CSCE 313-200
Introduction to Computer Systems
Spring 2025

Deadlocks

Dmitri Loguinov
Texas A&M University

March 6, 2025

Chapter 6: Roadmap

- 6.1 Principles
- 6.6 Dining philosophers
- 6.2 Prevention
- 6.3 Avoidance
- 6.4 Detection
- 6.5 Integrated strategies
- 6.7 Unix
- 6.8 Linux
- 6.9 Solaris
- 6.10 Windows

Part II

Chapter 3: Processes
Chapter 4: Threads
Chapter 5: Concurrency
Chapter 6: Deadlocks

Principles

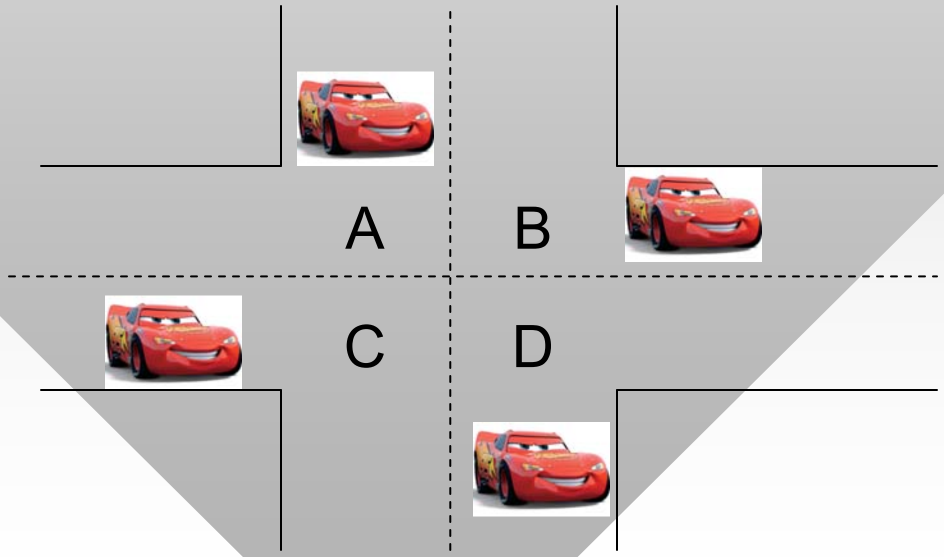
```
ThreadP () {
    mutexA.Lock();
    mutexB.Lock();
    // critical section
    mutexA.Unlock();
    mutexB.Unlock();
}
```

```
ThreadQ () {
    mutexB.Lock();
    mutexA.Lock();
    // critical section
    mutexB.Unlock();
    mutexA.Unlock();
}
```

- Deadlock is a permanent (infinite) wait for resources
  - Important problem in the field of synchronization
- Typical example with threads P and Q:
  - Two mutexes locked in different order
  - Common source of deadlocks in more general cases
- Another example:

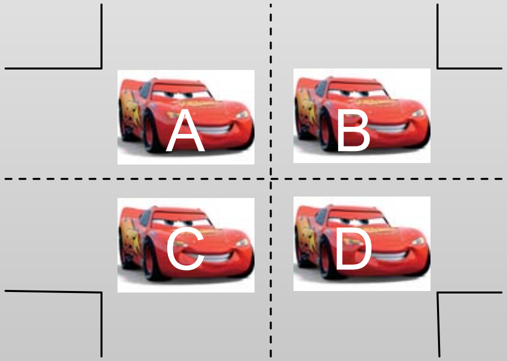
```
CarNorth () {
    mutexA.Lock();
    mutexC.Lock();
    // drive
    mutexA.Unlock();
    mutexC.Unlock();
}
```

```
CarWest () {
    mutexC.Lock();
    mutexD.Lock();
    // drive
    mutexC.Unlock();
    mutexD.Unlock();
}
```



