Deadlocks

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Operating Systems

CS 3430

Example 1

Deadlocks

- ***Deadlocks***: Occur when threads are waiting for resources with circular dependencies
  - Often involve ***nonpreemptable resources***, which cannot be taken away from its current thread without failing the computation (e.g., storage allocated to a file)

Deadlocks

- Deadlocks that involve ***preemptable resources*** (e.g., CPU) can usually be resolved by reallocation of resources
- ***Starvation***: a thread waits indefinitely
- A deadlock implies starvation

An Example of Deadlocks

Thread A	Thread B
P(x);	P(y);
P(y);	P(x);

- A deadlock won’t always happen with this code, but it might

Deadlocks, Deadlocks, Everywhere…

- Can happen with any kind of resource
  - Among multiple resources
- Cannot be resolved for each resource independently
  - A thread can grab all the memory
  - The other grabs all the disk space
  - Each thread may need to wait for the other to release

Deadlocks, Deadlocks, Everywhere…

- Round-Robin CPU scheduling cannot prevent deadlocks (or starvation) from happening
- Can occur whenever there is waiting...

A Classic Example of Deadlocks

- Dinning Philosophers
- Each needs two chopsticks to eat

Dining Philosophers

- If each first grabs the chopstick on their right before the one on their left, and all grab at the same time, we have a deadlock

(Personally, I prefer to starve than share chopsticks...)

A Dining Philosophers Implementation

```
semaphore chopstick[5] = {1, 1, 1, 1, 1};

person(int j) {
  while (TRUE) {
      P(chopstick[j]);
      P(chopstick[(j + 1) % 5];
      // eat
      V(chopstick[(j + 1) % 5];
      V(chopstick[j]);
  }
}
```

A Dining Philosophers Implementation

```
// chopstick[5] = {0, 0, 0, 0, 0};

person(int j) {
  while (TRUE) {
      P(chopstick[j]);
      P(chopstick[(j + 1) % 5];
      // eat
      V(chopstick[(j + 1) % 5];
      V(chopstick[j]);
  }
}
```

A Dining Philosophers Implementation

```
// chopstick[5] = {0, 0, 0, 0, 0};

person(int j) {
  while (TRUE) {
      P(chopstick[j]);
      P(chopstick[(j + 1) % 5];
      // eat
      V(chopstick[(j + 1) % 5];
      V(chopstick[j]);
  }
}
```

Conditions for Deadlocks

- Four necessary (but not sufficient) conditions
  - Limited access (lock-protected resources)
  - No preemption (if someone has the resource, it cannot be taken away)
  - Wait while holding (holding a resource while requesting and waiting for the next resource)
  - Circular chain of requests

Deadlock Prevention Techniques

- When encountering a deadlock
  - All four conditions must be true
- To prevent deadlocks
  - Remove one of the four conditions

Deadlock Prevention Techniques

1. Infinite resources (buy a very large disk)

Deadlock Prevention Techniques

2. No sharing (independent threads)

Deadlock Prevention Techniques

3. Allocate all resources at the beginning (if you need 2 chopsticks, grab both at the same time)

easier said than done...

Deadlock Prevention Techniques

3. Allocate all resources at the beginning (if you need 2 chopsticks, grab both at the same time)

```
semaphore chopstick[5] = {1, 1, 1, 1, 1}, s = 1;
person(int j) {
        while (TRUE) {
                P(s);
                        P(chopstick[j]);
                        P(chopstick[(j + 1) % 5];
                        // eat
                        V(chopstick[(j + 1) % 5];
                        V(chopstick[j]);
                V(s);
        }
}
```

Deadlock Prevention Techniques

3. Allocate all resources at the beginning (if you need 2 chopsticks, grab both at the same time)

1

```
semaphore chopstick[5] = {1, 1 → 0, 1 → 0, 1, 1}, s = 1 → 0;
person(int j) {
        while (TRUE) {
                P(s);
                        P(chopstick[j]);
                        P(chopstick[(j + 1) % 5];
                        // eat
                        V(chopstick[(j + 1) % 5];
                        V(chopstick[j]);
                V(s);
        }
}
```

