Pthreads condvars: POSIX compliance and the PI gap

Torvald Riegel
Principal Software Engineer

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Agenda

- Part 1: New glibc condition variable
  - POSIX requirements that required a new algorithm
  - How blocking with futexes makes this complicated
  - Brief overview of the new algorithm

- Part 2 by Darren: How PI makes this even more complicated

Condition variable

- Wait until a condition holds:

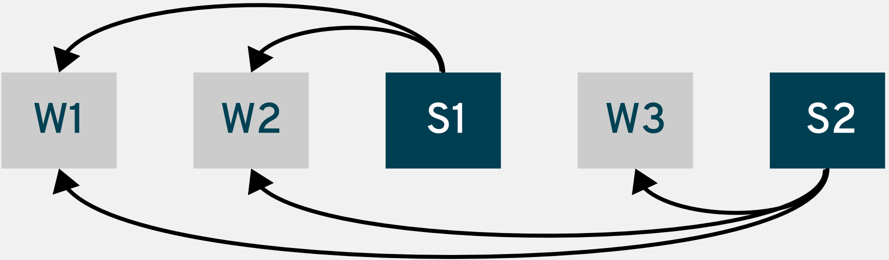
```
pthread_mutex_lock(m);
while (!condition)  // Spurious condvar wake-ups are allowed
   pthread_cond_wait(cond, m);
pthread_mutex_unlock(m);
```

- Satisfy a condition and signal that it (may have) changed:

```
pthread_mutex_lock(m); // Optional
condition = true;
pthread_cond_signal(cond);
pthread_mutex_unlock(m); // Optional
```

Condvar is an order of events, not just a counter

- POSIX, C++14: signals must wake one of the waiters that started to wait before the signal and have not been woken
  - Program can observe / construct ordering because cond_wait must release mutex atomically wrt start of waiting
  - Condvar must adhere to any ordering the program may have observed
- Condvar synchronization must model an order of waiters/signalers
  - For each signal, there is a set of eligible waiters allowed to consume the signal
  - Former (/ still current) algorithm did not prevent non-eligible waiters to steal signals from eligible waiters → new condvar algorithm required



If we only spin-wait, a simple sequence is enough

- Eligibility for wake-up determined through sequence of waiters (wseq, a simple shared counter)
- Waiters basically take 3 steps:
  1) Acquire position in wseq: Become eligible for subsequent signals
  2) Release mutex
  3) Spin-wait until as many signals sent as our position in wseq
- Signalers (assume program signals while having acquired the mutex):
  - If number of signals sent (ssent) >= wseq, nothing to do
  - Otherwise, increment ssent
- Results in FIFO condvar wake-up
- Timeouts, cancellation: Waiters send artificial signals to prevent lost wake-ups
  - Pretend they just consumed such an artifical signal immediately

1st attempt at using futexes

- Instead of spin-waiting, call futex_wait eventually (w/ ssent as futex word)
- Problem: Futex wake-up order (step 3 on previous slide) can be different from wseq order (step 1)
  - Waiters can only futex_wait after releasing the mutex
  - Futexes provide no wake-up ordering guarantees (non-PI case) nor means to request a certain order that relates to the wseq order we chose
  - Waking all threads blocked in futex_wait is bad for performance
- Workaround: Eligibility can also be claimed if a waiter's futex_wait happens before a signal's futex_wake
  - Waiters wake up if ssent is larger than their wseq position
  - Waiters also wake up if futex_wake returns 0
- Does this work?

