Design of Parallel and High-Performance Computing

Fall 2013

Lecture: Lock-Free and Distributed Memory

Instructor: Torsten Hoefler & Markus Püschel

TA: Timo Schneider

ETH

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Administrivia

- **Final project presentation: Monday 12/15 during last lecture**
  - Send slides to Timo by 12/15, 11am
  - 12 minutes per team (hard limit)

  - Rough guidelines:

    Summarize your goal/task

    Related work (what exists, literature review!)

    Describe techniques/approach (details!)

    Final results and findings (details)

    Pick one presenter (you may also switch but keep the time in mind)

KAUST – King Abdullah University of Science and Technology

Internships are for students in their last year of bachelor or for master students. They are 3 to 6 month long. Students will receive the following:

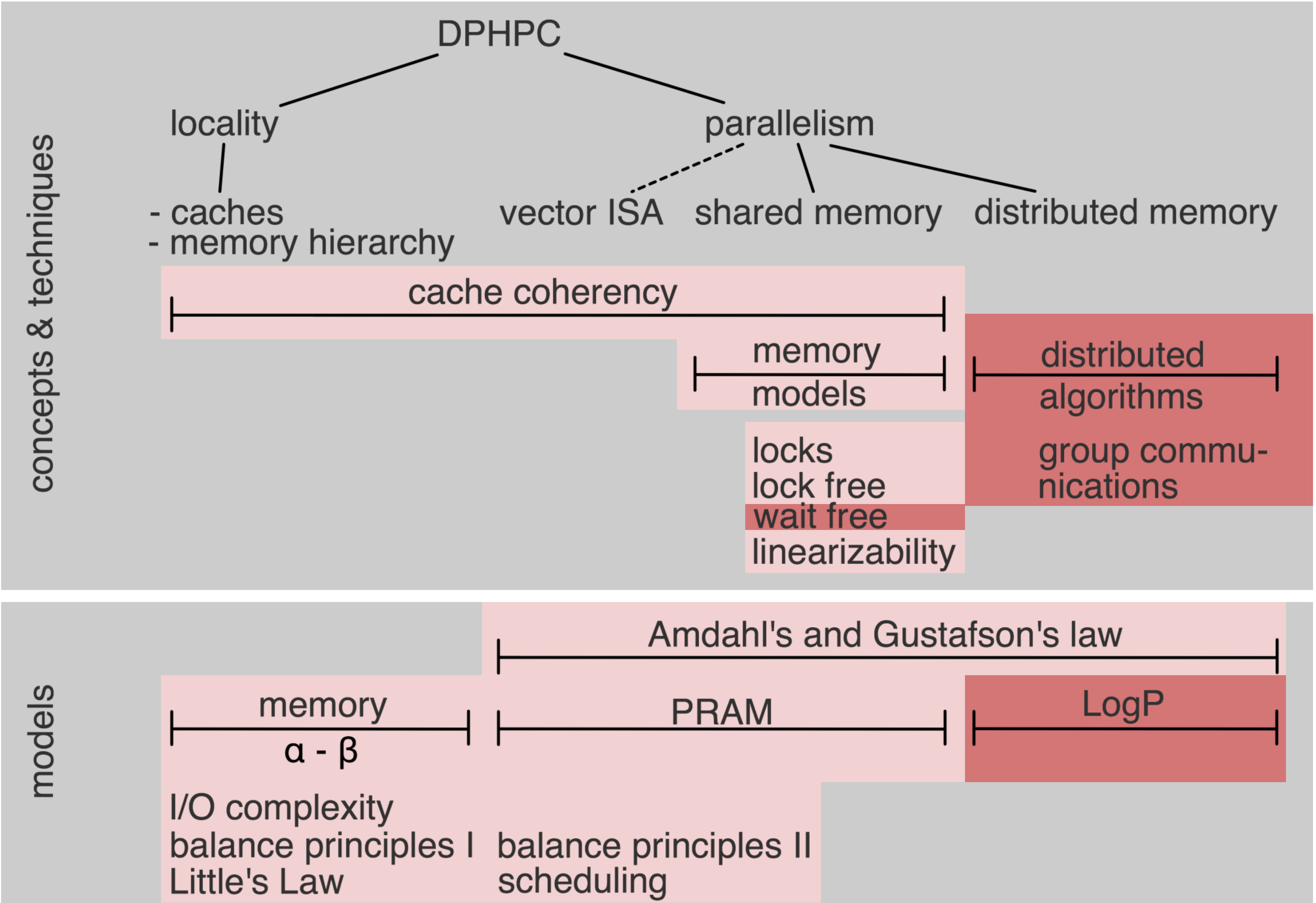
- Academic credit
- Monthly living allowance between $800 and $1200 (based upon field of research)
- Round-trip airfare to/from city of departure-Jeddah (KAUST)
- Health insurance
- Private bedroom & bath in a shared residential suite
- Visa fees (Students must have valid passport)
- Access to community recreational resources
- Social and cultural activities

If interested: http://vsrp.kaust.edu.sa/Pages/Internships.aspx
(look for Prof. David Keyes)

Review of last lecture

- **Abstract models**
  - Amdahl’s and Gustafson’s Law
  - Little’s Law
  - Work/depth models and Brent’s theorem
  - I/O complexity and balance (Kung)
  - Balance principles
- **Scheduling**
  - Greedy
  - Random work stealing
- **Balance principles**
  - Outlook to the future
  - Memory and data-movement will be more important

DPHPC Overview



Goals of this lecture

- **Finish lock-free tricks**
  - List example but they generalize well

- **Finish wait-free/lock-free**
  - Consensus hierarchy
  - The promised proof!

- **Distributed memory**
  - Models and concepts
  - Designing (close-to) optimal communication algorithms

Tricks Overview

1. **Fine-grained locking**
   - Split object into “lockable components”
   - Guarantee mutual exclusion for conflicting accesses to same component
2. **Reader/writer locking**
3. **Optimistic synchronization**
4. **Lazy locking**
5. **Lock-free**

Tricks Overview

1. **Fine-grained locking**
2. **Reader/writer locking**
   - Multiple readers hold lock (traversal)
   - contains() only needs read lock
   - Locks may be upgraded during operation

   Must ensure starvation-freedom for writer locks!
3. **Optimistic synchronization**
4. **Lazy locking**
5. **Lock-free**

Tricks Overview

1. **Fine-grained locking**
2. **Reader/writer locking**
3. **Optimistic synchronization**
   - Traverse without locking

     Need to make sure that this is correct!
   - Acquire lock if update necessary

     May need re-start from beginning, tricky
4. **Lazy locking**
5. **Lock-free**

Tricks Overview

1. **Fine-grained locking**
2. **Reader/writer locking**
3. **Optimistic synchronization**
4. **Lazy locking**
   - Postpone hard work to idle periods
   - Mark node deleted

     Delete it physically later
5. **Lock-free**

Tricks Overview

1. **Fine-grained locking**
2. **Reader/writer locking**
3. **Optimistic synchronization**
4. **Lazy locking**
5. **Lock-free**
   - Completely avoid locks
   - Enables wait-freedom
   - Will need atomics (see later why!)
   - Often very complex, sometimes higher overhead

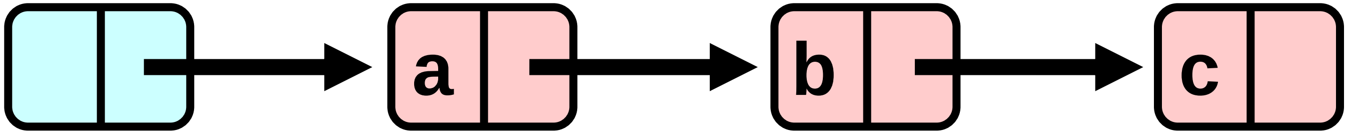
Trick 1: Fine-grained Locking

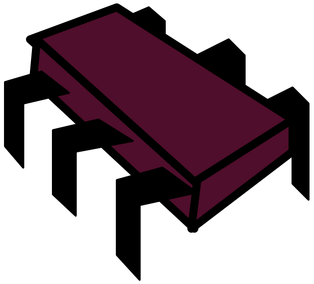
- **Each element can be locked**
  - High memory overhead
  - Threads can traverse list concurrently like a pipeline
- **Tricky to prove correctness**
  - And deadlock-freedom
  - Two-phase locking (acquire, release) often helps
- **Hand-over-hand (coupled locking)**
  - Not safe to release x’s lock before acquiring x.next’s lock

    will see why in a minute
  - Important to acquire locks in the same order

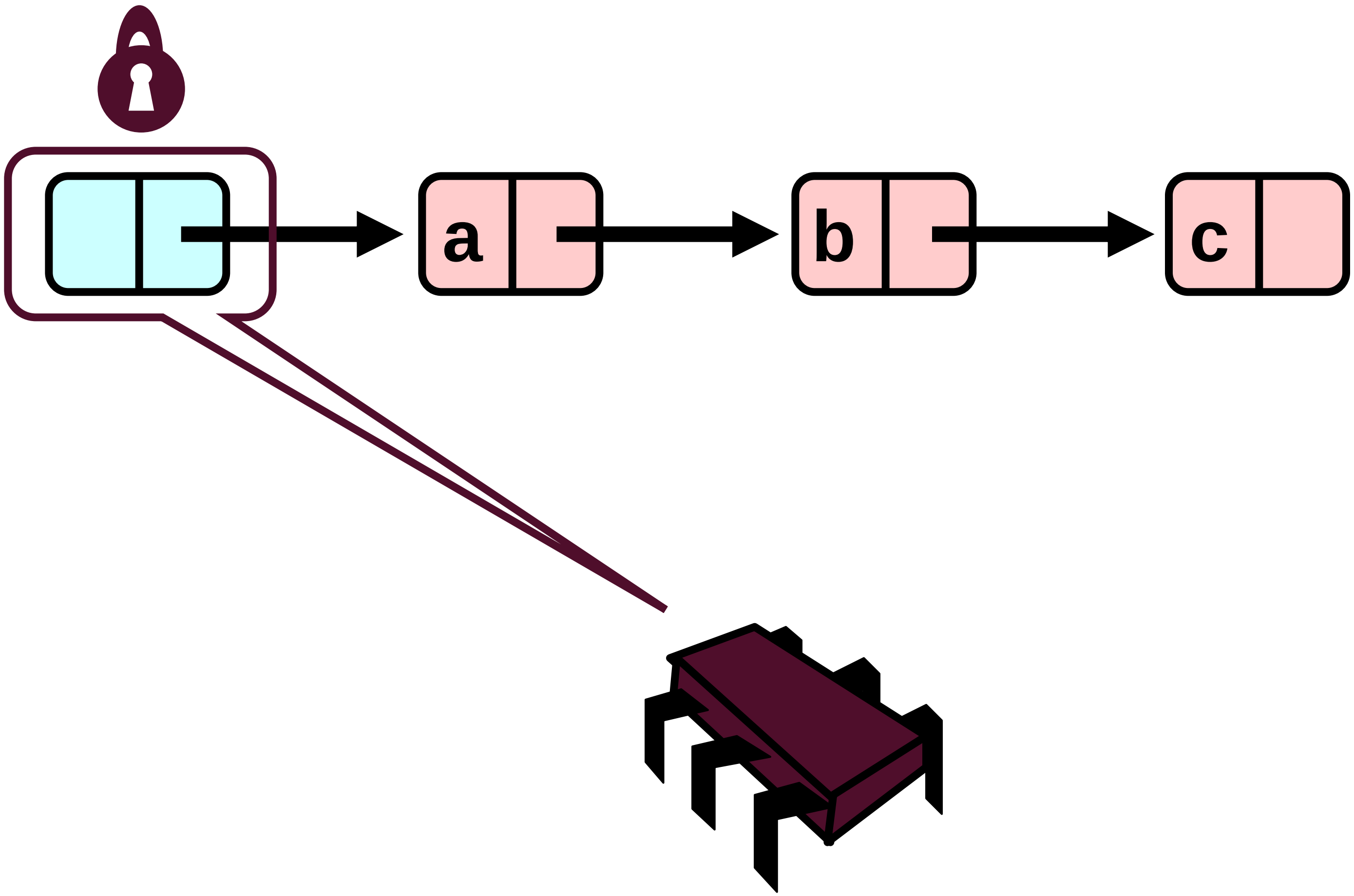
```
typedef struct {
  int key;
  node *next;
  lock_t lock;
} node;
```

Hand-over-Hand (fine-grained) locking

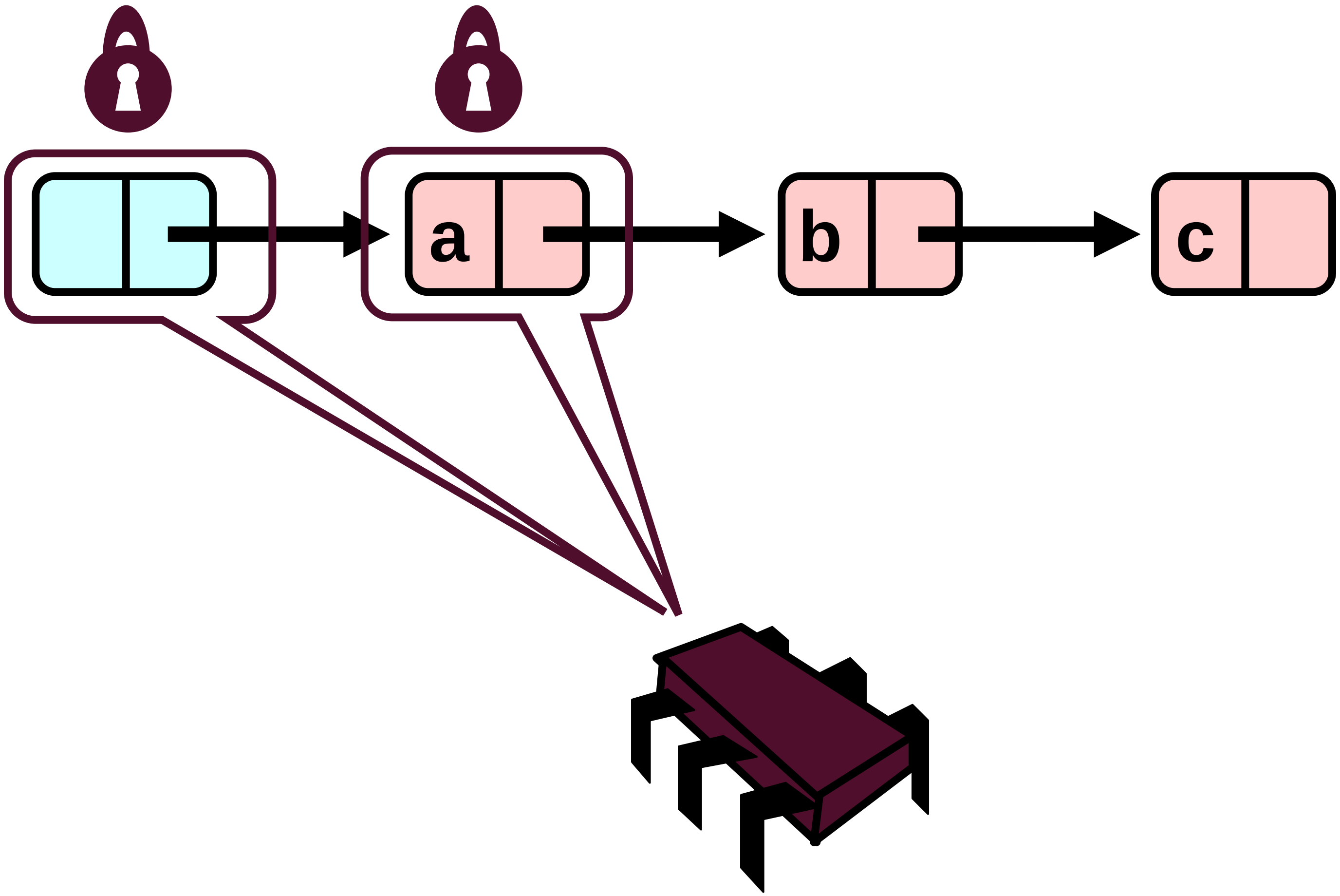




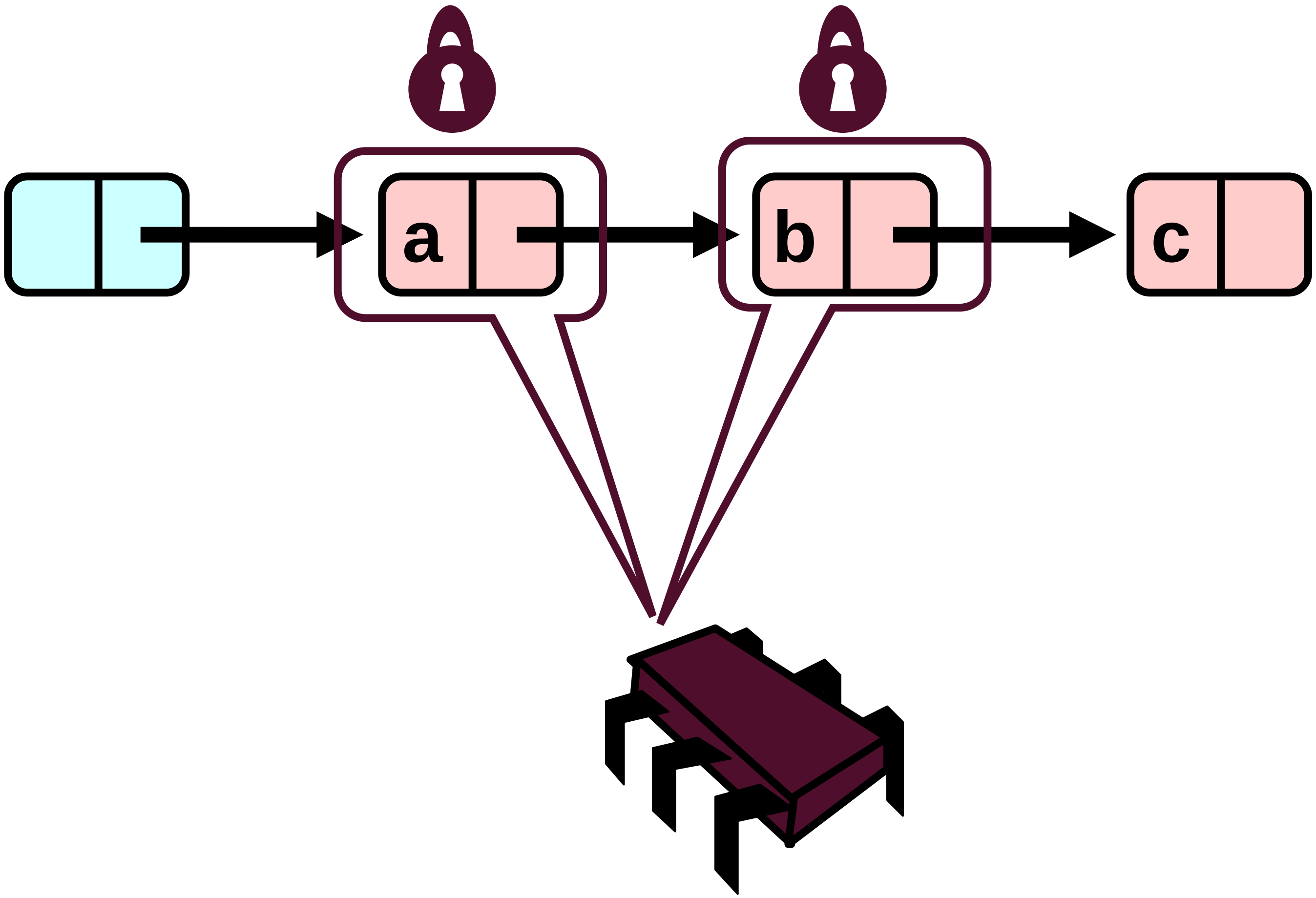
Hand-over-Hand (fine-grained) locking



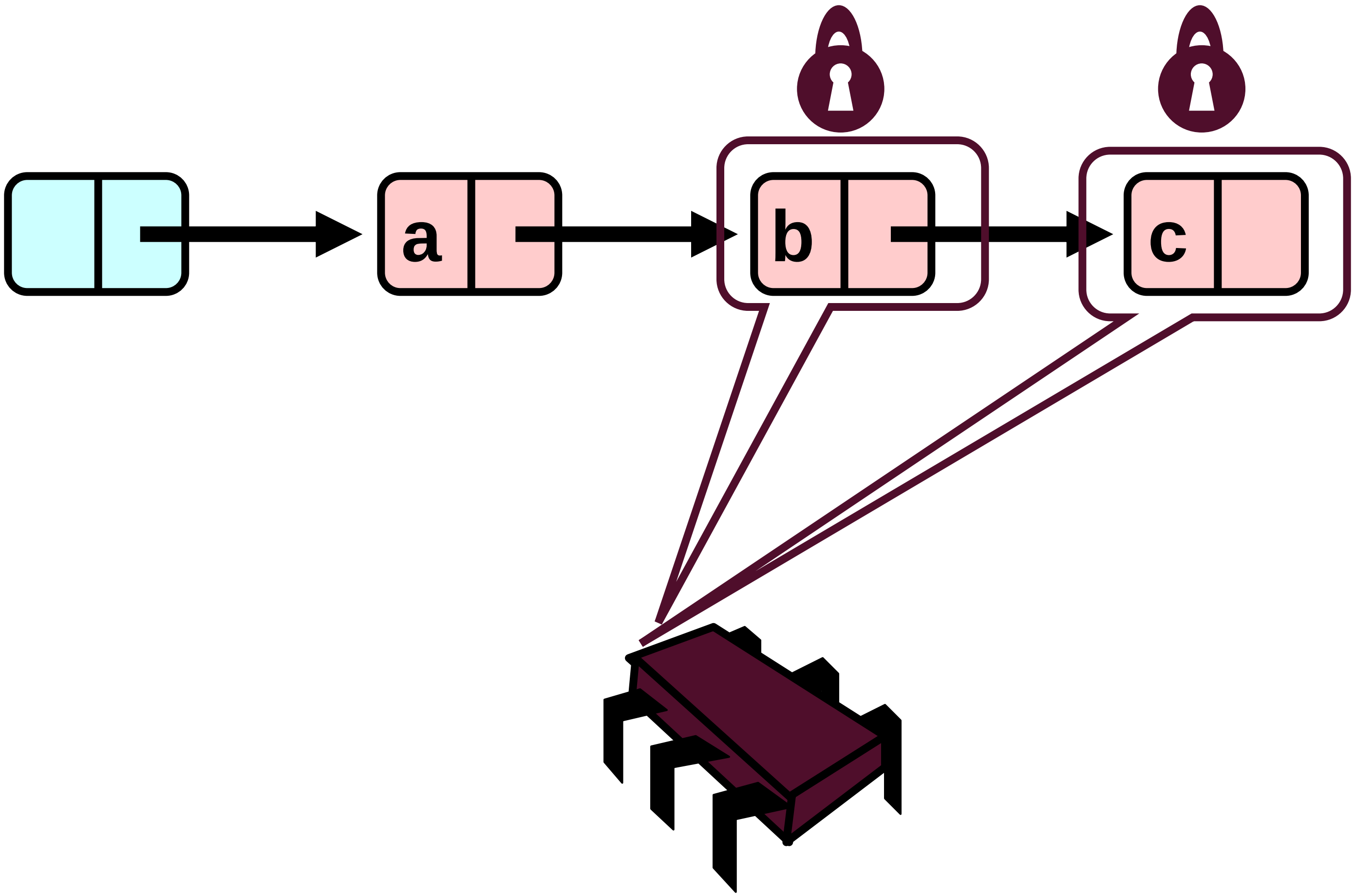
Hand-over-Hand (fine-grained) locking



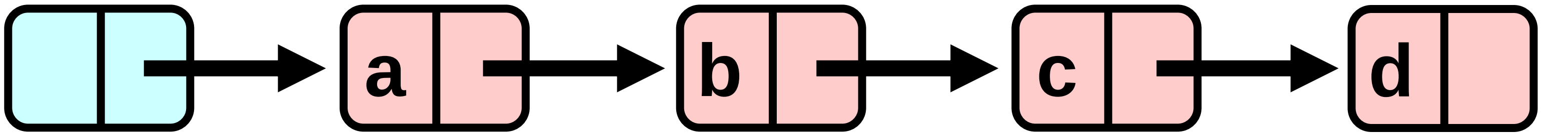
Hand-over-Hand (fine-grained) locking

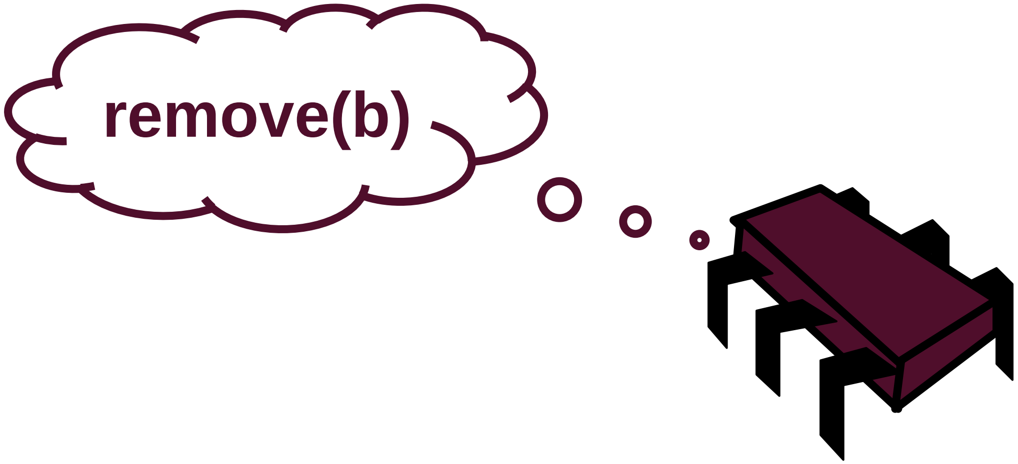


Hand-over-Hand (fine-grained) locking

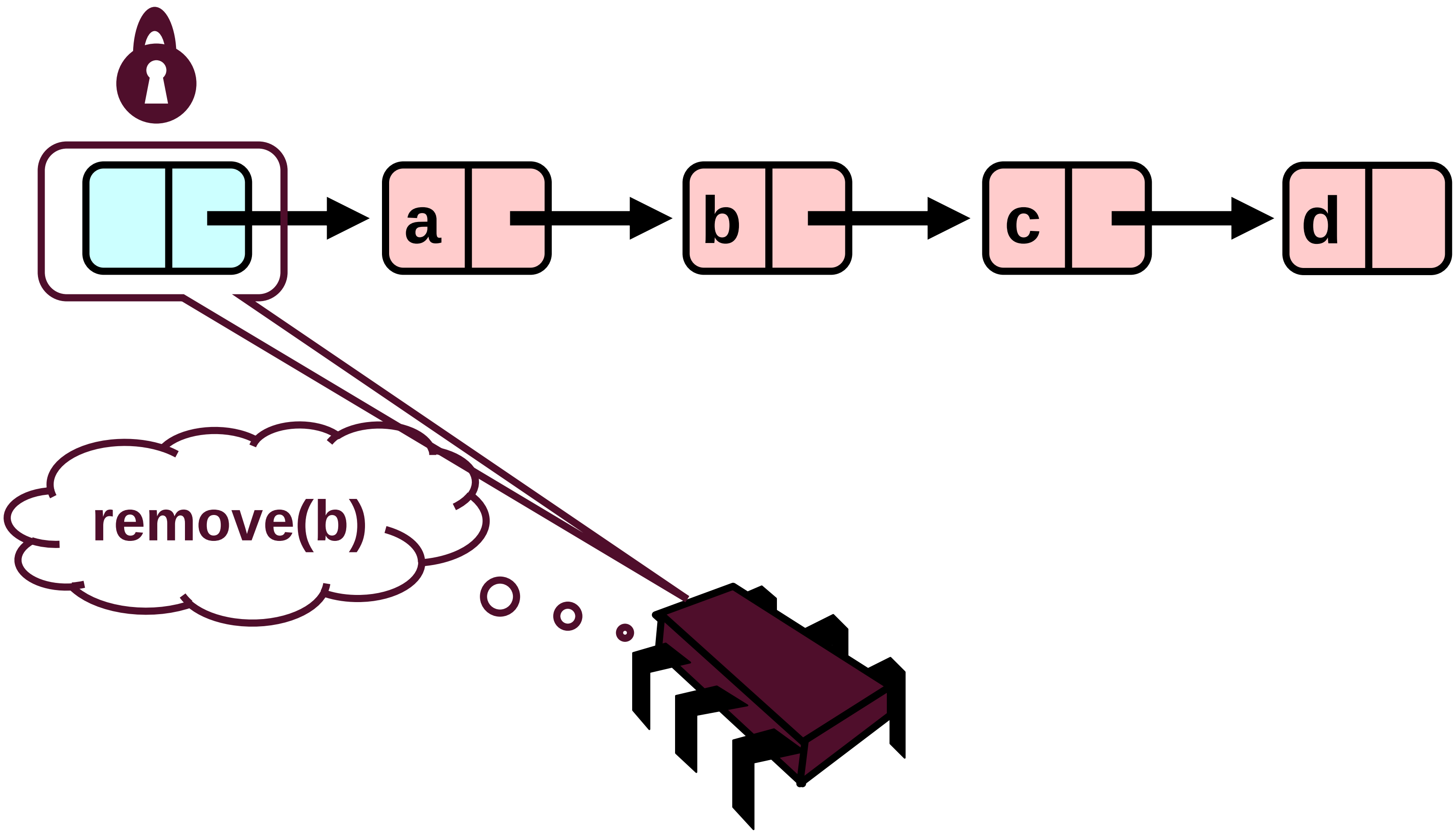


Removing a Node

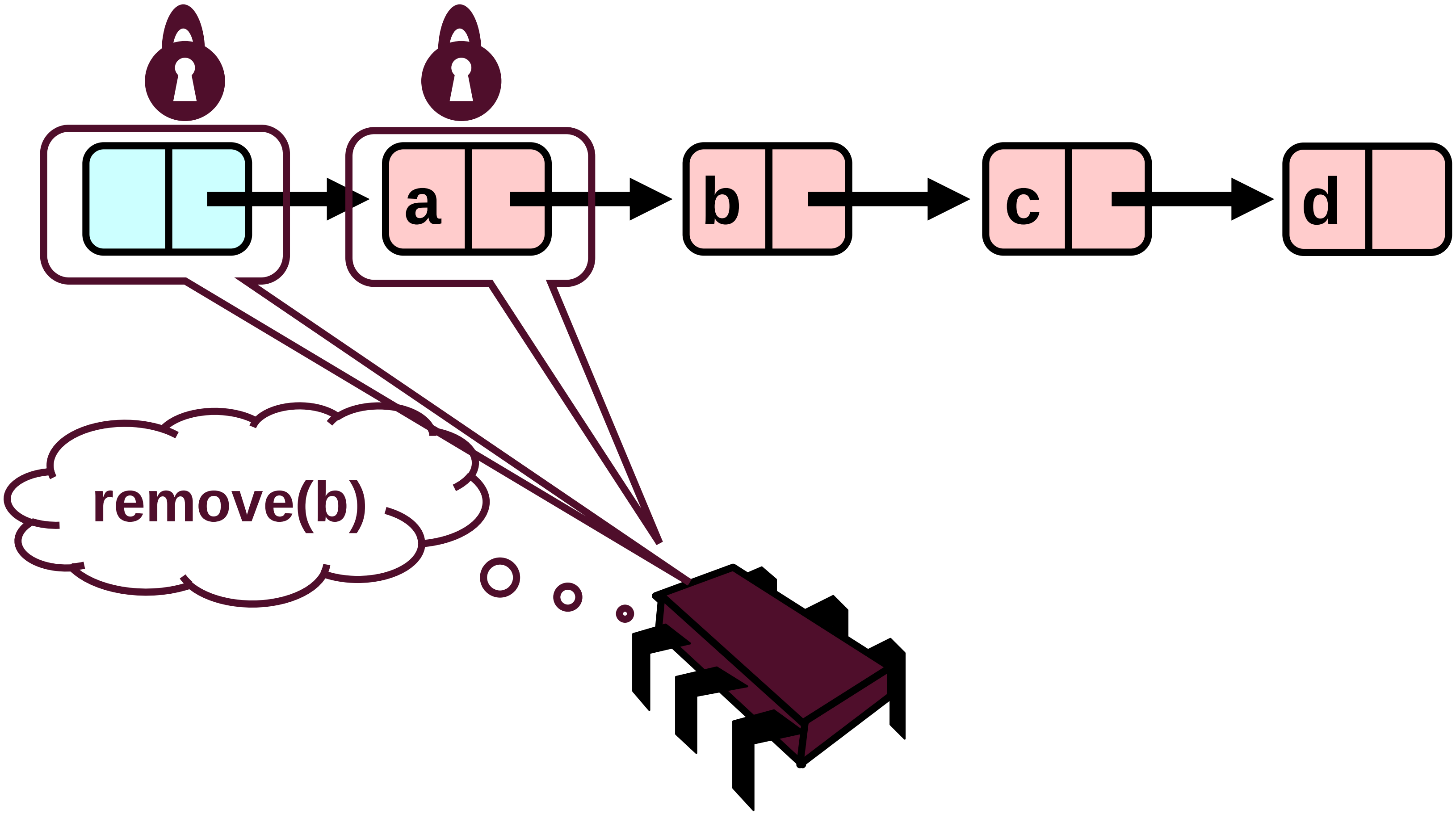




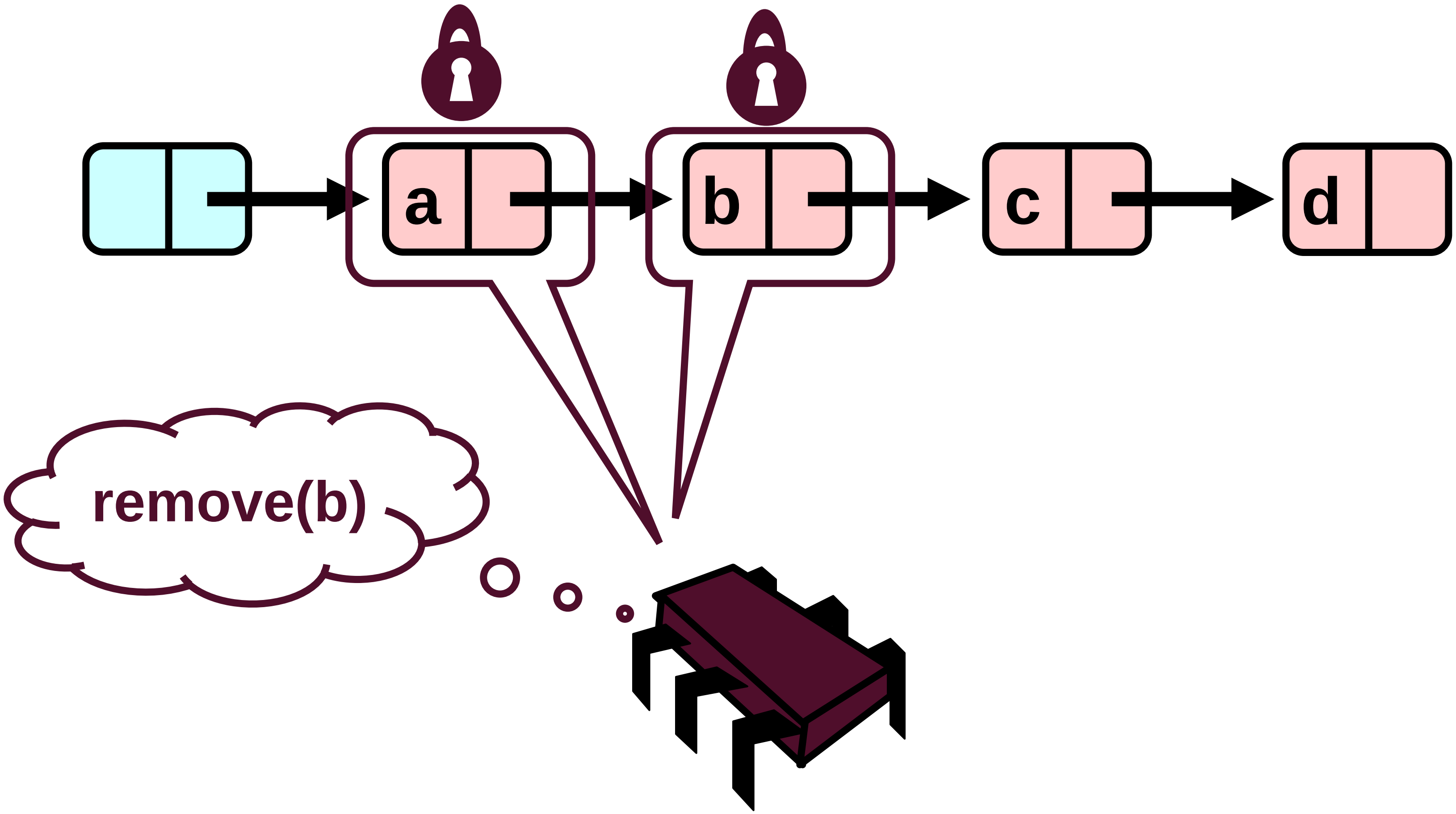
Removing a Node



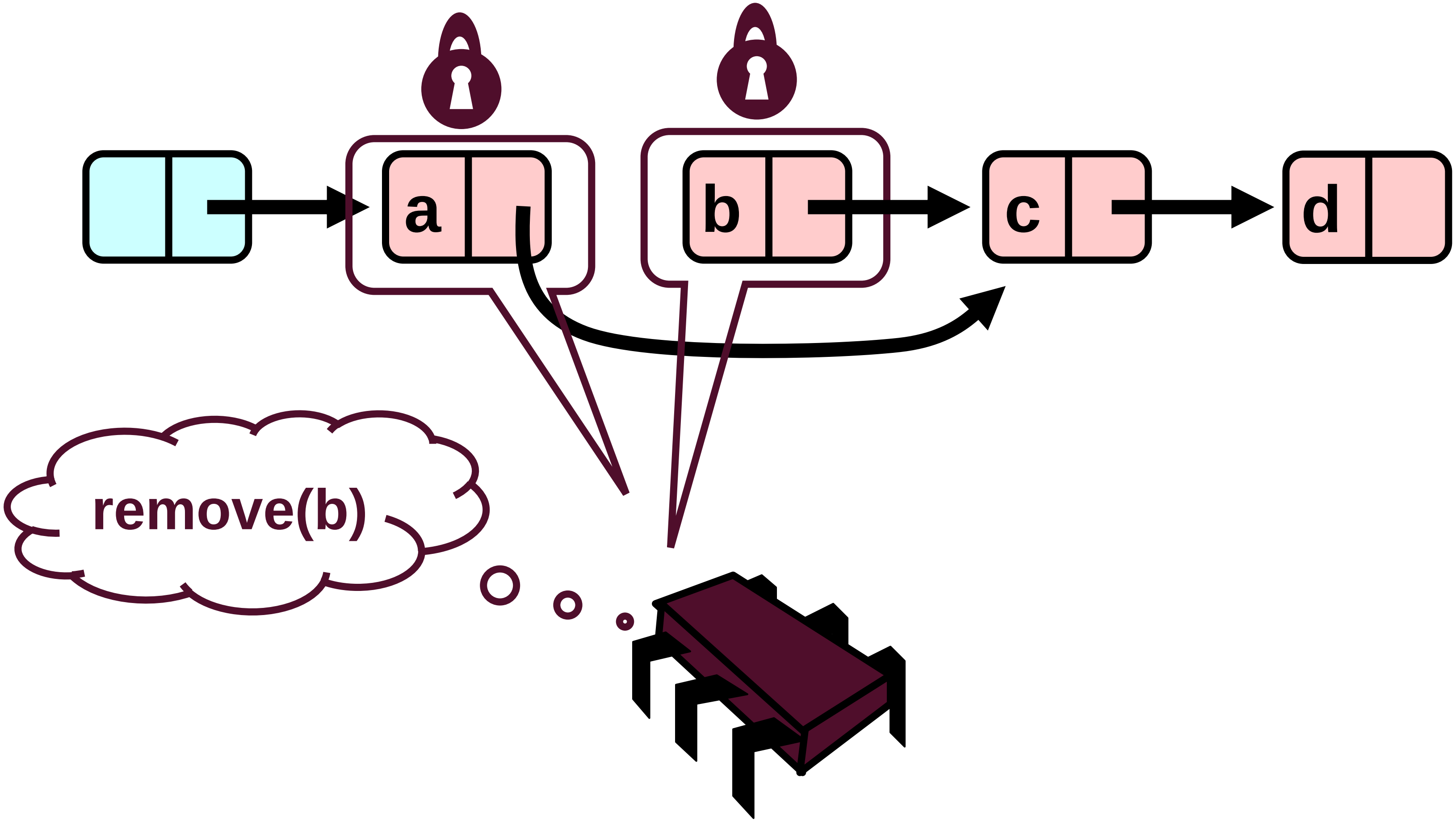
Removing a Node



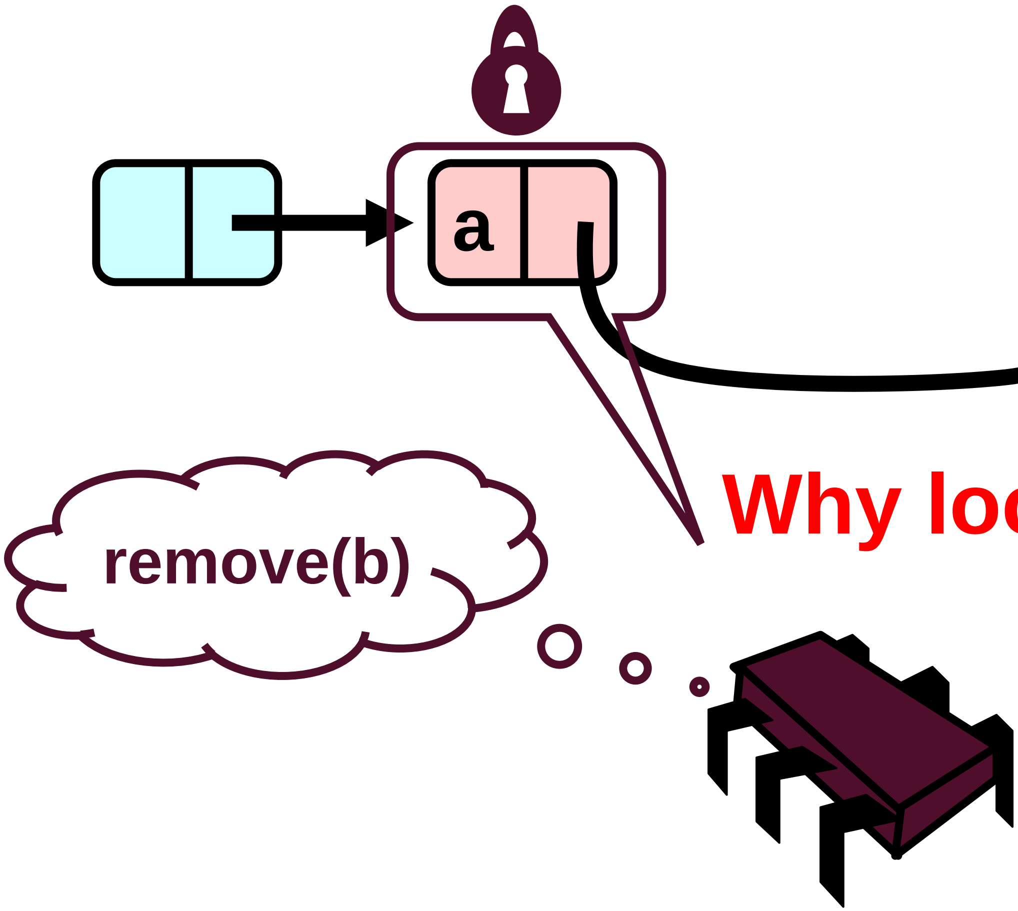
Removing a Node



Removing a Node

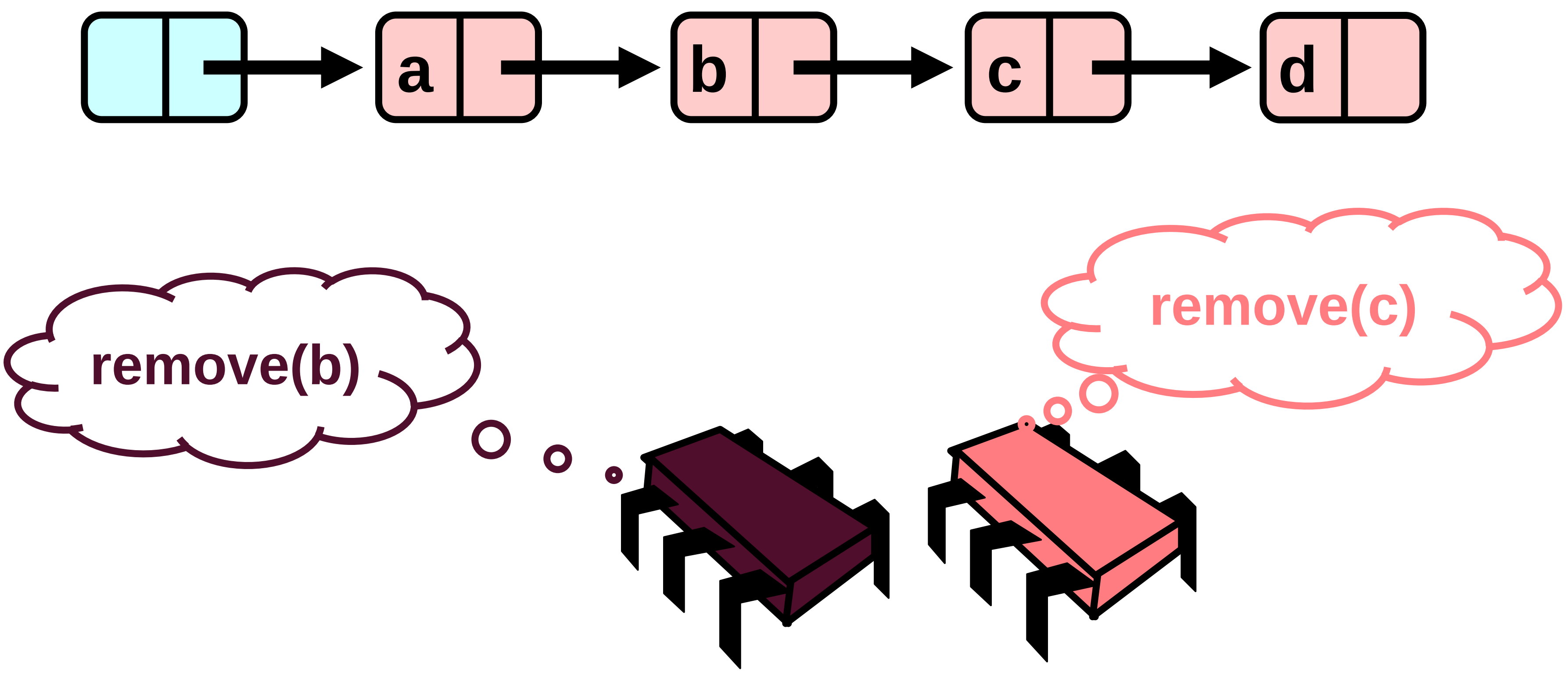


Removing a Node

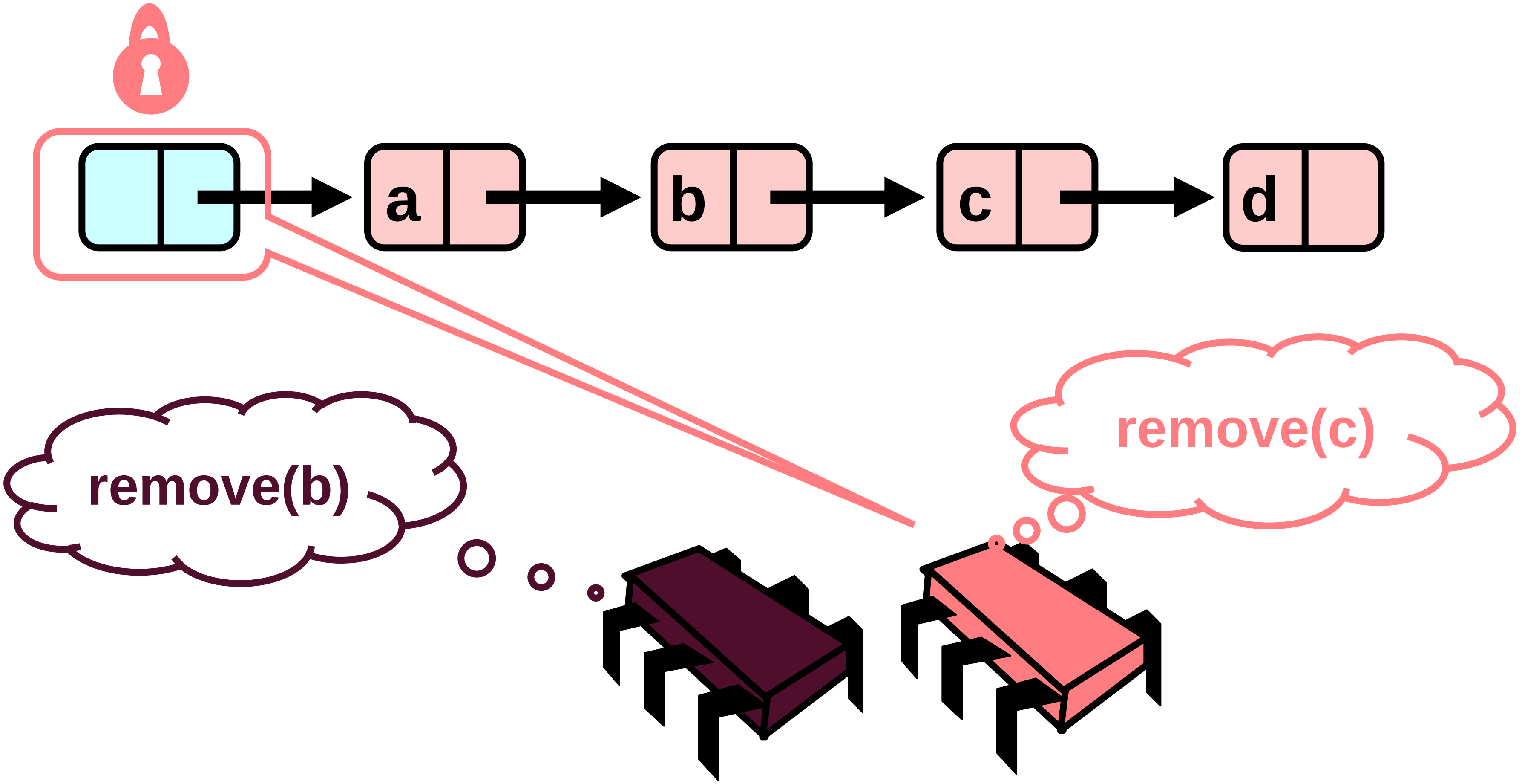


Why lock target node?

