Linux-CR: Transparent Application Checkpoint-Restart in Linux

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Application C/R

- Application Checkpoint/Restart:

  a mechanism to save the state of a running application so that it can later resume its execution from that point

What is it good for ?

- Application roll back to the past
  - recover from faults
  - effective debugging
  - improved response time
  - retry a move in a game

What else is it good for ?

- Application suspend and resume
  - improved system utilization
  - suspend/resume a user's session

What more is it good for ?

- Application migration
  - load balancing and resource sharing
  - mobile desktop on a USB key
  - zero-downtime maintenance
  - improved availability

Application vs Virtual-Machine

	Application C/R	Virtual Machine
granularity	specific applications	operating system as a whole unit
saved state	application state only	entire operating system state
overhead	none	visible overhead

Some History

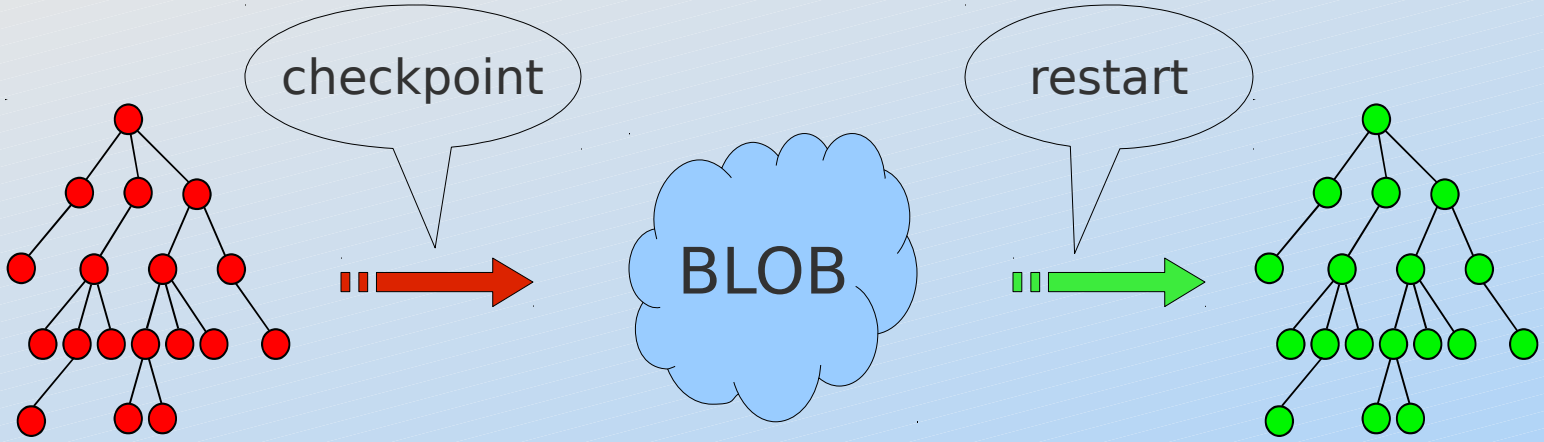
- Linux 2.4
  - EPCKPT (Rutgers)
  - CRAK (Columbia)
- Linux 2.6
  - BLCR (Berkeley)
  - OpenVZ (Parallels)
  - Zap (Columbia)

Requirements

- Reliable
  - if checkpoint succeeds – restart succeeds
- Transparent
  - applications are oblivious to operation
- Secure
  - must not introduce vulnerabilities
- Mainline
  - aim for inclusion in mainline kernel

Usage Model

- Checkpoint granularity
  - a process hierarchy
  - top-down traversal



Checkpoint Categories

- Container-checkpoint
- Subtree-checkpoint
- Self-checkpoint

Namespaces

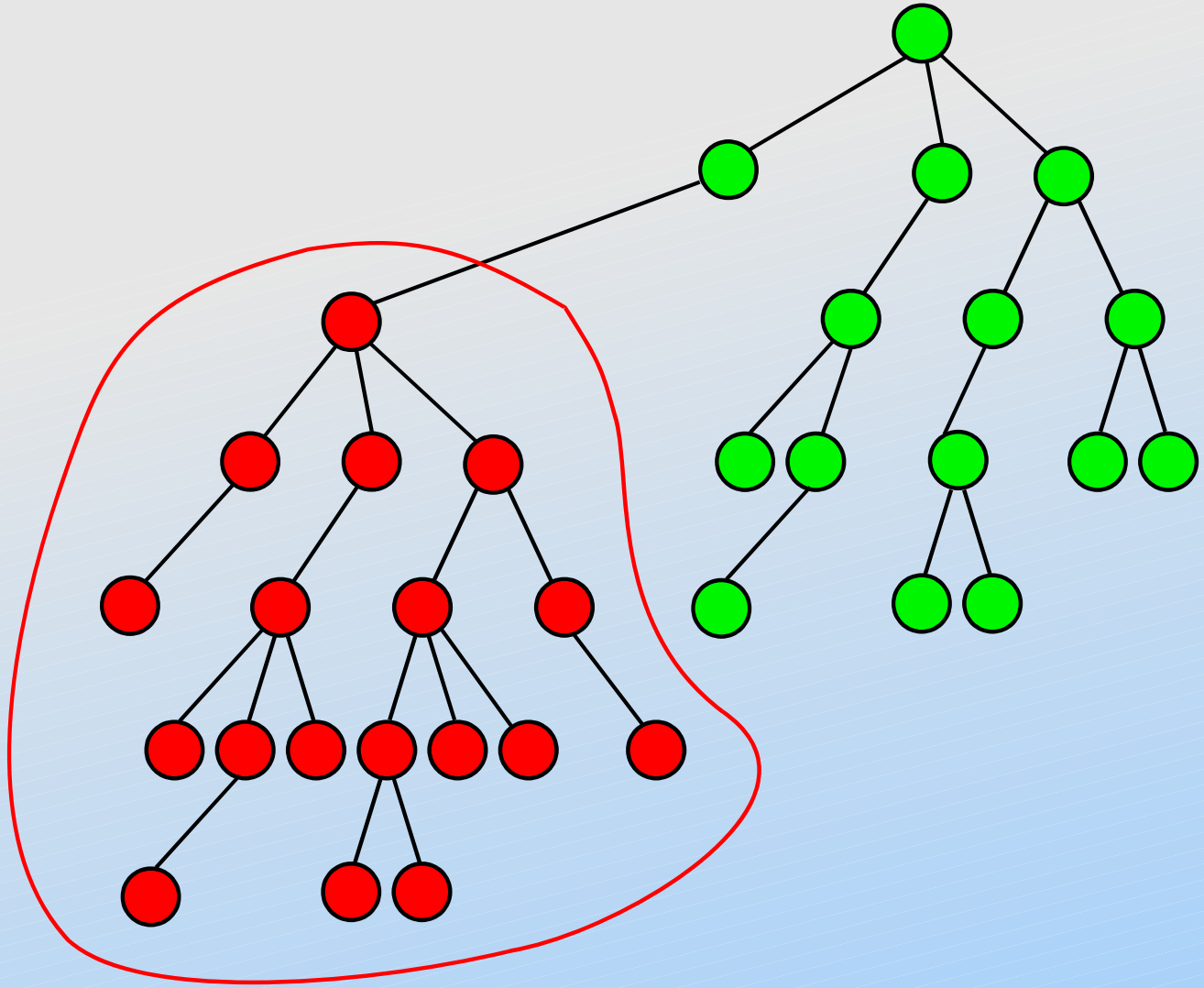
- Private and virtual view of resources
  - e.g. pid, mount, ipc, network...
- Private view
  - provide isolation from other processes
- Virtual view
  - decouple from underlying kernel instance

Container Checkpoint

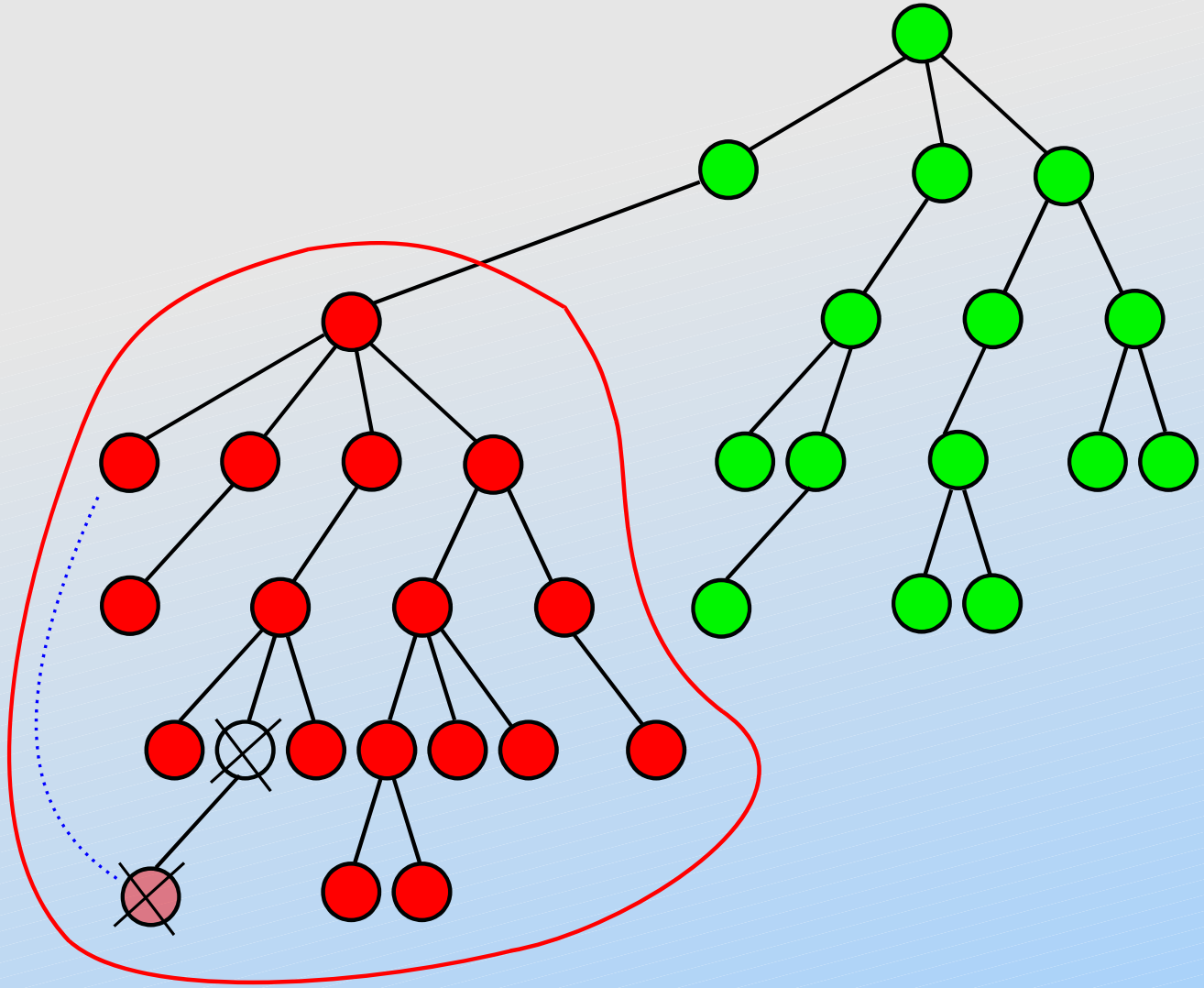
- Hierarchy is self-contained
  - includes all the processes that are referenced within the hierarchy
- Hierarchy is isolated
  - resources only referenced by processes that belong to the hierarchy

