

# Outline

- 1 Cache coherence – the hardware view
- 2 Synchronization and memory consistency review
- 3 C11 Atomics
- 4 Avoiding locks

# Important memory system properties

- **Coherence – concerns accesses to a single memory location**
  - There is a total order on all updates
  - Must obey program order if access from only one CPU
  - There is bounded latency before everyone sees a write
- **Consistency – concerns ordering across memory locations**
  - Even with coherence, different CPUs can see the same write happen at different times
  - Sequential consistency is what matches our intuition (As if operations from all CPUs interleaved on one CPU)
  - Many architectures offer weaker consistency
  - Yet well-defined weaker consistency can still be sufficient to implement [thread API contract from concurrency lecture](#)

# Multicore cache coherence

- **Performance requires caches**
  - Divided into chunks of bytes called lines (e.g., 64 bytes)
  - Caches create an opportunity for cores to disagree about memory
- **Bus-based approaches**
  - “Snoopy” protocols, each CPU listens to memory bus
  - Use write-through and invalidate when you see a write bits
  - Bus-based schemes limit scalability
- **Modern CPUs use networks (e.g., AMD infinity fabric, intel UPI, CXL [between CPUs and devices])**
  - CPUs pass each other messages about cache lines

# MESI coherence protocol

- **Modified**
  - Exactly one cache has a valid copy
  - That copy is dirty (needs to be written back to memory)
  - Must invalidate all copies in other caches before entering this state
- **Exclusive**
  - Same as Modified except the cache copy is clean
- **Shared**
  - One or more caches and memory have a valid copy
- **Invalid**
  - Doesn't contain any data
- **Owned (for enhanced "MOESI" protocol)**
  - Cached copy may be dirty (like Modified state)
  - But have to broadcast modifications (sort of like Shared state)
  - Can have one owned + multiple shared copies of cache line

# Core and Bus Actions

- **Actions performed by CPU core**
  - Read
  - Write
  - Evict (modified/owned? must write back)
- **Transactions on bus (or interconnect)**
  - Read: without intent to modify, data can come from memory or another cache
  - Read-exclusive: with intent to modify, must invalidate all other cache copies
  - Writeback: contents put on bus and memory is updated

- **Old machines used *dance hall* architectures**
  - Any CPU can “dance with” any memory equally
- **An alternative: Non-Uniform Memory Access (NUMA)**
  - Each CPU has fast access to some “close” memory
  - Slower to access memory that is farther away
  - Use a directory to keep track of who is caching what
- **Originally for esoteric machines with many CPUs**
  - But AMD and then intel integrated memory controller into CPU
  - Faster to access memory controlled by the local socket (or even local die in a multi-chip module)
- **cc-NUMA = cache-coherent NUMA**
  - Rarely see non-cache-coherent NUMA (BBN Butterfly 1, Cray T3D)

# Real World Coherence Costs

- See [David] for a great reference. Xeon results:
  - 3 cycle L1, 11 cycle L2, 44 cycle LLC, 355 cycle local RAM
- **If another core in same socket holds line in modified state:**
  - load: 109 cycles (LLC + 65)
  - store: 115 cycles (LLC + 71)
  - atomic CAS: 120 cycles (LLC + 76)
- **If a core in a different socket holds line in modified state:**
  - NUMA load: 289 cycles
  - NUMA store: 320 cycles
  - NUMA atomic CAS: 324 cycles
- **But only a partial picture**
  - Could be faster because of out-of-order execution
  - Could be slower if interconnect contention or multiple hops

# NUMA and spinlocks

- **Test-and-set spinlock has several advantages**
  - Simple to implement and understand
  - One memory location for arbitrarily many CPUs
- **But also has disadvantages**
  - Lots of traffic over memory interconnect (especially w.  $> 1$  spinner)
  - Not necessarily fair (lacks bounded waiting)
  - Even less fair on a NUMA machine
- **Idea 1: Avoid spinlocks altogether (today)**
- **Idea 2: Reduce interconnect traffic with better spinlocks (next lecture)**
  - Design lock that spins only on local memory
  - Also gives better fairness

