Extending C++ with Co-Array semantics

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Context

Issues coming from the hardware

- *Data access* more costly than *data processing*
- More and more disjoint memories to increase the bandwidth
- More and more complex parallel architectures to increase the peak performance

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Software solutions to adapt to these changes

- Data locality with *Single Programming Mutiple Data*
- Remote Memory Access with a *Partitioned Global Address Space*
- Load balance flexibility with *Asynchronous programming*

Plan

What are Co-Arrays and why are they important

HPX - High Performance Parallex

Implementation of Co-arrays in C++

Performance evaluation

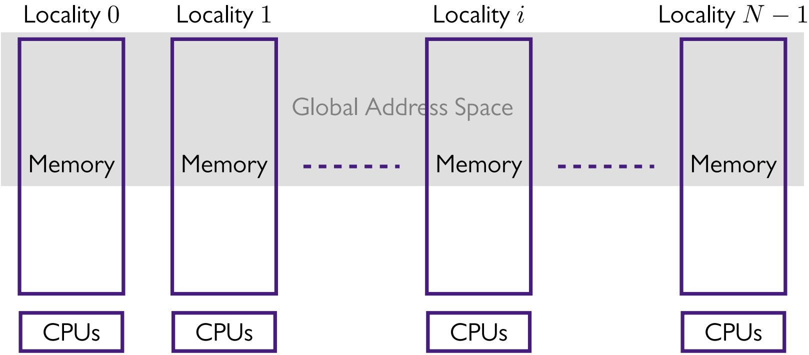
Co-arrays in few words

- Fortran extension introduced by Numrich and Reid [1]
- Co-array is a strict implementation of the PGAS Model
- Part of the actual Fortran Standard[2]

[1] *Co-array Fortran for Parallel Programming*, - R.W. Numrich et al. - ACM SIGPLAN Fortran forum, 1998

[2] *Co-arrays in the next Fortran Standard* - R.W. Numrich et al. - ACM SIGPLAN Fortran forum, 2005

Illustration



Illustration

```
real :: a(3)
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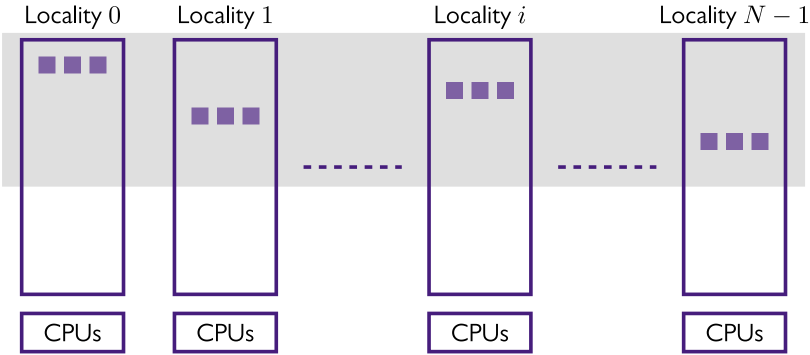

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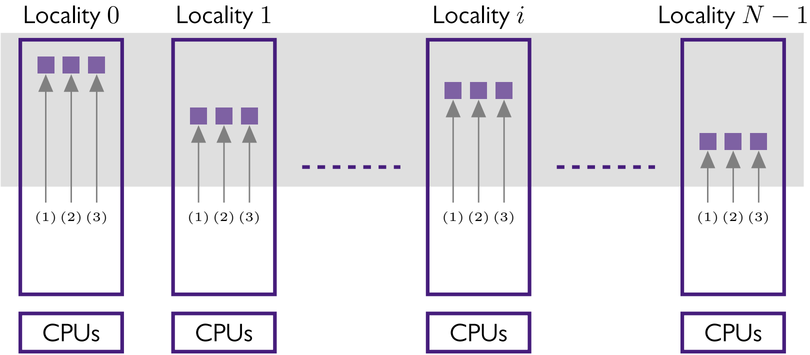
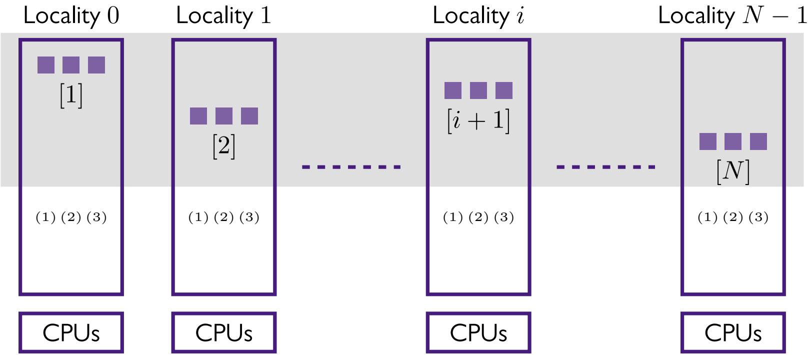


Illustration

