CS5460/6460: Operating Systems

Lecture 11: Locking

Anton Burtsev
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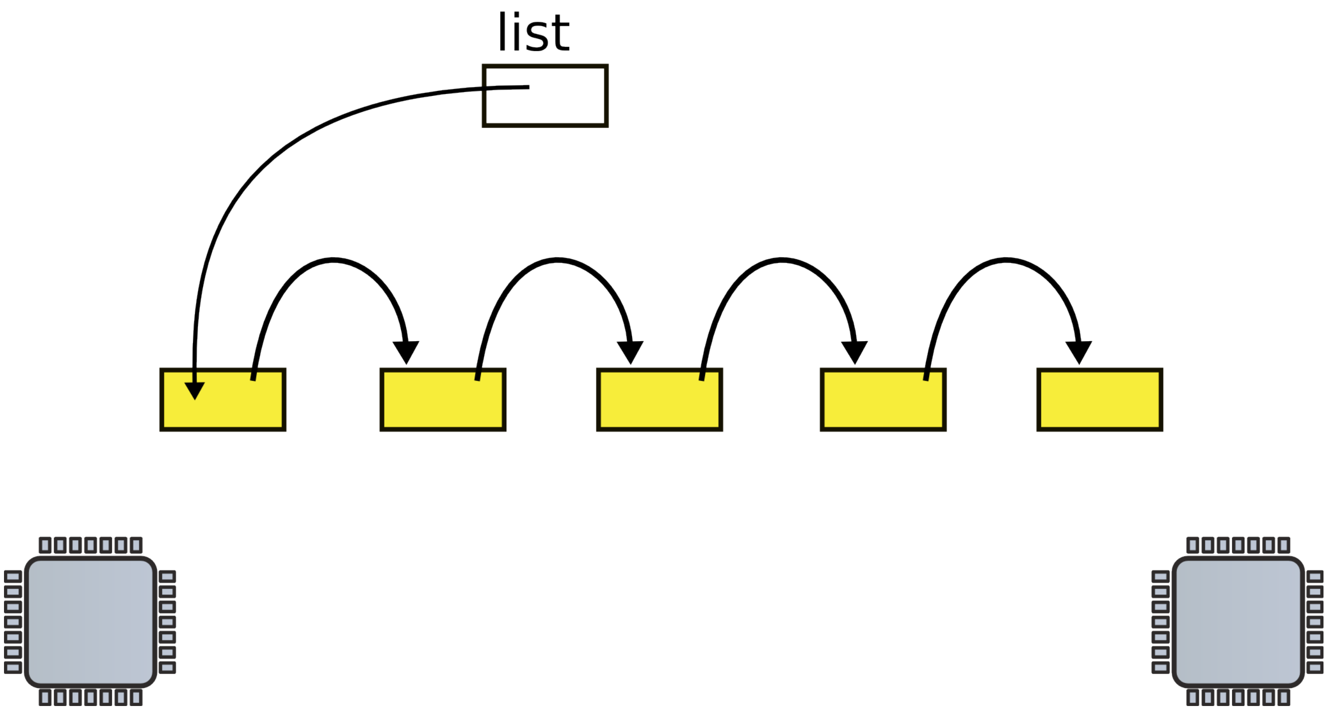
Race conditions

- Disk driver maintains a list of outstanding requests
- Each process can add requests to the list

