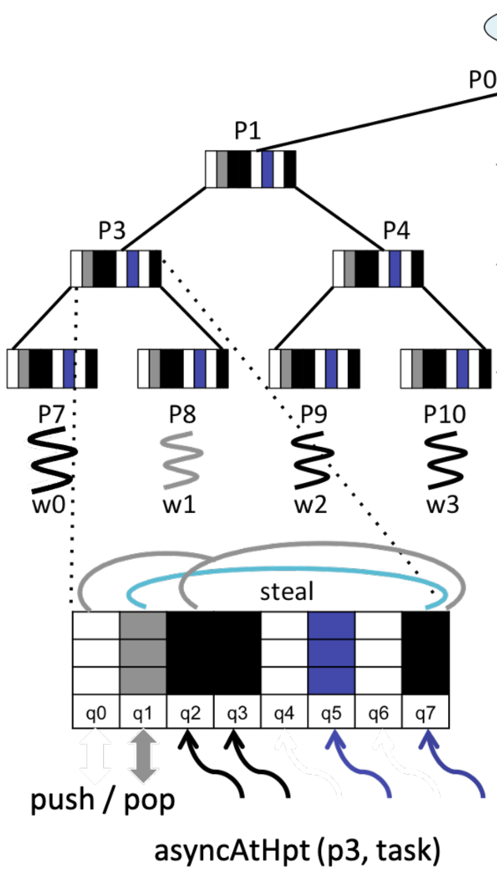
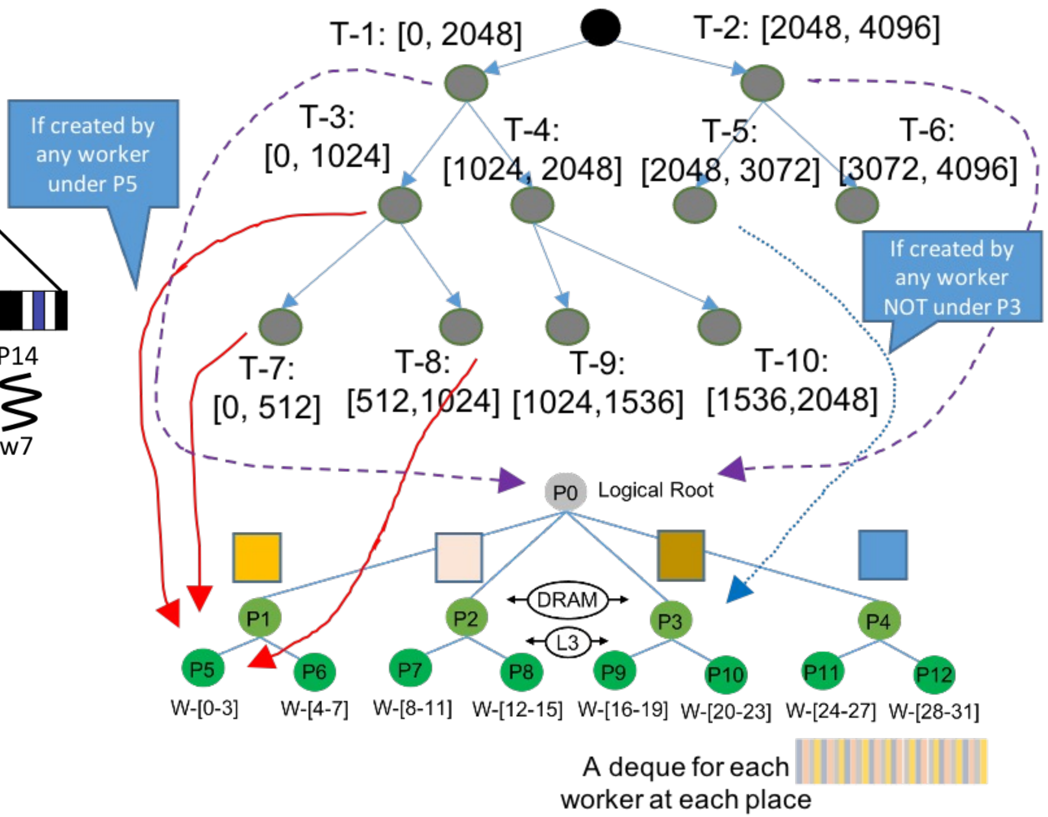
Lecture 10: Trace and Replay of Task Parallel Programs

Vivek Kumar
Computer Science and Engineering
IIIT Delhi
vivekk@iiitd.ac.in

Last Lecture (Recap)

```
int A[SIZE];
asyncAtHPT(A, lowBound, highBound, lambda);
```





Today's Class

- Trace and replay of asynchronous tasks

Runtime Profiling

- It is a technique for understanding the behavior of the parallel runtime / program during the execution
  - High-level details
    - Total number of tasks created
    - Total number of tasks stolen
    - Total number of tasks migrated across NUMA domains
    - Total number of failed steals
    - Task execution time, etc.
  - Low-level details
    - Tracing the program execution (computation graph)
    - Computation type (compute-bound / memory-bound)
    - Power usage
    - Instructions retired for each task
    - Total CPU stalls, etc.

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Easily obtained using thread local counters

Runtime Profiling

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Requires special support

Runtime Profiling

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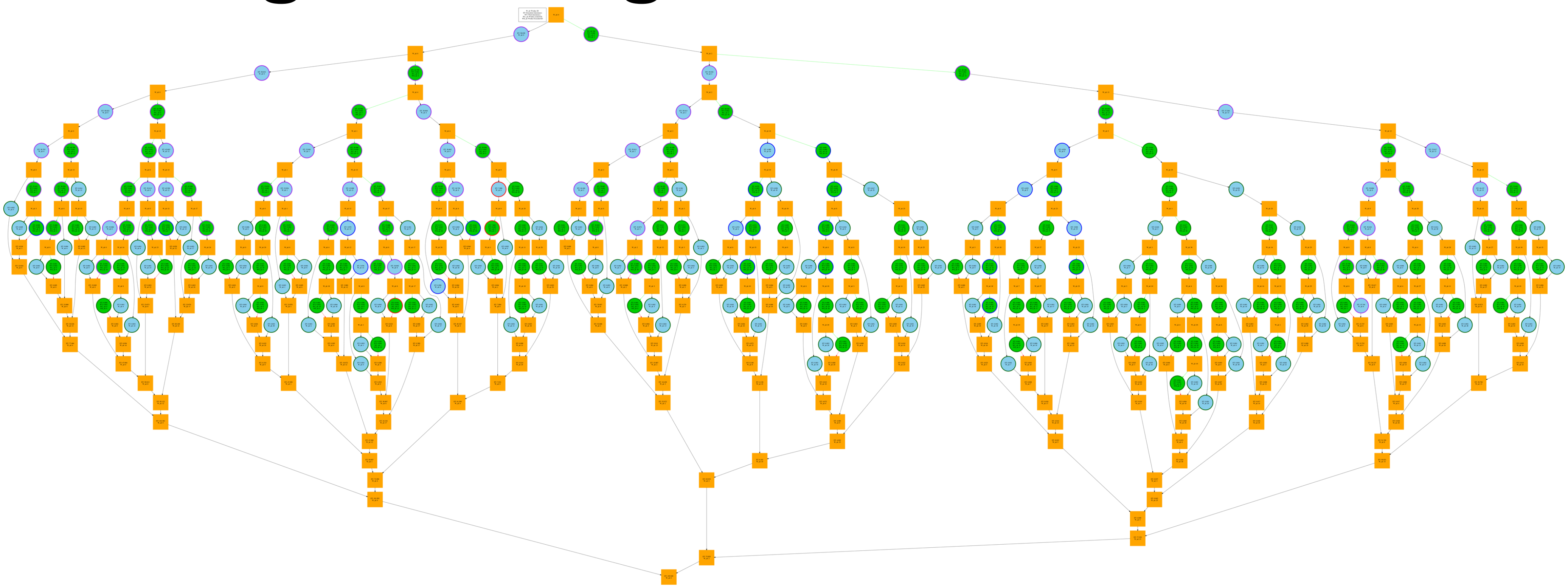
    - Total CPU stalls, etc.

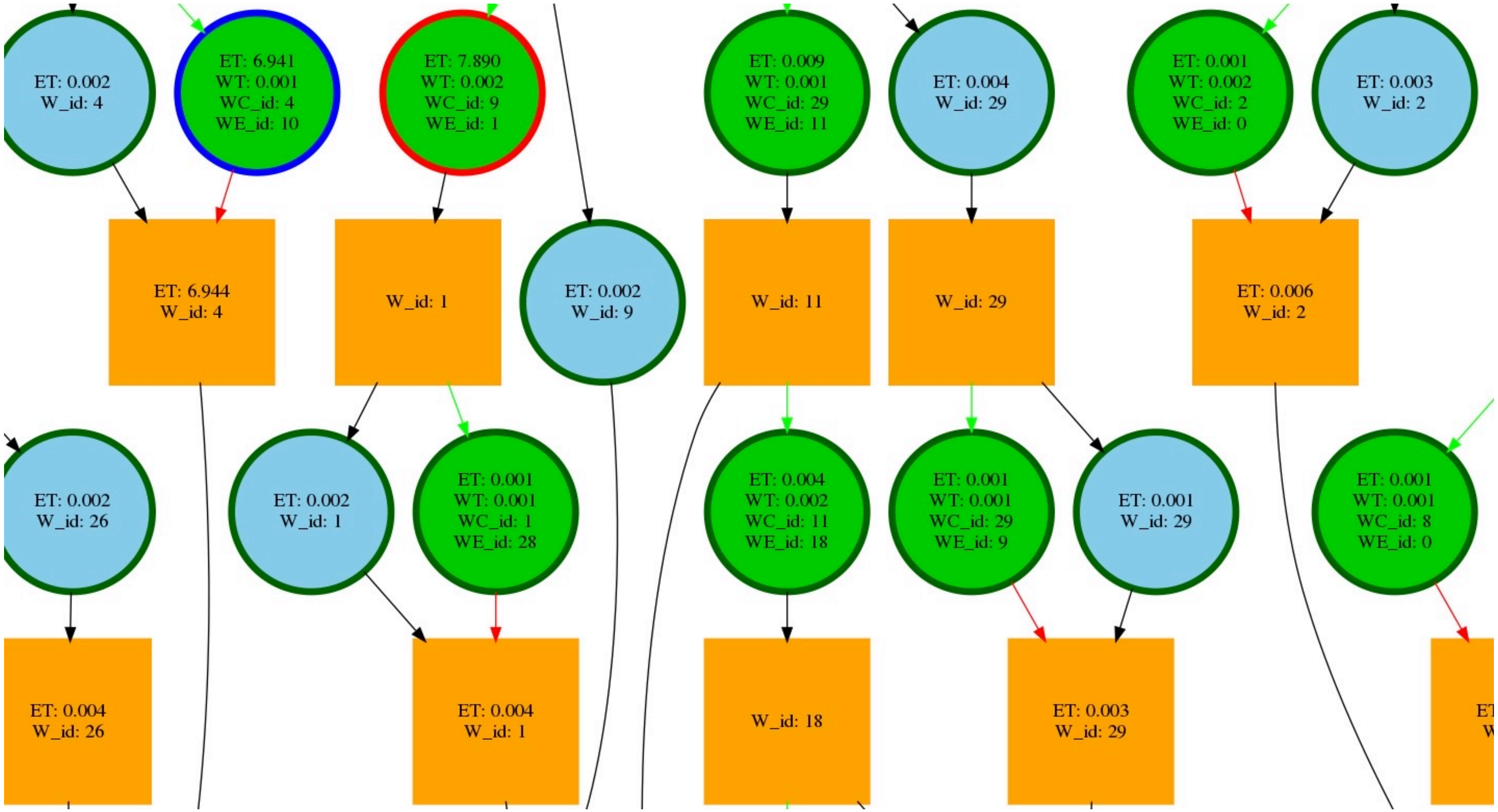
Overall goal: profiling with minimal overheads!

Tracing the Program Execution



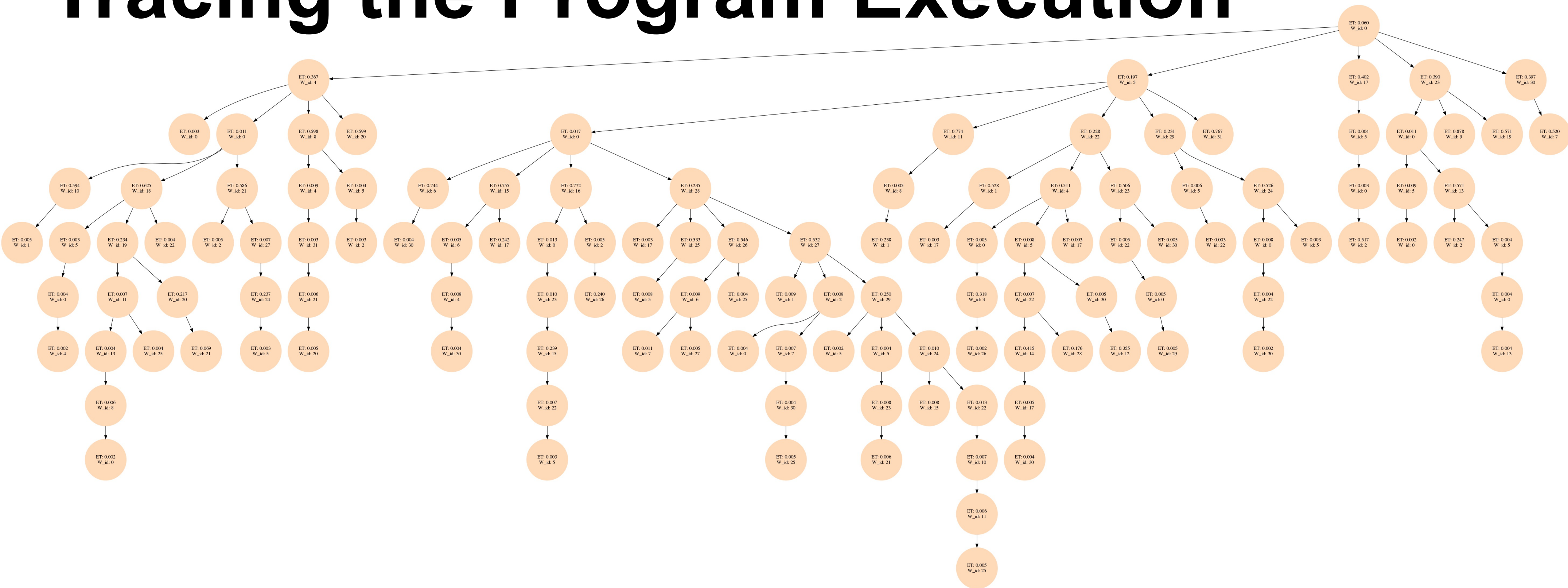
- Recursive task parallel Fibonacci number calculation (N=20, threshold=10)
  - Graph will be too big to fit in the slide for large N, hence small value chosen
- Blue node represents fib(n-2), green node represents async fib(n-1), and orange rectangular boxes are the synchronization scope for tasks created in that scope

Tracing the Program Execution



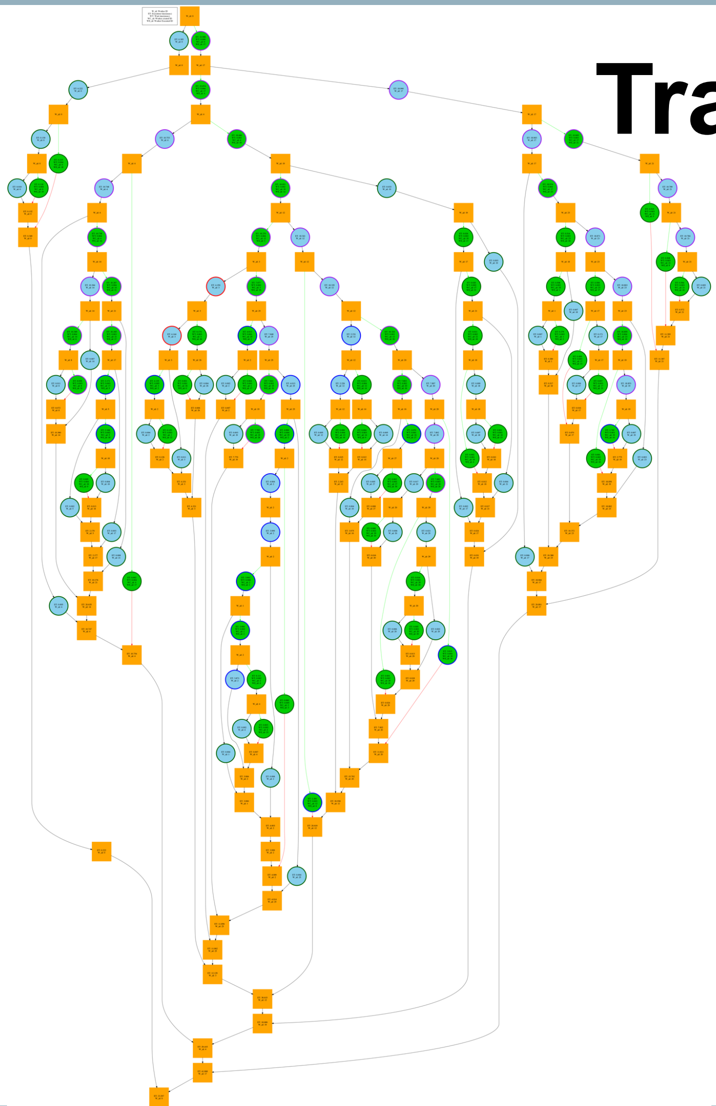
- Enlarging the nodes from the computation graph of Fibonacci
- ET=Execution time
- WT: Wait time
- WC_id: Id of worker who created this task
- WE_id: Id of the worker who executed this task (due to stealing)

Tracing the Program Execution



- Steal tree of the same Fibonacci execution using 32 workers

Tracing the Program Execution



- Recursive task parallel QuickSort
  - Array size 1024, and chunk threshold 32
- Blue node represents sequential task, green node represents an async, and orange rectangular boxes are the synchronization scope for tasks created in that scope

Tracing the Program Execution

- Advantages
  - Offline analysis can help in reducing/increasing the task threshold if its not done automatically by the runtime
  - Reducing task management overheads in iterative applications
    - How?

