

Advanced MPI and Debugging

Parallel Programming for Engineers

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Advanced MPI and Debugging

Review

Introduction

One-Sided Communication

Profiling Interface

Debugging

Summary

- Which functionality is not used for high-speed networking?
 1. Remote direct memory access
 2. Zero copy
 3. Vectorization
 4. Kernel bypass

- Which functionality is not used for high-speed networking?
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 2. Zero copy
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 4. Kernel bypass

- Which technology improves at the fastest rate?
 1. Storage capacity
 2. Storage throughput
 3. Network throughput
 4. Memory throughput
 5. Computation

- Which technology improves at the fastest rate?
 1. Storage capacity
 2. Storage throughput
 3. Network throughput
 4. Memory throughput
 5. Computation ✓

- When does Amdahl's Law apply?
 1. Fixed problem size
 2. Fixed runtime
 3. Serial portion is smaller than 10 %
 4. Multiple programs, multiple data streams (MPMD)

- When does Amdahl's Law apply?
 1. Fixed problem size ✓
 2. Fixed runtime
 3. Serial portion is smaller than 10 %
 4. Multiple programs, multiple data streams (MPMD)

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 1. Weak scaling
 2. Strong scaling
 3. Both are equally good

- Which scaling behavior is preferable?
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 1. Increase problem size with task count
 2. Increase task count with constant problem size
 3. Increase runtime with constant task count
 4. Decrease problem size with constant task count

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 1. Increase problem size with task count
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- MPI supports basic and complex operations
 - Point-to-point and collective communication
 - Groups, communicators and topologies
 - Environment checks
 - Parallel I/O
- Advanced functionality
 - Dynamic process management
 - Non-blocking collectives
 - Profiling interface
 - One-sided communication

- One-sided communication enables more efficient interaction
 - Optimizations like RDMA, zero copy etc. can be utilized easily
 - One-sided communication is similar to shared memory programming
- Profiling interface gives insight into internals
 - Can be used for performance measurements, debugging etc.
 - Frameworks can hook into the profiling interface (for example, Score-P)

- Dedicated debugging support for parallel applications
 - Deadlocks or race conditions can be hard to find and correct
- Sophisticated optimizations can lead to hard-to-debug problems
 - Parallelization introduces deadlocks and race conditions
 - Traditional languages do not have means to detect problems
- New languages with native support for parallelism
 - Rust can detect data races at compile time due to its ownership concept

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- One-sided communication provides remote memory access (RMA)
 - Can be handled efficiently by appropriate hardware
 - Both Ethernet and InfiniBand support native RDMA
- Point-to-point requires knowledge on both sides
 - For some applications or communication schemes, this might be difficult
 - Only the process doing the accesses might know what data to put where
- Theoretically offers better performance than other communication schemes
 - Other side can continue performing computation during communication

- Functions for basic operations
 - Write: `MPI_Put` and `MPI_Rput`
 - Read: `MPI_Get` and `MPI_Rget`
- More complex functionality is also available
 - Update: `MPI_Accumulate` and `MPI_Raccumulate`
 - Read and update: `MPI_Get_accumulate`, `MPI_Rget_accumulate` and `MPI_Fetch_and_op`
 - Atomic swap: `MPI_Compare_and_swap`
- Blocking or request-based variants
 - R stands for request-based and behaves like non-blocking
 - Request-based calls have to be finished with `MPI_Wait` etc.

- One-sided communication still does not allow access to whole address space
 - In contrast to shared memory, where everything is shared by default
- Memory regions have to be exposed via windows
 - Enables access to specified memory regions within a process
- Two main types of windows
 1. Allocated windows (includes backing memory)
 - Either local or shared memory
 2. Created windows (requires existing backing memory)
 - Either static or dynamic windows

- MPI_Win_create
 - Base: Memory address
 - Size: Memory size
 - Displacement unit: Element size
 - Info: Implementation hints
 - Communicator: Process mapping
 - Window: Exposed memory

```
1 void window_create(void) {
2     MPI_Win win;
3     char str[100];
4     snprintf(str, 100,
5              "Hello from %d\n", rank);
6
7     MPI_Win_create(str,
8                   sizeof(str), 1,
9                   MPI_INFO_NULL,
10                  MPI_COMM_WORLD,
11                  &win);
12     MPI_Win_free(&win);
13 }
```

