

# User-Level Socket-Based Checkpointing for Distributed and Parallel Computation

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## Abstract

We present a preliminary description of a user-level checkpointing package, DMTCP, for Linux. The socket-based approach presents a novel method for checkpointing distributed processes. This includes checkpointing of any dynamically created POSIX threads and forked child processes. It also includes checkpointing of remotely spawned processes via *ssh* and other mechanisms. As with all user-level checkpointing, no modification of the kernel is needed, and the application code is not modified. The package also checkpoints signal handlers, ordinary file descriptors, socket descriptors, and certain other types of file descriptors. Each checkpointed process has an associated checkpoint file. Hence, process migration, and even migration of an entire computation to a new cluster, are achieved through the simple expedient of copying checkpoint files to a new host. However, process migration adds the additional restriction that the source and destination host must be homogeneous.

## 1 Introduction

The growing size of computations is leading to ever larger distributed computations. In 2005, more than half of the Top500 supercomputers [Top] surpassed 1,000 processors, and multi-cluster computations are becoming more common. Such large computations are likely to see a node failure every day. Hence, checkpointing of distributed computations is now becoming almost a necessity.

A package for coordinated checkpointing a multi-process, multi-threaded, distributed computation is presented. Such issues as open file descriptors, signal handlers, and memory-mapped segments are also supported. The package is based on Linux. In order to ease the job of porting

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to other dialects of UNIX, most of the software is based on POSIX, with some exceptions that are explicitly noted. We also inherit the multi-threaded checkpointing capability of MTCP [RAC06].

There has been a great deal of work on user-level checkpointing. Much of this work divides into two broad categories. Some packages provide user-level checkpointing for a single process or process group on a single processor [ASSB99, CLH<sup>+</sup>99, DJ01, LTBL97, PBKL95, RAC06, ZM03, ZCZX05]. Other packages provide user-level distributed checkpointing for particular dialects of MPI [BBC<sup>+</sup>02, CG96, GCD<sup>+</sup>02, KOW97, SSBL05, Ste96, ZWZ05, ZSK04], although there is often a restriction that the application be single-threaded. One mixture of the two approaches checkpoints master-worker computations by checkpointing the master process, along with some auxiliary information [CAM06].

The novelty of this paper is user-level distributed, multi-threaded checkpointing that is not restricted to MPI applications. By basing our user-level approach on sockets, we gain additional flexibility. For example, a node of a distributed computation may take advantage of such system services as the forking of a child process, or spawning a remote processes via *ssh*. The new local or remote process will then automatically be checkpointed at the time of the next checkpoint. This is an important advantage, since a MPI-specific checkpointing strategies would not allow a node to make calls to *fork* or to invoke *ssh*, since the new processes would be unknown to MPI, and so would not be checkpointed.

Our sockets-based approach is motivated by the need to checkpointing general scientific problem-solving environments. Examples of this are SciLab [Sci] (open source, component-based platform for numerical computation), SAGE [SAG] (component-based Software for Algebra and Geometry Experimentation), and packages that call on MPI-based PETSc [BBG<sup>+</sup>01] as a subprocess.

The approach of this paper is easily generalized to capture other distributed mechanisms. For example, checkpointing can propagate to remote processes through mechanisms other than *ssh*, such as *gsissh* for the Globus protocols and the Grid. In addition, the method of process hijacking [ZML99] could be adapted to further extend this mechanism.

Sockets also provide an efficiency advantage over MPI-based library-level checkpointing. Our checkpointing package need only drain the kernel network buffers prior to checkpointing. In many applications, the kernel buffers are much smaller than the MPI buffers. In such cases, system calls to *read* and *write* will terminate sooner (with a return condition such as EINTR or EAGAIN). This allows checkpointing to begin sooner.

Periodically, the checkpoint control process sends a message to a checkpoint manager thread in each user process. The checkpoint manager thread then uses signals to gain control of other threads prior to checkpointing. By basing our method on sockets, we are also able to quickly checkpoint as soon as the kernel socket buffer (typically on the order of kilobytes) has been drained. In contrast, an MPI-based approach would have to wait for the full application message to be sent, which could be megabytes.

