Concurrency Wrap-up
Deadlock Handling

Computer Operating Systems, Fall 2023

Instructor: Travis McGaha

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TAs:

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Daniel Da	Jerry Wang	Ria Sharma	Zhiyan Lu
Ernest Ng	Jinghao Zhang	Rohan Verma	

Administrivia

- Full PennOS is due Wed Nov 29
  - You will schedule a time to meet with your TA to demonstrate your working code
  - Can submit via gradescope now
  - Reach out to TA’s to schedule PennOS Demo
- Check-in due before Lecture next week
- Recitation after class is open OH

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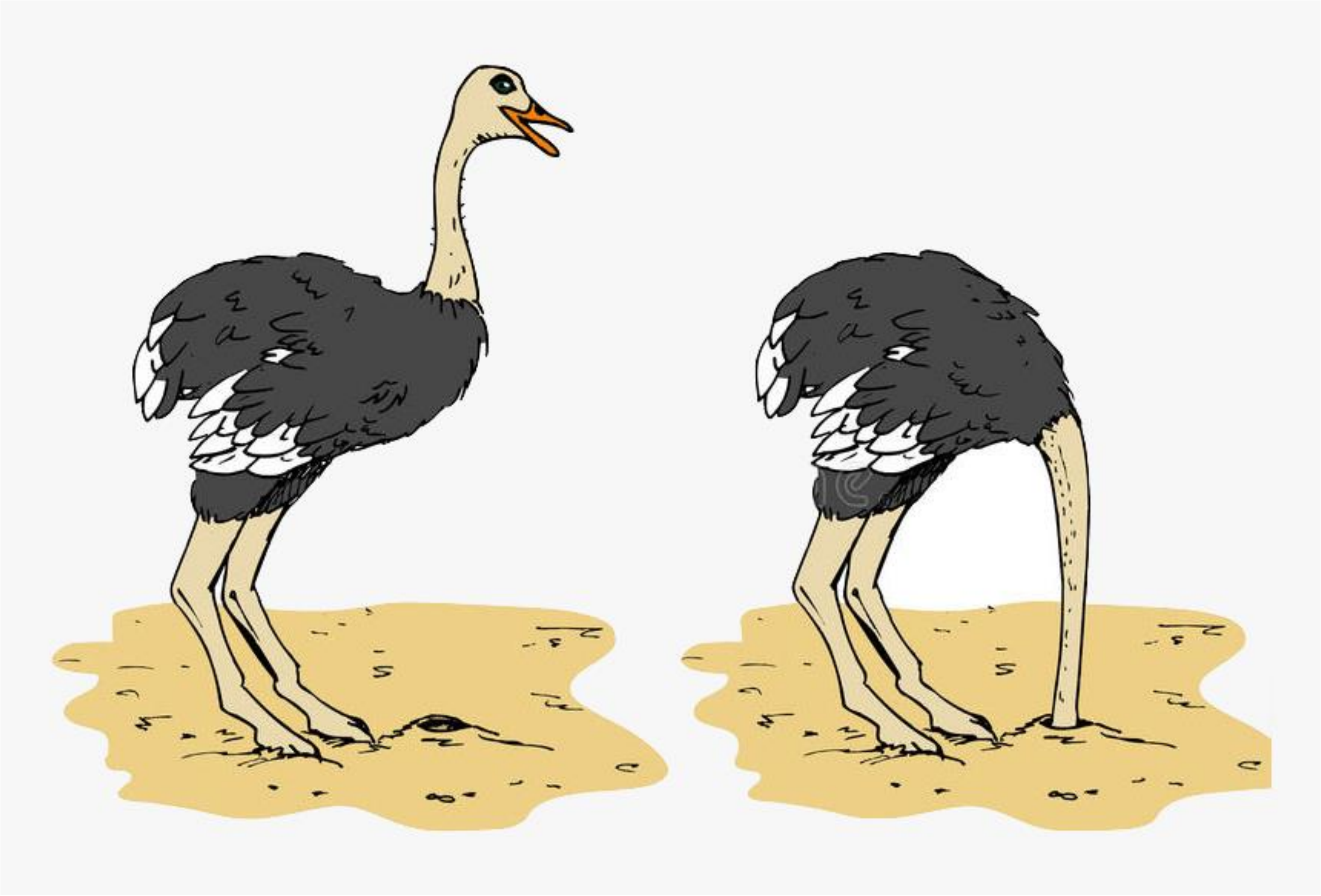
- Any questions, comments or concerns from last lecture?

Lecture Outline

- **Deadlock Handling (start)**
  - **Ostrich**
  - **Prevention**
  - **Detection**
  - **Avoidance**
- Parallel Analysis
  - Recurrences
  - Amdahl's Law

Deadlock Handling: Ostrich Algorithm

Deadlock Handling: Ostrich Algorithm



Ostriches don't actually do this, but it is an old myth

Deadlock Handling: Ostrich Algorithm

- Ignoring potential problems
  - Usually under the assumption that it is either rare, too expensive to handle, and/or not a fatal error

- Used in real world contexts, there is a real cost to tracking down every possible deadlock case and trying to fix it
  - Cost on the developer side: more time to develop
  - Cost on the software side: more computation for these things to do, slows things down

Deadlock Handling: Prevention

- Ad Hoc Approach
  - Key insights into application logic allow you to write code that avoids cycles/deadlock
  - Example: Dining Philosophers breaking symmetry with even/odd philosophers

- Exhaustive Search Approach
  - Static analysis on source code to detect deadlocks
  - Formal verification: model checking
  - Unable to scale beyond small programs in practice
    Impossible to prove for any arbitrary program (without restrictions)

Detection

- If we can't guarantee deadlocks won't happen, we can instead try to detect a deadlock just before it will happen **and then intervene**.

- Two big parts
  - Detection algorithm. This is usually done with tracking metadata and graph theory
  - The intervention/recovery. We typically want some sort of way to "recover" to a safe state when we detect a deadlock is going to happen

Detection Algorithms

- The common idea is to think of the threads and resources as a graph.
  - If there is a cycle: deadlock
  - If there is no cycle: no deadlock

- Finding cycles in a graph is a common algorithm problem with many solutions.

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- Consider the following example with 5 threads and 5 resources that require mutual exclusion is this a deadlock?
  - Thread 1 has R2 but wants R1
  - Thread 2 has R1 but wants R3, R4 and R5
  - Thread 3 has R4 but wants R5
  - Thread 4 has R5 but wants R2
  - Thread 5 has R3

Resource Allocation Graph

- We can represent this deadlock with a graph:
  - Each resource and thread is a node
  - If a thread has a resource, draw an arrow pointing at the thread form that resource
  - If a thread wants to acquire a resource but can’t, draw an arrow pointing at the resource from the thread trying to acquire it

