
  - Defining **month_lengths** : number of days for each 12 months

```
<!-- the simplified Darian calendar -->
<calendar  type="user_defined" day_length="88775"
          month_lengths="(1,24) [28 28 28 28 28 27 28 28 28 28 28 27 28 28 28 28 28 27 28 28 28 28 28
27]" />
```

  - Or if you don't want to specify month, you need to define **year_length** in second.

```
<!-- 300 days per year -->
<calendar  type="user_defined" day_length="86400" year_length="25920000"
        start_date="2020-10 12" />
```

  - In this way, the format for "date" will no longer contain "month". In Fortran interface, "month"=1

- Possibility to define leap year
  - Attributes : **leap_year_month**, **leap_year_drift**, **leap_year_drift_offset**
  - See XIOS user guide

Fortran interface for calendar

Duration

- Fortran derived type : **TYPE(xios_duration)**
  - **(REAL) : year, month, day, hour, minute, second, timestep**
  - **xios_year, xios_month**
    xios_day, xios_hour
    xios_minute
    xios_second
    xios_timestep

```
TYPE(xios_duration) :: duration
duration%second = 1800
duration = 1800 * xios_second
duration = 0.5 * xios_hour
```

Half an hour

Date

- Fortran derived type : **TYPE(xios_date)**
  - **(INTEGER) : year, month, day,**
    hour, minute, second

```
TYPE(xios_date) :: date(2014,12,15,10,15,0)
date%year = 2015
```

Date and duration operation

- **duration±duration, duration*real, -duration, ==, !=, >, <**
- **date-date, ==, !=, >=, >, <=, <**
- **date±duration**
- String conversion : **xios_duration_convert_[to/from]_string,**
  xios_date_convert_[to/from]_string
- Useful functions : **xios_date_get_second_of_year, xios_date_get_day_of_year,**
  xios_date_get_fraction_of_year, xios_date_get_fraction_of_day

Fortran interface for calendar

Setting calendar from Fortran interface

```
CHARACTER(LEN=*) :: type
TYPE(xios_duration) :: timestep
TYPE(xios_date) :: start_date, time_origin
```

- Within single call
  - **SUBROUTINE xios_define_calendar(type, timestep, start_date, time_origin, ...)**
  - **type** is mandatory.
- Or with individual call
  - **SUBROUTINE xios_set_timestep(timestep)**
  - **SUBROUTINE xios_set_time_origin(time_origin)**
  - **SUBROUTINE xios_set_start_date(start_date)**
- calendar **type** must be defined at first.

Hands-on 2-1

XIOS scalar

- Scalar description : the scalar element <scalar />

- Attributes
  - (double) value
  - (string) name
  - (string) long_name
  - (string) scalar_ref

- More often used in data transformation
  - see later

XIOS axis

Axis description : the axix element <axis />

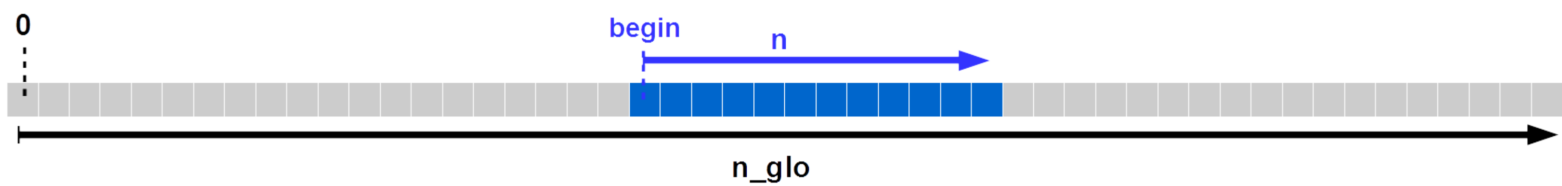
- Describe 1D axis, generally vertical axis
- **CALL xios_set_axis_attr("axis_id", ...)**

Defining the global size of the axis

- **(integer) n_glo** : global size

Defining the data parallelism distribution across MPI processes

- **(integer) n** : local axis size distribution
- **(integer) begin** : local axis distribution beginning with respect to the global axis
  - C-convention, starting from 0.
- If nothing specified, the axis is considered as not distributed.



Defining axis coordinate values and boundaries

- **(real 1D-array) value[n]**
- **(real 2D-array) bounds[2,n]**

XIOS axis

Defining how data are stored in memory

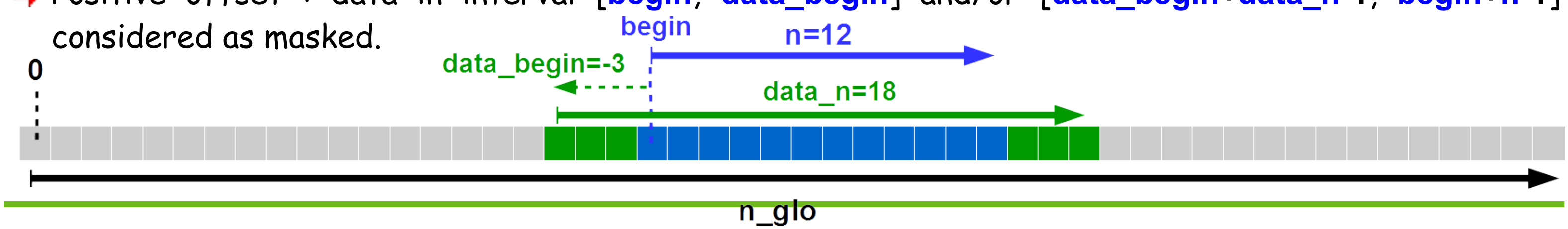
- Data are stored in memory as Fortran array
- But data can be masked, or ghost cells are not valid data, or axis value can be compressed
- XIOS will extract only required value from memory
- Must describe valid data with attributes
- Whole data are valid by default

Masking Data (optional)

- **(boolean 1D-array) mask[n] (false/zero : data masked)**
- Masked data will not be extracted from memory and will appear as missing values in output files

Defining ghost cells (optional)

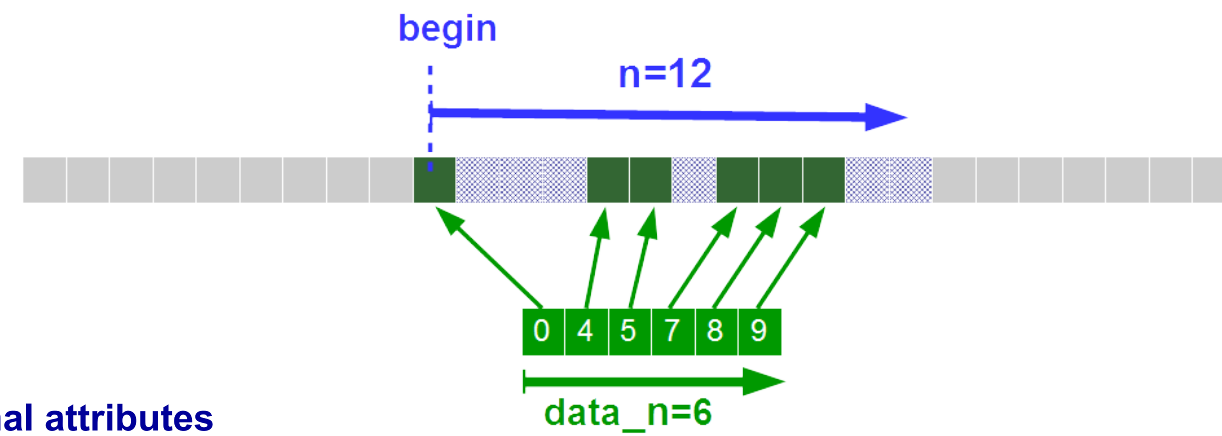
- **(integer) data_n** : size of the data in memory (default : **data_n=n**)
- **(integer) data_begin** : offset with respect to local axis distribution beginning
  - default : **data_begin=0**
  - Negative offset : data outside of the local distribution will not be extracted (ghost cell)
  - Positive offset : data in interval [**begin**, **data_begin**] and/or [**data_begin+data_n-1**, **begin+n-1**] are considered as masked.



XIOS axis

Defining compressed data (optional)

- Data can be compressed in memory (ex : land point), and can be decompressed for output
- Undefined data are considered as masked and will be output as missing value
- **(integer 1D-array)** **data_index**
  - Define the mapping between data in memory and the corresponding index into the local axis distribution
  - **data_index[i]=0** map the beginning of the local distribution
  - Negative index or greater than **n-1** will be outside of the distribution and will not be extracted



Other optional attributes

- **(string)** **name**
- **(string)** **long_name**
- **(string)** **unit**
- **(bool)** **positive** : set "**positive**" CF attribute in Netcdf output

XIOS axis

LSCE

Using distributed axis within grid

- Global 3D-grid of size 100x50x20
- Describe a local 3D distribution of size 10x5x20 beginning at the index (20,10,0) of the global grid

```
<grid id="grid_3d">   <!-- grid 3D of global dimension 100x50x20 -->
  <axis n_glo="100" begin="20" n="10" />
  <axis n_glo="50"  begin="10" n="5" />
  <axis n_glo="20"> <!–- not distributed -->
</grid >
```

- Data distribution is different for each MPI process, not suitable for XML description
  - Attributes only known at run-time can be passed dynamically using the Fortran interface
  - See section Fortran interface setting attributes

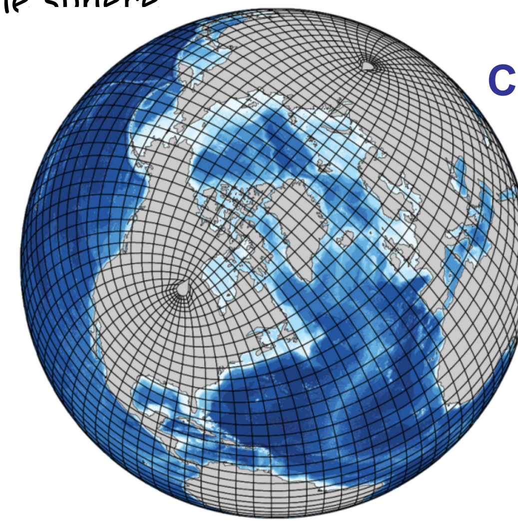
Masking grid point individually

- In the last example, masking one point in the 3rd axis means masking a full 2D layer in the 3d grid
- Grid point can be masked using the mask attribute
- Regarding of the dimensionality of mask arrays, version mask_1d to mask_7d are allowed
  - Total mask size must be equal to the local domain size
  - Ex : `<grid id="grid_3d"  mask_3d="(0,9)x(0,4)x(0,19)[0 1 1 0 ... 0 1]">`
  - or `<grid id="grid_3d"  mask_1d="(0,9990)[0 1 1 0 ... 0 1]">`
  - Not practical with xml. Better set mask via Fortran API.

Hands-on 2-2

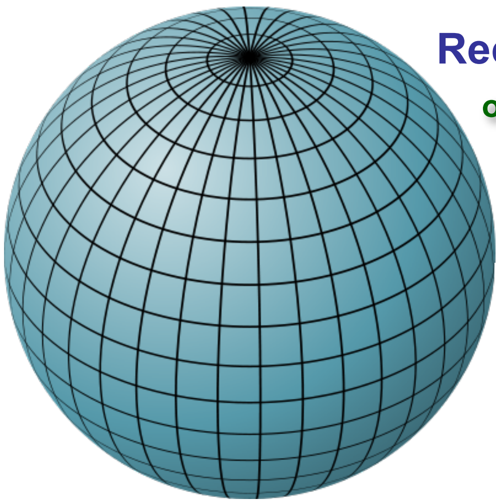
XIOS domain

- **2D horizontal layer description : the domain element <domain />**
  - Describe generally 2D layers mapping the surface of the sphere
  - Large variety of 2D domains can be described
  - **(string)type** :
    - "**rectilinear**", "**curvilinear**", "**unstructured**", "**gaussian**"



