

Debugging Tool for Localizing Faulty Processes in Message Passing Programs

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ABSTRACT

In message passing programs, once a process terminates with an unexpected error, the terminated process can propagate the error to the rest of processes through communication dependencies, resulting in a program failure. Therefore, to locate faults, developers must identify the group of processes involved in the original error and *faulty processes* that activate faults. This paper presents a novel debugging tool, named *MPI-PreDebugger* (MPI-PD), for localizing faulty processes in message passing programs. MPI-PD automatically distinguishes the original and the propagated errors by checking communication errors during program execution. If MPI-PD observes any communication errors, it backtraces communication dependencies and points out potential faulty processes in a timeline view. We also introduce three case studies, in which MPI-PD has been shown to play the key role in their debugging. From these studies, we believe that MPI-PD helps developers to locate faults and allows them to concentrate in correcting their programs.

KEYWORDS: parallel processing; message passing; debugging; fault localization

1 Introduction

In recent years, cluster/grid computing [Buy99, FK98] is emerging as a cost-effective methodology for high performance computing. The message passing paradigm [Mes94] is a widely employed programming paradigm that gives us efficient parallel programs on these computing environments.

However, debugging message passing programs is usually time-consuming, since we have to investigate a large amount of debugging information compared to sequential programs. Furthermore, once a process terminates with an unexpected error [MSR77], the terminated process can propagate the error to the rest of processes through communication dependencies. For example, if a process terminates before sending an intended message, the receiver process that has no original fault also terminates, since it fails to receive the expected message. This *error propagation* makes it complicated to locate the hidden faults from a number of observed errors.

To give developers valuable insights for debugging, a number of debugging tools have been developed for message passing programs. Post-mortem performance debuggers such as ParaGraph [HE91], ATEMPT [KGV96], XMPI [LAM02], and Vampir [Pal99] visualize detailed timeline view of communications, so that developers can intuitively understand program behaviors.

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Source-level debuggers such as TotalView [Etn02], MPIGDB [BGL00], and CDB [WCS02] allow stepwise execution of programs. TotalView also has a facility for visualizing, named Message Queue Graph (MQG), which shows the states of the pending send and receive operations. MPIGDB is based on a sequential debugger, GDB [SPS02], and allows developers to broadcast terminal input to all GDB processes attached to computing processes. CDB also provides a similar debugging environment by employing GDB at its lower layer.

Fault localization [JHS02] is another approach for debugging programs. *Relative debugging* [HJ00, WA01] is a kind of fault localization for programs that have been ported from sequential to parallel architectures or between different parallel architectures. It dynamically compares data between two executing programs, so that can locate errors in the compared programs. In [NBDK96], Netzer et al. have pointed out that unforeseen consequences of bugs can cause messages to arrive in unexpected orders. Their algorithm dynamically locates errors by detecting unintended nondeterminism, or race conditions.

Process grouping [Kra02b, Kun93, SNdK00] is a fundamental technique for scalable visualizing and debugging. DeWiz [Kra02a, Kra02b] aims at identifying closely related processes and reducing the amount of trace data. Given a specific process, DeWiz isolates the related processes according to the accumulated length of transmitted messages.

Thus, a number of tools provide useful debugging functions. However, developers still suffer for selecting the original error from a number of observed errors, including original and propagated errors. Once the original error is given to developers, they can immediately investigate faults by using existing debuggers and concentrate in correcting them.

In this paper, we propose a novel debugging tool, named *MPI-PreDebugger* (MPI-PD), for localizing faulty processes in message passing programs. Current MPI-PD supports programs written using the Message Passing Interface (MPI) standard [Mes94] and focuses on faults that terminate program execution. MPI-PD aims at reducing developers' workloads required for localizing faulty processes in timeline visualization.

To achieve this, MPI-PD dynamically checks communication errors in accordance with the error definition in a program execution model. If MPI-PD observes any communication errors, it then generates a trace file, backtraces communication dependencies and points out potentially faulty processes in a timeline view. Thus, MPI-PD reduces the amount of debugging information before developers visualize and investigate it by using performance debuggers and source-level debuggers.

The rest of this paper is organized as follows. Section 2 formally characterizes communication errors in MPI programs and makes clear the differences among faults, errors, and failures. Section 3 gives an algorithm for localizing faulty processes in a given trace file while Section 4 presents MPI-PD, which implements the proposed algorithm. Section 5 introduces three case studies assisted by MPI-PD. At last, Section 6 concludes this paper.

2 Modeling Behavior of Message Passing Programs

This section shows a definition of communication errors in MPI programs. We define it by extending the program execution model described in [NM92].

2.1 Event graph: program execution model

An execution of a message passing program is defined as a directed graph, $G = (E, \rightarrow)$, where E represents a finite set of *events* while \rightarrow represents the *happened-before relation* [Lam78] defined over E [NM92]. In the following, we call this directed graph the *event graph* [Kra02a].

An event in this context represents the execution instance of a set of consecutively executed statements in some process [NM92]. Any event $e \in E$ is observed during a program execution. In the following, let $e_{p,i}$ be the i^{th} event on process p .

The happened-before relation \rightarrow shows how events potentially affect one another [Lam78]. This relation is defined as the irreflexive transitive closure of the union of two other relations: $\rightarrow = (\overset{S}{\rightarrow} \cup \overset{C}{\rightarrow})^+$. Here, $\overset{S}{\rightarrow}$ and $\overset{C}{\rightarrow}$ respectively represent the sequential order relation and the concurrent order relation as follows [Kra02a]:

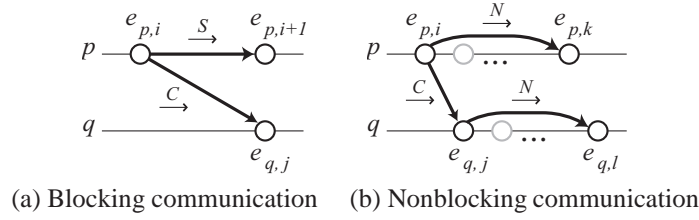


Figure 1: Order relations between events. A node represents an event and an arrow represents a relation.

