Overview of previous and current lectures

- **Locks create serial code**
  - Serial code gets no speedup from multiprocessors
- **Test-and-set spinlock has additional disadvantages**
  - Lots of traffic over memory bus
  - Not fair on NUMA machines
- **Idea 1: Avoid spinlocks**
  - We saw lock-free algorithms last lecture
  - Introduced RCU last time, dive deeper today
- **Idea 2: Design better spinlocks**
  - Less memory traffic, better fairness
- **Idea 3: Hardware turns coarse- into fine-grained locks!**
  - While also reducing memory traffic for lock in common case

Outline

Read-copy update [McKenney]

- **Some data is read way more often than written**
  - Routing tables consulted for each forwarded packet
  - Data maps in system with 100+ disks (updated on disk failure)
- **Optimize for the common case of reading without lock**
  - Have global variable: `_Atomic(routing_table *) rt;`
  - Use it with no lock

```
#define RELAXED(var) \
  atomic_load_explicit(&(var), memory_order_relaxed)

/* ... */

  route = lookup(RELAXED(rt), destination);
```

- **Update by making copy, swapping pointer**

```
routing_table *newrt = copy_routing_table(rt);
update_routing_table(newrt);
atomic_store_explicit(&rt, newrt, memory_order_release);
```


Is RCU really safe?

- **Consider the use of global `rt` with no fences:**

```
lookup(RELAXED(rt), route);
```

- **Could a CPU read new pointer but then old contents of `*rt`?**
- **Yes on alpha, No on all other existing architectures**
- **We are saved by *dependency ordering* in hardware**
  - Instruction *B* depends on *A* if *B* uses result of *A*
  - Non-alpha CPUs won't re-order dependent instructions
  - If writer uses release fence, safe to load pointer then just use it
- **This is the point of `memory_order_consume`**
  - Should be equivalent to acquire barrier on alpha
  - But should compile to nothing (be free) on other machines
  - But hard to get semantics right (temporarily deprecated in C++)

Preemptible kernels

- **Recall *kernel process context* from lecture 1**
  - When CPU in kernel mode but executing on behalf of a process (e.g., might be in system call or page fault handler)
  - As opposed to interrupt handlers or context switch code
- **A *preemptible kernel* can preempt process context code**
  - Take a CPU core away from kernel process context code between any two instructions
  - Give the same CPU core to kernel code for a different process
- **Don't confuse with:**
  - Interrupt handlers can always preempt process context code
  - Preemptive threads (always have for multicore)
  - Process context code running concurrently on other CPU cores
- **Sometimes want or need to disable preemption**
  - E.g., before acquiring spinlock also used by interrupt handler
  - Or in code that must not be migrated between CPUs

Garbage collection

- **When can you free memory of old routing table?**
  - When you are guaranteed no one is using it—how to determine?
- **Definitions:**
  - *temporary variable* – short-used (e.g., local) variable
  - *permanent variable* – long lived data (e.g., global `rt` pointer)
  - *quiescent state* – when all a thread's temporary variables dead
  - *quiescent period* – time during which every thread has been in quiescent state at least once
- **Free old copy of updated data after quiescent period**
  - How to determine when quiescent period has gone by?
  - E.g., keep count of syscalls/context switches on each CPU
- **Restrictions:**
  - Can't hold a pointer across context switch or user mode (Never copy `rt` into another permanent variable)
  - Must disable preemption while consuming RCU data structure