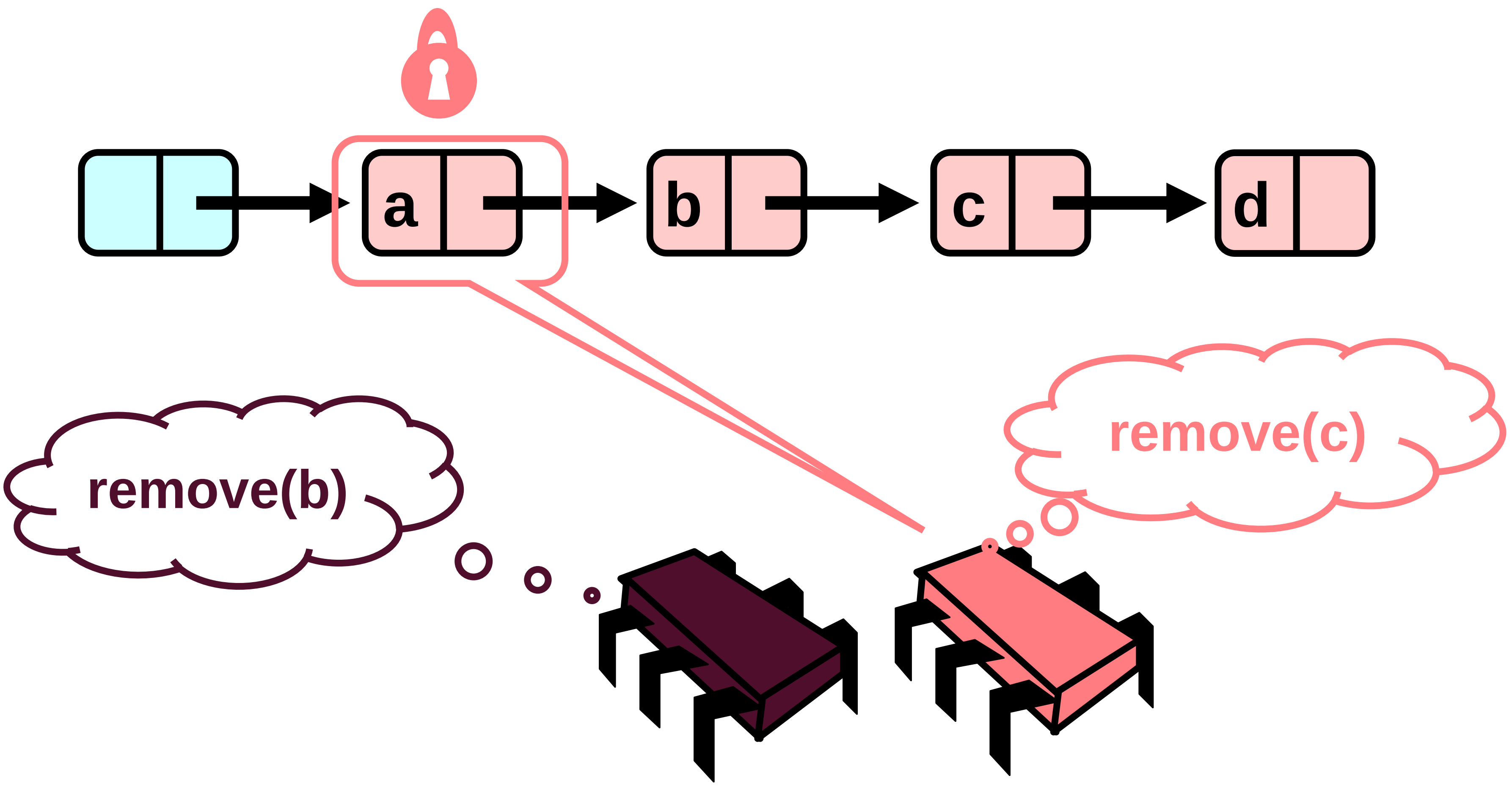
Concurrent Removes



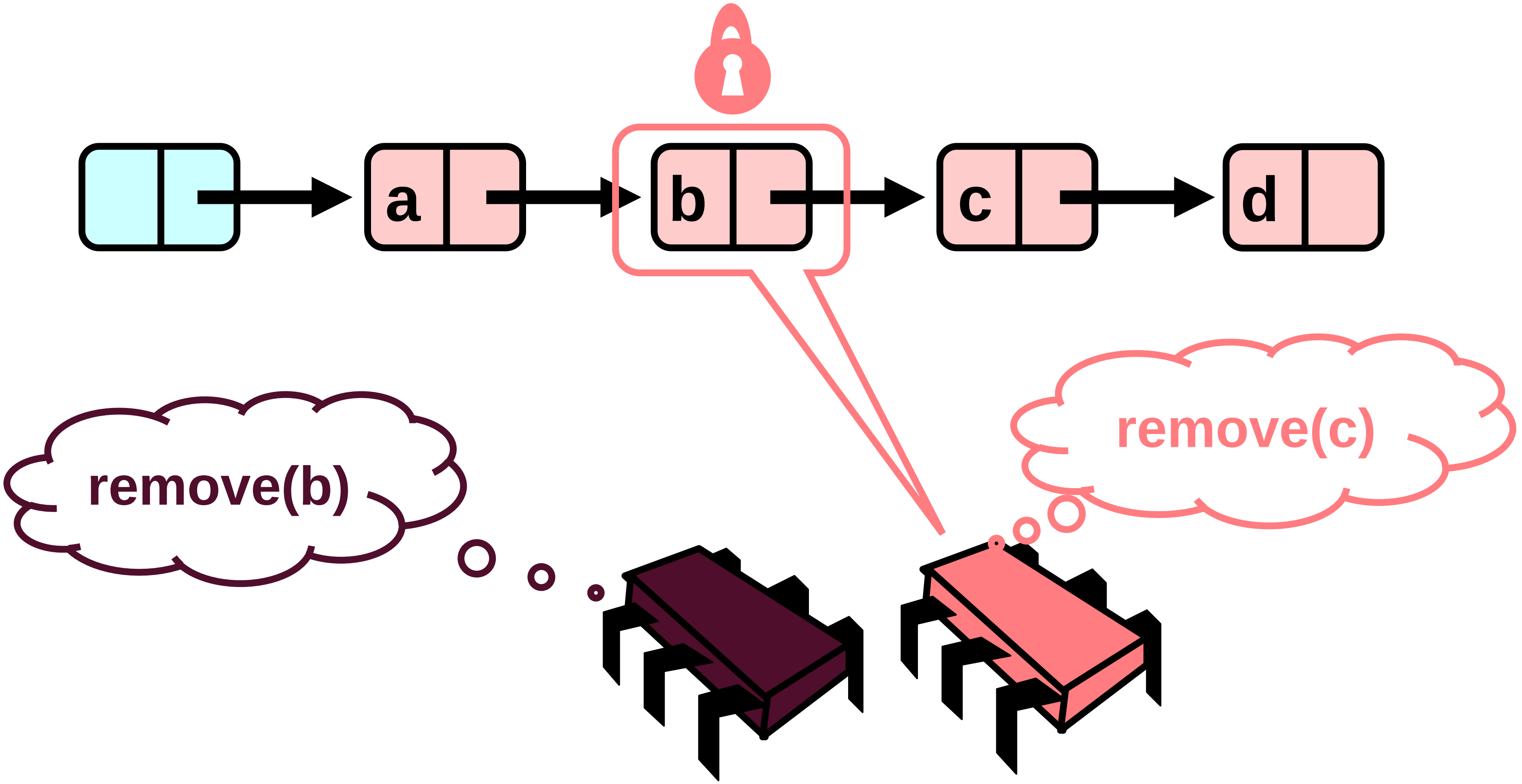
Concurrent Removes



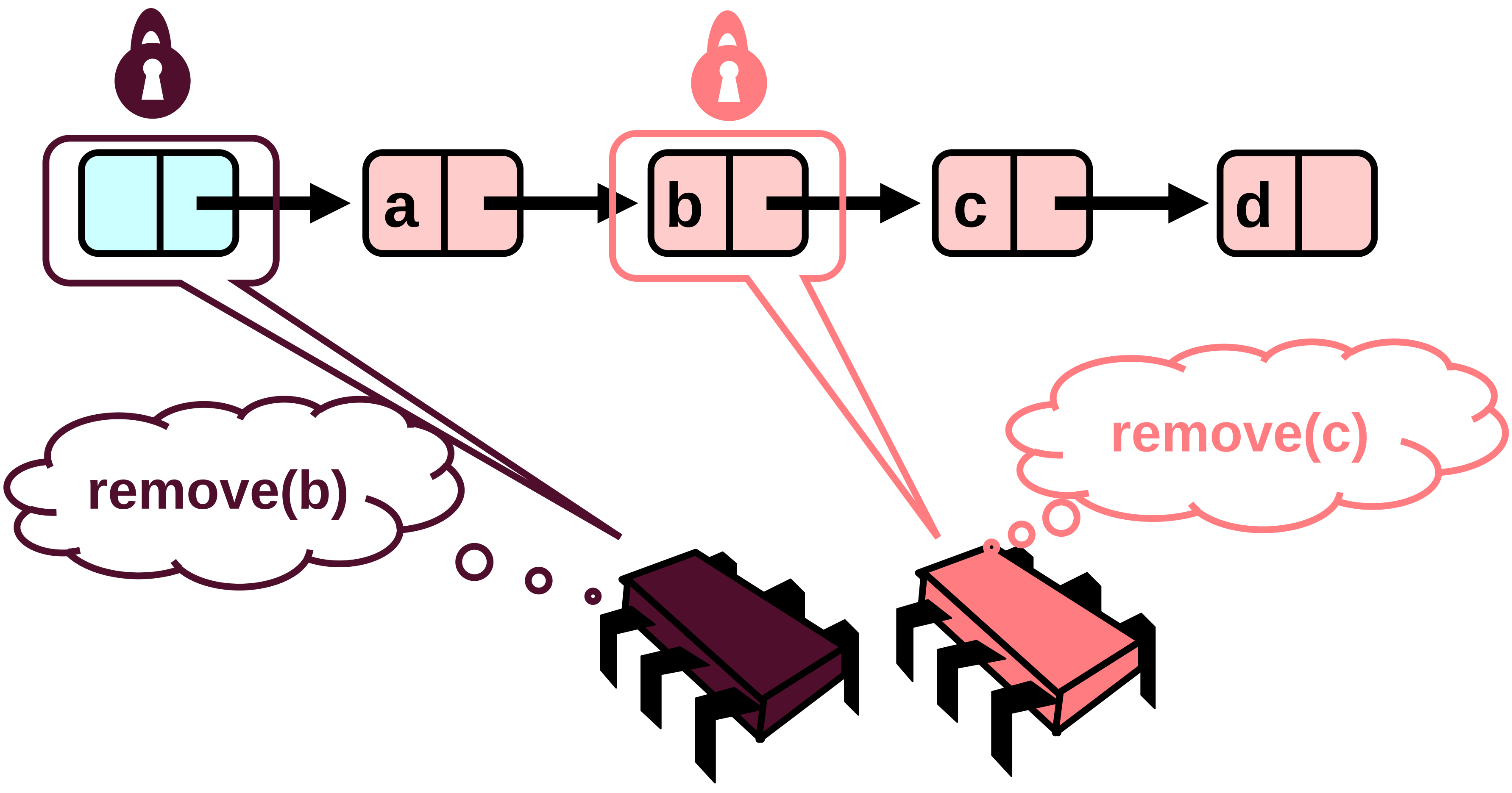
Concurrent Removes



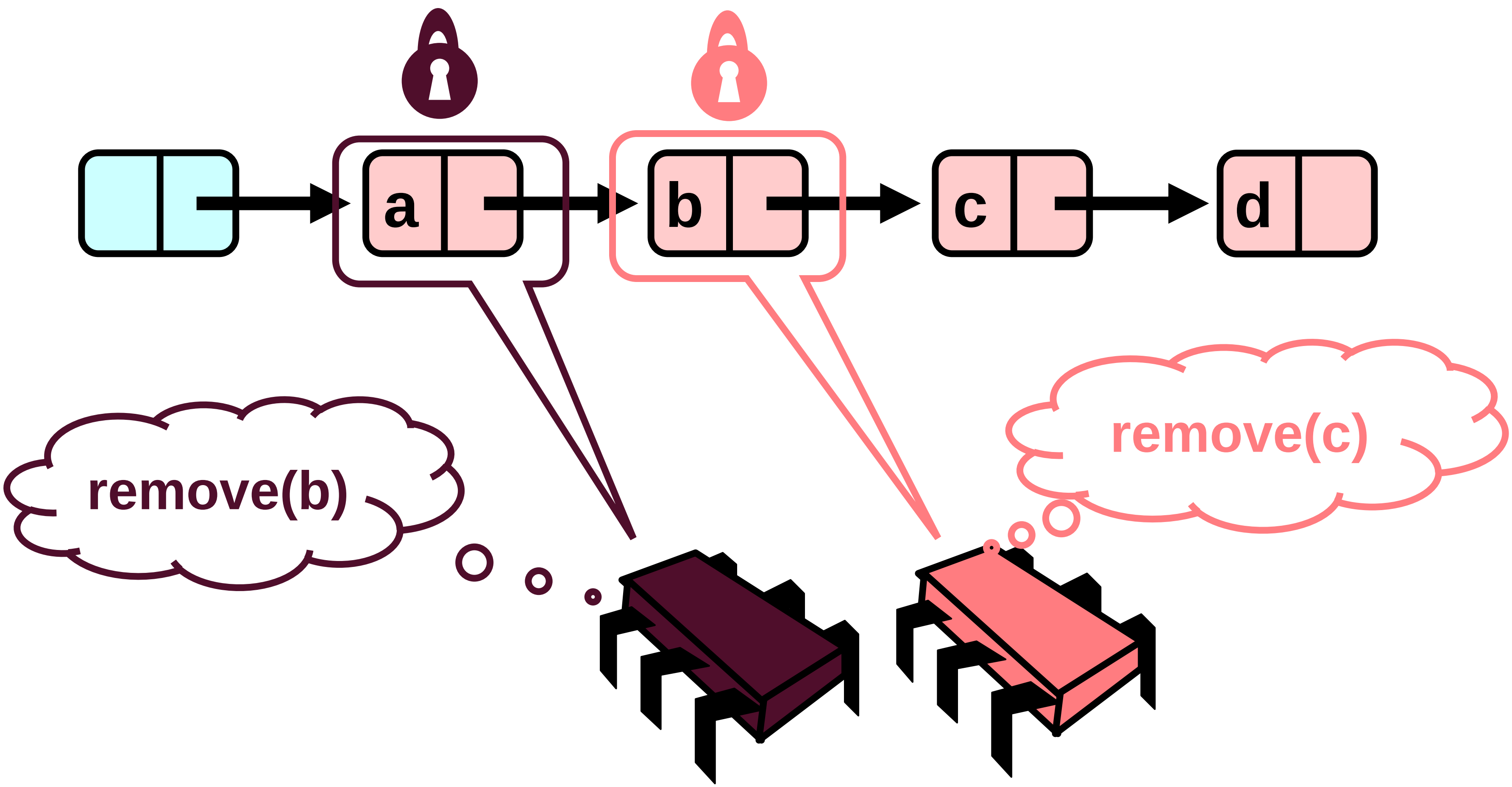
Concurrent Removes



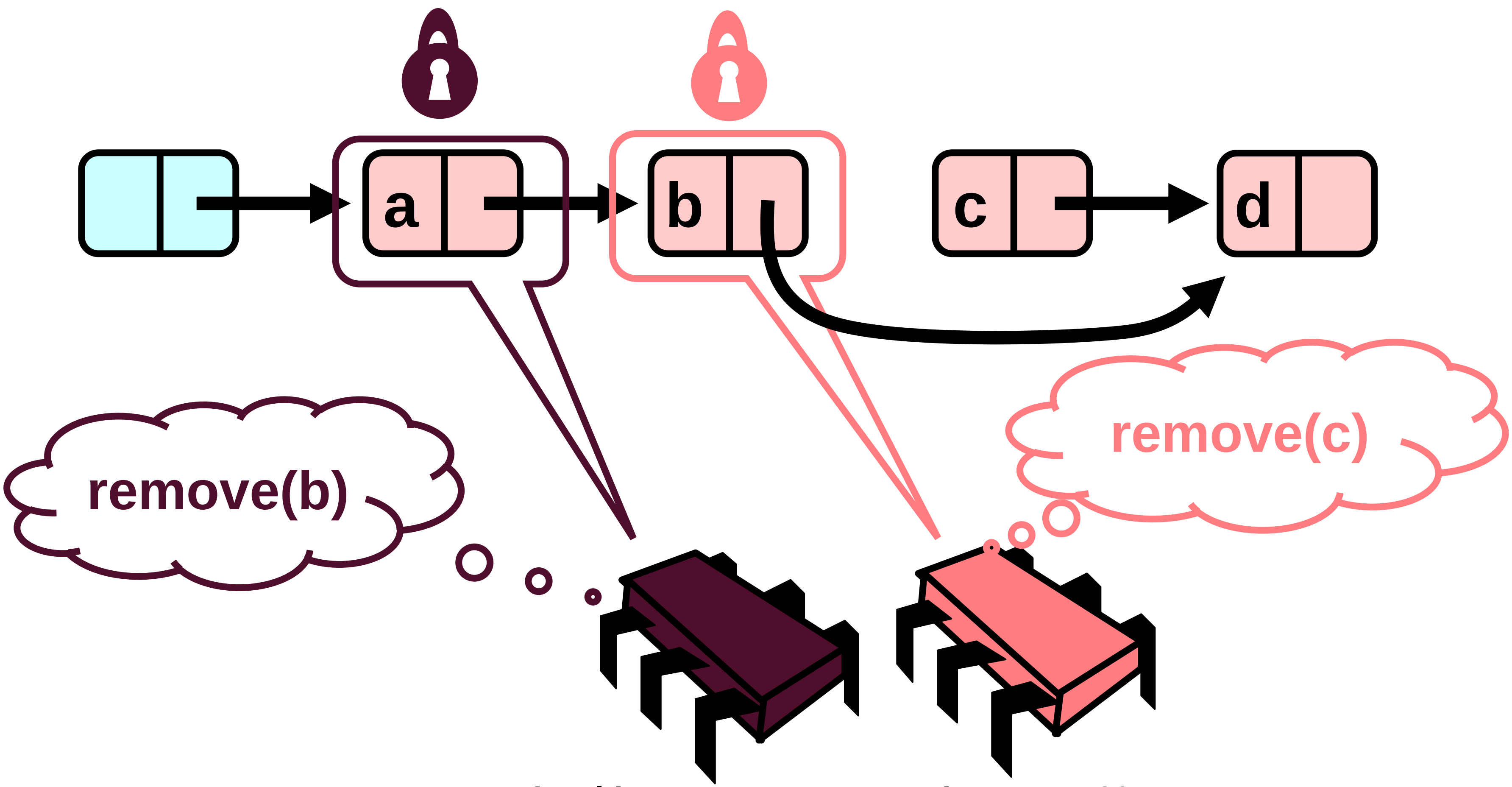
Concurrent Removes



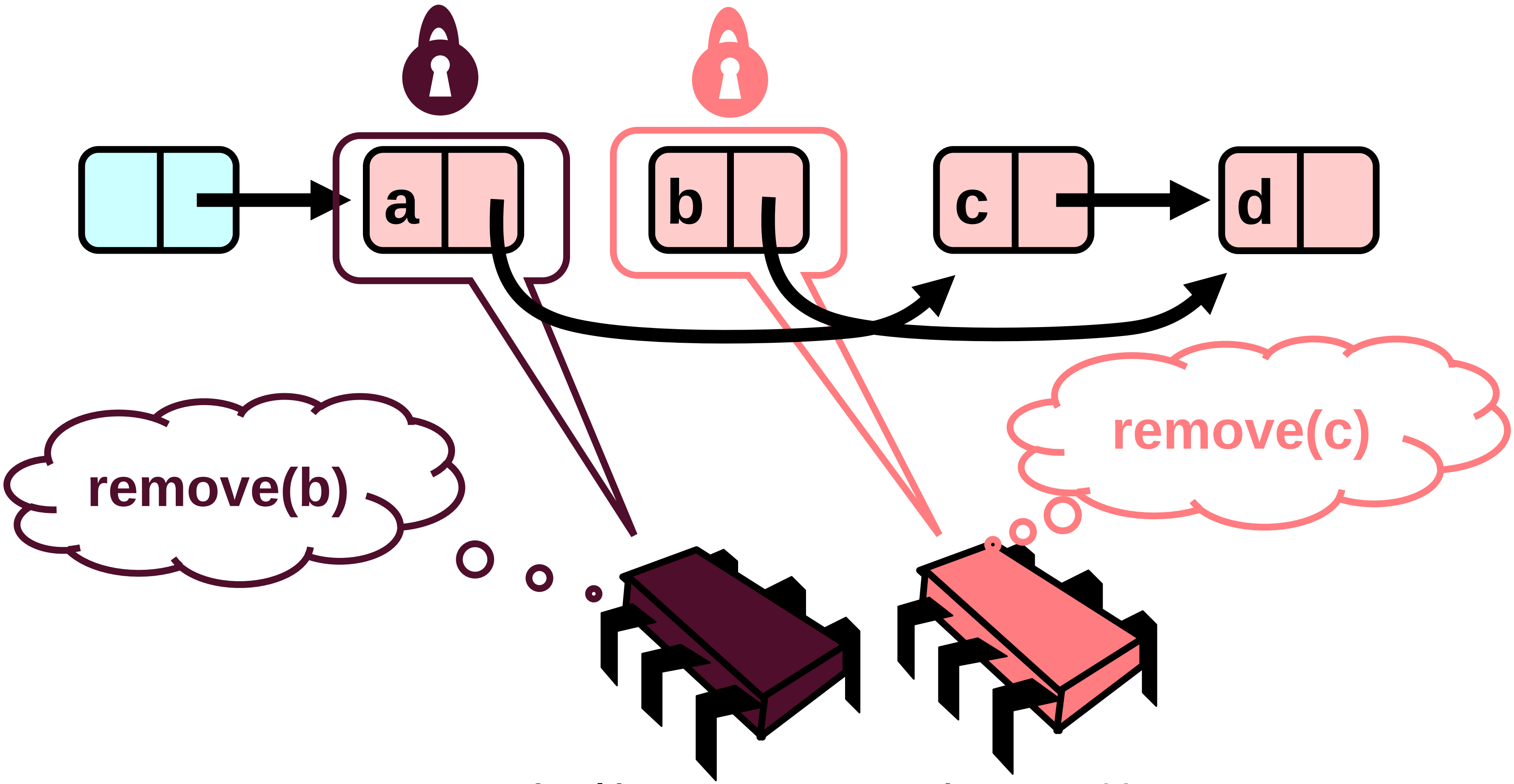
Concurrent Removes



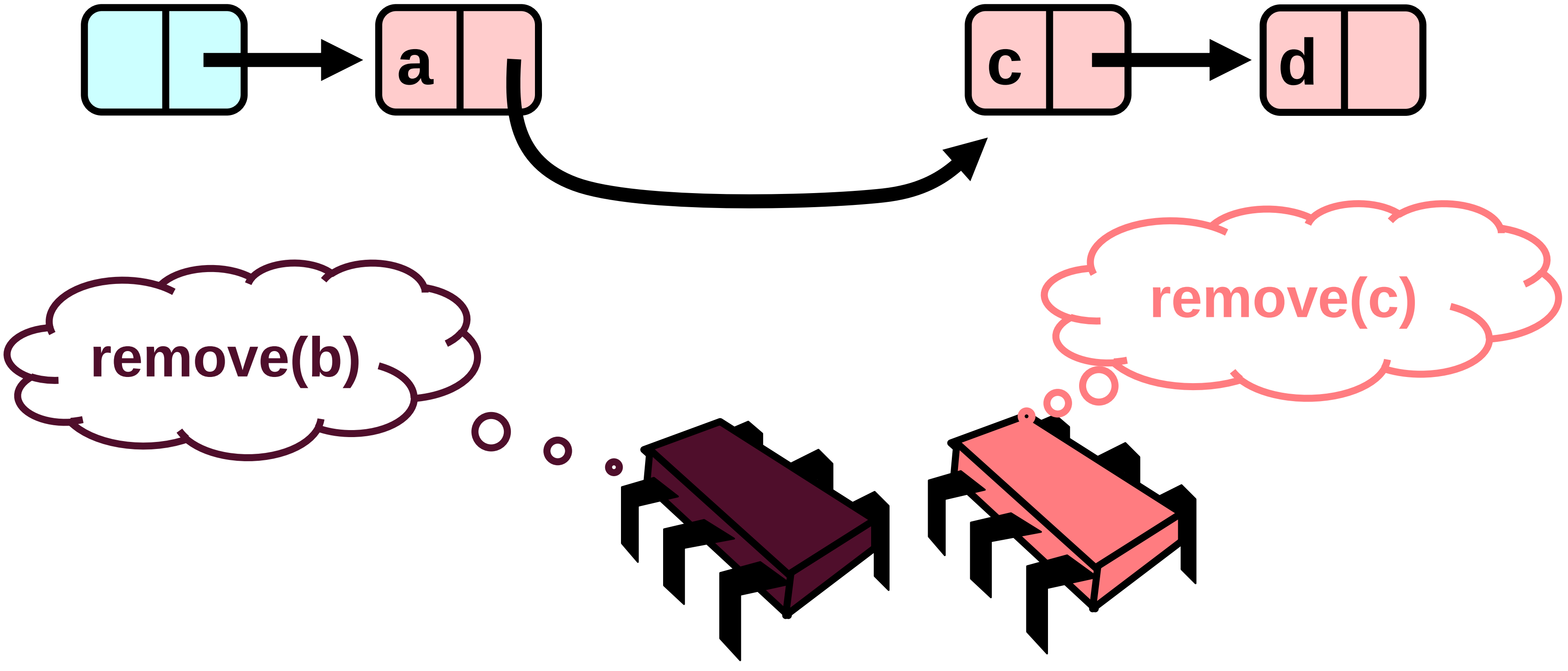
Concurrent Removes



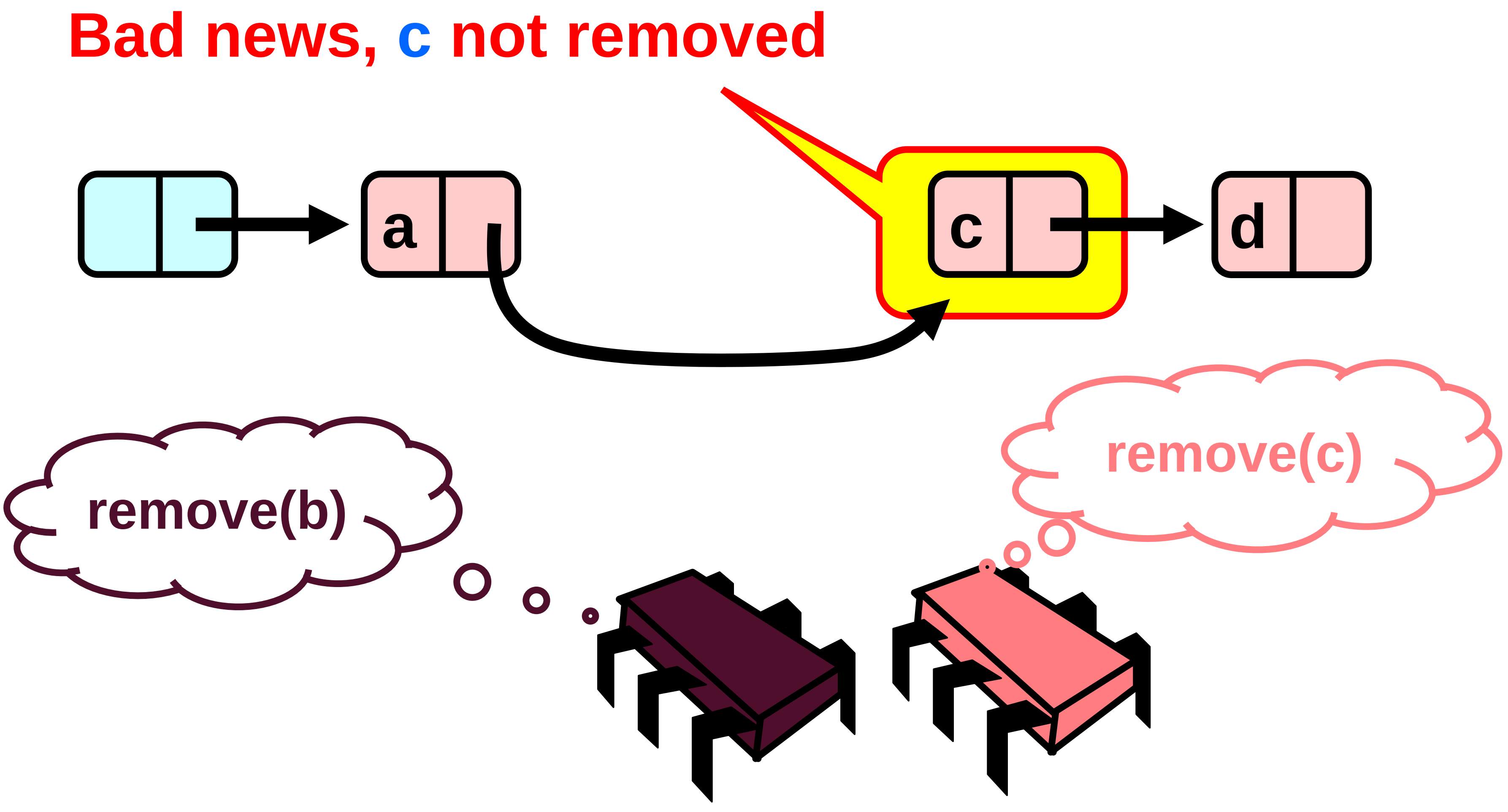
Concurrent Removes



Uh, Oh



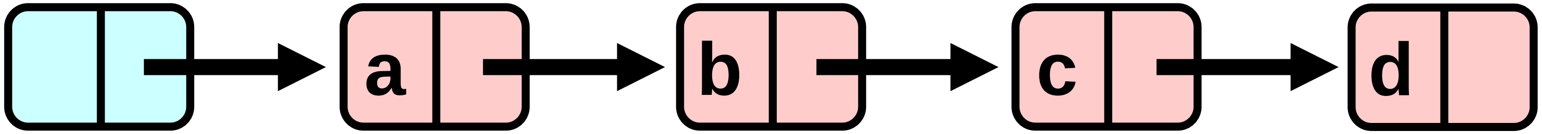
Uh, Oh

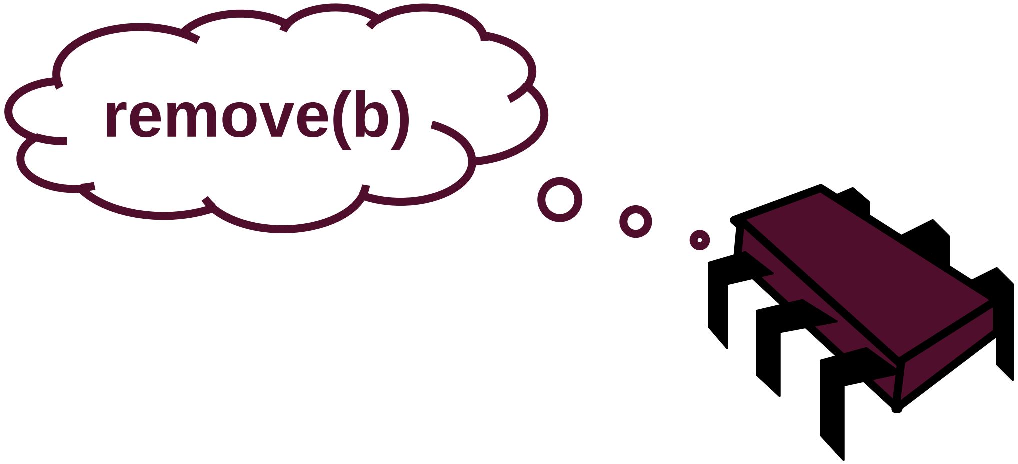


Insight

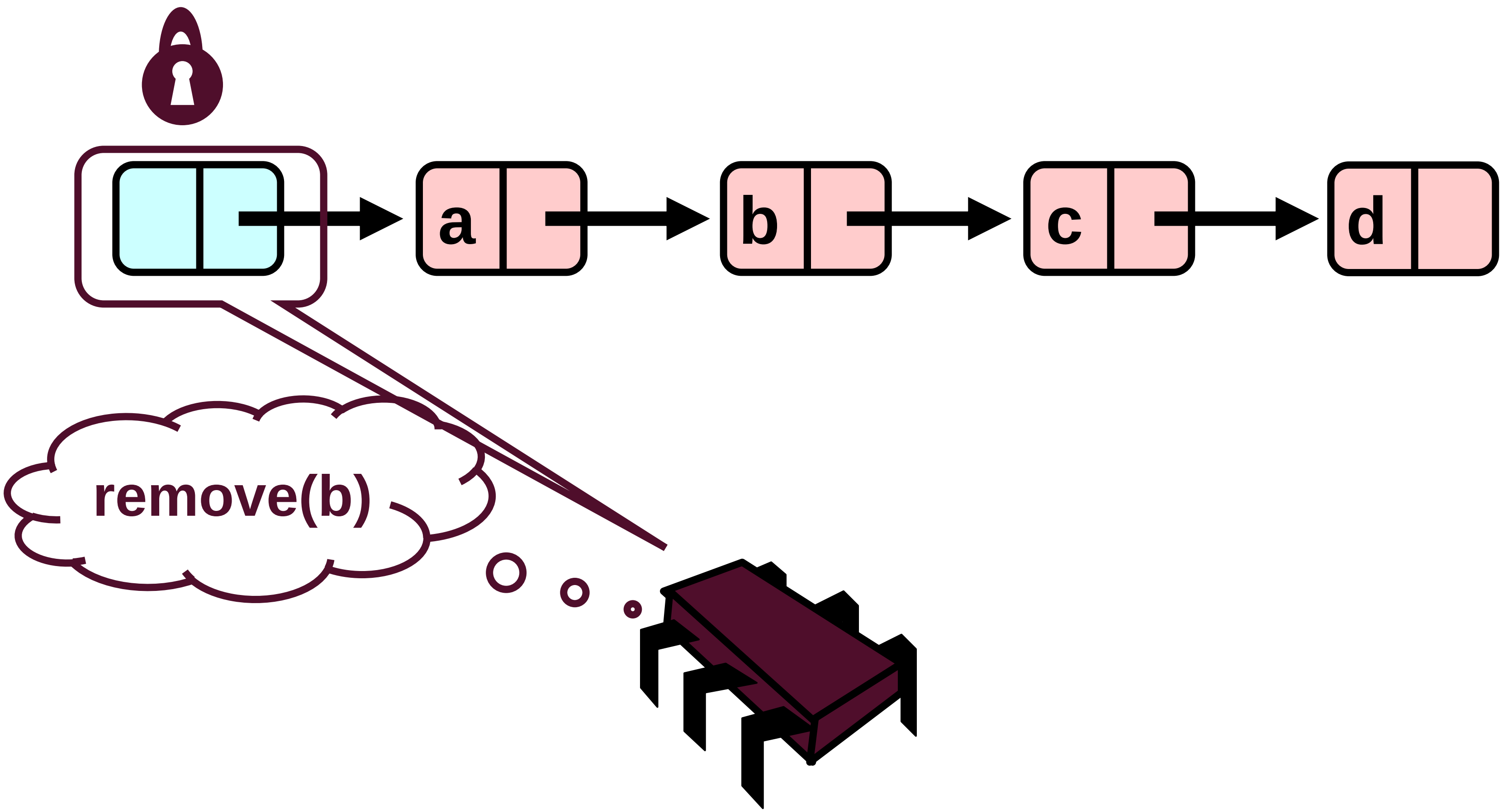
- **If a node x is locked**
  - Successor of x cannot be deleted!
- **Thus, safe locking is**
  - Lock node to be deleted
  - And its predecessor!
  - → hand-over-hand locking