Sequential order relation, \xrightarrow{S} : As illustrated in Figure 1(a), the sequential order of events, $e_{p,i} \xrightarrow{S} e_{p,i+1}$, defines that the i^{th} event $e_{p,i}$ on any sequential process p occurred before the $i+1^{\text{st}}$ event $e_{p,i+1}$.

Concurrent order relation, \xrightarrow{C} : As illustrated in Figure 1(a), the concurrent order of events, $e_{p,i} \xrightarrow{C} e_{q,j}$, defines that the i^{th} event $e_{p,i}$ on any process p occurred directly before the j^{th} event $e_{q,j}$ on another process q , if $e_{p,i}$ is the sending of a message by process p and $e_{q,j}$ is the receipt of the same message by another process q .

Although the event graph is a sufficient model for visualizing the behavior of message passing programs, we have to add one relation to this graph to characterize the errors relevant to nonblocking communications [Mes94]. This additional relation exists between a pair of events caused by the initiation and the completion of a nonblocking send/receive operation:

Nonblocking order relation, \xrightarrow{N} : As illustrated in Figure 1(b), the nonblocking order relation, \xrightarrow{N} , shows the order in which nonblocking messages are initialized and then completed: $e_{p,i} \xrightarrow{N} e_{p,k}$ defines that $e_{p,i} \xrightarrow{S} e_{p,k}$, if $e_{p,i}$ is the send/receipt initiation of a message by process p and $e_{p,k}$ is the completion of the same message by the same process p .

In our extended event graph, the happened-before relation is redefined as $\rightarrow = (\xrightarrow{S} \cup \xrightarrow{C} \cup \xrightarrow{N})^+$.

2.2 Fault, error, and failure

The concepts of faults, errors, and failures [MSR77] used in our discussion are briefly explained as follows: a program with a bug has a fault in itself and an active fault causes an error. If the error fails to be corrected, it causes a failure.

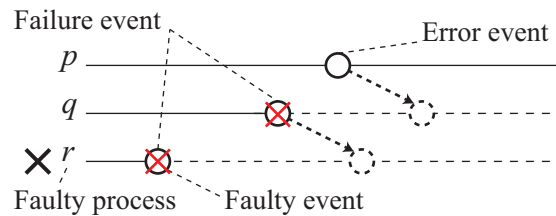


Figure 2: Fault, error, and failure events. While a crossed node represents an unexpectedly terminated event, a dotted node represents expected but non-occurred event.

Figure 2 shows an example that interprets these three concepts on events. In this example, process r is the faulty process, since it executes a faulty statement and causes a faulty event. It also terminates against developer's intension, so that causes a failure event. After this, process q fails to pass a message to process r , so that causes an error event, resulting in a failure event (since it terminates). Process p also faces with a communication error, however, its error handler avoids its failure.

Let $is_failed(e)$ denote whether event e causes a failure or not. Since failure events have no successor and occur when programs unexpectedly terminate, $is_failed(e)$ is defined as follows:

$$is_failed(e) = \text{the program terminated unexpectedly.}$$

2.3 Communication errors in MPI programs

In MPI programs, an event causes a communication error, if it satisfies one of the following two conditions: isolated or truncated, defined as follows;

- *Isolated events.*
 - An event $e_{p,i}$ ($e_{q,j}$) is called an isolated send (receive) event, if $\neg \exists e_{q,j} \in E$ ($e_{p,i} \in E$) such that $e_{p,i} \xrightarrow{C} e_{q,j}$, respectively [Kra02a].
 - An event $e_{p,i}$ ($e_{p,k}$) is called an isolated send/receive initiation (completion) event, if $\neg \exists e_{p,k} \in E$ ($e_{p,i} \in E$) such that $e_{p,i} \xrightarrow{N} e_{p,k}$, respectively.
- *Truncated events.*
 - Two events $e_{p,i}$ and $e_{q,j}$ are called truncated events, if $e_{p,i} \xrightarrow{C} e_{q,j}$ and $len(e_{p,i}) > len(e_{q,j})$, where $len(e_{p,i})$ and $len(e_{q,j})$ represent the length of the send buffer specified in event $e_{p,i}$ and the receive buffer specified in event $e_{q,j}$, respectively.

Isolated events are caused under the following two situations. One is the mismatch of occurred events and the other is the non-occurrence of expected events. First, occurred but mismatched events can trigger off an error propagation. For example, an MPI routine call with an invalid tag/communicator [Mes94] or an invalid source/destination rank fails to pass the intended message. Similar mismatch can occur between the initiation and the completion of a nonblocking send/receive operation. Next, expected but non-occurred events cause serious problems, since they can propagate errors through all processes. For example, if a process terminates before sending an intended message, the receiver process that has no original fault also terminates, since it fails to receive the expected message. Thus, isolated events propagate errors similarly to the domino effect, leading to a program failure.

A pair of truncated events indicates an occurrence of an overflow at the receive buffer. In a strict sense, a message should be passed between the send and the receive operations with the same buffer length [Kra02a]. However, as MPI does, we also permit passing a message between events $e_{p,i}$ and $e_{q,j}$ such that $e_{p,i} \xrightarrow{C} e_{q,j}$ and $len(e_{p,i}) < len(e_{q,j})$. In practice, some nondeterministic applications require this flexibility, because the receiver processes in these applications want to receive a variable length message at one receive operation. Therefore, we permit passing a message between events with different buffer length except for truncated events.

Thus, the error of an event can depend on that of an event on another process. In this paper we call that processes p and q have a *communication dependency* if the error of event $e_{p,i}$ on process p determines that of event $e_{q,j}$ on another process q .