List implementation no locks

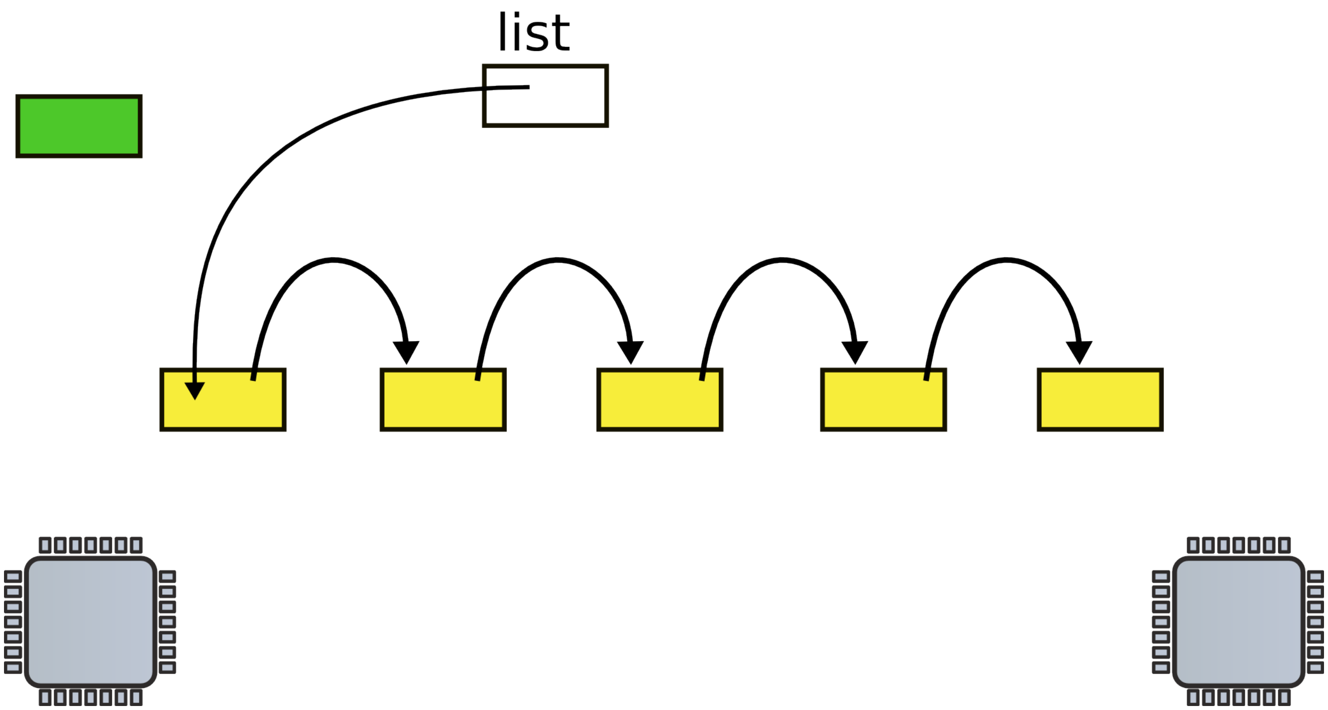
```c
struct list {
  int data;
  struct list *next;
};
...
struct list *list = 0;
...
insert(int data)
{
   struct list *l;

   l = malloc(sizeof *l);
   l->data = data;
   l->next = list;
   list = l;
}
```

Request queue (e.g. incoming network packets)

