Supporting general data structures and execution models in runtime environments

PhD. Dissertation

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Outline

Introduction

The Hitmap library

Unified support for dense and sparse data

A portable dataflow model and framework

Conclusions

Introduction

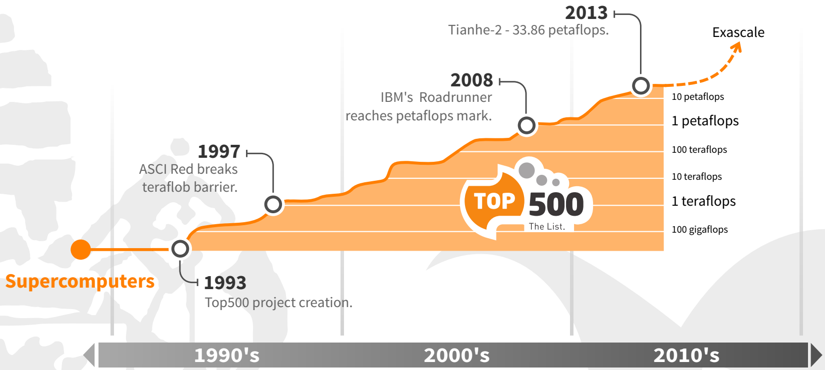
Parallel computing

- **What?**
  The simultaneous use of multiple computational resources to solve a problem.

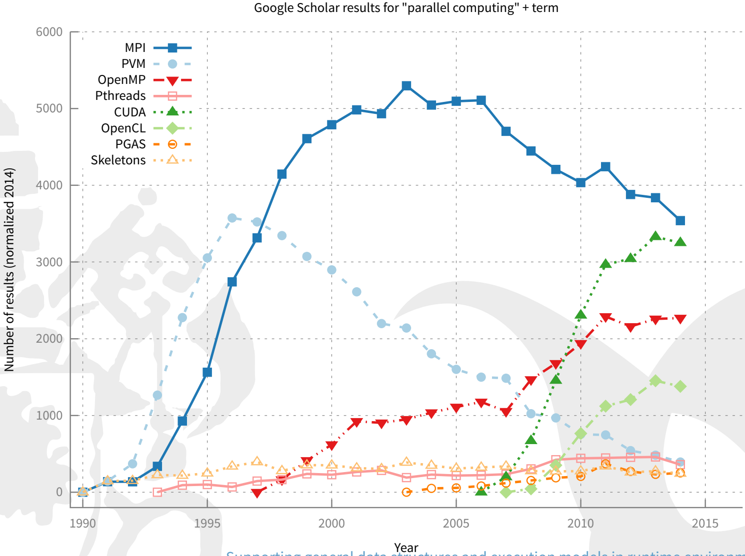
- **Why?**
  Many computing problems are so costly that they cannot be solved sequentially in a reasonable time.

- **Where?**
  Usually associated to high-performance computing but nowadays also for mainstream computing.

The evolution of parallel computing systems



Common tools for parallel computing



Common tools for parallel computing II

Google Scholar search:

$$\frac{\text{TERM} + \text{“parallel computing”}}{\text{“parallel computing”}}\%$$

Most popular parallel tools in 2014:

- MPI 18%
- CUDA 17%
- OpenMP 12%

The most cited parallel programming tools are message-passing for distributed-memory, threads models for shared-memory environments, or kernel solutions for accelerators.

How do we currently develop programs for these systems?

We need to know:

- Sequential programming

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- Distributed memory

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We need to know:

- Sequential programming
- Distributed memory
- Shared memory

How do we currently develop programs for these systems?

We need to know:

- Sequential programming
- Distributed memory
- Shared memory
- Accelerator offloading

How do we currently develop programs for these systems?

We need to know:

- Sequential programming
- Distributed memory
- Shared memory
- Accelerator offloading

A programmer must be proficient in all these technologies to be able to take advantage of the current parallel systems.

Development of parallel programs: How should it be?

- We need:
  - Frameworks with unified parallel models.
  - High-level abstractions to represent parallel algorithms.

- So:
  - Programmers can focus on the design
  - while compilers do the complex optimizations
  - using highly-efficient and adaptable runtime systems.

Related work

- Compiler auto-parallelization:
  - High Performance Fortran [1].
  - Polyhedral model, e.g. Pluto [2].
- Multi-paradigm models:
  - Partitioned Global Address Space languages: e.g. Chapel [3].
  - Heterogeneous platforms: e.g. OpenCL [4].

[1] High Performance Fortran Language Specification, HPF Forum, 1993.
[2] PLUTO+: near-complete modeling of affine transformations for parallelism and locality, Acharya and Bondhugula, ACM PPoPP, 2015.
[3] User-defined distributions and layouts in chapel, Chamberlain et al, HotPar 2010.
[4] The OpenCL specification, Khronos group, 2008.

Work carried out by Trasgo group

- Trasgo programming framework: [5]
  - A modular parallel programming framework.
  - Its model is based on high-level, nested-parallel specifications.
  - The high-level parallel code is transformed into a source code with Hitmap calls.
- Hitmap runtime library: [6]
  - A library for hierarchical tiling and mapping of arrays.
  - Provides a global view of the parallel computation.
  - Module system to perform data partition.
  - Communications are adapted based on the partition.

