Section 9
Safe Memory Reclamation

Hazard Pointers

Main Ideas

- In the vast majority of algorithms for lock-free dynamic objects, a thread holds only a small number of pointers that may later be used without further validation for accessing the contents of dynamic nodes, or as targets of expected values of ABA-prone atomic comparison primitives.

Methodology

- Associate a number of single-writer multi-reader shared pointers, called hazard pointers, to each process.
- The number of hazard pointers required for each process depends on its algorithm.
- For simplicity, assume that this number is a constant K, the same for all processes.
- The technique is split into two components:
  - the algorithm for processing retired nodes
  - the extensions to the implementation that should be made in order to ensure that the conditions to guarantee the safety of memory reclamation and ABA prevention are met.

Hazard Pointers: Access Hazard – ABA hazard

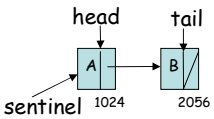
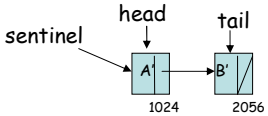
```
shared head, tail;
     // intially, both point to a dummy node

void enq(T value ) {
    NODE *next , *last ;

1.  NODE *p = newcell(NODE) ;
2.  p->value = value ;
3.  p->next = NULL;

4.  while (TRUE) {
5.      last = tail ;
6.      next = last->next ;
7.     if (last != tail) continue;
8.      if (next != NULL) {
9.           CAS(tail, last, next);
10.        continue;
11.     }
12.     if (CAS(last->next , NULL , p)
                 break ;
13.  } // while
14.    CAS(tail, last, p );
} // Enqueue
```

Identify **hazards** and **hazardous references**

1. Lines 2 and 3 are safe (p points to some node after the execution of line 1)
2. the access on line 6 may be hazardous:
   - between the read of tail (line 5) and the execution of line 6, more nodes may have been inserted and all nodes, including the node pointed to by last, may have been removed (and become free).
3. Line 7: ABA hazard (the ABA problem could appear here)
4. Line 9: ABA hazard
5. Line 12 may be hazardous:
   - access hazard -> accessing the next field of last is not safe (since the node pointed to by last may have been released)
   - ABA hazard
6. Line 14: ABA hazard

The ABA Problem

Thread 0	Thread 1

boolean **deq**(int *pvalue) {
  Node *first, *last, *next;
  while (1) {
  first = head;
  last = tail;
  next = first->next;
  if (first == head) {
  if (first == last) {
  if (next == NULL)
  return FALSE;
  CAS(tail, last, next);
  }
  else {
  *pvalue = next->value; → B
 	
  if (CAS(head, first, next)) break;
  }
  return TRUE; → INCORRECT!
	
	deq()
	enq(A')
	deq()
	enq(B')
	 

Hazard Pointers: Access Hazard – ABA Hazard

```
boolean deq(QUEUE *Q, T *pvalue) {
  NODE *first, *last, *next;

1.  while (TRUE)
2.     first = head;
3.     last = tail;
4.     next = first->next;
5.     if (first != head) continue;
6.     if (next == NULL)
7.        return EMPTY;
8.     if (first = last) {
9.        CAS(tail, last, next);
10.       continue;
       }
11.    *pvalue = next->value;
12.    if (CAS(head, first, next))
          break;
    } // while
13. return TRUE;
} // Dequeue
```

Identify **hazards** and **hazardous references**

1. the access on line 4 may be hazardous:
   - between the read of head (line 2) and the execution of line 4, the node pointed to by first may have been removed (and become free).
2. Line 5: ABA hazard
3. Line 9: ABA hazard
4. Line 11: Access hazard (node pointed to by next may have been de-allocated.
5. Line 12: ABA hazard

Application of Hazard Pointers: Methodology

1. Examine the target algorithm as follows:
   a. Identify hazards/hazardous references
   b. For each distinct hazardous reference, determine the point where it is created and the last hazard that uses it. During this period, a hazard pointer needs to be dedicated to that reference.
   c. Compare the periods for all hazardous references, and determine how many hazard pointers are required for each process.
2. For each hazardous reference, enhance the algorithm as follows:
   a. write the address of the node that is the target of the reference to an available hazard pointer.
   b. Validate that the node is safe.
      - if the validation succeeds, continue normally.
      - if not, skip the rest of the execution and follow the path of the target algorithm when a conflict is detected.
3. Before returning from an operation, release the hazard pointers that have been used during the execution of the operation.
4. At carefully chosen points of the execution of the operation, call RetireNode() to identify that a node has been deleted.