Deadlock Prevention Techniques

3. Allocate all resources at the beginning (if you need 2 chopsticks, grab both at the same time)

3

1

```
// chopstick[5] = {1, 0, 0, 1, 1}, s = 0;
person(int j) {
        while (TRUE) {
                P(s);
                        P(chopstick[j]);
                        P(chopstick[(j + 1) % 5];
                        // eat
                        V(chopstick[(j + 1) % 5];
                        V(chopstick[j]);
                V(s);
        }
}
```

Deadlock Prevention Techniques

3. Allocate all resources at the beginning (if you need 2 chopsticks, grab both at the same time)

```
// chopstick[5] = {1, 1, 1, 1, 1}, s = 1;
person(int j) {
        while (TRUE) {
                P(s);
                        P(chopstick[j]);
                        P(chopstick[(j + 1) % 5];
                V(s);
                        // eat
                P(s);
                        V(chopstick[(j + 1) % 5];
                        V(chopstick[j]);
                V(s);
        }
}
```

Deadlock Prevention Techniques

3. Allocate all resources at the beginning (if you need 2 chopsticks, grab both at the same time)

```
// chopstick[5] = {1, 1 → 0, 1 → 0, 1, 1}, s = 1 → 0 → 1;
person(int j) {
        while (TRUE) {
                P(s);
                        P(chopstick[j]);
                        P(chopstick[(j + 1) % 5];
                V(s);
                        // eat
                P(s);
                        V(chopstick[(j + 1) % 5];
                        V(chopstick[j]);
                V(s);
        }
}
```

1

Deadlock Prevention Techniques

3. Allocate all resources at the beginning (if you need 2 chopsticks, grab both at the same time)

1 3

```
// chopstick[5] = {1, 0, 0, 1 → 0, 1 → 0}, s = 1 → 0 → 1;
person(int j) {
        while (TRUE) {
                P(s);
                        P(chopstick[j]);
                        P(chopstick[(j + 1) % 5];
                V(s);
                        // eat
                P(s);
                        V(chopstick[(j + 1) % 5];
                        V(chopstick[j]);
                V(s);
        }
}
```

Deadlock Prevention Techniques

3. Allocate all resources at the beginning (if you need 2 chopsticks, grab both at the same time)

1 3 2

```
// chopstick[5] = {1, 0, 0, 0, 0}, s = 1 → 0;
person(int j) {
        while (TRUE) {
                P(s);
                        P(chopstick[j]); // deadlock
                        P(chopstick[(j + 1) % 5];
                V(s);
                        // eat
                P(s);
                        V(chopstick[(j + 1) % 5];
                        V(chopstick[j]);
                V(s);
        }
}
```

Deadlock Prevention Techniques

3. Allocate all resources at the beginning (if you need 2 chopsticks, grab both at the same time)

```
// chopstick[5] = {1, 0, 0, 0, 0}, s = 0;
person(int j) {
        while (TRUE) {
                P(s);
                        P(chopstick[j]);
                        P(chopstick[(j + 1) % 5];
                V(s);
                        // eat
                P(s); // deadlock
                        V(chopstick[(j + 1) % 5];
                        V(chopstick[j]);
                V(s);
        }
}
```

New Solution

- Don’t lock around the chopsticks that are being released

Deadlock Prevention Techniques

3. Allocate all resources at the beginning (if you need 2 chopsticks, grab both at the same time)

```
// chopstick[5] = {1, 1, 1, 1, 1}, s = 1;
person(int j) {
        while (TRUE) {
                P(s);
                        P(chopstick[j]);
                        P(chopstick[(j + 1) % 5];
                V(s);
                        // eat

                        V(chopstick[(j + 1) % 5];
                        V(chopstick[j]);

        }
}
```

