Operating Systems

INF-333

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Course website

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Based On

cs212.stanford.edu

OSC-10 Slides

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

Overview of previous and current lectures

Idea 1: Avoid spinlocks

- We saw lock-free algorithms last lecture
- Mentioned 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

Read-Copy Update

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);
```

Read-copy update [McKenney]

Update by making copy, swapping pointer:

```
/* update mutex held here, serializing updates */
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

Is RCU really safe?

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*:

- When CPU is in kernel mode but doing process work (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

Preemptible kernels

Don't confuse with:

- Interrupt handlers can always preempt process context
- Preemptive threads (always have for multicore)
- Process context code running concurrently on other CPU cores

Sometimes want or need to disable preemption

- Code that must not be migrated between CPUs (per-CPU structs)
- Before acquiring spinlock (could improve performance)

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 of a thread's temporary variables are dead
  quiescent period: time during which every thread has been in quiescent state at least once

Garbage collection

- 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

Improving spinlock performance

Useful macros

Atomic compare and swap: `CAS (mem, old, new)`

- If `*mem == old`, then swap `*mem`↔`new` and return `true`, else `false`
- On x86, can implement using locked `cmpxchg` instruction
- In C11, use `atomic_compare_exchange_strong`
  (note: C atomics version sets `old = *mem` if `*mem != old`)

Atomic swap: `XCHG (mem, new)`

- Atomically exchanges `*mem`↔`new`
- Implement w. C11 `atomic_exchange`, or `xchg` on x86

Useful macros

- Atomic fetch and add: `FADD (mem, val)`
  - Atomically sets `*mem += val` and returns *old* value of `*mem`
  - Implement w. C11 `atomic_fetch_add`, `lock add` on x86
- Atomic fetch and subtract: `FSUB (mem, val)`
- Note: atomics return previous value
  (like `x++`, not `++x`)
- All behave like sequentially consistent fences
  - In C11, weaker `_explicit` versions 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 cache-coherent (cc) machines, improve fairness
- Each CPU has a `qnode` structure in local memory

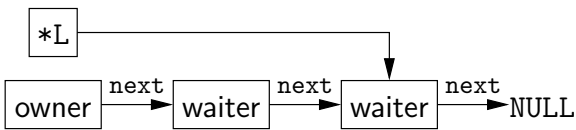
MCS lock

- Local can mean local memory in NUMA machine
- Or just its own cache line that gets cached in exclusive mode
- While waiting, spin on *your local* `locked` flag
- 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 (or NULL when unlocked)

MCS Acquire

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

```
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);
  }
}
```



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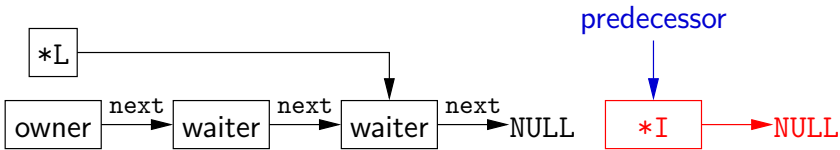

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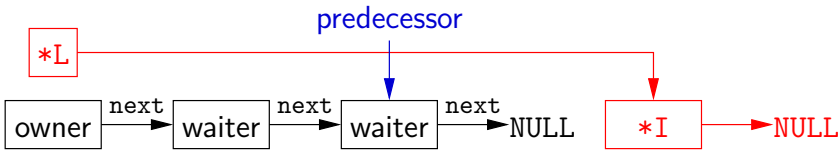

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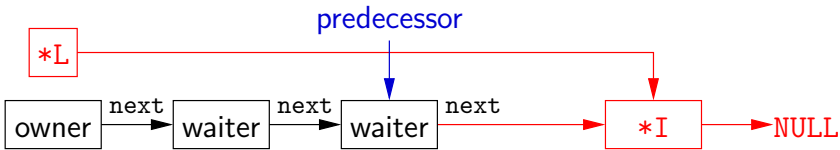
  XCHG (*L, predecessor);
  if (predecessor != NULL) {
    I->locked = true;
    predecessor->next = I;
    while (I->locked);
  }
}
```

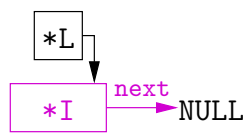


MCS Release with CAS

If `I->next` NULL and `*L == I`

- No one else is waiting for lock, OK to set `*L = NULL`

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

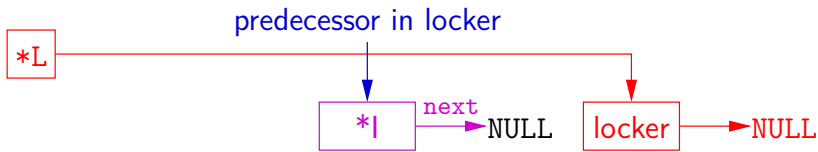


MCS Release with CAS

If `I->next` NULL and `*L != I`

- Another thread is in the middle of `acquire`
- Just wait for `I->next` to be non-NULL

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

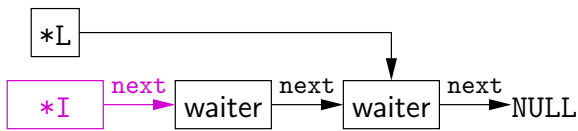


MCS Release with CAS

If `I->next` is non-NULL

- `I->next` oldest waiter, wake up with `I->next->locked = false`

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



Kernel interface for sleeping locks

Kernel support for sleeping locks

Sleeping locks must interact with scheduler

- For processes or native threads, must go into kernel (expensive)
- Common case is you can acquire lock—how to optimize?

Kernel support for sleeping locks

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.

Race condition

