Threads & Deadlock

Computer Operating Systems, Spring 2025

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Poll Everywhere

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- Any planned courses for Fall 2025?

Administrivia

- PennOS
  - Groups have been assigned
  - TA's have been assigned to groups
  - You have the first milestone, which needs to be done sometime next week
  - Your group (or at least most of your group) needs to meet with your assigned TA and display the expectations laid out in the PennOS Specification
  - We will send emails to every group that had to be filled by course staff soon (let us know if you don't get this by the end of the week)

- Will post a small assignment with some readings sometime before next lecture
  - Details coming soon

Administrivia

- PennOS Advice:
  - Will announce this on Ed as well
  - In your FAT code you may do something like this:

```
lseek(FAT_FD, offset, SEEK_SET);
write(FAT_FD, contents, size);
```

    - Sometimes though, the write and lseek will return a success, but it won't actually write to your file system
    - Most commonly happens with blocks near the end of the FAT
      (as in blocks not in the allocation table but show up shortly after the end of the allocation table)
    - Most likely related to an issue between mmap and write
    - Shows up inconsistently!
    - What's the fix?
      Just do it twice, that usually fixes it.

```
lseek(FAT_FD, offset, SEEK_SET);
write(FAT_FD, contents, size);
lseek(FAT_FD, offset, SEEK_SET);
write(FAT_FD, contents, size);
```

Lecture Outline

- **Mutex refresher**
- Mutex alternatives
  - tsl
  - Disable interrupts
  - Petersons
- Deadlocks
- Dining Philosophers
- Deadlock Handling

pthreads and Locks

- Another term for a lock is a mutex ("mutual exclusion")
  - `pthread.h` defines datatype `pthread_mutex_t`

- ```
  int pthread_mutex_init(pthread_mutex_t* mutex,
                         const pthread_mutexattr_t* attr);
  ```
  - Initializes a mutex with specified attributes
- ```
  int pthread_mutex_lock(pthread_mutex_t* mutex);
  ```
  - Acquire the lock – blocks if already locked Un-blocks when lock is acquired
- ```
  int pthread_mutex_unlock(pthread_mutex_t* mutex);
  ```
  - Releases the lock
- ```
  int pthread_mutex_destroy(pthread_mutex_t* mutex);
  ```
  - "Uninitializes" a mutex – clean up when done

pthread Mutex Examples

- See `total.c`
  - Data race between threads
- See `total_locking.c`
  - Adding a mutex fixes our data race
- How does `total_locking` compare to sequential code and to `total`?
  - Likely *slower* than both– only 1 thread can increment at a time, and must deal with checking the lock and switching between threads
  - One possible fix: each thread increments a local variable and then adds its value (once!) to the shared variable at the end
    - See `total_locking_better.c`

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- The code below has three functions that could be executed in separate threads. Note that these are not thread entry points, just functions used by threads:
  - Assume that "lock" has been initialized

- Thread-1 executes line 8 while Thread-2 executes line 21.
  Choose one:
  - Could lead to a race condition.
  - There is no possible race condition.
  - The situation cannot occur.

- Thread-1 executes line 15 while Thread-2 executes line 15.
  Choose one:
  - Could lead to a race condition.
  - There is no possible race condition.
  - The situation cannot occur.

```
1  // global variables
2  pthread_mutex_t lock;
3  int g =    0;
4  int k = 0;
5
6  void fun1() {
7    pthread_mutex_lock(&lock);
8    g += 3;
9    pthread_mutex_unlock(&lock);
10   k++;
11 }
12
13 void fun2(int a, int b) {
14   g += a;
15   a += b;
16   k = a;
17 }
18
19 void fun3() {
20   pthread_mutex_lock(&lock);
21   g = k + 2;
22   pthread_mutex_unlock(&lock);
23 }
```

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- The code below has three functions that could be executed in separate threads. Note that these are not thread entry points, just functions used by threads:
  - Assume that "lock" has been initialized

- Thread-1 executes line 8 while Thread-2 executes line 14
  Choose one:
  - Could lead to a race condition.
  - There is no possible race condition.
  - The situation cannot occur.

- Thread-1 executes line 14 while Thread-2 executes line 16.
  Choose one:
  - Could lead to a race condition.
  - There is no possible race condition.
  - The situation cannot occur.

```
1   // global variables
2   pthread_mutex_t lock;
3   int g =    0;
4   int k = 0;
5
6   void fun1() {
7     pthread_mutex_lock(&lock);
8     g += 3;
9     pthread_mutex_unlock(&lock);
10    k++;
11  }
12
13  void fun2(int a, int b) {
14    g += a;
15    a += b;
16    k = a;
17  }
18
19  void fun3() {
20    pthread_mutex_lock(&lock);
21    g = k + 2;
22    pthread_mutex_unlock(&lock);
23  }
```

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  - **tsl**
  - **Disable interrupts**
  - **Petersons**
- Deadlocks
- Dining Philosophers
- Deadlock Handling

TSL

- TSL stands for **T**est and **S**et **L**ock, sometimes just called **test-and-set**.

- TSL is an atomic instruction that is guaranteed to be atomic at the hardware level

- `TSL R, M`
  - Pass in a register and a memory location
  - R gets the value of M
  - M is set to 1 AFTER setting R

TSL to implement Mutex

- A mutex is pretty much this:

```
pthread_mutex_lock(lock) {
    prev_value = TSL(lock);

    // if prev_value = 1, then it was already locked
    while (prev_value == 1) {
        block();
        prev_value = TSL(lock);
    }
}

pthread_mutex_unlock(lock) {
   lock = 0;
   wakeup_blocked_threads(lock);
}
```

Disabling Interrupts

- If data races occur when one thread is interrupted while it is accessing some shared code….

  What is we don’t switch to other threads while executing that code?