Section 2 describes checkpointing as it appears to the user. Section 3 describes how DMTCP is initialized, and how it propagates to other local and remotely spawned process. Section 4 then describes the underlying single-process MTCP checkpointing, upon which DMTCP depends. Section sec:dmtcpExtensions then describes how DMTCP extends MTCP in order to support dis-

tributed checkpointing. Section 6 describes the implementation issues encountered in implementing DMTCP.

## 1.1 Review of Primary Checkpointing Strategies.

The central problem of checkpointing is to checkpoint the full state of a process: both the user-space memory and the associated kernel state of a process. There are three primary strategies for achieving this goal. They differ according to whether their strategy is to modify the behavior of the kernel, the application, or the library. This paper describes a library-based approach. The traditional system-level and user-level description of implementations corresponds to modifications of the kernel behavior and of the library behavior. Before continuing, we review the three primary strategies.

1. *system-level*: The kernel is modified, perhaps through kernel modules. When a checkpoint request is generated, the kernel participates by saving associated kernel state along with the user-space memory.
2. *user-level*: Neither kernel nor application code is modified. A view of the associated kernel state of the process is maintained in user-space memory through wrappers around calls to the system libraries and through the proc filesystem. For this reason, we also sometimes refer to this as *library-level checkpointing*. When a checkpoint request is generated, all of user-space memory is saved. The associated kernel state information is included in user-space memory.
3. *application-level*: The application is modified, typically by adding code to declare which application data structures should be saved. When a checkpoint request is generated, the designated application data structures are saved.

System-level checkpointing has the advantage of complete access to kernel data structures. It has the disadvantage that the checkpointing package must be continually updated as kernel data structures change.

User-level checkpointing has the advantage of providing the least burden to application writers. Neither kernel modifications nor application modifications are required. Additionally, by using only the standard API to the kernel (system calls and the proc filesystem), the implementation gains greater stability. The disadvantage is that with neither detailed kernel nor application information, a user-level checkpointing solution may also save onto disk unused information, with consequences for space and speed of checkpointing.

Application-level checkpointing has the advantage of saving only those portions of the application that the application writer deems necessary. This saves space, which is an important consideration in distributed computations, with their multiple processes. A disadvantage is the greater burden on the application writer to determine which data structures are required after restart.

## 1.2 Related Work

Examples of user-level checkpointing were provided in the introduction. Plank et al. [PBKL95] present an early example of single-process user-level checkpointing. Eduardo Pinheiro presents Epckpt [Pin], an early example of system-level checkpointing, upon which several other checkpointing projects are also based on EPCKPT. Bronevetsky et al. present application-level checkpointing packages both for distributed memory using MPI [BMPS03] and for shared memory using OpenMP [BMP<sup>+</sup>04]. A notable distributed, system-level solution is provided by Laadan et al. [LPN05]. Additional system-level checkpointing packages are referenced at [checkpointing.org](http://checkpointing.org) [Che], although not all of those packages work with the latest kernel.

In general, a problem of system-level checkpointing is that it requires modification of the kernel, while application-level checkpointing requires modification of the application source code. Hence, the system-level approach must be updated when the kernel is updated, while the application-level approach requires additional effort by the application writer. An application-level approach has the advantage of saving space, since the application writer specifies which data structures need to be checkpointed. A user-level or system-level approach can regain some of that benefit by providing an application hook by which the application declares regions of memory that can be excluded from checkpointing.

Such job management systems as LFS and PBS currently have hooks to support third-party checkpointing software. However, they do not currently checkpoint general, distributed computations. The LAM (as of version 7.0) implementation of MPI provides hooks to single-process checkpointing packages, in order to enable distributed checkpointing of MPI computations. It is not clear how easily LAM supports multi-threaded user applications.

Operating system features such as hibernation and software-suspend are related to checkpointing, but present substantially different technical issues. For example, there is no need to distinguish between user-space and kernel-space state.

