MARs: Memory Access Rearrangements in Open MPI Datatype Engine

*Note: Sub-titles are not captured in Xplore and should not be used

1st Given Name Surname
dept. name of organization (of Aff.)
name of organization (of Aff.)
City, Country
email address

2nd Given Name Surname
dept. name of organization (of Aff.)
name of organization (of Aff.)
City, Country
email address

3rd Given Name Surname
dept. name of organization (of Aff.)
name of organization (of Aff.)
City, Country
email address

4th Given Name Surname
dept. name of organization (of Aff.)
name of organization (of Aff.)
City, Country
email address

5th Given Name Surname
dept. name of organization (of Aff.)
name of organization (of Aff.)
City, Country
email address

6th Given Name Surname
dept. name of organization (of Aff.)
name of organization (of Aff.)
City, Country
email address

***Abstract*—This document is a model and instructions for LaTeX. This and the IEEEtran.cls file define the components of your paper [title, text, heads, etc.]. *CRITICAL: Do Not Use Symbols, Special Characters, Footnotes, or Math in Paper Title or Abstract.**

***Index Terms*—component, formatting, style, styling, insert**

I. Introduction

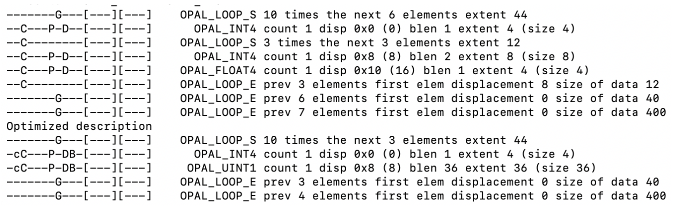
This document is a model and instructions for LaTeX. Please observe the conference page limits.

II. Related Work

III. Background

A. Open MPI Datatype Engine

Datatypes in Open MPI are consisted of basic datatypes, such as int, double, float, etc. When putting basic datatypes together, the combination is called derived datatype. The current Open MPI datatype engine will optimize the storage space for a derived datatype during commit time. First, lets examine how a datatype looks like in Open MPI.



```
-------G---[---][---]    OPAL_LOOP_S 10 times the next 6 elements extent 44
--C---P-D--[---][---]      OPAL_INT4 count 1 disp 0x0 (0) blen 1 extent 4 (size 4)
--C--------[---][---]    OPAL_LOOP_S 3 times the next 3 elements extent 12
--C---P-D--[---][---]      OPAL_INT4 count 1 disp 0x8 (8) blen 2 extent 8 (size 8)
--C---P-D--[---][---]    OPAL_FLOAT4 count 1 disp 0x10 (16) blen 1 extent 4 (size 4)
--C--------[---][---]    OPAL_LOOP_E prev 3 elements first elem displacement 8 size of data 12
-------G---[---][---]    OPAL_LOOP_E prev 6 elements first elem displacement 0 size of data 40
-------G---[---][---]    OPAL_LOOP_E prev 7 elements first elem displacement 0 size of data 400
Optimized description
-------G---[---][---]    OPAL_LOOP_S 10 times the next 3 elements extent 44
-cC---P-DB-[---][---]      OPAL_INT4 count 1 disp 0x0 (0) blen 1 extent 4 (size 4)
-cC---P-DB-[---][---]     OPAL_UINT1 count 1 disp 0x8 (8) blen 36 extent 36 (size 36)
-------G---[---][---]    OPAL_LOOP_E prev 3 elements first elem displacement 0 size of data 40
-------G---[---][---]    OPAL_LOOP_E prev 4 elements first elem displacement 0 size of data 400
```

Fig. 1. Datatype Description

Using Open MPI datatype feature, a datatype description can be exported using function ompi_datatype_dump (MPI_Datatype ddt). An arbitrary datatype description will look like the description in Figure #1. The top half of the figure is the description given by the user and the bottom part is the optimization description generated by the datatype engine. As Figure #1 shows, an example of an arbitrary datatype in Open MPI is consisted of three elements,

1) Loop_start
2) Data
3) Loop_end

Loop_start and Loop_end indicates what data elements and how many times the elements will be repeated. Each element in the datatype is described as follow:

```
Struct ddt_elem_desc{
    ddt_elem_id_description common;
    uint32_t                blocklen;
    size_t                  count;
    ptrdiff_t               extent;
    ptrdiff_t               disp;
};
typedef struct ddt_elem_desc ddt_elem_desc_t;
```

