Concurrency : Common Errors

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Lots of ways to mess up with concurrency

- Bugs are often unpredictable and hard to reproduce
- Subtle interactions between multiple actors that are timing dependent
- Adding debugging code or using the debugger can change the timing, making the bug temporarily hide
- Need to understand common concurrency problems
    1. Critical Section Problems (data races) — we’ve seen this
    2. Deadlock
    3. Starvation

What Types of Bugs Exist

- Focus on four major open-source applications
  - MySQL, Apach, Mozilla, OpenOffice

Application	What it does	Non-Deadlock	Deadlock
MySQL	Database Server	14	9
Apache	Web Server	13	4
Mozilla	Web Browser	41	16
Open Office	Office Suite	6	2
Total		**74**	**31**

Bugs In Modern Applications

Non-Deadlock Bugs

- Make up a majority of concurrency bugs
- Two major types of non deadlock bugs:
  - Atomicity violation
  - Order violation

Atomicity-Violation Bugs

- The desired serializability among multiple memory accesses is violated
  - Simple example found in MySQL:
    - Two different threads access the field proc_info

```
Thread1::
if(thd->proc_info){
   …
   fputs(thd->proc_info , …);
   …
}

Thread2::
thd->proc_info = NULL;
```

Atomicity-Violation Bugs (Cont.)

- Solution : Simply add locks around the shared-variable references

```
pthread_mutex_t lock = PTHREAD_MUTEX_INITIALIZER;

Thread1::
pthread_mutex_lock(&lock);
if(thd->proc_info){
      …
      fputs(thd->proc_info , …);
      …
}
pthread_mutex_unlock(&lock);

Thread2::
pthread_mutex_lock(&lock);
thd->proc_info = NULL;
pthread_mutex_unlock(&lock);
```

Order-Violation Bugs

- The desired order between two memory accesses is flipped
  - i.e. A should always be executed before B, but the order is not enforced during execution
  - Example: The code in Thread2 seems to assume that the variable mThread has already been initialized (and is not NULL).

```
Thread1::
void init(){
    mThread = PR_CreateThread(mMain, …);
}

Thread2::
void mMain(…){
    mState = mThread->State
}
```

Order-Violation Bugs (Cont.)

- Solution : enforce ordering using condition variables

```
pthread_mutex_t mtLock = PTHREAD_MUTEX_INITIALIZER;
pthread_cond_t mtCond = PTHREAD_COND_INITIALIZER;
int mtInit = 0;

Thread 1::
void init(){
    …
    mThread = PR_CreateThread(mMain,…);

    // signal that the thread has been created.
    pthread_mutex_lock(&mtLock);
    mtInit = 1;
    pthread_cond_signal(&mtCond);
    pthread_mutex_unlock(&mtLock);
    …
}

Thread2::
void mMain(…){
    …
```