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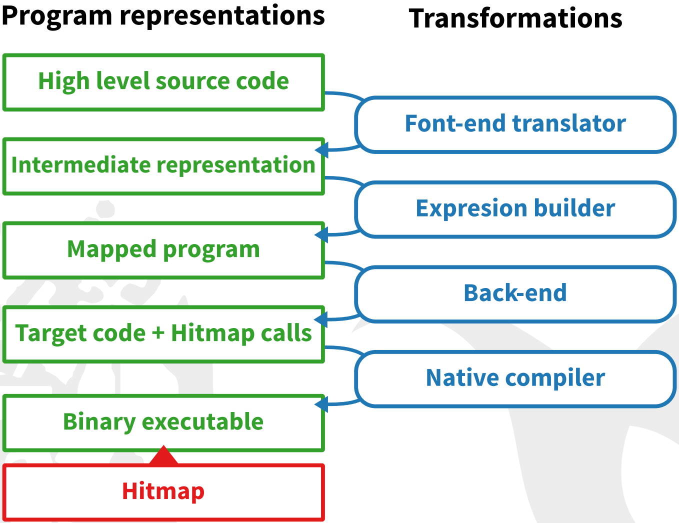
[5] Trasgo: a nested-parallel programming system, Gonzalez-Escribano et al, Springer JoS, 2009 (see Ref. [58])

[6] An Extensible System for Multilevel Automatic Data Partition and Mapping, Gonzalez-Escribano et al, IEEE TPDS, 2013 (see Ref. [59])

Trasgo framework architecture



Towards a unified programming model

Most parallel program models, including Hitmap, suffer from some limitations.

- Unified support for dense and sparse data.
- Integration of dynamic parallel paradigms and models.

Limitations I: Sparse support

- Common parallel tools do not offer integrate support for data structures.
  - MPI and OpenMP only give parallelism support.
- Most parallel languages offer support only for dense structures.
  - Such as HPF, UPC
- Some PGAS languages are being augmented with sparse support:
  - E.g. Chapel, Titanium.
- For sparse structures:
  - Manual management: implied a high programming effort.
  - Specific libraries: may not follow the same approach.
- Reusability of dense code was rather poor.

Limitations II: Dataflow structures

With common parallel solutions (e.g. MPI, OpenMP):

- Simple static parallel structures are easy to program.
- Programming dynamic and dataflow applications is still challenging.
- Low abstraction level to deal with complex synchronization:
  - Complex codes with many hard-wired decisions.

Research question

Is it possible to create a runtime system for a generic high level programming language that offers (1) common abstractions for dense and sparse data management, and (2) generic data-mapping and data-flow parallelism support for hybrid shared- and distributed-memory environments?

The Hitmap library

The Original Hitmap library

- Library for hierarchical tiling and mapping of arrays.
- Main features:
  - Use of a global view of the parallel computation.
  - Module systems of load-balancing and distribution techniques.
  - Communications are declared based on partition result.

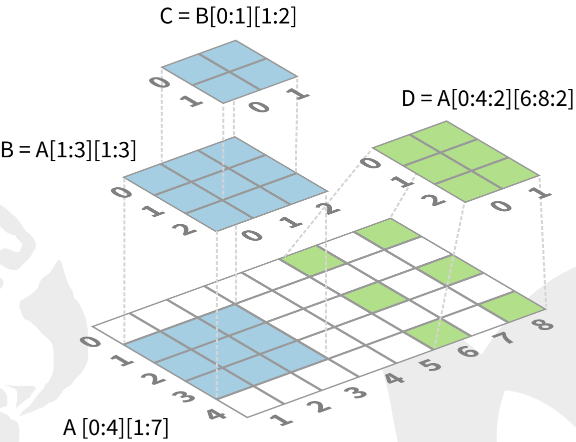
Features and terminology

- Three categories and six entities:

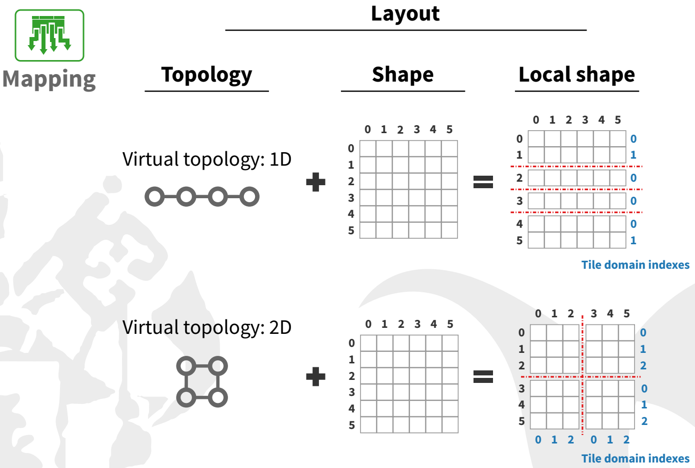
Tiling arrays	+	Mapping	+	Communication
Shape		Topology		Communication
Tile		Layout		Pattern

Tiling example

Tiling



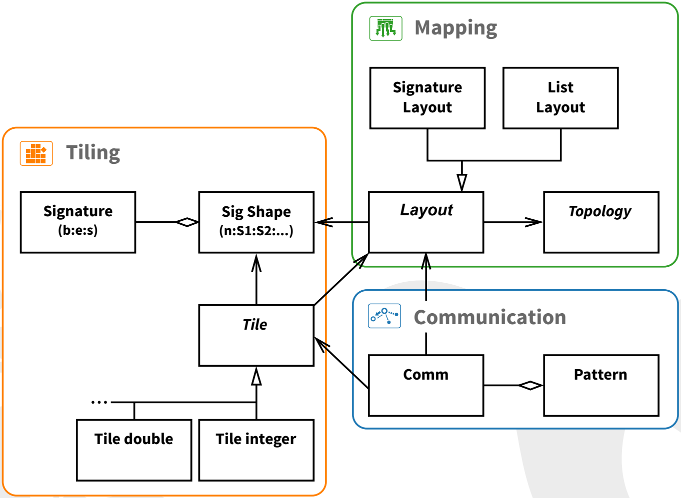
Mapping example



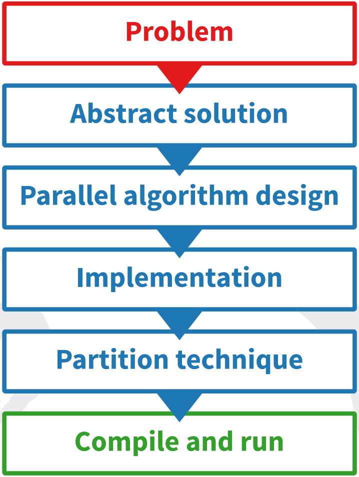
Communication

- Transmission of tile elements among virtual processors.
- Types: point-to-point communications, paired exchanges for neighbors, shifts along a virtual topology axis, collective communications, etc.
- Use of layouts information about neighborhood.
- Composed in reusable patterns.