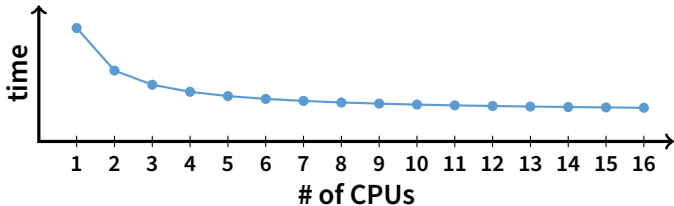
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# Amdahl's law

$$T(n) = T(1) \left( B + \frac{1}{n}(1 - B) \right)$$

- **Expected speedup limited when only part of a task is sped up**
  - $T(n)$ : the time it takes  $n$  CPU cores to complete the task
  - $B$ : the fraction of the job that must be serial
- **Even with massive multiprocessors,  $\lim_{n \rightarrow \infty} = B \cdot T(1)$**



- Places an ultimate limit on parallel speedup
- **Problem: synchronization increases serial section size**

# Locking basics

```
mutex_t m;  
  
lock(&m);  
cnt = cnt + 1; /* critical section */  
unlock(&m);
```

- **Only one thread can hold a mutex at a time**
  - Makes critical section atomic
- **Recall thread API contract**
  - All access to global data must be protected by a mutex
  - Global = two or more threads touch data and at least one writes
- **Means must map each piece of global data to one mutex**
  - Never touch the data unless you locked that mutex
- **But many ways to map data to mutexes**

# Locking granularity

- Consider two lookup implementations for global hash table:

```
struct list *hash_tbl[1021];
```

## coarse-grained locking

```
mutex_t m;  
    :  
    mutex_lock(&m);  
    struct list_elem *pos = list_begin (hash_tbl[hash(key)]);  
    /* ... walk list and find entry ... */  
    mutex_unlock(&m);
```

## fine-grained locking

```
mutex_t bucket_lock[1021];  
    :  
    int index = hash(key);  
    mutex_lock(&bucket_lock[index]);  
    struct list_elem *pos = list_begin (hash_tbl[index]);  
    /* ... walk list and find entry ... */  
    mutex_unlock(&bucket_lock[index]);
```

- Which implementation is better?

## Locking granularity (continued)

- **Fine-grained locking admits more parallelism**
  - E.g., imagine network server looking up values in hash table
  - Parallel requests will usually map to different hash buckets
  - So fine-grained locking should allow better speedup
- **When might coarse-grained locking be better?**

# Locking granularity (continued)

- **Fine-grained locking admits more parallelism**

- E.g., imagine network server looking up values in hash table
- Parallel requests will usually map to different hash buckets
- So fine-grained locking should allow better speedup

- **When might coarse-grained locking be better?**

- Suppose you have global data that applies to whole hash table

```
struct hash_table {  
    size_t num_elements;    /* num items in hash table */  
    size_t num_buckets;    /* size of buckets array */  
    struct list *buckets;  /* array of buckets */  
};
```

- Read `num_buckets` each time you insert
- Check `num_elements` on insert, possibly expand buckets & rehash
- Single global mutex would protect these fields

- **Can you avoid serializing lookups to growable hash table?**

# Readers-writers problem

- **Recall a `mutex` allows access in only one thread**
- **But a data race occurs only if**
  - Multiple threads access the same data, **and**
  - At least one of the accesses is a write
- **How to allow multiple readers *or* one single writer?**
  - Need lock that can be *shared* amongst concurrent readers
- **Can implement using other primitives (next slides)**
  - Keep integer `i` – # of readers or -1 if held by writer
  - Protect `i` with `mutex`
  - Sleep on condition variable when can't get lock

# Implementing shared locks

```
struct sharedlk {
    int i;    /* # shared lockers, or -1 if exclusively locked */
    mutex_t m;
    cond_t c;
};

void AcquireExclusive (sharedlk *sl) {
    lock (&sl->m);
    while (sl->i) { wait (&sl->m, &sl->c); }
    sl->i = -1;
    unlock (&sl->m);
}

void AcquireShared (sharedlk *sl) {
    lock (&sl->m);
    while (&sl->i < 0) { wait (&sl->m, &sl->c); }
    sl->i++;
    unlock (&sl->m);
}
```

## Implementing shared locks (continued)

```
void ReleaseShared (sharedlk *sl) {  
    lock (&sl->m);  
    if (!--sl->i)  
        signal (&sl->c);  
    unlock (&sl->m);  
}
```

```
void ReleaseExclusive (sharedlk *sl) {  
    lock (&sl->m);  
    sl->i = 0;  
    broadcast (&sl->c);  
    unlock (&sl->m);  
}
```

- Any issues with this implementation?

