Introduction to FastFlow programming

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SPM lecture 6

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High-level Parallel Patterns

- Pattern-based Parallel Programming is nowadays a **well-recognized approach for raising the level of abstraction in parallel computing** without sacrificing performance and performance portability features.

Notable Parallel Patterns

Data parallel	Stream parallel	Higher level	Control parallel
• Map	• Pipeline	• Divide & conquer	• Conditional
• Reduce	• Farm	• Convolution	• Speculative
• Stencil	• Iteration	• Pool evolution	• DAG
• Mapreduce	• Filter	• Data Parallel Stream Pattern (windowed)	
• Divide&Conquer			

Are they enough? Do we have all we need?

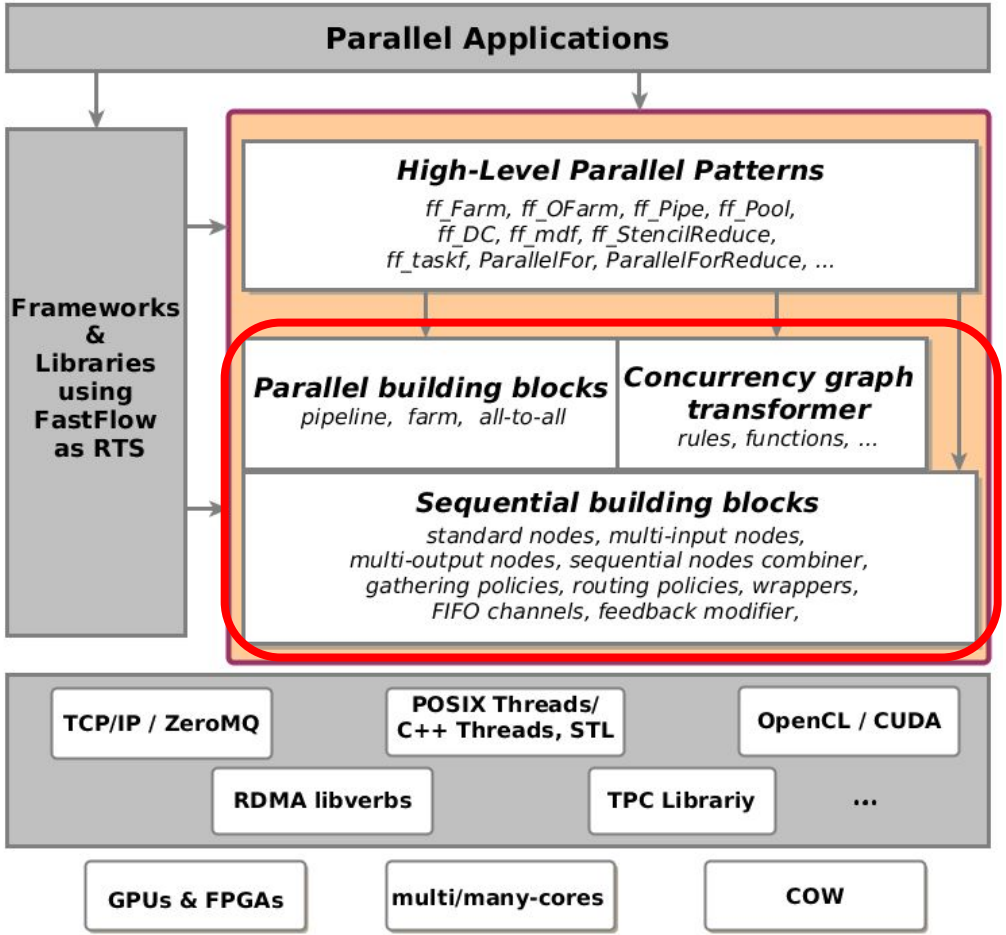
Do it yourself!

By combining and customizing **core patterns** and **basic mechanisms**

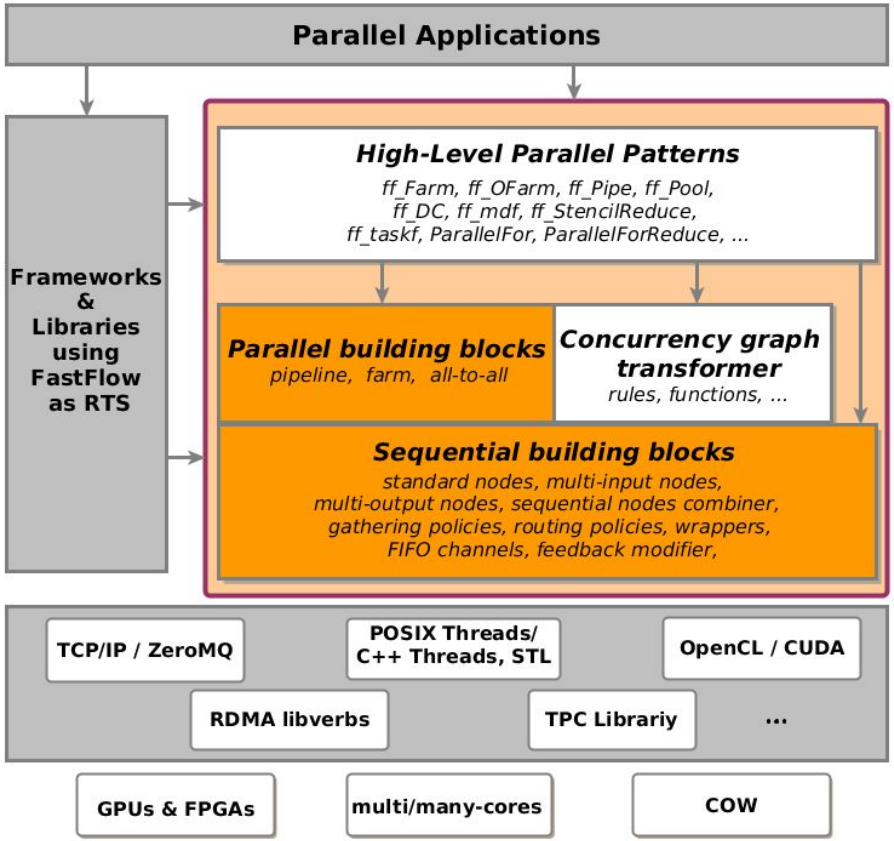
By using the **structured parallel programming methodology** even for building high-level parallel patterns

FastFlow stack

- High-level Parallel Patterns targeting the application programmer
- Parallel and Sequential Building Blocks targeting the Run-Time System (RTS) programmer
- Concurrency graph transformer & helper functions



FastFlow Builing Block layer



Why Building Blocks?

- Promote **LEGO-style parallel programming**
- They have a clear *functional* and *parallel semantics*
- Promote **Performance Portability**
  - they may have different implementations for different platforms
- They “simplify the life” of the RTS programmer
  - … while Parallel Patterns mainly “simplify the life” of Application Programmers
- Simple/Efficient **Producer-Consumer Data-Flow semantics**
  - PC semantics enables memory/cache optimizations
- The concurrency graph composed by building blocks can be ***decomposed and re-assembled*** *in different ways* ***enabling performance optimizations and increasing flexibility***
  - *chaining/fusion, fission, pipeline composition, etc…*

Aldinucci, S. Campa, M. Danelutto, P. Kilpatrick, and M. Torquati. “**Design patterns percolating to parallel programming framework implementation**.” International Journal of Parallel Programming, Vol. 42, 2014. DOI:10.1007/s10766-013-0273-6

