FLIP-15 Redesign Iterations (Scoping, Flow Control and Termination)

Status

Current state: *Pending*

Discussion thread: Archived

JIRAs:

- *Loops and Nesting* FLINK-5089 - *Introduce Loop functions and Enforce Nesting on Data Streams* OPEN
- *Job Termination* FLINK-2390 - *Replace iteration timeout with algorithm for detecting termination* CLOSED

Pull Requests:

1. Loops + StreamScope API prototype branch (PR pending)
2. Job Termination prototype branch (PR pending)

Released: Not Yet

Please keep the discussion on the mailing list rather than commenting on the wiki (wiki discussions get unwieldy fast).

Motivation

This FLIP addresses three, currently interconnected problems : The arbitrary structure of the existing iteration model and the inconsistency of the current job termination protocol due to pending iterative computation and possible deadlocks.

1) Loops API

The current implementation of loops (or Iterations) on the streaming API of Flink does not allow for a deterministic termination of jobs and depends on user-defined timeouts to enforce termination. This impacts correctness, resulting to incomplete processing or/and inconsistent state when iterations exist in the topology. We propose a new functional, yet compositional API (i.e. nested loops) for expressing asynchronous DataStream loops with proper scoping and a distributed coordination algorithm for graph termination that exploits scoping information.

2) Cyclic Flow Control (Deadlock and Starvation-Free)

Currently, Flink's backpressure mechanism might have deadlocks. The heart of the problem is that there are finite resources (i.e., number of network buffers) along the conceptual cyclic backpressure graph.

3) Termination

Currently, an iteration head and tail are two obscure, interconnected dataflow operators that utilize an in-memory blocking queue. A fixed timeout at the consumer side (head) terminates the head task and subsequently allows for a graceful, yet irregular, shut-down of the dataflow graph in topological operator order.

Problems with Existing Mechanism

- An arbitrary loop timeout does not necessarily mean that all computation in the dataflow graph has finished. With the existing mechanism it is possible to end up terminating a job non-deterministically in a non-final state when computation is still pending. This can trivially lead to inconsistent processing and boils down to at-most-once guarantees when loops exist in the dataflow graph.(Note: Setting a very large value by default does not really solve the issue. Operators can take an arbitrary amount of time to execute, i.e. due to checkpointing very large state, communicating with another service etc).
- It introduces an unnecessary lower latency cap to the termination process.
- It adds execution details (i.e. timeouts) to the user-facing API. The user should not really worry about queue staleness timeouts, especially since this is something that the runtime can instead figure out and execute in speculative manner.

Public Interfaces

In the current Iteration API users can open and close iterations (i.e. add feedback edges) in an arbitrary manner. This means that users can nest iterations, yet close them outside outer iterations, since there is no notion of scopes. Apart from being a rather inconvenient programming paradigm, it makes things hard when we want to establish global properties, such as the state of an iterative computation and as a result of the whole dataflow graph, in a decentralized way (Termination and timeout elimination are addressed in part II of the FLIP).

In order to address iterations in a more consistent way that allows for proper scoping, we propose the following API, as a first step towards that direction.

The Loops API

A loop can be defined in terms of a LoopFunction which takes an input Data Stream and returns the feedback and the output Data Streams. Each loop has its own unique context. This API allows the system to create a separate context per loop and make operators and tasks aware of their current scope in the graph (i.e. their loop and outer loops in which they reside).

The LoopFunction which wraps the logic of an iteration, looks as follows in Java:

```
@Public
public interface LoopFunction<T, R> extends Function, Serializable {
   Tuple2<DataStream<T>, DataStream<R>> loop(DataStream<T> value);
}
```

For loops with a different feedback type, we propose the CoLoopFunction that takes a connected stream of the input and the feedback streams instead.

```
@Public
public interface CoLoopFunction<T, F, R> extends Function, Serializable {
   Tuple2<DataStream<F>, DataStream<R>> loop(ConnectedStreams<T, F> input);
}
```

The iterate operation of the DataStream will also support these two flavors of loops as follows:

```
public <R> DataStream<R> iterate(LoopFunction<T, R> loopFun)
```

```
public <F,R> DataStream<R> iterateWithFeedback(CoLoopFunction<T, F, R> coLoopFun)
```

Loops can be trivially nested as shown below:

```
DataStream loop = map1.iterate(new LoopFunction<Integer, String>() {
 @Override
 public Tuple2<DataStream<Integer>, DataStream<Integer>>


  loop(DataStream<Integer> input) {
     input.map(...).iterate(new LoopFunction<Integer, Integer>() {
               @Override
               public Tuple2<DataStream<Integer>,DataStream<Integer>>



                loop(DataStream<Integer> input2) {
                    DataStream<> tmp=input2.map(...).split(...);
                    return new Tuple2<>(tmp.select(...), tmp.select(..));
                }
            });
            return new Tuple2<>(nestedLoop, nestedLoop);
        }
...
});
```

API Restrictions

All binary operations can and should be restricted on data streams of the same StreamScope (see next section).