# Implementing shared locks (continued)

```
void ReleaseShared (sharedlk *sl) {  
    lock (&sl->m);  
    if (!--sl->i)  
        signal (&sl->c);  
    unlock (&sl->m);  
}
```

```
void ReleaseExclusive (sharedlk *sl) {  
    lock (&sl->m);  
    sl->i = 0;  
    broadcast (&sl->c);  
    unlock (&sl->m);  
}
```

- **Any issues with this implementation?**
  - Prone to starvation of writer (no bounded waiting)
  - How might you fix?

# Review: Test-and-set spinlock

```
struct var {  
    int lock;  
    int val;  
};
```

```
void atomic_inc (var *v) {  
    while (test_and_set (&v->lock))  
        ;  
    v->val++;  
    v->lock = 0;  
}
```

```
void atomic_dec (var *v) {  
    while (test_and_set (&v->lock))  
        ;  
    v->val--;  
    v->lock = 0;  
}
```

- **Is this code correct without sequential consistency?**

# Memory reordering danger


- Suppose no sequential consistency (& don't compensate)
- Hardware could violate program order

## Program order on CPU #1

```
v->lock = 1;  
register = v->val;  
v->val = register + 1;  
v->lock = 0;
```

## View on CPU #2

```
v->lock = 1;  
  
v->lock = 0;  
/* danger */;  
v->val = register + 1;
```



- If `atomic_inc` called at `/* danger */`, bad val ensues!

# Ordering requirements

```
void atomic_inc (var *v) {
    while (test_and_set (&v->lock))
        ;
    v->val++;
    /* danger */
    v->lock = 0;
}
```

- **Must ensure all CPUs see the following:**
  1. `v->lock = 1` ran *before* `v->val` was read and written
  2. `v->lock = 0` ran *after* `v->val` was written
- **How does #1 get assured on x86?**
  - Recall `test_and_set` uses `xchgl %eax, (%edx)`
- **How to ensure #2 on x86?**

# Ordering requirements

```
void atomic_inc (var *v) {
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- **How does #1 get assured on x86?**
  - Recall `test_and_set` uses `xchgl %eax, (%edx)`
  - `xchgl` instruction always “locked,” ensuring barrier
- **How to ensure #2 on x86?**

# Ordering requirements

```
void atomic_inc (var *v) {  
    while (test_and_set (&v->lock))  
        ;  
    v->val++;  
    asm volatile ("sfence" ::: "memory");  
    v->lock = 0;  
}
```

- **Must ensure all CPUs see the following:**

1. `v->lock = 1` ran *before* `v->val` was read and written
2. `v->lock = 0` ran *after* `v->val` was written

- **How does #1 get assured on x86?**

- Recall `test_and_set` uses `xchgl %eax, (%edx)`
- `xchgl` instruction always “locked,” ensuring barrier

- **How to ensure #2 on x86?**

- Might need fence instruction after, e.g., non-temporal stores
- Definitely need compiler barrier

# Gcc extended `asm` syntax [gnu]

```
asm volatile (template-string : outputs : inputs : clobbers);
```

- Puts *template-string* in assembly language compiler output
  - Expands %0, %1, ... (a bit like printf conversion specifiers)
  - Use “%%” for a literal % (e.g., “%%cr3” to specify %cr3 register)
- *inputs/outputs* specify parameters as “**constraint**” (*value*)

```
int outvar, invar = 3;
asm ("movl %1, %0" : "=r" (outvar) : "r" (invar));
/* now outvar == 3 */
```

- *clobbers* lists other state that get used/overwritten
  - Special value “memory” prevents reordering with loads & stores
  - Serves as *compiler barrier*, as important as hardware barrier
- `volatile` indicates side effects other than result
  - Otherwise, gcc might optimize away if you don't use result

# Correct spinlock on alpha

- Recall implementation of `test_and_set` on alpha (with much weaker memory consistency than x86):