Here notice that MPI has four communication modes [Mes94]: the standard, buffered, synchronous, and ready modes. These modes differ by when they solve the matching of outgoing messages. For example, when two processes send a message to each other, they fall into a deadlock in the synchronous mode while they are deadlock-free in the buffered mode. Therefore, we have to check communication errors without destroying these communication semantics in the target programs. That is, outgoing messages have to be checked in the same mode as their original mode. The error detection mechanism employed in MPI-PD is presented later in Section 4.2.

For collective communications, since they can be implemented by using point-to-point communications, we repeatedly apply the above error definition to all of the point-to-point messages that compose the collective communication.

In the following, let $is_isolated(e_{p,i})$ denote whether event $e_{p,i}$ is isolated event or not. Let $is_truncated(e_{p,i}, e_{q,j})$ also denote whether events $e_{p,i}$ and $e_{q,j}$ are truncated events or not.

3 Algorithm for Localizing Faulty Processes

This section presents the details of our proposed algorithm. We describe how to localize faulty processes in a given event graph. We assume here that the event graph is already generated by the error detection mechanism presented later in Section 4.2.

```

1. Algorithm LocalizeFaultyProcesses( $P, G, P_e, E_e$ )
2.   // Input:  $P$ , a set of process ranks.
3.   //        $G$ , an event graph.
4.   // Output:  $P_e$ , a set of localized faulty process ranks.
5.   //        $E_e$ , a set of failure events on each processes.
6. begin
7.   // (1) Identify failure events occurred on each processes.
8.    $E_e := \emptyset$ ;
9.   foreach ( $p \in P$ ) begin
10.    if  $e_{p,i}$  such that  $is\_failed(e_{p,i}) = true$  exists. then  $fe_p := e_{p,i}$ 
11.    else  $fe_p := null$ 
12.    endif
13.     $E_e := E_e \cup \{fe_p\}$ ;
14.  end
15.  // (2) Localize faulty processes by recursive analysis.
16.   $P_e := \emptyset$ ;
17.  foreach ( $p \in P$ ) begin
18.    if  $(BacktraceCommDep(p, \emptyset) \neq 0)$  then  $P_e := P_e \cup \{p\}$ ;    // Process  $p$  has faults.
19.  end
20. end
21. // A recursive function that backtraces communication dependencies from process  $p$ .
22. function BacktraceCommDep( $p, P_{dep}$ )
23. begin
24.   if  $((p \in P_e) \parallel ((fe_p = null) \&\& (P_{dep} = \emptyset)))$  then return 0;    //  $p$  is already traced or valid.
25.   else if  $(fe_p \text{ is a calculation event})$  then return -1;    // (a) Calculation fault.
26.   else if  $(fe_p = null)$  then return -2;    // (b) Non-occurred event.
27.   else if  $(p \in P_{dep})$  then return  $p$ ;    // (c) Deadlock or (d) Overflow.
28.   endif
29.    $q := ptr(fe_p)$ ;    // Source/destination rank for  $fe_p$ 
30.    $Q_{dep} := P_{dep} \cup \{p\}$ ;    // Update the call history.
31.    $retval := BacktraceCommDep(q, Q_{dep})$ ;
32.   if  $(retval \neq 0)$  then  $P_e := P_e \cup \{q\}$ ;    // Process  $q$  has faults.
33.   if  $(retval = p)$  then  $retval := 0$ ;
34.   else if  $(retval < 0)$  then  $retval++$ ;
35.   endif
36.   return  $retval$ ;
37. end

```

Figure 3: Algorithm for localizing faulty processes.

Figure 3 shows our algorithm, which requires a set of process ranks, P , and an event graph, G , and returns sets of localized faulty processes and the failure events on each process, P_e and E_e , respectively. Our algorithm consists of two stages as follows:

- Identification of failure events (see line 7–14 in Figure 3).
- Localization of faulty processes (see line 15–37 in Figure 3).

At the first stage, the algorithm identifies all failure events. After this stage, it localizes faulty processes by backtracing communication dependencies in a recursive manner. Our algorithm then classifies program failure into the following four situations:

- (a) **Calculation fault:** Figure 4(a) illustrates this situation. As a result of backtracing, our algorithm finds that process s terminates unexpectedly and has no communication dependency to any other processes. Therefore, the algorithm determines that the faulty process is process s , which causes a calculation fault.

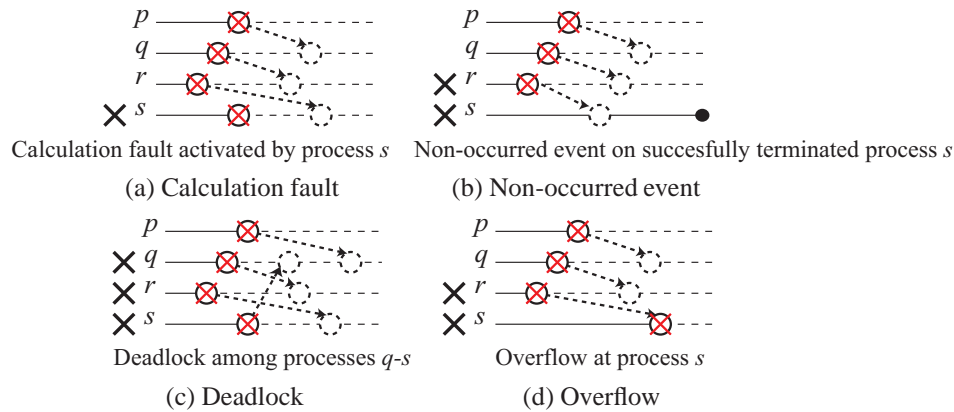


Figure 4: Four failure situations classified by proposed algorithm.

