Implement Checkpointing for Android

(to speed up boot time and development process)

Kito Cheng (程皇嘉) <kito@0xlab.org>

Jim Huang (黃敬群) <jserv@0xlab.org>

Developer, 0xlab

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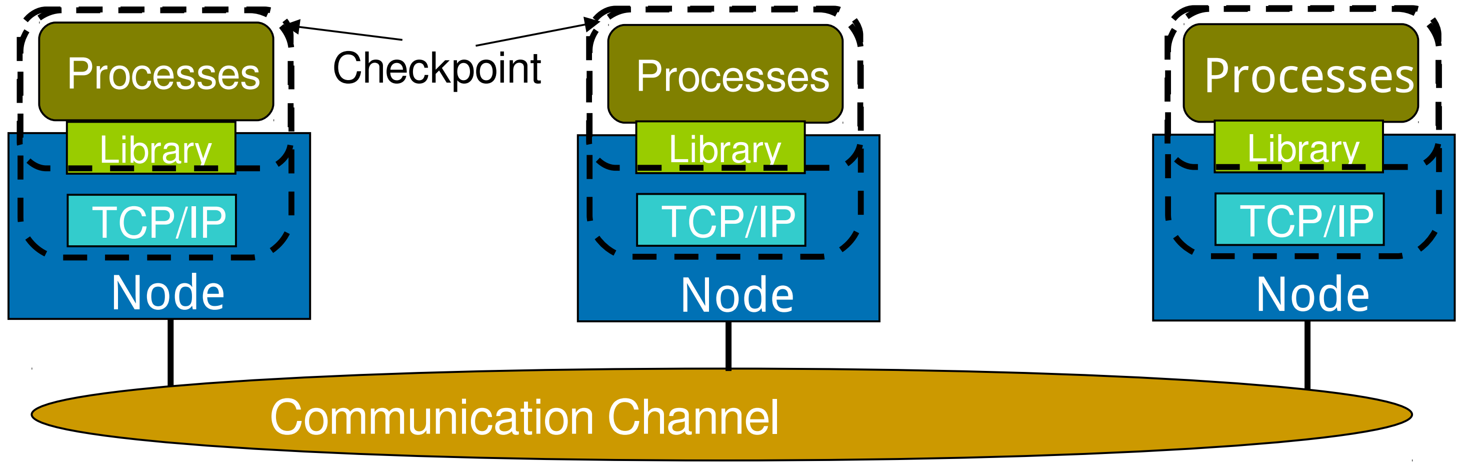
Rights to copy

Basic Idea: Process Migration

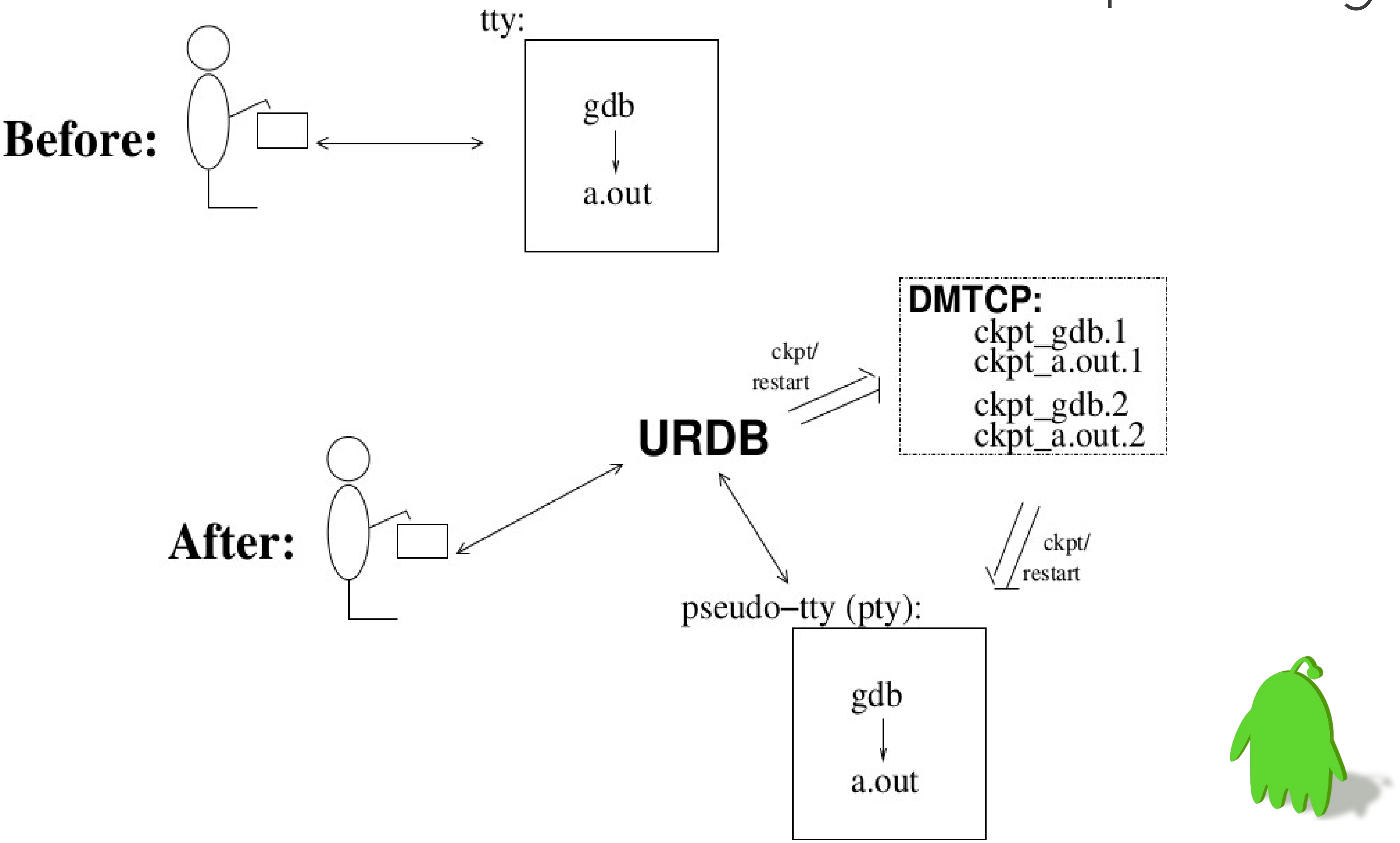
- Process Migration (in past applications)
  - Distributed Load Balancing
  - Efficient Resource Utilization
- Crash Recovery and Rollback Transaction
  - Useful to system admin



Checkpointing

- From Wikipedia:
  - … is a technique for inserting fault tolerance into computing systems. It basically consists of storing a snapshot of the current application state, and later on, use it for restarting the execution in case of failure.
- Used in distributed shared memory systems
- Even used in reversible debugger
- Different from virtual machine level snapshot/resume mechanisms
  - Checkpointing emphasizes on process level.

Reversible Debugger using Checkpointing



Reasons to Implement Checkpointing for Android

- Resume to stored state for faster Android boot time
- Better product field trial experience due to regular checkpointing
- Deploy problematic states for engineering analysis and debugging transparently
- Q&A stress test purpose

Expectations of Checkpointing

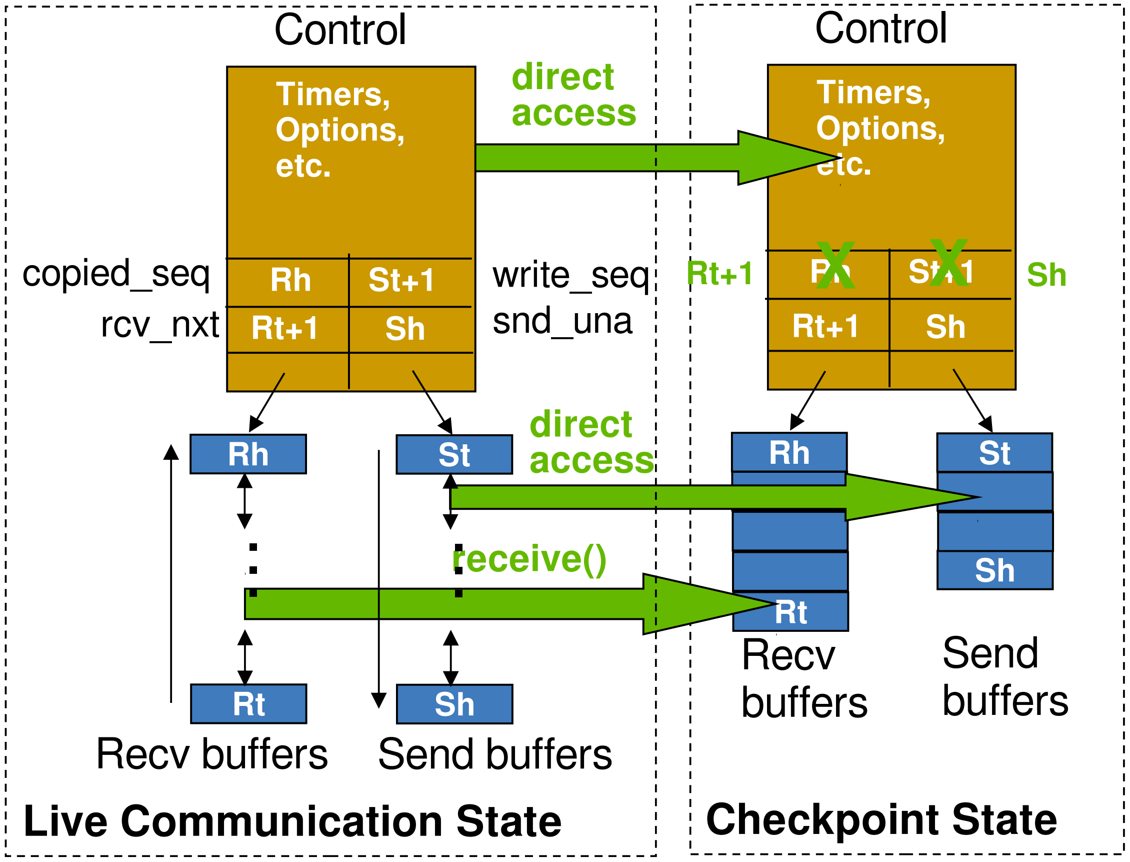
- Application-transparent
  - supports applications without modifications or recompilation
- Supports a broad class of applications
  - Databases
  - parallel / MPI apps
  - desktop apps
- Comprehensive support for user-level state, kernel-level state, and distributed computation and communication state
- Supported on unmodified Linux kernel
  - checkpoint-restart should be integrated by addons

Challenges in checkpoint and restore

- Network stack will continue to execute even after application processes are stopped
- No system call interface to read or write control state
- No system call interface to read send socket buffers
- No system call interface to write receive socket buffers
- Consistency of control state and socket buffer state