```
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

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

```
// 0=unlocked, 1=locked no waiters, 2=locked+waiters
struct lock { 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);
  }
}
```

Deadlock

The Deadlock Problem

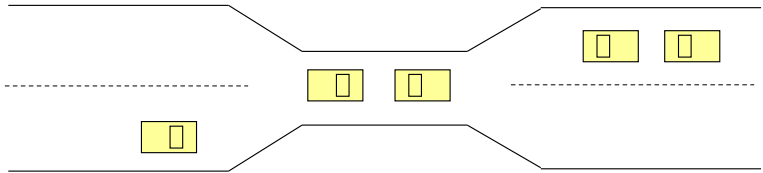
```
mutex_t m1, m2;
void p1 (void *ignored) {
  lock (m1); lock (m2);
  /* critical section */
            unlock (m2); unlock (m1);
}
void p2 (void *ignored) {
  lock (m2); lock (m1);
  /* critical section */
            unlock (m1); unlock (m2);
}
```

- 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 I

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

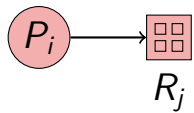
Deadlock conditions II

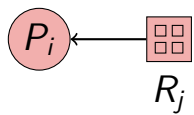
- All of 1–4 necessary for deadlock to occur
- Two approaches to dealing with deadlock:
  - Pro-active: prevention
  - Reactive: detection + corrective action

Prevent by eliminating one condition

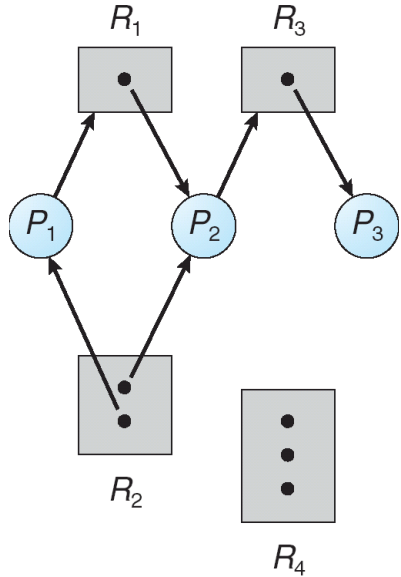
1. Limited access (mutual exclusion):
   - Buy more resources, split into pieces, or virtualize to make "infinite" copies
   - Threads: threads have copy of registers = no lock
2. No preemption:
   - Physical memory: virtualized with VM, can take physical page away and give to another process!
3. Multiple 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

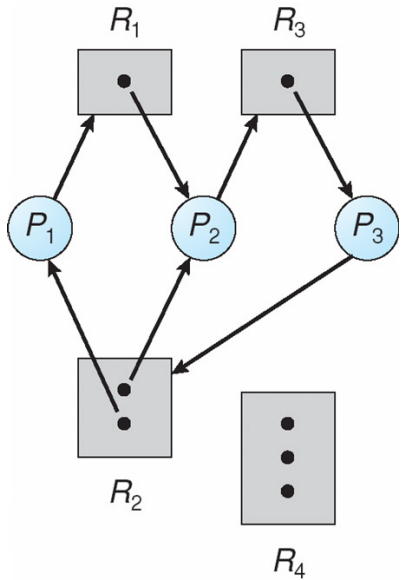
- View system as graph
  - Processes and Resources are nodes
  - Resource Requests and Assignments are edges
- Process: 
- Resource with 4 instances: 
- P_i requesting R_j: 

- P_i holding instance of R_j: 