- (b) **Non-occurred event:** Figure 4(b) illustrates this situation, in which process s has a communication dependency from r but terminates successfully. In this situation, we think whether process r could have sent a message redundantly or process s could have missed to call a receive routine. However, it seems to be difficult to automatically identify the faulty process from processes r and s . Therefore, our algorithm determines that the faulty processes are both of processes r and s , or a process left by a normally terminated process and the terminated process.
- (c) **Deadlock:** A deadlock occurs if there exists a cyclic communication dependency. In Figure 4(c), processes q , r and s fall into a deadlock. Our algorithm determines that the faulty processes are all the processes that participate in the deadlock.
- (d) **Buffer overflow:** In Figure 4(d), process s causes a buffer overflow. As same as situation (b), it also seems to be difficult to identify which of processes r and s has called an MPI routine with an invalid buffer length. Therefore, our algorithm determines that the faulty processes are both of processes r and s , which have a pair of truncated events.

Notice that the algorithm described in Figure 3 backtraces communication dependencies by assuming that all the source/destination ranks are valid. Therefore, if a faulty process calls an MPI routine with an invalid source/destination, this algorithm can omit the faulty process from the localized processes. We discuss this problem later in Section 5.1.

4 MPI-PreDebugger

This section presents the details of MPI-PD, including its environment for debugging and its mechanism for run-time error detection.

4.1 Overview of debugging environment

Figure 5 shows the debugging process with MPI-PD. The debugging functions in MPI-PD are implemented using the C++ language and the Ruby-GNOME toolkit [Rub02] and composed of three components: the instrument tool `mpi2pd`, the run-time error detection library `libpdmpi.a`, and the localize and visualize tool `pdview`.

The instrument tool `mpi2pd` automatically replaces all of the MPI routines in programs with instrumented MPI routines based on pattern-match rules. The instrumented routine is a combination of the original MPI routine and the run-time error detection function. After this replacement, developers have to generate the object codes by compiling their programs and the executable binary file by linking the object codes with the run-time error detection library.

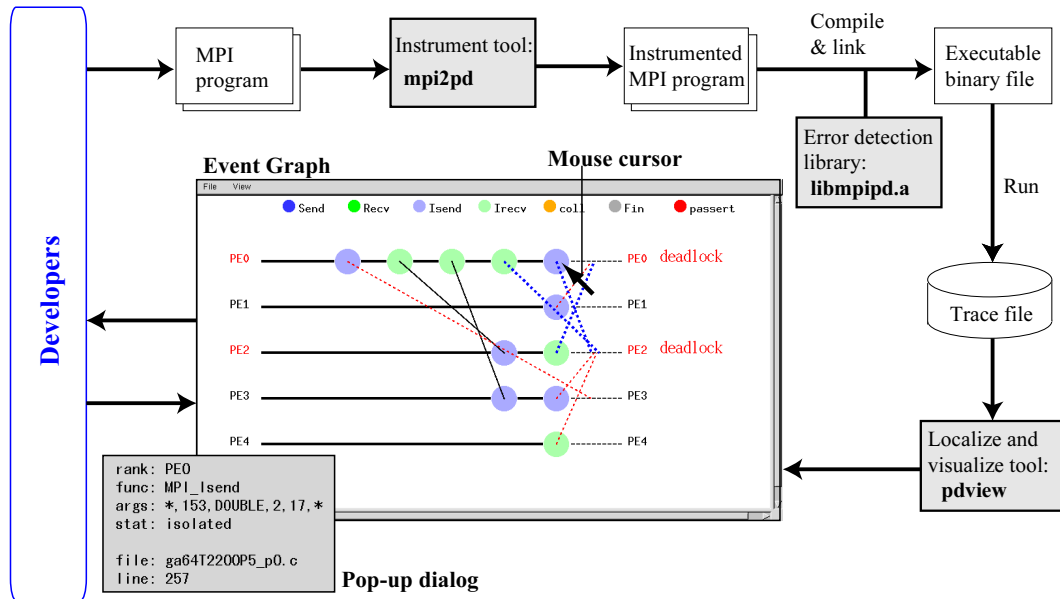


Figure 5: Debugging process with MPI-PD.

The run-time error detection library checks communication errors whenever the processes call the instrumented MPI routines (see Section 4.2). If the library detects any communication error, it terminates program execution and generates a trace file. The trace file has the following information for every event observed during program execution: (1) event number, (2) process rank, (3) corresponding line in source code and its file name, and (4) corresponding MPI routine and its arguments.

Given a trace file, the visualization tool `pdview` allows developers to view the behavior of the terminated program, as shown in Figure 5. It visualizes the event graph, which has the process axis in vertical and the time axis in horizontal, and shows the result of the fault localization described in Section 3. In the event graph, a colored node corresponds to an event and the type of the MPI operation that caused the event decides its color. A solid line between two nodes corresponds to a successful communication while a dotted line corresponds to a failure communication.

In default mode, `pdview` avoids visualizing the entire event graph. It visualizes all of failure events occurred on each process and the successful events occurred directly before the failure events. Furthermore, `pdview` can isolate faulty processes from the event graph. Developers can visualize an isolated event graph by selecting process whichever they want. In addition to these visualization functions, `pdview` also shows following information:

- Faulty processes localized by the proposed algorithm.
- Failure situation selected from four situations (see Figure 4).

Furthermore, developers can investigate every visualized event. If they click the mouse on a node in the visualized event graph, then `pdview` pops up a dialog, which shows information (1)–(4) about the corresponding event and its error reason (isolated/truncated). This information is useful for developers to locate faults in programs. After this fault localization, source-level debuggers can effectively assist developers to investigate the detailed behavior of the localized part.

4.2 Mechanism for run-time error detection

MPI-PD checks the occurrence of communication errors during program execution. If it detects any errors, it generates a trace file.