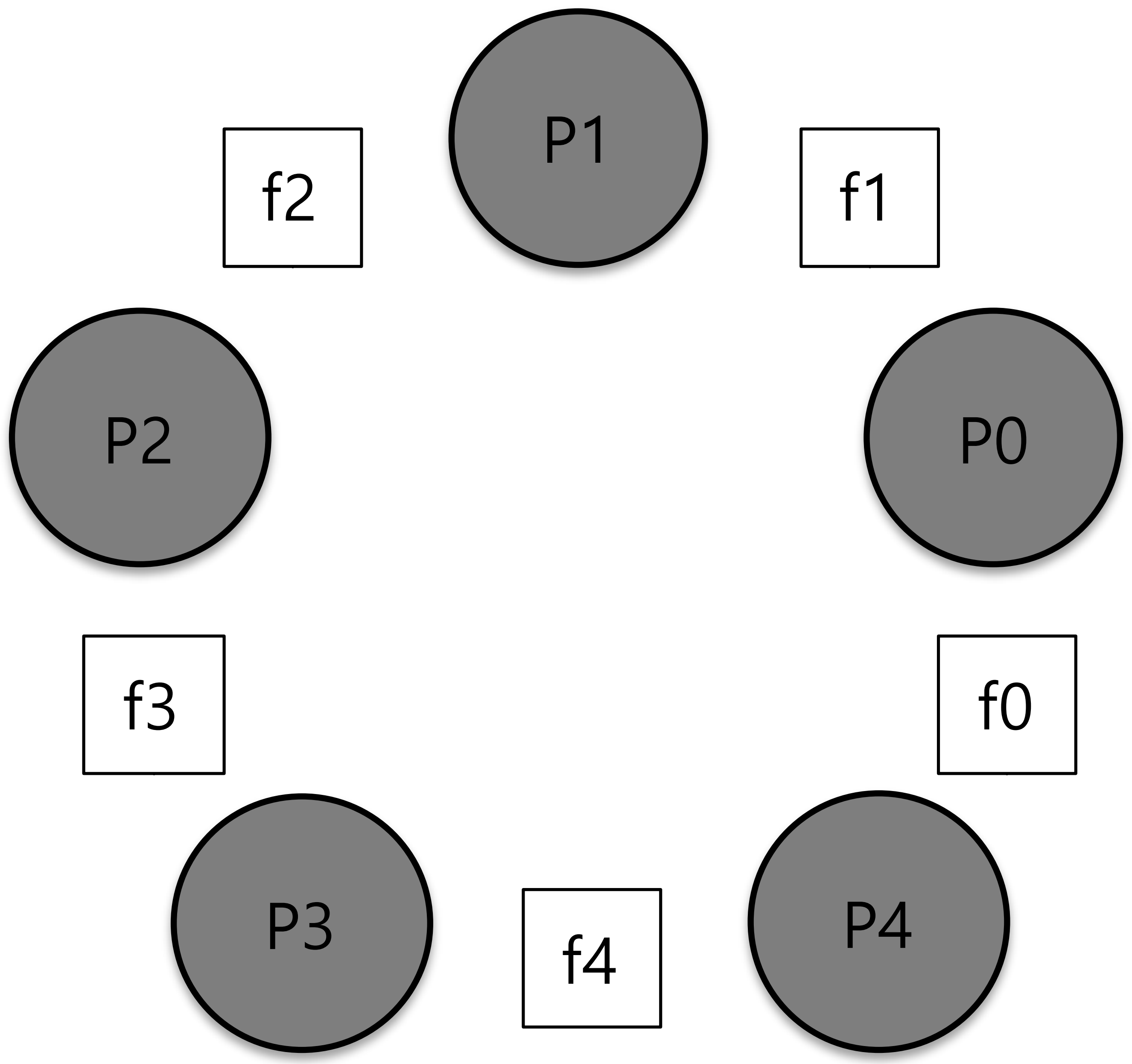
Order-Violation Bugs (Cont.)

```
    // wait for the thread to be initialized …
    pthread_mutex_lock(&mtLock);
    while(mtInit == 0)
        pthread_cond_wait(&mtCond, &mtLock);
    pthread_mutex_unlock(&mtLock);

    mState = mThread->State;
    …
}
```

The Dining Philosophers

- Assume there are five “philosophers” sitting around a table
  - Between each pair of philosophers is a **single fork** (five total)
  - The philosophers each have times where they **think**, and don’t need any forks, and times where they **eat**
  - In order to eat, a philosopher needs **two forks**, both the one on their left and the on on their right
  - **There is contention for these forks**



The Dining Philosophers (Cont.)

- Key Challenge:
  - There is no deadlock
  - No philosopher starves and never gets to eat
  - Concurrency is high

```
while (1) {
      think();
      getforks();
      eat();
      putforks();
}
```

Basic loop of each philosopher

```
// helper functions
int left(int p) { return p; }

int right(int p) {
      return (p + 1) % 5;
}
```

Helper functions (Downey's solutions)

- Philosopher p wishes to refer to the fork on their left : call left(p)
- Philosopher p wishes to refer to the fork on their right : call right(p)

The Dining Philosophers (Cont.)