```
real :: a(3)[*]
```



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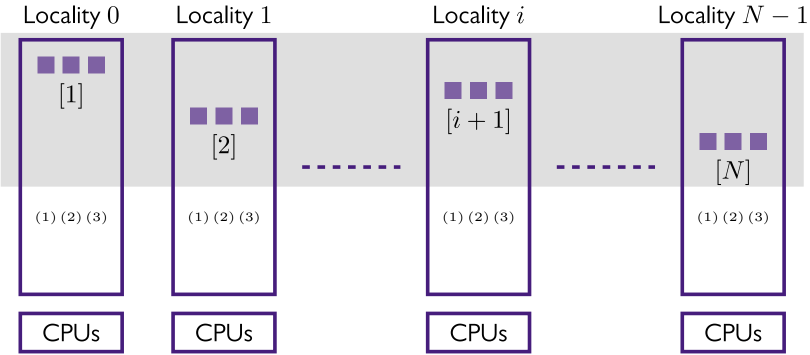
Where is the element $\Longrightarrow$ `a(2)[N]` ?



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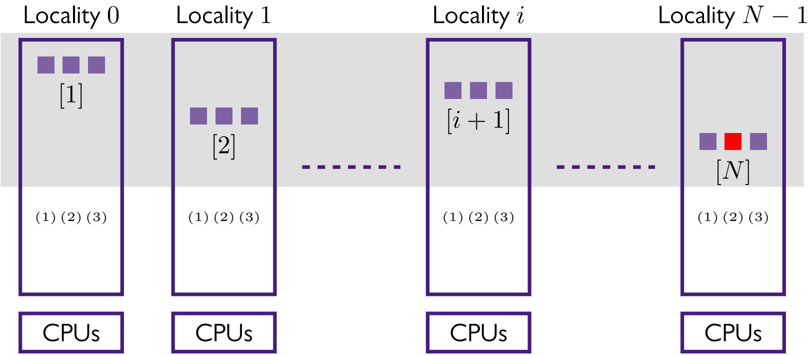

From Co-array Fortran to Co-array C++

Why co-arrays ?

- Improve data locality in distributed applications
- Access to remote references are done via array-based subscripts
- Widely accepted by the Fortran community

[3] *Extending C++ with co-array semantics* - A. Tran Tan et al - ACM SIGPLAN ARRAY, 2016 (soon)

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Our Approach[3]

- Enable co-array semantics with a C++ library approach
- Use of a C++ runtime system to manage parallel/distributed tasks
- New features of the C++ Standard 11/14 $\Longrightarrow$ Easy API design

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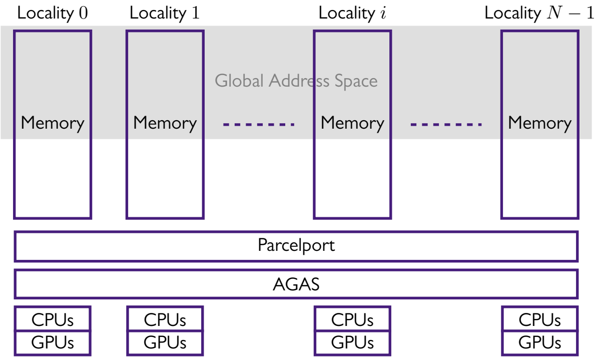
HPX : High Performance Parallex

A C++ runtime system for applications of any scale [4,5]



[4] *Parallex an advanced parallel execution model for scaling-impaired applications*- H. Kaiser et al - ICPPW, 2009

[5] *A Task Based Programming Model in a Global Address Space* - H. Kaiser et al - PGAS, 2014

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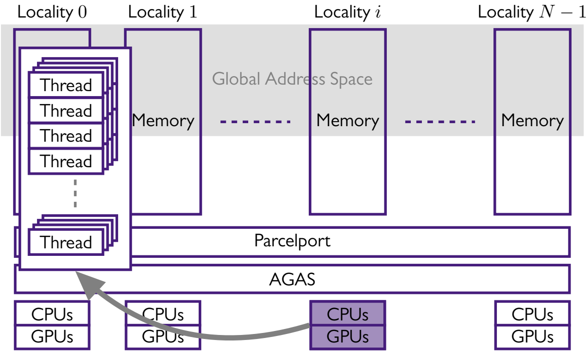

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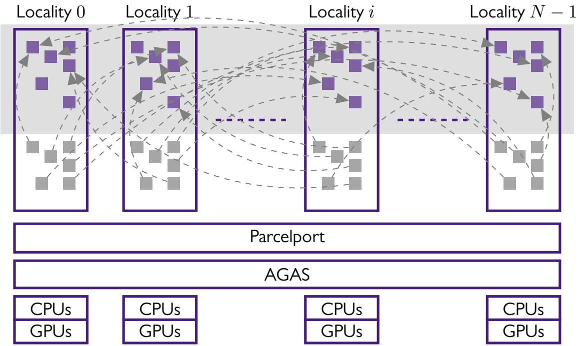

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Instantiation of a co-array object : Fortran vs C++

