Non-Blocking Synchronization and Object-Oriented Operating System Design

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Our Goal

The design of a

Object-Oriented

Non-Blocking

Operating System

Our Goal

The design of a *language to support*

Object-Oriented

Non-Blocking

Operating Systems

Why Object-Oriented?

Clear interfaces and strong encapsulation provide for:

- Safety
  - Software protection mechanisms.
- Ease
  - Clean composition semantics.
  - Uniform synchronization.
- Performance
  - Specialized implementations.
  - Natural grouping/locality.

Why Non-Blocking?

- Increased robustness
  - No deadlocks, no bookkeeping.
- Better decoupling
  - Better code structure; protection from asynchronous events.
- Increased parallelism
  - No idle processors, no convoys.
- Low overhead
  - No semaphore queue maintenance.
- Progress guarantees
  - Real-time properties; no priority inversion.

Outline

- Survey prior non-blocking O-O Operating Systems:
  - Synthesis [Massalin and Pu 1991]
  - Cache Kernel [Greenwald and Cheriton 1996]
- A more general approach:
  - Language support for synchronization
  - Functional Arrays
  - Single-object protocol
  - Multiple-object protocol
  - Lock-free functional arrays
- Assessment and conclusions

The Synthesis Kernel

- Synthesis is a lock-free OS implemented by Massalin and Pu.
- Explored use of run-time specialization for efficiency.
- Object encapsulation required to enable specialization; objects called quajects.
- Implemented in 680x0 assembly; macro support for quajects.
- Extremely high performance.

The Synthesis Kernel, cont.

Types of quajects:

- Threads
- Memory segments
- Symbol tables
- Data channels (I/O, pipes, filters, . . .)

Three quajects for synchronization:

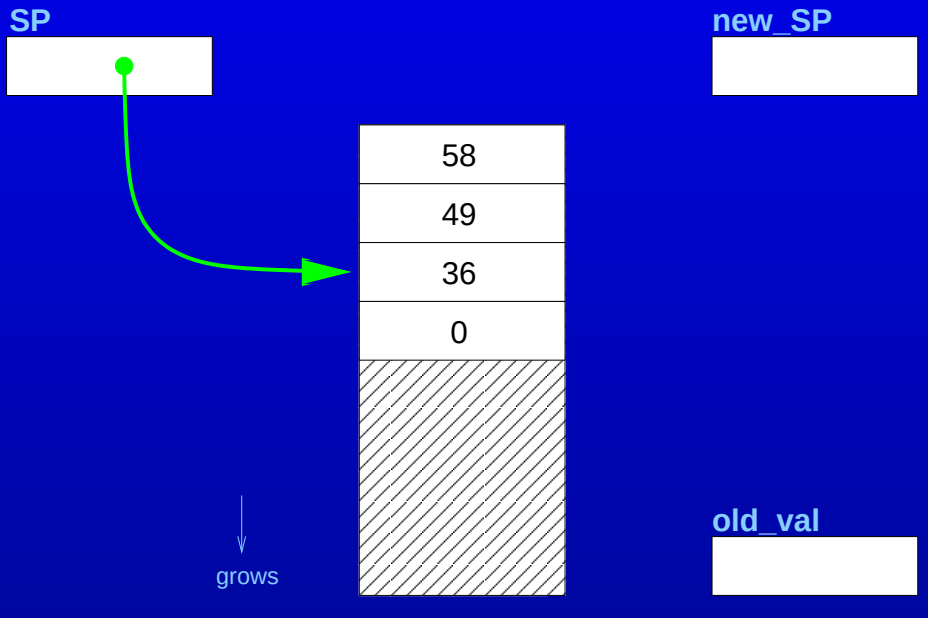
- LIFO stack
- FIFO queue (4 variants)
- Linked list

Synthesis Synchronization Errors

Three synchronization errors found in published lock-free algorithms for Synthesis.

- One ABA problem in LIFO stack.
- One likely race in MP-SC FIFO queue.
- One interesting corner case in quaject callback handling.

LIFO stack: Push

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Push(elem)
{
retry:
    old_SP = SP;
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    if(DCAS(old_SP, old_val,
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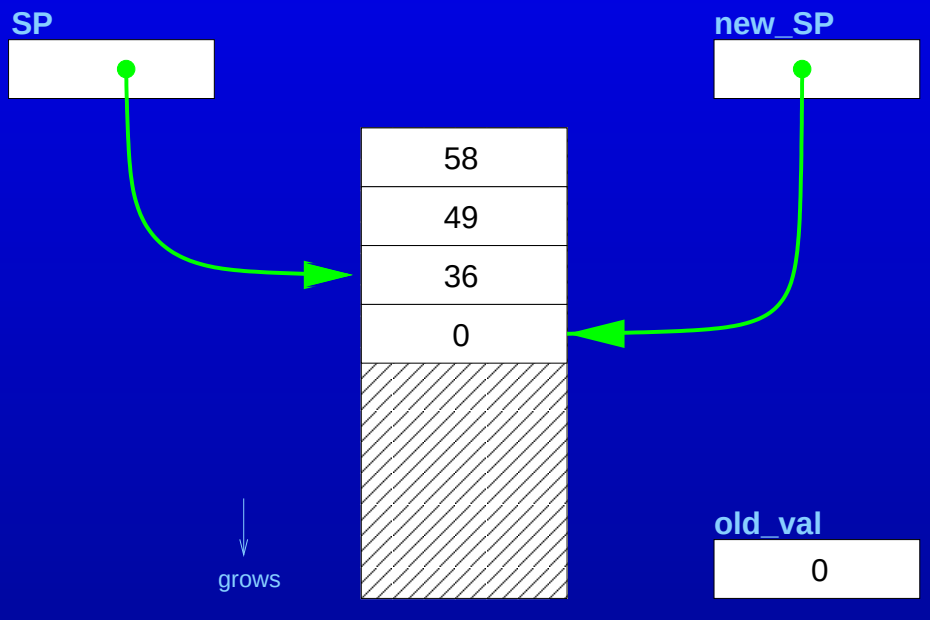

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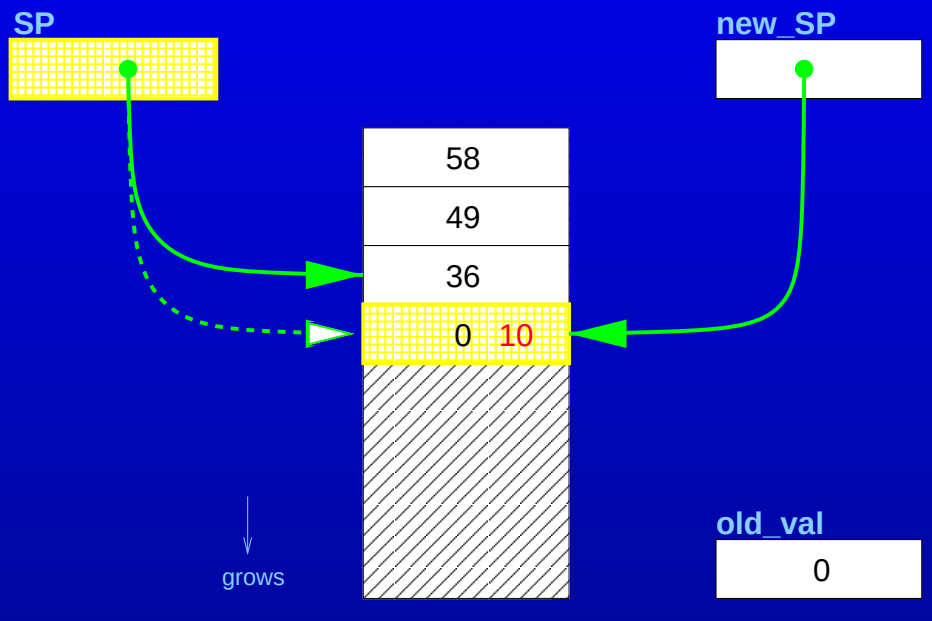

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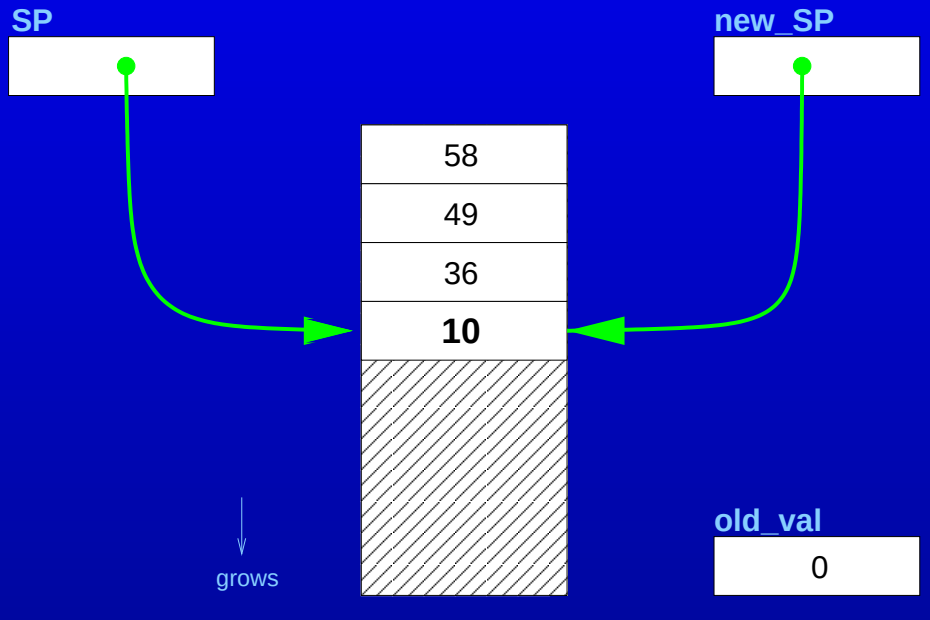


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}
```

LIFO stack: Pop

```
Pop()
{
retry:
    old_SP = SP;
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    elem = *old_SP;
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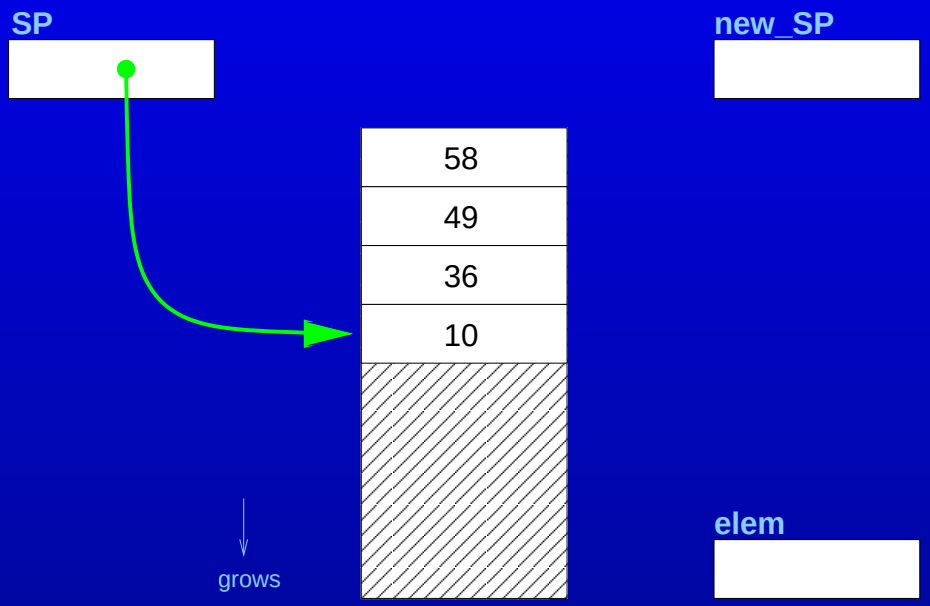

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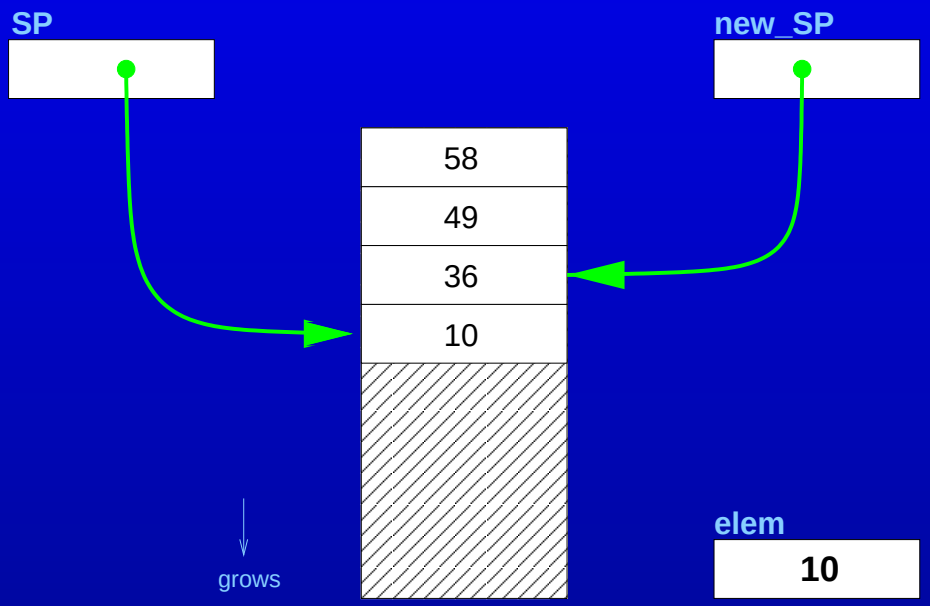