- This can be done by disabling interrupts: no interrupts means that the clock interrupt won’t go off and interrupt the currently running thread

Disabling Interrupts

- Consider that sum_total starts at 0 and two threads try to execute

```
++sum_total
```

sum_total = 1

Thread 0

```
disable_interrupts();
++sum_total;
enable_interrupts();
```

Thread 1

```
disable_interrupts();
++sum_total;
enable_interrupts();
```

Disabling Interrupts

- Advantages:
  - This is one way to fix this issue

- Disadvantages
  - This is usually overkill
  - This can stop threads that aren't trying to access the shared resources in the critical section. May stop threads that are executing other processes entirely
  - If interrupts disabled for a long time, then other threads will starve
  - In a multi-core environment, this gets complicated

Discuss

- Lets try a more complicated software approach..
- We create two threads running thread_code, one with **`arg = 0`**, other thread has **`arg = 1`**
- Each thread tries to increment sum_total. Does this work?

```
int sum_total = 0;
bool flag[2] = {false, false};
int turn = 0

void thread_code(int arg) {
  int me = arg;

  flag[me] = true;
  turn = 1 - me;
  while((flag[1-me] == true) && (turn != me)) { }
  ++sum_total;
  flag[me] = false;
}
```

Check the index of the other thread

Peterson's Algorithm

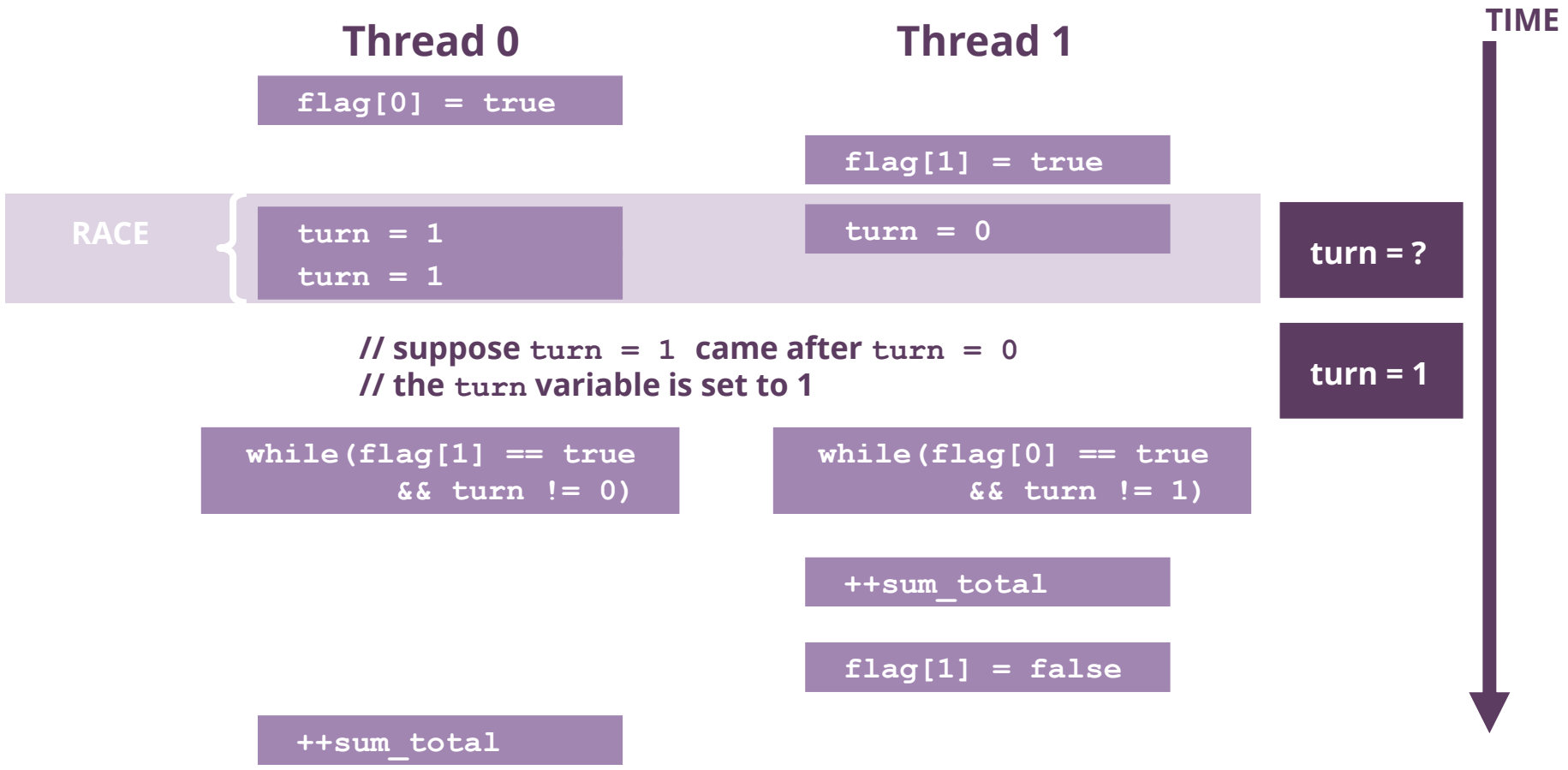
- What we just did was Peterson's algorithm
- Why does it work? (using an analogy)
  - Each thread first declares that they want to enter the critical section by setting their flag
  - Each thread then states (once) that the other should "go first".
    - This is done by setting the turn variable to 1 – me
    - One of these assignments to the turn variable will happen last, that is the one that decides who goes first
  - One of the thread goes first (decided by the value of turn) and accesses the critical section, before saying it is done (by changing their flag to false)

Peterson's Algorithm

- What we just did was Peterson's algorithm
- Why does it work?
  - Case1:
    If P0 enters critical section, flag[0] = true, turn = 0. It enters the critical section successfully.
  - Case2:
    If P0 and P1 enter critical section, flag[0] and flag[1] = true

    Race condition on turn. Suppose P0 sets turn = 0 first. Final value is turn = 1. P0 will get to run first.

Explanation



Peterson's Assumptions

- Some operations are atomic:
  - Reading from the flag and turn variables cannot be interrupted
  - Writing to the flag and turn variables cannot be interrupted
  - E.g setting turn = 1 or 0 will set turn to 0 or 1, you can be interrupted before or after, but not "during" when turn may have some intermediate value that is not 0 or 1

- That the instructions are executed in the specific order laid out in the code

Atomicity

- Atomicity: An operation or set of operations on some data are *atomic* if the operation(s) are indivisible, that no other operation(s) on that same data can interrupt/interfere.