Hand-Over-Hand Again

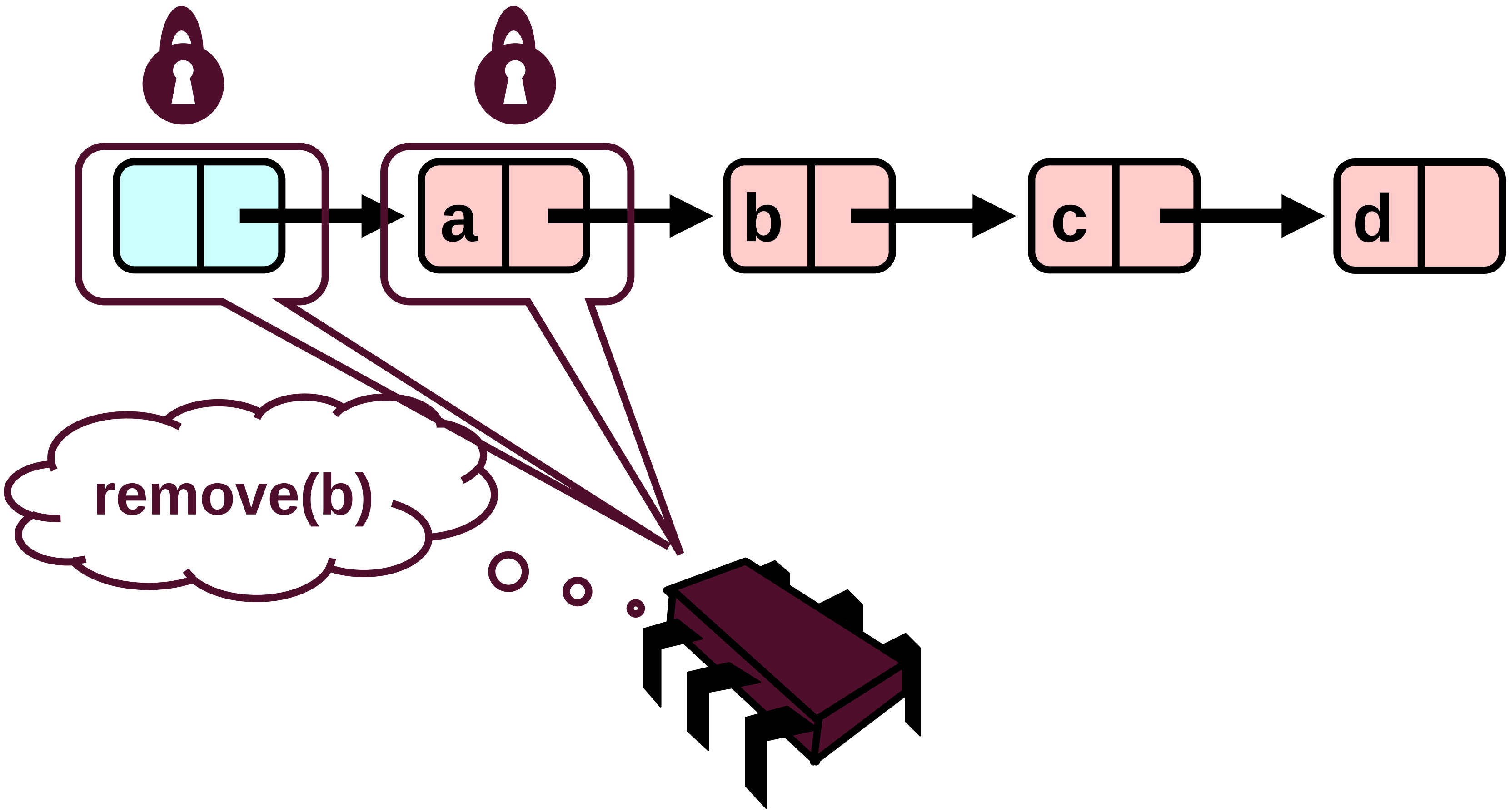




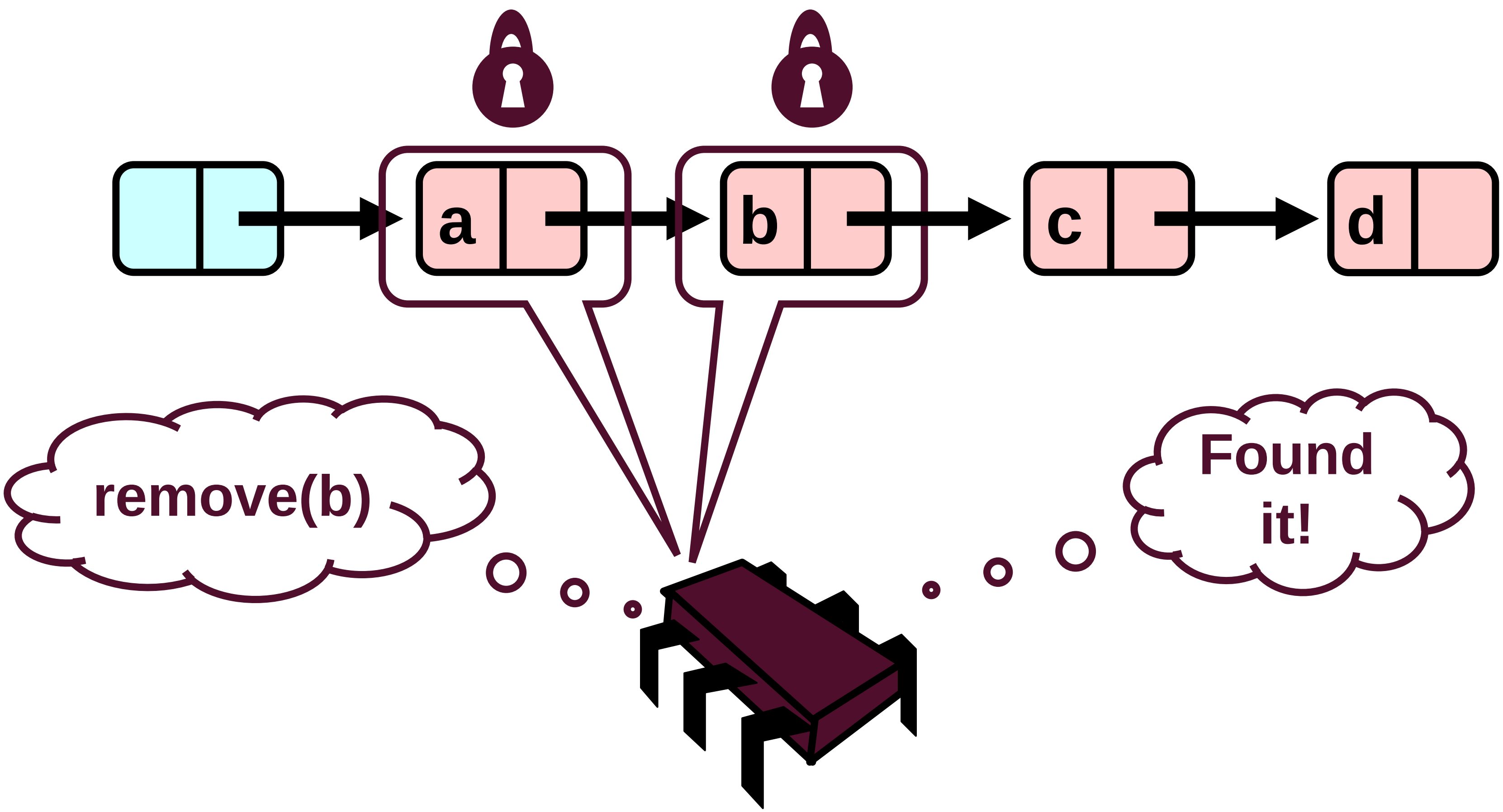
Hand-Over-Hand Again



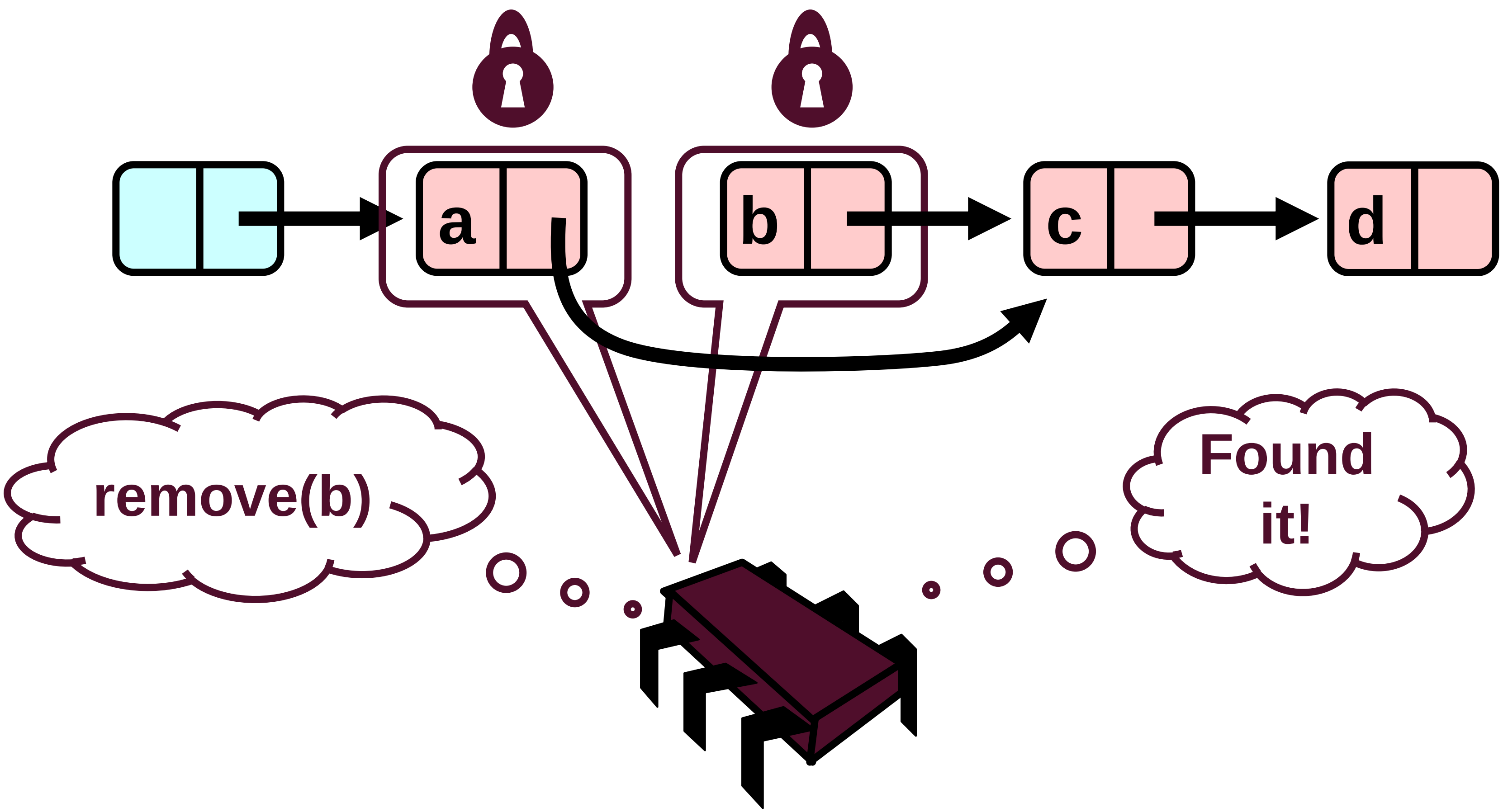
Hand-Over-Hand Again



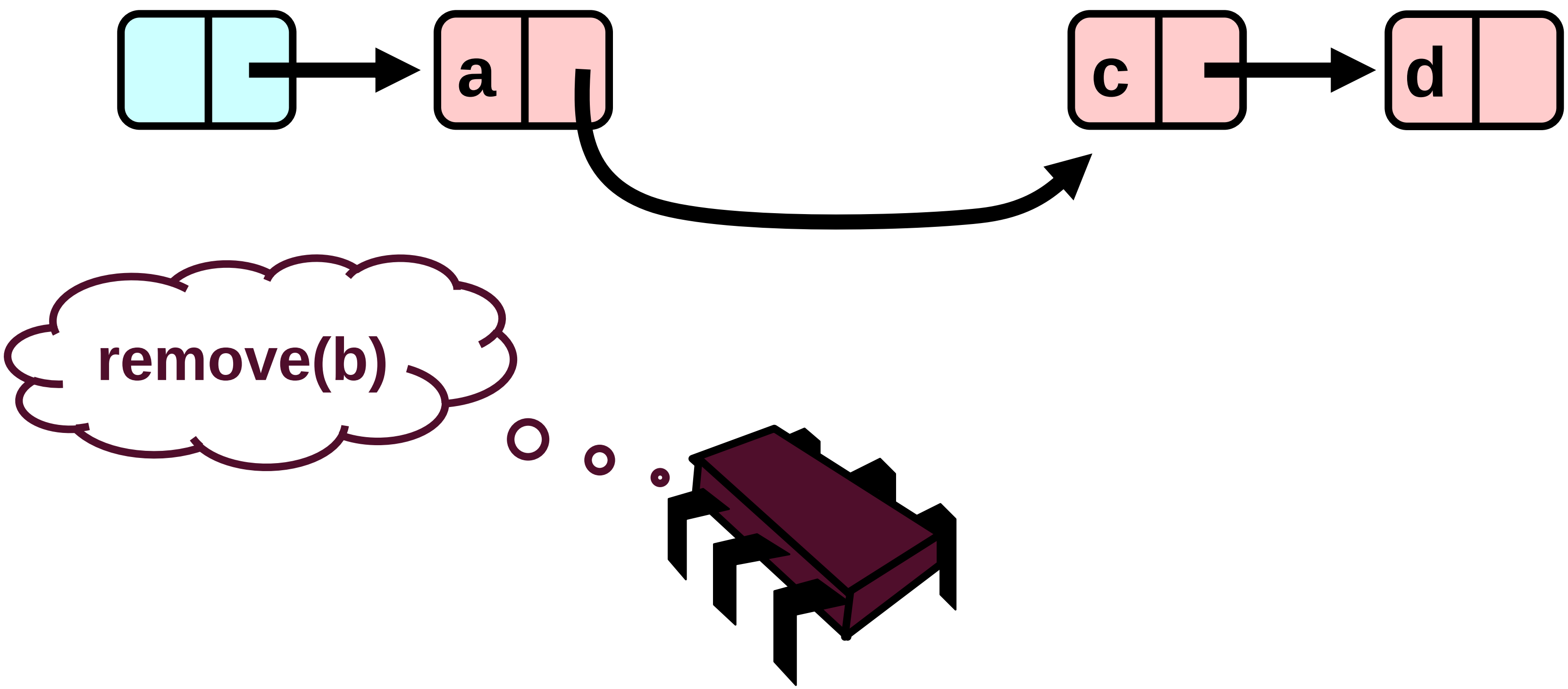
Hand-Over-Hand Again



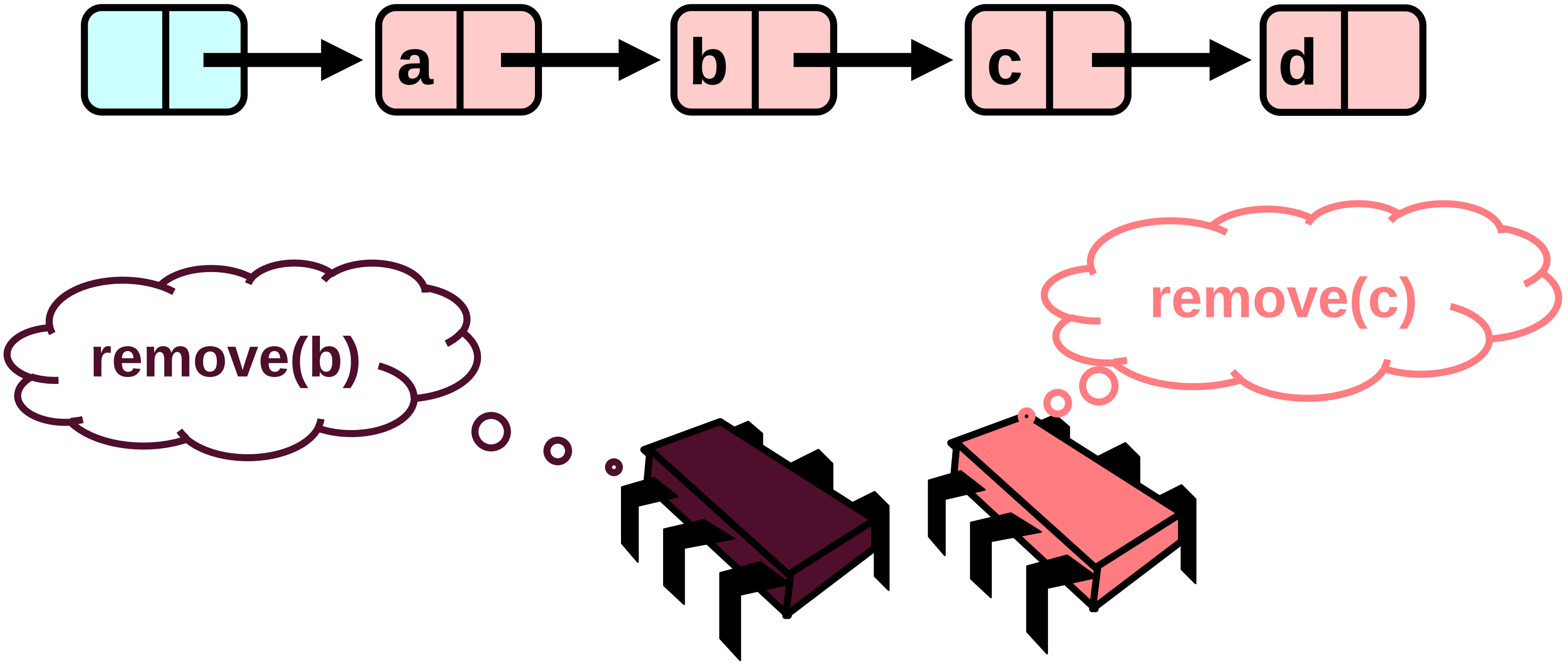
Hand-Over-Hand Again



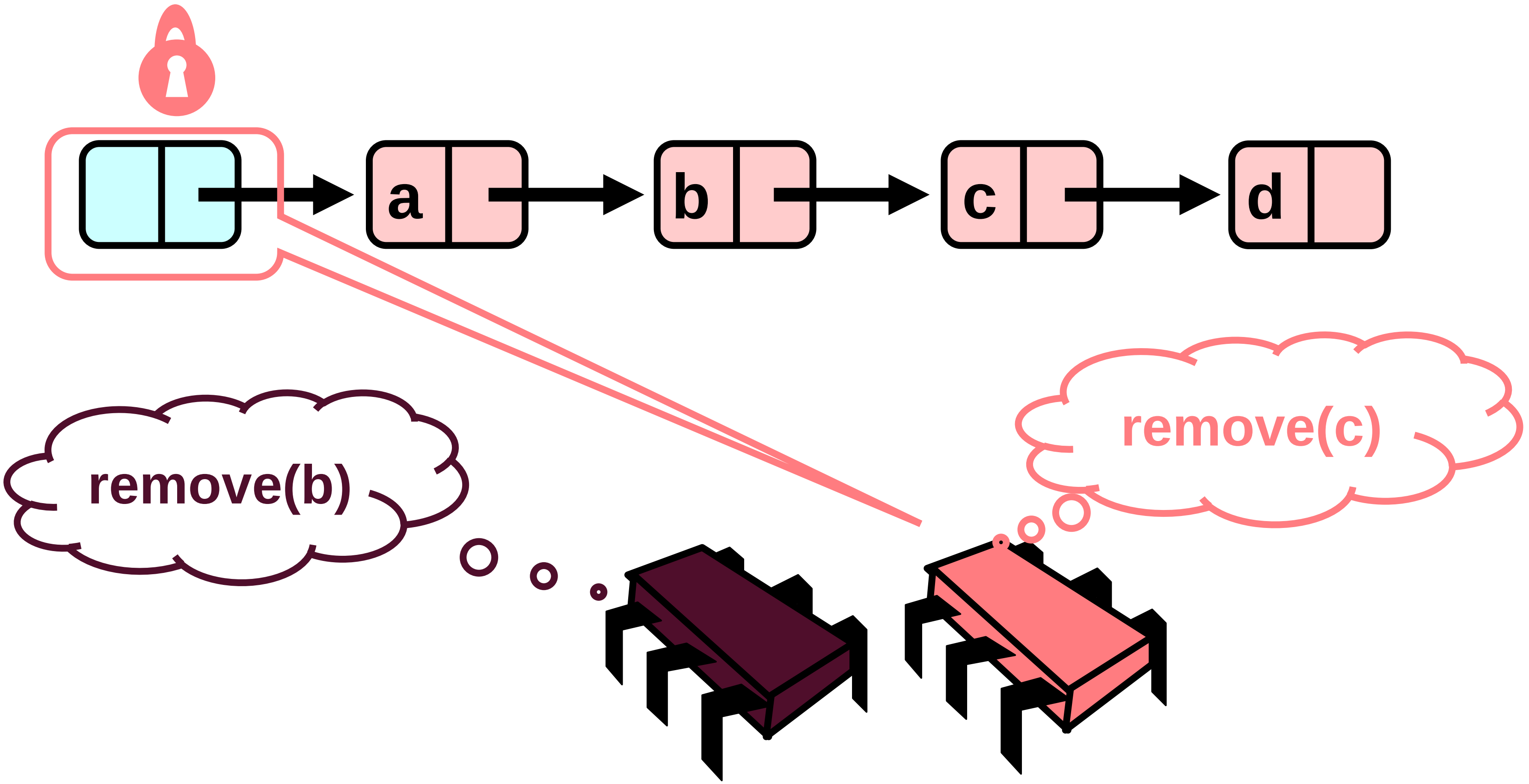
Hand-Over-Hand Again



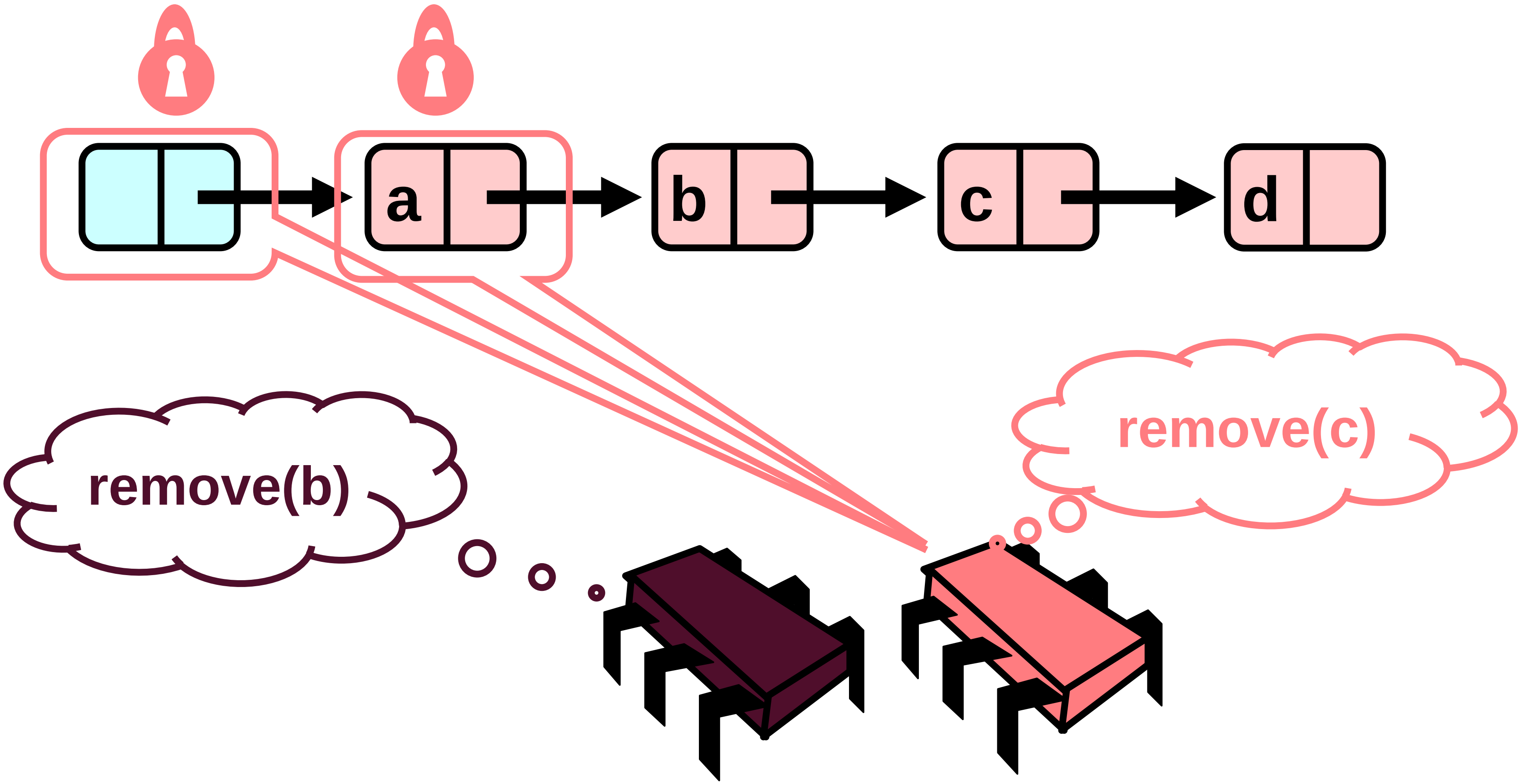
Removing a Node



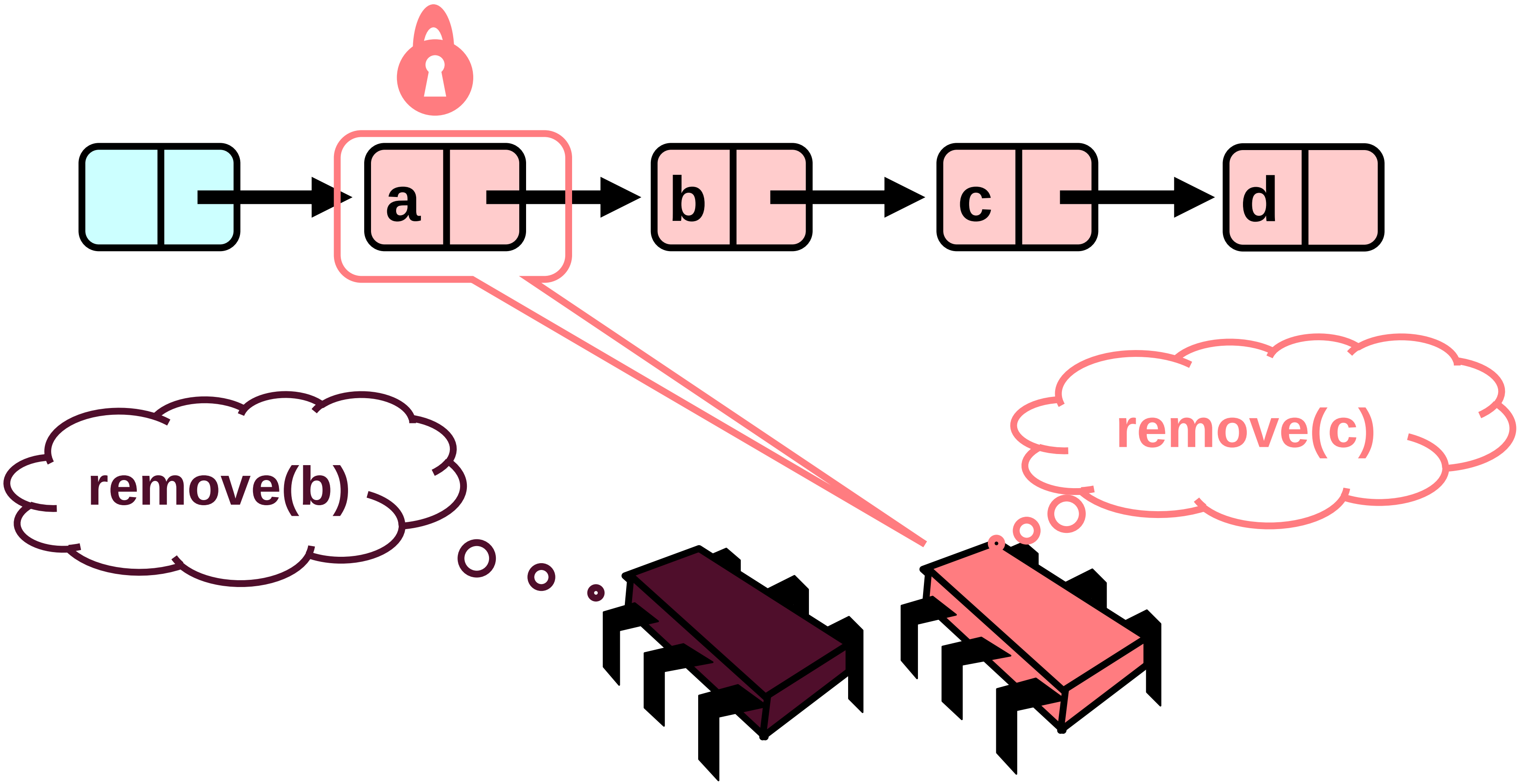
Removing a Node



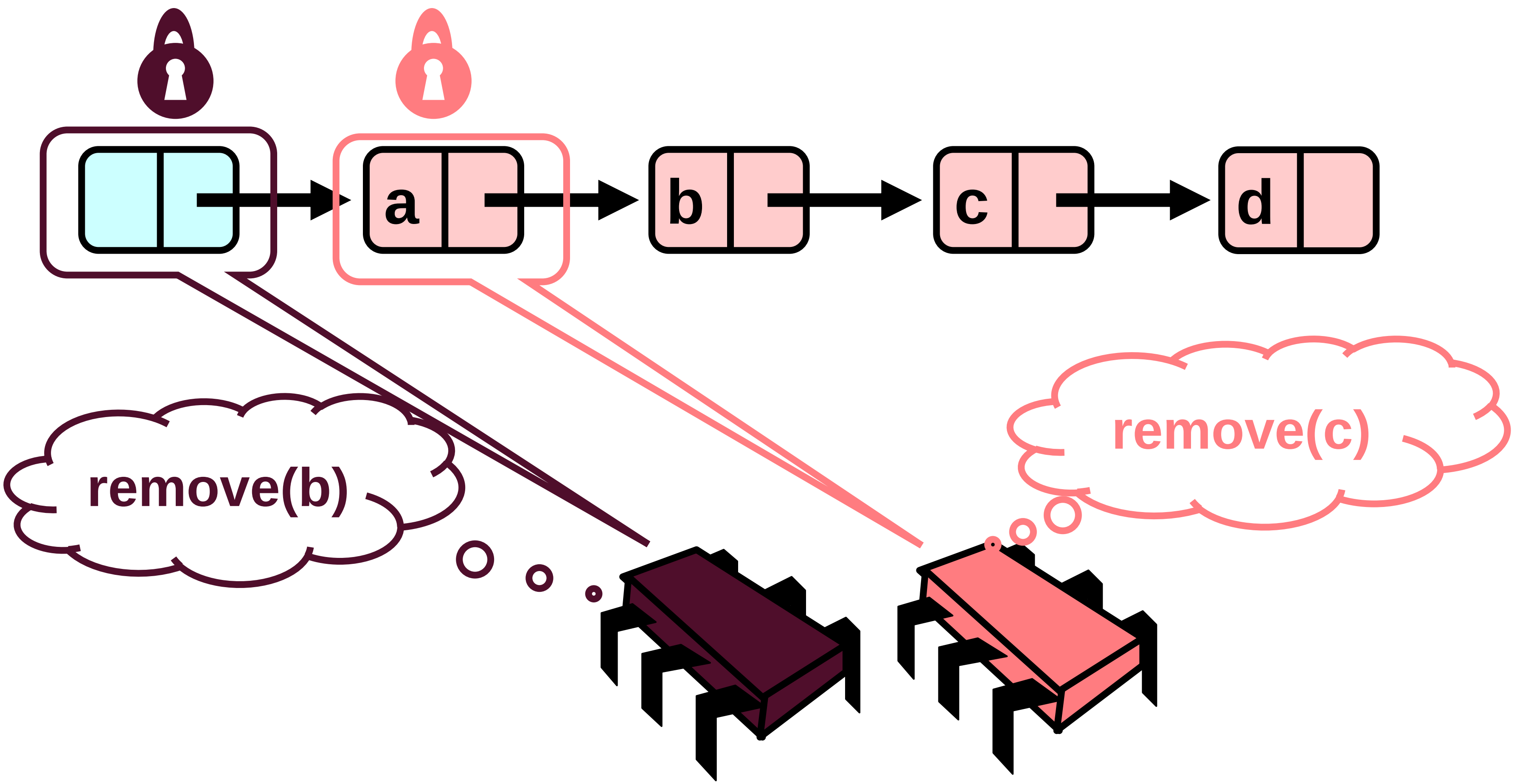
Removing a Node



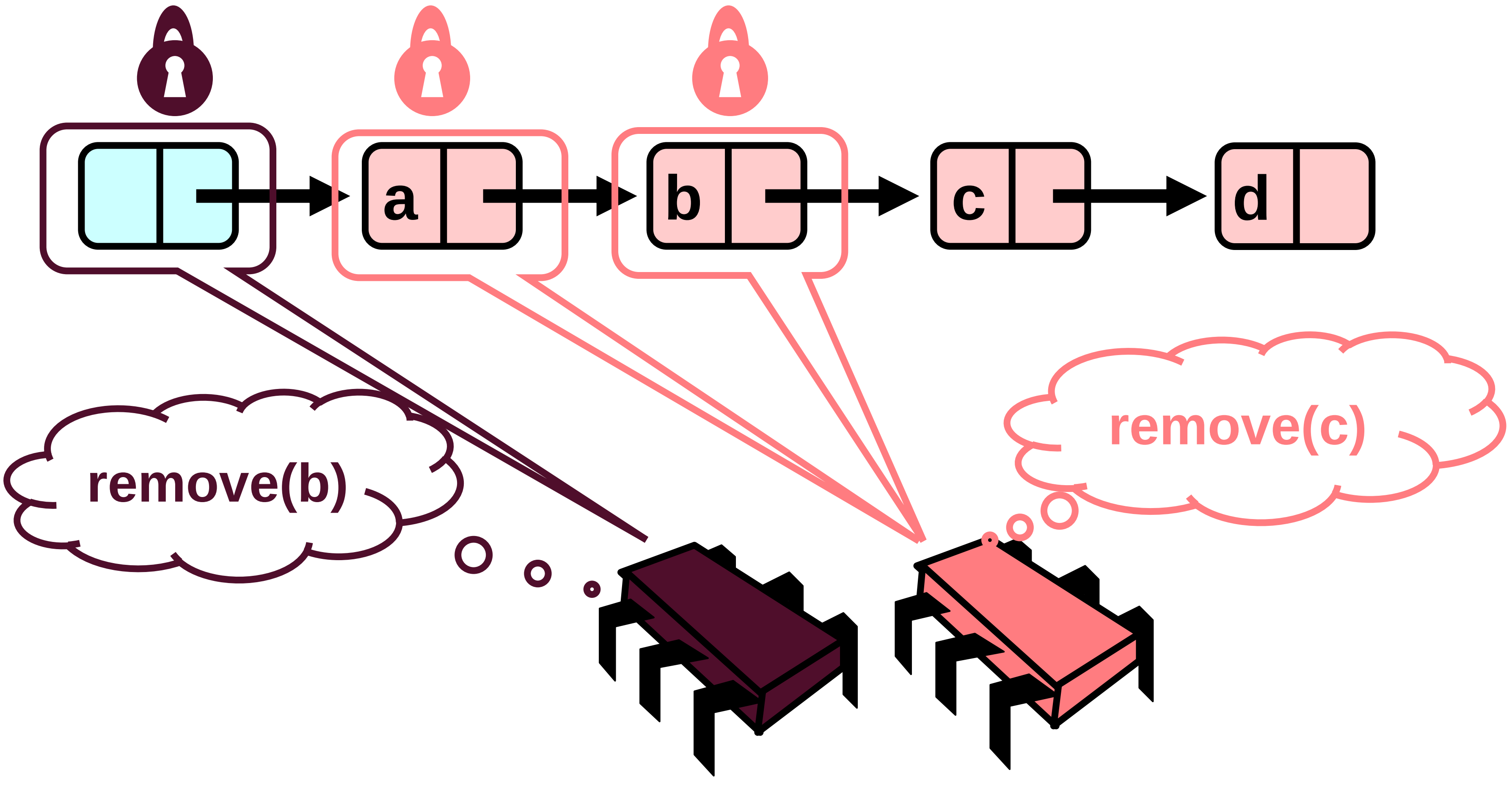
Removing a Node



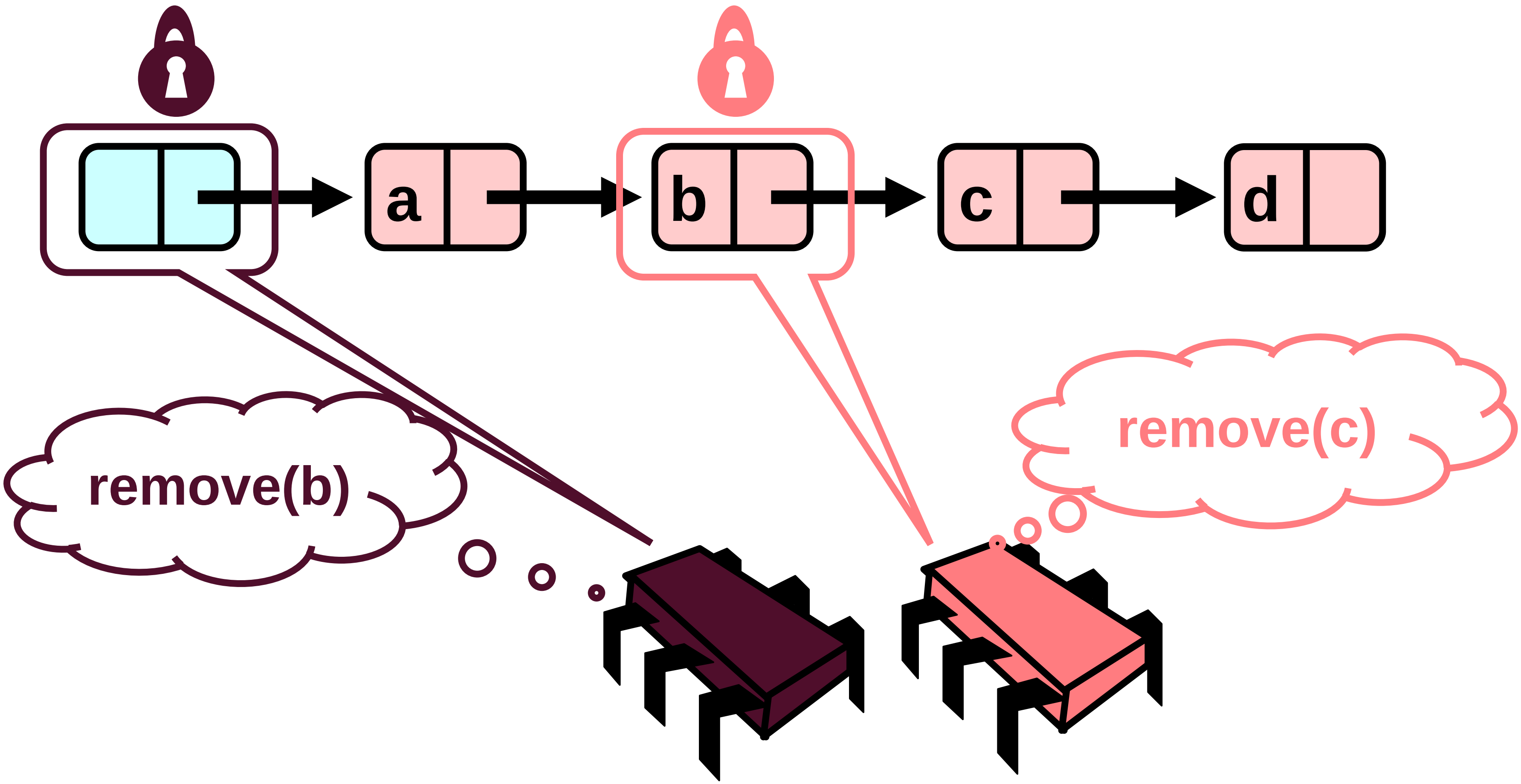
Removing a Node



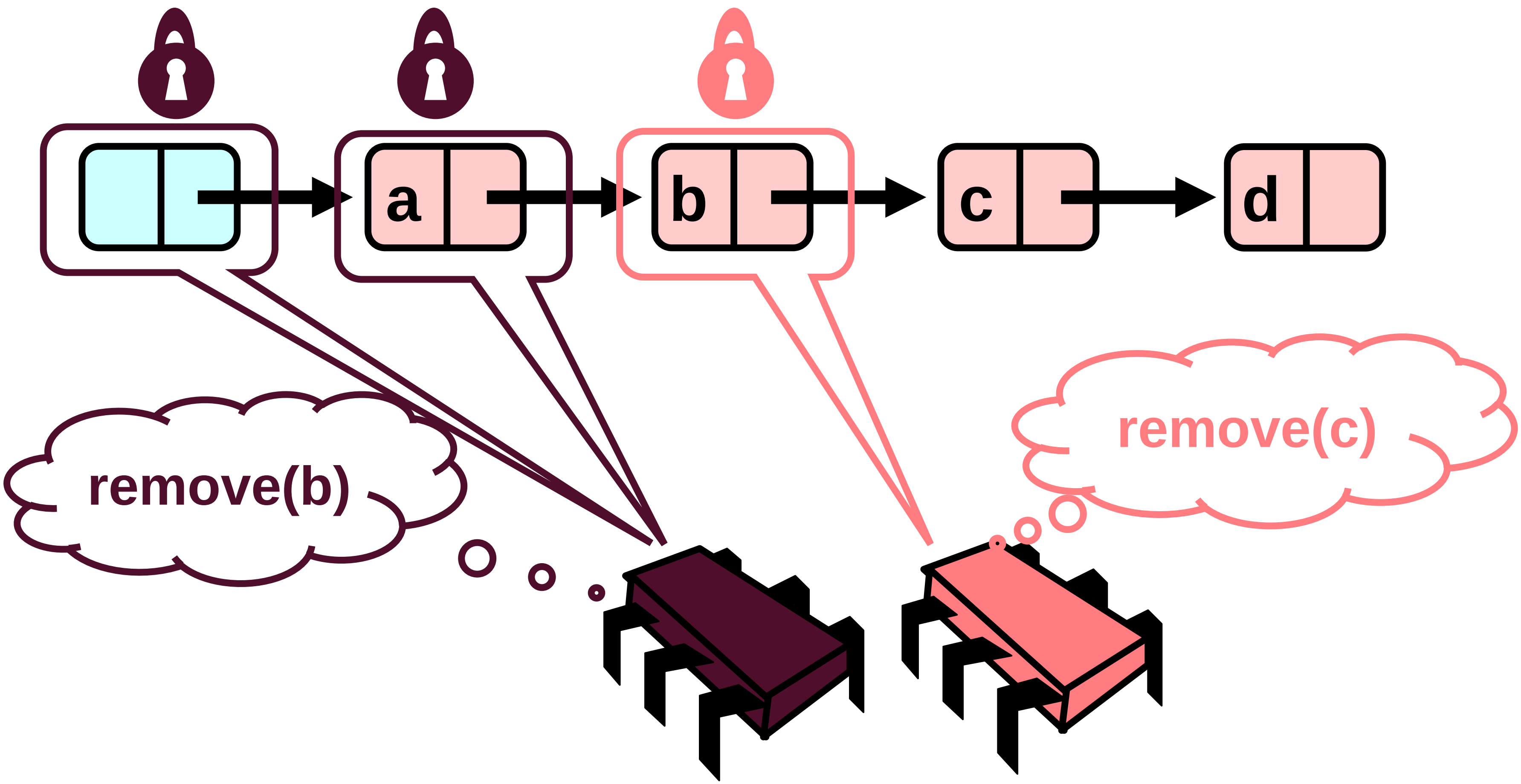
Removing a Node



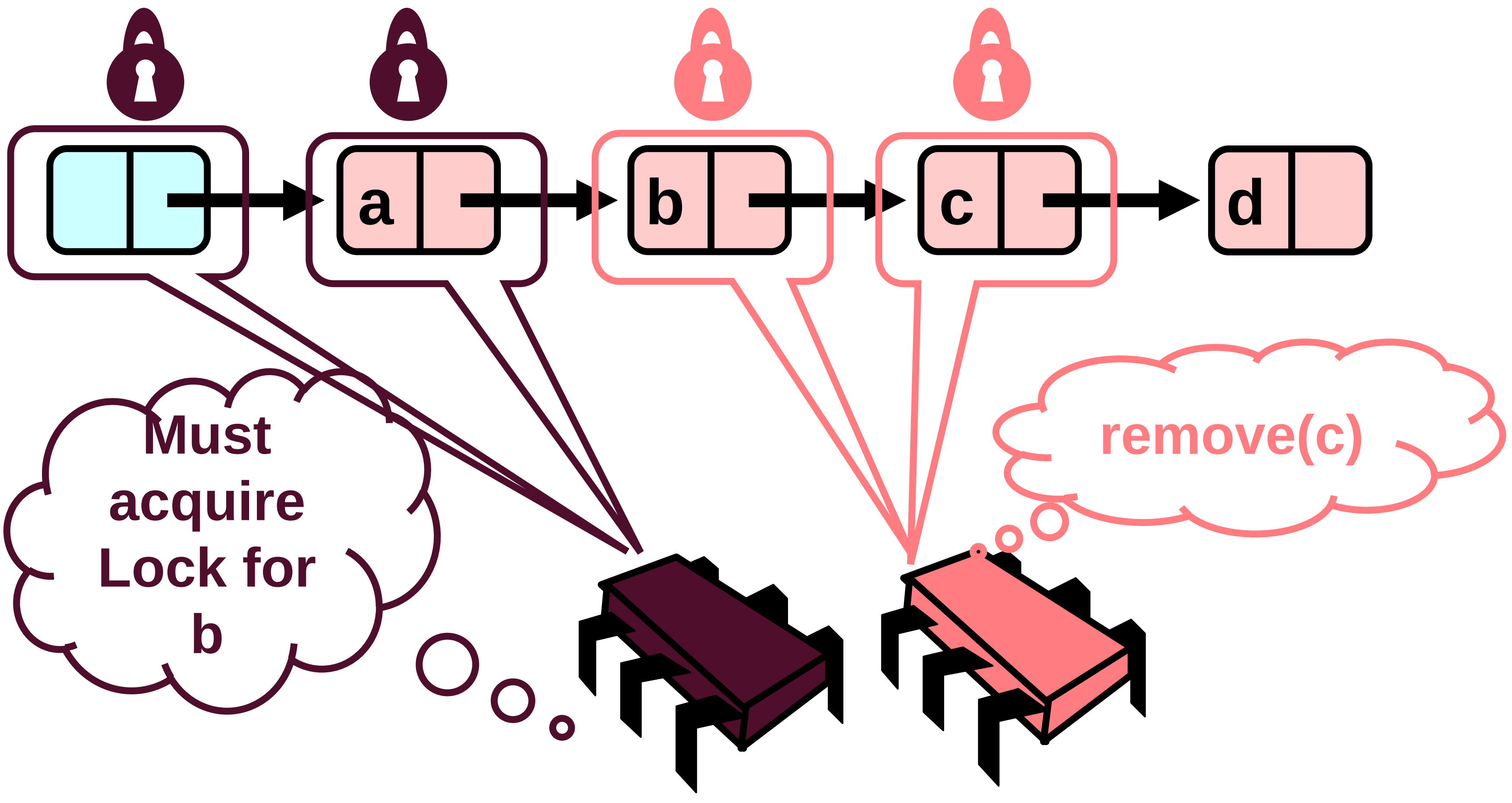
Removing a Node



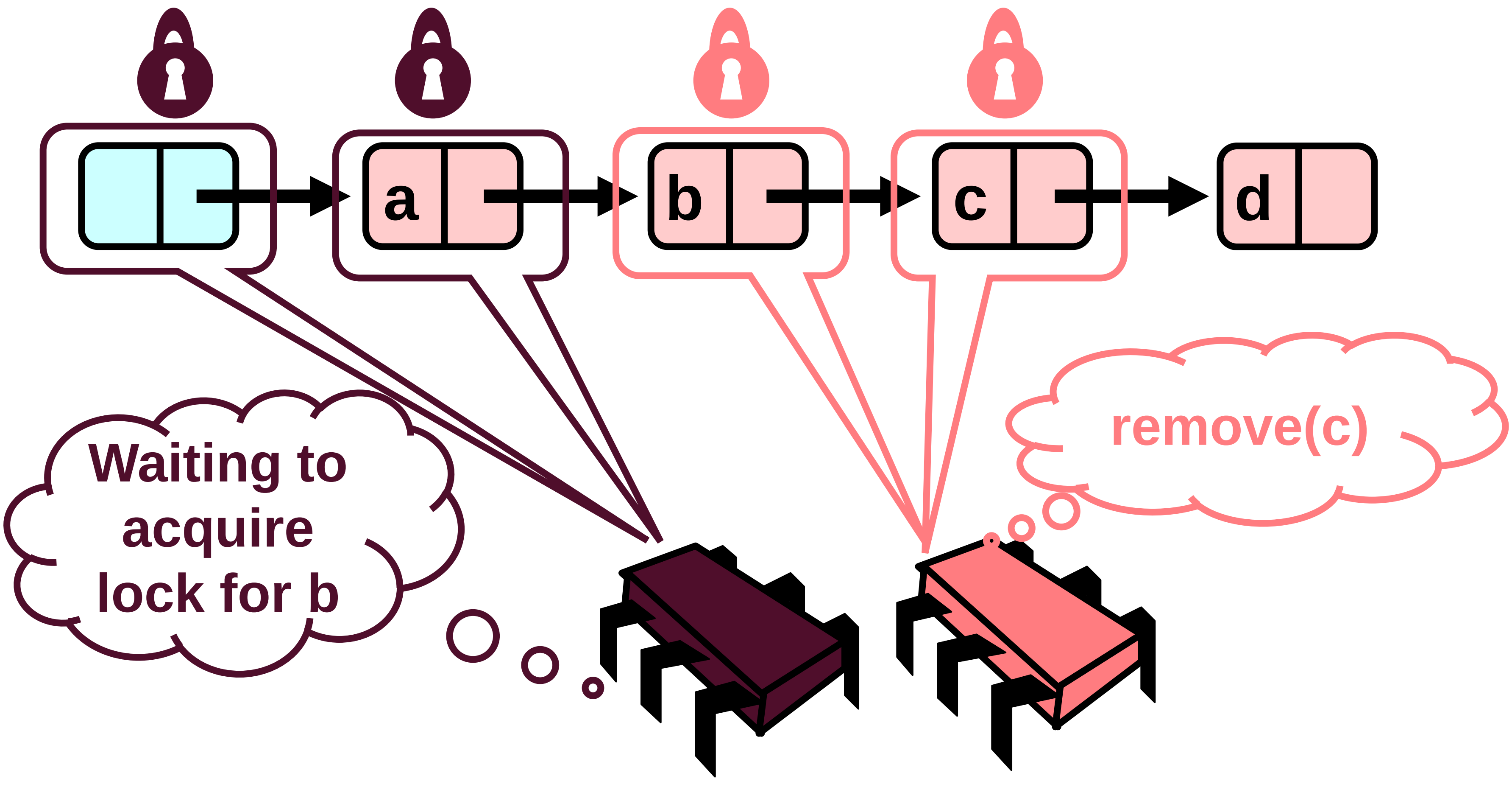
Removing a Node



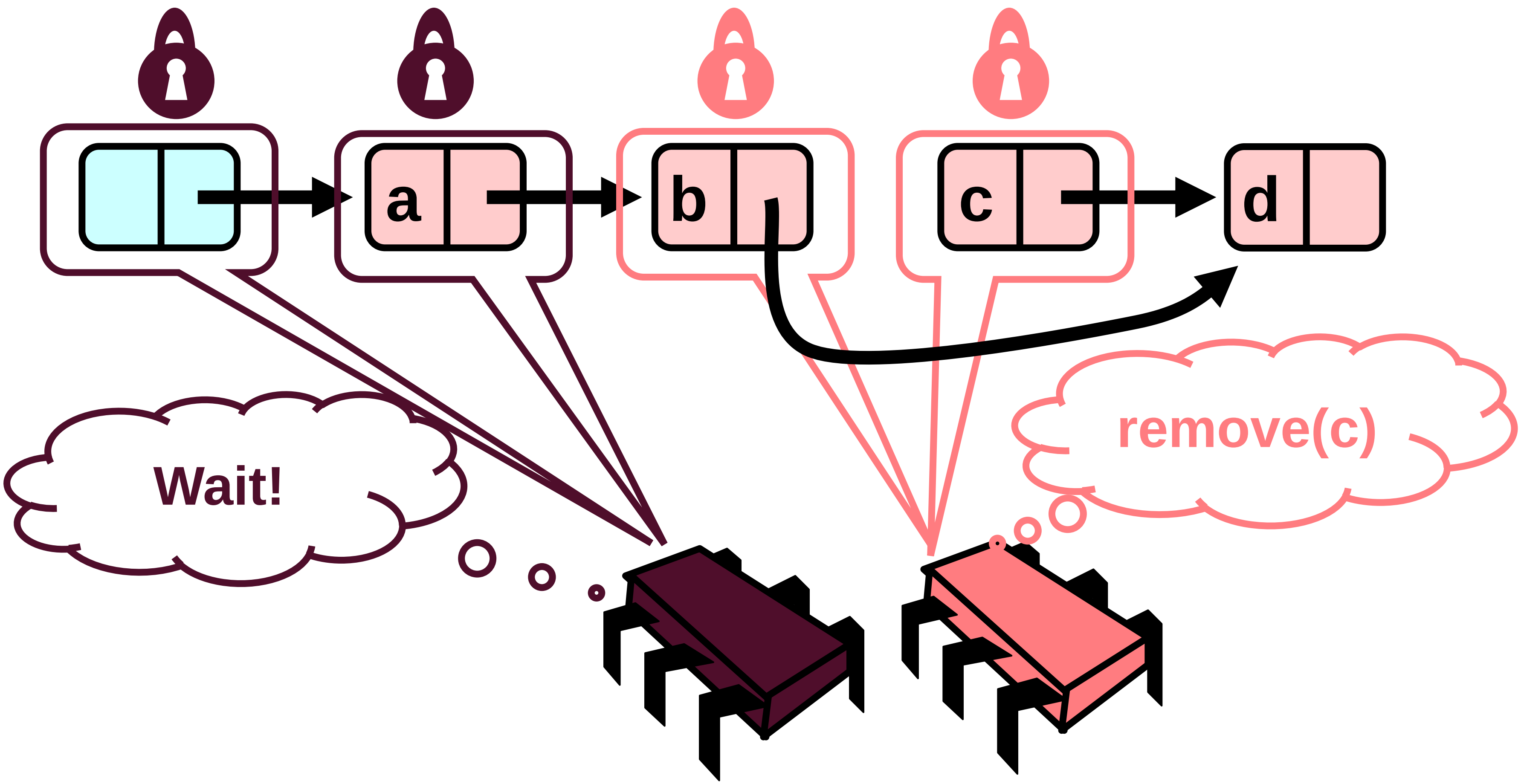
Removing a Node



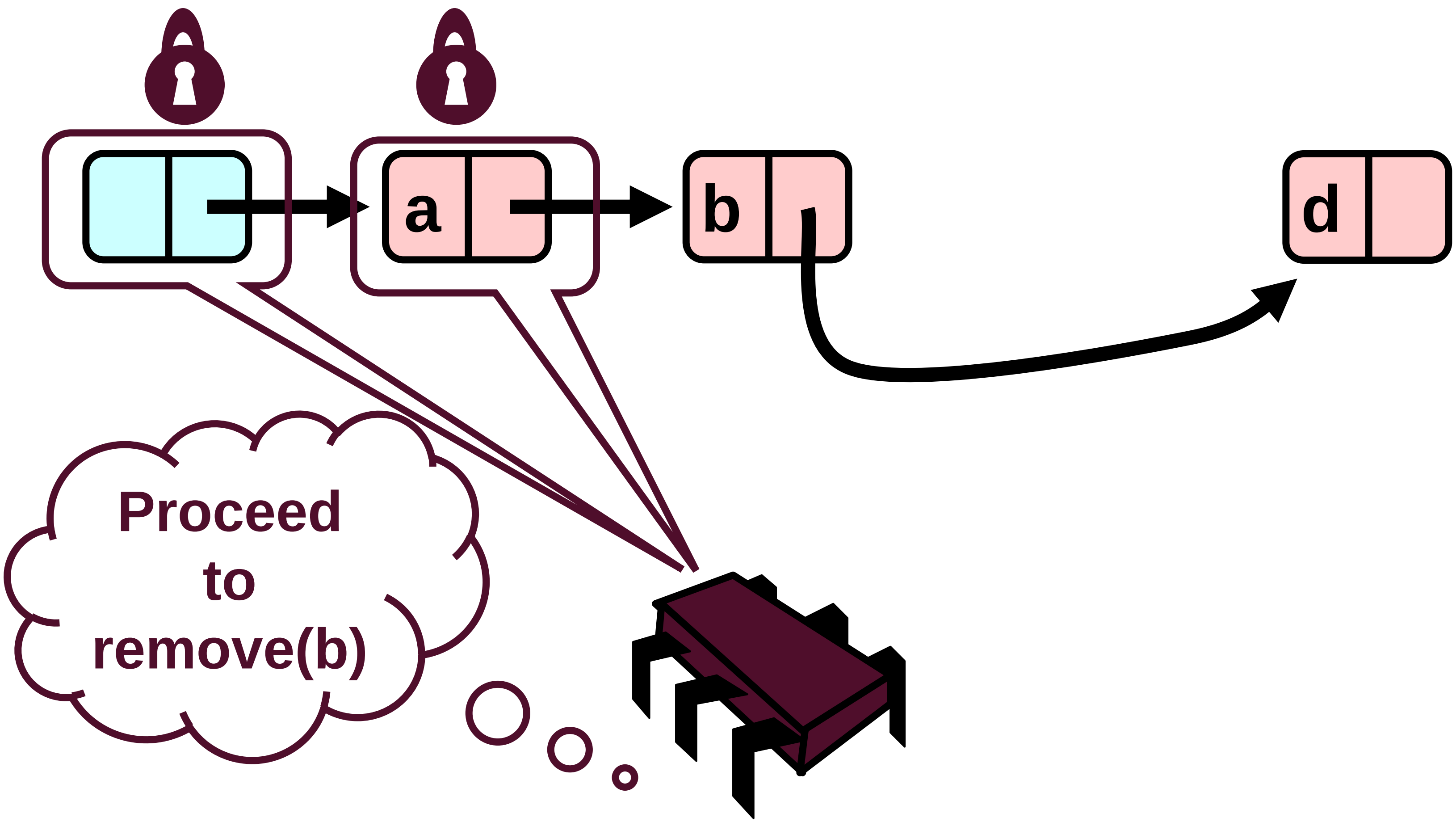
Removing a Node



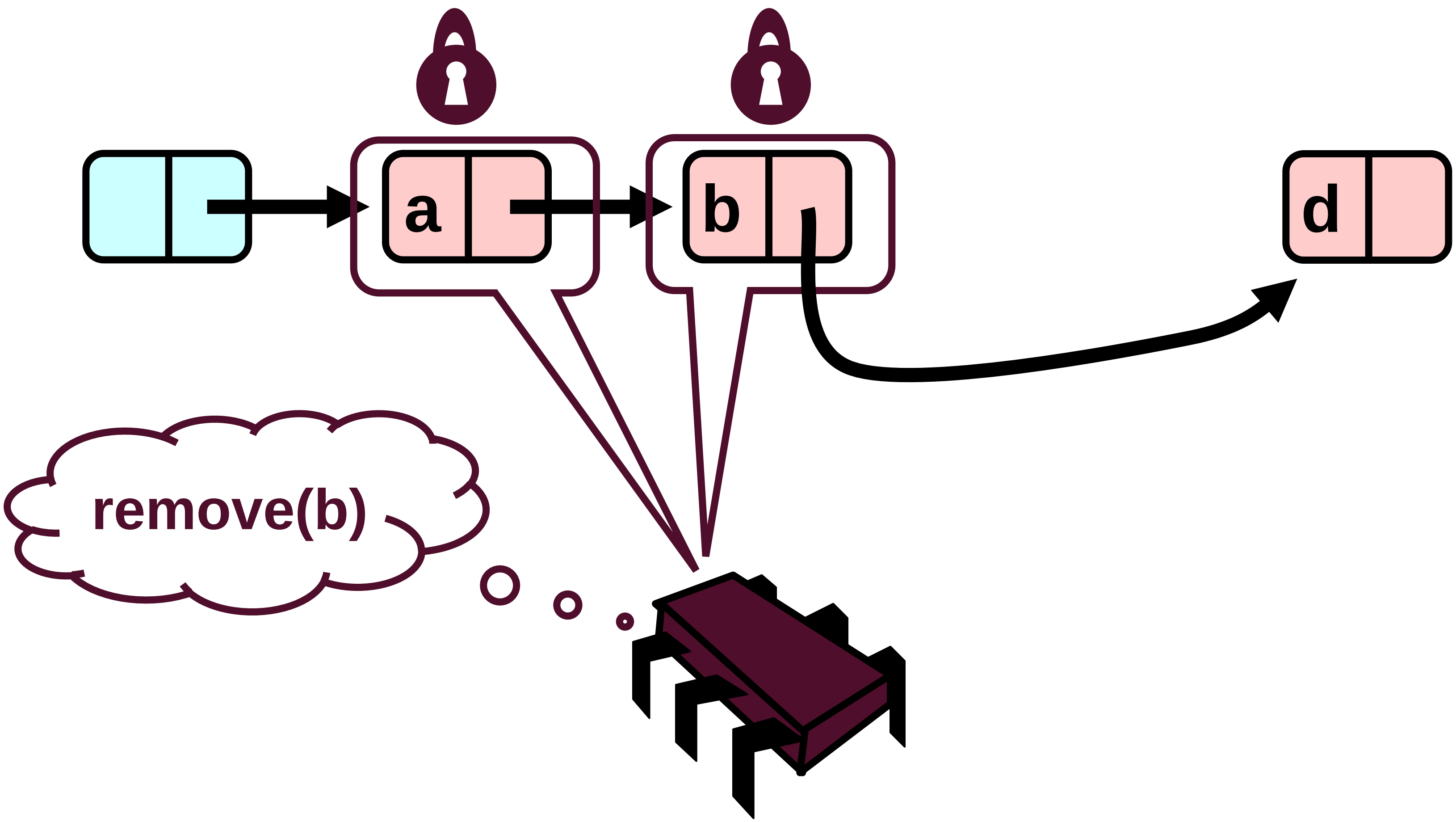
Removing a Node



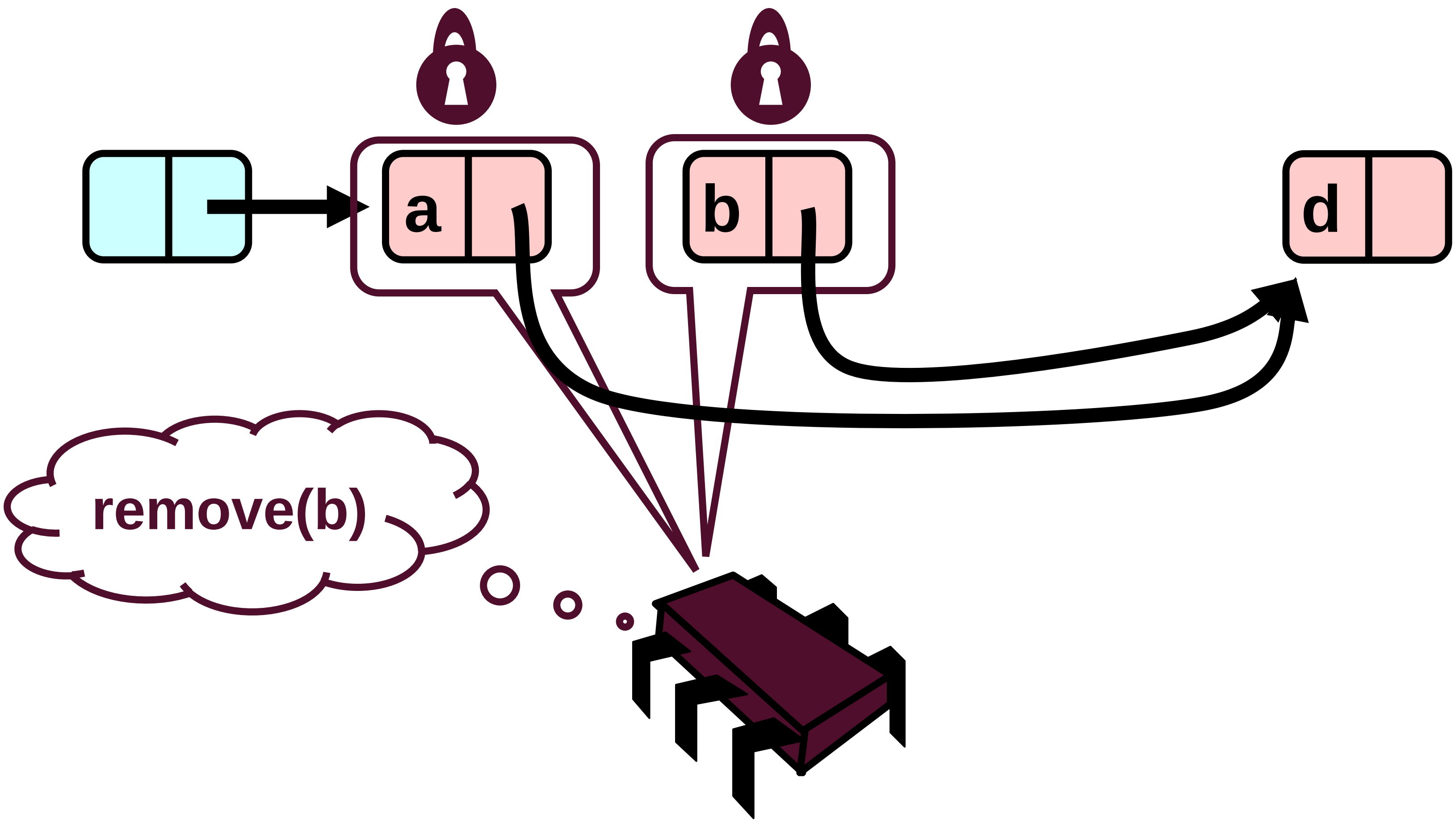
Removing a Node



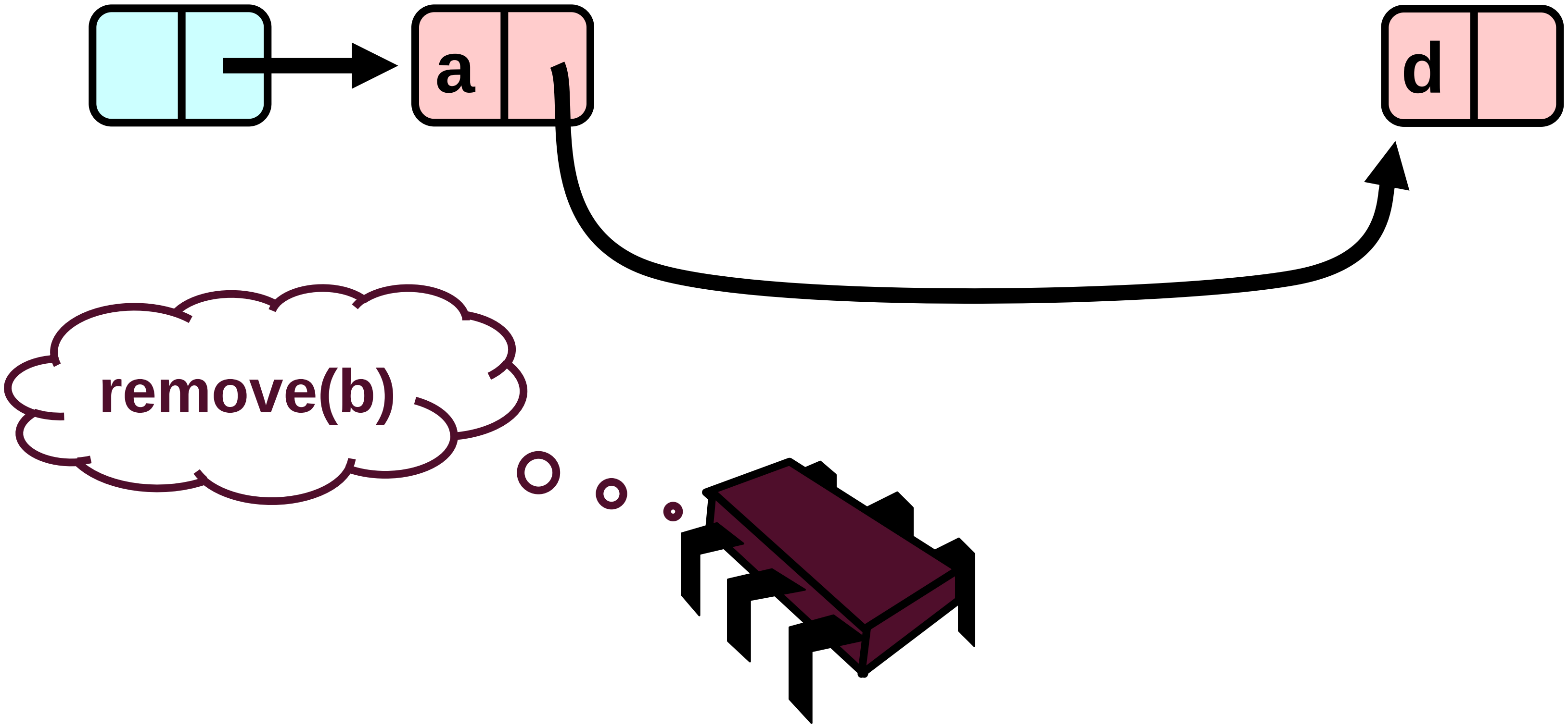
Removing a Node



Removing a Node



Removing a Node



What are the Issues?