Resource Allocation Graph Example

- Thread 1 has R2
  but wants R1
- Thread 2 has R1
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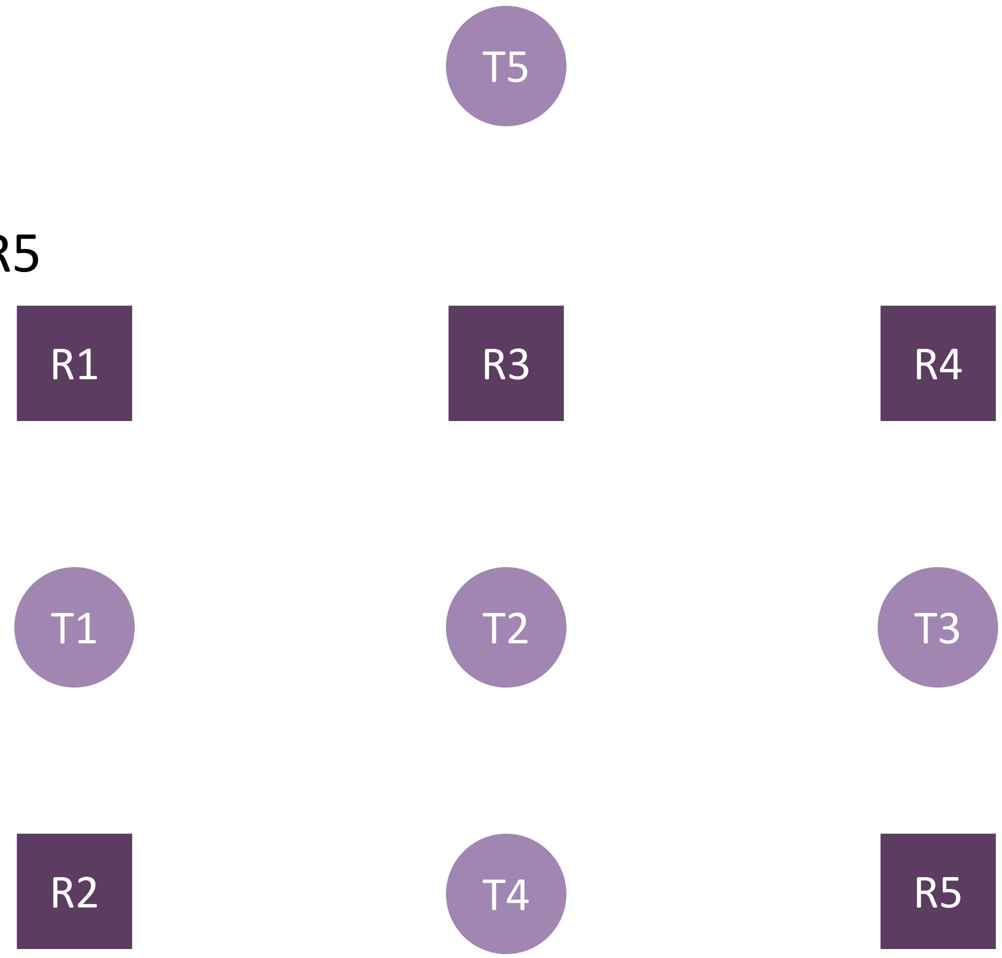

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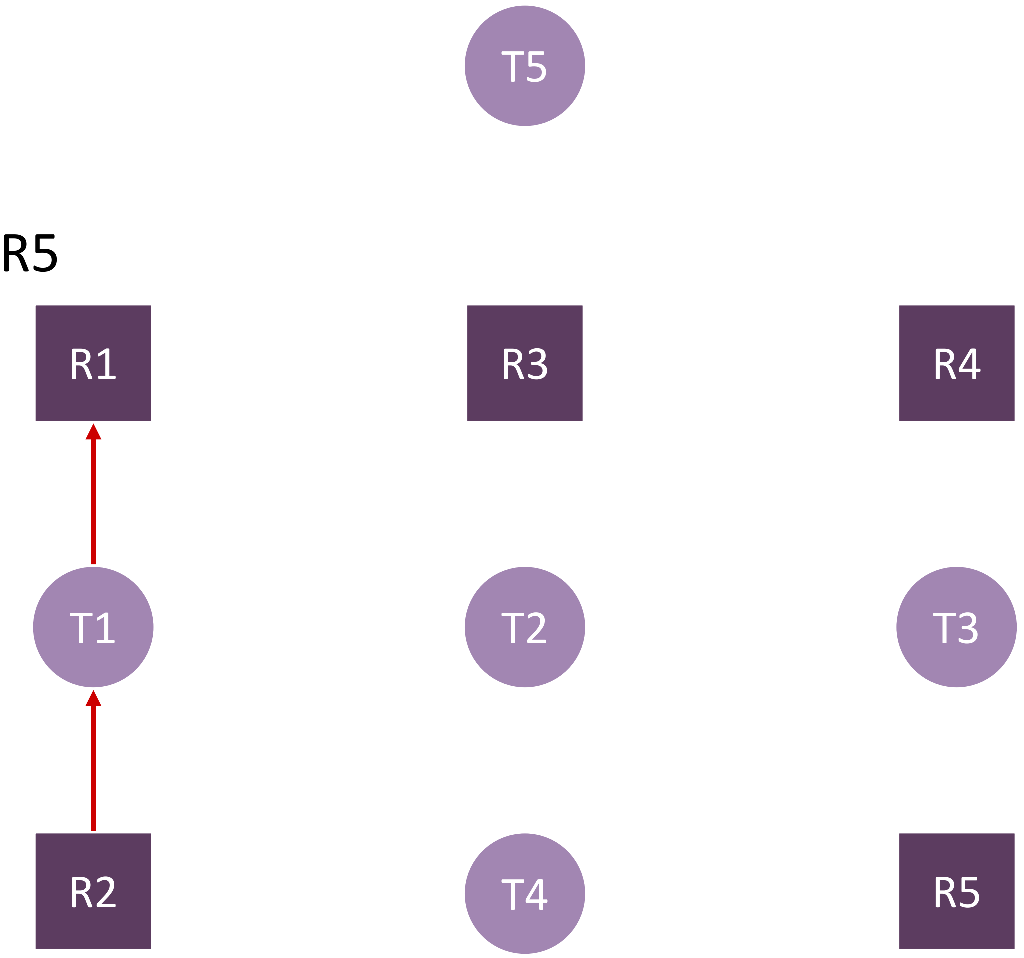

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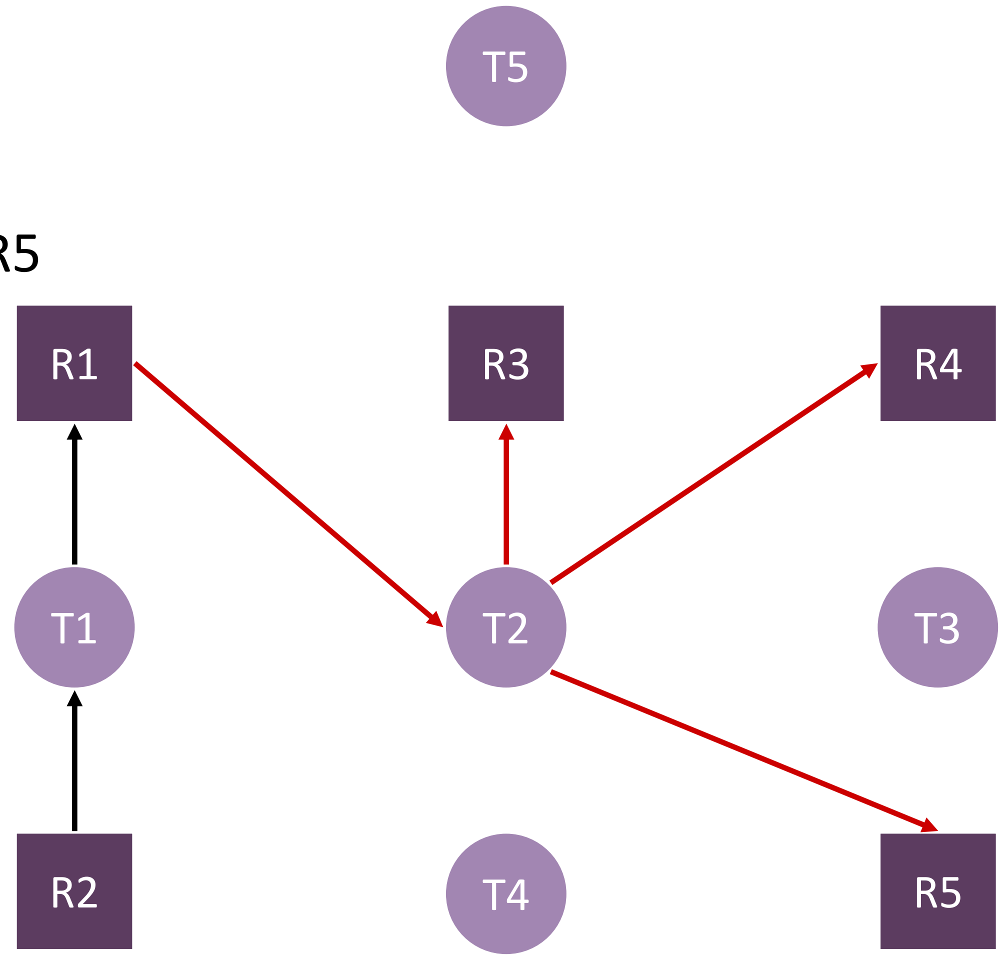