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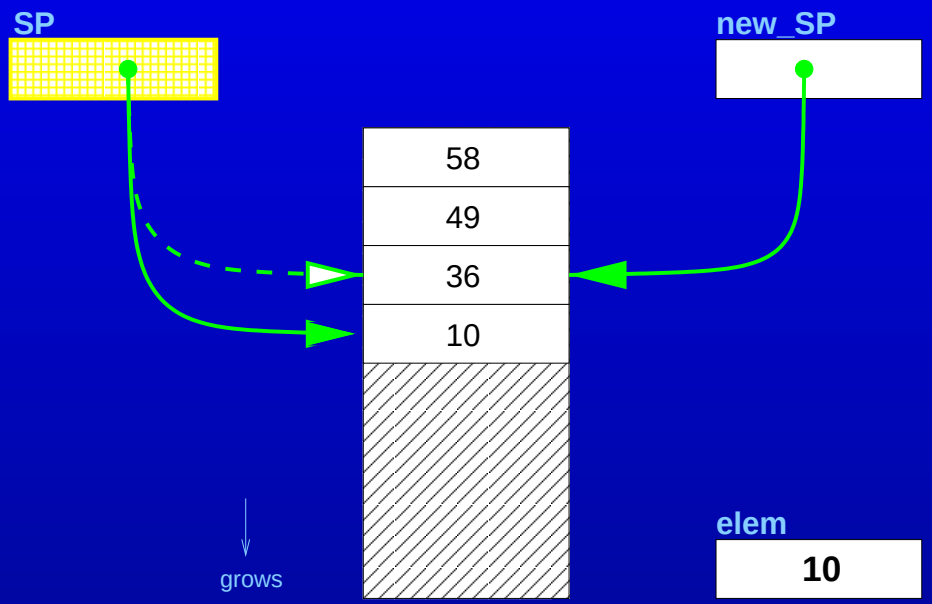


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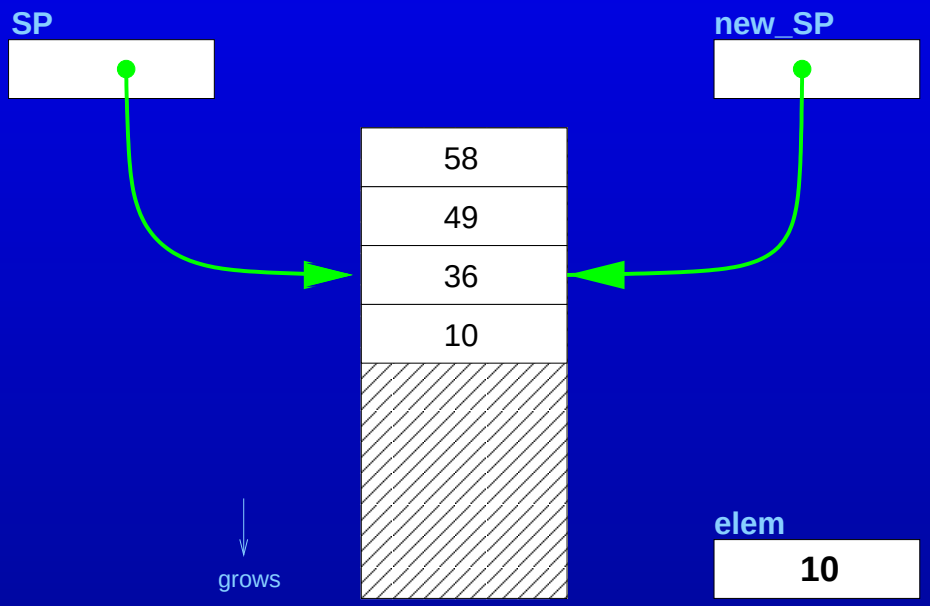

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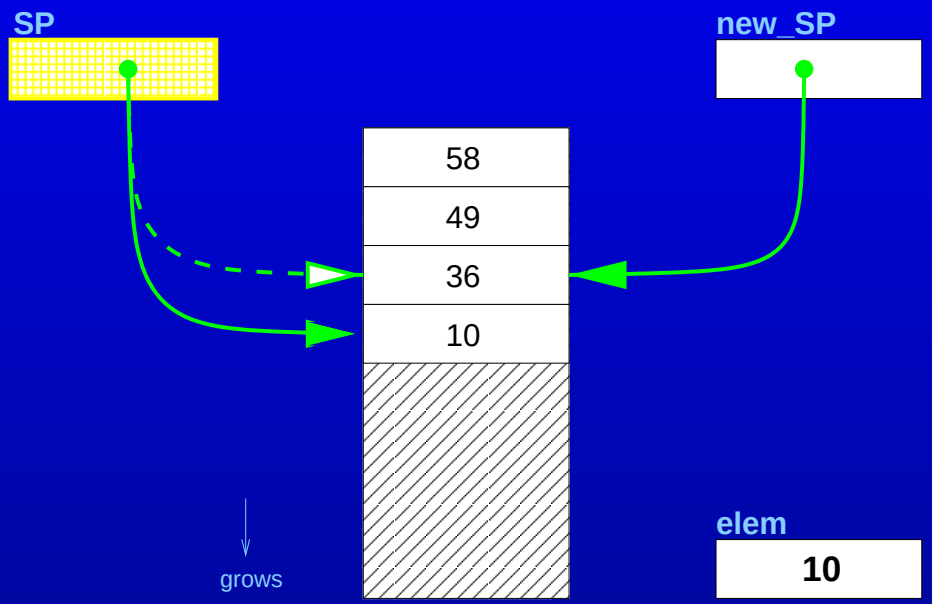


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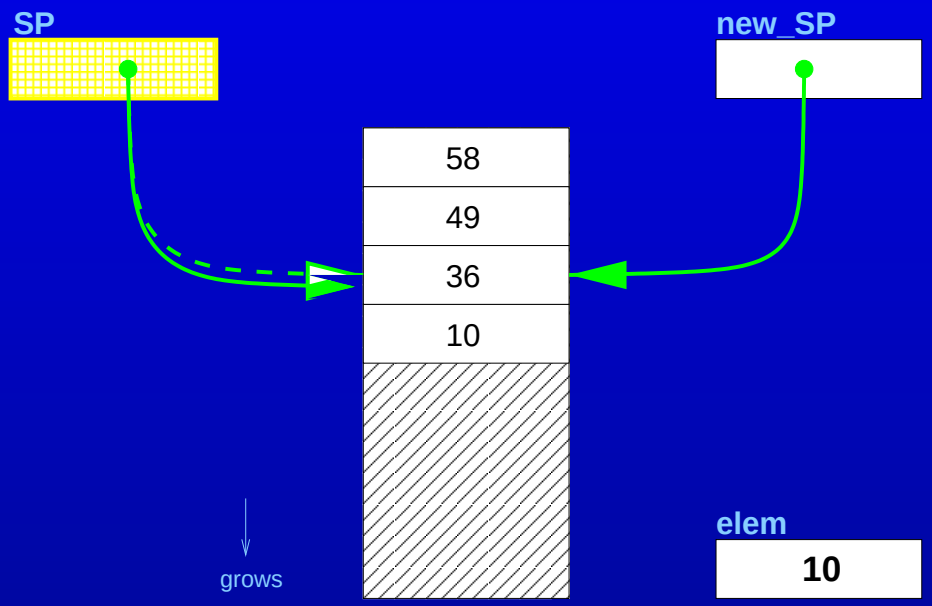


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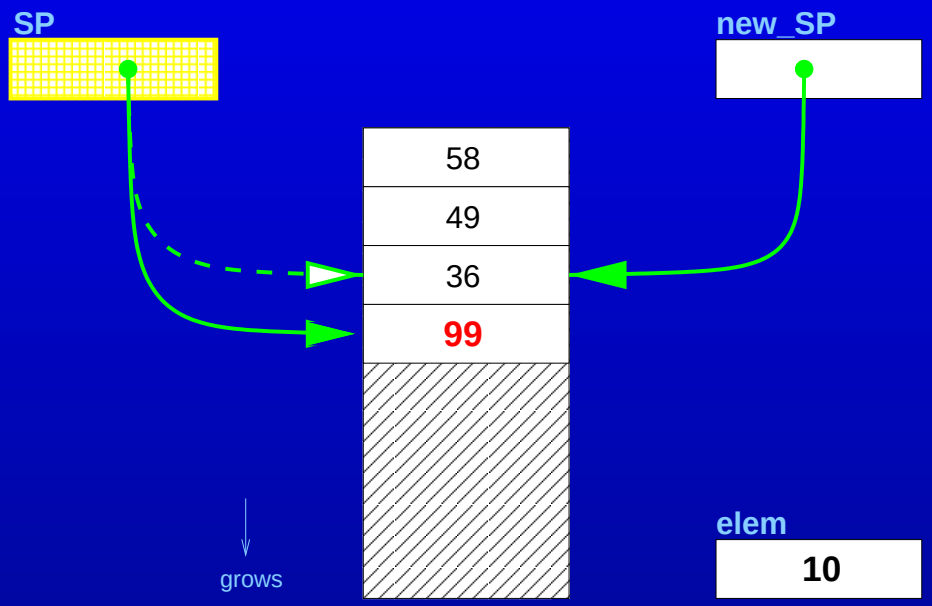