Communication state checkpoint

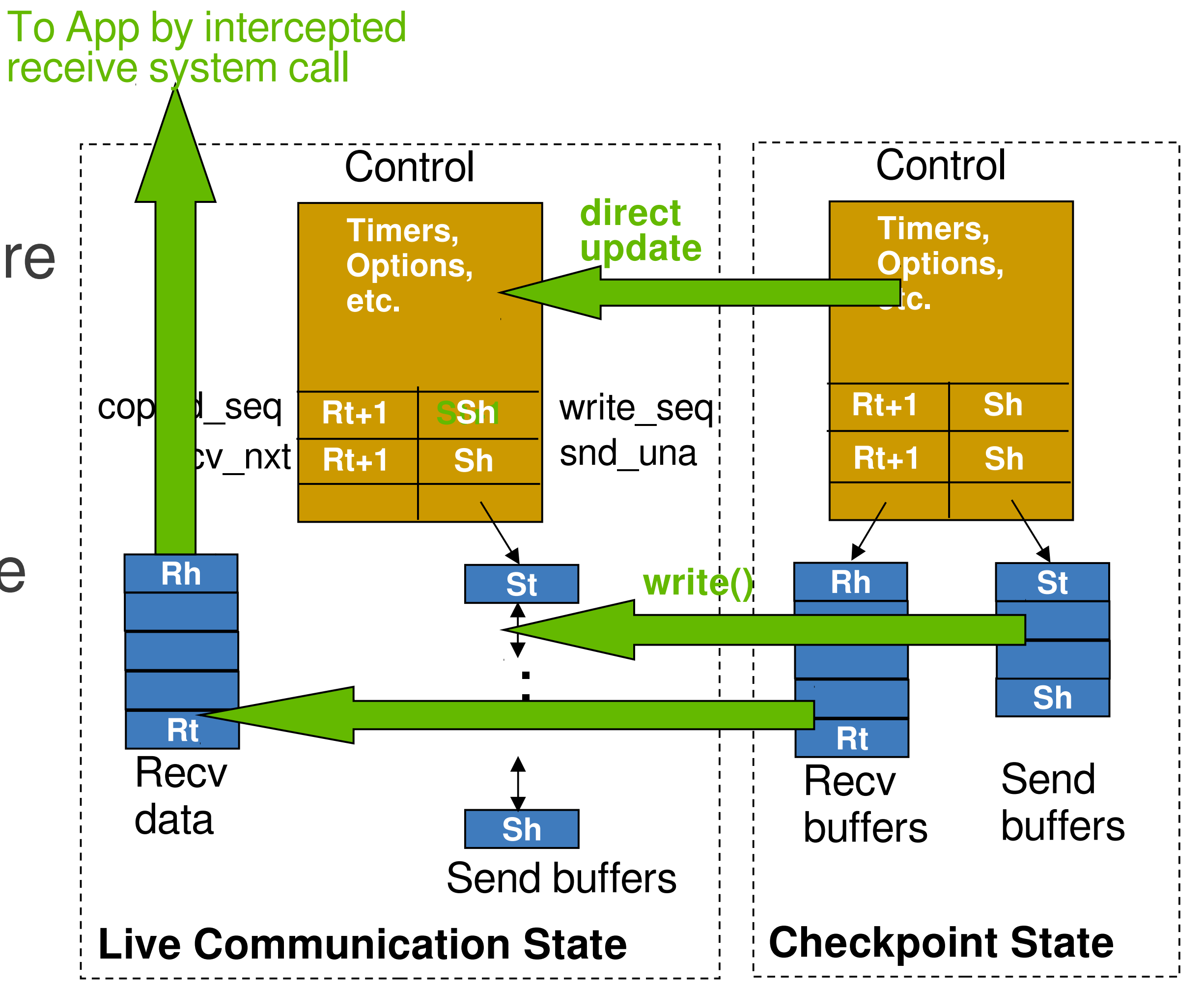
- Acquire network stack locks to freeze TCP processing
- Save receive buffers using socket receive system call in peek mode
- Save send buffers by walking kernel structures
- Copy control state from kernel structures
- Modify two sequence numbers in saved state to reflect empty socket buffers



State for one socket

Communication state restart

- Create a new socket
- Copy control state in checkpoint to socket structure
- Restore checkpointed send buffer data using the socket write call
- Deliver checkpointed receive buffer data to application on demand



State for one socket

Existing Checkpointing mechanisms

- CryoPID
  - http://cryopid.berlios.de/
- BLCR (Berkeley Lab Checkpoint/Restart)
  - https://ftg.lbl.gov/projects/CheckpointRestart/
- DMTCP
  - http://dmtcp.sourceforge.net/

Implementation Considerations

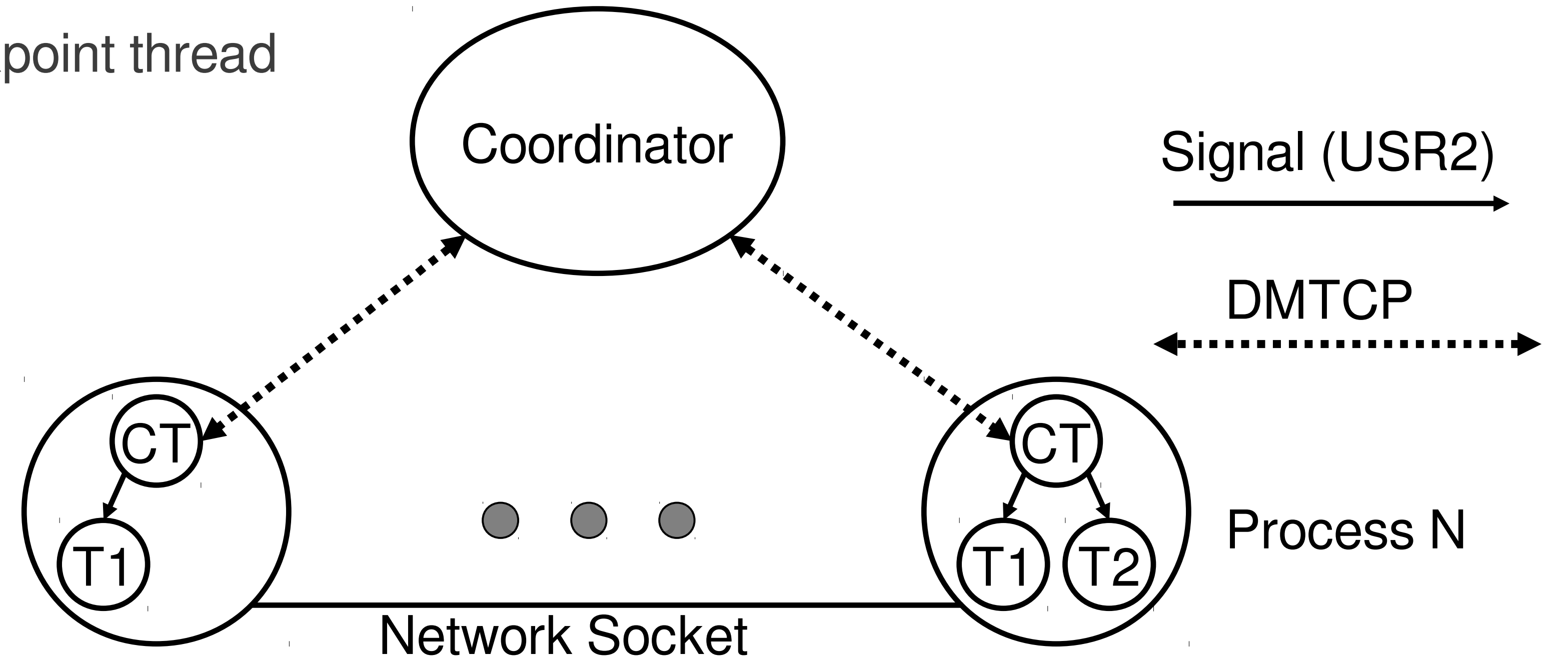
- Checkpointing can be implemented in
  - kernel modifications + helpers in userspace
  - pure userspace
- Introduce a virtualization layer groups processes into specific states with private virtual name space
  - Intercepts system calls to expose only virtual identifiers (e.g., vpid)
  - Preserves resource names and dependencies across migration
- Mechanism to checkpoint and restart states
  - User and kernel-level state
  - Primarily uses system call handlers
  - File system not saved or restored

DMTCP

- **D**istributed **M**ulti-**T**hreaded **C**heck**P**ointing.
- Works with Linux Kernel 2.6.9 and later.
- Supports sequential and multi-threaded computations across single/multiple hosts.
- Entirely in user space (no kernel modules or root privilege).
  - Transparent (no recompiling, no re-linking).
- Written in Northeastern University and MIT and under active development since 2006.
- License: GNU LGPL (allows freely using and linking)

Process Structure

CT = DMTCP checkpoint thread
T = User Thread

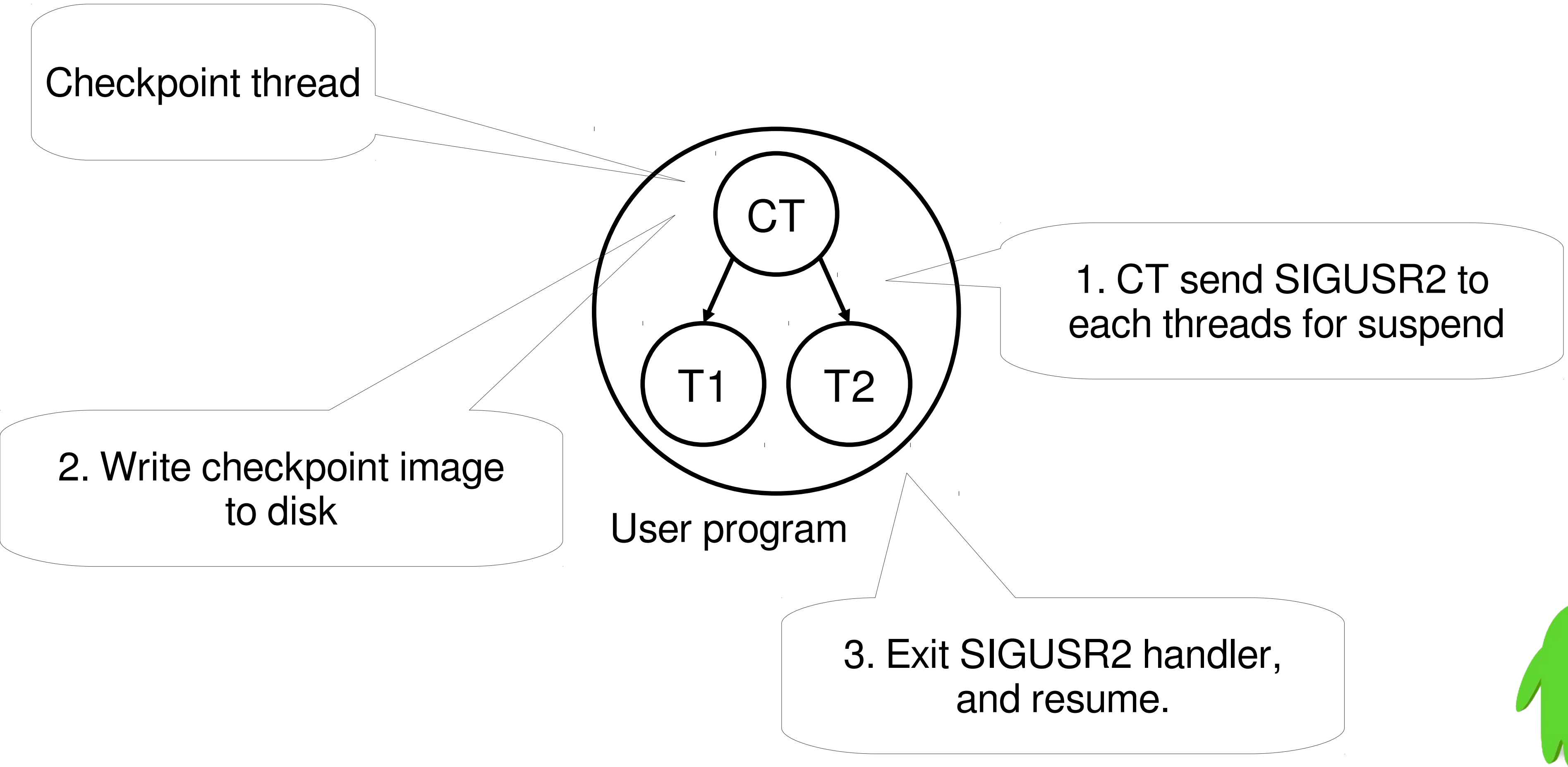


```
dmtcp_checkpoint <EXE> # starts coordinator
dmtcp_command -c       # talks to coordinator
dmtcp_restart ckpt_<EXE>-*.dmtcp
```

- Coordinator: a stateless synchronization server for the distributed checkpointing algorithm.
- Checkpoint/Restart performance related to size of memory, disk write speed, and synchronization.

