LAIK: A Library for Fault Tolerant Distribution of Global Data for Parallel Applications

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Abstract: HPC applications usually are not written in a way that they can cope with dynamic changes in the execution environment, such as removing or integrating new nodes or node components. However, for higher flexibility in regard to scheduling and fault tolerance strategies, adequate application-integrated reaction would be worthwhile. With legacy MPI codes, this is difficult to achieve. In this paper, we present LAIK, a lightweight library for distributed index spaces and associated data containers for parallel programs supporting fault tolerance features. By giving LAIK control over data and its partitioning, the library can free compute nodes before failure and do replication for rollback schemes on demand. Applications become more adaptive to changes of available resources. We show an example of using LAIK and present first results on a prototype implementation.

Keywords: High Performance Computing, Parallel Data Containers, Parallel Programming Models.

1 Introduction

Modern High Performance Computers (HPC) systems become more and more parallel nowadays. To achieve the goal of exascale computing, technologies like on-chip parallelism is increasingly used in these supercomputers [SDM10]. This development greatly challenges programmers, especially on managing the data across all these distributed compute nodes. For future systems, Defense Advance Research Projects Agency (DARPA) expects that existing technology such as *Checkpoint & Restart* requires extensive amount of resource, which is contradictive to the expected high efficiency of HPC. Therefore, it is no longer enough to handle the evolving requirements on fault tolerance and reliability [Be08]. Towards exascale computing, different approaches are possible to increase the system reliability. For example, attempts[5] to add fault tolerant components [FD00] to the 4th version of Message Passing Interface (MPI) exists. Furthermore, mechanisms like process level migration [Wa12] or virtual machines [Na07] are presented to achieve a fault tolerant environment, which is transparent to the application programmer. However, these solutions often require a significant amount of resources similar to the classical *Checkpoint & Restart* technique and limit an application's scalability, providing only limited applicability to emerging exascale requirements.

In extension of application-transparent strategies mentioned above, we point out that there is another possibility to make applications fault tolerant. Instead of speculating on the pro-

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[5] `https://svn.mpi-forum.ort/trac/MPI-Forum-Web/wiki/FaultToleranceWikiPage`

grammers' intention and applications' execution, one can ask the programmer to write the program in a manner that includes some a fault tolerance features. This results not only in reduced resource management overhead by the framework that provides fault tolerance, but also keeps this framework lightweight, with the application keeping control over any additional overhead required e.g. from redundancy. This way, we can achieve simple, lightweight and scalable fault tolerance on modern exascale HPC.

However, one cannot expect the programmer to write fault-tolerance features from scratch. To this end, in this paper, we propose a lightweight library to do that: LAIK focuses on providing fault tolerance by taking over control of the partitioning of data containers. If a node or node component is expected to fail, the library can be instructed to free the corresponding part of an HPC system from any computing load and application data. This is done by repartitioning within LAIK. Furthermore, to help with spontanoues failures, LAIK can be asked to maintain redundant copies of important data structures by updating copies on nearside nodes (local checkpointing). The update frequency can be controlled by a predicted probability of failure. If a fault-tolerant MPI implementation detects node failure, a local rollback and repartitioning can be done with the help of LAIK.

In this work, we present our requriements for LAIK, an API proposal, and a first prototype implementation using an MPI communication backend. The latter is available as open-source on Github[6]. Furthermore, we show first scalability measurements.

2 Related Work

The currently most-used de-facto parallel programming model for legacy HPC applications is MPI [Fo12], which allows to do message passing or one-sided communication via mapping of remote address spaces, both on a low level. For higher productivity, the Partitioned Global Address Space (PGAS) model was proposed which provides global address spaces and allows to program for good locality of accesses by making the fact whether an address is local or remote explicit. Implementations come either in new programming languages such as Chapel [ZCC07] and X10 [Sa14], or as libraries such as Global Array Toolkit (GAT) [Ni06], GASPI [Al13], and DASH [Fü14, IFG16]. The drawback of Chapel or X10 is that programs have to be rewritten which can be painful for legacy code. The library GAT allows programmers to do put and get operations from local memory to data structures in a global address space. Similarly, GASPI provides a global address space with distributed data and allows access via RDMA (remote direct memory access) operations provided e.g. by Infiniband, which should result in better asynchronous communication than MPI. DASH uses C++ templates to provide a selection of standard data structures for the application programmer. The communication of DASH is built on top of DART - a run-time system which provides abstraction of different communication libraries.

