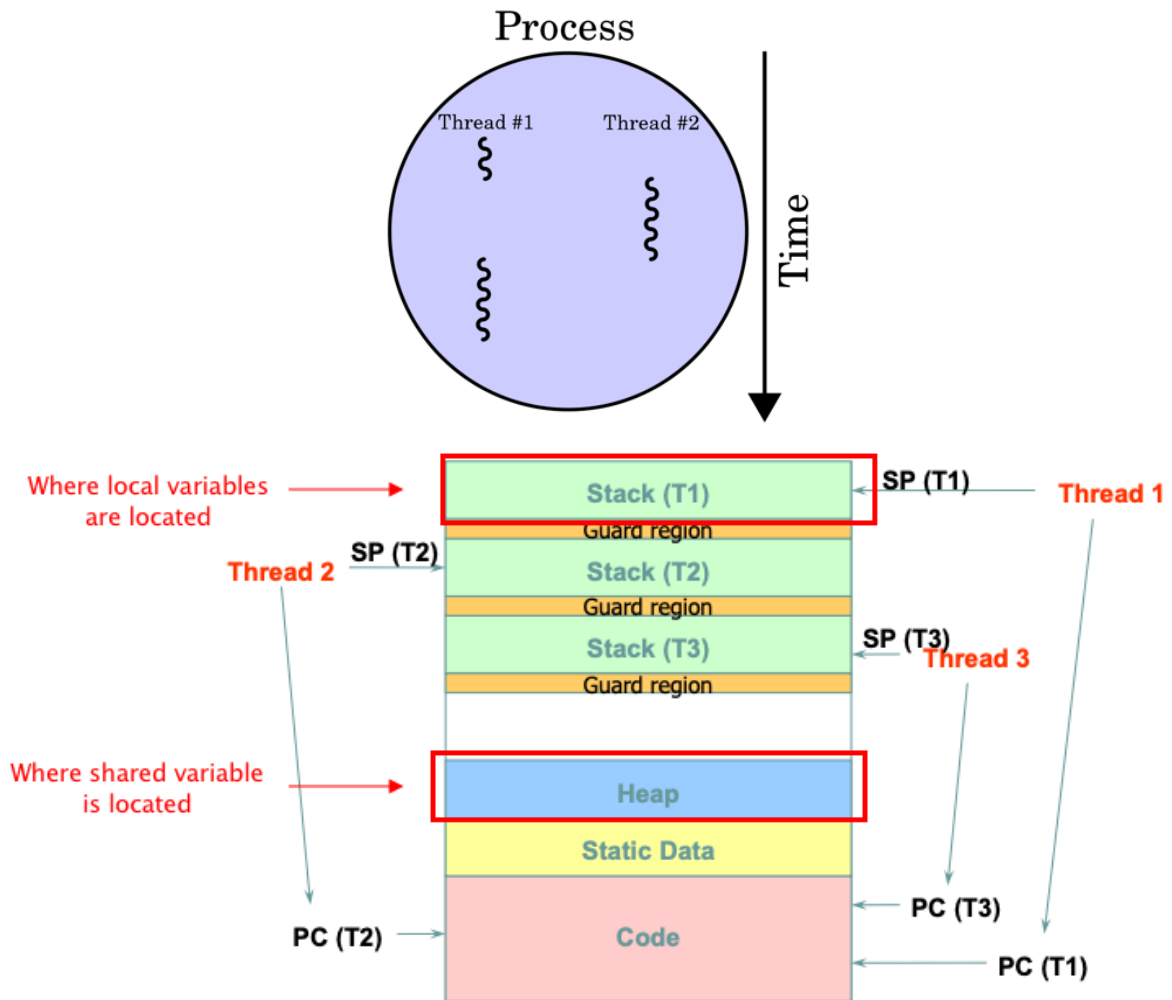


# 1 Critical Section

- Is a piece of code that accesses a *shared* resource, usually a variable or data structure

# 2 Thread

- Is a lightweight process that can be managed independently by a scheduler <sup>[4]</sup>
- Improves the application performance using parallelism. (e.g. peach)



- A thread is bound to a single process
- A process can have multiple threads
- Has two types
  - **User-level Threads:**

- \* Are implemented by users and kernel is not aware of the existence of these threads
  - \* Are represented by a program counter(PC), stack, registers and a small process control block
  - \* Are small and much faster than kernel level threads
- **Kernel-level Threads:**
- \* Are handled by the operating system directly
  - \* Thread management is done by the kernel
  - \* Are slower than user-level threads