The original Hitmap library architecture



Hitmap usage methodology



Unified support for dense and sparse data

Sparse support in parallel frameworks

- Common parallel tools do not offer integrate support for data structures.
  - MPI and OpenMP only give parallelism support.
- Most parallel frameworks only integrate support for dense structures:
  - The Partitioned Global Address Space languages: UPC [7], Coarray Fortran [8].
- Some frameworks have a limited sparse support:
  - Titanium [9]: Sparse Array Copying.
  - Chapel[10]: Sparse domain distribution.

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[7] Introduction to UPC, Carlson et al, Tech. rep. CCS-TR-99-157, 1999 (see Ref. [23])

[8] Fortran 2008 standard, ISO/IEC 2010 (see Ref. [78])

[9] Titanium Language Reference Manual, Bonachea et al, 2006. (see Ref. [21])

[10] User-defined distributions and layouts in Chapel, Chamberlain et al, HotPar 2010 (Ref. [27])

Alternatives

- Manual management: implies a high programming effort.
- Specific libraries: may not follow the same approach.
  - Sparse management libraries: Sparskit [11].
  - Sparse partitioning tools: Metis [12].
  - Mathematical solver libraries: PETSc [13].

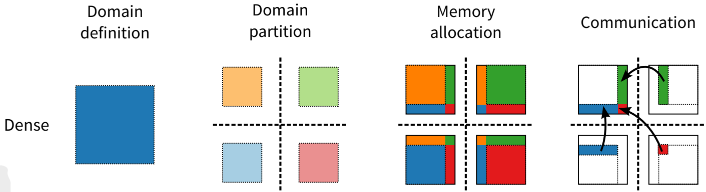
[11] SPARSKIT: a basic tool kit for sparse matrix computations, Saad, Tech. rep. 1994, (Ref. [109])
[12] MeTiS–A Software for Partitioning Graphs, Karypis et al, Tech. rep. 1998, (see Ref. [80])
[13] PETSc Users Manual, Balay et al, Tech. rep. 2014, (see Ref. [13])

Our proposal

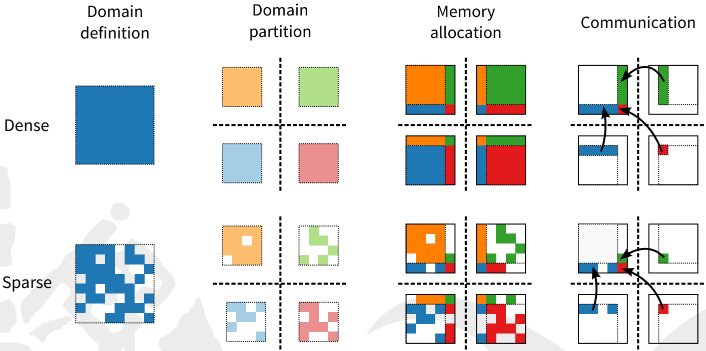
- We present a solution to handle sparse and dense data domains using the same conceptual approach.

- Stages of a parallel program:
  - Sparse/Dense parallel design follows the same steps.
  - The differences appear at the implementation stage.

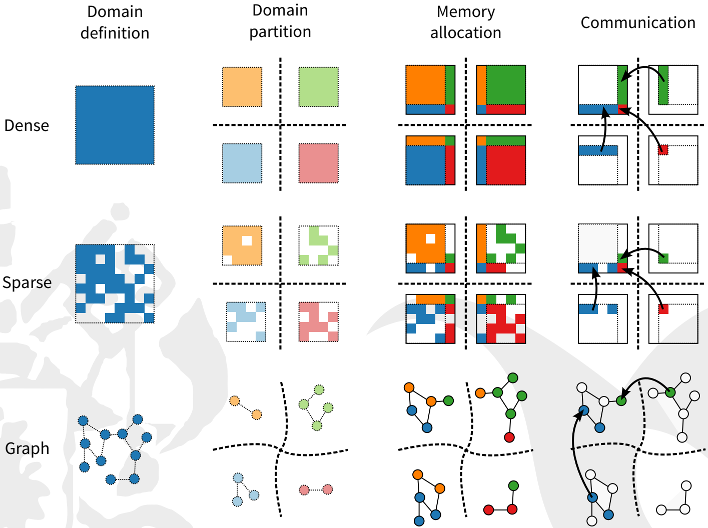
Stages of a parallel program: Stencil example



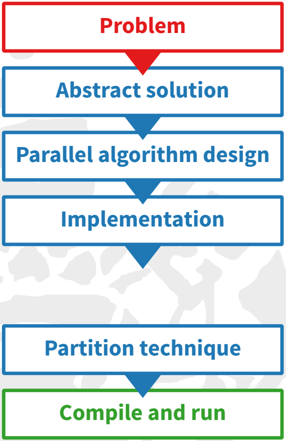
Stages of a parallel program: Stencil example



