Deterministic Futexes Revisited

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Futexes

- ***Futexes***: underlying mechanism for thread synchronization in Linux
- libc provides:
  - Mutexes and Condition Variables
  - Semaphores, Reader-Writer Locks, Barriers, …
- Linux kernel provides system calls to:
  - suspend the calling thread
  - wake a given number of waiting threads
- First prototype in Linux kernel version 2.5.7

Futexes

- Linux Futex API

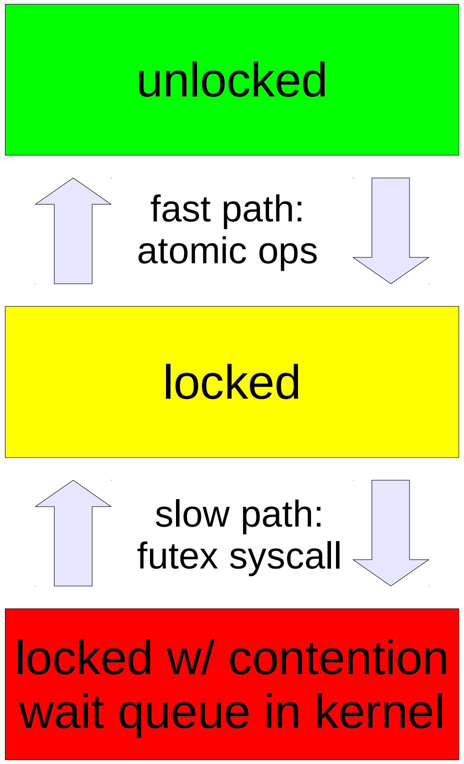
```
#include <linux/futex.h>

int SYS_futex(int *uaddr, int op, int val,
    const struct timespec *timeout,    int
*uaddr2, int val3);
```

- Operations
  - **FUTEX_WAIT** Suspend calling thread on futex `uaddr`
  - **FUTEX_WAKE** Wake `val` threads waiting on futex `uaddr`
  - **FUTEX_REQUEUE** Move threads waiting on `uaddr` to `uaddr2`
  - … more operations available → see `FUTEX(2)` man page

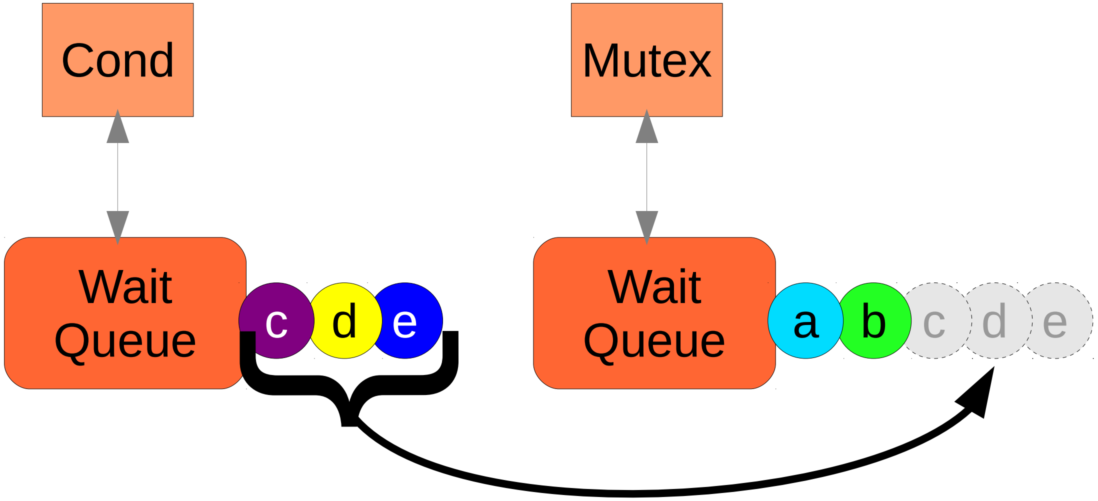
Mutex Example

- `mutex_lock` / `mutex_unlock`
  - Fast path: use atomic operations
    to change a 32-bit integer variable in user space
  - No system call involved!
- `mutex_lock` on contention
  - Atomically indicate pending waiters
  - **`futex_wait`** system call
    - Look-up wait queue
    - Check futex value again
    - Enqueue calling thread in wait queue
    - Suspend calling thread
- `mutex_unlock` on contention
  - **`futex_wake`** system call
    - Look-up wait queue
    - Wake first waiting thread



Condition Variable Example

- `cond_signal/broadcast`



  - Atomically increment futex value
  - Call **`futex_requeue`** to move one/all waiters from condition variable wait queue to mutex wait queue

Futexes

- Futex ↔ generic *compare-and-block* mechanism
- Implement POSIX synchronization mechanisms in user space

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- But:
  - Can we use futexes in real-time systems?
  - WCET?
  - Interference?
  - Determinism?

Outline

- Linux implementation
- Our OSPERT 2013 approach
- Requirements for determinism
- Our new approach
- Discussion

Linux Implementation

Linux Implementation

- Hash of *shared* wait queues
  - `num_cpus` x 256 hash buckets
  - all operations in O(1) time
- Wait queues
  - Priority-sorted linked list
    - O(n) find
    - O(p) insertion
    - O(1) removal
- Locking: per hash bucket

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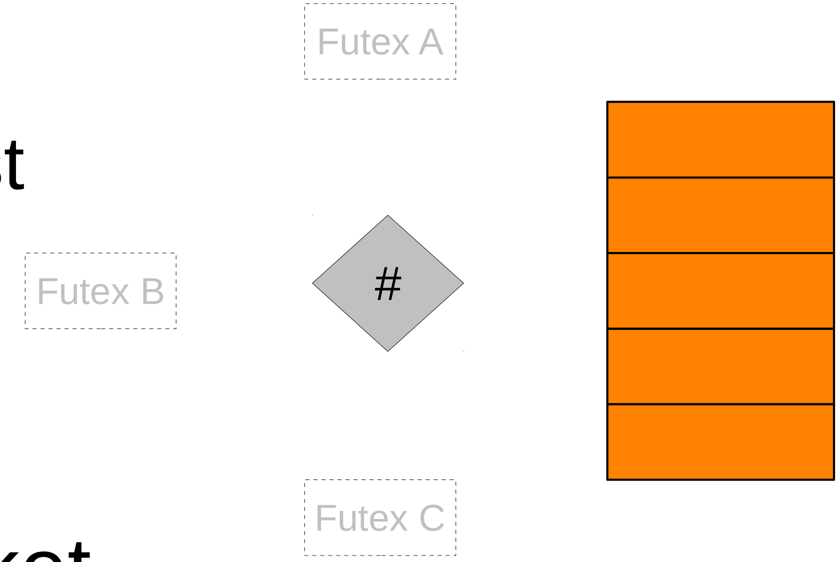

