

3.11 Completion Continuations

Some applications may need to handle large numbers of requests or require fast reaction to changes in the state of an active request, i.e., the completion or cancellation of the operation. The reaction to the completion of an operation can be expressed as a *continuation*, i.e., a call-back function provided by the application that is invoked by MPI once completion or cancellation of the operation is detected. This alleviates the pressure on the application to repeatedly test large numbers of requests and allows for fast reaction to state changes.

Continuations are *attached* to either a single request or a set of requests and *registered* with a *continuation request*. A continuation request has to be initialized and freed by the application and can be used to test or wait for the completion of all registered continuations. Continuation requests themselves may have a continuation attached, which will be invoked once all continuations registered with it have been executed. Attaching a continuations to a non-persistent request returns ownership of that request back to MPI, i.e., the request may not be used to test or wait for the completion of the respective operation. Persistent requests, on the other hand, remain valid after attaching a continuation. However, the outcome of attaching more than one continuation to an active request is undefined.

By default, continuations may be executed by the MPI library at any time and on any thread after the completion of the associated operation or operations. This behavior can be controlled using info keys listed in Section 3.11.3.

When attaching a continuation to an operation request, a status object may be passed, which will be filled before the continuation is invoked. The pointer to the status object is then passed to the continuation. It is the application's responsibility to ensure that the status objects are accessible until the continuation is invoked. The application may also pass `MPI_STATUS_IGNORE`, in which case this value will also be passed to the continuation.

Example 3.20 uses continuations in order to avoid explicitly tracking buffers and to facilitate a simple throttling mechanism. Similar behavior can be achieved using `MPI_TESTSOME` and manually managing a set of active requests. However, continuations tie the request directly to an action to be executed upon completion of the respective operation, managed by MPI.

Example 3.20 One process sending messages to all others, using continuations to avoid tracking buffers and to limit the number of concurrently active send operations.

```
#include <stdlib.h>
#include <mpi.h>

#define NUM_VARS 1024
#define TAG 1001
#define MAX_ACTIVE_SEND 3
static int num_active_send = 0;

void completion_cb(MPI_Status *status, void *user_data)
{
    --num_active_send;
    free(user_data);
}
```

```
int main(int argc, char *argv[])
{
    int rank, size, flag;
    double *vars;
    MPI_Request op_request, cont_request;
    MPI_Comm comm = MPI_COMM_WORLD;

    MPI_Init(&argc, &argv);
    MPI_Comm_size(comm, &size);
    MPI_Comm_rank(comm, &rank);
    MPI_Continue_init(MPI_INFO_NULL, &cont_request);

    if (rank == 0) {
        /* Send message to each peer, not exceeding MAX_ACTIVE_SEND */
        for (int i = 1; i < size; ++i) {
            /* don't exceed the limit */
            while(num_active_send >= MAX_ACTIVE_SEND) {
                MPI_Test(&flag, cont_request, MPI_STATUS_IGNORE);
            }
            ++num_active_send;
            vars = malloc(sizeof(double)*NUM_VARS);
            compute_vars_for(vars, i);
            MPI_Isend(vars, NUM_VARS, MPI_DOUBLE, i, TAG, comm, &op_request);
            /* Attach continuation that frees the buffer once complete */
            MPI_Continue(&op_request, &completion_cb, vars,
                MPI_STATUS_IGNORE, cont_request);
        }
        /* Wait for remaining continuations to complete */
        MPI_Wait(&cont_request, MPI_STATUS_IGNORE);
    } else {
        vars = malloc(sizeof(double)*NUM_VARS);
        MPI_Recv(vars, NUM_VARS, MPI_DOUBLE, 0, TAG, comm, MPI_STATUS_IGNORE);
        compute_vars_from(vars, 0);
        free(vars);
    }
    MPI_Request_free(&contreq);
    MPI_Finalize();
    return 0;
}
```

3.11.1 Continuation Requests

```
MPI_CONTINUE_INIT(info, cont_req)
```

IN	info	info argument (handle)
OUT	cont_req	continuation request (handle)

C binding

```
int MPI_Continue_init(MPI_Info info, MPI_Request *cont_req)
```

Fortran 2008 binding

```
MPI_Continue_init(info, cont_req, ierror)
  TYPE(MPI_Info), INTENT(IN) :: info
  TYPE(MPI_Request), INTENT(OUT) :: cont_req
  INTEGER, OPTIONAL, INTENT(OUT) :: ierror
```

Fortran binding

```
MPI_CONTINUE_INIT(INFO, CONT_REQ, IERROR)
  INTEGER INFO, CONT_REQ, IERROR
```

This function creates a new continuation request that can be used to register continuations for active operation requests and test or wait for the completion of registered continuations. The `info` argument can be used to control parameters of the registered continuations. A list of available `info` keys can be found in Section 3.11.3.