All of the mentioned approaches provide application programmers a full interface for all possible communication needs of an application. In contrast to that, LAIK only provides one specific functionality and can be used in cooperation with existing communication

[6] `https://github.com/envelope-project/laik`

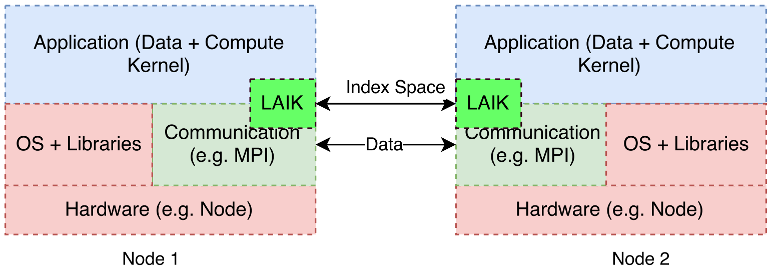

Figure 1: LAIK and Communication Backend

libraries, by asking a communication backend to do required actions for LAIK. The latter can be provided by the application itself to ensure correct embedding into already existing communication behavior of an application.

3 Design of the LAIK Library

The idea behind LAIK is to provide lightweight management for the distribution of global data containers for parallel applications using index spaces. By giving LAIK control over partitioning, it should be able to provide application-integrated fault tolerance features. To this end, the library is expected to sit in-between the application and the communication library used by the application, as shown in Figure 1.

First, we state our requirements guiding the design. Similar to MPI, LAIK should support SPMD-like programming with collective functions. That is, every participant in a parallel application, a LAIK task, executes the same code. Most LAIK functions are collective operations, this is all LAIK tasks have to call into this same LAIK function for correct behavior. For highest flexibility of using LAIK with existing application codes, LAIK is expected to work in cooperation with other communication libraries such as MPI. Communication backends in LAIK should have a documented API and may be implemented by the application itself. For convenience, we will provide standard backends for MPI and multi-threaded shared memory (which mostly reduces communication to synchronization) which may be customized by applications. Furthermore, we want porting of existing codes to LAIK to be done in an incremental way, step by step: the programmer can put one data structure after the other into LAIKs responsibility. This should not mean that the actual allocation of memory resources now has to be done by LAIK, as the programmer still may want to use allocator functions of another library. To this end, programmers should be able to specify an allocator interface (alloc/realloc/free) which LAIK will use to get real memory resources. Applications may use complex data structures such as compressed matrices in an application-specific format. It would be difficult to make LAIK aware of how to handle all kind of such data structures. To still allow LAIK to take control over partitioning of such data, the programmer should be able to use LAIKs core abstraction, which is about distributed (possibly multi-dimensional) index spaces. Whenever the partitioning of the index space changes, the application can request to get a call-back with parameters specifying which parts of the index space should migrate among LAIK tasks.

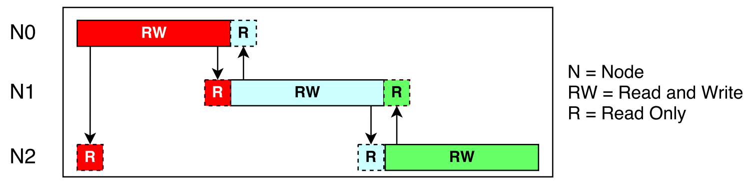

Figure 2: An example of a partitioning specification for a 1d data structure.

With these requirements in mind, we now list the features we want LAIK to provide. The goal of LAIK is to provide a fault tolerant, yet efficient way of distributing data across different nodes. Towards this goal, the following functionalities must be supported:

Partitioning and Repartitioning of Data: For application data to be globally distributed among different parallel tasks, LAIK should be able to take control over the partitioning. Here, a data partition for a given task specifies which data should be available locally to the task using direct memory access. Different program phases or algorithms may expect different parts of data to be available locally. This requires the declaration of multiple partitionings the application may want to switch back and forth. For such switches, LAIK is expected to calculate and execute the data transfers required to satisfy the requirements for task-local data accesses as specified by the partitionings. To allow for minimal data exchanges, the application should specify the type of access done during the time a partitioning is active. E.g. switching to a partitioning where after the switch all data will be overwritten anyway does not need any communication at all. Access types are *read-only, read-write, write-only*. A data element may be wanted to be locally available at multiple tasks for reading, but usually only at one task for writing. However, multiple writers can be supported if a conflict resolution is provided which decides about the resulting value. Reduction operations such as Sum, Product, or Minimum, are typical conflict resolutions. The operations are triggered when the program switches to a partitioning with read access to the given data elements. decrease programming effort.