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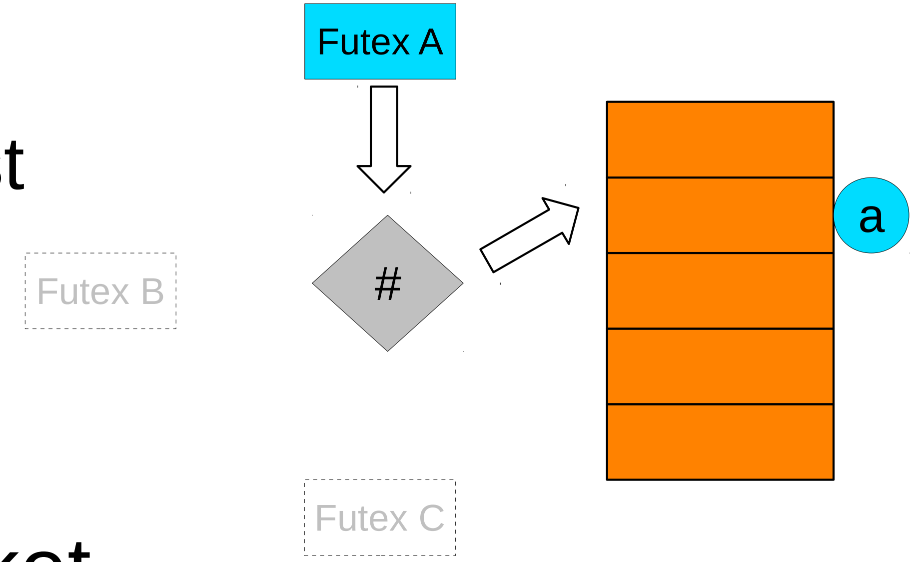

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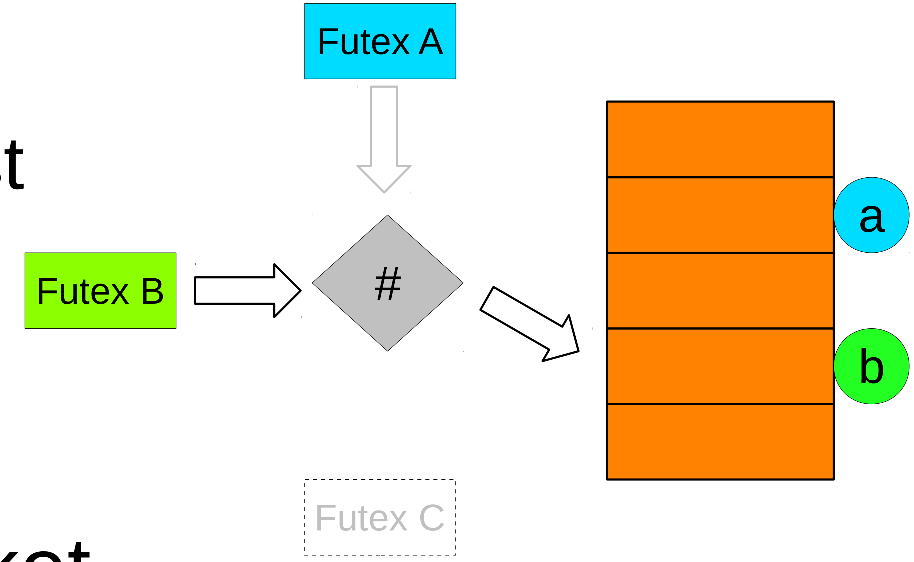

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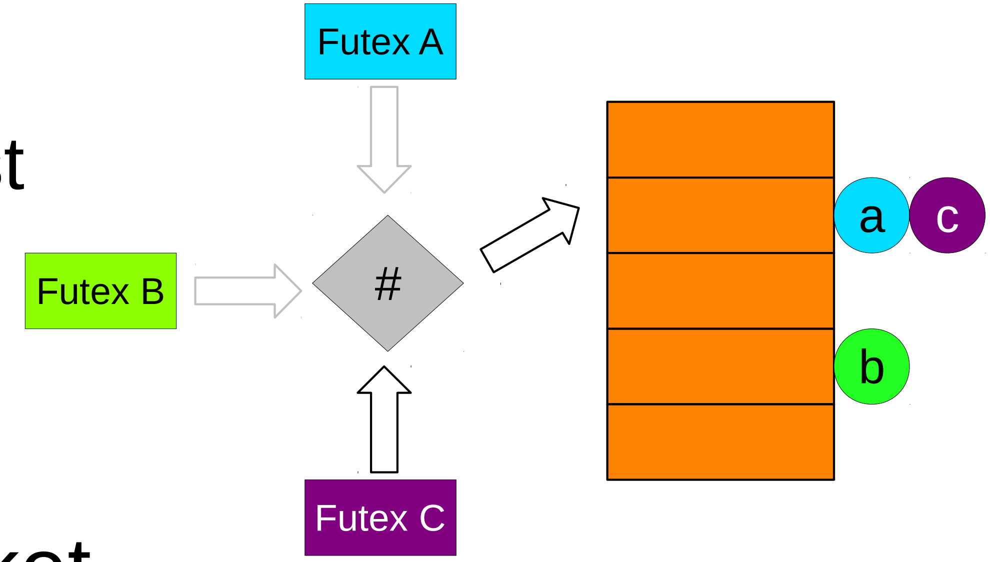