Hazard Pointers Applications

```
void enq(T value ) {   // code for process p_i
    NODE *next , *last ;

1.  NODE *p = newcell(NODE) ;
2.  p->value = value ;
3.  p->next = NULL;

4.  while (TRUE) {
5.      last = tail ;
        *hp[i][0] = last;
        if (last != tail) continue;
6.      next = last->next ;
7.      if (last != tail) continue;
8.      if (next != NULL) {
9.          CAS(tail, last, next);
10.         continue;
11.     }
12.     if (CAS(last->next , NULL , p)
                break ;
13. } // while
14. CAS(tail, last, p);
15. *hp[i][0] = NULL;
} // Enqueue
```

```
boolean deq(QUEUE *Q, T *pvalue) {
    // code for process p_i
    NODE *first, *last, *next;
1.  while (TRUE)
2.      first = head;
        *hp[i][0] = first;
        if (head != first) continue;
3.      last = tail;
4.      next = first->next;
        *hp[i][1] = next;
5.      if (first != head) continue;
6.      if (next == NULL) {
          *hp[i][0] = *hp[i][1] = NULL;
7.        return EMPTY;
        }
8.      if (first = last) {
9.          CAS(tail, last, next);  continue;
          }
11.     *pvalue = next->value;
12.       if (CAS(head, first, next)) {
              RetireNode(first);
              break;
          }
    } // while
    *hp[i][0] = *hp[i][1] = NULL;
13. return TRUE;
} // Dequeue
```


Hazard Pointers

- Each process p_i uses two persistent local variables, $rlist_i$, and $rcount_i$. These are used to maintain a private list of retired nodes.
- RetireNode() by process p_i
  - Insert the retired node into the list of retired nodes of process p_i
  - Whenever the size of the list of retired nodes reaches a threshold R, call find-hazard() to get a list of the nodes that are currently hazardous.
- Scan() by process p_i
  - Scan the HP array for non-null values. Each non-null value is inserted in a local list, called plist.
  - Check each node in rlist, whether it is included in the plist.
    - If no, the node can be de-allocated (no hazard pointer points to it)
    - If yes, the node is returned in the rlist to be checked again next time.

Hazard Pointers

Shared and private structures used by the algorithm

```
NODE **Hp[n][K];
// initialize each element of HP to some
// pointer address using newcell() (the
// first K such pointers are the hazard
// pointers of p0, etc.) Each of these
// memory cells contain NULL, initially.

// persistent private variables
int rcount_i = 0;
List rlist_i; // list of retired nodes

void RetireNode(NODE *node) {
// code for process p_i
    push(rlist_i, node);
    rcount_i++;
    if (rcount_i >= R) Scan();
}
```

```
void Scan(void) { // code for process p_i
    // Stage 1: Scan HP list and insert
    // non-null values in plist
    init(plist);// plist is a temporary list
    for (i = 0; i < n; i++) {
        for (j = 0; j < K; j++) {
            hptr = *HP[i][j];
            if (hptr != NULL)
                insert(plist, hptr);
        }
    }
    // 2nd stage: search plist
    move all items of rlist_i to tmplist;
    rcount_i  = 0;
    node = pop(tmplist);
    while (node != NULL) {
        if (lookup(plist, node)) {
            push(rlist_i, node);
            rcount_i++;
        } else PrepareForReuse(node);
    }
    node = pop(tmplist);
}
```