Lecture 10: Avoiding Locks

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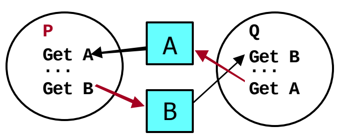
(with thanks to Paul McKenney)

Locking: A necessary evil?

- Locks are an easy to understand solution to critical section problem
  - Protect shared data from corruption due to simultaneous updates
  - Protect against inconsistent views of intermediate states
- But locks have lots of problems
  - Deadlock
  - Priority inversion
  - Not fault tolerant
  - Convoying
  - Expensive, even when uncontended
- Not easy to use correctly!

Deadlock

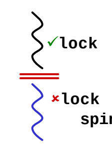
- Textbook definition: Set of threads blocked waiting for event that can only be caused by another thread in the same set
- Classic example:



- Self-deadlock also a big issue
  - Thread holds lock on shared data structure and is interrupted
  - Interrupt handler needs same lock!
    - Solutions exist (e.g., disable interrupts while holding lock), but add complexity

Priority Inversion

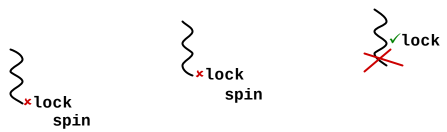
- Lower priority thread gets spinlock
- Higher priority thread becomes runnable and preempts it
  - needs lock, starts spinning
  - Lock holder can't run and release lock
    - May get to run on another CPU



- Solutions exist (e.g. disable preemption while holding spinlock, implement priority inheritance, etc.), but add complexity

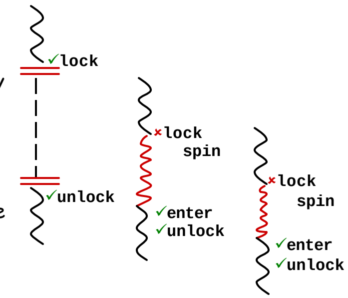
Not fault tolerant

- Lock holder crashes, or suffers indefinite delay, no one makes progress



Convoying

- Suppose we have set of threads, similar work per thread, but started at different times, occasionally accessing shared data
  - E.g. multi-threaded web server
- Expect access to shared objects (and hence times when locks are needed) to be spread out over time
  - Delay of lock holder allows other threads to catch up
  - Lock becomes contended and tends to stay that way

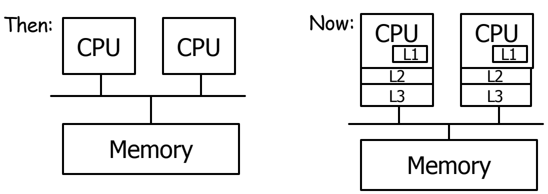


Expensive, even when uncontended

Operation	Nanoseconds
Instruction	0.24
Clock Cycle	0.69
Atomic Increment	42.09
Cmpxchg Blind Cache Transfer	56.80
Cmpxchg Cache Transfer and Invalidate	59.10
SMP Memory Barrier (eieio)	75.53
Full Memory Barrier (sync)	92.16
CPU-Local Lock	243.10

McKenney, 2005

Causes: Deeper Memory Hierarchy



- Memory speeds have not kept up with CPU speeds
  - 1984: no caches needed, since instructions slower than memory accesses
  - 2005: 3-4 level cache hierarchies, since instructions orders of magnitude faster than memory accesses
- Synch. ops typically execute at memory speed

Causes: Deeper Pipelines

Then: Fetch | Execute | Retire

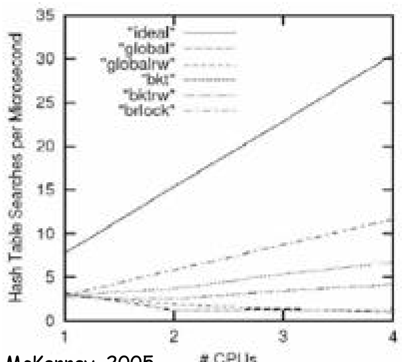
Now:

- 1984: Many cycles per instruction
- 2005: Many instructions per cycle
  - 20 stage pipelines
  - CPU logic executes instructions out-of-order to keep pipeline full
  - Synchronization instructions must not be reordered
    - Or you could execute instructions inside c.s. without completing entry instructions
  - So synchronization stalls the pipeline

Performance

- Main issue with lock performance used to be contention
  - Techniques were developed to reduce overheads in contended case
- Today, issue is degraded performance even when locks are always available
  - Together with other concerns about locks
- Quick look at lock performance…

Hash Table Microbenchmark



McKenney, 2005

- Read only
- Best case with brlock gets only 2X speedup on 4 CPUs
  - Linux "Big Reader Lock", per-cpu reader lock, writers must acquire all

Locks: ~~A necessary~~ evil?