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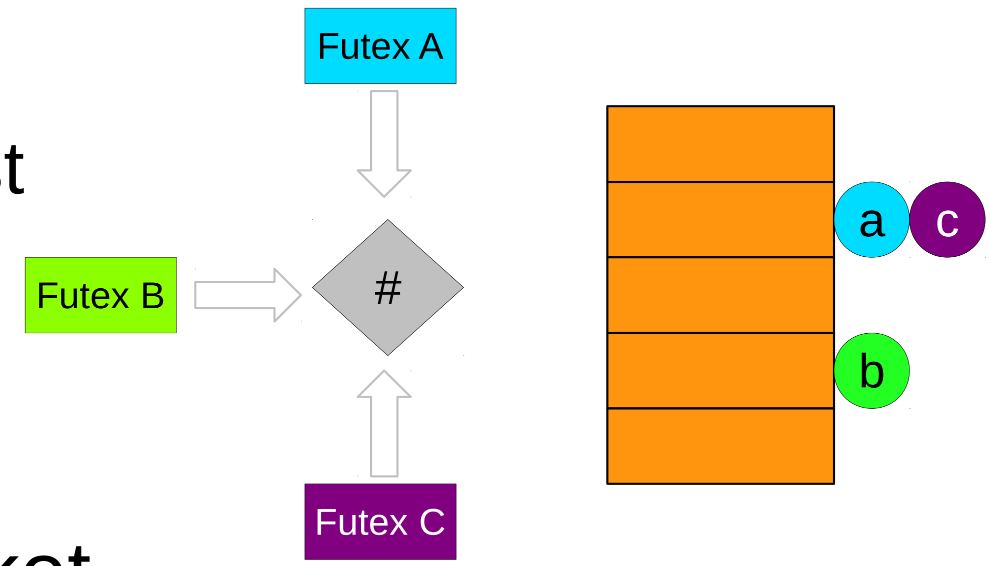
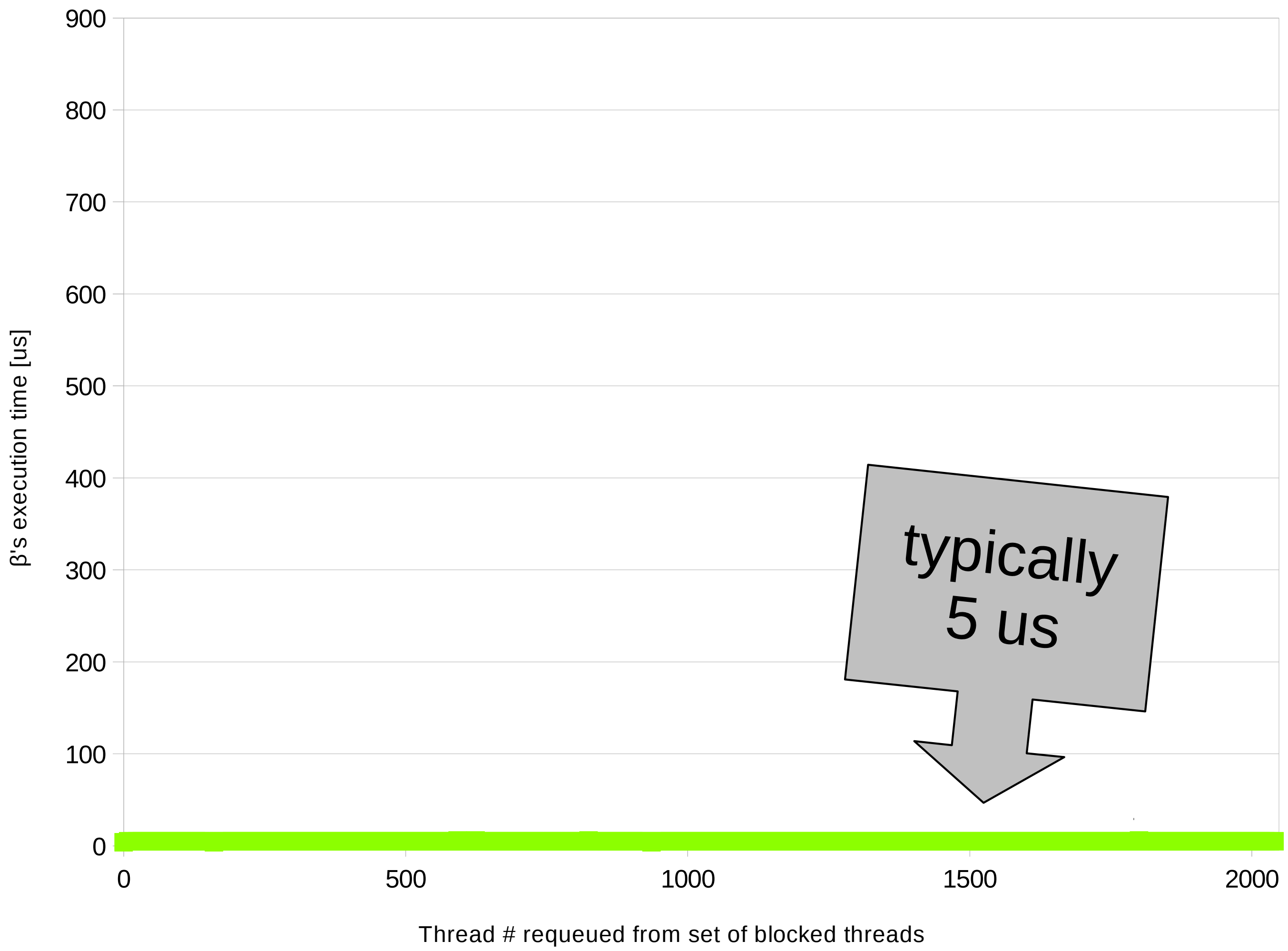
Hash Collision!



Linux Implementation

- Experiment
  - Two processes
  - 2048 blocked threads each
  - Process α requeues 2048 threads from α_{src} to α_{dst}
  - Process β requeues 1 thread from β_{src} to β_{dst}
  - Measure β's execution time
  - Note: four wait queues!