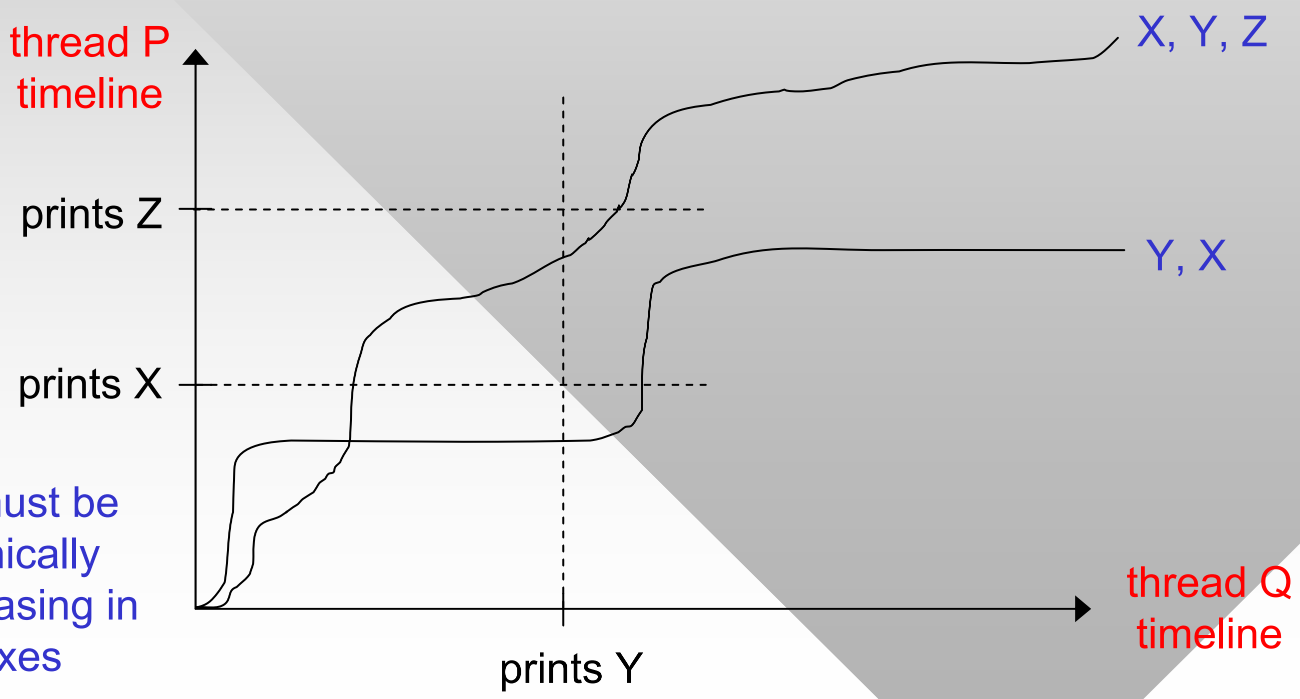
Principles

- Example (cont'd): deadlock possible in general and...
  - Certain when each grabs their first mutex:
- Conditions for a deadlock to be possible
  - 1) Mutual exclusion (no sharing)
  - 2) Hold and wait (allowed to hold one resource and wait for another, i.e., acquisition of multiple mutexes is *not* atomic)
  - 3) No preemption (held resources not released until critical section has been successfully completed)
- Conditions for it to be certain
  - 1)-3) plus 4) circular wait



Progress Diagram

- Assume two threads P and Q in parallel execution
  - Denote by t the absolute time
  - Progress diagram is a 2D parametric curve (x(t),y(t)) where x(t) is the number of instructions executed by Q and y(t) by P