Iterative Averaging

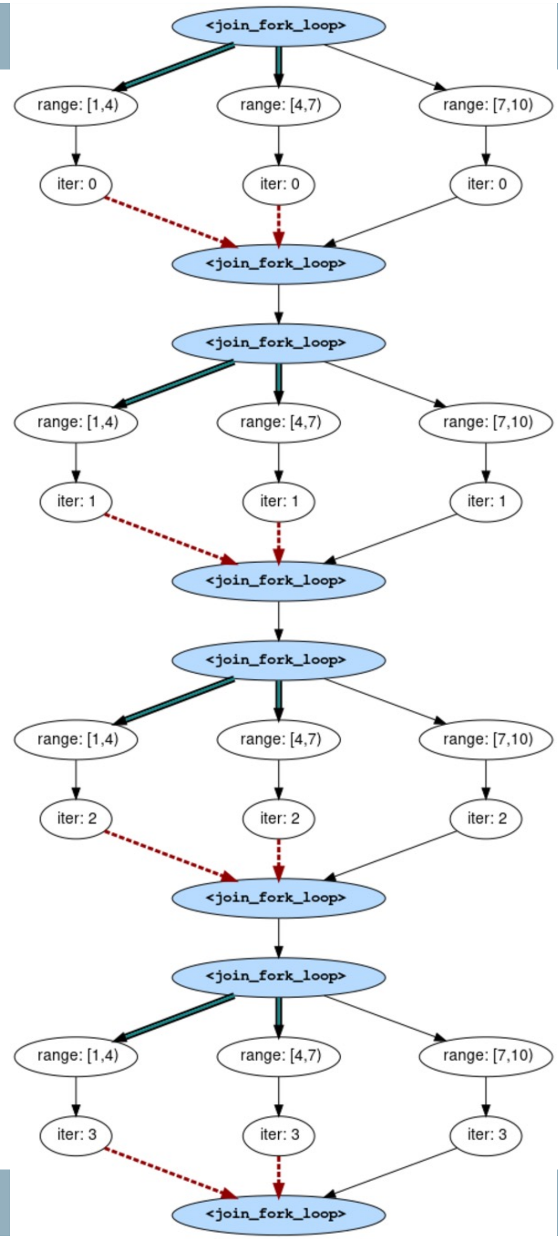
```
double A[SIZE+2], A_shadow[SIZE+2];

void recurse(int low, int high) {
  if((high - low) > THRESHOLD) {
    int mid = (high+low)/2;
    finish ([=](){
      async([=](){ recurse(low, mid); });
      recurse(mid, high);
    });
  } else {
    for(int j=low; j<high; j++) {
      A_shadow[j] = (A[j-1] + A[j+1])/2.0;
    }
  }
}
void compute(int MAX_ITERS) {
  for(int i=0; i<MAX_ITERS; i++) {
    recurse(1, SIZE+1);
    double* temp = A_shadow;
    A_shadow = A;
    A = temp;
  }
}
```

- Initialize a one-dimensional array of (SIZE+2) double's with boundary conditions, A[0] = 0 and A[SIZE+1] = 1
- In each iteration, each interior element A[j] in 1…SIZE is replaced by the average of its left and right neighbours
  - Two separate arrays are used in each iteration, one for old values and the other for the new values
- After a sufficient number of iterations, we expect each element of the array to converge to A[j] = (A[j-1]+A[j+1])/2, for all j in 1…SIZE

Details: https://classes.engineering.wustl.edu/cse231/core/index.php/Iterative_Averaging

Iterative Averaging

- Observations
  - Exact same computation graph in each for loop iteration in compute()
- Optimization
  - Improved locality if each workers executes the exact same set of tasks in each for loop iteration of compute
  - Random work-stealing
    - It would result in poor locality as each worker could get different set of tasks in each for loop iteration of compute
  - Trace/Replay for improving locality
    - Trace (i.e., record) the tasks executed by each worker during the first iteration of for loop inside compute
    - For the rest of iterations of the above for loop of compute, disable random work-stealing and use the information gathered during the Trace (i.e., record) phase to replay the exact set of tasks at each worker



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Tracing the Program Execution

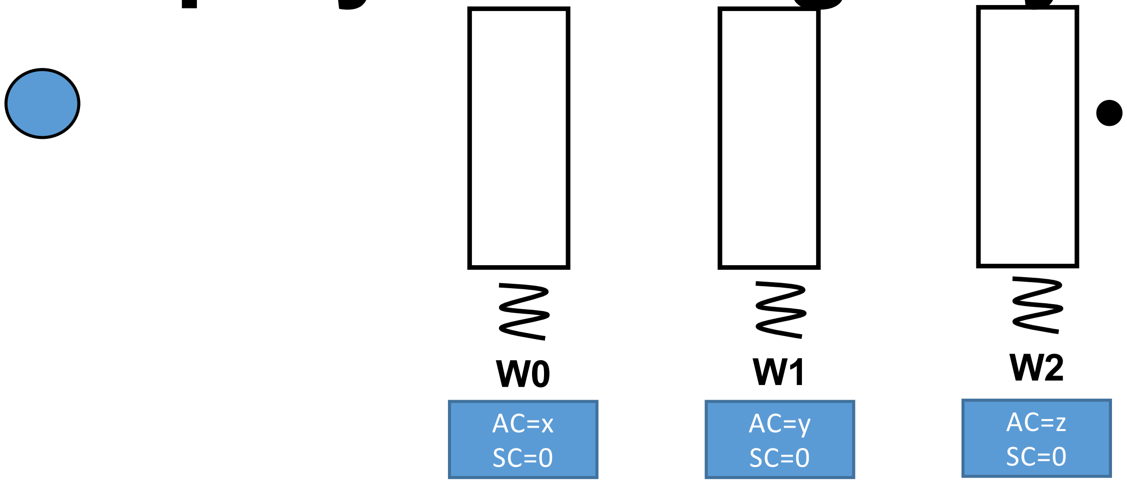
- Advantages
  - Offline analysis can help in reducing/increasing the task threshold if its not done automatically by the runtime
  - Reducing task management overheads in iterative applications
    - How?
  - Data-race detection
    - If there is NO path to connect between two nodes (i.e., they may execute in parallel), and if they perform read/write or write/write operation on a shared memory location then it's a data race

Tracing the Program Execution

- Advantages
  - Offline analysis can help in reducing/increasing the task threshold if its not done automatically by the runtime
  - Reducing task management overheads in iterative applications
    - How?
  - Data-race detection
    - If there is NO path to connect between two nodes (i.e., they may execute in parallel), and if they perform read/write or write/write on a shared memory location then it's a data race
- Drawbacks
  - Recording details for each and every task will consume too much memory (e.g., millions of tasks in Fibonacci 40)
  - Profiling overheads as each worker has to do some extra work

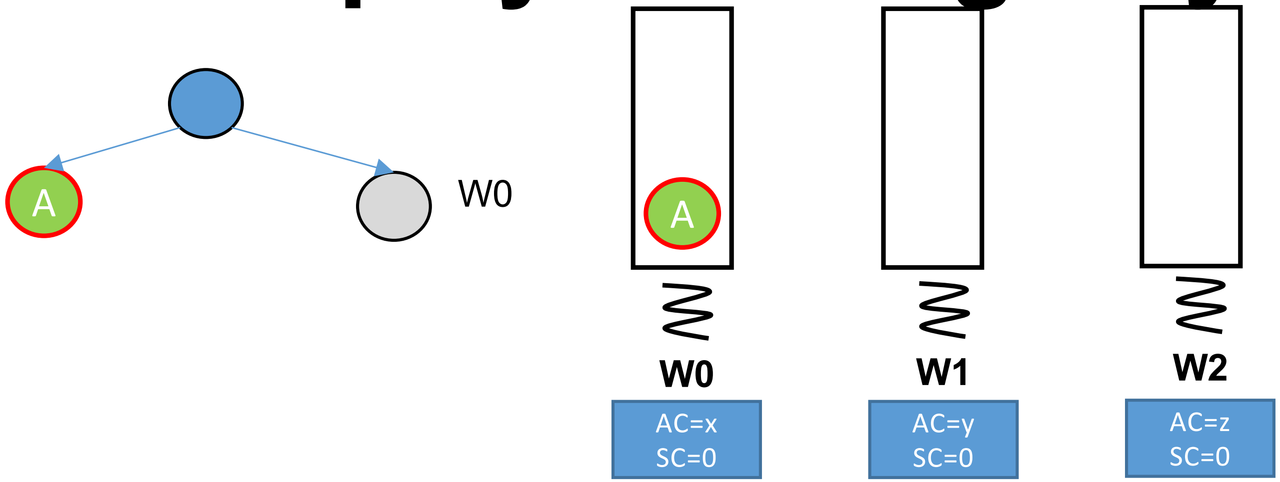
How to avoid these overheads?

Trace & Replay: Tracing Async



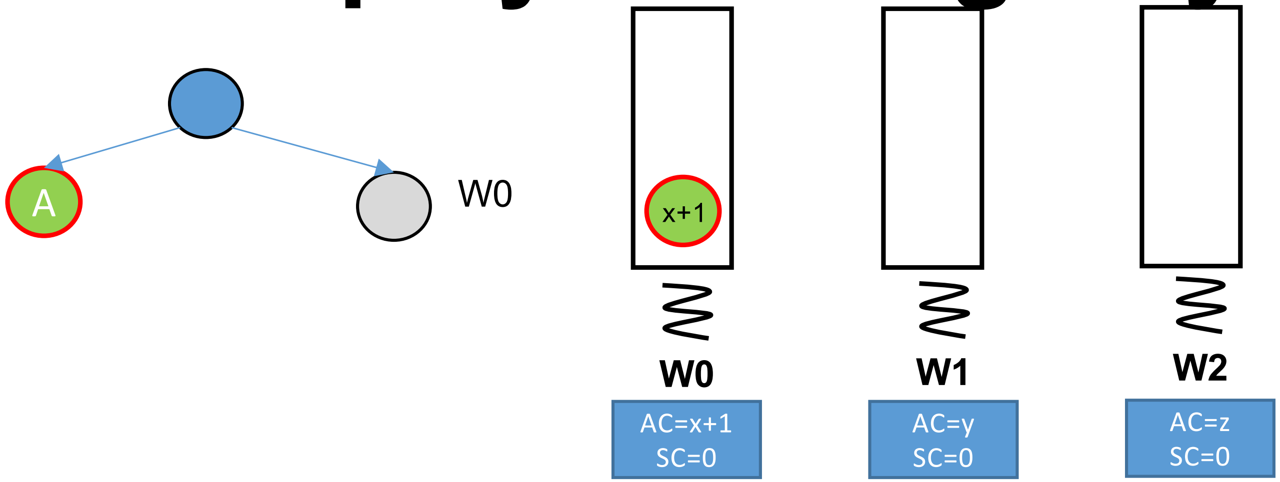
- Let there be three workers in a work-stealing based parallel runtime
  - Worker encountering an async will push that task into its deque, and would start working on the statement after the async
- Each worker has two counters
  - Async Counter (AC)
    - Each worker initializes its AC value = workerID * INT_MAX/numWorkers
    - To assign a unique id to each async
  - Steal Counter (SC)
    - Initialized to zero

Trace & Replay: Tracing Async



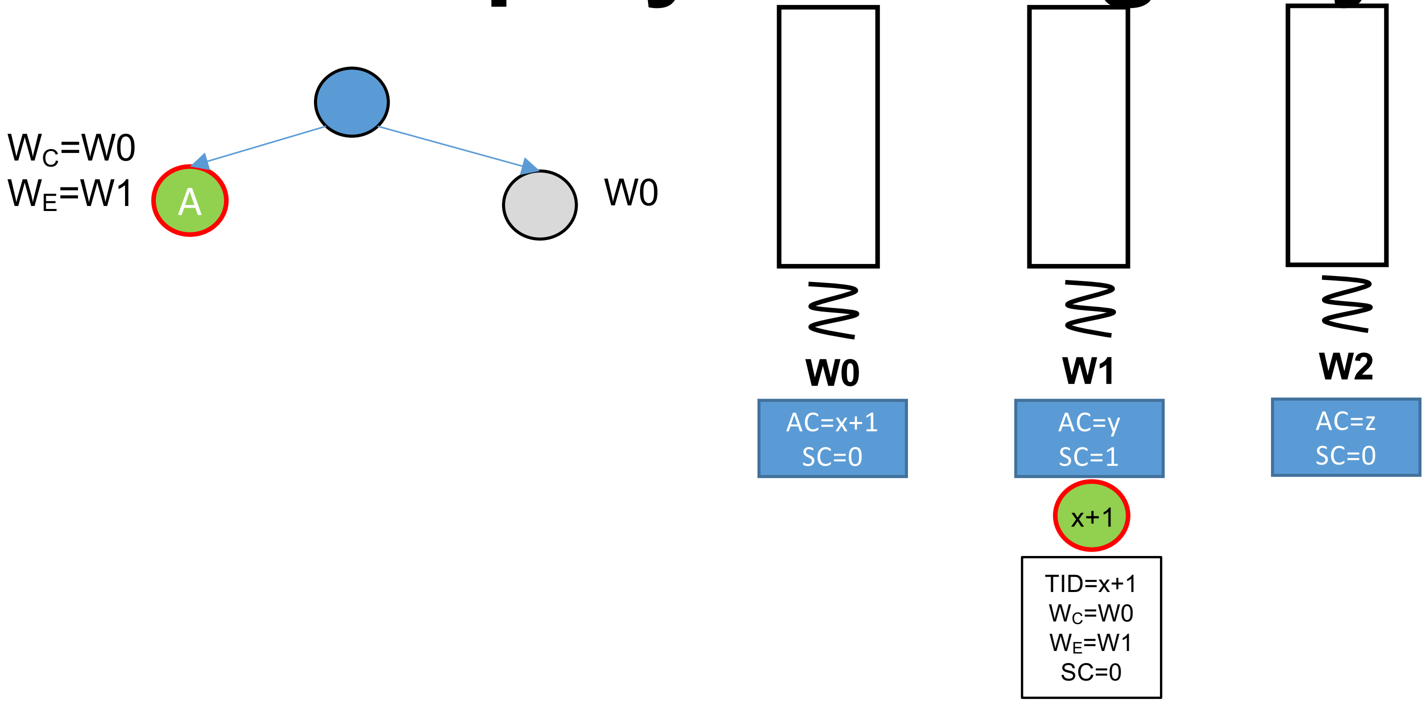
- Worker W0 starts a recursive task parallel application
- W0 creates an async A that is pushed into its deque

Trace & Replay: Tracing Async



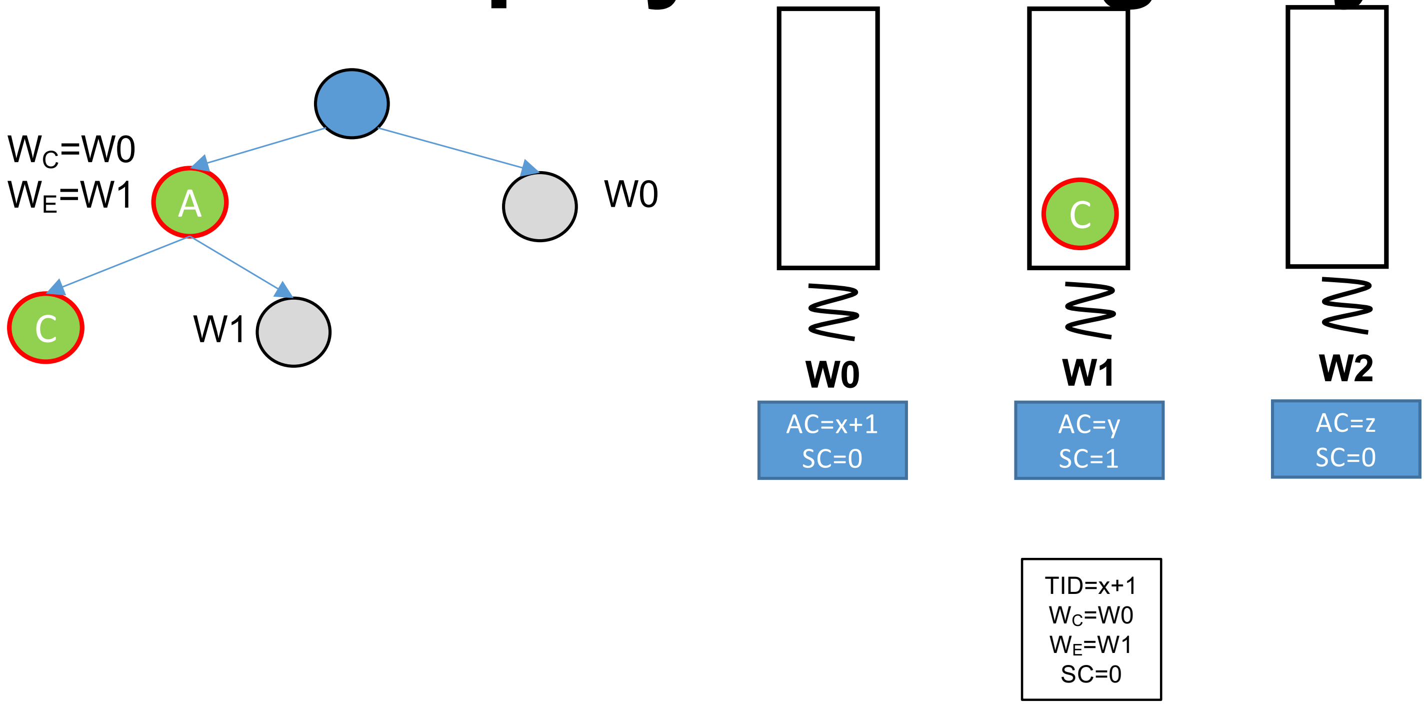
- AC at W0 is incremented and is assigned as the ID of the Task A **before** its pushed into W0's deque

Trace & Replay: Tracing Async



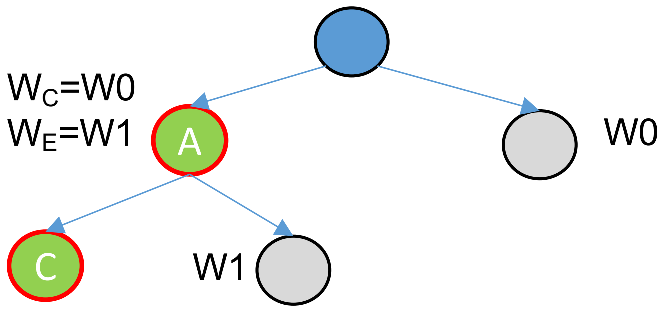
- W1 steals the task A from W0
- It appends a node in a private linked list containing info about this stolen task A
  - ID of the task (TID=x+1)
  - Worker who created this task (W_C=W0)
  - Worker who executed (stolen) this async (W_E=W1)
  - Current Steal Counter at W1 (SC=0)
- W1 then increment its Steal Counter (SC) before executing this stolen task