At first glance, it seems it is excessive to describe one single element with extent and count, but this is an optimal description when the given datatype is a regular pattern memory layout. Any regular pattern datatype, vector-like patterns, can be described using one ddt_elem_desc_t, just like the example from Figure #2. Within the datatype, when theres one element describes as a full vector type, in this case, 9 counts of block length of 40 bytes with extent of 44 bytes, using such datatype description, datatype engine has fully minimized the memory to store the datatype. If looking closely, the datatype in Figure #2 is the same as Figure #1. Since both are defined using different methods, the genetics of

Identify applicable funding agency here. If none, delete this.

the datatype (memory layouts) are the same. The difference of the optimized description comes from the optimization process during commit time.

B. Commit Time Optimization

Optimization during commit time is a typical place for MPI to minimize the storage space and rearrange the description to help datatype engine handle data movements faster and more efficiently. In Open MPI, optimization will

1) combine datatype elements that are sequential in pack/unpack order and
2) group datatype elements that repeats the same pattern using Loop_start and Loop_end

Although the optimization process does well in most cases, we did find scenarios, like the ones above, result in different optimized descriptions.

//reason of optimization being different and paper to cite optimization could use n$^3 time$

Before we examine the performance of the Open MPI datatype engine, we should first closely look at how datatype description is used in pack/unpack functions.

C. Pack/Unpack Functions

There are several pack/unpack functions built inside Open MPI to deal with different systems. We choose and examine the most common one, opal_generic_simple_pack_function and opal_generic_simple_unpack_function. Both functions have the exact same routine but with opposite data flows.

```
Struct dt_stack_t {
    int32_t      index;
    int16_t      type;
    int16_t      padding;
    size_t       count;
    ptrdiff_t    disp;
};
typedef struct dt_stack_t dt_stack_t;
```

In Open MPI, in order to maintain the leisure of achieving pipelining, it uses a structure called convertor to keep track of the position. The convertor contains information such as datatype description, count of datatype needs to be packed/unpacked, total data size that needs to be moved, and etc. Along with these information, it also uses stack to keep the positioning within the user buffer. As figure #3 explains what a stack is consisted of.

- Index: correspond to ddt_elem_desc_t, keeps track of which element in the datatype description the convertor is at
- Count: number of the whole datatype left to be done
- Disp: the current displacement in respect to the start of the user buffer

The convertor in pack/unpack function will go through the datatype description element by element. As it moves along the description, it will keep checking if it has reached the pipeline size. If it does, it will record the position in stack and wait till next pack/unpack pipeline is being called. Since user could tell Open MPI to pack/unpack X number of datatype, the convertor will also go through the datatype description X number of times.

IV. Motivations

Open MPI datatype engine supports communication layer for data handling. It alleviates the workload from user to hard-code data movements and ensures a high and stable performance. A typical point-to-point communication starts with a process packs non-contiguous data into a contiguous buffer and push it through the network. On the other side, after receiving the contiguous buffer from the first process, it unpacks the contiguous buffer into non-contiguous memory layout. We are interested in speeding up this whole process. The total communication time can be calculated as:

$$Pack(Tp)+PackOverhead(Tpo)+NetworkLatency(L)+UnpackOve \tag{1}$$

Because the network latency is scaled linearly in respect to the size of contiguous buffer, Open MPI uses pipelining during communication to further reduce the communication time by overlapping pack/unpack with communication, thus, hiding network latency behind pack/unpack. And the total time for pipelining is calculated as

$$SmallerPack(Tp)+SmallerPackOverhead(Tpo)+SmallerNetwork \tag{2}$$

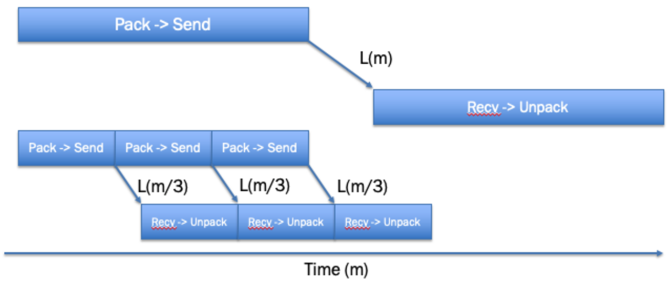


Fig. 2. Pipeline example

Since network latency is hidden and pipelining with small segments wouldnt fully utilize the bandwidth of the network, with the right pipeline size, the bottleneck for the communication lies within pack/unpack, thus, increasing the pack/unpack performance is what we are interested in. Knowing there is a bottleneck for every datatype in turns of how fast the non-contiguous data can be put together to form the contiguous buffer, we can easily calculate the ideal/maximum bandwidth using the sparsity (data size / datatype extent) with the theoretical peak bandwidth of the system as for a given datatype:

$$Theoreticalpeakbandwidth = datasize/datatypeextent*theoreticalpe \tag{3}$$

While improving pack/unpack, we did observe that inconsistent in datatype optimization also leads to inconsistent in pack/unpack performance. Thus, we also aim to revamp datatype description and optimization process to have consistent performance across all scenarios.

V. IOVEC Datatype Representation

Our first goal is to find a datatype representation that could result in consistent optimization form and pack/unpack performance. A flattened, easy-to-maintain datatype description that is consisted of an array of IOVECs is the perfect choice. IOVEC datatype representation is created during commit time optimization. Each IOVEC corresponding to a data space and the IOVECs, as one datatype, contain all the memory locations and sizes. During the commit optimization, IOVEC representation is created by traversing the Open MPI datatype description. It will merge any two or more IOVECs that can be combined to into one single contiguous element. Since less MEMCPYs equals to better performance, while current datatype optimization could not, IOVEC representation always guarantees the minimal number of MEMCPYs. Because IOVEC representation is flattened and expands storage space based on the number of non-contiguous elements, using current pack/unpack methods (going through description X times), the performance would easily take a toll when IOVEC description is huge in memory and pack/unpack has to access the description over and over. Such implementation isnt cache optimal since the description could take out a chunk of cache and leave less for the actual data. Thus, we also revamp pack function to accommodate IOVEC description.

VI. IOVEC Memory Access Rearrangements (MARs)

Our goal to revamp pack function is to minimize the IOVEC description access. By doing so, we would free up cache that is required to keep IOVEC description in reach. In the meantime, we could also maximize the cache usage. Given todays memory hierarchy, the time for data to travel from one cache level to another is almost nothing comparing to the time from main memory to highest level of cache. We proposed Memory Access Rearrangements (MARs) method in replace to todays datatype engines sequential packing order. In a typical MARs operation, instead of packing elements by elements in datatype description, MARs only look at one element (E) at a time and pack all X (user defined) times of E and then move on to the next element in the description.

Figure #4 demonstrate how MARs comparing to todays packing sequence. Giving a datatype that has two elements, a double starts at displacement 0 and a double starts at displacement 16 with extent of 64 bytes. With the packed buffer being the same, the number represents the packing order. Such access rearrangements have two major benefits,

1) it greatly reduces burden on cache to have constant access to datatype, it only need to access datatype once
2) most datatypes with user given high count number have irregular memory access pattern, hardware could not optimize with hardware prefetch, however, with MARs, the irregular access pattern is altered into multiple regular access patterns and the number of multiple access patterns is correlated to the number of elements in datatype description

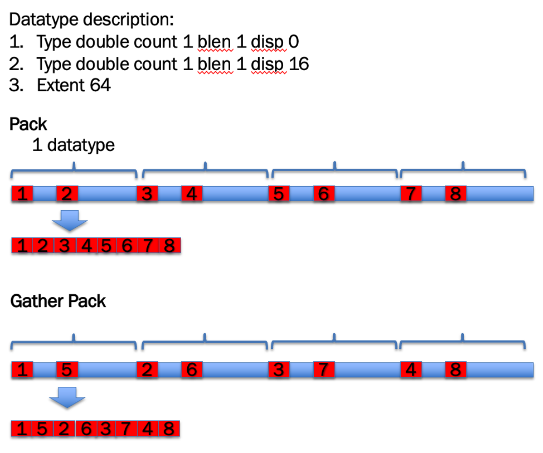


Fig. 3. MARs example

There is a hidden and need-to-be-exploit benefit of using MARs. Because of the access pattern MARs provide, all the other elements within the same granularity have been brought into cache before MARs move on to them.