SP-SC FIFO queue

```
next(x) { return (x+1) % Q_size; }

Q_put(data) {
    h = Q_head;
    if (next(h) == Q_tail)
        wait;
    Q_buf[h] = data;
    Q_head = next(h);
}
Q_get() {
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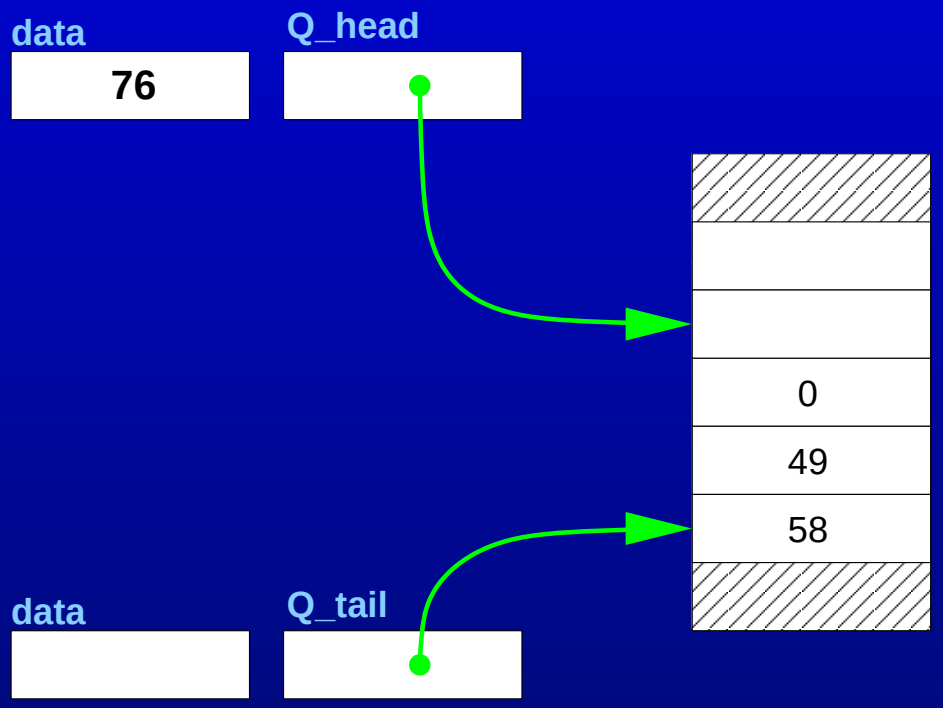

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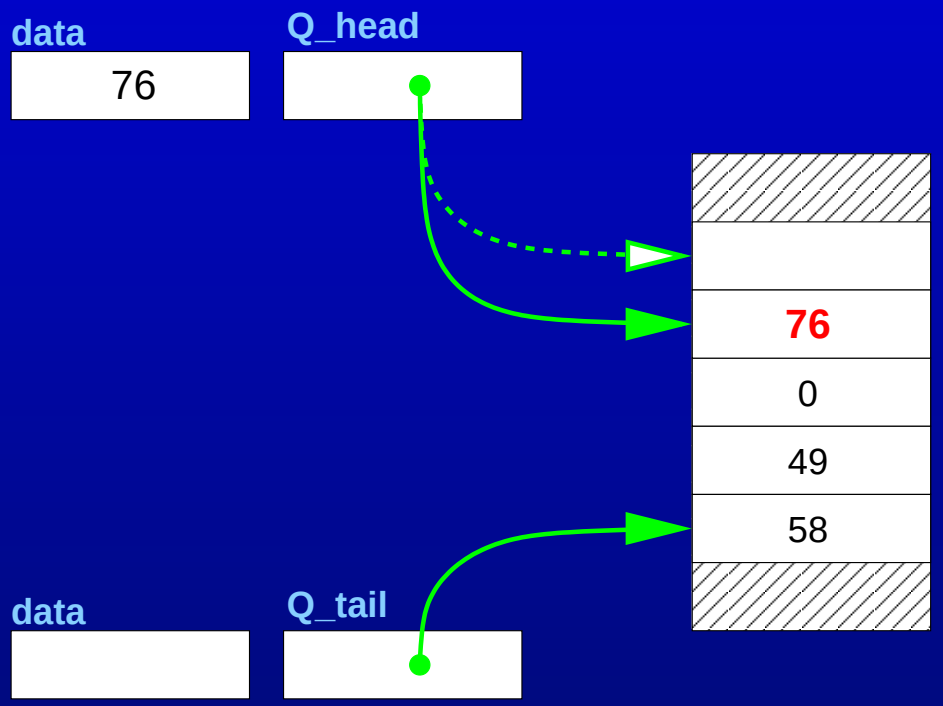

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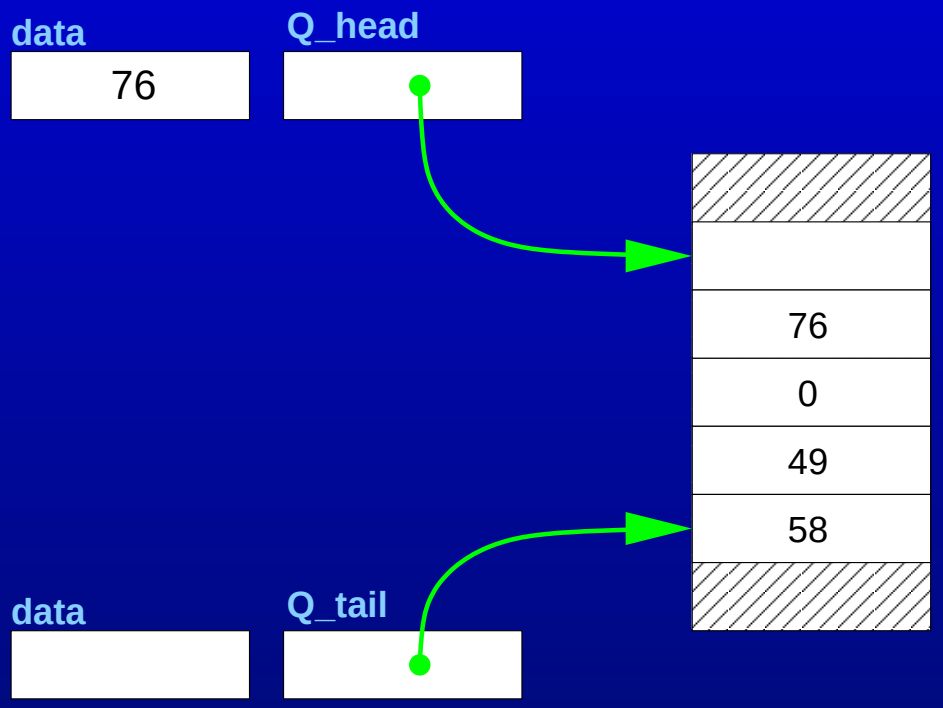

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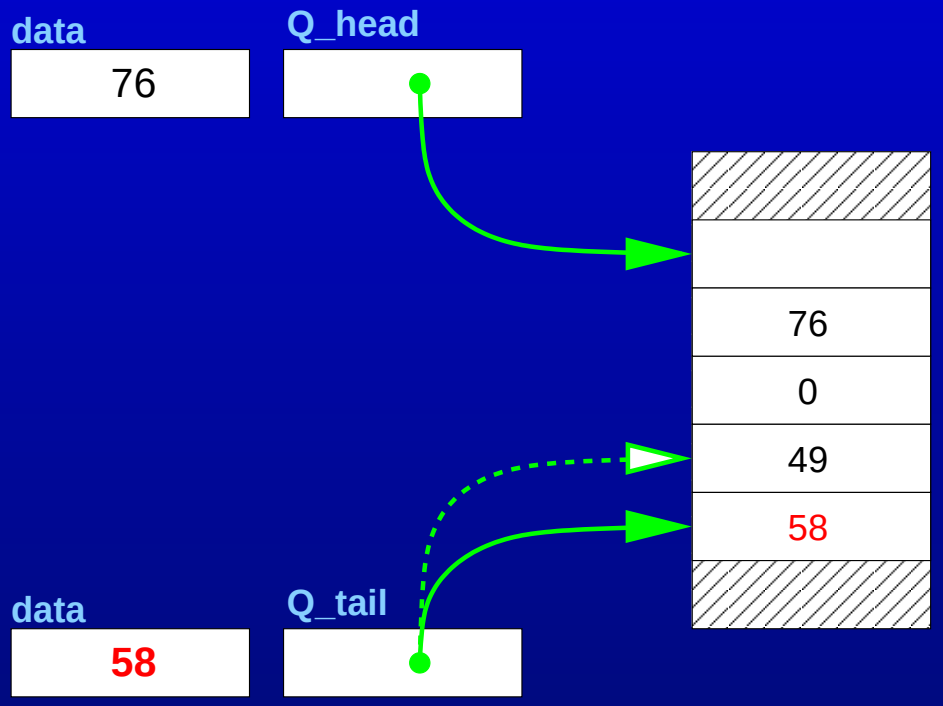

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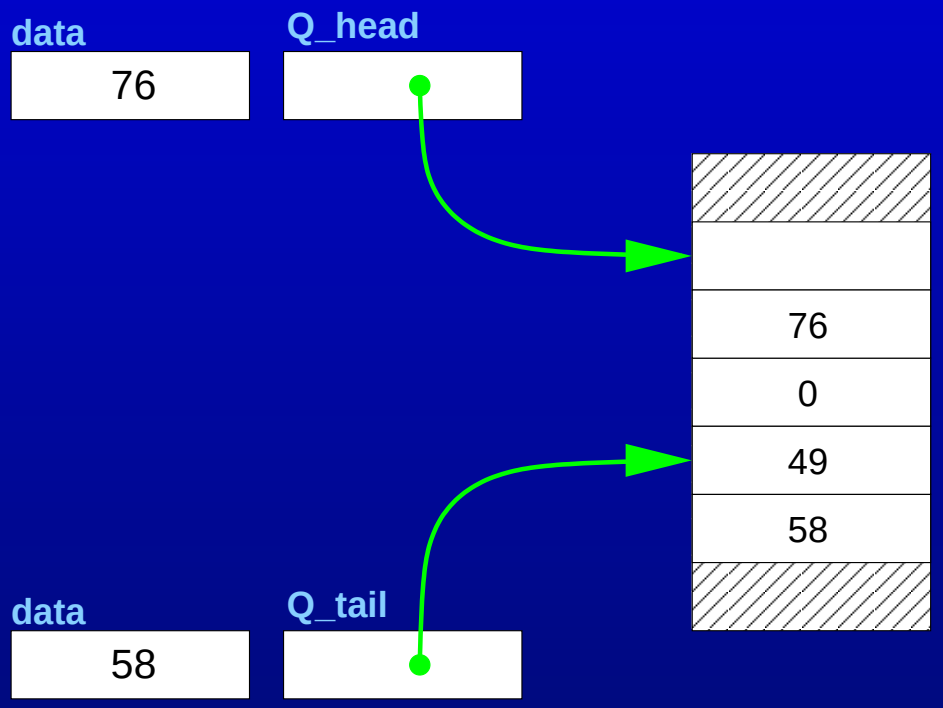

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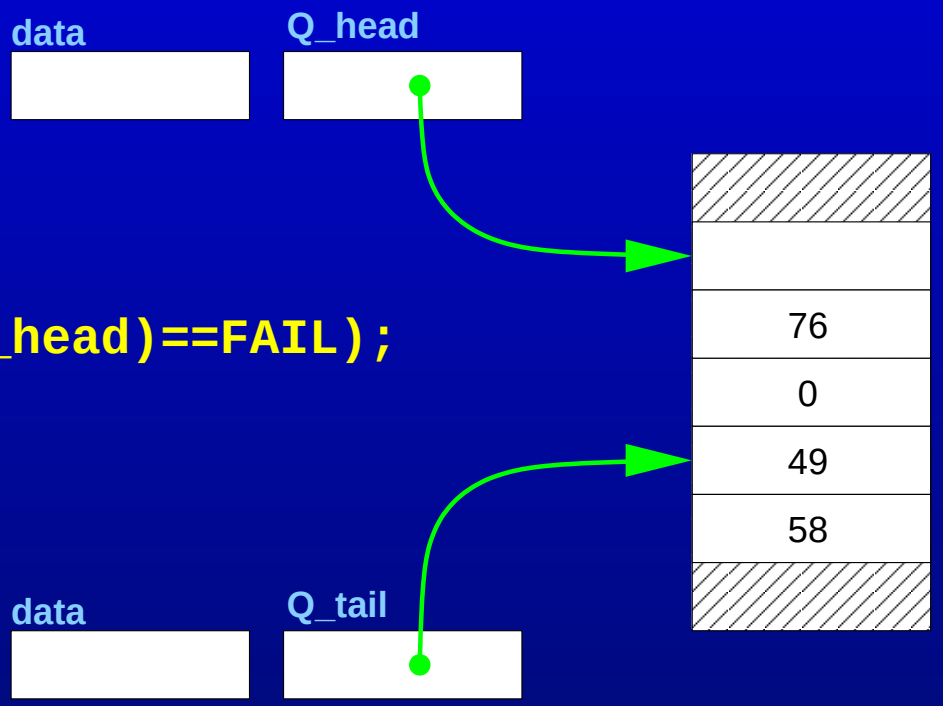

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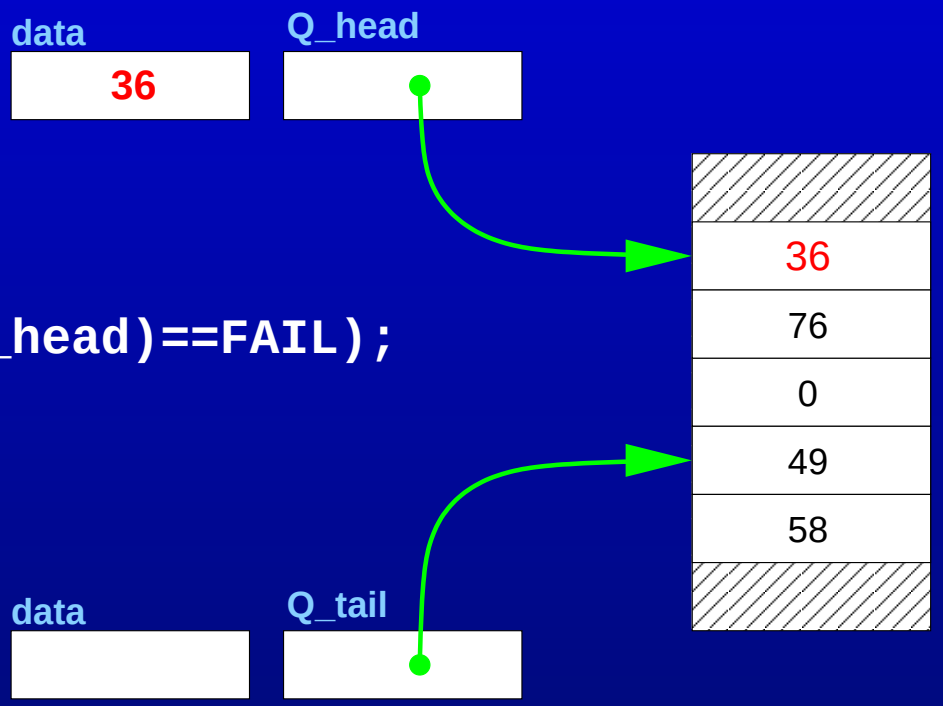

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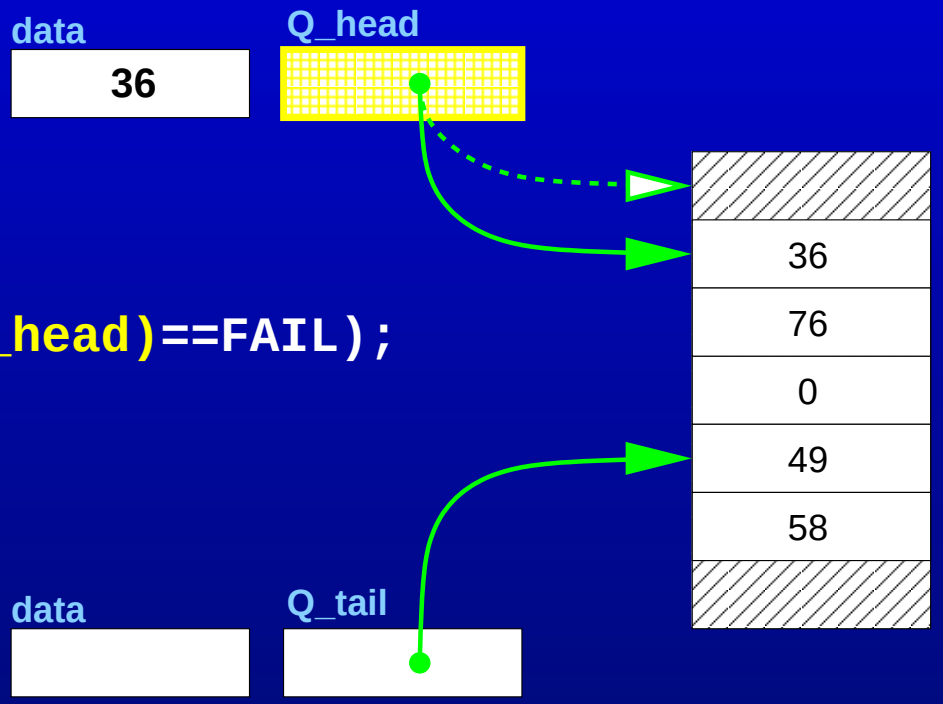

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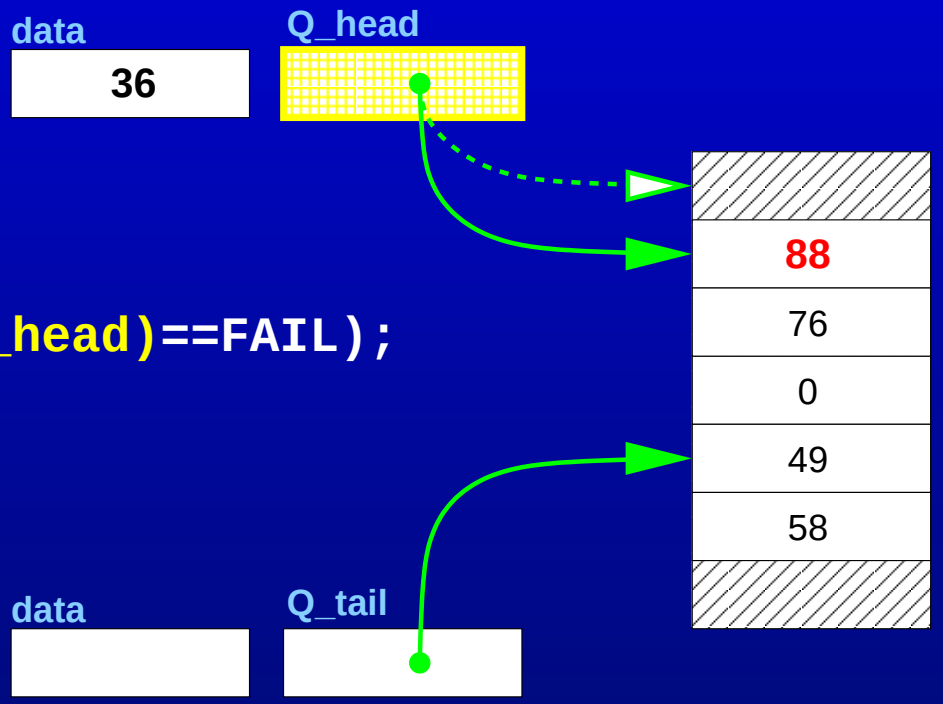

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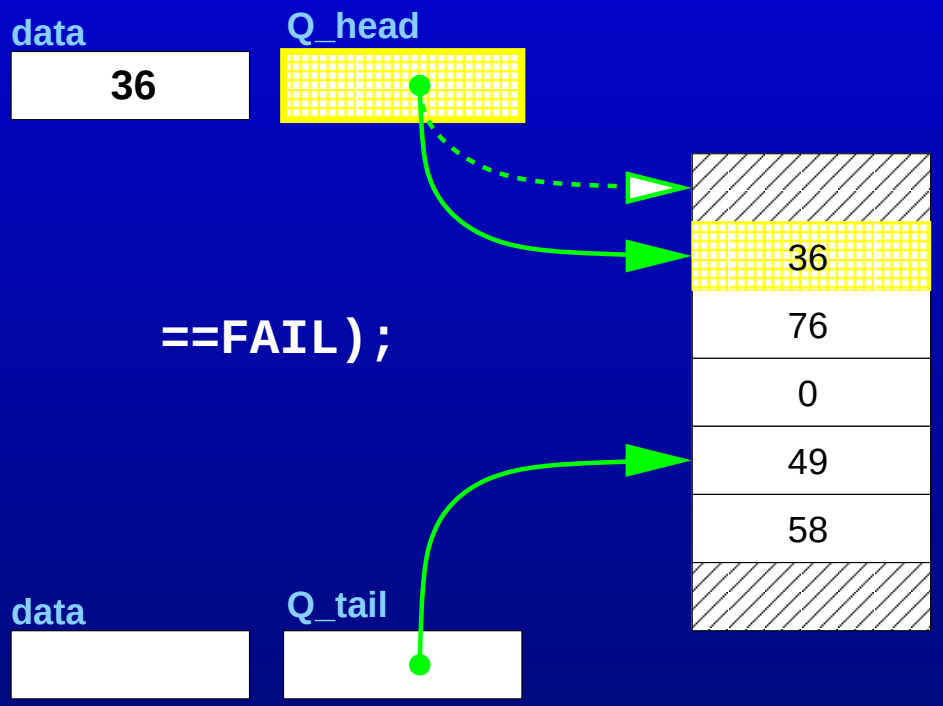

Quaject callback

Queue quaject hooked up to a hardware interrupt (consumer) and a user thread (producer).

Kind of Reference	User Thread		ByteQueue	ByteQueue	Device Driver		Hardware
callentry	**write**	$\Longrightarrow$	`Q_put`	`Q_get`		$\Longleftarrow$	*send-complete* interrupt
callback	**suspend**	$\Longleftarrow$	`Q_full`	`Q_empty`		$\Longrightarrow$	turn off *send-complete*
callback	**resume**	$\Longleftarrow$	`Q_full-1`	`Q_empty-1`		$\Longrightarrow$	turn on *send-complete*