- Checkpoint is consistent and reliable

Container Checkpoint



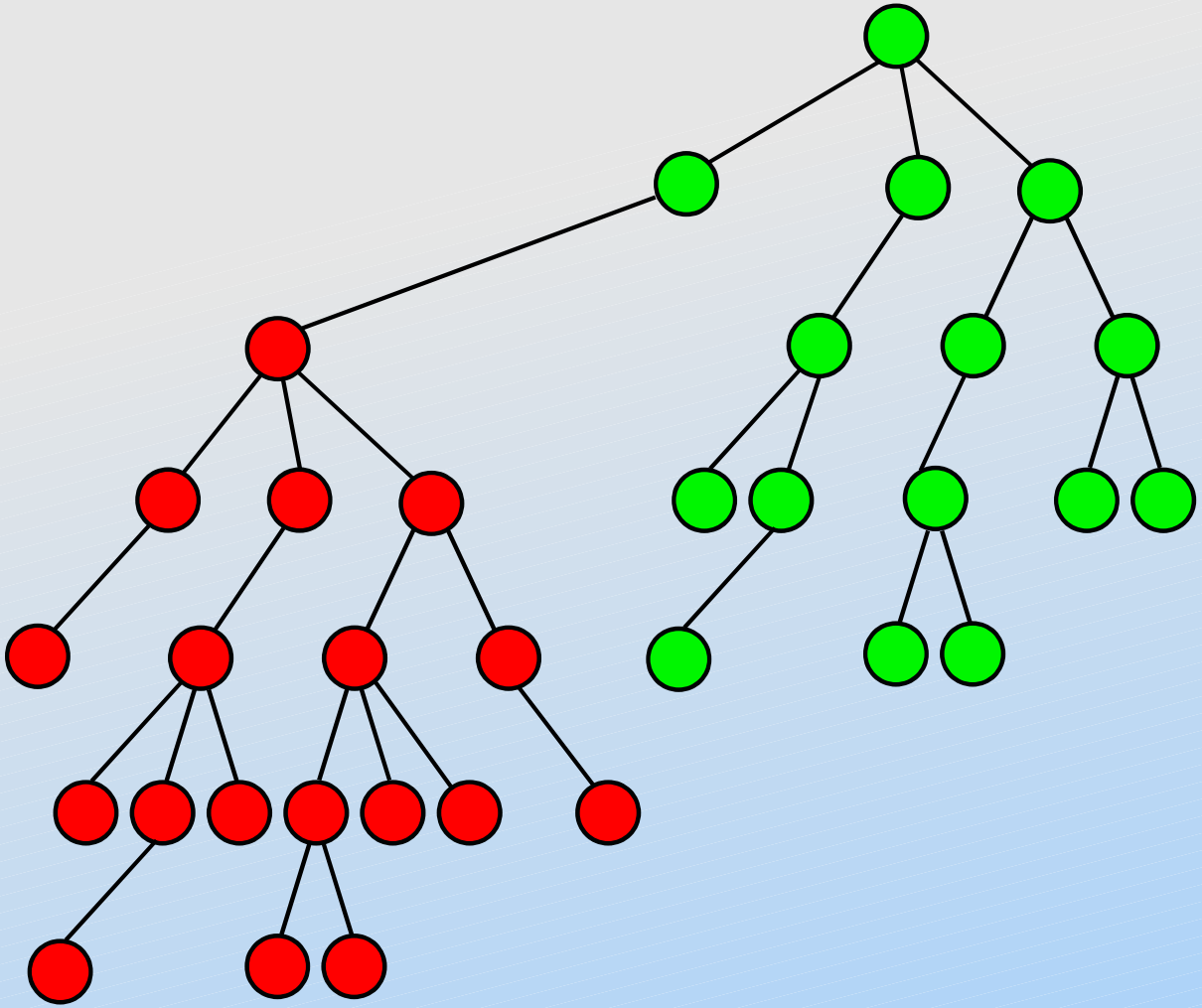
Container Checkpoint



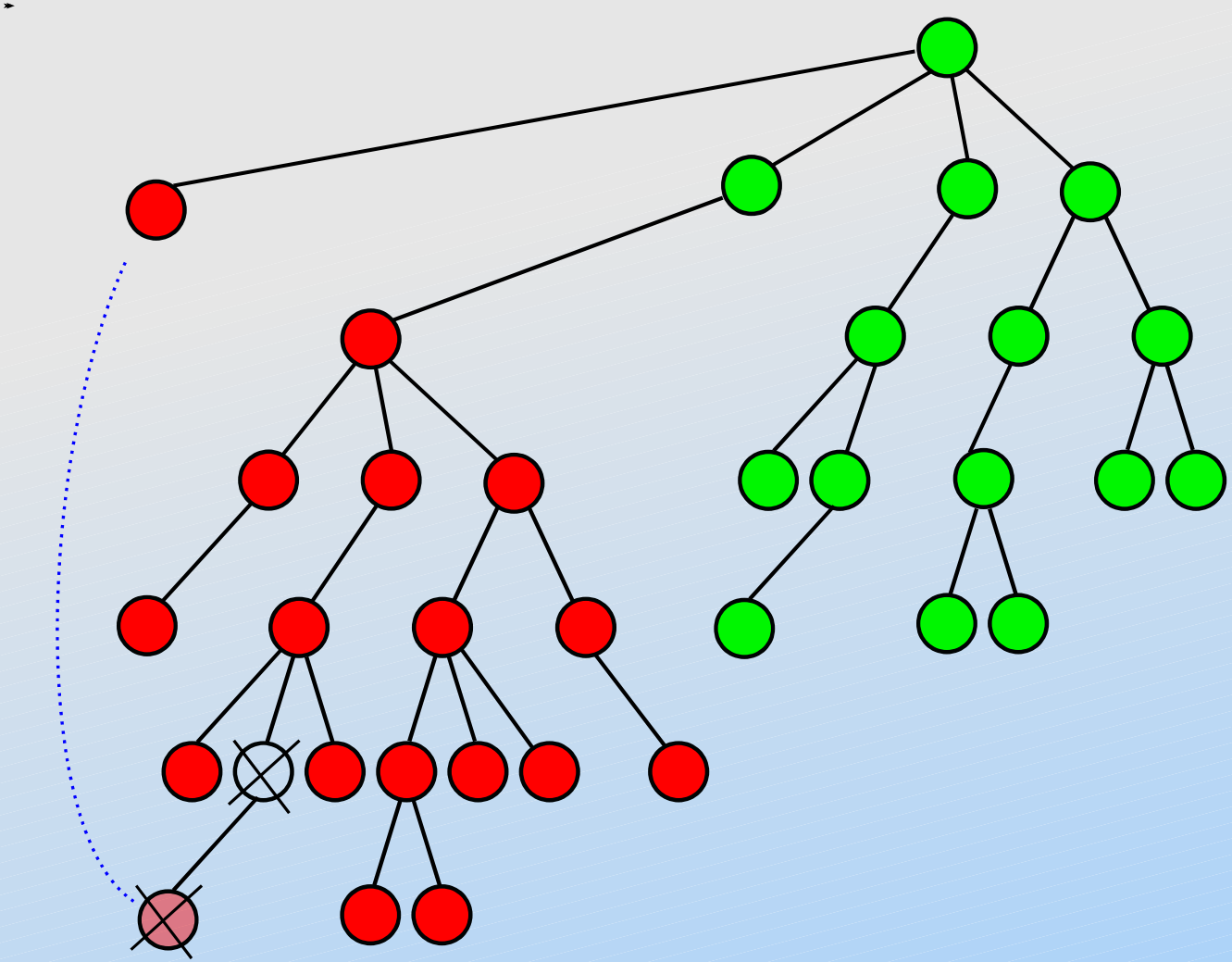
Subtree Checkpoint

- Arbitrary process hierarchy
  - no constraints on the target hierarchy
  - simplifies admin, but no guarantees
  - suitable for many use-cases

Subtree Checkpoint



Subtree Checkpoint



Self-Checkpoint

- For a process to save its state
  - record only current process
  - ignore sharing and dependencies
  - Analogous to *fork* syscall:

```
…
ret = checkpoint(0, fd, flags, -1);
if (ret < 0)
   return ret;
else if (ret)
   printf("checkpoint succeeded\n");
else
   printf("returned from restart\n");
…
```

System Calls

`long checkpoint(pid, fd, flags, logfd)`

- target hierarchy with root task `@pid`
- output to `@fd`, log to `@logfd`

`long restart(pid, fd, flags, logfd)`

- New hierarchy with coordinator `@pid`
- Input from `@fd`, log to `@logfd`

Example

```
cat > myscript.sh << EOF
#!/bin/sh
echo $$ > /cgroup/1/tasks
exec 0>&- ; exec 1>&- ; exec 2>&-
/usr/sbin/sshd -p 9999
screen -A -d -m -S mysession somejob.sh
EOF
```

Example

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mkdir -p /cgroup
mount -t cgroup -o freezer cgroup /cgroup
mkdir /cgroup/1
```

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nohup nsexec -tgcmpiUP pid.out myscript.sh &
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PID=`cat pid.out`
echo FROZEN >  /cgroup/1/freezer.state
checkpoint $PID -l clog.out -o image.out
kill -9 $PID
echo THAWED > /cgroup/1/freezer.state
```

Example

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checkpoint $PID -l clog.out -o image.out
kill -9 $PID
echo THAWED > /cgroup/1/freezer.state