- We need some semaphore, one for each fork: set_t forks[5]

```
void getforks() {
sem_wait(forks[left(p)]);
sem_wait(forks[right(p)]);
}

void putforks() {
sem_post(forks[left(p)]);
sem_post(forks[right(p)]);
}
```

The `getforks()` and `putforks()` Routines (Broken Solution)

- What is wrong with this solution?

The Dining Philosophers (Cont.)

- We need some semaphore, one for each fork: set_t forks[5]

```
void getforks() {
sem_wait(forks[left(p)]);
sem_wait(forks[right(p)]);
}

void putforks() {
sem_post(forks[left(p)]);
sem_post(forks[right(p)]);
}
```

The `getforks()` and `putforks()` Routines (Broken Solution)

- Deadlock occur!
  - If each philosopher happens to grab the fork on their left before any grabs a fork on their right
  - Each will be stuck holding one fork and waiting for the other, forever

A Solution : Breaking the Dependency

- Change how forks are acquired
  - Let’s assume that philosopher 4 acquire the forks in a different order

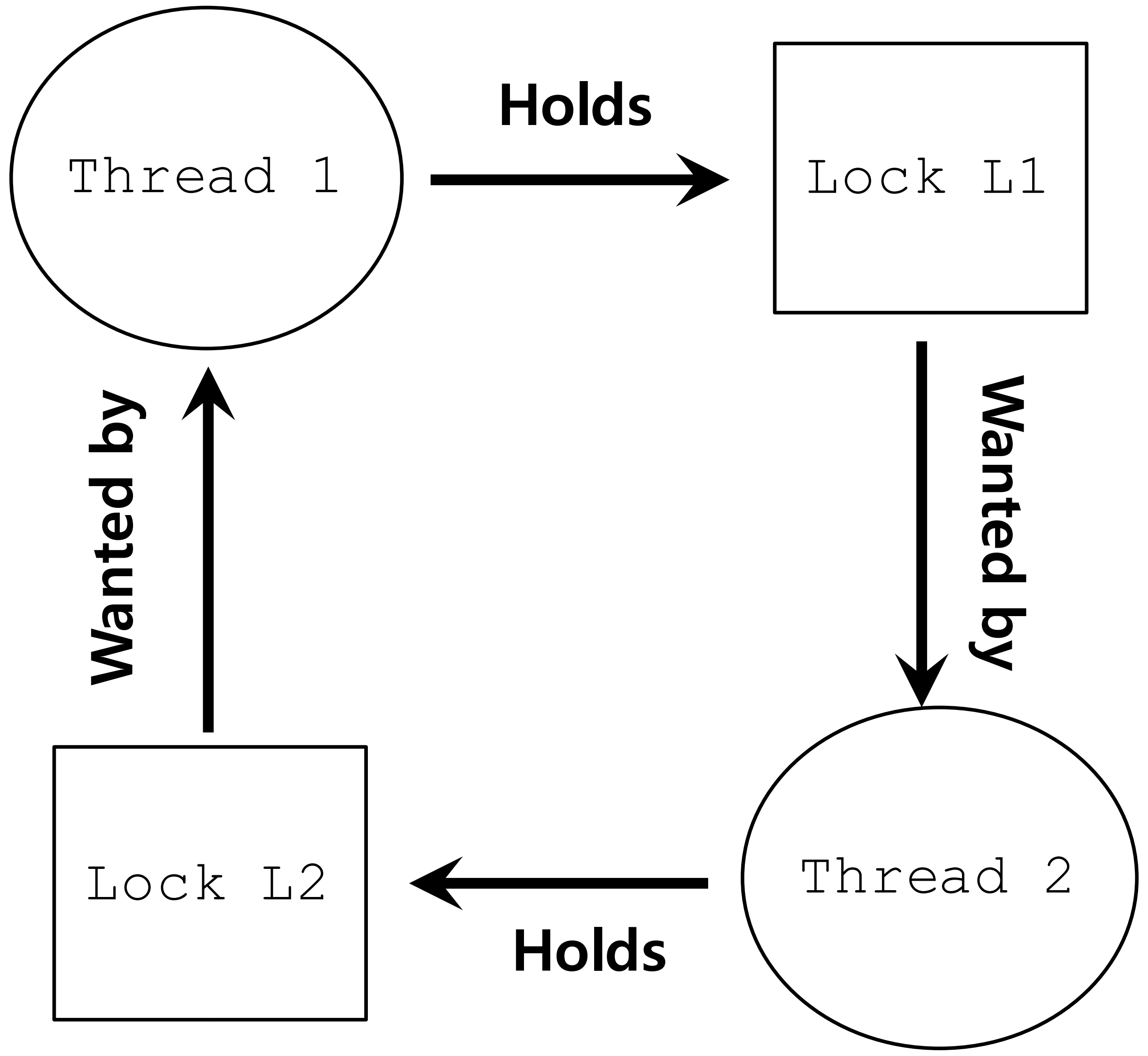
```
void getforks() {
if (p == 4) {
        sem_wait(forks[right(p)]);
        sem_wait(forks[left(p)]);
} else {
        sem_wait(forks[left(p)]);
        sem_wait(forks[right(p)]);
}
}
```