Outline

Useful macros

- **Atomic compare and swap:** `CAS (mem, old, new)`
  - In C11: `atomic_compare_exchange_strong`
  - On x86: `cmpxchg` instruction provides this (with `lock` prefix)
  - If `*mem == old`, then swap `*mem`↔`new` and return `true`, else `false`
- **Atomic swap:** `XCHG (mem, new)`
  - C11 `atomic_exchange`, can implement with `xchg` on x86
  - Atomically exchanges `*mem`↔`new`
- **Atomic fetch and add:** `FADD (mem, val)`
  - C11 `atomic_fetch_add`, can implement with `lock add` on x86
  - Atomically sets `*mem += val` and returns *old* value of `*mem`
- **Atomic fetch and subtract:** `FSUB (mem, val)`
- **Note: atomics return previous value (like `x++`, not `++x`)**
- **All behave like sequentially consistent fences, too**
  - Unlike `_explicit` versions, which take a `memory_order` argument

MCS lock

- **Idea 2: Build a better spinlock**
- **Lock designed by Mellor-Crummey and Scott**
  - Goal: reduce bus traffic on cc machines, improve fairness
- **Each CPU has a `qnode` structure in local memory**

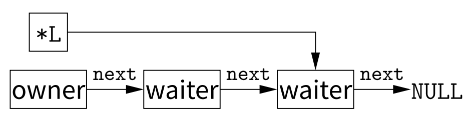
```
typedef struct qnode {
  _Atomic (struct qnode *) next;
  atomic_bool locked;
} qnode;
```

  - Local can mean local memory in NUMA machine
  - Or just its own cache line that gets cached in exclusive mode
- **A lock is a `qnode` pointer:** `typedef _Atomic (qnode *) lock;`
  - Construct list of CPUs holding or waiting for lock
  - `lock` itself points to tail of list list
- **While waiting, spin on *your local* `locked` flag**

MCS Acquire

```
acquire (lock *L, qnode *I) {
  I->next = NULL;
  qnode *predecessor = I;
  XCHG (*L, predecessor);
  if (predecessor != NULL) {
    I->locked = true;
    predecessor->next = I;
    while (I->locked)
      ;
  }
}
```

- **If unlocked, `L` is `NULL`**
- **If locked, no waiters, `L` is owner's `qnode`**
- **If waiters, `*L` is tail of waiter list:**



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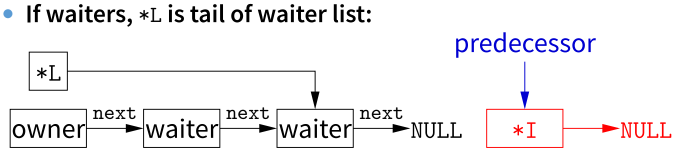

MCS Acquire

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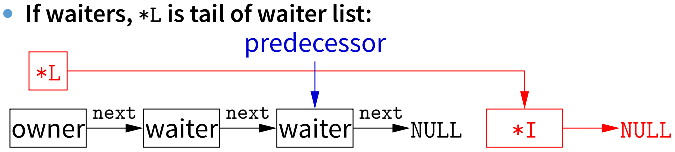

MCS Acquire

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  if (predecessor != NULL) {
    I->locked = true;
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    while (I->locked)
      ;
  }
}
```

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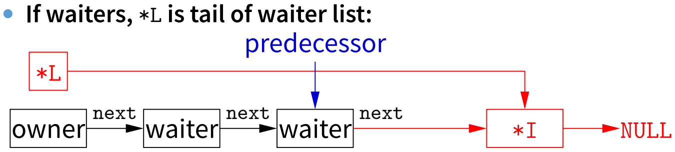
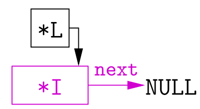


MCS Release with CAS

```
release (lock *L, qnode *I) {
  if (!I->next)
    if (CAS (*L, I, NULL))
      return;
  while (!I->next)
    ;
  I->next->locked = false;
}
```

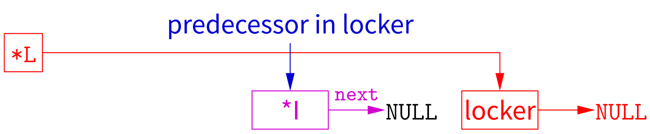
- **If `I->next` NULL and `*L == I`**
  - No one else is waiting for lock, OK to set `*L = NULL`



MCS Release with CAS