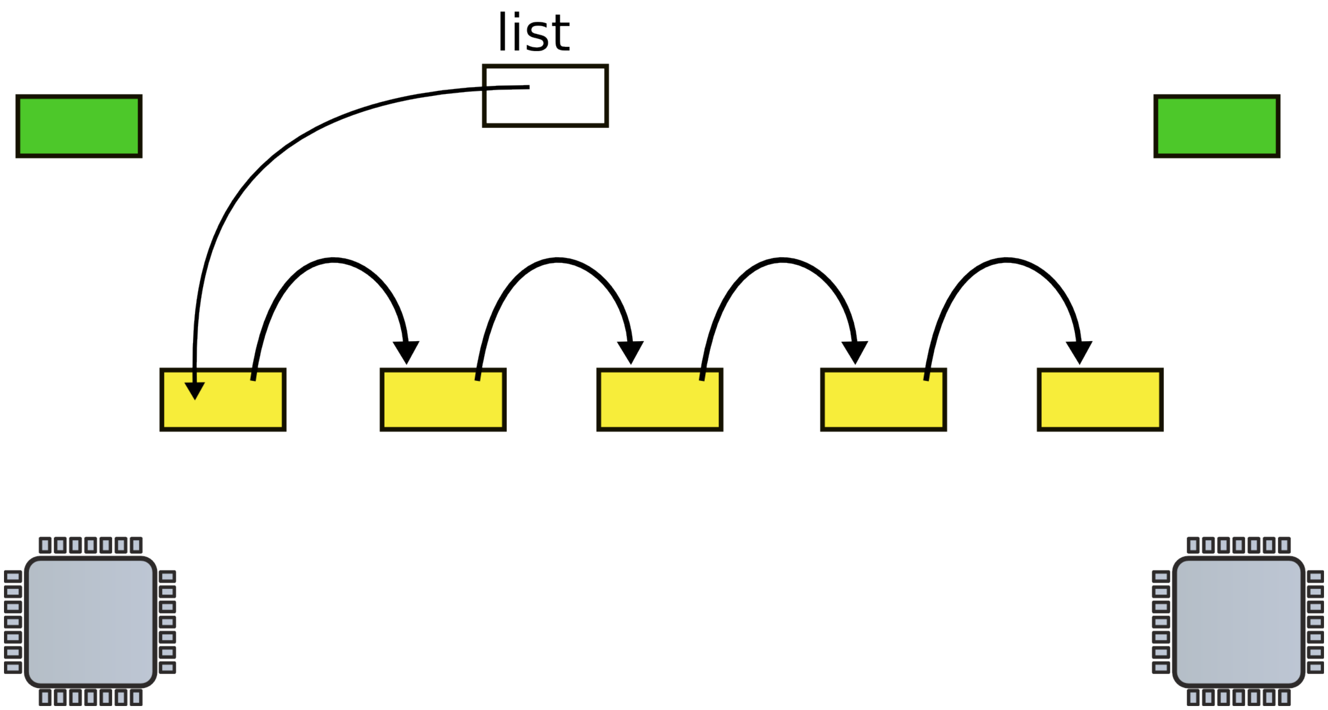


- Linked list, list is pointer to the first element

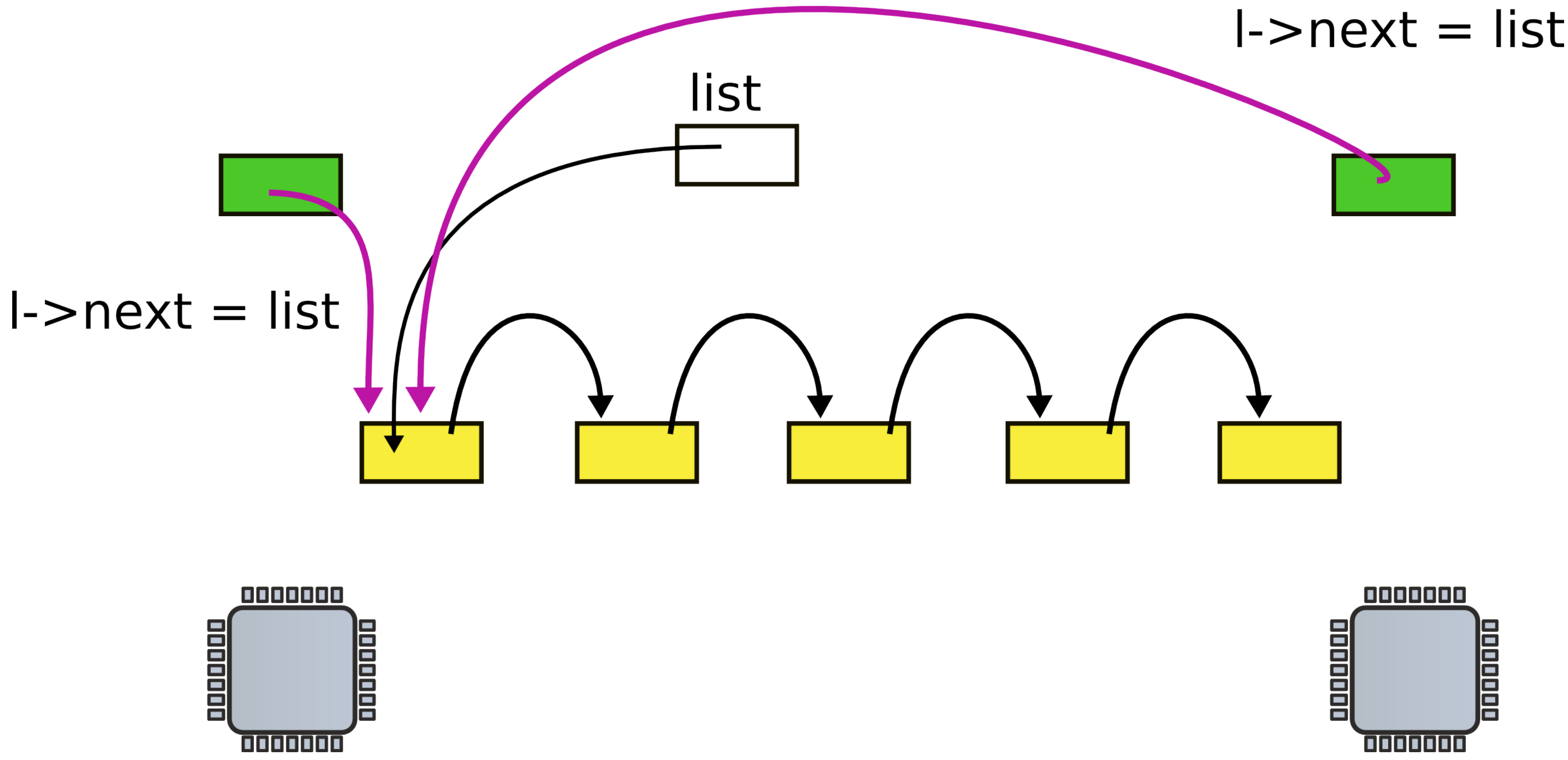
CPU1 allocates new request



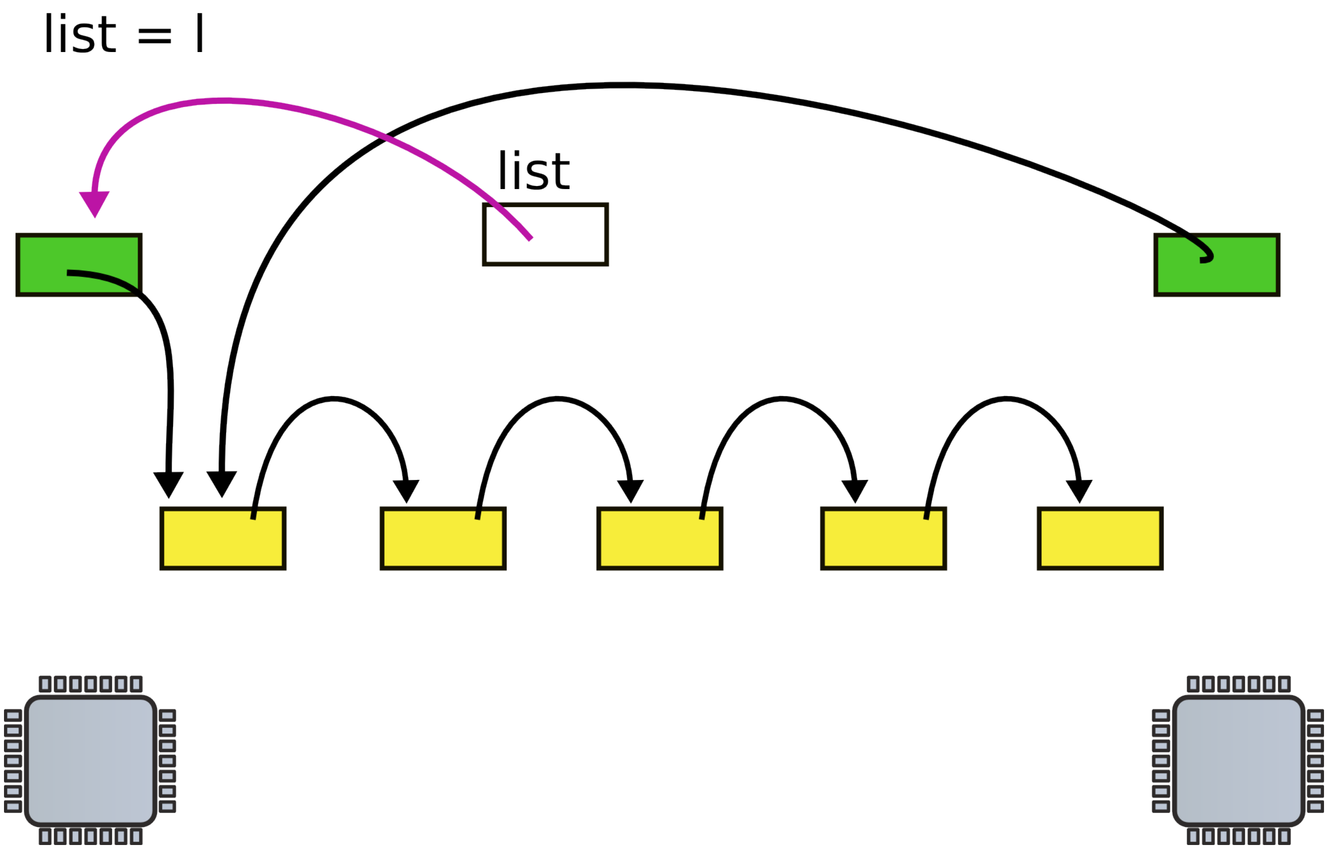
CPU2 allocates new request



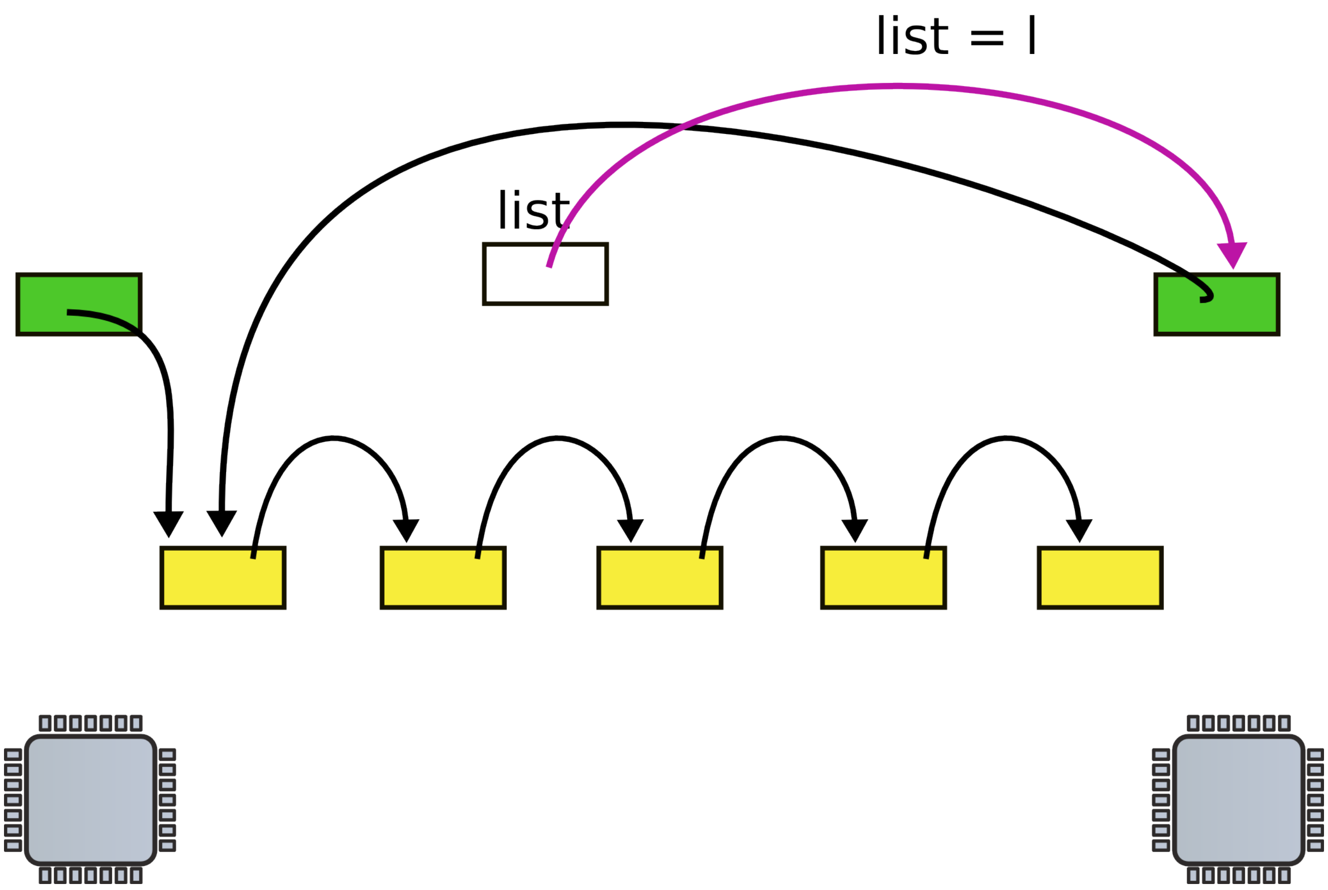
CPUs 1 and 2 update next pointer



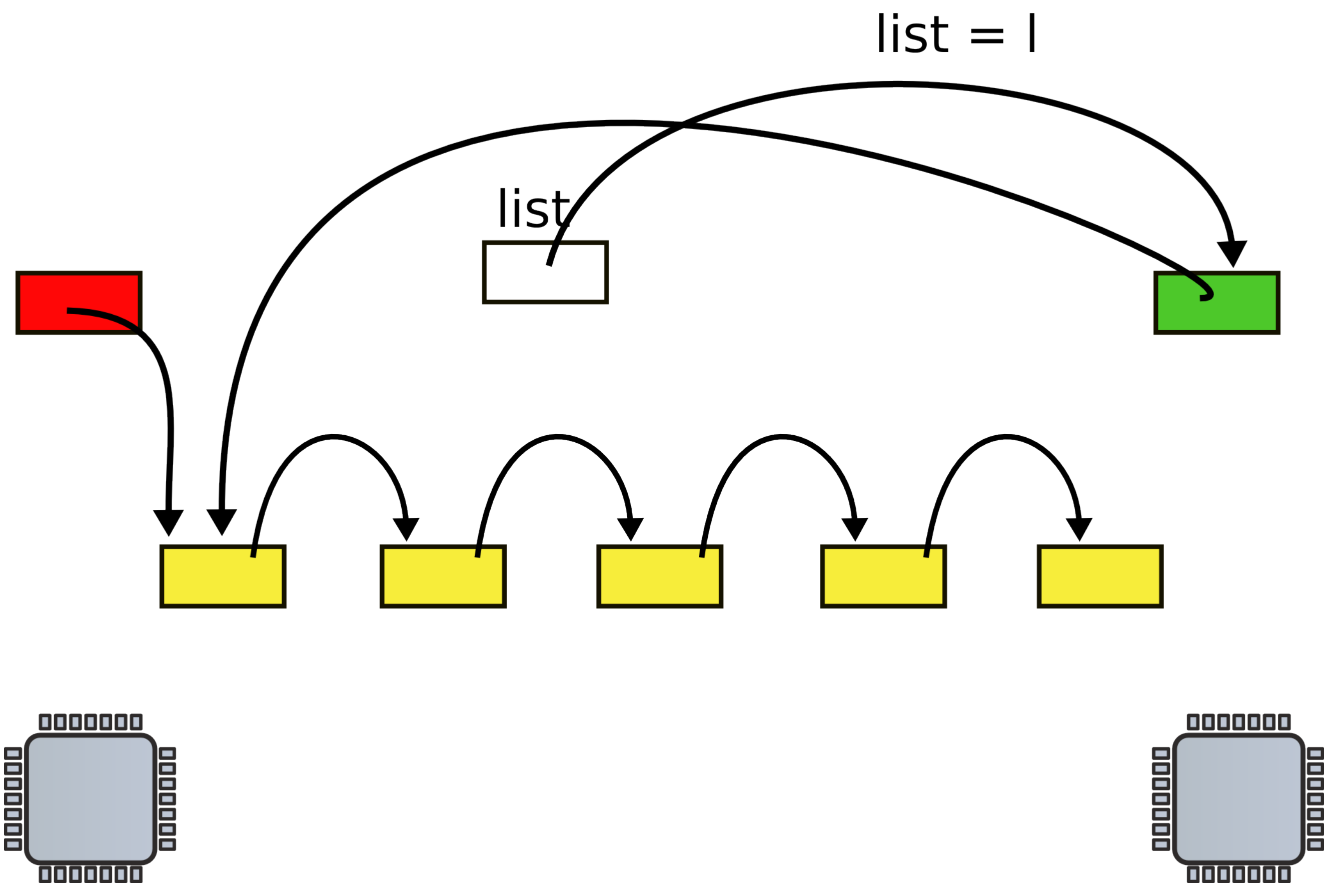
CPU1 updates head pointer