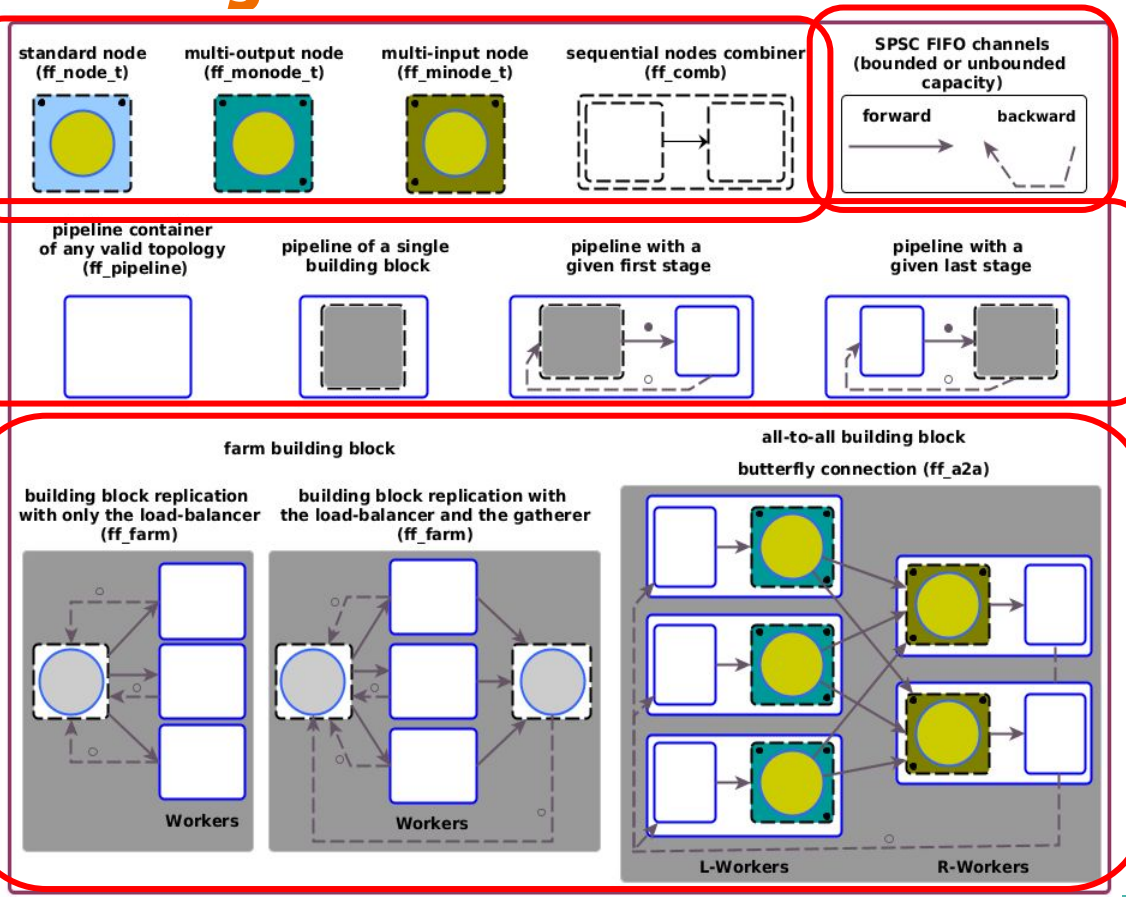
FastFlow Building Blocks

sequential nodes

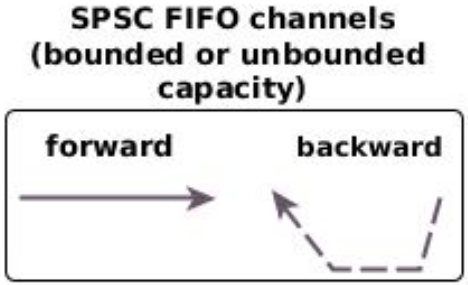
Pipeline composition

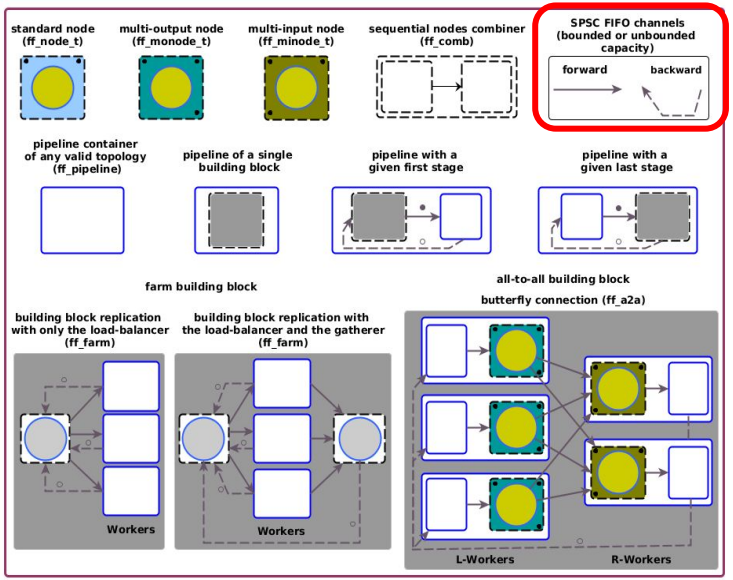
channels

Parallel nodes



FastFlow BBs, channels

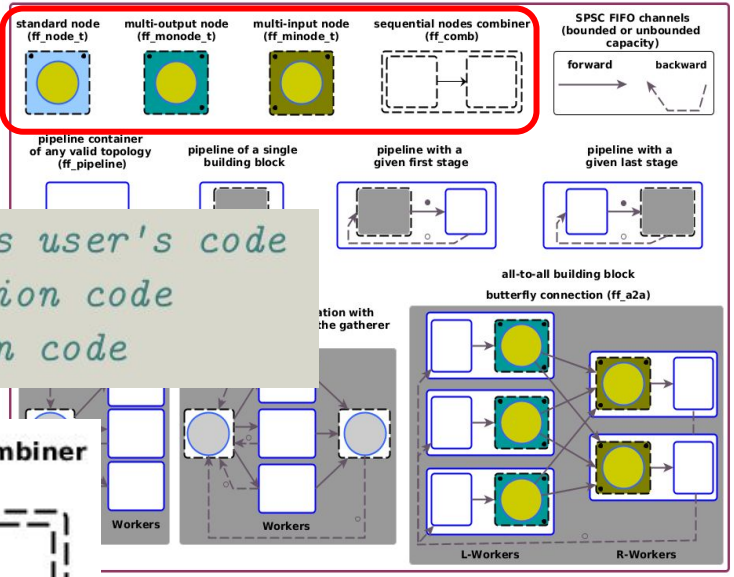


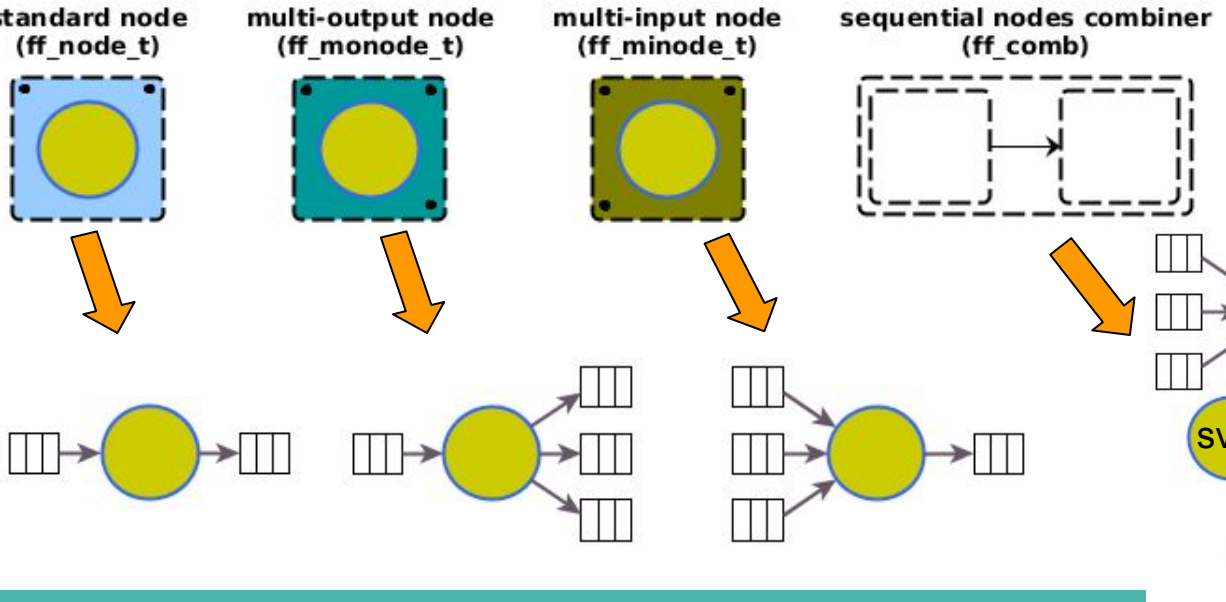


- Channels built on top of a lock-free SPSC FIFO queue
- Bounded and unbounded capacity (configurable)
    - Backward channels have always unbounded capacity
- Concurrency control: blocking and non-blocking (automatic experimental)

FastFlow BBs, nodes & combiner

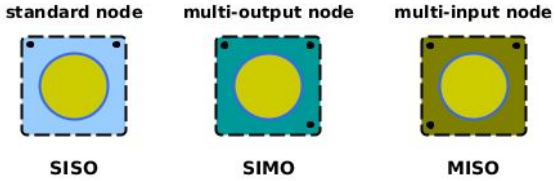
```
virtual TOUT* svc(TIN* task) = 0;    // encapsulates user's code
virtual int   svc_init();            // initialization code
virtual void  svc_end();             // finalization code
```



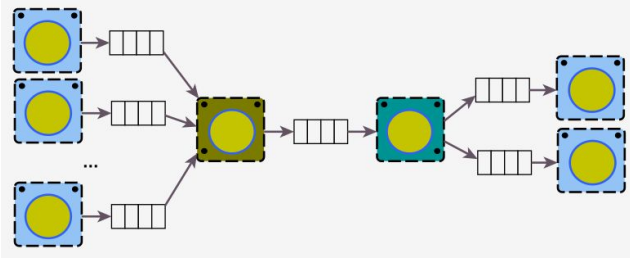


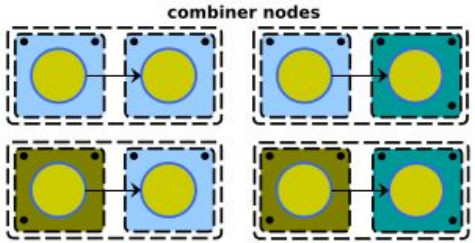
$r = svc_3(svc_2(svc_1(x)))$

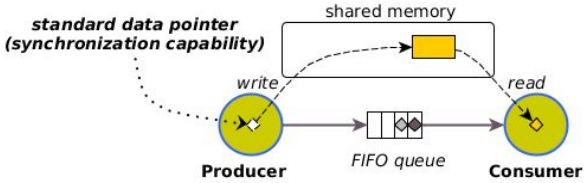
Sequential BBs



- Classified according their input/output cardinality:
  - **SISO**, **MISO**, **SIMO**
- The cardinality of MISO, SIMO is defined when they are connected to other nodes
- The connection between two BBs is a FIFO SPSC channel
  - Blocking and non-blocking concurrency control
- Sequential nodes can be combined. The aim is to decouple nodes from their concrete implementations (i.e. threads)
- Data-Flow semantics
- Physical shared-memory used for efficiency