Coupling Partitionings Of Data Structures: Applications often use multiple different data structures at the same time. Thus, if LAIK decides that only a given portion of a data structure will be available locally at one task, the application may want simultanous access to elements in other data structures. To provide flexible coupling of partitionings, the user actually should be able to specify coupling of (partial) index spaces according to the data pattern of algorithms. E.g. for matrix vector multiplication, we want to couple the row dimension of the 2d index space of the matrix to the 1d space of the vector. Another example are compute kernels which, for writing to an element in one data structure, may need read access to corresponding data elements in another structure and its neighbors in the index space (for so-called ghost layers in stencil codes). Switching between partitionings of one data structure thus may result in automatic switching also for other data structures.

Communication backend: LAIK shall support different communication libraries to execute data migration demands due to switches between partitionings. Standard backends to be supported are *MPI* and *Shared Memory*. The latter is wanted to allow multi-threaded programs to use LAIK for synchronization. Furthermore, LAIK should work together with

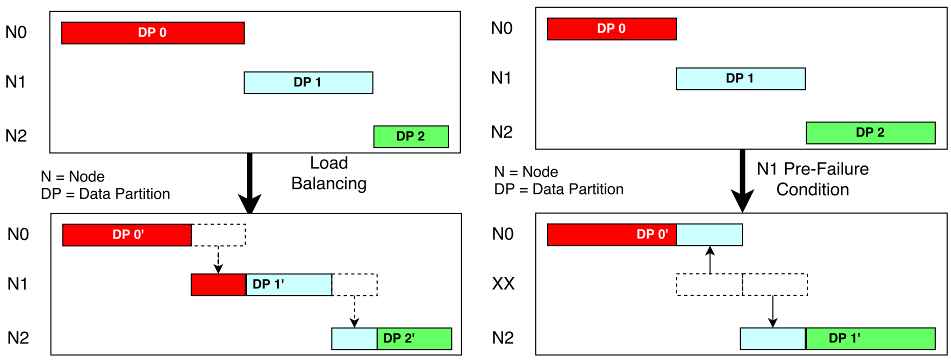

Figure 3: Load Balancing (left), Remove work from N1 due to failure prediction (right).

any communication library used by an application. This should be supported by allowing application programmers to implement their own LAIK backend.

Efficient Fault Tolerance: The application data shall be recoverable upon system failure. The LAIK library shall support both recovery-based (e.g. *Checkpoint & Restart*) and proactive (e.g. *Fault Prediction*) fault tolerance. We want LAIK to support local recovery, that is on node failure, a near-side node should be able to take over the computation of the failed node by using duplicated data. This way, LAIK can support a more efficient scheme than classical global *Checkpoint & Restart*. For failure prediction, we expect that there is a way to do online monitoring of hardware health via adequate sensors. However, this is out of scope for LAIK. Any support to react to outside sources should be implementable as a thin layer on top of LAIK. This may regularly poll (synchronous to program phases) for incoming messages using IPC mechanisms or protocols like Message Queue Telemetry Transport (MQTT).

Load Balancing: A task within a parallel application usually has a work load depending on size of data it has access to. As LAIK provides partitions to tasks, this influences the work load distribution. We want LAIK to support automatic workload distribution via regular repartitioning of data structures. For that, LAIK should be able to make use of task-related profile data (such as time measurements of program phases). To be able to

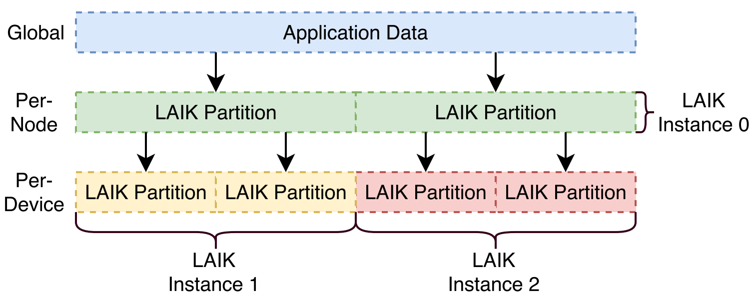

Figure 4: Hierarchical LAIK Instances

support different load balancing mechanisms, both static and dynamic, a key-value store may be needed to have historical data available. This must be persistant to allow static load balancing.