### 3 Thread API

- pthread\_create

– **syntax:**

```
1 int pthread_create(pthread_t *thread,  
2                   const pthread_attr_t *attr,  
3                   void * (*start_routine) (void*),  
4                   void * arg)
```

- \* thread
  - is a pointer to a structure of type pthread\_t
- \* attr
  - is used to specify any attributes this thread might have
  - is initialized with a separate call pthread\_attr\_init()
  - set default by passing NULL
- \* (start\_routine)
  - means which function this thread should start running in?
  - setting void pointer (void \*) as an argument to function start\_routine allows us to pass in any type of argument
  - setting void pointer (void \*) as return type allows us to return any type of result
- \* args
  - is where to pass the arguments for the function pointer ((start\_routine))

#### Example

```

1  #include <stdio.h>
2  #include <pthread.h>
3
4  typedef struct {
5      int a;
6      int b;
7  } myarg_t;
8
9  void *mythread(void *arg) {
10     myarg_t *args = (myarg_t *) arg;
11     printf("%d %d\n", args->a, args->b);
12     return NULL;
13 }
14
15 int main(int argc, char *argv[]) {
16     pthread_t p;
17     myarg_t args = { 10, 20 };
18
19     int rc = pthread_create(&p, NULL, mythread, &args);
20     ...
21 }

```

Struct is copied here

Argument is initialized here

- `pthread_cond_wait`
  - Puts the calling thread to sleep (a blocked state)
  - Waits for some other thread to signal it

### Example

```

pthread_mutex_t lock = PTHREAD_MUTEX_INITIALIZER;
pthread_cond_t cond = PTHREAD_COND_INITIALIZER;

pthread_mutex_lock(&lock);
while (ready == 0)
    pthread_cond_wait(&cond, &lock);
pthread_mutex_unlock(&lock);


```

Puts calling thread cond to sleep

- `pthread_cond_signal`
  - Is used to unblocks at least one of the threads that are blocked on the specified condition variable cond

### Example

```
Pthread_mutex_lock(&lock);  
ready = 1;  
Pthread_cond_signal(&cond);  
Pthread_mutex_unlock(&lock);
```



Wakes a thread that's been put to sleep  
on cond variable

## 4 Condition Variable

- is an explicit queue that threads can put themselves on when some state of execution is not as desired (so it can be put to sleep)
- when states are changed, one or more of the waiting threads can be awoken and be allowed to continue (done by **signaling** the condition)
- queue is **FIFO**
- `wait()` call is used to put thread to sleep
- `signal()` call is used to awake thread from sleep
- **Syntax (initialization):**

```
pthread_cond_t c = PTHREAD_COND_INITIALIZER
```

### Example

```
1  int done = 0;
2  pthread_mutex_t m = PTHREAD_MUTEX_INITIALIZER;
3  pthread_cond_t c = PTHREAD_COND_INITIALIZER;
4
5  void thr_exit() {
6      Pthread_mutex_lock(&m);
7      done = 1;
8      Pthread_cond_signal(&c);
9      Pthread_mutex_unlock(&m);
10 }
11
12 void *child(void *arg) {
13     printf("child\n");
14     thr_exit();
15     return NULL;
16 }
17
18 void thr_join() {
19     Pthread_mutex_lock(&m);
20     while (done == 0)
21         Pthread_cond_wait(&c, &m);
22     Pthread_mutex_unlock(&m);
23 }
24
25 int main(int argc, char *argv[]) {
26     printf("parent: begin\n");
27     pthread_t p;
28     Pthread_create(&p, NULL, child, NULL);
29     thr_join();
30     printf("parent: end\n");
31     return 0;
32 }
```



Initialized here

- Syntax (Wait):

`Pthread_cond_wait(pthread_cond_t *c, pthread_mutex_t *m)`

### Example

```
1  int done = 0;
2  pthread_mutex_t m = PTHREAD_MUTEX_INITIALIZER;
3  pthread_cond_t c = PTHREAD_COND_INITIALIZER;
4
5  void thr_exit() {
6      Pthread_mutex_lock(&m);
7      done = 1;
8      Pthread_cond_signal(&c);
9      Pthread_mutex_unlock(&m);
10 }
11
12 void *child(void *arg) {
13     printf("child\n");
14     thr_exit();
15     return NULL;
16 }
17
18 void thr_join() {
19     Pthread_mutex_lock(&m);
20     while (done == 0)
21         Pthread_cond_wait(&c, &m);
22     Pthread_mutex_unlock(&m);
23 }
24
25 int main(int argc, char *argv[]) {
26     printf("parent: begin\n");
27     pthread_t p;
28     Pthread_create(&p, NULL, child, NULL);
29     thr_join();
30     printf("parent: end\n");
31     return 0;
32 }
```