Linux Implementation

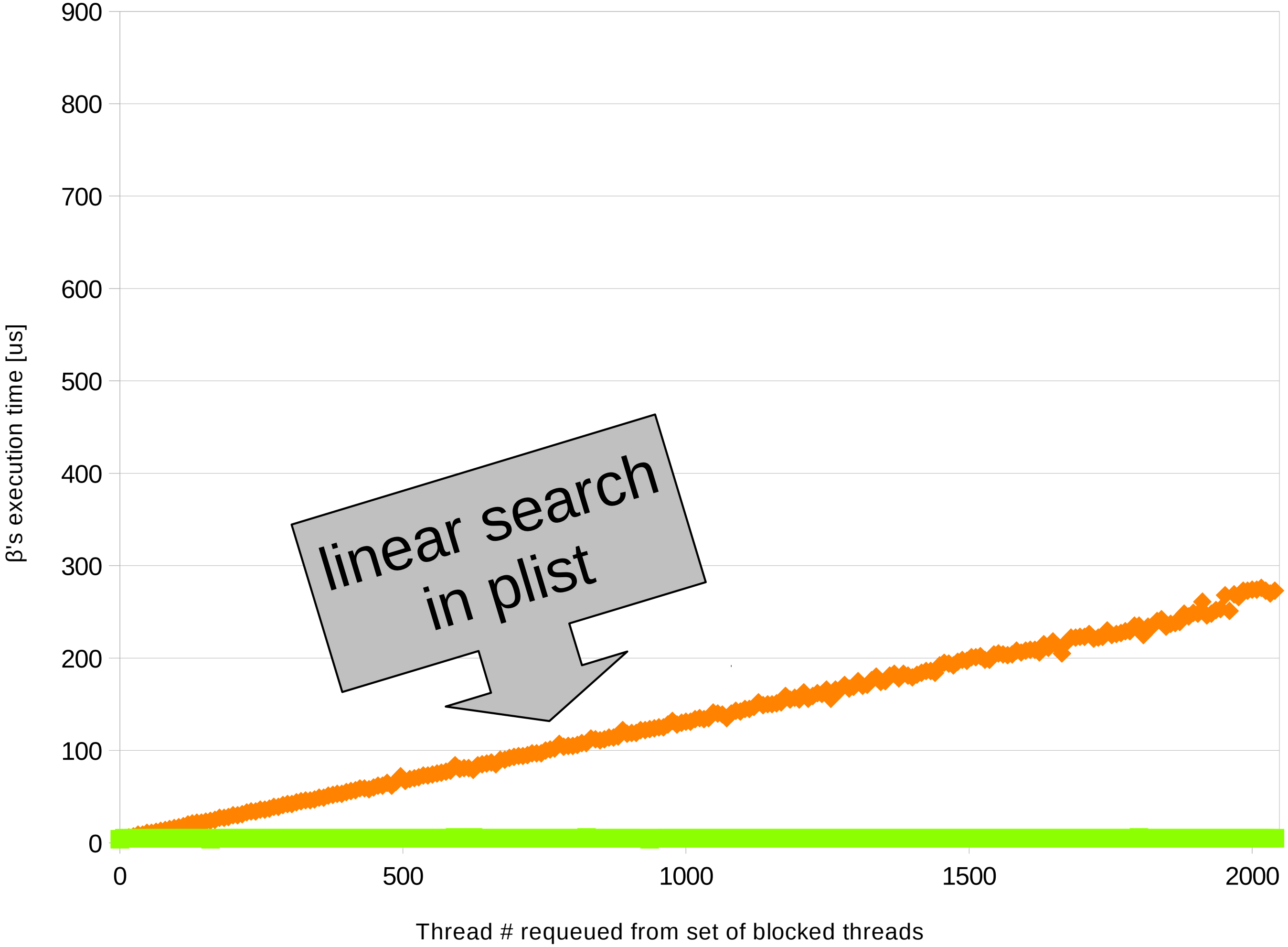


#1 distinct wait queues
$\beta_{src} \neq \beta_{dst}$, $\alpha_{...} \neq \beta_{...}$
operations in constant time

#1: β requeues to distinct futex wait queues
α not involved

Core 2 Duo @ 3.00 GHz, Linux 4.6.12-rt5, Ubuntu 16.04

Linux Implementation



#2 shared wait queue for β
$\beta_{src} = \beta_{dst}$, $\alpha_{...} \neq \beta$…
linear search in plist,
threads remain in place

#1 distinct wait queues
$\beta_{src} \neq \beta_{dst}$, $\alpha_{...} \neq \beta_{...}$
operations in constant time

#2: β requeues to same futex wait queue
α not involved

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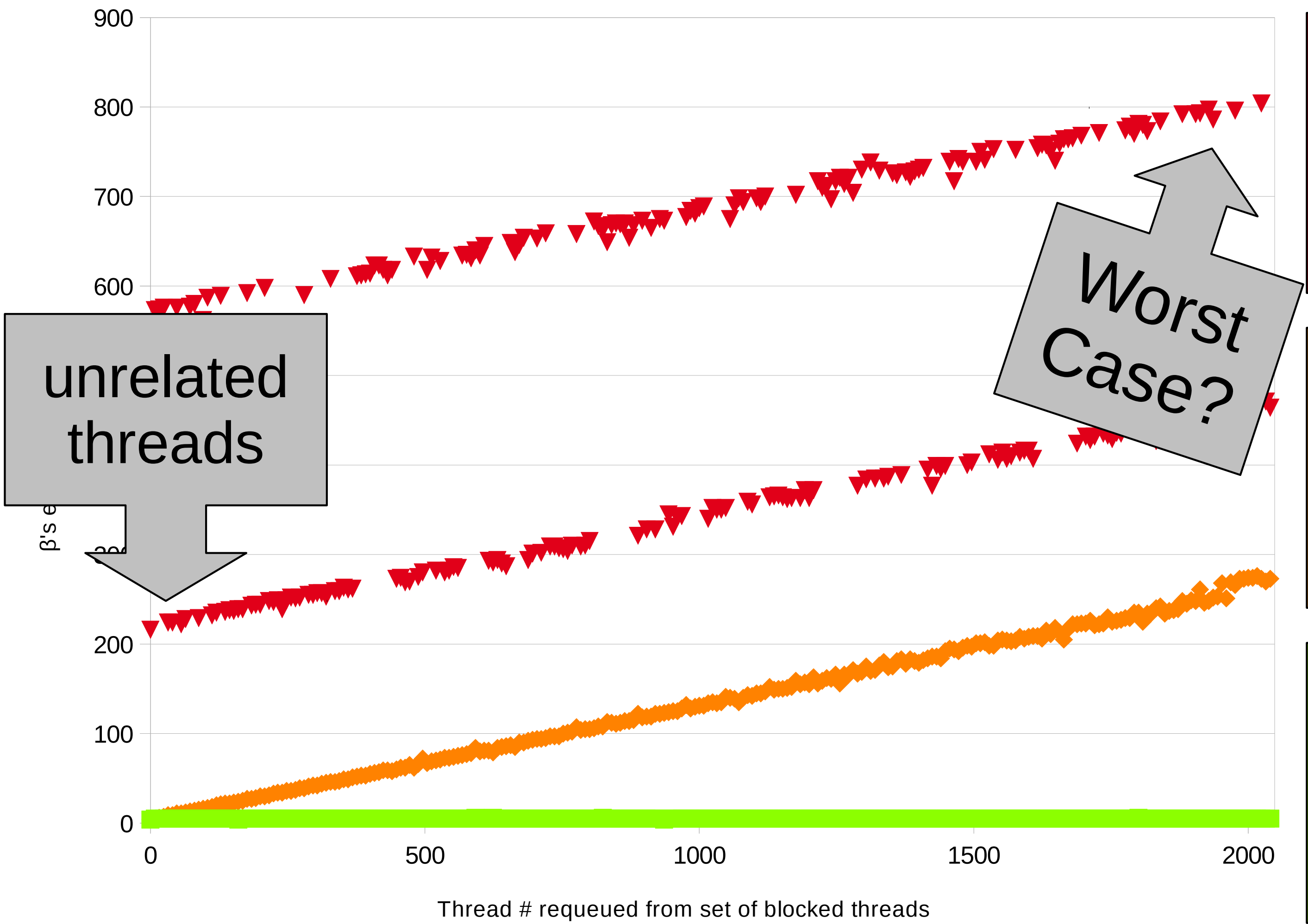
Linux Implementation