Continuation requests may be passed to `MPI_TEST` and `MPI_WAIT` to test or wait for the completion of the execution of all registered continuations. A call to a test or wait function indicating completion of a continuation request does not free the request. A continuation request is complete until the first continuation is registered, at which point the request is marked as incomplete until the last continuation has completed its execution.

A continuation request may be freed through a call to `MPI_REQUEST_FREE`, which marks the request for deallocation. The request will be deallocated once all registered continuations have been executed.

TODO: which field will be set in the status when waiting for a cont request?

3.11.2 Attaching Continuations

Continuations are attached to requests representing initiated operations using either `MPI_CONTINUE` or `MPI_CONTINUEALL`.

The continuation callback function has the type `MPI_Continue_cb_function` and upon invocation is passed the pointer to the status object(s) and the user-provided pointer to additional data.

```
typedef void MPI_Continue_cb_function(MPI_Status *array_of_statuses,
  void *user_data);
```

ABSTRACT INTERFACE

```
SUBROUTINE MPI_Continue_cb_function(array_of_statuses, user_data, ierror)
  TYPE(MPI_Status) :: array_of_statuses(*)
  INTEGER(KIND=MPI_ADDRESS_KIND) :: user_data
  INTEGER, OPTIONAL :: ierror
```

```

SUBROUTINE MPI_CONTINUE_CB_FUNCTION(ARRAY_OF_STATUSES, USER_DATA, IERROR)
  INTEGER ARRAY_OF_STATUSES(MPI_STATUS_SIZE, *), IERROR
  INTEGER(KIND=MPI_ADDRESS_KIND) USER_DATA

```

The statuses in the `array_of_statuses` will be set before the continuation callback is invoked. The application is responsible for allocating and releasing the memory backing the `array_of_statuses` and that memory shall be accessible for the time between attaching the continuation and the invocation of the continuation. If `MPI_STATUS_IGNORE` or `MPI_STATUSES_IGNORE` was passed during registration, then these values will be passed to the callback function invocation instead.

TODO: is it safe to conflate `MPI_STATUS_IGNORE` and `MPI_STATUSES_IGNORE` in the callback? Do we need two different callbacks for `continue` and `continueall`?

TODO: by passing the status to the callback we may be giving the impression that this is memory managed magically managed by MPI. The user could just as well pass the status in the `user_data` if needed...

```

MPI_CONTINUE(op_request, cb, cb_data, status, cont_request)

```

INOUT	<code>op_request</code>	operation request (handle)
IN	<code>cb</code>	callback to be invoked once the operation is complete (function)
IN	<code>cb_data</code>	pointer to a user-controlled buffer
IN	<code>status</code>	status object (array of status)
IN	<code>cont_request</code>	continuation request (handle)

C binding

```

int MPI_Continue(MPI_Request *op_request, MPI_Continue_cb_function cb,
                void *cb_data, MPI_Status *status, MPI_Request cont_request)

```

Fortran 2008 binding

```

MPI_Continue(op_request, cb, cb_data, status, cont_request, ierror)
  TYPE(MPI_Request), INTENT(INOUT) :: op_request
  MPI_Continue_cb_function, INTENT(IN) :: cb
  INTEGER(KIND=MPI_ADDRESS_KIND), INTENT(IN) :: cb_data
  TYPE(MPI_Status), INTENT(IN), ASYNCHRONOUS :: status(1)
  TYPE(MPI_Request), INTENT(IN) :: cont_request
  INTEGER, OPTIONAL, INTENT(OUT) :: ierror

```

Fortran binding

```

MPI_CONTINUE(OP_REQUEST, CB, CB_DATA, STATUS, CONT_REQUEST, IERROR)
  INTEGER OP_REQUEST, STATUS(MPI_STATUS_SIZE, 1), CONT_REQUEST, IERROR
  MPI_Continue_cb_function CB
  INTEGER(KIND=MPI_ADDRESS_KIND) CB_DATA

```

This function attaches a continuation to the operation request `op_request` and registering it with the continuation request `cont_request`. The callback function `cb` will be invoked after the MPI implementation finds the operation represented by `op_request` to be complete. Upon invocation, the `status` pointer will be passed to the callback function together with

1 the `cb_data` pointer. The `cont_request` must be a continuation request created through a
 2 call to `MPI_CONTINUE_INIT`.