restart -l rlog.out -i image.out
```

Architecture

- Reliability
- Transparency
- Kernel vs userspace
- Checkpoint image
- Shared resources
- Leak detection

Architecture: Reliability

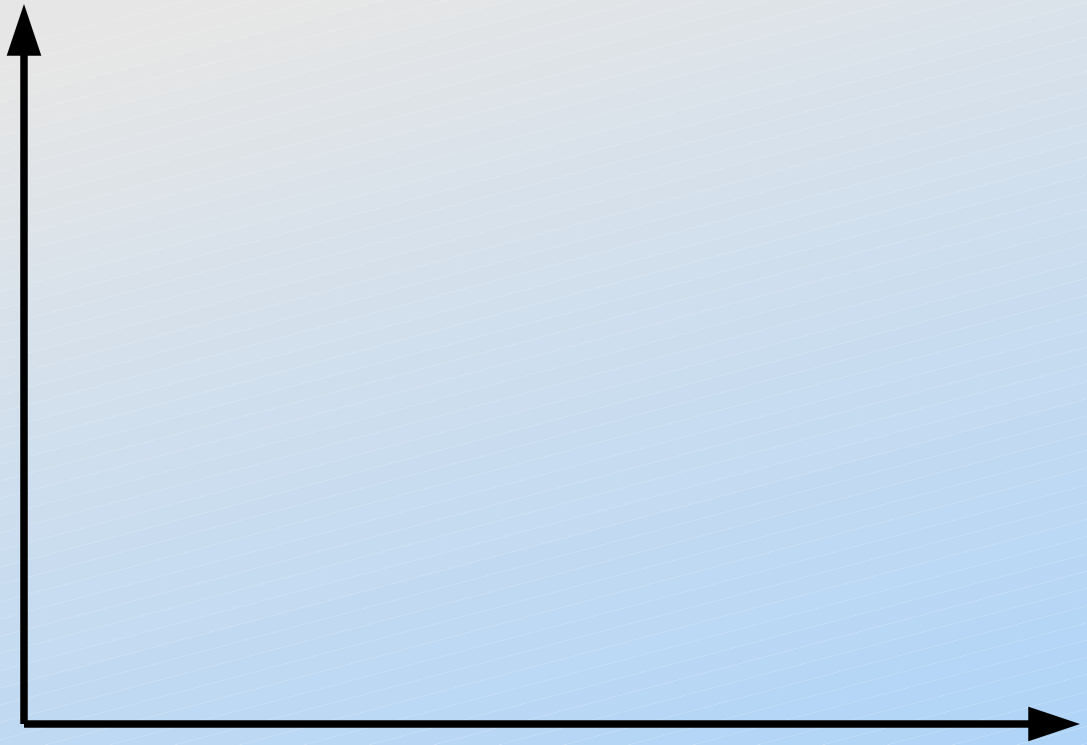
- How to maintain global consistency ?
- Requirements:
  - keep tasks frozen
  - keep resources unmodified
- Outcome: state is protected
  - from tasks in the hierarchy
  - from tasks outside the hierarchy

Architecture: Transparency

- How to maintain transparency ?
- Requirements:
  - include all resources in use by tasks
  - preserve resources identifiers on restart
- Outcome: state visible as before
  - all necessary state is restored
  - state accessible via same identifiers

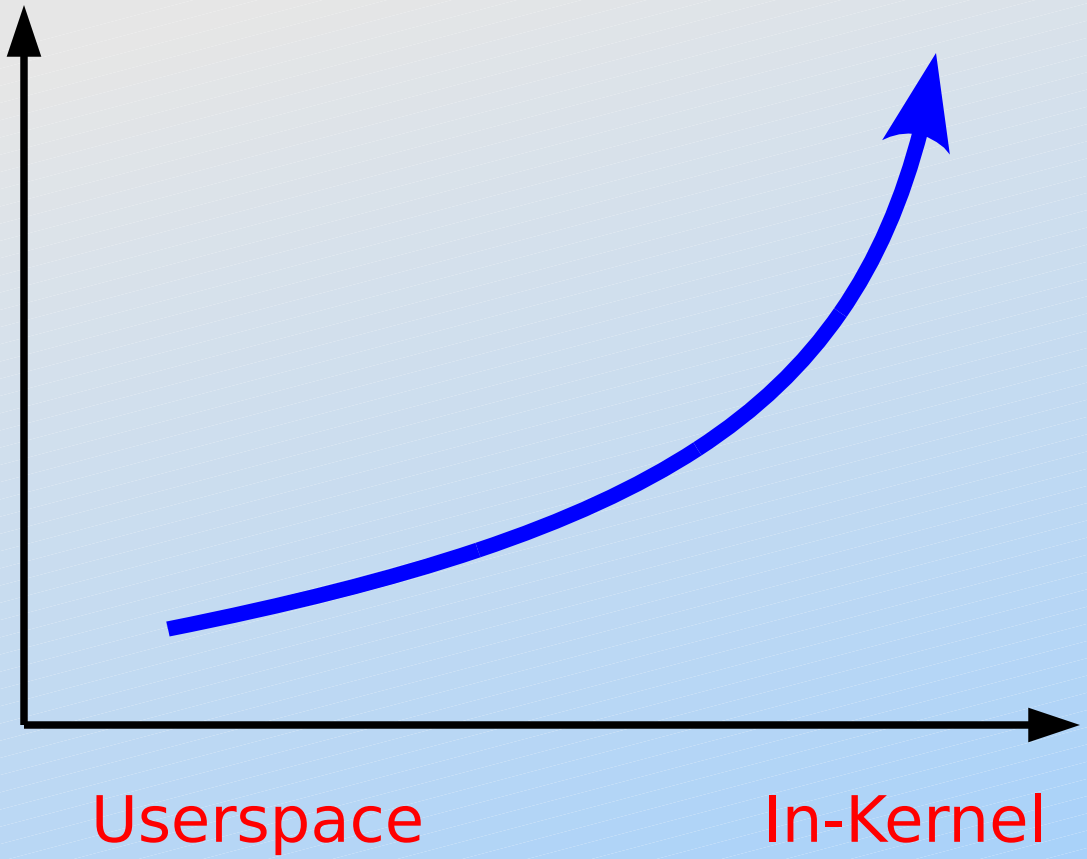
Kernel vs. Userspace

Completeness
Transparency
Extensibility



Kernel vs. Userspace

Completeness
Transparency
Extensibility



Kernel vs. Userspace

- The rule: in-kernel implementation
  - transparency, completeness
  - leverage extensive kernel API
- The exception: userspace possible
  - if straightforward with existing APIs
  - if provides significant added value
  - If occurs before entering the kernel

Checkpoint

(1) Freeze process hierarchy

(2) Save global data

(3) Save process hierarchy