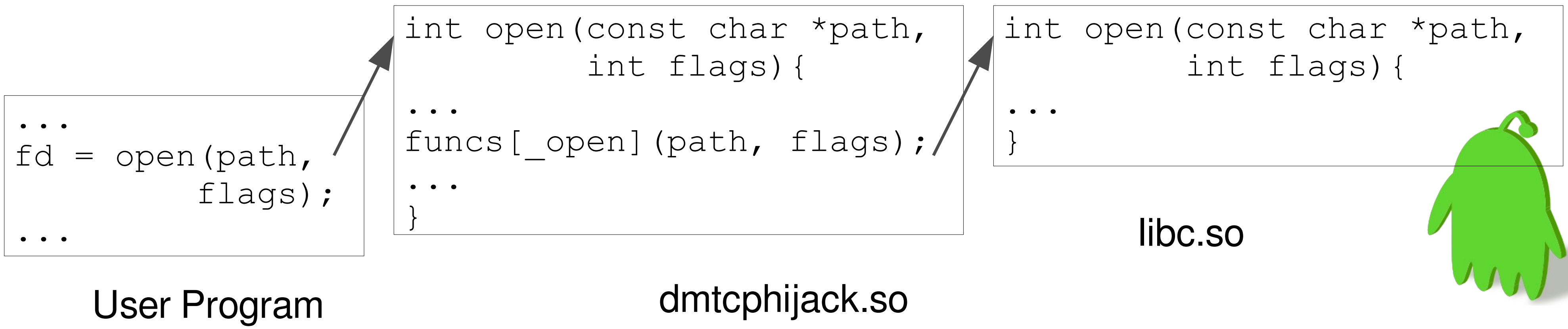
How DMTCP works (1/4)

- MTCP : component for checkpoint single-process
- SIGUSR2: Used internally from checkpoint thread to user threads.


Checkpoint thread
CT
T1
T2
1. CT send SIGUSR2 to each threads for suspend
2. Write checkpoint image to disk
User program
3. Exit SIGUSR2 handler, and resume.

How DMTCP works (2/4)

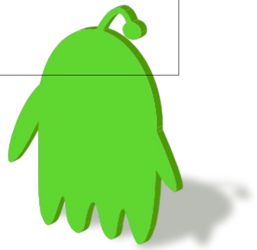
- LD_PRELOAD: Transparently preloads checkpoint libraries \`dmtcphijack.so\` which installs libc wrappers and checkpointing code.
- Wrappers: Only on less heavily used calls to libc
  - `open, fork, exec, system, pipe, bind, listen, setsockopt, connect, accept, clone, close, ptsname, openlog, closelog, signal, sigaction, sigvec, sigblock, sigsetmask, sigprocmask, rt_sigprocmask, pthread_sigmask`
  - Overhead is negligible.



```
...
fd = open(path,
          flags);
...
```

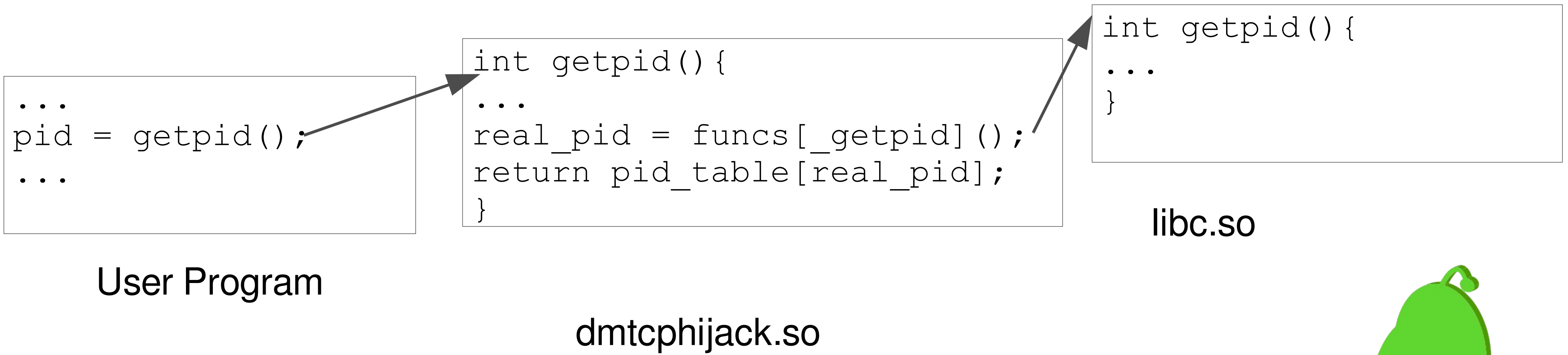
```
int open(const char *path,
         int flags){
...
funcs[_open](path, flags);
...
}
```

```
int open(const char *path,
         int flags){
...
}
```



How DMTCP works (3/4)

- Additional wrappers when process id & thread id virtualization is enabled
  - `getpid, getppid, gettid, tcgetpgrp, tcsetprgrp, getgrp, setpgrp, getsid, setsid, kill, tkill, tgkill, wait, waitpid, waitid, wait3, wait4`



```
...
pid = getpid();
...
```

User Program

```
int getpid(){
...
real_pid = funcs[_getpid]();
return pid_table[real_pid];
}
```

dmtcphijack.so

```
int getpid(){
...
}
```

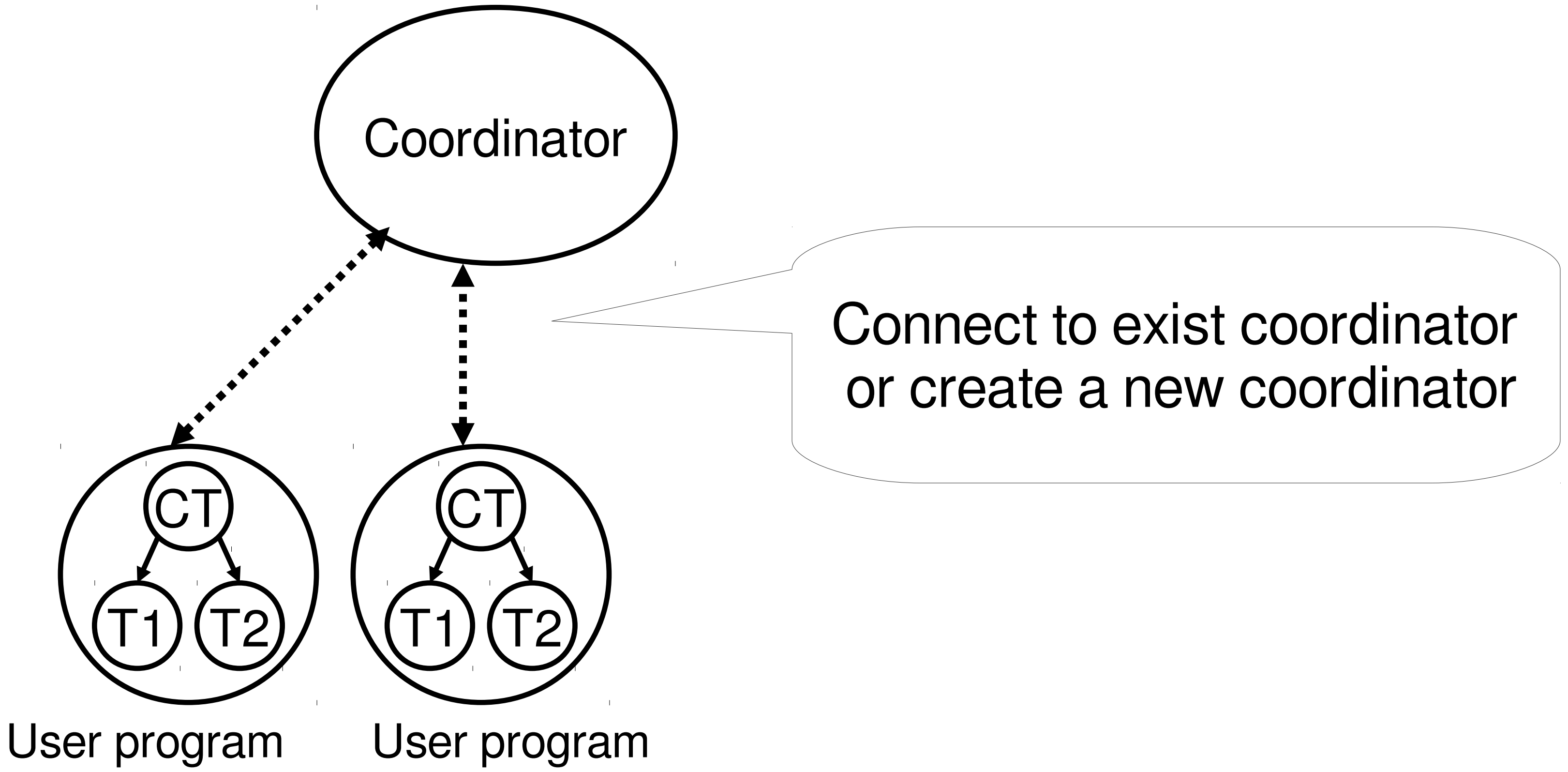
libc.so

How DMTCP works (4/4)

- Checkpoint image compression on-the-fly (default).
- Currently only supports dynamically linking to libc.so. Support for static libc.a is feasible, but not implemented.