- Aside on terminology:
  - Often interchangeable with the term “Linearizability”
  - Atomic has a different (but similar-ish) meaning in the context of data bases and ACID.

Aside: Instruction & Memory Ordering

- Do we know that **t** is set before **g** is set?

```
bool g = false;
int t = 0

void some_func(int arg) {
  t = arg;
  g = true;
}
```

Aside: Instruction & Memory Ordering

- The compiler may generate instructions with different ordering if it does not appear that it will affect the semantics of the function
  - Since `g = true;` is not affected by `t = arg;` then either one could execute first.

- The Processor may also execute these in a different order than what the compiler says

- Why? Optimizations on program performance
  - If you want to know more, look into “Out-of-Order Execution” and “Memory Order”

Aside: Memory Barriers

- How do we fix this?

- We can emit special instructions to the CPU and/or compiler to create a "memory barrier"
  - "all memory accesses before the barrier are guaranteed to happen before the memory accesses that come after the barrier"

  - A way to enforce an order in which memory accesses are ordered by the compiler and the CPU

  - This is done for us when we mark a variable as atomic or use a lock.

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Liveness

- Liveness: A set of properties that ensure that threads execute in a timely manner, despite any contention on shared resources.

- When `pthread_mutex_lock();` is called, the calling thread blocks (stops executing) until it can acquire the lock.
  - What happens if the thread can never acquire the lock?

Liveness Failure: Releasing locks

- If locks are not released by a thread, then other threads cannot acquire that lock

- See `release_locks.c`
  - Example where locks are not released once critical section is completed.

Liveness Failure: Deadlocks

- Consider the case where there are two threads and two locks
  - Thread 1 acquires lock1
  - Thread 2 acquires lock2
  - Thread 1 attempts to acquire lock2 and blocks
  - Thread 2 attempts to acquire lock1 and blocks

Neither thread can make progress ☹

- See `milk_deadlock.c`

- Note: there are many algorithms for detecting/preventing deadlocks

Liveness Failure: Mutex Recursion

- What happens if a thread tries to re-acquire a lock that it has already acquired?

- See `recursive_deadlock.c`

- By default, a mutex is not re-entrant.
  - The thread won't recognize it already has the lock, and block until the lock is released

Aside: Recursive Locks

- Mutex's can be configured so that you it can be re-locked if the thread already has locked it. These locks are called *recursive locks* (sometimes called *re-entrant locks*).

- Acquiring a lock that is already held will succeed
- To release a lock, it must be released the same number of times it was acquired

- Has its uses, but generally discouraged.

Deadlock Definition

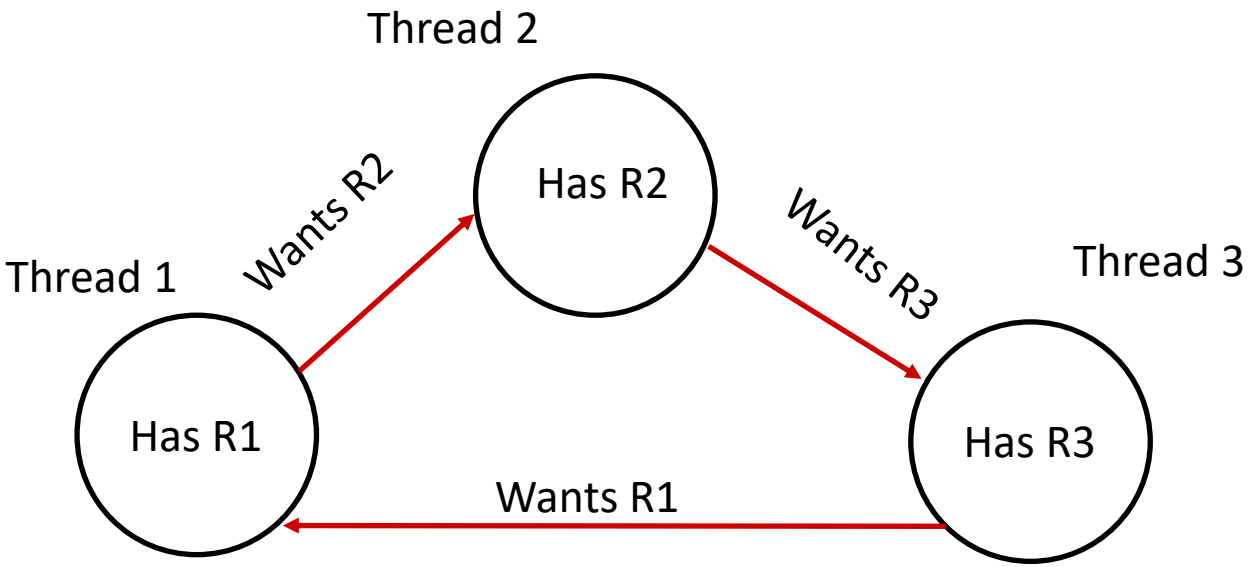
- A computer has multiple threads, finite resources, and the threads want to acquire those resources
  - Some of these resources require exclusive access
- A thread can acquire resources:
  - All at once
  - Accumulate them over time
  - If it fails to acquire a resource, it will (by default) wait until it is available before doing anything
- Deadlock: Cyclical dependency on resource acquisition so that none of them can proceed
  - Even if all unblocked threads release, deadlock will continue

Preconditions for Deadlock

- Deadlock can only happen if these occur simultaneously:
  - **Mutual Exclusion**: at least one resource must be held exclusively by one thread
  - **Hold and Wait**: a thread must be holding a resource, requesting a resource that is held by a thread, and then waiting for it.
  - **No preemption**: A resource is held by a thread until it explicitly releases it. It cannot be preempted by the OS or something else to force it to release the resource
  - **Circular Wait**:
    Can be a chain of more than 2 threads
    Each thread must be waiting for a resource that is held by another thread. That other thread must waiting on a resource that forms a chain of dependency

Circular Wait Example

- A cycle can exist of more than just two threads:



Discuss

- Can a thread deadlock if there is only one thread?