Hierarchical Data Partitioning: In order to make the LAIK library even more usable, LAIK shall be able to run in a nested multi-instance mode. It should be possible to connect different LAIK instances on different hierarchy levels. Thus, a partition in one LAIK instance should map to a top-level index space in a lower LAIK instance. To this end, LAIK index spaces must be able to shrink or expand. Data migration request may be passed between instances. Thus, a repartitioning happening in a lower LAIK instance is ignored in a higher LAIK instance, but a repartitioning of a higher instance will potentially result in size changes of index spaces in lower LAIK instances, resulting in forced repartitionings in the lower instances. The expected use for this nesting functionality is that large HPC systems may have a hierarchical topology with different resource capabilities (network, processors, accelerators) at different levels. This can be represented by adequate LAIK nesting. In the simplest case this would be inter-node and intra-node.

Figure 2 shows an example partitioning of 1d data among nodes N0, N1, and N2 (rows). For each element, exactly one node is the owner with read and write access. As shown in the figure, we want LAIK to provide copies for reading of the neighbor elements at the border of owned regions. This is useful for stencil codes. This example shows that it is useful to "switch" to the same partitioning, which ensures consistency of the values of elements to be accessable at multiple nodes. This, instead of a switch, it is better to talk about *enforcing consistency requirements* of a given partitioning. In the example, this will result in copying data as shown by the arrows in the figure. To support communication asynchronous to computation, a program first has to acquire access to parts of a LAIK partition with different access permission right after a switch: in the example separately for the RW and R parts. This may allow to already do computations on the inner parts of the owned regions while commmuncation for the border elements is still going on.

Figure 3 (left) shows an example of data re-distribution for load balancing. First, the data is distributed unequally across nodes. Upon a load balancing request, recalculating of partition borders from profile data results in a data redistributing with better load balancing. Figure 3 (right) shows an example of data reacting to failure prediction as part of a pro-active fault tolerance scheme. A pre-failure condition for node N1 results in LAIK initiating a repartitioning such that the failing compute node is excluded from execution. Here we assume that a system health monitor with integrated fault predictor exists. Related works such as [Li06] shows the possibility of predicting system failure.

Figure 4 shows a hierarchical configuration using different nested LAIK instances. Application data is first divided into LAIK data partitions node-wise. These data partitions then are mapped to top-level spaces if the inner LAIK instances. These divide the data again to be assigned to different devices (for example CPU cores or multiple GPUs) within the node.

```
#include "laik-backend-mpi.h"
int main(int argc, char* argv[])
{
  Laik_Instance* inst = laik_init_mpi(&argc,&argv);
  Laik_Group* world = laik_world(inst);

  // allocate global 1d double (8 bytes) array: 1 mio entries
  Laik_Data* a = laik_alloc_1d(world, 8, 1000000);

  // initialize at master (others do nothing)
  laik_set_new_partitioning(a, LAIK_PT_Master, LAIK_AP_WriteOnly);
  laik_map(a, LAIK_DL_CANONICAL, (void**) &base, &count);
  double* base; uint64_t count;
  for(uint64_t i = 0; i < count; i++) base[i] = (double) i;

  // distribute data equally among all tasks, do partial sums
  laik_set_new_partitioning(a, LAIK_PT_Stripe, LAIK_AP_ReadWrite);
  laik_map(a, LAIK_DL_CANONICAL, (void**) &base, &count);
  double mysum = 0.0;
  for(uint64_t i = 0; i < count; i++) mysum += base[i];

  // write partial sums as input for sum reduction
  Laik_Data* sum = laik_alloc_1d(world, 8, 1);
  laik_set_new_partitioning(sum, LAIK_PT_All, LAIK_AP_SUM);
  laik_map(sum, LAIK_DL_CANONICAL, (void**) &base, &count);
  *base = mysum;
  // master-only: does sum reduction to be read at master
  laik_set_new_partitioning(sum, LAIK_PT_Master, LAIK_AP_ReadOnly);
  if (laik_myid(world) == 0) {
    laik_map(sum, LAIK_DL_CANONICAL, (void**) &base, &count);
    printf("Sum: \%.0f", *base[0]);
  }
  laik_finalize(inst);
}
```

Figure 5: Example using LAIK for parallel vector initialization and sum.