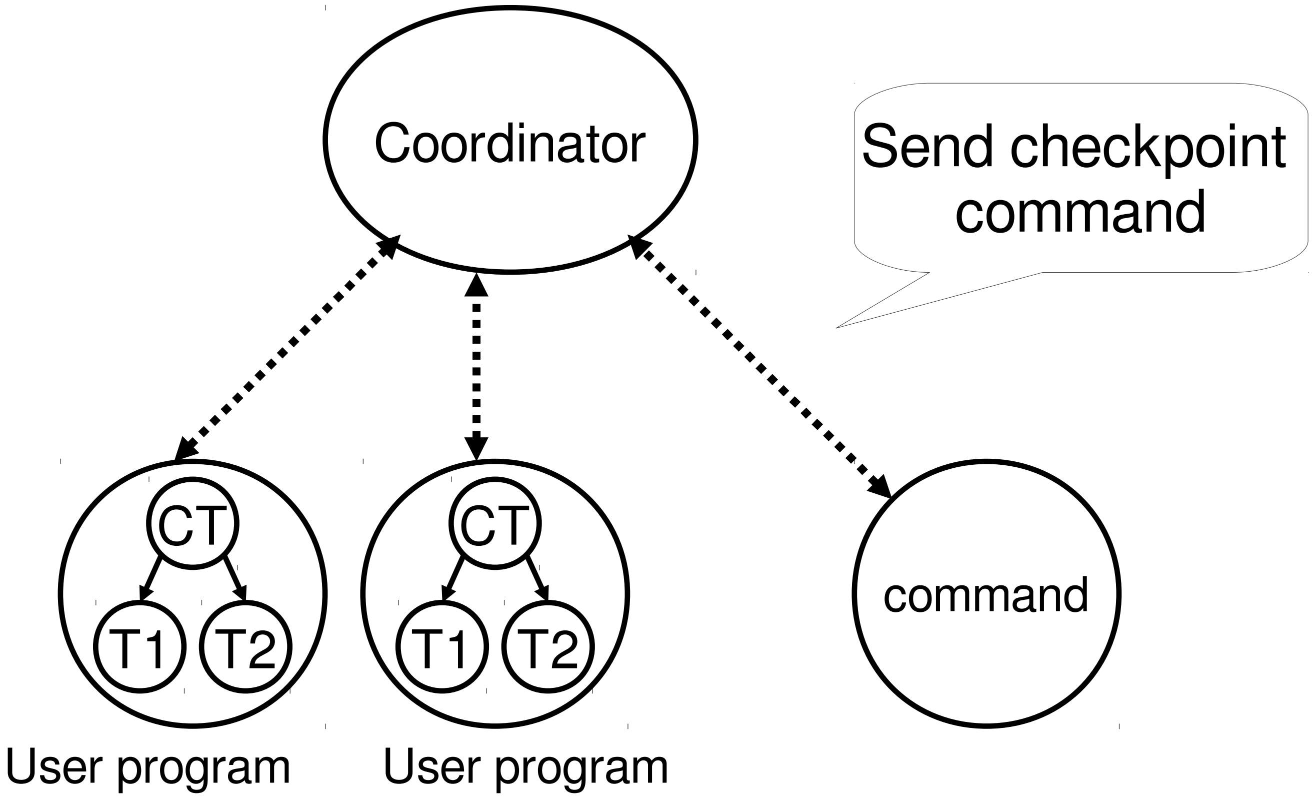
Checkpoint under DMTCP(1/7)

- dmtcphijack.so and libmtcp.so present in executable's memory.
  - **`dmtcp_checkpoint`** `<EXE>`



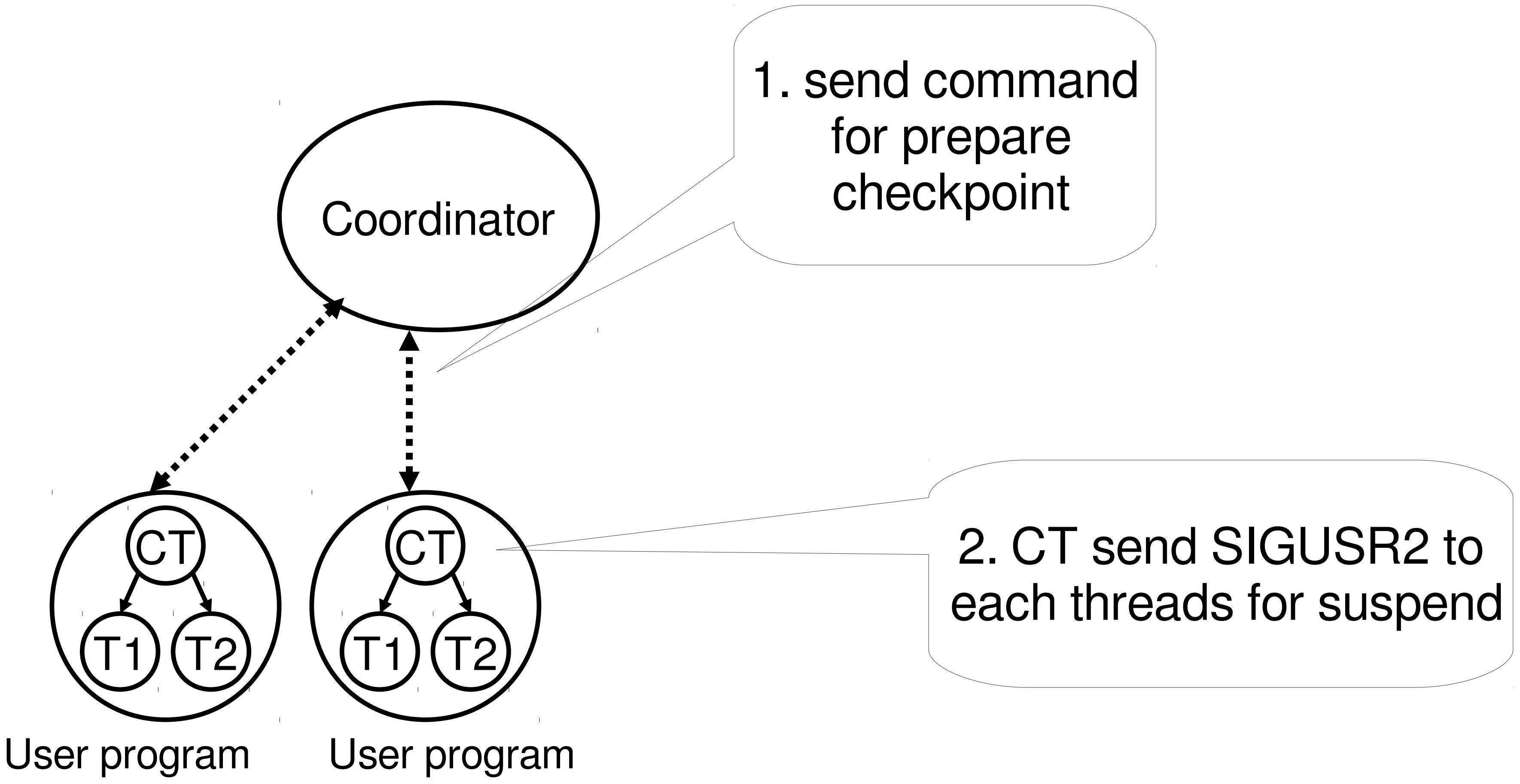
Checkpoint under DMTCP(2/7)

- Ask coordinator process for checkpoint via dmtcp_command.
  - `dmtcp_command -c`
- DMTCP also provides API to send command or query status



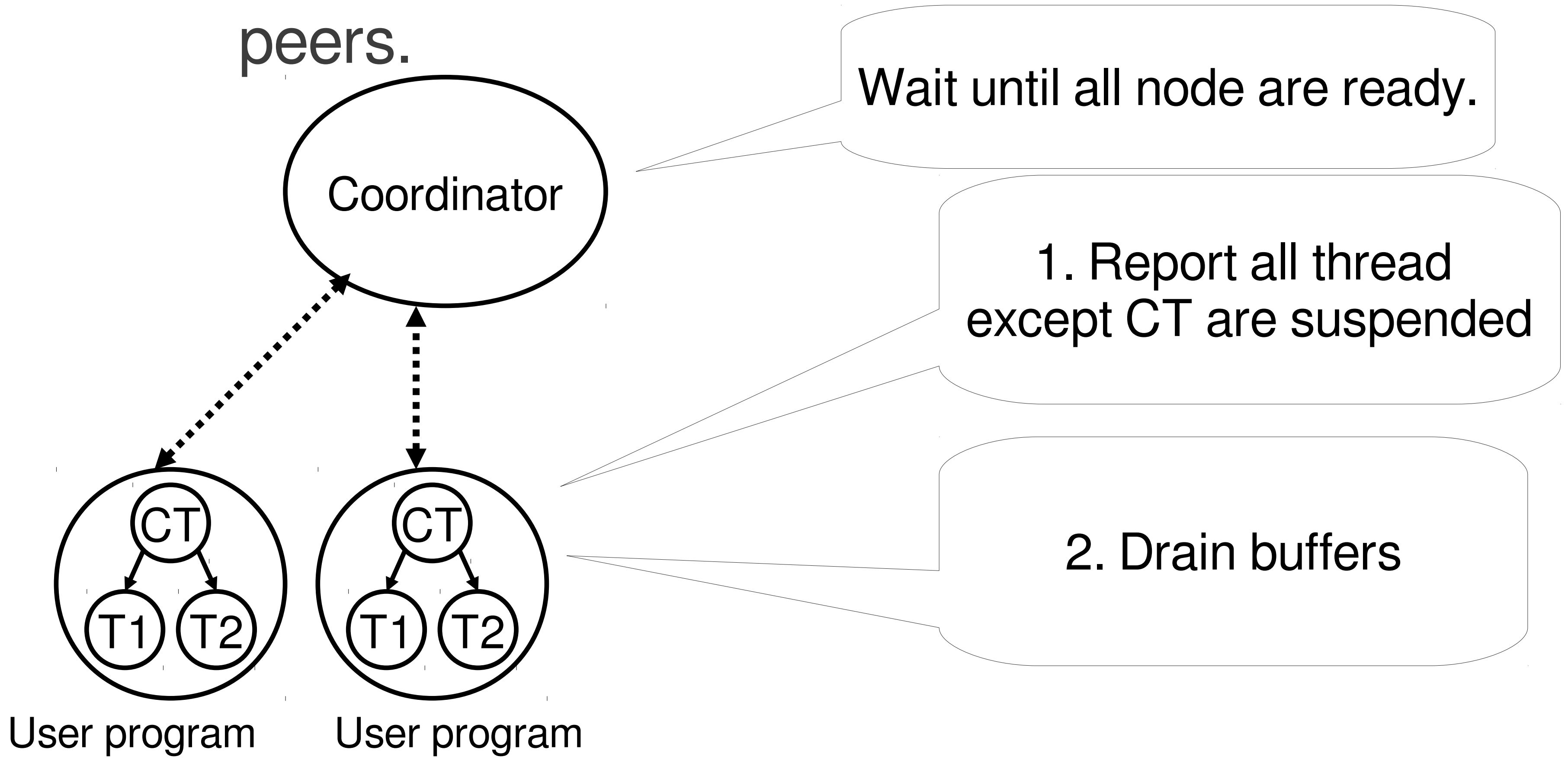
Checkpoint under DMTCP(3/7)

- Suspend user threads with SIGUSR2.