3 If the operation represented by `op_request` is complete at the time of the call to
 4 `MPI_CONTINUE`, the implementation may invoke the `cb` immediately, unless the
 5 "mpi_continue_enqueue_complete" info key is set to "true" during the creation of the
 6 `cont_request`.

7 Unless `MPI_STATUS_IGNORE` is passed as `status`, the status object pointed to must be
 8 accessible until the callback is invoked.

9 For non-persistent requests, the `op_request` is set to `MPI_REQUEST_NULL` before the
 10 call returns. The outcome of passing a non-persistent operation request to another MPI
 11 function after it was passed to `MPI_CONTINUE` is undefined.

12 A persistent operation request will not be set to `MPI_REQUEST_NULL` before returning
 13 from the call and may be passed to other MPI procedures. Upon invocation of the attached
 14 continuation, the persistent request will be inactive and can be started inside the contin-
 15 uation. The outcome of attaching more than one continuation to an operation request is
 16 undefined.

17
 18
 19 `MPI_CONTINUEALL(count, array_of_op_requests, cb, cb_data, array_of_statuses,`
 20 `cont_request)`

21	IN	<code>count</code>	list length (non-negative integer)
22	INOUT	<code>array_of_op_requests</code>	array of requests (array of handles)
23			
24	IN	<code>cb</code>	callback to be invoked once the operation is complete (function)
25			
26	IN	<code>cb_data</code>	pointer to a user-controlled buffer
27	IN	<code>array_of_statuses</code>	array of status objects (array of status)
28			
29	IN	<code>cont_request</code>	continuation request (handle)

31 C binding

```
32 int MPI_Continueall(int count, MPI_Request array_of_op_requests[],
33                   MPI_Continue_cb_function cb, void *cb_data,
34                   MPI_Status array_of_statuses[], MPI_Request cont_request)
```

35 Fortran 2008 binding

```
36 MPI_Continueall(count, array_of_op_requests, cb, cb_data,
37                array_of_statuses, cont_request, ierror)
38 INTEGER, INTENT(IN) :: count
39 TYPE(MPI_Request), INTENT(INOUT) :: array_of_op_requests(count)
40 MPI_Continue_cb_function, INTENT(IN) :: cb
41 INTEGER(KIND=MPI_ADDRESS_KIND), INTENT(IN) :: cb_data
42 TYPE(MPI_Status), INTENT(IN), ASYNCHRONOUS :: array_of_statuses(*)
43 TYPE(MPI_Request), INTENT(IN) :: cont_request
44 INTEGER, OPTIONAL, INTENT(OUT) :: ierror
```

46 Fortran binding

```
47 MPI_CONTINUEALL(COUNT, ARRAY_OF_OP_REQUESTS, CB, CB_DATA,
48                ARRAY_OF_STATUSES, CONT_REQUEST, IERROR)
```

```

INTEGER COUNT, ARRAY_OF_OP_REQUESTS(*),
        ARRAY_OF_STATUSES(MPI_STATUS_SIZE, *), CONT_REQUEST, IERROR
MPI_Continue_cb_function CB
INTEGER(KIND=MPI_ADDRESS_KIND) CB_DATA

```

Similar to `MPI_CONTINUE`, this function is used to attach a continuation callback to a set of operation requests. The callback will be invoked once all operations in the set `array_of_op_requests` have completed. If `MPI_STATUSES_IGNORE` is not passed for `array_of_statuses`, the statuses will be set before the continuation is invoked and the provided pointer passed to the callback. Otherwise, `MPI_STATUSES_IGNORE` is passed to the callback function. The rules regarding persistent and non-persistent requests described for `MPI_CONTINUE` also apply here.

3.11.3 Predefined Info Keys

The behavior of continuations and continuation requests can be controlled using the following info keys:

"mpi_continue_poll_only" Continuations registered with a continuation request created with this key set to "true" will only be executed once the associated continuation request is tested or waited for completion. The default is "false".