To realize this, we employ three methodologies. We first discuss on the synchronous blocking send (MPI_Ssend) then others. The three methodologies are as follows:

- **Manager process:** To generate trace files under a deadlock situation, we employ a manager process M_p for every process p . M_p checks the value of $is_failed(e_{p,i})$ before its responsible process p executes event $e_{p,i}$. We present later how to check $is_failed(e_{p,i})$ at next paragraph. If M_p obtains $is_failed(e_{p,i}) = false$, it allows p to execute event $e_{p,i}$ and pushes the information about $e_{p,i}$ into its local Event Graph E_p . Otherwise, it detects a communication error, terminates p and generates a trace file from E_p .
- **Message queue:** To handle nonblocking communications, we employ a message queue. For nonblocking communications, to decide the failure of completion event $e_{p,k}$, we have to refer the information about its corresponding initiation event $e_{p,i}$ ($e_{p,i} \xrightarrow{N} e_{p,k}$). Therefore, for all processes p , manager M_p has its own message queue Q_p for referring to the information about the past events.
- **Timeout mechanism:** We also employ a timeout mechanism due to the difficulty in distinguishing the valid and the invalid computation. For example, a receive event $e_{q,j}$ that never receive a message has to be decided as $is_isolated(e_{q,j}) = true$. However, it is hard for M_q to identify whether the sender p sends the message or not. That is, p can send the message after heavy computation or can fall into an infinite loop. Therefore, M_p holds a timeout time $t(e_{p,i})$ for every $e_{p,i}$ and decides $is_isolated(e_{p,i}) = true$ when the time is up.

Figure 6 shows the process of run-time error detection for MPI_Ssend. In Figure 6, the manager of the sender has three states (states C, S1 and S2) and that of the receiver has four states (states C, R1, R2 and R3) as follows:

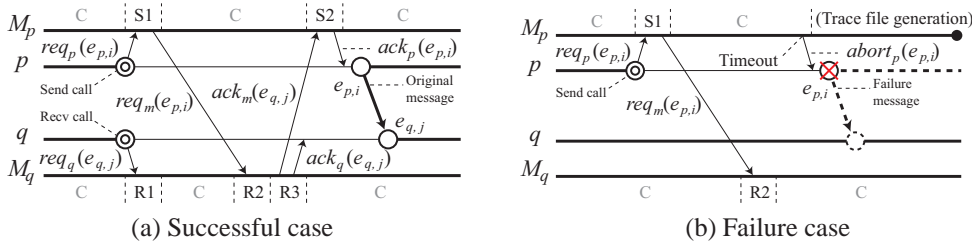


Figure 6: Process of run-time error detection for the synchronous blocking send (MPI_Ssend). Events $e_{p,i}$ and $e_{q,j}$ correspond to MPI_Ssend and MPI_Recv calls, respectively.

Common state for the sender/receiver:

State C: *Timeout checking and control-message waiting.* In this state, M_p continues to check Q_p whether there exist any timeout events, until it receives any control message (ack or request messages) from p or another manager. If M_p detects a timeout event $e_{p,i}$, then it decides $is_failed(e_{p,i}) = true$ and sends an abort request $abort_p(e_{p,i})$ to p . It also adds the failure event $e_{p,i}$ to E_p and terminates. If M_p receives a control message, then it changes its state to an appropriate state.

States for the sender:

State S1: *Send initiating.* If M_p receives a send request $req_p(e_{p,i})$ from p , then it pushes the information about $e_{p,i}$ into Q_p with $t(e_{p,i})$. It also checks the destination rank of $e_{p,i}$ and transmits a send request $req_m(e_{p,i})$ to the destination process's manager, M_q (go to state C).

State S2: *Message sending.* If M_p receives an ack $ack_m(e_{q,j})$ from another manager, then it searches Q_p and selects $e_{p,i}$ such that $is_isolated(e_{p,i}) = false$. It also checks whether $e_{p,i}$ and $e_{q,j}$ are truncated events.

- If $is_truncated(e_{p,i}, e_{q,j}) = false$, M_p decides $is_failed(e_{p,i}) = false$ and sends an ack $ack_p(e_{p,i})$ to p . After this acknowledgement, it deletes $e_{p,i}$ from Q_p , and adds both $e_{p,i}$ and $e_{q,j}$ to E_p (go to state C).
- Otherwise, M_p decides $is_failed(e_{p,i}) = true$ and sends an abort request $abort_p(e_{p,i})$ to p . It also adds both $e_{p,i}$ and $e_{q,j}$ to E_p as failure events and terminates.

States for the receiver:

State R1: *Receive initiating*. If M_q receives a receive request $req_q(e_{q,j})$, it then searches Q_q and selects $e_{p,i}$ such that $is_isolated(e_{p,i}) \vee is_isolated(e_{q,j}) = false$.

- If such $e_{p,i}$ exists, M_q decides that $e_{p,i}$ and $e_{q,j}$ are the matching events (go to state R3).
- Otherwise, it leaves the error detection on $e_{q,j}$ and pushes the information about $e_{q,j}$ into Q_q with $t(e_{q,j})$ (go to state C).

State R2: *Send-request receiving*. If M_q receives a request $req_m(e_{p,i})$ from another manager, then it searches Q_q and selects $e_{q,j}$ such that $is_isolated(e_{p,i}) \vee is_isolated(e_{q,j}) = false$.

- If such $e_{q,j}$ exists, M_q decides that $e_{p,i}$ and $e_{q,j}$ are the matching events (go to state R3).
- Otherwise, it leaves the error detection on $e_{p,i}$ and pushes the information about $e_{p,i}$ into Q_q with $t(e_{p,i})$ (go to state C).

State R3: *Message receiving*. M_q sends an ack $ack_m(e_{q,j})$ to M_p . It then checks if $e_{p,i}$ and $e_{q,j}$ are truncated events.

- If $is_truncated(e_{p,i}, e_{q,j}) = false$, then M_q decides $is_failed(e_{q,j}) = false$ and sends an ack $ack_r(e_{q,j})$ to q . After this acknowledgement, it deletes $e_{q,j}$ ($e_{p,i}$) from Q_q and adds both $e_{p,i}$ and $e_{q,j}$ to E_q (go to state C).
- If $is_truncated(e_{p,i}, e_{q,j}) = true$, then M_q decides $is_failed(e_{q,j}) = true$ and sends an abort request $abort_q(e_{q,j})$ to q . It also adds both $e_{p,i}$ and $e_{q,j}$ to E_q as failure events and terminates.