#3 shared wait queue for α, β

$\beta_{src} = \beta_{dst} = \alpha_{src} = \alpha_{dst}$

linear search in plist,
2048 unrelated threads

#2 shared wait queue for β

$\beta_{src} = \beta_{dst}$, $\alpha_{...} \neq \beta$...

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threads remain in place

#1 distinct wait queues

$\beta_{src} \neq \beta_{dst}$, $\alpha_{...} \neq \beta_{...}$

operations in constant time

#3: β requeues to same futex wait queue

α also requeues 2048 threads

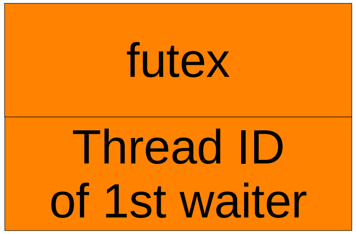
Core 2 Duo @ 3.00 GHz, Linux 4.6.12-rt5, Ubuntu 16.04

Linux Implementation

- Drawbacks of Linux implementation
  - Shared wait queues
  - Dynamic memory allocations for PI mutexes
  - Not preemptive

Our OSPERT 2013 Approach

OSPERT 2013 Approach*



- Save thread ID of first waiter next to the futex in user space
  - → O(1) look-up of wait queue
- FIFO ordering in wait queue
  - → wait queues use linked lists
- `futex_requeue` appends whole linked lists
  - → in O(1) time
- other operations: also O(1) time

* A. Zuepke, *“Deterministic Fast User Space Synchronization”*, OSPERT 2013

OSPERT 2013 Approach*

- Limitations of paper version:
  - Limited set of futex operations
  - No “wake all” operation (for barriers)
  - Only FIFO ordering
- Overcoming these limitations is possible:
  - Priority ordering of wait queue
  - Preemptive “wake_all” operation

* A. Zuepke, *“Deterministic Fast User Space Synchronization”*, OSPERT 2013

OSPERT 2013 Approach*

- Particular Problems:
  - Consistency of linked list during deletion/timeout handling while another thread walks this list
  - “Sneak-in”: prevent woken threads from re-entering a wait queue
  - Scalability: requires a global lock design

→ Result: complex implementation

→ Take a fresh look ...

* A. Zuepke, *“Deterministic Fast User Space Synchronization”*, OSPERT 2013

Requirements for Determinism

Use dedicated wait queues!

Requirements

0. Do not share wait queues
1. No dynamic memory allocations
2. Priority ordered wait queues; FIFO order on tie
3. Wait queue: use binary search tree (BST)
4. Wait queue look-up: use BST as well
5. Preemptible “wake/preempt all” operations
6. Prevent “sneak-in”
7. Transparent preemption
8. Fine granular locking

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OSPERT
2018-07-03
A. Zuepke

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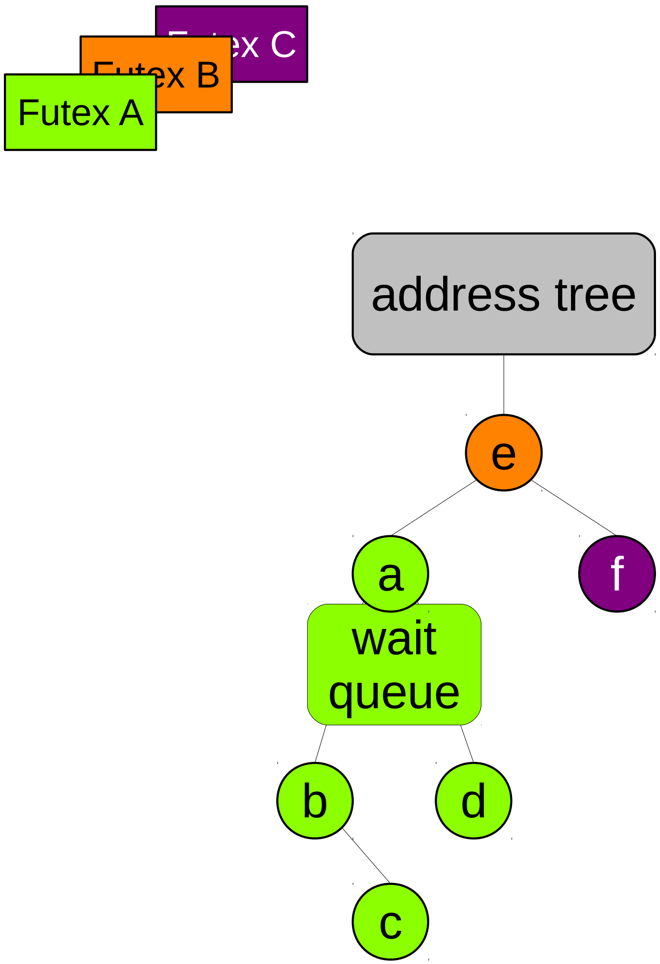
Problem of preemptible implementation

Optional feature

New Approach*

(* this paper)