```
_test_and_set:
    ldq_l   v0, 0(a0)           # v0 = *lockp (LOCKED)
    bne    v0, 1f              # if (v0) return
    addq   zero, 1, v0         # v0 = 1
    stq_c  v0, 0(a0)           # *lockp = v0 (CONDITIONAL)
    beq    v0, _test_and_set   # if (failed) try again
    mb
    addq   zero, zero, v0      # return 0
1:  ret    zero, (ra), 1
```

- Memory barrier instruction `mb` (like `mfence`)**
  - All processors will see that everything before `mb` in program order happened before everything after `mb` in program order
- Need barrier before releasing spinlock as well:**

```
asm volatile ("mb" ::: "memory");
v->lock = 0;
```

# Memory barriers/fences

- **Fortunately, consistency need not overly complicate code**
  - If you do locking right, only need a few fences within locking code
  - Code will be easily portable to new CPUs
- **Most programmers should stick to mutexes**
- **But advanced techniques may require lower-level code**
  - Later this lecture will see some wait-free algorithms
  - Also important for optimizing special-case locks (E.g., linux kernel `rw_semaphore`, ...)
- **Algorithms often explained assuming sequential consistency**
  - Must know how to use memory fences to implement correctly
  - E.g., see [\[Howells\]](#) for how Linux deals with memory consistency
  - And another plug for [Why Memory Barriers](#)
- **Next: How C11 allows portable low-level code**

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# Atomics and portability

- **Lots of variation in atomic instructions, consistency models, compiler behavior**
  - Changing the compiler or optimization level can invalidate code
- **Different CPUs today: Many laptops (not Apple) are x86, while your cell phone uses ARM**
  - x86: Total Store Order Consistency Model, CISC
  - arm: Relaxed Consistency Model, RISC
- **Could make it impossible to write portable kernels and applications**
- **Fortunately, the C11 standard has builtin support for atomics**
  - If not on by default, use `gcc -std=gnu11` or `-std=gnu17`
- **Also available in C++11, but won't discuss today**

## Background: C memory model [C11]

- **Within a thread, many evaluations are *sequenced***
  - E.g., in “`f1(); f2();`”, evaluation of `f1` is sequenced before `f2`
- **Across threads, some operations *synchronize with others***
  - E.g., releasing mutex `m` synchronizes with a subsequent acquire `m`
- **Evaluation *A happens before B*, which we'll write  $A \rightarrow B$ , when:**
  - *A* is sequenced before *B* (in the same thread),
  - *A* synchronizes with *B*,
  - *A* is dependency-ordered before *B* (ignore for now—means *A* has release semantics and *B* consume semantics for same value), or
  - There is another operation *X* such that  $A \rightarrow X \rightarrow B$ .<sup>1</sup>

---

<sup>1</sup>Except chain of “ $\rightarrow$ ” cannot end: ..., dependency-ordered, sequenced before

# C11 Atomics: Big picture

- **C11 says a *data race* produces **undefined behavior (UB)****
- A write *conflicts* with a read or write of same memory location
- Two conflicting operations *race* if not ordered by happens before
- Undefined can be anything (e.g., delete all your files, ...)
- Think UB okay in practice? See [\[Wang\]](#), [\[Lattner\]](#)
- **Spinlocks (and hence mutexes that internally use spinlocks) synchronize across threads**
- Synchronization adds happens before arrows, avoiding data races
- **Yet hardware supports other means of synchronization**
- **C11 atomics provide direct access to synchronized lower-level operations**
- E.g., can get compiler to issue `lock` prefix in some cases

# C11 Atomics: Basics

- **Include new** `<stdatomic.h>` **header**
- **New** `_Atomic` **type qualifier: e.g.**, `_Atomic int foo;`
  - Convenient aliases: `atomic_bool`, `atomic_int`, `atomic_ulong`, ...
  - Must initialize specially:

```
#include <stdatomic.h>
_Atomic int global_int = ATOMIC_VAR_INIT(140);
    :
    Atomic_(int) *dyn = malloc(sizeof(*dyn));
    atomic_init(dyn, 140);
```

- **Compiler emits read-modify-write instructions for atomics**
  - E.g., `+=`, `-=`, `|=`, `&=`, `^=`, `++`, `--` do what you would hope
  - Act atomically and synchronize with one another
- **Also functions including** `atomic_fetch_add`,  
`atomic_compare_exchange_strong`, ...

# Locking and atomic flags

- **Implementations might use spinlocks internally for most atomics**
  - Could interact badly with interrupt/signal handlers
  - Can check if `ATOMIC_INT_LOCK_FREE`, etc., macros defined
  - Fortunately modern CPUs don't require this
- `atomic_flag` **is a special type guaranteed lock-free**
  - Boolean value without support for loads and stores
  - Initialize with: `atomic_flag mylock = ATOMIC_FLAG_INIT;`
  - Only two kinds of operation possible:
    - ▶ `_Bool atomic_flag_test_and_set(volatile atomic_flag *obj);`
    - ▶ `void atomic_flag_clear(volatile atomic_flag *obj);`
  - Above functions guarantee sequential consistency (atomic operation serves as memory fence, too)

# Exposing weaker consistency

```
enum memory_order { /*...*/ };

_Bool atomic_flag_test_and_set_explicit(
    volatile atomic_flag *obj, memory_order order);
void atomic_flag_clear_explicit(
    volatile atomic_flag *obj, memory_order order);

C atomic_load_explicit(
    const volatile A *obj, memory_order order);
void atomic_store_explicit(
    volatile A *obj, C desired, memory_order order);

bool atomic_compare_exchange_weak_explicit(
    A *obj, C *expected, C desired,
    memory_order succ, memory_order fail);
```

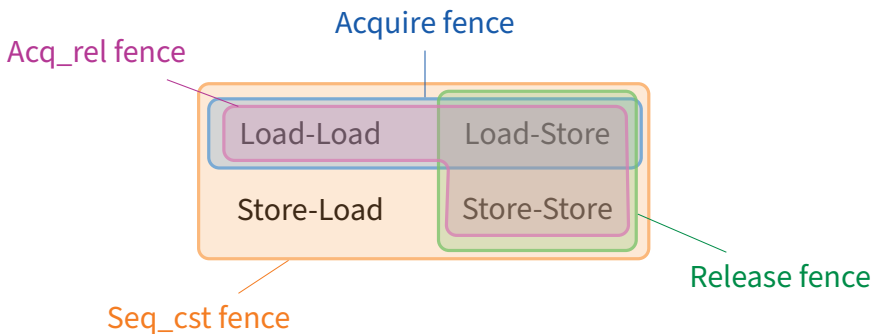
- **Atomic functions have `_explicit` variants**

- These guarantee coherence but *not* sequential consistency
- May allow compiler to generate faster code

# Memory ordering

- **Six possible** `memory_order` **values:**
  1. `memory_order_relaxed`: no memory ordering
  2. `memory_order_consume`: super tricky, see [\[Preshing\]](#) for discussion
  3. `memory_order_acquire`: for start of critical section
  4. `memory_order_release`: for end of critical section
  5. `memory_order_acq_rel`: combines previous two
  6. `memory_order_seq_cst`: full sequential consistency
- **Also have fence operation not tied to particular atomic:**  
`void atomic_thread_fence(memory_order order);`
- **Suppose thread 1 releases and thread 2 acquires**
  - Thread 1's preceding accesses can't move past **release** store
  - Thread 2's subsequent accesses can't move before **acquire** load
  - Warning: other threads might see a completely different order

# Types of memory fence<sup>2</sup>



- **$X$ - $Y$  fence = operations of type  $X$  sequenced before the fence happen before operations of type  $Y$  sequenced after the fence**

<sup>2</sup>Credit to [Preshing] for explaining it this way

## Example: Atomic counters

```
_Atomic(int) packet_count;

void recv_packet(...)
{
    atomic_fetch_add_explicit(&packet_count, 1,
                              memory_order_relaxed);
    :
}

void reset_counter()
{
    atomic_store_explicit(&packet_count, 0,
                          memory_order_relaxed);
}
```

- **Need to count packets accurately**
- **Don't need to order other memory accesses across threads**
- **Relaxed memory order can avoid unnecessary overhead**
  - On x86, `recv_packet` doesn't benefit, but `reset_counter` uses `mov` compared to `xchgl` for `packet_count = 0`

## Example: Producer, consumer 1