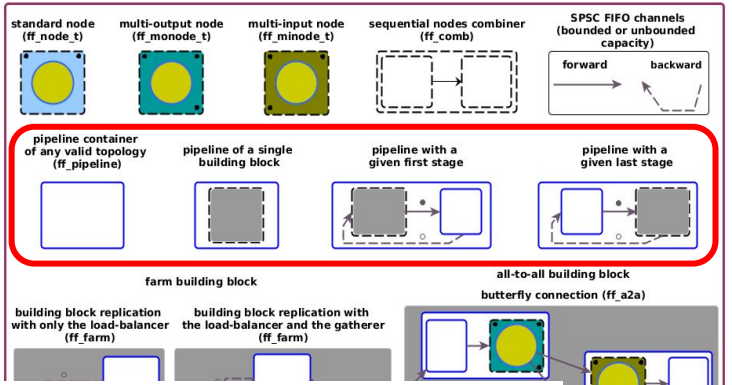


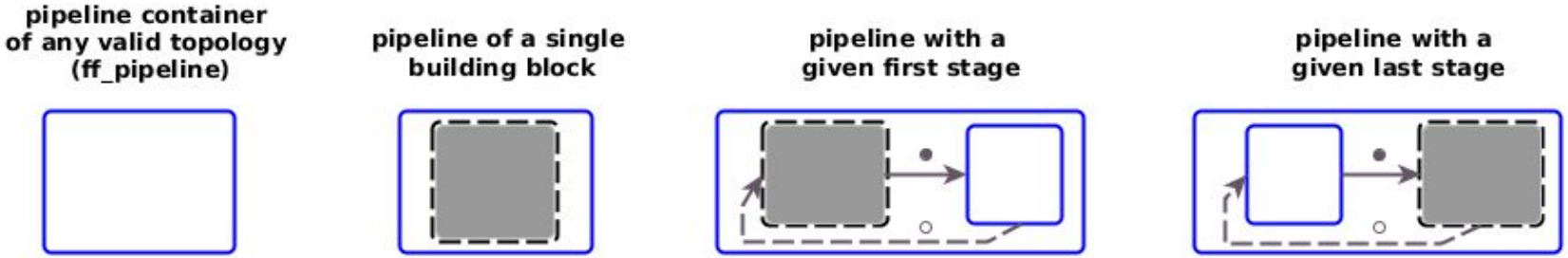


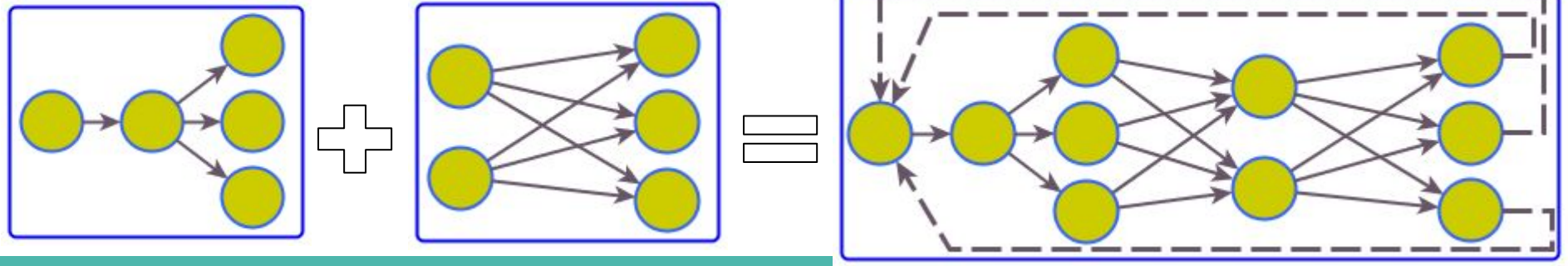


FastFlow BBs, pipeline

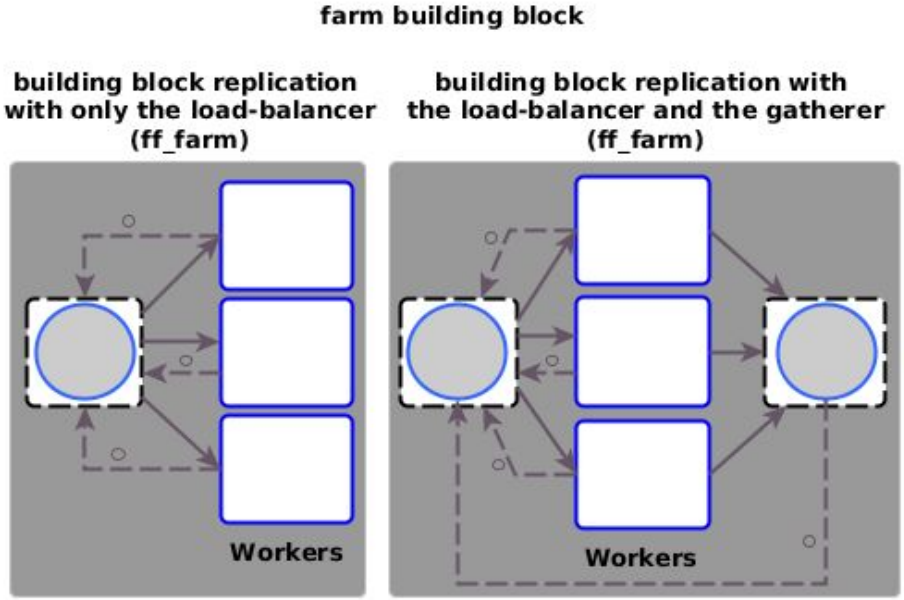
- Building blocks' container
- Data-Flow executor

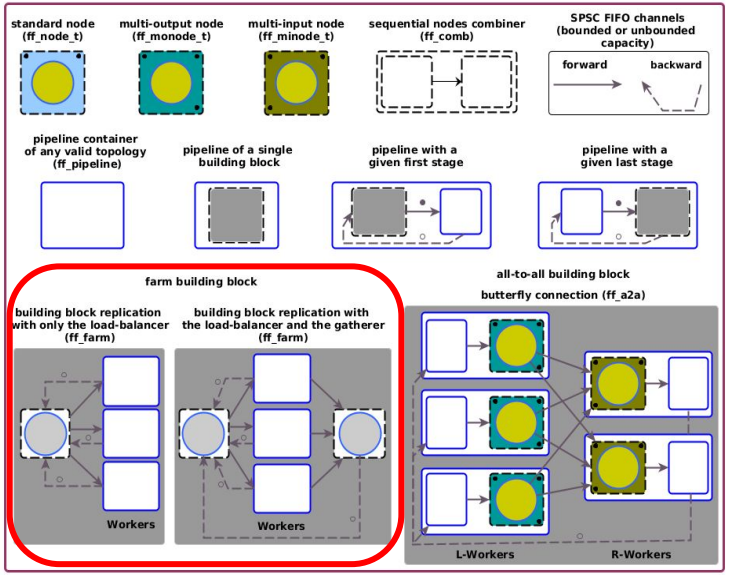






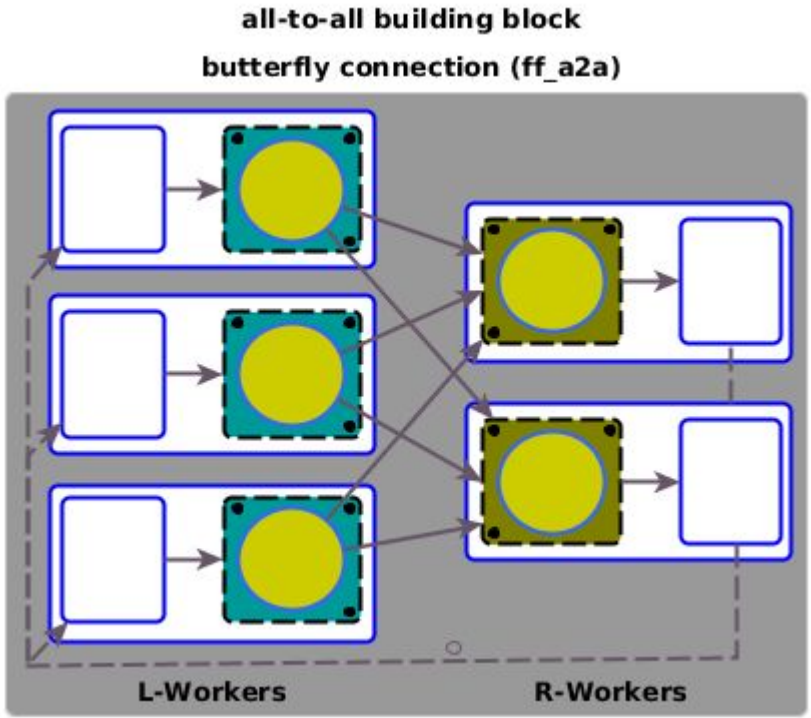
FastFlow BBs, farm

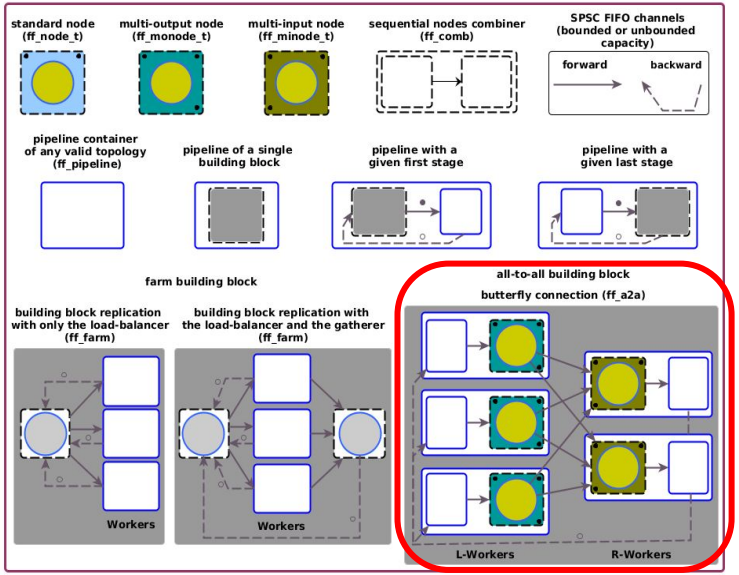




- Master-worker model variants
- Configurable and user-defined scheduling and gathering policies
- Concurrency throttling (extra functional feature)
- Feedback channel modifier (optional)

FastFlow BBs, all-to-all

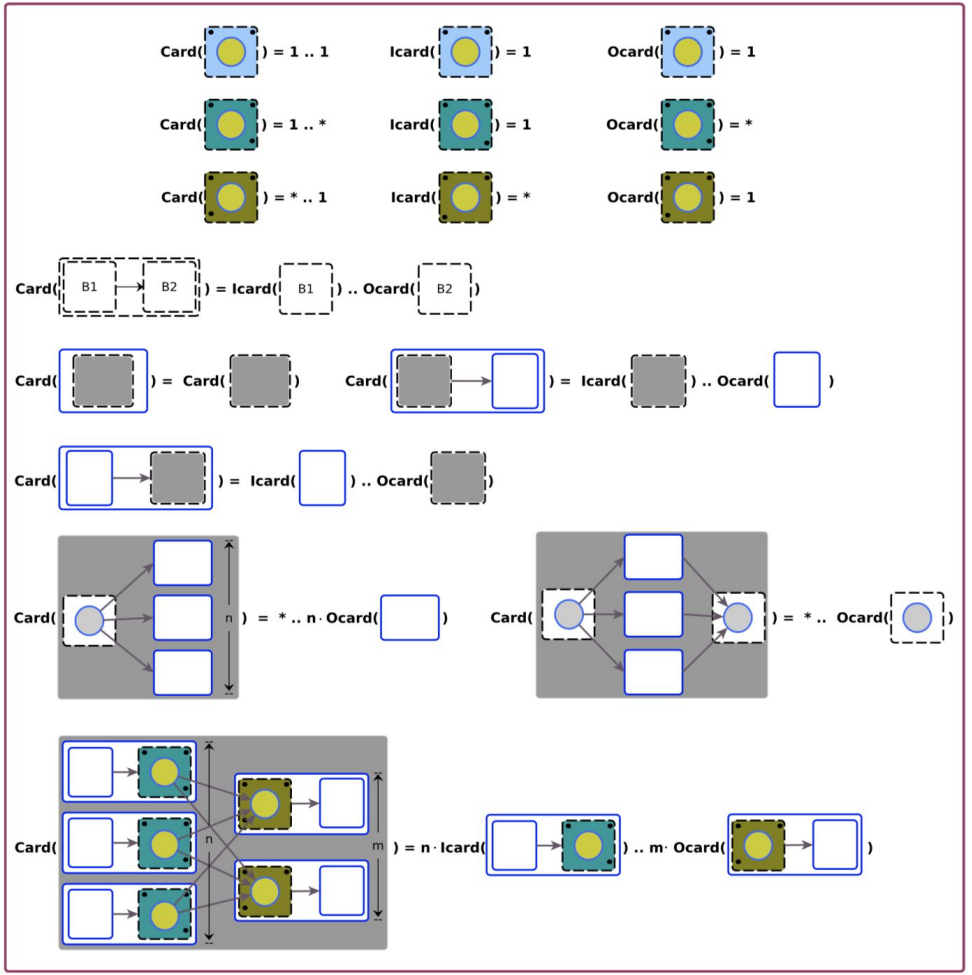




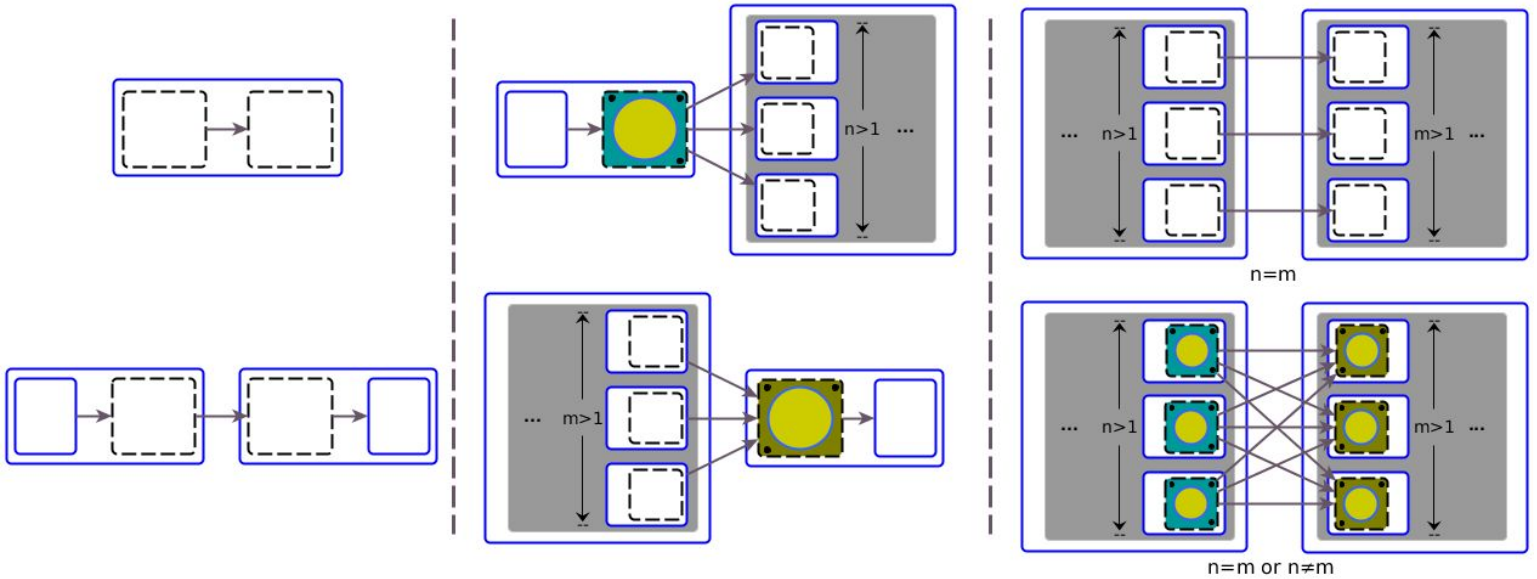
- Multi functional replication
- No master node
- Shuffle communication pattern
- Scheduling and gathering policies are user-defined
- Feedback channel (optional)