  - There is no situation where each philosopher grabs one fork and is stuck waiting for the other. The cycle of waiting is broken.

Deadlock Bugs

```
Thread 1:          Thread 2:
lock(L1);          lock(L2);
lock(L2);          lock(L1);
```

- The presence of a cycle
  - `Thread1` is holding a lock `L1` and waiting for another one, `L2`.
  - `Thread2` that holds lock `L2` is waiting for `L1` to be release.



Why Do Deadlocks Occur?

- Reason 1:
  - In large code bases, complex dependencies arise between components
- Reason 2:
  - Due to the nature of encapsulation
    - Hide details of implementations and make software easier to build in a modular way
    - Such modularity does not mesh well with locking

Why Do Deadlocks Occur? (Cont.)

- Example : Java Vector class and the method AddAll()

```
Vector v1,v2;
v1.AddAll(v2);
```

- Locks for both the vector being added to (v1) and the parameter (v2) need to be acquired
  - The routine acquires said locks in some arbitrary order (v1 then v2)
  - If some other thread calls v2.AddAll(v1) at nearly the same time : we have the potential for deadlock

Conditional for Deadlock

- Four conditions need to hold for a deadlock to occur

Condition	Description
Mutual Exclusion	Threads claim exclusive control of resources that they require.
Hold-and-wait	Threads hold resources allocated to them while waiting for additional resources
No preemption	Resources cannot be forcibly removed from threads that are holding them.
Circular wait	There exists a circular chain of threads such that each thread holds one more resources that are being requested by the next thread in the chain

- If any of these four conditions are not met, deadlock cannot occur

Prevention : Circular Wait

- Provide a total ordering on lock acquisition
  - This approach requires careful design of global locking strategies
- Example :
  - There are two locks in the system (L1 and L2)
  - We can prevent deadlock by always acquiring L1 before L2

Prevention : Hold-and-wait

- Acquire all locks at once, atomically

```
lock(prevention);
lock(L1);
lock(L2);
…
unlock(prevention);
```

- This code guarantees that no untimely thread switch can occur in the midst of lock acquisition
- Problem:
  - Require us to know when calling a routine exactly which locks must be held and to acquire them ahead of time
  - Decrease concurrency

Prevention : No Preemption

- Multiple lock acquisition often gets us into trouble because when waiting for one lock we are holding another
- trylock()
  - Used to build a deadlock-free, ordering-robust lock acquisition protocol
  - Grab the lock (if it is available)
  - Or, return -1 : you should try again later

```
top:
    lock(L1);
    if( tryLock(L2) == -1 ){
            unlock(L1);
            goto top;
    }
```

Prevention : No Preemption (Cont.)