- Idea: Don't lock if we don't need to
- Non-Blocking Synchronization (NBS)
  - "non blocking" refers to progress guarantees in the presence of thread failures; it does not mean that individual threads do not sleep or get interrupted
    - Wait-free → everyone makes progress
    - Lock-free → someone makes progress
    - Obstruction-free → someone makes progress in the absence of contention
  - We won't worry about these distinctions
    - Use lockless to describe strategies that avoid locking

NBS Basics

- Make change optimistically, roll back and retry if conflict detected

```
atomic_inc(int *counter) {
        int value;
        do {
                value = *counter;
        } while (!CAS(counter, value, value+1);
}
```

- Complex updates (e.g. modifying multiple values in a structure) are hidden behind a single commit point using atomic instructions

Example: Stack Data Structure

- Lock-based synchronization:

```
typedef struct node_s {
  int val;
  struct node_s *next;
} node_t;

typedef struct stack_s {
  node_t *top;
  lock_t *stack_lock;
} stack_t;

void push(stack_t S, node_t
*n) {
  lock(S.stack_lock);
  n->next = S.top; S.top=n;
  unlock(S.stack_lock);
}
```

```
node_t* pop(stack_t S){
    node_t *rnode = NULL;
    lock(S.stack_lock);
    if (S.top != NULL) {
      rnode = S.top;
      S.top = S.top->next;
    }
    unlock(S.stack_lock);
    return rnode;
}
```


Non-blocking stack (take 1)

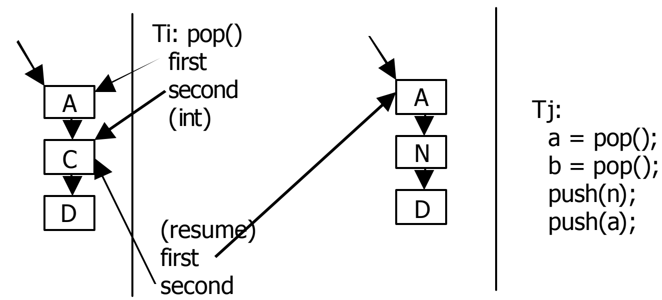
```
typedef struct node_s {
  int val;
  struct node_s *next;
} node_t;

typedef node_t *stack_t;

void push(stack_t *S, node_t
*n) {
  node_t *first;
  do {
    first = *S;
    n->next = first;
  } while (!CAS(S,first,n));
}
```

```
node_t* pop(stack_t *S) {
  node_t *first, *second;
  do {
    first = *S;
    if (first != NULL) {
      second = first->next;
    } else return NULL;
  } while
      (!CAS(S,first,second));
  return first;
}
```

What's wrong?

ABA Problem

- CAS(x, y, z) succeeds if value stored at x matches y



One Solution

- Include a version number with every pointer
  - pointer_t = <pointer, version>
  - Increment version number (atomically) every time you modify pointer
  - Change to version number guarantees CAS will fail if pointer has changed
  - Requires double-word CAS operation (not every architecture provides this)
  - May restrict reuse of memory

Using NBS

- Good for simple data structures, update heavy
- When you need NBS constraints/guarantees
  - Progress in face of failure
  - Linearizability
    - Everyone agrees on all intermediate states
- Both constraints are often irrelevant!

Constraints Irrelevant?

- Real systems don't fail the way theoretical ones do
  - Software bugs are not always fail-stop
  - Preemption/interrupt is not a failure
    - And can be controlled by system programmer or scheduler-conscious synchronization
  - Page fault is not a failure
    - Over-provision memory… if shared data really is paged out, it will have to be brought into memory before progress is made anyway
- Don't always need intermediate states, just final
  - Linearizability implies dependency → limits parallelism
  - If events are unrelated, asynchronous, does it matter which happened first?