CPU2 updates head pointer



State after the race



List implementation with locks

```
struct list {
  int data;
  struct list *next;
};
struct list *list = 0;
struct lock listlock;
insert(int data)
{
   struct list *l;
   l = malloc(sizeof *l);
   acquire(&listlock);
   l->data = data;
   l->next = list;
   list = l;
   release(&listlock);
}
```

Spinlock

```
void
acquire(struct spinlock *lk)
{
  for(;;) {
    if(!lk->locked) {
      lk->locked = 1;
      break;
    }
  }
}
```

Still incorrect

```
21 void
22 acquire(struct spinlock *lk)
23 {
24   for(;;) {
25     if(!lk->locked) {
26       lk->locked = 1;
27       break;
28     }
29   }
30 }
```

- Two CPUs can reach line #25 at the same time
  - See not locked, and
  - Acquire the lock
- Lines #25 and #26 need to be atomic
  - I.e. indivisible

Compare and swap: xchg

- We switch between processes now

Correct implementation

```
void
acquire(struct spinlock *lk)
{
...
  // The xchg is atomic.
  // It also serializes, so that reads after acquire are not
  // reordered before it.
  while(xchg(&lk->locked, 1) != 0)
  ;
...
}
```

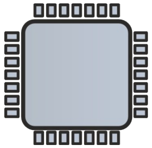
Compare and swap

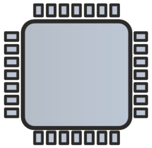
```
static inline uint
xchg(volatile uint *addr, uint newval)
{
  uint result;

  // The + in "+m" denotes a read-modify-write operand.
  asm volatile("lock; xchgl %0, %1" :
               "+m" (*addr), "=a" (result) :
               "1" (newval) :
               "cc");
  return result;
}
```