- **We have fine-grained locking, will there be contention?**
  - Yes, the list can only be traversed sequentially, a remove of the 3rd item will block all other threads!
  - This is essentially still serialized if the list is short (since threads can only pipeline on list elements)
- **Other problems, ignoring contention?**
  - Must acquire O(|S|) locks

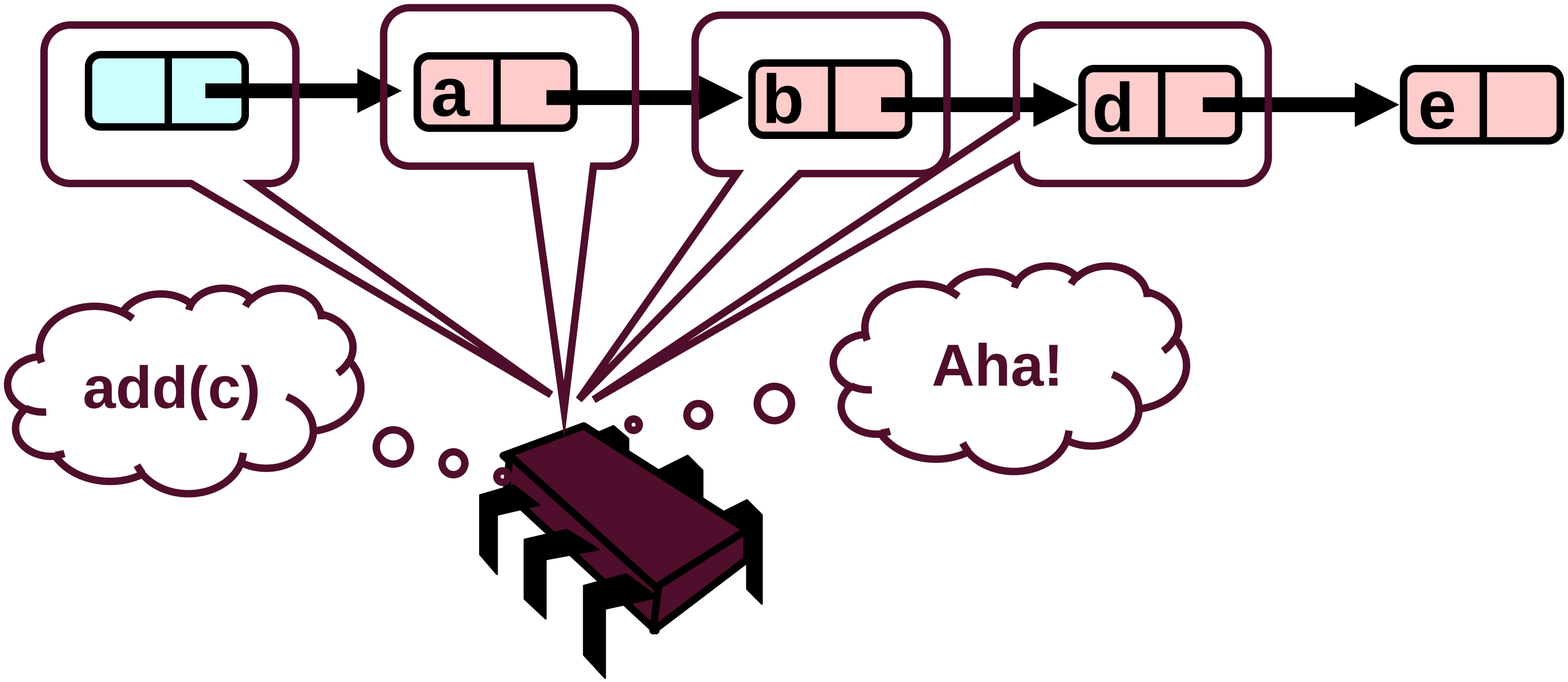
Trick 2: Reader/Writer Locking

- **Same hand-over-hand locking**
  - Traversal uses reader locks
  - Once add finds position or remove finds target node, upgrade **both** locks to writer locks
  - Need to guarantee deadlock and starvation freedom!
- **Allows truly concurrent traversals**
  - Still blocks behind writing threads
  - Still O(|S|) lock/unlock operations

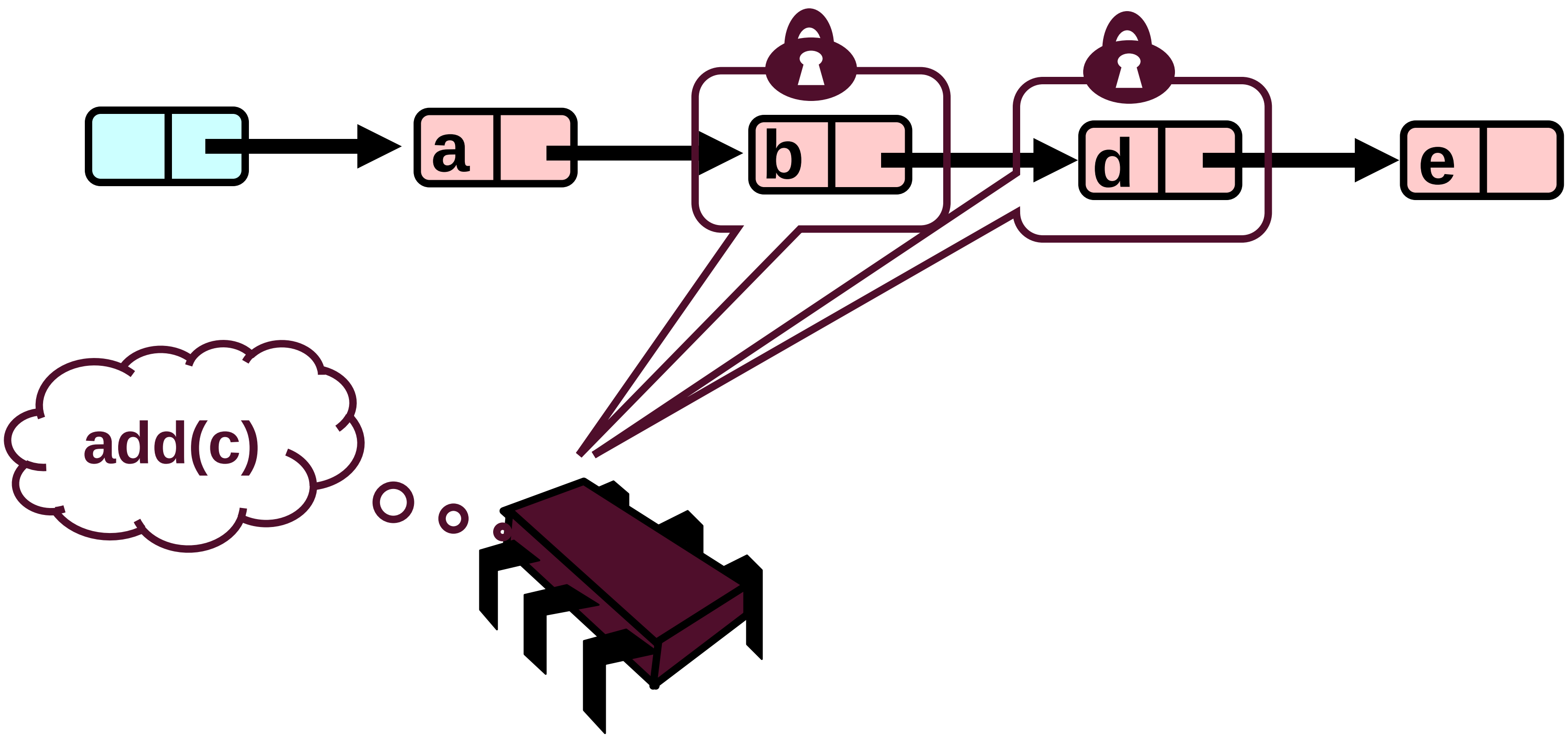
Trick 3: Optimistic synchronization

- **Similar to reader/writer locking but traverse list without locks**
  - Dangerous! Requires additional checks.
- **Harder to proof correct**

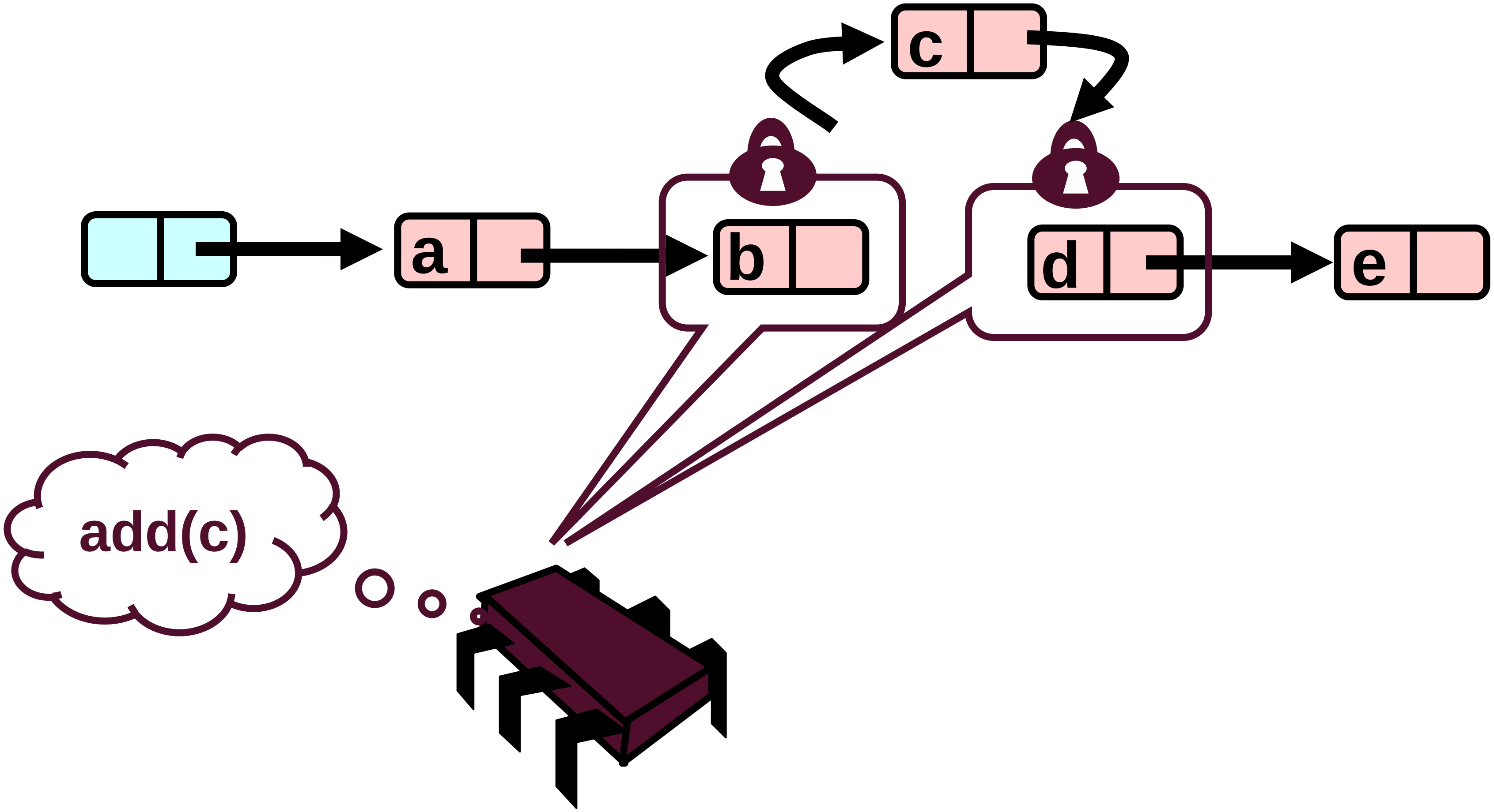
Optimistic: Traverse without Locking



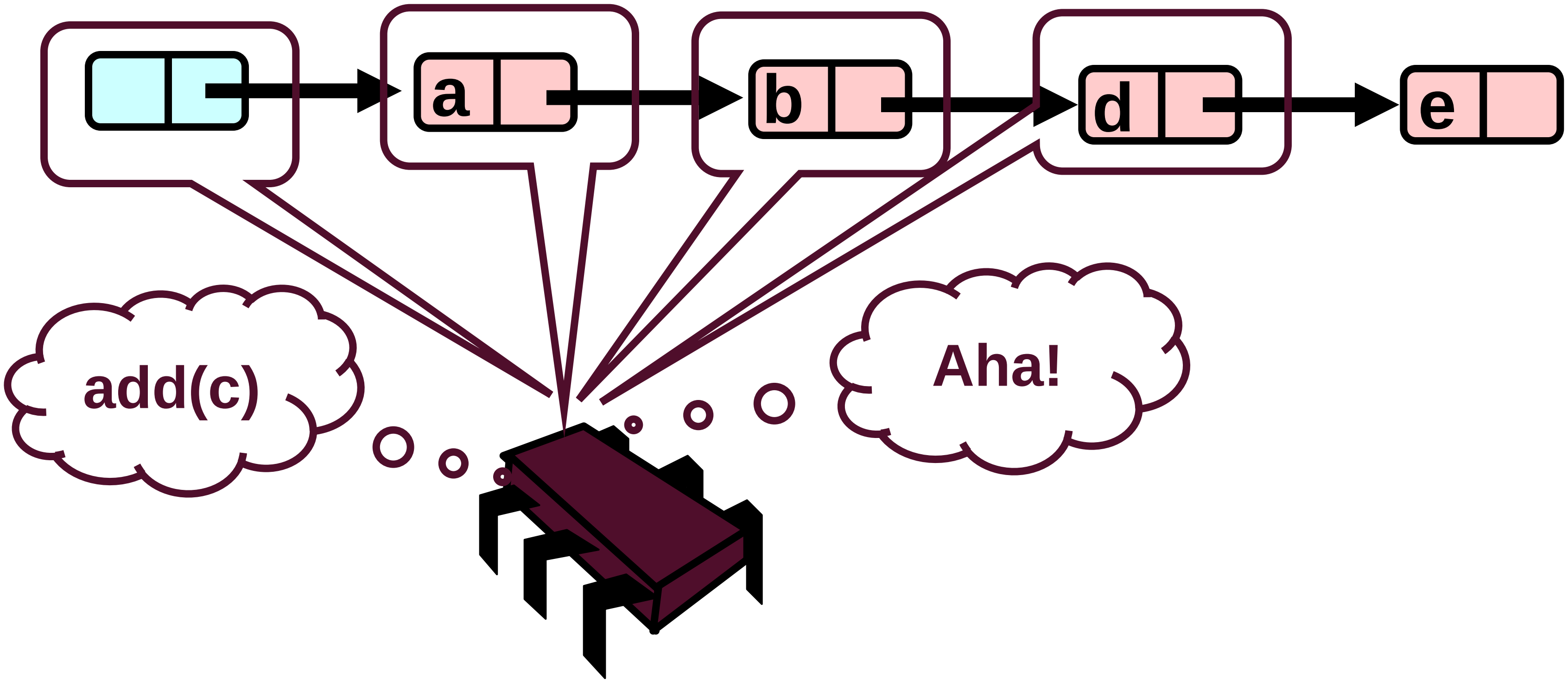
Optimistic: Lock and Load



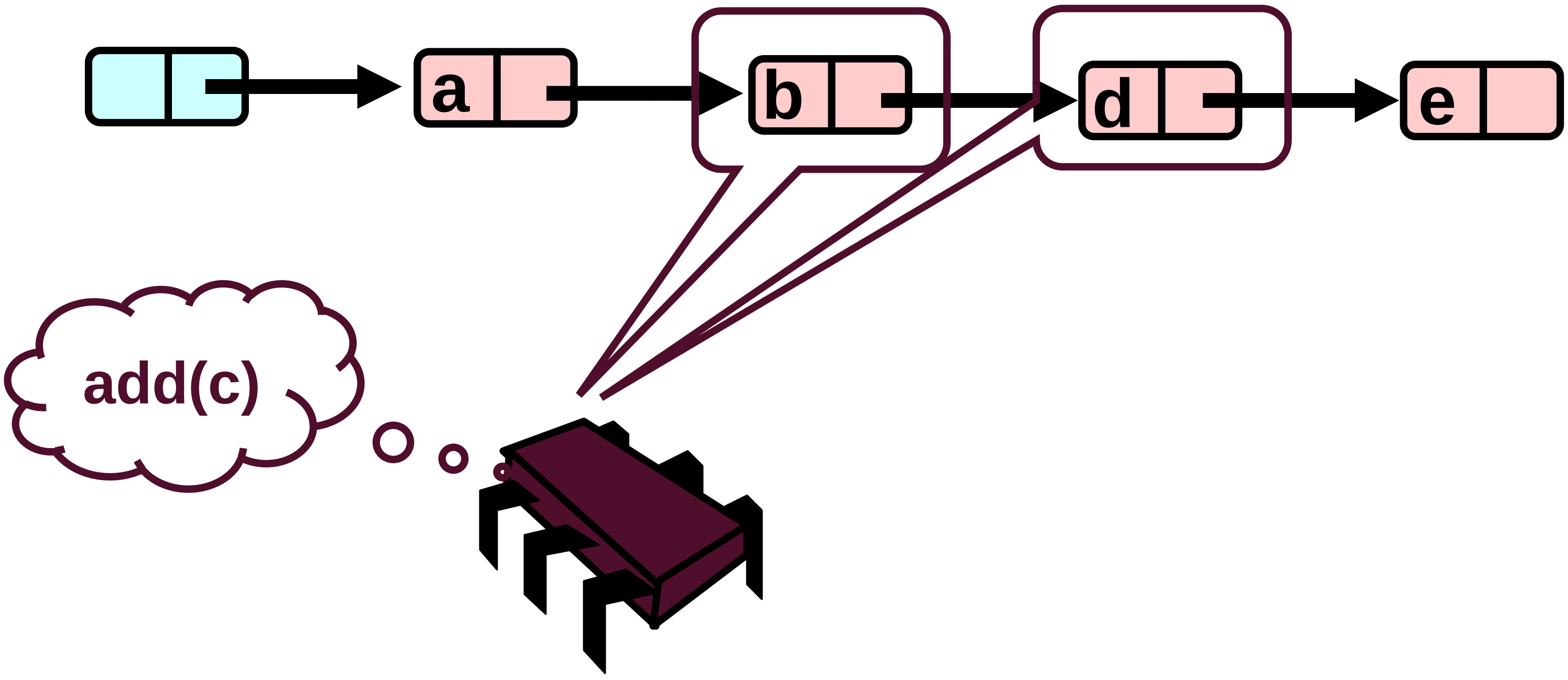
Optimistic: Lock and Load



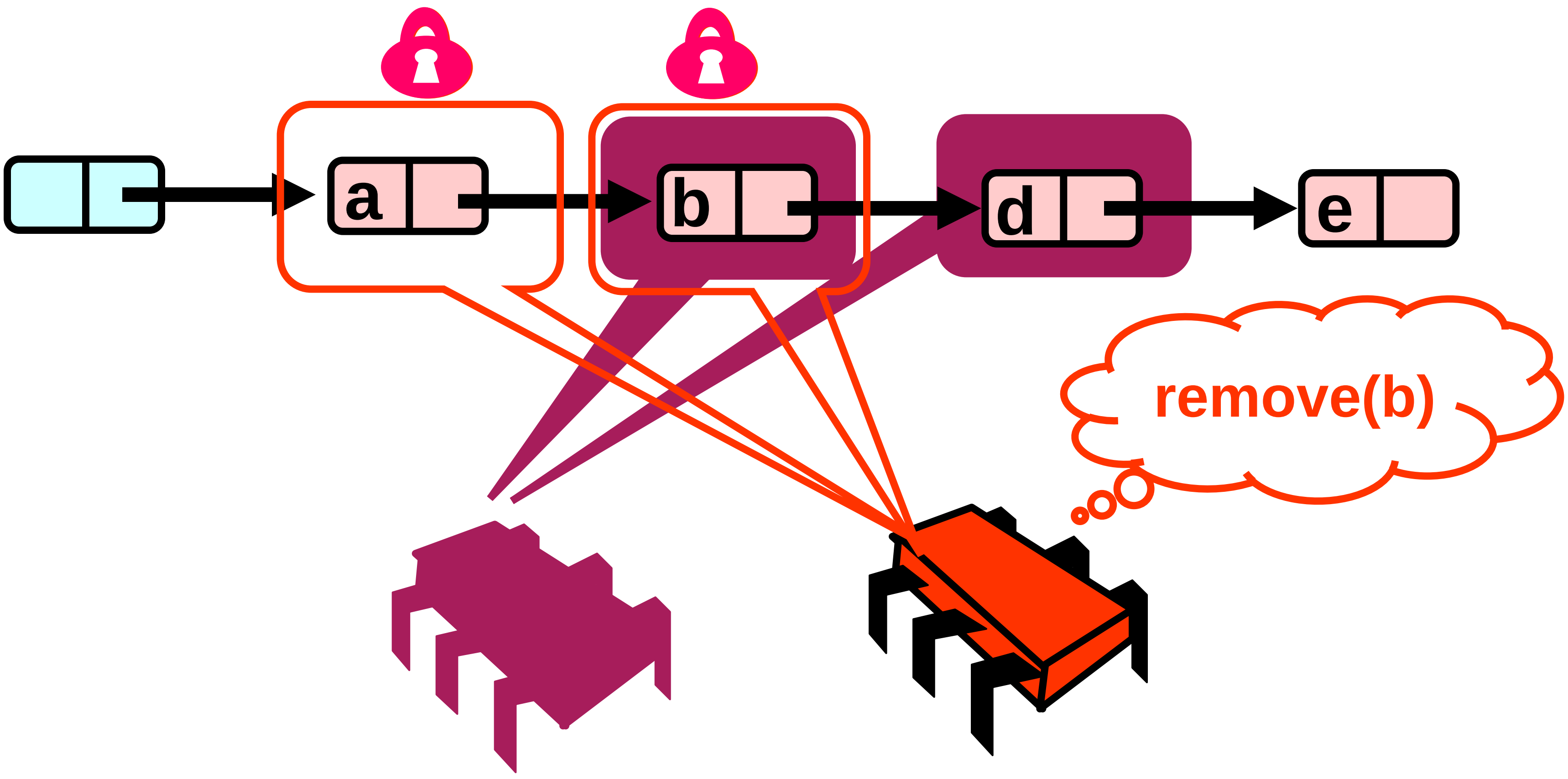
What could go wrong?