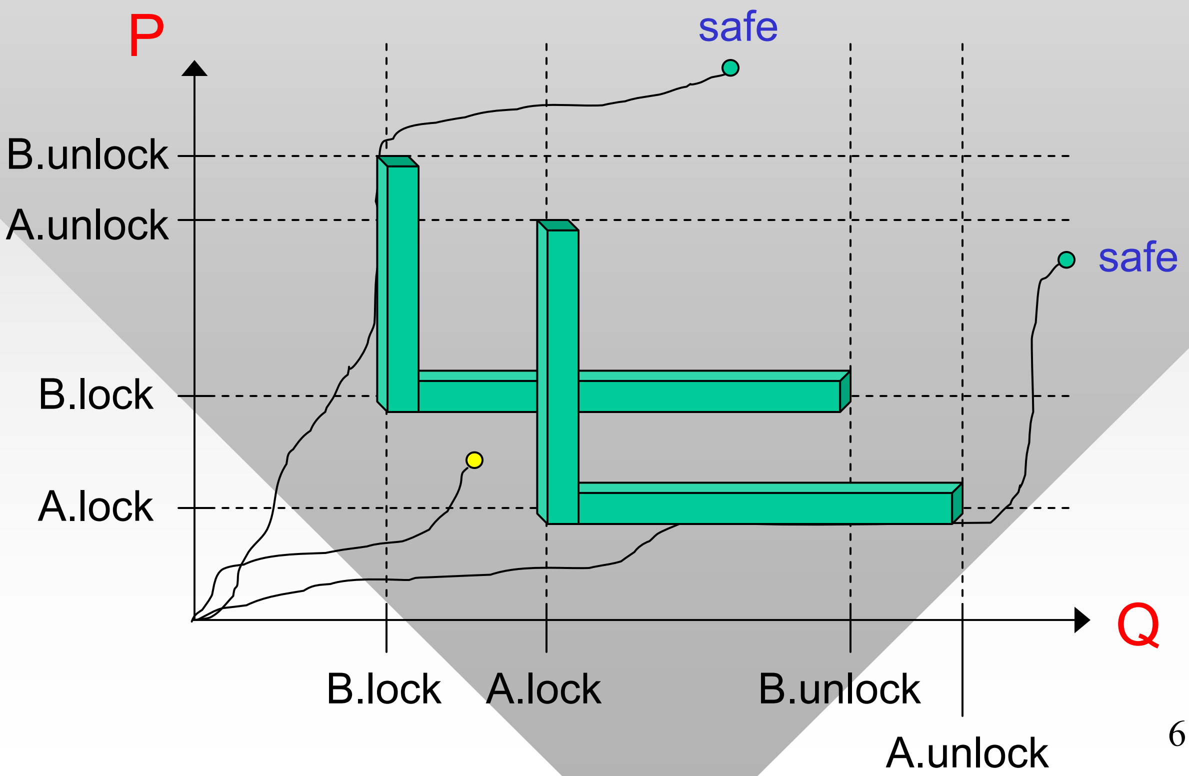
Curves must be monotonically non-decreasing in both axes

Progress Diagram

- Back to our example with P and Q
- Mutexes place L-shaped obstacles/barriers on the progress diagram that cannot be crossed