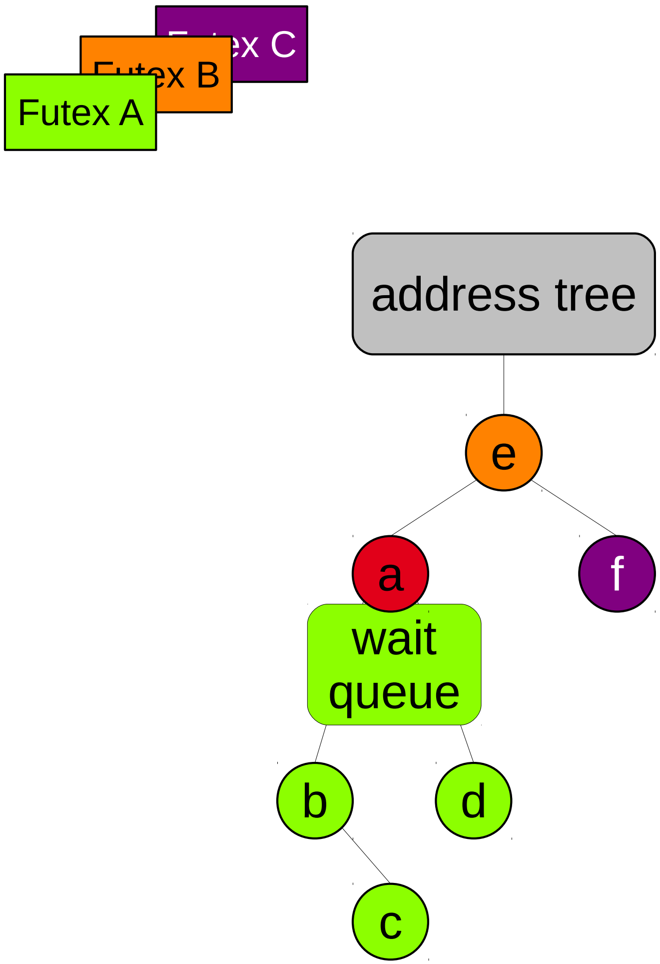
New Approach



- Use *two* nested BST
- Keep all data in TCB
- Create wait queues on demand

- *Address tree* for wait queue look-up
- *Wait queue* keeps blocked threads

New Approach



- Wait queue changes require care
- Example: timeout of *a*
- *a* is wait queue root
- *c* becomes new root
- Copy WQ information
- Swap *a* and *c* in address tree
- Remove *a*

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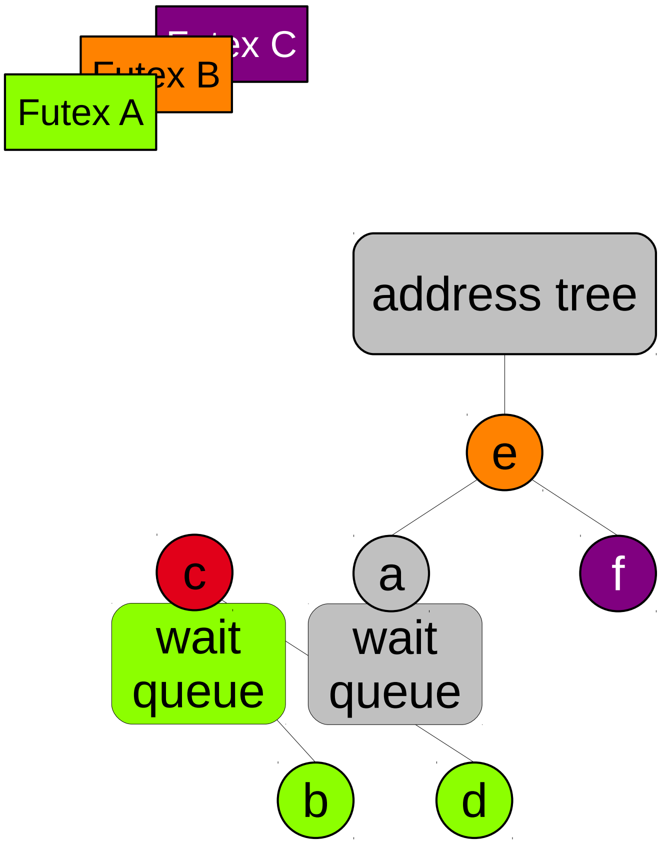

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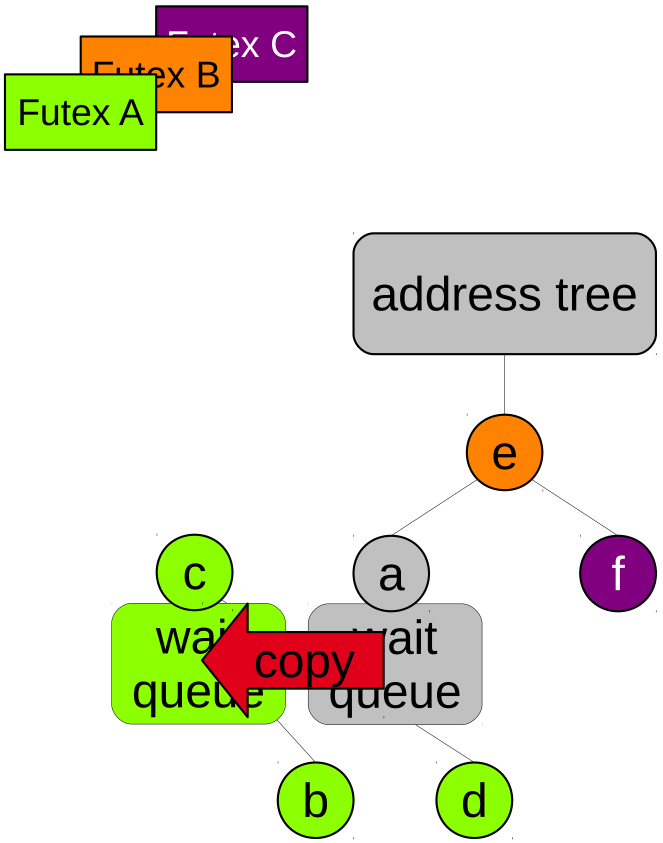

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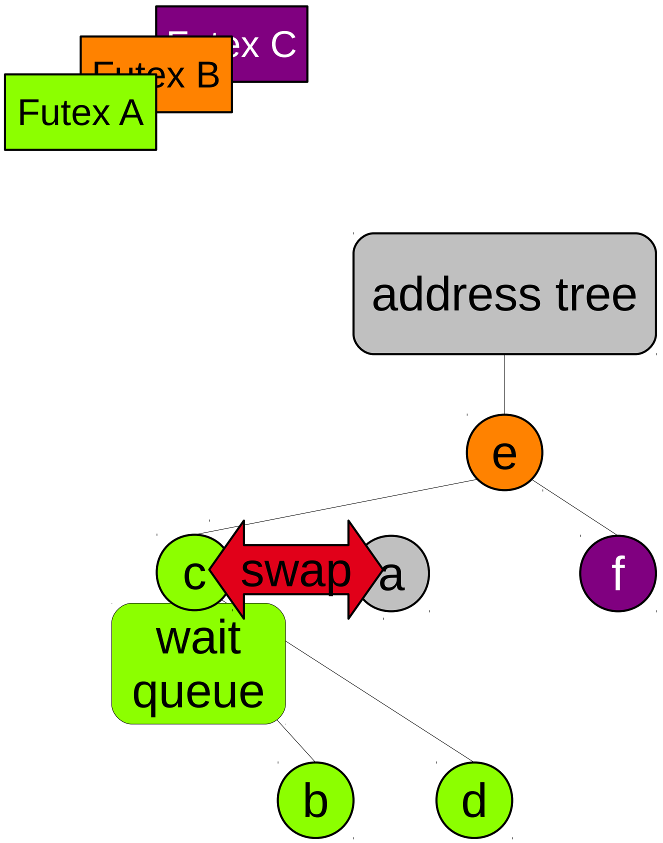