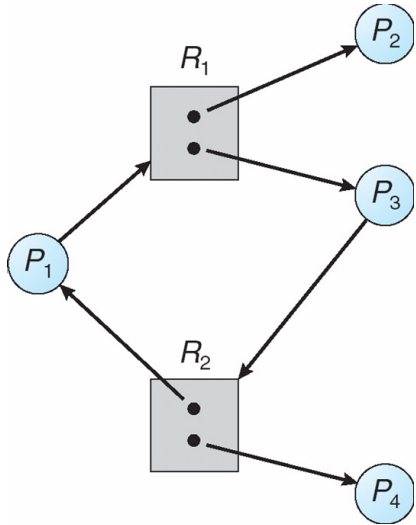
Example resource allocation graph



Graph with deadlock



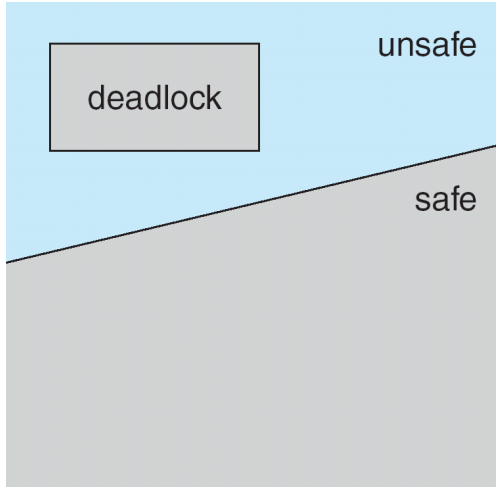
Is this deadlock?



Cycles and deadlock

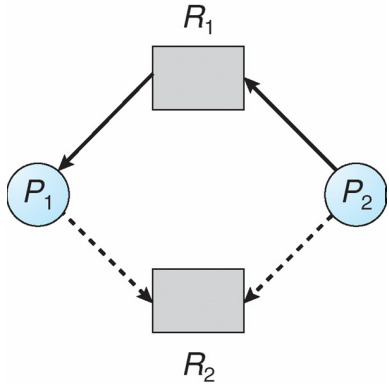
- If graph has no cycles $\Longrightarrow$ no deadlock
- If graph contains a cycle
  - Definitely deadlock if only one instance per resource
  - Otherwise, maybe deadlock, maybe not
- Prevent deadlock with partial order on resources
  - E.g., always acquire mutex m_1 before m_2
  - Usually design locking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

Prevention



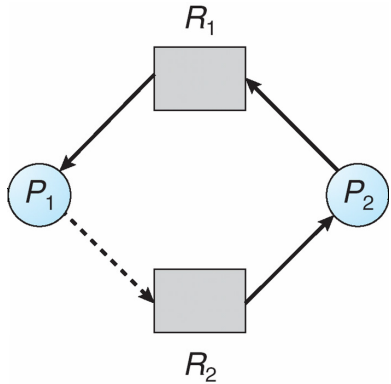
- Determine safe states based on *possible* resource allocation
- Conservatively prohibits non-deadlocked states

Claim edges



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

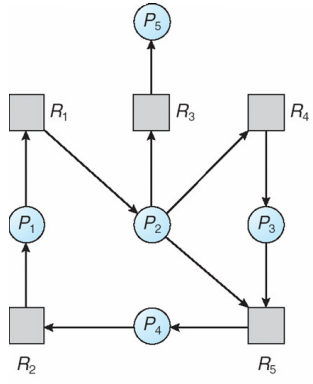
Example: unsafe state

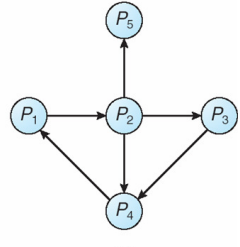


- Note cycle in graph
  - P_1 might request R_2 before relinquishing R_1
  - Would cause deadlock

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]

Transactional Memory

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

[1] Not applicable to topics in this lecture

Transactions

Transactions are 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

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)

Transactional memory

During transaction, processor tracks accessed memory

- Keeps read-set and write-set of cache lines
- Nothing gets written back to memory during transaction
- Transaction aborts (at `xend` or earlier) if any conflicts
- Otherwise, all dirty cache lines are "written" atomically
  (in practice switch to non-transactional M state of MESI)

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

Using transactional memory

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)

Hardware lock elision (HLE)

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!

Detecting data races

- Static methods (hard)
- Debugging painful—race might occur rarely
- Instrumentation—modify program to trap memory accesses
- Lockset algorithm (eraser [Savage]) particularly effective:
  - For each global memory location, keep a "lockset"
  - On each access, remove any locks not currently held
  - If lockset becomes empty, abort: No mutex protects data
  - Catches potential races even if they don't occur

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