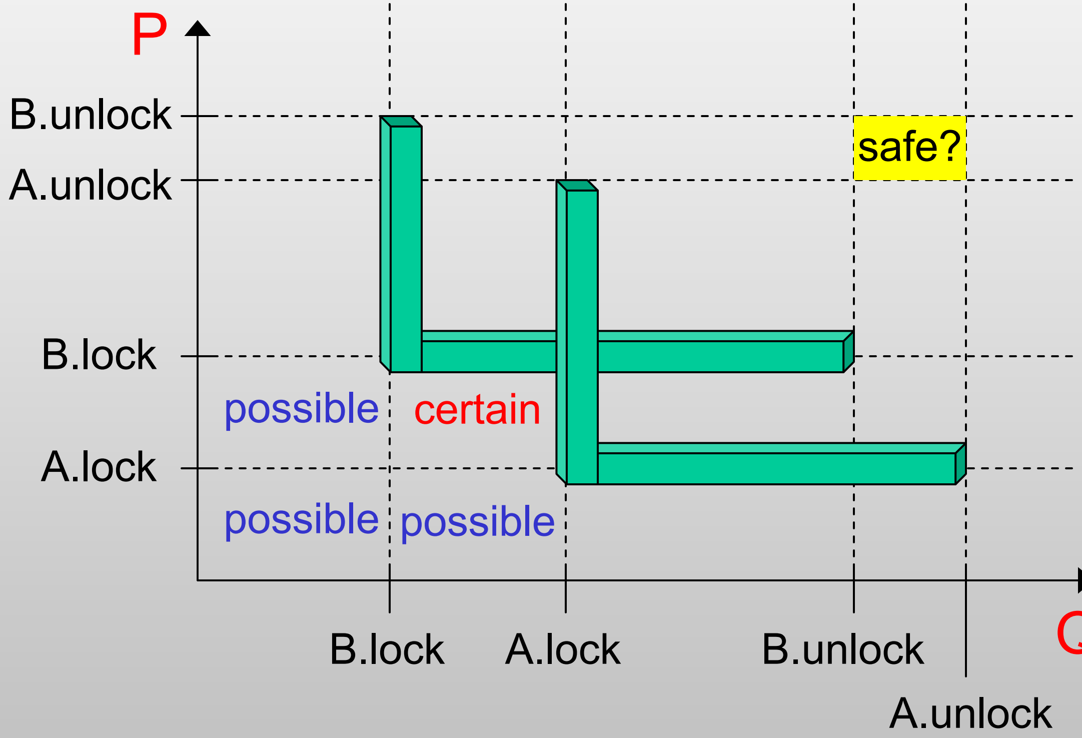
```
ThreadP () {
    mutexA.Lock();
    mutexB.Lock();
    // critical section
    mutexA.Unlock();
    mutexB.Unlock();
}
```

```
ThreadQ () {
    mutexB.Lock();
    mutexA.Lock();
    // critical section
    mutexB.Unlock();
    mutexA.Unlock();
}
```