Process migration is also related to checkpointing, but is potentially simpler [IvdLH<sup>+</sup>00, LTBL97, Ope]. A common process migration strategy is to maintain a stub process in place of the original process, and the system calls of the migrated process will be intercepted and passed on to the stub process, which provides appropriate virtualization services. This is the core of the strategy used by the ground-breaking system, Condor [LTBL97].

## 2 Checkpointing from the User Viewpoint

The package in this paper is called Distributed MTCP (DMTCP), where MTCP is the package Multi-Threaded CheckPointing [RAC06]. From the user's point of view, its invocation is as simple as typing

```
checkpoint ./a.out
```

Child processes and remote processes created through *ssh* are then automatically checkpointed. These processes are known as *dependent processes*. Periodically, the checkpoint control process

signals all threads of the original process, and all threads of each dependent process. Currently the SIGUSR2 signal, but this is user-configurable. A draft POSIX standard suggests a new signal for the future: SIGCKPT.

Within the signal handler, all application threads save their thread-specific context and wait for the checkpoint to finish. The checkpoint manager thread then drains the kernel socket buffers. The checkpoint manager thread also creates one checkpoint file per process, using the MTCP mechanism.

Each checkpoint file includes information about the open sockets of that process, and the destination of that socket, as a TCP address. Sockets in the UNIX domain are replaced by IP domain sockets. Hence, local processes may be migrated into remote processes upon restart. The current version does not handle pipes, but this is expected to be remedied in the next version.

In order to restart, the user executes:

```
restart checkpoint_file
```

Currently, this must be executed once for each checkpointed process, on each processor where checkpoint files exist. A future version will write a single file `a.out.ckpt.sockets` for the original checkpointed process, and use that information to discover and restart all dependent processes, including remote ones. Prior to restarting, one may move a checkpoint file to a new processor, providing the source and destination processors are homogeneous. That process will then restart on the new processor, with all restarted socket connections appropriately redirected. This feature allows the user to easily migrate a single process to a new processor, or even migrate the processes of an entire cluster to a new cluster.

### 3 DMTCP Initialization and Propagation to All Dependent Processes

DMTCP initially gains its thread of control when the user types `checkpoint a.out`. The C++ checkpoint utility sets the environment variable `LD_PRELOAD` associated with the Linux dynamic linker. After setting this and a few other environment variables (such as setting `LOAD_LIBRARY_PATH`, the search path for the run-time checkpointing library `mtcp.so`), the `checkpoint` utility execs to the application program. Hence, the `checkpoint` launcher and the application program have the same process id. Since child processes inherit environment variables, they automatically gain the same benefits as the original process. Hence, all child local dependent processes of a checkpointed process are also checkpointed.

Hence, the `checkpoint` utility is little more than a wrapper for

```
LD_PRELOAD=DMTCP_PATH/dmtcphi jack.so a.out
```

This causes the dynamic library `dmtcphi jack.so` to be loaded prior to execution of `a.out`. The library `dmtcphi jack.so` includes code for initialization of a global object in a C++ program. This global initialization in `dmtcphi jack.so` runs prior to any invocation of the *main* routine of the application binary.

Child processes created through *fork* (or indirectly through *fork*, via a call to *system*) will inherit the environment variable, and so DMTCP will gain initial control to initialize its checkpointing prologue. The *exec* family of system calls does not change the environment variables, and so DMTCP continues to gain initial control. (The system calls *execle* and *execve* are exceptions to this, since they specify their own environment variable. This case could be handled by wrappers.)

Invocations of dependent processes via *ssh* (or *gsissh* in the case of the Globus protocols for the grid) are handled similarly. This case is important since most implementations of MPI on UNIX use this mechanism. The creation of a local child process, *ssh*, allows DMTCP to gain control. DMTCP can inspect its command line argument (for example through the *proc* interface, */proc/self/cmdline*), and then invoke *ssh* again via *execvp*, but with a new command line, such as: `ssh checkpoint a.out`.