```
struct message msg_buf;
_Atomic(_Bool) msg_ready;

void send(struct message *m) {
    msg_buf = *m;
    atomic_thread_fence(memory_order_release);
    /* Prior loads+stores happen before subsequent stores */
    atomic_store_explicit(&msg_ready, 1,
                          memory_order_relaxed);
}

struct message *recv(void) {
    _Bool ready = atomic_load_explicit(&msg_ready,
                                       memory_order_relaxed);
    if (!ready)
        return NULL;
    atomic_thread_fence(memory_order_acquire);
    /* Prior loads happen before subsequent loads+stores */
    return &msg_buf;
}
```

## Example: Producer, consumer 2

```
struct message msg_buf;
_Atomic(_Bool) msg_ready;

void send(struct message *m) {
    msg_buf = *m;
    atomic_store_explicit(&msg_ready, 1,
                          memory_order_release);
}

struct message *recv(void) {
    _Bool ready = atomic_load_explicit(&msg_ready,
                                       memory_order_acquire);
    if (!ready)
        return NULL;
    return &msg_buf;
}
```

- **This is potentially faster than previous example**
  - E.g., atomic other stores after `send` can be moved before `msg_buf`

## Example: Test-and-set spinlock

```
void
spin_lock(atomic_flag *lock)
{
    while(atomic_flag_test_and_set_explicit(lock,
                                             memory_order_acquire))
        ;
}

void
spin_unlock(atomic_flag *lock)
{
    atomic_flag_clear_explicit(lock, memory_order_release);
}
```

## Example: Better test-and-set spinlock

```
void spin_lock(atomic_bool *lock)
{
    while(atomic_exchange_explicit(lock, 1,
                                   memory_order_acquire)) {
        while(atomic_load_explicit(lock, memory_order_relaxed)) {
#if __i386 || __x86_64
            __builtin_ia32_pause();
#elif __ARM_ARCH >= 7 && __clang__
            __builtin_arm_yield();
#endif
        }
    }
}

void spin_unlock(atomic_bool *lock)
{
    atomic_store_explicit(lock, 0, memory_order_release);
}
```

- See [\[Rigtorp\]](#) for a good discussion

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## Recall producer/consumer (lecture 3)

```
/* PRODUCER */
for (;;) {
    item *nextProduced
        = produce_item ();

    mutex_lock (&mutex);
    while (count == BUF_SIZE)
        cond_wait (&nonfull,
                  &mutex);

    buffer[in] = nextProduced;
    in = (in + 1) % BUF_SIZE;
    count++;
    cond_signal (&nonempty);
    mutex_unlock (&mutex);
}
```

```
/* CONSUMER */
for (;;) {
    mutex_lock (&mutex);
    while (count == 0)
        cond_wait (&nonempty,
                  &mutex);

    nextConsumed = buffer[out];
    out = (out + 1) % BUF_SIZE;
    count--;
    cond_signal (&nonfull);
    mutex_unlock (&mutex);

    consume_item (nextConsumed);
}
```

# Eliminating locks

- One use of locks is to coordinate multiple updates of single piece of state
- How to remove locks here?
  - Factor state so that each variable only has a single writer
- Producer/consumer example revisited
  - Assume one producer, one consumer
  - Why do we need `count` variable, written by both?  
*To detect buffer full/empty*
  - Have producer write `in`, consumer write `out` (both `_Atomic`)
  - Use `in/out` to detect buffer state  
(sacrifice one buffer slot to distinguish completely full and empty)
  - But note next example busy-waits, which is less good

# Lock-free producer/consumer

```
atomic_int in, out;
```

```
void producer (void *ignored) {  
    for (;;) {  
        item *nextProduced = produce_item ();  
        while (((in + 1) % BUF_SIZE) == out) thread_yield ();  
        buffer[in] = nextProduced;  
        in = (in + 1) % BUF_SIZE;  
    }  
}
```

```
void consumer (void *ignored) {  
    for (;;) {  
        while (in == out) thread_yield ();  
        nextConsumed = buffer[out];  
        out = (out + 1) % BUF_SIZE;  
        consume_item (nextConsumed);  
    }  
}
```

[Note fences not needed because no relaxed atomics]

# Version with relaxed atomics