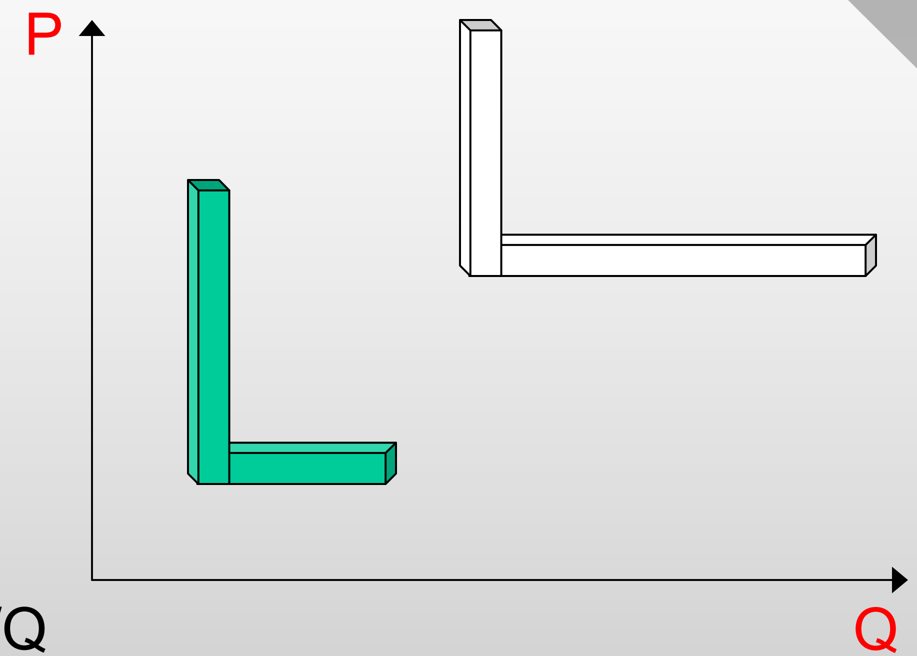
Progress Diagram

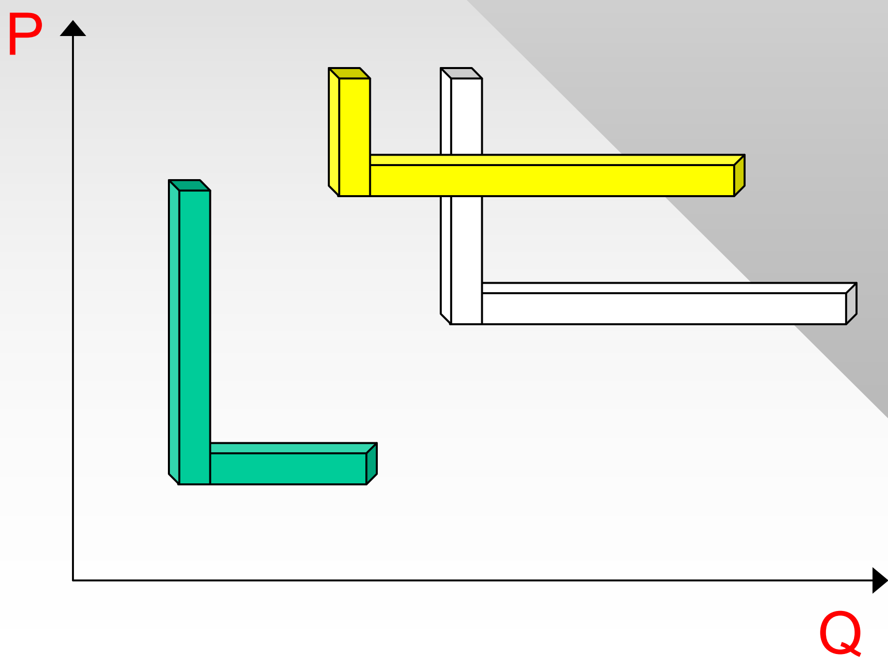
- In three quadrants near the origin, deadlock possible
  - In the fourth, it is certain
- All other sections are safe
  - Except impossible states behind barriers
- Static or dynamic analysis to detect deadlocks
- What happens with N threads?
  - N-dimensional diagram

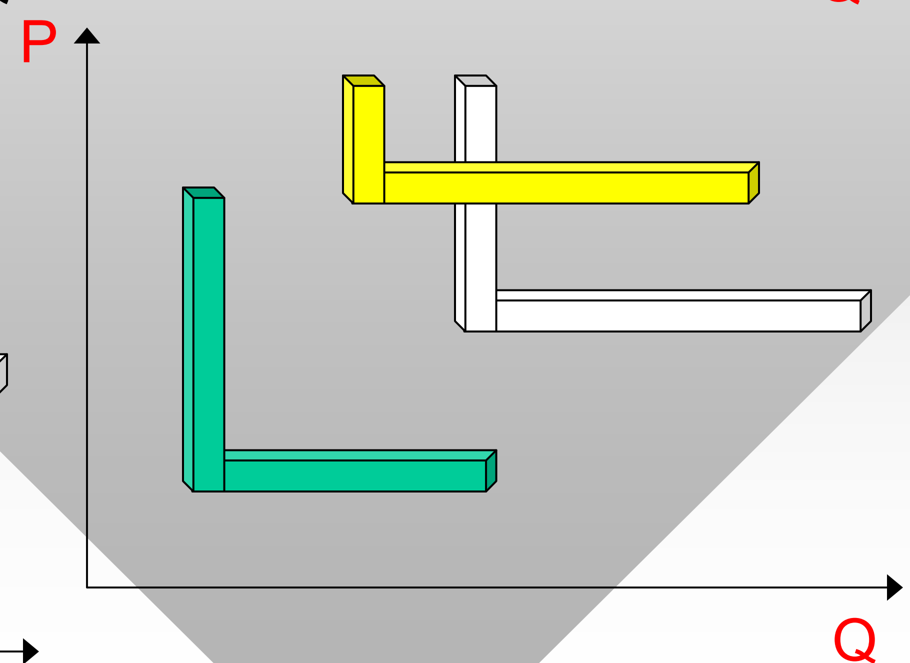


Progress Diagram

- How about these diagrams?
- In what order are mutexes acquired?
  - Write pseudo code for P/Q