Stages of a parallel program: Stencil example

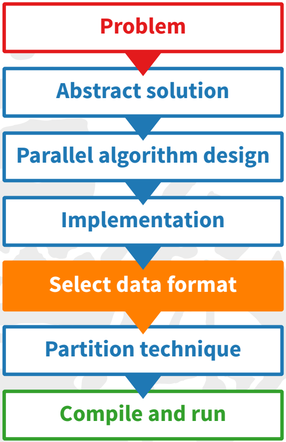


Adding support for sparse domains to Hitmap



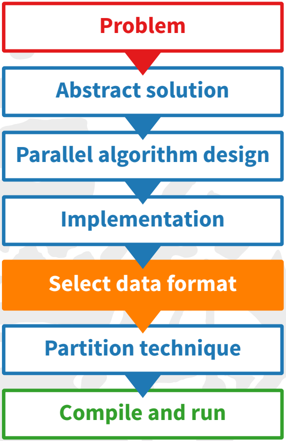
- New step in the Hitmap programming methodology.

Adding support for sparse domains to Hitmap



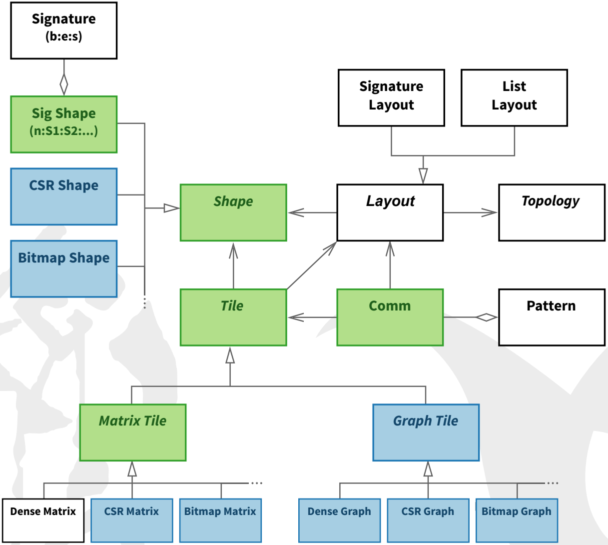
- New step in the Hitmap programming methodology.

Adding support for sparse domains to Hitmap



- New step in the Hitmap programming methodology.
- Shape and Tile classes in abstract interfaces.
- Two new kinds of sparse domains: CSR, Bitmap
- Tiles with several data spaces: edges and vertices.
- New layouts with graph partitioning.
- New communications.

New architecture



Programing with Hitmap dense/sparse support

Abstract Design

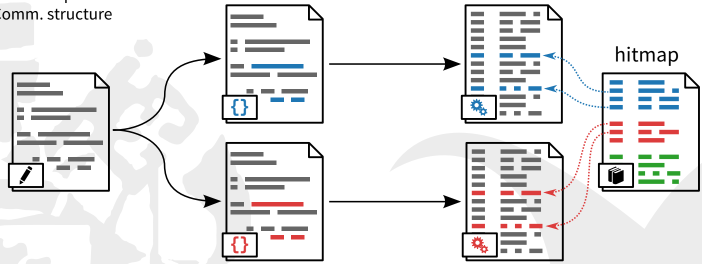
- Virtual Topology
- Data domain
- Local computation
- Comm. structure

Implementation

- Particular data format
- Partition technique

Executable

- Adapts at run-time depending on the real topology



Dense example: distributed matrix initialization

```
// Load the global matrix.
HitShape sglobal = hit_shapeStd(2,ROWS,COLS);

// Create the topology object.
HitTopology topo = hit_topology(plug_topArray2D);

// Distribute the matrix among the processors.
HitLayout lay = hit_layout(layBlocks,topo,&sglobal);

// Get the shape for the local matrix.
HitShape shape = hit_layShape(lay);

// Allocate the matrix.
HitTile_double M;
hit_tileDomainShapeAlloc(&M, double, shape);

// Init the matrix values.
int i,j;
hit_shapeIterator(j,shape,0){
   hit_shapeIterator(j,shape,1){
      hit_tileElemAt(2,M,i,j) = 0.0;
   }
}
```

Sparse example: distributed graph initialization

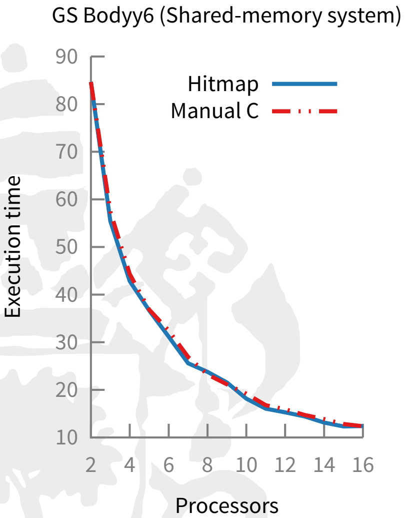
```
// Load the global matrix.
HitShape sglobal = hit_fileHBMatrixRead("file.rb");

// Create the topology object.
HitTopology topo = hit_topology(plug_topPlain);

// Distribute the matrix among the processors.
HitLayout lay = hit_layout(laySparse,topo,&sglobal);

// Get the shape for the local matrix.
HitShape shape = hit_layShape(lay);

// Allocate the matrix.
HitTile_double M;
hit_mcTileDomainShapeAlloc(&M, double, shape);

// Init the matrix values.
int i,j;
hit_cShapeRowIterator(i,shape){
   hit_cShapeColumnIterator(j,shape,i){
      hit_mcTileElemIteratorAt(M,i,j) = 0.0;
   }
}
```