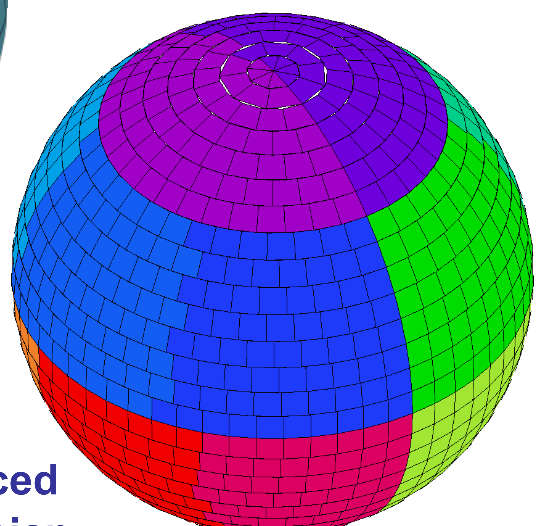
Curvilinear

nemo

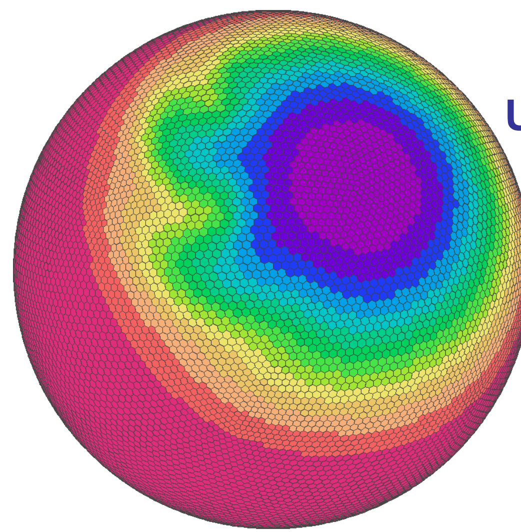


Rectilinear

orchidee & lmdz



Reduced Gaussian

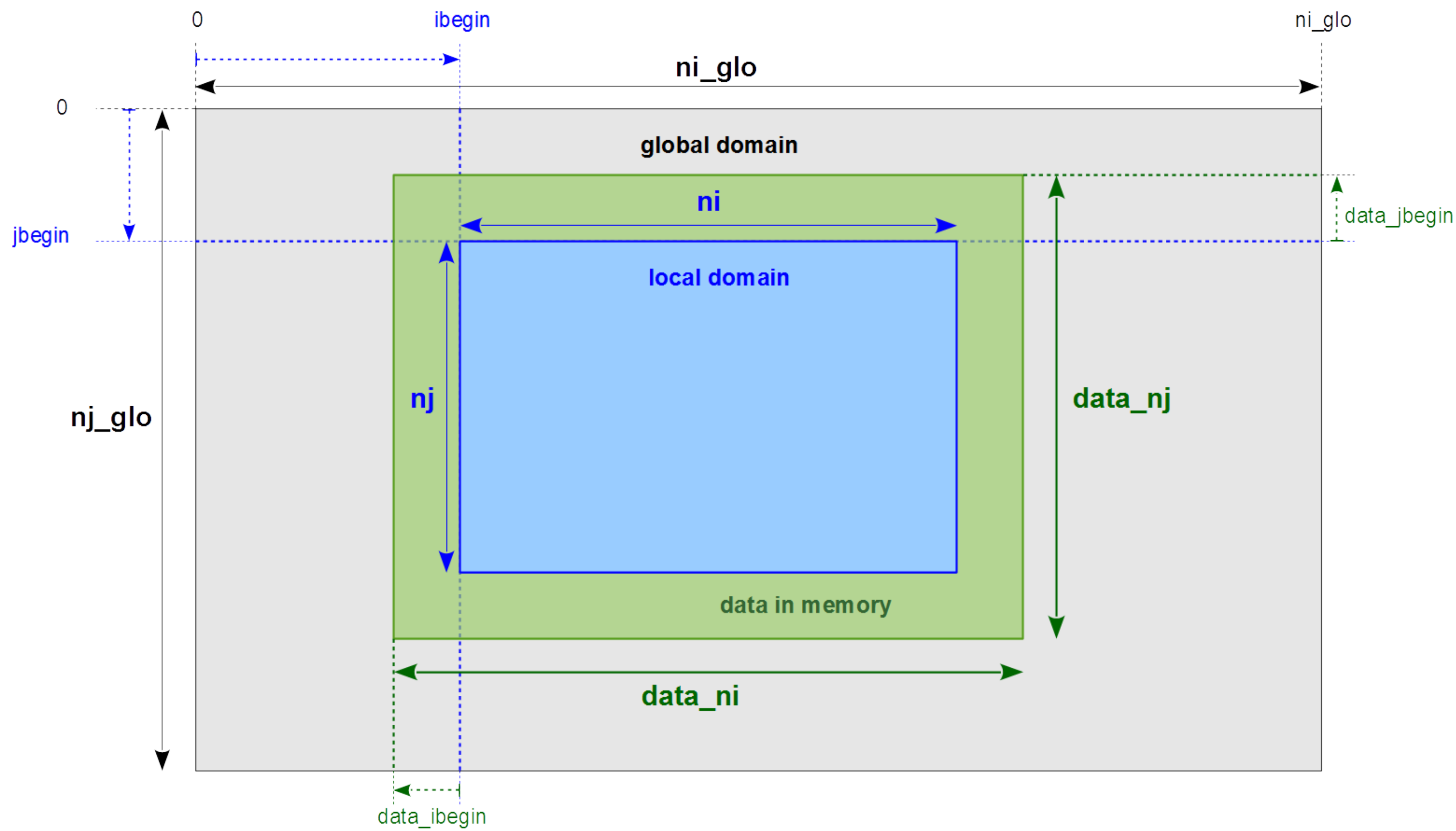


Unstructured

dynamico

XIOS domain

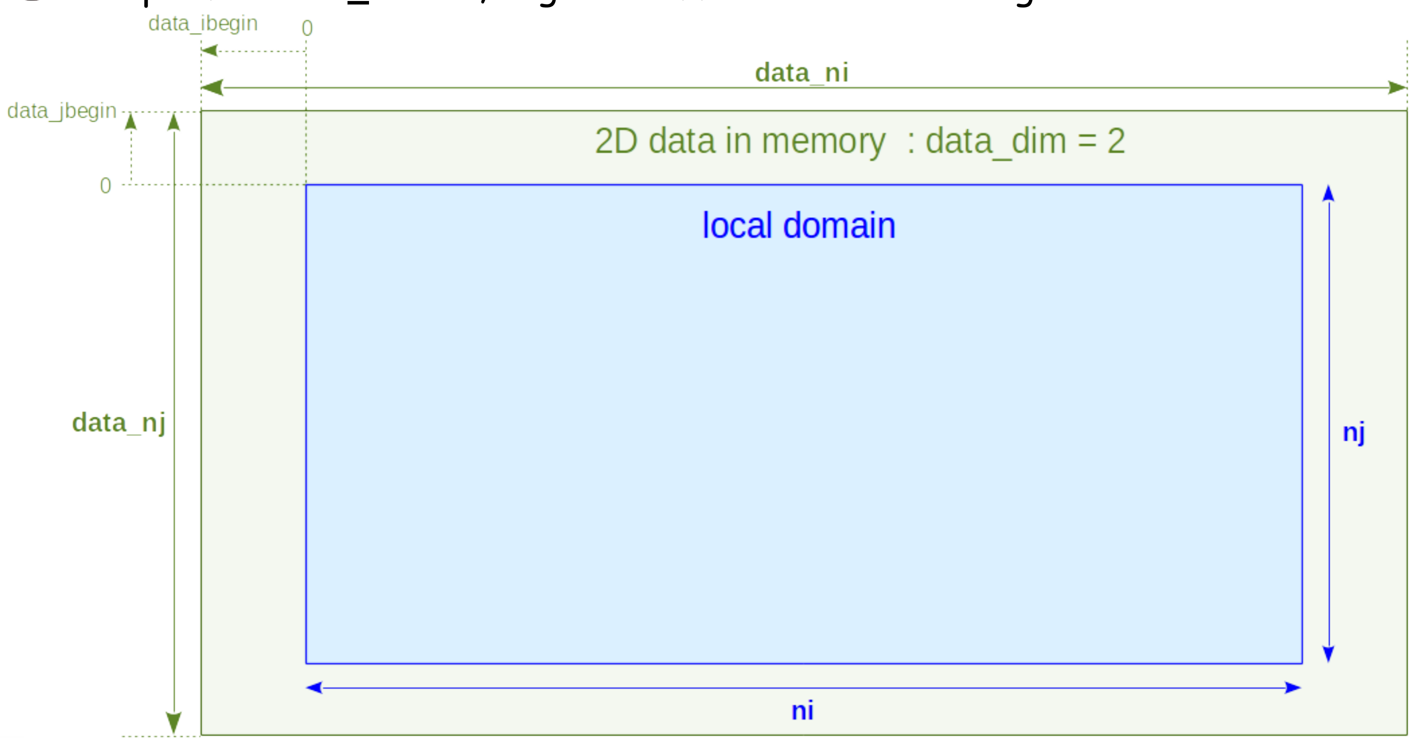
- **Rectilinear or curvilinear domains have a 2D description**
  - **(integer) ni_glo, nj_glo** : global domain size for each direction (longitude and latitude)
  - **(integer) ibegin, ni, jbegin, nj** : local domain definition



XIOS domain

Data representation in memory : similar to 1D-axis but for 2 dimensions

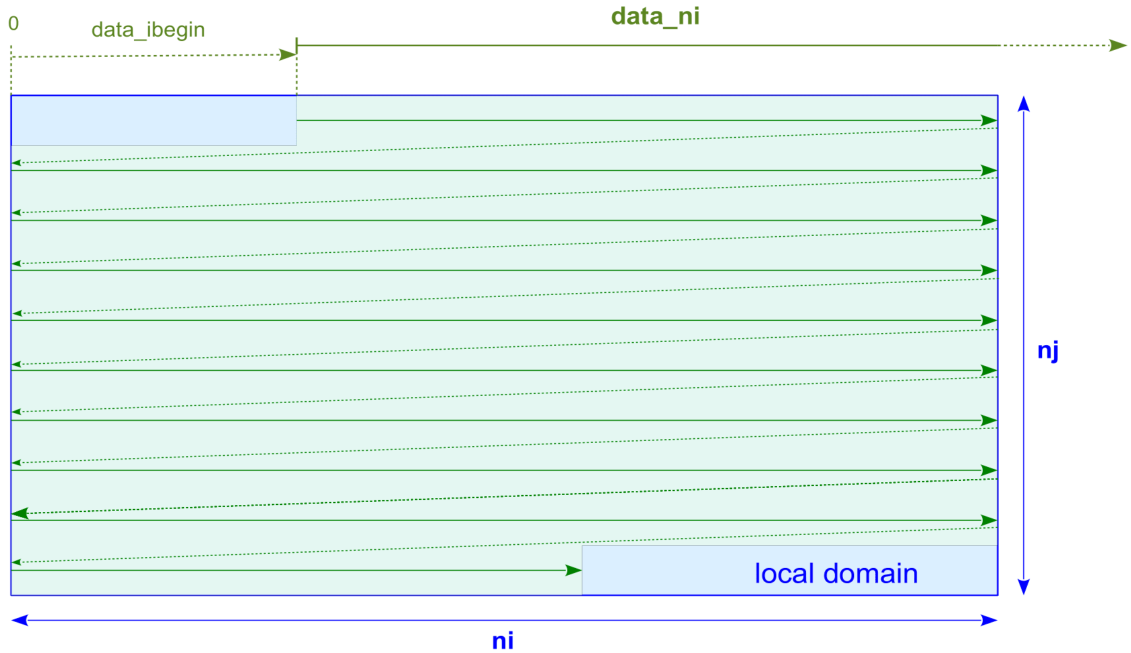
- Can be 1D-array (horizontal layer as a vector) or 2D-array
  - **(integer)** **data_dim** attribute : **1(default)** or **2**
- **(integer)** **data_ni** : size of the first array dimension
- **(integer)** **data_ibegin** attribute : Offset for the first dimension with respect to local domain distribution beginning : may be negative or positive (default : **data_ibegin=0**)
- [if **data_dim=2**] **data_nj, data_jbegin** : 2nd dimension (default: **data_nj=nj**, **data_jbegin=0**)
- Example for **data_dim=2**, negative offsets to eliminate ghost cells



XIOS domain

- Example for **data_dim=1** : horizontal layer seen as a vector
  - Positive offsets, local domain from different processes can overlap

1D data in memory :   data_dim = 1



XIOS domain

LSCE

Unstructured domain have a 1D description

- Vector of cells
  - **ni_glo**, **ni** and **ibegin** can be specified
  - **nj_glo**, **nj** and **jbegin** are meaningless
- Data in memory is always a vector
  - **data_dim=1**

Compressed data (on "data")

- For **data_dim=1** (decompressed data is a 1D-array)
  - **data_i_index[data_ni]** : index for decompressed local domain represented by vector (exclusive with **data_ibegin**)
- For **data_dim=2** (decompressed data is a 2D-array)
  - **data_nj** must be equal to **data_ni**
  - **data_i_index[data_ni]**, **data_j_index[data_ni]** : indexes for decompressed local domain represented as a 2D-array (exclusive with **data_ibegin**, **data_jbegin**)

Masking data (on "grid")

- (boolean 1D-array) **mask_1d** attribute : 1d array version
  - **mask_1d[ni*nj]** for rectilinear and curvilinear domain
  - **mask_1d[ni]** for unstructured
- (boolean 2D-array) **mask_2d** attribute : 2d array version
  - **mask_2d[ni,nj]** for rectilinear and curvilinear domain only

LSCE

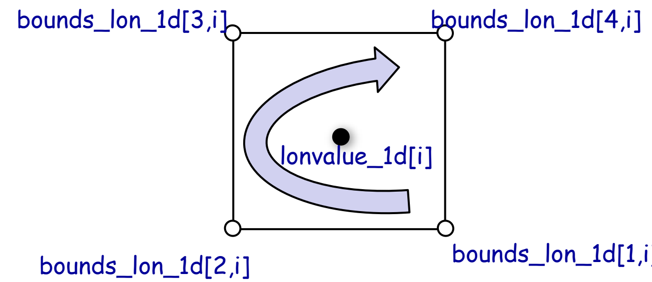
Defining coordinates

For rectilinear domain

- **latvalue_1d[nj]** : latitude coordinates of cells
- **lonvalue_1d[ni]** : longitude coordinates of cells
- **bounds_lat_1d[4,nj]** : latitudes boundaries of cell corners
- **bounds_lon_1d[4,ni]** : longitudes boundaries of cell corners

For curvilinear

- **latvalue_2d[ni,nj]**
- **lonvalue_2d[ni,nj]**
- **bounds_lat_2d[4,ni,nj]**
- **bounds_lon_2d[4,ni,nj]**



For unstructured domain

- **(integer) nvertex** : max number of corners/edges among cells
- **(double) latvalue_1d[ni]**
- **(double) lonvalue_1d[ni]**
- **(double) bounds_lat_1d[nvertex,ni]**
- **(double) bounds_lon_1d[nvertex,ni]**

Hands-on 2-3

LSCE

Describing the mesh : the grid element <grid />

- Can describe element of dimension : 0, 1, ..., 7
- Defined by composition of **scalar**, **axis** and **domain**
- Empty grid is representing a scalar
- 0D : (**scalar**)
- 1D : (**axis**)
- 2D : (**domain**), or (**axis**, **axis**)
- 3D : (**domain**, **axis**), or (**axis**, **axis**, **axis**)
- ...
- recommend using element reference
- can also define element inside

```
<grid_definition />

  <grid id="grid_3d">
    <domain domain_ref="domain"/>
    <axis axis_ref="axis_Z"/>
  </grid >

  <grid id="grid_4d">
    <domain id="new_domain" ... />
    <axis id="axis_P" ... />
    <axis id="axis_Q" ... />
  </grid >

</ grid_definition />
```