(4) Save state of all tasks

In-Kernel

(?) Filesystem snapshot

(5) Thaw/kill process hierarchy

Restart

(1) Create container

(?) Restore (stage) filesystem

(3) Create process hierarchy

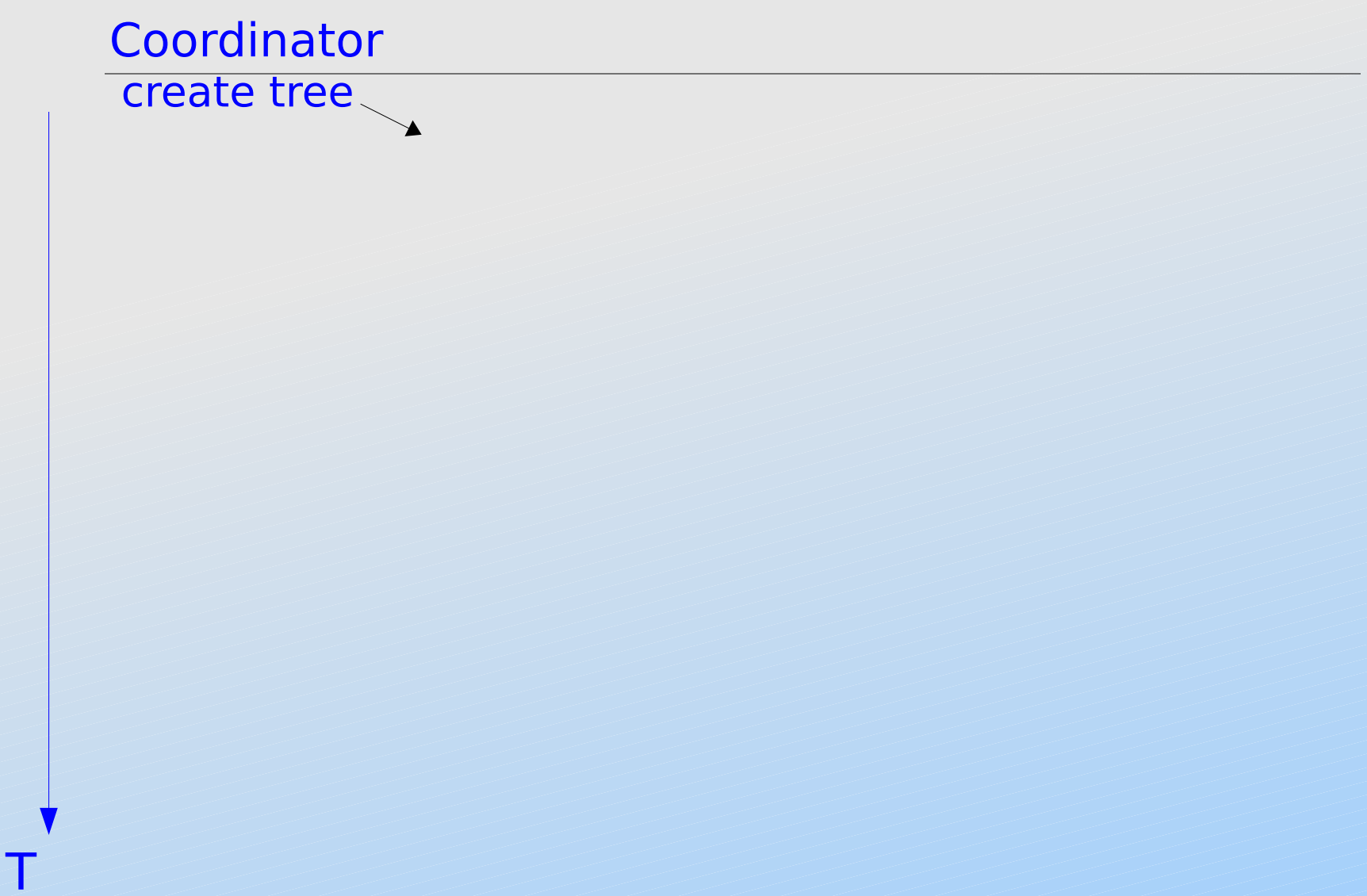
(4) Restore state of all tasks } In-Kernel

(5) Resume execution

Restart: Create Hierarchy

- *DumpForest*
  - convert hierarchy data to instructions
- *CreateForest*
  - execute instructions to re-create tasks
  - proceeds from root task recursively
- Curious how it works ?
  - see USENIX 2007 paper (Zap)
  - read comments in code

Restart Coordination



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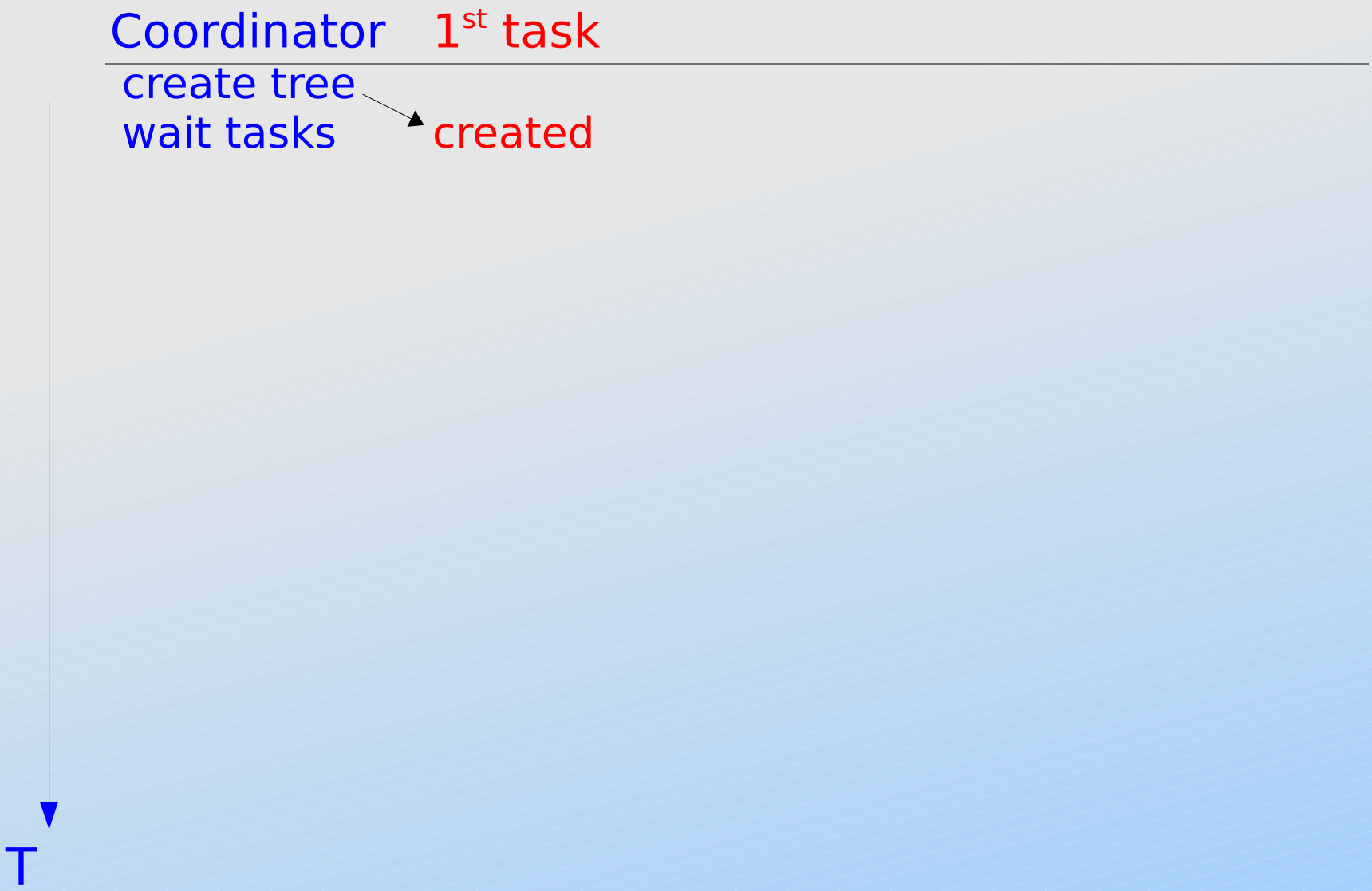

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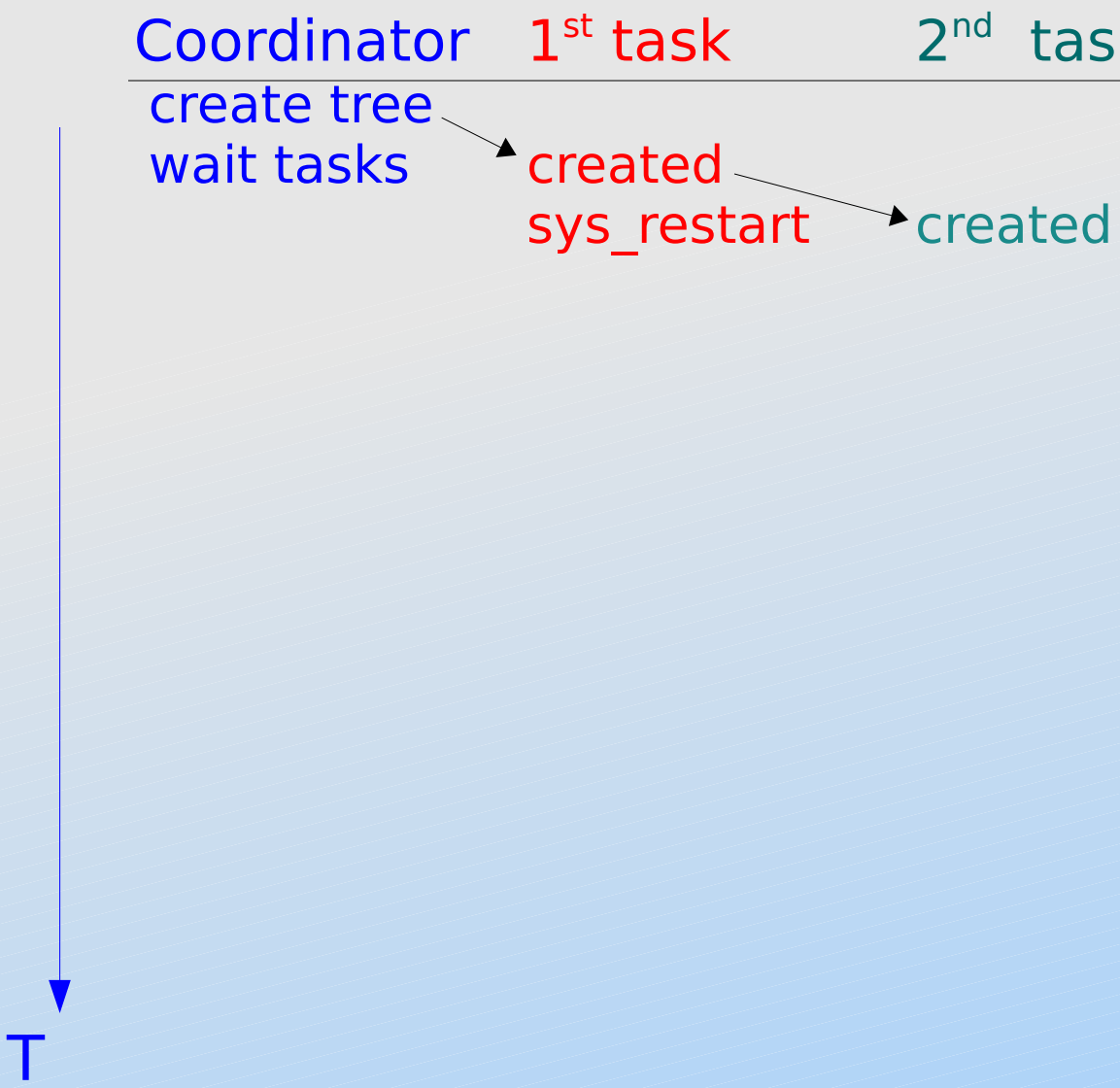

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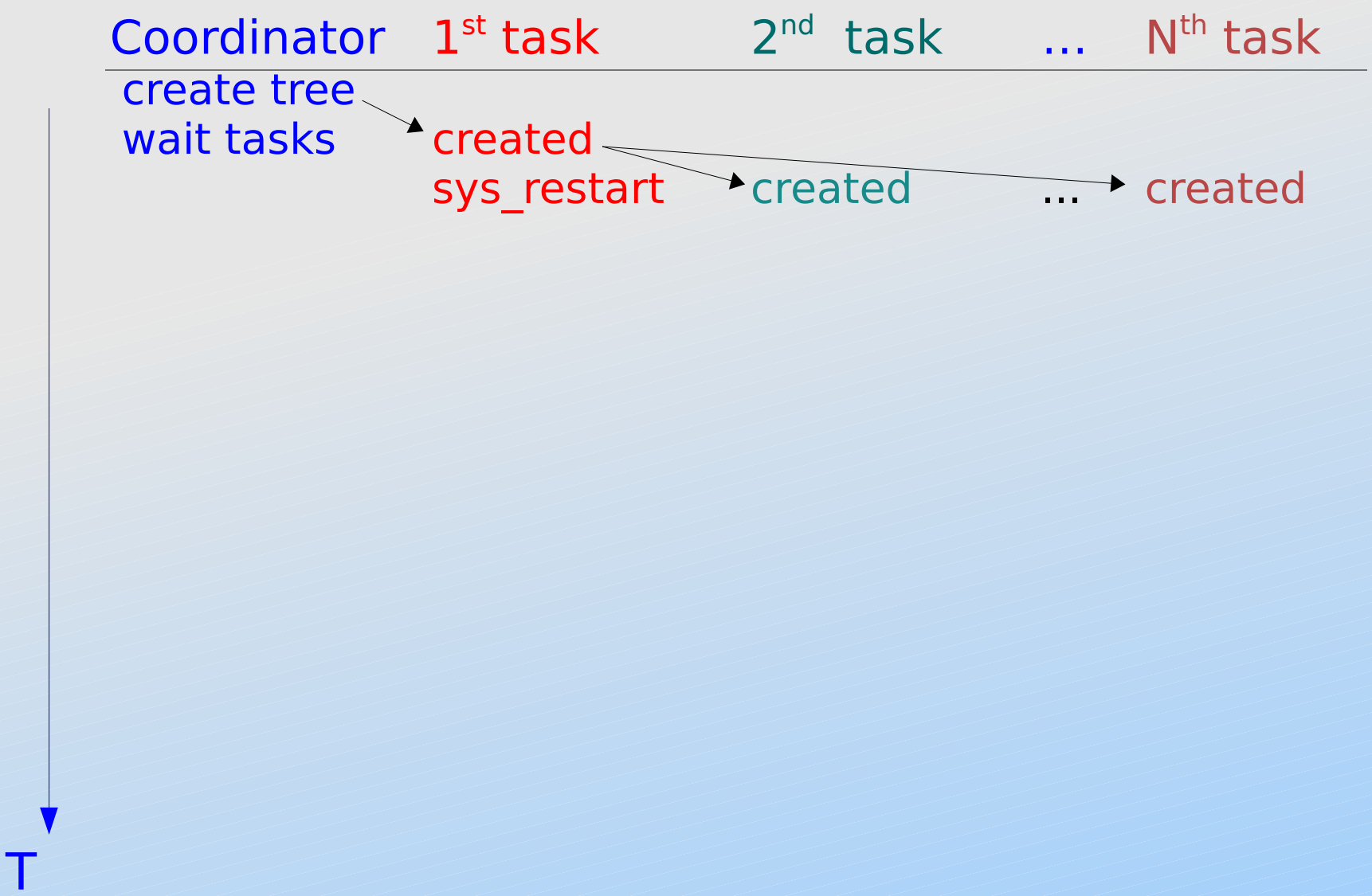
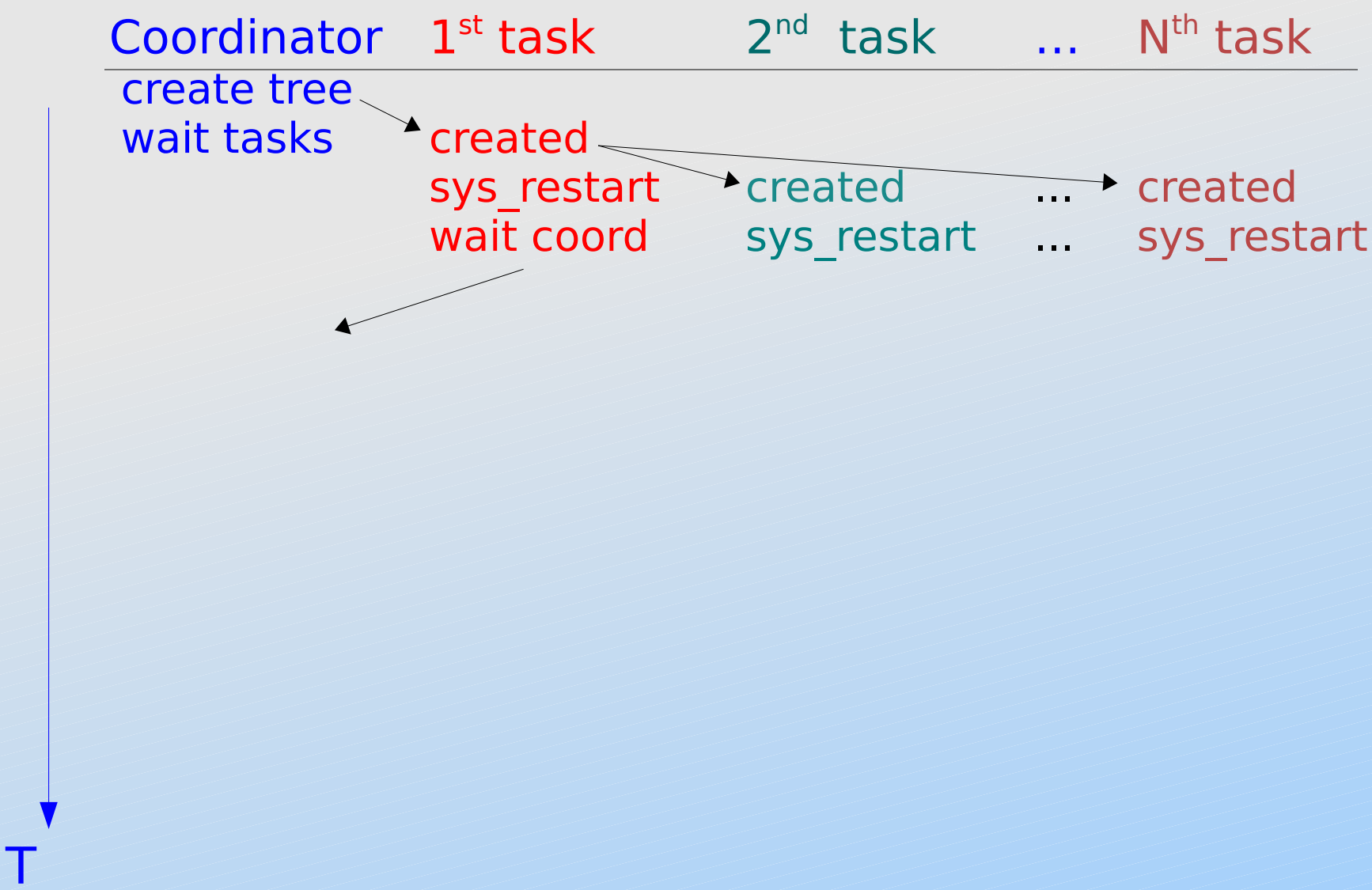


Restart Coordination



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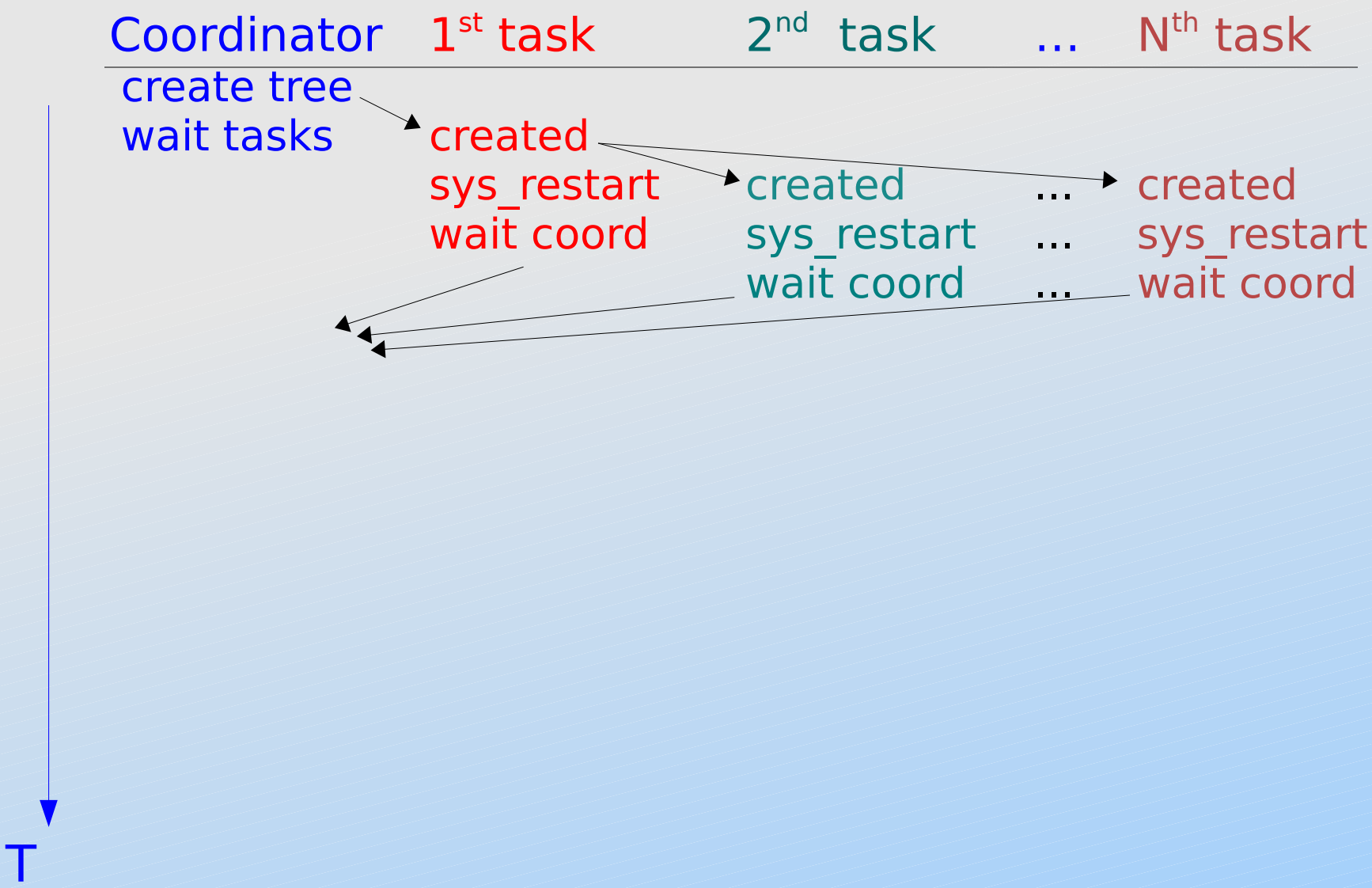

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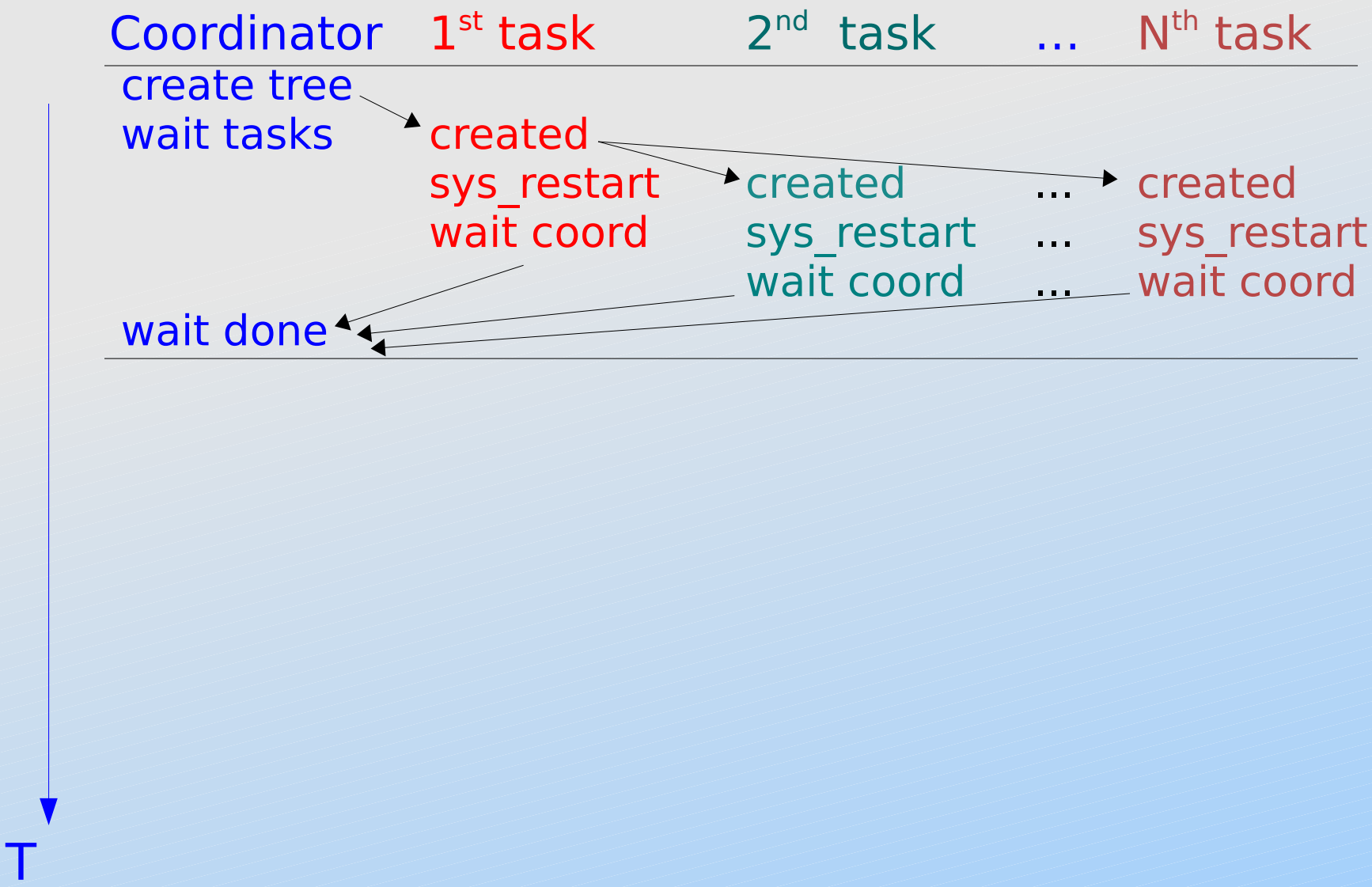

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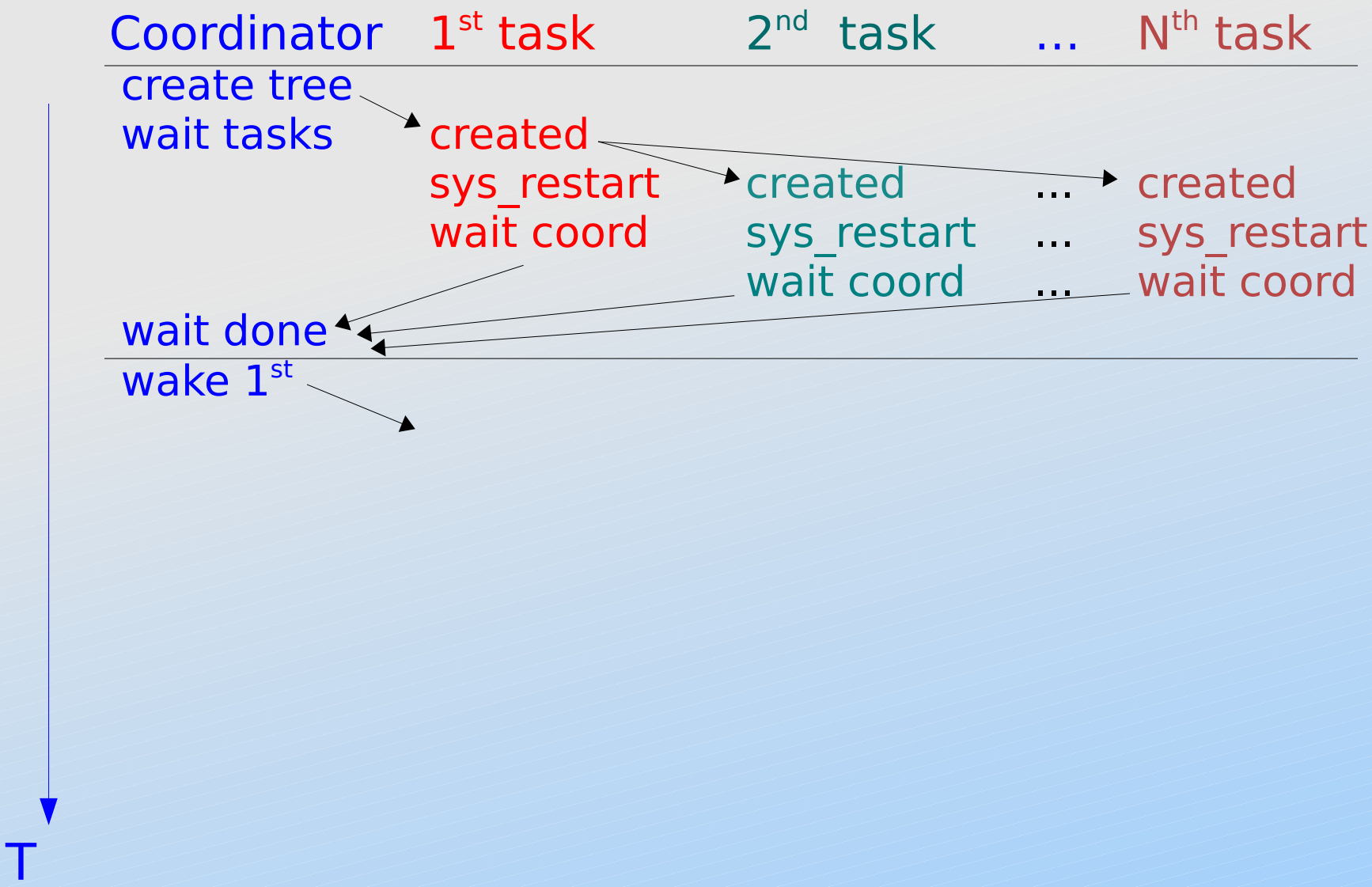

