Enforced Deterministic Execution in the Linux Kernel

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Parallel Programming

- Hardware transitioning from single to multiple cores
- Software is following suit
- Nondeterministic programming model dominates
- Easy to write programs
- Difficult to write correct programs

Nondeterminism

- Race conditions
  - Low-level races (e.g. accessing linked list without proper locking)
  - High-level races (e.g. “time of check to time of use” security exploits)
- Deadlock
- Unpredictable

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- Record-and-replay debuggers
- Deterministic environments
  - Special hardware
  - Custom programming languages/compilers
  - Userspace deterministic schedulers

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    Arbitrary (unpredictable) schedules, buggy or malicious programs can interfere with scheduler

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- Novel programming model: "naturally and pervasively deterministic"
- High-level user library emulates many familiar abstractions
  - Fork/join
  - Pthreads-like API
  - In-memory, deterministic file system

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- Runs on conventional hardware (x86)
- Programs written in general-purpose languages (C)
- Evaluated compute bound applications against Linux
  - Coarse-grained applications run efficiently with little overhead
  - Fine-grained parallel applications have unacceptable overhead

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Let's give it a shot...

Outline

- Introduce parallelism and Determinator
- **Recapitulate Determinator paper**
- Design goals/non-goals for deterministic Linux
- Implementation
- Evaluation
- Conclusion

Sources of nondeterminism

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  - Explicit nondeterminism
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  - Nondeterministic scheduling abstractions
  - Globally shared namespaces

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- Determinator turns these inputs into explicit I/O
  - Controllable
  - Can be recorded for replay

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  - Eliminate shared memory, no file system access
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  - Eliminates read-write races
  - Write-write races detected by OS, generate exception