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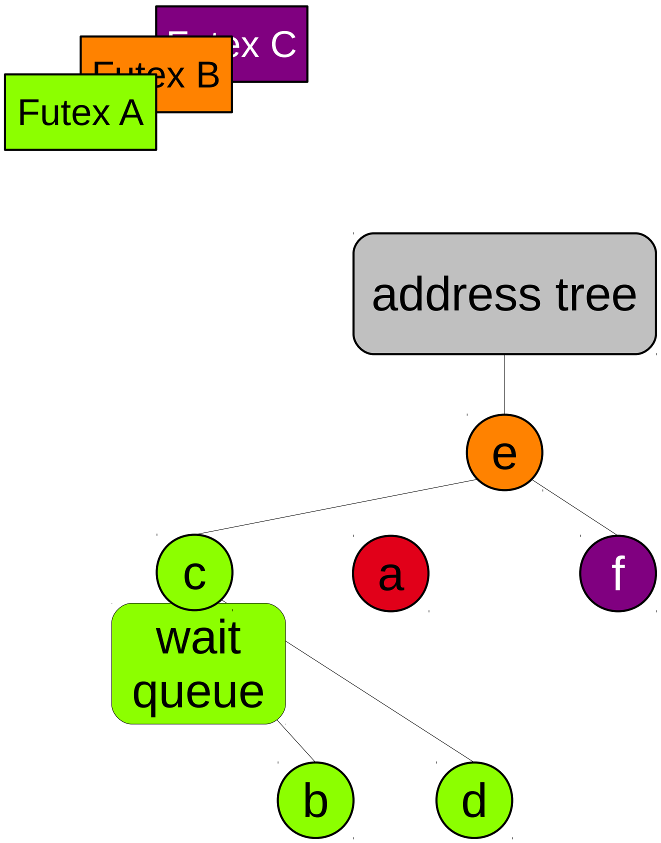

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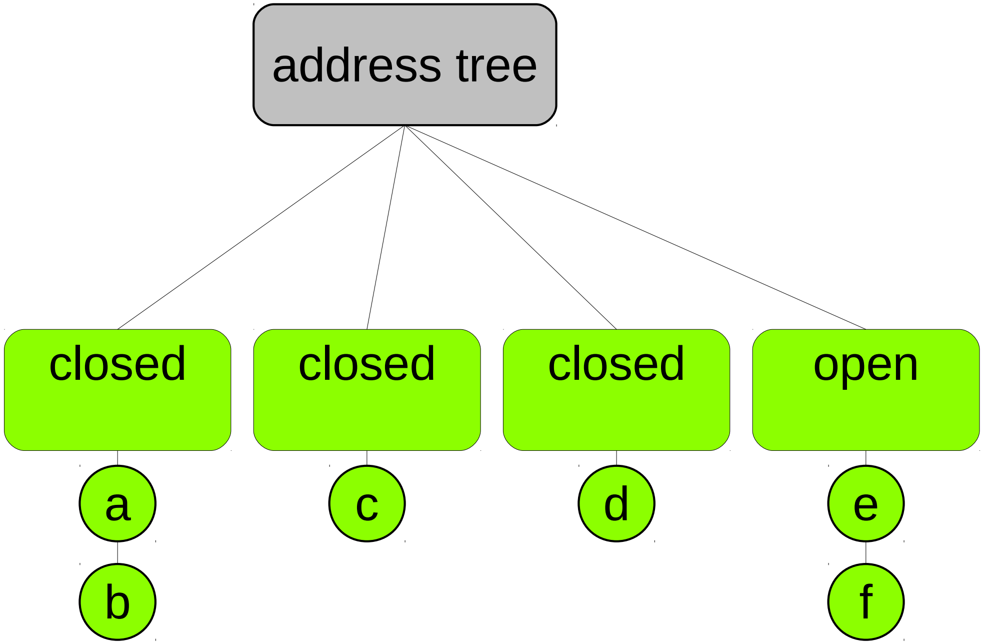
New Approach

- Preemptible Operations
  - For `futex_wake(all)` and `futex_requeue(all)`
  - Prevent re-insertion in wait queues ("sneak in")
  - Use lowest bit of wait queue's futex address
    - Open: allow adding threads
    - Closed: only allow wake-up/requeueing
  - `futex_*(all)` operations close wait queues
    - Clear *open* bit → order in address tree is preserved

→ but now multiple closed wait queues may exist

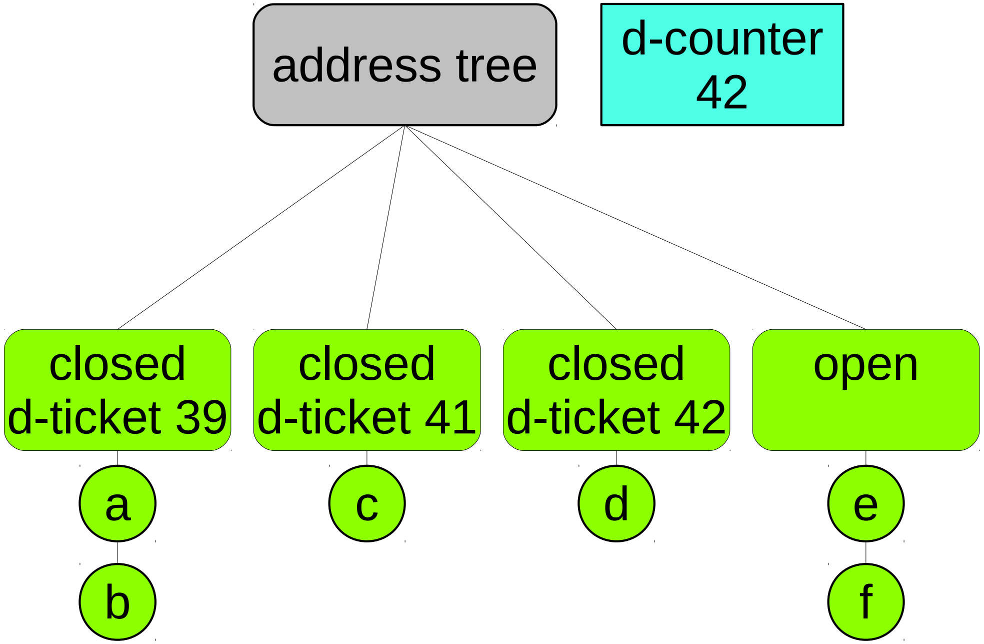
New Approach

- Preemptible Operations
  - Problem: multiple wait queues in *closed* state



New Approach

- Preemptible Operations
  - Problem: multiple wait queues in *closed* state
  - Global 64-bit *drain counter*
  - On close: drain counter++, draw a *drain ticket*