Field geometry is provided by the underlying mesh description

Can be virtual

Hands-on 2-4

LSCE

- The field element <field />
- Represent incoming or outgoing data flux from models
- Data can be sent or received at each time step from model through the Fortran interface
  - Sending data

    ```
    CALL xios_send_field("field_id", field)
    ```

  - Receiving data

    ```
    CALL xios_recv_field("field_id", field)
    ```

- Fields geometry and parallel distribution is hosted by the underlying grid description
  - **(string) grid_ref** attribute : id of the grid
  - For more flexibility fields can refer to a domain
    - **(string) domain_ref** attributes => create a virtual 2D grid composed of the referred domain
  - Or a domain and an axis to create a virtual 3D grid
    - **domain_ref** and **axis_ref**

```
<grid id="grid_3d">
  <domain id="domain_2d/>
  <axis id="axis_1d" />
</grid>
…
<field id="temp" grid_ref="grid_3d"/>
```

~

```
<axis id="axis_1d" />
<domain id="domain_2d/>
…
<field id="temp" domain_ref="domain_2d"
              axis_ref="axis_1d/>
```

LSCE

Field data from models must be conform to the grid description

- Fields can be declared of any dimensions in single or double precision

- But total **size** and **data order** must be the same as declared in the grid
  - Example :

```
<grid id="grid_3d">
  <domain id="domain_2d" type="rectilinear" ni_glo="100" ni="10" data_ni="12"
                         nj_glo="50"  nj="5"  data_nj="7"/>
  <axis id="axis_1d" n_glo="20"/>
</grid>
…
<field id="temp" grid_ref="grid_3d"/>
```

  - Global grid : 100x50x20
  - Local grid : 10x5x20
  - Data in model memory : **data_ni × data_nj × n_glo = 12×7×20 = 1680**
  - Can be declared as :
    - **REAL(kind=4) :: temp(12,7,20)**
    - **REAL(kind=4) :: temp(1680)**
    - **REAL(kind=8) :: temp(1680)**
  - but data order follows the column major order Fortran convention

XIOS field

LSCE

Field can be output to files

- Will appear as a child element of file element
- A field can appear, in multiple files
  - using the reference attribute : **field_ref**

```
<field_definition>
  <field id="temp"     grid_ref="grid_3d"/>
  <field id="precip"   grid_ref="grid_3d"/>
  <field id="pressure" domain_ref="domain_2d"/>
</field_definition>

<file_definition>
  <file name="daily_output" freq_output="1d">
    <field field_ref="temp" />
    <field field_ref="pressure" />
  </file>

  <file name="monthly_output" freq_output="1mo">
    <field field_ref="temp" />
    <field field_ref="precip" />
  </file>
</file_definition>
```

XIOS field

Field attributes

Field description :

- **(string) name** : name of the field in the file. If not specified, "**id**" will be used in place
- **(string) long_name** : set "**long_name**" netcdf attribute conforming to CF compliance
- **(string) standard_name** : set "**standard_name**" netcdf attribute
- **(string) unit** : set "**unit**" netcdf attribute
- **(double) valid_min/valid_max** : set **valid_min** & **valid_max** nectdf attribute

Enable/disable field output :

- **(boolean) enabled** : if false, field will not be output (**default=true**)
- **(integer) level** : set the output level of the field (**default=0**) with respect to the file attribute "**level_output** ". I f (**level>level_output**) the field will not be output.

Precision and compression :

- **(integer) prec** : define the output precision of the field : **8->double, 4->single, 2->2-byte integer**
- **(double) add_offset, scale_factor** : output will be **(field+add_offset)/scale_factor**
- **(integer) compression_level (0-9)** : set the gzip compression level provided by netcdf4/hdf5: due to HDF5 limitation, doesn't work for parallel writing. If not set data is not compressed.
- **(boolean) indexed_output** : if set to true, only not masked value are output.

LSCE

Field time integration

- At each time step , data field are exposed from model (**xios_send_field**)
- Data are extracted according to the grid definition
- Time integration can be performed on incoming flux
- The time integration period is fixed by file output frequency (**output_freq** attribute)
- **(string) operation** attribute : time operation applied on incoming flux
  - **once** : data are used one time (first time)
  - **instant** : instant data values will be used
  - **maximum** : retains maximum data values over the integration period
  - **minimum** : retains minimum data values over the integration period
  - **average** : make a time average over the period
  - **cumulate** : cumulate date over the period
- Example : each day, output the time average and instant values of "**temp**" field

```
<file name="output" output_freq="1d">
  <field field_ref="temp" name="temp_average" operation="average"/>
  <field field_ref="temp" name="temp_instant" operation="instant"/>
</file>
```

LSCE

Time sampling management

- Some field are not computed every time step
- **(duration)** **freq_op** attribute: field will be extract from model at "**freq_op**" frequency
- **(duration)** **freq_offset** attribute: time offset before extracting the field at "**freq_op**" frequency
- Strongly advised to set **freq_op** and **freq_offset** as a multiple of time step

- Example : for making a daily averaging, get "**temp**" value every 10 time step. The first value extracted will be at 2nd time step.

```
<file name="output" freq_output="1d">
  <field field_ref="temp" operation="average" freq_op="10ts" freq_offset="1ts"/>
</file>
```

Undefined values and time operation

- Undefined values must not participate to time integration operation
  - Set **default_value** attribute as the undefined value (missing value). If not defined, missing value will be 0.
  - **(boolean)** **detect_missing_value** : for the current time step, all field value equal to **default_value** (undefined value) will not be taking into account to perform the time integration (**average**, **minimum**, **maximum**, **cumulate**)
- Very expensive since each value of the mesh must be tested

Hands-on 2-5

XIOS file

- **Output file : the file element <file />**
- **Defining fields to be written**
  - File elements can contains field elements or field_group elements
  - All listed field elements are candidates for output
  - **(string) field_group_ref** attribute: fields included in the referred field group will be included in file

```
<field_definition>
  <field_group id="fields_3d" grid_ref="grid_3d"/>
    <field id="temp"   >
    <field id="precip" >
  </field_group>
  <field id="pressure" domain_ref="domain_2d"/>
</field_definition>
<file_definition>
  <file name="daily_output" freq_output="1d">
    <field_group (?)group_ref="fields_3d" operation="average"/>
    <field_group operation="instant"/>
      <field field_ref="temp" name="temp_inst" />
      <field field_ref="pressure" name="pressure_inst" />
    </field_group>
    <field field_ref="pressure" operation="average" /> (?)
  </file>
</file_definition>
```

- Variables output as average :
  - **temp**
  - **precip**
  - **pressure**
- Variables output as instant
  - **temp_inst**
  - **pressure_inst**

XIOS file

LSCE

Hands-on 2-6

Enabling /disabling output

- Field can be enabled/disabled individually
  - **(bool) enabled** field attribute
- Enable/disable with level output
  - **(integer) output_level** file attribute : set level of output
  - **(integer) level** field attribute : if **level** > **output_level**, field is disabled
- Enable/disable all fields
  - **(bool) enabled** file attribute : if set to **false**, all fields are disabled
- Files with all fields disabled will not be output

File format

- For now file output format is only **NETCDF**
  - **Grib2** and **HDF5** output format will be considered in future
- Can choose between parallel write into a single file or multiple file (1 file by xios server)
  - **(string) type** attribute : select output mode "**one_file**" / "**multiple_file**"
  - For "**multiple_file**" mode, files are suffixed with xios servers ranks
- Can choose between **netcdf4** et **netcdf4 classical** format
  - **(string) format** attribute : "**netcdf4**" for **netcdf4/hdf5** or "**netcdf4_classical"** for historical **netcdf3** format
  - In "**one_file**" mode, use **hdf5** parallel for **netcdf4** format and **pnetcdf** for classical format.
  - Sequential **netcdf** library can be used in **multiple_file** mode
- Data can be compressed : only available with **netcdf4** format (**hdf5**) in sequential write (**multiple_file**)
  - **(integer) compression_level** attribute : compression level (**0-9**), can be fixed individually with field attribute

XIOS variable

Setting parameters : the variable element <variable/>

- Variable are used to define parameters
- Variable can be set or queried from model
  - Could replace Fortran **namelist** or IPSL **run.def** files
- Used internally by XIOS to define its own parameters

Attributes

- **(string) name** : name of the attribute (optional)
- **(string) type** : type of the variable (optional)
  - **"bool", "int16", "int", "int32", "int64", "float", "double", "string"**

Setting variable values from XML

- Values are defined in the content section

```
<file>
   <variable id="int_var"  type="int"> 10 </variable>
   <variable id="string_var" type="string">a string variable</variable>
</file>
```

variable_group

XIOS variable

Set or query value from model

- Set variable : **ierr = xios_setvar('var_id',variable)**
- Get variable : **ierr = xios_getvar('var_id',variable)**
  - Return **true** if **'var_id'** is defined and second argument contains the read value
  - return **false** if **'var_id'** is not defined and second argument value is unchanged

```
<variable_definition>
   <variable id="int_var"  type="int"/> 10 </var>
   <variable id="string_var" type="string">a string variable</variable>
</variable_definition>




USE xios
...
INTEGER :: int_var
CHARACTER(LEN=256) :: string_var
LOGICAL :: ierr

 ierr=xios_getvar('int_var',intvar)
 ierr=xios_setvar('int_var',intvar+2)
 ierr=xios_getvar('int_var',intvar)          ! -> int_var=12
 ierr=xios_getvar('string_var',string_var)    ! -> string_var="a string variable"
```

Data distribution and mask

UNDER DEV

reinforce the notion from previous slides

On axis

On domain

On grid

Hands-on 3

Output file structure

File structure

- XIOS respects CF convention as much as possible
- One time record (unlimited dimension) by file
  - **(duration) output_freq** attribute : define the output frequency and the time axis
  - **time_counter** dimension and axis are written conforming to CF convention
- Can mix instant and average time operation
  - Axis **time_instant** or **time_centred** may be written with the associated bounds
- Fields of different grids can be in same file
  - Longitude, latitude and verticals axis are automatically written with the associate metadata following CF convention
  - Axis boundaries will be also written if available
- Some fields attributes (**standard_name**, **long_name**, **unit**,…) will be output as field metadata

Output file structure

- Example of **netcdf** file output with XIOS

```
netcdf output_atmosphere_2D_HR {
dimensions:
        axis_nbounds = 2 ;
        lon = 200 ;
        lat = 200 ;
        time_counter = UNLIMITED ; // (30 currently)
variables:
        float lat(lat) ;
                lat:axis = "Y" ;
                lat:standard_name = "latitude" ;
                lat:long_name = "Latitude" ;
                lat:units = "degrees_north" ;
                lat:nav_model = "domain_atm_HR" ;
        float lon(lon) ;
                lon:axis = "X" ;
                lon:standard_name = "longitude" ;
                lon:long_name = "Longitude" ;
                lon:units = "degrees_east" ;
                lon:nav_model = "domain_atm_HR" ;
        float tsol(time_counter, lat, lon) ;
                tsol:long_name = "Surface Temperature" ;
                tsol:online_operation = "average" ;
                tsol:interval_operation = "3600 s" ;
                tsol:interval_write = "1 d" ;
                tsol:cell_methods = "time: mean (interval: 3600 s)" ;
                tsol:coordinates = "time_centered" ;
        double time_centered(time_counter) ;
                time_centered:standard_name = "time" ;
                time_centered:long_name = "Time axis" ;
                time_centered:calendar = "gregorian" ;
                time_centered:units = "seconds since 1999-01-01 15:00:00" ;
                time_centered:time_origin = "1999-01-01 15:00:00" ;
                time_centered:bounds = "time_centered_bounds" ;
        double time_centered_bounds(time_counter, axis_nbounds) ;
        double time_counter(time_counter) ;
                time_counter:axis = "T" ;
                time_counter:standard_name = "time" ;
                time_counter:long_name = "Time axis" ;
                time_counter:calendar = "gregorian" ;
                time_counter:units = "seconds since 1999-01-01 15:00:00" ;
                time_counter:time_origin = "1999-01-01 15:00:00" ;
                time_counter:bounds = "time_counter_bounds" ;
        double time_counter_bounds(time_counter, axis_nbounds) ;

// global attributes:
                :name = "output_atmosphere_2D_HR" ;
                :description = "Created by xios" ;
                :title = "Created by xios" ;
                :Conventions = "CF-1.5" ;
                :production = "An IPSL model" ;
                :timeStamp = "2015-Dec-14 15:20:26 CET" ;
```

More on the output file

Adding specific metadata

- Using variable element <**variable**/>
- Variable as file child will be output as a global **netcdf** file attribute
- Variable as field child will be output as a **netcdf** variable attribute
- Example :

```
<file name="daily_output" freq_output="1d">
  <field field_ref="pressure" operation="average" >
    <variable name="int_attr" type="int"> 10 </variable>
    <variable name="double_attr" type="double"> 3.141592654 </variable>
  </field>
  <variable name="global_attribute" type="string"> A global file attribute </variable>
</file>
```

Flushing files

- File can be flushed periodically in order to force data in cache to be written
- **(duration) sync_freq** file attribute : flush file at **sync_freq** period

More on the output file

Appending data to an existing file

- When restart models, field data can be appended to a previous XIOS output file
- **(bool)** **append** attribute : if set to true and if file is present, data will be appended
  - Otherwise a new file will be created
  - Default is creating a new file (**append**=**false**)

Splitting files

Hands-on 4

- In order to avoid big file, file can be split periodically
- File suffixed with start date and end date period
- **(duration)** **split_freq** : split file **at** **split_freq** period

Generating time series (CMIP requirement)

- Fields included into a single file may be automatically spread into individual files
- One field by file, file name based on field name
  - **(string)** **ts_prefix** file attribute : prefix for time series files
  - **(bool)** **ts_enabled** field attribute : is set to true, field is candidate to be output as time series
  - **(duration)** **ts_split_freq** field attribute: individual field split frequency (default is file splitting frequency)
- **(string)** **timeseries** file attribute (none / only / both / exclusive) : activate time series output
  - **none** : standard output, no time series
  - **only** : only field **with** **ts_enabled**=**"true"** will be output as time series and no other output
  - **both** : timeseries + full file
  - **exclusive** : field **with** **ts_enabled**=**"true"** will be output as time series, the other field in a single file

Read data with XIOS

LSCE

Reading data from file

- **(string) mode** attribute **("read" / "write")** : if set to read, file will be an input
- Each time record will be read at every **freq_output** frequency (a little ambiguous but ...)
- Value can be get from models at the corresponding time step using :

  CALL xios_recv_field("field_id", field)
- First time record will sent to model at time step 0 (before time loop).
- Except using **freq_offset** field attribute
  - Exemple : **freq_offset="1ts"** : first record will be read at first time step and not 0

```
--- xml ---

<file name="daily_output" freq_output="1ts" mode="read" >
   <field id="temp" operation="instant" freq_offset="1ts" grid_ref="grid_3d"/>
</file>

--- model ---

DO ts=1,n
  CALL xios_update_timestep(ts)
  CALL xios_recv_field("temp",temp)
ENDDO
```

Hands-on 5

- Field with no time record will be read only once

XIOS workflow functionalities

LSCE

Why Workflow ?