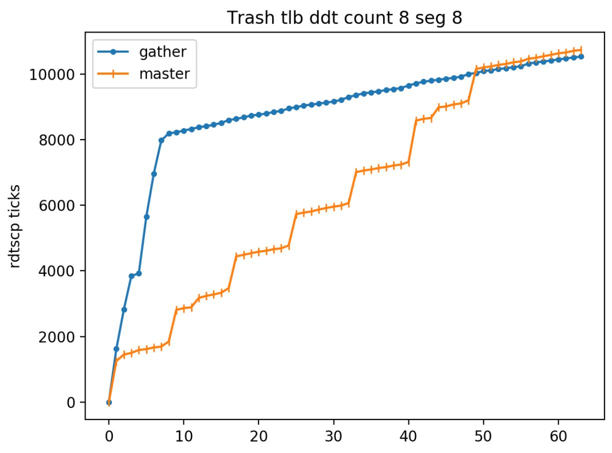


Fig. 4. Trash TLB Datatype count 8 segment size 8

To visualize this phenomenon, after each MEMCPY in pack function, we call rdtscp and replace the destination memory in MEMCPY with the timestamp. Figure #5 shows how the timestamp increments with each MEMCPY. For current pack function in Open MPI, the linear time incrementation corresponds to the sequential access of data. Since each access brought the next 3 elements into cache, after two accesses with pack, the next three accesses are already in cache, thus, much faster accesses than the first two. With MARs, the accesses for all X first elements are not in cache and are 8 pages apart, thus, much longer accesses for the first X accesses, but after that all the data has been brought into cache and creates faster accesses. We could fully utilize the benefit of using MARs by increasing the number of datatypes in each segment. However, infinitely increasing the segment sizes could lead to huge performance loss.

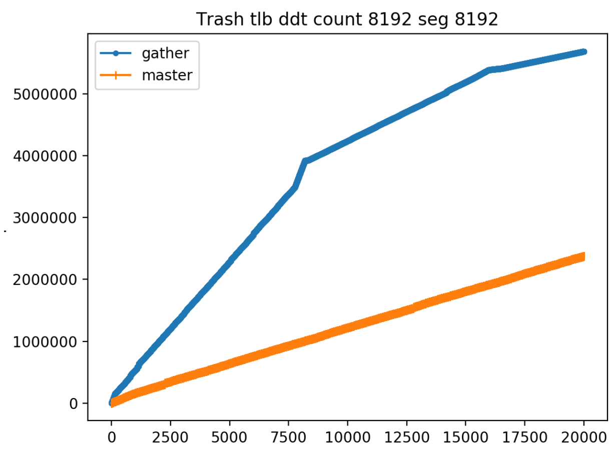


Fig. 5. Trash TLB Datatype count 8192 segment size 8192

As Figure #6 shows, when disregarding the segment size, the access time for each element with MARs is far from optimal. This is because of the size limitation on cache. When MARs keep reaching deep into the main memory, there is only limited number of cache lines the cache can hold. After that, the cache starts to evict data back into main memory. When MARs move on the next element in description, it will be evicted and will take time to be fetched back into cache again. Such back and forth movement will cause huge disruption and delay in performance. To solve this issue, we purpose to use segmentation or pipeline within MARS.

VII. MARs Segmentation/Pipeline

Because of the access pattern from MARs, every first access in datatype results in bringing more data within the granularity into the cache. The idea to use segmentation/pipeline on MARs is trying to keep every possible reuse of data inside cache and to keep data eviction at minimum.

Figure #7 is an example that MARs perform 20% better in a large count scenario with correct segment sizes. However, the segmentation/pipeline sizes can vary from datatype to datatype and from platform to platform. After observing a few of datatype performance using MARs, we suspect the best performances using MARs segmentation/pipeline is correlated to number of factors:

1) Size of the cache in each level
2) Number of physical pages in each cache level
3) Size of the data in datatype
4) Number of cache lines occupied by the data
5) Extent of the datatype