- Calls to `Q_put` (`Q_get`) return immediately as long as queue is not full (empty), otherwise the `Q_full` (`Q_empty`) callback is invoked.
- When the queue later empties (fills) the `Q_full-1` (`Q_empty-1`) callback is invoked.

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- Intended to emulate blocking I/O when callbacks are hooked up to thread suspend/resume.
- BUT what if queue empties between invocation of `Q_full` and the actual thread suspend?

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- Solution #1: Disable signals/interrupts in this critical region.
- Solution #2: Atomically add to suspend list iff queue is still full. What about additional compare?

The Cache Kernel
[Greenwald and Cheriton 1996]

- Minimal microkernel with only three operating system object types:
  - Address spaces
  - Threads
  - Application kernels
- Only one interprocess notification mechanism: asynchronous signals.
- Lock-free implementation to handle large amount of asynchrony w/o coupling.
- Lock-free sync allows pushing OS functions into userland w/o deadlock when user threads are terminated.

Cache Kernel synchronization

General strategy for lock-free data structures:

- Each data structure has a version number.
- Each modification to the data structure increments the version number.

To make a one-word change:

- Read and remember v, the current version number.
- Traverse the structure to compute the change.
- Use DCAS to atomically apply the change and increment the version number, conditional on the current version number still being equal to v.

Lock-Free Linked List