```
//  Fortran Code
real :: z[10,*]

// C++ Code
spmd_block block;
coarray<double,2> z( block, "z", {10,_}, partition<double>(1));
```


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Co-Array C++ sample code

```
spmd_block block;
coarray<double,1> z( block, "z", {_}, partition<double>(1));

if ( block.this_image() == 0 )
{
    std::cin  >> z.data(_);

    int num_images = block.get_num_images();
    for( int image = 1; image < num_images; image++ )
    {
        z(image) = z.data(_);
    }
}

block.barrier_sync("b");  // sync_all() in Fortran
```

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coarray<double,1> z( block, "z", {_}, partition<double>(1));

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    int num_images = block.get_num_images();
    for( int image = 1; image < num_images; image++ )
    {
        z(image) = z.data(_);
    }
}

future<void> fb = block.barrier("b");
```

Traversal of co-indexed elements with iterators

```
spmd_block block;
coarray<double,3> a ( block, "a", {4,4,_}, partition<double>(5));

int idx = 0;
if ( block.this_image() == 0 )
{
    for (auto i = a.begin(); i != a.end(); i++ )
        *i = std::vector<double>(5,idx++);
}
block.barrier_sync("b");

auto alocal = local_view(a);

for (auto ii = alocal.begin(); ii != alocal.end(); ii++)
{
    std::vector<double> & ref = *ii;
    ...
}
```

... with range-based *for* loops

```
spmd_block block;
coarray<double,3> a ( block, "a", {4,4,_}, partition<double>(5));

int idx = 0;
if ( block.this_image() == 0 )
{
    for (auto && proxy : a)
        proxy = std::vector<double>(5,idx++);
}
block.barrier_sync("b");

auto alocal = local_view( a );

for (std::vector<double> & ref : alocal)
{
    ...;
}
```

Creation of a distributed vector in HPX

A coarray is a *multi-dimensionnal view* tied to a distributed vector

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```
int N, n;

std::vector<hpx::id_type> locs = hpx::find_all_localities();

auto layout = hpx::container_layout(n, locs);

// Creation of the distributed vector
hpx::partitioned_vector<double> v(N, 0.0, layout);
```

Creation of a SPMD region

A SPMD region is the mean to invoke *images* in multiple localities

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A SPMD region is the mean to invoke *images* in multiple localities

```
void example_image(spmd_block block)
{   ...
}
HPX_DEFINE_PLAIN_ACTION(example_image, my_action);

int main()
{
    std::vector<hpx::id_type> locs = hpx::find_all_localities();

    // Invocation of the spmd region
    define_spmd_block( locs, my_action );