Input/Output cardinality

- The input and output channel cardinality of a single building block or of a composition of building blocks can be computed considering the rules showed aside (the symbol “*” denotes a cardinality *not statically defined*)
- A given building block may have different cardinalities on the basis of the number of edge-nodes and on the basis of the sequential node used for implementing edge-nodes

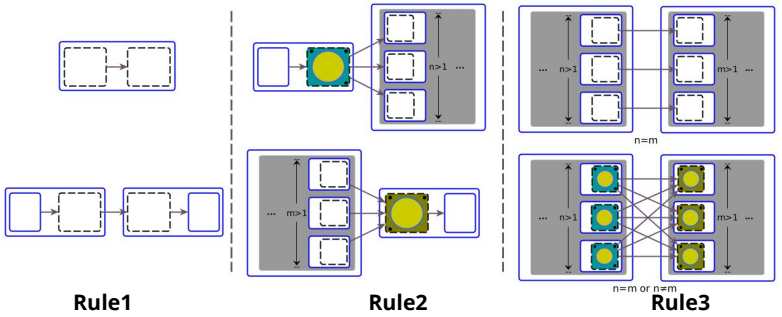


Composition Rules for the BBs



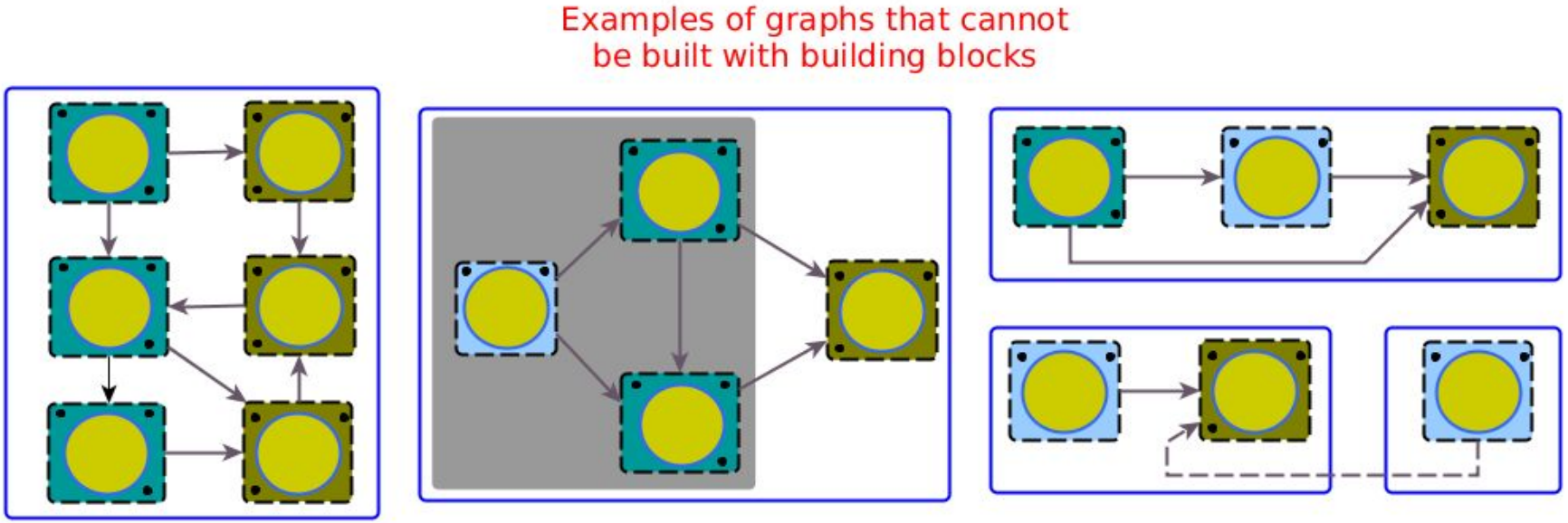
Rule1 **Rule2** **Rule3**

Composition Rules for the BBs



- ***Rule1***: two sequential building blocks can be connected in pipeline regardless their input/output cardinality
- ***Rule2***: a parallel building block can be connected to a sequential building block through a multi-output (SIMO) and multi-input (MISO) node
- ***Rule3***: two parallel building block can be connected either if they have the same number of nodes regardless their input/output cardinality or through multi-input/multi-output nodes if they have a different number of nodes
    - All-to-all introduction rule between two pipelines

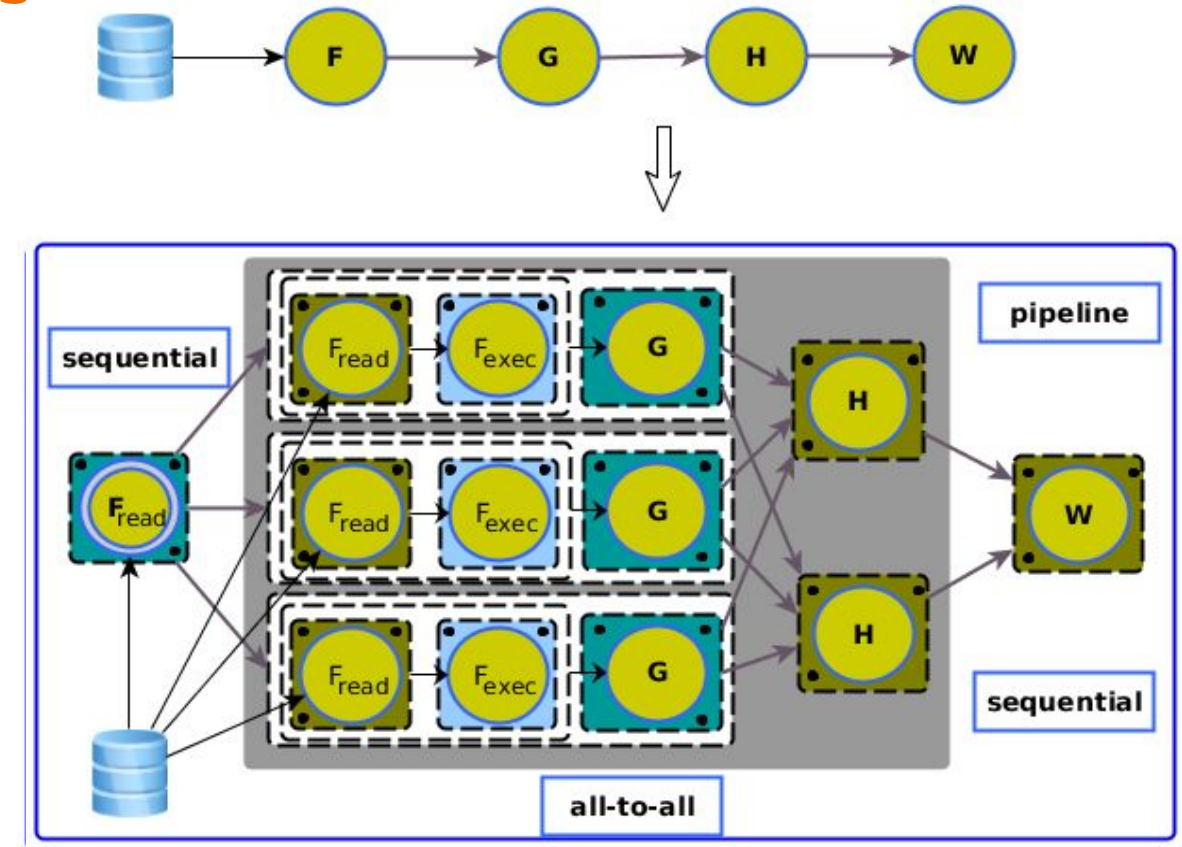
Graphs that cannot be built with Building Blocks



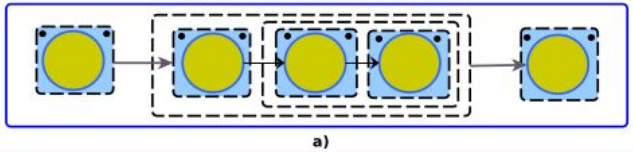
Only a subset of all possible concurrency graphs can be built ….

… all the interesting ones (structured approach)

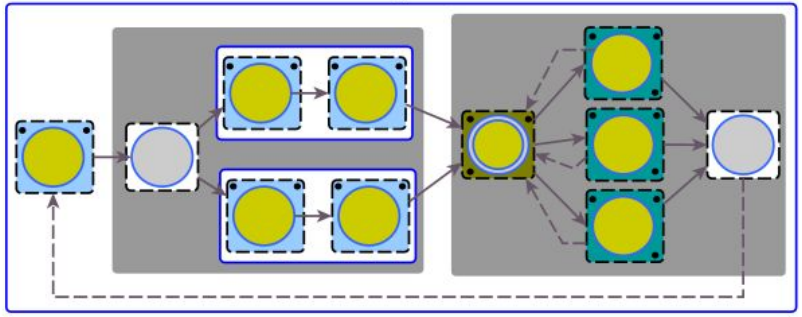
Building Blocks composition example



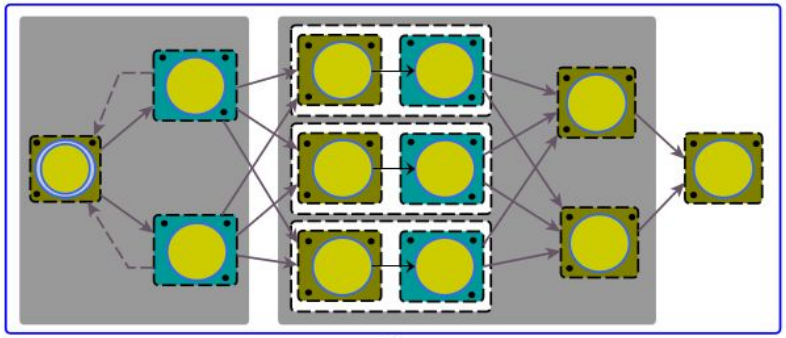
Building Blocks composition examples



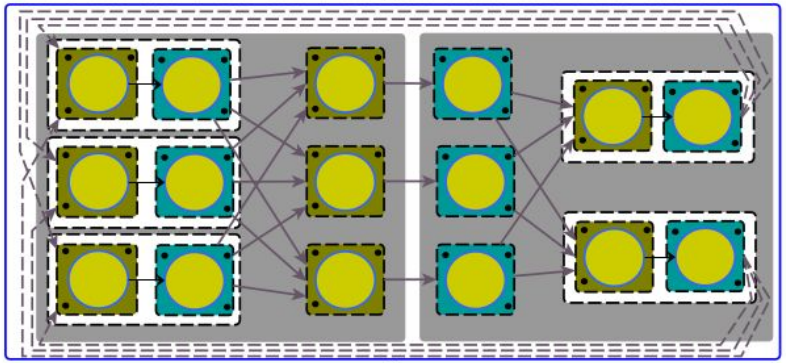
a)



b)



c)



d)