Deadlock Prevention

- If we can remove the conditions for deadlock, we could avoid prevent deadlock from every happening

Deadlock Prevention: Mutual Exclusion

- **Mutual Exclusion**: at least one resource must be held exclusively by one thread

- You usually need mutual exclusion or you don't, so it is hard to avoid.
- Some resources require exclusive access

- A lot of work done related to this
  - called: Lock-free programming, Lock-less programming, or Non-blocking algorithms
  - General idea is to take advantage of operations that are atomic at the hardware level when sharing is needed

Deadlock Prevention: Hold and Wait

- **Hold and Wait**: a thread must be holding a resource, requesting a resource that is held by a thread, and then waiting for it.

- What if we had each thread acquire all resources it needs in the beginning "at once"
  - Not always practical, a thread may not know ahead of time all the resources it will need

Deadlock Prevention: No Preemption

- **No preemption**: A resource is held by a thread until it explicitly releases it. It cannot be preempted by the OS or something else to force it to release the resource

- If we force a thread to release a resource, how do we ensure it is in a valid state?
  - Undoing actions and recovering valid state is complex (more on this next lecture)

Deadlock Prevention: Circular Wait

- **Circular Wait**: Each thread must be waiting for a resource that is held by another thread. That other thread must waiting on a resource that forms a chain of dependency

- Break cycles in resource acquisition.
- We could enforce an ordering to resource acquisition.

- Challenge: Still we may not know all resources we need ahead of time

Deadlock Prevention Summary

- Prevent deadlocks by removing any one of the four deadlock preconditions
- But eliminating even one of the preconditions is often hard/impossible
  - Mutual Exclusion is necessary in a lot of situations
  - Forcing a lower priority process to release resources early requires rollback of execution
  - Not always possible to know all resources that an operating system or process will use upfront

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- **Dining Philosophers**
- Deadlock Handling

Dining Philosophers

- Assume the following situation
  - There are N philosophers (computer scientists) that are trying to eat rice.
  - They only have one chopstick each!
    - Need two chopsticks to eat ☹
  - Alternate between two states:
    - Thinking
    - Eating
  - They are arranged in a circle with a chopstick between each of them

Dining Philosophers

- Philosophers have good table manners
  - Must acquire two chopsticks to eat
  - Only one philosopher can have a chopstick at a time
- Useful abstraction / "standard problem" try to achieve:
  - Deadlock Free
    - No state where no one gets to eat
  - Starvation Free
    - Solution guarantees that all philosophers occasionally eat
    - Ideally maximize parallel eating

First Solution Attempt

- If we number each philosopher 0 – N and then each chopstick is also 0 – N, we can model the problem with mutexes, each chopstick is a mutex and each philosopher is a thread
  - To eat, thread I must acquire lock `I` and `I + 1`
  - This ensures that each chopstick is only in use by one philosopher at a time

```
while (true) {
  pthread_mutex_lock(&chopstick[i]);
  pthread_mutex_lock(&chopstick[(i + 1) % N]);
  eat();
  pthread_mutex_unlock(&chopstick[(i + 1) % N]);
  pthread_mutex_unlock(&chopstick[i]);
  think();
}
```

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- What's wrong with this? Any Ideas on how to fix it?
  - Reminder: we number each philosopher 0 – N and then each chopstick is also 0 – N

```
while (true) {
  pthread_mutex_lock(&chopstick[i]);
  pthread_mutex_lock(&chopstick[(i + 1) % N]);
  eat();
  pthread_mutex_unlock(&chopstick[(i + 1) % N]);
  pthread_mutex_unlock(&chopstick[i]);
  think();
}
```

Second Attempt: Round Robin

- Our first attempt deadlocks.
- What if we instead we tried doing this “round robin”, we pass around a token that says “it is your turn to eat”
- Can this deadlock?
- What issues arise with this solution?

Third Attempt: Global Mutex

- What if instead, we add another “global” mutex that controls permission to pick up chopsticks. Once a philosopher has chopsticks, they can release the lock before they eat
- In our metaphor, this means that each philosopher “waits in line” to pick up chopsticks
- Can this deadlock?
- What issues arise with this solution?

Fourth Attempt: More Human Approach

- What if instead, if a philosopher fails to get a chopstick, it puts down any chopsticks it has, waits for a little bit and then tries again?

- Can we do this in code?
  - `pthread_mutex_trylock`: if the lock can't be acquired, return immediately
  - `pthread_mutex_timedlock`: timeout after trying to get a mutex for some specified amount of time

- Can this deadlock?
- What issues arise with this solution?

Fifth Attempt: Break the Symmetry

- What if the even numbered philosophers and odd numbered philosophers do things differently?
  - Even Numbered: Grab chopstick on their left and then right
  - Odd Numbered: Grab chopstick on their right and then left

- Can this deadlock?

- What issues arise with this solution?