- MPI_Win_allocate
 - Size: Memory size
 - Displacement unit: Element size
 - Info: Implementation hints
 - Communicator: Process mapping
 - Base: New memory address
 - Window: Exposed memory

```
1 void window_allocate(void) {
2     MPI_Win win;
3     char* str;
4
5     MPI_Win_allocate(100, 1,
6                     MPI_INFO_NULL,
7                     MPI_COMM_WORLD,
8                     &str, &win);
9     snprintf(str, 100,
10             "Hello from %d\n", rank);
11     MPI_Win_free(&win);
12 }
```

- MPI differentiates between public and private memory
 - Public: Exposed main memory, addressable by all processes
 - Private: Caches etc. that are only addressable by the local process
- There are two memory models based on public and private memory
 1. Separate: No assumptions about memory consistency, portable (non-coherent)
 - Changes to public require RMA calls to synchronize to private memory
 2. Unified: Updates to public memory are synchronized to private memory (coherent)
 - Public and private memory are always identical and require no synchronization
 - Without synchronization, data might still be inconsistent while in progress

- MPI_Win_get_attr
 - Window: Exposed memory
 - Key: Attribute to query
 - Value: Pointer to store value in
 - Flag: Whether attribute could be queried
- Create flavor
 - Find out how window was allocated
- Memory model
 - Get information about memory model

```
1 void print_win(MPI_Win win) {
2     int* val;
3     int flag;
4
5     MPI_Win_get_attr(win,
6         MPI_WIN_CREATE_FLAVOR,
7         &val, &flag);
8     print_flavor(*val);
9
10    MPI_Win_get_attr(win,
11        MPI_WIN_MODEL,
12        &val, &flag);
13    print_model(*val);
14 }
```

- MPI_Win_get_attr
 - Window: Exposed memory
 - Key: Attribute to query
 - Value: Pointer to store value in
 - Flag: Whether attribute could be queried
- Create flavor
 - Find out how window was allocated
- Memory model
 - Get information about memory model

```
flavor=create  
model=unified  
flavor=allocate  
model=unified
```

- MPI clearly defines processes involved in RMA communication
 - Origin: Process that performs a call
 - Target: Process that is accessed by a call
- Might lead to unintuitive situations
 - Putting data into another process's memory
 - Source of the data is the origin
 - Destination for the data is the target
 - Getting data from another process's memory
 - Source of the data is the target
 - Destination for the data is the origin

- MPI supports two modes for one-sided communication
 1. Active target communication
 2. Passive target communication
- Active target communication
 - Both origin and target are involved in the communication
 - Similar to message passing where both sides are involved
 - All arguments provided by one process, the other just participates in synchronization
- Passive target communication
 - Only origin process is involved in communication
 - Close to shared memory programming where other threads are not influenced

- Communication calls must happen inside an access epoch
 - Epoch starts with a synchronization call on window
 - Followed by arbitrarily many communication calls
 - Epoch completes with another synchronization call
- Active target communication also has exposure epochs
 - Epoch starts with a synchronization call by target process
 - One-to-one matching of access and exposure epochs
- Passive target communication does not have synchronization on target
 - There also is no exposure epoch

- Two synchronization mechanisms for active target communication
 - `MPI_Win_fence` is a collective synchronization call
 - Starts access and exposure epochs
 - `MPI_Win_start`, `MPI_Win_complete`, `MPI_Win_post` and `MPI_Win_wait` are fine-grained
 - Only communicating processes synchronize
 - `MPI_Win_start` and `MPI_Win_complete` start and stop access epochs
 - `MPI_Win_post` and `MPI_Win_wait` start and stop exposure epochs
- One synchronization mechanism for passive target communication
 - `MPI_Win_lock`, `MPI_Win_lock_all`, `MPI_Win_unlock` and `MPI_Win_unlock_all`

- Every process exposes a window
 - Other processes can write into it and read from it
 - Access is only possible via window
- Put local string into remote memory
 - str should be copied into window

```
1 char str[100];
2 char buf[100];
3
4 MPI_Win win;
5
6 void window(void) {
7     snprintf(str, 100,
8         "Hello from %d\n", rank);
9     MPI_Win_create(buf,
10        sizeof(buf), 1,
11        MPI_INFO_NULL,
12        MPI_COMM_WORLD, &win);
13 }
```