1st attempt bug 1: (wseq-ssent) < #blocked waiters

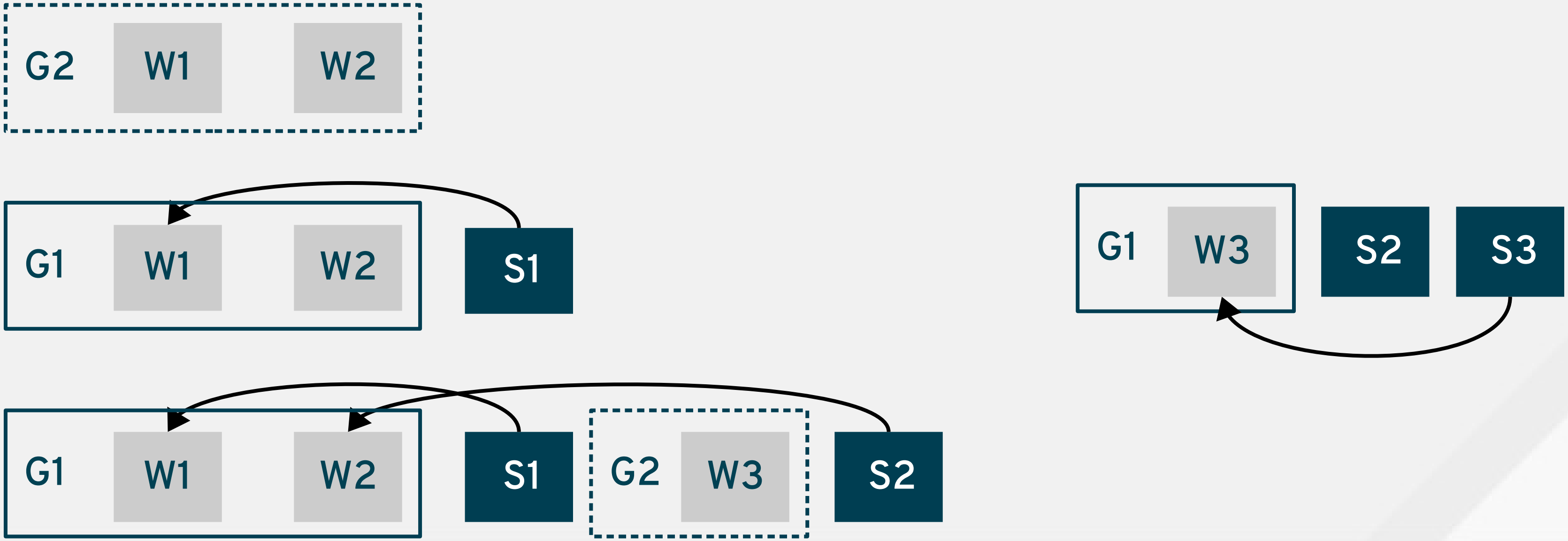
- Scenario: Program can count how many waiters are still blocked, and only send that many signals
- If 2 waiters wake because of one cond_signal call (1 through observing ssent, 1 through futex_wait), then ssent is not incremented by 2 → lost wake-ups
- Can waiters increment ssent if futex_wait returns 0?
  - cond_signal's ssent>=wseq check will hit early, so might run one futex_wake less → lost wake-ups
  - We might be able to count these events and find a work-around
- Any workaround will probably result in spurious condvar wake-ups whenever wseq order does not match futex wake-up order

1st attempt bug 2: Can't distinguish spurious futex wake-ups

- But… the kernel doesn't wake spuriously?!
  - POSIX requires that mutexes can be destroyed as soon as no thread is blocked anymore on the mutex (similar for condvars)
  - General futex design: Userspace fastpaths and futex ops are not atomic
  - Spurious wake-ups in practice because of this and memory reuse :
    1) Thread 1 releases mutex in userspace, gets suspended
    2) Thread 2 acquires mutex in userspace, destroys it, reuses memory for another futex
    3) Thread 1 resumes, calls futex_wake, other futex is woken spuriously
- Condvar can't distinguish between spurious and non-spurious wakeups
  - Spurious wake-ups don't increment ssent → We're back to bug 1, but worse

2nd attempt: Maintain groups of eligible and non-eligible waiters

- New waiters start as non-eligible (group G2)
- Eligible group (G1) contains only eligible waiters
  - Each signal wakes <u>some</u> thread in G1: All eligible, a counter is sufficient
- When G1 is completely signaled, G2 becomes new G1