4 Examples

Figure 5 shows the implementation of a parallel vector sum using LAIK with the MPI backend. The compiled binary can be run with "mpirun" using the number of LAIK tasks as requested as number of MPI tasks. First, the vector is initialized on the master node using a master partitioning giving all elements write access just at master. To actually write the values, the partitions have to be "mapped" to local memory using an canonical ordering: the index into the 1d array is equal to the offset in memory (more data layout options are planned for 2d or 3d data). Afterwards, we switch to a Stripe partitioning with equal size for all tasks, resulting in MPI messages from master to other nodes. After another mapping request for direct access, partial sums are done with the result written to

```
double getEW(uint64_t i, void* d) {
  SpM* m = (SpM*) d;
  return (double) (m->row[i + 1] - m->row[i]); }

main {
  ...
  Laik_Data* r = laik_alloc_1d(world, 8, SIZE);
  Laik_Space* s = laik_get_space(r);
  Laik_Partitioning* p = laik_new_base_partitioning(s,
    LAIK_PT_Stripe, LAIK_AP_ReadWrite);
  laik_set_index_weight(p, getEW, matrix);
  laik_set_partitioning(resD, p);

  laik_my_slice(p, &from, &to);
  laik_map(r, LAIK_DL_CANONICAL, (void**) &res, &count);
  for(int r = from; r < to; r++) { res[r-from] += ... }
  ...
}
```

Figure 6: Using element-wise weighting balancing workload involving a sparse matrix.

```
0/3 partng-0: 0:[0-999999], 1:(empty), 2:(empty)
...
0/3 partng-1: 0:[0-333332], 1:[333333-666665], 2:[666666-999999]
0/3 partng-0 => partng-1: locl: [0-333332]
      send: [333333-666665] => T1, [666666-999999] => T2
1/3 partng-0 => partng-1: recv: T0 => [333333-666665]
2/3 partng-0 => partng-1: recv: T0 => [666666-999999]
```

Figure 7: Excerpt of debug output from Example 1 (vsum). This shows the computed migration of indexes for switching between master and Stripe partitioning.

another LAIK array with just 1 element by every task. This shows how LAIK can be asked to do a sum reduction, which actually happens when this array is switched to a partitioning with only master having read rights to print out the final result.

Figure 6 shows excerpts from an example using LAIK to do computation on a sparse matrix distributed in row dimension for partitions containing a similar number of non-zero elements. For this, we use a index space which also is bound to vector “r”, which has the same number of elements as there are rows in the sparce matrix. To calculate the requested weighted Stripe partitioning, LAIK will call into an application provided function (getEW) that returns a weight for each element in a 1d index space, equal to the number of elements in that row. Here the struct type “SpM” encapsulates a matrix stored in CSR format. Afterwards, each task does a loop over all matrx rows belonging to its partition.

5 Prototype Implementation and First Results

Our current prototype of the LAIK library[7] comes with an MPI backend, support for 1d data and different kinds of partitionings. The most important one is a Stripe partitioning, which slices an 1d space into an ordered sequence of consecutive partitions, one for each task. This partitioning type supports element-wise and task-wise weighting. Element-wise weighting is shown in Fig. 6, task-wise weighting similarly uses a function called by LAIK e.g. returning time measurements for load balancing. We do not yet provide support for reacting in events from the outside, such as a request to free a given compute node.

The LAIK prototype source code provides examples as shown in the previous section (vsum and spmv, respectively). As expected, with enough parallel work load, we can achieve the same scalability as if an example directly would have used MPI. Optionally, debug output can be printed which includes the calculated partitionings of index spaces as well as the transition actions needed to migrate from one partitioning to another. This is shown in Fig. 7.

6 Conclusion

In this paper, we presented our design and a prototypical implementation of LAIK, a leigth-weight library for the distribution of data containers among tasks of a parallel application. The idea is to separate the decision making of how to best partition application data from the application code. This allows partitioning strategies which not only take program-internal information (such as profiling data for load balancing) but also external sources into account. This enables support for application-integrated fault tolerance features, such as pro-active requests for removing computation from nodes predicted to fail soon. As future work, we will support real-world applications which need coupling of index spaces of used data structures, as well as support for multi-dimensional data. Further, we want to show how a local checkpoint/restart functionality involving rollback only for data recovered with the help of redundant data duplication within LAIK.

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