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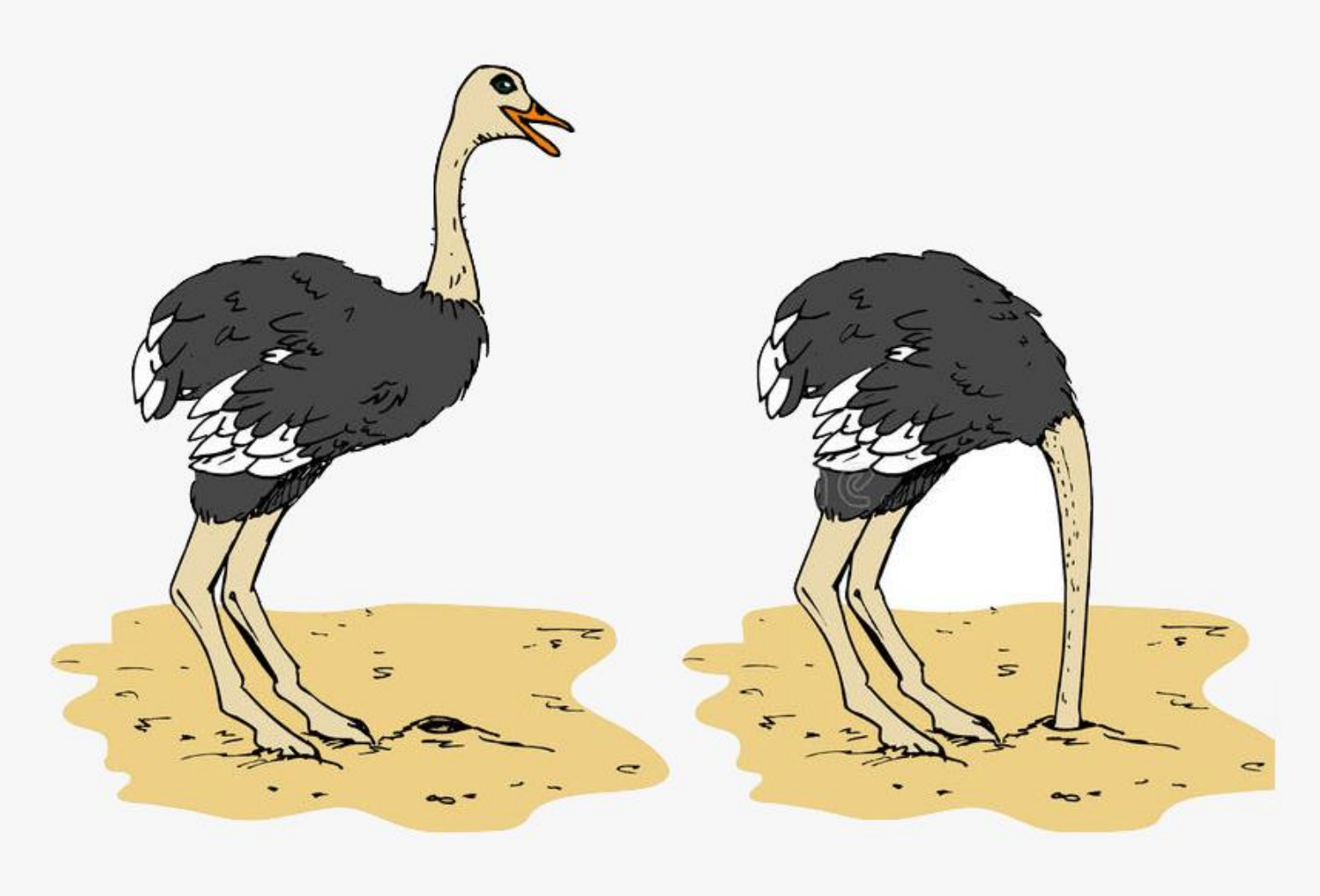
Deadlock Handling: Ostrich Algorithm

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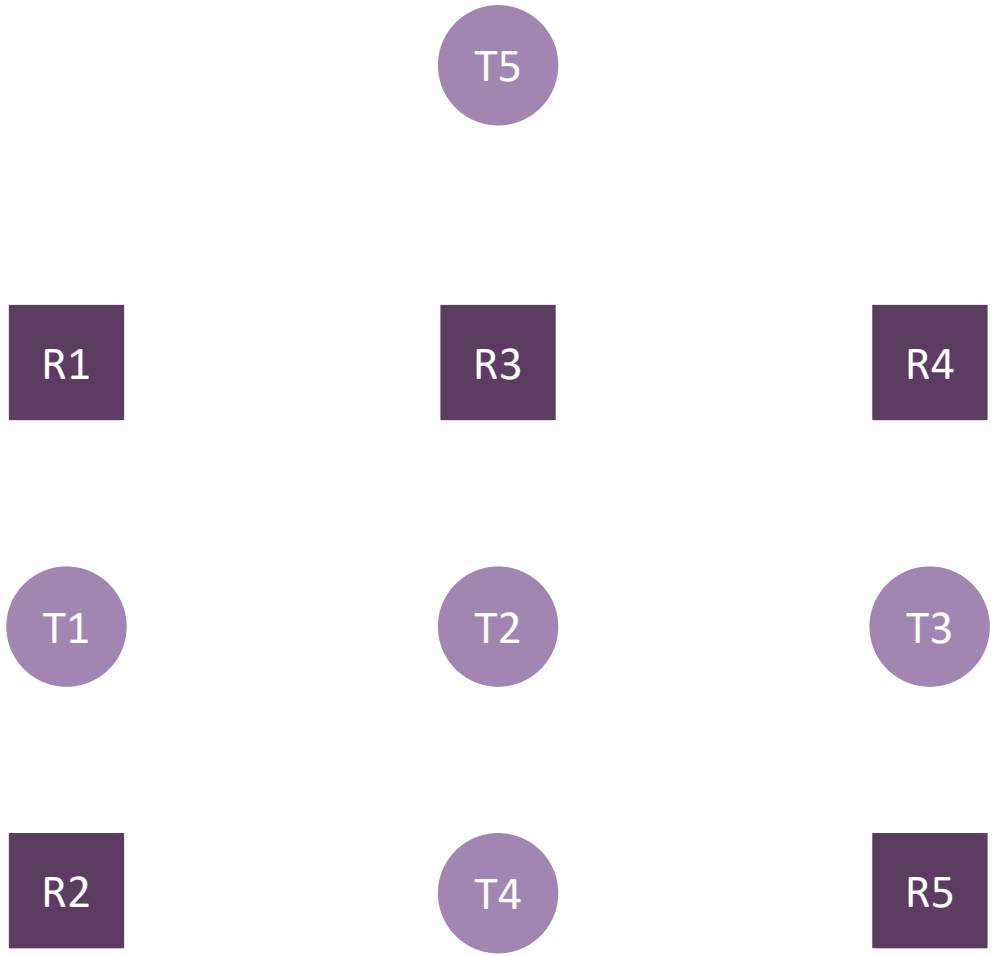
- Consider the following example with 5 threads and 5 resources that require mutual exclusion is this a deadlock?
  - Thread 1 has R2 but wants R1
  - Thread 2 has R1 but wants R3, R4 and R5
  - Thread 3 has R4 but wants R5
  - Thread 4 has R5 but wants R2
  - Thread 5 has R3

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
  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