Put thread to sleep until done

- Syntax (Signal):

`Pthread_cond_signal(pthread_cond_t *c)`

Example

```
1  int done = 0;
2  pthread_mutex_t m = PTHREAD_MUTEX_INITIALIZER;
3  pthread_cond_t c = PTHREAD_COND_INITIALIZER;
4
5  void thr_exit() {
6      Pthread_mutex_lock(&m);
7      done = 1;
8      Pthread_cond_signal(&c);
9      Pthread_mutex_unlock(&m);
10 }
11
12 void *child(void *arg) {
13     printf("child\n");
14     thr_exit();
15     return NULL;
16 }
17
18 void thr_join() {
19     Pthread_mutex_lock(&m);
20     while (done == 0)
21         Pthread_cond_wait(&c, &m);
22     Pthread_mutex_unlock(&m);
23 }
24
25 int main(int argc, char *argv[]) {
26     printf("parent: begin\n");
27     pthread_t p;
28     Pthread_create(&p, NULL, child, NULL);
29     thr_join();
30     printf("parent: end\n");
31     return 0;
32 }
```



Awake thread here

## 5 Spinlock

- Is the simplest lock to build
- Uses a lock variable
  - 0 - (available/unlock/free)
  - 1 - (acquired/locked/held)
- Has two operations
  1. acquire()

```
boolean test_and_set(boolean *lock)
{
    boolean old = *lock;
    *lock = True;
    return old;
}

boolean lock;

void acquire(boolean *lock) {
    while (test_and_set(lock));
}
```

2. release()

```
void release(boolean *lock) {
    *lock = false;
}
```

- Allows a single thread to enter critical section at a time
- Spins using CPU cycles until the lock becomes available.
- May spin forever

## 6 Livelock

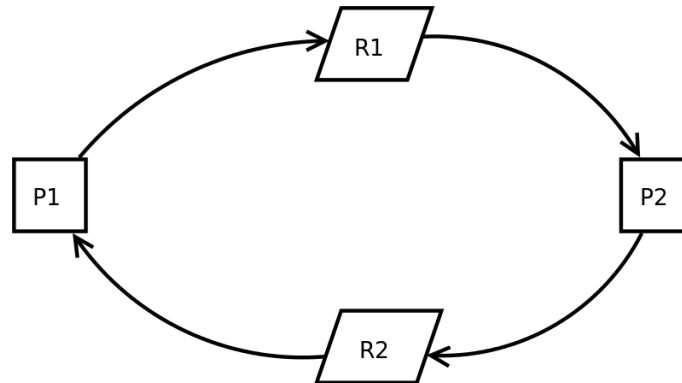
- Two or more threads repeatedly attempting this code over and over (e.g acquiring lock), but progress is not being made (e.g acquiring lock)
- Solution: Add a random delay before trying again (decrease odd of livelock)

## 7 Mutual Exclusion

- Is a guarantee that if one thread is executing within the critical section, the others will be prevented from doing so.

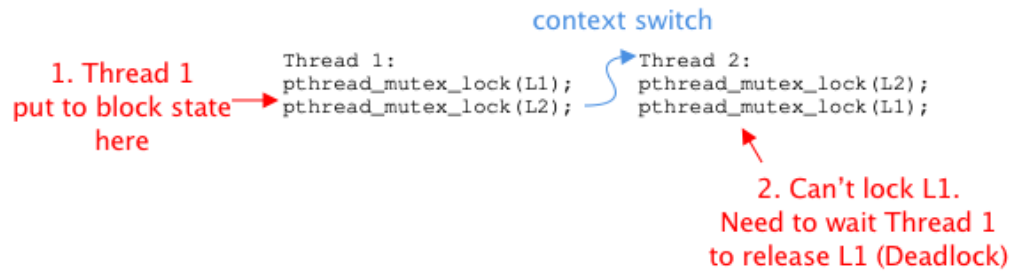


## 8 Deadlock



- Is a state in which each member of a group is waiting for another member including itself, to take action (e.g. releasing lock)
- Conditions for Deadlock (All four must be met)
  - **Mutual Exclusion**
    - \* Occurs when threads claim exclusive control of resources that they require (e.g. thread grabbing a lock)
  - **Hold-and-wait**
    - \* Occurs when threads hold resources allocated to them (e.g. locks that they have already acquired) while waiting for additional resources (e.g. locks that they wish to acquire)
  - **No Preemption**
    - \* Occurs when resource cannot be forcibly removed from threads that are holding them
  - **Circular Wait**
    - \* Occurs when there exists a circular chain of threads such that each threads hold one or more resources (e.g. locks) that are being requested by the next thread in the chain.