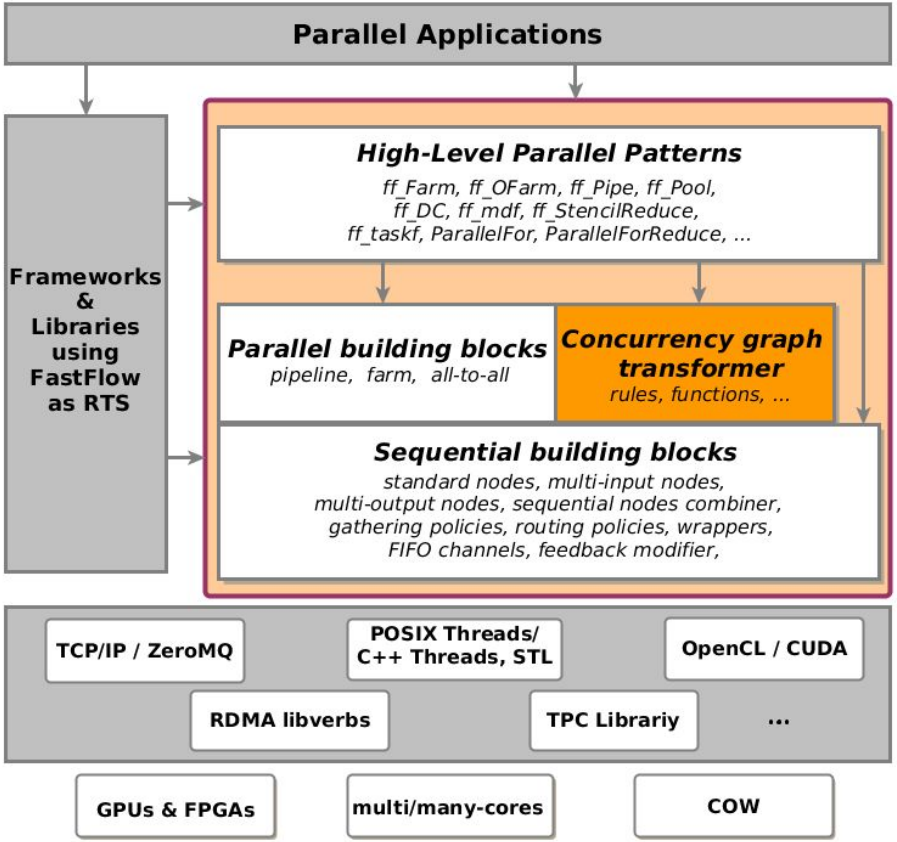
Simple usage examples

```
#include <ff/ff.hpp>
using namespace ff;
// user-defined ...
Emitter   E; // ... emitter
Collector C; // ... collector
Worker    W;
// creating the pool of workers
std::vector<ff_node*> V;
for(int i=0;i<nworkers;++i)
  V.push_back(new Worker(W));
ff_farm farm(V,E,C);
farm.set_scheduling_ondemand();
farm.cleanup_workers();
if (farm.run_and_wait_end()<0)
  error("running farm");
```

- Let's see ***farm_square1_BBs.cpp*** and ***primes_a2a.cpp***

```
#include <ff/ff.hpp>
using namespace ff;
// user-defined workers
Worker1    W1; // standard node
Worker2    W2; // multi-output node
MultiInputHelper1 H1;// helper node
MultiInputHelper2 H2;// helper node

// creating the L-Workers
std::vector<ff_node*> V1;
for(int i=0;i<nworkers1;++i)
  V1.push_back(new ff_comb(H1,W1));

// creating the R-Workers
std::vector<ff_node*> V2;
for(int i=0;i<nworkers2;++i)
  V2.push_back(new ff_comb(H2,W2));

ff_a2a a2a;
a2a.add_firstset(V1, 0, true);
a2a.add_secondset(V2, true);
a2a.wrap_around();
if (a2a.run_and_wait_end()<0)
  error("running a2a");
```

Concurrency Graph Transformer

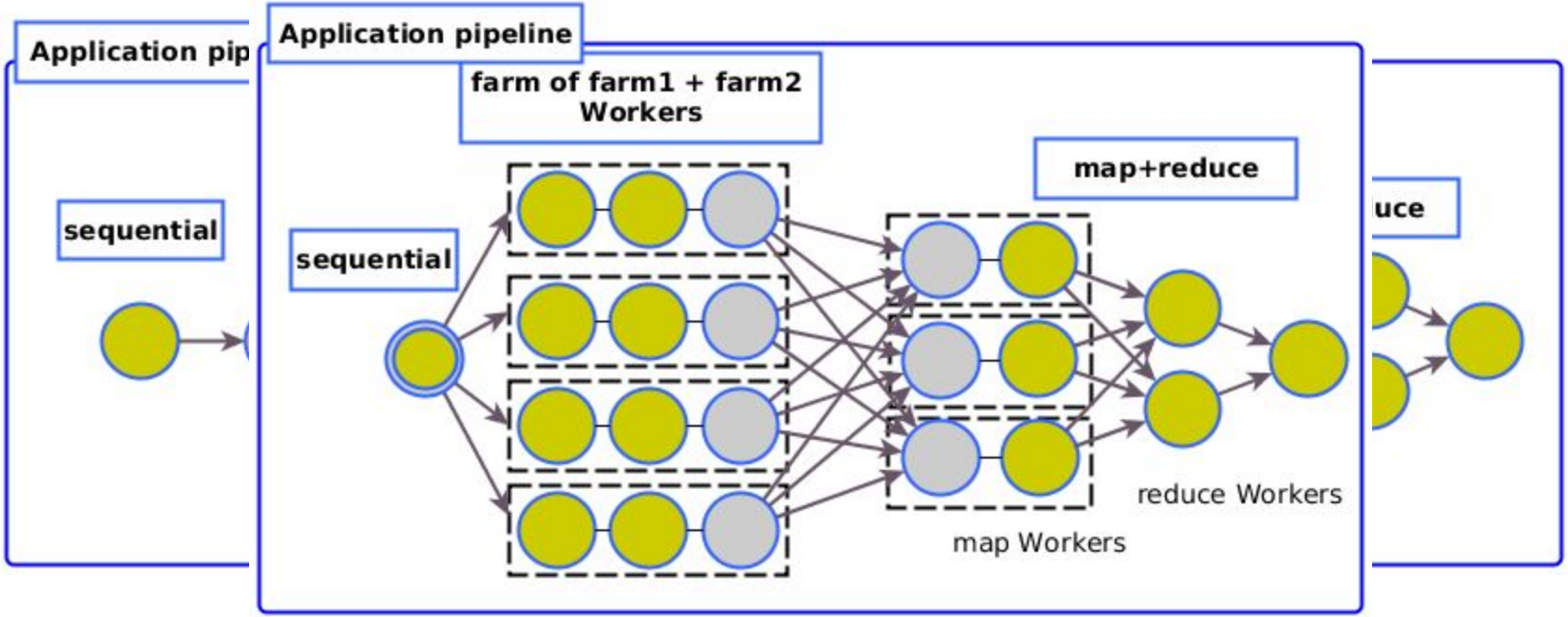


Basic idea

- The concurrency graph transformer provides functions to refactor the FastFlow graph
- **Objectives**: to reduce the number of nodes (i.e. default Emitters/Collectors) and to enable advanced combinations of BBs
- A simple interface function, called ***optimize_static()***, is provided to the FastFlow programmer to automatically apply transformations to the pipeline composition of BBs
  - These transformations are applied only if specific conditions hold so to not modify the semantics of the transformed program (user-hints)
  - The programmer can force some transformations using a proper API provided by the layer taking the responsibility of the transformations
- Automatic transformations currently supported are:

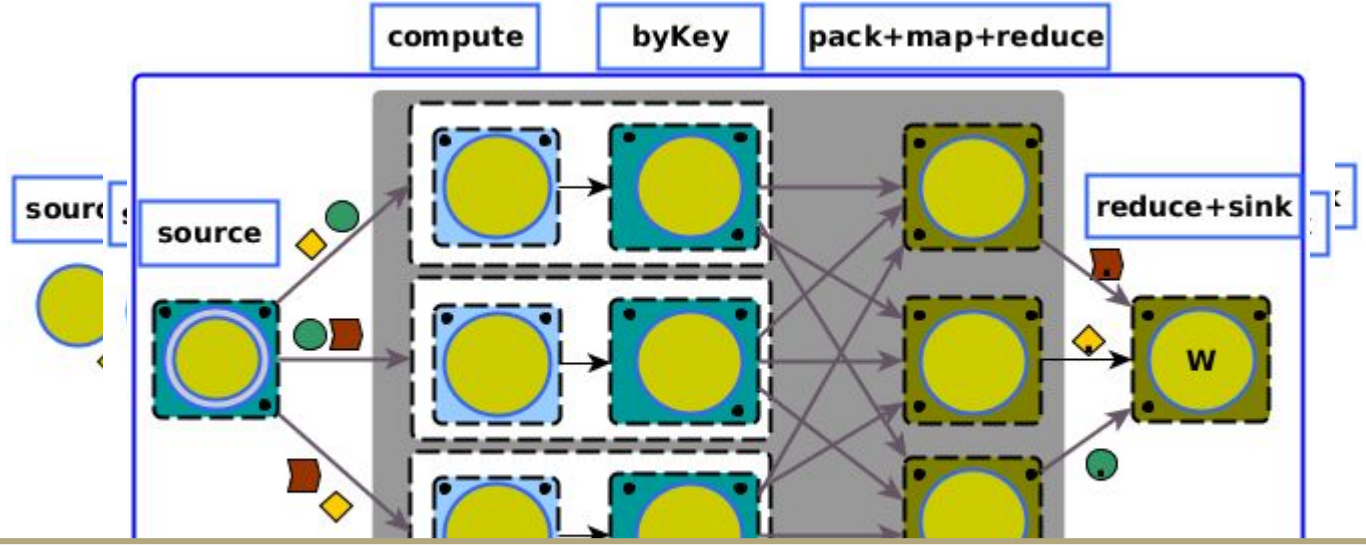
  nodes reduction, ***farm fusion***, ***farm combine***, ***All-to-All introduction***
- *Extra-functional operations supported* : *concurrency control* (blocking vs non-blocking), initial barrier removal, default-mapping of threads (enabled by default, can be disabled), ...