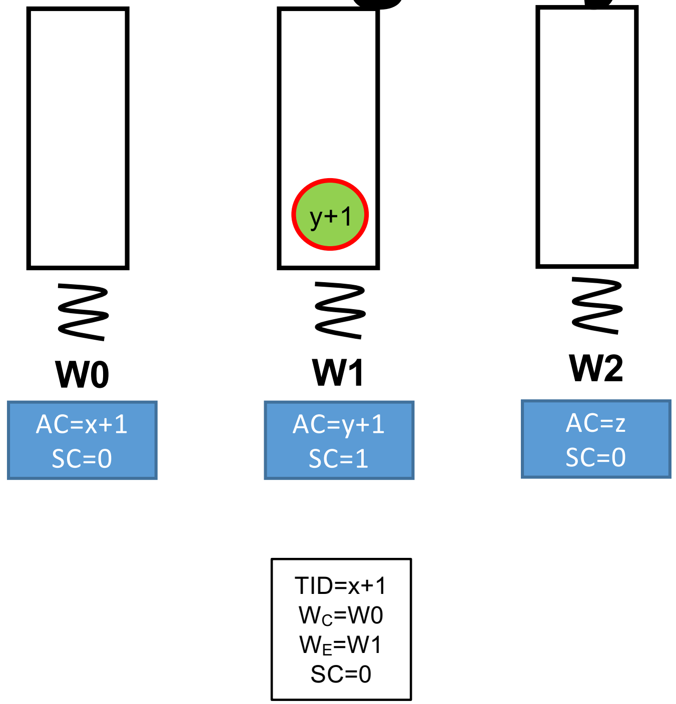
Trace & Replay: Tracing Async



- W1 creates an async C

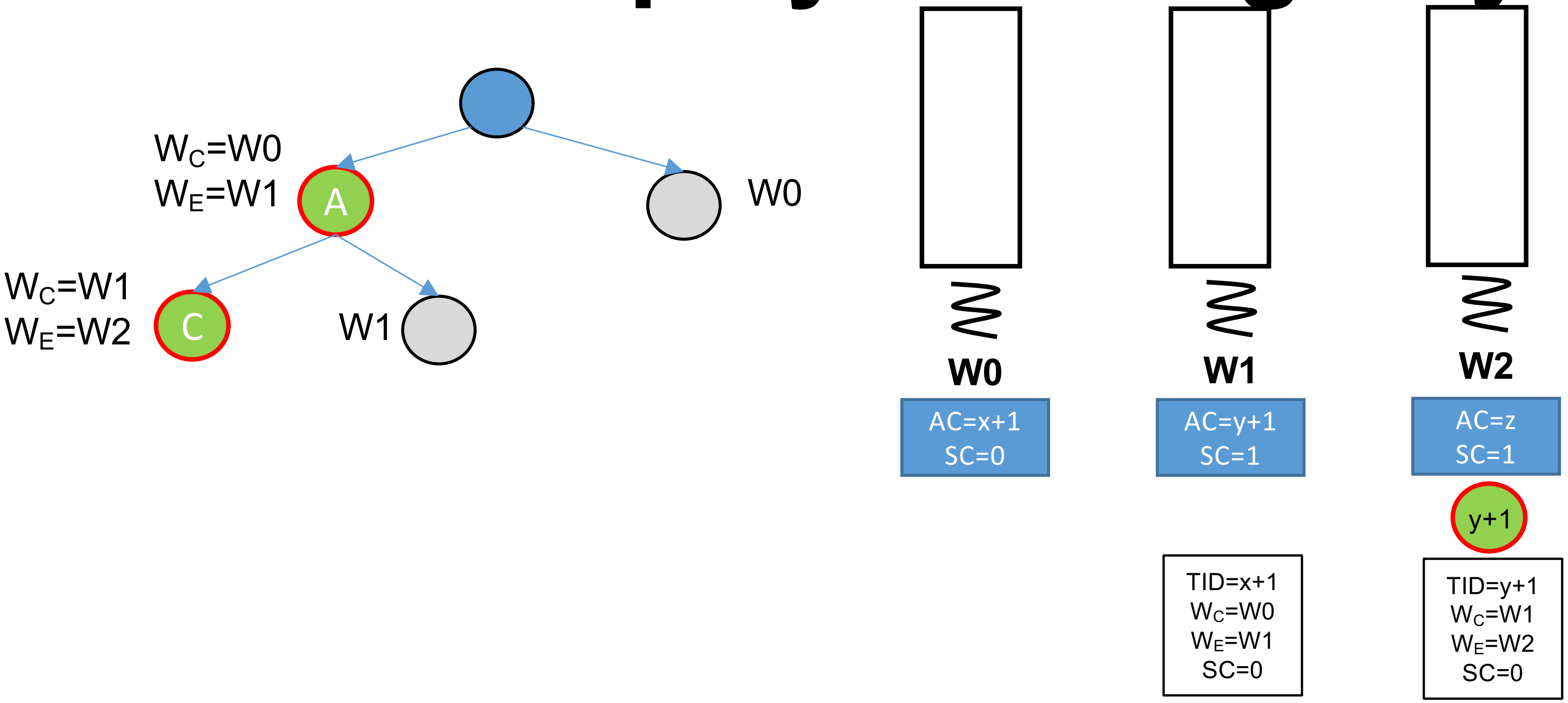
Trace & Replay: Tracing Async





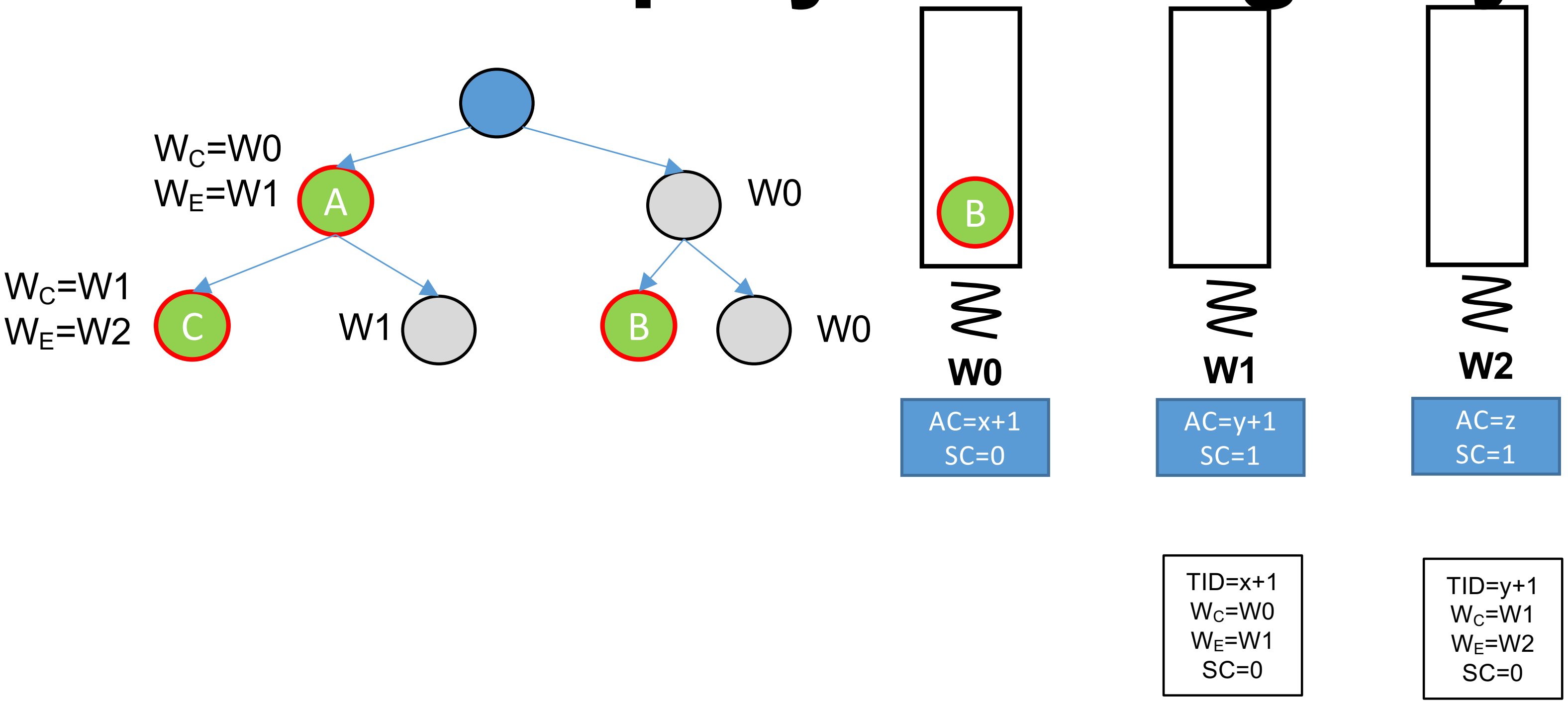
- AC at W1 is incremented and is assigned as the ID of the Task C **before** its pushed into W1's deque

Trace & Replay: Tracing Async



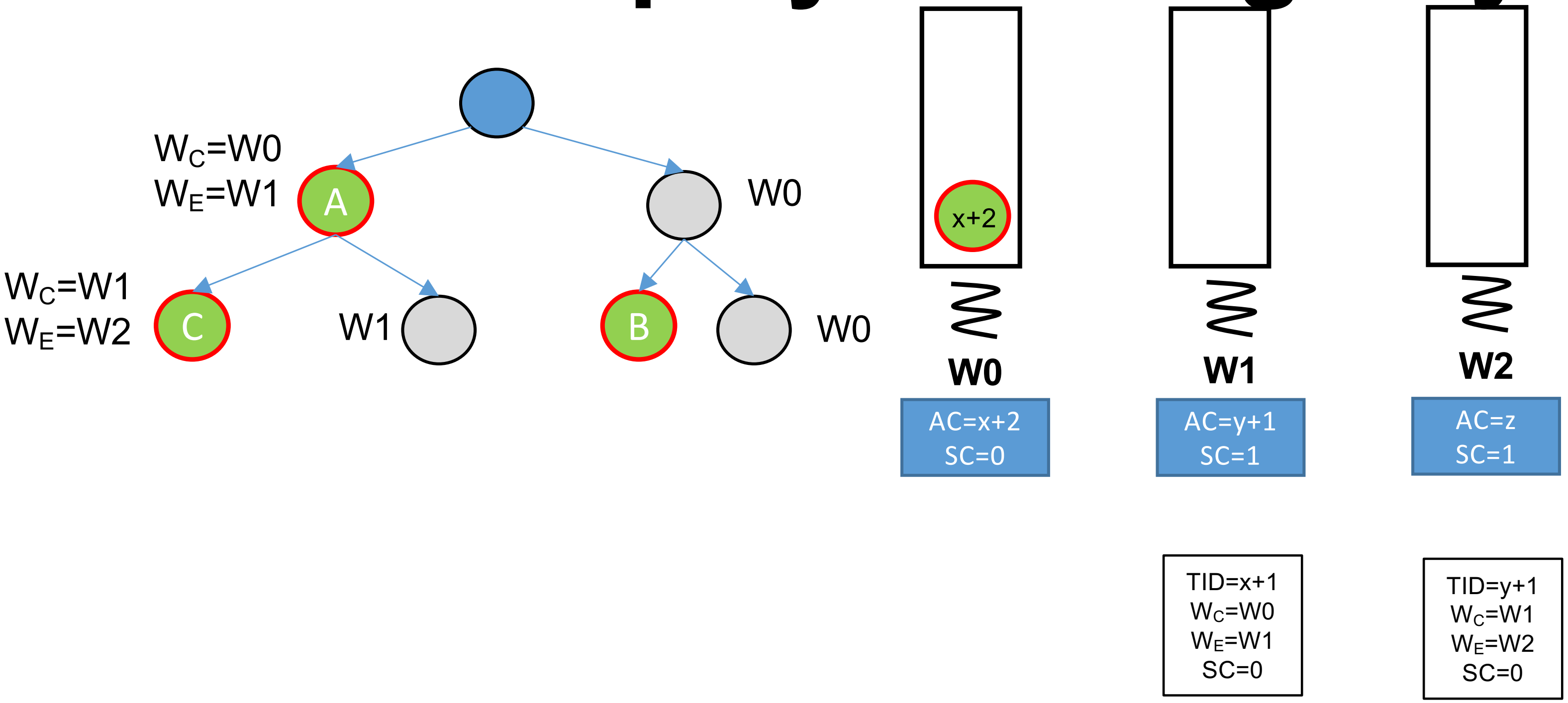
- W2 steals the task C from W1
- It appends a node in a private linked list containing info about this stolen task C
  - ID of the task (TID=y+1)
  - Worker who created this task (W_C=W1)
  - Worker who executed (stolen) this async (W_E=W2)
  - Current Steal Counter at W2 (SC=0)
- W2 then increment its Steal Counter (SC) before executing this stolen task

Trace & Replay: Tracing Async



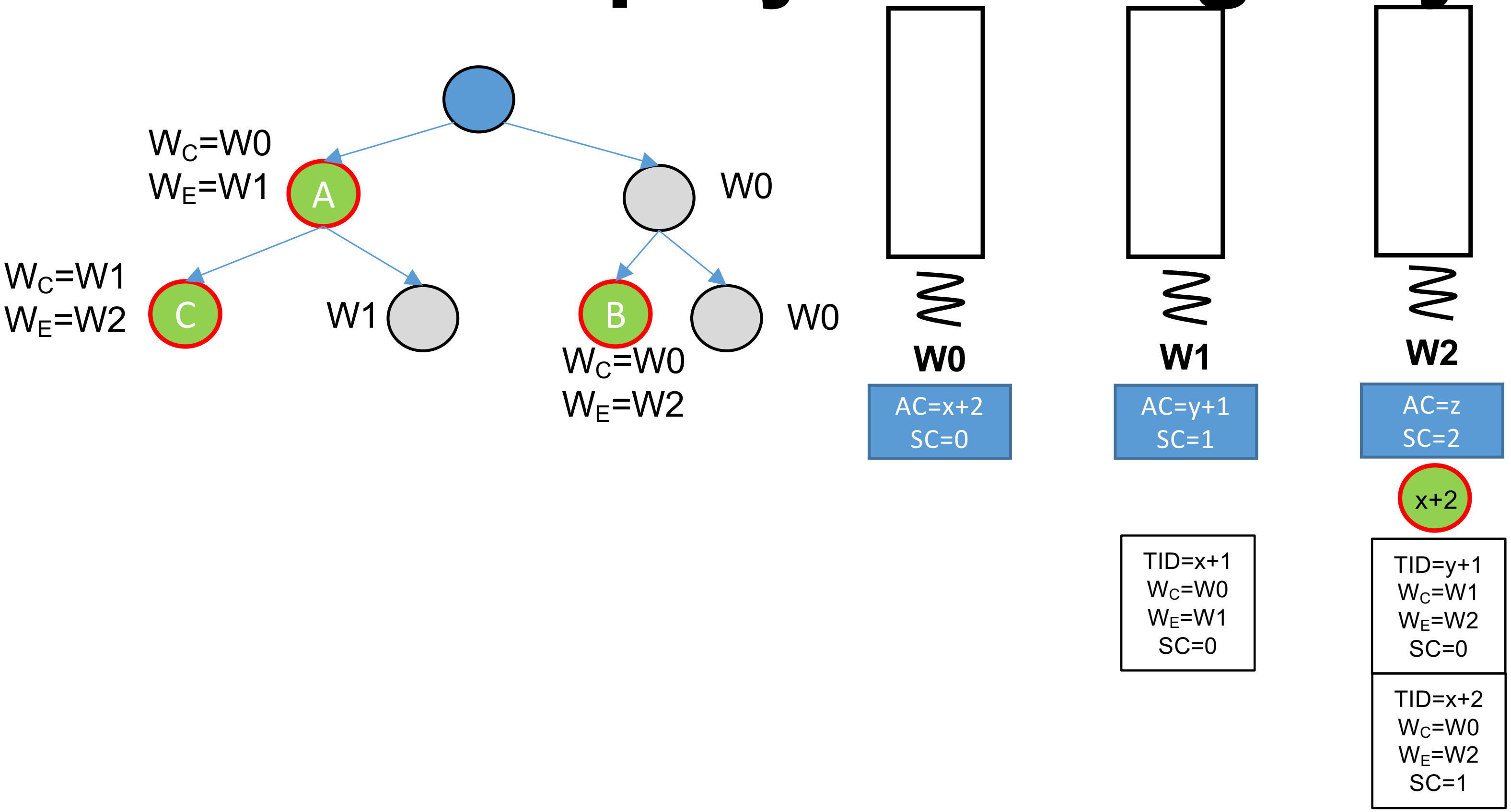
- W0 creates an async B

Trace & Replay: Tracing Async



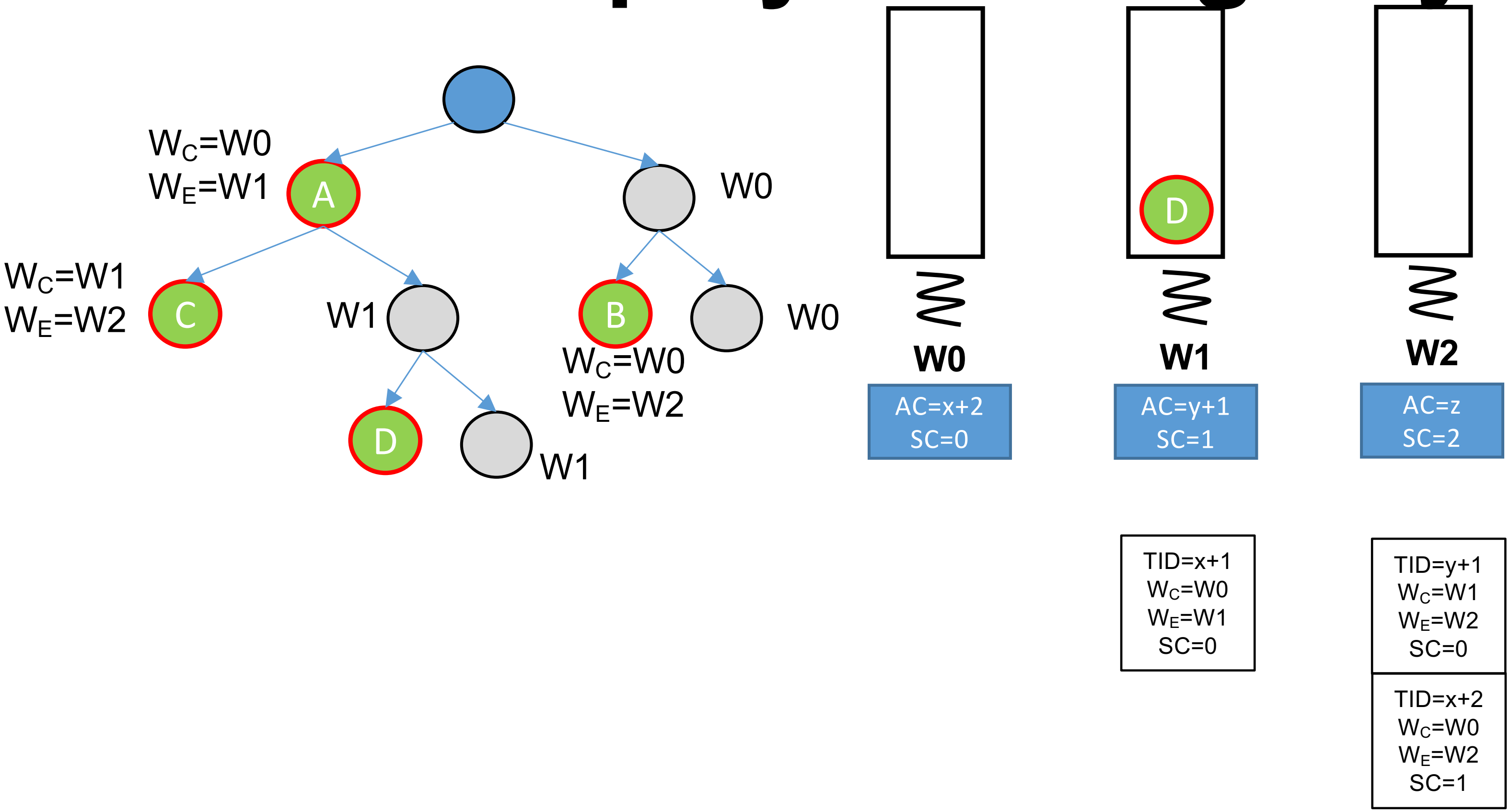
- AC at W0 is incremented and is assigned as the ID of the Task B **before** its pushed into W0's deque

Trace & Replay: Tracing Async



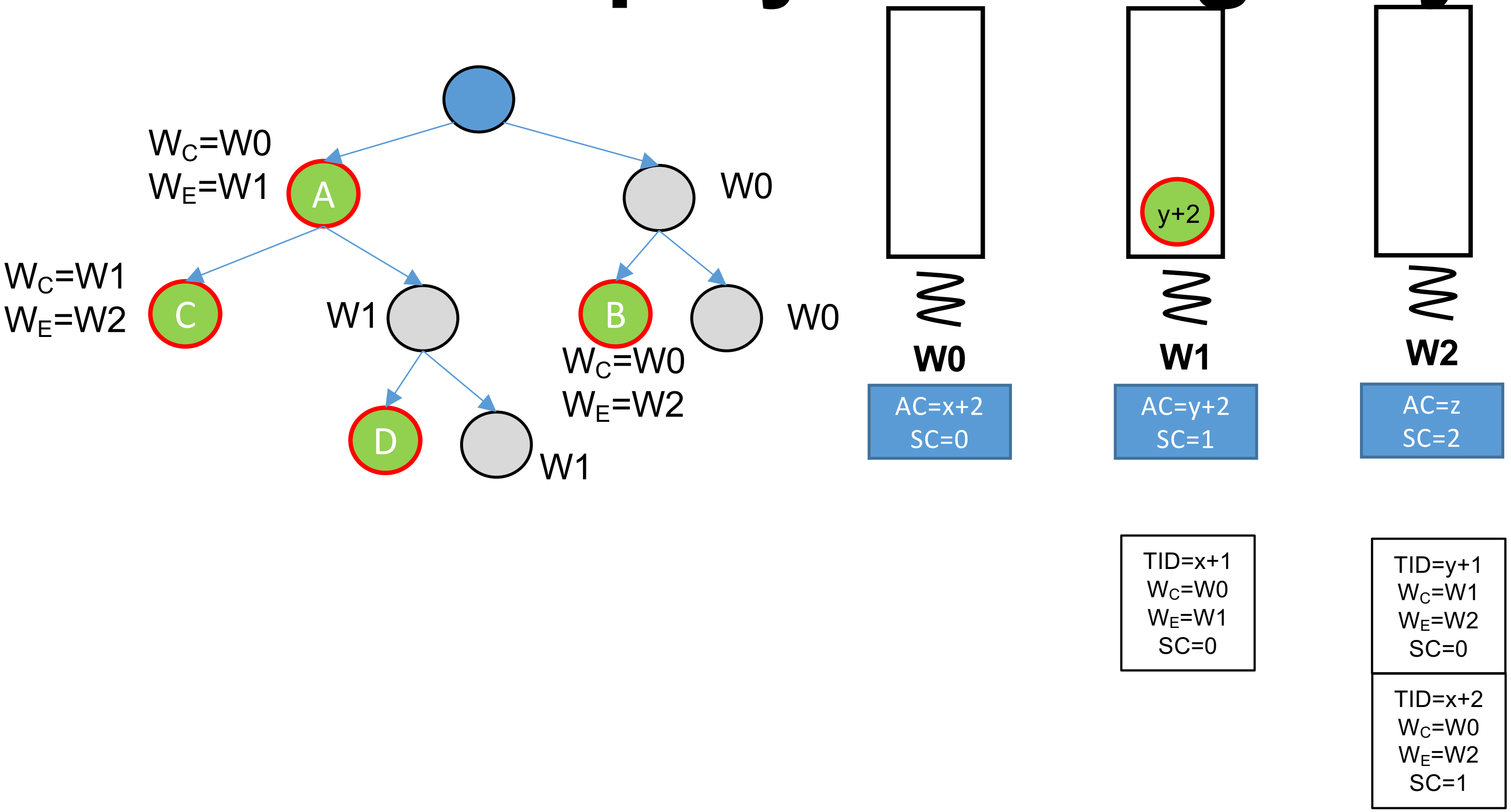
- W2 steals the task B from W0
- It append a node in a private linked list containing info about this stolen task B
  - ID of the task (TID=x+2)
  - Worker who created this task (W_C=W0)
  - Worker who executed (stolen) this async (W_E=W2)
  - Current Steal Counter at W2 (SC=1)
- W2 then increment its Steal Counter (SC) before executing this stolen task