G1/G2 are roles mapped to 2 group slots in pthread_cond_t

- Condvar keeps track of which slot has which role
    - There always is a G2 for waiters to enter
    - wseq is still maintained, so waiters can detect aliasing of groups
- Reusing G1 as G2 requires quiescence to avoid ABA in futex_wait
    - Only need to wait for completion of futex_wait calls
- Incoming signal switches groups if G1 fully signaled
    - Quiesce G1 and make it the new G2
    - Make G2 the new G1 and add a signal to it
- G2 to G1 switch is simple
    - No change for existing G2 threads, no need to switch futexes

Priority Inheritance

Darren Hart
Principal Engineer / Intel Open Source Technology Center

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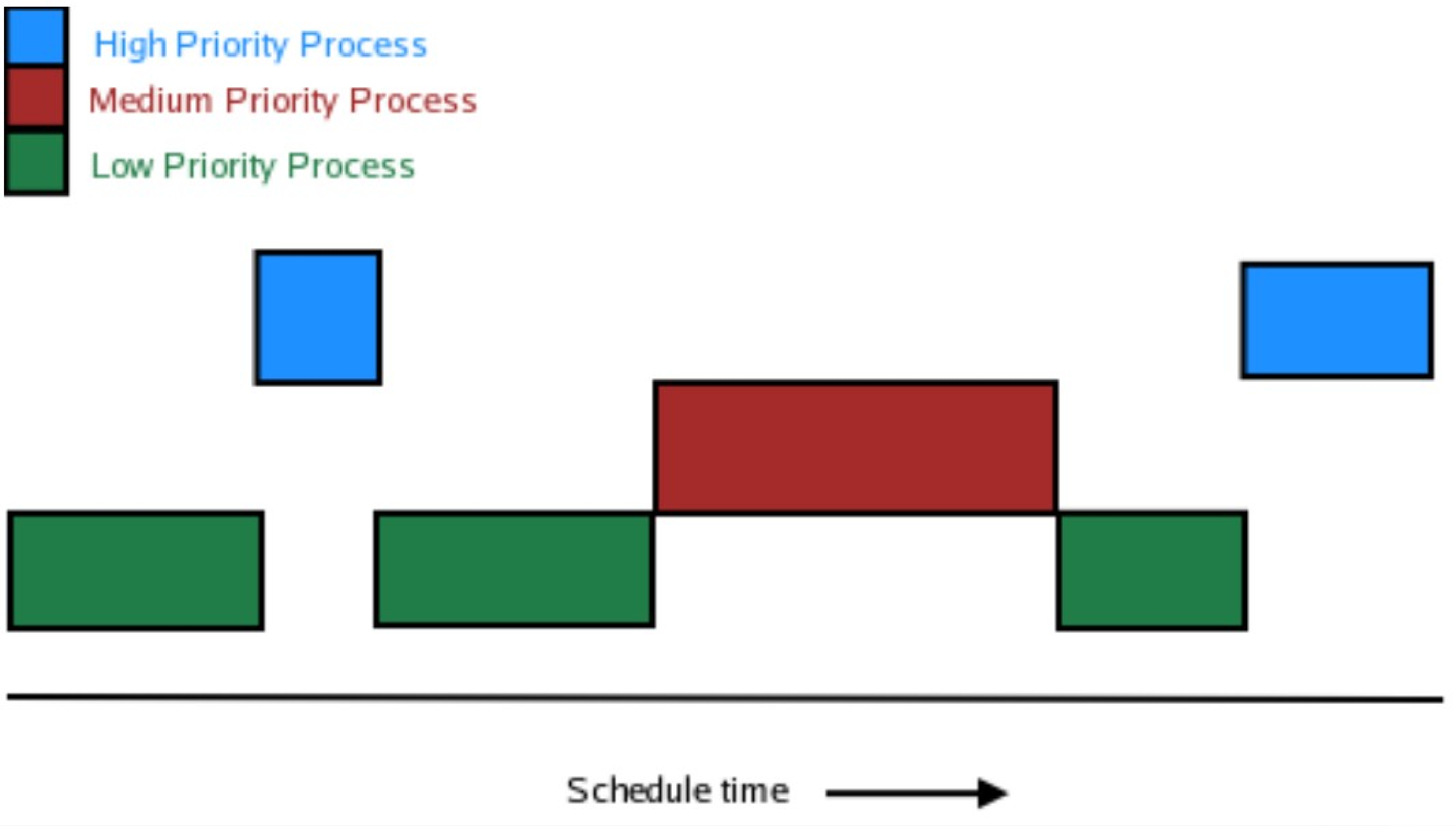
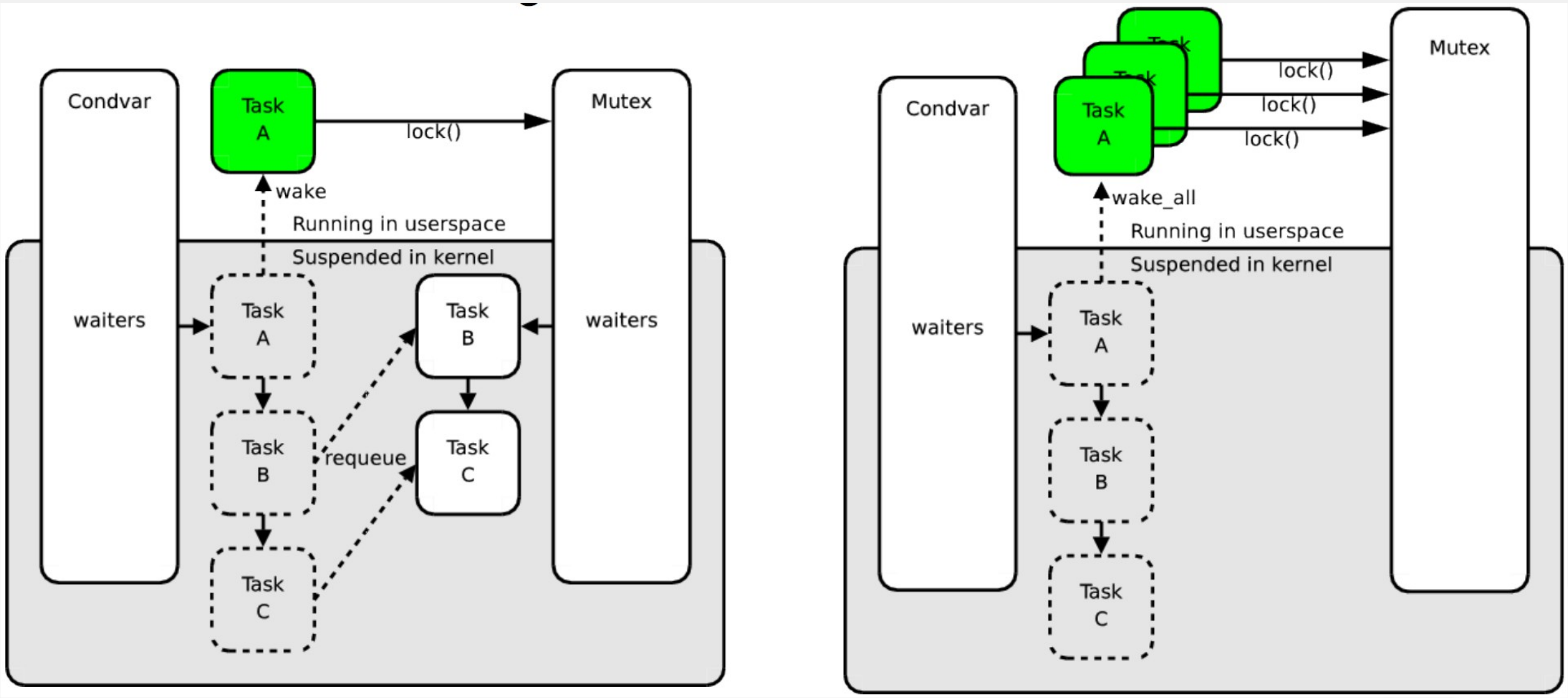
Unbounded Priority Inversion