Deadlock Prevention Techniques

3. Allocate all resources at the beginning (if you need 2 chopsticks, grab both at the same time)

```
// chopstick[5] = {1, 1 → 0, 1 → 0, 1, 1}, s = 1 → 0 → 1;
person(int j) {
        while (TRUE) {
                P(s);
                        P(chopstick[j]);
                        P(chopstick[(j + 1) % 5];
                V(s);
                        // eat

                        V(chopstick[(j + 1) % 5];
                        V(chopstick[j]);

        }
}
```

1

Deadlock Prevention Techniques

3. Allocate all resources at the beginning (if you need 2 chopsticks, grab both at the same time)

```
// chopstick[5] = {1, 0, 0, 1 → 0, 1 → 0}, s = 1 → 0 → 1;
person(int j) {
        while (TRUE) {
                P(s);
                        P(chopstick[j]);
                        P(chopstick[(j + 1) % 5];
                V(s);
                        // eat

                        V(chopstick[(j + 1) % 5];
                        V(chopstick[j]);

        }
}
```

1 3

Deadlock Prevention Techniques

3. Allocate all resources at the beginning (if you need 2 chopsticks, grab both at the same time)

```
// chopstick[5] = {1, 0, 0, 0, 0}, s = 1 → 0;
person(int j) {
        while (TRUE) {
                P(s);
                        P(chopstick[j]); // wait
                        P(chopstick[(j + 1) % 5];
                V(s);
                        // eat

                        V(chopstick[(j + 1) % 5];
                        V(chopstick[j]);
                }
}
```

1 3 2

Deadlock Prevention Techniques

3. Allocate all resources at the beginning (if you need 2 chopsticks, grab both at the same time)

```
// chopstick[5] = {1, 0, 0, 0 → 1, 0 → 1}, s = 0;
person(int j) {
2       while (TRUE) {
                P(s);
                        P(chopstick[j]); // wait
1     3                 P(chopstick[(j + 1) % 5];
                V(s);
                        // eat

                        V(chopstick[(j + 1) % 5];
                        V(chopstick[j]);
                }
}
```

Deadlock Prevention Techniques

3. Allocate all resources at the beginning (if you need 2 chopsticks, grab both at the same time)

```
// chopstick[5] = {1, 0, 0 → 1, 1, 1}, s = 0;
lawyer(int j) {
2       while (TRUE) {
                P(s);
                        P(chopstick[j]); // wait
                        P(chopstick[(j + 1) % 5];
1               V(s);
                        // eat

                        V(chopstick[(j + 1) % 5]; //wakup!
                        V(chopstick[j]);
                }
}
```

Deadlock Prevention Techniques

3. Allocate all resources at the beginning (if you need 2 chopsticks, grab both at the same time)

```
// chopstick[5] = {1, 0, 1 → 0, 1 → 0, 1}, s = 0;
person(int j) {
        while (TRUE) {
                P(s);
                        P(chopstick[j]);
                        P(chopstick[(j + 1) % 5];
                V(s);
                        // eat

                        V(chopstick[(j + 1) % 5];
                        V(chopstick[j]);
                }
}
```

2

1

More Elaborate Solution

- Allocate some counters
- If someone can’t pick up both chopsticks after taking the lock, release the lock

Deadlock Prevention Techniques

3. Allocate all resources at the beginning (if you need 2 chopsticks, grab both at the same time)

```
int counter[5] = {1, 1, 1, 1, 1}; semaphore chopstick[5] = {1, 1, 1, 1, 1}, s = 1;
person(int j) {
        while (TRUE) {
                P(s);
                // if both counters j  and (j + 1) % 5 > 0, decrement counters
                // and grab chopstick[j] and chopstick[(j + 1) % 5]
                V(s);
                // if holding both chopsticks, eat
                P(s);
                // release chopsticks and increment counters as needed
                V(s);
        }
}
```