- Livelock:
  - Both systems are running through the code sequence over and over again
  - Progress is not being made
  - Solution : add a random delay before looping back and trying the entire thing over again

Prevention : Mutual Exclusion

- Wait-Free
  - Using powerful hardware instruction
  - You can build data structures in a manner that does not require explicit locking

```
int CompareAndSwap(int *address, int expected, int new){
    if(*address == expected){
        *address = new;
        return 1; // success
    }
    return 0;
}
```

Prevention : Mutual Exclusion (Cont.)

- We now wanted to atomically increment a value by a certain amount:

```
void AtomicIncrement(int *value, int amount){
    do{
        int old = *value;
    }while( CompareAndSwap(value, old, old+amount)==0);
}
```

- Repeatedly tried to update the value to the new amount and uses the compare-and-swap to do so
- No lock is acquired
- No deadlock can arise
- Livelock is still a possibility

Prevention : Mutual Exclusion (Cont.)

- More complex example : list insertion

```
void insert(int value){
    node_t * n = malloc(sizeof(node_t));
    assert( n != NULL );
    n->value = value ;
    n->next  = head;
    head     = n;
}
```

- If called by multiple threads at the same time, this code has a race condition

Prevention : Mutual Exclusion (Cont.)

- Solution :
  - Surrounding this code with a lock acquire and release

```
void insert(int value){
    node_t * n = malloc(sizeof(node_t));
    assert( n != NULL );
    n->value = value ;
    lock(listlock); // begin critical section
    n->next  = head;
    head     = n;
    unlock(listlock) ;  //end critical section
}
```

  - Wait-free manner using the compare-and-swap instruction

```
void insert(int value) {
    node_t *n = malloc(sizeof(node_t));
    assert(n != NULL);
    n->value = value;
    do {
            n->next = head;
    } while (CompareAndSwap(&head, n->next, n));
}
```

Automatic Anti-Deadlock Techniques

- Deadlock avoidance : OS or runtime should be smart enough to keep deadlock from being able to happen
- Deadlock prevention : detect that deadlock is about to or is occurring and then break it (by rebooting or killing threads?)

Deadlock Avoidance via Scheduling

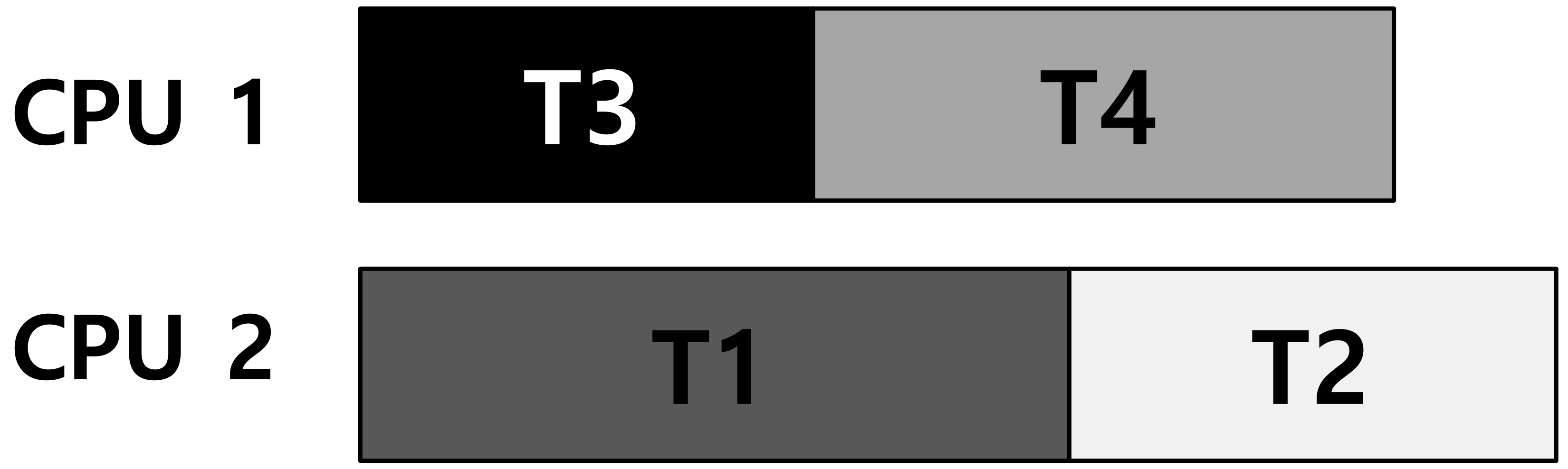
- In some scenarios deadlock avoidance is preferable
  - Global knowledge is required
    - Which locks various threads might grab during their execution
    - Subsequently schedules said threads in a way as to guarantee no deadlock can occur