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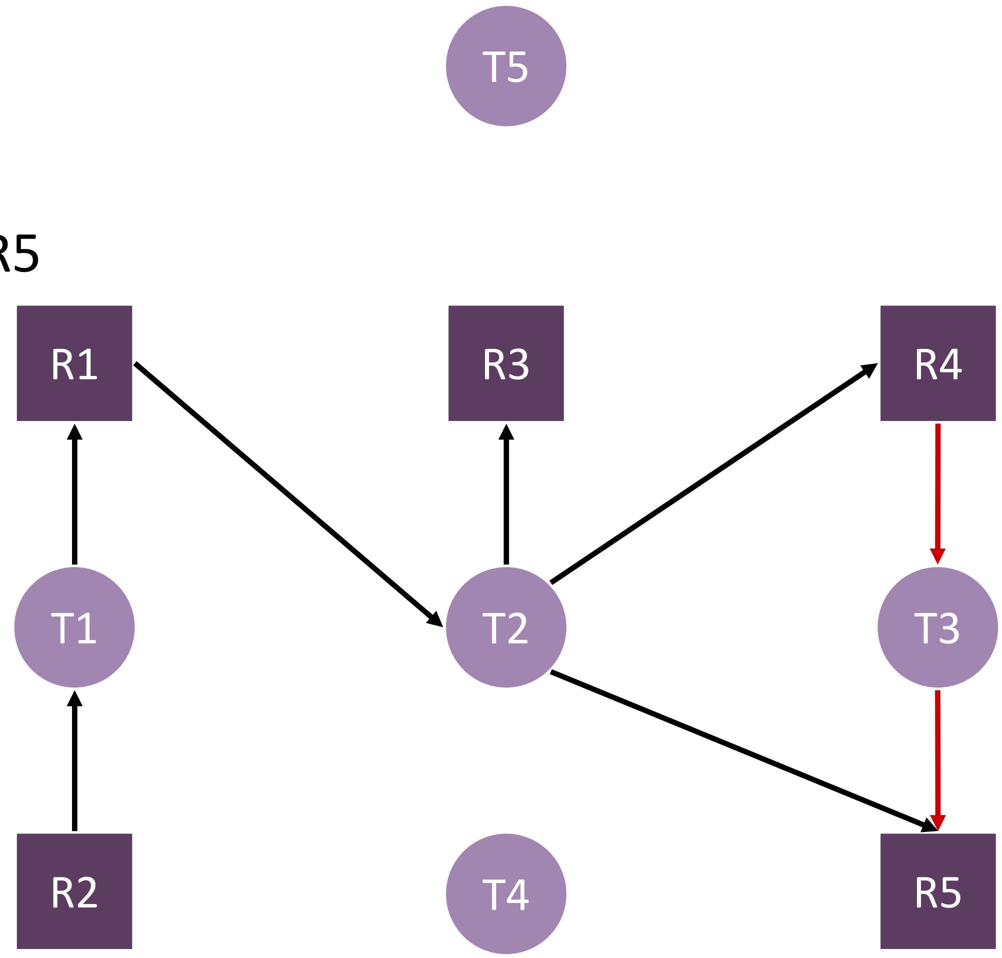

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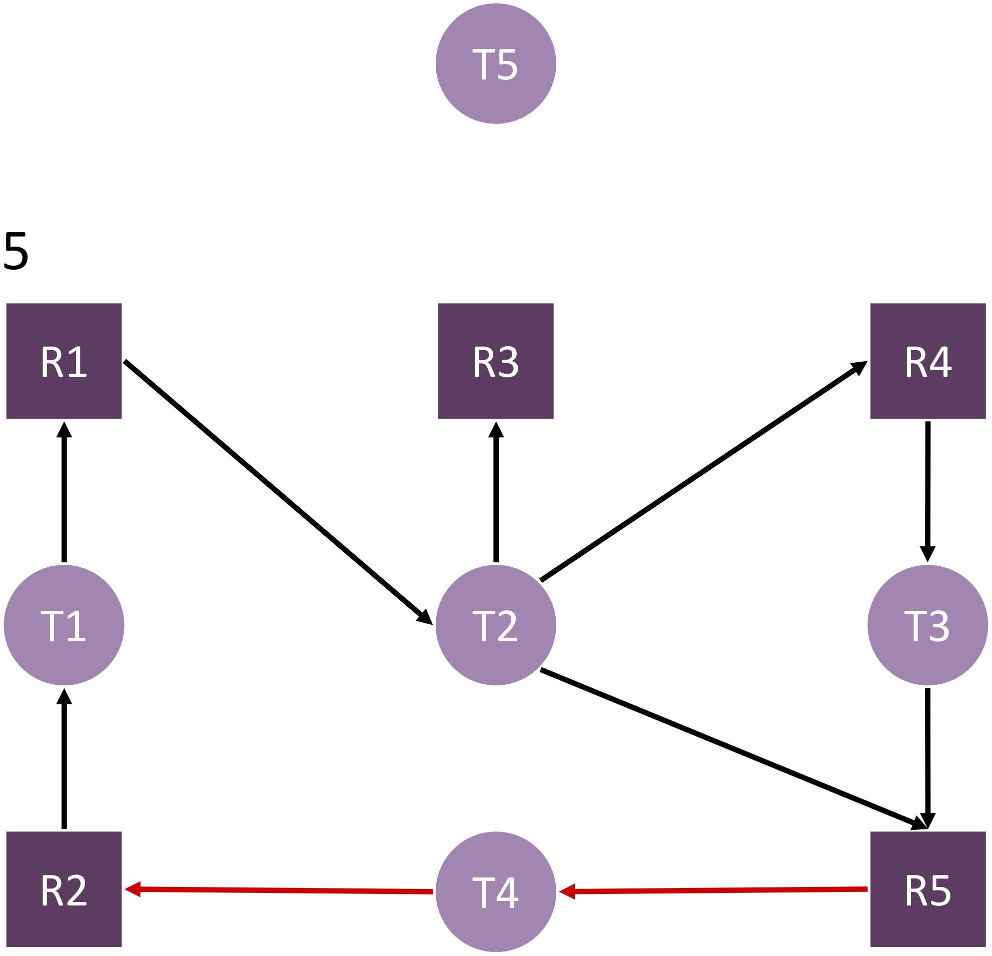