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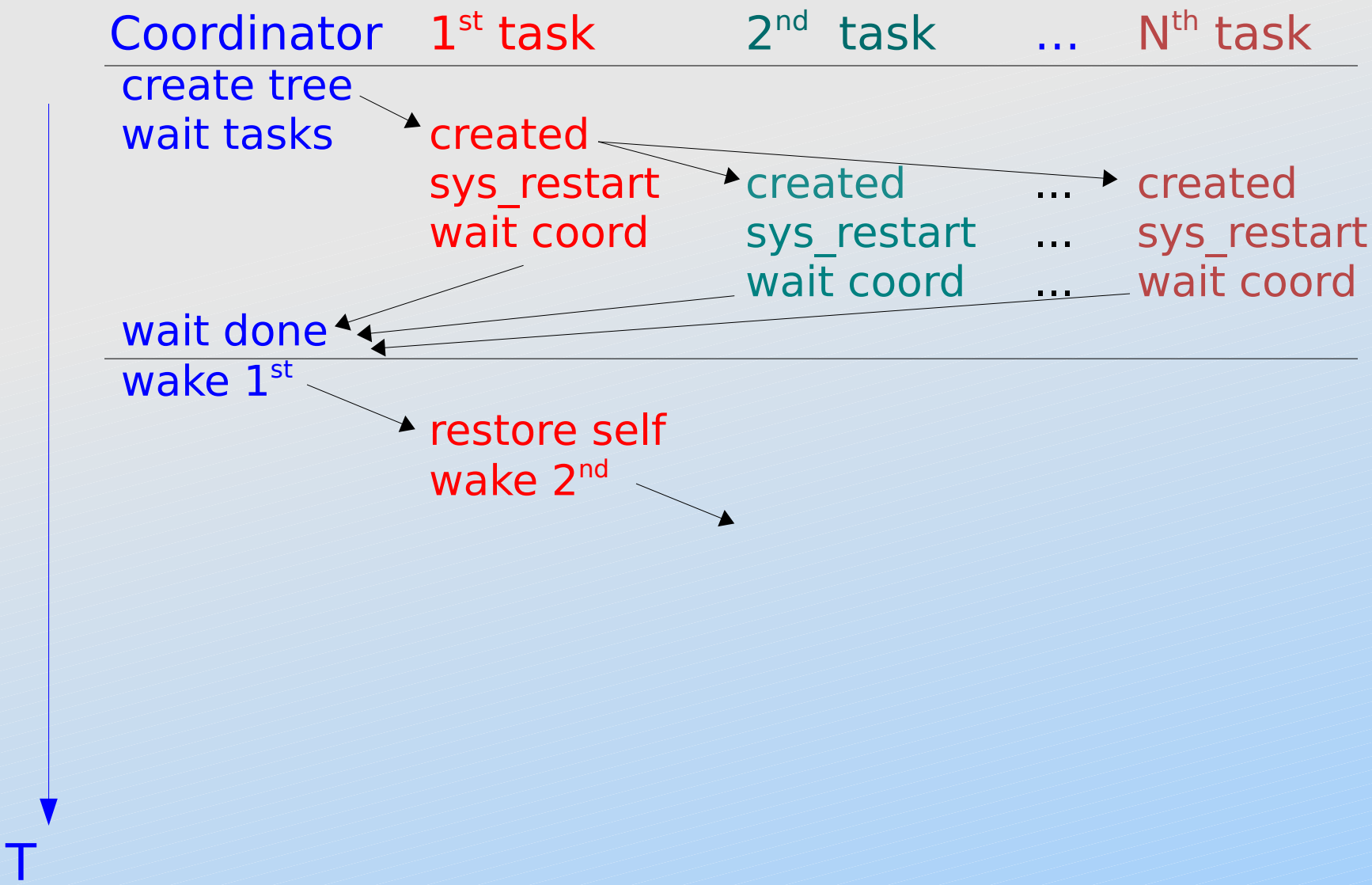

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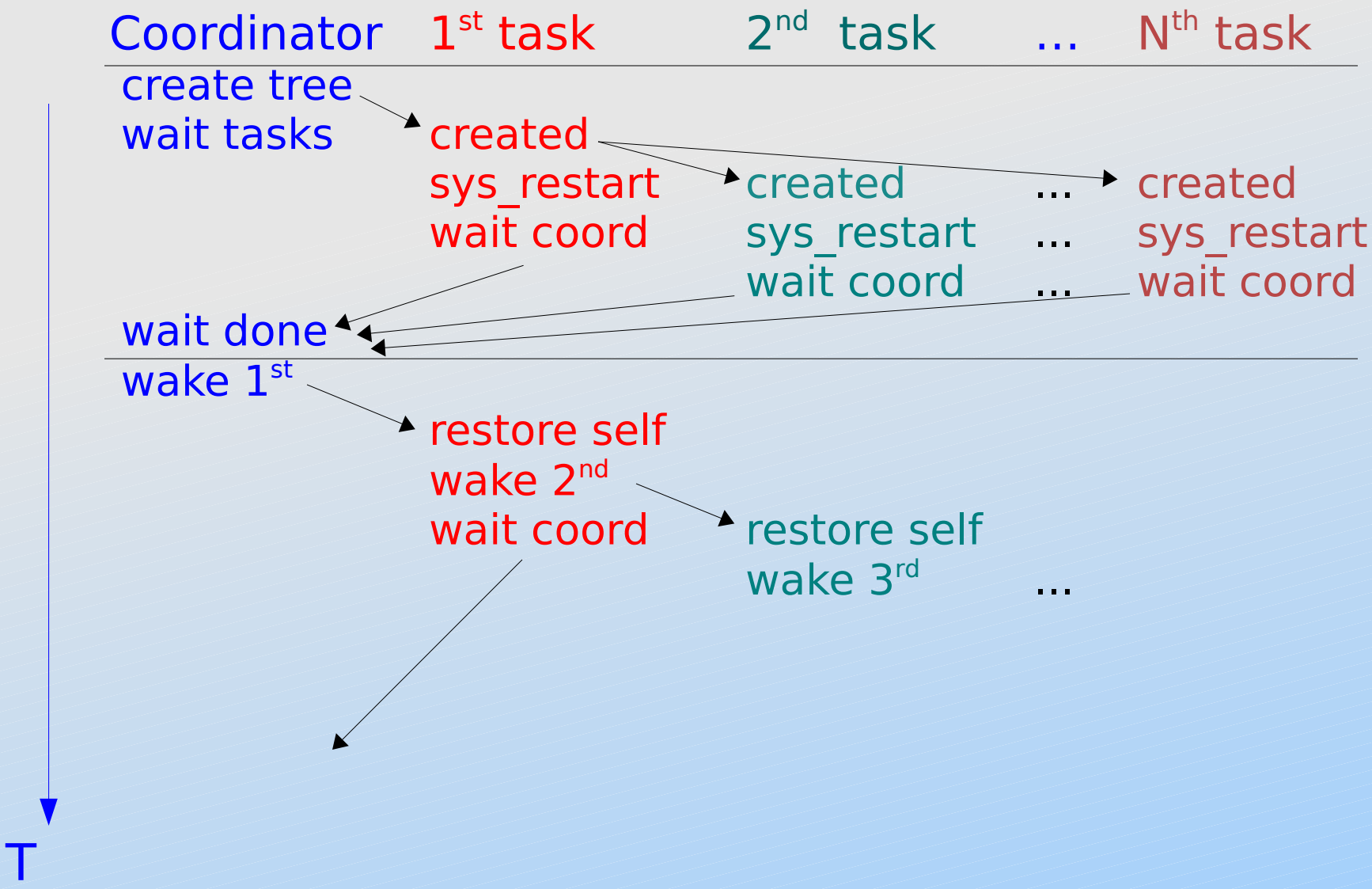

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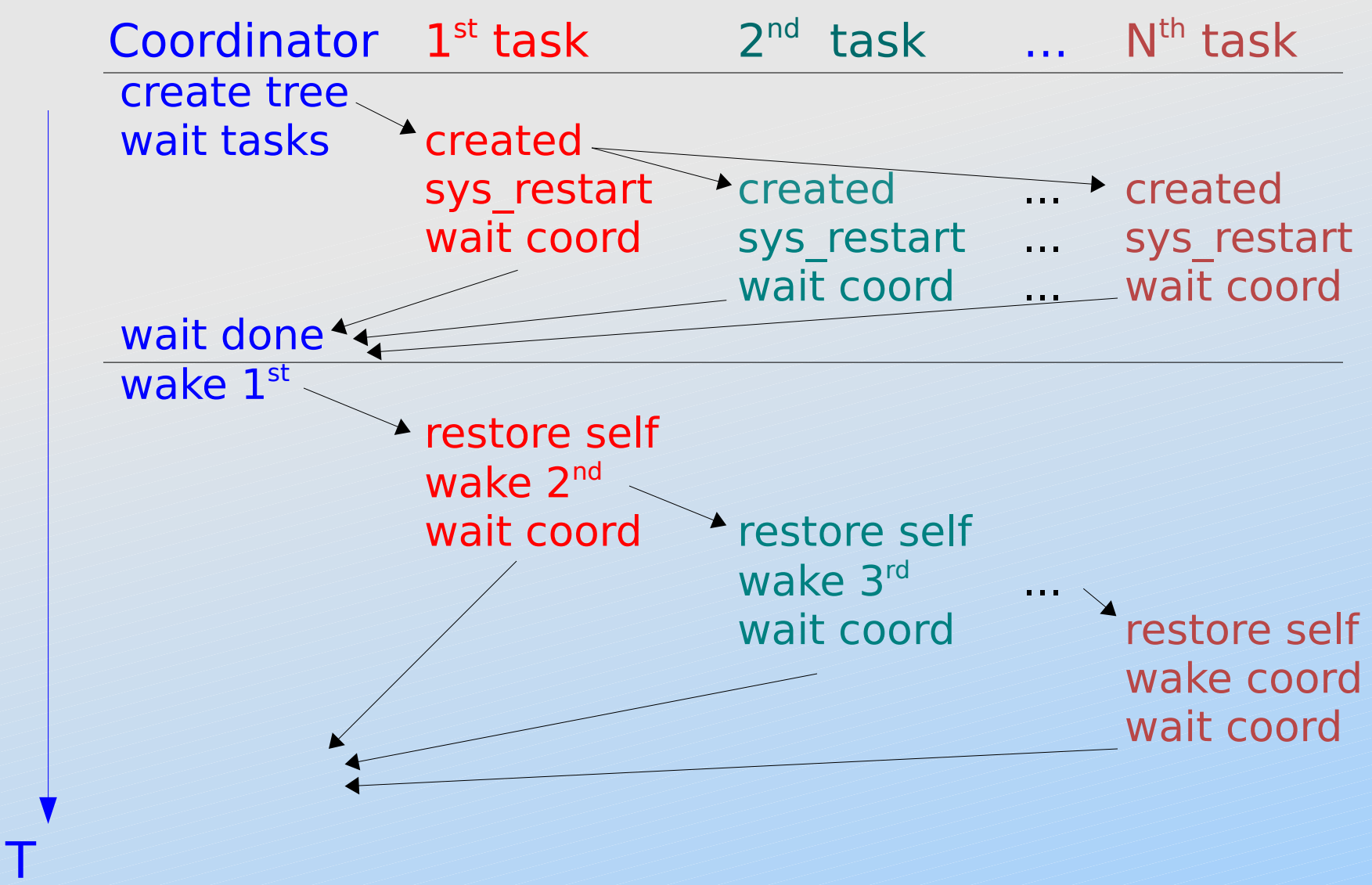

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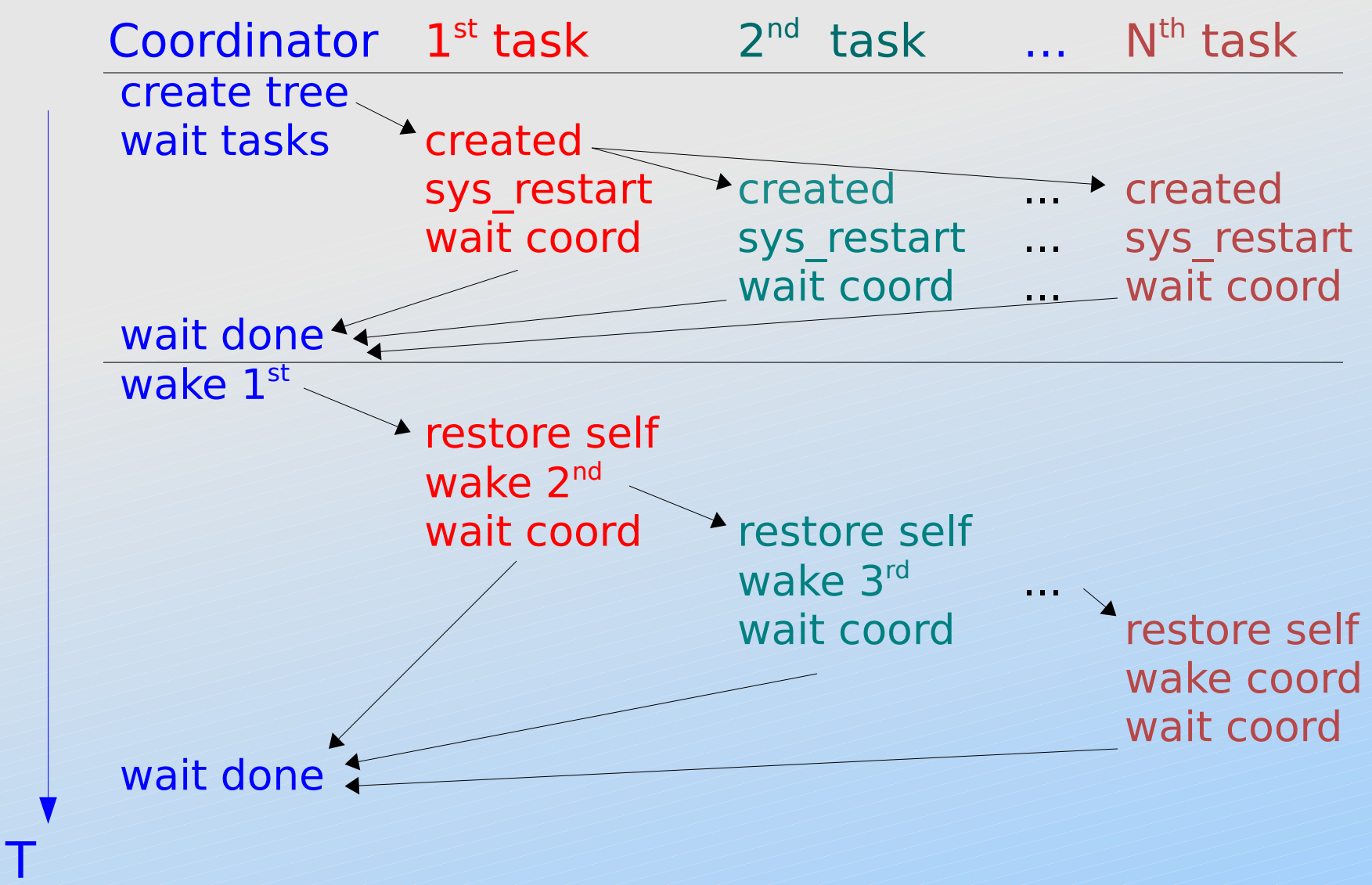

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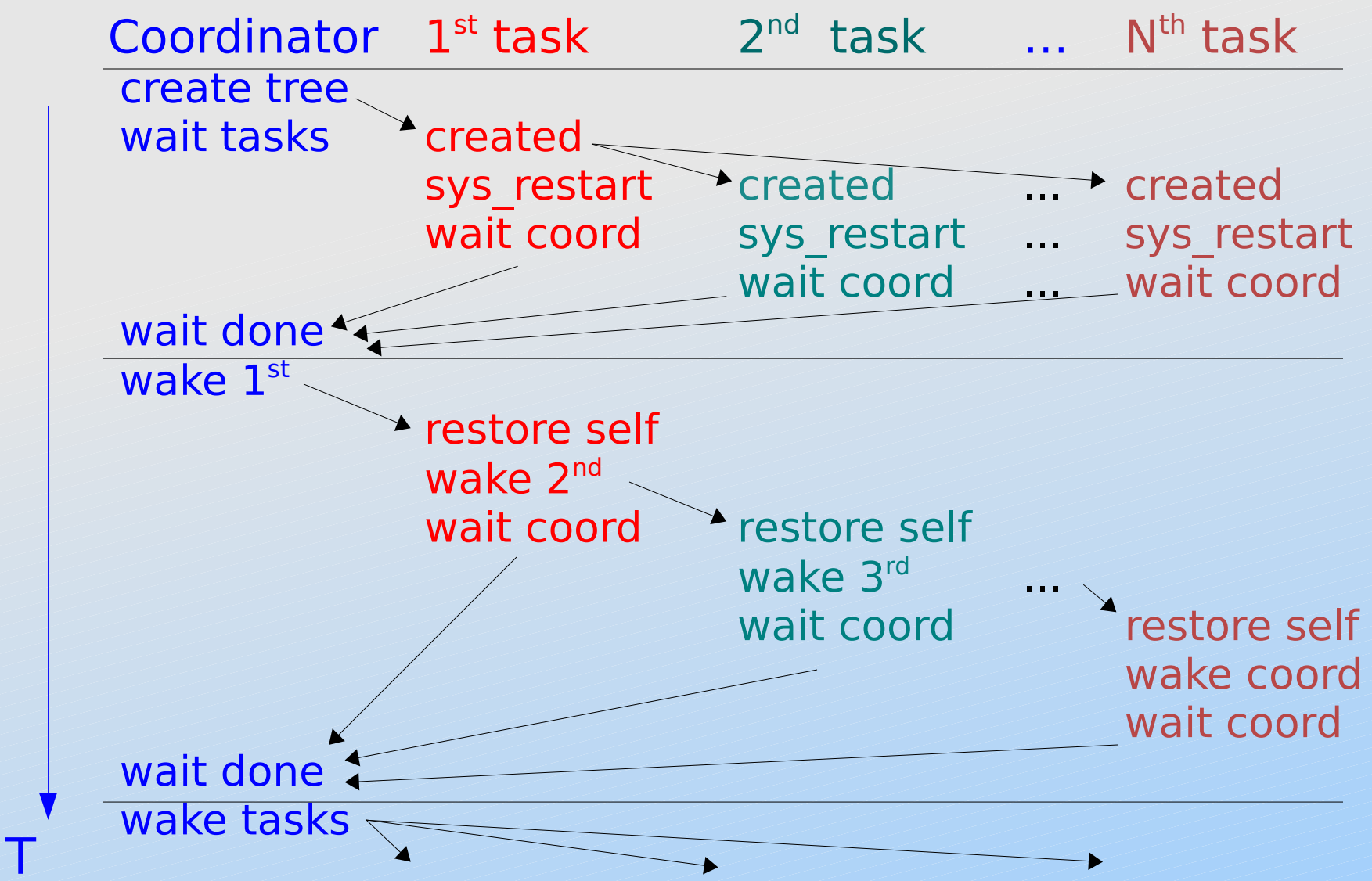

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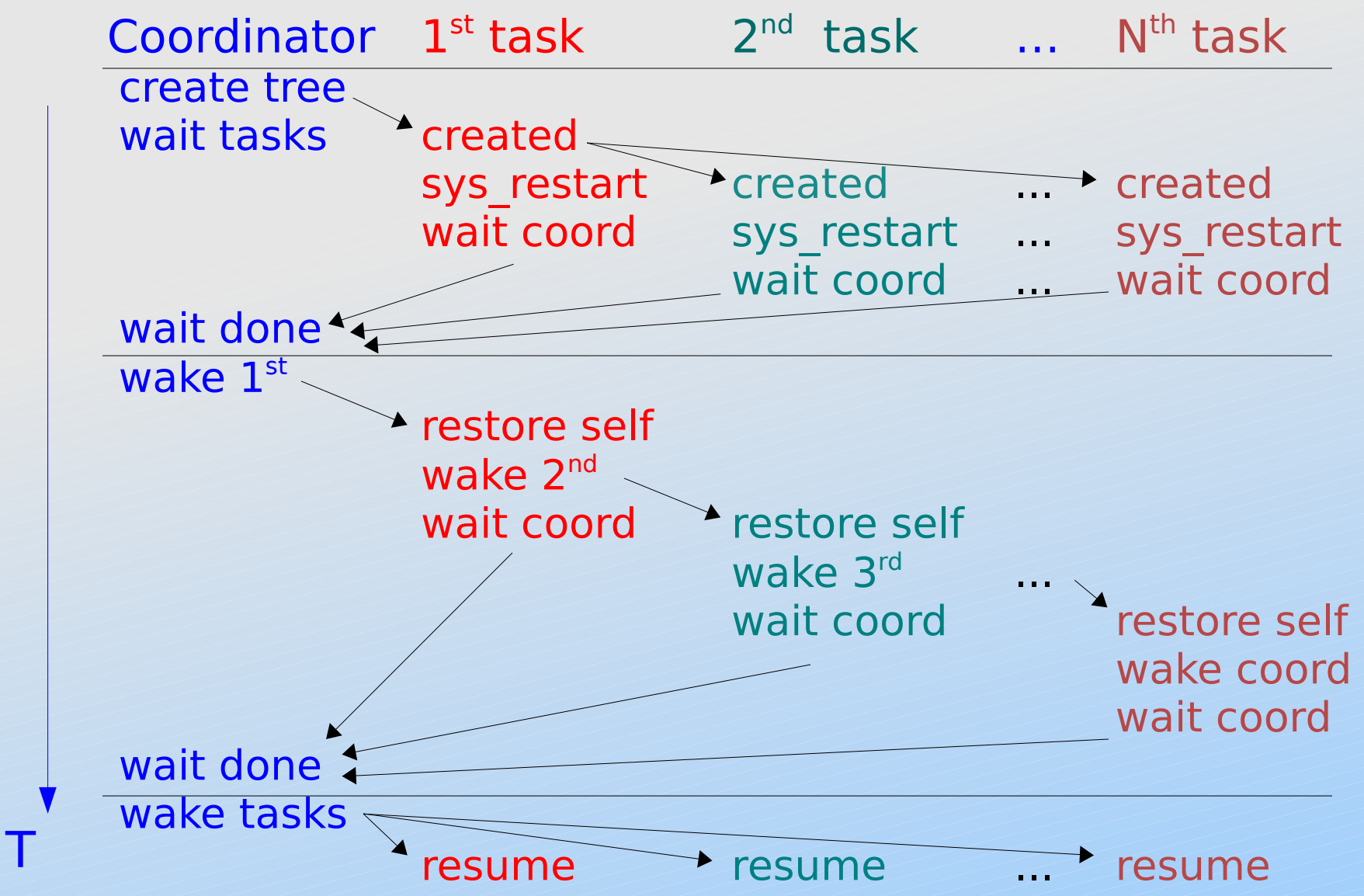


Checkpoint/Restart Compared

Checkpoint	Restart
auxiliary process	restore in context
tasks are passive	tasks participate
detect non-restartable	detect non-secure
non-intrusive (errors)	cleanup (errors)

Checkpoint Image

- The image is a BLOB
  - internals may change over time
  - conversion to be done in userspace
- Designed for streaming
  - for migration, or for image filters: sign, compress, encrypt, convert, etc.

Checkpoint Image

- Representation of kernel data
  - already need to inspect on restart
  - compatibility across kernel versions
  - does not save unnecessary fields
  - unified format for 32/64 bit architectures

Checkpoint Image

- a sequence of object records
- records have header and payload