## 4 Outline of Checkpoint/Restart Algorithm for MTCP

We first review the behavior of MTCP (single process, multiple threads).

To detect new threads MTCP provides a wrapper for the libc function for the Linux system call *clone*. This wrapper sets up checkpointing for this thread and then calls the original version of *clone* which has been included as part of *mtcp.so*. If the user's program is statically linked to libc.a then *clone* can not be replaced dynamically and checkpointing will fail. To checkpoint this type of program, the program must be recompiled so that the wrapped symbol for *clone* is dynamically linked to *mtcp.so* during recompilation. In this special situation we would need access to the object modules of the application.

### Steps of Checkpointing

1. Signal all threads with SIGUSR2 (configurable)
2. All threads go into our signal handler, which checkpoints thread state (thread local storage, registers/signals (*getcontext*)) and waits until checkpoint complete
3. Save all memory segments (*proc* filesystem), file descriptor state (from *proc* filesystem and *lseek*), and signal state
4. Wake all threads and return to user code

### Steps of Restart

1. Reloads *mtcp.so* from the checkpoint file into its original address in memory
2. Switch to a temporary stack (by setting the stack pointer) local to the restored *mtcp.so*
3. Unmaps all memory except the restored *mtcp.so*

4. Remaps all segments from the checkpoint file to their original locations
5. Restore file descriptor and signal state
6. Restart all user threads and restore thread local storage (TLS) and registers (setcontext)

Item 1 can fail if the original location of `mtcp.so` is in use in the restart program. For example, the address of `mtcp.so` in the original checkpointed application may conflict with the new address of `libc.so` in the `mtcp_restart` application.

We next consider some details of startup of DMTCP for distributed checkpointing.

### DMTCP Application runtime

1. At start time the environmental variable `LD_PRELOAD` is set to `dmtcphijack.so`.
2. An initialization function, `dmtcp :: DmtcpWorker :: DmtcpWorker`, in `dmtcphijack.so` is called by the dynamic loader before main. This `DmtcpWorker` is the constructor for a global object defined in C++.
3. This function `DmtcpWorker` does the following:
  - (a) Connects to the `dmtcp_master` server.
  - (b) Loads `mtcp.so` using `dlopen`.
  - (c) Sets up MTCP to call the DMTCP callbacks.
  - (d) Initializes MTCP by calling `mtcp_init` with `dlsym`.
4. All calls to `clone` are intercepted via a wrapper function defined in `mtcp.so`. The wrapper function calls the original implementation, which has been included in `mtcp.so`. This wrapper sets up checkpointing for each new thread. Put new thread in thread table. Set signal stuff.
5. All calls to `socket`, `connect`, `bind`, `listen`, `accept`, and `setsockopt` are intercepted via wrapper functions defined in `dmtcphijack.so`. The wrapper function calls the original implementation in `libc.so` using `dlopen` and `dlsym`. These wrappers privately record the state of all open sockets. On connect a DMTCP handshake is performed transparently before control of the socket is handed to the application. This handshake allows the server end of the sock to know a unique DMTCP process identifier, which will be used at restart time to reconnect processes which may have moved to new computers.
6. MTCP maintains a manager thread which periodically checkpoints. When MTCP is run without DMTCP, this thread simply sleeps. When running under DMTCP, this behavior is moved to a callback function in DMTCP which waits for a checkpoint signal from the `dmtcp_master` process.

## 5 Extension of MTCP to Support Distributed Checkpointing

DMTCP is designed around wrappers for POSIX calls related to sockets. It is based on MTCP [RAC06]. *MTCP* provides a system for multi-threaded checkpointing of a single node. we expand this to an entire cluster. When MTCP starts, it spawns a checkpointing thread. Periodically this checkpointing thread will use signals to gain control of all other threads in the process. It then systematically saves all memory, registers, thread local storage (TLS), and file descriptor state to disk. At restart time, MTCP unmaps all memory of the process except a small restore segment. It then proceeds to remap all of memory to look like the original process. Then it uses, the system call, *clone()* to spawn threads to restore each of the original process threads.