The manager processes buffer all events until they detect an error, so that their local memory are possibly full. Our algorithm described in Figure 3 requires failure events on each process. Therefore, if local memory of M_p is full, we allow M_p to delete information about the oldest successful event from E_p .

Here, recall that we have to keep the communication semantics, as explained in Section 2.3. Therefore, for the blocking buffered mode send (MPI_Bsend), we alter the sequence of error detection. That is, to keep the buffered behavior of message passing, process p passes the original message immediately after sending request $req_p(e_{p,i})$ to its manager M_p . This alternation omits receiving an ack $ack_p(e_{p,i})$ from M_p . Instead of this omission, p checks an abort message $abort_p(e_{p,i})$ from M_p whenever it calls an instrumented MPI routine. If p receives the abort message $abort_p(e_{p,i})$, it terminates its execution. Otherwise, it continues processing the original routine. This alteration allows p to execute a few events after an original faulty event, however there is no influence on faulty process localization since M_p identifies the faulty event correctly.

For nonblocking communications, we process states S1 and R1 at the send initiation and the receive initiation of nonblocking operations, respectively; and process send acks at the completion of the nonblocking operations. For collective communications, we can apply the same approach as for the blocking mode point-to-point routines, since the collective communications can be implemented by using those point-to-point routines.

Thus, exchanging information about every event among managers enables us to detect communication errors and generate trace files before program failure.

Table 1: Summary of case studies. $|L|$, $|P|$, and $|E|$ represent the numbers of lines, processes, and events, respectively.

Case study	Details of program			Details of trace file	
	Developer	$ L $	Employed MPI routines	$ P $	$ E $
1. Applicability	Beginner	300	Send, Recv, Isend, Irecv, Wait	4	412
2. Scalability	Expert	40,000	Send, Recv, Sendrecv	64	9,774
3. Usability	Compiler	20,000	Isend, Irecv, Waitall	15	253

Table 2: Application results of MPI-PD.

Debugging phase	Number of programs	
	Success	Failure
MPI Program execution	13 of 28	15 of 28
Event graph visualization	15 of 15	0 of 15
Faulty process localization	12 of 15	3 of 15

5 Case Studies: Debugging Message Passing Programs with MPI-PD

In this section we introduce three case studies. The aim of each study is to investigate the effectiveness of MPI-PD from the following point of view:

1. *Applicability*: We investigated what kinds of faults are effective for MPI-PD. To do this, we applied MPI-PD to a few ten of the Gaussian programs developed by MPI beginners (see Section 5.1).
2. *Scalability*: This study shows an example of scalable debugging using MPI-PD. We applied MPI-PD to a parallel rendering program [TIH03] developed by MPI experts on 64 processes (see Section 5.2).
3. *Usability*: We investigated the usability of faulty process localization. To do this, we applied MPI-PD to a complicated program generated automatically by a parallelizing compiler [YTFH02]. We also compared visualization results between proposed MPI-PD and existing TotalView [Etn02] (see Section 5.3).

Table 1 shows a summary of the above studies. In the following, we omit “MPI_”, the prefix of MPI routines, as shown in Table 1.

In these studies we used a PC cluster with 64 symmetric multiprocessor (SMP) nodes. Each node in the cluster has two Pentium III 1GHz processors and connects to a Myrinet-2000 switch [BCF⁺95]. We also employed an MPI implementation, MPICH-GM [Myr02].

5.1 Study 1: Applicability of MPI-PD

In this study, we applied MPI-PD to 28 faulty programs developed by six graduate students through a practice in MPI programming. These programs solve simultaneous equations using Gaussian elimination.

We first executed the programs on our PC cluster and then visualized localization results by using MPI-PD. Table 2 shows the application results at each debugging phase.

At the execution phase, 15 of 28 programs unexpectedly terminated. As we mentioned in Section 1, since current MPI-PD focuses on faults with program failures, it failed to visualize the event graph for the remaining 13 programs that never terminated but returned incorrect results. These programs contain semantic faults such as invalid specifications of operators/variables and invalid writing to message buffers before the completion of nonblocking communications.

At the localization phase, MPI-PD successfully localized faulty processes for 12 of 15 programs while it failed to localize them for the remaining three programs. These three programs have calculation faults activated by all processes at the same statement. Therefore, every process terminated outside the instrumented MPI routines, so that their trace files contained no information about failure events. Thus, MPI-PD failed to localize their faulty processes. However, in these cases, since every process terminates without any communication dependency, error propagation is unable to occur. Therefore, developers have to investigate every process. That is, they have to investigate their programs between the last MPI routine executed in a success and the next MPI routine expected to be executed, especially where the common statements that every process executes.

The 12 programs which MPI-PD successfully localized had a variety of faults classified into following four types. Notice that MPI-PD localized not the faults but the faulty processes which activate them.

- Invalid source/destination rank (six programs).
- Invalid length of message buffer (three programs).
- Calculation fault (two programs).
- Deadlock occurred when passing long messages (one program).

We next confirmed that there was no faulty process omitted from the localized results. For all cases where invalid source/destination ranks were specified, MPI-PD pointed out deadlock processes, including the faulty process. Therefore, the deadlock processes pointed out by MPI-PD can include valid processes, so that there exists a room for improving the accuracy of localization. However, this redundancy was a little problem for the programs applied in this study. Since their faults appear on any number of processes, developers are allowed to scale down the number of processes without missing the activated faults.