```
release (lock *L, qnode *I) {
  if (!I->next)
    if (CAS (*L, I, NULL))
      return;
  while (!I->next)
    ;
  I->next->locked = false;
}
```

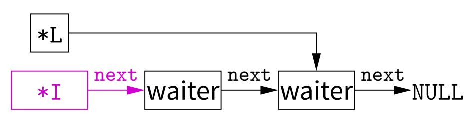
- **If `I->next` NULL and `*L != I`**
  - Another thread is in the middle of `acquire`
  - Just wait for `I->next` to be non-NULL



MCS Release with CAS

```
release (lock *L, qnode *I) {
  if (!I->next)
    if (CAS (*L, I, NULL))
      return;
  while (!I->next)
    ;
  I->next->locked = false;
}
```

- **If `I->next` is non-NULL**
  - `I->next` oldest waiter, wake up with `I->next->locked = false`



MCS Release w/o CAS

- **What to do if no atomic CAS (consensus number ∞), but do have XCHG (consensus number 2)?**
- **Be optimistic—read `*L` with two `XCHG`s:**
  1. Atomically swap NULL into `*L`
     - If old value of `*L` was `I`, no waiters and we are done
  2. Atomically swap old `*L` value back into `*L`
     - If `*L` unchanged, same effect as `CAS`
- **Otherwise, we have to clean up the mess**
  - Some "userper" attempted to acquire lock between **1** and **2**
  - Because `*L` was `NULL`, the userper succeeded
    (May be followed by zero or more waiters)
  - Stick old list of waiters on to end of new last waiter
    (Sacrifice small amount of fairness, but still safe)

MCS Release w/o C&S code

```
release (lock *L, qnode *I) {
  if (I->next)
    I->next->locked = false;
  else {
    qnode *old_tail = NULL;
    XCHG (*L, old_tail);
    if (old_tail == I)
      return;

    /* old_tail != I? CAS would have failed, so undo XCHG */
    qnode *userper = old_tail;
    XCHG (*L, userper);
    while (I->next == NULL)
      ;
    if (userper)  /* someone changed *L between 2 XCHGs */
      userper->next = I->next;
    else
      I->next->locked = false;
  }
}
```

Outline

1. RCU
2. Improving spinlock performance
3. Kernel interface for sleeping locks
4. Deadlock
5. Transactions
6. Scalable interface design

Kernel support for sleeping locks

- **Sleeping locks must interact with scheduler**
  - For processes or kernel threads, must go into kernel (expensive)
  - Common case is you can acquire lock—how to optimize?
- **Idea: never enter kernel for uncontested lock**

```
struct lock {
  atomic_flag busy;
  _Atomic (thread *) waiters; /* wait-free stack/queue */
};
void acquire (lock *lk) {
  while (atomic_flag_test_and_set (&lk->busy)) { /* 1 */
    atomic_push (&lk->waiters, self);           /* 2 */
    sleep ();
  }
}
void release (lock *lk) {
  atomic_flag_clear(&lk->busy);
  wakeup (atomic_pop (&lk->waiters));
}
```


Race condition

- **Unfortunately, previous slide not safe**
  - What happens if release called between lines 1 and 2?
  - `wakeup` called on `NULL`, so `acquire` blocks
- ***futex* abstraction solves the problem [Franke]**
  - Ask kernel to sleep only if memory location hasn't changed
- `void futex (int *uaddr, FUTEX_WAIT, int val...);`
  - Go to sleep only if `*uaddr == val`
  - Extra arguments allow timeouts, etc.
- `void futex (int *uaddr, FUTEX_WAKE, int val...);`
  - Wake up at most `val` threads sleeping on `uaddr`
- **`uaddr` is translated down to offset in VM object**
  - So works on memory mapped file at different virtual addresses in different processes

Futex example