1. send command for prepare checkpoint
Coordinator
CT
T1
T2
User program
CT
T1
T2
User program
2. CT send SIGUSR2 to each threads for suspend

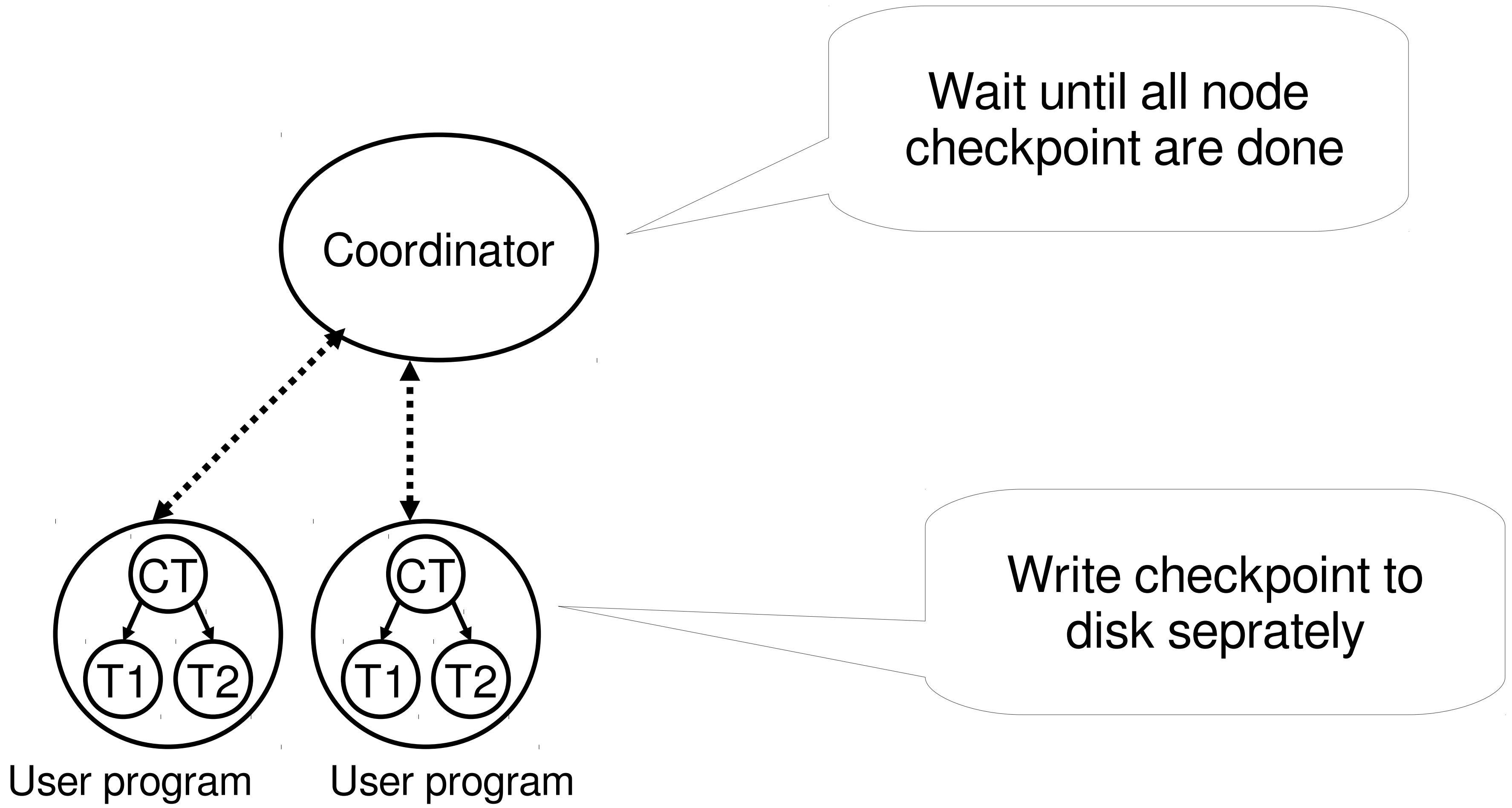
Checkpoint under DMTCP(4/7)

- Pre-checkpoint stage
- Synchronize every node and elect shared file descriptor leaders.
- Drain kernel buffers and do network handshake with peers.


Wait until all node are ready.
Coordinator
1. Report all thread except CT are suspended
2. Drain buffers
CT
T1
T2
CT
T1
T2
User program
User program

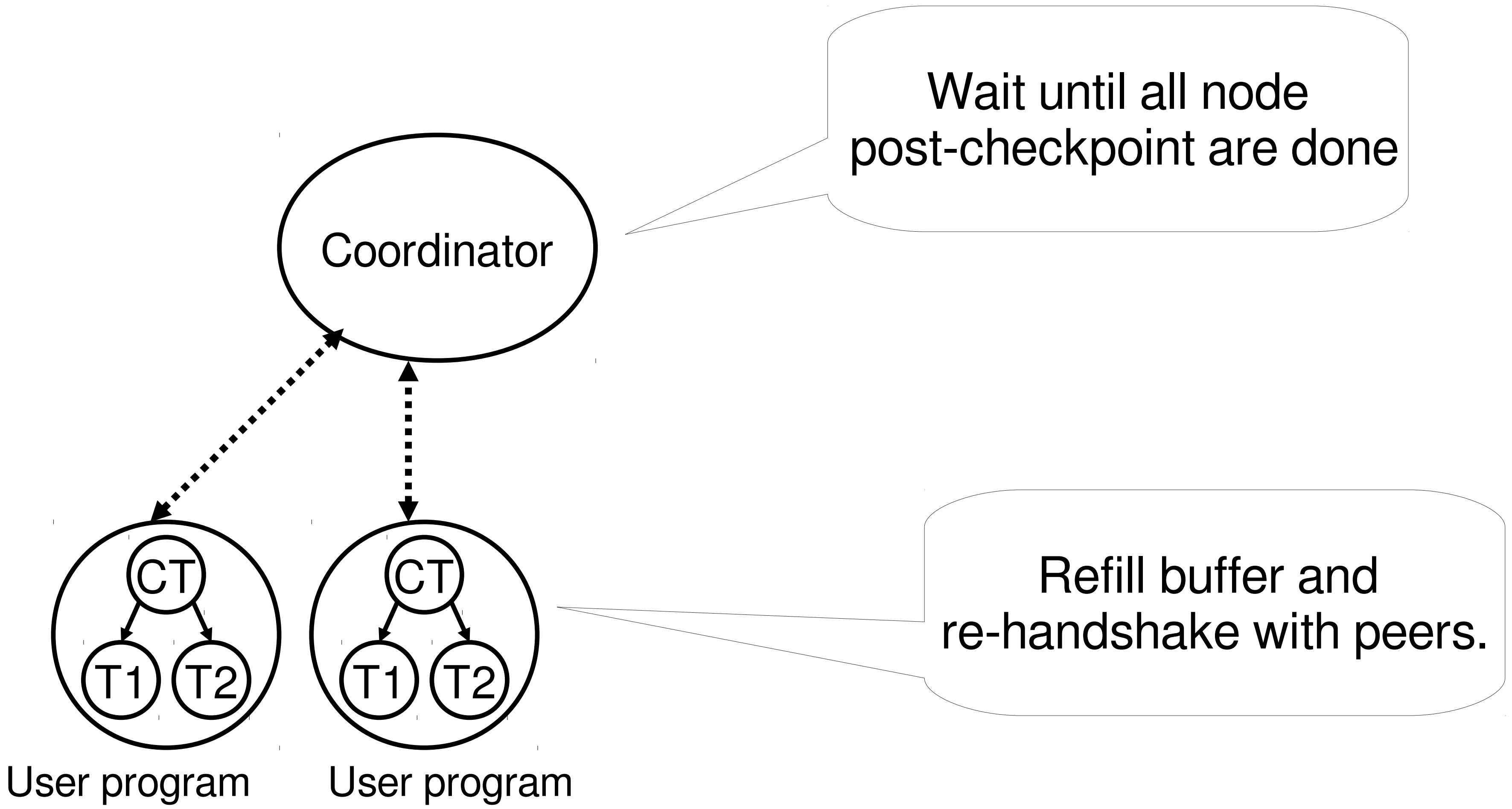
Checkpoint under DMTCP(5/7)

- Write checkpoint to disk
  - One checkpoint file per process
  - ckpt_<EXE>_<uid>.dmtcp


Wait until all node checkpoint are done
Coordinator
CT
T1
T2
CT
T1
T2
Write checkpoint to disk seprately
User program
User program

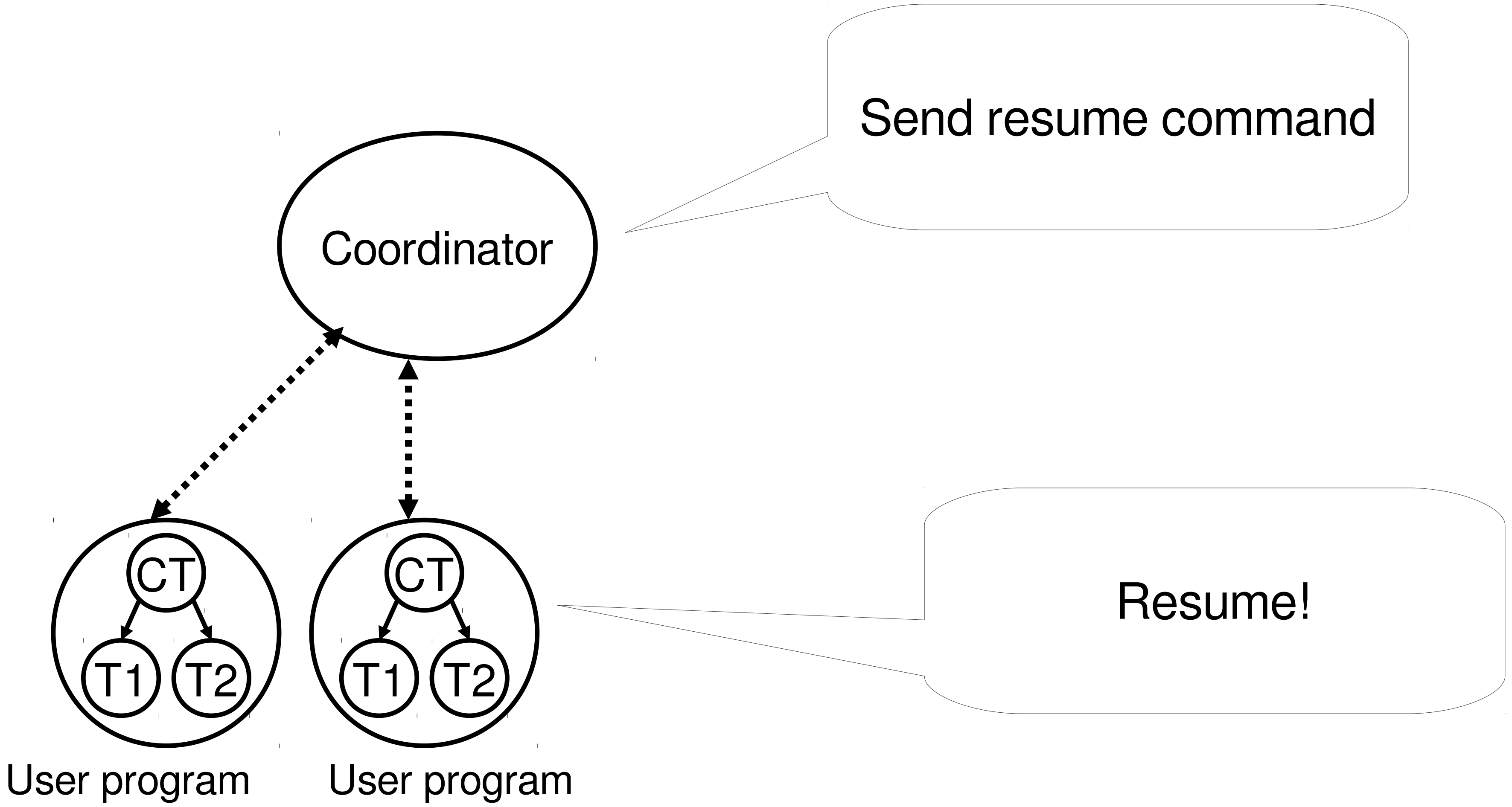
Checkpoint under DMTCP(6/7)

- Post-Checkpint stage
- Refill kernel buffers


Wait until all node post-checkpoint are done
Coordinator
CT
T1
T2
CT
T1
T2
User program
User program
Refill buffer and re-handshake with peers.