```
Delete(elt) {
    do {
    retry:
        backoffIfNeeded();
        version = list->version;

        for (p = list->head; p->next != elt; p = p->next) {
            if (p==NULL) {              /* Not found */
                if (version != list->version)
                    goto retry;           /* Changed */
                return NULL;    /* Really not found */
            }
    } while (!DCAS(&(list->version), &(p->next),
                   version,           elt,
                   version+1,         elt->next));
    return elt;
}
```

Version-Number/DCAS Limitations

Version number protects *entire* data structure.

- Concurrent mutations to non-interfering sections of data structure not allowed.
- Workaround: break up data structure. List of lists, etc.

Only one-word mutations are allowed.

- Copy-and-swap larger objects.
  - Copying is expensive!
- Remove, mutate, and add.
  - Results in “best-effort” data structures which require high-level timeout and retry mechanisms.

Outline

- Survey prior non-blocking O-O Operating Systems:
  - Synthesis [Massalin and Pu 1991]
  - Cache Kernel [Greenwald and Cheriton 1996]
- A more general approach:
  - Language support for synchronization
  - Functional Arrays
  - Single-object protocol
  - Multiple-object protocol
  - Lock-free functional arrays
- Assessment and conclusions

A More General Scheme

Ad hoc impl. of lock-free data structures are:

- Hard to get right!
  - Three errors in Synthesis.
- Limited
  - Small number of hand-coded data structures.
- Brittle
  - Small number of atomic actions.
  - Forced to copy-and-swap to make larger actions atomic.
  - Copy-and-swap works poorly on large objects.

Solution: integrate synchronization into the language.

Monitor Synchronization

- Introduced by Emerald [Black et al 1986]; familiar now in Java.
- Every object contains a monitor which:
  - Enforces mutual exclusion
  - Serves as a signalling mechanism
- Certain methods are monitored
- Shared variables of objects can only be accessed by monitored methods.
  - Java doesn't enforce this.

Not sufficient to prevent unexpected parallel behavior!

Synchronization Failures

```
class A { // OK!
    int x; // shared variable
    synchronized int inc() {
        return x++;
    }
}

class B { // Race-free, but not OK.
    int x; // shared variable
    synchronized int get() { return x; }
    synchronized void set(int y) { x=y; }
    int inc() { // not monitored
        int t = get();
        t++;
        set(t);
        return t;
    }
}
```

Atomic Blocks

```
public class Count {
 private int cntr = 0;
 void inc() {
  synchronized(this) {
   cntr = cntr + 1;
  }
 }
}
```

- Traditionally, monitors associated with each object provide mutual exclusion between concurrent accesses to the object.

Atomic Blocks

```
public class Count {
 private int cntr = 0;
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  }
 }
}
```

$\Rightarrow$

```
public class Count {
 private int cntr = 0;
 void inc() {
  atomic {
   cntr = cntr + 1;
  }
 }
}
```

- Instead we provide an `atomic` block, and make linearizablity guarantees without (necessarily) providing mutual exclusion.

Language Design for OSes

- We'll start with Java
  - C-like expressions, O-O structure, type-safety.
- Add low-level constructs
  - Interrupt linkage, fixed object layout for memory-mapped I/O
  - JEPES [Schultz et al 2003], Lisaac [Sonntag and Colnet 2002]
- Use software protection mechanisms
  - Remove address spaces from kernel
  - DrScheme [Flatt et al 1999]
- Provide atomic operation blocks
  - Implement with non-blocking synchronization

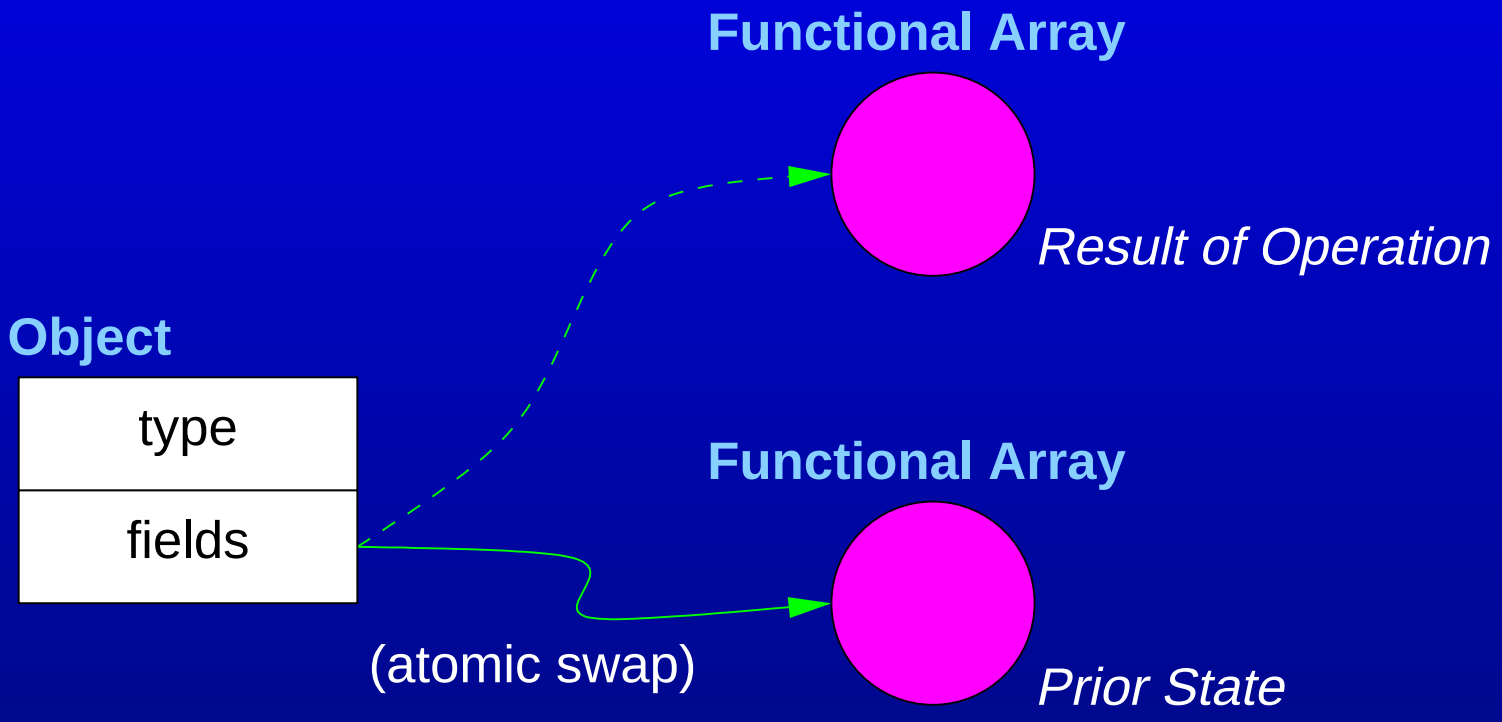
Functional Arrays

Our implementation of `atomic` blocks will be based on fast *functional arrays*.

- Functional arrays are persistent; after an element is updated both the new and the old contents of the array are available for use.
- Fundamental operation:
  $\textsc{Update}(A, i, v) : A \to \mathbb{N}_0 \to V \to A$
- Arrays are just mappings from integers to values; any persistent map can be used as a functional array.
- A *fast* functional array will have $O(1)$ access and update “for the common cases”.

Single Object Protocol

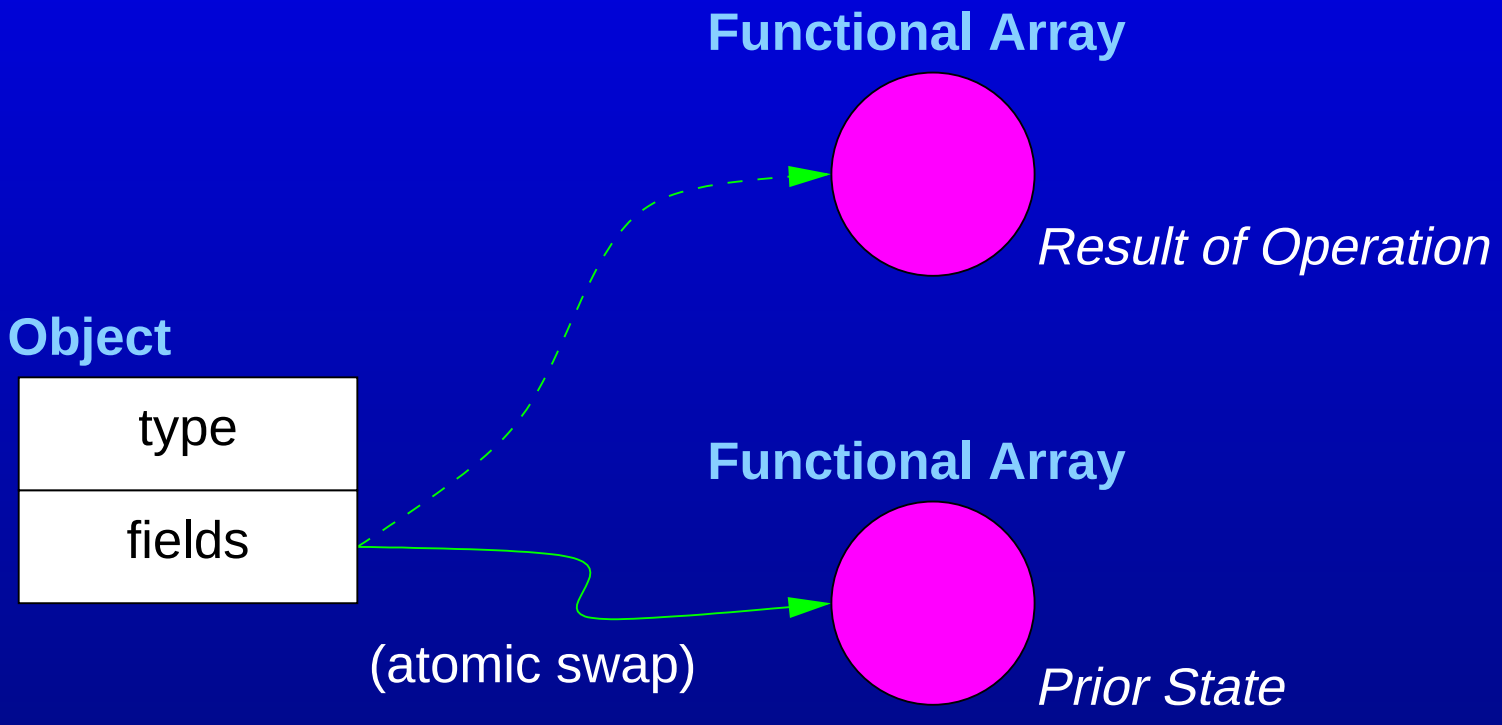
Valid for operations on a single object only.



- Object representation contains a pointer to a functional array.
- Object mutation inside `atomic` creates new functional array.

Single Object Protocol

Valid for operations on a single object only.



- At start of `atomic` block load and remember fields array pointer as *prior state*.
- At end of `atomic` block compare-and-swap the *result of operation* for the *prior state*.

Problems with Multiple Objects

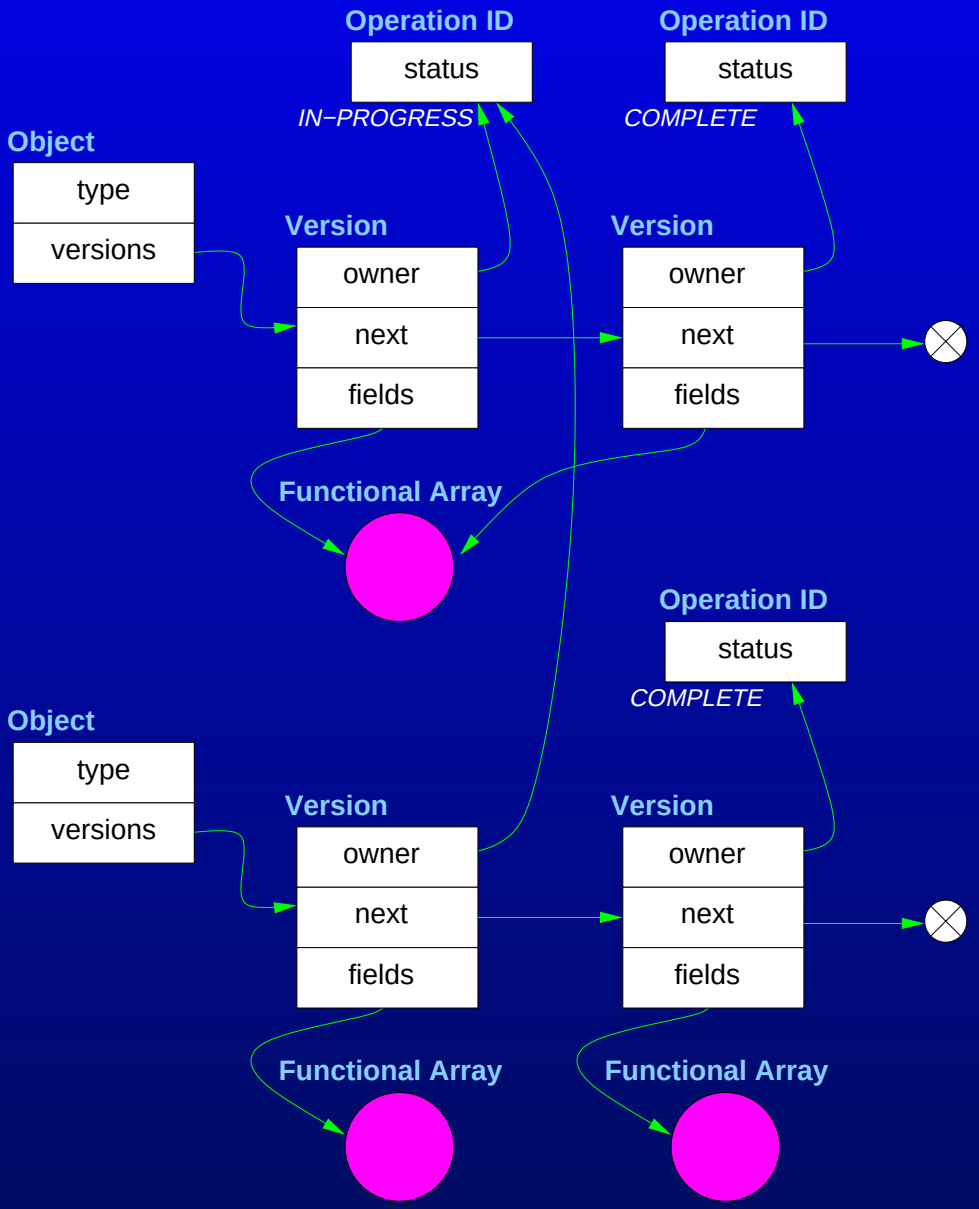
The case of the StringBuffer