Resource Allocation Graph Example

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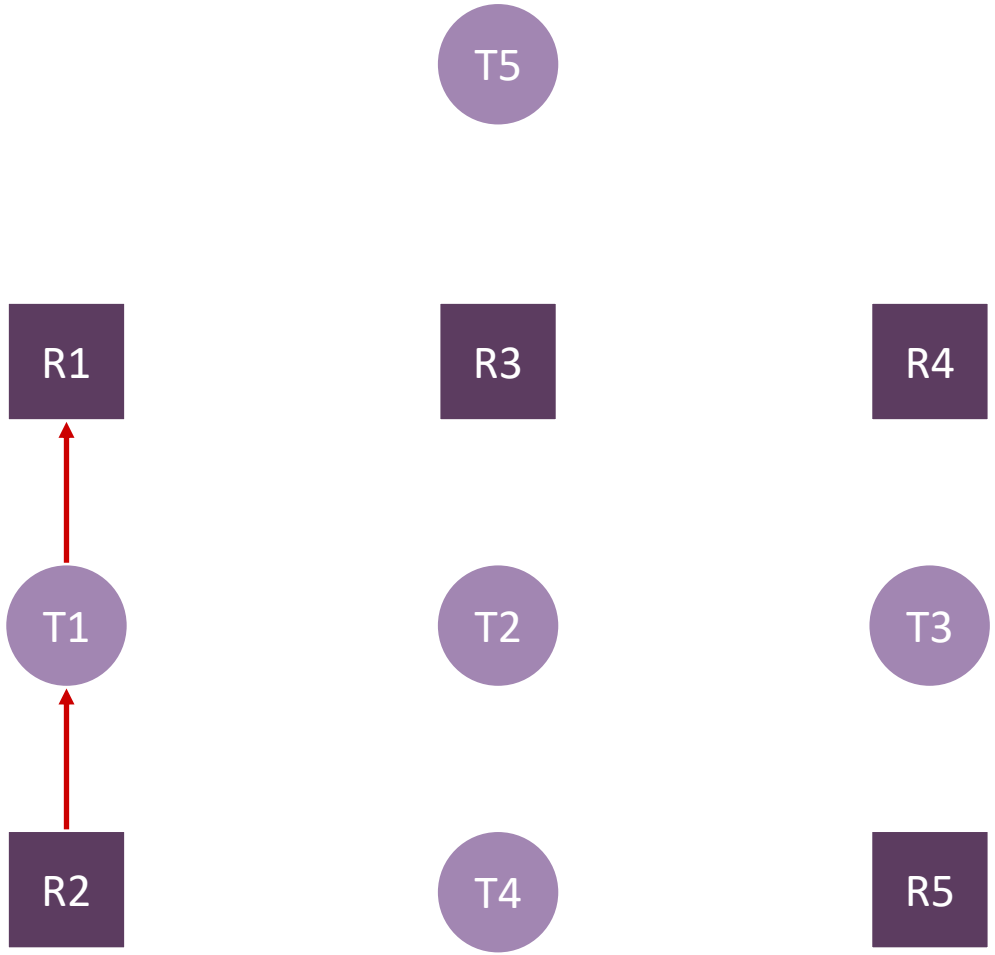

Resource Allocation Graph

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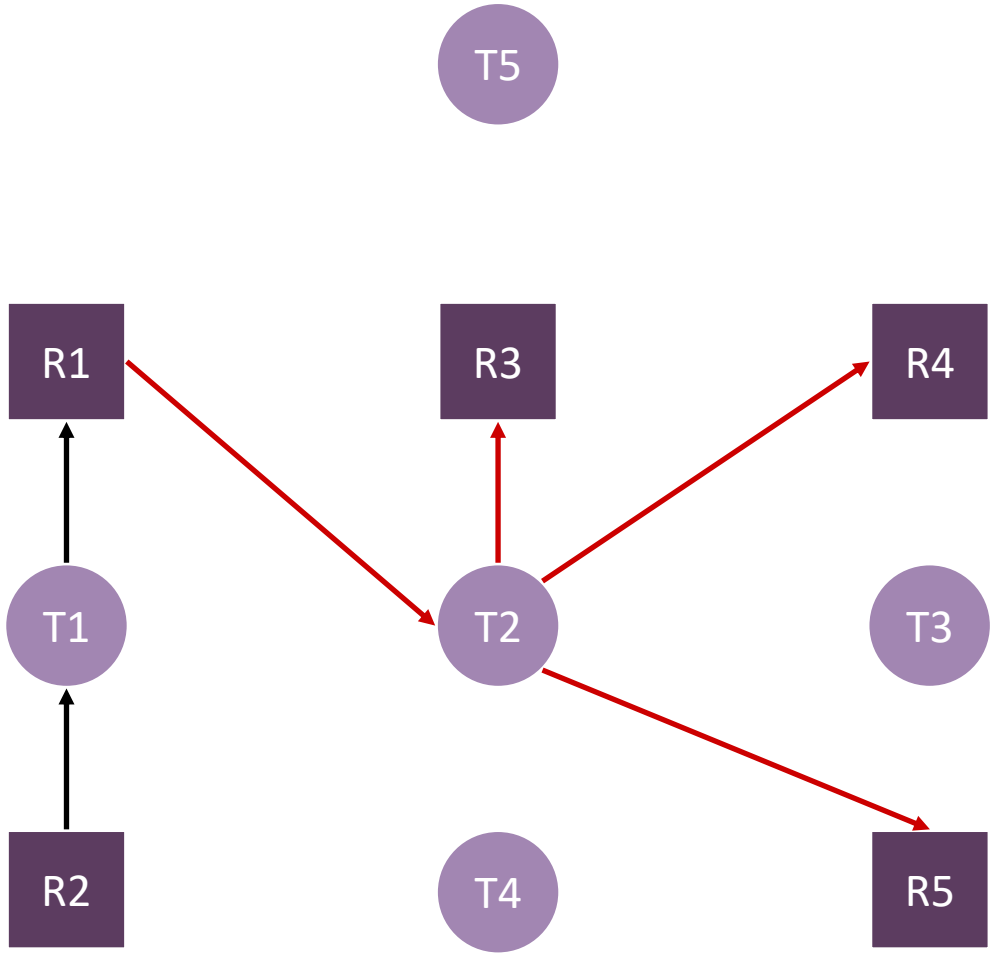