```
struct lock {
  atomic_flag busy;
};
void acquire (lock *lk) {
  while (atomic_flag_test_and_set (&lk->busy))
    futex(&lk->busy, FUTEX_WAIT, 1);
}
void release (lock *lk) {
  atomic_flag_clear (&lk->busy);
  futex(&lk->busy, FUTEX_WAKE, 1);
}
```

- **What's suboptimal about this code?**
- **See [Drepper] for these examples and a good discussion**

Futex example

```
struct lock {
  atomic_flag busy;
};
void acquire (lock *lk) {
  while (atomic_flag_test_and_set (&lk->busy))
    futex(&lk->busy, FUTEX_WAIT, 1);
}
void release (lock *lk) {
  atomic_flag_clear (&lk->busy);
  futex(&lk->busy, FUTEX_WAKE, 1);
}
```

- **What's suboptimal about this code?**
  - `release` requires a system call (expensive) even with no contention
- **See [Drepper] for these examples and a good discussion**

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Futex example, second attempt

```
static_assert (ATOMIC_INT_LOCK_FREE >= 2);

struct lock {
  atomic_int busy;
};
void acquire (lock *lk) {
  int c;
  while ((c = FADD(&lk->busy, 1)))                  /* 1 */
    futex((int*) &lk->busy, FUTEX_WAIT, c+1);  /* 2 */
}
void release (lock *lk) {
  if (FSUB(&lk->busy, 1) != 1) {
    lk->busy = 0;
    futex((int*) &lk->busy, FUTEX_WAKE, 1);
  }
}
```

- **Now what's wrong with this code?**

Futex example, second attempt

```
static_assert (ATOMIC_INT_LOCK_FREE >= 2);

struct lock {
  atomic_int busy;
};
void acquire (lock *lk) {
  int c;
  while ((c = FADD(&lk->busy, 1)))                /* 1 */
    futex((int*) &lk->busy, FUTEX_WAIT, c+1); /* 2 */
}
void release (lock *lk) {
  if (FSUB(&lk->busy, 1) != 1) {
    lk->busy = 0;
    futex((int*) &lk->busy, FUTEX_WAKE, 1);
  }
}
```

- **Now what's wrong with this code?**
  - Two threads could interleave lines 1 and 2, never sleep
  - Could even overflow the counter, violate mutual exclusion

Futex example, third attempt

```
struct lock {
  // 0=unlocked, 1=locked no waiters, 2=locked+waiters
  atomic_int state;
};
void acquire (lock *lk) {
  int c = 1;
  if (!CAS (&lk->state, 0, c)) {
    XCHG (&lk->state, c = 2);
    while (c != 0) {
      futex ((int *) &lk->state, FUTEX_WAIT, 2);
      XCHG (&lk->state, c = 2);
    }
  }
}
void release (lock *lk) {
  if (FSUB (&lk->state, 1) != 1) { // FSUB returns old value
    lk->state = 0;
    futex ((int *) &lk->state, FUTEX_WAKE, 1);
  }
}
```


Outline

1. RCU
2. Improving spinlock performance
3. Kernel interface for sleeping locks
4. Deadlock
5. Transactions
6. Scalable interface design

The deadlock problem

```
mutex_t m1, m2;

void p1 (void *ignored) {
  lock (m1);
  lock (m2);
  /* critical section */
  unlock (m2);
  unlock (m1);
}
void p2 (void *ignored) {
  lock (m2);
  lock (m1);
  /* critical section */
  unlock (m1);
  unlock (m2);
}
```

- **This program can cease to make progress – how?**
- **Can you have deadlock w/o mutexes?**

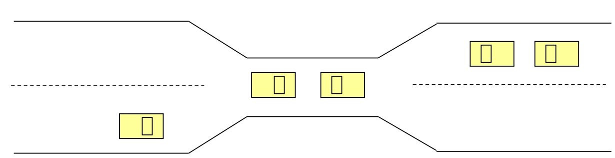
More deadlocks

- **Same problem with condition variables**
  - Suppose resource 1 managed by c_1, resource 2 by c_2
  - A has 1, waits on $c2$, B has 2, waits on $c1$
- **Or have combined mutex/condition variable deadlock:**