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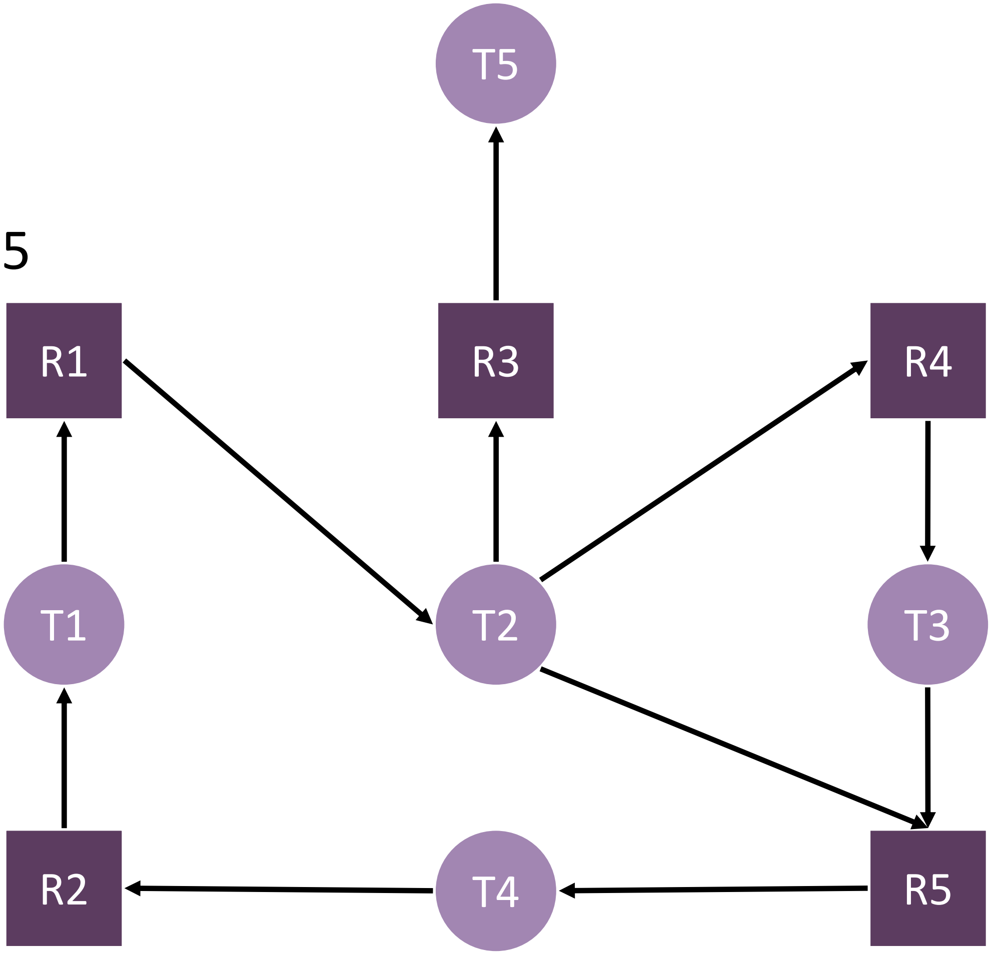
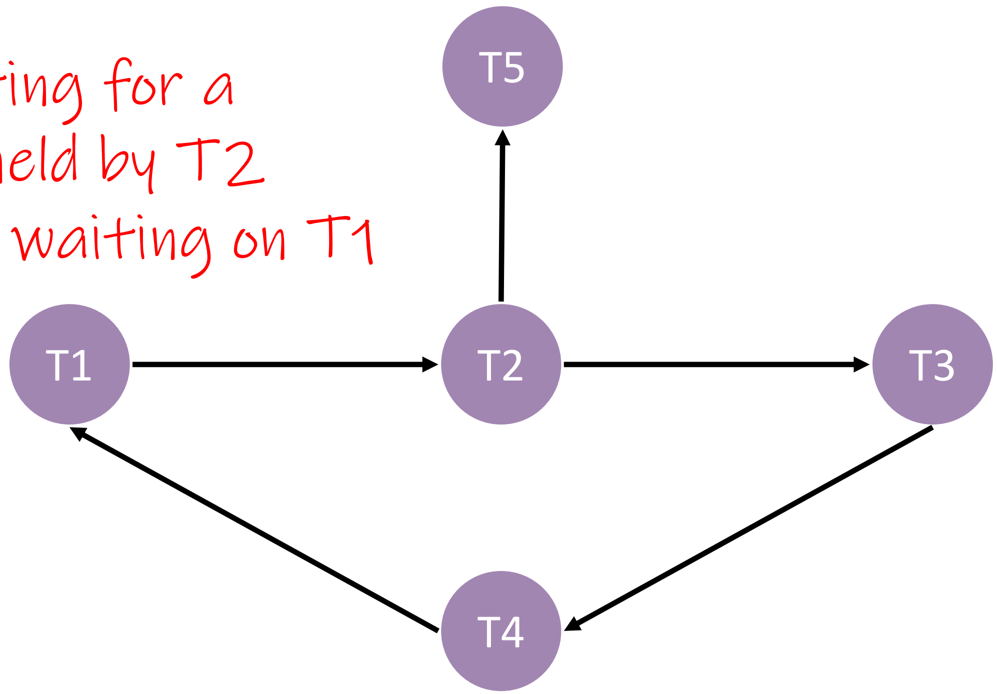


Resource Allocation Graph

Alternate graph

- Instead of also representing resources as nodes, we can have a "wait for" graph, showing how threads are waiting on each other

T1 is waiting for a resource held by T2 and T4 is waiting on T1



Wait For Graph

Recovery after Detection

- Preemption:
  - Force a thread to give up a resource
  - Often is not safe to do or impossible
- Rollback:
  - Occasionally checkpoint the state of the system, if a deadlock is detected then go back to the checkpointed “Saved state”
  - Used commonly in database systems
  - Maintaining enough information to rollback and doing the rollback can be expensive
- Manual Killing:
  - Kill a process/thread, check for deadlock, repeat till there is no deadlock
  - Not safe, but it is simple

Overall Costs

- Doing Deadlock Detection & Recovery solves deadlock issues, but there is a cost to memory and CPU to store the necessary information and check for deadlock

- This is why sometimes the ostrich algorithm is preferred

Avoidance

- Instead of detecting a deadlock when it happens and having expensive rollbacks, we may want to instead avoid deadlock cases earlier

- Idea:
  - Before it does work, it submits a request for all the resources it will need.
  - A deadlock detection algorithm is run
    - If acquiring those resources would lead to a deadlock, deny the request. The calling thread can try again later
    - If there is no deadlock, then the thread can acquire the resources and complete its task
  - The calling thread later releases resources as they are done with them

Avoidance

- Pros:
  - Avoids expensive rollbacks or recovery algorithms

- Cons:
  - Can't always know ahead of time all resources that are required
  - Resources may spend more time being locked if all resources need to be acquired before an action is taken by a thread, could hurt parallelizability
    - Consider a thread that does a very expensive computation with many shared resources.
    - Has one resources that is only updated at the end of the computation.
    - That resources is locked for a long time and other threads that may need it cannot access it

Aside: Bankers Algorithm

- This gets more complicated when there are multiple copies of resources, or a finite number of people can access a resources.

- The Banker's Algorithm handles these cases
  - But I won't go into detail about this
  - There is a video linked on the website under this lecture you can watch if you want to know more

Lecture Outline

- Deadlock Handling (start)
  - Ostrich
  - Prevention
  - Detection
  - Avoidance
- **Parallel Analysis**
  - **Recurrences**
  - **Amdahl's Law**

Parallel Algorithms

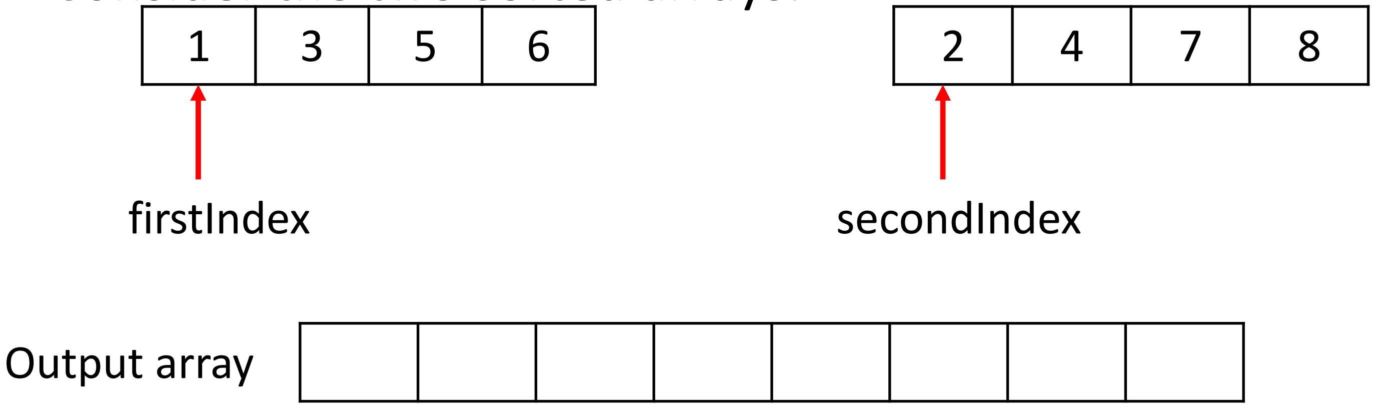
- One interesting applications of threads is for faster algorithms