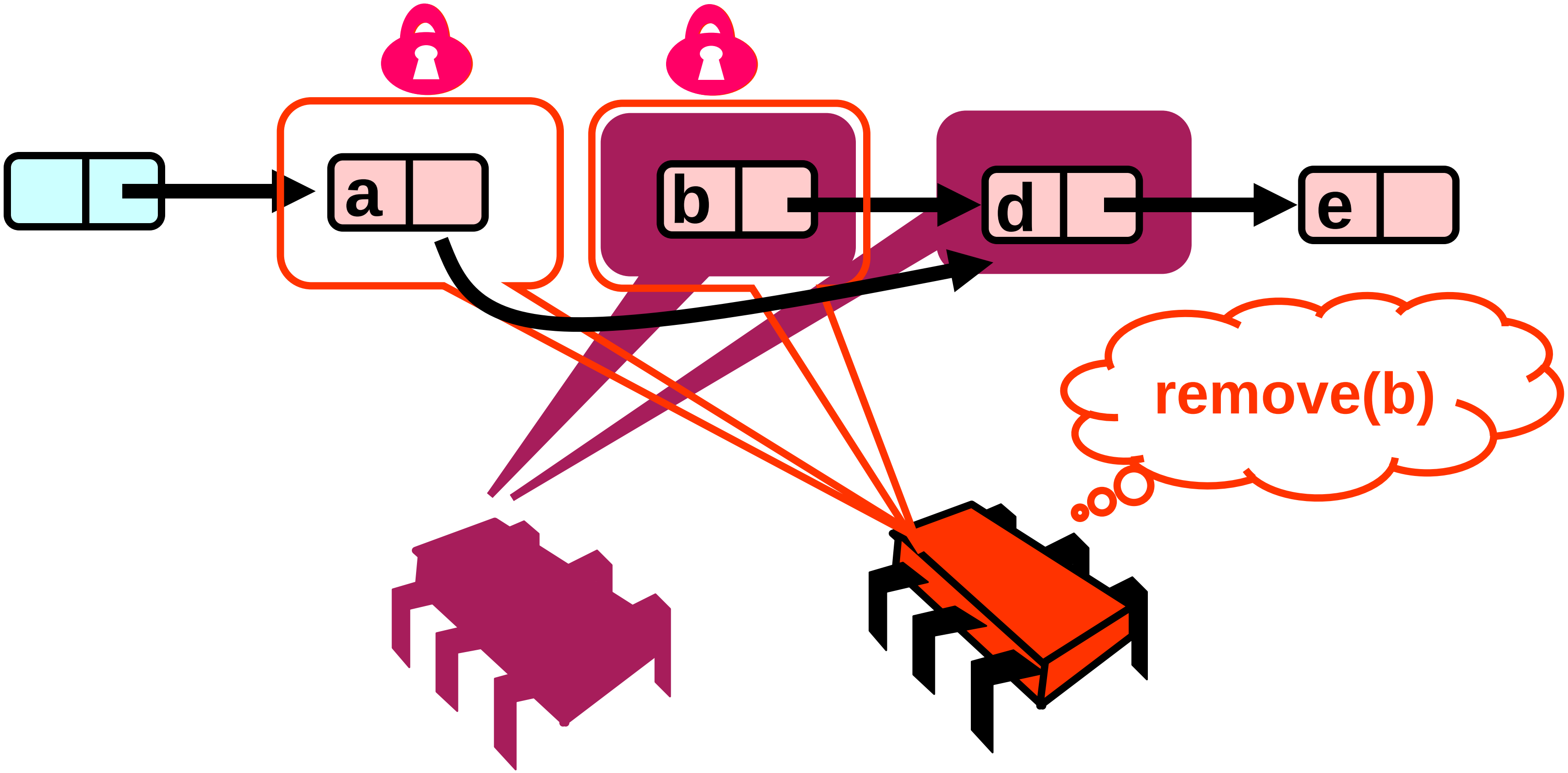
What could go wrong?



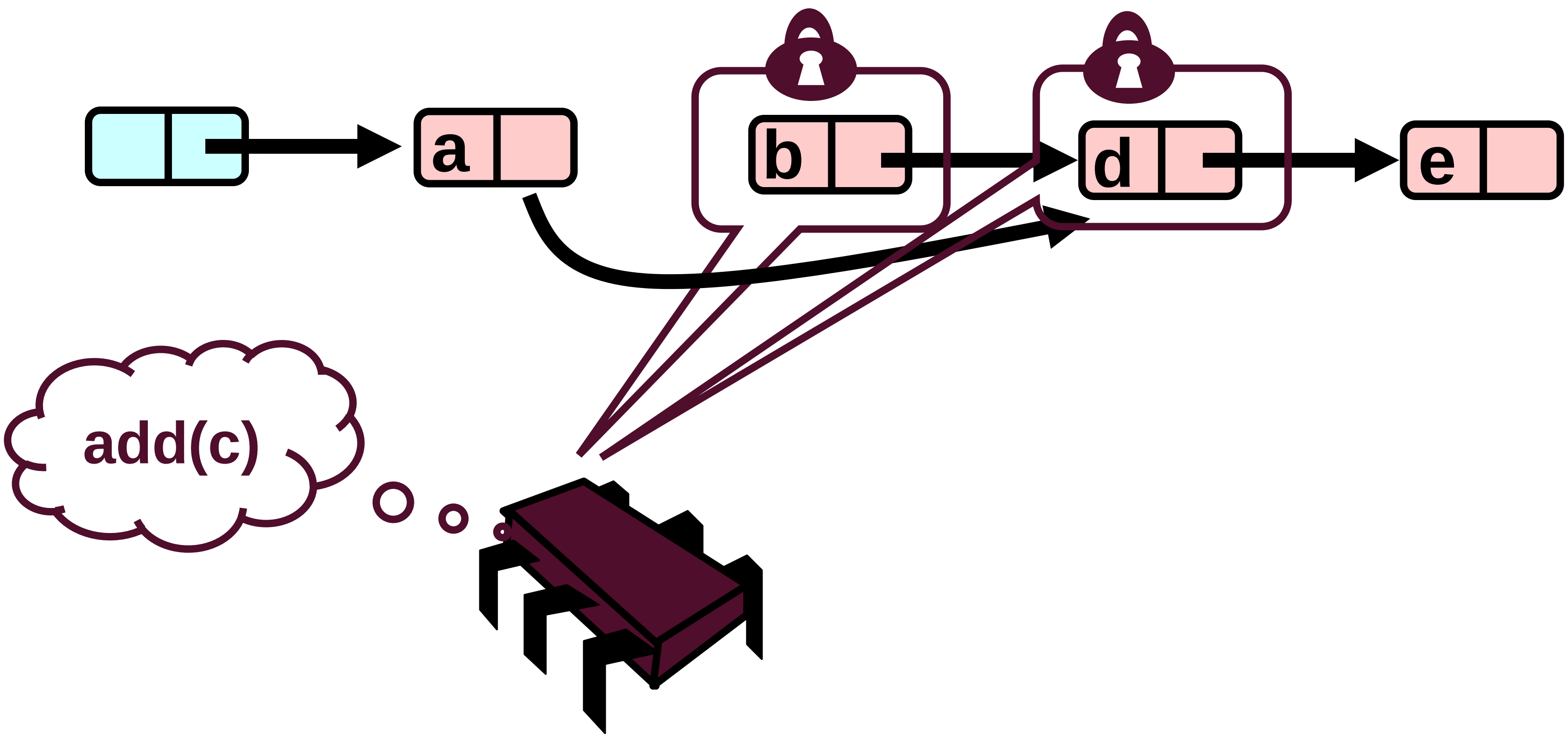
What could go wrong?



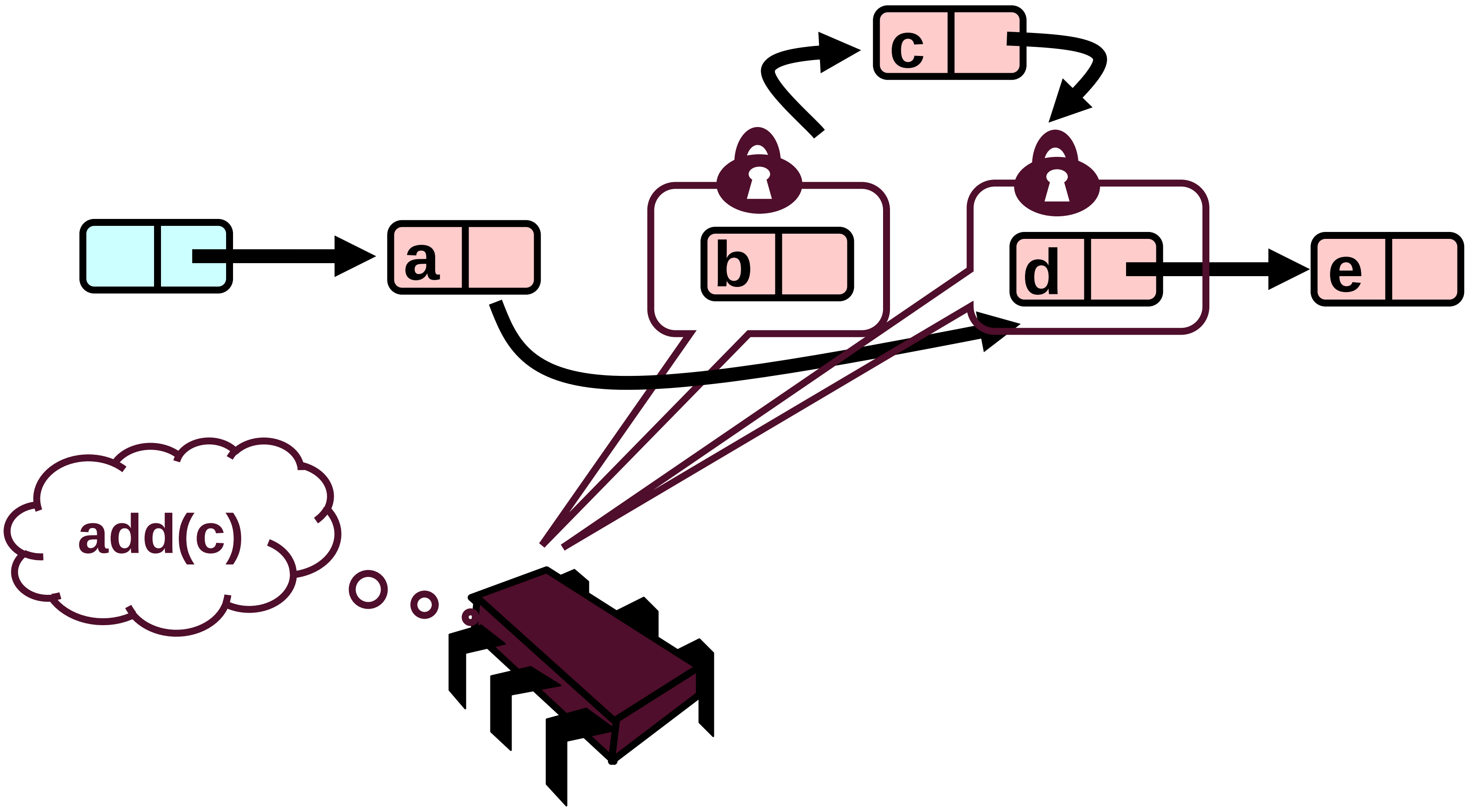
What could go wrong?



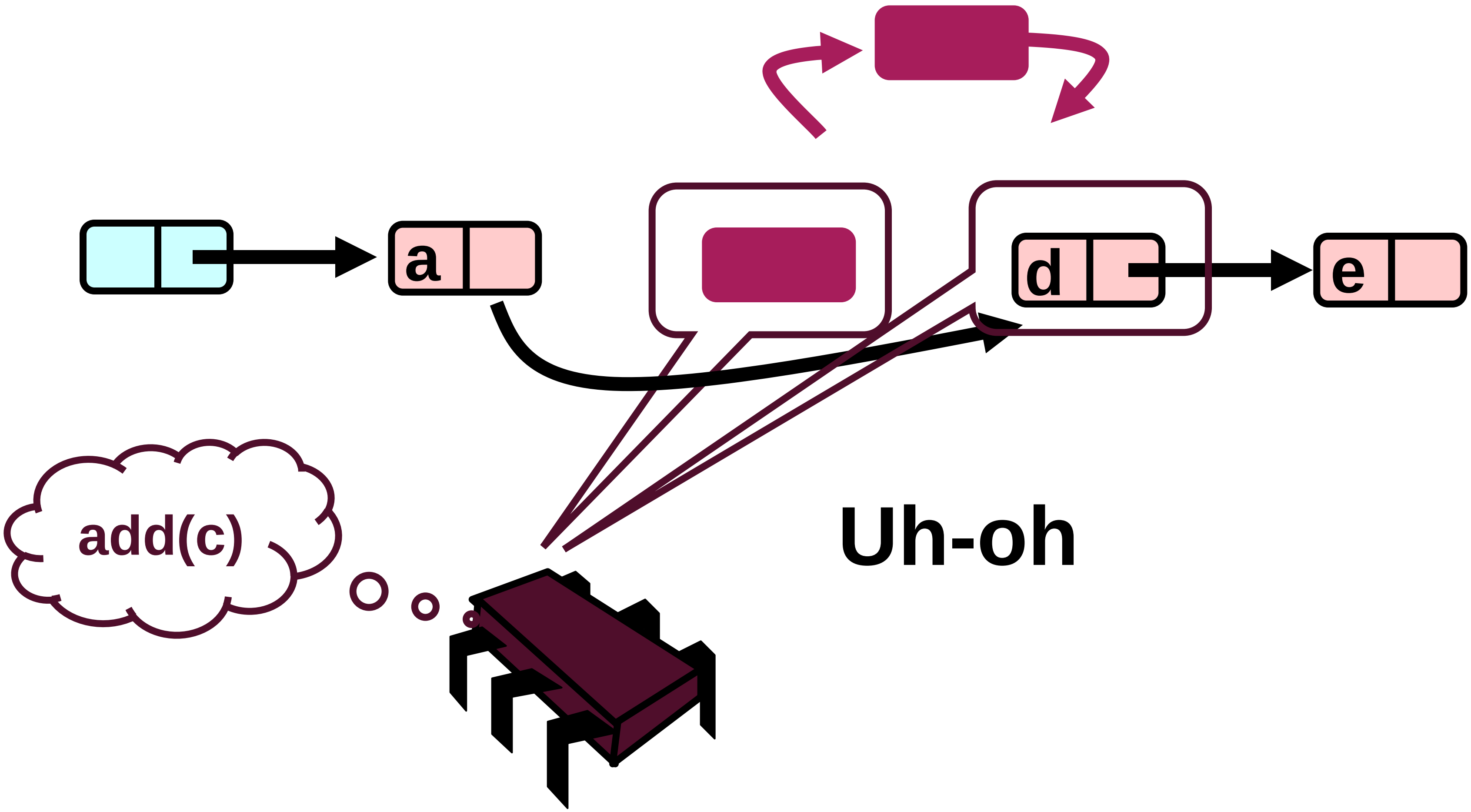
What could go wrong?



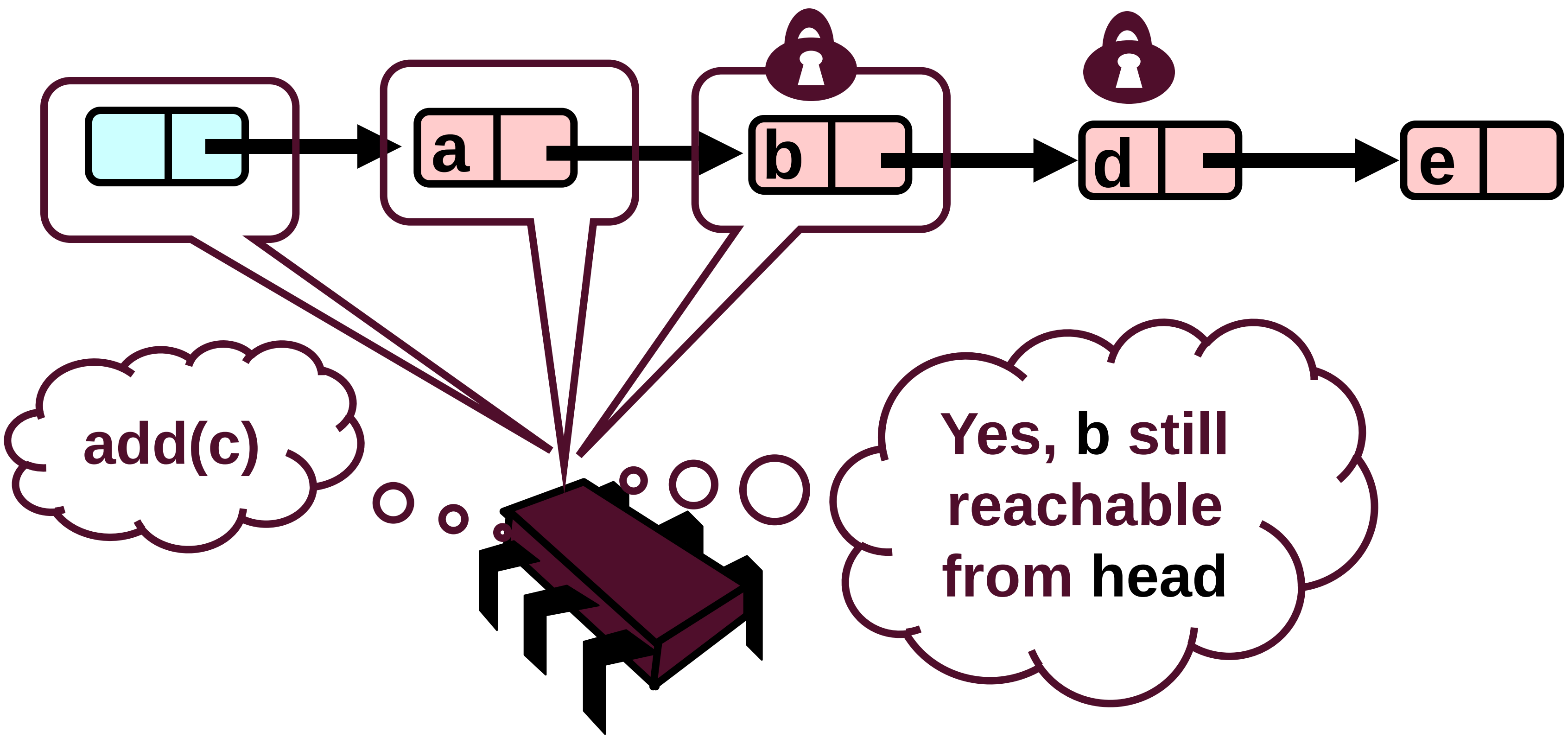
What could go wrong?



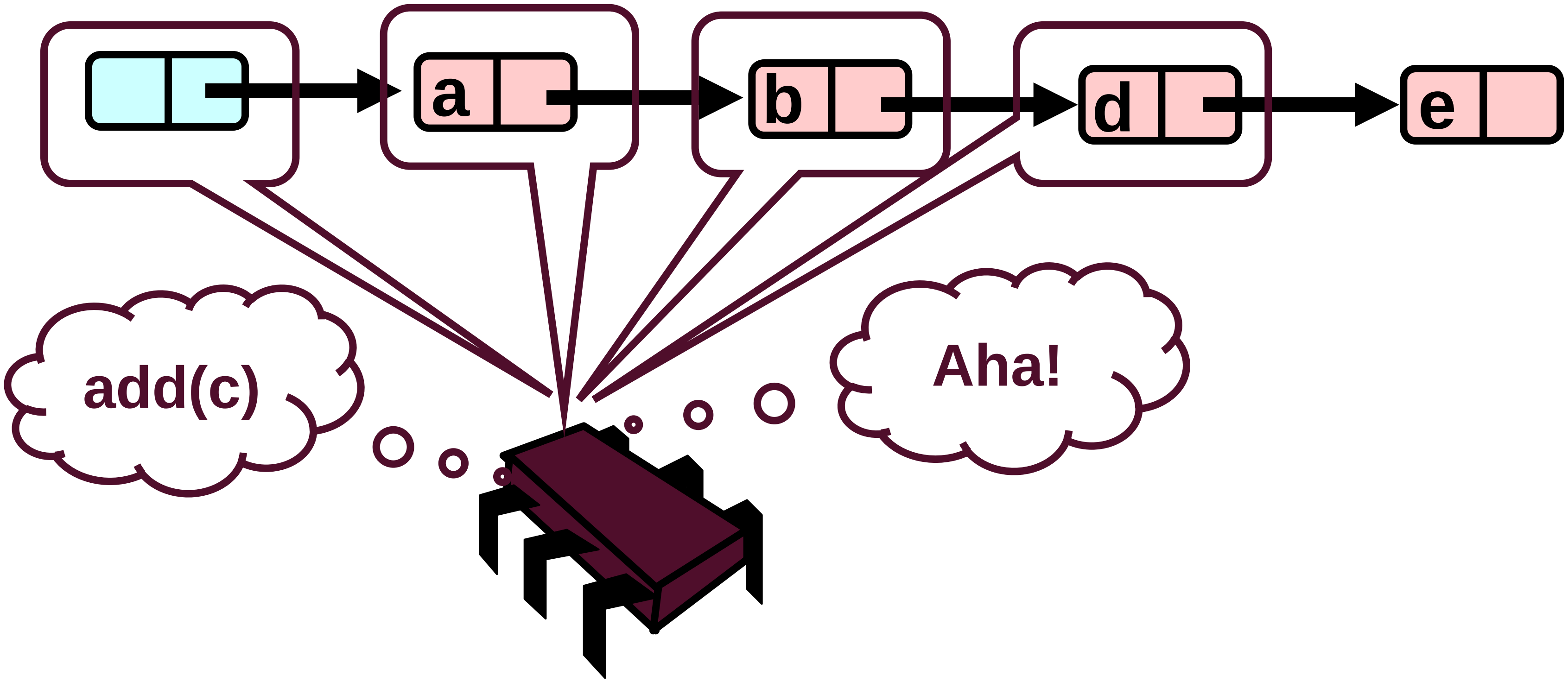
What could go wrong?



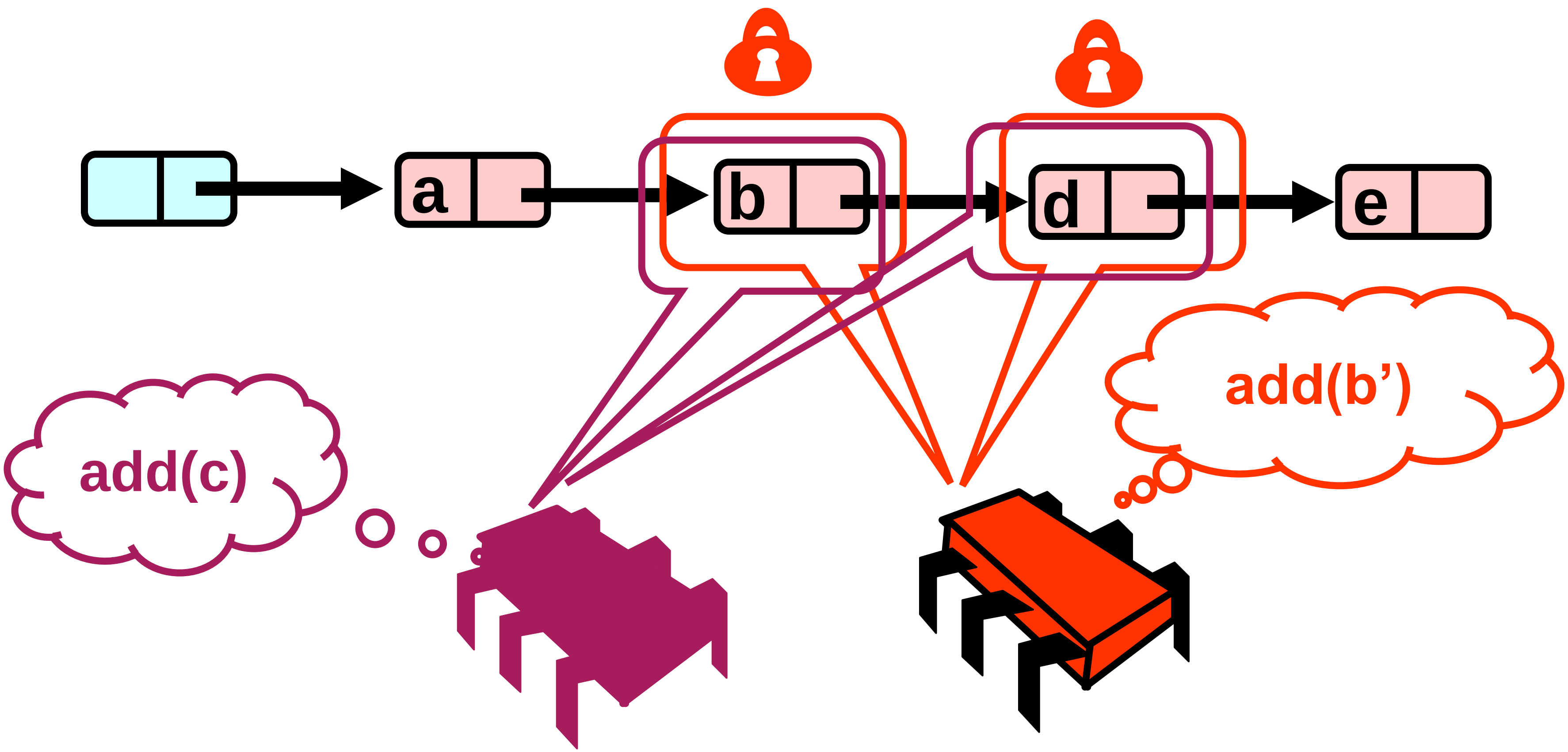
Validate – Part 1



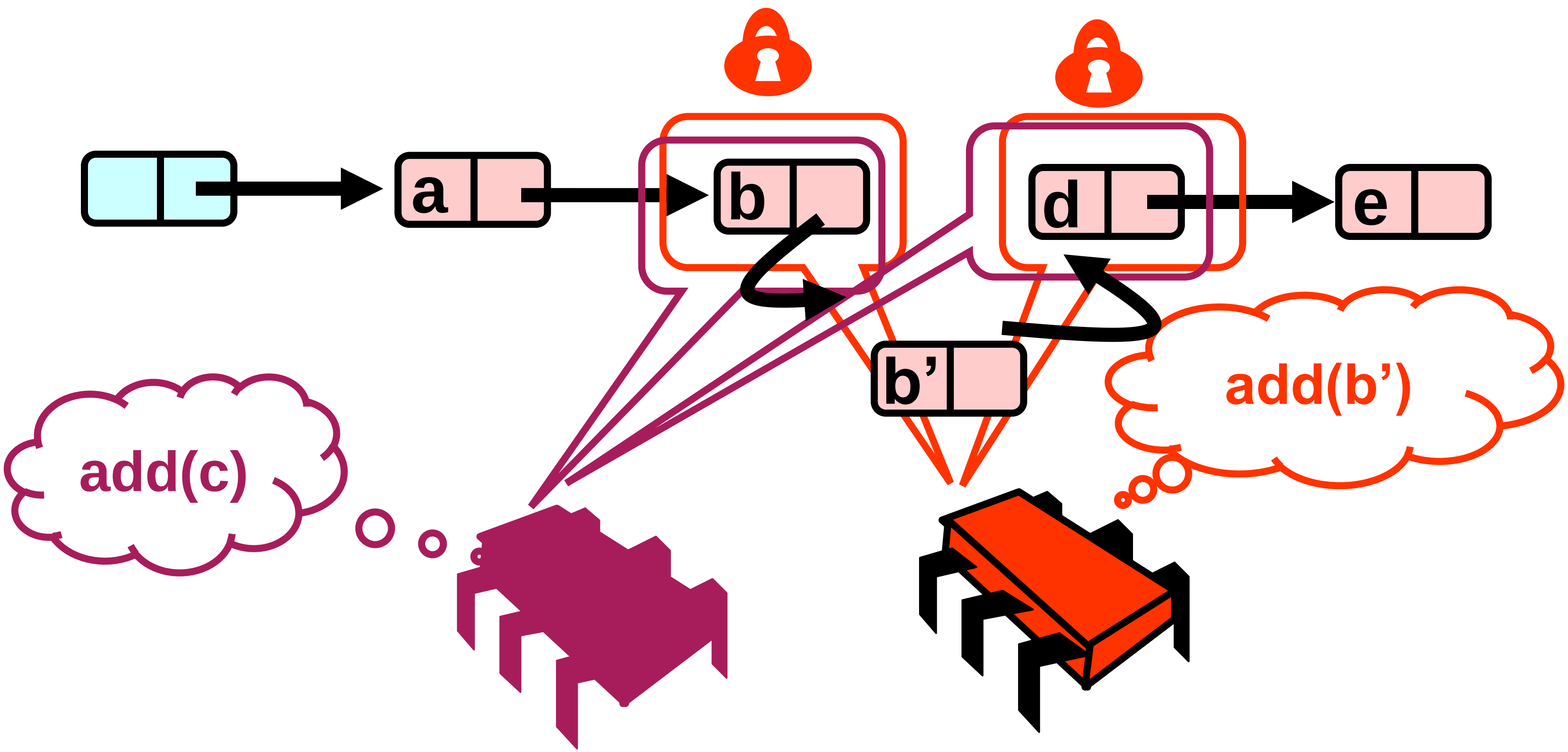
What Else Could Go Wrong?



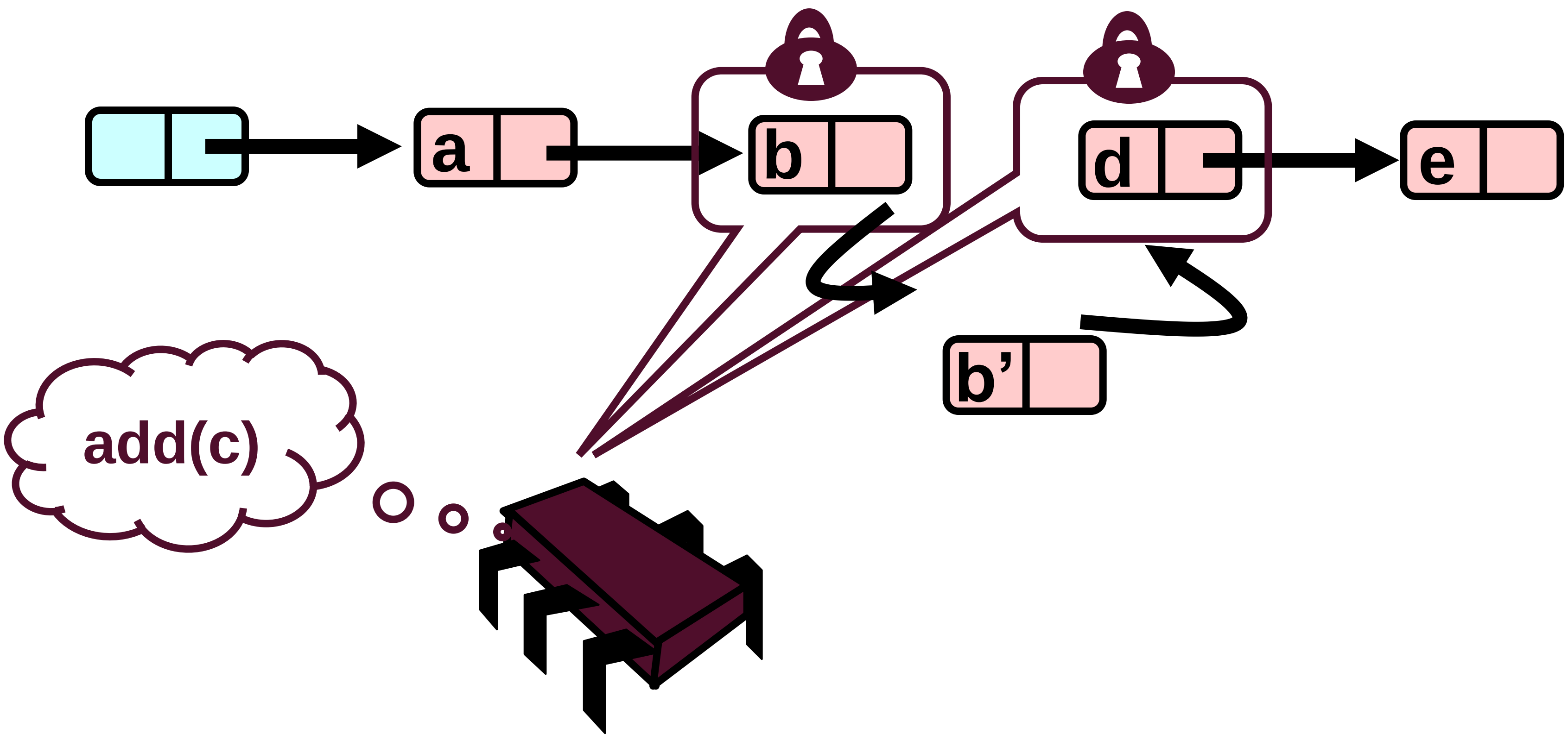
What Else Could Go Wrong?



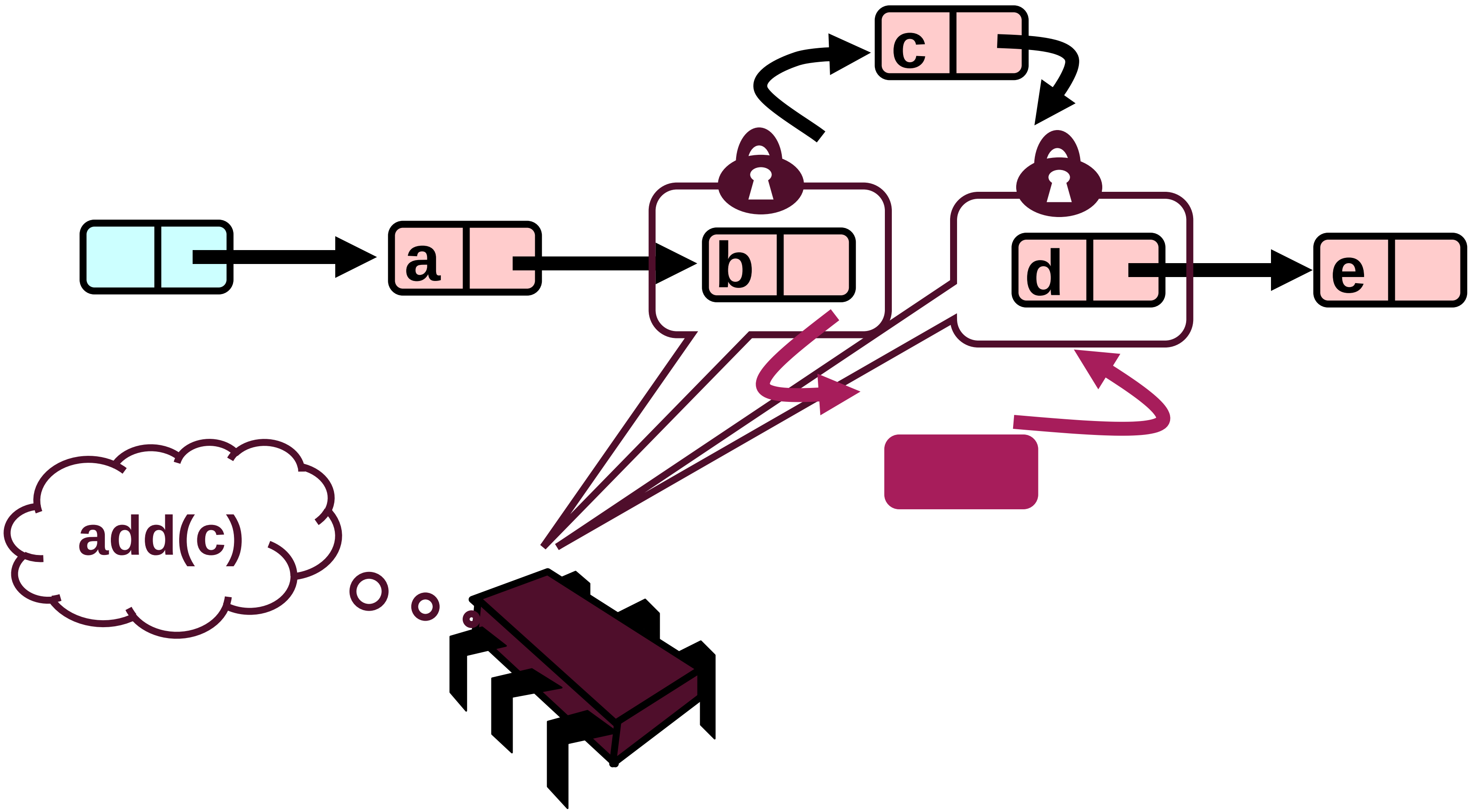
What Else Could Go Wrong?



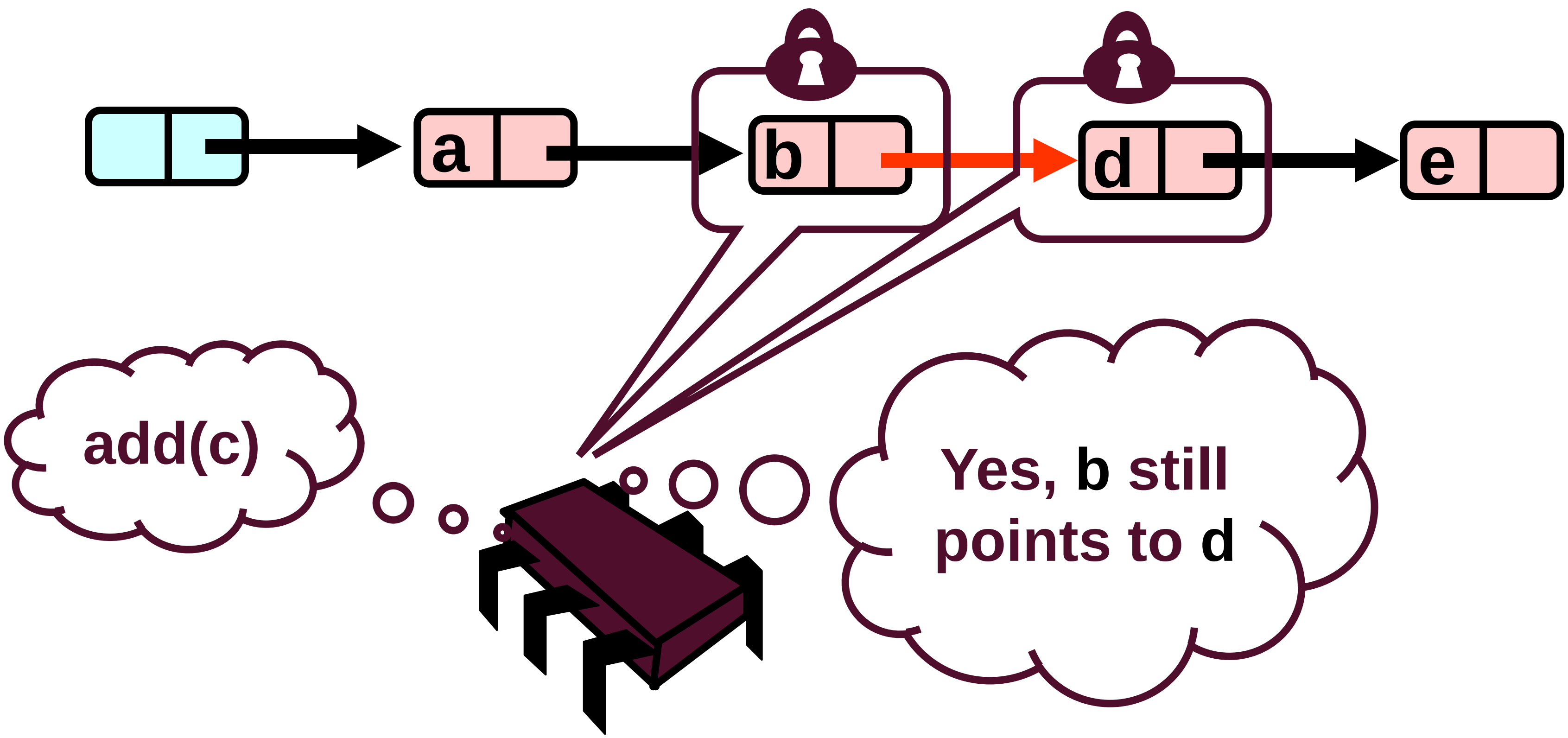
What Else Could Go Wrong?



What Else Could Go Wrong?



Validate Part 2 (while holding locks)



Optimistic synchronization

- **One MUST validate AFTER locking**
  1. Check if the path how we got there is still valid!
  2. Check if locked nodes are still connected
  - If any of those checks fail?

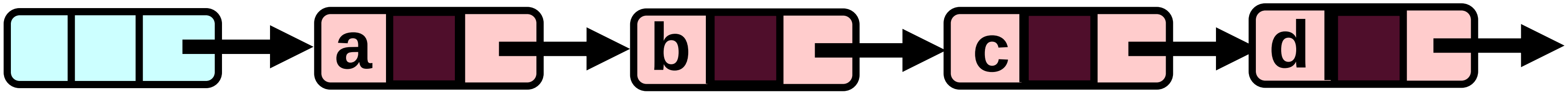
    Start over from the beginning (hopefully rare)
- **Not starvation-free**
  - A thread may need to abort forever if nodes are added/removed
  - Should be rare in practice!
- **Other disadvantages?**
  - All operations requires two traversals of the list!
  - Even contains() needs to check if node is still in the list!