Trace & Replay: Tracing Async



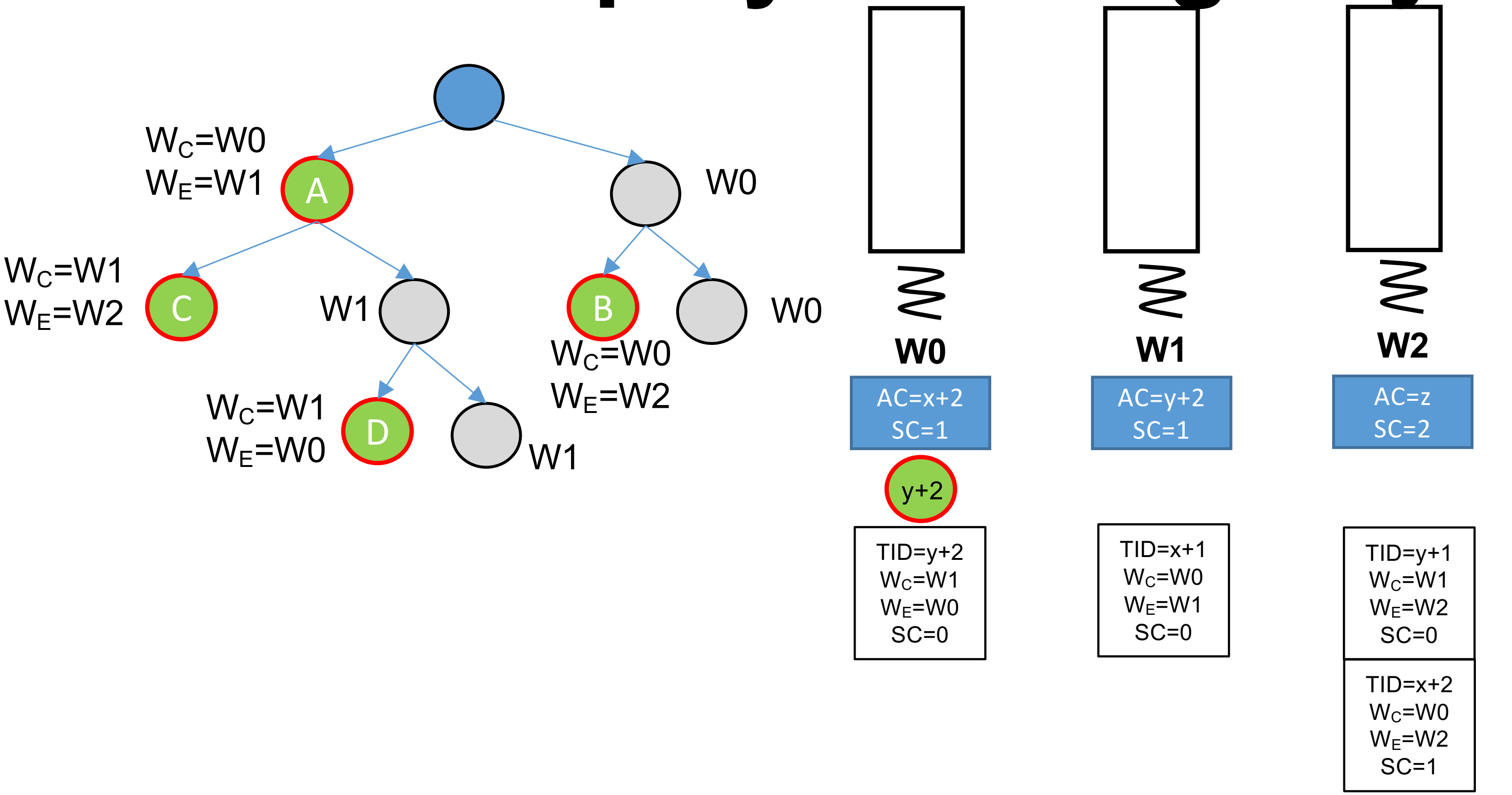
- W1 creates an async D

Trace & Replay: Tracing Async



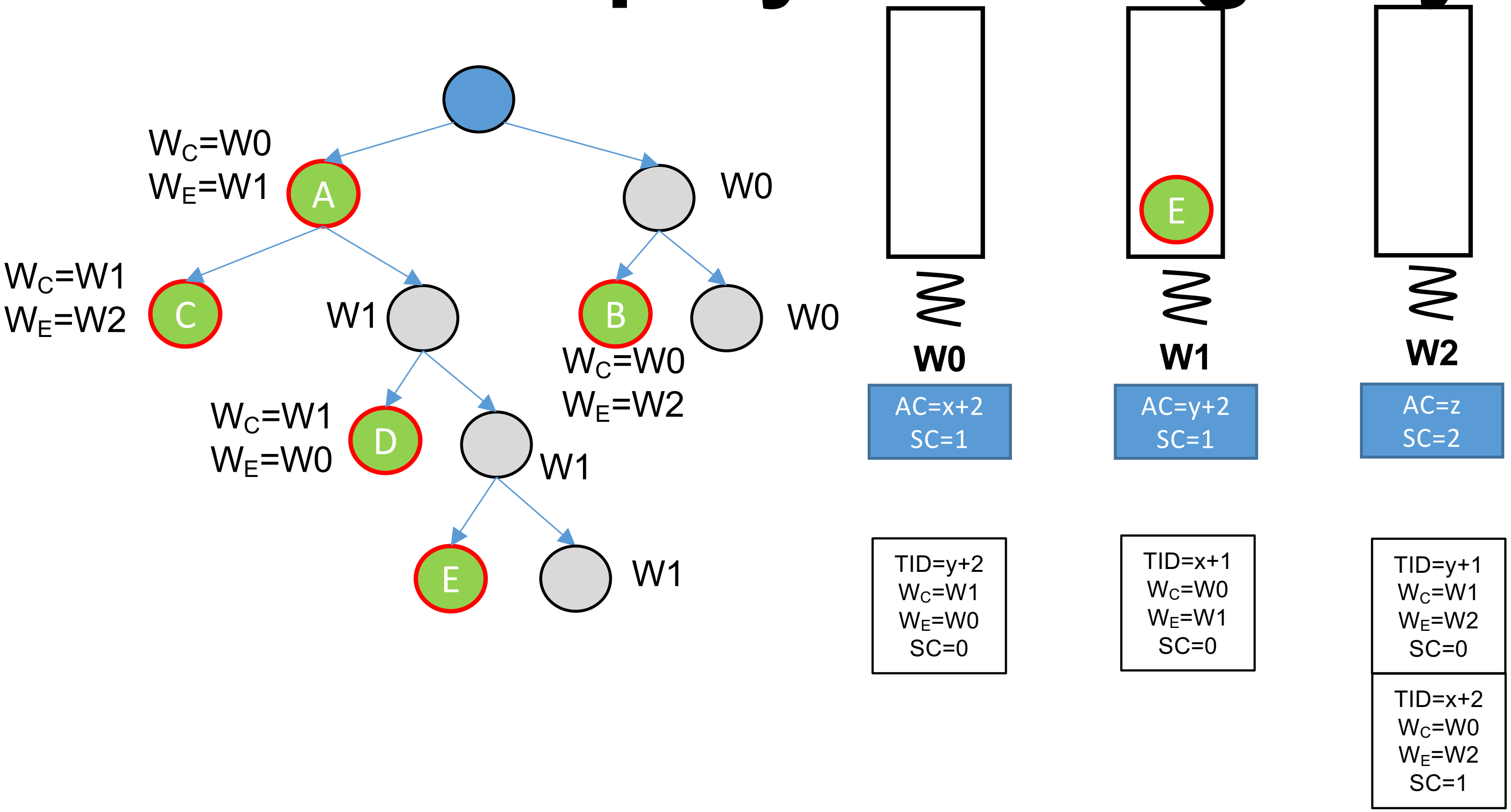
- AC at W1 is incremented and is assigned as the ID of the Task D **before** its pushed into W1's deque

Trace & Replay: Tracing Async



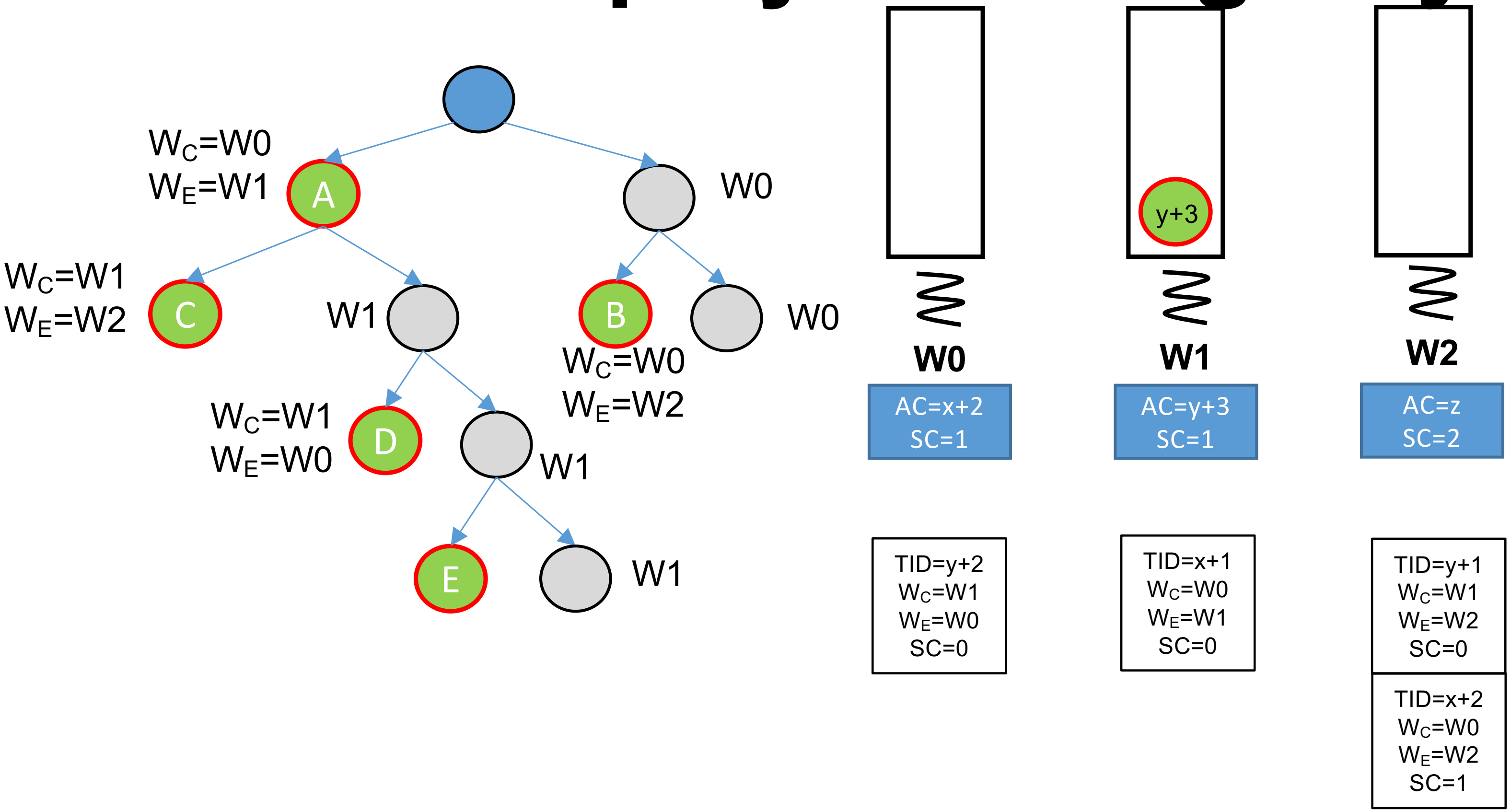
- W0 steals the task D from W1
- It append a node in a private linked list containing info about this stolen task D
  - ID of the task (TID=y+2)
  - Worker who created this task (W_C=W1)
  - Worker who executed (stolen) this async (W_E=W0)
  - Current Steal Counter at W0 (SC=0)
- W0 then increment its Steal Counter (SC) before executing this stolen task

Trace & Replay: Tracing Async



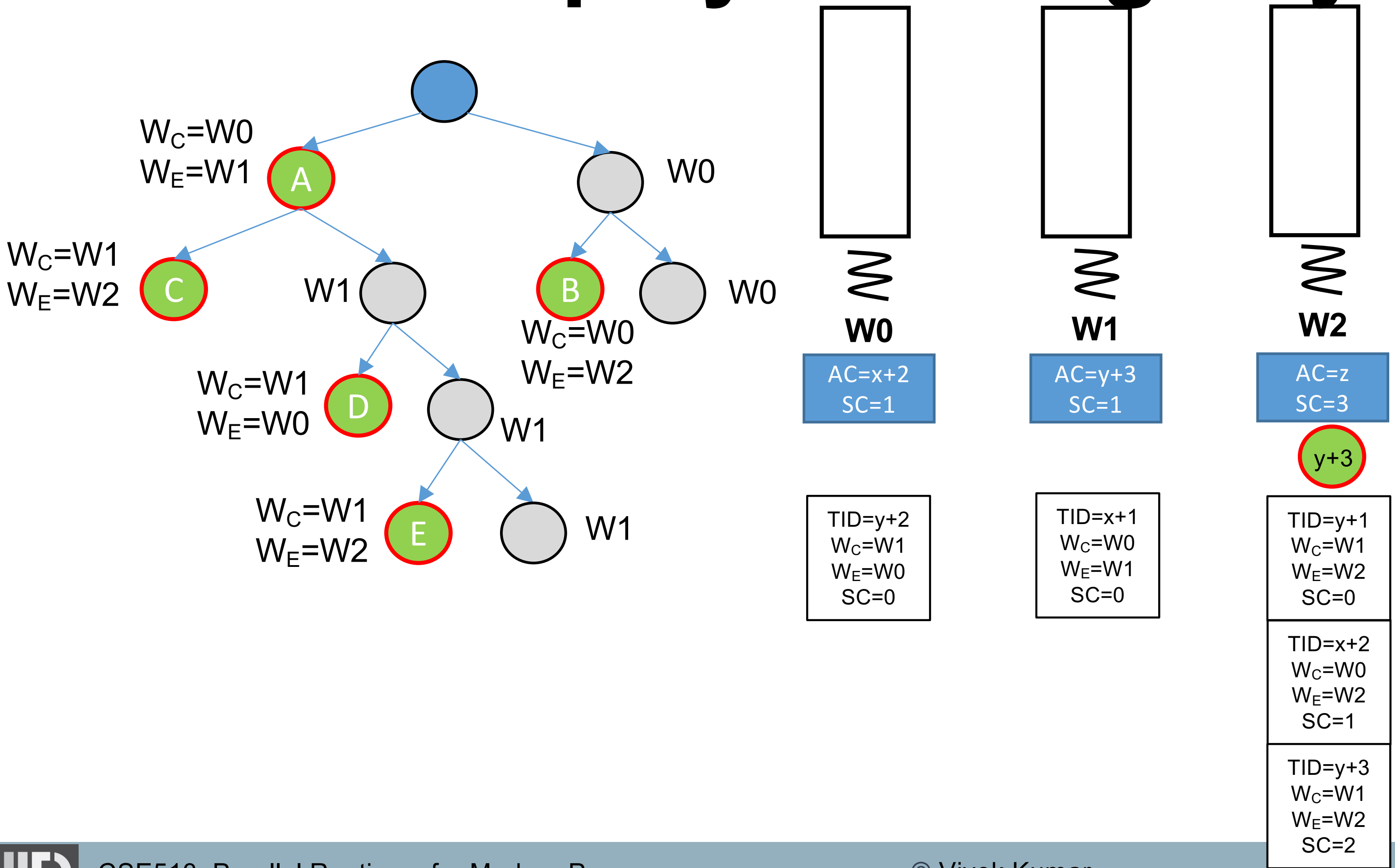
- W1 creates an async E

Trace & Replay: Tracing Async



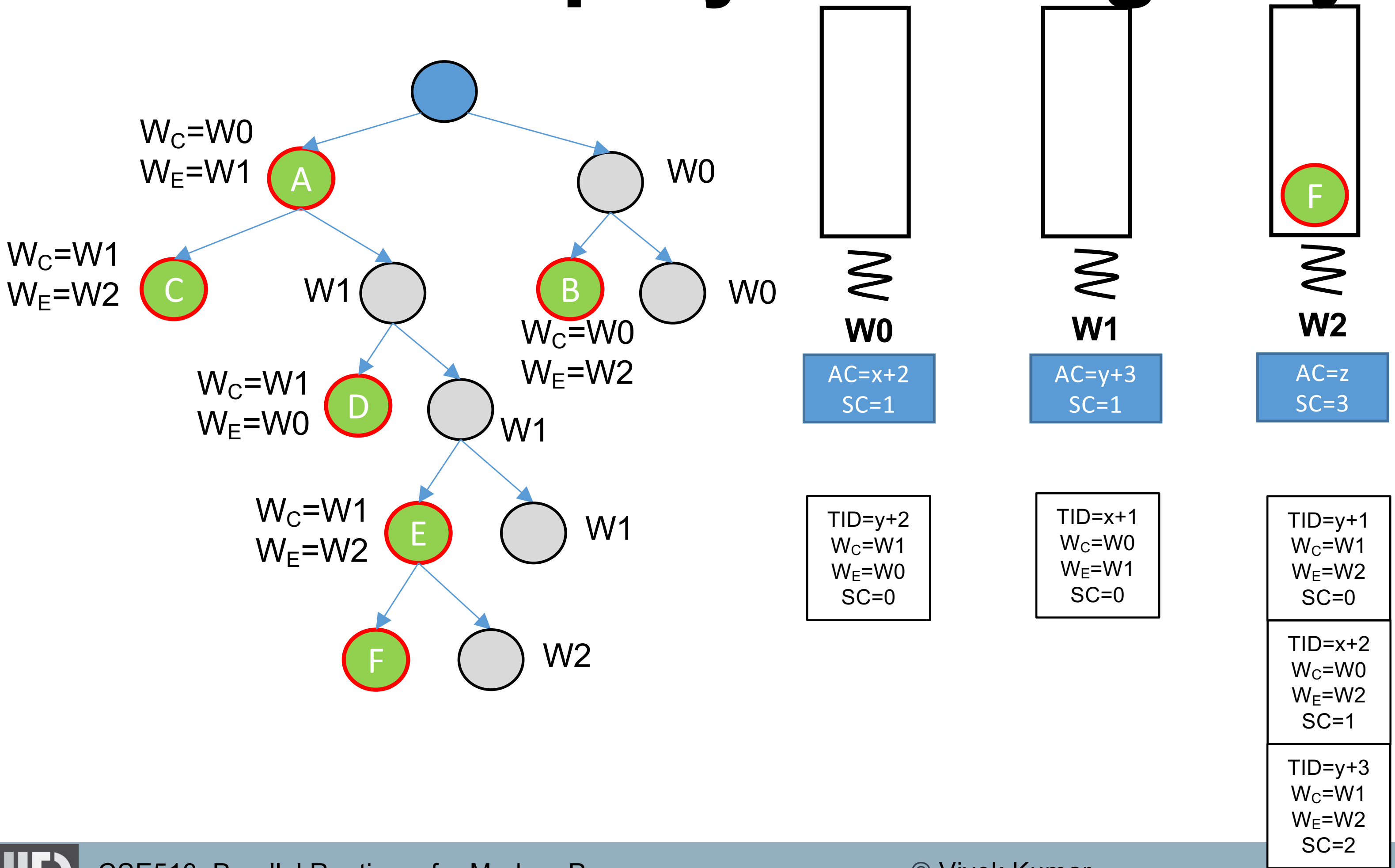
- AC at W1 is incremented and is assigned as the ID of the Task E **before** its pushed into W1's deque