Example of Deadlock Avoidance via Scheduling(1)

- We have two processors and four threads:
  - Lock acquisition demand of the threads:

	T1	T2	T3	T4
L1	yes	yes	no	no
L2	yes	yes	yes	no

  - A smart scheduler could compute that as long as T1 and T2 are not run at the same time, no deadlock could ever arise

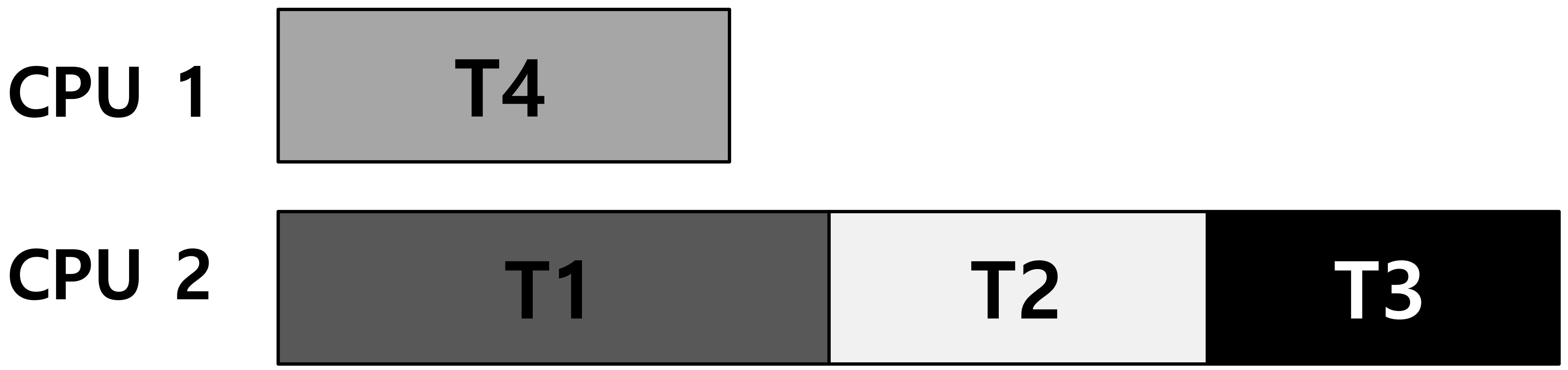


Example of Deadlock Avoidance via Scheduling(2)

- More contention for the same resources

	T1	T2	T3	T4
L1	yes	yes	yes	no
L2	yes	yes	yes	no

- A possible schedule that guarantees that no deadlock could ever occur



- The total time to complete the jobs is lengthened considerably

Detect and Recover

- Allow deadlock to occasionally occur and then take some action
    - Example : If OS froze, you would reboot it
- Many database systems employ deadlock detection and recovery technique
    - A deadlock detector runs periodically
    - Building a resource graph and checking it for cycles
    - In deadlock, the system needs to be restarted