```
public final class StringBuffer ...{
    ...
    private int count;

    public synchronized StringBuffer append(StringBuffer sb) {
        if (sb == null) { sb = NULL; }
        int len = sb.length(); // len may be stale.
        int newcount = count + len;
        if (newcount > value.length) expandCapacity(newcount);
        sb.getChars(0, len, value, count); // use of stale len
        count = newcount;
        return this;
    }
    public synchronized int length() { return count; }
    public synchronized void getChars(...)  { ...}
}
```

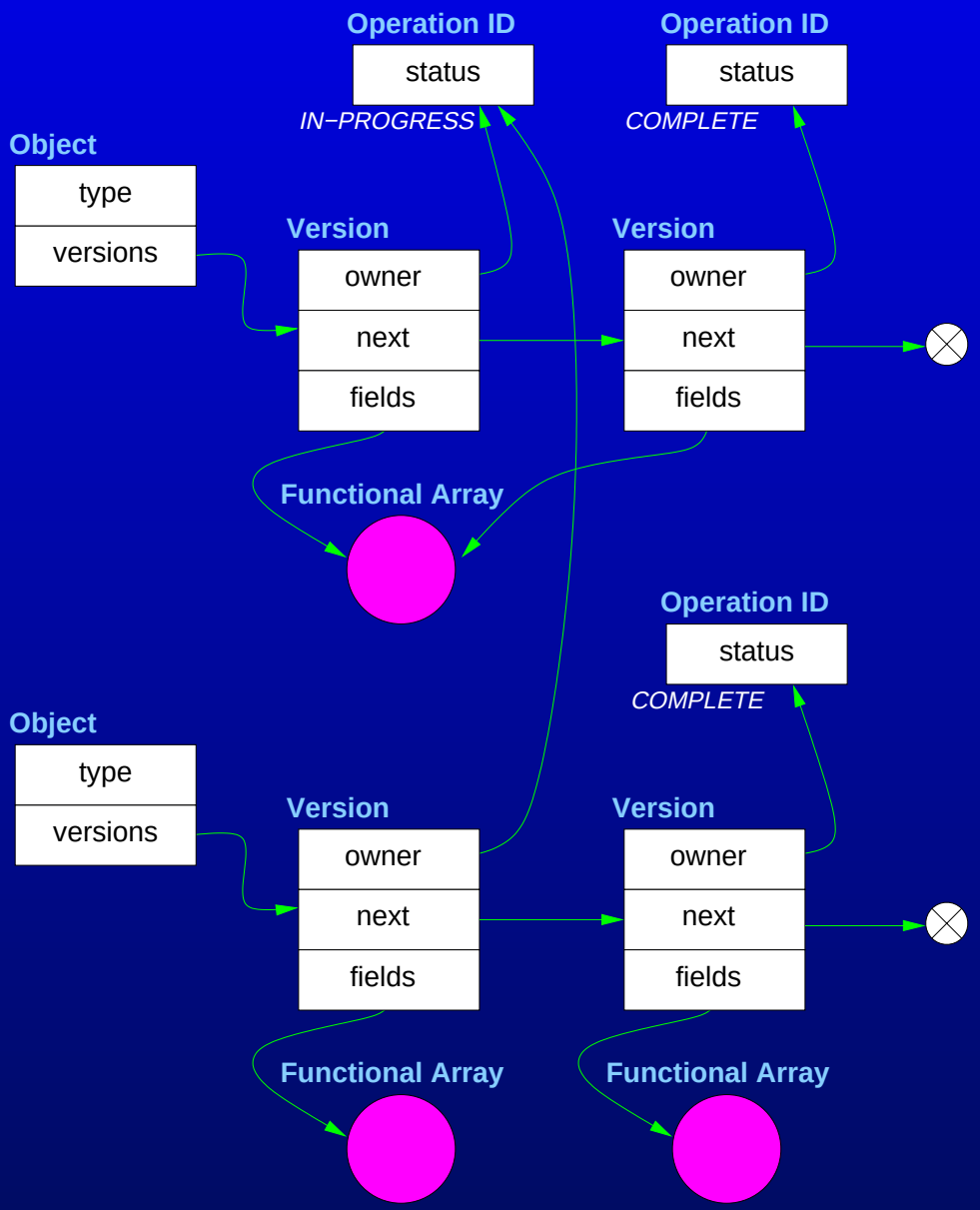
Multiple Object Protocol

- Objects point to version lists.
- Each version has an associated operation ID and field array reference.
- Operation IDs are initialized to *IN-PROGRESS* and are changed exactly once to *COMPLETE* or *DISCARDED*.



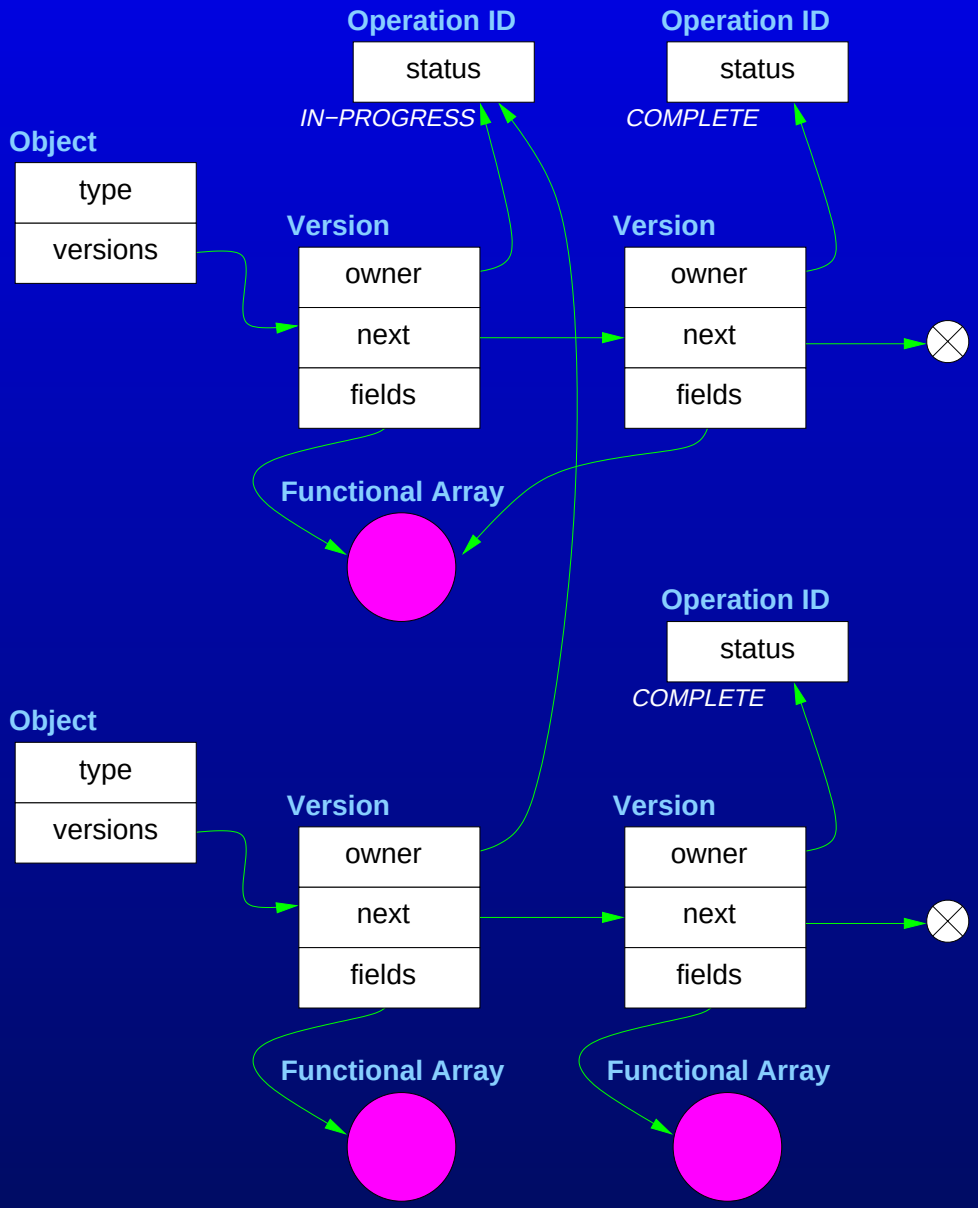
Multiple Object Protocol

- At end of atomic block, attempt to set Operation ID to *COMPLETE*.
- Value of object is value of first committed version.
- Old or *DISCARDED* versions can be trimmed.



Multiple Object Protocol

- Only one *IN-PROGRESS* version allowed on versions list, and it must be at the head.
- Before we can link a new version onto the versions list, we must ensure that every other version is either *COMPLETE* or *DISCARDED*.



Outline

- Survey prior non-blocking O-O Operating Systems:
  - Synthesis [Massalin and Pu 1991]
  - Cache Kernel [Greenwald and Cheriton 1996]
- A more general approach:
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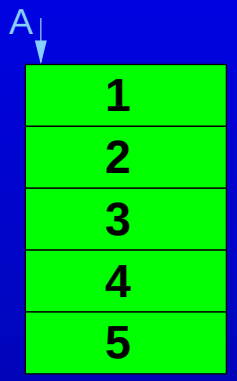
  - Functional Arrays
  - Single-object protocol
  - Multiple-object protocol
  - Lock-free functional arrays
- Assessment and conclusions

Functional Arrays using Shallow Binding