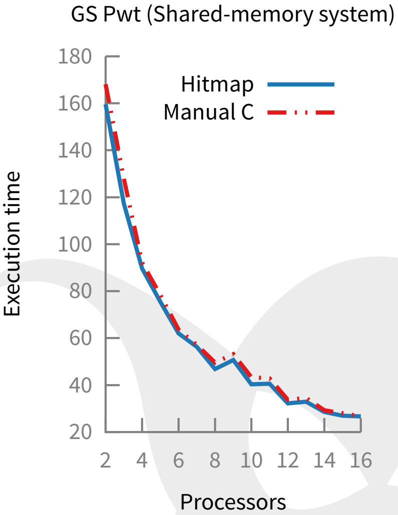
Experimental evaluation

- Three benchmarks:
  - Graph synchronization: Stencil-type operation in a graph.
  - Sparse matrix-vector multiplication.
  - Finite Element Method.
- Implementations:
  - Manual C+MPI.
  - Hitmap.
  - PETSc.
- Computing environments:
  - Geopar: A shared-memory system with 16 cores.
  - Beowulf DC: A cluster with 20 dual-core nodes.
  - Beowulf SC: A cluster with 19 single-core nodes.

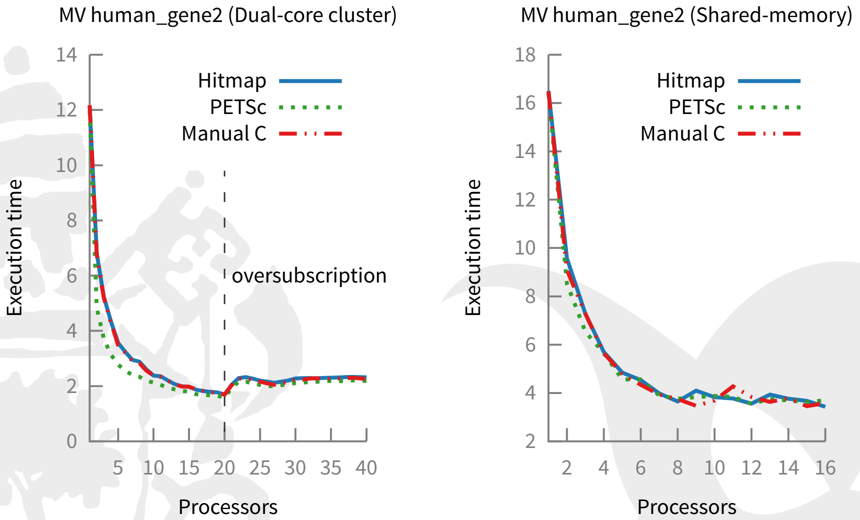
Only most relevant result follow.

Results graph synchronization

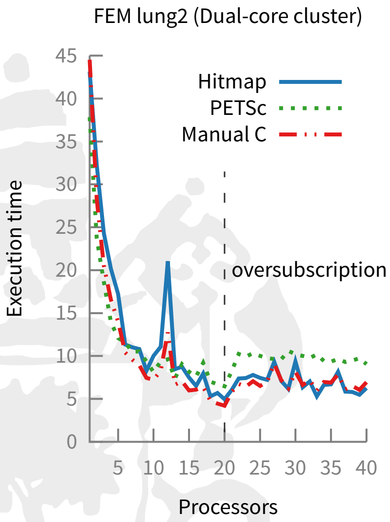


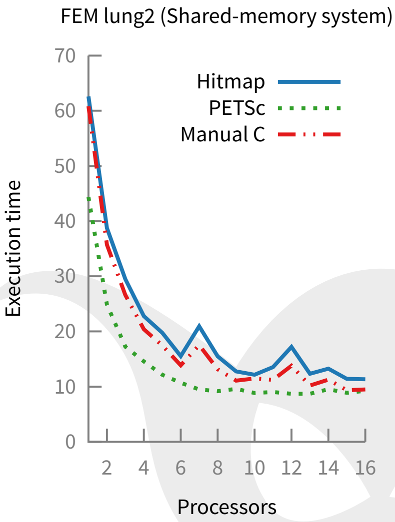


Results matrix multiplication

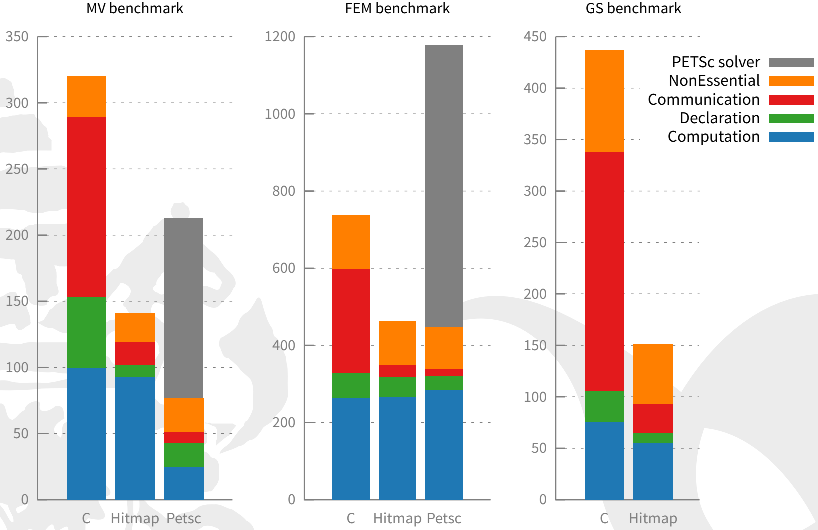


Results Finite Element Method





Lines of code comparison



Support for sparse domains: Conclusions

- A new approach to integrate dense and sparse data management in parallel programming.
- The communication structure adapts to the data structure and partition technique.
- Hitmap abstractions simplify the writing of a parallel program with a similar performance compared to other solutions.
- The runtime for our generic parallel system now supports dense and sparse programs with the same methodology.