- Passive target communication
 - Lock and unlock necessary
 - Put will be finished after unlock
- MPI_Win_lock
 - Type: Exclusive or shared
 - Rank: Target rank
 - Assert: Optimization hints
 - Window: Exposed memory
- MPI_Win_unlock
 - Rank: Target rank
 - Window: Exposed memory

```
1 void put(void) {
2     MPI_Win_lock(MPI_LOCK_EXCLUSIVE,
3                 (rank + 1) % size,
4                 MPI_MODE_NOCHECK, win);
5     MPI_Put(str, 100, MPI_CHAR,
6            (rank + 1) % size, 0,
7            100, MPI_CHAR, win);
8     MPI_Win_unlock(
9                 (rank + 1) % size, win);
10
11     MPI_Barrier(MPI_COMM_WORLD);
12     printf("%d: %s", rank, buf);
13 }
```

- MPI_Put
 - Origin buffer: Data to put
 - Origin count: Number of elements
 - Origin datatype: Type of elements
 - Target rank: Where to put data
 - Target displacement: Offset in window
 - Target count: Number of elements
 - Target datatype: Type of elements
 - Window: Exposed memory

```
1 void put(void) {
2     MPI_Win_lock(MPI_LOCK_EXCLUSIVE,
3                 (rank + 1) % size,
4                 MPI_MODE_NOCHECK, win);
5     MPI_Put(str, 100, MPI_CHAR,
6            (rank + 1) % size, 0,
7            100, MPI_CHAR, win);
8     MPI_Win_unlock(
9                 (rank + 1) % size, win);
10
11     MPI_Barrier(MPI_COMM_WORLD);
12     printf("%d: %s", rank, buf);
13 }
```

- Ring communication
 - Each process copies string into next process's memory
- Target is not involved
 - Origin locks remote window
 - Afterwards, data is put there

```
$ mpiexec -n 4 ./put
0: Hello from 3
1: Hello from 0
2: Hello from 1
3: Hello from 2
```

- What happens without MPI_Barrier?
 1. The same as with the barrier
 2. buf can be empty
 3. Processes crash
 4. Processes deadlock

```
1 void put(void) {
2     MPI_Win_lock(MPI_LOCK_EXCLUSIVE,
3                 (rank + 1) % size,
4                 MPI_MODE_NOCHECK, win);
5     MPI_Put(str, 100, MPI_CHAR,
6            (rank + 1) % size, 0,
7            100, MPI_CHAR, win);
8     MPI_Win_unlock(
9                 (rank + 1) % size, win);
10
11     MPI_Barrier(MPI_COMM_WORLD);
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- What happens without MPI_Barrier?
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```
1 void put(void) {
2     MPI_Win_lock(MPI_LOCK_EXCLUSIVE,
3                 (rank + 1) % size,
4                 MPI_MODE_NOCHECK, win);
5     MPI_Put(str, 100, MPI_CHAR,
6            (rank + 1) % size, 0,
7            100, MPI_CHAR, win);
8     MPI_Win_unlock(
9                 (rank + 1) % size, win);
10
11     MPI_Barrier(MPI_COMM_WORLD);
12     printf("%d: %s", rank, buf);
13 }
```

- Schema is inverted with get
 - Every process exposes their string
 - Other processes can write into it and read from it
- Get remote string into local memory
 - Window should be copied into buf

```
1 char str[100];
2 char buf[100];
3
4 MPI_Win win;
5
6 void window(void) {
7     snprintf(str, 100,
8         "Hello from %d\n", rank);
9     MPI_Win_create(str,
10        sizeof(str), 1,
11        MPI_INFO_NULL,
12        MPI_COMM_WORLD, &win);
13 }
```

- MPI_Get
 - Origin buffer: Where to get data
 - Origin count: Number of elements
 - Origin datatype: Type of elements
 - Target rank: From where to get data
 - Target displacement: Offset in window
 - Target count: Number of elements
 - Target datatype: Type of elements
 - Window: Exposed memory

```
1 void put(void) {
2     MPI_Win_lock(MPI_LOCK_EXCLUSIVE,
3                 (size + rank - 1) % size,
4                 MPI_MODE_NOCHECK, win);
5     MPI_Get(buf, 100, MPI_CHAR,
6            (size + rank - 1) % size, 0,
7            100, MPI_CHAR, win);
8     MPI_Win_unlock(
9                 (size + rank - 1) % size,
10                win);
11
12     printf("%d: %s", rank, buf);
13 }
```