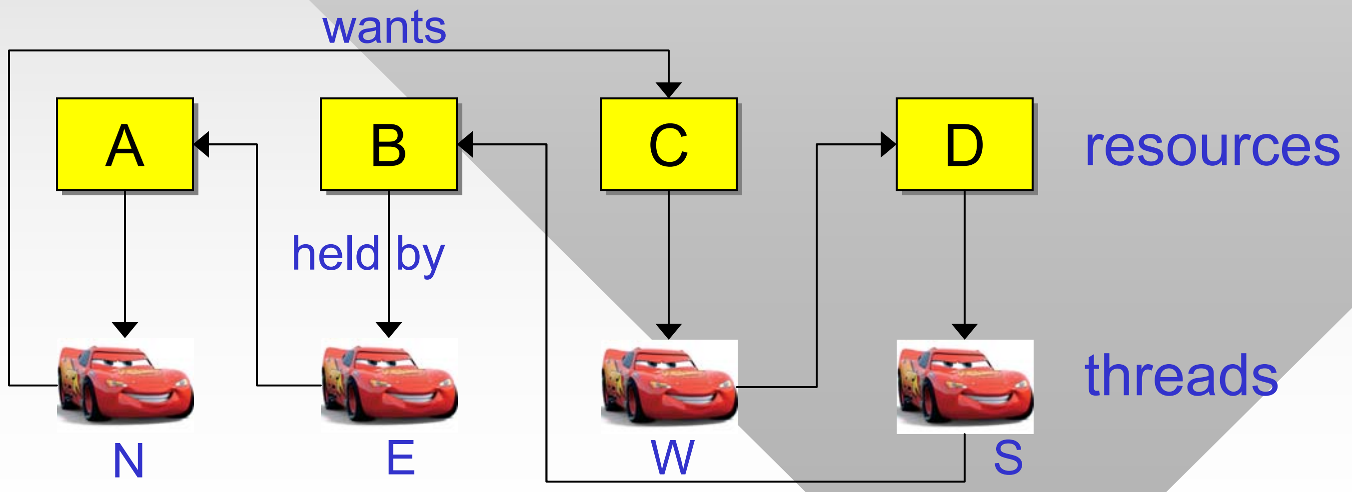






Resource Allocation Graph

- To visualize deadlocks, often a graph is drawn between all threads and resources
  - Edges of this bipartite graph are labeled with “held by” (resources → threads) and “wants” (threads → resources)
- If this directed graph has a cycle, there is a deadlock
  - Car labels (N, E, W, S) map to North/East/West/South position

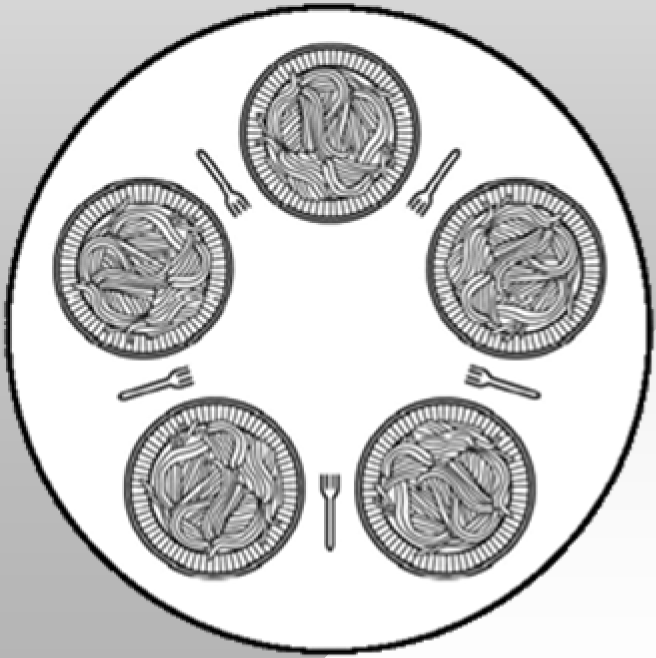


Chapter 6: Roadmap

- 6.1 Principles
- 6.6 Dining philosophers
- 6.2 Prevention
- 6.3 Avoidance
- 6.4 Detection
- 6.5 Integrated strategies
- 6.7 Unix
- 6.8 Linux
- 6.9 Solaris
- 6.10 Windows