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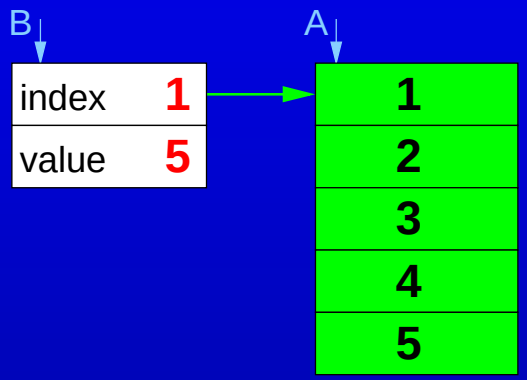

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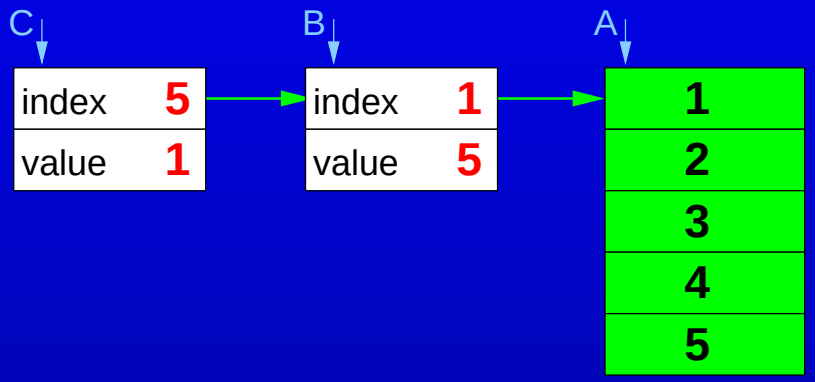

Functional Arrays using
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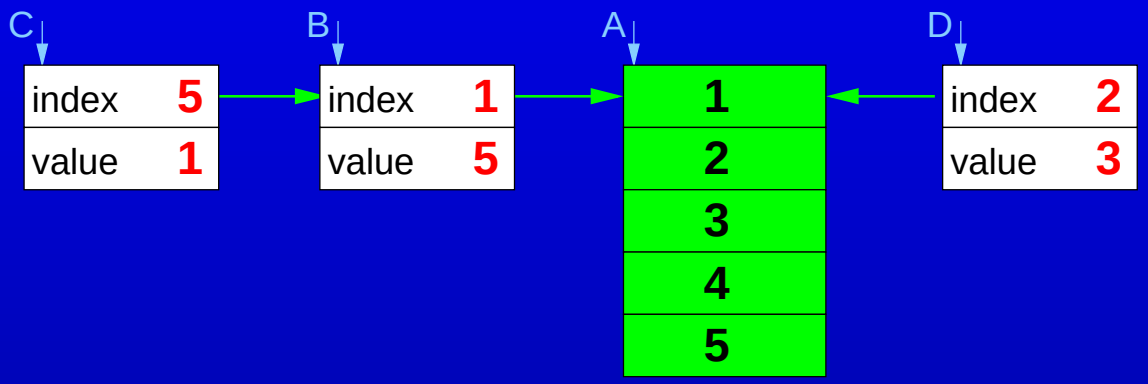

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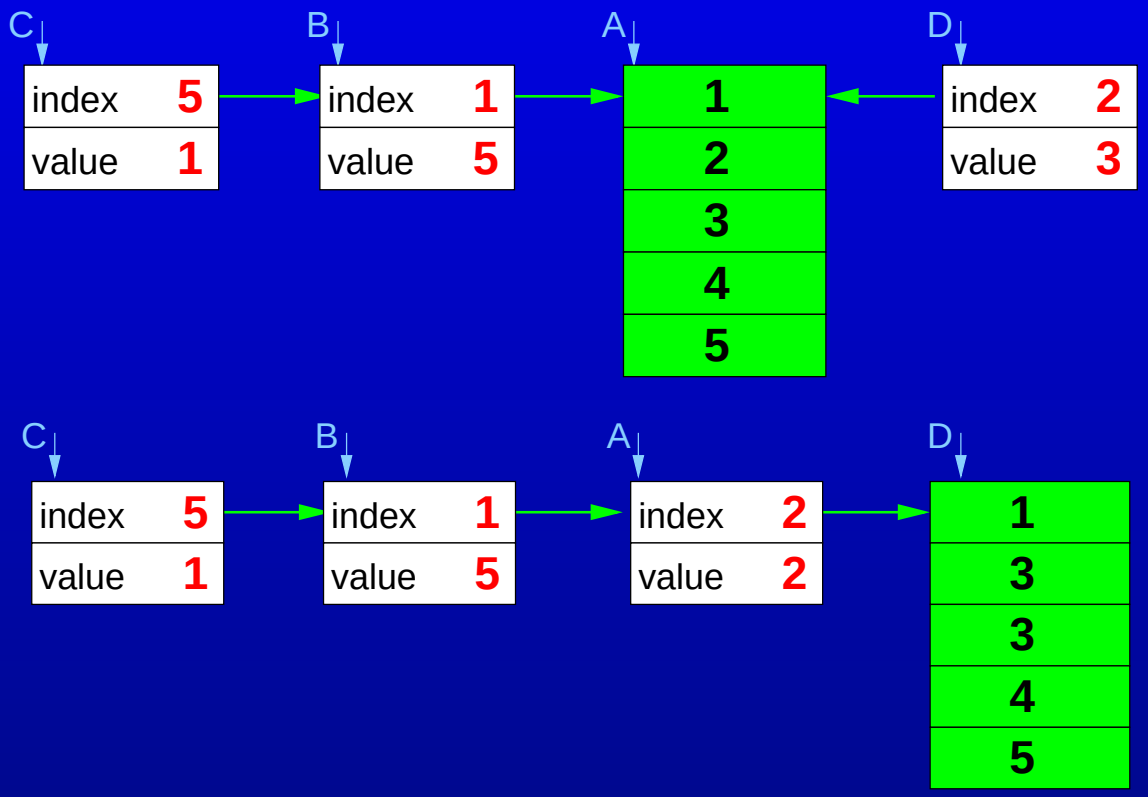

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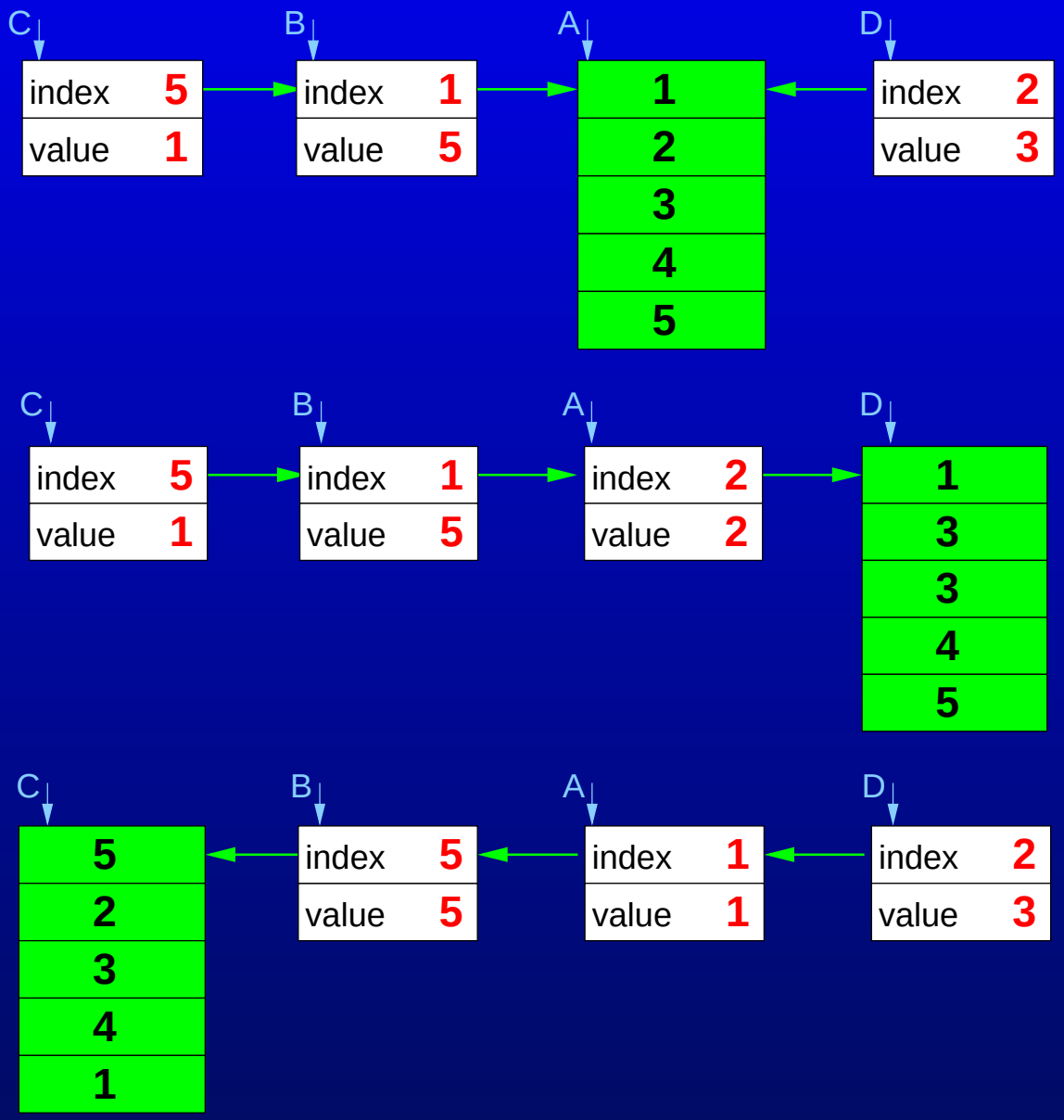

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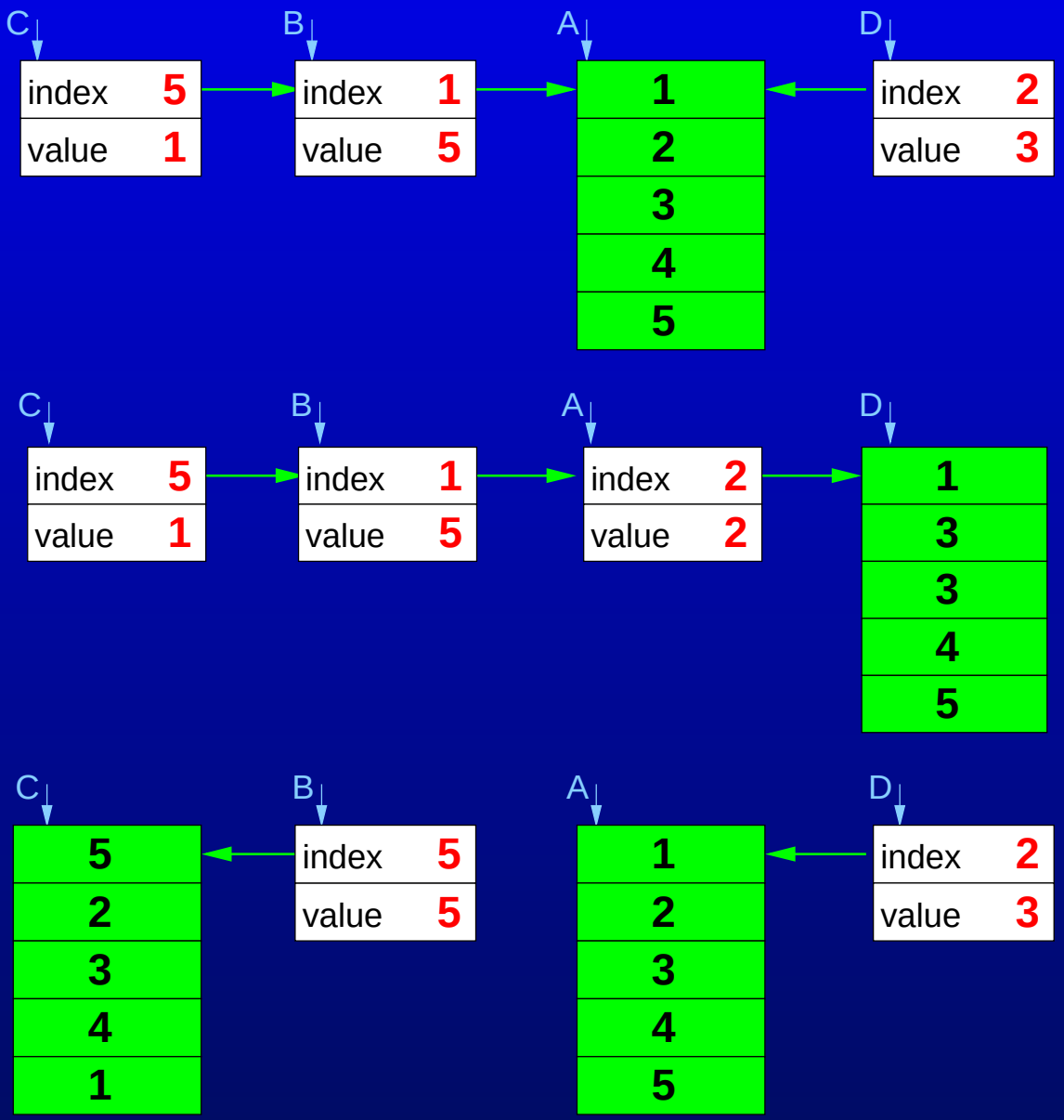
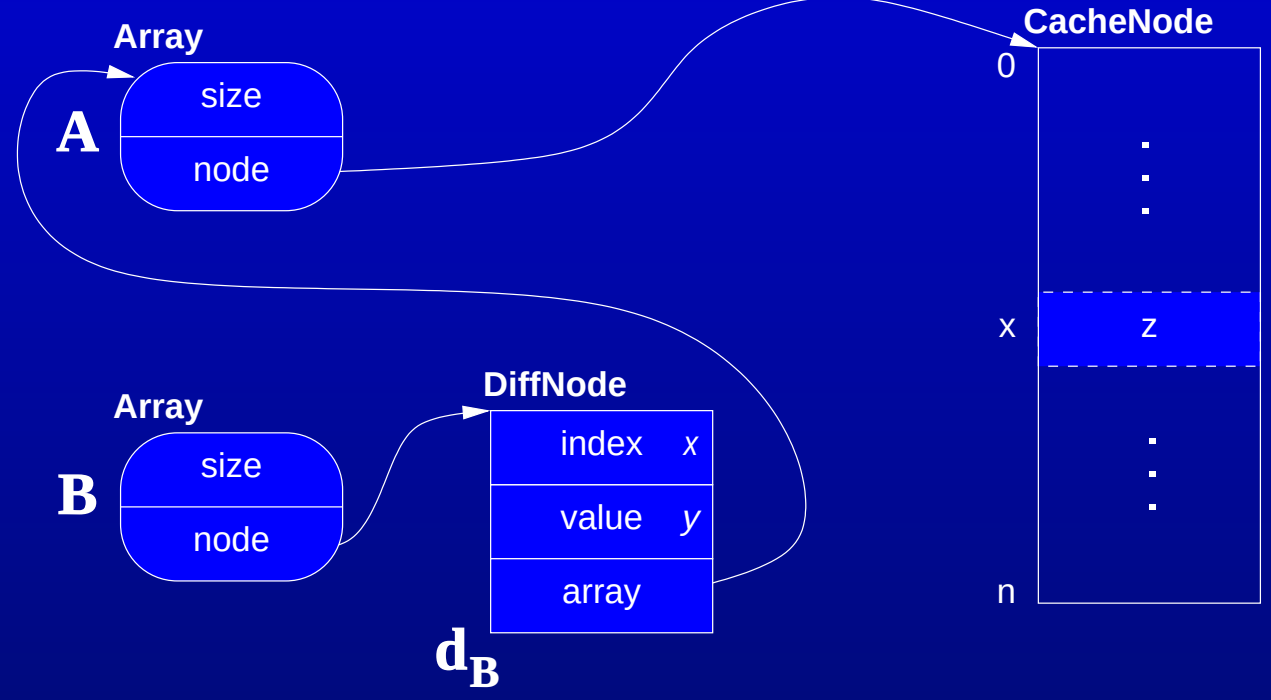


Lock-free Rotations

Unique pointer to cache acts as reservation.



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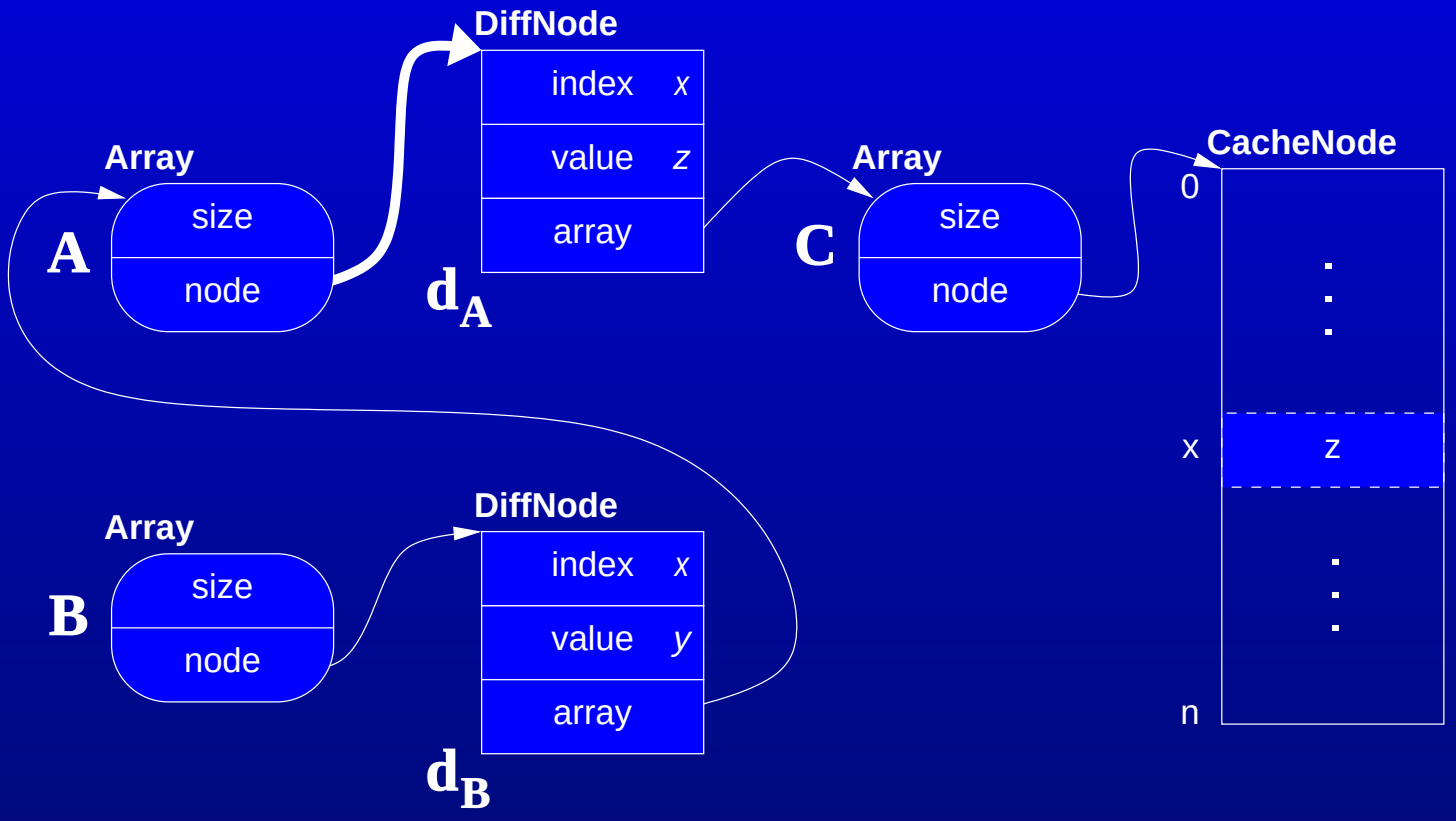

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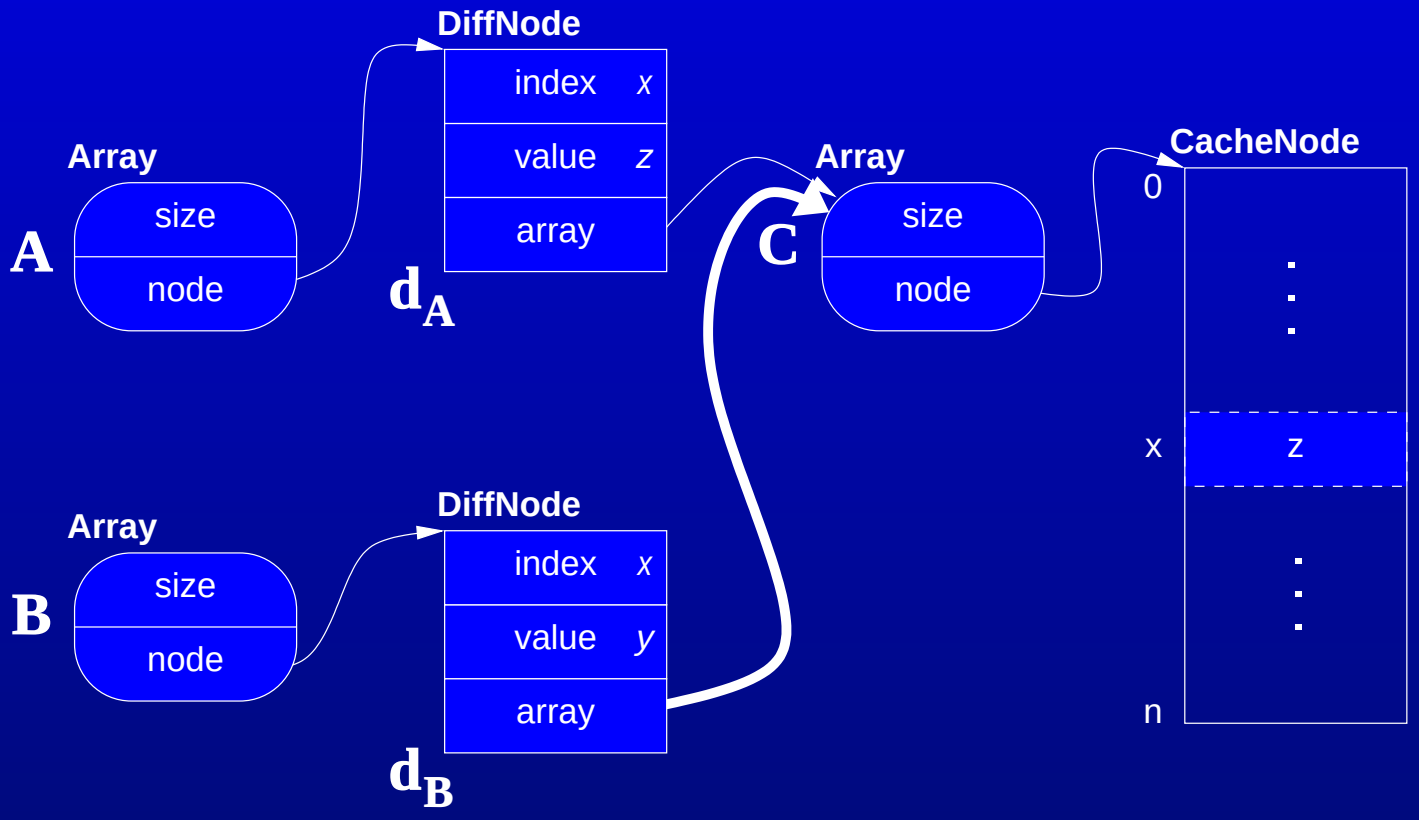

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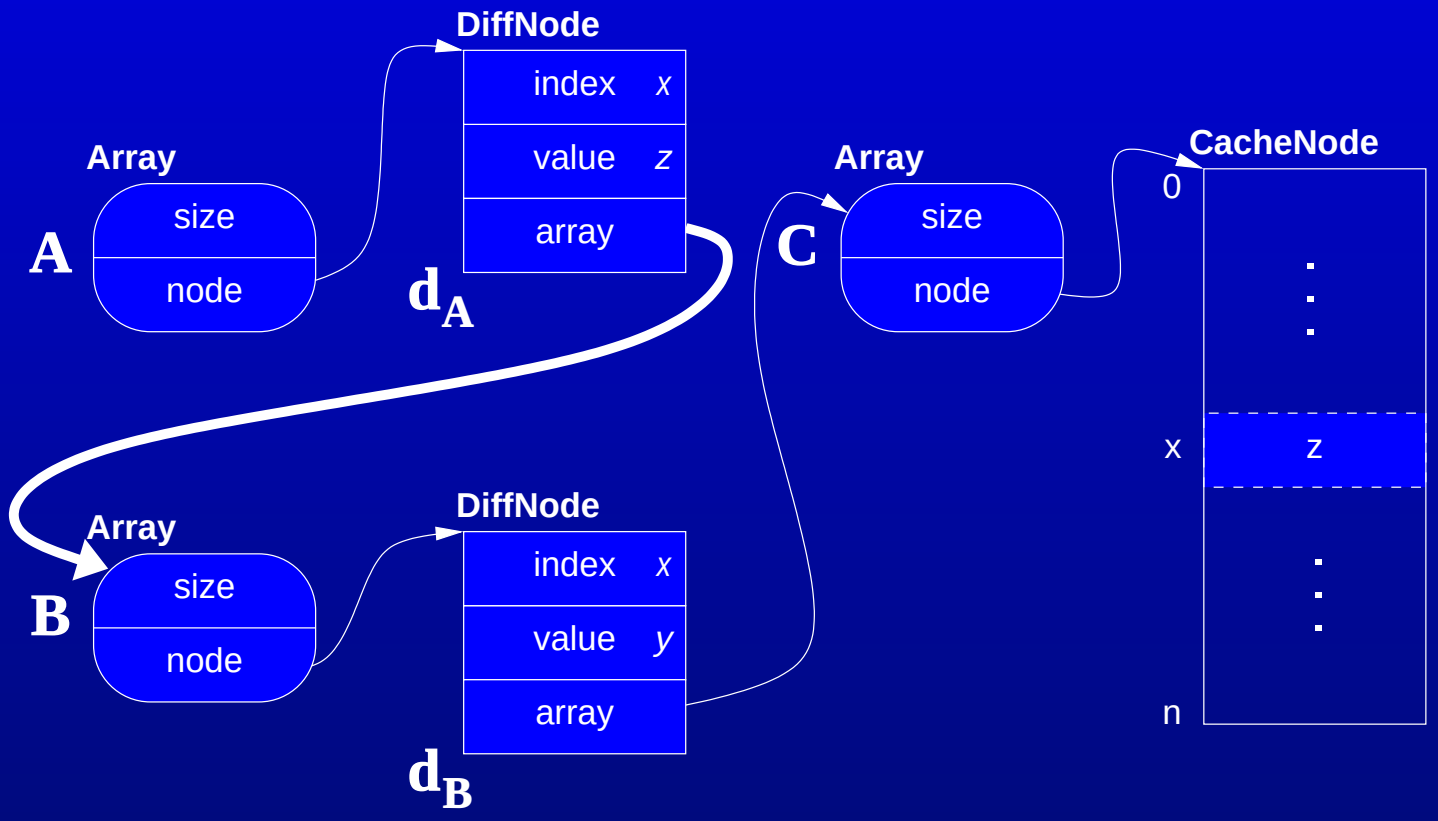

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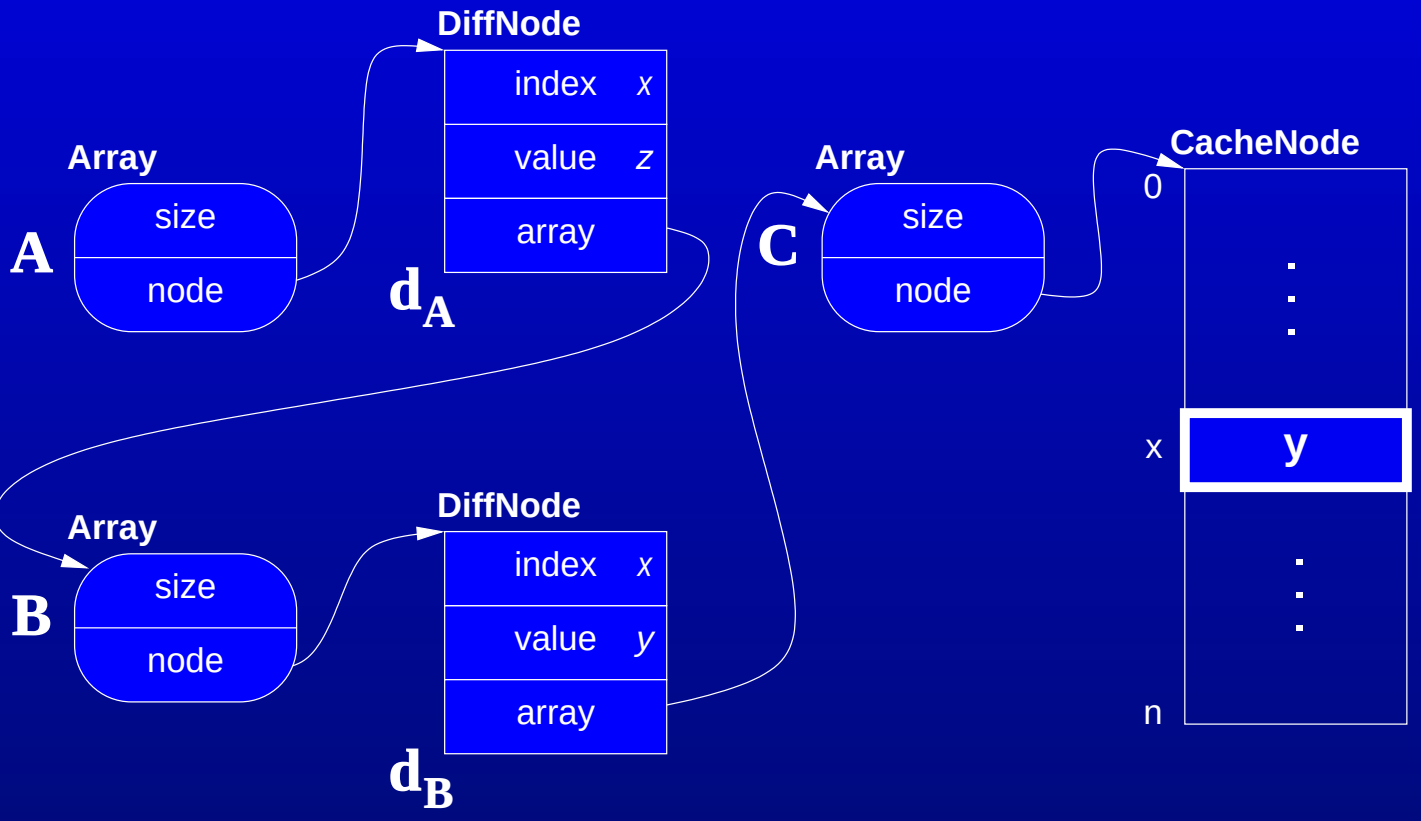

DCAS

Lock-free Rotations

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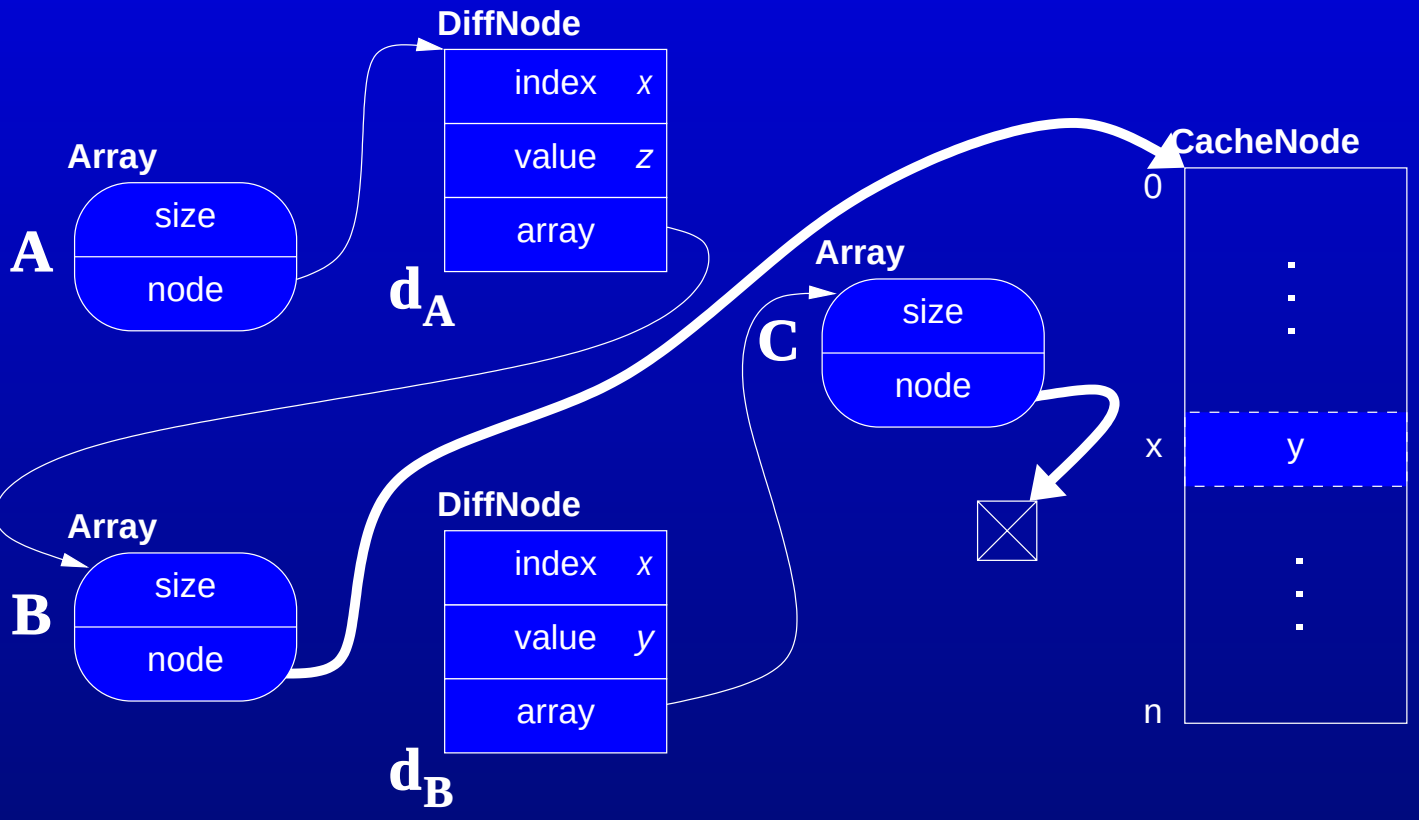

DCAS

A Few Optimizations

- Use hardware small-transaction support to implement rotations
- Naïve functional arrays for small objects
- Only use synchronization protocol for shared data

Outline

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Assessment and conclusions

- Surveyed Synthesis and Cache Kernel
  - Ad hoc implementations are hard to get right.
  - Version-number scheme is better, but very limited.
- Presented language design for non-blocking object-oriented operating system.
  - Novel feature: compiler-supported non-blocking `atomic` regions.
- Presented algorithms for implementing non-blocking `atomic` regions in O-O languages