- Ring communication
 - Each process copies string from previous process's memory
- Target is not involved again
 - Origin locks remote window
 - Afterwards, get operation is performed

```
$ mpiexec -n 4 ./get
0: Hello from 3
1: Hello from 0
2: Hello from 1
3: Hello from 2
```

- Why is no MPI_Barrier used?
 1. It is a bug, barrier is required
 2. Implicit synchronization
 3. Window is small enough

```
1 void put(void) {
2     MPI_Win_lock(MPI_LOCK_EXCLUSIVE,
3                 (size + rank - 1) % size,
4                 MPI_MODE_NOCHECK, win);
5     MPI_Get(buf, 100, MPI_CHAR,
6            (size + rank - 1) % size, 0,
7            100, MPI_CHAR, win);
8     MPI_Win_unlock(
9                 (size + rank - 1) % size,
10                win);
11
12     printf("%d: %s", rank, buf);
13 }
```

- Why is no MPI_Barrier used?
 1. It is a bug, barrier is required
 2. Implicit synchronization ✓
 3. Window is small enough

```
1 void put(void) {
2     MPI_Win_lock(MPI_LOCK_EXCLUSIVE,
3                 (size + rank - 1) % size,
4                 MPI_MODE_NOCHECK, win);
5     MPI_Get(buf, 100, MPI_CHAR,
6            (size + rank - 1) % size, 0,
7            100, MPI_CHAR, win);
8     MPI_Win_unlock(
9                 (size + rank - 1) % size,
10                win);
11
12     printf("%d: %s", rank, buf);
13 }
```

- MPI supports accumulate operations
 - Similar to reduce operations in collective communication
- Collect maximum rank across all processes
 - Works like MPI_Reduce with MPI_MAX

```
1  int buf = 0;
2
3  MPI_Win win;
4
5  void window(void) {
6      MPI_Win_create(&buf,
7                    sizeof(buf), 1,
8                    MPI_INFO_NULL,
9                    MPI_COMM_WORLD, &win);
10 }
```

- MPI_Accumulate
 - Origin buffer: Data to accumulate
 - Origin count: Number of elements
 - Origin datatype: Type of elements
 - Target rank: Where to accumulate data
 - Target displacement: Offset in window
 - Target count: Number of elements
 - Target datatype: Type of elements
 - Op: Operation to perform
 - Window: Exposed memory

```
1 void put(void) {
2     MPI_Win_lock(MPI_LOCK_EXCLUSIVE,
3                 0, 0, win);
4     MPI_Accumulate(&rank, 1,
5                  MPI_INT, 0, 0, 1,
6                  MPI_INT, MPI_MAX, win);
7     MPI_Win_unlock(0, win);
8
9     MPI_Barrier(MPI_COMM_WORLD);
10
11     printf("%d: %d\n", rank, buf);
12 }
```

- Maximum is accumulated on rank 0
 - All other processes keep original value
- Accumulated value has to be distributed
 - For instance, using MPI_Broadcast

```
$ mpiexec -n 4 ./accumulate
0: 3
1: 0
2: 0
3: 0
```

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Summary

- Profiling interface allows debugging and performance analysis
 - Function calls can be intercepted and recorded
- Many different MPI implementations exist
 - Source code for a specific implementation may not be available
 - Some are proprietary and cannot be inspected
- Realized via a second set of function names
 - Functions are prefixed with `PMPI_` instead of `MPI_`

- Can also be used for other purposes
 - For instance, choose different functions from different implementations
- `MPI_Pcontrol` must be provided by implementations
 - Enable or disable profiling, flush buffers etc.
 - Default implementation does nothing
- Implementation
 - Weak symbols: Compiler takes care of symbols
 - Otherwise: Link in correct order (`-lmylib -lmpi -lmpi`)

- Override functions with own definition
 - Compiler calls own definition
 - Weak symbols allow overriding
- Implementation available via PMPI_
 - Easy to cause infinite recursions

```
1  int MPI_Send(const void* buf,
2              int count,
3              MPI_Datatype datatype,
4              int dest, int tag,
5              MPI_Comm comm) {
6      printf("MPI_Send: buf=%p,"
7            " count=%d, datatype=%d,"
8            " dest=%d, tag=%d,"
9            " comm=%d\n", buf, count,
10             datatype, dest, tag, comm);
11     return PMPI_Send(buf, count,
12                      datatype, dest, tag, comm);
13 }
```