- Common Example: Merge sort

Merge Sort: Core Ideas

- It is easier to sort small arrays than big arrays
- It is quicker to merge two sorted arrays than sort an unsorted array

  - Consider the two sorted arrays:



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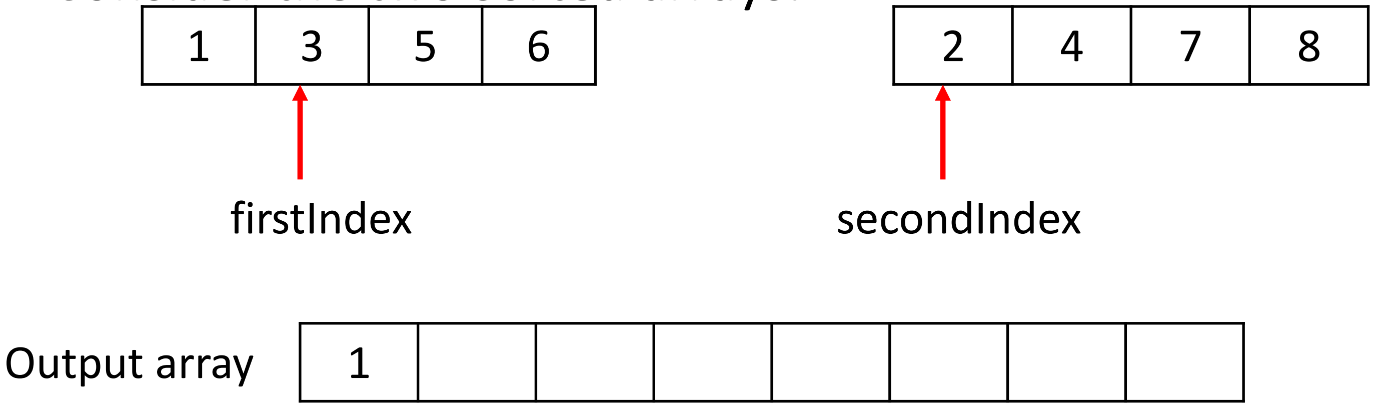

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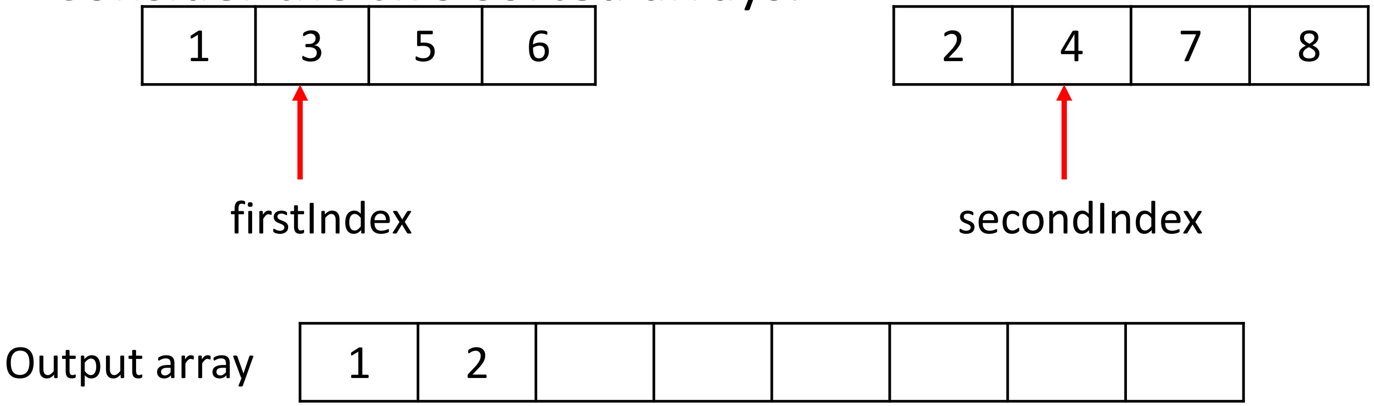

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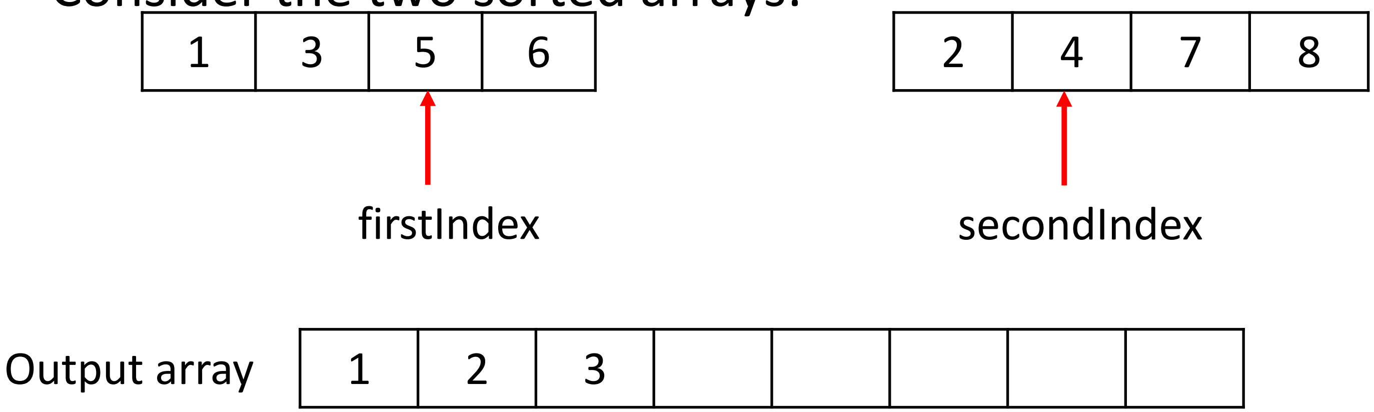

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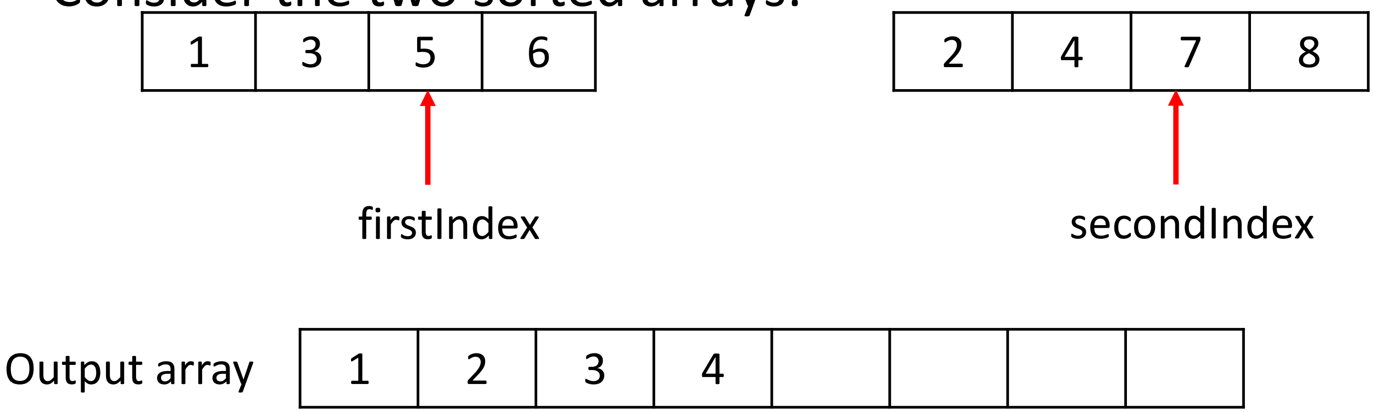