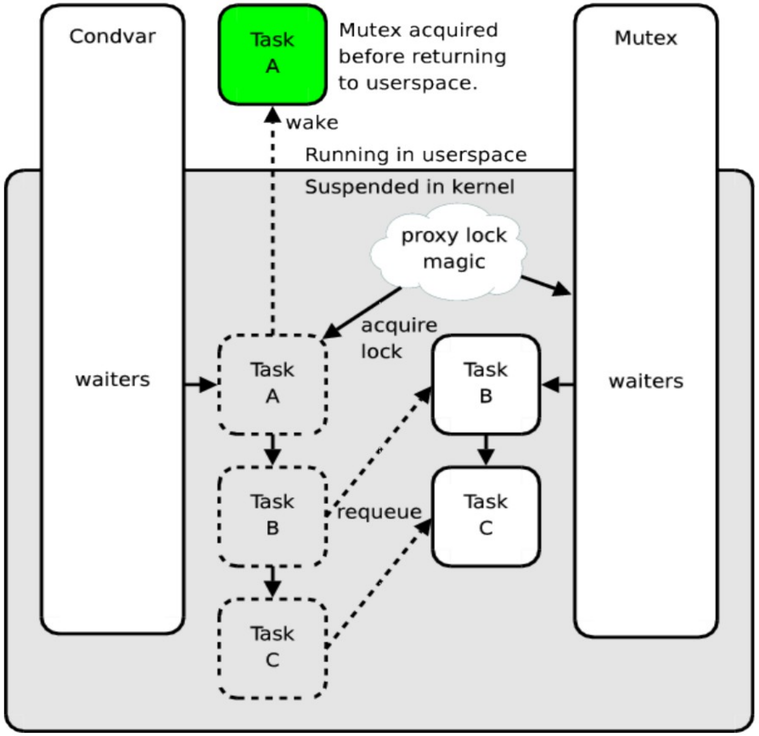
Priority Inheritance Goals

1. Guarantee wakeup of highest priority **eligible** waiter
2. Avoid the thundering herd



Implementation Restrictions

- rt_mutex cannot be in a state with waiters and no owner
- PI futexes impose value policy on the futex word (stores the TID and WAITERS), so cannot encode sequence information



Considerations

- Concerned with Unbounded Priority Inversion with respect to the target mutex and locking implementation (not forward progress toward satisfying the condition)
- Priority Inheritance applies to SCHED_FIFO, SCHED_RR – but not SCHED_DEADLINE
- What are we interesting in solving?

Discussion

PI problem: Group quiescence

- When switching from G1 to G2, need to avoid futex_wait ABA
  - Need to quiesce group 1: Threads that ran futex_wake need to confirm that they have been woken
- Need to boost prio of those threads, but they have not acquired a lock
- No helper-futex-per-waiter possible because we need to support process-shared condvars

Potential solutions for the PI gap

- What do you really want? Is it really a condvar?
- Make the base condvar algorithm simpler
    - Other futex_wait conditions than simple inequality (eg, make wake-up conditional on futex word value and some relation)?
    - Let callers request a certain wake-up order?
- Solve PI vs. quiescence
    - 64b futex operations so we can version futex words and make ABA impossible in practice?
    - PI mechanism to boost all threads blocked on or having acquired a lock without actually acquiring the lock?
        - Requeueing threads is not sufficient, we need confirmation that they are not going to run a pending futex_wait call next to avoid the ABA issue
        - FUTEX_WAIT_REQUEUE_PI is just requeueing, but not preventing pending old futex_wait calls