    return 0;
}
```

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Benchmark 1 : *Matrix Transpose*

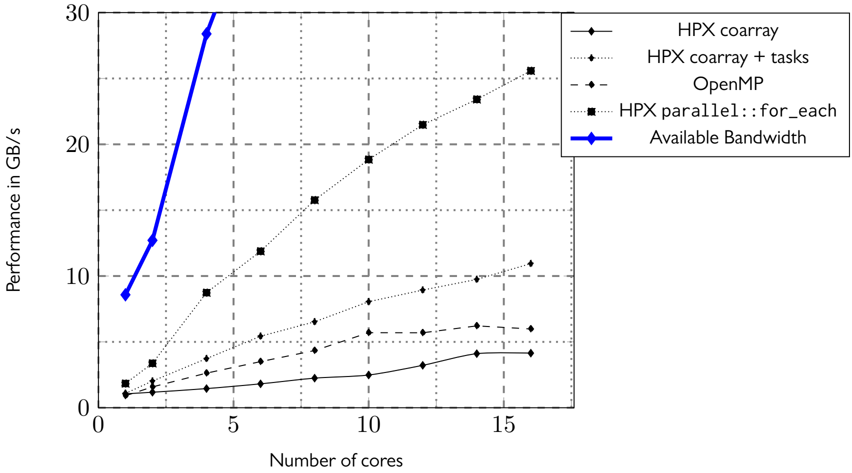
```
void transpose_coarray(  spmd_block & block
                       , coarray<double,2> & out
                       , coarray<double,2> & in
                       , int height, int width
                       , int local_height
                       , int local_width
                       , int local_leading_dimension)
{
    // Outer Transpose operation
    for(int j = 0; j<width; j++)
    for(int i = 0; i<height; i++)
    {
      // Put operation
        out(j,i) = in(i,j);
    }
    block.barrier_sync("outer_transpose");

    /* */
```

Benchmark 1 : *Matrix Transpose*

```
    /* */

    auto out_local = local_view(out);

    // Inner Transpose operation
    for (std::vector<double> & elt : out_local)
    {
        for(int jj = 0; jj<local_width-1;  jj++)
        for(int ii = jj+1; ii<local_height; ii++)
        {
            std::swap( elt[jj + ii*local_leading_dimension]
                     , elt[ii + jj*local_leading_dimension]);
        }
    }
    block.barrier_sync("inner_transpose");
}
```

Benchmark 1 : *Matrix Transpose*

performed in a 2×8 core machine



Benchmark 2 : *Sparse Matrix Vector Multiplication*

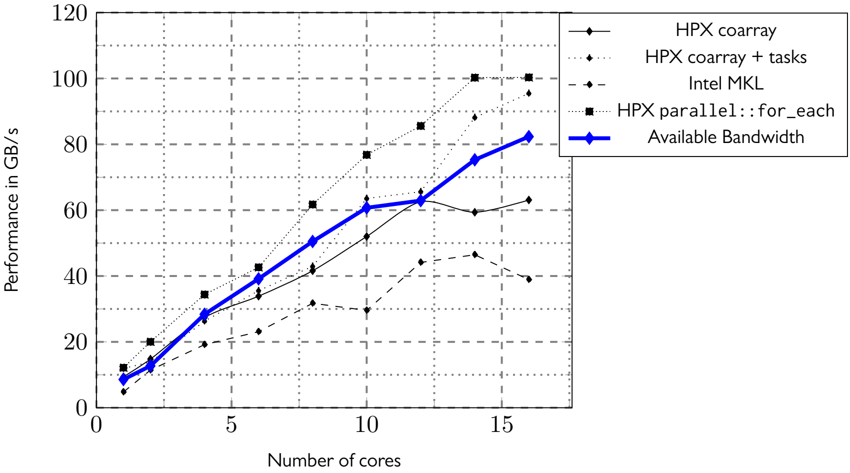
```
struct spmatrix
{
    // Constructor definition ...

    int m_, n_, nnz_;
    std::vector<int> rows_, indices_;
    std::vector<double> values_;
    std::vector<int> begins_, sizes_;
};

void spmv_coarray( spmd_block & block
                 , spmatrix const & a, std::vector<double> & x
                 , coarray<double,1> & y)
{
    int image_id = block.this_image();
    int begin = a.begins_[image_id];
    int chunksize = a.sizes_[image_id];

    /* */
```

Benchmark 2 : *Sparse Matrix Vector Multiplication*

```
    /* */

    double * out = y.data(_).data();
    const int * row = a.rows_.data() + begin;
    const int * idx = a.indices_.data() + *row - 1;
    const double * val = a.values_.data() + *row - 1;

    for(int i = 0; i < chunksize; i++, row++, out++)
    {
        double tmp = 0.;
        int end = *(row + 1);

        for( int o = *row; o < end; o++, val++, idx++)
            tmp += *val * x[*idx - 1];

        *out = tmp;
    }
    block.barrier_sync("spmv");
}
```

Benchmark 2 : *Sparse Matrix Vector Multiplication*

performed in a 2 × 8 core machine



Thanks for your attention