- Override functions with own definition
 - Compiler calls own definition
 - Weak symbols allow overriding
- Implementation available via PMPI_
 - Easy to cause infinite recursions

```
1  int MPI_Recv(void* buf, int count,
2              MPI_Datatype datatype,
3              int source, int tag,
4              MPI_Comm comm,
5              MPI_Status* status) {
6      printf("MPI_Recv: buf=%p,"
7            " count=%d, datatype=%d,"
8            " source=%d, tag=%d,"
9            " comm=%d, status=%p\n",
10             buf, count, datatype,
11             source, tag, comm,
12             (void*)status);
13     return PMPI_Recv(buf, count,
14                      datatype, source, tag,
15                      comm, status);
16 }
```

- Override functions with own definition
 - Compiler calls own definition
 - Weak symbols allow overriding
- Implementation available via PMPI_
 - Easy to cause infinite recursions
- Easy to log all parameters
 - Frameworks like Score-P use this
 - Can be visualized with Vampir etc.

```
$ mpiexec -n 2 ./profiling
MPI_Send: [...], count=100, [...],
    ↪ dest=1, tag=0, [...]
MPI_Recv: [...], count=100, [...],
    ↪ source=1, tag=0, [...]
0: Hello from 1
MPI_Send: [...], count=100, [...],
    ↪ dest=0, tag=0, [...]
MPI_Recv: [...], count=100, [...],
    ↪ source=0, tag=0, [...]
1: Hello from 0
```

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- Example: Race condition
 - Incrementing consists of three steps
 1. Loading the variable
 2. Modifying the variable
 3. Storing the variable
 - Have to be performed atomically

```
1  static int counter = 0;
2
3  void* thread_func(void* data) {
4      (void)data;
5
6      for (int i = 0; i < 1000; i++) {
7          counter++;
8      }
9
10     return NULL;
11 }
```

- Example: Race condition
 - Incrementing consists of three steps
 1. Loading the variable
 2. Modifying the variable
 3. Storing the variable
 - Have to be performed atomically

T0	T1	V
Load 0		0
Inc 1		0
Store 1		1
	Load 1	1
	Inc 2	1
	Store 2	2

- Example: Race condition
 - Incrementing consists of three steps
 1. Loading the variable
 2. Modifying the variable
 3. Storing the variable
 - Have to be performed atomically

T0	T1	V
Load 0		0
Inc 1		0
Store 1		1
	Load 1	1
	Inc 2	1
	Store 2	2

T0	T1	V
Load 0		0
Inc 1	Load 0	0
Store 1	Inc 1	1
	Store 1	1

- Example: Race condition
 - Incrementing consists of three steps
 1. Loading the variable
 2. Modifying the variable
 3. Storing the variable
 - Have to be performed atomically
- Two new error classes
 1. Deadlocks
 2. Race conditions

T0	T1	V
Load 0		0
Inc 1		0
Store 1		1
	Load 1	1
	Inc 2	1
	Store 2	2

T0	T1	V
Load 0		0
Inc 1	Load 0	0
Store 1	Inc 1	1
	Store 1	1

- Deadlocks cause parallel applications to stop progressing
 - Can have different causes, most often due to locking
 - May not be reproducible if there is time-dependent behavior
- Error condition can be difficult to find
 - Trying to lock an already acquired lock results in a deadlock
 - Erroneous communication patterns (everyone waits for the right neighbor)
- Error effect is typically easy to spot
 - Spinlocks or livelocks can look like computation, though



- Race conditions can lead to differing results
 - Debugging often hides race conditions
- Error condition is often very hard to find
 - Can be observed at runtime or be found by static analysis
 - Modern programming languages like Rust can detect data races
- Error effect is sometimes not observable
 - Slight variations in the results are not obvious
 - The correct result cannot be determined for complex applications
 - Repeating a calculation can be too costly

- Access to counter is not synchronized
 - Race condition results in wrong value
- Output is non-deterministic
 - Depends on timing, scheduling etc.
 - Output is sometimes correct
- Compiler cannot help
 - Developer has to spot error manually

```
1  static int counter = 0;
2
3  void* thread_func(void* data) {
4      (void) data;
5
6      for (int i = 0; i < 1000; i++) {
7          counter++;
8      }
9
10     return NULL;
11 }
```