Trick 4: Lazy synchronization

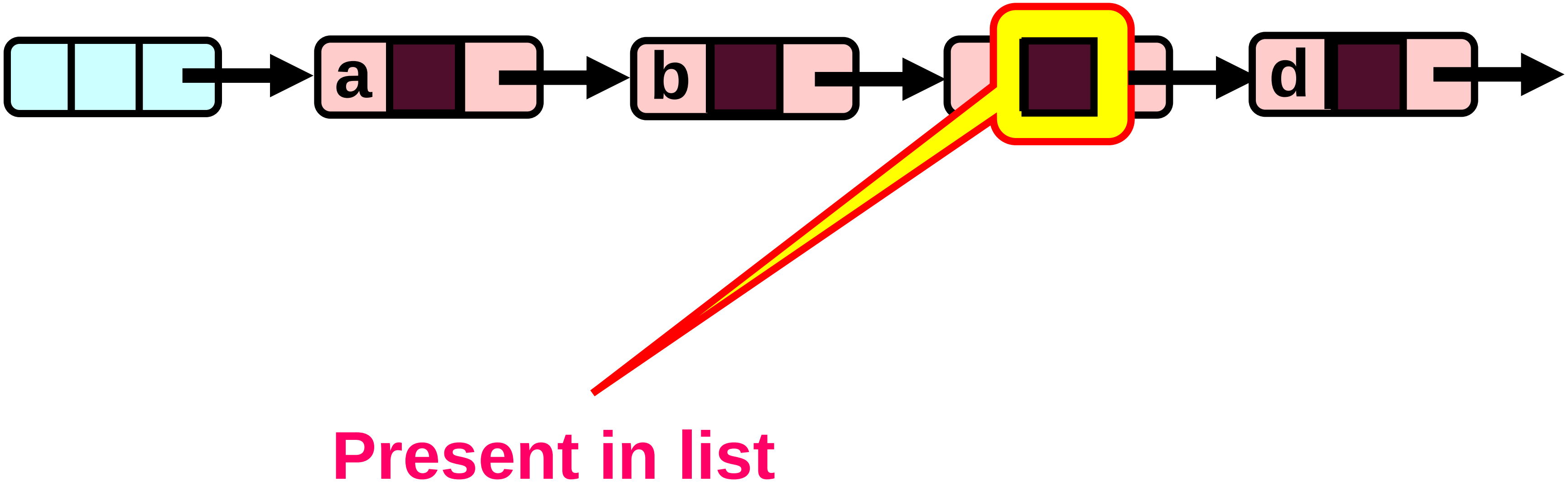
- **We really want one list traversal**
- **Also, contains() should be wait-free**
  - Is probably the most-used operation
- **Lazy locking is similar to optimistic**
  - Key insight: removing is problematic
  - Perform it "lazily"
- **Add a new "valid" field**
  - Indicates if node is still in the set
  - Can remove it without changing list structure!
  - Scan once, contains() never locks!

```
typedef struct {
  int key;
  node *next;
  lock_t lock;
  boolean valid;
} node;
```

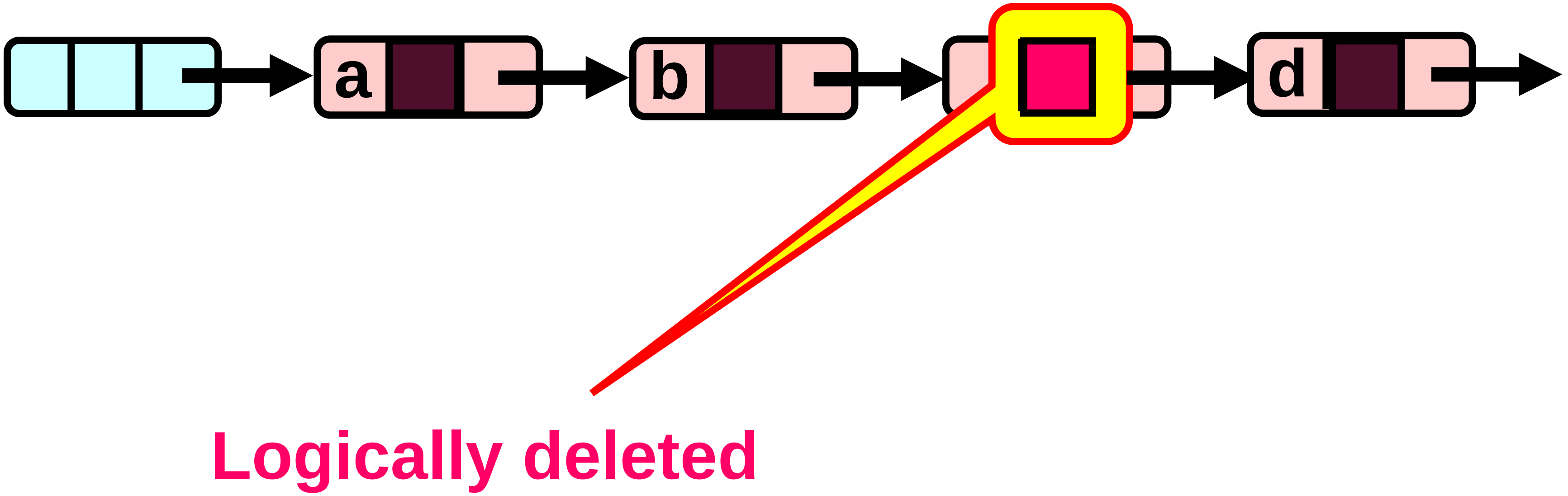
Lazy Removal



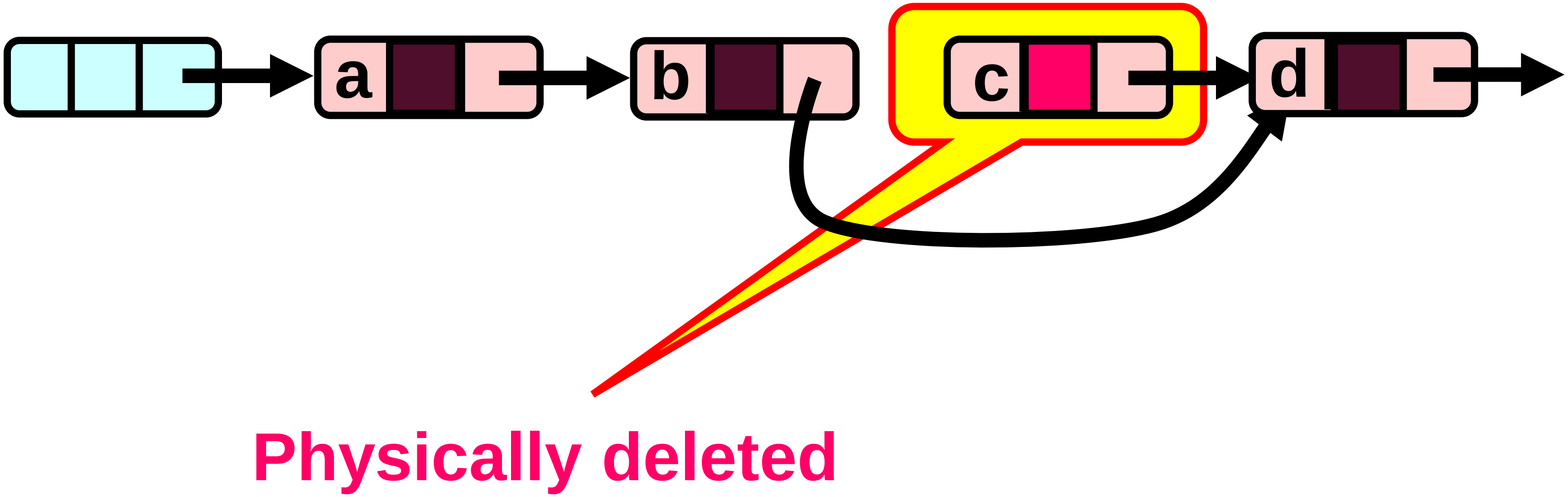
Lazy Removal



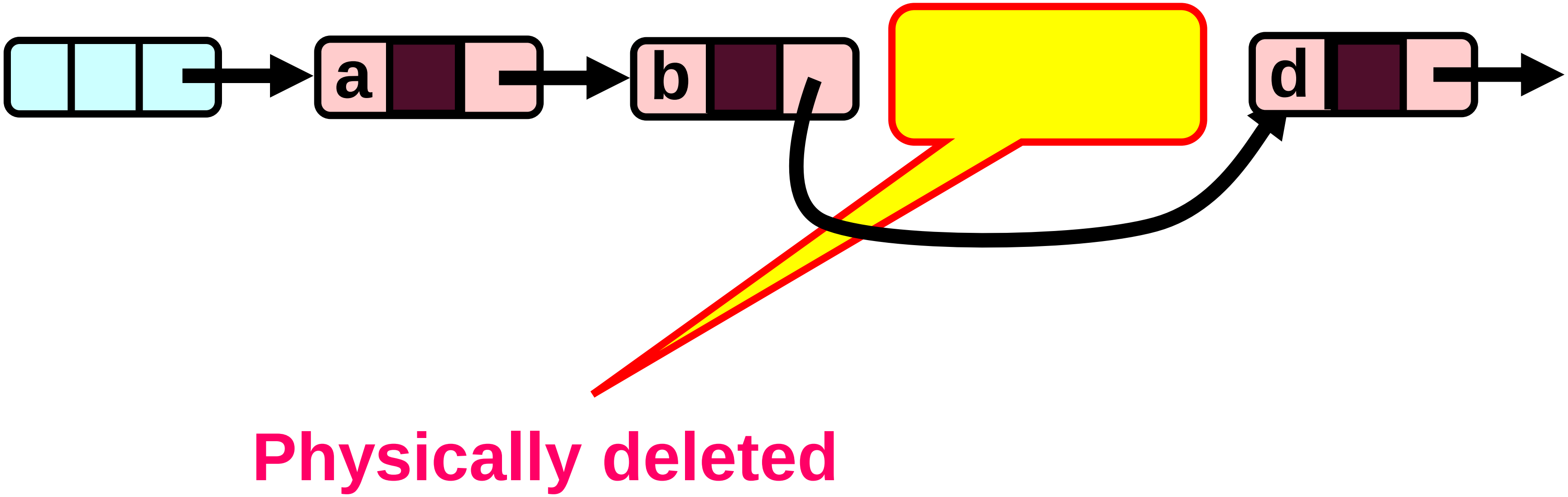
Lazy Removal



Lazy Removal



Lazy Removal

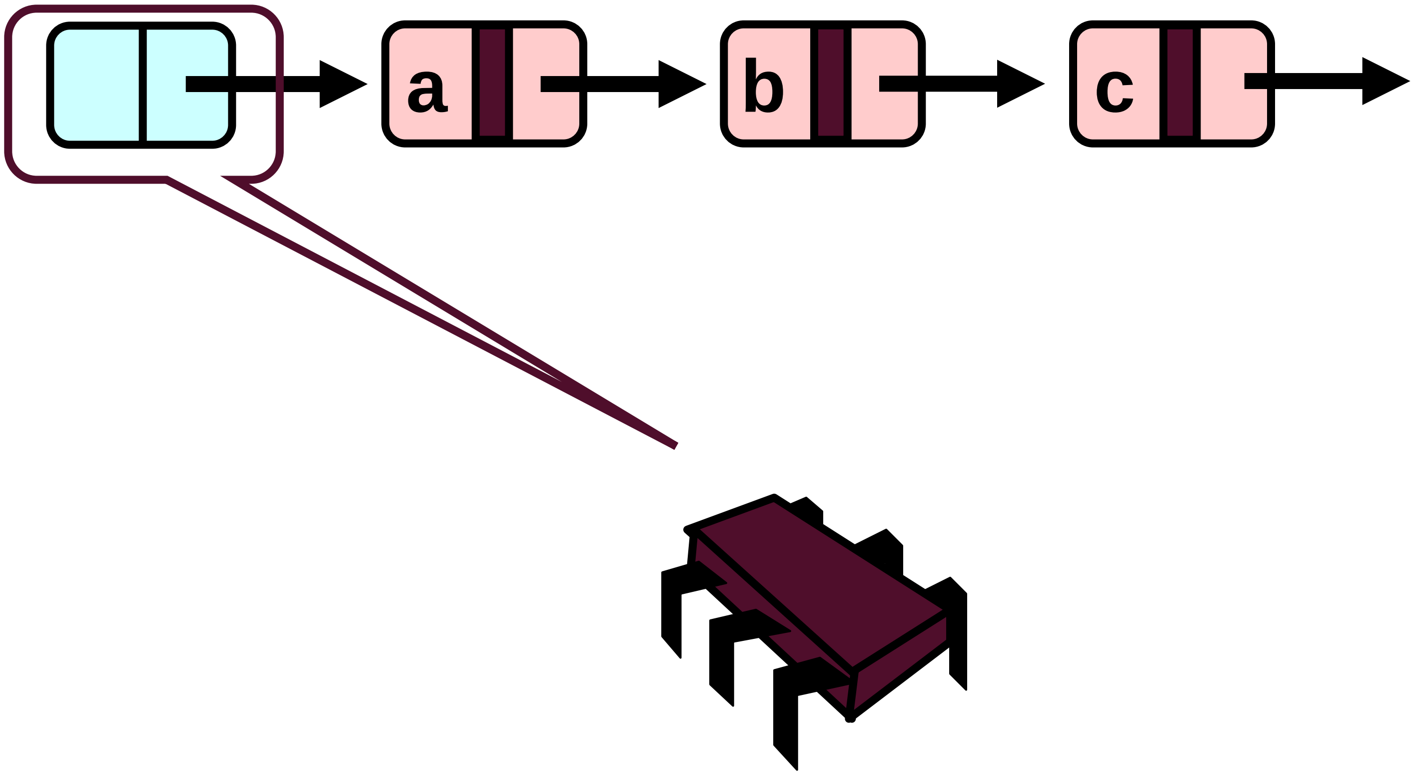


How does it work?

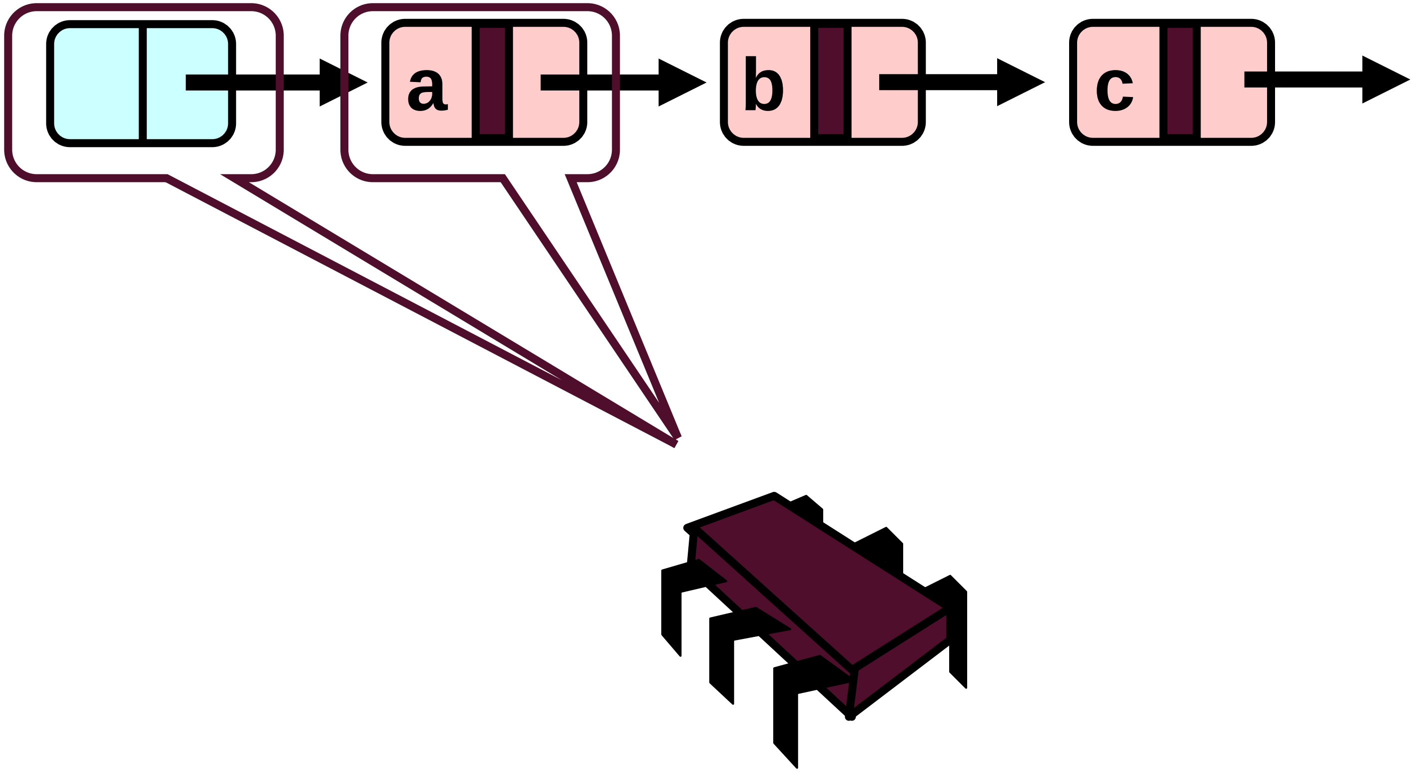
- **Eliminates need to re-scan list for reachability**
  - Maintains invariant that every **unmarked** node is reachable!
- **Contains can now simply traverse the list**
  - Just check marks, not reachability, no locks
- **Remove/Add**
  - Scan through locked and marked nodes
  - Removing does not delay others
  - Must only lock when list structure is updated

    Check if neither pred nor curr are marked, pred.next == curr

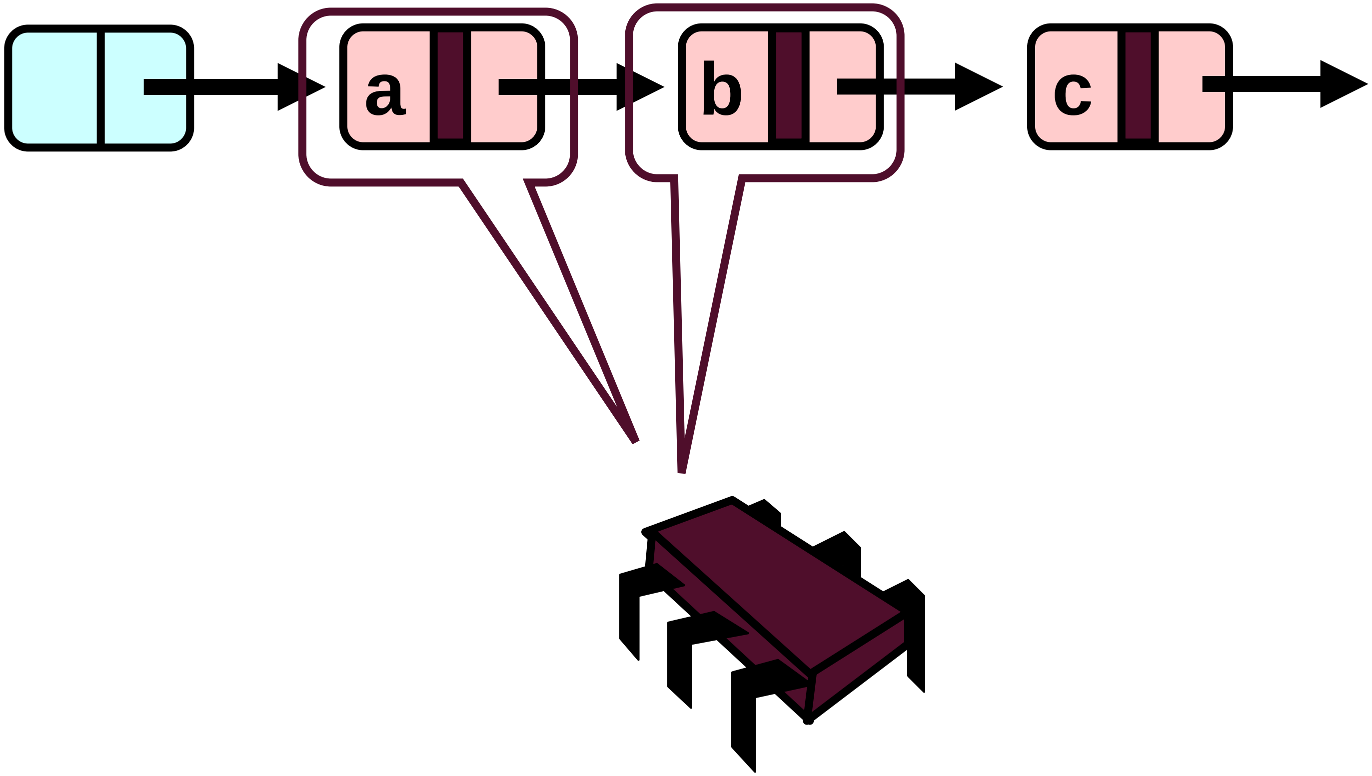
Business as Usual



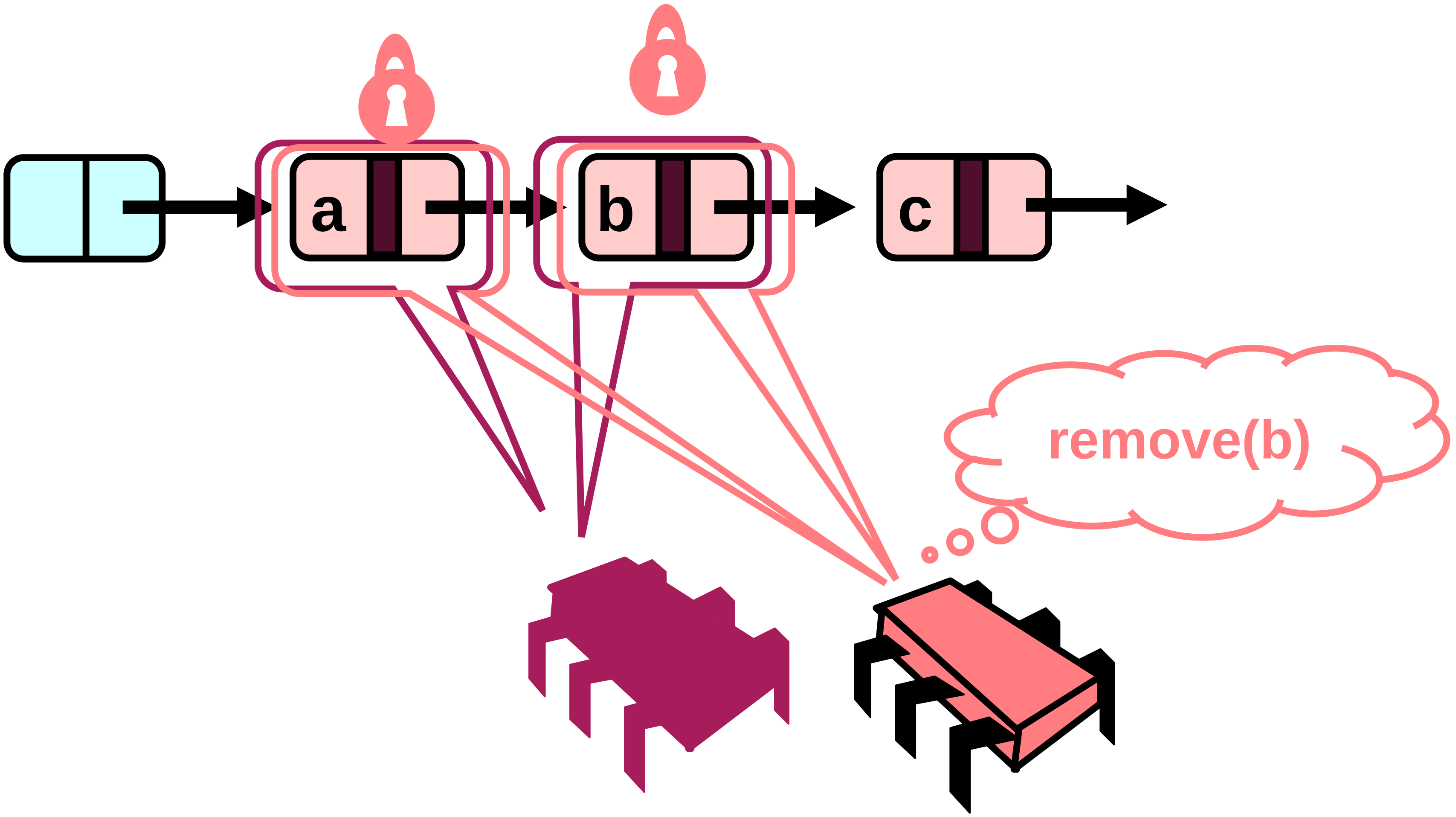
Business as Usual



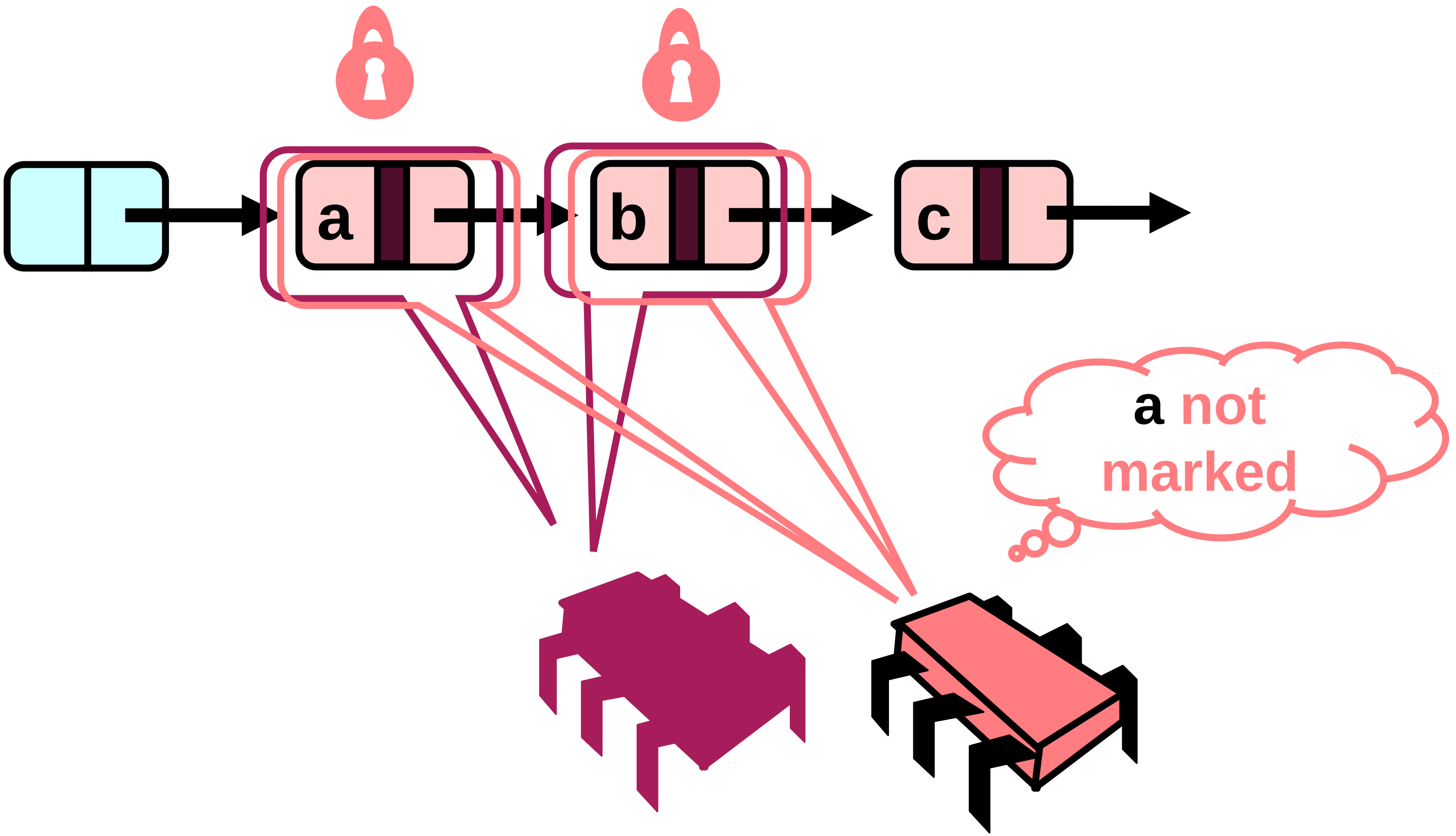
Business as Usual



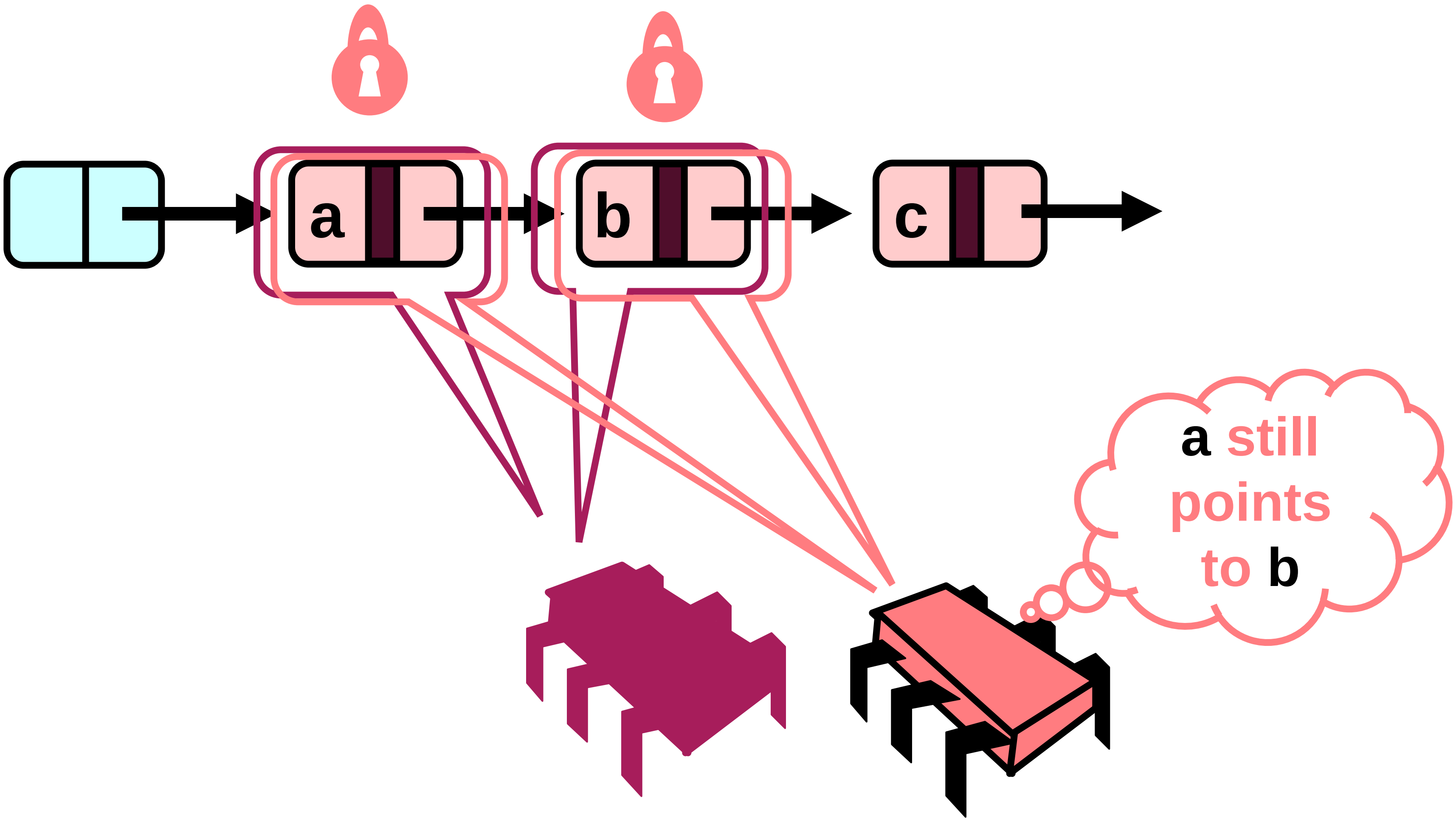
Business as Usual



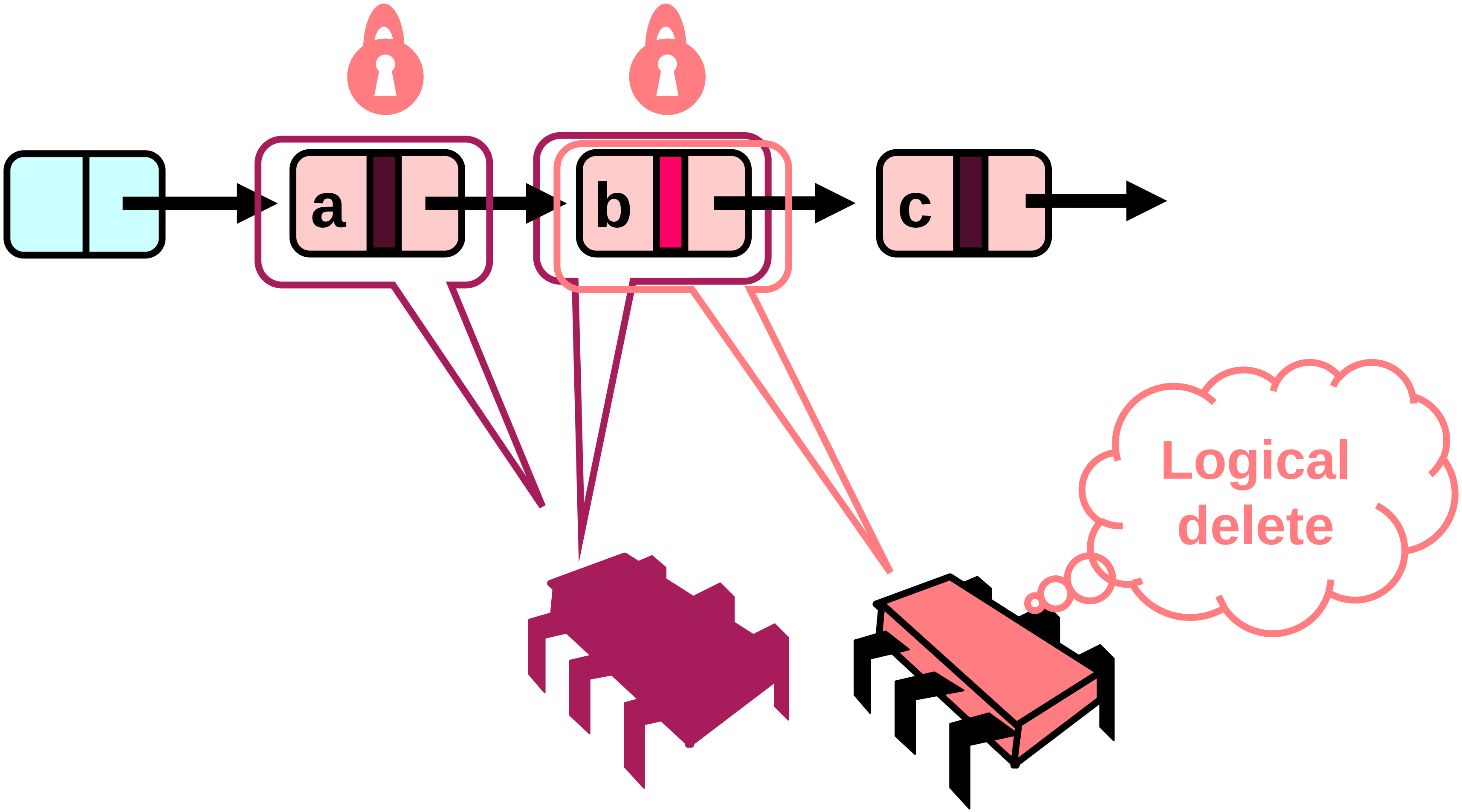
Business as Usual



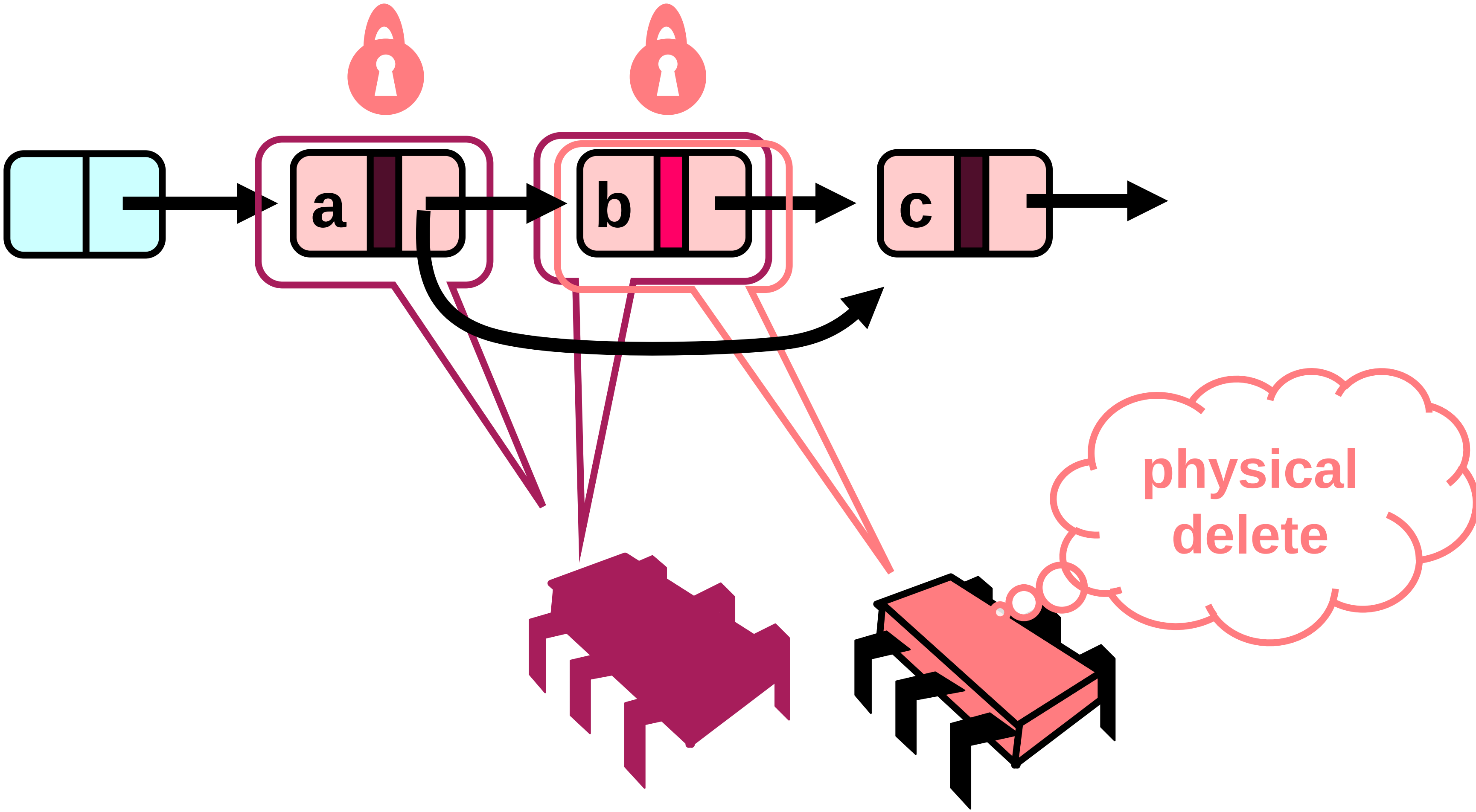
Business as Usual



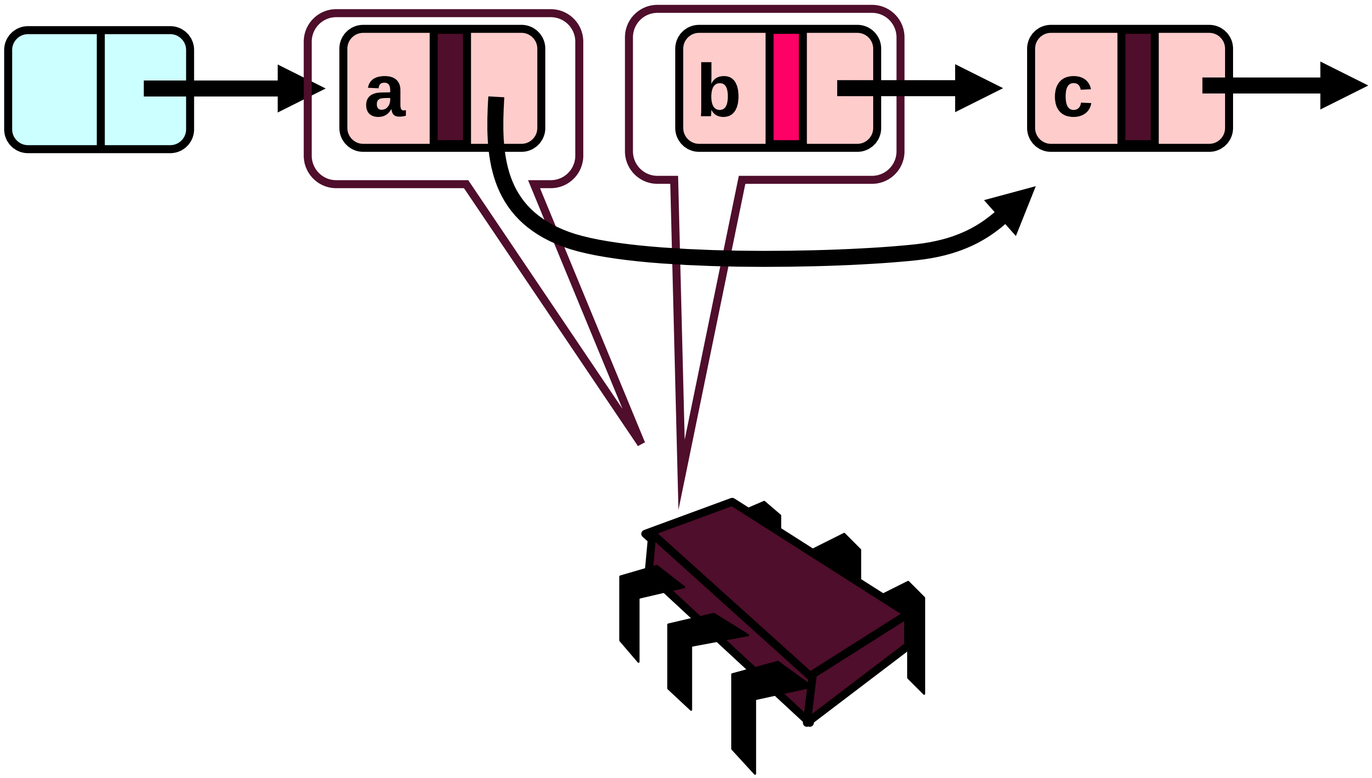
Business as Usual



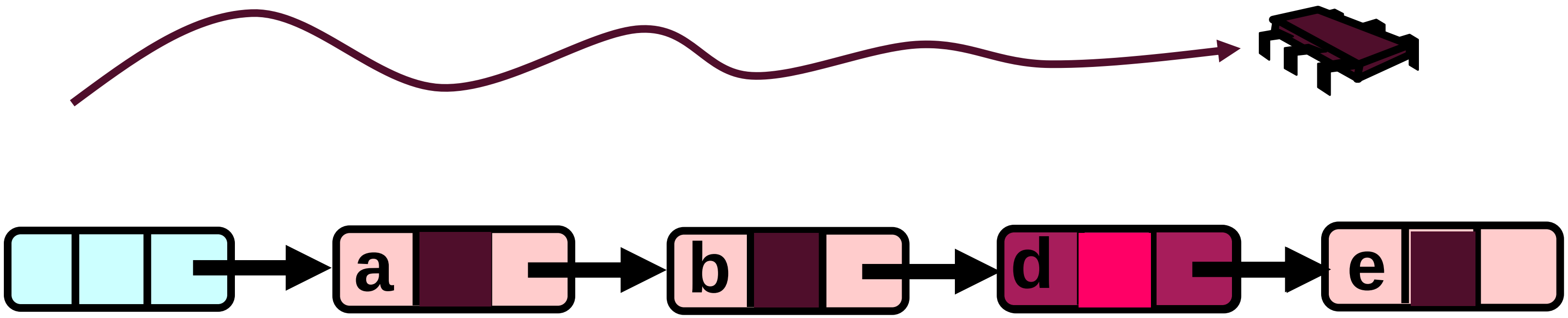
Business as Usual



Business as Usual



Summary: Wait-free Contains



Use Mark bit + list ordering

1. Not marked → in the set
2. Marked or missing → not in the set

Lazy add() and remove() + Wait-free contains()

Problems with Locks

- **What are the fundamental problems with locks?**
- **Blocking**
  - Threads wait, fault tolerance
  - Especially when things like page faults occur in CR
- **Overheads**
  - Even when not contended
  - Also memory/state overhead
- **Synchronization is tricky**
  - Deadlock, other effects are hard to debug
- **Not easily composable**

Lock-free Methods

- **No matter what:**
  - Guarantee minimal progress

    I.e., some thread will advance
  - Threads may halt at bad times (no CRs! No exclusion!)

    I.e., cannot use locks!
  - Needs other forms of synchronization

    E.g., atomics (discussed before for the implementation of locks)

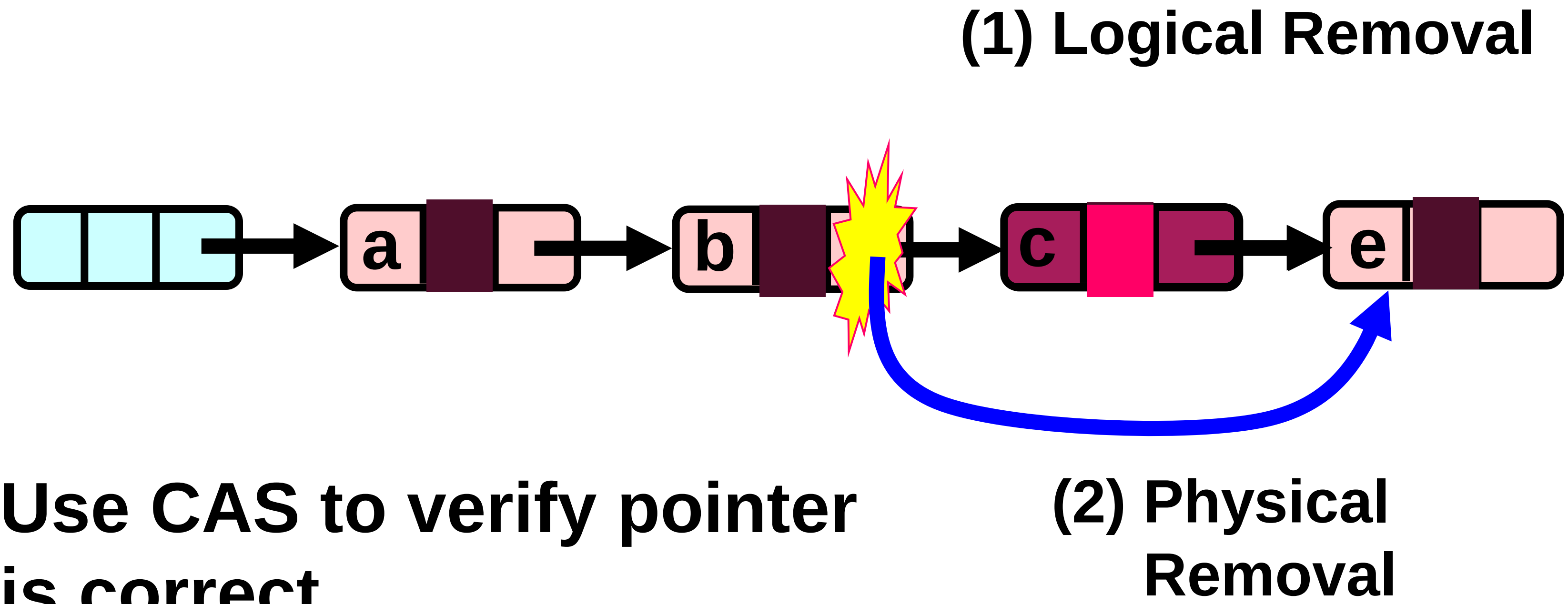
    Techniques are astonishingly similar to guaranteeing mutual exclusion

Trick 5: No Locking

- **Make list lock-free**
- **Logical succession**
  - We have wait-free contains
  - Make add() and remove() lock-free!