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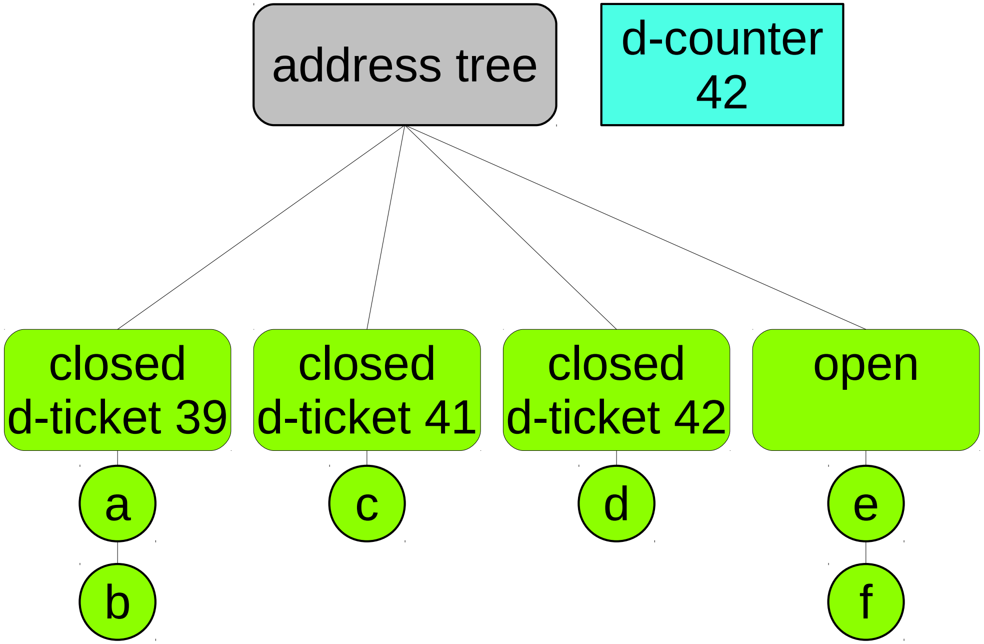

Loop:

- look up closed wait queues
- Stop if wait queue's drain ticket > drawn drain ticket
- perform wake up/requeue operation on one thread
- next preemption point ...

New Approach

- Preemptible Operations
  - Problem: multiple wait queues in *closed* state
  - But: It is OK to drain older wait queues?
  - Requeue and wake-up all operations are not atomic!

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  - Requeue and wake-up all operations are not atomic!
- Condition Variables
  - POSIX: caller of `cond_broadcast()` should have the support mutex locked → uses requeue internally
- Barriers
  - POSIX does not guarantee any scheduling order

New Approach

- Fine Granular Locking
  - Idea: nested locks
  - Example: Look-up a wait queue
    - Lock address tree
    - Locate wait queue & lock wait queue
    - Unlock address tree

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Not solved → use a single lock

New Approach

- Summarized
  - Dedicated wait queues per futex
  - No dynamic memory allocations
  - O(log n) look-up/insert/remove of wait queues
  - O(log n) handling inside wait queues
  - Preemptible operations of *wake all* and *requeue all*
    - Maximum of *n-1* threads in *all* operations

Discussion

Discussion

- Our new approach compared to Linux
  - Missing use cases
    - No “wake arbitrary number of threads”
      → but not needed for POSIX synchronization mechanisms
    - No priority inheritance protocol for mutexes
    - No `FUTEX_WAKE_OP`
    - No `FUTEX_WAIT/WAKE_BITSET`
  - Different API
    - Caller of `futex_wait` must provide requeue target futex
  - But
    - Priority ceiling protocol possible (unrelated to futex API)

Discussion

	Our new approach	Our old approach	Linux
Futexes share wait queues	no	no	yes
Wait queue look-up	BST $O(\log m)$	via `TID` $O(1)$	hash table $O(1)$
Wait queue implementation - find - insertion - removal	priority-sorted BST $O(\log n)$ $O(\log n)$ $O(\log n)$	FIFO-ordered linked list $O(1)$ $O(1)$ $O(1)$	priority-sorted linked list $O(n)$ $O(p)$ $O(1)$
Locking	global	global	per hash bucket
`futex_requeue` - one thread - arbitrary number of threads - all threads - preemptive implementation	 yes no yes yes	 yes no yes not needed	 yes yes yes no
`futex_wake` - one thread - arbitrary number of threads - all threads - preemptive implementation	 yes no yes yes	 yes no not provided not needed	 yes yes yes no
Priority ceiling protocol	yes	yes	yes
Priority inheritance protocol	no	no	yes
	for n threads, m futexes, and p priority levels		

Thank you for your attention!

Questions?

Backup Slides

Priority Inheritance Mutexes

- Priority Inheritance Mutexes
  - POSIX: `PTHREAD_PRIO_INHERIT`
  - On contention, blocked threads boost the cheduling priority of the current lock holder
  - Implemented in Linux via `FUTEX_LOCK_PI` API
- Problems
  - Nested locks: applied recursively ...
  - Potentially unbounded recursion!
  - Cycles in dependency graph lead to deadlocks

Priority Ceiling Mutexes

- Priority Ceiling Mutexes
  - POSIX: `PTHREAD_PRIO_PROTECT`
  - Each mutex has an assigned *ceiling priority*
  - Before locking: increase scheduling priority to ceiling priority
  - After locking: restore previous scheduling priority
  - Implemented independently of futex API
- Can be implemented without system calls

  → *Fast User Space Priority Switching*, OSPERT 2014

The End