Proposed Changes

Given the new Loops API we define two changes that build on it, namely Stream Scopes and a new Termination protocol.

I - Introduce StreamScope, an internal representation of the operator context in the graph

Given the proposed way of defining loops, the system can now infer scopes in a structured way. A StreamScope is an immutable data structure, specified per loop context and it basically contains the chain of all of its outer scopes. This is very powerful, not only for distributed termination but also for future additions in the systems such as progress tracking (see TimelyDataflow) for iterative computations and stream supersteps later on. These are the properties of StreamScope :

- All operators that do not reside within a loop contain the default StreamScope.
- The two main operations of a StreamScope are nest() and unnest()
- Every invocation of the DataStream iterate operation generates a new StreamScope, nested on its outer scope.
- The level of each StreamScope (getLevel()) is the number of its outer scopes. Fig.2 shows the assigned scope levels on each operator in an example graph.
- StreamScopes can be compared topologically (isInnerOf(..), isOuterOf()).
- Operators who reside in the exact same loop should have equal StreamScope
- All outer scopes of a StreamScope can be retrieved
    - (e.g. scope.getContextForLevel(scope.getLevel()-2), or scope.unest().unest())

II - Cyclic Flow Control and Physical Implementation of Feedback Channels

Optimally, we want to achieve a simple approach to stream cycles that is performant and satisfies deadlock-free and starvation-free execution.

I) Simple design: Currently Iteration Head and Tail are artificial operators that introduce complexity to the graph building and scheduling process. We should therefore replace them with a special feedback channel that a stream entry operator can differentiate. Another big advantage of having a special channel is that the fault tolerance logic for cycles (upstream logging) can be embedded there.

II) Deadlock-free execution: For deadlock-free execution we simply need to make one of the cyclic resources conceptually 'infinite' and thus break the back-pressure cycle. The special feedback-edge can spill to disk when local network buffers are utilised in order to compensate with any accumulated feedback traffic to enable progress.

III) Starvation-free execution: Starvation can happen when a flow control mechanism prioritises fully a specific flow, thus, living another data flow behind leading to unsustainable execution skew. Obviously, having an extra, specialised feedback channel allows for custom flow control. There are two alternative approaches under discussion regarding input prioritisation within loops which are summarised below:

1. **feedback-first:**
   +it is simple and most predictable
   +discourages spilling
   +lowers latency per iterative operation
   - lowers throughput -> stages loops and discourages pipelining
   - restricts loop logic to staged execution (waiting until all cyclic operations are done and output is flushed out of the loop)
   - it can create some form of temporary starvation when the feedback queue is constantly non-empty. This can stale fault tolerance barriers and other events that serve operational system needs.
2. **feedback-first when feedback queue buffers are utilised:**
   + discourages spilling
   + lower end-to-end latency and higher throughput
   +/- it limits the possibility of temp starvation only when feedback queue is excessively busier
   - it can increase latency per-loop operation due to multiplexing
   - less predictable and more complex conceptually

III - The Job Termination Protocol

Note: Given that Head and Tail are under negotiation, the loop termination ingress logic below can be placed either within the channel or as a special operator in the cycle.

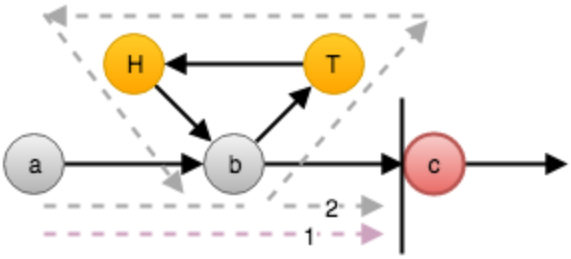
For graphs with no loops, the termination happens in topological sequential order, from sources to sinks. Starting with the end-of-stream on all regular sources, each operator terminates in-order after all prior operators have already terminated. This is trivial when we have a DAG, but not likewise when loops exist in the pipeline. Computation might still be pending in the distributed dataflow graph, even when all regular sources are done. There is, however, a practical way to terminate any arbitrary dataflow graph with or without cycles. For a correct termination, the operators can determine in a decentralized manner that there is no pending data/computation in the pipeline. Here is a simple protocol that puts this logic into practice.

Technique Overview

The main idea of the decentralised graph termination algorithm is that when loops are scoped, we can trivially coordinate the termination decision recursively, starting from outermost loop of the graph down to the innermost and then back. The important thing is to get knowledge of the status of all operators within a scope and its inner scopes. Thus, we propose an abortable, distributed passing-the-baton approach to traverse the graph and collect all statuses of the operators in order to determine whether termination is feasible.