- Field are exposed from model at each time step
  - internally representing data flux assigned to a timestamp
- Each data flux can be connected to one or more filters
- Filters are connected to one or more input flux and generate a new flux on output
- All filters can be chained together to achieve complex operations
- All filters are parallel
- XML file describe a full graph of parallel tasks

Workflow entry point

- Input flux can be a field sent from model (**xios_send_field**)
- Input flux can be a field read from an input file (**mode="read"**)

Workflow end point

- Output flux can be sent to servers and written to file (**mode="write"**)
- Output flux can be read from model (**xios_recv_field**)
  - **(bool) read_access** field attribute : field read from models must set **read_access="true"**
  - Field read from file have automatically **read_access="true"**

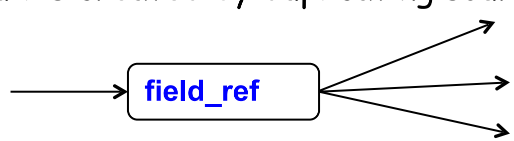
XIOS workflow functionalities

```
--- xml ---
<field id="precip" grid_ref="grid_3d"/>
<field id="pressure" field_ref="p" read_access="true" unit="Pa" / >
<field id="precip_read" field_ref ="precip" read_access="true" />

<file name="daily_output" freq_output="1ts">
   <field id="temp" operation="instant" grid_ref="grid_3d"/>
   <field id="p"    operation="instant" domain_ref="domain_2d"/>
</file>

--- model ---
DO ts=1,n
  CALL xios_update_timestep(ts)
  CALL xios_send_field("precip",precip)
  CALL xios_send_field("temp",temp)
  CALL xios_recv_field("pressure",pressure)
  CALL xios_recv_field("precip_read",precip_read)  ! Now precip_read==precip
ENDDO
```

- **field_ref attribute : duplicate flux from the referenced field**
  - For each reference to field, a new flux is created by duplicating source flux



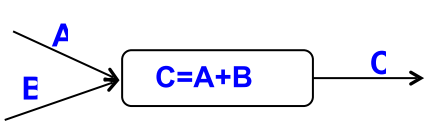
  - Also, make XML inheritance

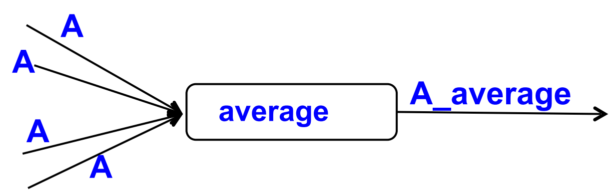
LSCE

Defining filters and transformations

Actually 3 kinds of filters

- Arithmetic filters : combine flux together
- Temporal filters : integrate flux over a period of time
- Spatial filters : transform the geometry of the incoming flux





Arithmetic filters

- Arithmetic filter can combine different flux of same timestamp with arithmetic operator or function
- All incoming flux must be on the same grid
  - Perform same operations for each grid point
- Arithmetic filter are defined in the content section of a field element
- Computed flux value will replace actual flux, even if coming from reference

```
<field id="temp" unit="°C" grid_ref="grid_3d"/>
<field id="temp_K" unit="°K" field_ref="temp"> temp+273.15 </field>
```

- Specific "**this**" (auto-reference) keyword representing the incoming flux of the current field

```
<field id="temp" unit="°K" grid_ref="grid_3d"> this+273.15 </field>
```

- Arithmetic filters can be easily chained,
  - Computed flux can be reused

$$C = \frac{A + B}{A * B}$$

$$D = \frac{e^{-C*D}}{3}$$

```
<field id="A" />
<field id="B" />
<field id="C"  > (A + B) / (A*B)    </field>
<field id="D"  >  exp(-C*this) / 3  </field>
```

XIOS temporal filter

LSCE

Time integration filters

- **Time filters of are specified with the "operation" field attribute**
  - Possible value : "**once**", "**instant**", "**maximum**", "**minimum**", "**average**", "**accumulate**"
  - A new flux is generated at the end of the time integration period

- **Time filter is enabled only if :**
  - Field is included into a file
    - **output_freq** define the period over which integration is done
    - Generated flux is the sent to server to be recorded
  - Flux can be reused by an other field after time integration
    - The @ operator : means that time integration is performed over the flux
    - The time integration period is given by value of **freq_op** attribute of new flux

```
<field id="temp" operation="average" />
<field id="temp_ave" freq_op="1d"/> @temp </field>
```

- New flux "**temp_ave**" is created every day (**freq_op**="**1day**") by time averaging of "temp" flux

XIOS temporal filter

Chaining time filters

- Using the @ operator
- Example : compute and output the monthly average of the daily maximum and minimum of temperature and the monthly maximum and minimum of the daily temperature average

```
--- xml ---

<field id="temp"                    operation="average"/>
<field id="temp_min" field_ref="temp" operation="minimum" />
<field id="temp_max" field_ref="temp" operation="maximum" />

<file name="monthly_output" output_freq="1mo" />
  <field name="ave_daily_min" operation="average"  freq_op="1d"> @temp_min </field>
  <field name="ave_daily_max" operation="average"  freq_op="1d"> @temp_max </field>
  <field name="min_daily_ave" operation="minimum"  freq_op="1d"> @temp     </field>
  <field name="max_daily_ave" operation="maximum" freq_op="1d"> @temp     </field>
</file>
```

2nd 1st

```
--- model ---

CALL xios_send_field("temp", temp)
```

LSCE

Chaining and combine time filters and arithmetic's filters

- Compute the time variance of a temperature field $\sigma \approx \sqrt{\langle T^2 \rangle - \langle T \rangle^2}$

```
--- xml ---

<field id="temp" operation="average"/>
<field id="temp2" field_ref="temp" /> temp*temp </field>

<file name="monthly_output" output_freq="1mo" />
  <field name="sigma_T" operation="instant" freq_op="1mo"> sqrt(@temp2-pow(@temp,2)) </field>
</file>



--- model ---

CALL xios_send_field("temp",temp)
```

Hands-on 6

XIOS spatial filter

LSCE

Spatial filters

- Spatial filters may change the geometry, dimensionality and the parallelism data distribution of a flux
- Algorithms must be parallel and scalable in order to perform the flux transformation on whole allocated parallel resources of a simulation
- More filters under development

Using spatial filter

- Spatial filters are enabled when the grid of a referenced field is different of the current grid field
  - No spatial filter enabled (same grid ref)

```
<field id="temp" grid_ref="grid_regular"/>
<field id="new_temp" field_ref="temp" grid_ref="grid_regular" />
```

  - Trigger spatial filter (different grid ref)

```
<field id="temp" grid_ref="grid_regular"/>
<field id="new_temp" field_ref="temp" grid_ref="grid_unstruct" />
```

- If grid are not matching exactly, try to find a way to transform source grid into target grid
  - If not possible an error is generated
  - Otherwise filter will be used

XIOS spatial filter

- To find which filter to activate, a matching is done between domain and axis composing the grid.
  - An exact matching between element do not activate filter
  - If not matching, see if it is possible to transform the source element domain or axis into target element with a transformation.
  - Otherwise an error is generated

```
<axis id="vert_axis" n_glo="100" />
<domain id="regular"  ni_glo="360" nj_glo="180" type="rectilinear" />
<domain id="unstruct" ni_glo="10000"          type="unstructured" />

<grid id="grid_regular">
  <domain domain_ref="regular>
  <axis axis_ref="vert_axis" >
</grid>

<grid id="grid_unstruct">
  <domain domain_ref="unstructured">
    <interpolate_domain/>
  <domain/>
  <axis axis_ref="vert_axis" >
</grid>

<field id="temp" grid_ref="grid_regular"/>
<field id="new_temp" field_ref="temp" grid_ref="grid_unstruct" />
```

XIOS spatial filter

- More than one filter can be implemented in same transformation

```
<axis id="vert_src" n_glo="100" />
<axis id="vert_dst" n_glo="50" />

<domain id="regular"  ni_glo="360" nj_glo="180" type="rectilinear" />
<domain id="unstruct" ni_glo="10000"          type="unstructured" />

<grid id="grid_regular">
  <domain domain_ref="regular/>
  <axis axis_ref="vert_src" />
</grid>

<grid id="grid_unstructured">
  <domain domain_ref="unstructured">
    <interpolate_domain/>
  <domain/>
  <axis axis_ref="vert_dst">
    <interpolate_axis/>
  </axis>
</grid>
```

- Domain interpolation will be perform first "**regular**" -> "**unstructured**"
- Axis interpolation will be perform in 2nd time "**vert_src**" -> "**vert_dst**"

LSCE

Available spatial filters :

Extract

- Extract sub-part of data : extract_axis, extract_domain

- Extract axis to scalar
  - **(integer) position** : position of the element to be extract from axis.

- Extract axis to axis
  - **(integer) begin** : begin position of the element to be extract from axis.
  - **(integer) n** : number of elements to be extract from axis.
  - **(1D-array) index** : array including all indexes of elements to be extract from axis.

- Extract domain to axis
  - **(string) direction** : **"iDir" or "jDir"**
  - **(integer) position** : position of the slice to be extract from domain.

- Extract domain to domain
  - **(integer) ni** : number of elements to be extract from domain along the i-direction.
  - **(integer) nj** : number of elements to be extract from domain along the j-direction.
  - **(integer) ibegin** : i-position of starting element to be extract from domain.
  - **(integer) jbegin** : j-position of starting element to be extract from domain.

XIOS spatial filter

```
<domain id="regular" ni_glo="360" nj_glo="180" type="rectilinear" />
<axis id="axis" n_glo="100" />

<grid id="grid_src">
  <domain domain_ref="regular"/>
  <axis axis_ref="axis"/>
</grid>

<grid id="grid_extract">
  <domain domain_ref="regular">
    <extract_domain ibegin="20" ni="50" jbegin="100" nj="60" />
  <domain/>
  <axis axis_ref="axis">
    <extract_axis begin="30" n="10"/>
  </axis>
</grid>

<field id="field" grid_ref="grid_src"/>
<field id="field_extracted" field_ref="field" grid_ref="grid_extract" />
```

- Extract data of size (50,60,10) starting at index (20,100,30)
- Only the extracted part will be output to files

Hands-on 7-1

Hands-on 7-2

XIOS spatial filter

Available spatial filters :

Reduce

- Reduce data : **reduceac_scalar, reduce_axis, reduce_domain**

Hands-on 7-3

Hands-on 7-4

- Reduce scalar to scalar
  - **(string) operation** : sum, average, max, min. Perform a MPI-Reduce
- Reduce axis to scalar
  - **(string) operation** : sum, average, max, min.
- Reduce axis to axis
  - **(string) operation** : sum, average, max, min. Perform a MPI-Reduce
- Reduce domain to scalar
  - **(string) operation** : sum, average, max, min.
  - **(bool) local** : whether the reduction should be performed locally on data owned by each process or on the global domain (default **"**false**"**)
- Reduce domain to axis
  - **(string) operation** : sum, average, max, min.
  - **(string) direction** : **"iDir" or "jDir"**
  - **(bool) local** : whether the reduction should be performed locally on data owned by each process or on the global domain (default **"**false**"**)

XIOS spatial filter

LSCE

- **Inverse**
  - **inverse_axis**

- **Duplicate**
  - **duplicate_scalar** : duplicate scalar to axis

- **Reorder**
  - **reorder_domain** : duplicate scalar to axis
    - **(bool)** **invert_lat** : define whether the latitude should be inverted. (default **"**false**"**)
    - **(double)** **shift_lon_fraction** : longitude offset. Represents a fraction of **ni_glo**. (default **"**0**"**)
    - **(double)** **max_lon** : optional.
    - **(double)** **min_lon** : optional.
    - If both **min_lon** and **max_lon** are defined, domain will be reordered with latitude values ranging from **min_lon** to **max_lon** .