  - Avoids “large object” problems.
  - Good complexity bounds, due to fast functional arrays.

The Graveyard Of Unused Slides follows this point.

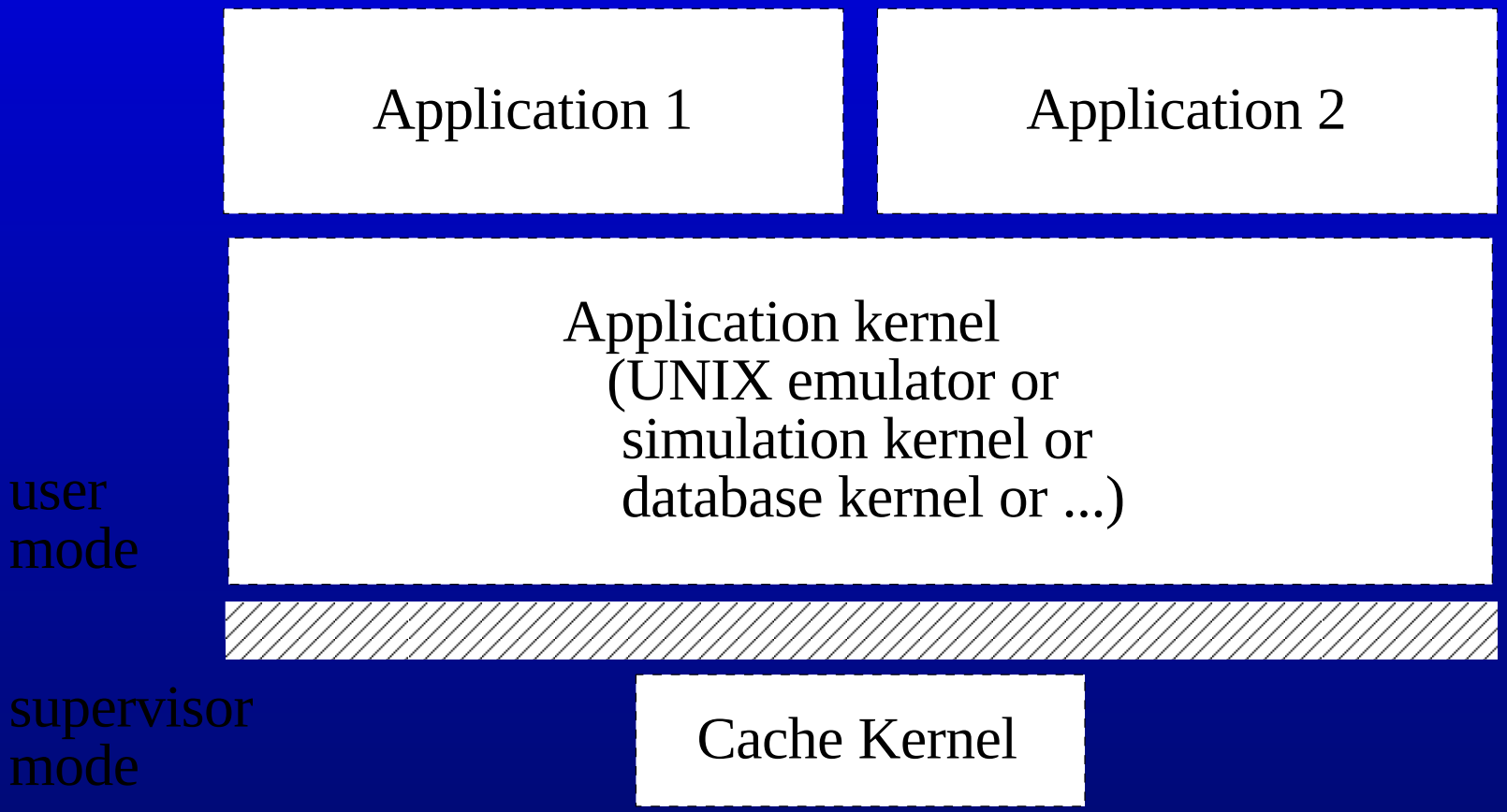
Blocking Synchronization

- Spin-locks
  - Processor runs in tight loop while waiting to enter a critical region.
  - Cheap, but wastes processor cycles.
- Semaphores
  - Maintain a waiting queue of blocked processes.
  - Queue maintenance and semaphore operations expensive.
- Hybrids
  - Spin-lock for short time periods.
  - Semaphore for long waits.

Non-blocking Synchronization

- Wait-free
  - Any process can complete any operation in finite # of steps, regardless of activities of other processes.
  - “Recursive helping.”
- Lock-free
  - *Some* process will complete in a finite # of steps.
  - Allows starvation.
- Obstruction-free
  - Processes will always complete if executed in isolation.
  - Contention can halt all progress indefinitely.
- Other (Lamport, . . .)

V++/Cache Kernel structure



Account example

```
class Account {

    int balance = 0;

    synchronized int deposit(int amt) {
        int t = this.balance;
        t = t + amt;
        this.balance = t;
        return t;
    }

    synchronized int readBalance() {
        return this.balance;
    }

    synchronized int withdraw(int amt) {
        int t = this.balance;
        t = t - amt;
        this.balance = t;
```

Optimistic parallelism

```
for (...)
  optimistically {
    ...do an iteration ...
  }
```

```
conquer(A[n], n) {
  ...
  optimistic spawn
    conquer(A, n/2);
  optimistic spawn
    conquer(A+n/2, n-n/2);
}
```

Programmer notes that the iterations or spawns are *expected* to be independent. Iff there are dynamic dependencies, the computations are serialized.