To extend MTCP in a modular manner we introduced three hooks to which new functionality can be attached. They are in the form of callback function pointers passed to MTCP before initialization.

1. *callback\_sleep\_between\_checkpoints*, is called when MTCP wants to wait for the next checkpoint time. In MTCP this would just be a *sleep(n)*, but in our package it will trigger a communication with the checkpoint master server to wait for the next checkpoint time.
2. *callback\_pre\_checkpoint* is called by MTCP after it has gained control of all process threads but before it writes out the checkpoint file. This gives DMTCP an opportunity to save socket state.
3. *callback\_post\_checkpoint* is called after a checkpoint and after a restore, but before user threads are resumed. This callback gives DMTCP the opportunity to restore sockets and perform synchronization.

Aside from these three callbacks MTCP remains completely unmodified, thus allowing parallel development.

In order to keep track of user sockets, we create wrapper functions around various socket-related system calls. We create these wrappers by defining our own versions of these functions, which in turn use *dlopen* and *dlsym* to call the system implementations. The system calls for which we define wrappers are *socket*, *connect*, *bind*, *listen*, *accept*, and *setsockopt*. Monitoring the user's calls to these functions allow us to keep an internal table of all open sockets in the user's process. The system calls *close* and *shutdown* are not monitored, since the proc filesystem already allows us to reliably detect if a socket is still active.

We have also created a program called *dmtcp\_master*. This is the central controller for an entire cluster of checkpointed applications. It periodically coordinates a checkpoint and coordinates the restore process after a checkpoint. Checkpointing occurs in phases, with a barrier between phases. The barrier synchronization is handled by the DMTCP master. The phases are: running normally, suspended (where all user threads are stopped), checkpointed (after a checkpoint), and running normally again.



**Suspend phase.** One issue we faced during the suspend phase was to drain all kernel socket buffers. The operating system silently buffers both sends and receives in approximately two kilobyte buffers that are asynchronously emptied and filled. The receive buffer is easy to empty through a nonblocking call to *read*, but the send buffer is trickier. The kernel lumps sends together using Nagle’s algorithm.

There is no direct way to query the state of the send buffer or to empty it. Many of the socket options that could intuitively be used to empty the send buffer fail silently when called on sockets in use.

The DMTCP solution is to drain application sockets prior to writing checkpoint files, and then to retransmit that data after the checkpoint file has been written. In order to drain the socket buffer data, DMTCP causes the sender to send a “magic cookie” through sockets, and on the receive side DMTCP reads or “drains” the data until the magic cookie is found. This ensures that all data in the buffers has successfully reached its destination. To handle the unlikely event of the “magic cookie” also occurring in the user’s data, DMTCP continues trying to read for a short amount of time at the receive end to ensure there is no more data waiting.

After the checkpoint files have been written, the data that was drained from the sockets by DMTCP is sent from the receiver back to the sender, and DMTCP then causes the sender to retransmit it. In a restart situation, this same strategy is followed, but only after the DMTCP restart routine has created new application sockets. Of course in a restart situation, the socket data to resend has been copied from the checkpoint files back into memory, and the resend then proceeds as if DMTCP were resuming execution after a checkpoint.

**File Checkpoint phase.** Once the data from the socket buffers is in user space, the process can be safely checkpointed. At restart time, the socket buffer data will be re-transmitted, thus restoring that data to kernel space.

**Restart.** At restart time, the master maintains a table of all nodes that have been restarted, and all nodes that are “missing.” When a new restarted node comes online, it connects to the DMTCP master and attempts to find the new location of the nodes to which it was connected. If the node it was connected to is not missing, a connection is established. If the node it was connected to is “missing,” then the node waits for the missing node to connect to the master, after which it will be instructed to complete its connections. Once all nodes have been restarted and reconnected, kernel buffers are refilled as described above. The user threads in each application are then restarted, and computation continues. We rely on MTCP to handle the details of restarting user threads, and restoring memory, and open file descriptors.