Shared state

```
struct actor_state actor[nactors];

update_actor(i)
  // Examine other actor state and update
  //  actor[i] accordingly.

main()
  // Initialize actor[] state
  for(time = 0; ; time++)
    for (i = 0; i < nactors; i++)
      if (thread_fork(i) == IN_CHILD)
        update_actor(i);
        thread_exit();
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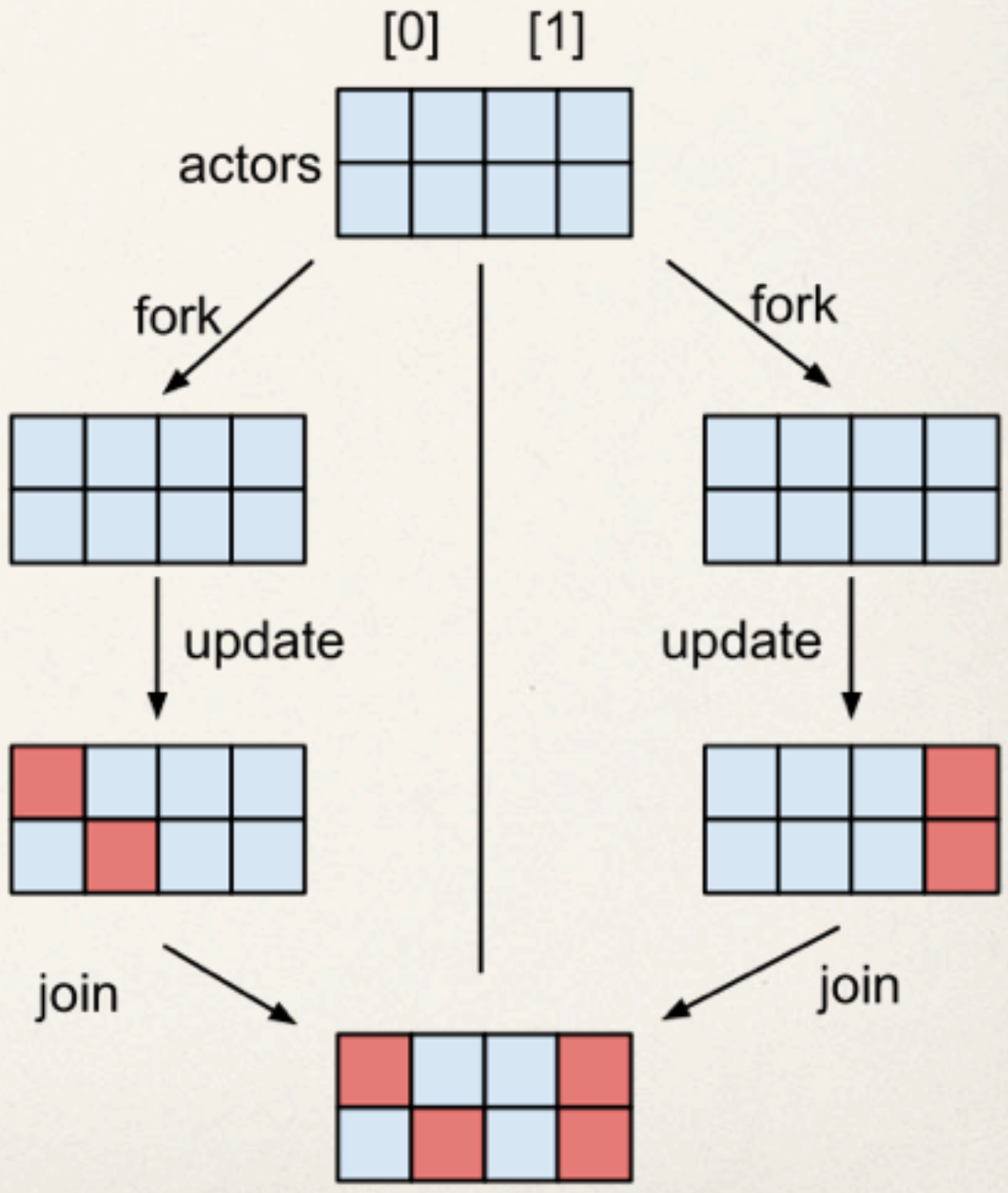

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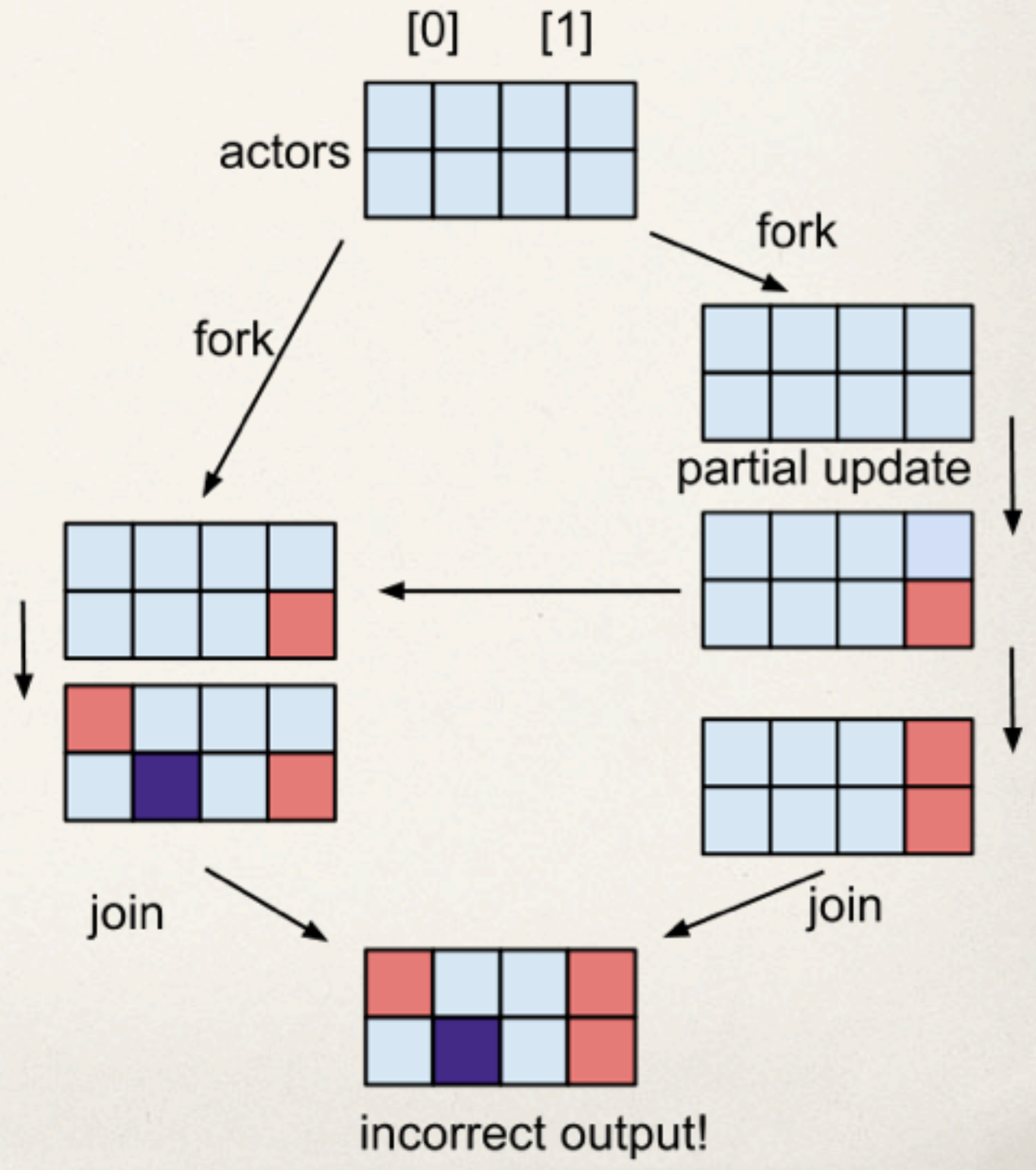

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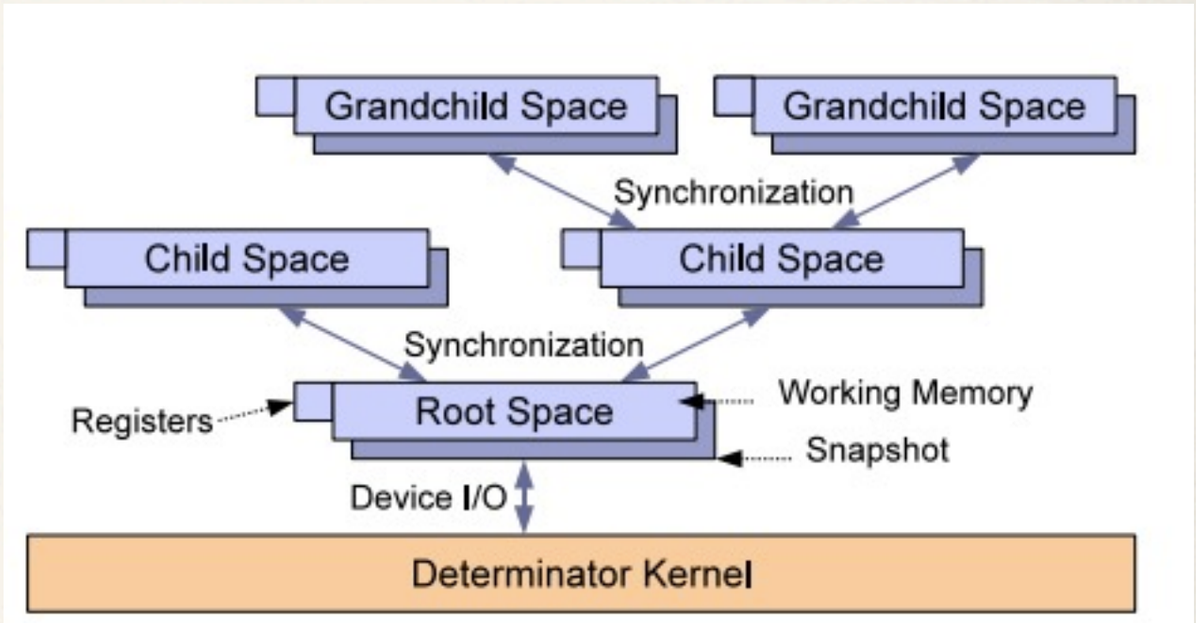
- Determinator doesn't choose identifiers, user programs do
- E.g. fork() takes explicit process ID as input

Determinator Kernel

- Nested process model (hierarchical)
- Interact only with parent and children
- Children cannot outlive parent
- No shared memory, file system
- No direct I/O access
- Only the *root* process may access I/O