```
- lock (a); lock (b); while (!ready) wait (b, c);
  unlock (b); unlock (a);
- lock (a); lock (b); ready = true; signal (c);
  unlock (b); unlock (a);
```

- **One lesson: Dangerous to hold locks when crossing abstraction barriers!**
  - I.e., `lock (a)` then call function that uses condition variable

Deadlocks w/o computers



- **Real issue is *resources* & how required**
- **E.g., bridge only allows traffic in one direction**
  - Each section of a bridge can be viewed as a resource.
  - If a deadlock occurs, it can be resolved if one car backs up (preempt resources and rollback).
  - Several cars may have to be backed up if a deadlock occurs.
  - Starvation is possible.

Deadlock conditions

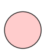
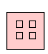
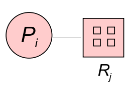
1. **Limited access (mutual exclusion):**
   - Resource can only be shared with finite users
2. **No preemption:**
   - Once resource granted, cannot be taken away
3. **Multiple independent requests (hold and wait):**
   - Don't ask all at once
     (wait for next resource while holding current one)
4. **Circularity in graph of requests**

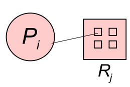
- **All of 1–4 necessary for deadlock to occur**
- **Two approaches to dealing with deadlock:**
  - Pro-active: prevention
  - Reactive: detection + corrective action

Prevent by eliminating one condition

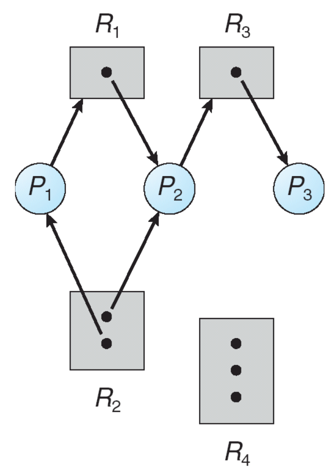
1. **Limited access (mutual exclusion):**
   - Buy more resources, split into pieces, or virtualize to make "infinite" copies
   - Threads: threads have copy of registers = no lock
2. **No preemption:**
   - Physical memory: virtualized with VM, can take physical page away and give to another process!
3. **Multiple independent requests (hold and wait):**
   - Wait on all resources at once (must know in advance)
4. **Circularity in graph of requests**
   - Single lock for entire system: (problems?)
   - Partial ordering of resources (next)

Resource-allocation graph

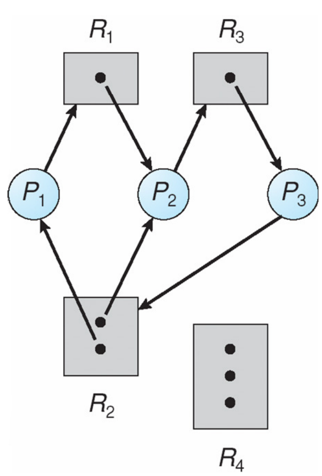
- **View system as graph**
  - Processes and Resources are nodes
  - Resource Requests and Assignments are edges
- **Process:** 
- **Resource with 4 instances:** 
- P_i **requesting** R_j: 

- P_i **holding instance of** R_j: 

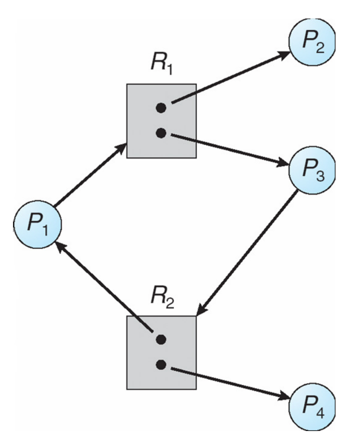
Example resource allocation graph



Graph with deadlock



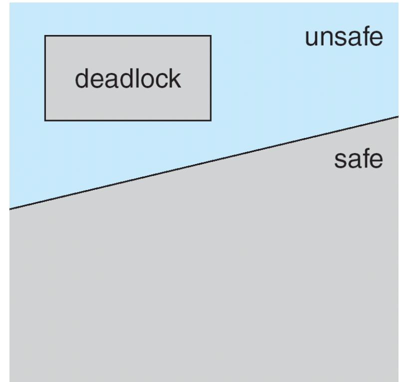
Is this deadlock?



Cycles and deadlock

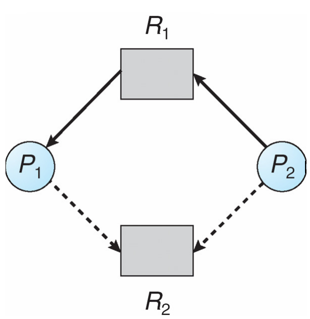
- **If graph has no cycles $\Longrightarrow$ no deadlock**
- **If graph contains a cycle**
  - Definitely deadlock if only one instance per resource
  - Otherwise, maybe deadlock, maybe not
- **Prevent deadlock with partial order on resources**
  - E.g., always acquire mutex m_1 before m_2
  - Usually design locking discipline for application this way