Example


Application pip
Application pipeline
farm of farm1 + farm2
Workers
sequential
sequential
map+reduce
uce
reduce Workers
map Workers

Example

- Transformations that modify the original functional semantics might still be still acceptable if acknowledged by the programmer

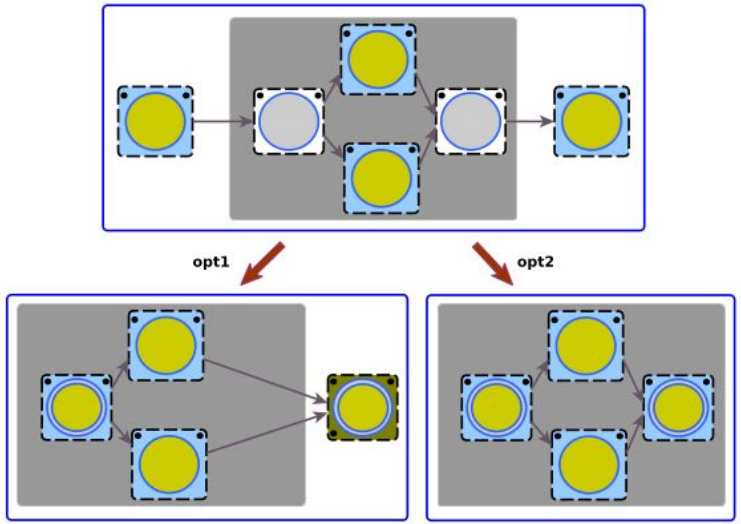


How to help the programmer to introduce such transformations in the FF's high-level layer? Specialized nodes? New patterns?

Nodes reduction

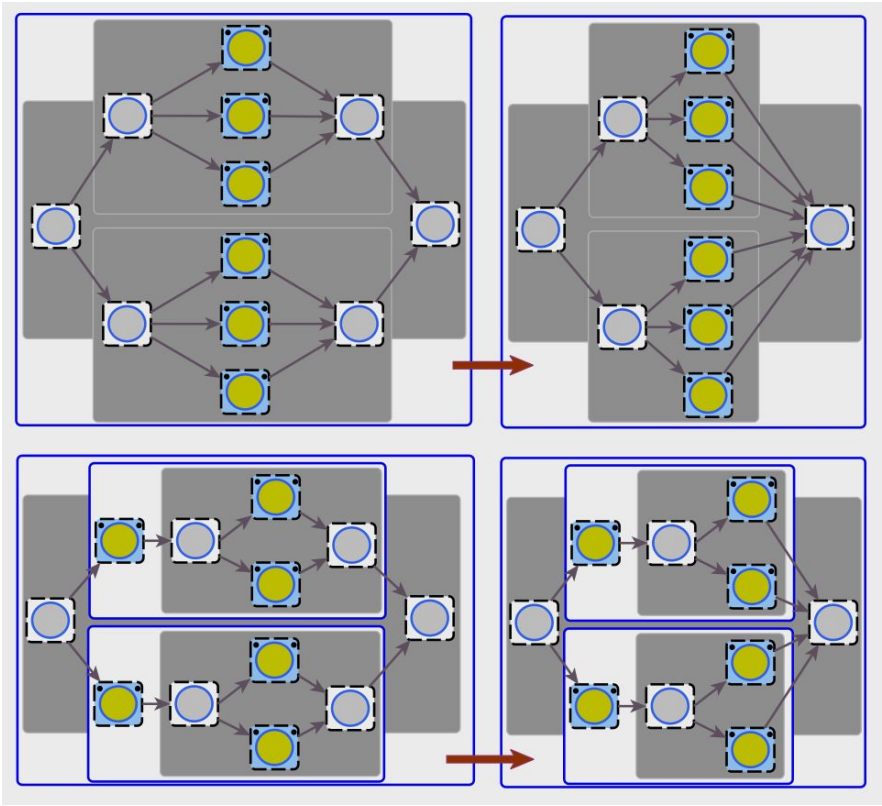
- The ff_Farm pattern uses by default an Emitter and Collector nodes (not user-defined)
- We may want to avoid having dedicated nodes performing only scheduling and gathering functionalities
- We can merge them with the previous/subsequent pipeline node
- Example: three-staged pipeline where the middle stage is a farm with default emitter/collector

```
... // creating Stage1, myFarm and Stage2
ff_Pipe<> pipe(Stage1, myFarm, Stage2);

OptLevel opt;
opt.remove_collector  =true;
opt.merge_with_emitter=true;
optimize_static(pipe, opt);

.... // adding the transformed pipe to another pipe
ff_Pipe<> pipe2(Stage0, pipe, Stage3);
...
pipe2.run();
```



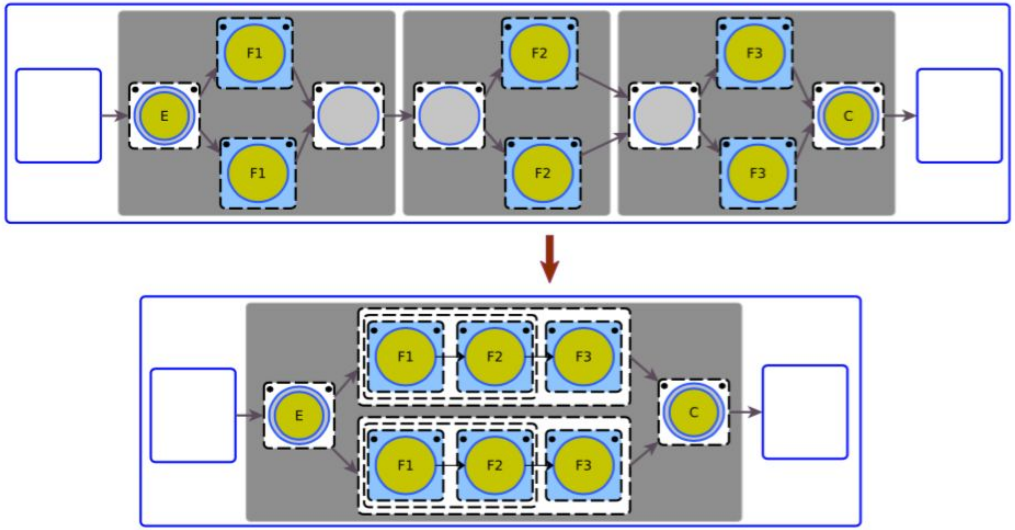
Nodes reduction

- Extra nodes added when nesting a farm BB into a farm or a pipeline
  - Top: the results produced by the inner farm Workers will be directly forwarded to the collector of the outermost farm which will do the collection
  - Bottom: each Worker is a pipeline where the farm is the last stage containing a default collector.



Farm fusion

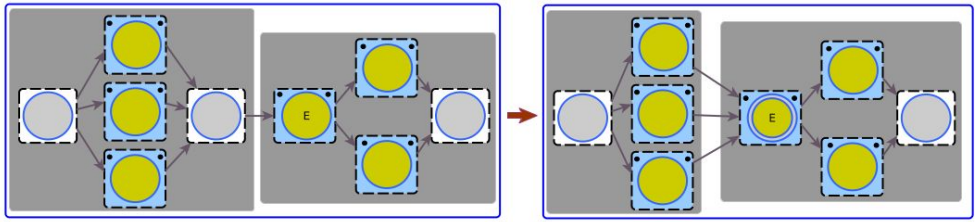
- Two farms are consecutive stages of a pipeline and they have the same parallelism degree (number of Workers)
- The result of the fusion is a **unique farm** merging the two original ones.
- Besides reducing nodes also in this case, this optimization may be useful
  - to reduce latency (number of hops)
  - to avoid bottlenecks between the Collector of the first farm and the Emitter of the second one



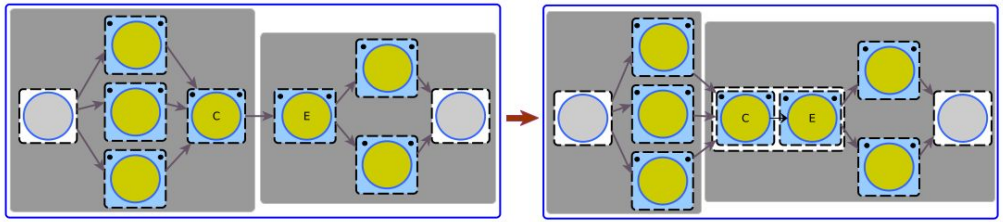
Farm combine

- Two farms in pipeline without any constraint on their parallelism degree and on their emitter/collector nodes (they can be either default or custom nodes)
- Similar operation to “farm fusion” but limited to the Emitter and Collector nodes

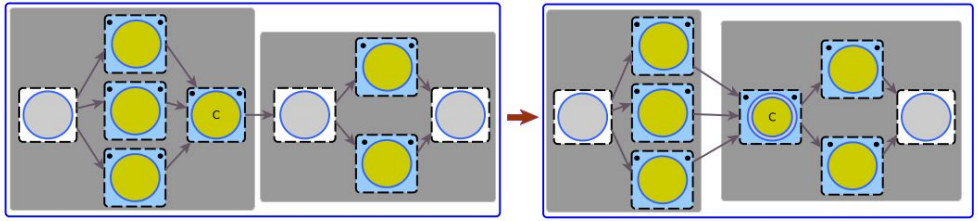
Case1



Case2



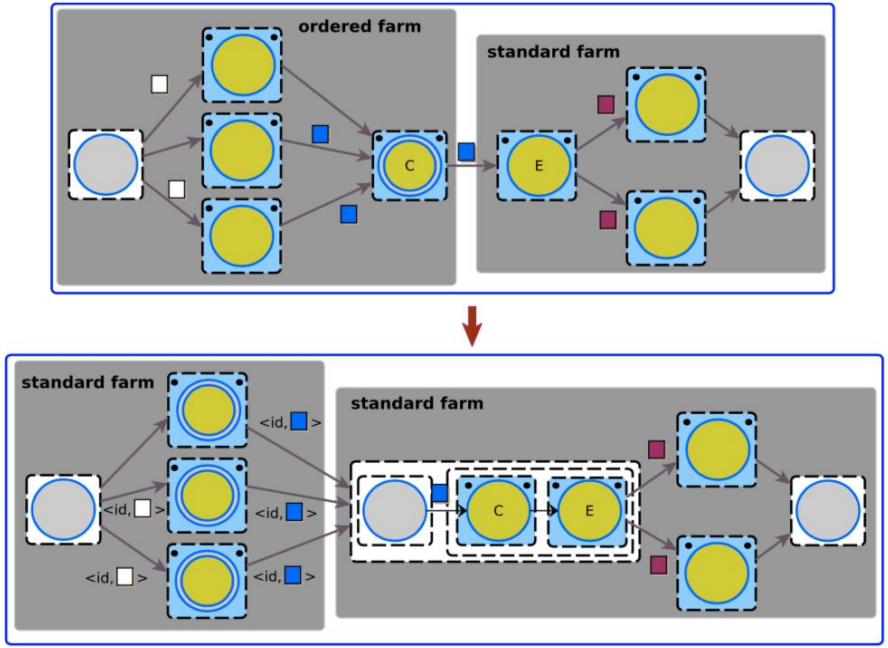
Case3



Farm combine

- An interesting case of the farm combine transformation is given when one of the two farms to be combined is an ordered farm instance
- This case introduces some constraints in order to preserve the ordering of stream elements

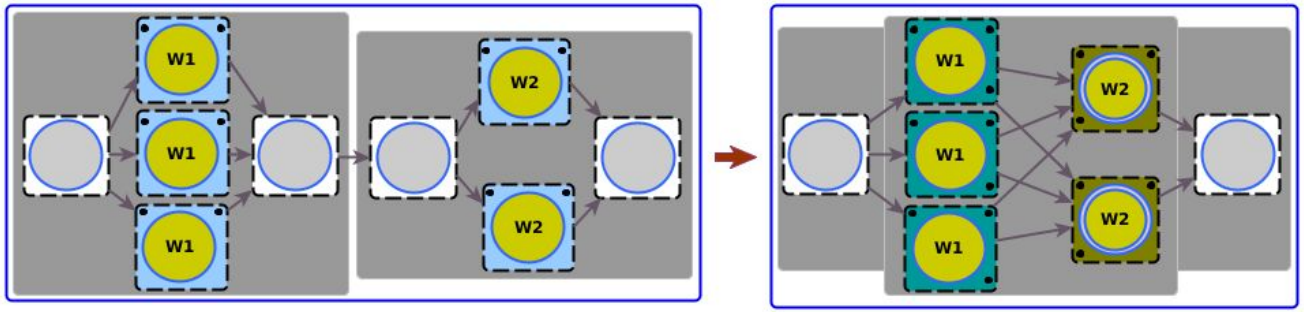
- Case1: The first farm is a standard farm while the second one is an ordered farm. Simplest case (not shown)
- Case2: The opposite of Case1. The new Emitter of the first farm adds unique identifiers to the input elements. The Emitter of the second farm combines a special ordering collector which orders and remove the identifiers to the results.