### Example



- **Preventions**

- **Circular Wait**

- \* Write code such that circular wait is never induced
- \* Is the most practical prevention technique
- \* Requires deep understanding of the code base
- \* **Total Ordering** (Most straightforward)

### Example

Given two locks in the system (L1 and L2), always acquire L1 before L2

- \* **Partial Ordering** (Applied to complex systems)

### Example

Memory mapping code in Linux (has then different groups).

(Simple) `i_mutex` before `i_mmap_mutex`

(More complex) `i_mmap_mutex` before `private_lock` before `swap_lock`  
before `mapping->tree_lock`

- **Hold-and-wait**

- \* Can be avoided by acquiring all locks at once
- \* Can be problematic
- \* Must know which lock must be held and acquire ahead of time
- \* Is likely to decrease concurrency (since all need to be acquired over their needs)

### Example

```

1 pthread_mutex_lock(prevention); // begin acquisition
2 pthread_mutex_lock(L1);
3 pthread_mutex_lock(L2);
4 ...
5 pthread_mutex_unlock(prevention); // end
  
```

] Lock all in  
order that doesn't cause deadlock  
] unlock in  
the same order

### – No Preemption

- \* Can be avoided by adding code that force unlock if not available

#### Thread 1

```

1 top:
2   pthread_mutex_lock(L1);
3   if (pthread_mutex_trylock(L2) != 0) {
4     pthread_mutex_unlock(L1);
5     goto top;
6   }

```

1. Check if L2 is locked or not available

2. Unlock L1 forcibly (to avoid deadlock)

#### Thread 2

```

1 top:
2   pthread_mutex_lock(L2);
3   if (pthread_mutex_trylock(L1) != 0) {
4     pthread_mutex_unlock(L2);
5     goto top;
6   }

```

- \* pthread\_mutex\_trylock tries to lock the speicied mutex.
- \* pthread\_mutex\_trylock returns 0 if lock is available
- \* pthread\_mutex\_trylock returns the following error if occupied

EBUSY - Mutex is already locked

EINVAL - Is not initialized mutex

EFAULT - Is in valid pointer

- \* May result in **live lock**

### – Mutual Exclusion

- \* Idea: Avoid the mutual exclusion at all
- \* Use **lock-free**/**wait-free** approach: building data structures in a manner that does not require explicit locking using hardware instructions

#### Example

```

1 int CompareAndSwap(int *address, int expected, int new) {
2   if (*address == expected) {
3     *address = new;
4     return 1; // success
5   }
6   return 0; // failure
7 }

```

- Avoidance

### – Banker's Algorithm

## 9 Process

- Is a program in execution
- Is named by it's process ID or PID
- Can be described by the following states at any point in time
  - Address Space
  - CPU Registers
  - Program Counter
  - Stack Pointer
  - I/O Information

(wait. this is PCB)

- Exists in one of many different **process states**, including
  1. Running
  2. Ready to Run
  3. Blocked
  - Different events (Getting Scheduled, descheduled, or waiting for I/O) transitions one of these states to the other

### Coarse-grained-locking

- Is one big lock that is used any time any critical section is accessed
- Is easy to write
- Is easy to prove correctness
- No fault-tolerance but deadlock-free
- Performs poorly when contention (the need for performance due to load) is high
  - No concurrent access

### Example

```
pthread_mutex_t lock = PTHREAD_MUTEX_INITIALIZER;
pthread_cond_t cond = PTHREAD_COND_INITIALIZER;

pthread_mutex_lock(&lock);
while (ready == 0)
    pthread_cond_wait(&cond, &lock);
pthread_mutex_unlock(&lock);
```

One lock for all threads  
(coarse-grained lock)

Notice that only one thread  
can pass at a time

## 10 Fine-grained-locking

- Uses different locks to often protect different data and data structures
- Allows more threads to be in locked code at once