Prevention



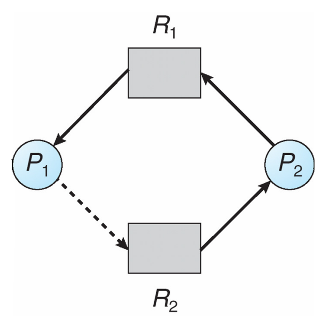
- **Determine safe states based on *possible* resource allocation**
- **Conservatively prohibits non-deadlocked states**

Claim edges



- **Dotted line is *claim edge***
  - Signifies process *may* request resource

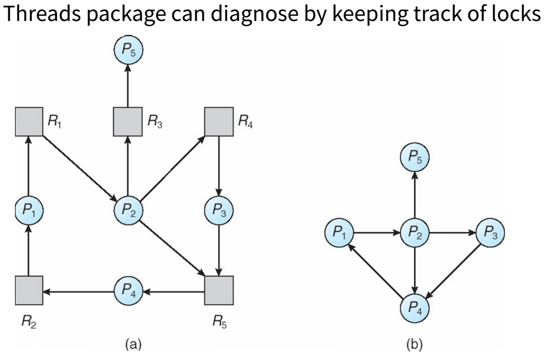
Example: unsafe state



- **Note cycle in graph**
  - P_1 might request R_2 before relinquishing R_1
  - Would cause deadlock

Detecting deadlock

- **Static approaches (hard)**
- **Dynamically, program grinds to a halt**
  - Threads package can diagnose by keeping track of locks held:



Resource-Allocation Graph   Corresponding wait-for graph

Fixing & debugging deadlocks

- **Reboot system / restart application**
- **Examine hung process with debugger**
- **Threads package can deduce partial order**
  - For each lock acquired, order with other locks held
  - If cycle occurs, abort with error
  - Detects *potential* deadlocks even if they do not occur
- **Or use *transactions*...**
  - Another paradigm for handling concurrency
  - Often provided by databases, but some OSes use them
  - *Vino* OS used transactions to abort after failures [Seltzer]

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Transactions

- **A *transaction* T is a collection of actions with**
  - *Atomicity* – all or none of actions happen
  - *Consistency* – T leaves data in valid state
  - *Isolation* – T's actions all appear to happen before or after every other transaction
  - *Durability*[1] – T's effects will survive reboots
  - Often hear mnemonic *ACID* to refer to above
- **Transactions typically executed concurrently**
  - But *isolation* means must *appear* not to
  - Must roll-back transactions that use others' state
  - Means you have to record all changes to undo them
- **When deadlock detected just abort a transaction**
  - Breaks the dependency cycle

[1] Not applicable to topics in this lecture

Transactional memory

- **Some modern processors support *transactional memory***
- **Transactional Synchronization Extensions (TSX) [intel1§16]**
  - `xbegin abort_handler` – begins a transaction
  - `xend` – commit a transaction
  - `xabort $code` – abort transaction with 8-bit code
  - Note: nested transactions okay (also `xtest` tests if in transaction)
- **During transaction, processor tracks accessed memory**
  - Keeps read-set and write-set of cache lines
  - Nothing gets written back to memory during transaction
  - On `xend` or earlier, transaction aborts if any conflicts
  - Otherwise, all dirty cache lines are written back atomically

Using transactional memory

- **Idea 3: Use to get "free" fine-grained locking on a hash table**
  - E.g., concurrent inserts that don't touch same buckets are okay
  - Should *read* spinlock to make sure not taken (but not write) [Kim]