Hands-on 7-5

LSCE

- **Generate domain**
  - **Generate_rectilinear_domain**
    - **(double) lon_start, lon_end, lat_start, lat_end**
    - **(double) bounds_lon_start, bounds_lon_end, bounds_lat_start, bounds_lat_end**
    - Range in [0°, 360°] for longitude, [-90°, 90°] for latitude
    - Useful to perform automatic interpolation on regular grid
    - Generate automatically parallel distribution, longitude and latitude values
    - **ni_glo** and **nj_glo** must be defined in the domain element

LSCE

Interpolate (only polynomial)

interpolate_domain

- Perform interpolation between any kind of domain
- Compute weight on the fly and in parallel at XIOS closing definition step
- Interpolation is done on parallel on the incoming distributed flux
- Current algorithm is only conservative remapping of 1st or 2nd order

- **(integer) order** : set the order (1 or 2) of the conservative interpolation (default “2”)
- **(bool) renormalize** : used in case where targeted cells intersect masked source cells. If set to “true”, flux is renormalized prorate of the non masked intersected area. (default “false”)
- **(bool) quantity** : set to “true” to preserve extensive property of the field (default “false”)
- **(bool) detect_missing_value** : if set to “true” , input data of the field to be interpolated are analyzed to detect missing values. (default “false”)
- **(bool) use_aera** : if set to “true”, area for source and target domain (if any) will be used to renormalize compute weight by the ratio given area / computed area. Default value is false. Used with domain **radius** attribute
- **(string) mode** : “read”, “compute”, “read_or_compute”. This attribute determines the way to obtain interpolation weight information. Default “compute”
- **(bool) write_weight** : set to “true” to write the computed weight to file.
- **(string) weight_filename** : define the file name where the weights will be written or read. If not specified, when trying to read or write, a name will be automatically generated (contextid_srcdomain_destdomain).
- **(string) read_write_convention** : index will begin from 0 if set to “c”, from 1 if set to “fortran”

Hands-on 7-6

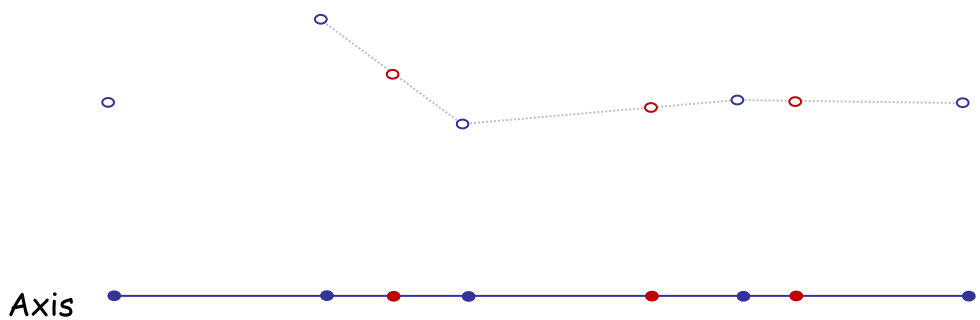
LSCE

Interpolate (only polynomial)

interpolate_axis

- **(integer) order** : optional. set the order of the polynomial interpolation (default "1")
- **(string) type** : "polynomial" only. Optional
- **(string) coordinate** : defines the coordinate (**value**) associated with an axis on which interpolation will be performed
- Apply only on 3D field

Hands-on 7-7



XIOS spatial filter

LSCE

Chaining spatial transformation

- Chaining can be easily achieved by referencing intermediate field
  - Ex : interpolate unstructured grid to regular and then make a zoom

```
<field id="temp_unstr"                          grid_ref="grid_unstruct"/>
<field id="temp_reg"        field_ref="temp_unstr" grid_ref="grid_regular"/>
<field id="temp_reg_extract" field_ref="temp_reg"   grid_ref="grid_regular_extract"/>
```

- To avoid intermediate field definition, use **grid_path** attribute
  - **(string) grid_path** attribute : define the list of intermediate grid (**grid_path="grid1,grid2"**)

```
<field id="temp_unstr"       grid_ref="grid_unstruct"/>

<field id="temp_reg_extract" field_ref="temp_unstr" grid_path="grid_regular"
                   grid_ref="grid_regular_extract"/>
```

- Other possibilities is to chain transformation in domain or axis definition

```
<field id="temp_unstr"                          domain_ref="unstructured" />
<field id="temp_reg_extract" field_ref="temp_unstr" domain_ref="regular_extract"/>

<domain id="unstructured"   n_glo="10000" type="untructured" />

<domain id="regular_extract" ni_glo="360" nj_glo="180"  type="rectilinear">
  <generate_rectilinear_domain/>
  <interpolate_domain/>
  <extract_domain ibegin="20" ni="50" jbegin="100" nj="60" />
</domain>
```

Hands-on 7-8

Hands-on 8

XIOS workflow graph

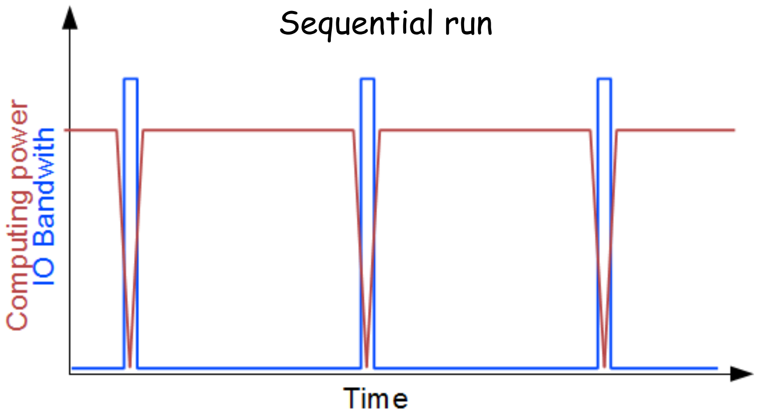
A good tool for visualize workflow

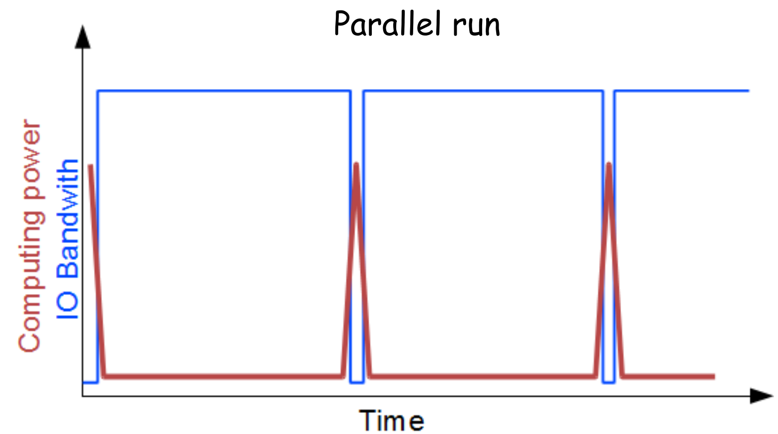
- Field attribute
  - **(bool)** **build_workflow_graph** : set to "true" to enable workflow
- Can be inherited by reference
- https://forge.ipsl.jussieu.fr/ioserver/chrome/site/XIOS_TEST_SUITE/graph.html
- Interactive
- One graph file per context.
  - graph_data_*.json
- Can be useful for debugging

Hands-on 9

The I/O Problem

Performance





- IO become a big bottleneck in parallel computing up to O(10000) cores
  - Often, data are gathered to one master process which write file
  - Ok if done just for initialization or finalize but memory problem may occur
  - Big impact on computing performance

- One file by process ?
  - Good way to achieve moderate scalability but :
  - Depending on the file system, performance may break down when attempting to write simultaneously thousand of files
  - Files need to be rebuilt into a single file in order to be analyzed
  - Rebuilt may take a longer time than the simulations

The I/O Problem

LSCE

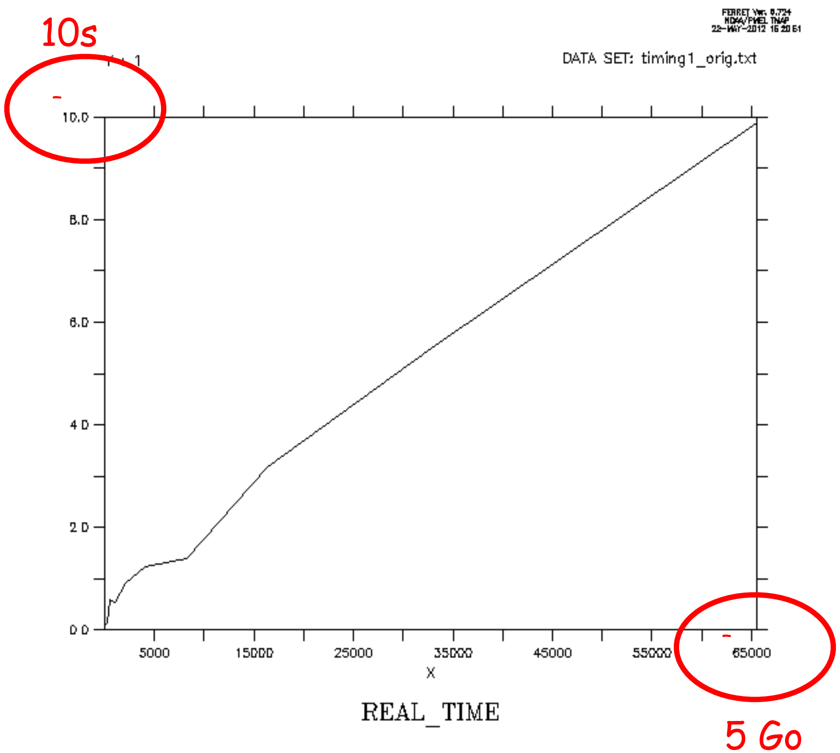
- Using parallel IO ?
  - Best way to achieve scalable IO without rebuild file
  - But difficult to aggregate a lot of I/O bandwidth with a big number of writing processes
  - Parallel IO are very less scalable than models due to hardware restriction (pricy and not took into account for performance evaluation)
  - Impact on the computing performances.

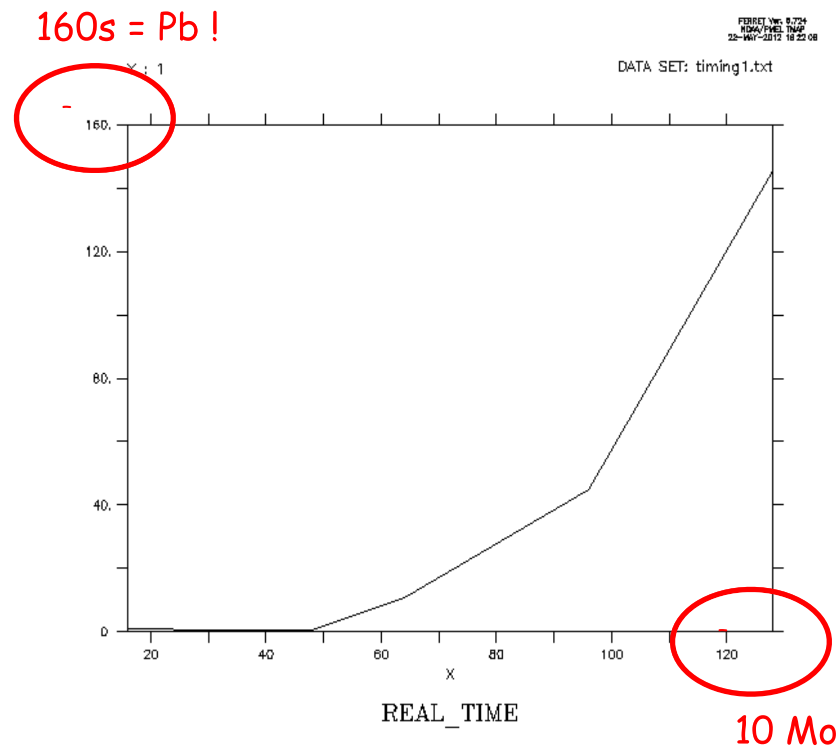
- Using asynchronous parallel IO ?
  - Good way to overlap IO by computing
  - MPI/IO : difficult to manage, load balancing problem…
  - High level library (HDF5, netcdf…) generally don't implement asynchronous IO.

- I/O performances are very system dependent
  - Example : Curie Tier 0 computer with LUSTRE file system
  - 150 GB/s theoretical capability
  - Optimally tuned MPI-IO parallel benchmark : 10 GB/s
  - HDF5 layer ~ 5GB/s
  - NETCDF4-HDF5 layer ~ 4GB/s

The I/O Problem

- Achieving good parallel IO performance is not so easy :
  - A lot of recipes to avoid very bad performance
  - Example with netcdf4, trying to perform naïve parallel IO