Trace & Replay: Tracing Async



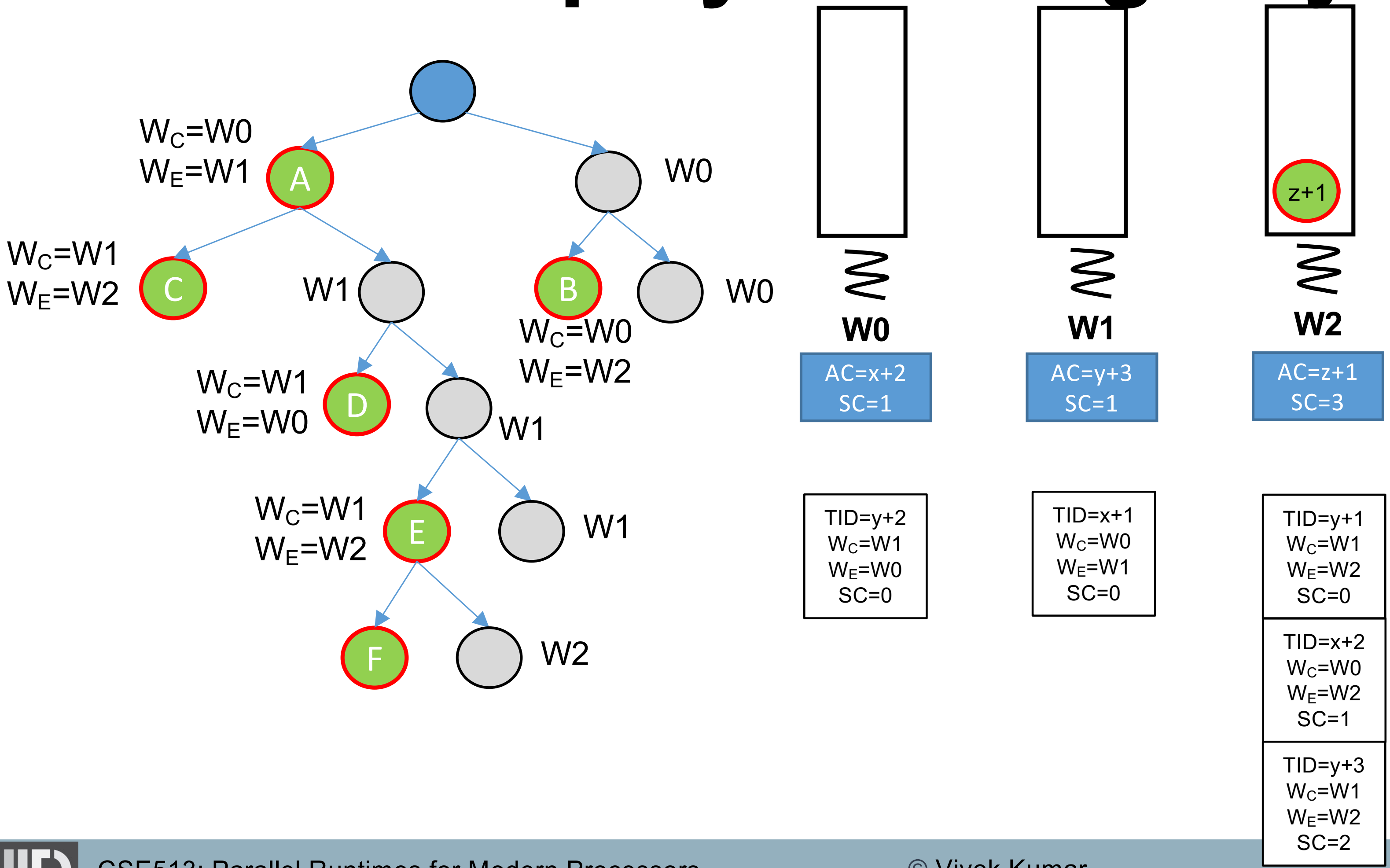
- W2 steals the task E from W1
- It append a node in a private linked list containing info about this stolen task E
  - ID of the task (TID=y+3)
  - Worker who created this task (W_C=W1)
  - Worker who executed (stolen) this async (W_E=W2)
  - Current Steal Counter at W2 (SC=2)
- W2 then increment its Steal Counter (SC) before executing this stolen task

Trace & Replay: Tracing Async



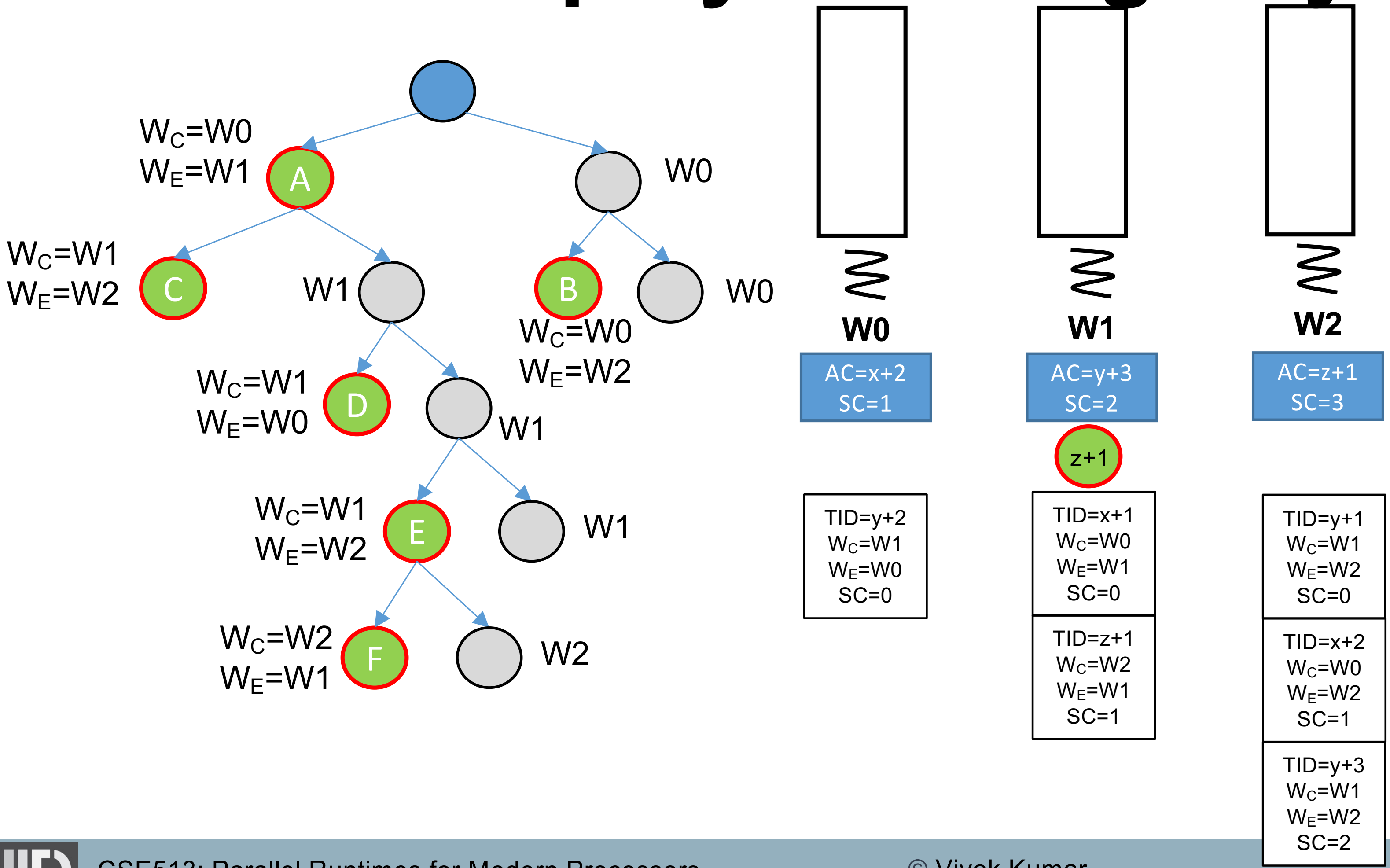
- W2 creates an async F

Trace & Replay: Tracing Async



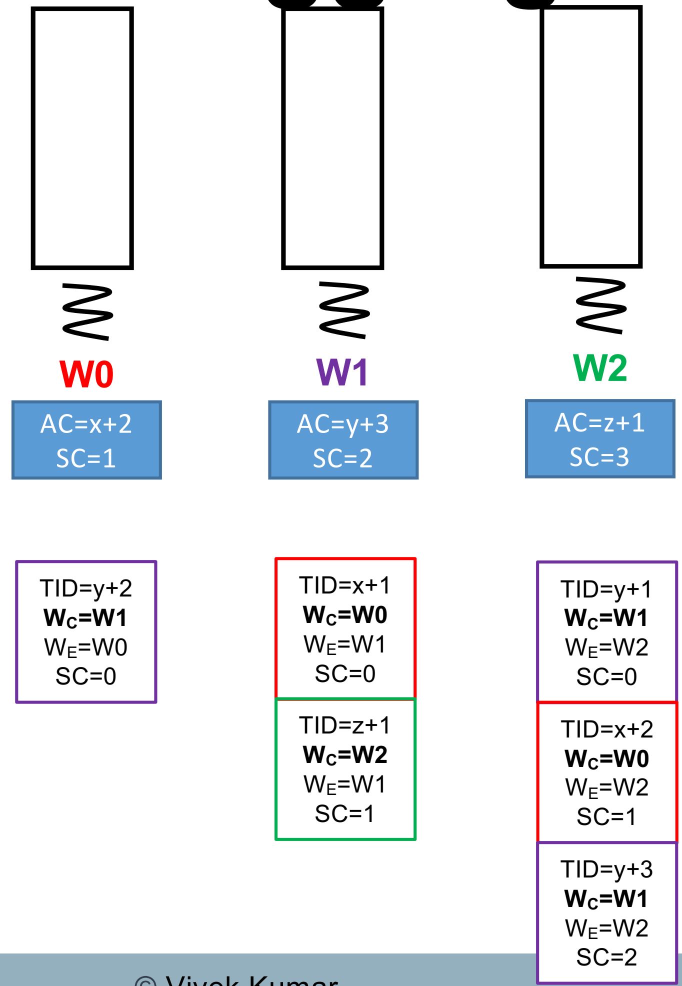
- AC at W2 is incremented and is assigned as the ID of the Task F **before** its pushed into W2’s deque

Trace & Replay: Tracing Async



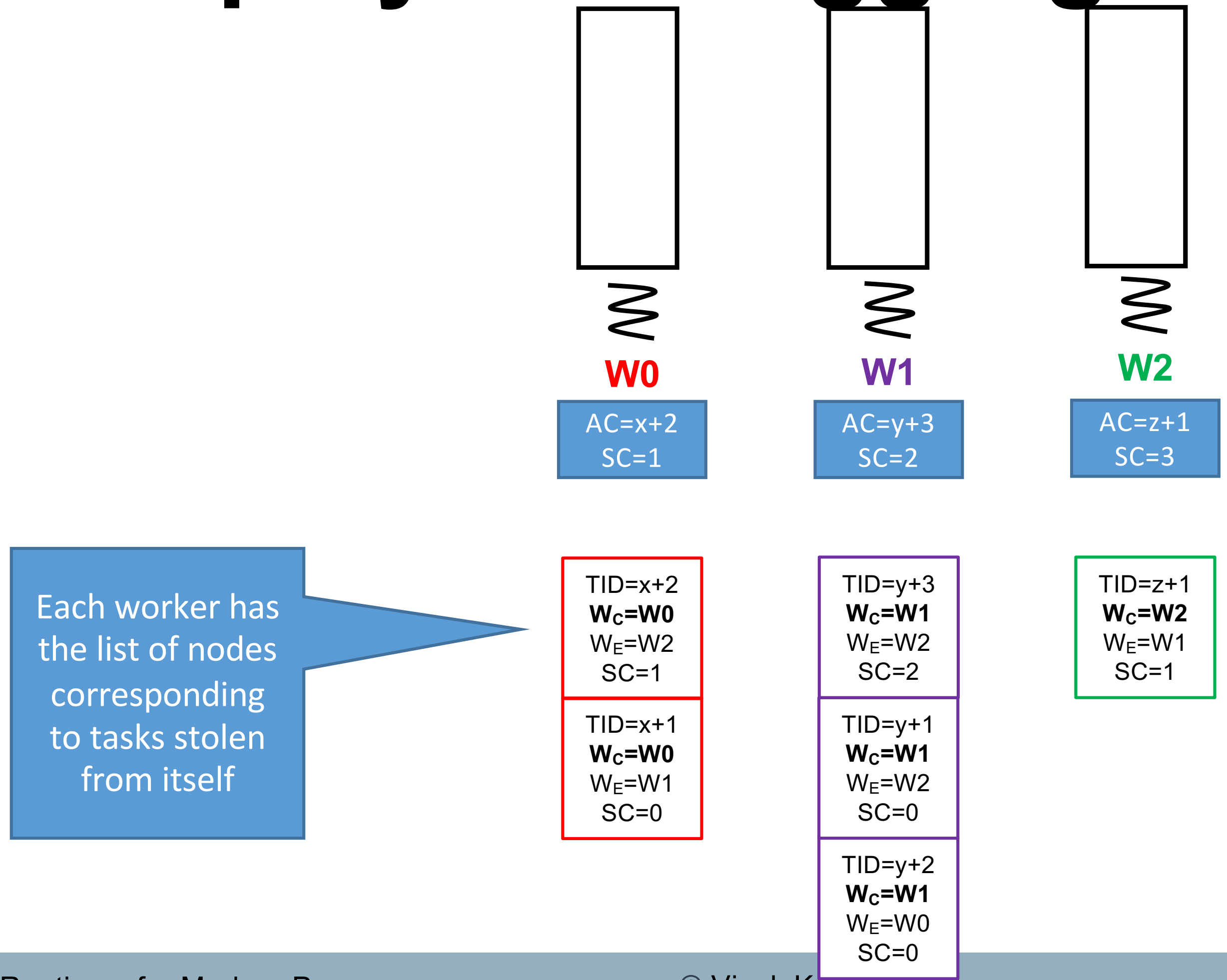
- W1 steals the task F from W2
- It append a node in a private linked list containing info about this stolen task F
  - ID of the task (TID=z+1)
  - Worker who created this task (W_C=W2)
  - Worker who executed (stolen) this async (W_E=W1)
  - Current Steal Counter at W1 (SC=1)
- W1 then increment its Steal Counter (SC) before executing this stolen task

Trace & Replay: List Aggregation

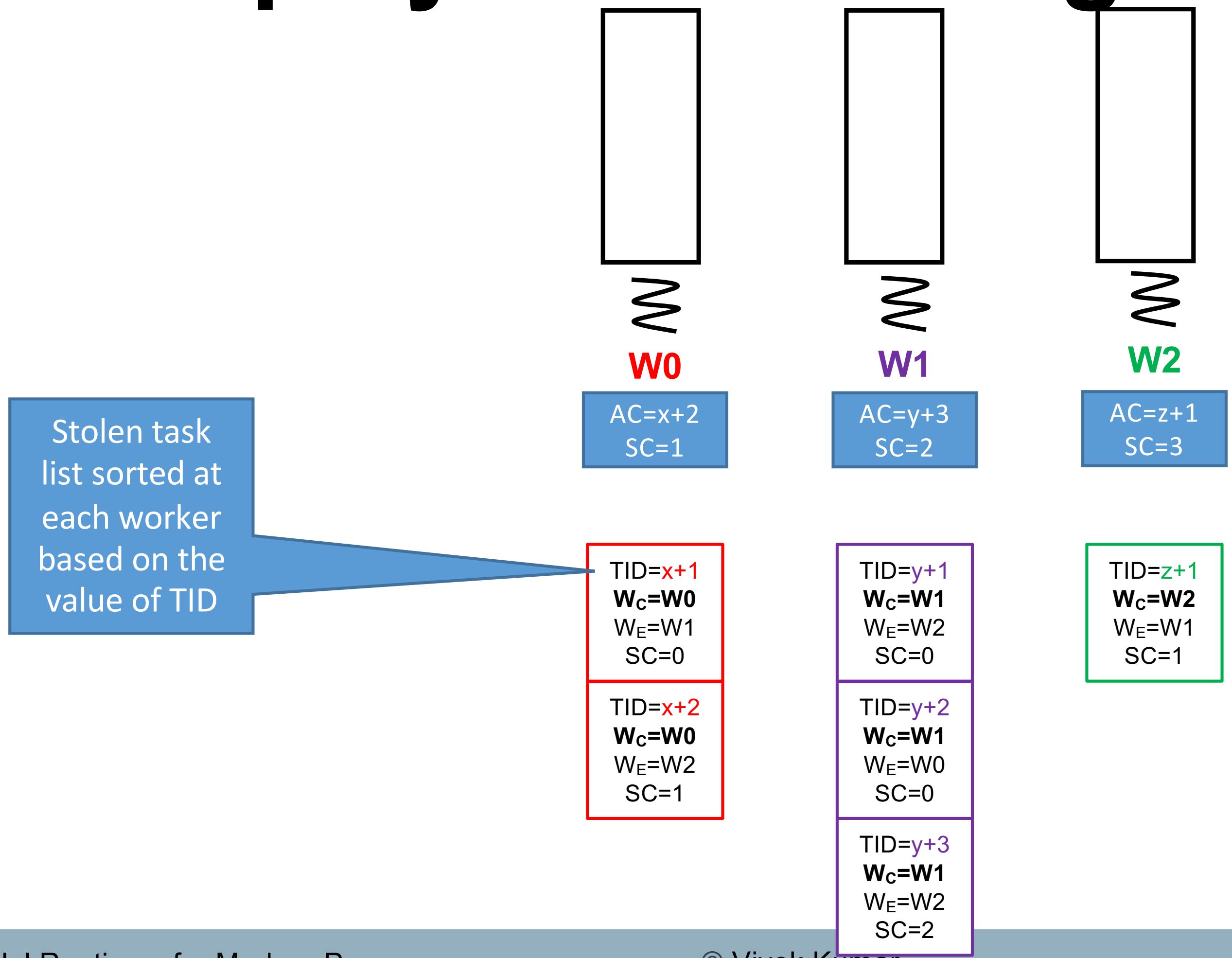


- Recursive task parallel computation has now completed
- W0 now iterates over the linked list stored at each worker
- W0 aggregates each of the linked list nodes based on the worker who actually created the task corresponding to that node (value of W_C)
  - Hence, there would be numWorker number of linked lists
  - Each worker would finally have nodes with W_C value corresponding to itself

Trace & Replay: List Aggregation

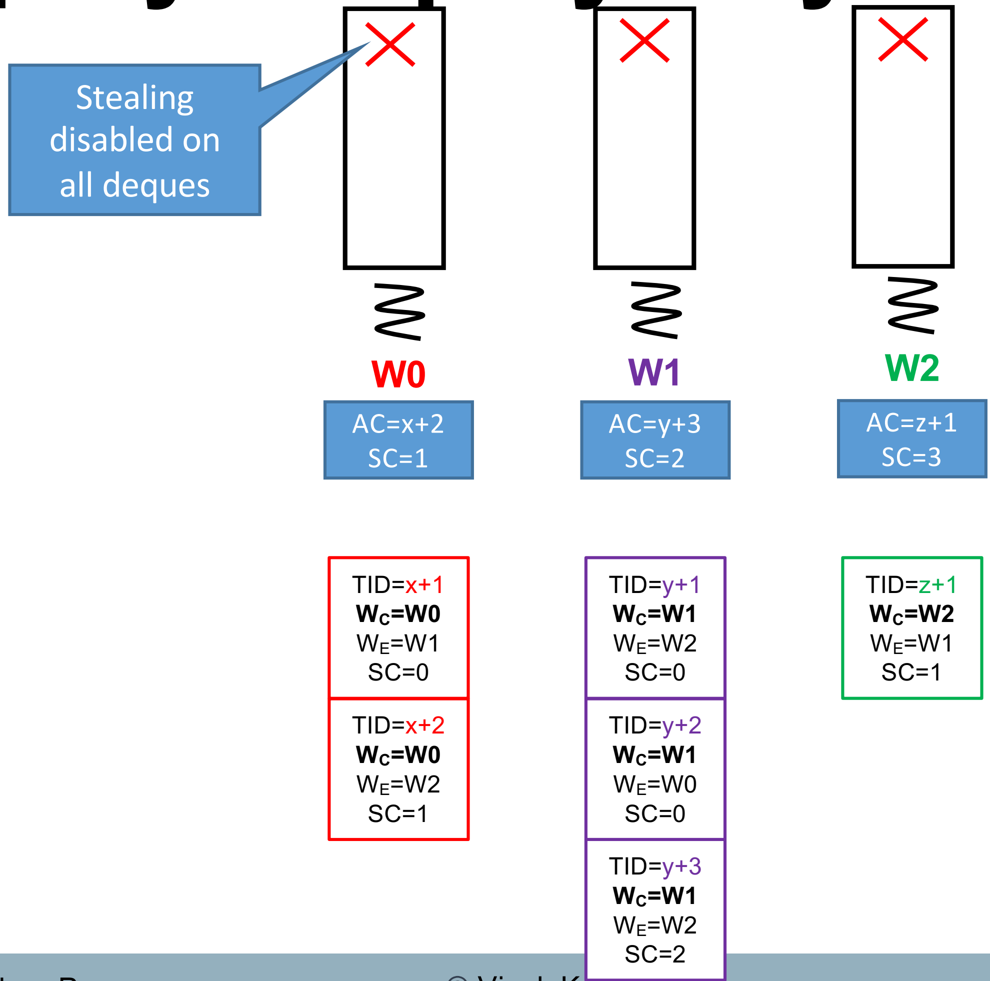


Trace & Replay: List Sorting



- W0 will sort each of these lists (at each worker) based on the TID stored inside the nodes