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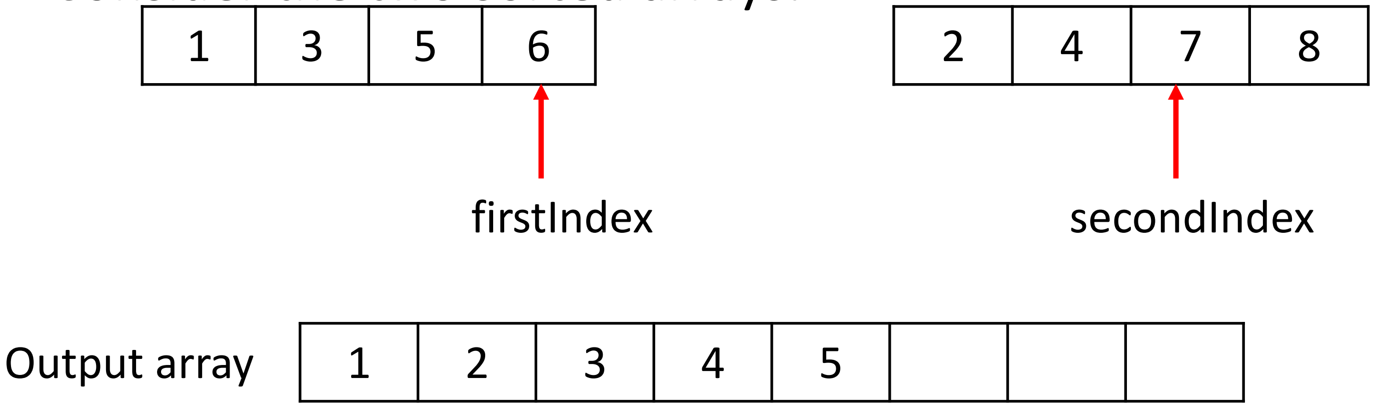

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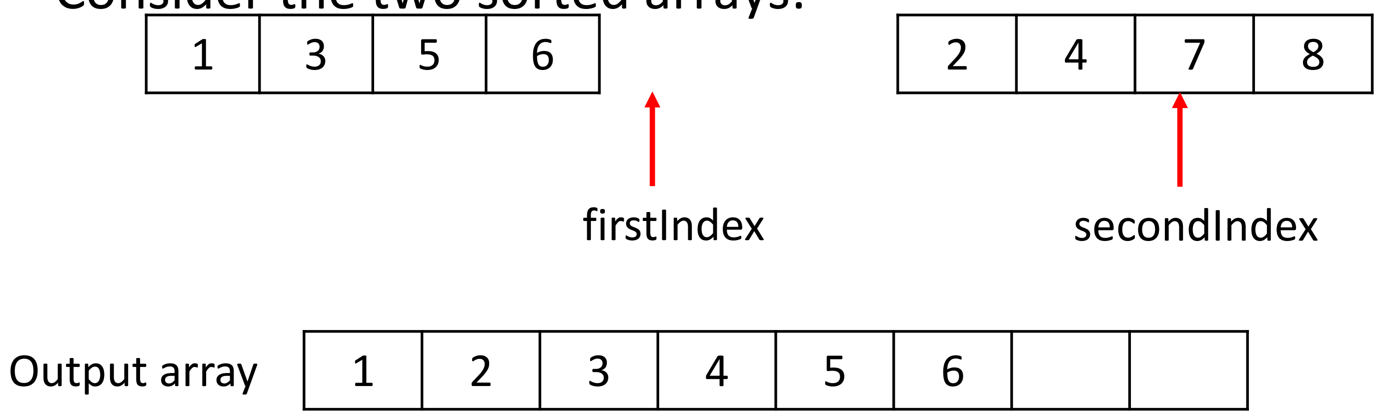

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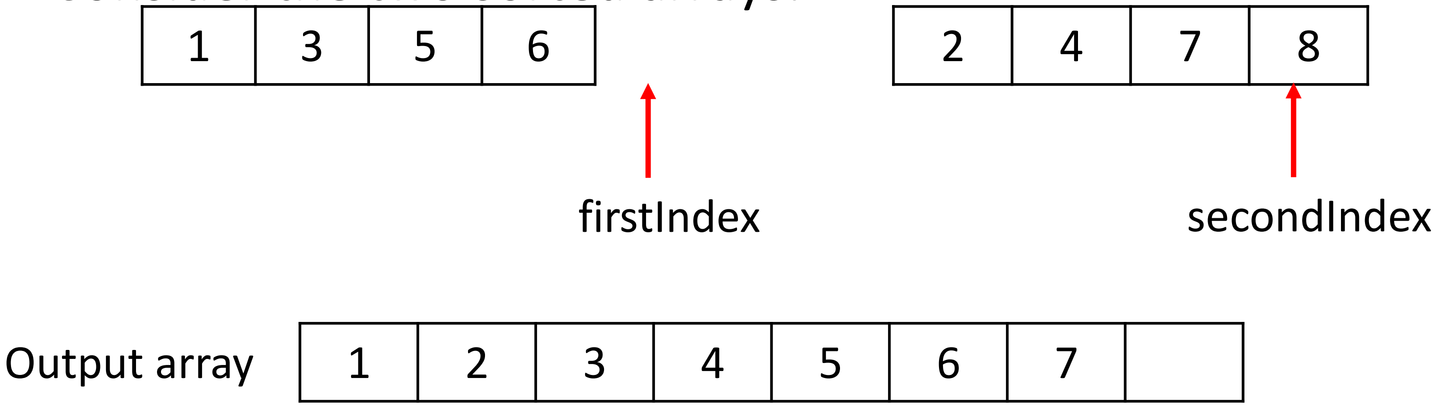

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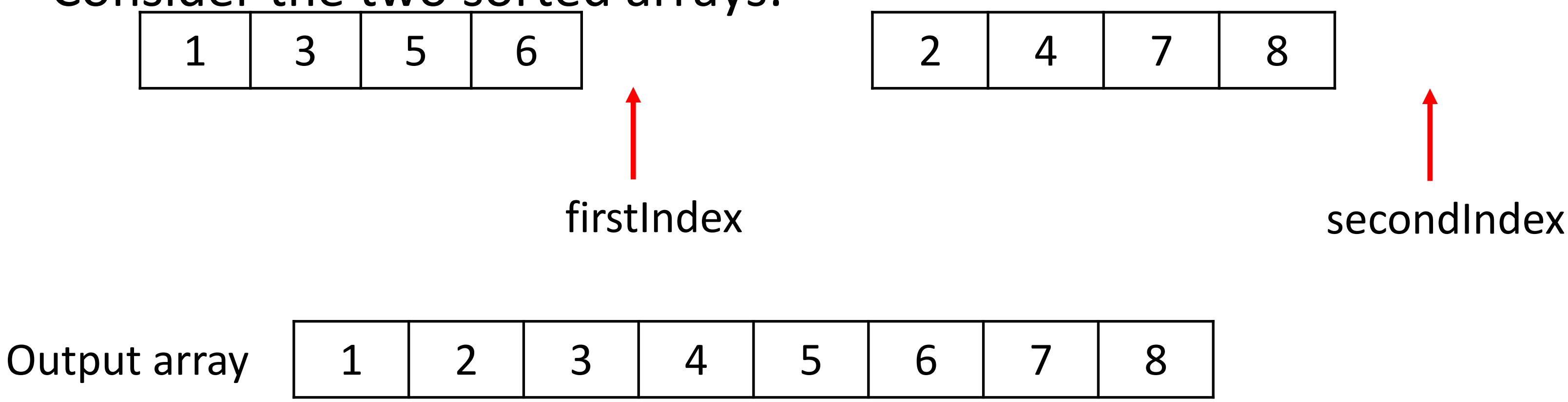