All-to-all introduction

- Two farms in pipeline regardless their parallelism degree
- We want to remove the potential bottleneck introduced by the Collector and Emitter without changing the amount of concurrency of the worker nodes

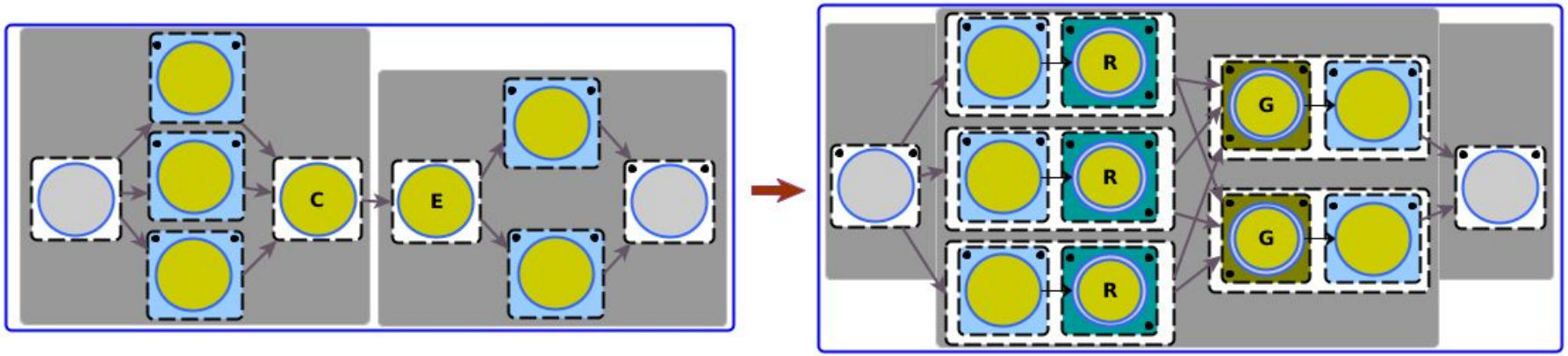
Example



- The Workers of the first and second farm are **automatically transformed into multi-output and multi-input nodes**, respectively
- The Workers of the first farm are added to the L-Worker set of the all-to-all while the Workers of the second farm are added to the R-Worker set of the same all-to-all building block

All-to-all introduction

- What about if the Emitter and/or the Collector are user-defined?
- The transformation has to be “guided” by the user

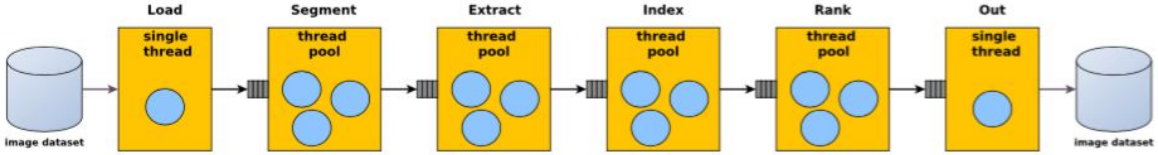


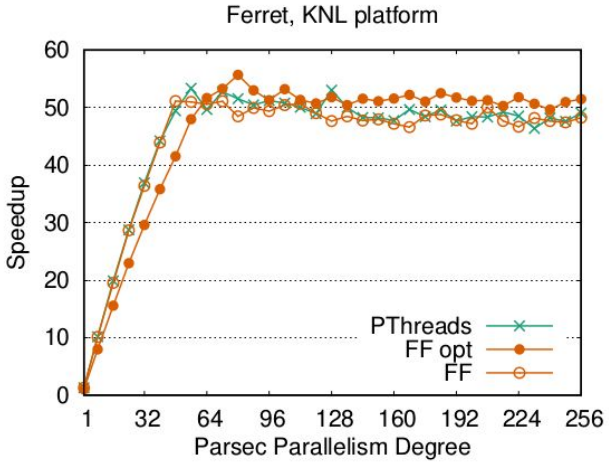
- In the figure: **R=E and G=C**.
- R and G can be any sequential composition of nodes such that they are a multi-output node and a multi-input node, respectively

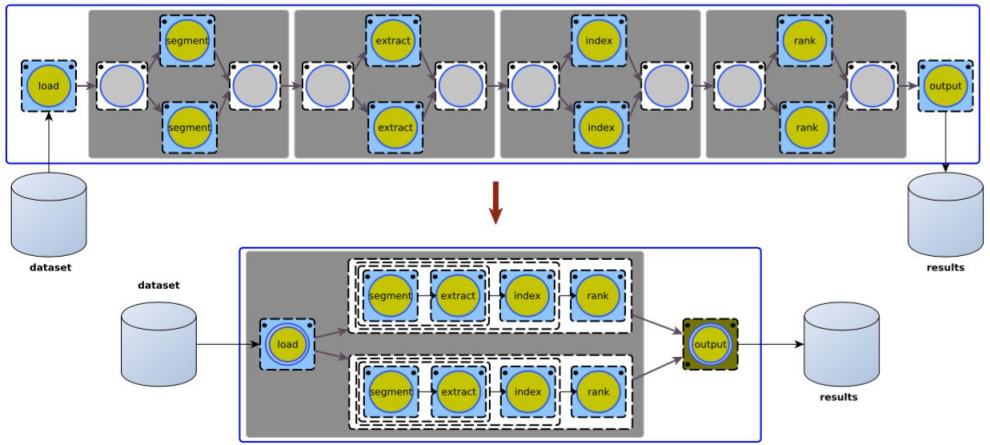
```
template<typename R_t, typename G_t>
const ff_pipeline combine_farms(ff_farm& farm1, const R_t *R,
                                ff_farm& farm2, const G_t *G,
                                bool merge);
```

Ferret Example (from P3ARSEC)

- Ferret applications from the PARSEC benchmark suite (Princeton Application Repository for Shared-Memory Computers)
- Ferret: content-based similarity search of feature-rich data such as audio, images, video, and 3D shapes





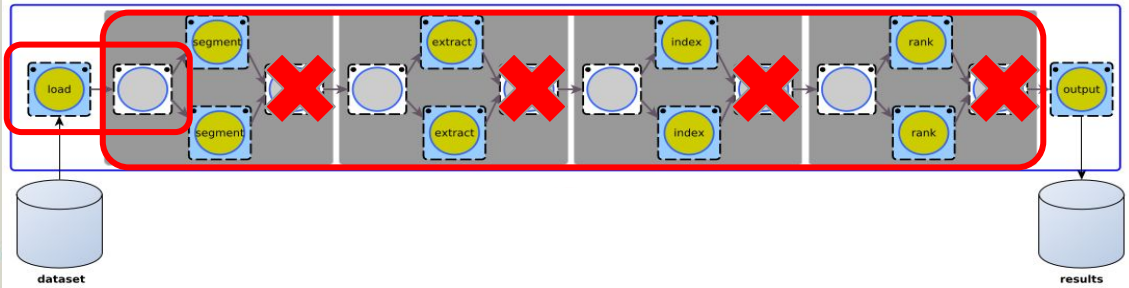


Ferret FastFlow code

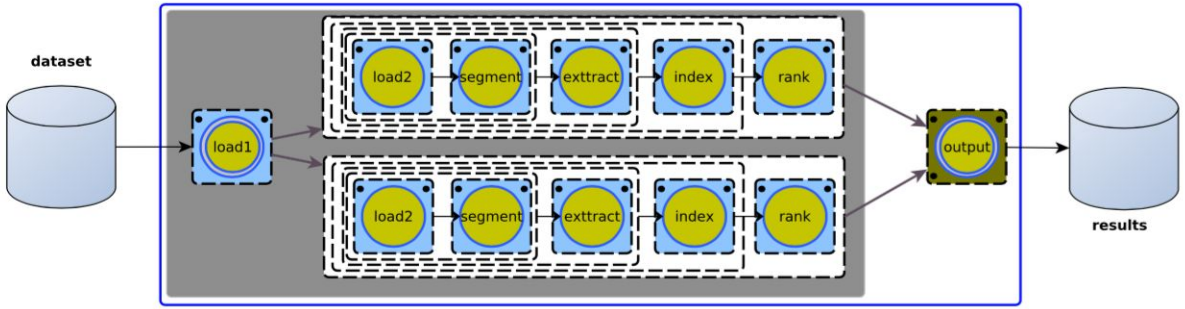
```
struct Load: ff_node_t<long,load_data> {  // first stage
    load_data *svc(long*) { <business logic code> };
} In;
struct Segment:ff_node_t<load_data,seg_data> { // second stage
    seg_data *svc(load_data *in) { <business-logic code> };
};
struct Extract:ff_node_t<seg_data,extr_data> { // third stage
    extr_data *svc(seq_data *in) { <business-logic code> };
};
struct Index:ff_node_t<extr_data,vec_query_data> { // fourth stage
    vec_query_data *svc(extr_data *in) { <business-logic code> };
};
struct Rank:ff_node_t<vec_query_data,rank_data> { // fifth stage
    rank_data *svc(vec_query_data *in) { <business-logic code>};
};
struct Output:ff_node_t<rank_data> { // sixth stage
    void *svc(rank_data *in) { <busines-logic code> };
} Out;
auto farm1 = ...; auto farm2 = ...; // creating farms stages
auto farm3 = ...; auto farm4 = ...;
ff_Pipe<> pipe(In, farm1, farm2, farm3, farm4, Out);
OptLevel opt;
opt.remove_collector  =true;
opt.merge_with_emitter=true;
opt.merge_farms       =true;
optimize_static(pipe, opt);
pipe.run_and_wait_end(); // pipeline execution
```