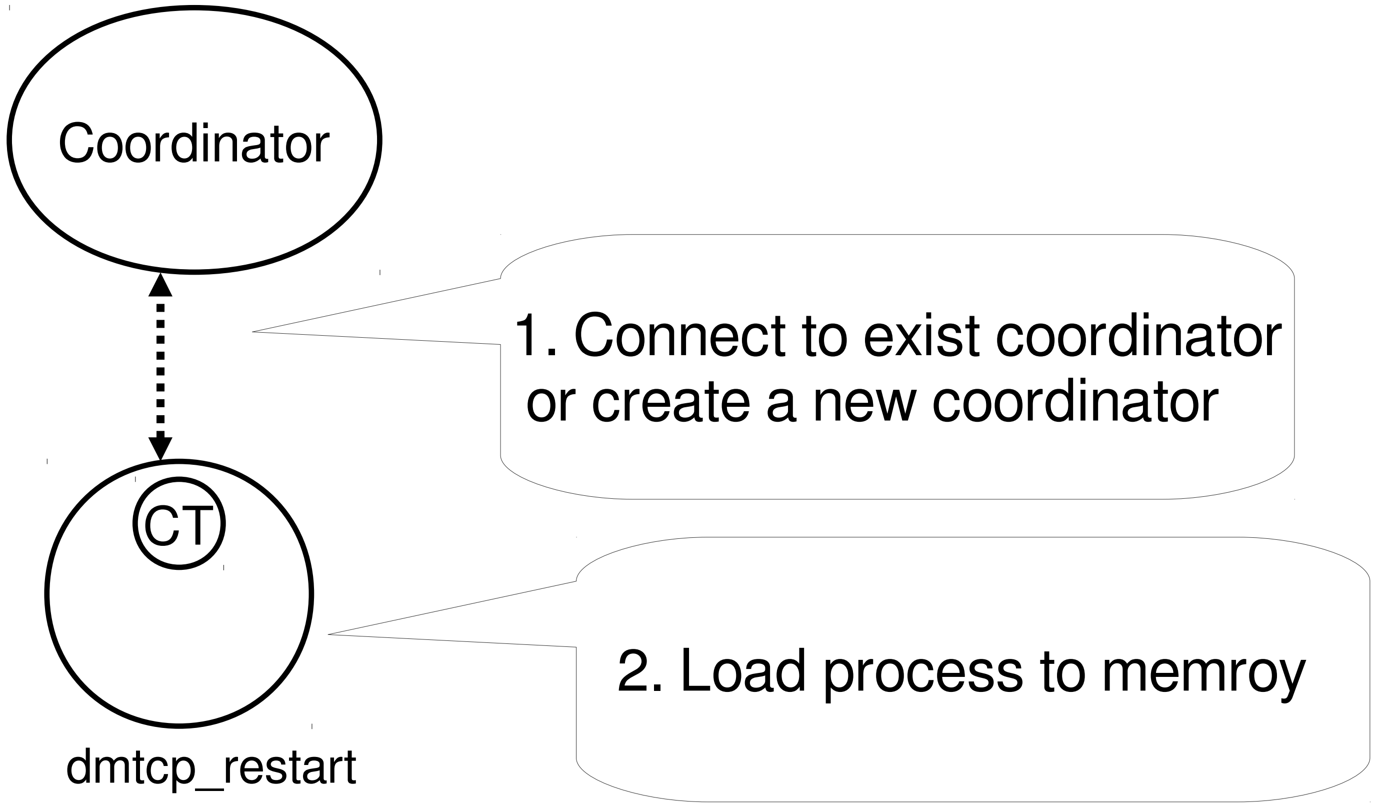
Checkpoint under DMTCP(7/7)

- Resume user threads.



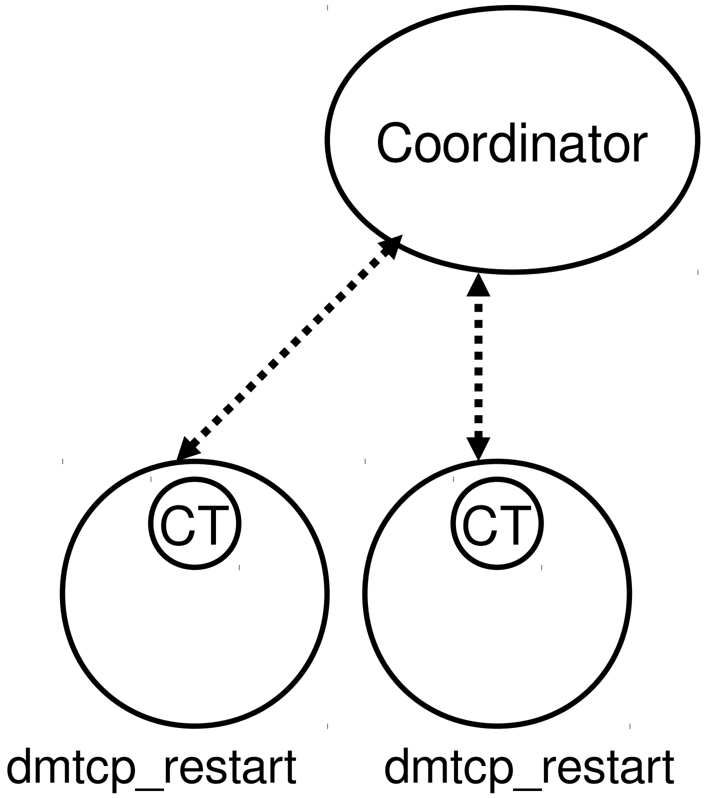
Restart under DMTCP(1/6)

- Restart Process loads in memory.
  - `dmtcp_restart ckpt_<EXE>_<uid>.dmtcp`


Coordinator
CT
dmtcp_restart
1. Connect to exist coordinator or create a new coordinator
2. Load process to memroy

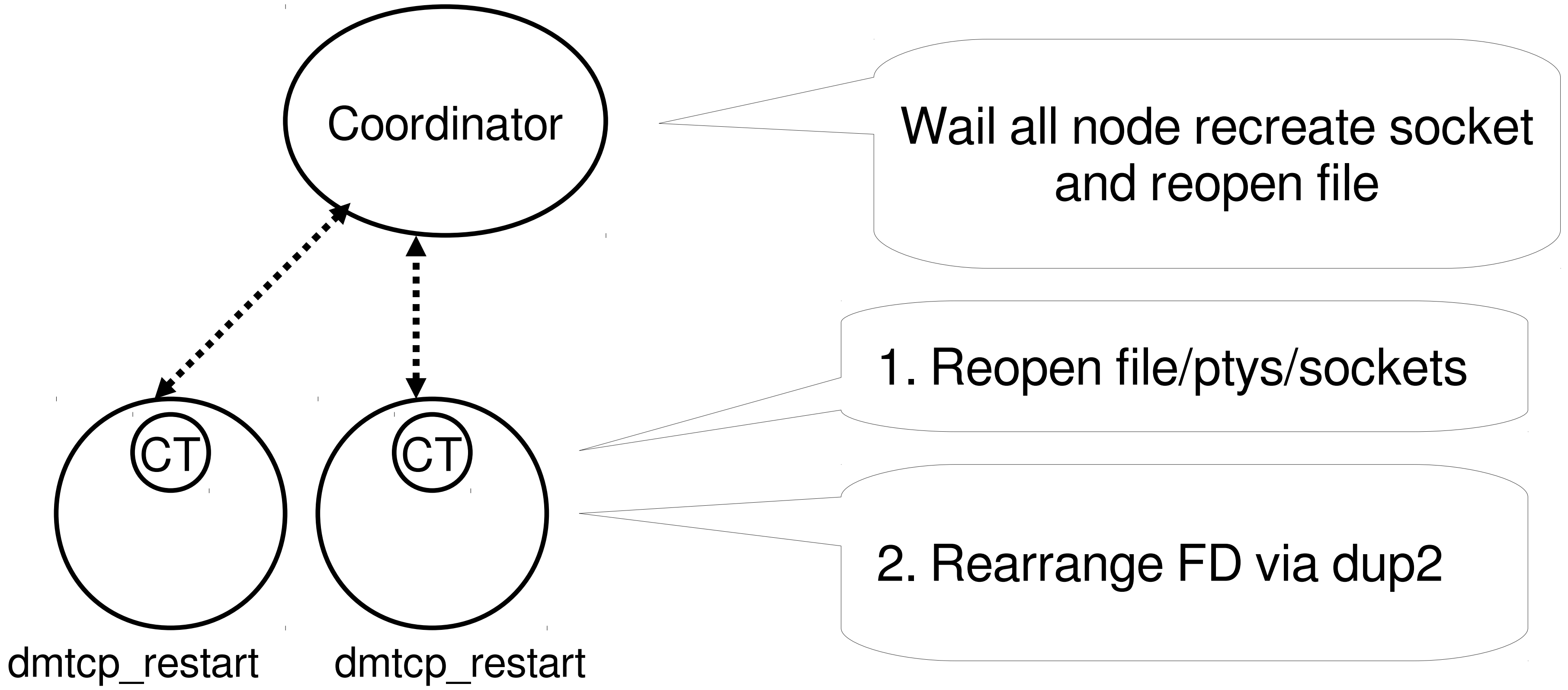
Restart under DMTCP(2/6)