```
struct ckpt_hdr {
   __u32 type;
   __u32 len;
};

struct ckpt_hdr_task {
   struct ckpt_hdr h;
   __u32 state;
   ...
};
```

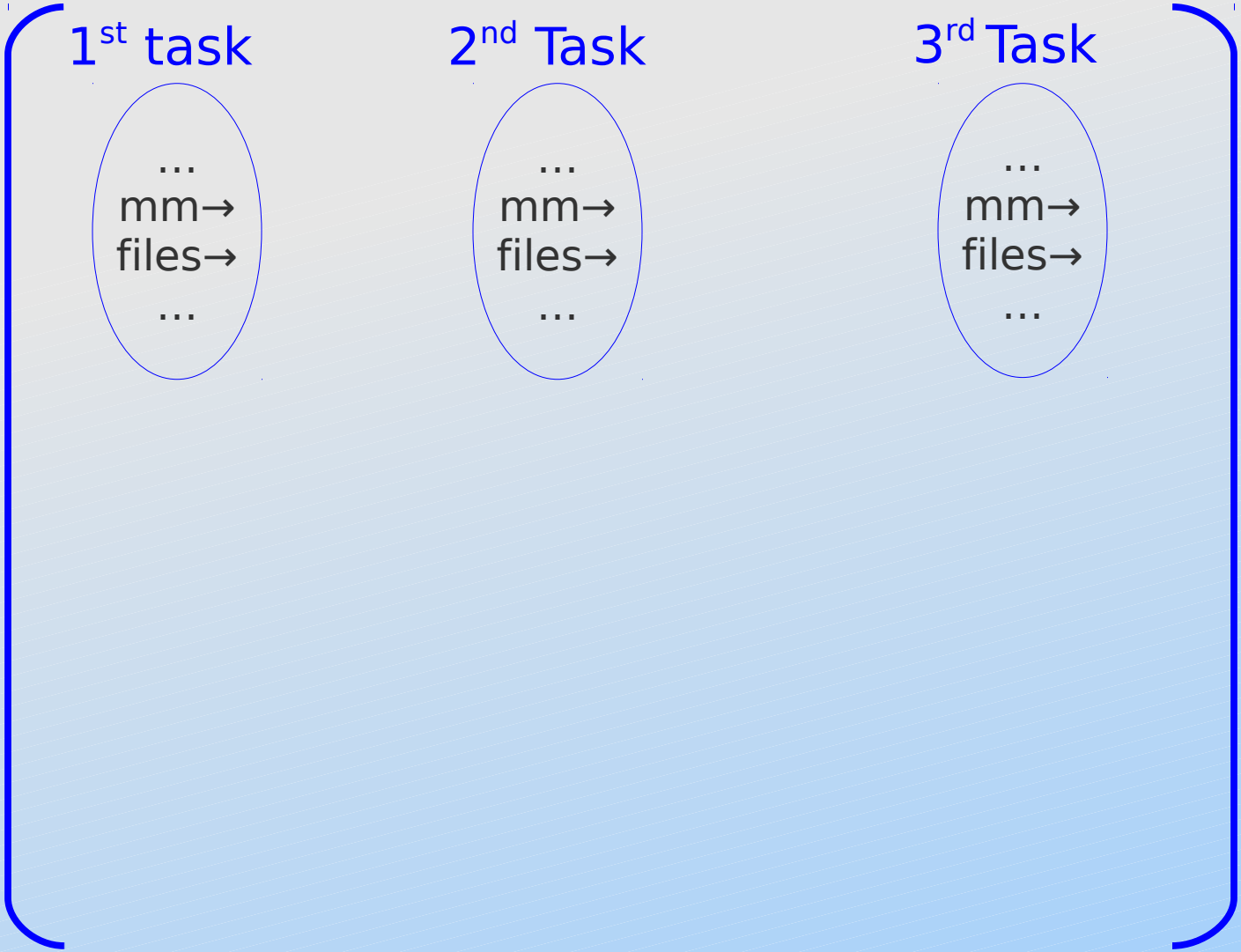
Shared Resources

- Resources in use by multiple tasks
  - open files, namespaces, signals, handlers, memory descriptor
  - only checkpoint/restore once each
  - use a hash-table to track instances

Shared Resources

- Checkpoint:
  - physical pointer → unique tag
  - save before the “parent” object
  - “parent” objects saves only tag
- Restart
  - unique tag → (new) physical pointer
  - restore before the “parent” object
  - use tag in “parent” to locate instance

Shared Resources



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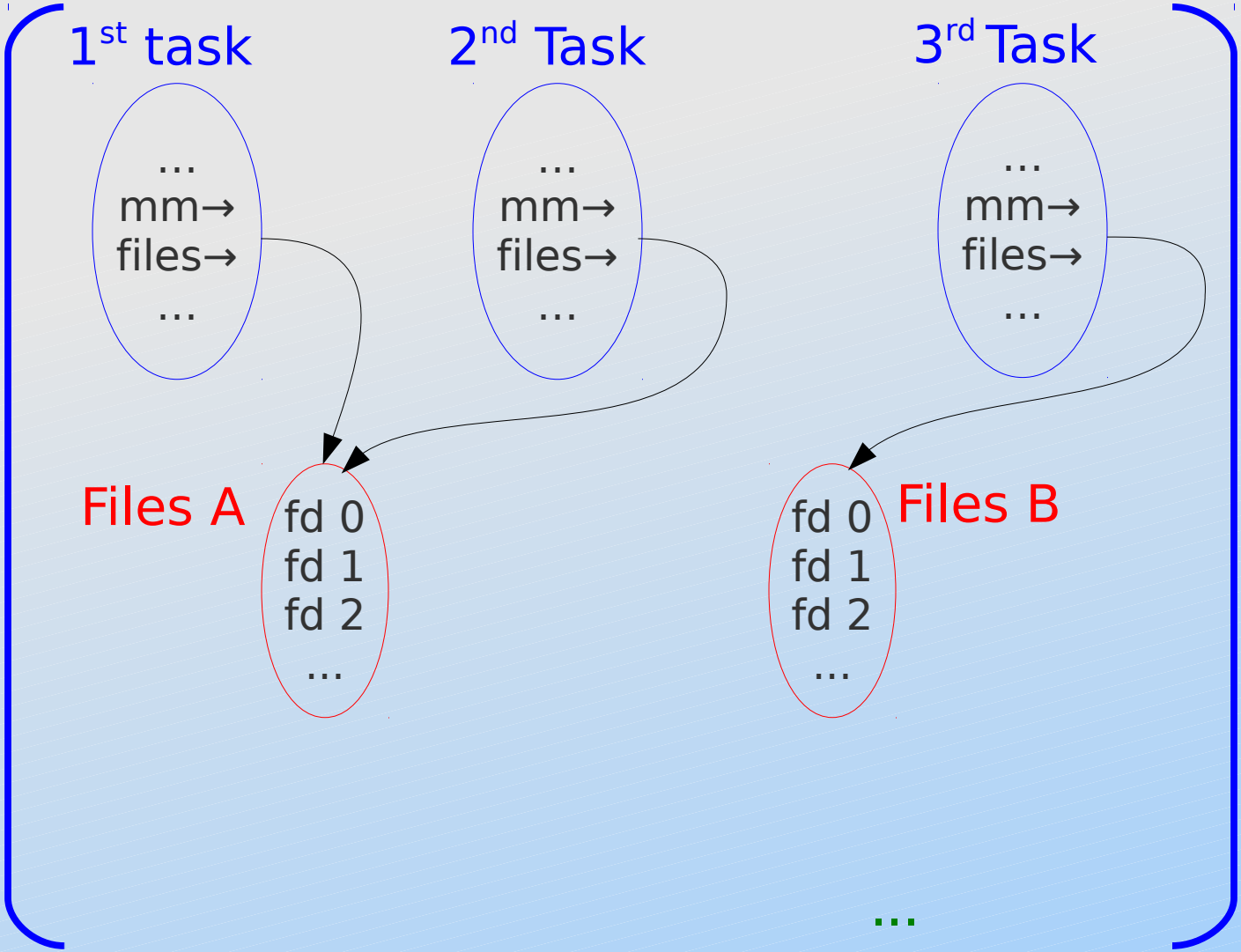

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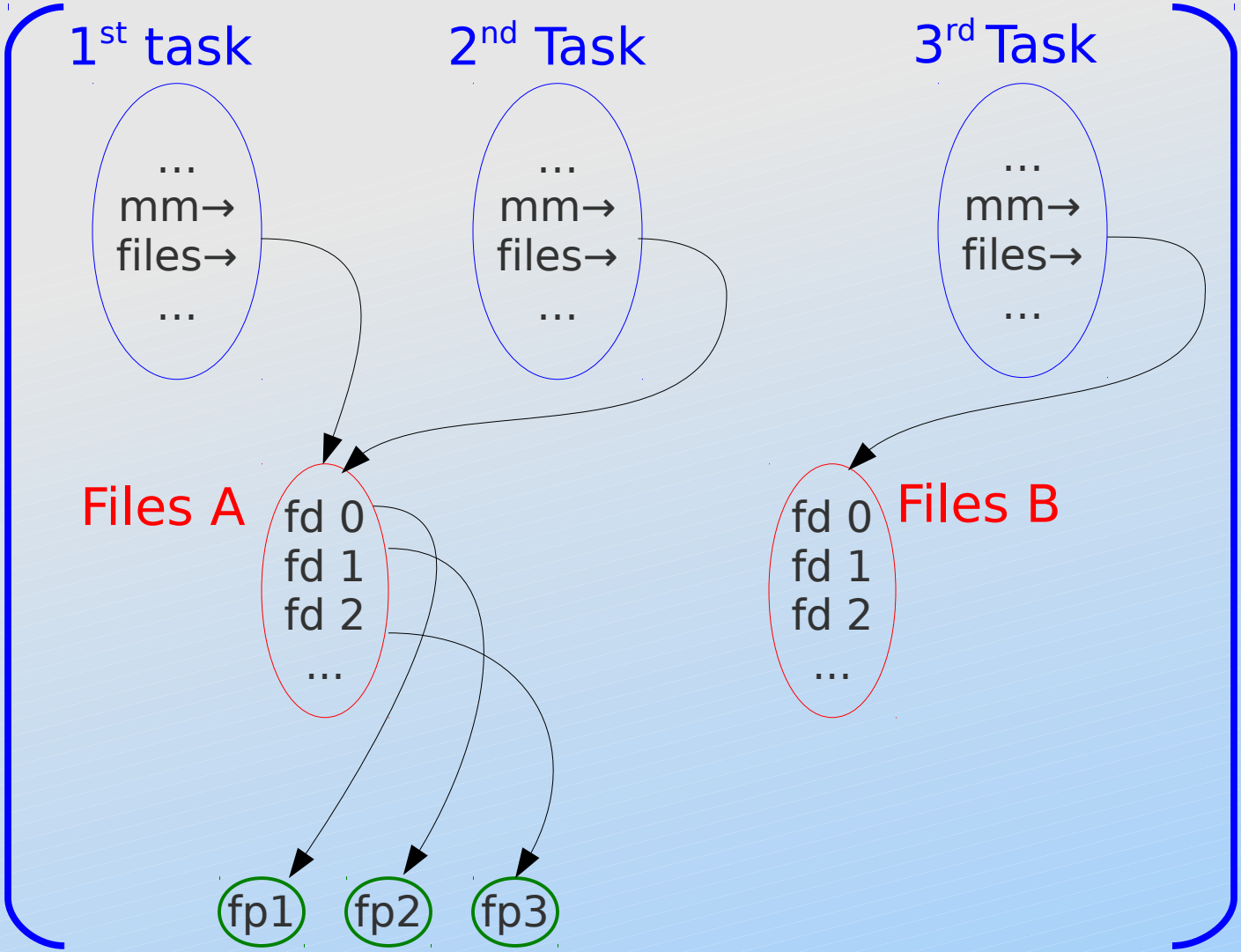

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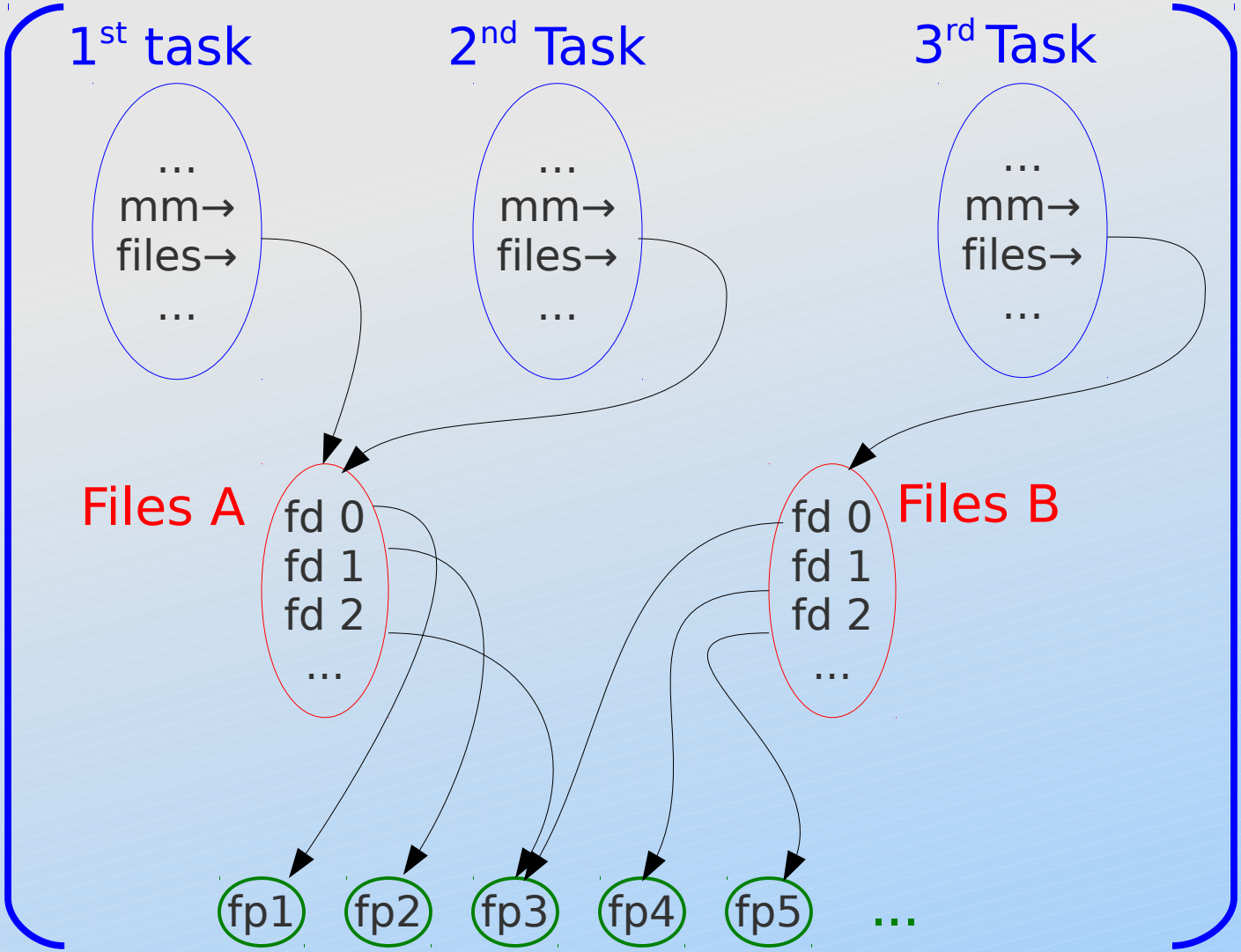
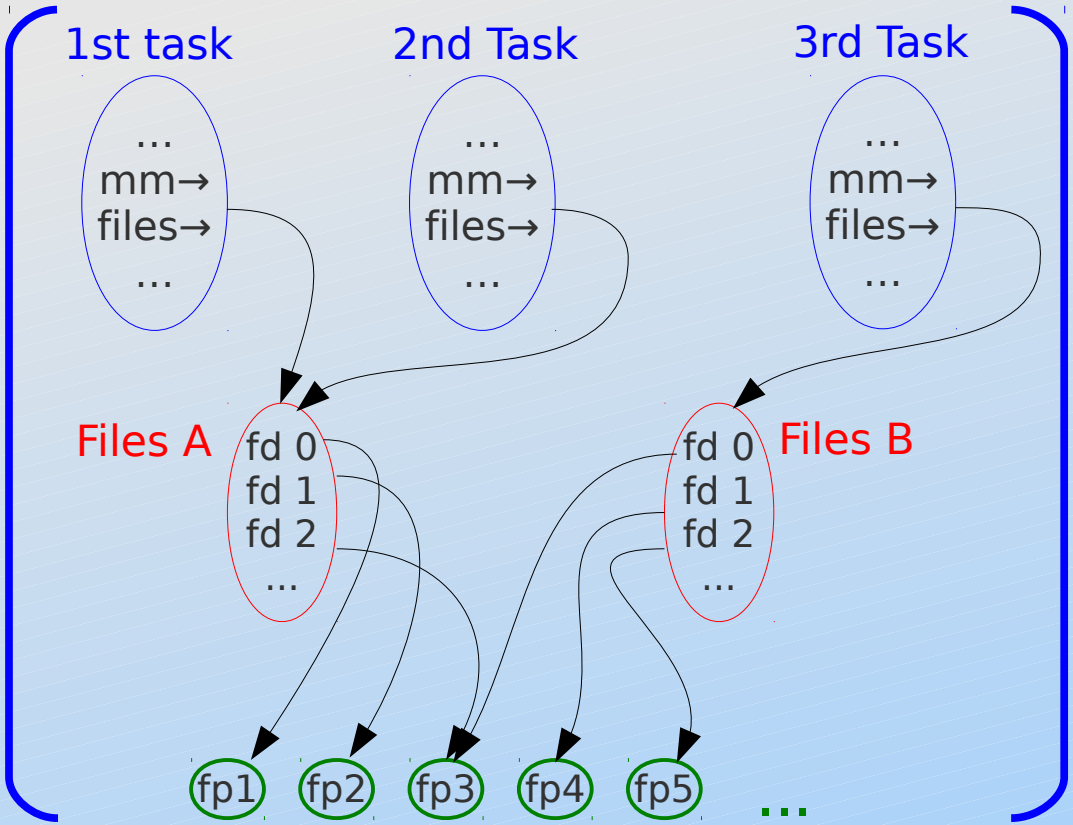


Checkpoint Image Example

...
hdr_mm [1st]
hdr_fd [fp1]
hdr_fd [fp2]
hdr_fd [fp3]
hdr_files [files A]
hdr_task [1st]
...



Checkpoint Image Example

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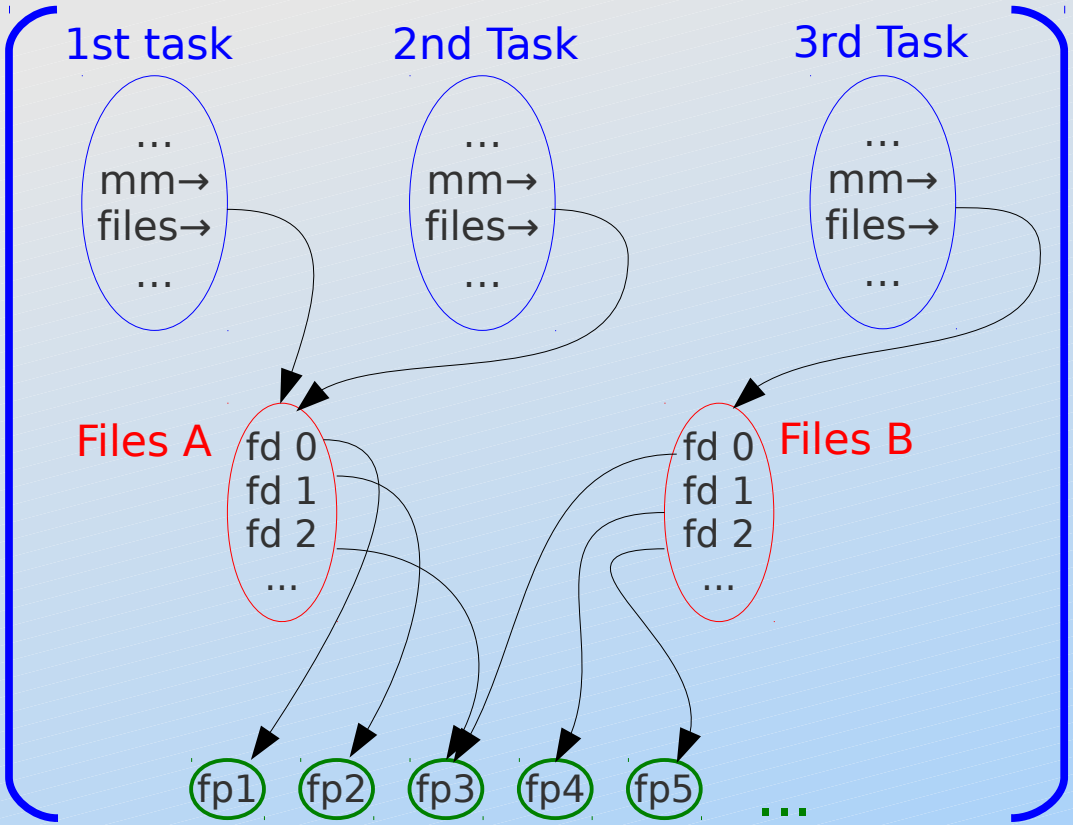
hdr_task [1st]
...
hdr_mm [2nd]
hdr_task [2st]
...



Checkpoint Image Example

...