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  - “Merge” memory changes since last snapshot
- Ret() - Interacts with parent
  - Blocks execution until parent issues a Put

Kernel Interface

- Put and Get take an explicit child process ID argument
- Put and Get block until a child issues a Ret
- Processor exceptions (e.g. divide-by-zero) generate implicit Ret
- These requirements ensure synchronization at well defined points
- Put/Get/Ret "make the [process] hierarchy a deterministic Kahn network"

High-level Library

- Similar to standard C library
- Emulate Unix-style abstractions
- Process/thread management
- In-memory file system with Unix-like interface
- I/O facilities (stdin/stdout via in-memory file system)

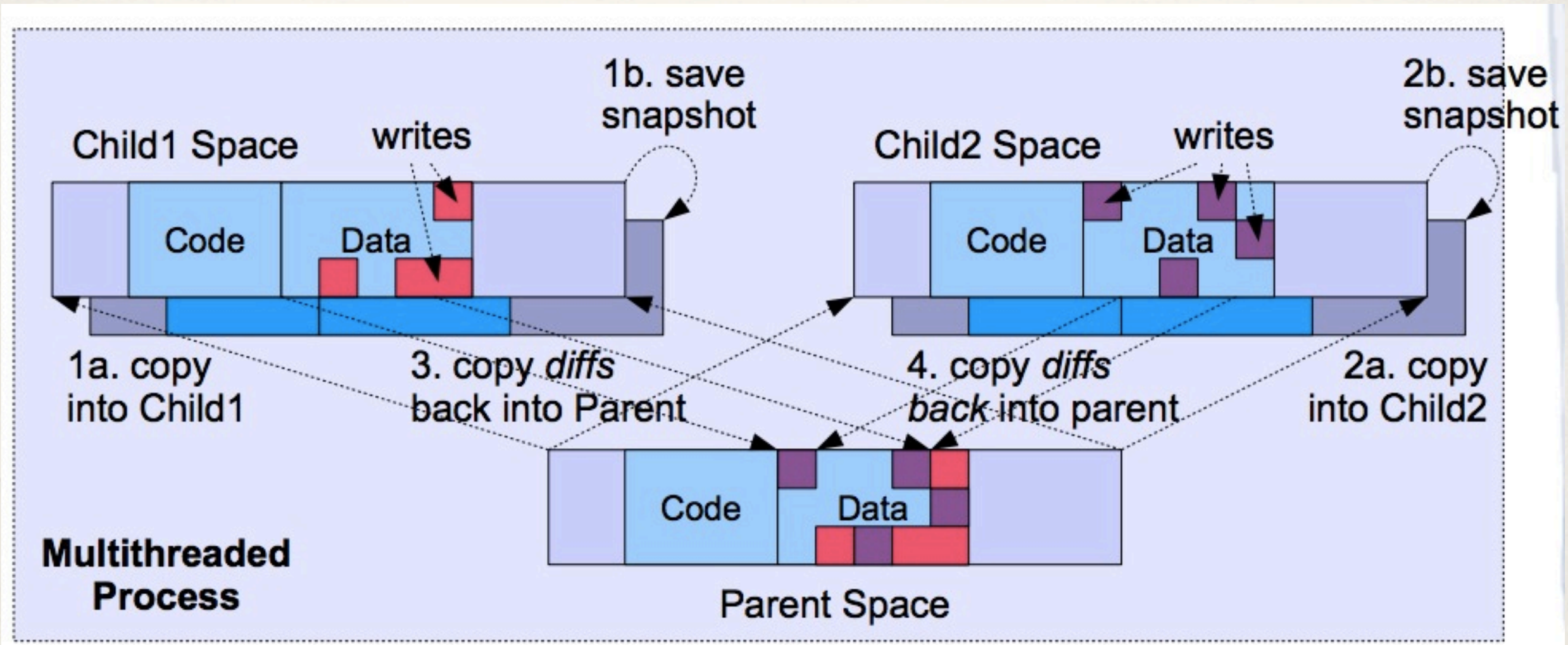
Example: fork/join/exec

- To fork a thread, use Put to snapshot the parent's virtual memory image into a new child and starts the child
- To join on a thread, issue a Get to merge the child's virtual memory changes into the parent