  - Hardware will detect there was no conflict
- **Can also use to poll for one of many asynchronous events**
  - Start transaction
  - Fill cache with values to which you want to see changes
  - Loop until a write causes your transaction to abort
- **Note: Transactions are never guaranteed to commit**
  - Might overflow cache, get false sharing, see weird processor issue
  - Means abort path must always be able to perform transaction (e.g., you do need a lock on your hash table)

Hardware lock elision (HLE)

- **Idea: make it so spinlocks rarely need to spin**
  - Begin a transaction when you acquire lock
  - Other CPUs won't see lock acquired, can also enter critical section
  - Okay not to have mutual exclusion when no memory conflicts!
  - On conflict, abort and restart without transaction, thereby visibly acquiring lock (and aborting other concurrent transactions)
- **Intel support:**
  - Use `xacquire` prefix before `xchgl` (used for test and set)
  - Use `xrelease` prefix before `movl` that releases lock
  - Prefixes chosen to be noops on older CPUs (binary compatibility)
- **Hash table example:**
  - Use `xacquire xchgl` in table-wide test-and-set spinlock
  - Works correctly on older CPUs (with coarse-grained lock)
  - Allows safe concurrent accesses on newer CPUs!

Outline

1. RCU
2. Improving spinlock performance
3. Kernel interface for sleeping locks
4. Deadlock
5. Transactions
6. Scalable interface design

Scalable interfaces

- Not all interfaces can scale
- How to tell which can and which can't?
- Scalable Commutativity Rule: *"Whenever interface operations commute, they can be implemented in a way that scales"* [Clements]

Are fork(), execve() broadly commutative?

```
pid_t pid = fork();
if (!pid)
  execlp("bash", "bash", NULL);
```


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```

- No, `fork()` doesn't commute with memory writes, many file descriptor operations, and all address space operations
  - E.g., `close(fd); fork();` vs. `fork(); close(fd);`
- `execve()` often follows `fork()` and undoes most of `fork()`'s sub operations
- `posix_spawn()`, which combines `fork()` and `execve()` into a single operation, is broadly commutative
  - But obviously more complex, less flexible
  - Maybe Microsoft will have the last laugh?

Is open() broadly commutative?

```
int fd1 = open("foo", O_RDONLY);
int fd2 = open("bar", O_RDONLY);
```


Is open() broadly commutative?

```
int fd1 = open("foo", O_RDONLY);
int fd2 = open("bar", O_RDONLY);
```

- Actually `open()` does not broadly commute!
- Does not commute with any system call (including itself) that creates a file descriptor
- Why? POSIX requires new descriptors to be assigned the lowest available integer
- If we fixed this, `open()` would commute, as long as it is not creating a file in the same directory as another operation