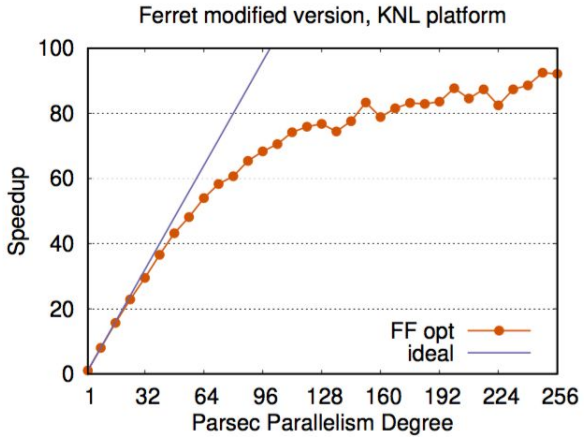
Ferret transformations

```
auto farm1 = ...; auto farm2 = ...; // creating farms stages
auto farm3 = ...; auto farm4 = ...;
ff_Pipe<> pipe(In, farm1, farm2, farm3, farm4, Out);
OptLevel opt;
opt.remove_collector=true;
opt.merge_with_emitter=true;
opt.merge_farms=true;
optimize_static(pipe, opt);
pipe.run_and_wait_end(); // pipelin
```



Ferret optimized

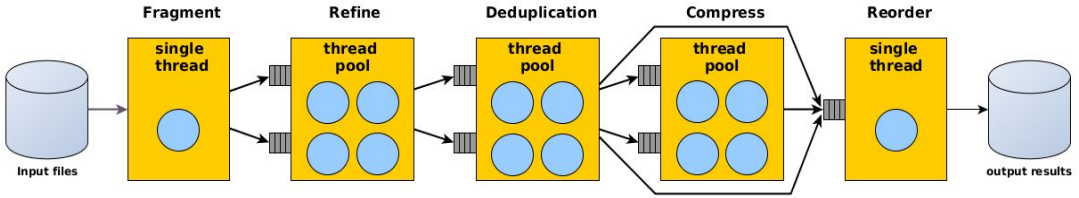


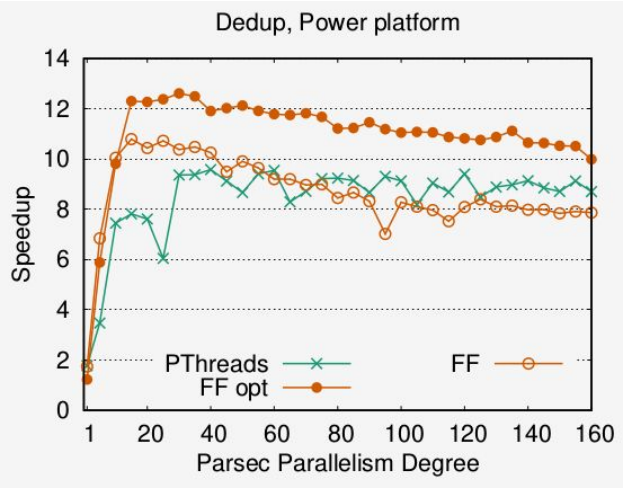


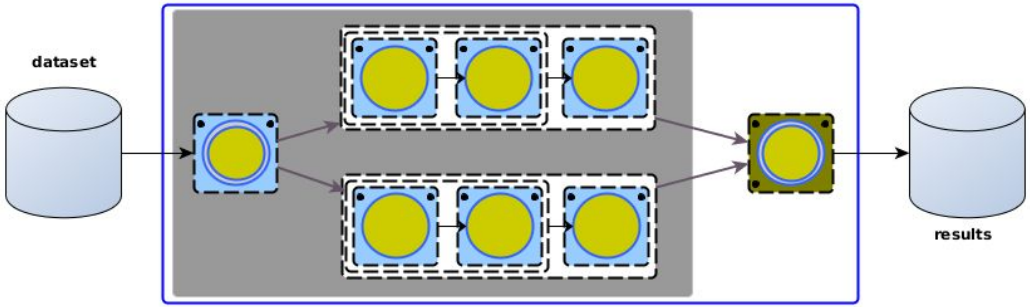
	max. speedup FF opt
Xeon	25.8
KNL	92.5
Power	35.2

Dedup Example

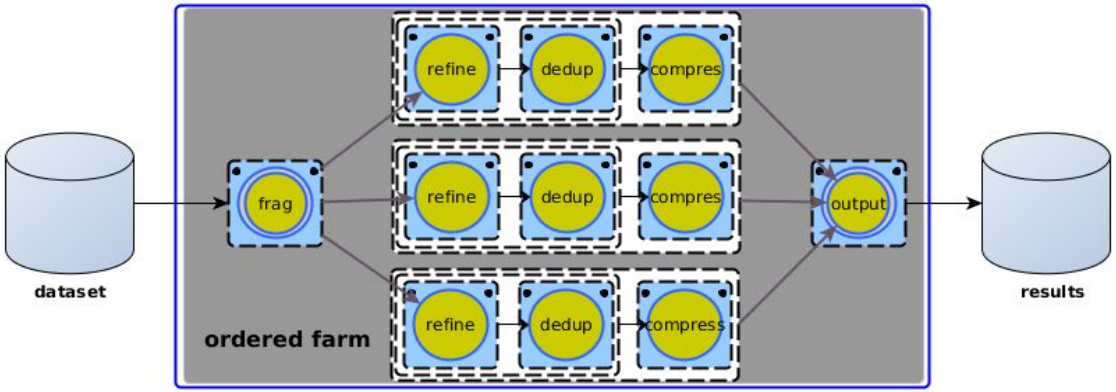
- Dedup: it compresses a data stream with a combination of global and local compression phases



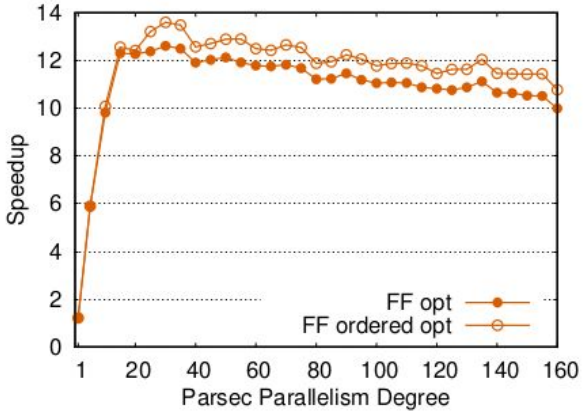




Dedup optimized with the ordered farm



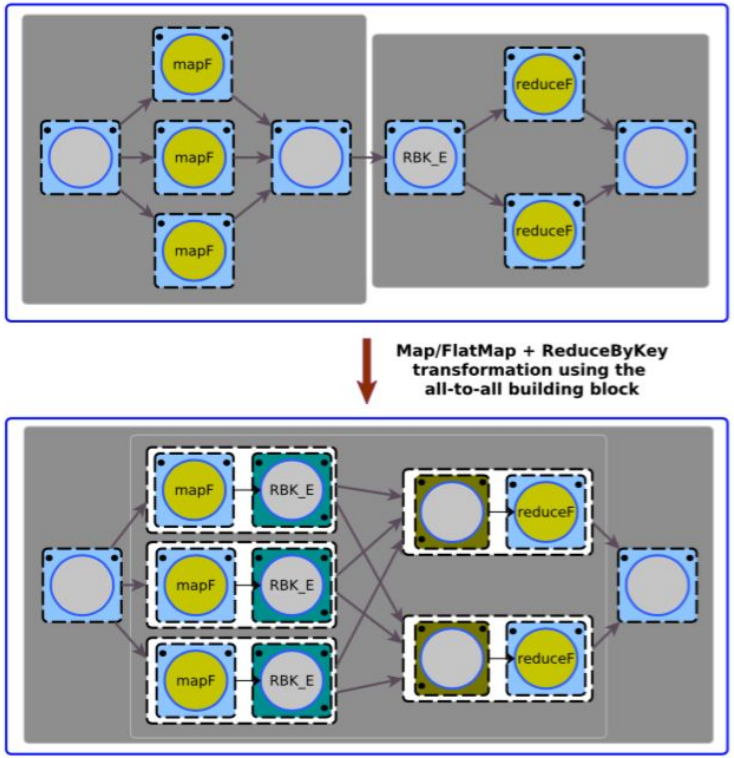
Dedup ordered farm, Power platform



	max. speedup FF opt
Xeon	9.3
KNL	6.6
Power	13.6

All-to-all introduction example

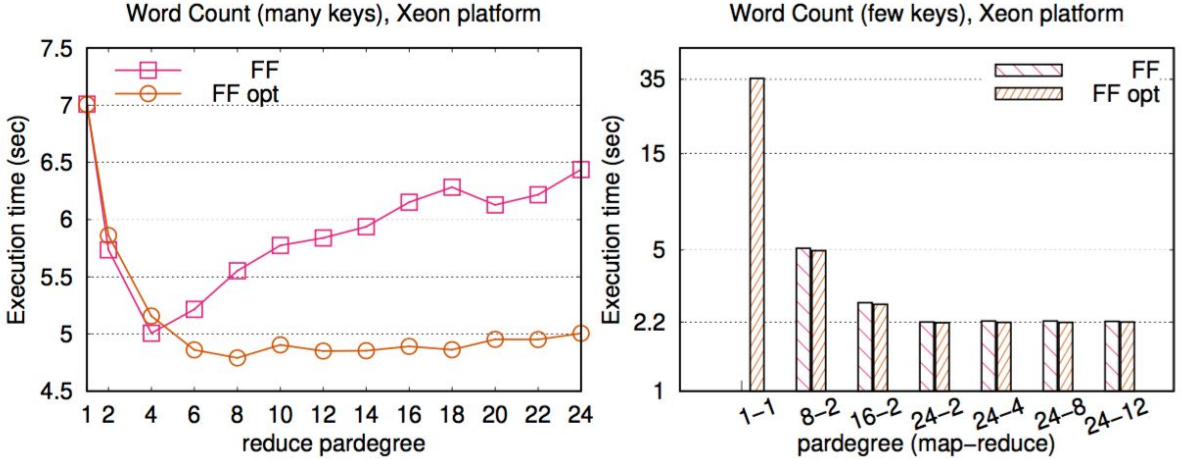
- To evaluate the advantage of A2A introduction, we consider a classical benchmark used to evaluate framework for big data analytics: WordCount (PiCO library)



- A pipeline of two parallel transformations (map-reduce)
  - a “flatmap” operator in charge of producing for each word of a text file a pair (1, word)
  - a “reduce” operator merging all the pairs with the same word in a unique pair (n, word), where n is the number of pairs with that word as key
- Shuffling can be applied to avoid bottlenecks

All-to-all introduction example

- Results obtained testing the WordCount on the Xeon platform with different number of keys that change the cost of the distribution
- More than 350K different words (keys) in the “many keys” scenario, only 10K in the “few keys” case



- Parallelism degree of the FlatMap fixed to 24. Slightly better performance and more stable behavior by increasing the degree of parallelism in the reduce phase
- In the test with few keys, the reduce phase is fixed to use parallelism degree equal to 2. No additional cost of using the A2A here

Further extension/research to/on BBs

1. **Introduce more advanced static transformations**

   Some transformations need "*helper nodes*" to fulfill the Composition Rules. **These nodes could be introduced automatically** so to enlarge the options of automatic transformations
2. **Transformations applied at run-time** while the program is running (e.g., the initial program can be compiled into multiple versions):
   - To adapt to fluctuating workloads (in addition to concurrency throttling)
   - To use them in different places of the program (as for the *ParallelFor*)
3. **Implement/Rethink some already-existing high-level parallel patterns with the new BBs features**

   e.g, ParallelForPipeReduce, MDF