Resource Allocation Graph

Resource Allocation Graph Example

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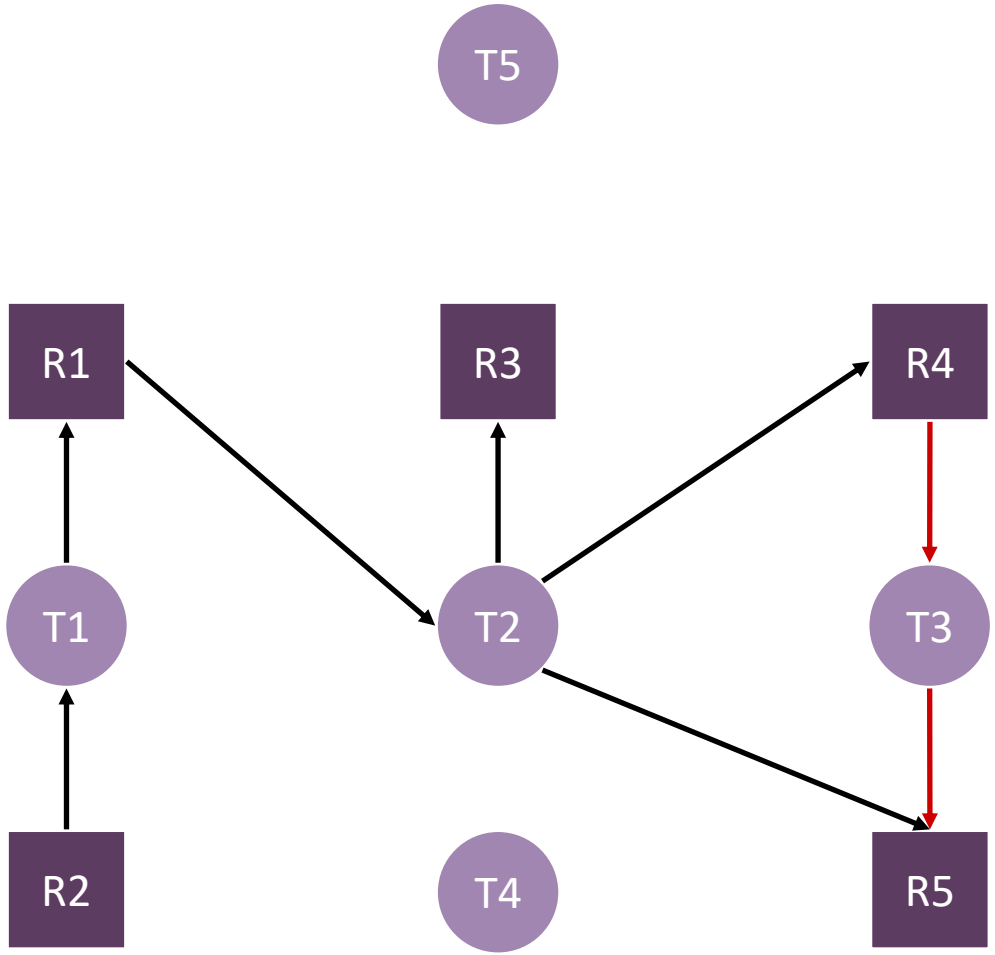

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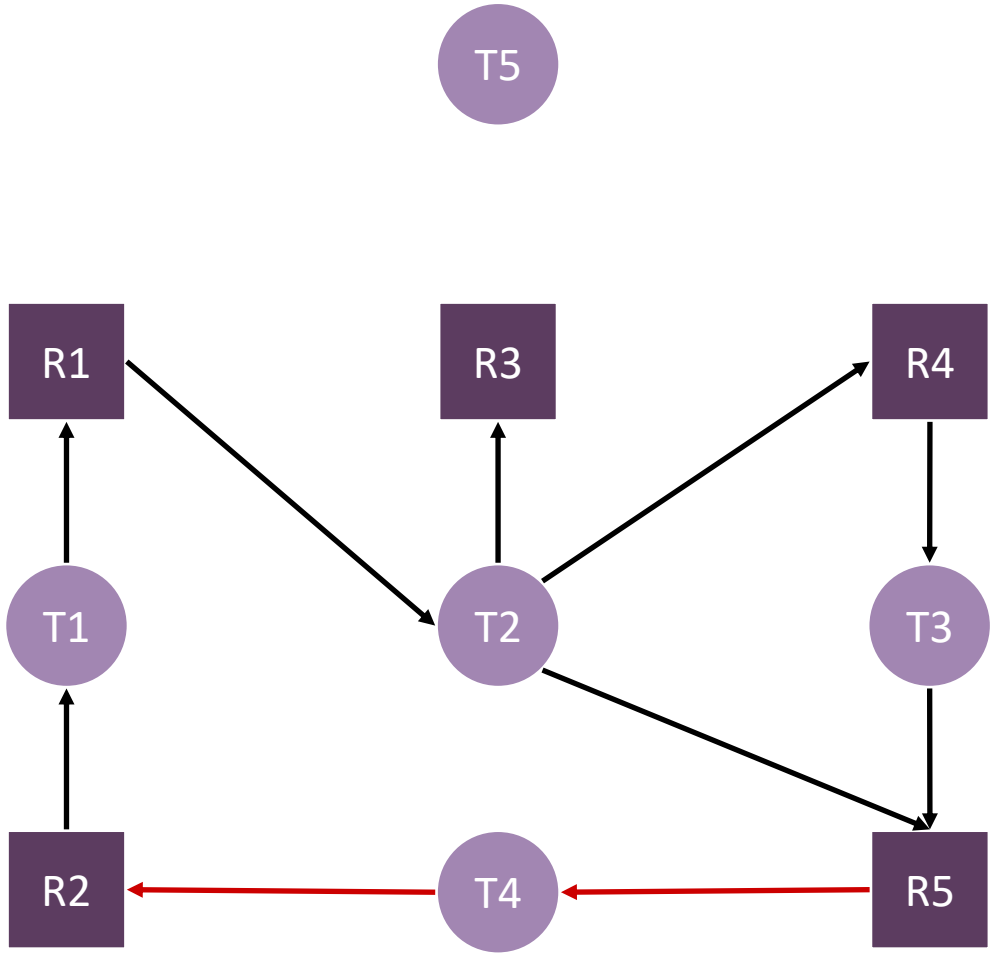