Deadlock Prevention Techniques

3. Allocate all resources at the beginning (if you need 2 chopsticks, grab both at the same time)

```
// counter[5] = {1, 0, 0, 1, 1}; chopstick[5] = {1, 0, 0, 1, 1}, s = 1;
person(int j) {
        while (TRUE) {
                P(s);
                // if both counters j and (j + 1) % 5 > 0, decrement counters
                // and grab chopstick[j] and chopstick[(j + 1) % 5]
                V(s);
                // if holding both chopsticks, eat
                P(s);
                // release chopsticks and increment counters as needed
                V(s);
        }
}
```

1

(1, 2)

Deadlock Prevention Techniques

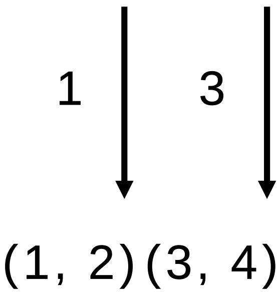
3. Allocate all resources at the beginning (if you need 2 chopsticks, grab both at the same time)

```
// counter[5] = {1, 0, 0, 1, 1}; chopstick[5] = {1, 0, 0, 1, 1}, s = 1;
person (int j) {
    while (TRUE) {
            P(s);
            // if both counters j and (j + 1) % 5 > 0, decrement counters
            // and grab chopstick[j] and chopstick[(j + 1) % 5]
            V(s);
            // if holding both chopsticks, eat
            P(s);
            // release chopsticks and increment counters as needed
            V(s);
    }
}
```

1 (1, 2) 2 ()

Deadlock Prevention Techniques

3. Allocate all resources at the beginning (if you need 2 chopsticks, grab both at the same time)




```
// counter[5] = {1, 0, 0, 0, 0}; chopstick[5] = {1, 0, 0, 0, 0}, s = 1;
person(int j) {
    while (TRUE) {
        P(s);
        // if both counters j  and (j + 1) % 5 > 0, decrement counters
        // and grab chopstick[j] and chopstick[(j + 1) % 5]
        V(s);
        // if holding both chopsticks, eat
        P(s);
        // release chopsticks and increment counters as needed
        V(s);
    }
}
```

Deadlock Prevention Techniques

4. Make everyone use the same ordering in accessing resource (All threads must call P(x) before P(y)

```
// chopstick[5] = {1, 1, 1, 1, 1};

person(int j) {
        while (TRUE) {
                P(chopstick[min(j, (j + 1) % 5)]);
                P(chopstick[max(j, (j + 1) % 5)]);
                // eat
                V(chopstick[max(j, (j + 1) % 5)]);
                V(chopstick[min(j, (j + 1) % 5)]);
        }
}
```

Deadlock Prevention Techniques

4. Make everyone use the same ordering in accessing resource (All threads must call P(x) before P(y)

```
// chopstick[5] = {1 → 0, 1, 1, 1, 1};

person(int j) {
        while (TRUE) {
                P(chopstick[min(j, (j + 1) % 5)]);
                P(chopstick[max(j, (j + 1) % 5)]);
                // eat
                V(chopstick[max(j, (j + 1) % 5)]);
                V(chopstick[min(j, (j + 1) % 5)]);
        }
}
```

0

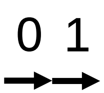
→

Deadlock Prevention Techniques

4. Make everyone use the same ordering in accessing resource (All threads must call P(x) before P(y)

```
// chopstick[5] = {0, 1 → 0, 1, 1, 1};

person(int j) {
        while (TRUE) {
                P(chopstick[min(j, (j + 1) % 5)]);
                P(chopstick[max(j, (j + 1) % 5)]);
                // eat
                V(chopstick[max(j, (j + 1) % 5)]);
                V(chopstick[min(j, (j + 1) % 5)]);
        }
}
```