"mpi_continue_enqueue_complete" If this info key is set to "true", then a continuation will not be executed during a call to `MPI_CONTINUE` or `MPI_CONTINUEALL` even if the associated operation(s) are complete immediately. Instead the continuation is enqueued for later execution, e.g., when polling on the associated continuation request. The default is "false".

"mpi_continue_max_poll" This key sets the maximum number of continuations that should be invoked once the continuation request is tested. This may be useful in cases where limited time should be spent on processing continuations at once, e.g., an application-level communication thread responsible for handling both incoming and outgoing messages. The default is "-1", meaning unlimited. Setting both "mpi_continue_max_poll" to "0" and "mpi_continue_poll_only" to "true" is erroneous as it would cause no continuation registered with this continuation request to ever be executed.

Advice to users. MPI has no knowledge or control over what actions the continuation it invokes will perform. Thus, MPI cannot decide on its own how many or at what time to execute continuations. Continuations that take long to execute may block the calling thread and prevent progress of other aspects of the application. It may thus be necessary for the application to balance the need for quick reaction to MPI operation completions with reactivity in other (non-communication related) aspects of the application. (*End of advice to users.*)

The execution context of continuations can be controlled using the following info keys:

"mpi_continue_thread" This key may be set to one of the following two values: "application" and "any". The "application" value indicates that continuations may only be executed by threads controlled by the application, i.e., any application thread that calls into MPI. This is the default. The value "any" indicates that continuations may be executed

by *any* thread, including MPI-internal progress threads if available. This key has no effect on implementations that do not use an internal progress thread.

Rationale. Some applications may rely on thread-local data being initialized outside of the continuation or use callbacks that are not thread-safe, in which case the use of "any" would lead to correctness issues. (*End of rationale.*)

"**mpi_continue_async_signal_safe**" If the value is set to "true", the application provides a hint to the implementation that the continuations are async-signal safe and thus may be invoked from within a signal handler. This limits the capabilities of the callback, excluding calls back into the MPI library and other unsafe operations. The default is "false".

3.11.4 Examples

Example 3.21 Using a continuation on persistent receive request, restarting the request after processing an incoming message. This examples uses MPI_WAIT to wait for the completion of all continuations registered with the continuation request and thus to wait for all messages to be processed.

```

#include <stdlib.h>
#include <mpi.h>

#define NUM_VARS 1024
#define TAG 1001

static MPI_Request recv_request, cont_request;
static volatile int num_recvs = 0;
static int world_size;

void completion_cb(MPI_Status *status, void *user_data)
{
    process_vars(user_data);
    if (num_recvs++ < world_size-1) {
        MPI_Start(&recv_request);
        MPI_Continue(&recv_request, &completion_cb, vars,
                    status, cont_request);
    }
}

int main(int argc, char *argv[])
{
    int rank;
    MPI_Status status;
    MPI_Init(&argc, &argv);
    MPI_Comm comm = MPI_COMM_WORLD;
    MPI_Comm_size(comm, &world_size);
    MPI_Comm_rank(comm, &rank);

```

```

double *vars = malloc(sizeof(double)*NUM_VARS);
if (rank == 0) {
    MPI_Continue_init(MPI_INFO_NULL, &cont_request);
    MPI_Recv_init(vars, NUM_VARS, MPI_DOUBLE, MPI_ANY_SOURCE, TAG,
                 comm, &recv_request);
    MPI_Start(&recv_request);
    MPI_Continue(&recv_request, &completion_cb, vars,
                &status, cont_request);
    /* wait for all messages to be received */
    MPI_Wait(&cont_request, MPI_STATUS_IGNORE);
    MPI_Request_free(&recv_request);
    MPI_Request_free(&cont_request);
} else {
    create_vars(vars);
    MPI_Send(vars, NUM_VARS, MPI_DOUBLE, 0, TAG, comm);
}

free(vars);
MPI_Finalize();
return 0;
}

```

Example 3.22 Using continuations to react to an arbitrary number of messages (sender not shown) in a library and checking for cancellation of the receive request inside the continuation. The progress function should be called periodically by the library's user.

```

#include <mpi.h>

#define TAG 1001

static MPI_Request recv_request, cont_request;
static MPI_Status status;

void completion_cb(MPI_Status *status, void *user_data)
{
    int cancelled;
    /* test whether the receive was cancelled, process otherwise */
    MPI_Test_cancelled(status, &cancelled);
    if (cancelled) {
        MPI_Request_free(&recv_request);
    } else {
        process_msg(user_data);
        MPI_Start(&recv_request);
        MPI_Continue(&recv_request, &send_completion_cb, vars,
                    status, cont_request);
    }
}