- To exec, the user library forks a new child, reads the new executable from the in-memory file system into the child, then starts the child

Example: Snapshot/Merge

- Snapshot duplicates page tables via copy-on-write into the child
- Creates second duplicate as a reference for Merge comparison
- Merge does a three way diff
- Examine page table entries: check dirty bits
- Only do byte-by-byte comparison when parent and child page table entries are dirtied

Example: Snapshot/Merge



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Design Goals

- We wish to make x86_64 Linux *deterministic*
- Adapt Determinator's kernel to Linux
- Legacy nondeterministic applications shall run alongside deterministic applications
- Legacy applications must be rewritten
- Write high-level user library as Determinator does
- Improve in-memory file system capabilities

Design Non-goals

- May not apply all of Determinator's features
  - Distributed computing
  - Put/Get support instruction limits, copying child subtree
- Linux features may be restricted
  - Huge pages (4MB vs 4KB)
  - Shared library support

Challenges

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- All challenges identified by Determinator apply
- Additionally, Linux supports signals, pipes, System V IPC
- Process model too flexible (reparenting)
- How to allow nondeterministic applications?
- Can't have only *root* be nondeterministic
- Can't use standard C library: uses nondeterministic syscalls

Challenges

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- Linux has many abstraction layers
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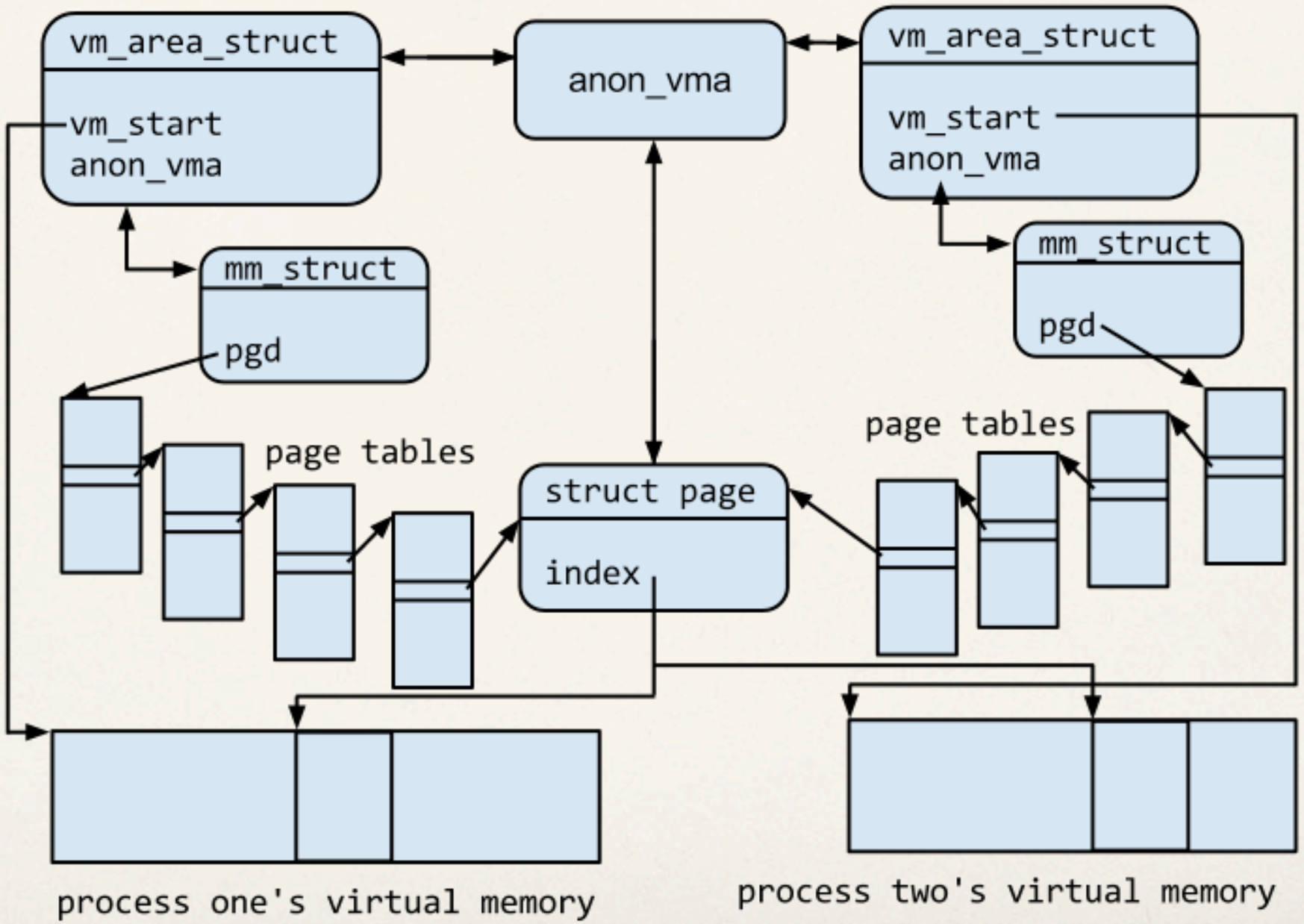
- Determinator only deals with page tables
- Linux has many abstraction layers
- Supports memory mapped files, huge pages, swapping to disk
- These are *implementation* challenges for a first time Linux kernel developer

Challenges: memory subsystem



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