- Fork user program



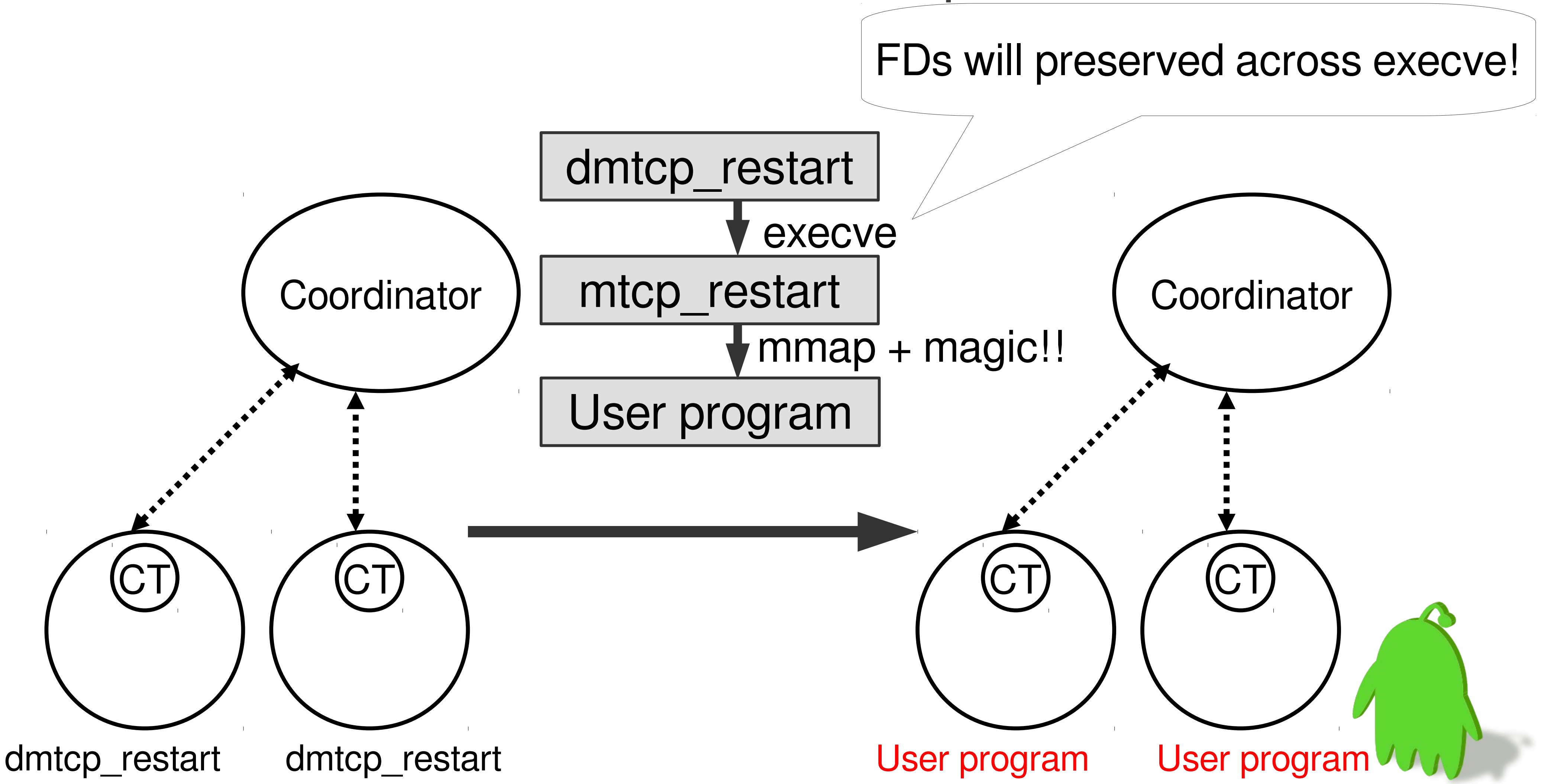
Restart under DMTCP(3/6)

- Reopen files and recreate ptys
- Recreate and reconnect sockets
- Rearrange file descriptors to initial layout


Coordinator
Wail all node recreate socket and reopen file
CT
CT
1. Reopen file/ptys/sockets
2. Rearrange FD via dup2
dmtcp_restart
dmtcp_restart

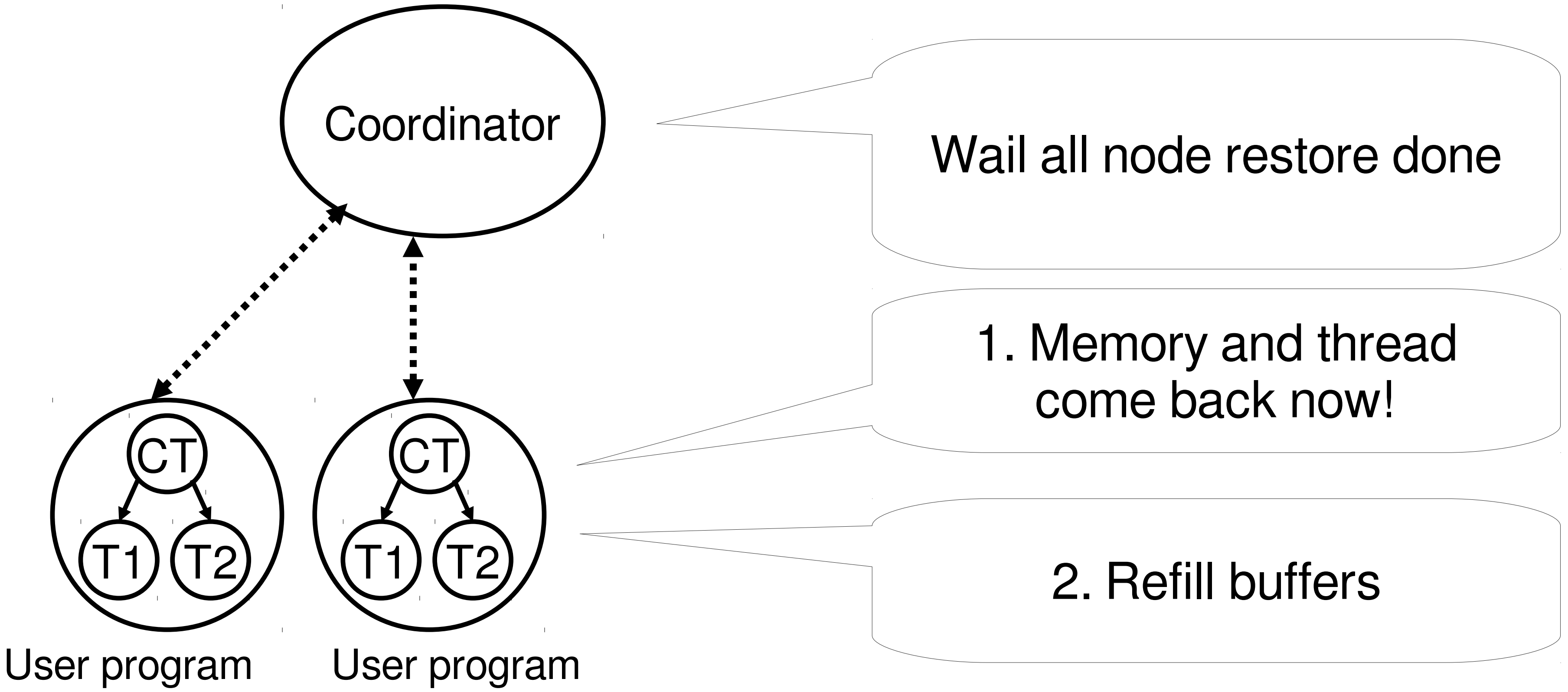
Restart under DMTCP(4/6)

- Restore memory content.
- Restore stack status for checkpoint thread.



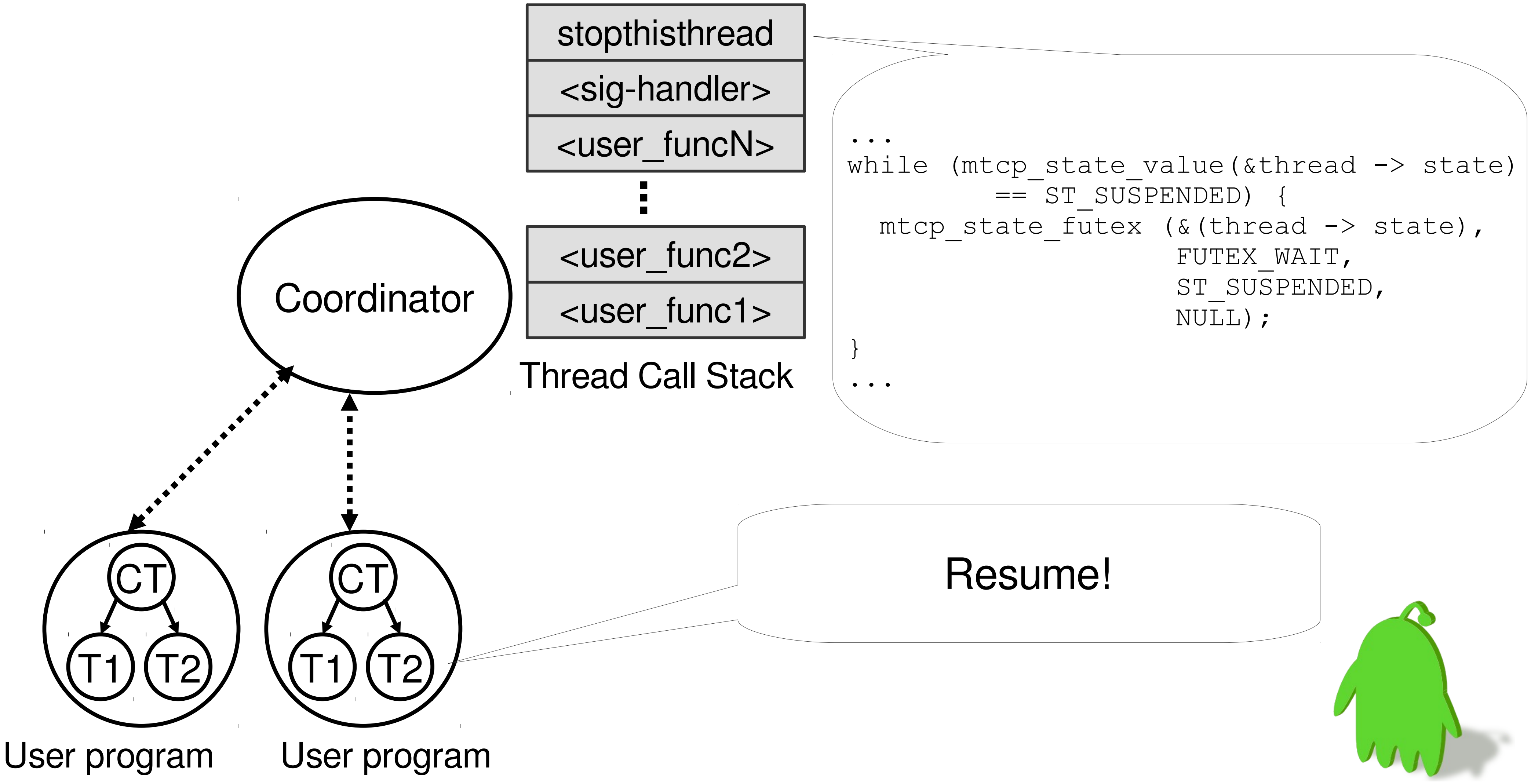
Restart under DMTCP(5/6)

- Restore other threads.
  - Recreate thread and restore stack and context.
  - Restore back to the post-checkpint stage
- Refill kernel buffer