5.2 Study 2: Scalable debugging with MPI-PD

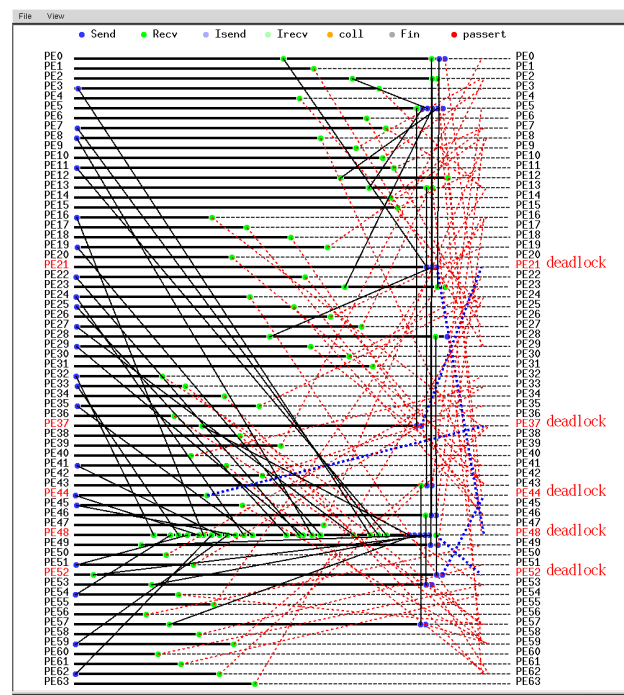


Figure 7: Localized faulty processes in event graph visualized by MPI-PD.

We applied MPI-PD to a parallel rendering program [TIH03] implemented on 64 processes. This program has a fault in gathering and compositing rendered images generated by distributed processors. For the purpose of high-speed compositing, the developers have implemented own collective communication routines for the gather and the broadcast operations by using point-to-point routines, `Send` and `Recv`. Their collective routines are called at every compositing stage with splitting the processes into two groups. That is, given n processes, each of 2^{i-1} groups performs collective communications at the i^{th} stage, where $1 \leq i \leq \log n$.

Figure 7 shows the event graph for all processes visualized by MPI-PD. While the program generates the total of 9,774 events, the visualized event graph is composed of 164 events classified into 64 failure events and 100 successful events occurred directly before the failure events. In Figure 7, MPI-PD points out five faulty processes from 64 processes: processes PE21, PE37, PE44, PE48, and PE52. It also points out that these five processes fall into a deadlock and that each of them has one failure event.

As we mentioned in Section 4.1, MPI-PD allows developers to visualize specific processes whichever they want. For example, developers can view only the deadlock processes as shown in Figure 8, so that easily know how the processes fell into the deadlock. They can also add related processes that communicated to the deadlock processes (see Figure 9), so that intuitively know process PE48 received many messages compared to the other four faulty processes: processes PE21, PE37, PE44, and PE52.

Thus, MPI-PD guided the developers to the five faulty events, so that they easily found that process PE48, the root process of a broadcast operation, called an excessive `Send` routine due to the lack of a `break` statement. Therefore, MPI-PD assists developers in scalable debugging, where the numbers of processes and events are too large for them to understand the behavior of programs.

We also indicate that the buffered send operation makes it complicated to locate faults, since this operation causes a gap between the faulty send event and the failure event. For example, when we executed the rendering program without error detection, since process PE48 pushed out messages in the buffered mode, it successfully returned from the faulty `Send` routine and terminated at a succeeding `Recv` routine. Therefore, without MPI-PD, the developers can investigate the `Recv` routine, which causes a non-original fault, or a fault due to error propagation. Thus, MPI-PD's run-time error detection is necessary for handling the buffered send operation.

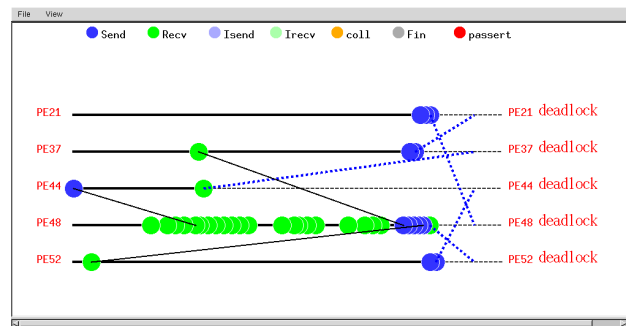


Figure 8: Faulty processes isolated by MPI-PD. This graph shows only faulty processes and communications among them.

5.3 Study 3: Comparison with existing debuggers

To make clear the usability of fault localization, we compared MPI-PD with TotalView [Etn02] by applying them to a complicated program. This program is automatically generated by a parallelizing compiler based on a task scheduling algorithm, Scheduling with Packaged Point-to-point Communications (SPPC) [YTFH02].

The MPI program generated by SPPC consists of two layers, the calculation and the communication layers, which repeatedly appear during program execution. In the calculation layer, each process independently performs calculation without any communication. In the communication layer, it exchanges messages by calling nonblocking communication routines. Each process first calls many initiation routines, `Isend` and `Irecv`, then a completion routine, `Waitall`. Since the parallelizing compiler mechanically generates large-scale MPI

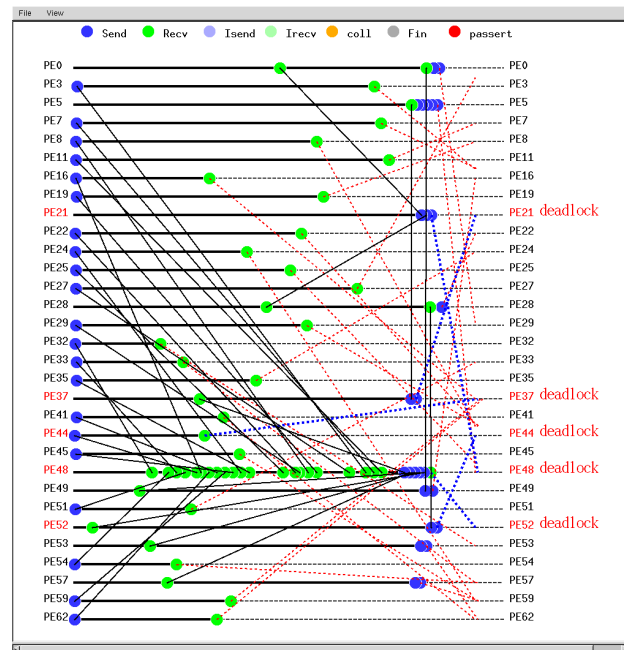


Figure 9: Faulty processes and their related processes isolated by MPI-PD. Related processes are such that faulty processes communicate with them.

programs, it requires a complicated work to debug them. Furthermore, since the `Waitall` routine completes all of initiated communications at a time, it is time-consuming to distinguish failure communications from a number of communications completed by the `Waitall` routine.