```



```

1  }
2
3  void init_rcv(void *buffer, int num_bytes)
4  {
5      /* initialize continuation request and start a receive */
6      MPI_Continue_init(MPI_INFO_NULL, &cont_request);
7      MPI_Recv_init(vars, num_bytes, MPI_BYTE, MPI_ANY_SOURCE, TAG,
8                  comm, &rcv_request);
9      MPI_Start(&rcv_request);
10     MPI_Continue(&rcv_request, &completion_cb, buffer,
11                &status, cont_request);
12 }
13
14 void progress()
15 {
16     int flag; // ignored
17     /* progress outstanding continuations */
18     MPI_Test(&cont_request, &flag, MPI_STATUS_IGNORE);
19 }
20
21 void end_rcv()
22 {
23     /* cancel the request and wait for the last continuation to complete */
24     MPI_Cancel(&rcv_request);
25     MPI_Wait(&cont_request, MPI_STATUS_IGNORE);
26     MPI_Request_free(&cont_request);
27 }
28

```

Example 3.23 Using continuations to handle detached OpenMP tasks communicating through MPI. An additional background thread is needed to ensure progress on outstanding continuations.

```

33 #include <stdlib.h>
34 #include <unistd.h>
35 #include <pthread.h>
36 #include <omp.h>
37 #include <mpi.h>
38
39 #define NUM_VARS 1024
40 #define TAG 1001
41
42 void send_completion_cb(MPI_Status *status, void *user_data)
43 {
44     free(user_data);
45 }
46
47 void rcv_completion_cb(MPI_Status *status, void *user_data)
48

```

```
{
  omp_fulfill_event((omp_event_t) user_data);
}

static volatile int need_progress = 1;
void* progress_thread(void *arg)
{
  int flag;
  MPI_Request *cont_request = (MPI_Request*)arg;
  while (need_progress) {
    MPI_Test(cont_request, &flag, MPI_STATUS_IGNORE);
    usleep(100);
  }
  return NULL;
}

int main(int argc, char *argv[])
{
  int rank, size;
  MPI_Request op_request, cont_request;
  omp_event_t event;

  MPI_Init(&argc, &argv);
  MPI_Comm comm = MPI_COMM_WORLD;
  MPI_Comm_size(comm, &size);
  MPI_Comm_rank(comm, &rank);
  MPI_Continue_init(MPI_INFO_NULL, &cont_request);
  /* thread that progresses outstanding continuations */
  pthread_t thread;
  pthread_create(&thread, NULL, &progress_thread, &cont_request);

  #pragma omp parallel master
  {
    if (rank == 0) {
      for (int i = 1; i < size; ++i) {
        #pragma omp task
        {
          double *vars = malloc(sizeof(double)*NUM_VARS);
          compute_vars_for(vars, i);
          MPI_Isend(vars, NUM_VARS, MPI_DOUBLE, i, TAG, comm, &op_request);
          /* attach continuation that frees the buffer once complete */
          MPI_Continue(&op_request, &send_completion_cb, vars,
                     MPI_STATUS_IGNORE, cont_request);
        }
      }
    }
    } else {
      /* task that receives values */
    }
  }
}
```

```
1     double *vars;
2     #pragma omp task depend(out: vars) detach(event)
3     {
4         MPI_Request op_request;
5         vars = malloc(sizeof(double)*NUM_VARS);
6         MPI_Irecv(vars, NUM_VARS, MPI_DOUBLE, 0, TAG, comm, &op_request);
7         MPI_Continue(&op_request, &recv_completion_cb, event,
8                     MPI_STATUS_IGNORE, cont_request);
9     }
10    /* task processing values, executed once the receiving task's
11       dependencies are released */
12    #pragma omp task depend(in: vars)
13    {
14        compute_vars_from(vars, 0);
15        free(vars);
16    }
17 }
18 }
19
20 need_progress = 0;
21 pthread_join(thread, NULL);
22
23 MPI_Request_free(&cont_request);
24 MPI_Finalize();
25 return 0;
26 }
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
```