Merge Sort: High Level Example

20	10	15	54	55	11	78	14

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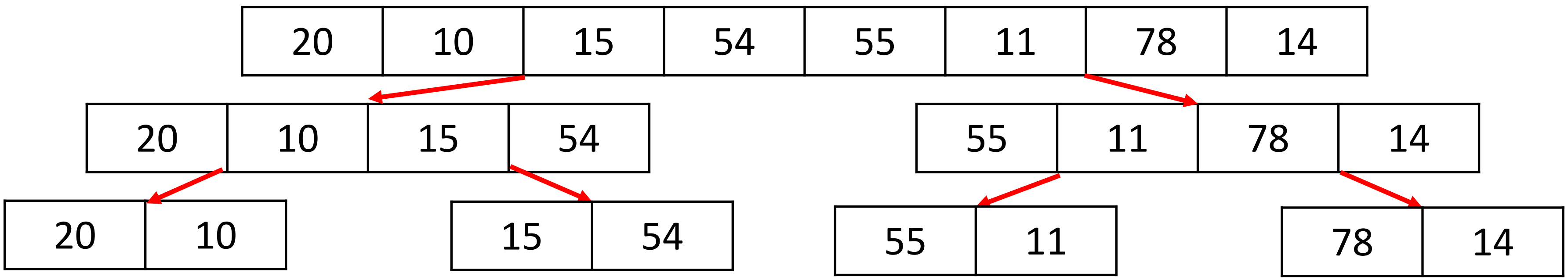

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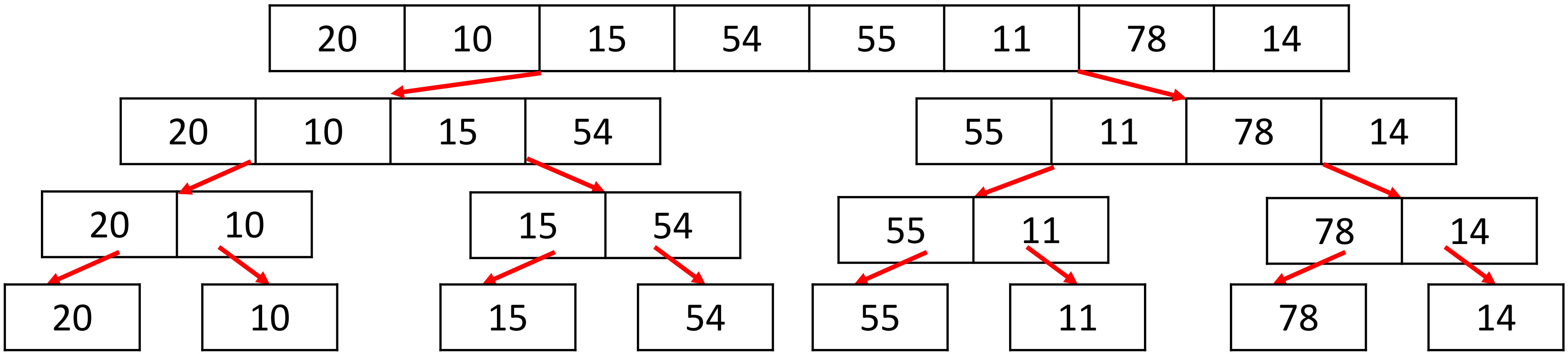

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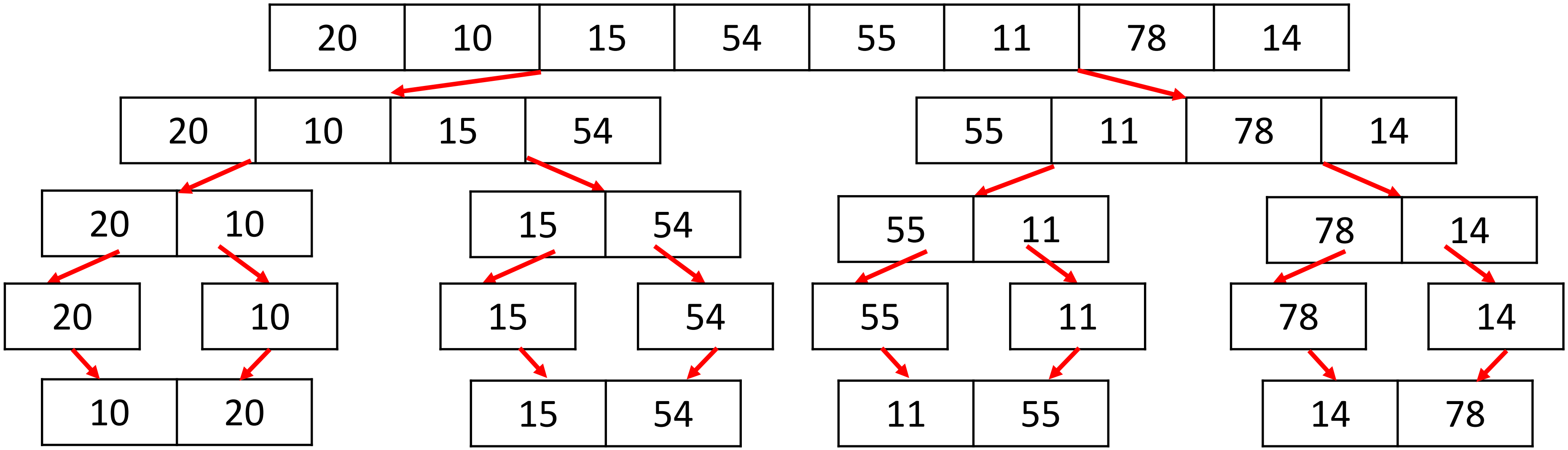

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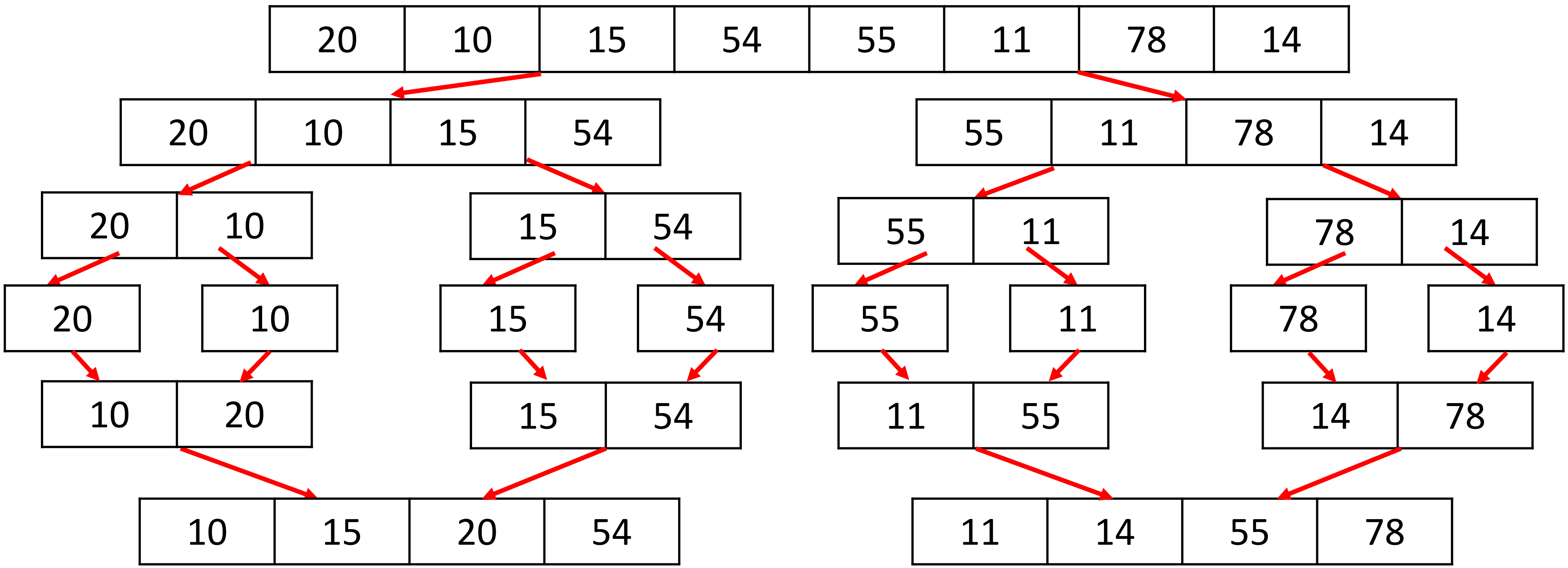