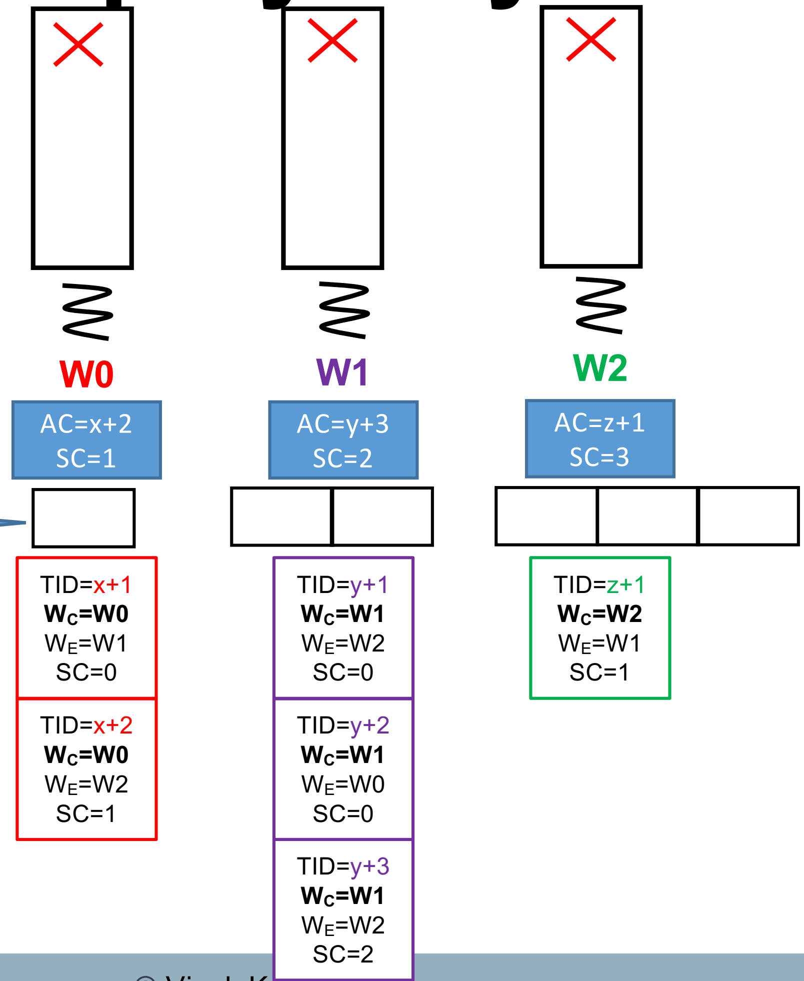
Trace & Replay: Replay Async



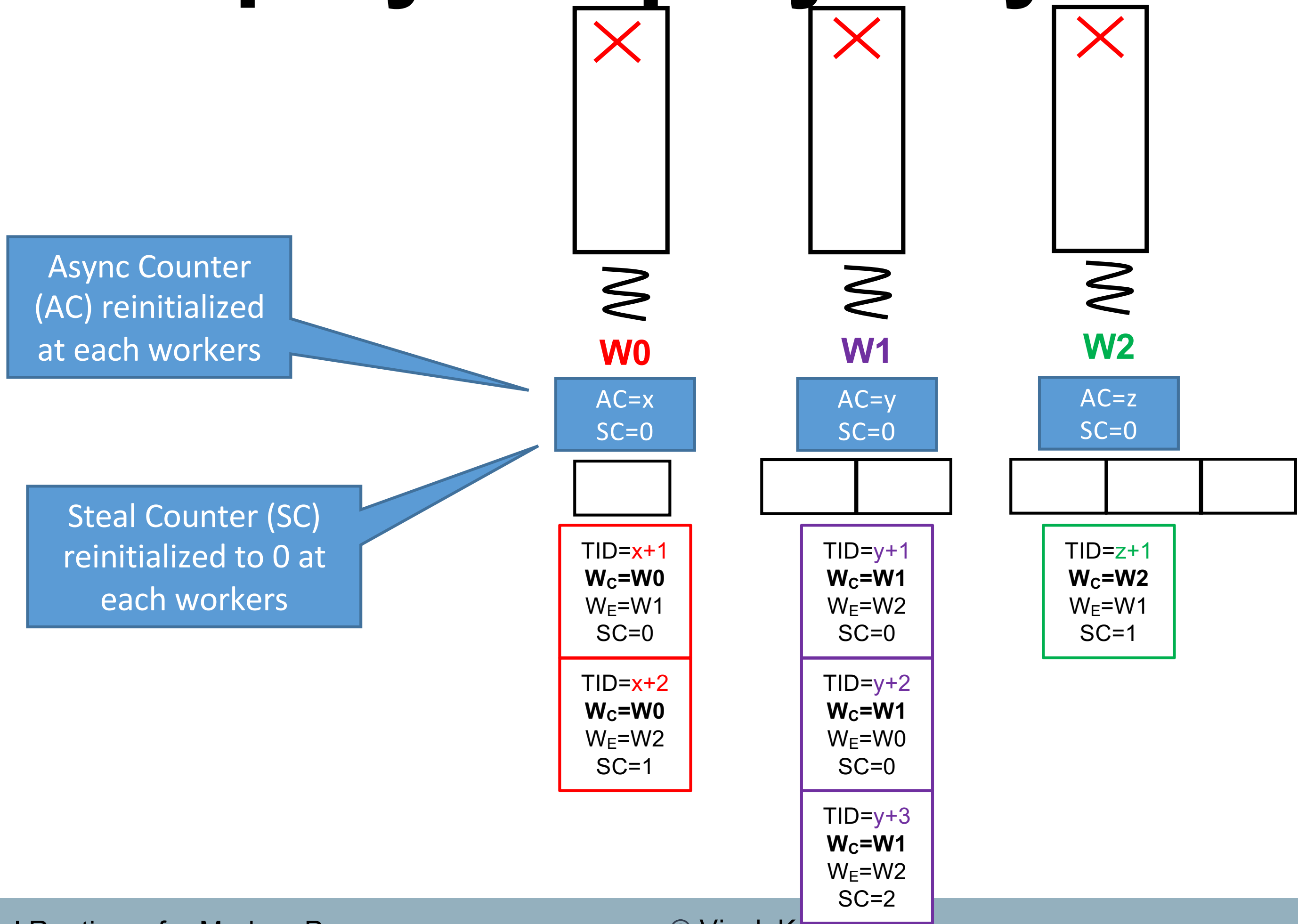
- Replay phase is essentially executing the same recursive task parallel program, but by using the steal information stored at each worker during the tracing phase
- During the replay phase, each worker would disable the direct steal operation on its deque

Trace & Replay: Replay Async

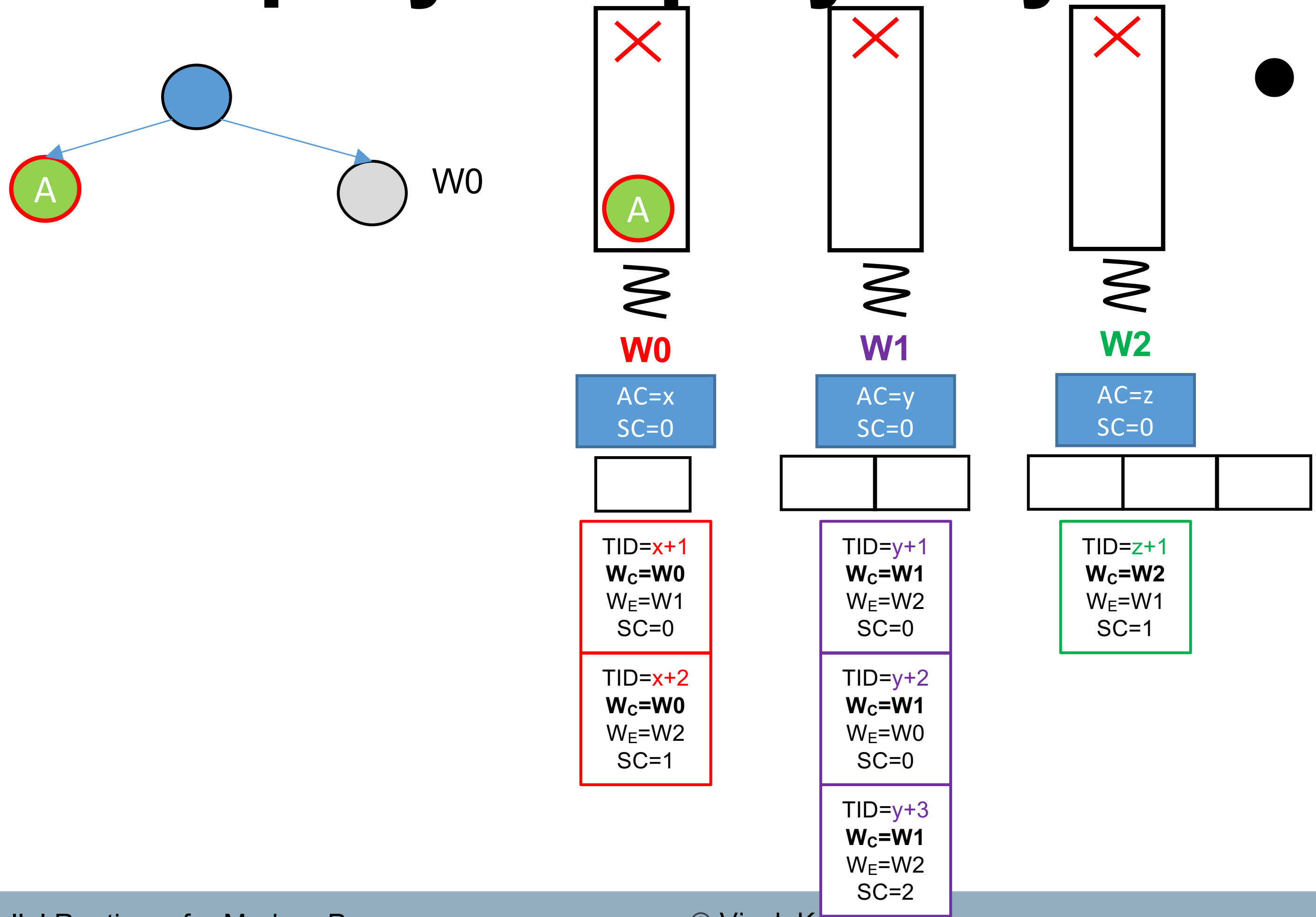
Arrays created at each worker to hold stolen tasks. Size of the array is the value of Steal Counter (SC) at that worker



Trace & Replay: Replay Async

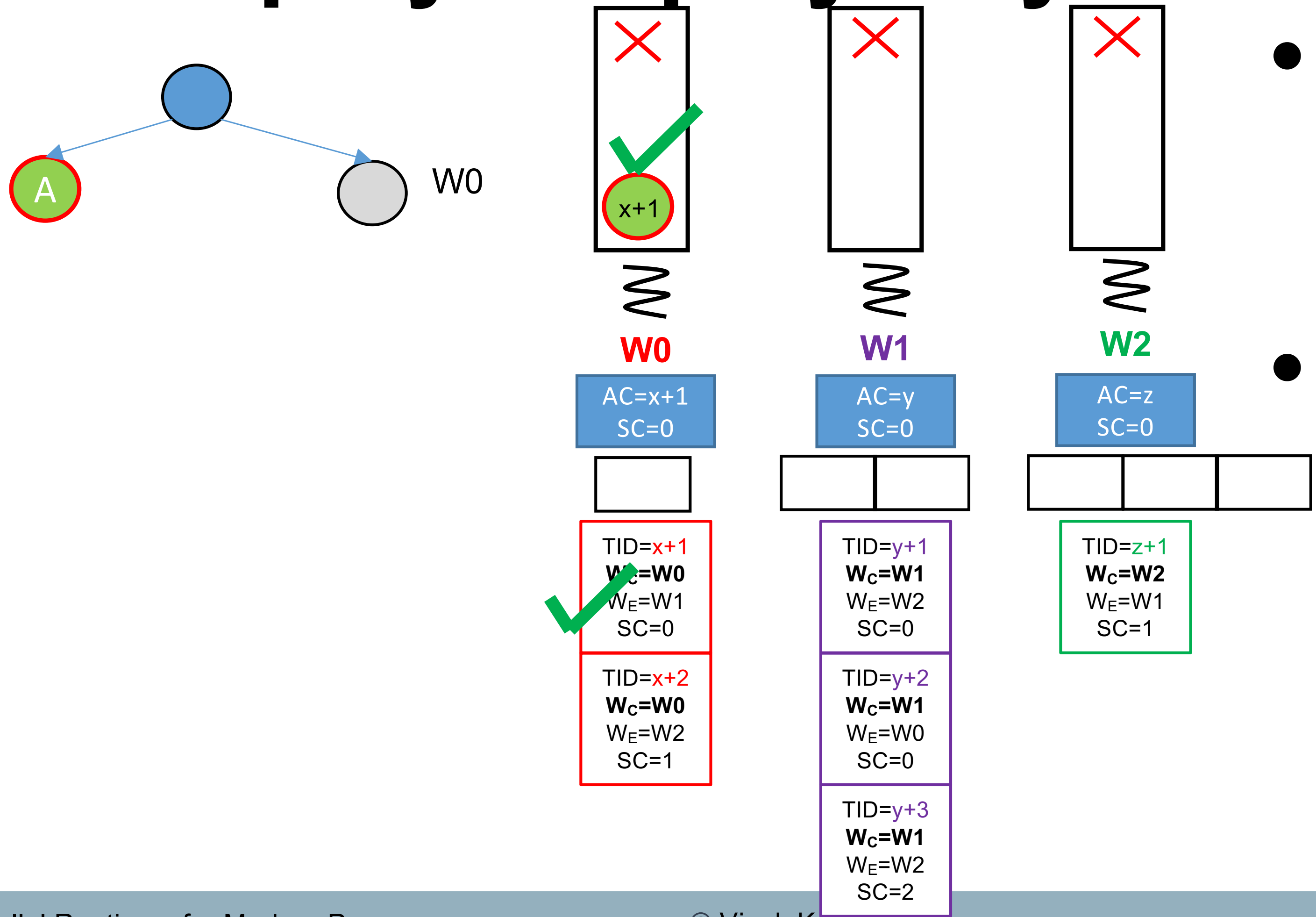


Trace & Replay: Replay Async



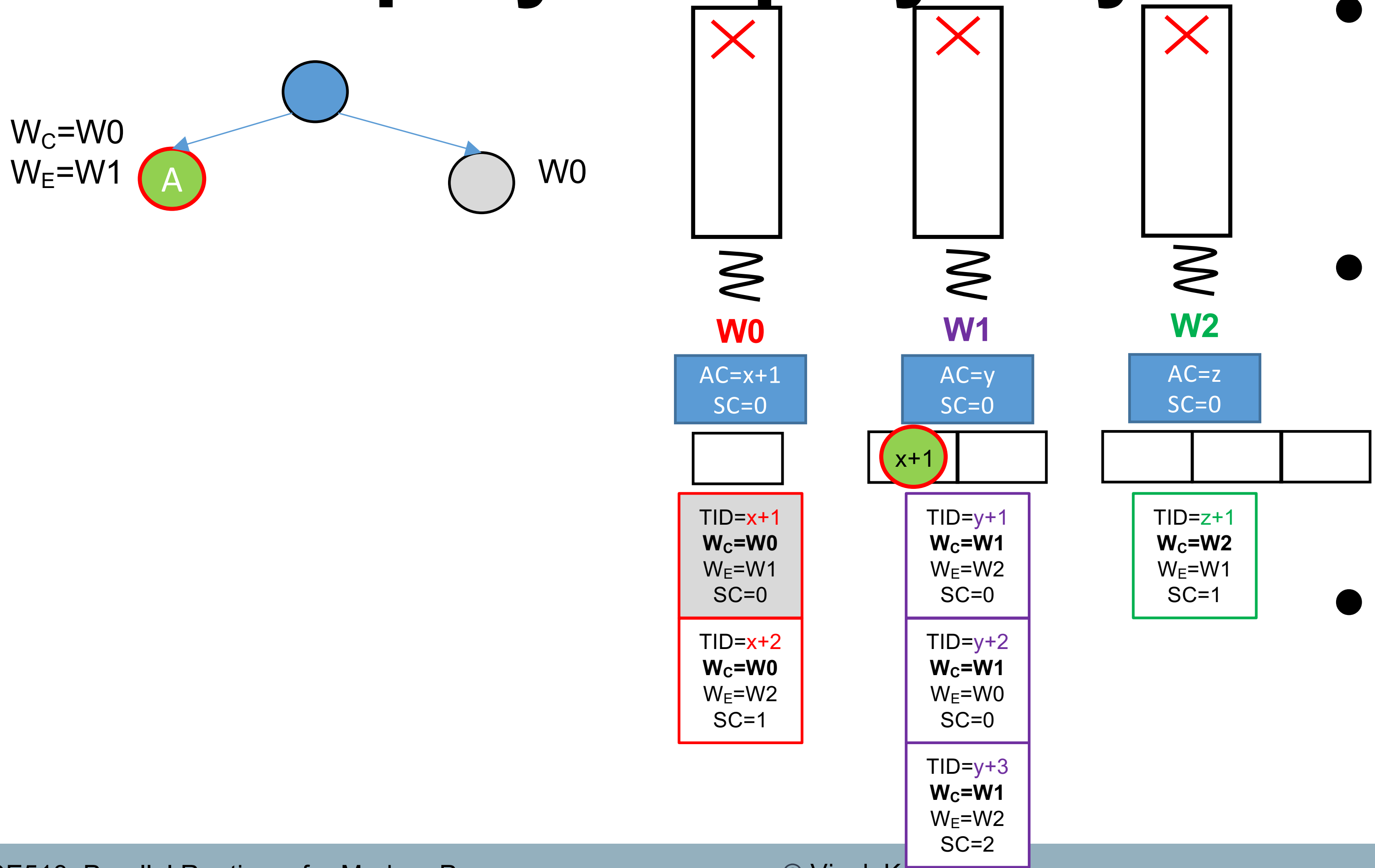
- W0 starts the computation and creates an async A