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hdr_fd [fp1]
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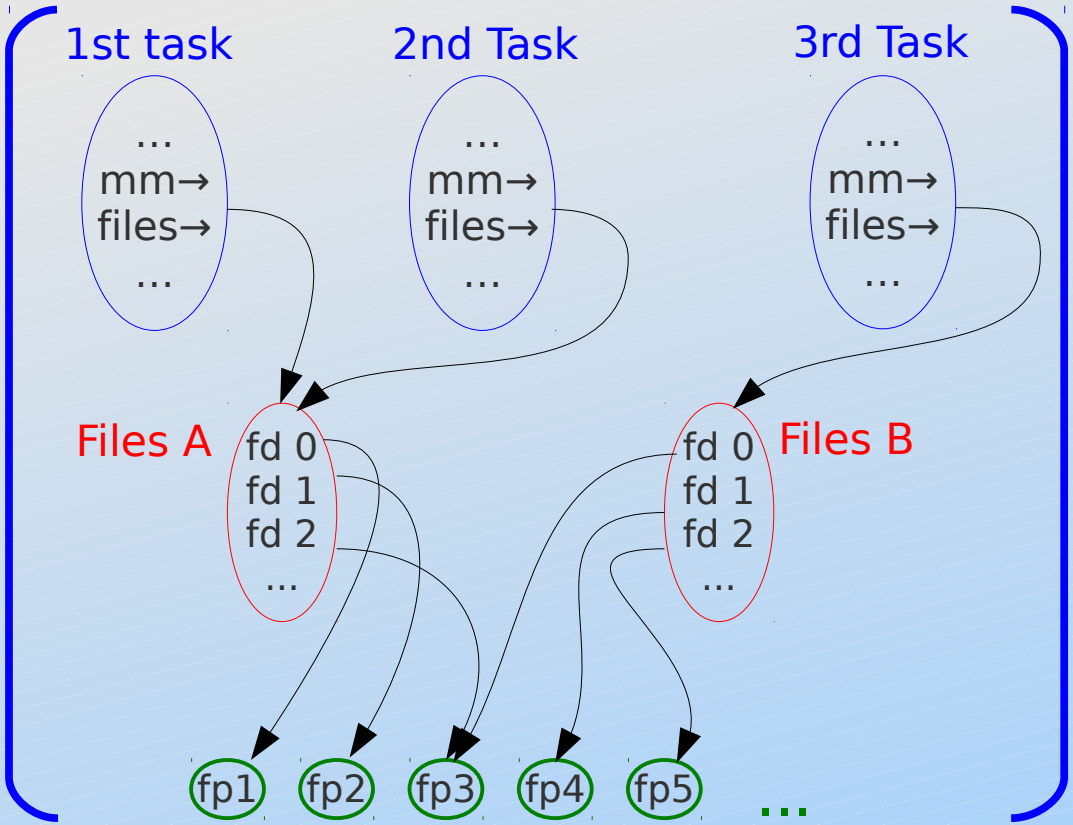
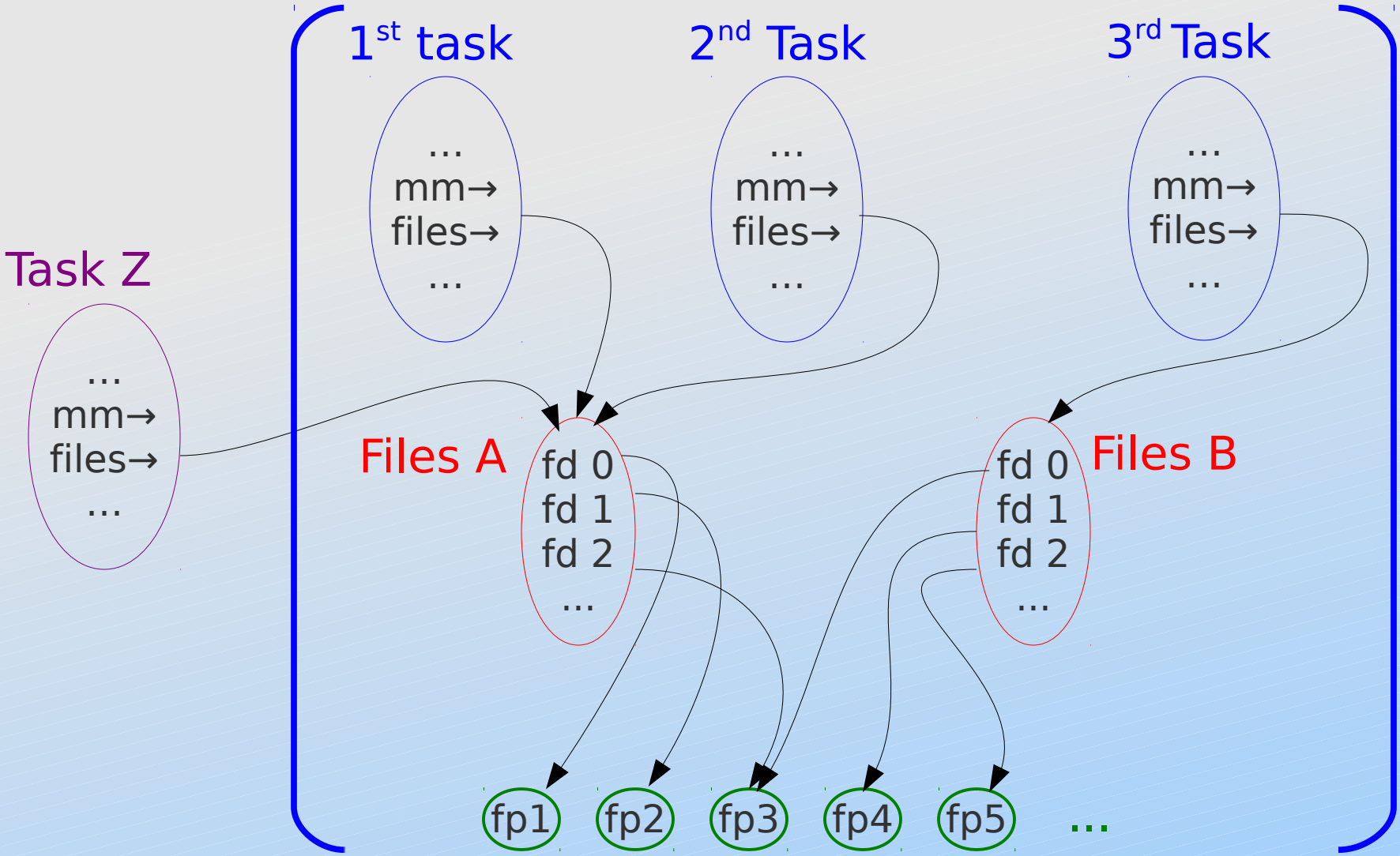
hdr_fd [fp3]
hdr_files [files A]
hdr_task [1st]
...
hdr_mm [2nd]
hdr_task [2st]
...
hdr_mm [3st]
hdr_fd [fp4]
hdr_fd [fp5]
hdr_files [files B]
hdr_task [3rd]
...



Leak Detection

- Resources in use must not be modified from outside the container
  - collect: count reference in hierarchy
  - compare with kernel reference count
  - leverage shared instances repository

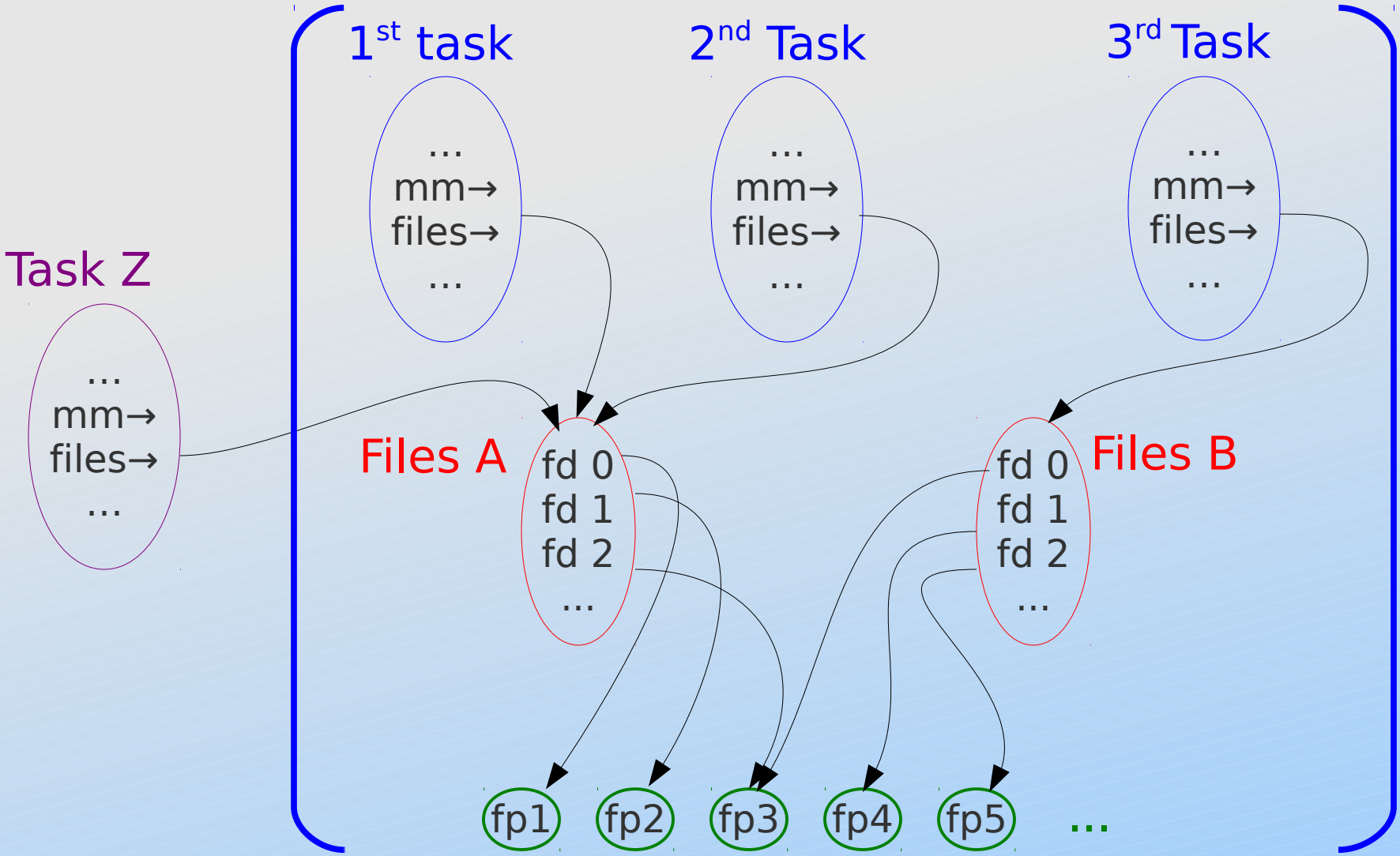
Leak Detection



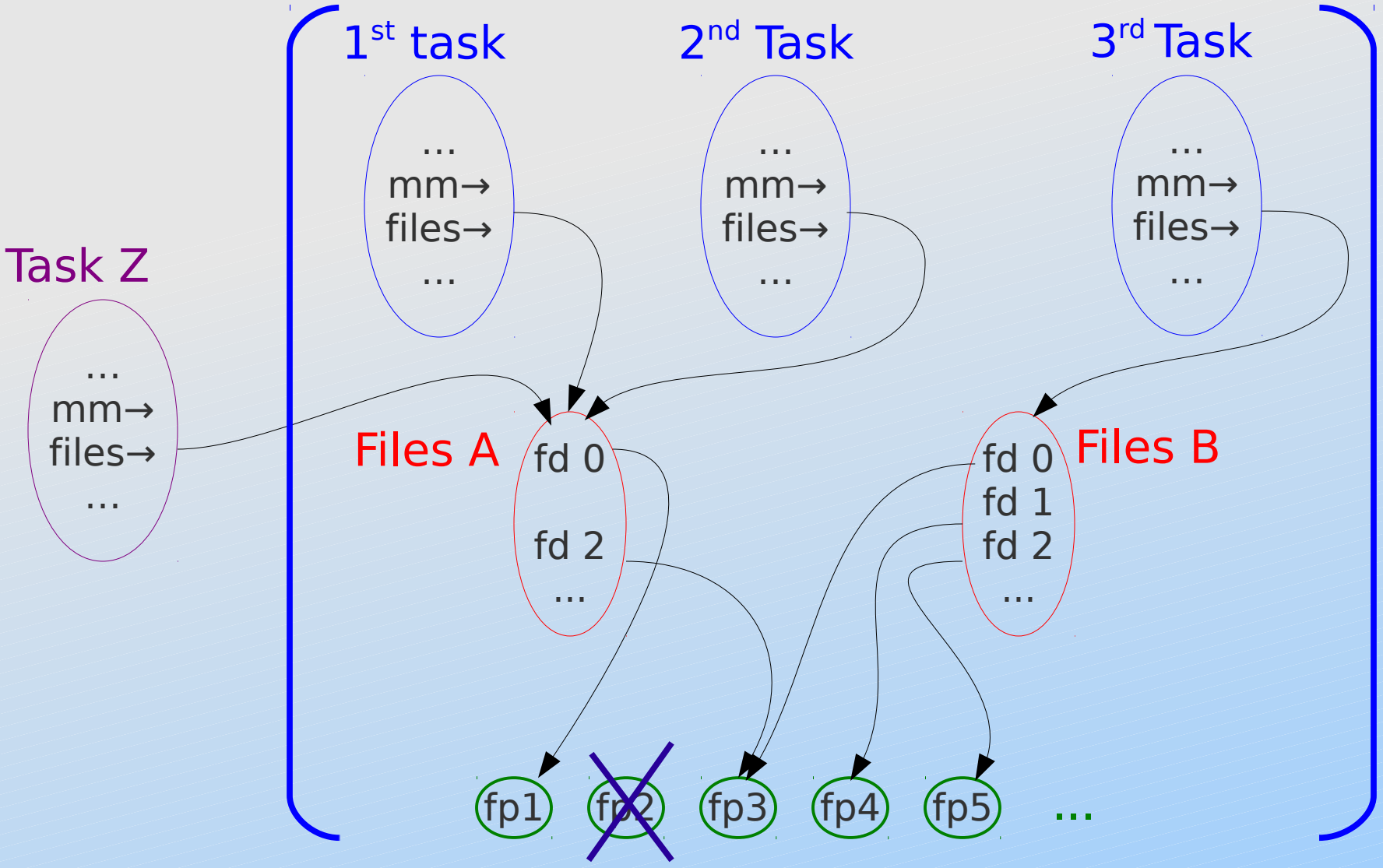
Leak Detection

- Resources in use must no be modified from outside the container
  - collect: count references in hierarchy
  - compare with kernel reference count
  - leverage shared instances repository
- What about races during collection ?

Leak Detection



Leak Detection



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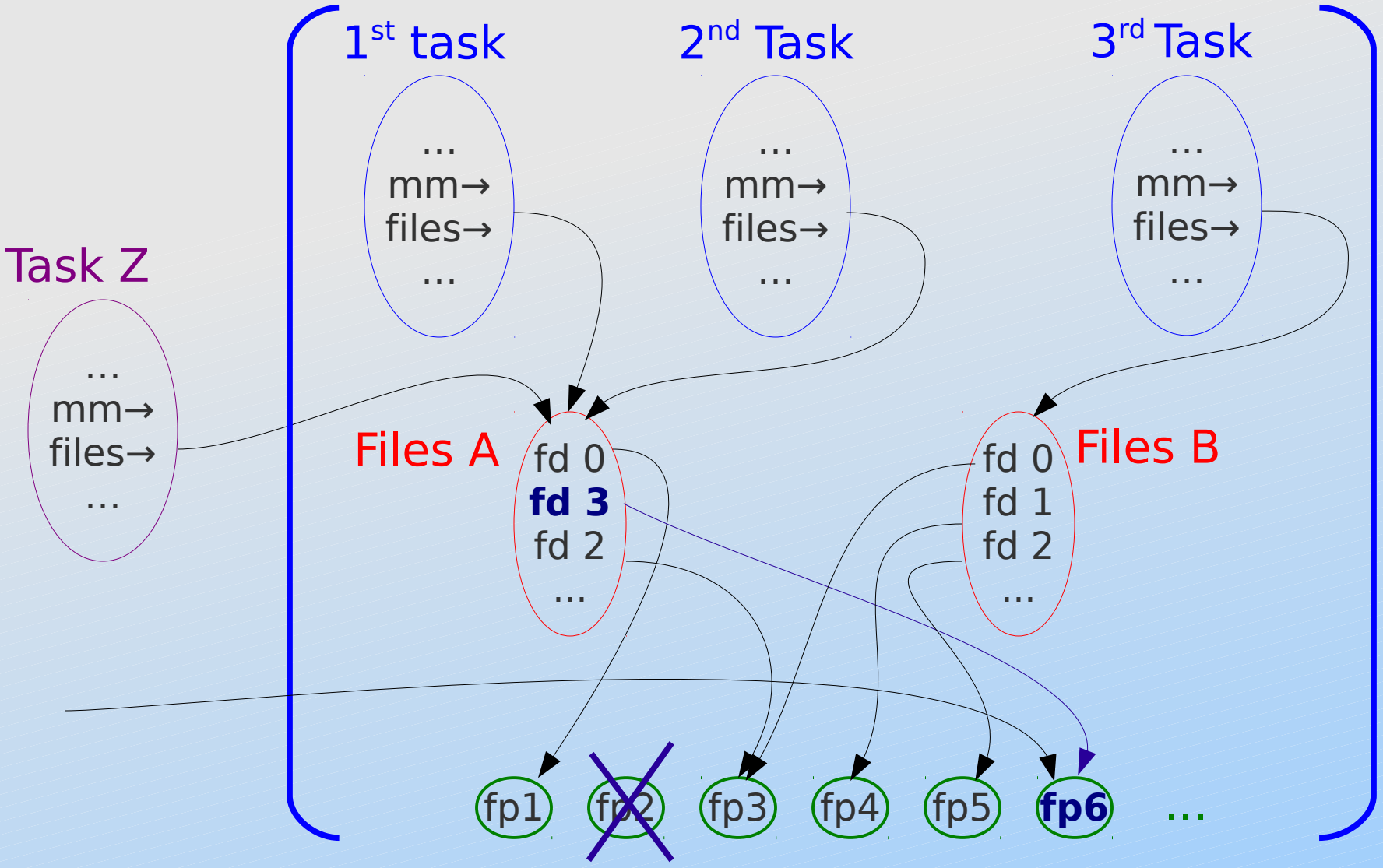
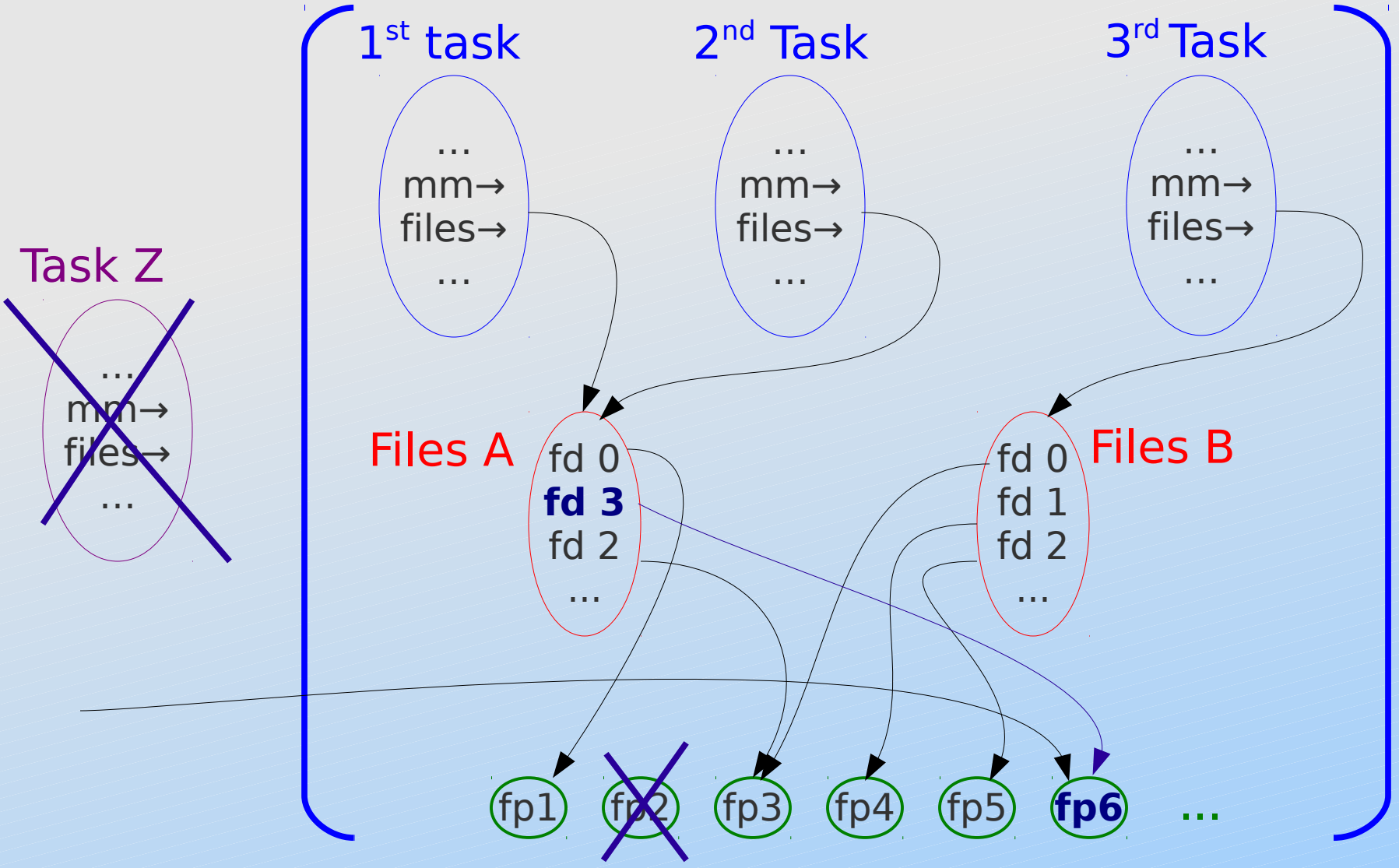


Leak Detection



Error Handling

- When error occurs:
  - syscall reports single error value
  - detailed log written to `@logfd`
  - users can examine the log

Kernel API - Overview

`ckpt_hdr_...()`: record handling (eg alloc/dealloc)

`ckpt_write_...()`: write records/data to image