A portable dataflow model and framework

Stream and dataflow libraries and languages

- Programming dynamic and dataflow applications is challenging with current parallel solutions.
- Stream and dataflow: FastFlow [14], OpenStream [15], or S-Net [16].
- They have models where sequential computation and the synchronization are defined separately.
- These models lack a generic system to represent:
  - Channels with generic loops.
  - Mechanisms to express task-to-task affinities.
- There some applications that can not be built.

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[14] FastFlow: high-level and efficient streaming on multi-core, Aldinucci et al. (see Ref. [5])
[15] OpenStream: Expressiveness and Data-Flow Compilation, Pop et al., (see Ref. [103])
[16] A Gentle Introduction to S-Net, Grelck et al., Parallel Process. Lett. 2008, (see Ref. [64])

A portable dataflow model and framework

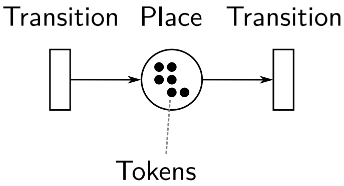
- We propose a new parallel programming model based on dataflow computations.
- Can be modelled using Colored Petri nets [17].
- Hitmap++: A supplement to the static communication structures available in Hitmap.

[17] Coloured Petri nets: modeling and validation of concurrent systems, Jensen and Kristensen, Springer 2009.

Our proposal

- Program: reconfigurable network of activities and typed data containers.
- MPMC channels with a work-stealing mechanism.
- Task-to-task affinity to exploit data locality.
- Single representation for shared and distributed memory.

Petri nets



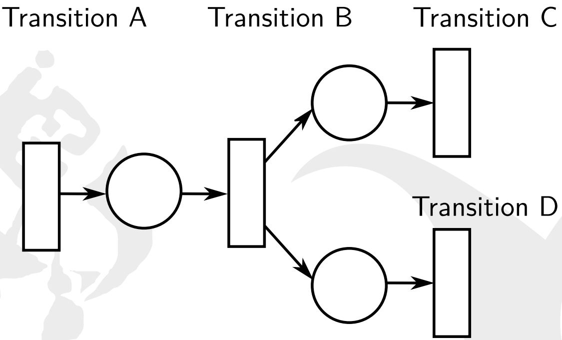
- A mathematical modeling language to describe systems.
- Directed bipartite graph:
  - *Places* and *Transitions* connected by *Arcs*.
  - Places are marked with *Tokens*.
  - A transition removes tokens from its input places and adds tokens to its output places.
- Colored Petri nets is an extension that adds data type primitives and the ability of writing transitions with different behaviors (for each type).

Mode-driven model formulation

- The modes are the transition states and they define a configuration of I/O channels.
- Used to:
  - Define mutually exclusive tasks inside a transition.
  - Exploit data locality.
  - Reconfigure the network.
- Transitions read tokens with the color of their current mode.
- Signal system:
  - Mode-change signal: Special token to mark a mode change.
  - A mode-change propagates the signals across the network.