### Example

```
1 void List_Init(list_t *L) {
2     L->head = NULL;
3     pthread_mutex_init(&L->lock, NULL);
4 }
5
6 void List_Insert(list_t *L, int key) {
7     // synchronization not needed
8     node_t *new = malloc(sizeof(node_t));
9     if (new == NULL) {
10         perror("malloc");
11         return;
12     }
13     new->key = key;
14
15     // just lock critical section
16     pthread_mutex_lock(&L->lock);
17     new->next = L->head;
18     L->head = new;
19     pthread_mutex_unlock(&L->lock);
20 }
21
22 int List_Lookup(list_t *L, int key) {
23     int rv = -1;
24     pthread_mutex_lock(&L->lock);
25     node_t *curr = L->head;
26     while (curr) {
27         if (curr->key == key) {
28             rv = 0;
29             break;
30         }
31         curr = curr->next;
32     }
33     pthread_mutex_unlock(&L->lock);
34     return rv; // now both success and failure
35 }
```

Fine-grained lock here :)

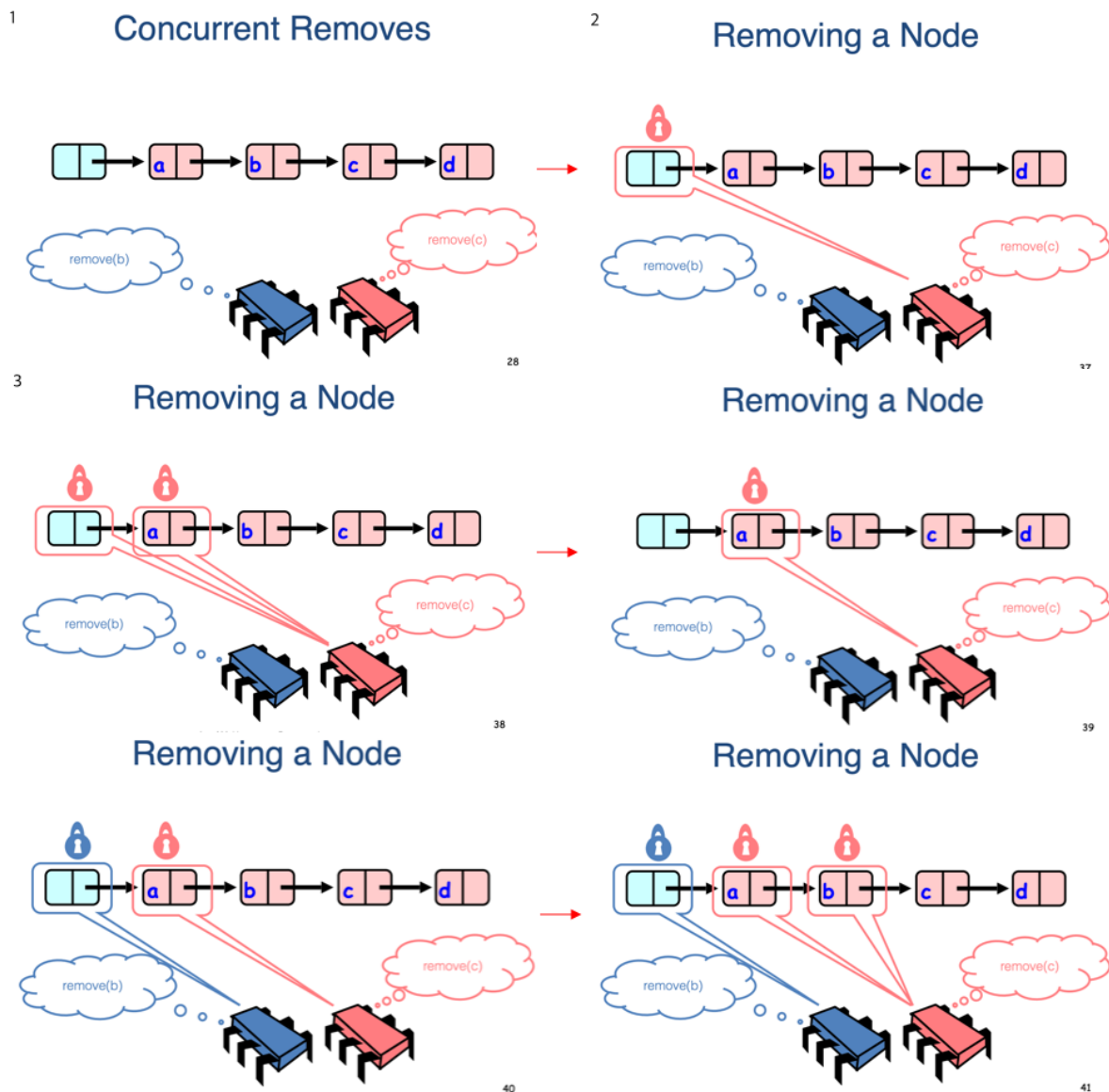
Notice lock is on a struct L

More threads can be locked  
at once

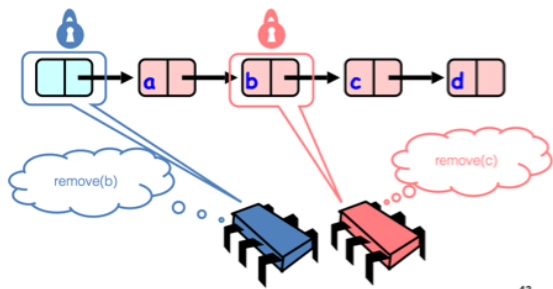
## 11 Hand-over-hand locking

- Idea: instead of having a single lock for the entire list, a lock per node of the list is added; when traversing the list, the list grabs the next node's lock, and releases the current node's lock
- Is a fine-grained-locking
- Holds at most 2 locks at a time

### Example

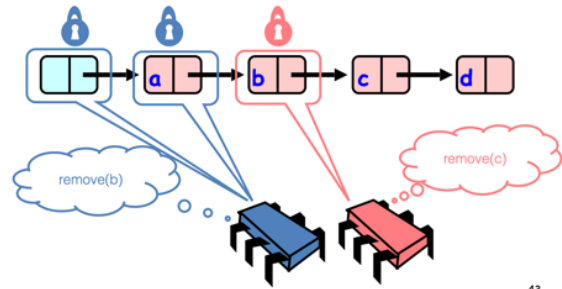


## Removing a Node



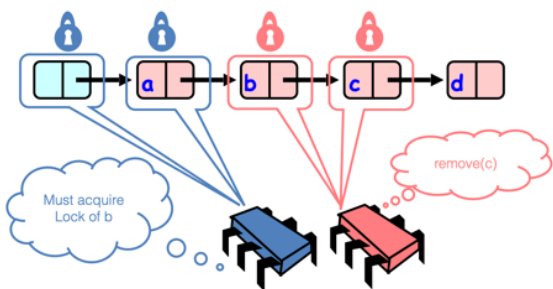
42

## Removing a Node



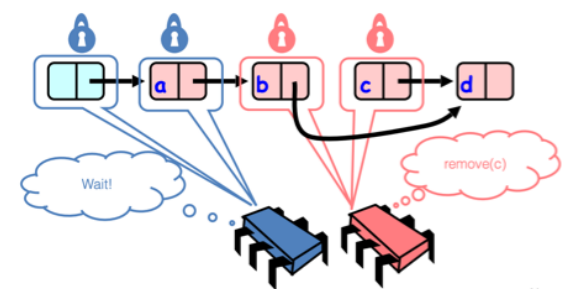
43

## Removing a Node



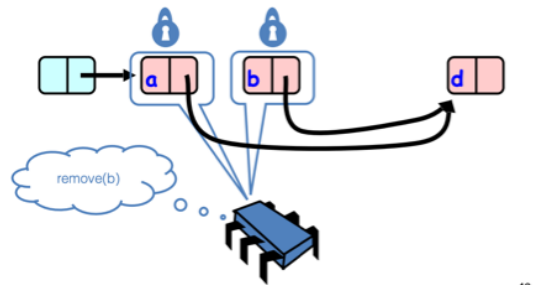
44

## Removing a Node



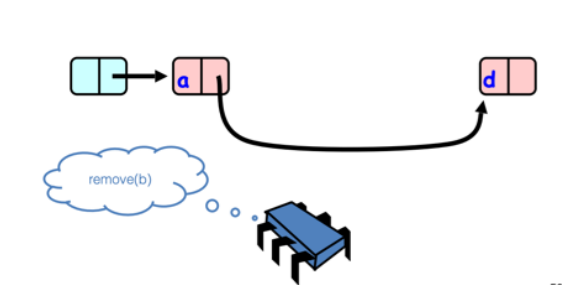
46

## Removing a Node



49

## Removing a Node



50

## Removing a Node



51