`ckpt_read_...()`: read records/data from image

`ckpt_msg_...()`: output to log file (and debug)

`ckpt_err_...()`: report an error condition

`ckpt_obj_...()`: manage objects and hash-table

Kernel API – Shared Objects

```
struct ckpt_obj_ops {
    char *obj_name;
    Int obj_type;
    void (*ref_drop)(...);
    int (*ref_grab)(...);
    int (*ref_users)(...);
    int (*checkpoint)(...);
    void (*restart)(...);
};
```

register/unregister object handlers

```
register_checkpoint_obj(ops):
unregister_checkpoint_obj(ops):
```

Current State

- Supported architectures:
  - x86-32, x86-64, s390x, PowerPC, ARM
- Features:
  - see up to date information at
    https://ckpt.wiki.kernel.org/index.php/Checklist
  - experimental integration with LXC

Contributions

- Sukadev Bhattiprolu, Serge Hallyn, Dave Hansen, Matt Helsley, Nathan Lynch, Dan Smith, and myself...
- Suggestion, ideas and reviews from many other people ... Thank You !

Join the Effort !

- Implement more features [kernel]
- Checkpoint optimizations [kernel]
- Convert between kernel versions [user]
- Inspection of checkpoint image [user]
- Plug-in architecture for restart [user]
- ... and more ...

Questions ?

- More information
  - Web page: http://www.linux-cr.org/
  - Git tree(s): git://www.linux-cr.org/git/
  - Email: orenl@cs.columbia.edu

Thanks You !