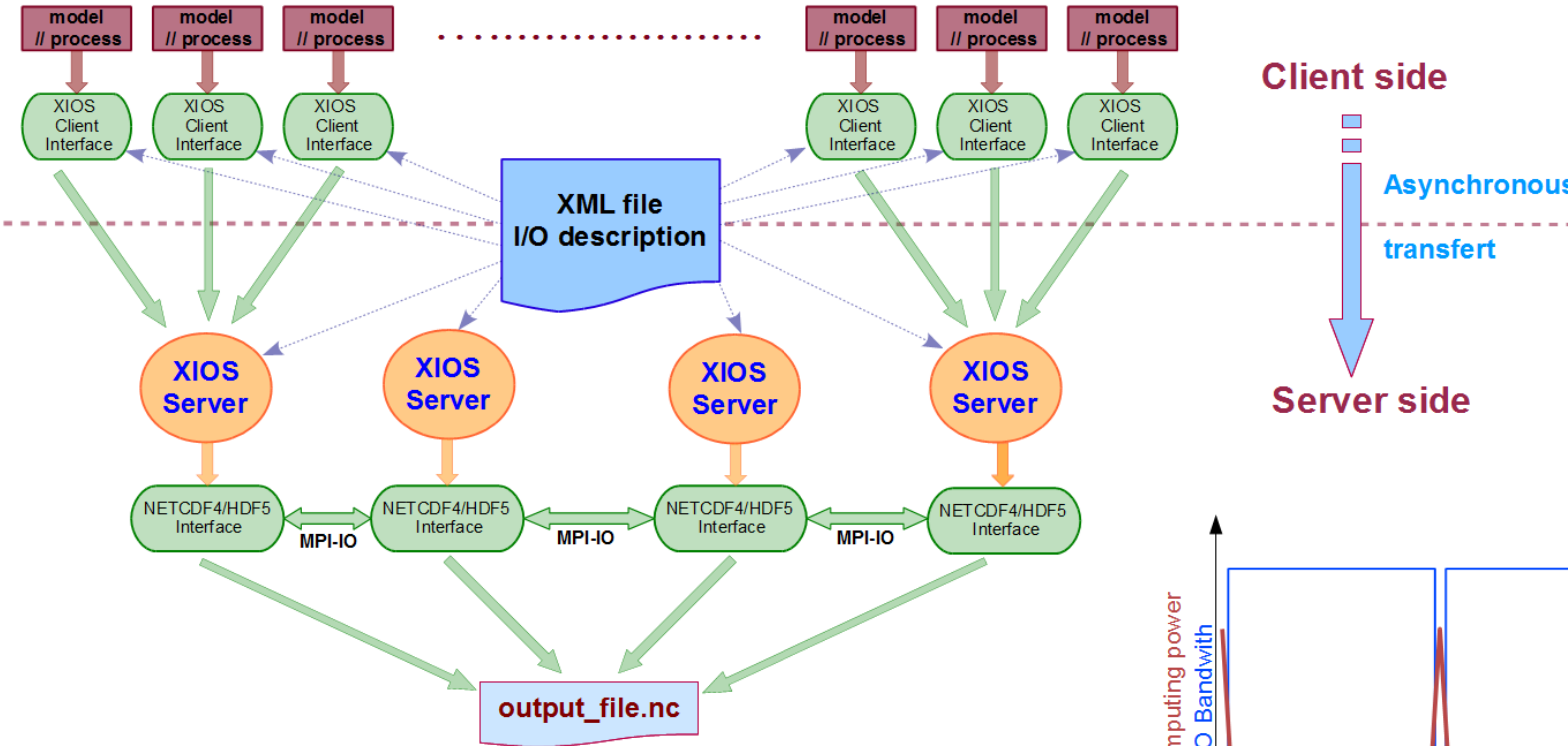


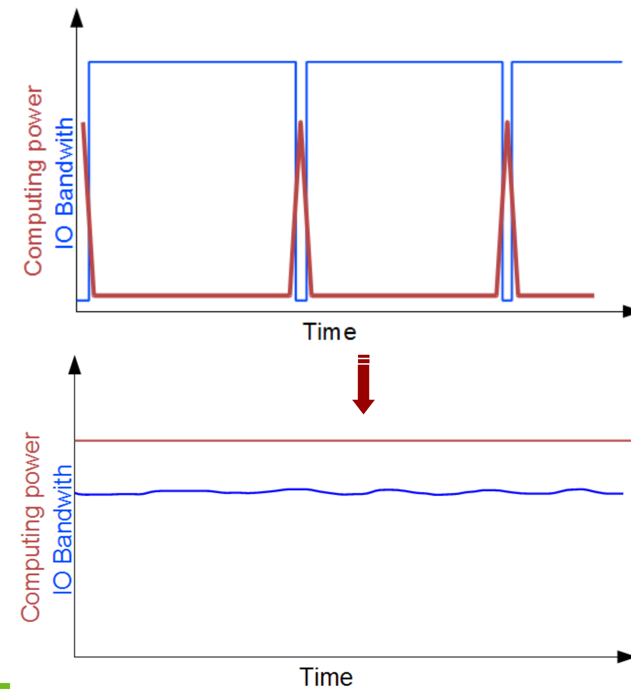


–Multiple file on 16 CPUs : 1 file by process = 16 files

–Single file on 16 CPUs : 1 rebuilt file (collective access or independent access)

X(ml) IO S(erver)





XIOS servers

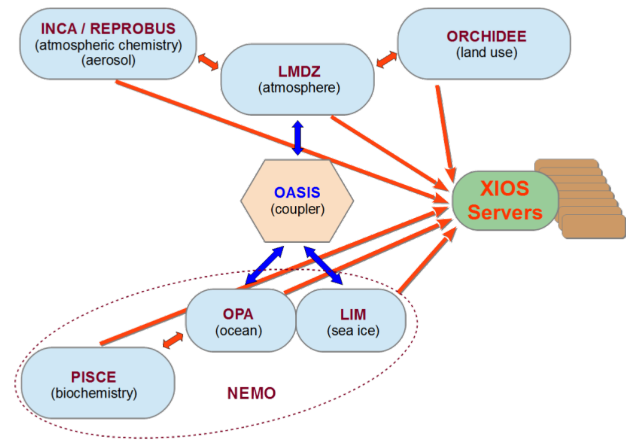
Pool of process dedicated to parallel I/O

- **XIOS : a software Burst Buffer ?**
  - Data are written all along the simulation
  - Smoothing I/O peaks
  - Constant I/O flow to file system
  - Overlap I/O by computation

LSCE

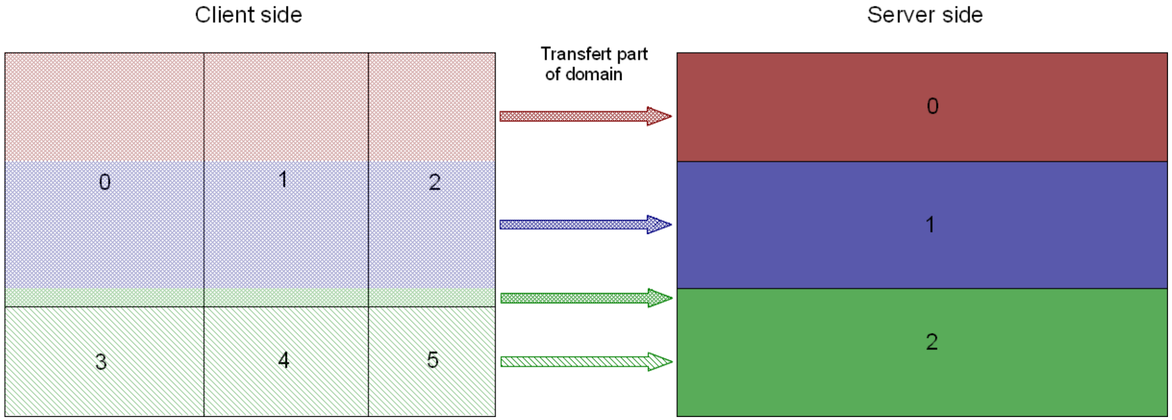
Complex and fully asynchronous protocol

- One way to send data from clients to servers
- One way to receive data from servers to clients



Same pools of I/O servers used in coupled model

Different data distribution between client and servers



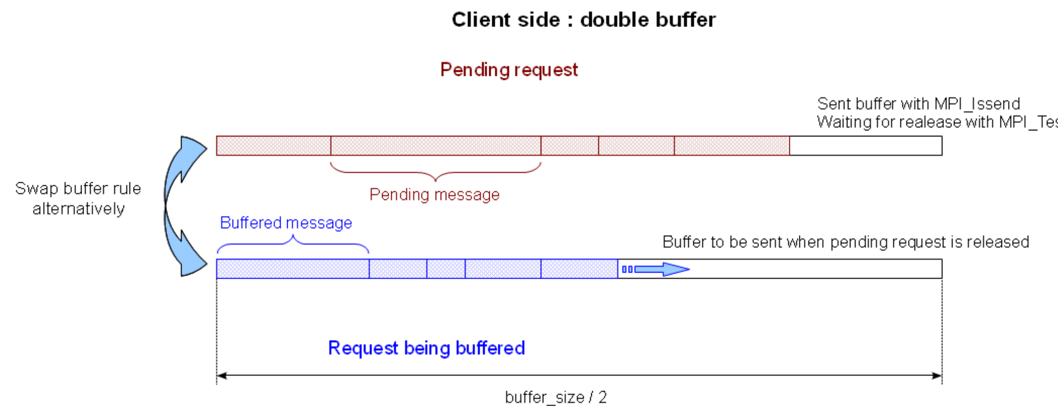
Data are sent asynchronously at writing time

- Use only MPI point to point asynchronous communication : MPI_Issend, MPI_Irecv, MPI_Test, MPI_Probe...
- No synchronization point between clients and server, and between servers
- No latency cost, communications are overlapped by computation
- Writing is also overlapped by computation

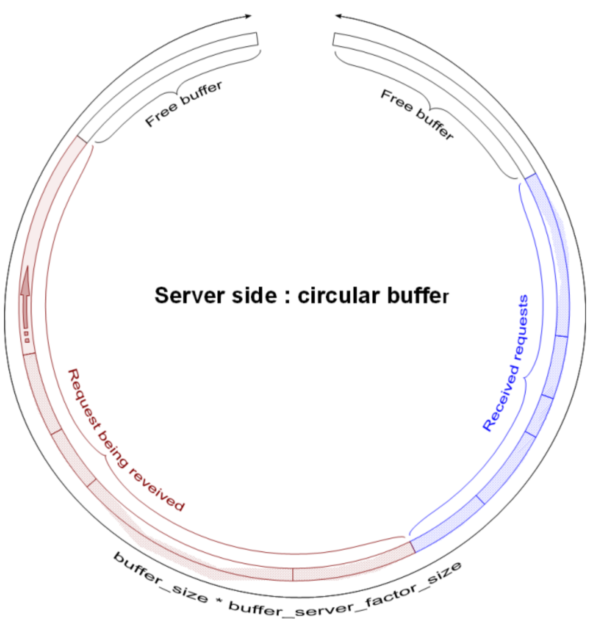
Data are received asynchronously with prefetching (by advance) on client side

XIOS buffer

- **Large usage of buffers**
  - Smoothing I/O peaks



- **Client Side : double buffers**
  - Outgoing message in transfer
  - Bufferization of the incoming flow



- **Server Side : circular buffer**
  - Received request are processed
  - In same time than receiving request from client

Overlapping data transfer and I/O by computing

Server mode vs. Attached mode

Server mode

- MPMD mode
  - mpirun -np 1024 model.exe : -np 16 xios_server.exe
- Placing XIOS servers in parallel partition
  - Strongly hardware dependent
  - But generally better to spread servers on different computing nodes

Attached mode

- To make development easier XIOS provide an "attach" mode
  - Don't need to launch xios servers executable
  - mpirun -np 12 model.exe
  - XIOS act only as a library
- Each client is itself a server for other clients
  - Pool of servers is equal to the number of clients
- Synchronous
  - Client must wait for the data to be written before continue
- Each client make parallel write
  - performance issue

XIOS 2-level server mode

LSCE

Why 2-level server?

- When number of XIOS servers increases, parallel I/O becomes inefficient due to I/O bandwidth
- Want XIOS servers to work with different output file

Intermediaries (level one) and writers (level two)

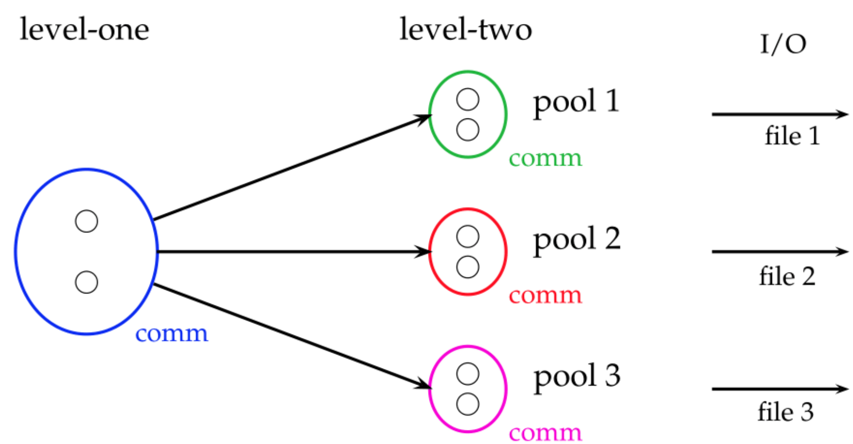
- Level-one servers will receive data from clients, redistribute, and send data to subsets of level-two servers (called "pools")
- Level-two servers will do the I/O
- Each file is written by only one pool
- No compression
- But if 1 process is assigned per pool (default option), I/O is then sequential and HDF5 compression can be used

Parameters: (context id="xios")

- **(bool) using_server2** : default **false**
- **(integer) ratio_server2** : default 50
- **(integer) number_pools_server2** :

  sets the number of server-two pools

  (default is number of second level servers)



Performance report

- Report is generated at XIOS finalization

Client side : xios_client_00.out
-> report : Performance report : total time spent for XIOS : 32.3497 s
-> report : Performance report : time spent for waiting free buffer : 1.1336 s
-> report : Performance report : Ratio : 3.50421 %
-> report : Performance report : This ratio must be close to zero. Otherwise it may be useful to increase buffer size or numbers of server

Server side : xios_server_00.out
-> report : Performance report : Time spent for XIOS : 51.0071
-> report : Performance report : Time spent in processing events : 21.5263
-> report : Performance report : Ratio : 42.2026%

Client side : Time spent for waiting free buffer is small compare to total time

- Every thing is OK, no impact of I/O on computing time

Client side : Time spent for waiting free buffer is not insignificant

- Server side : if ratio (total time / time for process event) is close to 100%
  - I/O throughput is not enough fast to maintains asynchronism
  - Add more servers
- Servers side : if ratio is much less than 100% (60-80%)
  - Servers are not overloaded but cannot absorb and smooth I/O peaks
  - Buffer are to small and need to be increased

LSCE

Memory consumption

- XIOS consumes memory internally
- XIOS uses large transfer buffer
- Part of memory is consumed by NETCDF4/HDF5
- But generally, memory consumption is scalable (client & server)

- Information about memory usage
- Buffer size is automatically computed
  - Can be different for each communication channel (client-server couple)
  - Dependent of the parallel data distribution
- 2 buffers for each client-server couple
  - 1 for sending data from client to server (I/O write)
  - 1 for receiving data from server to client (I/O read)