Deadlock Prevention Techniques

4. Make everyone use the same ordering in accessing resource (All threads must call P(x) before P(y)

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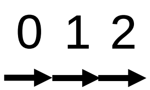
                // eat
                V(chopstick[max(j, (j + 1) % 5)]);
                V(chopstick[min(j, (j + 1) % 5)]);
        }
}
```



Deadlock Prevention Techniques

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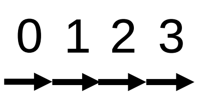
```
// chopstick[5] = {0, 0, 0, 1 → 0, 1};

person(int j) {
        while (TRUE) {
                P(chopstick[min(j, (j + 1) % 5)]);
                P(chopstick[max(j, (j + 1) % 5)]);
                // eat
                V(chopstick[max(j, (j + 1) % 5)]);
                V(chopstick[min(j, (j + 1) % 5)]);
        }
}
```



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4. Make everyone use the same ordering in accessing resource (All threads must call P(x) before P(y)

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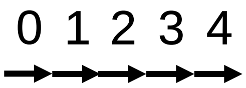
                // eat
                V(chopstick[max(j, (j + 1) % 5)]);
                V(chopstick[min(j, (j + 1) % 5)]);
        }
}
```



Deadlock Prevention Techniques

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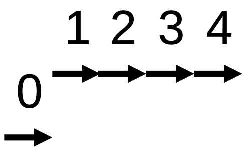


```
// chopstick[5] = {0, 0, 0, 0, 1};

person(int j) {
        while (TRUE) {
                P(chopstick[min(j, (j + 1) % 5)]);
                P(chopstick[max(j, (j + 1) % 5)]);
                // eat
                V(chopstick[max(j, (j + 1) % 5)]);
                V(chopstick[min(j, (j + 1) % 5)]);
        }
}
```

Deadlock Prevention Techniques

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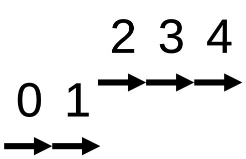
                // eat
                V(chopstick[max(j, (j + 1) % 5)]);
                V(chopstick[min(j, (j + 1) % 5)]);
        }
}
```



Deadlock Prevention Techniques

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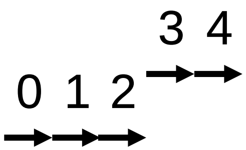
                P(chopstick[max(j, (j + 1) % 5)]);
                // eat
                V(chopstick[max(j, (j + 1) % 5)]);
                V(chopstick[min(j, (j + 1) % 5)]);
        }
}
```

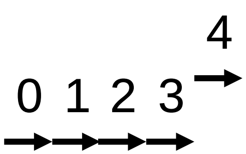


Deadlock Prevention Techniques

4. Make everyone use the same ordering in accessing resource (All threads must call P(x) before P(y)

```
// chopstick[5] = {0, 0, 0, 0, 1 → 0};

person(int j) {
        while (TRUE) {
                P(chopstick[min(j, (j + 1) % 5)]);
                P(chopstick[max(j, (j + 1) % 5)]);
                // eat
                V(chopstick[max(j, (j + 1) % 5)]);
                V(chopstick[min(j, (j + 1) % 5)]);
        }
}
```



Deadlock Prevention Techniques

4. Make everyone use the same ordering in accessing resource (All threads must call P(x) before P(y)

```
// chopstick[5] = {0, 0, 0, 0, 0};

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        while (TRUE) {
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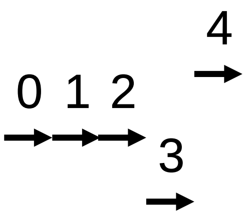
                // eat
                V(chopstick[max(j, (j + 1) % 5)]);
                V(chopstick[min(j, (j + 1) % 5)]);
        }
}
```