Dining Philosophers

- Yet another famous synchronization problem
  - Proposed by Dijkstra in 1965
- N philosophers are sitting at a round table with N forks between them
  - Usually N = 5 and the food is spaghetti, but this is not essential
- Each thinks for a random period of time until becoming hungry, then attempts to eat
  - Food requires usage of both adjacent forks



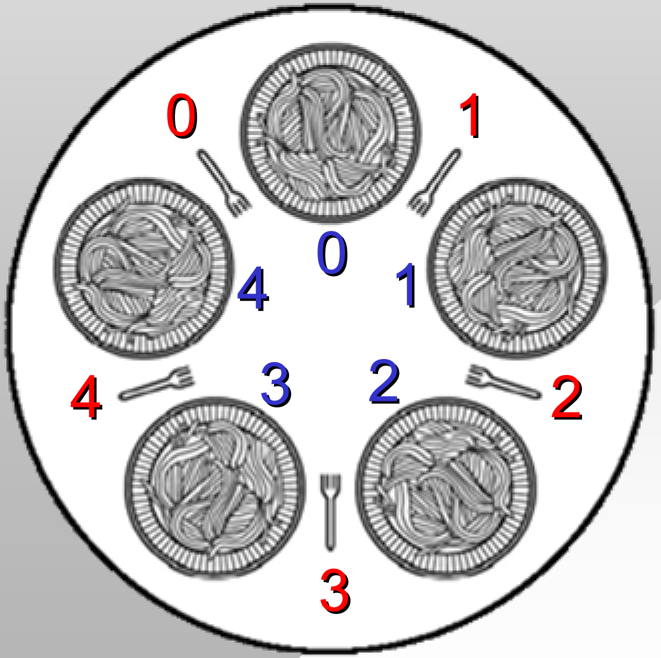
Dining Philosophers

- Operation of a philosopher (each is a separate thread $0 \le i \le N-1$)
- Forks are labeled 0 to N-1 as well

```
Philosopher (int i) {
    while (true) {
        Think ();
        GrabForks (i);
        Eat ();
        DropForks(i);
    }
}
```

```
Mutex mutexFork[N];  // one for each fork

DropForks (int i) {
    mutexFork[i].Unlock();
    mutexFork[(i+1)%N].Unlock();
}
```



- Basic approach DPH v1.0:

```
Mutex mutexFork[N];  // one for each fork

GrabForks (int i) {
    mutexFork[i].Lock();  // right fork
    mutexFork[(i+1)%N].Lock(); // left fork
}
```

- When all are hungry, deadlock is possible

Chapter 6: Roadmap

- 6.1 Principles
- 6.6 Dining philosophers
- 6.2 Prevention
- 6.3 Avoidance
- 6.4 Detection
- 6.5 Integrated strategies
- 6.7 Unix
- 6.8 Linux
- 6.9 Solaris
- 6.10 Windows

Prevention

- In deadlock prevention, the algorithm is modified by programmer to make one of the 4 conditions leading to deadlock impossible
- Condition #1: mutual exclusion
  - Typically cannot be safely eliminated (e.g., cars cannot drive on top of each other thru intersection)
- Condition #2: hold and wait
  - Can be overcome with WaitAll, DPH v1.1

WaitAll is either super slow (Windows) or absent (Unix)

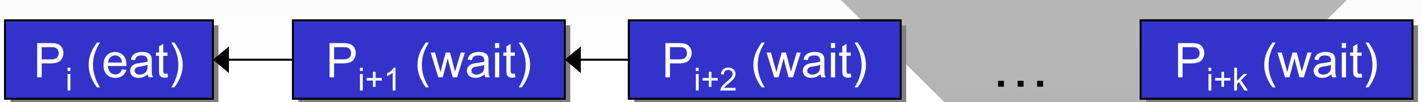
```
Mutex mutexFork[N];  // one mutex for each fork

GrabForks (int i) {
    WaitAll (mutexFork[i], mutexFork[(i+1)%N]); // both forks
}
```