- Access to counter is not synchronized
 - Race condition results in wrong value
- Output is non-deterministic
 - Depends on timing, scheduling etc.
 - Output is sometimes correct
- Compiler cannot help
 - Developer has to spot error manually

```
$ ./race
counter=10000
$ ./race
counter=9753
$ ./race
counter=10000
$ ./race
counter=10000
$ ./race
counter=9244
```

- Helgrind is part of Valgrind
 - Detects synchronization errors in C, C++ and Fortran
 - Supports POSIX threads
 - Also works with OpenMP but output can be confusing
- Supports three classes of errors
 1. Misuse of POSIX threads API
 2. Lock ordering problems
 3. Data races
- Helgrind analyzes memory access
 - Happens-before dependency graph

```
$ valgrind --tool=helgrind ./race
Helgrind, a thread error detector
[...]
Possible data race during read of
    ↪ size 4 at 0x404038 by thread #3
Locks held: none
    at 0x401157: [...]

This conflicts with a previous write
    ↪ of size 4 by thread #2
Locks held: none
    at 0x401160: [...]
Address 0x404038 is 0 bytes
    ↪ inside data symbol
    ↪ "counter"
```

- Thread sanitizer can detect thread bugs
 - Data races
 - Races on mutexes, file descriptors, barriers etc.
 - Destroying locked mutexes
 - Signal-unsafe behavior
 - Potential deadlocks
 - ... and more
- Sanitizers are offered by the compiler
 - Can instrument code at compile time
 - Instruments memory access instructions

```
$ ./race-sanitize
=====
WARNING: ThreadSanitizer: data race
    Read of size 4 at 0x000000404068
        ↳ by thread T2:
    #0 [...]

    Previous write of size 4 at
        ↳ 0x000000404068 by thread T1:
    #0 [...]

    Location is global '<null>' at
        ↳ 0x000000000000
        ↳ (...+0x000000404068)
```

- Mutex is locked but never unlocked
 - Application hangs immediately
 - No output is produced
- Reason can be hard to determine
 - Check stack traces with GDB
 - thread apply all bt
 - Unwieldy with many threads
 - Difficult to determine whether deadlocked or progressing

```
1 static int counter = 0;
2 static pthread_mutex_t mutex =
3     PTHREAD_MUTEX_INITIALIZER;
4
5 void* thread_func(void* data) {
6     (void) data;
7
8     for (int i = 0; i < 1000; i++) {
9         pthread_mutex_lock(&mutex);
10        counter++;
11    }
12
13    return NULL;
14 }
```

- Mutex is locked but never unlocked
 - Application hangs immediately
 - No output is produced
- Reason can be hard to determine
 - Check stack traces with GDB
 - thread apply all bt
 - Unwieldy with many threads
 - Difficult to determine whether deadlocked or progressing
- Helgrind will show held locks

```
$ valgrind --tool=helgrind ./dead
Helgrind, a thread error detector
[...]
Thread #2: Exiting thread still
    ↪ holds 1 lock
    at 0x4877EA0: [...]
```

- Lock ordering might lead to deadlocks
 - Relevant if multiple locks are involved
 - Locking should occur in same order
- Example
 - Thread 0 locks `m[0]`
 - Thread 1 locks `m[1]`
 - Thread 0 tries to lock `m[1]`
 - Thread 1 tries to lock `m[0]`

```
1 void* thread_func(void* data) {
2     uint64_t id = (uint64_t)data;
3     int j = id % 2;
4     int k = (id + 1) % 2;
5
6     for (int i = 0; i < 1000; i++) {
7         pthread_mutex_lock(&m[j]);
8         pthread_mutex_lock(&m[k]);
9         counter++;
10        pthread_mutex_unlock(&m[k]);
11        pthread_mutex_unlock(&m[j]);
12    }
13
14    return NULL;
15 }
```

- Lock ordering might lead to deadlocks
 - Relevant if multiple locks are involved
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- Example
 - Thread 0 locks `m[0]`
 - Thread 1 locks `m[1]`
 - Thread 0 tries to lock `m[1]`
 - Thread 1 tries to lock `m[0]`
- Helgrind can detect lock order problems

```
$ valgrind --tool=helgrind ./lock
Thread #3: lock order "0x4040A0
    ↪ before 0x4040C8" violated

Observed (incorrect) order is:
    ↪ acquisition of lock at
    ↪ 0x4040C8
followed by a later acquisition of
    ↪ lock at 0x4040A0

Required order was established by
    ↪ acquisition of lock at
    ↪ 0x4040A0
followed by a later acquisition of
    ↪ lock at 0x4040C8
```