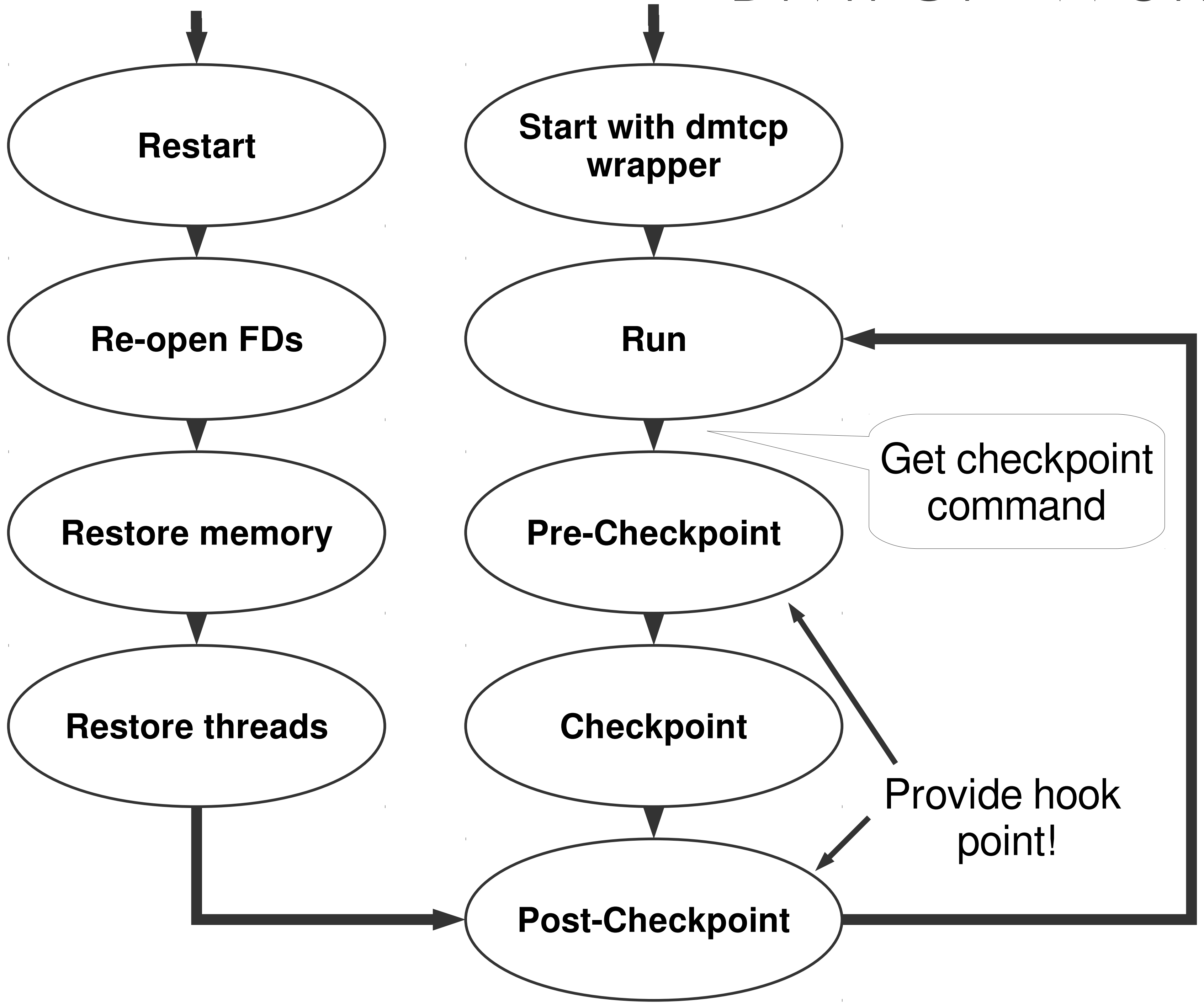
Restart under DMTCP(6/6)

- Resume user threads



```
...
while (mtcp_state_value(&thread -> state)
          == ST_SUSPENDED) {
  mtcp_state_futex (&(thread -> state),
                    FUTEX_WAIT,
                    ST_SUSPENDED,
                    NULL);
}
...
```

DMTCP Workflow



OS Features supported by DMTCP

- Threads, mutexes/semaphores, fork, exec
- Shared memory (via mmap), TCP/IP sockets, UNIX domain sockets, pipes, ptys, terminal modes, ownership of controlling terminals, signal handlers, open and/or shared fds, I/O (including the readline library), parent-child process relationships, process id & thread id virtualization, session and process group ids, and more…

DMTCP/Android: Additional Features

(LGPL; separated from Android)

- Binder IPC
  - Client-part: supported
  - Server-part: not supported
- Ashmem
  - Supported
- Logger
  - Supported
- Properties
  - Supported
- Wakelocks
  - Not supported

Support new FD type in DMTCP

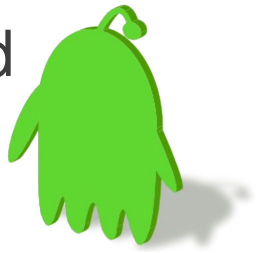
- In DMTCP, every FD has a corresponding \`Connection\`
  - **`TcpConnection`**, **`FileConnection`**, **`PtyConnection`**
- Implement a new subclass of Connection if you want to support a new FD type for Android:
  - **`AshmemConnection`**, **`BinderConnection`**, **`LoggerConnection`**, **`PropertyConnection`**
- And implement the **`preCheckpoint`**, **`postCheckpint`**, and any others if needed.

Interface of Connection

```
class Connection {
  public:
    virtual void preCheckpoint (const dmtcp::vector<int>&,
                                 KernelBufferDrainer&);
    virtual void postCheckpoint (const dmtcp::vector<int>&,
                                  bool);
    virtual void restore (const dmtcp::vector<int>&,
                          ConnectionRewirer *);
    virtual bool isDupConnection (const Connection&,
                                  dmtcp::ConnectionToFds&);
    virtual void doLocking (const dmtcp::vector<int>&);
    virtual void saveOptions (const dmtcp::vector<int>&);
    virtual void restoreOptions (const dmtcp::vector<int>& );
    virtual void doSendHandshakes (const dmtcp::vector<int>&,
                                   const dmtcp::UniquePid&);
    virtual void doRecvHandshakes (const dmtcp::vector<int>&,
                                   const dmtcp::UniquePid&);
    virtual void restartDup2 (int, int);
  protected:
    virtual void serializeSubClass (jalib::JBinarySerializer&);
};
```

Binder support for DMTCP

- BinderConnection
  - Reopen **`/dev/binder`** and reset option which is set via ioctl.
  - Restore the mmap region
- Hijack the whole libbinder!
  - Prevent libbinder from interpreting data twice
  - Implement necessary DMTCP hooks: **`preCheckpoint`**, **`postCheckpoint`**, **`postRestart`**
    - Re-initialize libbinder in **`postRestart`**
- The server part is not supported at the moment because binder server will call a blocked ioctl and block the whole checkpoint process.
  - We'll implement an early checkpoint stage to suspend such kind of thread soon.



Checkpoint for Zygote

- Experiment environment:
  - Android-x86 ICS emulated by VirtualBox
  - Host: Thinkpad x200 (Intel Core 2 Due @ 2.4 GHz)

	with gzip	without gzip
Checkpoint time	~10s	~5.5s
Restart time	~0.5s	~0.2s
Image size	~3M	~17M

Observations from logcat

```
--------- beginning of /dev/log/system
I/Vold    ( 1270): Vold 2.1 (the revenge) firing up
D/Vold    ( 1270): Volume usb state changing -1 (Initializing) -> 0 (No-Me
I/Netd    ( 1271): Netd 1.0 starting
I/        ( 1275): ServiceManager: 0x8062b50
I/        ( 1276): ServiceManager: 0x804fb98
I/AudioFlinger( 1276): Loaded primary audio interface from LEGACY Au
I/AudioFlinger( 1276): Using 'LEGACY Audio HW HAL' (audio.primary) a
...
D/AudioHardware( 1276): ### setVoiceVolume: 1.000000
I/AudioPolicyService( 1276): [1276]Loaded audio policy from LEGACY A
E/BatteryService( 1382): usbOnlinePath not found
D/AndroidRuntime( 1902):
D/AndroidRuntime( 1902): >>>>>> AndroidRuntime START com.androi
D/AndroidRuntime( 1902): CheckJNI is ON
I/SamplingProfilerIntegration( 1902): Profiling disabled.
I/Zygote  ( 1902): Preloading classes...
D/dalvikvm( 1902): GC_EXPLICIT freed 35K, 85% free 399K/2560K, pa
...
I/Zygote  ( 1902): ...preloaded 379 resources in 548ms.
D/dalvikvm( 1902): GC_EXPLICIT freed 20K, 1% free 6417K/6467K, pa
I/Zygote  ( 1902): ...preloaded 31 resources in 13ms.
D/dalvikvm( 1902): GC_EXPLICIT freed 14K, 1% free 6418K/6467K, pa
D/dalvikvm( 1902): GC_EXPLICIT freed 5K, 1% free 6412K/6467K, pau
D/dalvikvm( 1902): GC_EXPLICIT freed <1K, 1% free 6412K/6467K, pa
I/dalvikvm( 1902): System server process 1911 has been created
```

Normal bootup log message

```
--------- beginning of /dev/log/system
I/Vold    ( 1270): Vold 2.1 (the revenge) firing up
D/Vold    ( 1270): Volume usb state changing -1 (Initializing) -> 0 (No-Media)
I/Netd    ( 1271): Netd 1.0 starting
I/        ( 1275): ServiceManager: 0x8062b50
I/        ( 1276): ServiceManager: 0x804fb98
I/AudioFlinger( 1276): Loaded primary audio interface from LEGACY Audio H
I/AudioFlinger( 1276): Using 'LEGACY Audio HW HAL' (audio.primary) as the
....
D/AudioHardware( 1276): ### setVoiceVolume: 1.000000
I/AudioPolicyService( 1276): [1276]Loaded audio policy from LEGACY Audio
D/dalvikvm( 1373): GC_EXPLICIT freed 14K, 1% free 6418K/6467K, paused
D/dalvikvm( 1373): GC_EXPLICIT freed 5K, 1% free 6412K/6467K, paused 0
D/dalvikvm( 1373): GC_EXPLICIT freed <1K, 1% free 6412K/6467K, paused
I/dalvikvm( 1373): System server process 1382 has been created
```

Bootup log message with restart

Android Boottime with DMTCP

	1	2	3	4	5	6	7	8	9	10	avg
Boottime	27.96	27.95	32.89	26.59	32.33	32.36	33.22	32.99	36.47	32.85	31.56
Boottime with DMTCP (w/ gzip)	15.02	15.86	15.13	14.88	14.57	14.43	14.73	14.22	13.97	14.61	14.74
Boottime with DMTCP (w/o gzip)	14.98	15.13	14.61	13.90	14.72	14.84	15.46	15.06	15.32	15.39	14.94

Measured by uptime in `onStart`() of Launcher2

Reversible Debugger based on DMTCP

- URDB is a universal reversible debugger that can add reversibility gained through the use of DMTCP.
- A user debugging with gdb would then ask URDB to go back to a point in time to when:
  - the expression had a correct value
  - the next statement would cause the expression to take on an incorrect value.
- Project page: http://sourceforge.net/projects/urdb/

Reference

- "DMTCP: An New Linux Checkpointing Mechanism for Vanilla Universe Job", Condor Project, University of Wisconsin-Madison
- "Checkpointing using DMTCP, Condor, Matlab and FReD", Gene Cooperman Northeastern University, Boston
- URDB: Universal Reversible Debugger

  http://arxiv.org/abs/0910.5046
- Cruz: Application-Transparent Distributed Checkpoint-Restart on Standard Operating Systems, G. (John) Janakiraman, Jose Renato Santos, Dinesh Subhraveti, Yoshio Turner, HP Labs

0xlab

http://0xlab.org