  - Besides speed, main drawback is that all needed mutexes must be known ahead of time and acquired in bulk

Prevention

- Condition #4: circular wait
  - Design algorithm such that a circular deadlock cannot occur
- Notice that presence of 3 or fewer cars (4 or fewer philosophers) cannot cause a cyclic wait graph
  - Use a semaphore to control how many at the table
- Q: how many can eat concurrently?
  - If only ⌊N/2⌋, why allow all N to grab forks?
- How many should be allowed to use forks?
  - To achieve max concurrency, N-1, but …
  - Algorithm is prone to persistent chains of waits:



Prevention

- Suppose T > 0 is the eat+think delay in seconds
  - Max theoretical rate of algorithm is N / 2 * 1 / T
  - If T = 0, then mutex locking/unlocking is the bottleneck

```
CRITICAL_SECTION cs[N];  // one mutex for each fork
HANDLE sema = CreateSemaphore (..., N-1, N-1, ...);

GrabForks (int i) {
    WaitForSingleObject (sema, INFINITE);
    EnterCriticalSection (&cs[i]);
    EnterCriticalSection (&cs[(i+1)%N]);
}
```

DPH v1.2

T=0
450K/sec N = 5

T=100ms
10/sec N = 500

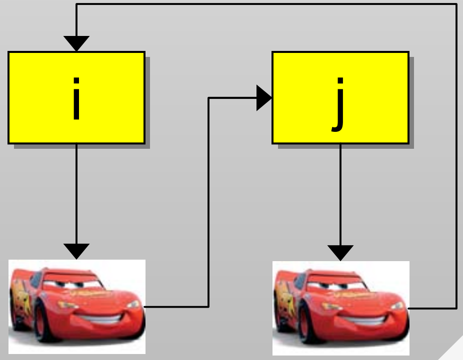
- Elegant semaphore solution, but slow
  - T=0: kernel-mode semaphore kills performance
  - T=100ms: prone to sequential chains of waits, in which case performance may deteriorate to 1/T = 10 per second
  - Improves if think delays are random (1700/sec), or semaphore starts at N/2 (1900/sec)

Prevention

- Another way to prevent circular wait is to request resources in the same order from all threads
- If thread holds resource i and wants j, then $j > i$
  - If all other threads comply with this rule, a loop back to i in the resource graph is impossible
- DPH v1.3

```
CRITICAL_SECTION cs[N];  // one mutex for each fork

GrabForks (int i) {
    if (i != N-1) {  // not the last guy
        EnterCriticalSection (&cs[i]);
        EnterCriticalSection (&cs[i+1]);
    }
    else {
        // special case, a leftie
        EnterCriticalSection (&cs[0]);
        EnterCriticalSection (&cs[N-1]);
    }
}
```



T=0
2M/sec N = 5

T=100ms
254/sec N = 500

Prevention

- Condition #3: no preemption of held mutexes
  - Let waiter (OS) forcefully remove forks and reassign them
- More realistic version:
  - If unable to make progress, threads can voluntarily release held mutexes, randomly sleep, and start again
- Similar to PC 3.4, which was the fastest in prior tests

```
CRITICAL_SECTION cs[N];  // one mutex for each fork

GrabForks (int i) {
    EnterCriticalSection (&cs[i]);
    do {
       if (TryEnterCriticalSection ( &cs[ (i+1)%N ] ) != 0)
          break;
       // unable to acquire
       LeaveCriticalSection (&cs[i]);
       Sleep (rand()*DELAY);
       EnterCriticalSection (&cs[i]);
    } while (true);
}
```

DPH v1.4

T=0
1.9M/sec
N = 5

T=100ms
2400/sec
N = 500