Trace & Replay: Replay Async



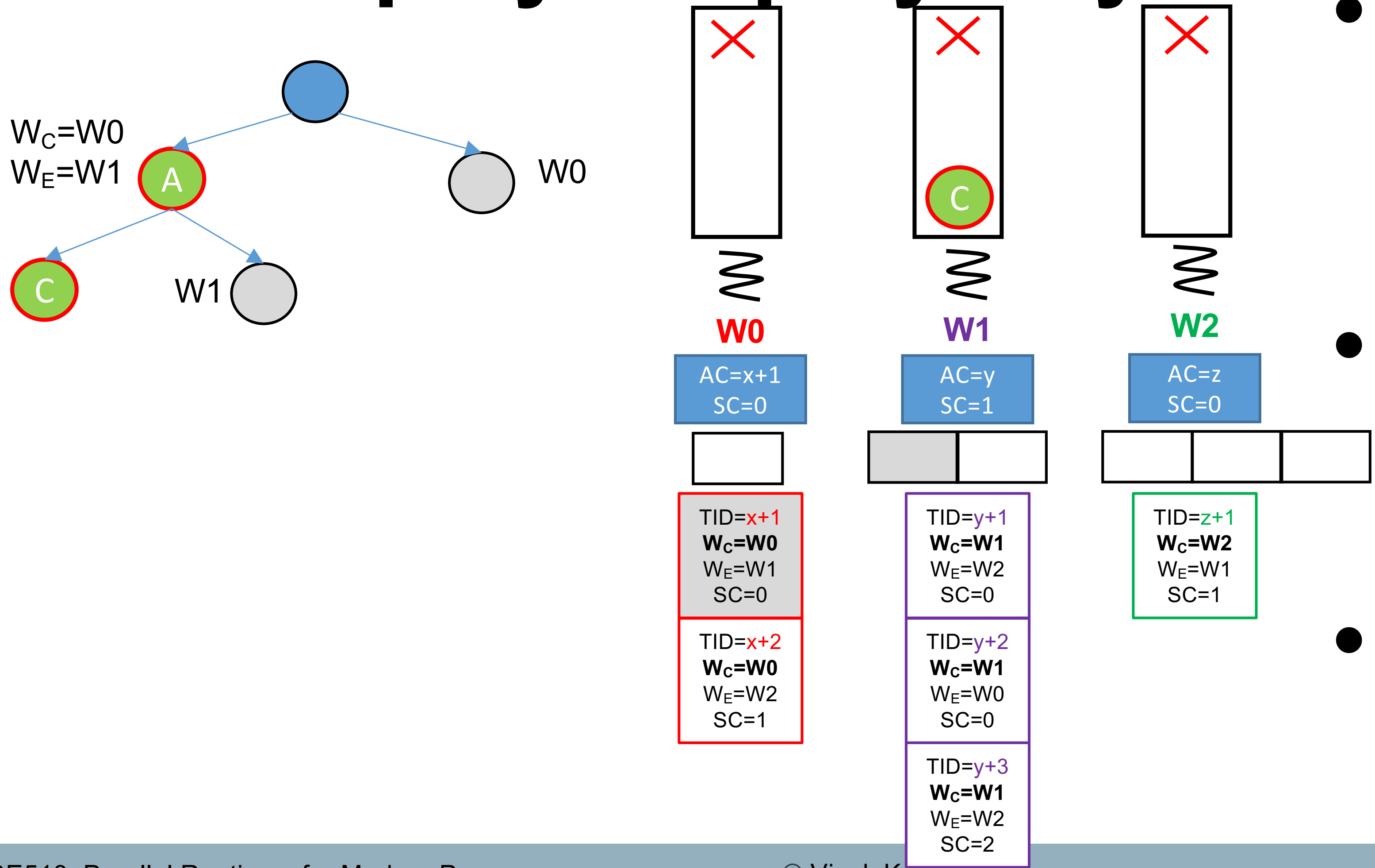
- AC at W0 is incremented and is assigned as the ID of the Task A **before** its pushed into W0's deque
- When W0 attempts to push task A into its deque, it would observe that the TID of A matches with the currently active steal node on its linked list

Trace & Replay: Replay Async



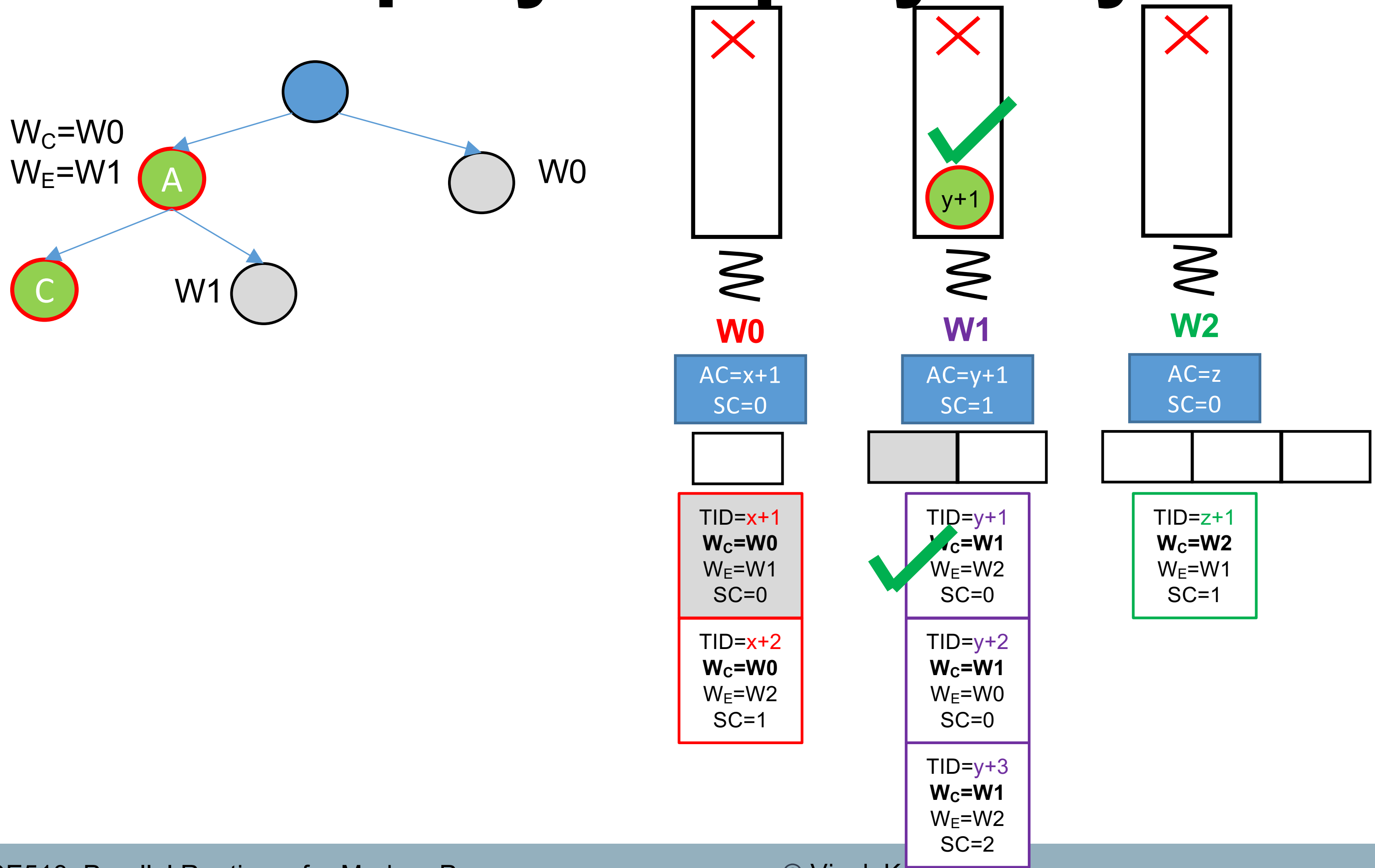
- W0 does not push task A into its deque, but directly copies it into the array at W1
- A is copied into an index value corresponding to SC counter stored inside the steal info node of task A at W0 (i.e., 0)
- W0 remove the currently pointing steal node from its linked list

Trace & Replay: Replay Async

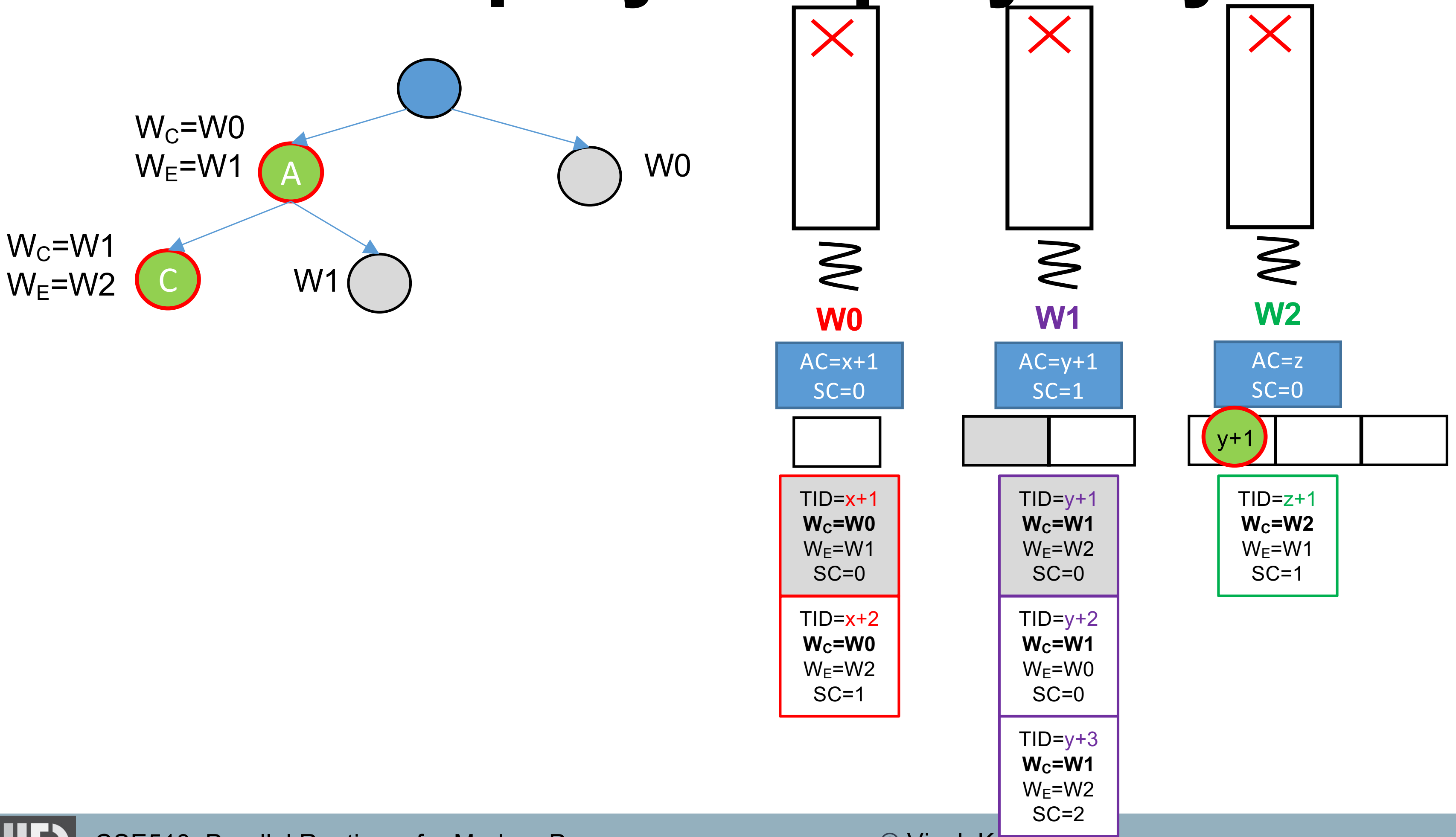


- Until now, W1 was waiting for a task to be available in its task array at an index of its current SC value (i.e., 0)
- After receiving the task, W1 will increment its SC value and will start executing the transferred task
- W1 generates an async C once it starts the execution of the transferred task