Deadlocks

```
acquire(A)
acquire(B) {
    while(xchg(&B->locked, 1) != 0)
}
```

```
acquire(B)
acquire(A) {
    while(xchg(&A->locked, 1) != 0)
}
```





Lock ordering

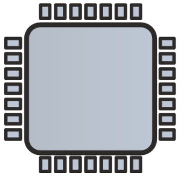
- Locks need to be acquired in the same order

Locks and interrupts

Network
interrupt

```
network_packet(){
    ....
    insert() {
        acquire(A)
        ...
    }

}
```

```
network_packet(){
    ....
    insert() {
        acquire(A)
        ...
    }

}
```



Locks and interrupts

- Never hold a lock with interrupts enabled

Disabling interrupts

```
void
acquire(struct spinlock *lk)
{
  pushcli(); // disable interrupts to avoid deadlock.
...
  // The xchg is atomic.
  // It also serializes, so that reads after acquire are not
  // reordered before it.
  while(xchg(&lk->locked, 1) != 0)
  ;
...
}
```

Simple disable/enable is not enough

- If two locks are acquired
- Interrupts should be re-enabled only after the second lock is released

- Pushcli() uses a counter

pushcli()

```c
void
pushcli(void)
{
  int eflags;

  eflags = readeflags();
  cli();
  if(cpu->ncli++ == 0)
    cpu->intena = eflags & FL_IF;
}
```

popcli()

```
void
popcli(void)
{
...
  if(--cpu->ncli < 0)
    panic("popcli");
  if(cpu->ncli == 0 && cpu->intena)
    sti();
}
```

Problems with locks

Problems with locks

- Deadlock
  - Locks break modularity of interfaces, easy to get wrong
- Priority inversion
  - Low-priority task holds a lock required by a higher priority task
  - Priority inheritance can be a solution, but can also result in errors (see What really happened on Mars)

Problems with locks

- Convoying
  - Several tasks need the locks in roughly the same order
  - One slow task acquires the lock first
  - Everyone slows to the speed of this slow task
- Signal safety
  - Similar to interrupts, but for user processes
  - Can't be disabled, thus can't use locks
  -

Problems with locks

- Kill safety
  - What if a task is killed or crashed while holding a lock?
- Preemption safety
  - What happens if a task is preempted while holding a lock?

Optimistic concurrency

Optimistic concurrency: main idea

- Instead of acquiring a lock try updating a data structure
  - When done, try committing changes
  - If there is a conflict, retry
- Similar to database transactions

Example: lock-free stack(), aka FIFO queue

```
class Node {

  Node * next;

  int data;

};

// ‘head of list’

Node * head;
```

Lock-free push()

```
void push(int t) {
  Node* node = new Node(t);
  do {
    node->next = head;
  } while (!cas(&head, node, node->next));
}
```

Lock-free pop()

```
bool pop(int& t) {
  Node* current = head;
  while(current) {
    if(cas(&head, current->next, current)) {
      t = current->data;
      return true;
    }
    current = head;
  }
  return false;
}
```

The ABA problem

- The value of a variable is changed from A to B and then back to A
- In our example the variable is a pointer to a stack element
- What if the head gets deallocated with free(), and allocated again?
  - There is a good chance that head will have the same pointer value
    - Memory allocators often choose recently deallocated values
  - But really this is a different stack element

ABA example

Thread 1: pop()

read A from head

store A.next `somewhere`

Thread 2:

pop()

Pops A, discards it

First element becomes B

pop(): pops B

push():

Memory manager recycles

A to hold a new variable

cas with A succeeds

ABA workaround

- Keep an `update counter' along with a pointer
  - Needs a double word CAS
- Don't recycle memory too soon

Nontrivial lock-free data structures

- For example, a linked list
  - Much more complex
    - Operations on two pointers
  - Insert
    - What if predecessor is removed?

Thank you!