Client side : **xios_client_00.out**

-> report : Memory report : Context <atmosphere> : client side : total memory used for buffer 2932872 bytes
-> report : Memory report : Context <atmosphere> : server side : total memory used for buffer 209733 bytes
-> report : Memory report : Minimum buffer size required : 209730 bytes
-> report : Memory report : increasing it by a factor will increase performance, depending of the volume of data wrote in file at each time step of the file

Server side : xios_server_00.out
-> report : Memory report : Context <atmosphere_server> : client side : total memory used for buffer 209733 bytes
-> report : Memory report : Context <atmosphere_server> : server side : total memory used for buffer 1710664 bytes

XIOS performance

Managing buffer size

- Buffer sizes are automatically computed
- User can choose between 2 behaviors (parameter **optimal_buffer_size**) :
- Buffer sizes optimized for memory
  - Size adjusted to the biggest transfer
  - Minimal memory consumption for buffer
  - But losing most part of asynchronous transfer
- Buffer sizes optimized for performance
  - Sizes are adjusted to bufferize all data between two output period
  - Fully asynchronous
- User can adjust size by itself using a multiplying factor
  - **(double) buffer_size_factor**

XIOS performance

Performance : what to expect…

- **XIOS is used on simulation with O(10 000) cores and more…**
  - Ex: CINES Big Challenges 2014 : DYNAMICO 1/8° and NEMO 1/60°

- **Bench test case : NEMO 1/12°**
  - Gyre configuration : 4322 x 2882 x 31 : 8160 cores
  - Curie supercomputer : Lustre file system : theoretical Bandwidth : 150 GB/s (announced)
  - Practical Bandwidth : NETCDF4/HDF5 file format : parallel write access on a single file (tuned): ~ 5 GB / s
  - 6 days simulation (2880 time steps) ~ 300 s run s

- **6-hours frequency output files (~200 GB of data produced, 4 files)**
  - 8160 NEMO, 32 XIOS servers
  - +5% penalty for I/O (comparable to OS jittering)

- **Extreme test case : hourly output files (~1.1 TB of data produced, 4 files)**
  - 8160 NEMO, 128 XIOS servers (1.5 % resources for I/O)
  - 15-20% penalty for I/O
  - 3.6 GB/s I/O flux continuously
  - **Generated data amount : ~300 TB by day, ~10 PB by month**

XIOS parametrization

LSCE

XIOS context is used for parametrization

- Specific XIOS context in XML file
- Used only for reading variable value
- Actually, all parameters are optional, just override default value

```xml
<context id="xios">
  <variable_definition>

     <variable id="optimal_buffer_size" type="string">performance</variable>
     <variable id="buffer_size_factor" type="double">1.0</variable>
     <variable id="min_buffer_size" type="int">100000</variable>
     <variable id="using_server" type="bool">false</variable>
     <variable id="using_oasis" type="bool">false</variable>
     <variable id="info_level" type="int">50</variable>
     <variable id="print_file" type="bool">true</variable>

  </variable_definition>
</context>
```

- "

XIOS PARAMETRIZATION

LSCE

- **(string) optimal_buffer_size** : specify buffer sizing behavior (**default : "performance"**)
  - **"performance" or "memory"**
- **(double) buffer_size_factor** : multiplying the computed buffer size by this factor
  - Use with caution
- **(integer) min_buffer_size** : fix the minimum size of buffers
  - Use only in case of bad computed size
  - Can help to workaround an unexpected problem
- **(boolean) using_server**: specify "server mode" or "attached mode"
  - XIOS try to determine itself the chosen mode by analyzing MPI communicator
  - Useful only for coupled model configuration
- **(boolean) using_oasis** : used when interfaced with oasis (expert mode), (**default=false**)
- **(integer) info_level**: level of xios information output (**0-100**), **0** nothing, **100** full, (**default=0**)
- **(boolean) print_file** : if true, xios standard output and error are redirected in files indexed by process rank, (**default=false**)

Hands-on 10

XIOS performance

Understand and analyze XIOS servers performance

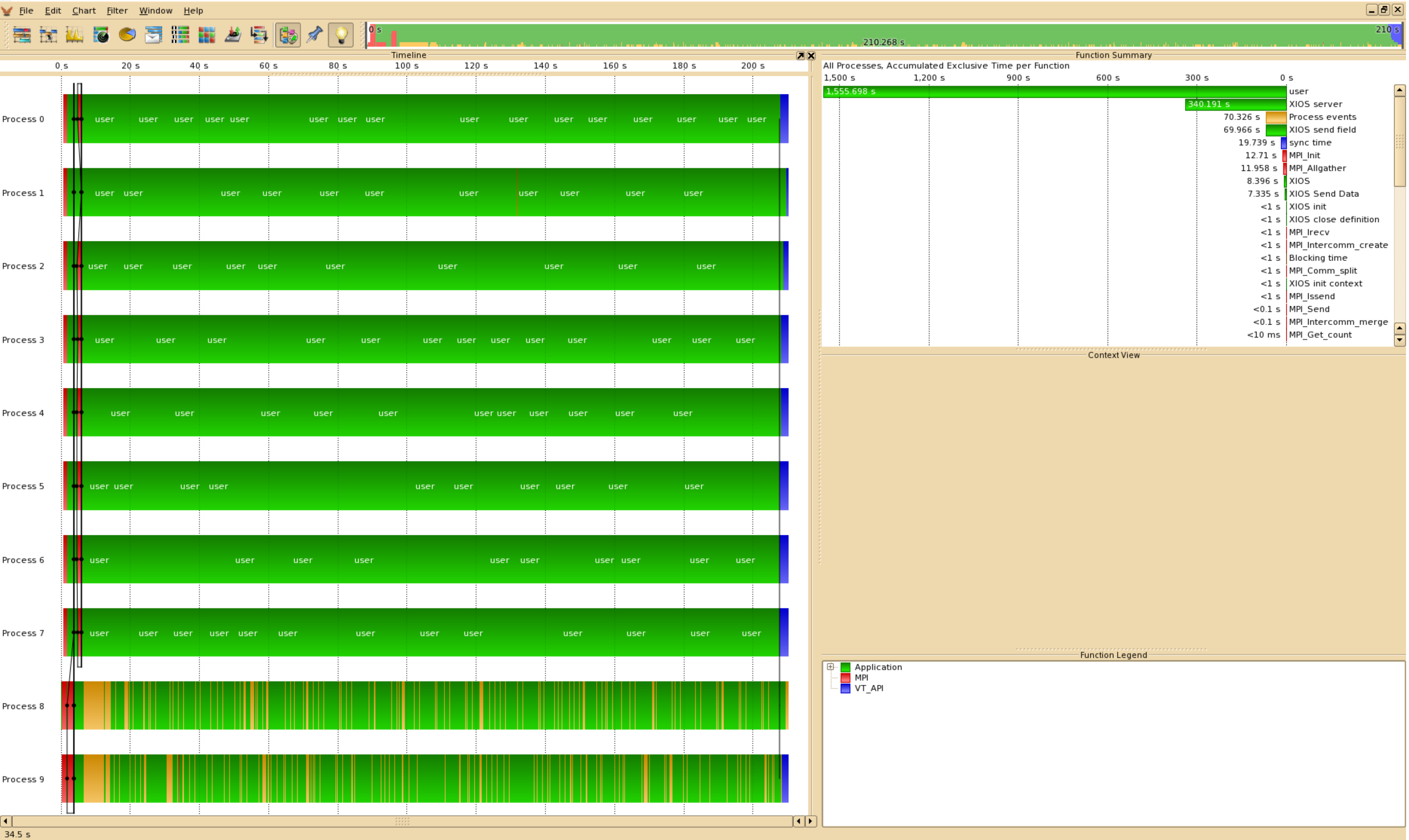
- Build a toy model
- Field is sent and written at each time step
- Some extra working time is simulate by a waiting call

```
-! Entering time loop
  DO ts=1, 1000
   CALL xios_update_calendar(ts)
   CALL xios_send_field("field", field)
   CALL wait_us(80000)   ! Wait 80 milliseconds to simulate some works
  ENDDO
```

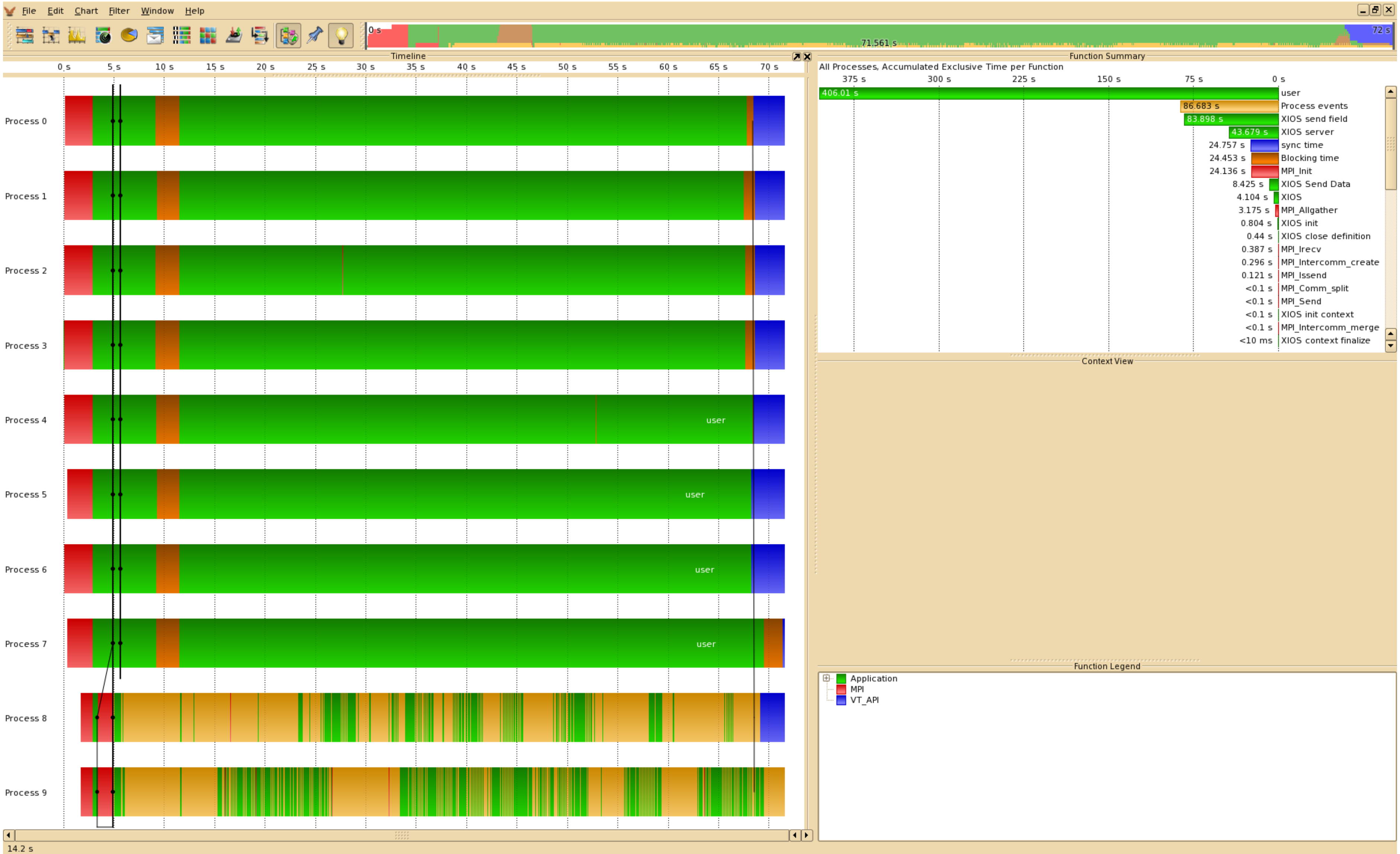
- Look at parallel vampir trace
  - Green : application time
  - Red : MPI function time
  - Orange : server working time
  - Brown : client waiting for free buffer and blocking