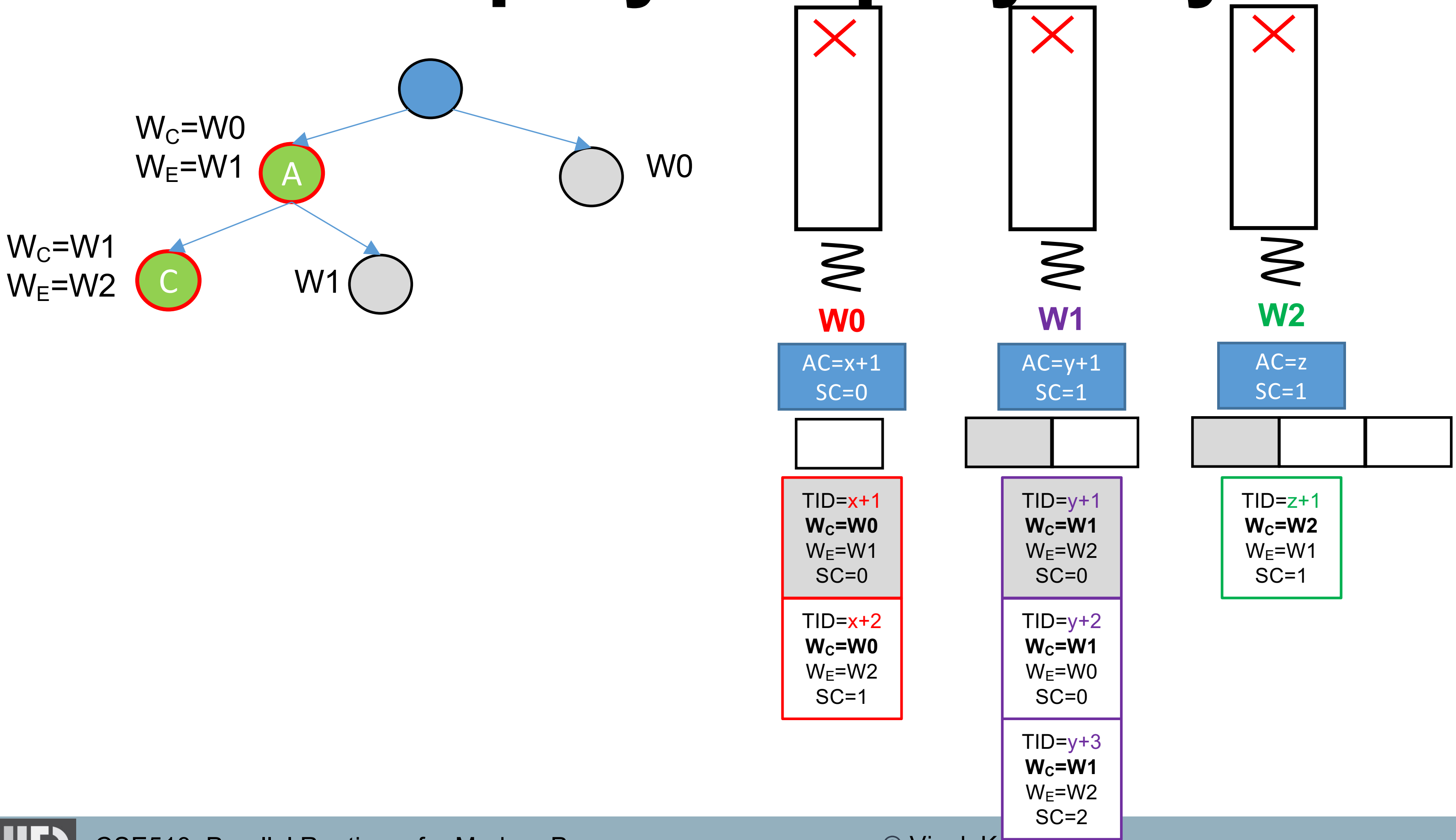
Trace & Replay: Replay Async



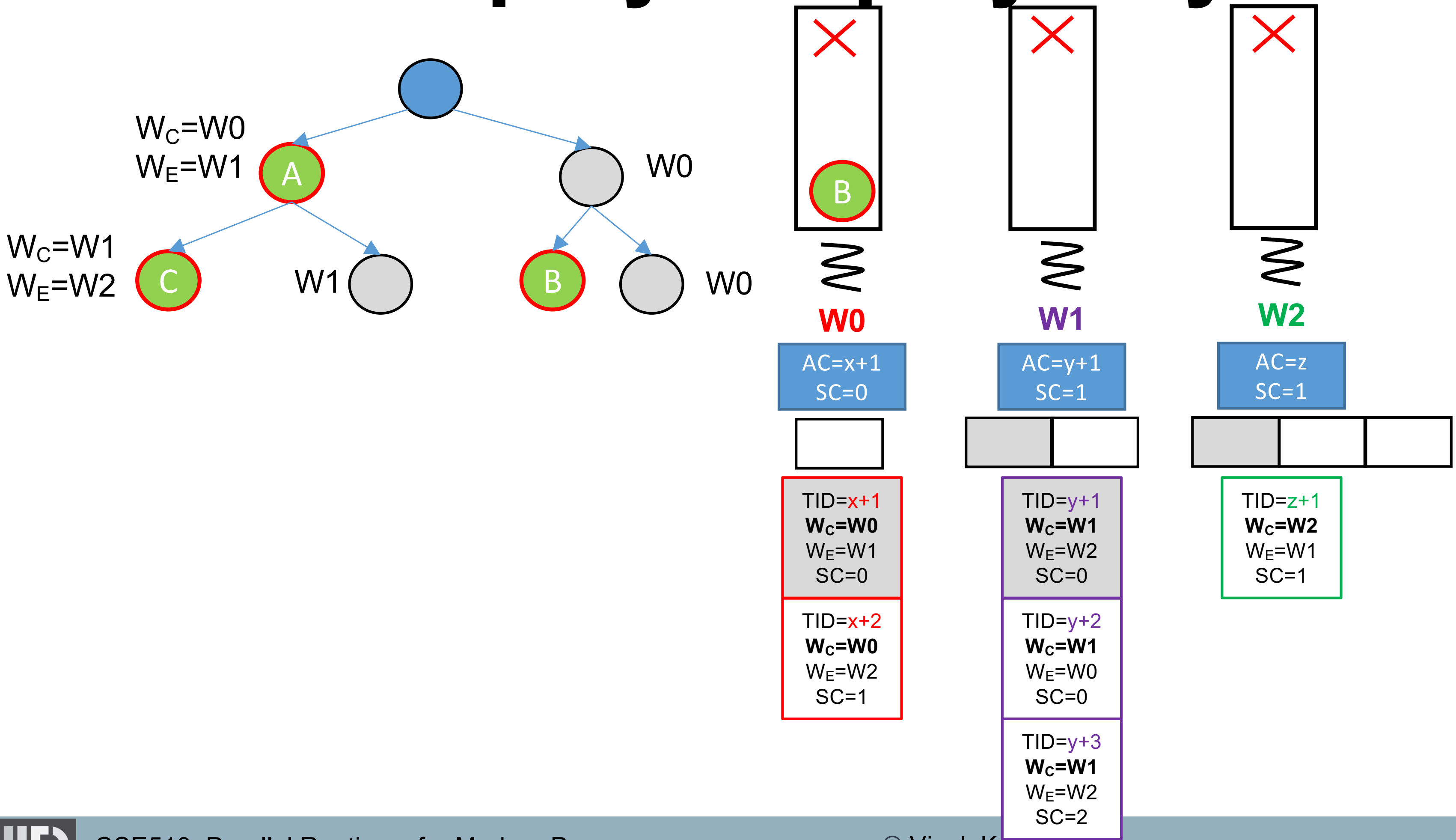
Trace & Replay: Replay Async



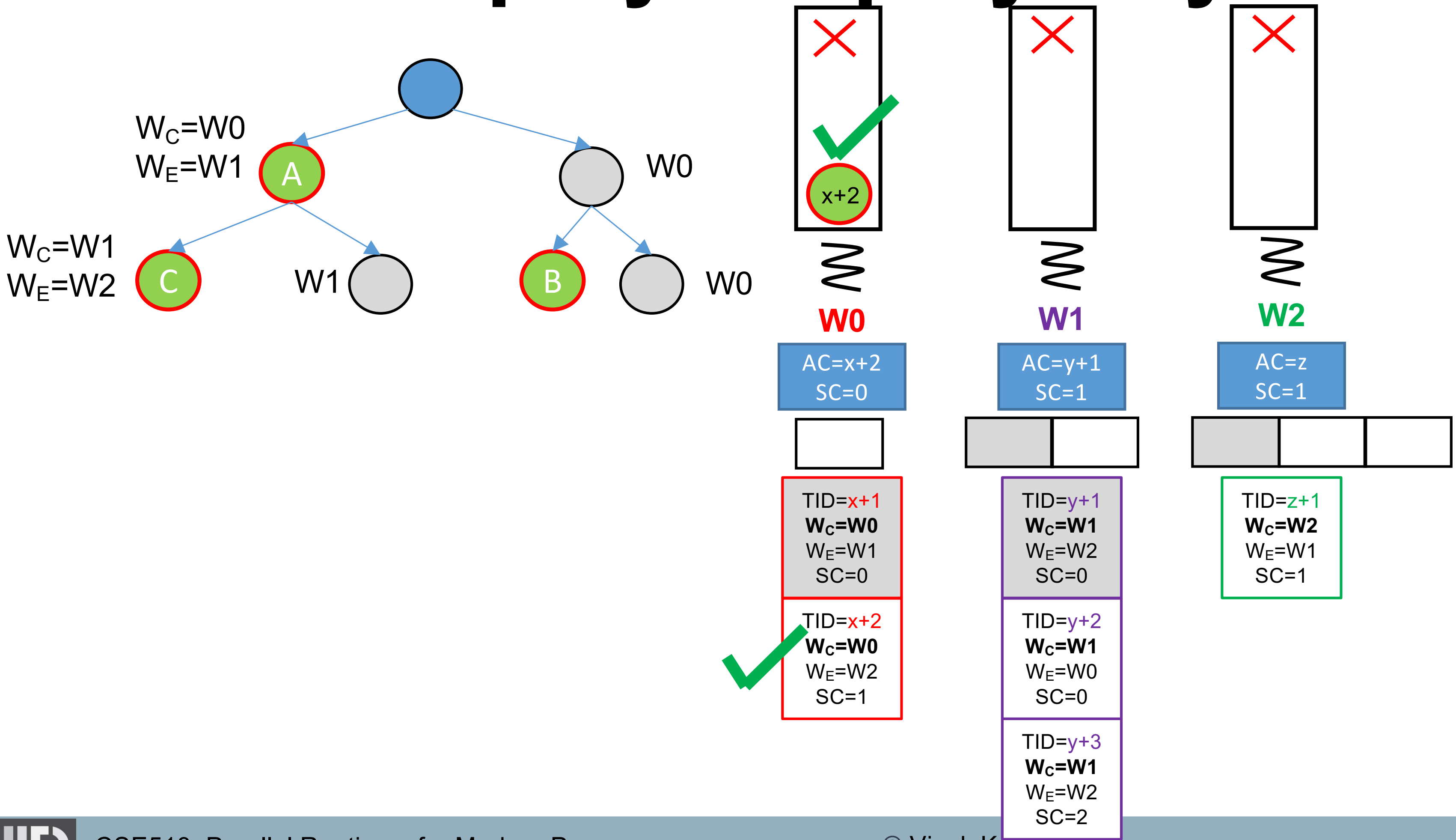
Trace & Replay: Replay Async



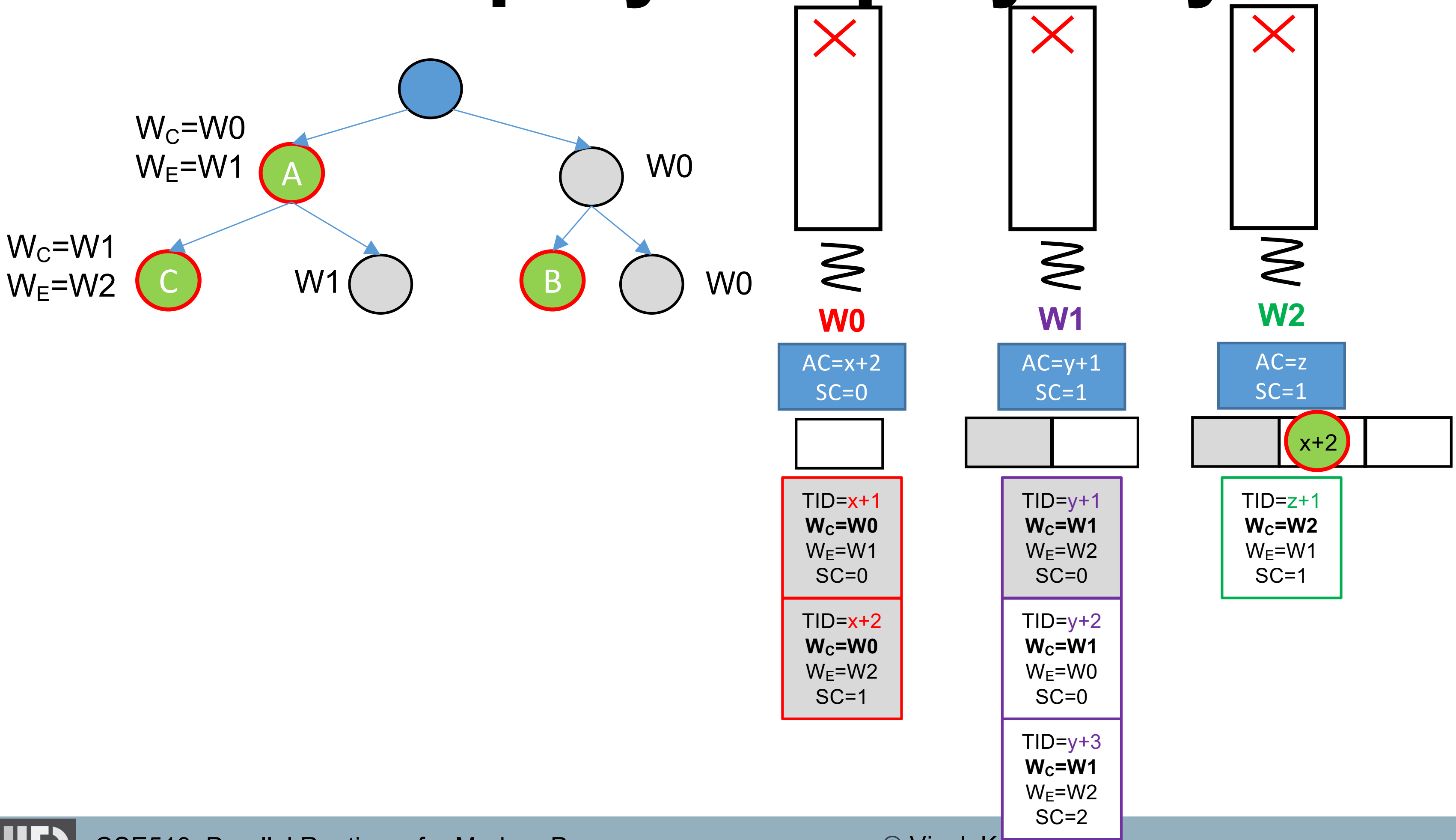
Trace & Replay: Replay Async



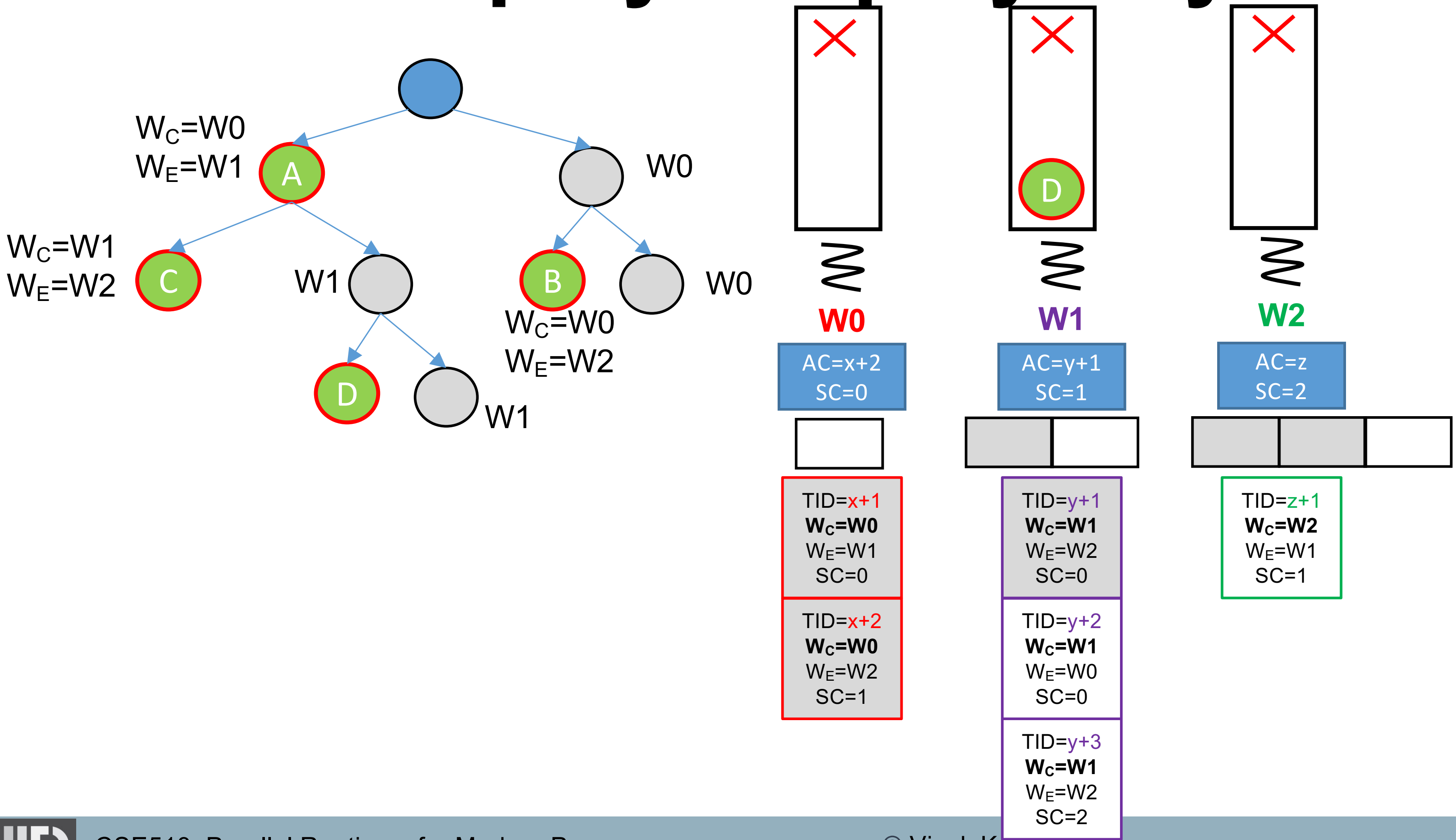
Trace & Replay: Replay Async



Trace & Replay: Replay Async



Trace & Replay: Replay Async



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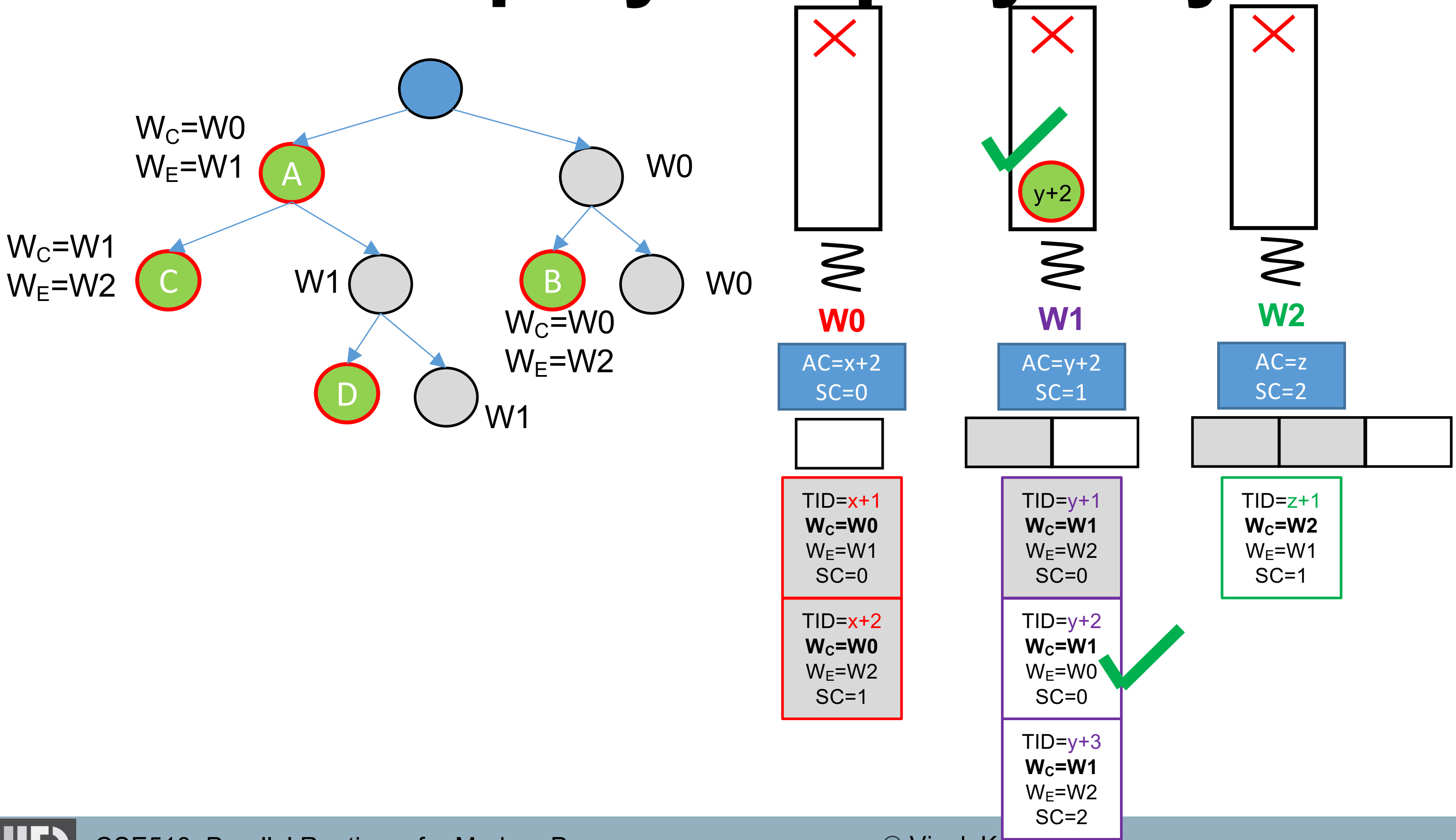

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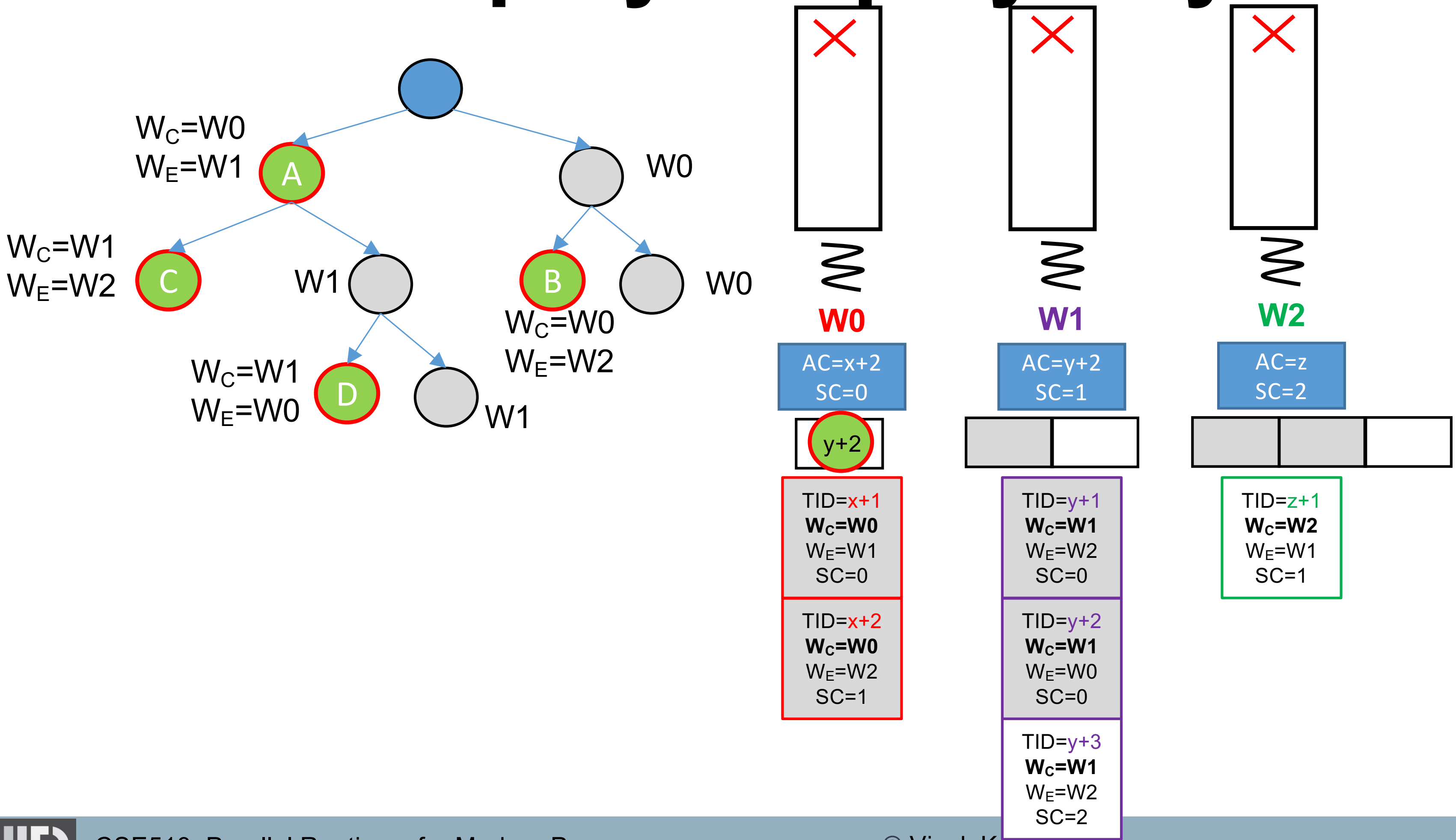
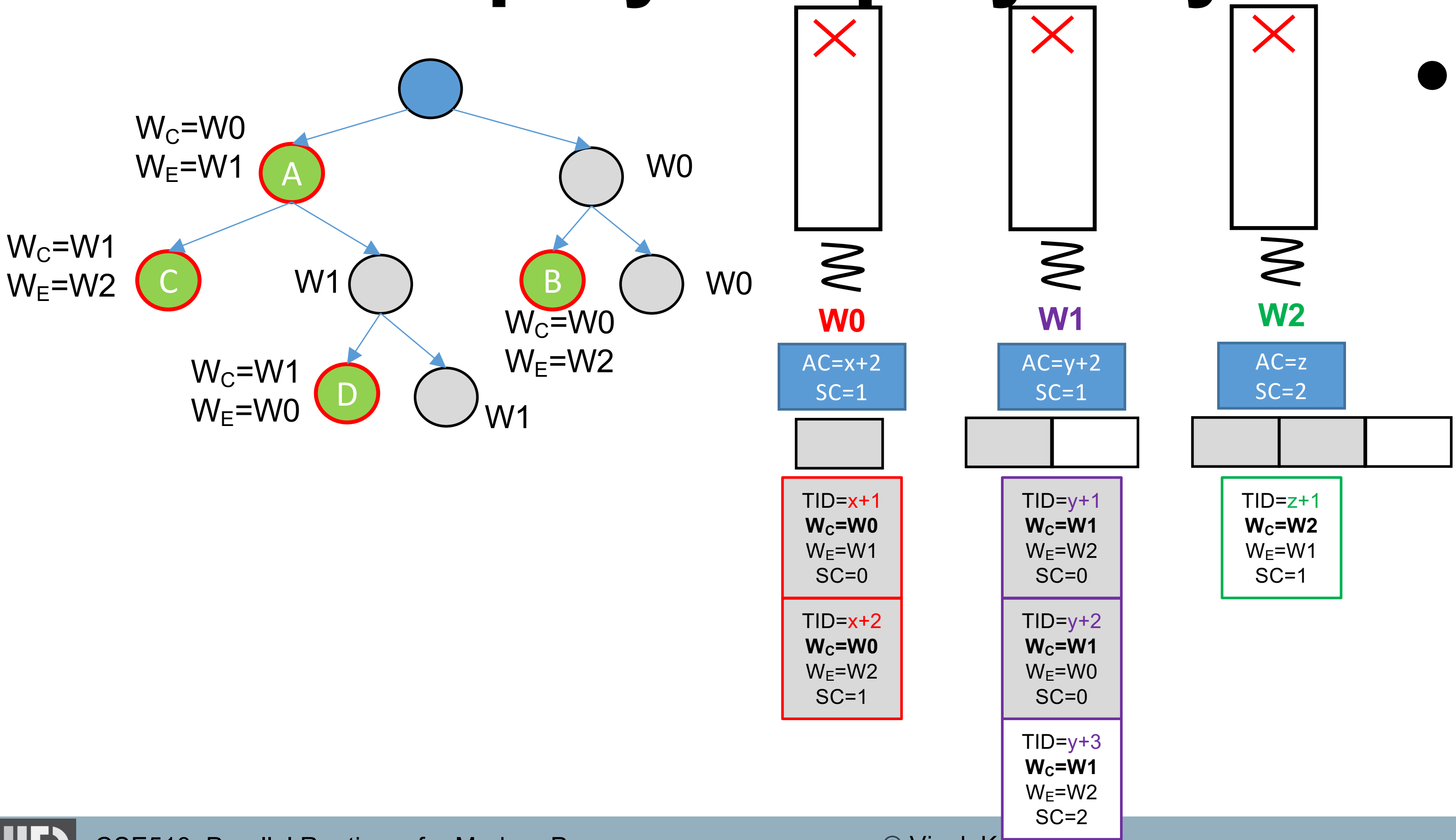


Trace & Replay: Replay Async



- Each worker would continue its execution until completion by using the tasks transferred by the victim instead of they themselves performing the steal operations

Reading Materials

- I am not providing any reading material on this topic, as the lecture slides should be sufficient

Next Lecture (#11)

- Context switching inside the userspace