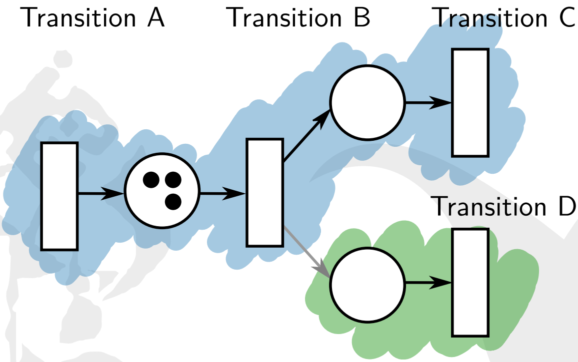
Mode example

Network creation



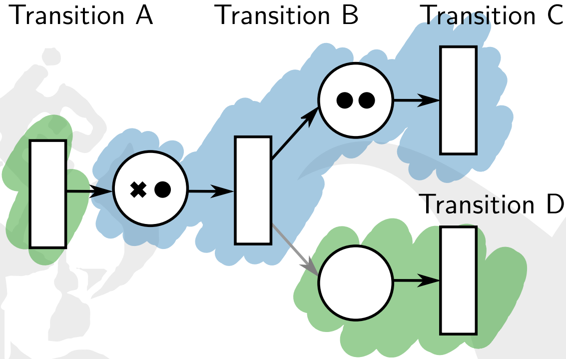
Mode example

Network execution



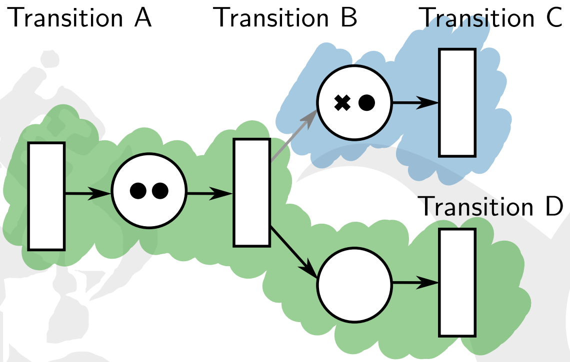
Mode example

Network execution

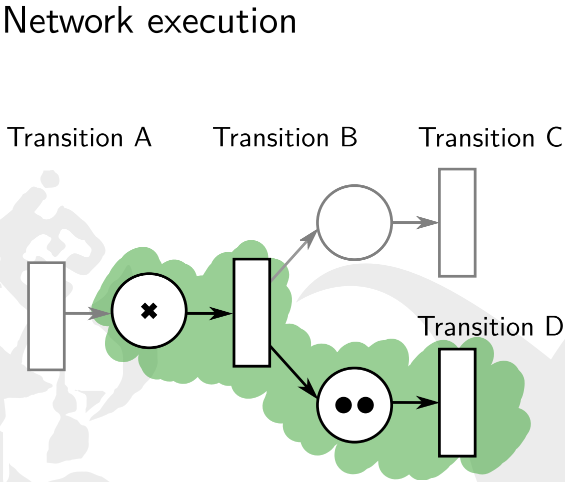


Mode example

Network execution

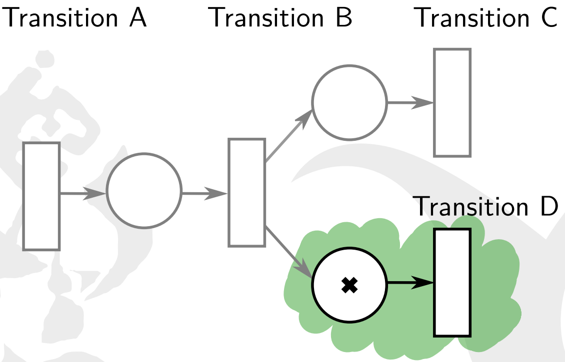


Mode example



Mode example

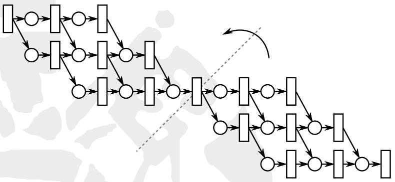
Network execution



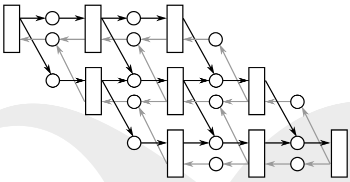
Modes to define data locality

Two-phased wavefront computation:

Network without modes

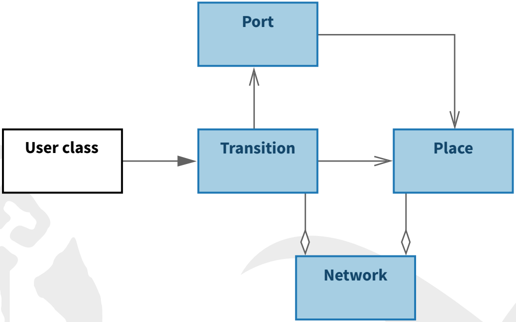


Network with modes



Programming with Hitmap++

- Framework prototype: MPI + Pthreds.



- How to use it?
  - Build the transitions extending the base class.
  - Create the network connecting transitions and places.

Building transitions - Example

```
class MyTransition2: public Transition {
public:
   void execute(){
      double d1, d2; int i1, i2;
      get(&d1, &i1);   // Get one pair of tokens
      get(&d2, &i2);   // Get other pair

      double result =  process(d1,d2,i1,i2);
      // Send a token to a particular place
      if(result > 0)
         put(&result,"place1");
      else
         put(&result,"place2");
   }
};
```

Building the network - Example

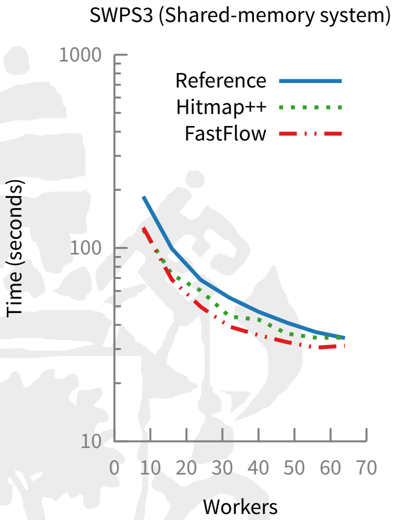
```
Place<double> placeA, placeB;  // Declare the places
placeA.setMaxSize(10);       // Set the place size

MyTransition transition;

// Add the method and places to the default mode
transition.addMethod(&MyTransition::execute);
transition.addInput(&placeA);
transition.addOutput(&placeB);
...

Net net;                    // Declare the net
net.add(&transition); // Add the transition
net.run();                  // Run the net
```

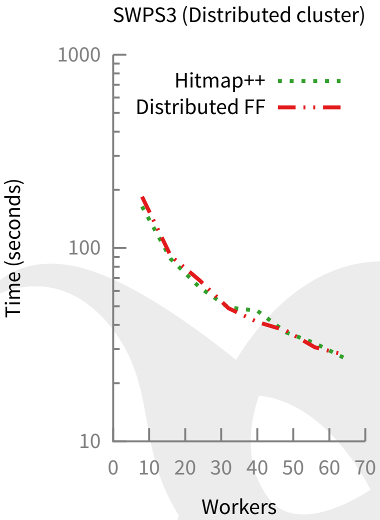
Experimental evaluation

- Benchmarks:
  - Smith Waterman (Swps3)
  - Cellular Automata
- Implementations:
  - Reference (shared-memory) (see Ref. [122]) / Manual C+MPI
  - Hitmap
  - FastFlow, FastFlow distributed extension
- Computing environments:
  - Atlas: A shared-memory system with 64 cores.
  - CETA-Ciemat: A cluster with quad-core nodes.