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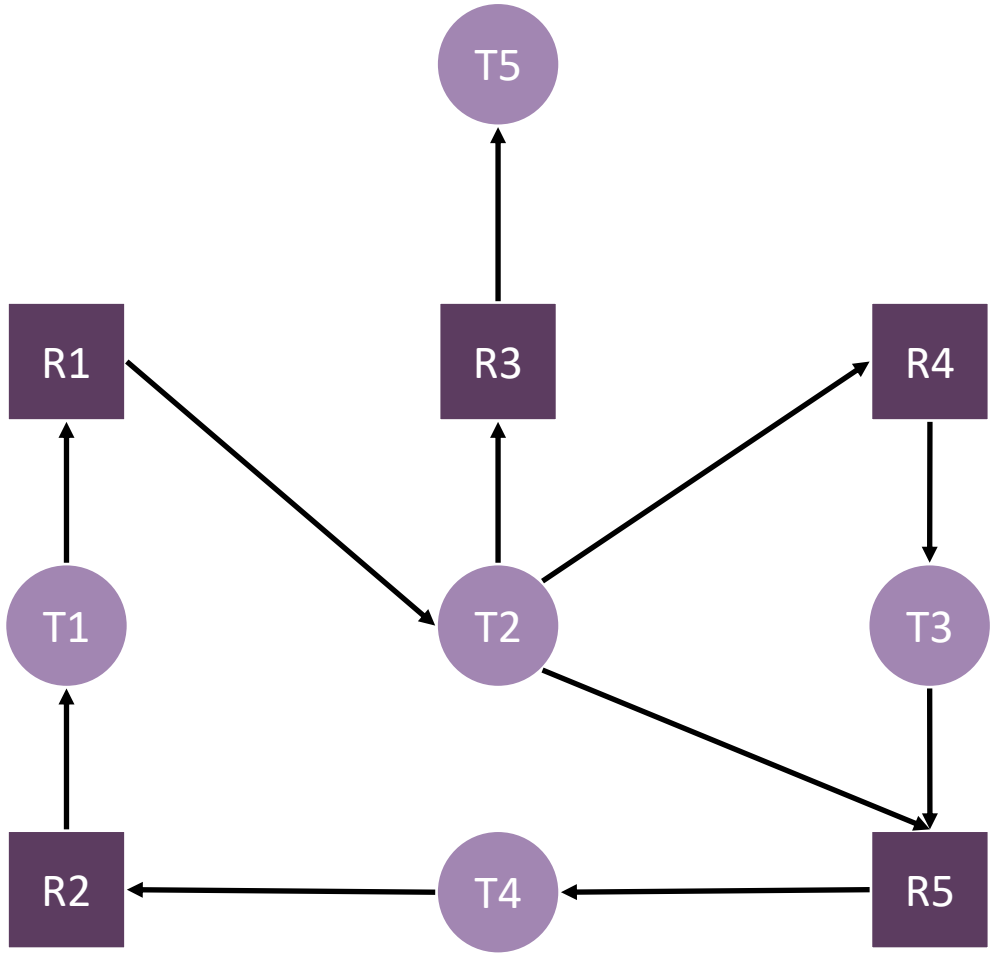
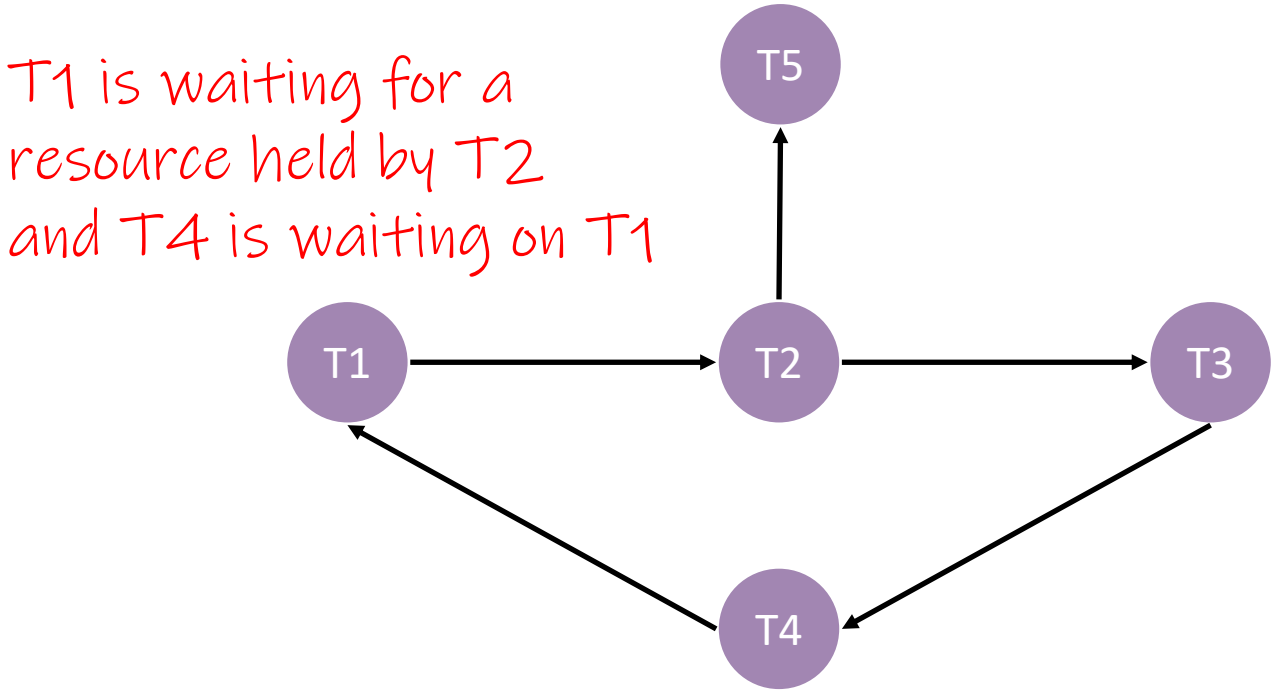


Resource Allocation Graph

Alternate graph

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



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