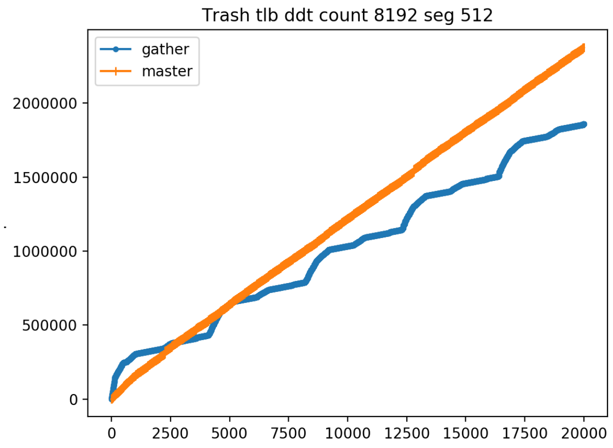


Fig. 6. Trash TLB Datatype count 8192 segment size 512

6) The gap sizes between elements
7) Element offset in regarding to the start of datatype
8) Number of layers in cache hierarchy
9) Associativity of the cache

These are the factors that we suspect that needed to be taken into consideration. However, we are yet to find a perfect calculation/equation to maximize all performance. We will present performance with a few segmentation/pipeline sizes in performance section.

VIII. Performance

A. *IOVEC vs. Current Datatype Description*

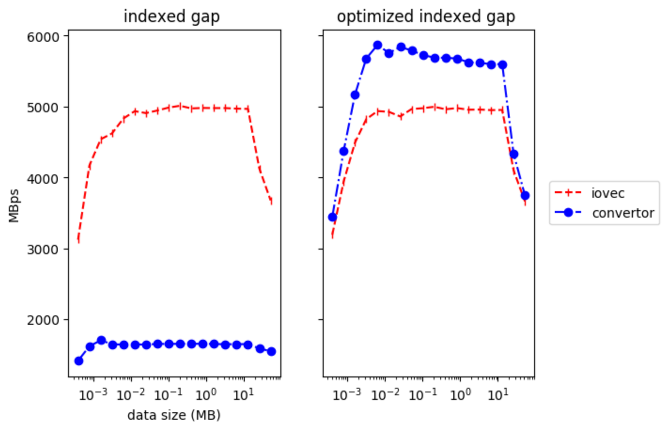


Fig. 7. Bad Datatype Description Optimization

B. *IOVEC vs. IOVEC MARs vs. Master Pack*

C. *IOVEC vs. IOVEC MARs Pipeline vs. Master Pack*

IX. Conclusion

References

Please number citations consecutively within brackets [1]. The sentence punctuation follows the bracket [2]. Refer simply to the reference number, as in [3]—do not use "Ref. [3]" or "reference [3]" except at the beginning of a sentence: "Reference [3] was the first . . ."

Number footnotes separately in superscripts. Place the actual footnote at the bottom of the column in which it was cited. Do not put footnotes in the abstract or reference list. Use letters for table footnotes.

Unless there are six authors or more give all authors' names; do not use "et al.". Papers that have not been published, even if they have been submitted for publication, should be cited as "unpublished" [4]. Papers that have been accepted for publication should be cited as "in press" [5]. Capitalize only the first word in a paper title, except for proper nouns and element symbols.

For papers published in translation journals, please give the English citation first, followed by the original foreign-language citation [6].

References

[1] G. Eason, B. Noble, and I. N. Sneddon, "On certain integrals of Lipschitz-Hankel type involving products of Bessel functions," Phil. Trans. Roy. Soc. London, vol. A247, pp. 529–551, April 1955.

[2] J. Clerk Maxwell, A Treatise on Electricity and Magnetism, 3rd ed., vol. 2. Oxford: Clarendon, 1892, pp.68–73.

[3] I. S. Jacobs and C. P. Bean, "Fine particles, thin films and exchange anisotropy," in Magnetism, vol. III, G. T. Rado and H. Suhl, Eds. New York: Academic, 1963, pp. 271–350.

[4] K. Elissa, "Title of paper if known," unpublished.

[5] R. Nicole, "Title of paper with only first word capitalized," J. Name Stand. Abbrev., in press.

[6] Y. Yorozu, M. Hirano, K. Oka, and Y. Tagawa, "Electron spectroscopy studies on magneto-optical media and plastic substrate interface," IEEE Transl. J. Magn. Japan, vol. 2, pp. 740–741, August 1987 [Digests 9th Annual Conf. Magnetics Japan, p. 301, 1982].

[7] M. Young, The Technical Writer's Handbook. Mill Valley, CA: University Science, 1989.