    Keep logical vs. physical removal
- **Simple idea:**
  - Use CAS to verify that pointer is correct before moving it

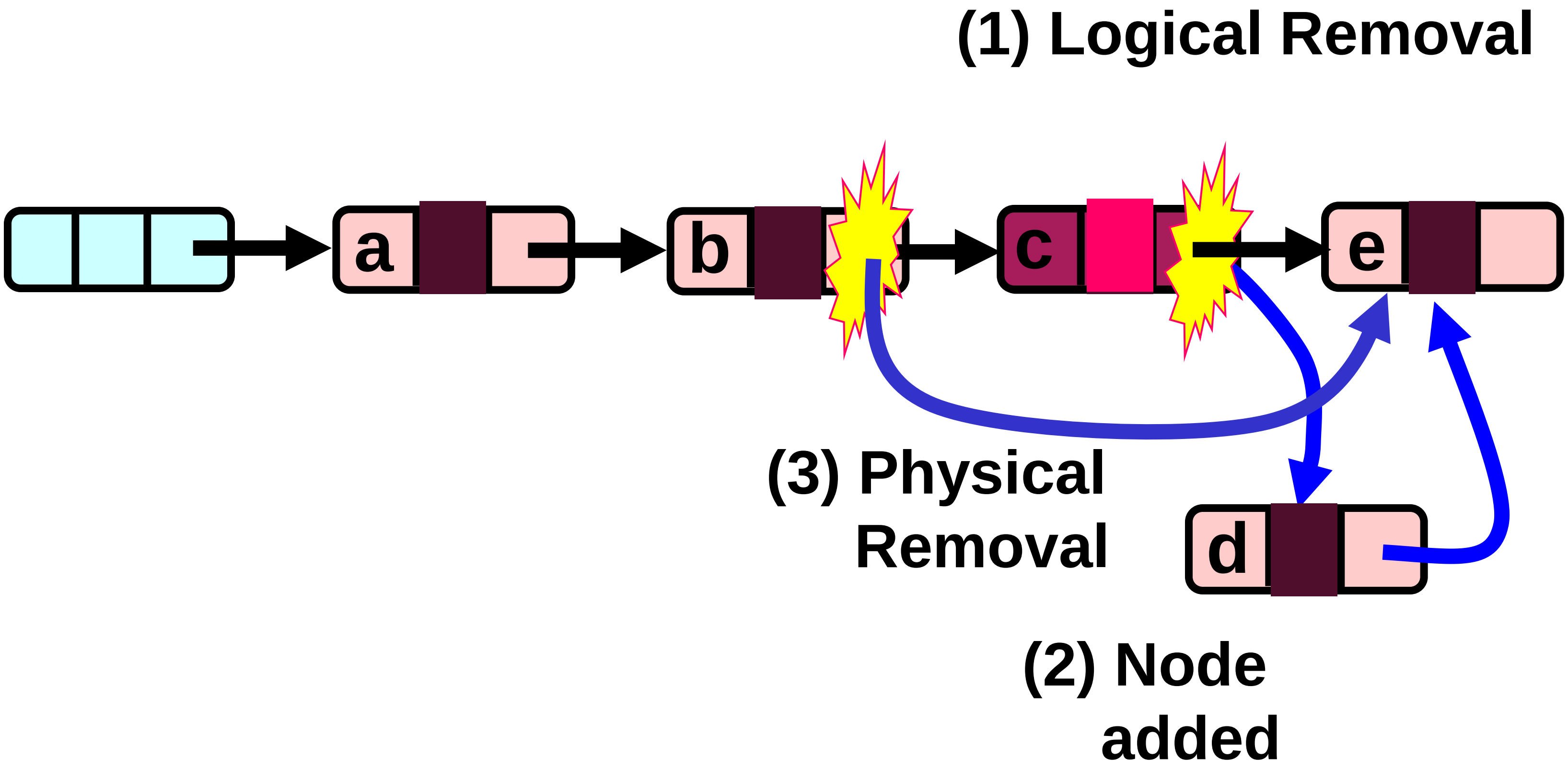
Lock-free Lists



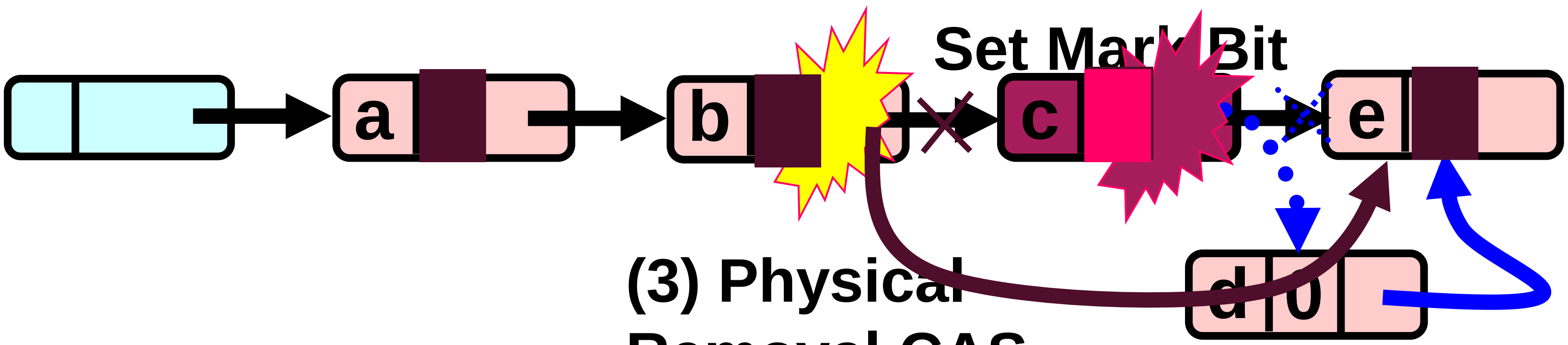
Use CAS to verify pointer is correct

Not enough! Why?

Problem…



The Solution: Combine Mark and Pointer

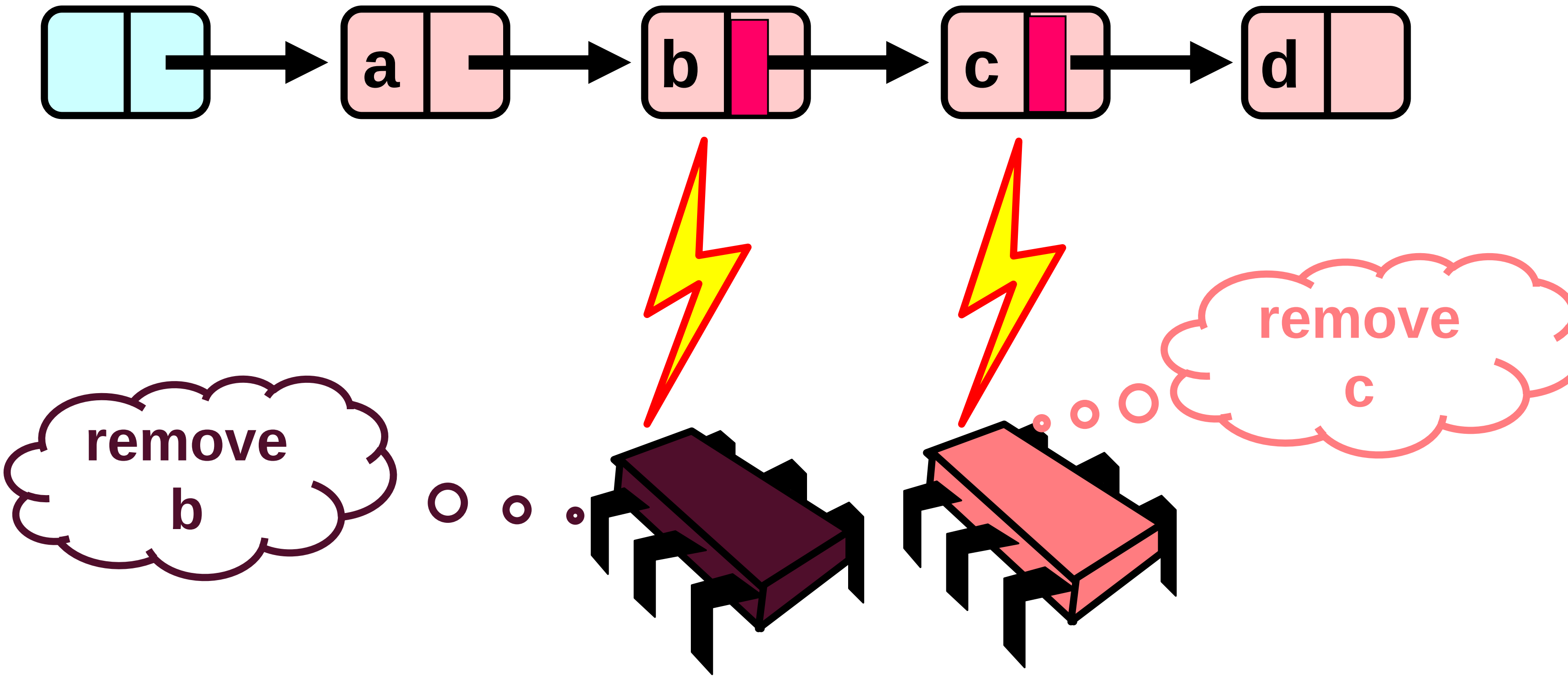


Mark-Bit and Pointer are CASed together!

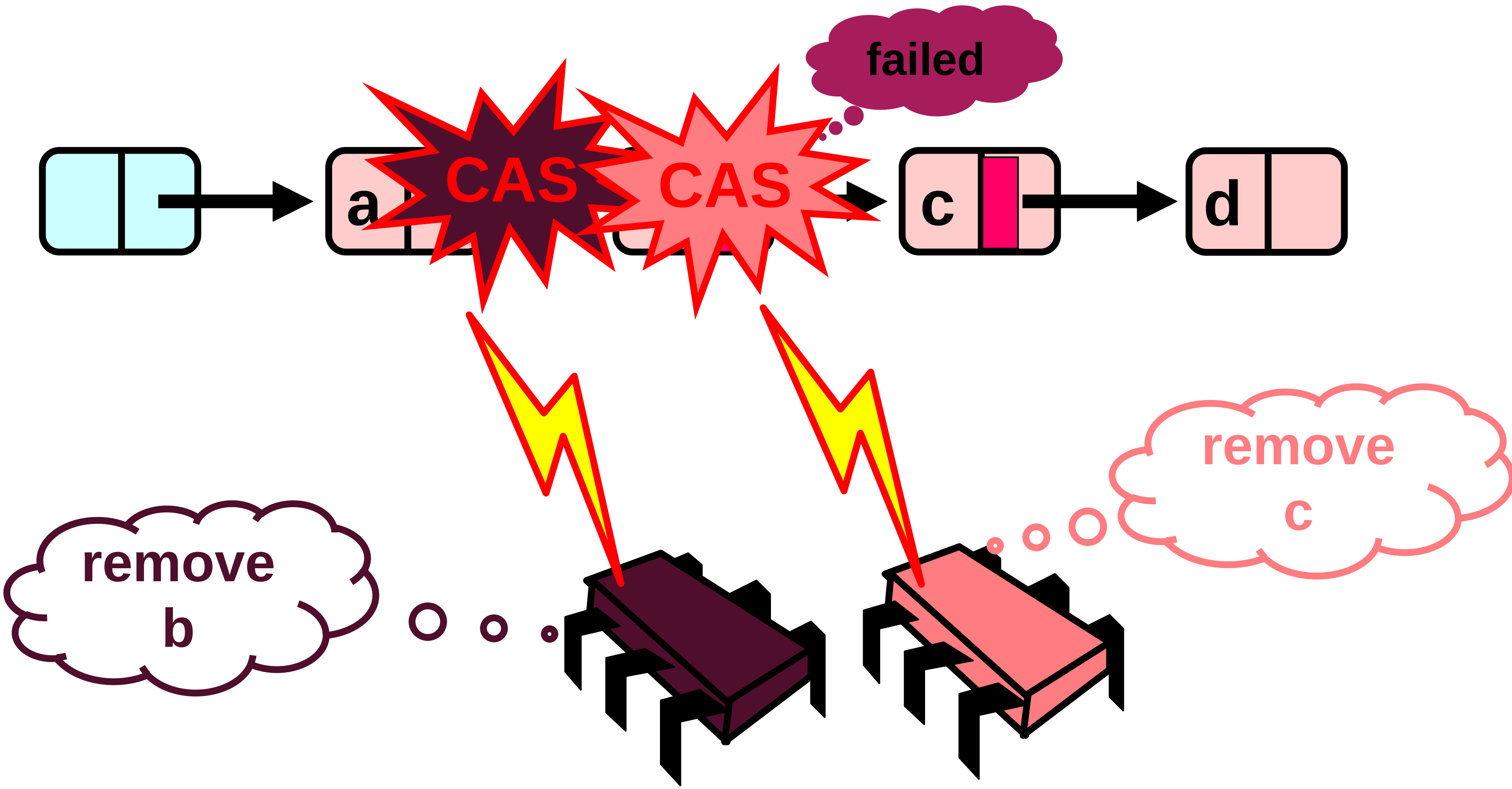
Practical Solution(s)

- **Option 1:**
  - Introduce “atomic markable reference” type
  - “Steal” a bit from a pointer
  - Rather complex and OS specific ☹
- **Option 2:**
  - Use Double CAS (or CAS2) ☺
    CAS of two noncontiguous locations
  - Well, not many machines support it ☹
    Any still alive?
- **Option 3:**
  - Our favorite ISA (x86) offers double-width CAS
    Contiguous, e.g., lock cmpxchg16b (on 64 bit systems)
- **Option 4:**
  - TM!
    E.g., Intel’s TSX (essentially a cmpxchg64b (operates on a cache line))

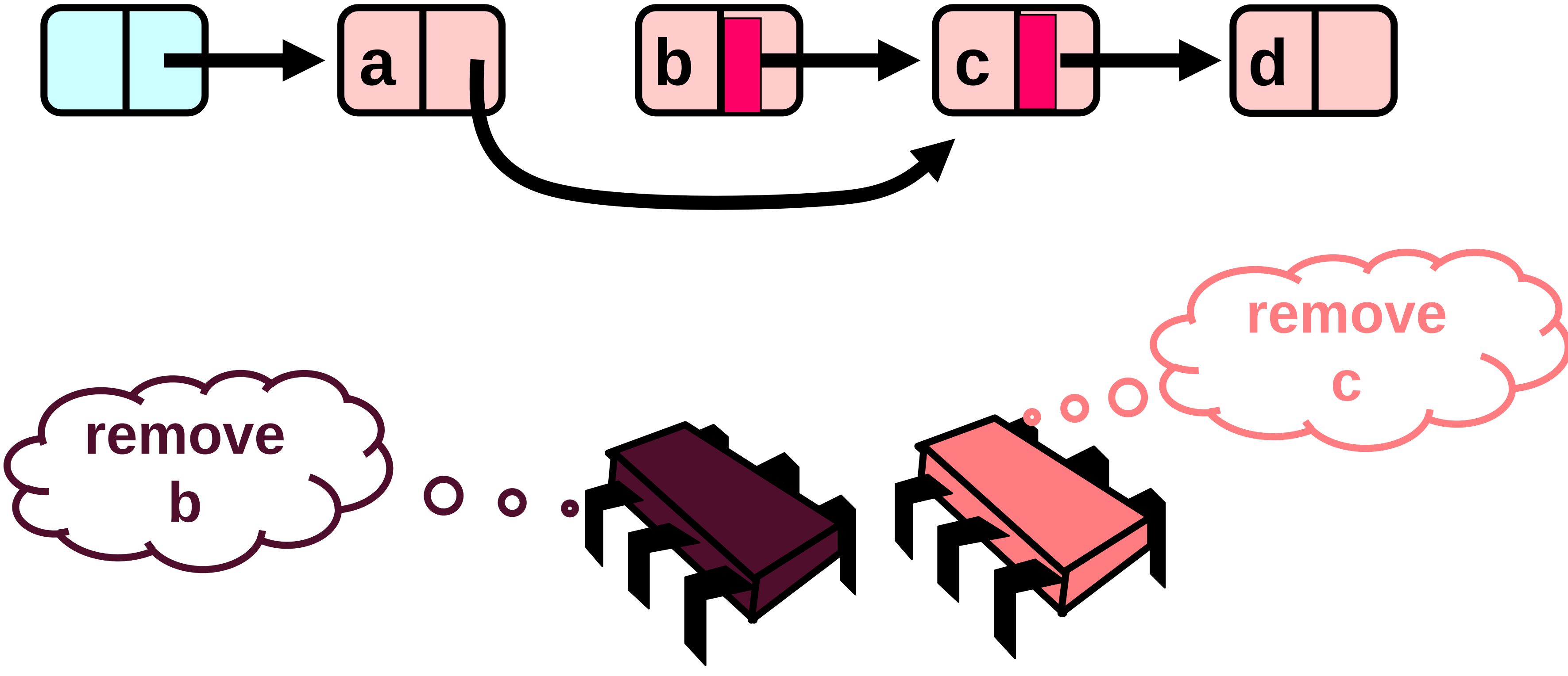
Removing a Node



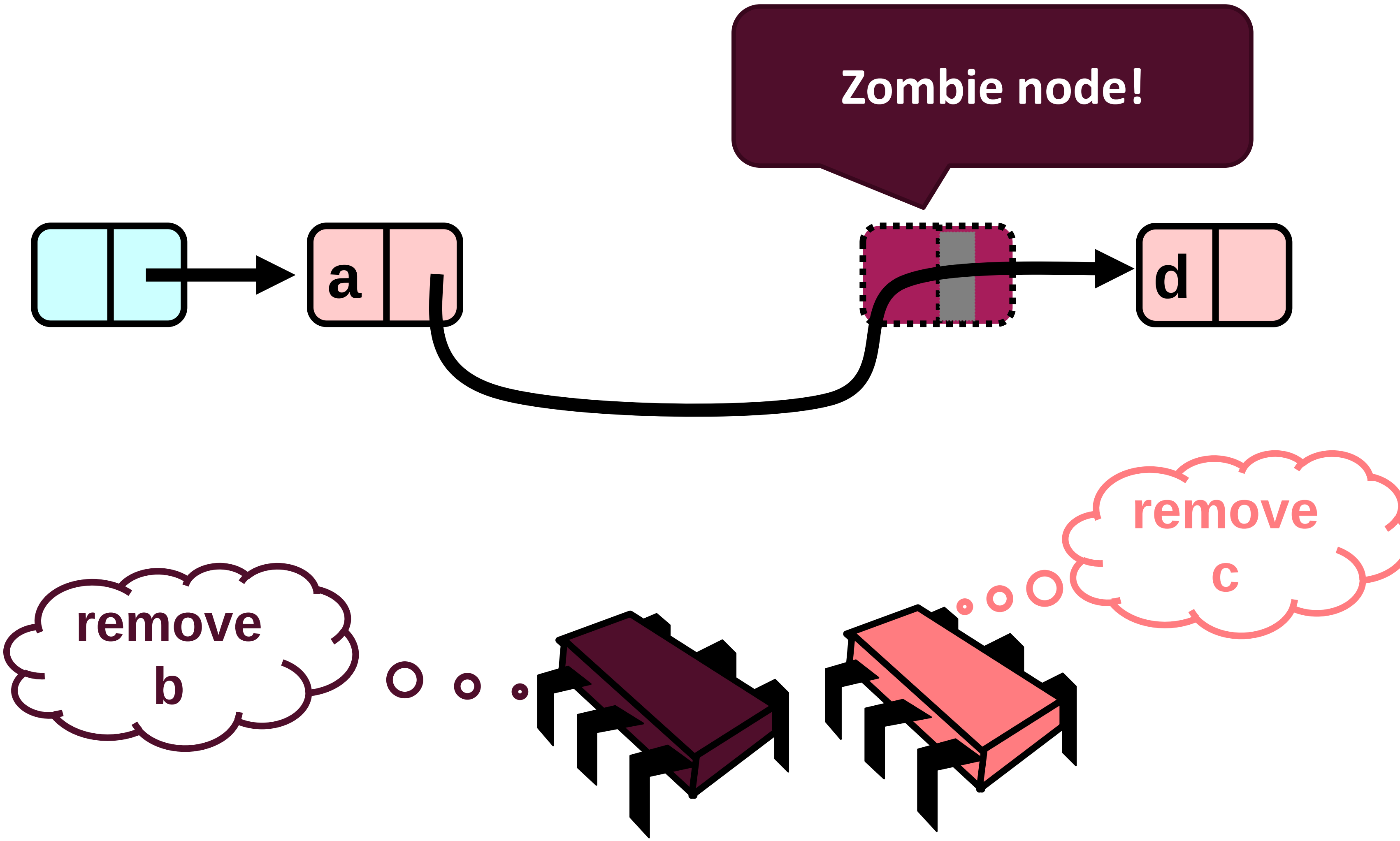
Removing a Node



Removing a Node



Uh oh – node marked but not removed!



Dealing With Zombie Nodes

- **Add() and remove() "help to clean up"**
  - Physically remove any marked nodes on their path
  - I.e., if curr is marked: CAS (pred.next, mark) to (curr.next, false) and remove curr

    If CAS fails, restart from beginning!
- **"Helping" is often needed in wait-free algs**
- **This fixes all the issues and makes the algorithm correct!**

Comments

- **Atomically updating two variables (CAS2 etc.) has a non-trivial cost**
- **If CAS fails, routine needs to re-traverse list**
  - Necessary cleanup may lead to unnecessary contention at marked nodes
- **More complex data structures and correctness proofs than for locked versions**
  - But guarantees progress, fault-tolerant and maybe even faster (that really depends)

More Comments

- **Correctness proof techniques**
  - Establish invariants for initial state and transformations

    E.g., head and tail are never removed, every node in the set has to be reachable from head, …
  - Proofs are similar to those we discussed for locks

    Very much the same techniques (just trickier)

    Using sequential consistency (or consistency model of your choice ☺)

    Lock-free gets somewhat tricky
- **Source-codes can be found in Chapter 9 of "The Art of Multiprocessor Programming"**

Lock-free and wait-free

- **A lock-free method**
  - guarantees that infinitely often **some** method call finishes in a finite number of steps
- **A wait-free method**
  - guarantees that **each** method call finishes in a finite number of steps (implies lock-free)
  - Was our lock-free list also wait-free?
- **Synchronization instructions are not equally powerful!**
  - Indeed, they form an infinite hierarchy; no instruction (primitive) in level x can be used for lock-/wait-free implementations of primitives in level z>x.

Concept: Consensus Number

- **Each level of the hierarchy has a “consensus number” assigned.**
  - Is the maximum number of threads for which primitives in level x can solve the consensus problem
- **The consensus problem:**
  - Has single function: decide(v)
  - Each thread calls it at most once, the function returns a value that meets two conditions:

    consistency: all threads get the same value

    valid: the value is some thread’s input
  - Simplification: binary consensus (inputs in {0,1})

Understanding Consensus

- **Can a particular class solve n-thread consensus wait-free?**
  - A class C solves n-thread consensus if there exists a consensus protocol using **any number** of objects of class C and **any number** of atomic registers
  - The protocol has to be wait-free (bounded number of steps per thread)
  - The consensus number of a class C is the largest n for which that class solves n-thread consensus (may be infinite)
  - Assume we have a class D whose objects can be constructed from objects out of class C. If class C has consensus number n, what does class D have?

Starting simple …

- **Binary consensus with two threads (A, B)!**
  - Each thread moves until it decides on a value
  - May update shared objects
  - Protocol state = state of threads + state of shared objects
  - Initial state = state before any thread moved
  - Final state = state after all threads finished
  - States form a tree, wait-free property guarantees a finite tree

    Example with two threads and two moves each!

Atomic Registers

- **Theorem [Herlihy'91]: Atomic registers have consensus number one**
  - Really?
- **Proof outline:**
  - Assume arbitrary consensus protocol, thread A, B
  - Run until it reaches critical state where next action determines outcome (show that it must have a critical state first)
  - Show all options using atomic registers and show that they cannot be used to determine one outcome for all possible executions!
    1) *Any thread reads (other thread runs solo until end)*
    2) *Threads write to different registers (order doesn't matter)*
    3) *Threads write to same register (solo thread can start after each write)*

Atomic Registers

- **Theorem [Herlihy'91]: Atomic registers have consensus number one**
- **Corollary: It is impossible to construct a wait-free implementation of any object with consensus number of >1 using atomic registers**
  - "perhaps one of the most striking impossibility results in Computer Science" (Herlihy, Shavit)
  - → We need hardware atomics or TM!
- **Proof technique borrowed from:**

  Impossibility of **distributed consensus** with one faulty process
  MJ Fischer, NA Lynch, MS Paterson - Journal of the ACM (JACM), 1985 - dl.acm.org
  Abstract The **consensus** problem involves an asynchronous system of processes, some of which may be unreliable. The problem is for the reliable processes to agree on a binary value. In this paper, it is shown that every protocol for this problem has the possibility of **...**
  Cited by 3180 Related articles All 164 versions

- **Very influential paper, always worth a read!**
  - Nicely shows proof techniques that are central to parallel and distributed computing!

Other Atomic Operations

- **Simple RMW operations (Test&Set, Fetch&Op, Swap, basically all functions where the op commutes or overwrites) have consensus number 2!**
  - Similar proof technique (bivalence argument)
- **CAS and TM have consensus number ∞**
  - Constructive proof!

Compare and Set/Swap Consensus

```
const int first = -1
volatile int thread = -1;
int proposed[n];

int decide(v) {
  proposed[tid] = v;
  if(CAS(thread, first, tid))
    return  v; // I won!
  else
     return proposed[thread]; // thread won
}
```

- **CAS provides an infinite consensus number**
  - Machines providing CAS are **asynchronous** computation equivalents of the Turing Machine
  - I.e., any concurrent object can be implemented in a wait-free manner (not necessarily fast!)

Now you know everything ☺

- **Not really … ;-)**
  - We'll argue about **performance** now!
- **But you have all the tools for:**
  - Efficient locks
  - Efficient lock-based algorithms
  - Efficient lock-free algorithms (or even wait-free)
  - Reasoning about parallelism!
- **What now?**
  - A different class of problems

    Impact on wait-free/lock-free on actual performance is not well understood
  - Relevant to HPC, applies to shared and distributed memory

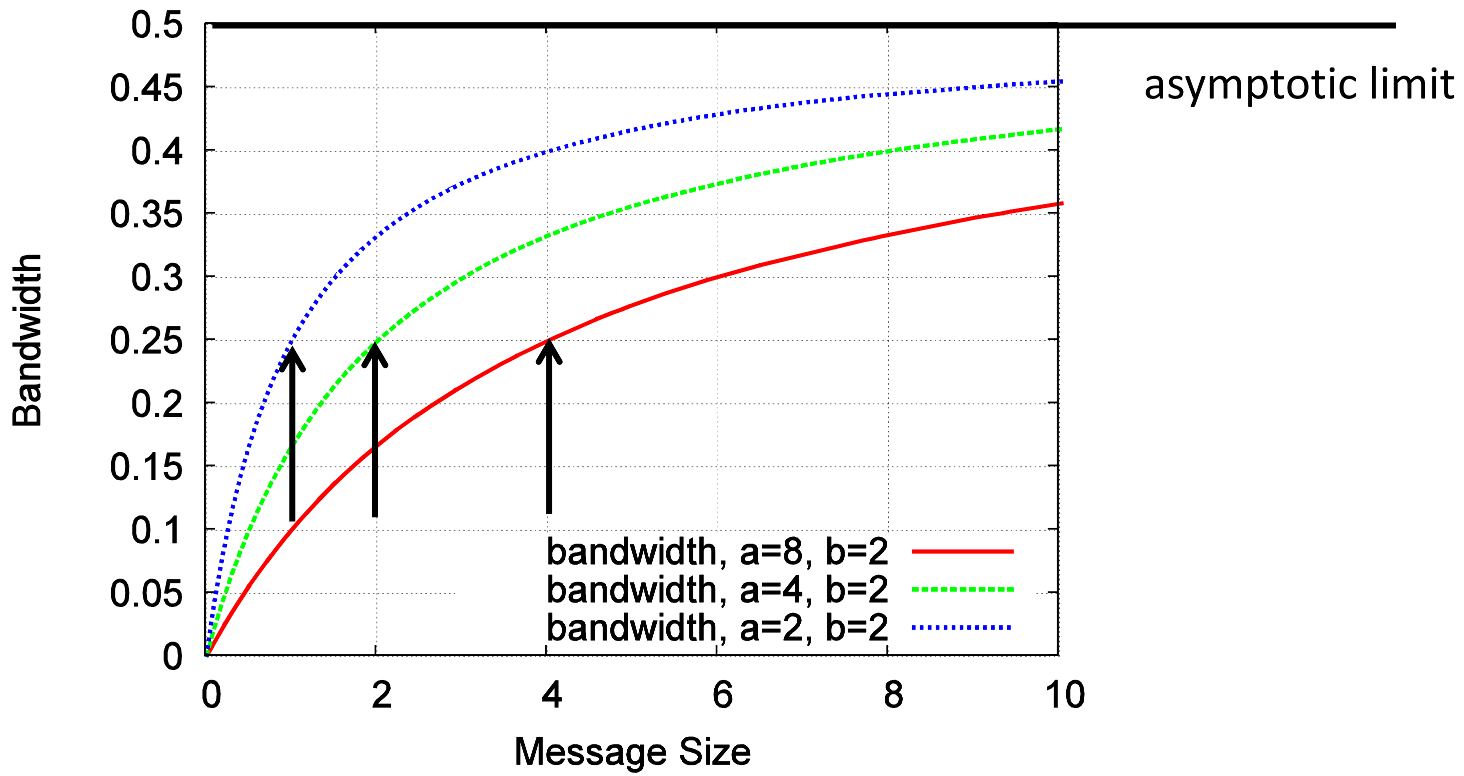
    → *Group communications*

Remember: A Simple Model for Communication

- **Transfer time $T(s) = \alpha+\beta s$**
  - α = startup time (latency)
  - β = cost per byte (bandwidth=$1/\beta$)
- **As s increases, bandwidth approaches $1/\beta$ asymptotically**
  - Convergence rate depends on α
  - $s_{1/2} = \alpha/\beta$
- **Assuming no pipelining (new messages can only be issued from a process after all arrived)**

Bandwidth vs. Latency

- **$s_{1/2} = \alpha/\beta$ often used to distinguish bandwidth- and latency-bound messages**
  - $s_{1/2}$ is in the order of kilobytes on real systems



Quick Example

- **Simplest linear broadcast**
  - One process has a data item to be distributed to all processes
- **Broadcasting s bytes among P processes:**
  - T(s) = (P-1) * (α+βs) = $\mathcal{O}(P)$
- **Class question: Do you know a faster method to accomplish the same?**

k-ary Tree Broadcast

- **Origin process is the root of the tree, passes messages to k neighbors which pass them on**
  - k=2 -> binary tree
- **Class Question: What is the broadcast time in the simple latency/bandwidth model?**
  - $T(s) \approx \lceil log_k(P) \rceil \cdot k \cdot (\alpha + \beta \cdot s) = \mathcal{O}(log(P))$ (for fixed k)
- **Class Question: What is the optimal k?**
  - $0 = \frac{ln(P) \cdot k}{ln(k)} \frac{d}{dk} = \frac{ln(P)ln(k) - ln(P)}{ln^2(k)} \rightarrow k = e = 2.71...$
  - Independent of P, α, βs? Really?

Faster Trees?

- **Class Question: Can we broadcast faster than in a ternary tree?**
  - Yes because each respective root is idle after sending three messages!
  - Those roots could keep sending!
  - Result is a k-nomial tree

    For k=2, it's a binomial tree
- **Class Question: What about the runtime?**
  - $T(s) = \lceil log_k(P) \rceil \cdot (k-1) \cdot (\alpha + \beta \cdot s) = \mathcal{O}(log(P))$
- **Class Question: What is the optimal k here?**
  - T(s) d/dk is monotonically increasing for k>1, thus $k_{opt}=2$
- **Class Question: Can we broadcast faster than in a k-nomial tree?**
  - $\mathcal{O}(log(P))$ is asymptotically optimal for s=1!
  - But what about large s?

Open Problems

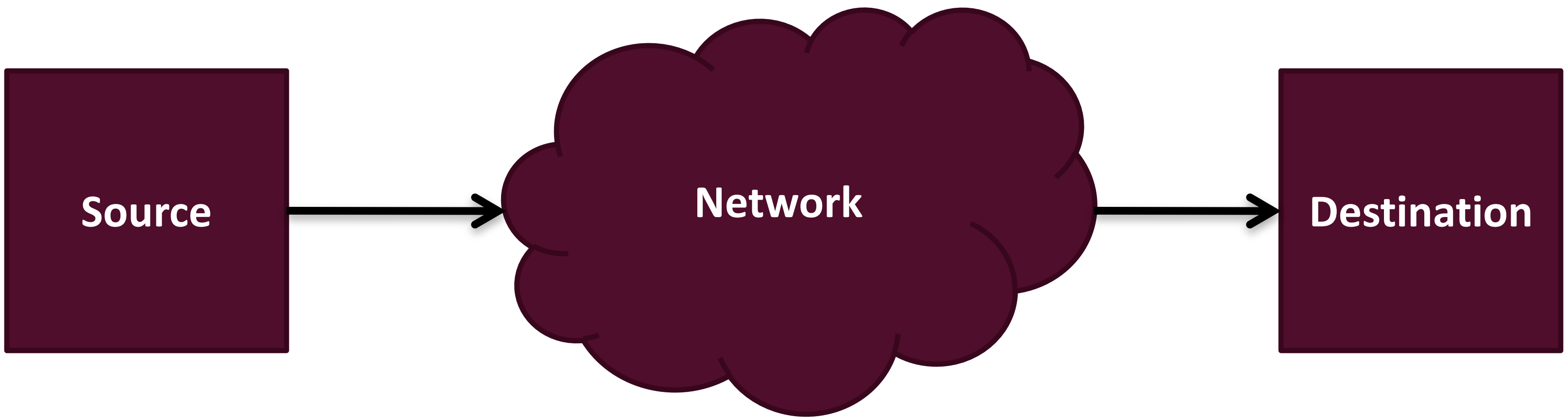
- **Look for optimal parallel algorithms (even in simple models!)**
  - And then check the more realistic models
  - Useful optimization targets are MPI collective operations

    Broadcast/Reduce, Scatter/Gather, Alltoall, Allreduce, Allgather, Scan/Exscan, …
  - Implementations of those (check current MPI libraries ☺)
  - Useful also in scientific computations

    Barnes Hut, linear algebra, FFT, …
- **Lots of work to do!**
  - Contact me for thesis ideas (or check SPCL) if you like this topic
  - Usually involve optimization (ILP/LP) and clever algorithms (algebra) combined with practical experiments on large-scale machines (10,000+ processors)

HPC Networking Basics

- **Familiar (non-HPC) network: Internet TCP/IP**
  - Common model:

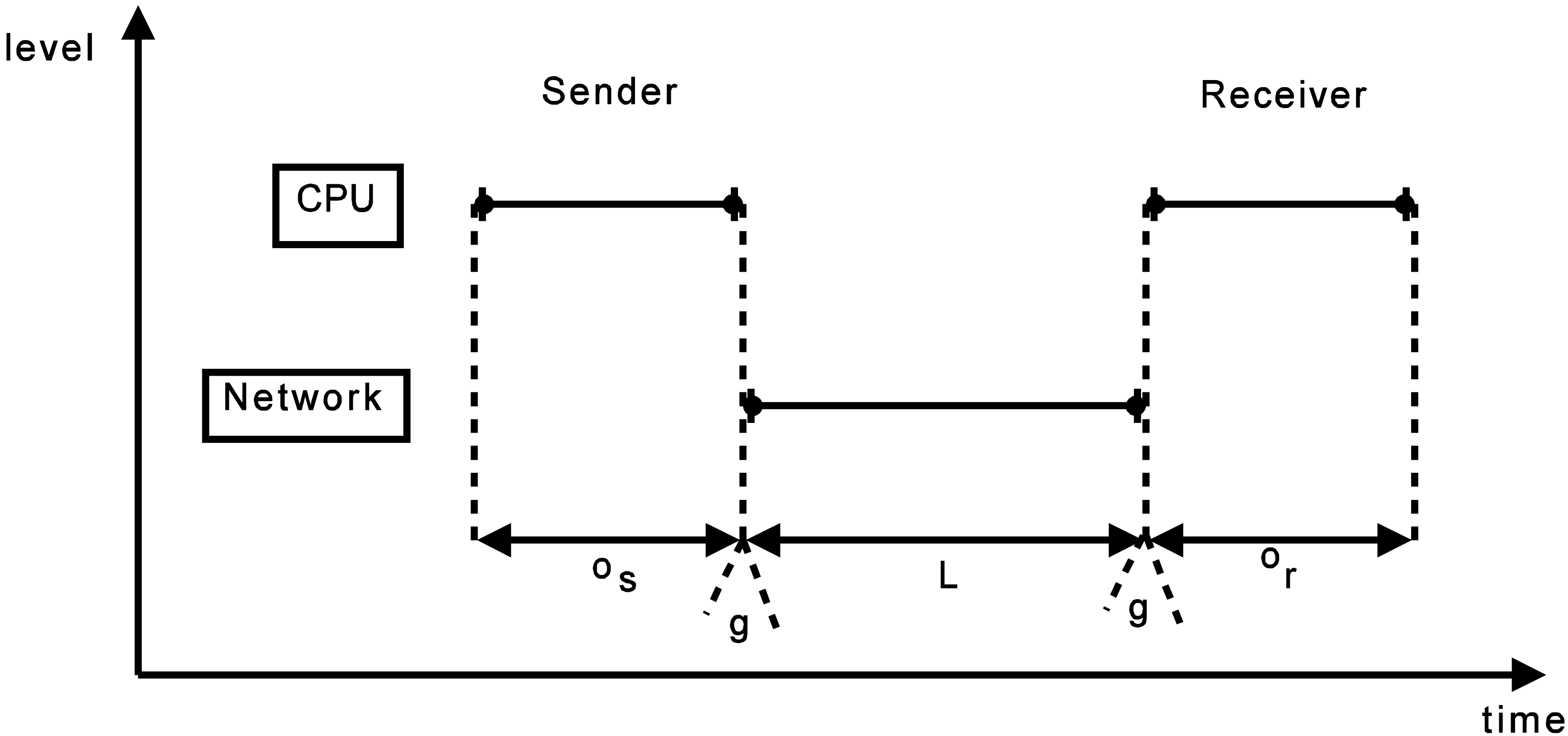


- **Class Question: What parameters are needed to model the performance (including pipelining)?**
  - Latency, Bandwidth, Injection Rate, Host Overhead

The LogP Model

- **Defined by four parameters:**
  - L: an upper bound on the latency, or delay, incurred in communicating a message containing a word (or small number of words) from its source module to its target module.
  - o: the overhead, defined as the length of time that a processor is engaged in the transmission or reception of each message; during this time, the processor cannot perform other operations.
  - g: the gap, defined as the minimum time interval between consecutive message transmissions or consecutive message receptions at a processor. The reciprocal of g corresponds to the available per-processor communication bandwidth.
  - P: the number of processor/memory modules. We assume unit time for local operations and call it a cycle.

The LogP Model



Simple Examples

- **Sending a single message**
  - T = 2o+L
- **Ping-Pong Round-Trip**
  - T_{RTT} = 4o+2L
- **Transmitting n messages**
  - T(n) = L+(n-1)*max(g, o) + 2o

Simplifications

- **o is bigger than g on some machines**
  - g can be ignored (eliminates max() terms)
  - be careful with multicore!
- **Offloading networks might have very low o**
  - Can be ignored (not yet but hopefully soon)
- **L might be ignored for long message streams**
  - If they are pipelined
- **Account g also for the first message**
  - Eliminates “-1”

Benefits over Latency/Bandwidth Model

- **Models pipelining**
  - L/g messages can be “in flight”
  - Captures state of the art (cf. TCP windows)
- **Models computation/communication overlap**
  - Asynchronous algorithms
- **Models endpoint congestion/overload**
  - Benefits balanced algorithms

Example: Broadcasts

- **Class Question: What is the LogP running time for a linear broadcast of a single packet?**
  - $T_{lin} = L + (P-2) * \max(o,g) + 2o$
- **Class Question: Approximate the LogP runtime for a binary-tree broadcast of a single packet?**
  - $T_{bin} \le \log_2 P * (L + \max(o,g) + 2o)$
- **Class Question: Approximate the LogP runtime for an k-ary-tree broadcast of a single packet?**
  - $T_{k\text{-}n} \le \log_k P * (L + (k-1)\max(o,g) + 2o)$

Example: Broadcasts

- **Class Question: Approximate the LogP runtime for a binomial tree broadcast of a single packet (assume L > g!)?**
  - $T_{bin} \leq \log_2 P * (L + 2o)$
- **Class Question: Approximate the LogP runtime for a k-nomial tree broadcast of a single packet?**
  - $T_{k\text{-}n} \leq \log_k P * (L + (k-2)\max(o,g) + 2o)$
- **Class Question: What is the optimal k (assume o>g)?**
  - Derive by k: $0 = o * \ln(k_{opt}) - L/k_{opt} + o$ (solve numerically)

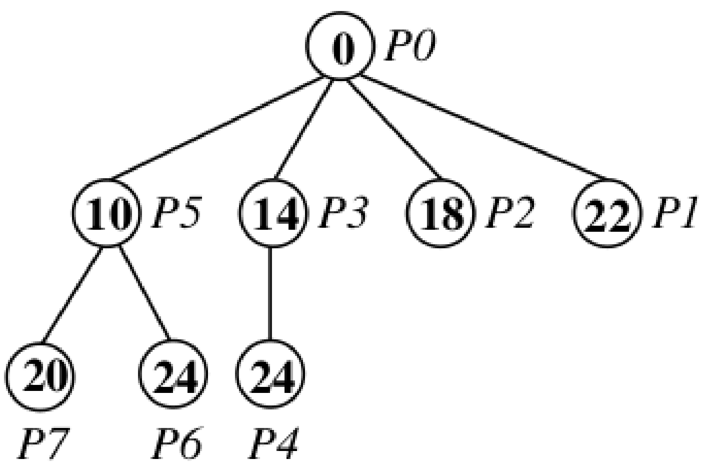
    For larger L, k grows and for larger o, k shrinks
  - Models pipelining capability better than simple model!