```
void producer (void *ignored) {
    int slot = atomic_load(&in);
    for (;;) {
        item *nextProduced = produce_item ();
        int next = (slot + 1) % BUF_SIZE;
        while (atomic_load_explicit(&out, memory_order_acquire) ==
            next)          // Could you use relaxed? ~~~~~~
            thread_yield();
        buffer[slot] = nextProduced;
        atomic_store_explicit(&in, next, memory_order_release);
        slot = next;
    }
}

void consumer (void *ignored) {
    // Use memory_order_acquire to load in (for latest buffer[myin])
    // Use memory_order_release to store out
}
```

# Non-blocking synchronization

- **Design algorithm to *avoid critical sections***
  - Any threads can make progress if other threads are preempted
  - Which wouldn't be the case if preempted thread held a lock
- **Requires that hardware provide the right kind of atomics**
  - Simple test-and-set is insufficient
  - Atomic compare and swap is good: CAS (`mem`, `old`, `new`)  
If `*mem == old`, then swap `*mem`  $\longleftrightarrow$  `new` and return `true`, else `false`
- **Can implement many common data structures**
  - Stacks, queues, even hash tables
- **Can implement any algorithm on right hardware**
  - Need operation such as atomic compare and swap (has property called *consensus number* =  $\infty$  [Herlihy])
  - Entire kernels have been written without locks [Greenwald]

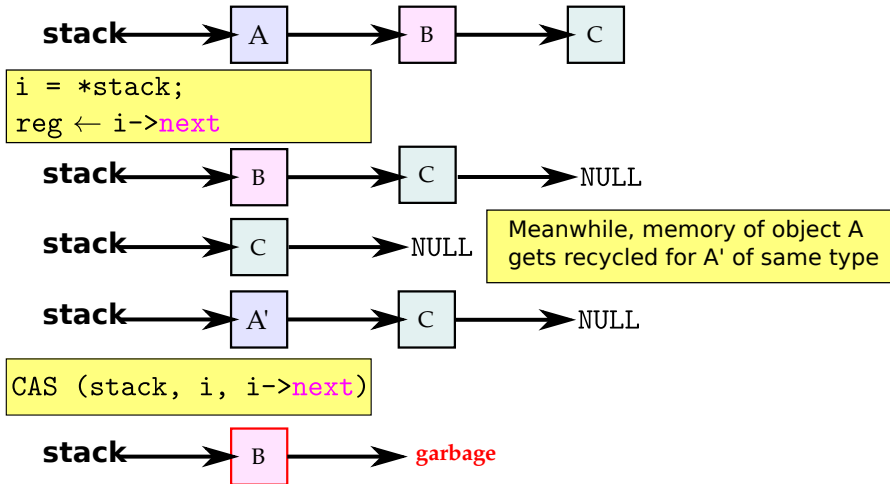
## Example: non-blocking stack

```
struct item {
    /* data */
    _Atomic (struct item *) next;
};
typedef _Atomic (struct item *) stack_t;

void atomic_push (stack_t *stack, item *i) {
    do {
        i->next = *stack;
    } while (!CAS (stack, i->next, i));
}

item *atomic_pop (stack_t *stack) {
    item *i;
    do {
        i = *stack;
    } while (!CAS (stack, i, i->next));
    return i;
}
```

# Wait-free stack issues



- “ABA” race in pop if other thread pops, re-pushes i
  - Can be solved by [counters](#) or [hazard pointers](#) to delay re-use

# “Benign” races

- Could also eliminate locks by having race conditions
- Maybe you think you care more about speed than correctness

```
++hits; /* each time someone accesses web site */
```

- Maybe you think you can get away with the race (**NOT!**, really)

```
if (!initialized) {  
    lock (m);  
    if (!initialized) {  
        initialize ();  
        atomic_thread_fence (memory_order_release); /* why? */  
        initialized = 1;  
    }  
    unlock (m);  
}
```

- But don't do this [Vyukov], [Boehm]! Not benign at all
  - Again, UB really bad! Like use-after free or array overflow bad
  - If needed for efficiency, use relaxed-memory-order atomics

# 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**
  - E.g., global variable: `routing_table *rt;`
  - Call `lookup (rt, route);` with no lock
- **Update by making copy, swapping pointer**

```
routing_table *newrt = copy_routing_table (rt);
update_routing_table (newrt);
atomic_thread_fence (memory_order_release);
rt = newrt;
```
- **Is RCU really safe? Stay tuned next lecture...**

# Next class

- **The exciting conclusion of RCU**
  - Spoiler: safe on all architectures except on alpha
- **Building a better spinlock**
- **What interface should kernel provide for sleeping locks?**
- **Deadlock**
- **Scalable interface design**