Tricky Part: Termination is staged between sections of the dataflow graph that contain at least one loop. To enforce staging, we use a form of alignment. We basically align the batons within and out of loops. The graph in Fig.1 shows a part of the execution of the algorithm from node ‘a’ to node ‘c’. Node ‘c’ will wait (align) to receive the event twice, via: abc and abTHbc.

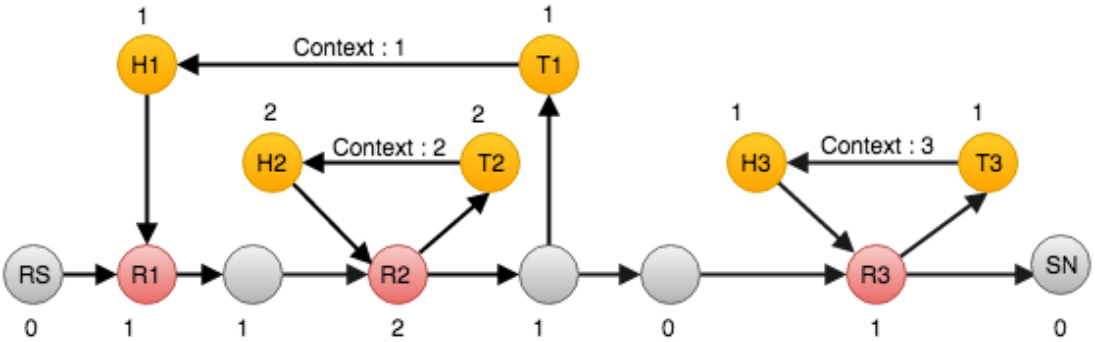
Fig.1 - Example of Alignment



In our implementation, the baton is represented as a TerminationAttempt event that contains the following properties:

1. The current StreamScope of the attempt
2. An attempt identifier (~epoch)
3. The scope level of the last visited operator (to decide on alignment)
4. The last completed scope level
5. The collective status of the operators visited in the current attempt

Fig.2 - A dataflow graph example that contains nested loops



In Fig. 2 we depict an example throughout all phases to use as a reference. The protocol works as follows:

Once all regular stream sources have reached the “end-of-stream” the system enters into a “Attempting” phase, upon which the following abortable protocol becomes active:

1. The regular stream sources broadcast a TerminationAttempt event to downstream operators
2. Three types of operators might receive this event
    a. Type 1 : Head Operators
    b. Type 2 : Operators with Feedback link, (Red nodes in Fig. 2)
    c. Type 3 : Other operators(Grey nodes in Fig. 2)
3. Each of the operators handles the TerminationAttempt as follows:
    a. Type 3: Add status (BUSY | IDLE) to the event and broadcast it.
    b. Type 2: If the event is not associated with a StreamScope, then operator will associate its outermost non-terminated StreamScope to this event. Add operator status to the event and broadcast it.
    c. Type 1: if the operator’s StreamScope is not the one in the event then it will just add its status to the event and forward it downstream. Otherwise, it will go into a local speculation mode on which protocol is activated :
4. The operator will enter an ATTEMPTING state, broadcast a TerminationAttempt downstream and wait to receive this event back via the feedback loop. Once it gets it back it executes the following steps:
    a. If the operator did not receive any data streams in between and the TerminationAttempt is collectively marked as IDLE, it will
        i. Mark its StreamScope as complete in this event and flag this context as terminated
        ii. Terminate and forward this event, which will cause all operators to terminate up until reaching another Type 2 operator.
    b. Otherwise, the Operator will repeat protocol from **step 4** with an increased attempt id

Compatibility, Deprecation, and Migration Plan

- The Proposed changes in the **PublicEvolving** Iteration API are not backward compatible and require the following changes:
    - Users need to discard the Iteration Timeout in existing Flink applications
    - All logic within Iterations need to be wrapped within a LoopFunction or CoLoopFunction
    - Binary Operations (union, connect, join, cogroup) are now dissallowed across different loop contexts

    - Chaining is now disabled across operators of different StreamScope (context)
- The old (currently deprecated) API can still be accessible until a major future release (e.g. Flink v2.0). This is up to discussion.
- Changes will affect third project integrations of Flink such as the Storm and Samoa compatibility libraries which allow arbitrary loops in the graph and do not require nesting.

Test Plan

All proposed changes need to be tested thoroughly. Thus, the following tests are proposed

- Add unit tests for API restrictions on binary graph operations across contexts (i.e. union, cogroup, join, connect etc)
- Remove old test functionality that depends on timeouts for loop termination
- Add unit test to validate the correct properties of StreamScopes with a unit test (e.g. unique contexts, scope levels and nesting)
- Test termination with a complex integration test which contains multiple nested levels and different iterations one after the other.

Rejected Alternatives

You can find the prior proposal that was rejected here (Part I). That is more general but requires more RPC communication which can be preferably avoided.