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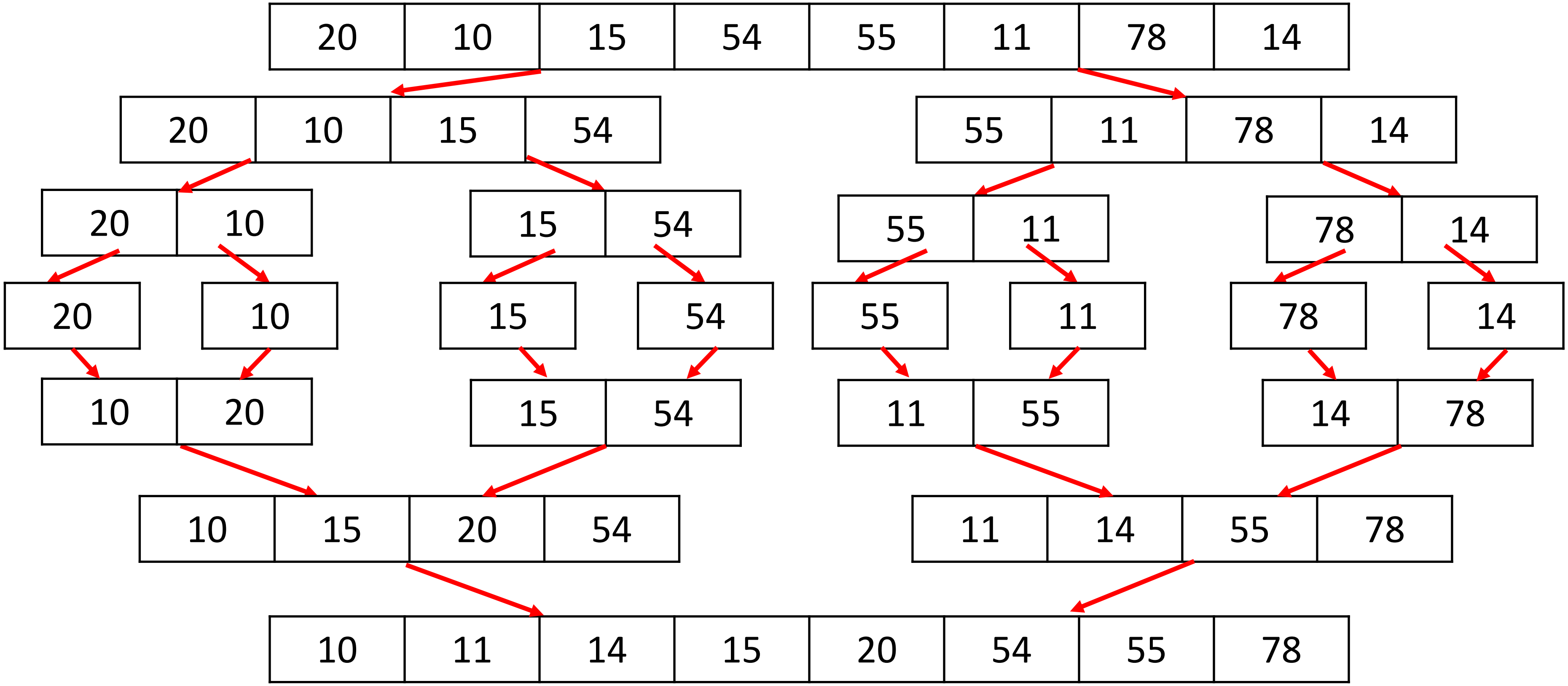

Merge Sort Algorithmic Analysis

- Algorithmic analysis of merge sort gets us to O(n * log(n)) runtime.

```
void merge_sort(int[] arr, int lo, int hi) {
  // lo high start at 0 and arr.length respectively
  int mid = (lo + hi) / 2;
  merge_sort(arr, lo, mid);  // sort the bottom half
  merge_sort(arr, mid, hi);  // sort the upper half

  // combine the upper and lower half into one sorted
  // array containing all eles
  merge(arr[lo : mid], arr[mid : hi]);
}
```

- We recurse $\log_2(N)$ times, each recursive “layer” does O(N) work

Merge Sort Algorithmic Analysis

- We can use threads to speed this up:

```
void merge_sort(int[] arr, int lo, int hi) {
  // lo high start at 0 and arr.length respectively
  int mid = (lo + hi) / 2;

  // sort bottom half in parallel
  pthread_create(merge_sort(arr, lo, mid));
  merge_sort(arr, mid, hi);  // sort the upper half

  pthread_join(); // join the thread that did bottom half

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```

  - Now we are sorting both halves of the array in parallel!

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```

  - Now we are sorting both halves of the array in parallel!
  - **How long does this take to run?**
  - **How much work is being done?**

Parallel Algos:

Will not test you on this

- We can define **T(n)** to be the running time of our algorithm

- We can split up our work between two parts, the part done sequentially, and the part done in parallel
  - T(n) = sequential_part + parallel_part
  - T(n) = O(n) *merging* + T(n/2) *sort half the array*
    - This is a recursive definition

- If we start recurring…
  - T(n) = O(n) + O(n/2) + T(n/4)
  - T(n) = O(n) + O(n/2) + O(n/4) + T(n/8)

Parallel Algos:

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  - …
  - Eventually we stop, there is a limit to the length of the array. And we can say an array of size 1 is already sorted, so T(1) = O(1)
- This approximates to T(n) = ~2 * O(n) = O(n)
  - This parallel merge sort is O(n), but there are further optimizations that can be done to reach ~O(log(n))
- There is a lot more to parallel algo analysis than just this, I am just giving you a sneak peek

Amdahl's Law

- For most algorithms, there are parts that parallelize well and parts that don’t. This causes adding threads to have diminishing returns
  - (even ignoring the overhead costs of creating & scheduling threads)

- Consider we have some parallel algorithm $T_1 = 1$
  - The 1 subscript indicates this is run on 1 thread
  - we define the work for the entire algorithm as 1

- We define S as being the part that can be parallelized
  - $T_1 = S + (1 – S)$ *// (1-S) is the sequential part*

Amdahl's Law

- For running on one thread:
  - $T_1 = (1 - S) + S$

- If we have P threads and perfect linear speedup on the parallelizable part, we get
  - $T_P = (1\text{-}S) + \frac{S}{P}$

- Speed up multiplier for P threads from sequential is:
  - $\frac{T_1}{T_P} = \frac{1}{1-S+\frac{S}{P}}$

Amdahl's Law

- Let's say that we have 100000 threads (P = 100000) and our algorithm is only 2/3 parallel? (s = 0.6666..)
  - $\frac{T_1}{T_p} = \frac{1}{1-0.6666+\frac{0.6666}{100000}} = 2.9999 \text{ times faster than sequential}$

- What if it is 90% parallel? (S = 0.9):
  - $\frac{T_1}{T_p} = \frac{1}{1-0.9+\frac{0.9}{100000}} = 9.99 \text{ times faster than sequential}$

- What if it is 99% parallel? (S = 0.99):
  - $\frac{T_1}{T_p} = \frac{1}{1-0.99+\frac{0.99}{100000}} = 99.99 \text{ times faster than sequential}$

Limitation: Hardware Threads

- These algorithms are limited by hardware.
- Number of Hardware Threads: The number of threads can genuinely run in parallel on hardware

- We may be able to create a huge number of threads, but only run a few (e.g. 4) in parallel at a time.

- Can see this information in with **`lscpu`** in bash
  - A computer can have some number of CPU sockets
  - Each CPU can have one or more cores
  - Each Core can run 1 or more threads