Figure 10 shows the visualizations obtained by MPI-PD and TotalView. While MPI-PD visualizes all of failure events occurred on each process and the successful messages occurred directly before the failure events, TotalView shows *pending sends/receives* and *unexpected messages* [CG99, Etn02] at an arbitrary execution step. Pending sends/receives represent the sends/receives that have been initiated but have not yet been matched. Unexpected messages represent messages that have been sent to a process but have not yet been received.

In this program, every process terminated at a call of `Waitall` routine. At the termination, the processes tried to complete the total of 171 nonblocking operations. For this faulty program, TotalView visualizes 50 pending receives, represented as arrows in Figure 10(b). However, it is time-consuming for the developers to investigate each of the 50 pending receives. On the other hand, MPI-PD checks the error of every communication and localizes faulty processes, so that it visualizes 34 of 171 events as shown in Figure 10(a). Since eight of 34 events are successfully communicated events, MPI-PD reduces the number of events that have to be investigated from 171 to 26 events. Furthermore, it points out that processes PE5 and PE10 fall into a deadlock. Here, processes PE5 and PE10 have three and seven error events, respectively, so that the number of events that have to be investigated is reduced further from 171 to 10 events.

With the assistance of MPI-PD, the developer has successfully debugged this program less than five minutes. He first investigated process PE5 and confirmed that it had no fault, and then process PE10. At last, he reached at the fault where an invalid source was specified at an `Irecv` routine.

Table 3 summarizes the difference among MPI-PD, TotalView, and DeWiz [Kra02a, Kra02b]. While MPI-PD is useful to reduce events that have to be investigated, TotalView allows us to execute the target program in stepwise. DeWiz also provides an analysis using the event graph. However, DeWiz aims at identifying closely related processes and reducing the total amount of trace data. In DeWiz, by giving a specific process, then its process grouping function accumulates the length of transmitted messages for every pair of processes and isolates related processes by using a certain threshold. Therefore, developers have to decide which processes have to be specified, and this is a similar problem addressed in this paper. Furthermore, since error propagation

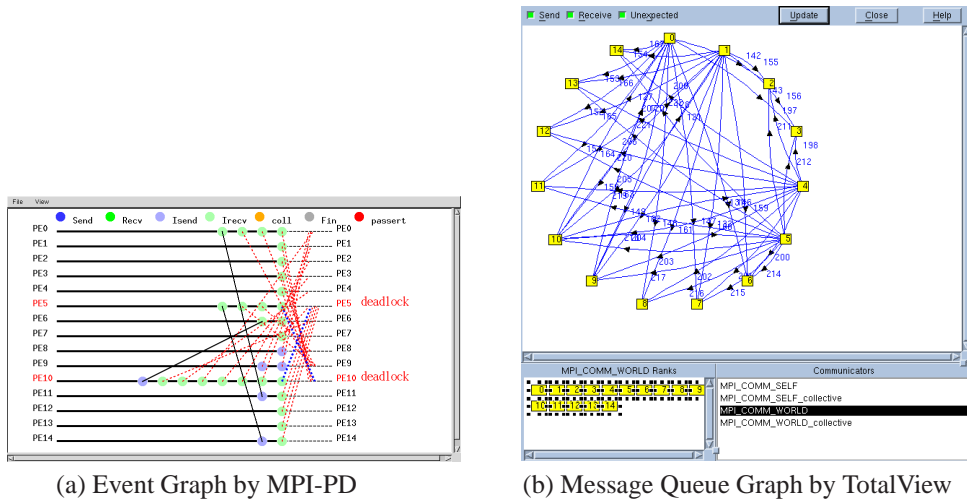


Figure 10: Visualizations obtained by MPI-PD and TotalView.

Table 3: Difference among MPI-PD, TotalView, and DeWiz.

Function	MPI-PD	DeWiz [Kra02a, Kra02b]	TotalView [Etn02]
1. Faulty process localization	by dependency analysis	—	—
2. Run-time error detection	every message	every message	every message
3. Process grouping	by dependency analysis	by message length	—
4. Timeline visualization	yes	yes	—
5. Trace file reduction	—	yes	—
6. Stepwise execution	—	—	yes

has no relevance to message length, their message length based approach is inappropriate for the purpose of faulty process localization.

Summarizing the above discussions, DeWiz is useful to reduce the total amount of trace files and TotalView is useful to investigate the detailed behavior of programs. MPI-PD is useful to reduce the number of events that have to be investigated for debugging. Therefore, we think that appropriate combined use of these tools is a good choice for debugging message passing programs. For example, we first localized faulty processes by using MPI-PD and next investigate them in detail by using TotalView.

6 Conclusions

We have presented a novel debugging tool, named MPI-PD, for localizing faulty processes in message passing programs, aiming at reducing developers' efforts. MPI-PD helps us to identify the source of failure from a number of observed errors by automatically checking communication errors during program execution. If MPI-PD observes any communication errors, it then generates a trace file, backtraces communication dependencies and points out potentially faulty processes in the event graph visualization.

MPI-PD reduces the amount of debugging information before visualizing and investigating it by using post-mortem performance debuggers and source-level debuggers, respectively. Therefore, we think that appropriate combined use of these tools is a good choice for debugging message passing programs.

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