It is assumed that the original files at the time of checkpointing are present at the time of restarting. If the user has decided to restart on a new processor, the pathname to the original file must also be valid on the new processor.

## 6 Implementation Issues

DMTCP depends on MTCP [RAC06] and inherits some of the same issues, while adding new ones. Because MTCP saves and restores an entire memory image, *libc.so* and other libraries do not need to be reinitialized. Memory segments are also restored at the original address. Because the checkpoint file includes all dynamic libraries, a restart should survive a system upgrade, providing the API to the kernel system calls are the same. It should also survive migration to another Linux 2.6 computer. In part for these reasons, we attempt to restrict ourselves to POSIX system calls. However, MTCP is forced to use *clone* instead of *pthread\_create*, in order to restart a thread and guarantee that it will use its restored thread stack.

All memory segments are detected through the *proc* filesystem, and are checkpointed and restored to their original address. The *proc* filesystem is useful, since memory segments arise in several ways. They are created by application calls to *mmap* and indirectly by calls to *malloc*, which in turn calls *mmap* for large memory requests. Memory segments are also created upon loading dynamic shared libraries.

Other state to be checkpointed includes thread local storage (handled by assembly routines) and signal handlers and floating point registers (saved and restored by *getcontext/setcontext*).

In order to detect the creation by an application of new threads and the location of their thread-local storage (TLS), MTCP creates a dynamic wrapper around the Linux-specific system call, *\_clone*, found in *libc.so*. However, if the application writer had linked statically with *libc.a*, a dynamic library wrapper will not work. To get around this, MTCP takes the unusual step of disassembling certain the *\_clone* routine and then re-assembling them inside a dynamic shared library, *mtcp.so*. (The use of *syscall* to create a wrapper around a system call from *libc.a* was pioneered by Condor [LTBL97]. However, this is not an option for us, since it would require re-compilation of the application in order to link our own static library prior to *libc.a*.)

Application calls to *pthread\_create* in Linux are eventually directed to *\_clone*. Dynamic library wrappers around *\_clone* are created using *dlopen* and *dlsym*. We also rely on the system include files, *asm/segment.h* and *asm/ldt.h*, for a specification of the global descriptor tables and the format of data in the thread-local tables so that they can be saved and restored. The thread-specific data structures are unknowingly passed by the application as arguments to a seven-argument call to *\_clone*.

We currently support only 32-bit Linux, although a port to 64-bit Linux is planned. One issue plaguing 32-bit implementations is the use of address space randomization [SPP<sup>+</sup>04] on recent 32-bit Linux kernels. Since MTCP restores the original memory image, the use of *exec-shield* is not a problem. However, randomizations to the *vdso* of *linux-gate.so* have been added in Linux 2.6.17 for security reasons. While this feature can be manually turned off, MTCP is being upgraded to work with the *vdso* modification.

According to POSIX, upon a call to *fork*, only the calling thread is required to exist in the child process. This is indeed the behavior of Linux. Hence, after an application forks, we must gain control of the child process to create a new checkpoint manager thread. This is done by creating a wrapper around *fork*.

We must also regain control of a process after a call to *exec*. However, since *LD\_PRELOAD* is part of the environment, this latter case is handled automatically. Similarly, calls to *system* are handled automatically due to *LD\_PRELOAD*.

Remote process spawning through *ssh* and similar calls is handled easily because *LD\_PRELOAD* causes us to gain control of *ssh* before its main routine begins executing. If we detect an *ssh* process, we examine the command line through */proc/self/cmdline* in the *proc* filesystem. Given a call *ssh . . . COMMAND*, we then invoke a new subprocess, *ssh env LD\_PRELOAD=dmtcp-hijack.so COMMAND*. Although checkpointing of remote shells is not currently supported, it is easy to add this capability.

Ideally, *getpid*, *getppid*, *kill*, *setpgid*, *setsid* and related calls should be virtualized so as to translate between the current process id and the pre-restart process id. This is not currently done. Similarly, the system calls *stat*, *fstat*, and *lstat*, along with other path and filesystem-related issues are not virtualized. It is also assumed that the user id and group id of the process are the same before and after restart. Additionally, resource limit modifications due to *setrlimit* are not currently restored.