Example: Broadcasts

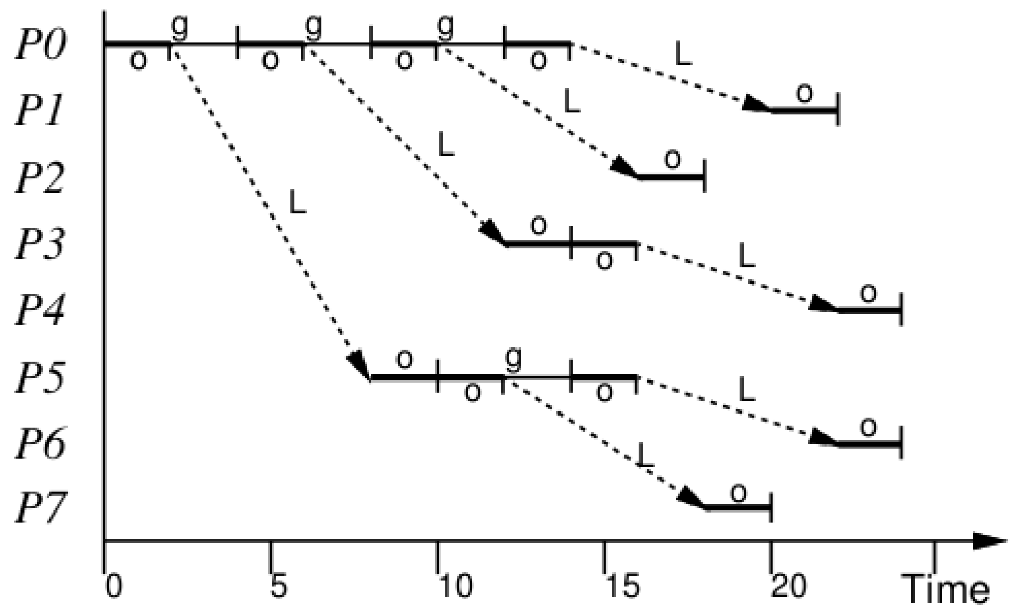
- **Class Question: Can we do better than k_{opt}-ary binomial broadcast?**
  - Problem: fixed k in all stages might not be optimal
  - We can construct a schedule for the optimal broadcast in practical settings
  - First proposed by Karp et al. in “Optimal Broadcast and Summation in the LogP Model”

Example: Optimal Broadcast

- **Broadcast to P-1 processes**
  - Each process who received the value sends it on; each process receives exactly once



P=8, L=6, g=4, o=2



Optimal Broadcast Runtime

- **This determines the maximum number of PEs (P(t)) that can be reached in time t**
- **P(t) can be computed with a generalized Fibonacci recurrence (assuming o>g):**

$$P(t) = \begin{cases} 1 : & t < 2o + L \\ P(t-o) + P(t-L-2o) : & \text{otherwise.} \end{cases} \tag{1}$$

- **Which can be bounded by (see [1]):** $2^{\left\lfloor \frac{t}{L+2o} \right\rfloor} \leq P(t) \leq 2^{\left\lfloor \frac{t}{o} \right\rfloor}$
  - A closed solution is an interesting open problem!

[1]: Hoefler et al.: “Scalable Communication Protocols for Dynamic Sparse Data Exchange” (Lemma 1)

The Bigger Picture

- **We learned how to program shared memory systems**
  - Coherency & memory models & linearizability
  - Locks as examples for reasoning about correctness and performance
  - List-based sets as examples for lock-free and wait-free algorithms
  - Consensus number
- **We learned about general performance properties and parallelism**
  - Amdahl's and Gustafson's laws
  - Little's law, Work-span, …
  - Balance principles & scheduling
- **We learned how to perform model-based optimizations**
  - Distributed memory broadcast example with two models
- **What next? MPI? OpenMP? UPC?**
  - Next-generation machines "merge" shared and distributed memory concepts → Partitioned Global Address Space (PGAS)

Partitioned Global Address Space

- **Two developments:**
  1. Cache coherence becomes more expensive

     May react in software! Scary for industry ;-)
  2. Novel RDMA hardware enables direct access to remote memory

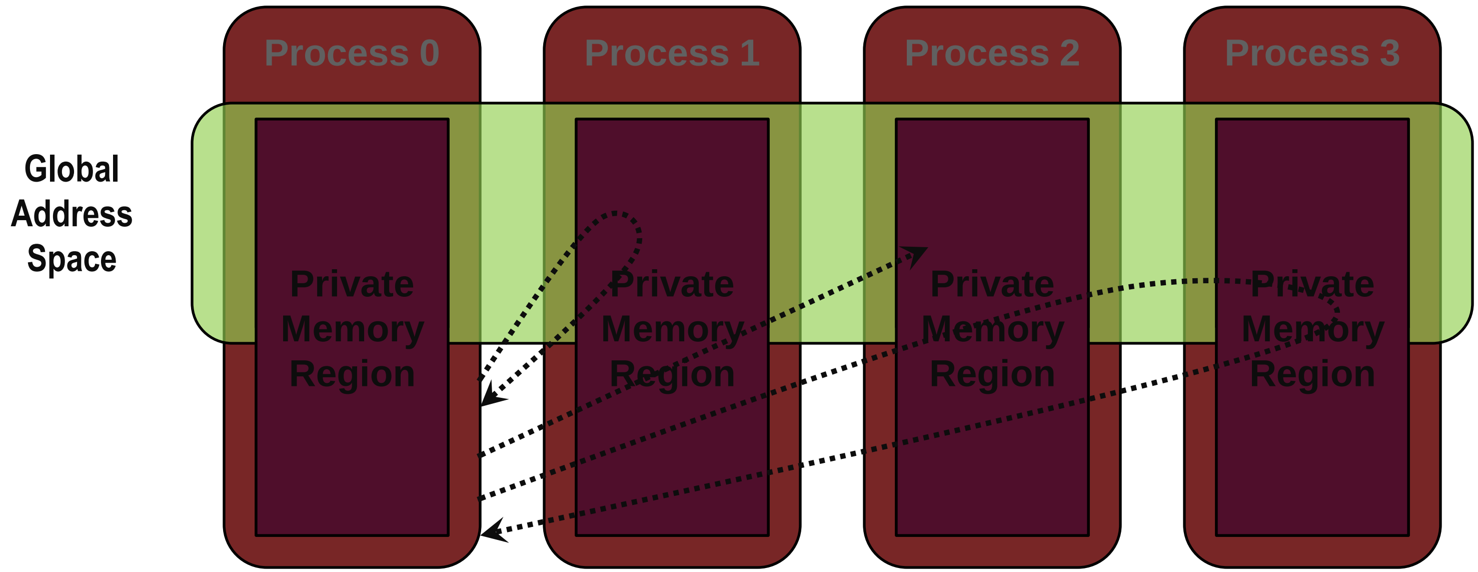
     May take advantage in software! An opportunity for HPC!

- **Still ongoing research! Take nothing for granted ☺**
  - Very interesting opportunities
  - Wide-open research field
  - Even more thesis ideas on next generation parallel programming

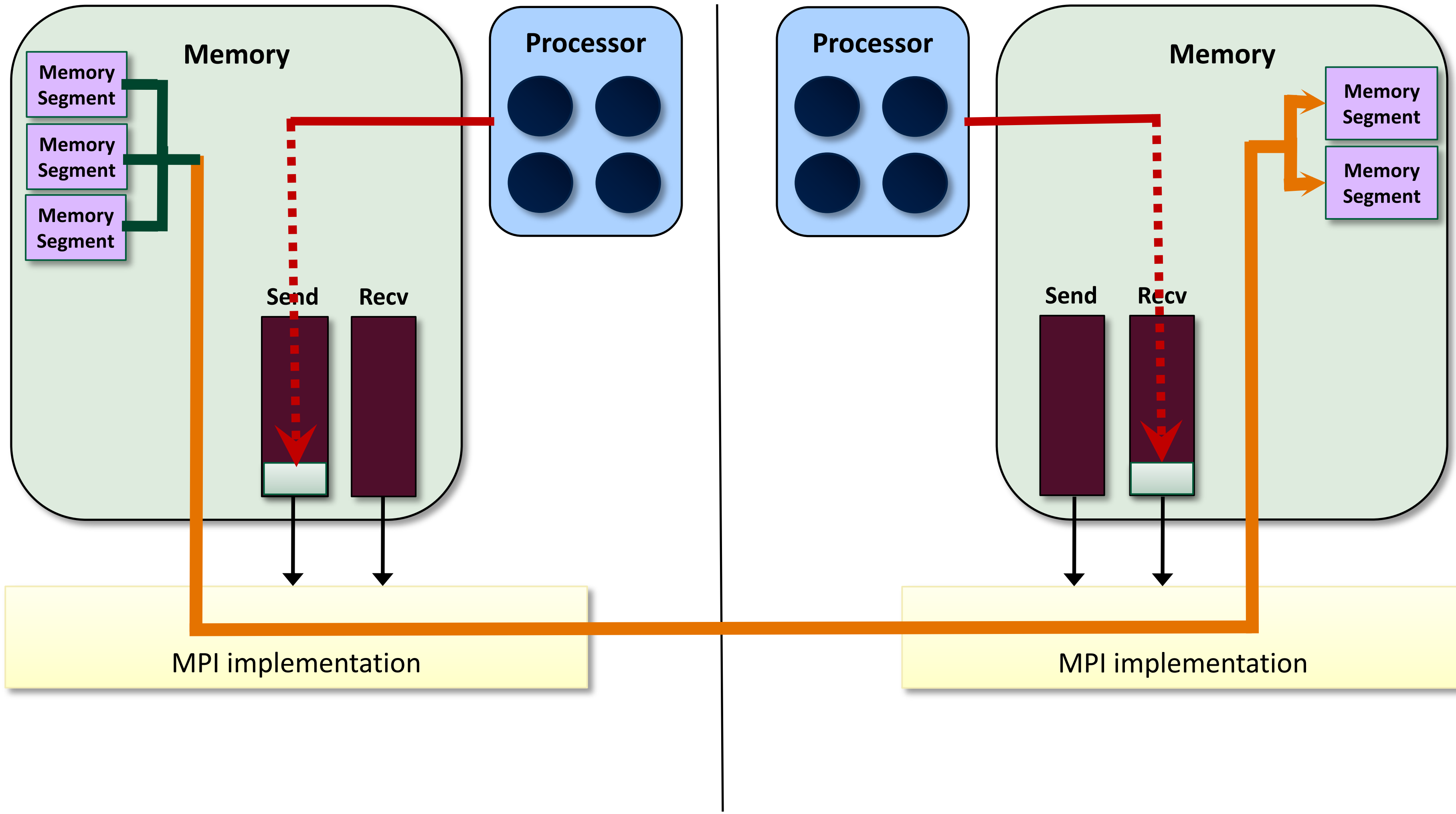
- **I will introduce the concepts behind the MPI-3.0 interface**
  - It’s nearly a superset of other PGAS approaches (UPC, CAF, …)

One-sided Communication

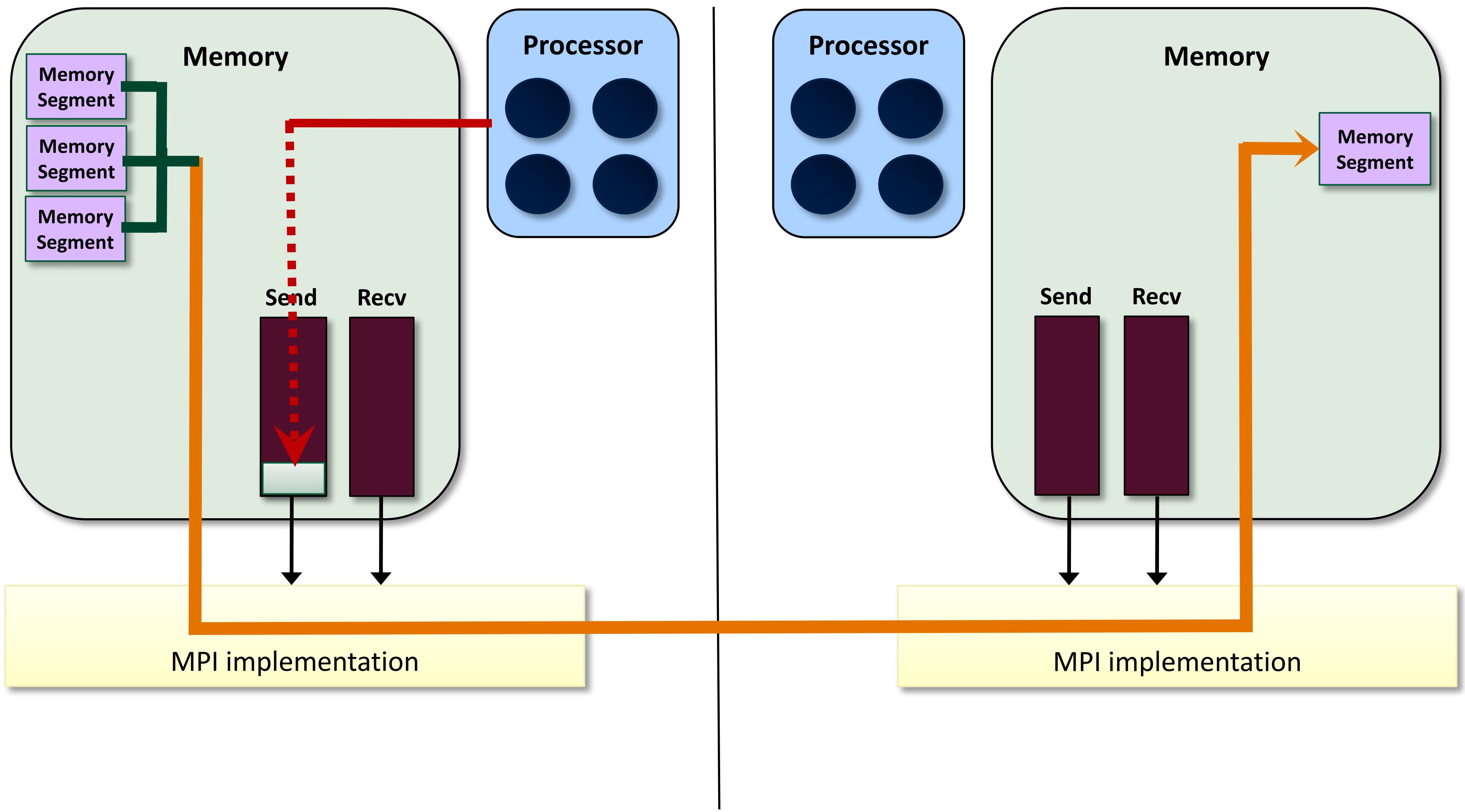
- **The basic idea of one-sided communication models is to decouple data movement with process synchronization**
  - Should be able move data without requiring that the remote process synchronize
  - Each process exposes a part of its memory to other processes
  - Other processes can directly read from or write to this memory



Two-sided Communication Example



One-sided Communication Example



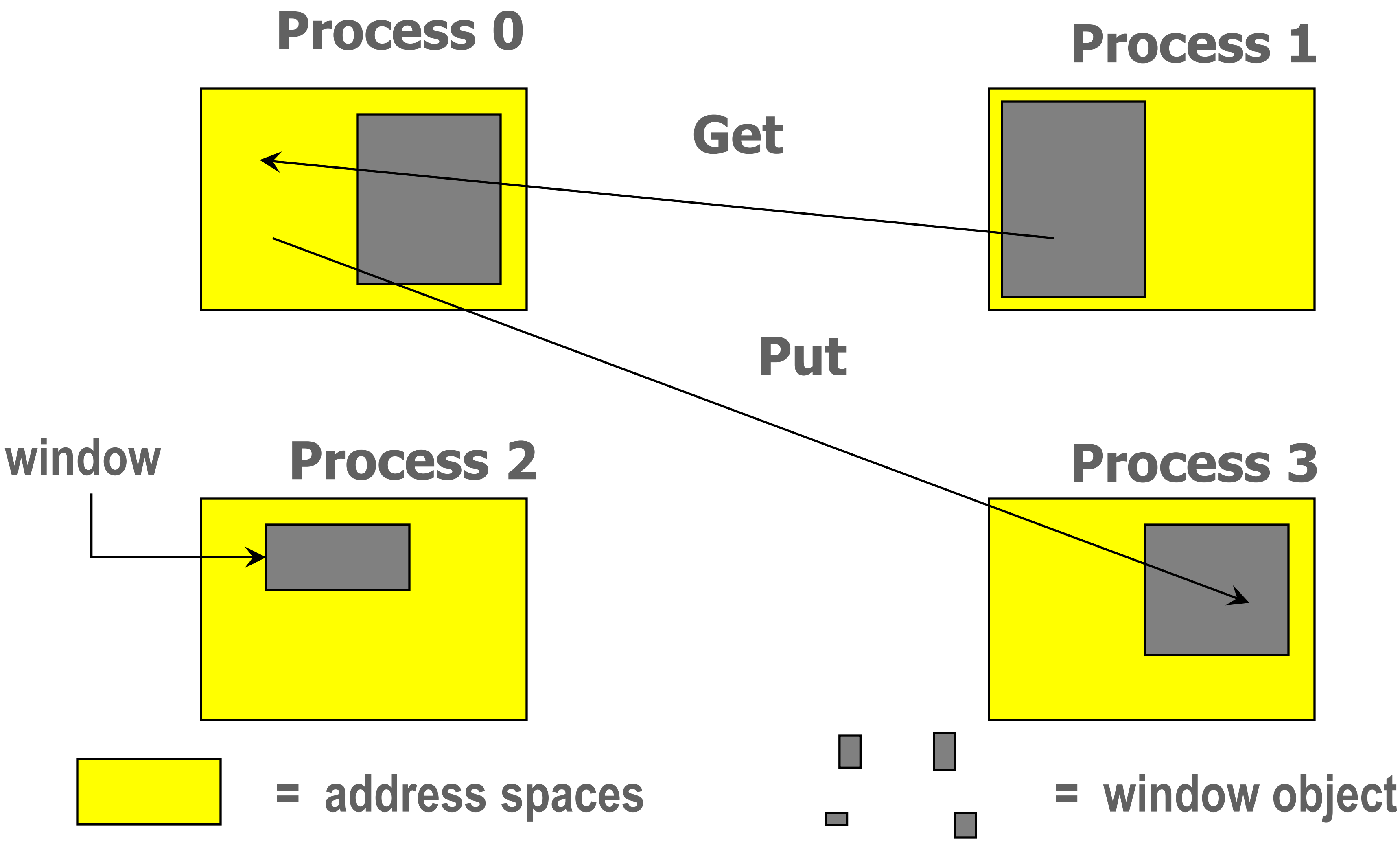
What we need to know in RMA

- How to create remote accessible memory?
- Reading, Writing and Updating remote memory
- Data Synchronization
- Memory Model

Creating Public Memory

- **Any memory used by a process is, by default, only locally accessible**
  - X = malloc(100);
- **Once the memory is allocated, the user has to make an explicit MPI call to declare a memory region as remotely accessible**
  - MPI terminology for remotely accessible memory is a “window”
  - A group of processes collectively create a “window”
- **Once a memory region is declared as remotely accessible, all processes in the window can read/write data to this memory without explicitly synchronizing with the target process**

Remote Memory Access



Basic RMA Functions

- **`MPI_Win_create` – exposes local memory to RMA operation by other processes in a communicator**
  - Collective operation
  - Creates window object
- **`MPI_Win_free` – deallocates window object**
- **`MPI_Put` – moves data from local memory to remote memory**
- **`MPI_Get` – retrieves data from remote memory into local memory**
- **`MPI_Accumulate` – atomically updates remote memory using local values**
  - Data movement operations are non-blocking
  - Data is located by a displacement relative to the start of the window
- **Subsequent synchronization on window object needed to ensure operation is complete**

Window creation models

- **Four models exist**
  - MPI_WIN_CREATE

    You already have an allocated buffer that you would like to make remotely accessible
  - MPI_WIN_ALLOCATE

    You want to create a buffer and directly make it remotely accessible
  - MPI_WIN_CREATE_DYNAMIC

    You don't have a buffer yet, but will have one in the future

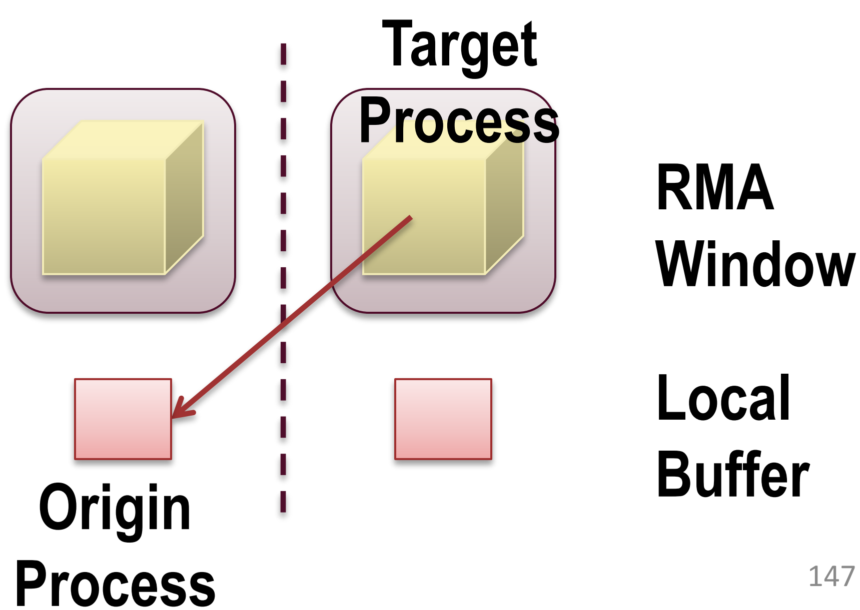
    You may want to dynamically add/remove buffers to/from the window
  - MPI_WIN_ALLOCATE_SHARED

    You want multiple processes on the same node share a buffer

Data movement: *Get*

```
MPI_Get(void * origin_addr, int origin_count,
        MPI_Datatype origin_datatype, int target_rank,
        MPI_Aint target_disp, int target_count,
        MPI_Datatype target_datatype, MPI_Win win)
```

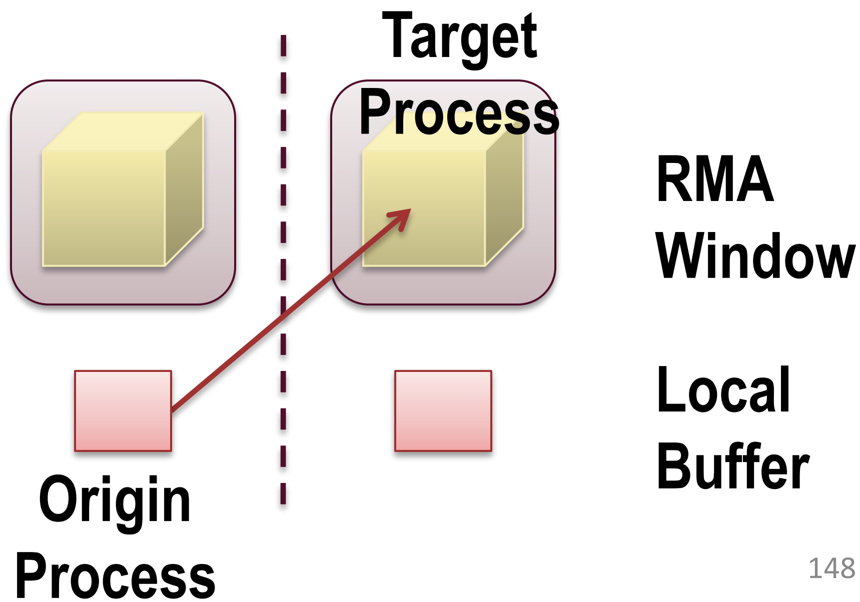
- Move data to origin, from target
- Separate data description triples for origin and target



Data movement: *Put*

```
MPI_Put(void * origin_addr, int origin_count,
        MPI_Datatype origin_datatype, int target_rank,
        MPI_Aint target_disp, int target_count,
        MPI_Datatype target_datatype, MPI_Win win)
```

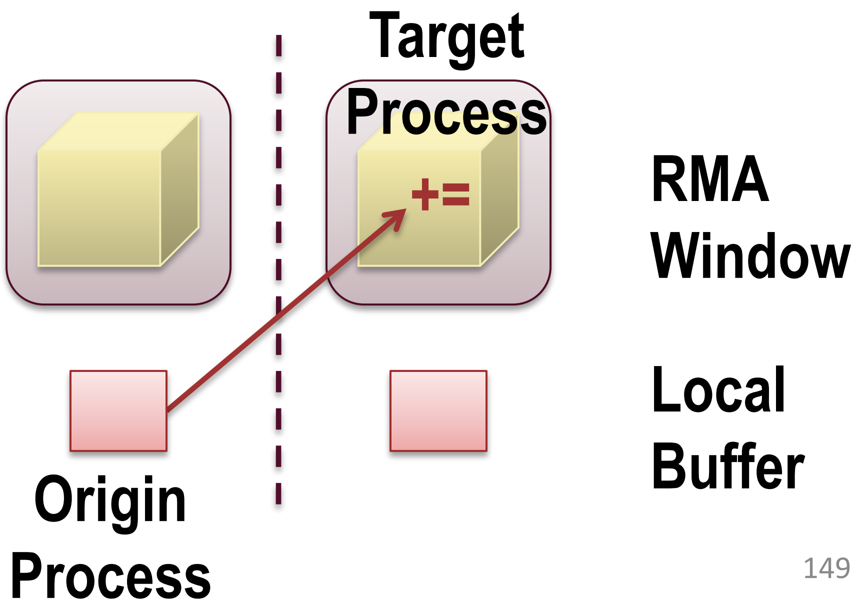
- Move data <u>from</u> origin, <u>to</u> target
- Same arguments as MPI_Get



Atomic Data Aggregation: *Accumulate*

```
MPI_Accumulate(void * origin_addr, int origin_count,
        MPI_Datatype origin_datatype, int target_rank,
        MPI_Aint target_disp, int target_count,
        MPI_Datatype target_dtype, MPI_Op op, MPI_Win win)
```

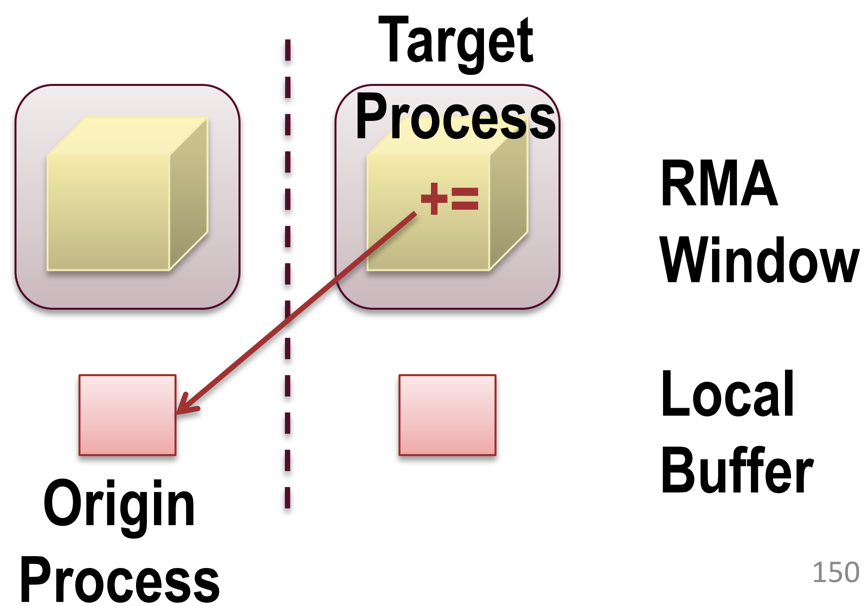
- **Atomic update operation, similar to a put**
  - Reduces origin and target data into target buffer using op argument as combiner
  - Predefined ops only, no user-defined operations
- **Different data layouts between target/origin OK**
  - Basic type elements must match
- **Op = MPI_REPLACE**
  - Implements *f(a,b)=b*
  - Atomic PUT



Atomic Data Aggregation: *Get Accumulate*

```
MPI_Get_accumulate(void *origin_addr, int origin_count,
          MPI_Datatype origin_dtype, void *result_addr,
          int result_count, MPI_Datatype result_dtype,
          int target_rank, MPI_Aint target_disp,
          int target_count, MPI_Datatype target_dype,
          MPI_Op op, MPI_Win win)
```

- **Atomic read-modify-write**
  - Op = MPI_SUM, MPI_PROD, MPI_OR, MPI_REPLACE, MPI_NO_OP, …
  - Predefined ops only
- **Result stored in target buffer**
- **Original data stored in result buf**
- **Different data layouts between target/origin OK**
  - Basic type elements must match
- **Atomic get with MPI_NO_OP**
- **Atomic swap with MPI_REPLACE**



Atomic Data Aggregation: *CAS and FOP*

```
MPI_Compare_and_swap(void *origin_addr,
        void *compare_addr, void *result_addr,
        MPI_Datatype datatype, int target_rank,
        MPI_Aint target_disp, MPI_Win win)
```

- **CAS: Atomic swap if target value is equal to compare value**
- **FOP: Simpler version of MPI_Get_accumulate**
  - All buffers share a single predefined datatype
  - No count argument (it's always 1)
  - Simpler interface allows hardware optimization

```
MPI_Fetch_and_op(void *origin_addr, void *result_addr,
        MPI_Datatype datatype, int target_rank,
        MPI_Aint target_disp, MPI_Op op, MPI_Win win)
```

RMA Synchronization Models

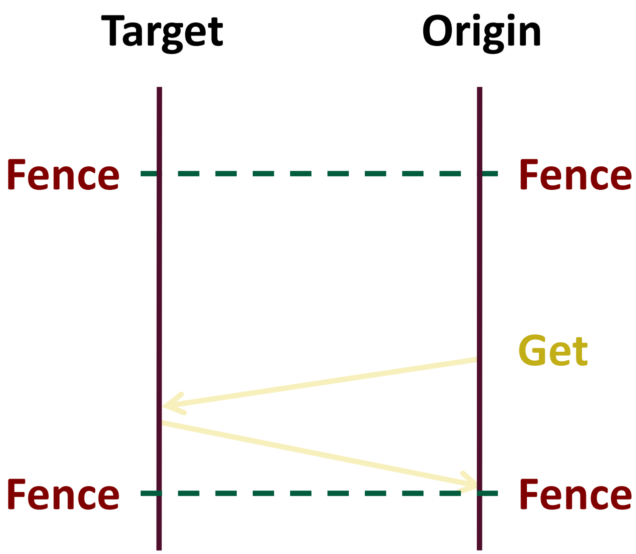
- **RMA data access model**
  - When is a process allowed to read/write remotely accessible memory?
  - When is data written by process X available for process Y to read?
  - RMA synchronization models define these semantics
- **Three synchronization models provided by MPI:**
  - Fence (active target)
  - Post-start-complete-wait (generalized active target)
  - Lock/Unlock (passive target)
- **Data accesses occur within "epochs"**
  - *Access epochs*: contain a set of operations issued by an origin process
  - *Exposure epochs*: enable remote processes to update a target's window
  - Epochs define ordering and completion semantics
  - Synchronization models provide mechanisms for establishing epochs

    E.g., starting, ending, and synchronizing epochs

Fence: Active Target Synchronization

MPI_Win_fence(int assert, MPI_Win win)

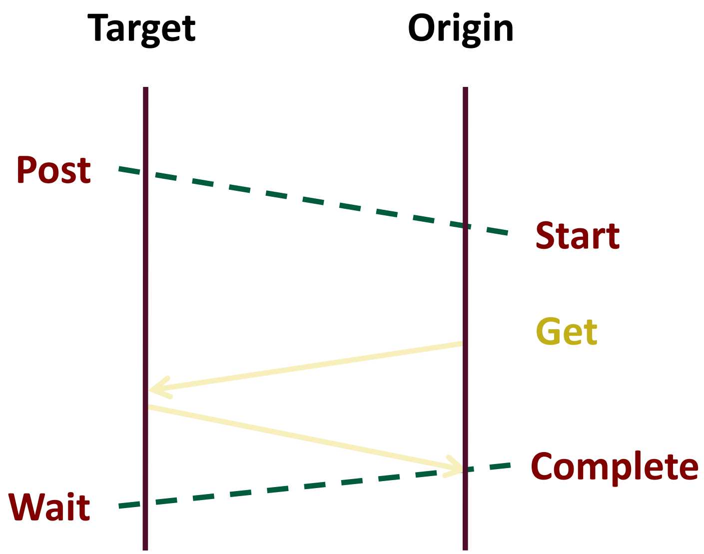
- Collective synchronization model
- Starts *and* ends access and exposure epochs on all processes in the window
- All processes in group of “win” do an MPI_WIN_FENCE to open an epoch
- Everyone can issue PUT/GET operations to read/write data
- Everyone does an MPI_WIN_FENCE to close the epoch
- All operations complete at the second fence synchronization



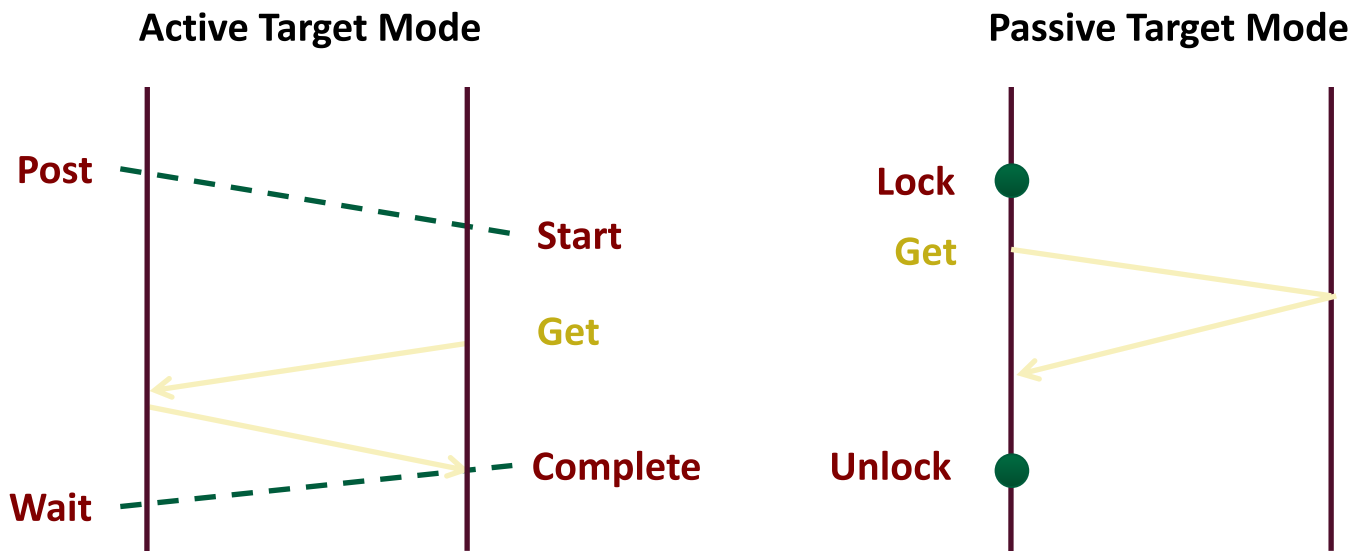
PSCW: Generalized Active Target

MPI_Win_post/start(MPI_Group, int assert, MPI_Win win)
MPI_Win_complete/wait(MPI_Win win)

- **Like FENCE, but origin and target specify who they communicate with**
- **Target: Exposure epoch**
  - Opened with MPI_Win_post
  - Closed by MPI_Win_wait
- **Origin: Access epoch**
  - Opened by MPI_Win_start
  - Closed by MPI_Win_compete
- **All synchronization operations may block, to enforce P-S/C-W ordering**
  - Processes can be both origins and targets



Lock/Unlock: Passive Target Synchronization



- **Passive mode: One-sided, *asynchronous* communication**
  - Target does **not** participate in communication operation
- **Shared memory-like model**

Passive Target Synchronization

```
MPI_Win_lock(int lock_type, int rank, int assert, MPI_Win win)

MPI_Win_unlock(int rank, MPI_Win win)
```

- **Begin/end passive mode epoch**
  - Target process does not make a corresponding MPI call
  - Can initiate multiple passive target epochs top different processes
  - Concurrent epochs to same process not allowed (affects threads)
- **Lock type**
  - SHARED: Other processes using shared can access concurrently
  - EXCLUSIVE: No other processes can access concurrently

Advanced Passive Target Synchronization

MPI_Win_lock_all(int assert, MPI_Win win)
MPI_Win_unlock_all(MPI_Win win)

MPI_Win_flush/flush_local(int rank, MPI_Win win)
MPI_Win_flush_all/flush_local_all(MPI_Win win)

- **Lock_all: Shared lock, passive target epoch to all other processes**
  - Expected usage is long-lived: lock_all, put/get, flush, …, unlock_all
- **Flush: Remotely complete RMA operations to the target process**
  - Flush_all – remotely complete RMA operations to all processes
  - After completion, data can be read by target process or a different process
- **Flush_local: Locally complete RMA operations to the target process**
  - Flush_local_all – locally complete RMA operations to all processes

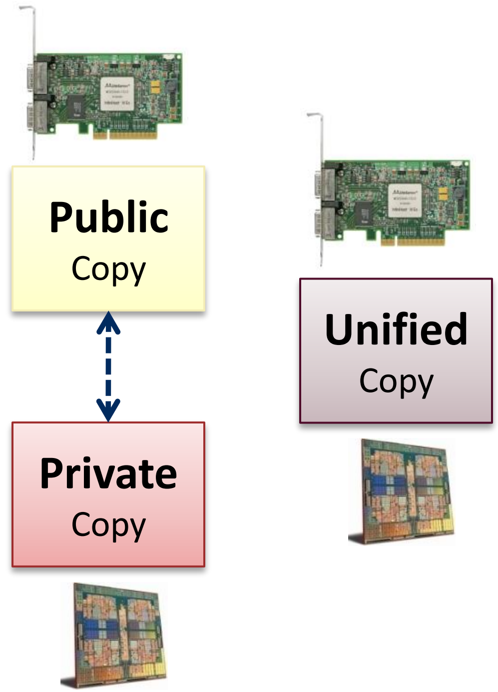
Which synchronization mode should I use, when?

- **RMA communication has low overheads versus send/recv**
  - Two-sided: Matching, queueing, buffering, unexpected receives, etc…
  - One-sided: No matching, no buffering, always ready to receive
  - Utilize RDMA provided by high-speed interconnects (e.g. InfiniBand)
- **Active mode: bulk synchronization**
  - E.g. ghost cell exchange
- **Passive mode: asynchronous data movement**
  - Useful when dataset is large, requiring memory of multiple nodes
  - Also, when data access and synchronization pattern is dynamic
  - Common use case: distributed, shared arrays
- **Passive target locking mode**
  - Lock/unlock – Useful when exclusive epochs are needed
  - Lock_all/unlock_all – Useful when only shared epochs are needed

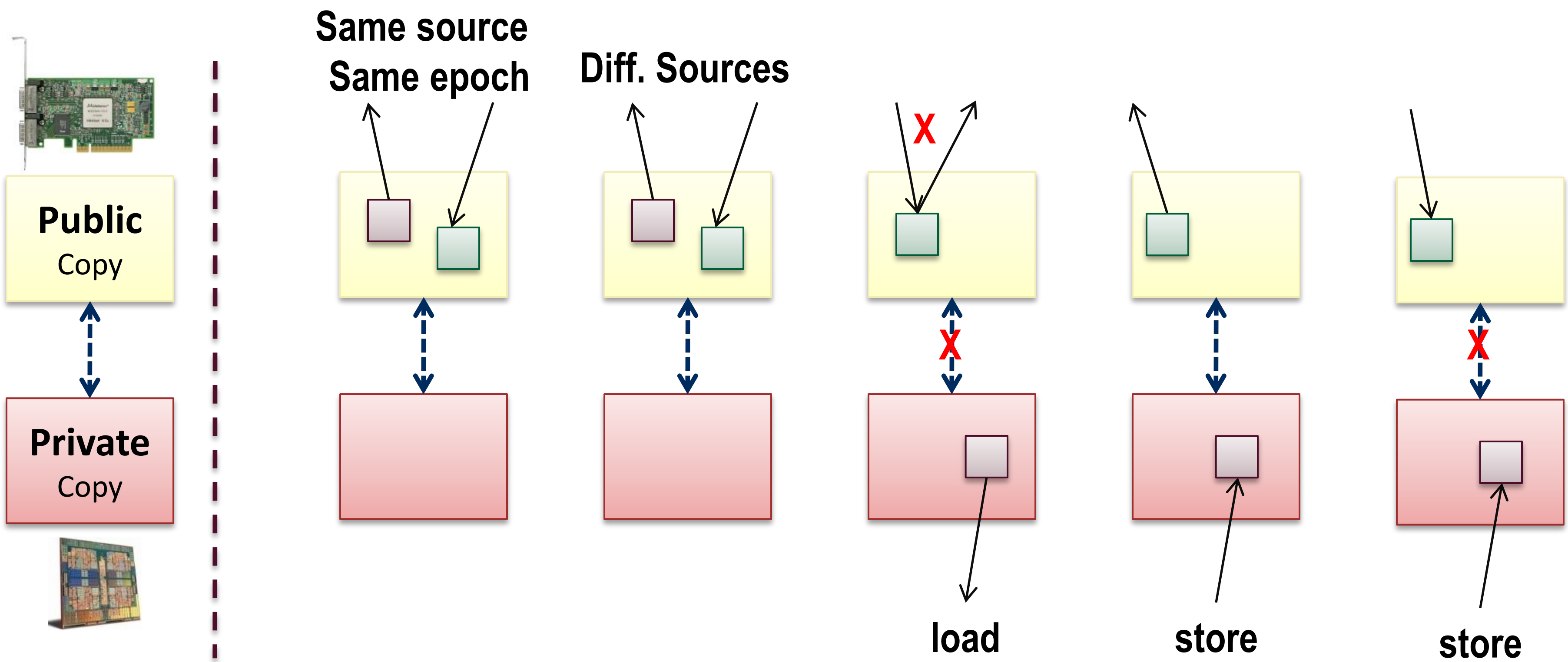
MPI RMA Memory Model

- **MPI-3 provides two memory models: separate and unified**
- **MPI-2: Separate Model**
  - Logical public and private copies
  - MPI provides software coherence between window copies
  - Extremely portable, to systems that don’t provide hardware coherence
- **MPI-3: New Unified Model**
  - Single copy of the window
  - System must provide coherence
  - Superset of separate semantics

    E.g. allows concurrent local/remote access
  - Provides access to full performance potential of hardware

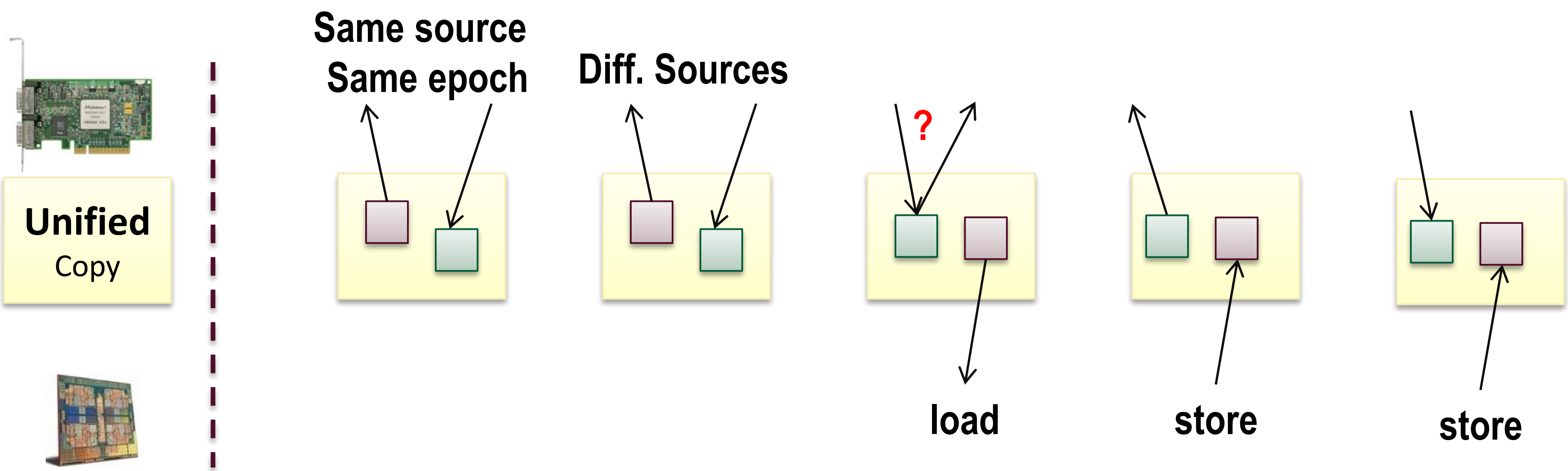


MPI RMA Memory Model (separate windows)



- Very portable, compatible with non-coherent memory systems
- Limits concurrent accesses to enable software coherence

MPI RMA Memory Model (unified windows)



- **Allows concurrent local/remote accesses**
- **Concurrent, conflicting operations don't "corrupt" the window**
  - Outcome is not defined by MPI (defined by the hardware)
- **Can enable better performance by reducing synchronization**

That’s it folks

- **Thanks for your attention and contributions to the class ☺**
- **Good luck (better: success!) with your project**
  - Don’t do it last minute!
- **Same with the final exam!**
  - Di 21.01., 09:00-11:00 (watch date and room in edoz)
- **Do you have any generic questions?**
  - Big picture?
  - Why did we learn certain concepts?
  - Why did we not learn certain concepts?
  - Anything else (comments are very welcome!)