- Make experiments by decreasing working time compared to I/O output

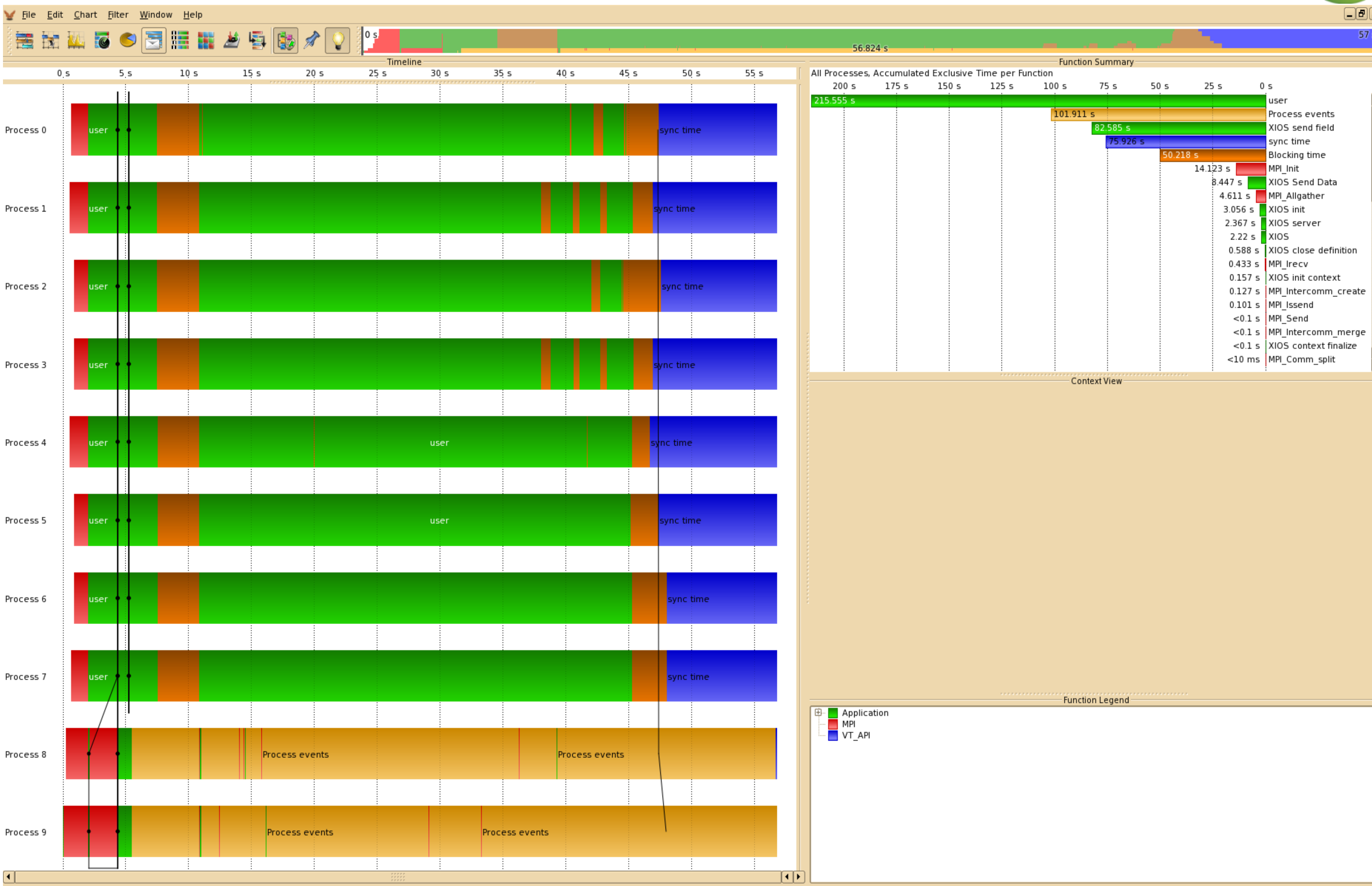
8 clients – 2 servers : working time by iteration: 80 ms



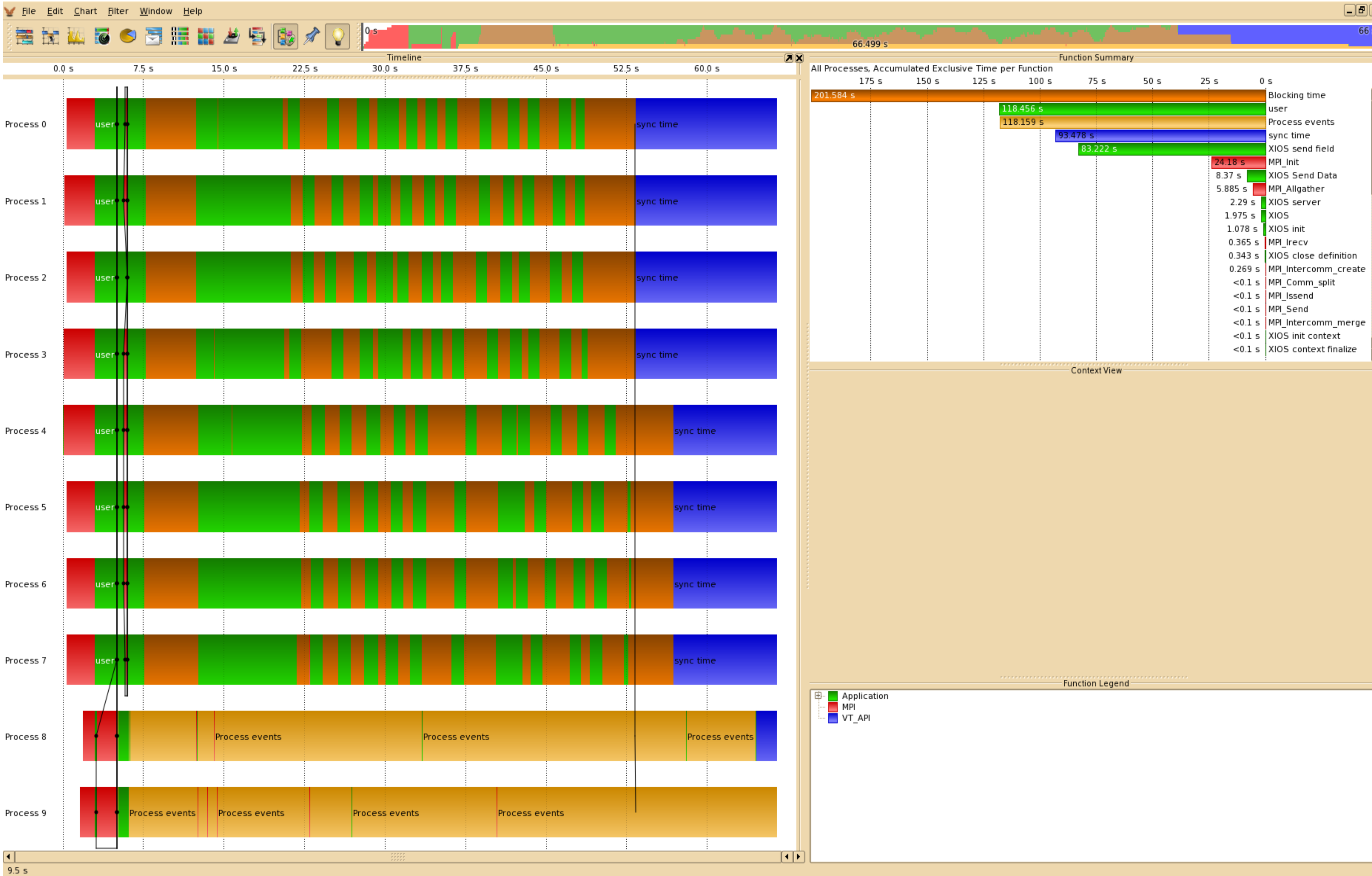
8 clients – 2 servers : working time by iteration: 20 ms



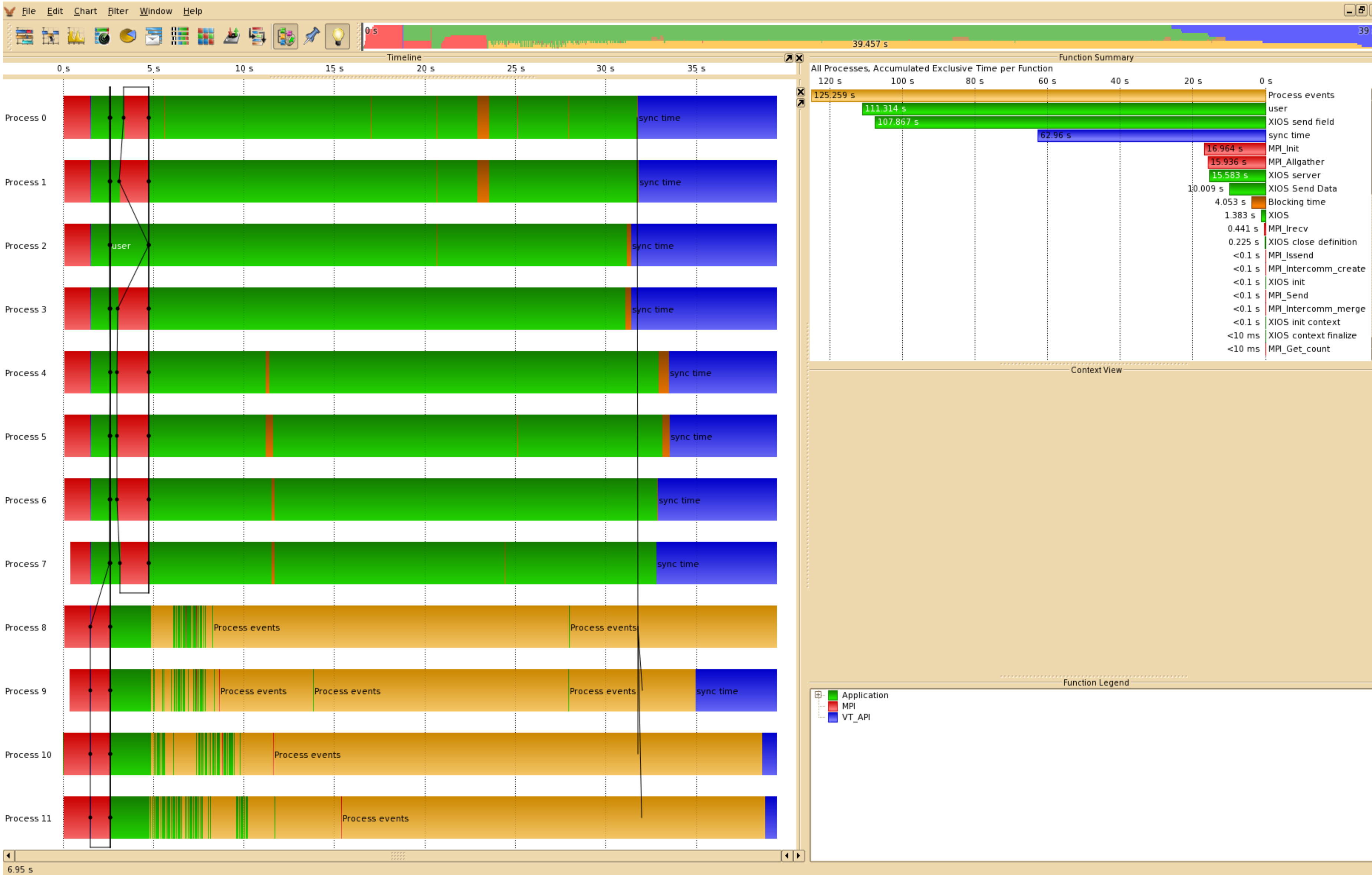
8 clients – 2 servers : working time by iteration: 10 ms



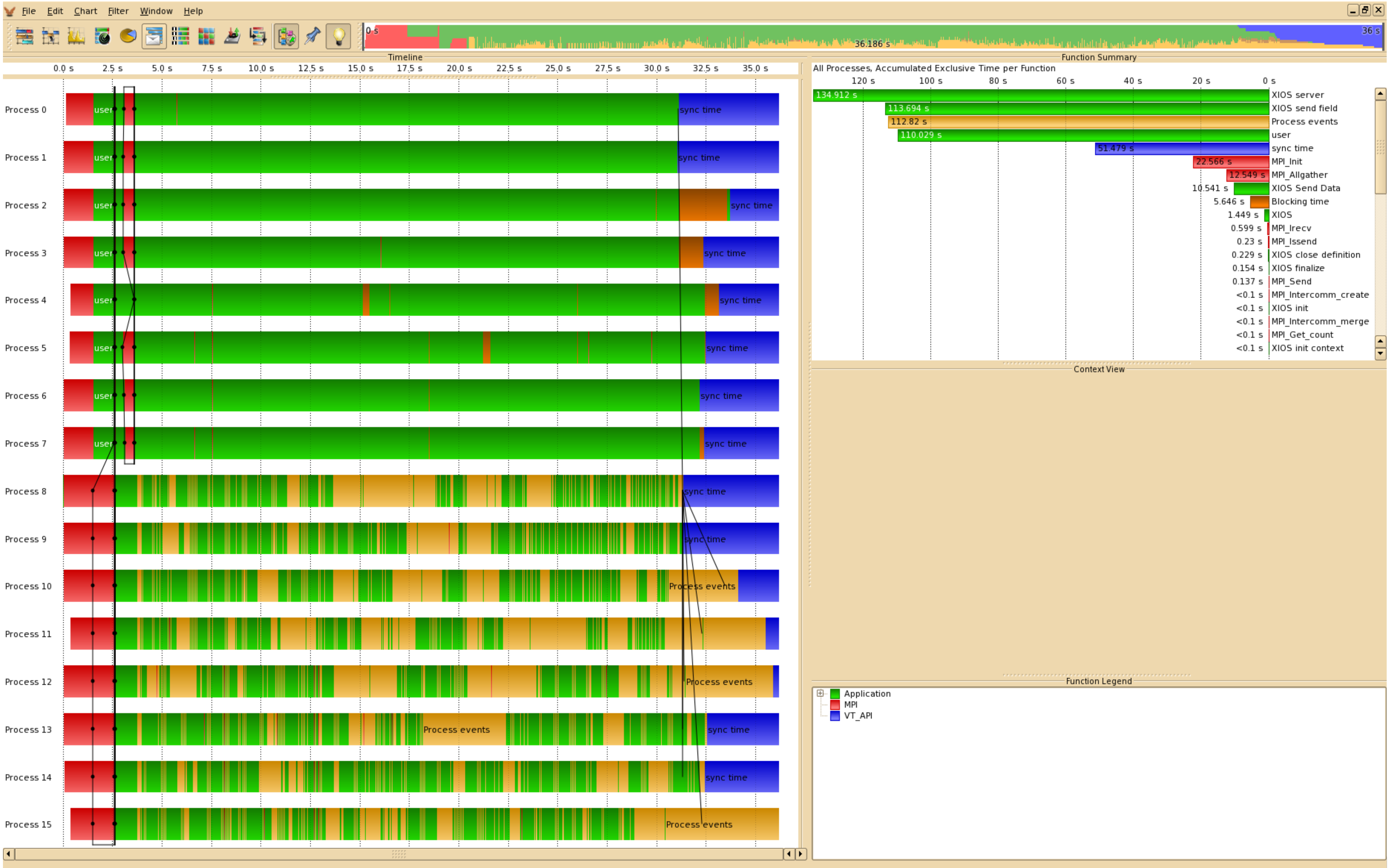
8 clients – 2 servers : working time by iteration: 5 ms



8 clients – 4 servers : working time by iteration: 5 ms



8 clients – 8 servers : working time by iteration: 5 ms



XIOS error stack

UNDER DEV

Hands-on 11

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