Data from file descriptors or socket descriptors must be safely sent to disk or the remote processes before checkpointing. We use *fsync* for file descriptors. We flush kernel socket buffer data as described in the suspend phase in Section 5.

File and socket descriptors must be restored upon restart. In the case of file descriptors, the file offset is restored on restart. If the file is open read-only, then it is assumed that the file data has not been changed. If the file is open for writing, then the file data from the beginning of the file to the current file offset should not have been changed since checkpoint. Furthermore the continuing computation should not depend on data beyond the current offset. This is motivated by the most typical usage case, in which the application sequentially writes, and the file offset is always at the end of the file.

Upon restart, UNIX domain sockets are “promoted” to TCP domain sockets. This enhances the ability to migrate a single process to a new host, but it can also incur a performance penalty. UDP domain sockets are currently not handled, since they are rarely used in computation-intensive programs.

Shared file and socket descriptors after a fork are an important outstanding issue for DMTCP. DMTCP does not currently restore the parent-child relationship among processes, although this is intended for a future version. Hence, for the interim, it is currently not possible for DMTCP to recreate shared file and socket descriptors.

This is also an issue for pipes. Pipes are not currently handled. Until we have the capability to restore parent-child relationships, we intend to convert pipes into socketpairs upon restart. This will promote pipe descriptors into socket descriptors. Until this is implemented, *popen* also will not work.

The semantics of *shared* file descriptors are seldom needed, and so shared file descriptors are currently restored as distinct file descriptors. Shared socket descriptors present a more subtle issue. They often arise through a call to *socketpair* and they have two common usage patterns. In one usage pattern, a socket connection may have been created before a fork as a “loopback” socket.

The same process both sends and receives to itself.

In the second usage pattern, a socket is used for one- or two-way communication between a parent and child process. Commonly, application writers neglect to close the socket not being used by the parent or by the child. The puzzle for DMTCP is: which socket is actively used by the parent, and which socket is actively used by the child? If checkpoint occurs immediately after the child process is forked, this becomes an exercise in predicting future usage patterns.

Since DMTCP does not yet implement shared socket descriptors (as part of the parent-child relationship), it takes the conservative approach of converting the two shared socket descriptors into two pairs of distinct socket descriptors — one pair for each process. Furthermore, upon restart, connections are created in an “X” pattern. DMTCP connects socket descriptor 1 on the parent to socket descriptor 2 on the child, and it connects socket descriptor 2 on the parent to socket descriptor 1 on the child. In this usage pattern, the application will then use only one of those connections, according to which socket descriptor is “owned” by which process.

We currently detect modified socket options through a wrapper around *setsockopt*. In the near future, we will do the same for I/O options specified by *ioctl*. In particular, non-blocking sockets and unusual socket buffer sizes are not restored upon restart.

We believe that a checkpoint occurring during a *malloc* operation will correctly restart, but this has not been intensively tested.

The signal *SIGUSR2* is used by DMTCP. Hence, application signal handlers for *SIGUSR2* are not supported. Although the choice of *SIGUSR2* is configurable by DMTCP, some signal is required. A draft POSIX 1003.m standard for checkpointing suggests a new signal, *SIGCKPT*.

The stdin, stdout and stderr file descriptors are typically bound to a particular tty or pseudotty. Typically, this is the controlling terminal. Upon restart, we do not currently reset these file descriptors to the new controlling terminal. This is intended for the next version. A related issue is to virtualize *ctermid*, *ttyname*, and *isatty*.

## 7 Conclusion

A socket-based, user-level checkpointing package for distributed computation, DMTCP, has been demonstrated. DMTCP is based on MTCP, which supports checkpointing of multi-threaded processes. MTCP also restores signal handlers and several types of open file descriptors upon restart. By draining kernel socket buffers at checkpoint time, and then restoring them, DMTCP avoids the excessive delay of draining an entire message at the application level.

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