- Lock ordering might lead to deadlocks
 - Relevant if multiple locks are involved
 - Locking should occur in same order
- Example
 - Thread 0 locks `m[0]`
 - Thread 1 locks `m[1]`
 - Thread 0 tries to lock `m[1]`
 - Thread 1 tries to lock `m[0]`
- Helgrind can detect lock order problems
- Thread sanitizer works as well

```
$ ./lock-sanitize
WARNING: ThreadSanitizer:
    ↪ lock-order-inversion
    ↪ (potential deadlock)
Cycle in lock order graph: M9
    ↪ (0x0000004040c0) => M10
    ↪ (0x0000004040e8) => M9
Mutex M10 acquired here while
    ↪ holding mutex M9 in thread
    ↪ T1:
#0 [...]
Mutex M9 acquired here while
    ↪ holding mutex M10 in
    ↪ thread T2:
#0 [...]
```

- MPI problems are harder to debug
 - Application is distributed across several nodes
 - Application is split into many processes
- There are debuggers for parallel applications
 - Arm DDT (part of Arm Forge, formerly Allinea DDT)
 - TotalView
 - Eclipse Parallel Tools Platform (PTP)
- Another approach is static analysis
 - MPI-Checker can analyze MPI applications
[Droste et al., 2015] [Alexander Droste, 2024]

- Non-blocking functions require waiting
 - Otherwise, it is not clear when buffer can be reused
 - MPI_Wait is missing
- Errors might be hard to observe
 - Works correctly most of the time
 - Behavior is timing-dependent and non-deterministic

```
1 void mysend(char* str, char* buf) {
2     MPI_Request req;
3
4     MPI_Isend(str, 100000, MPI_CHAR,
5              (rank + 1) % size,
6              0, MPI_COMM_WORLD, &req);
7     MPI_Recv(buf, 100000, MPI_CHAR,
8              (size + rank - 1) % size,
9              0, MPI_COMM_WORLD,
10             MPI_STATUS_IGNORE);
11
12     printf("%d: %s", rank, buf);
13 }
```

- Path-sensitive checks
 - Clang's static analyzer (LLVM 3.9)
 - Double non-blocking without wait
 - Missing wait for non-blocking operations
 - Waiting without non-blocking call
- Abstract syntax tree checks
 - Clang-Tidy (LLVM 4.0)
 - Type mismatches when communicating
 - Incorrect referencing of buffers

```
$ scan-build -enable-checker
↳ optin.mpi.MPI-Checker mpicc
↳ -std=c11 -Wall -Wextra
↳ -Wpedantic isend.c -o isend
isend.c:15:2: warning: Request
↳ 'req' has no matching wait.
↳ [optin.mpi.MPI-Checker]
MPI_Recv(buf, 100000, MPI_CHAR,
^~~~~~
1 warning generated.
```

Advanced MPI and Debugging

Review

Introduction

One-Sided Communication

Profiling Interface

Debugging

Summary

- MPI has support for basic and complex operations
 - Point-to-point and collective communication involved multiple processes
 - One-sided communication only involves one process at best
- MPI's profiling interface allows instrumenting the implementation
 - Can be used for debugging and performance analysis
- Parallel debugging is more complicated than normal debugging
 - Race conditions and deadlocks can be timing-dependent and non-deterministic
 - MPI applications are distributed and therefore harder to handle

References

[Alexander Droste, 2024] Alexander Droste (2024). **MPI-Checker**.

<https://github.com/0ax1/MPI-Checker>.

[Droste et al., 2015] Droste, A., Kuhn, M., and Ludwig, T. (2015). **MPI-checker: static analysis for MPI**. In Finkel, H., editor, *Proceedings of the Second Workshop on the LLVM Compiler Infrastructure in HPC, LLVM 2015, Austin, Texas, USA, November 15, 2015*, pages 3:1–3:10. ACM.

[Message Passing Interface Forum, 2015] Message Passing Interface Forum (2015). **MPI: A Message-Passing Interface Standard Version 3.1**.

<https://www.mpi-forum.org/docs/mpi-3.1/mpi31-report/mpi31-report.htm>.