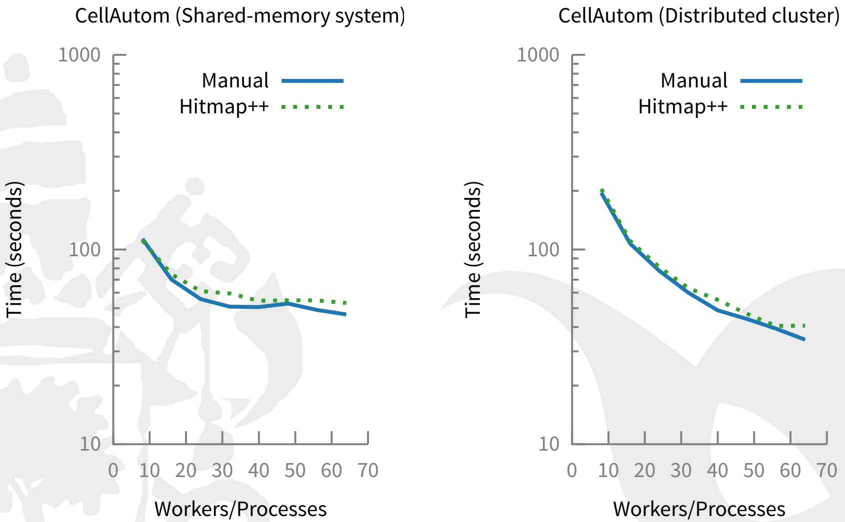
Only most relevant result follow.

Swps3

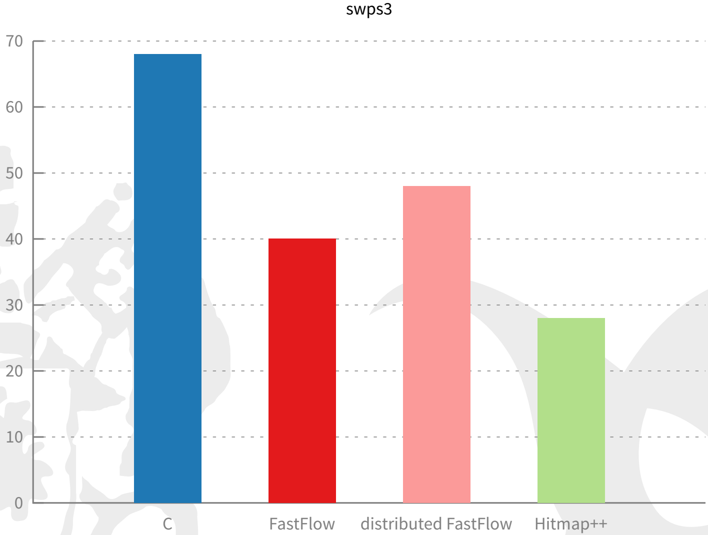

SWPS3 (Shared-memory system)
Reference
Hitmap++
FastFlow
1000
100
10
0
10
20
30
40
50
60
70
Time (seconds)
Workers


SWPS3 (Distributed cluster)
Hitmap++
Distributed FF
1000
100
10
0
10
20
30
40
50
60
70
Time (seconds)
Workers

Cellular Automata



Lines of code comparison



A portable dataflow model: Conclusions

- A new parallel programming model and framework based on the dataflow paradigm.
- Solves limitation of other proposals:
  - General MPMC system, with loops, and reconfigurable networks.
  - Transparently targets hybrid shared- and distributed-memory platforms.
- This framework extends the Hitmap library.

Conclusions

Research question

- This PhD. Thesis answers the research question affirmatively.

  It is possible to create a runtime system for a generic high level programming language that offers (1) common abstractions for dense and sparse data management, and (2) generic data-mapping and data-flow parallelism support for hybrid shared- and distributed-memory environments.

Thesis conclusions

- This Ph.D. Thesis gives an answer to these problems:
  - The unified support for dense and sparse data.
  - The integration of data-mapping and data-flow parallelism.
- Our implementation extends the Hitmap library:
  - To support dense and sparse data structures.
  - With a model for dataflow mechanisms.

Contributions I

Our first step: Study of Hitmap automatic data-layout techniques applied to multigrid methods.

- Journal article:
  - Gonzalez-Escribano, Torres, Fresno and Llanos. "An Extensible System for Multilevel Automatic Data Partition and Mapping". *IEEE Transactions on Parallel and Distributed Systems.* 2014.
- Conference article:
  - Fresno, Gonzalez-Escribano and Llanos. "Automatic Data Partitioning Applied to Multigrid PDE Solvers". *IEEE Euromicro Conf. on Parallel, Distributed and Network-Based Processing (PDP).* 2011.

Contributions II

Integration of dense and sparse data support into Hitmap.

- Journal articles:
  - Fresno, Gonzalez-Escribano and Llanos. “Blending Extensibility and Performance in Dense and Sparse Parallel Data Management”. *IEEE Transactions on Parallel and Distributed Systems (TPDS).* 2014.
  - —. “Extending a hierarchical tiling arrays library to support sparse data partitioning”. *Journal of Supercomputing.* 2013.
- Conference and workshop articles:
  - —. “Data abstractions for portable parallel codes”. *Int. Summer School on Advanced Computer Architecture and Compilation for High-Performance and Embedded Systems (ACACES).* 2013.
  - — “Integrating dense and sparse data partitioning”. *Int. Conf. Computational and Mathematical Methods in Science and Engineering (CMMSE).* 2011.

Contributions III

A new model for dataflow mechanisms.

- Conference article:
  - Fresno, Gonzalez-Escribano and Llanos. “Runtime Support for Dynamic Skeletons Implementation”. *Int. Conf. on Parallel and Distributed Processing Techniques and Applications (PDPTA).* 2013.
- Research stay:
  - —. “Exploiting parallel skeletons in an all-purpose parallel programming system”. *Science and Supercomputing in Europe - research highlights (HPC-Europa2 project).* 2012.

- —. “Dataflow Programming Model for Hybrid Distributed and Shared Memory Systems”. Work in progress for a journal publication.

Future directions

- Higher-level abstraction artifacts:
  - Specialized networks.
  - Skeletons.
- Development of new mapping policies:
  - Load balancing.
  - Heterogeneous systems.
- Transformation from high-level code:
  - Open issue: Data structure, topology, and layout selection.

Thanks

Supporting general data structures and execution models in runtime environments

PhD. Dissertation

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