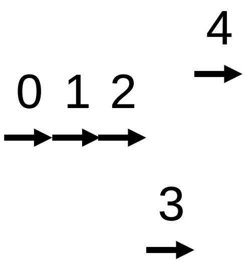


Deadlock Prevention Techniques

4. Make everyone use the same ordering in accessing resource (All threads must call P(x) before P(y)

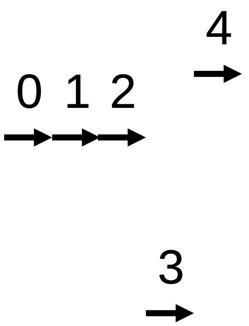
```
// chopstick[5] = {0, 0, 0, 0, 0 → 1};

person(int j) {
        while (TRUE) {
                P(chopstick[min(j, (j + 1) % 5)]);
                P(chopstick[max(j, (j + 1) % 5)]);
                // eat
                V(chopstick[max(j, (j + 1) % 5)]);
                V(chopstick[min(j, (j + 1) % 5)]);
        }
}
```



Deadlock Prevention Techniques

4. Make everyone use the same ordering in accessing resource (All threads must call P(x) before P(y)




```
// chopstick[5] = {0, 0, 0, 0 → 1, 1};

person(int j) {
        while (TRUE) {
                P(chopstick[min(j, (j + 1) % 5)]);
                P(chopstick[max(j, (j + 1) % 5)]);
                // eat
                V(chopstick[max(j, (j + 1) % 5)]);
                V(chopstick[min(j, (j + 1) % 5)]);
        }
}
```

Deadlock Prevention Techniques

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```
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person(int j) {
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                V(chopstick[max(j, (j + 1) % 5)]);
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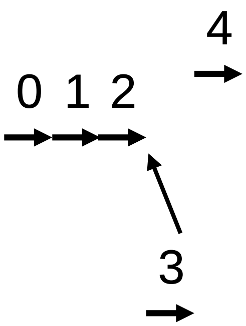
        }
}
```

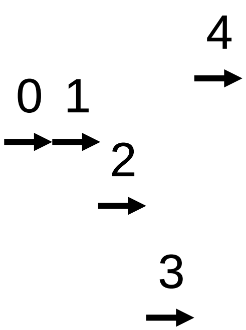


Deadlock Prevention Techniques

4. Make everyone use the same ordering in accessing resource (All threads must call P(x) before P(y)

```
// chopstick[5] = {0, 0, 0, 0, 1};

person(int j) {
        while (TRUE) {
                P(chopstick[min(j, (j + 1) % 5)]);
                P(chopstick[max(j, (j + 1) % 5)]);
                // eat
                V(chopstick[max(j, (j + 1) % 5)]);
                V(chopstick[min(j, (j + 1) % 5)]);
        }
}
```



Deadlock Prevention Techniques

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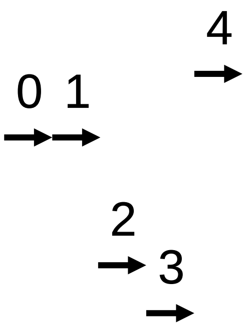


```
// chopstick[5] = {0, 0, 0, 0 → 1, 1};

person(int j) {
        while (TRUE) {
                P(chopstick[min(j, (j + 1) % 5)]);
                P(chopstick[max(j, (j + 1) % 5)]);
                // eat
                V(chopstick[max(j, (j + 1) % 5)]);
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Deadlock Prevention Techniques

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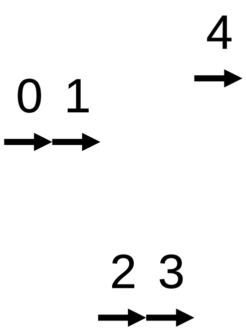



```
// chopstick[5] = {0, 0, 0 → 1, 1, 1};

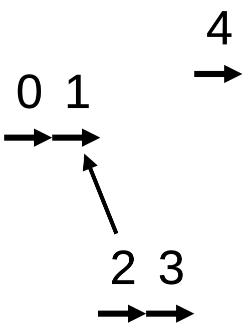
person(int j) {
        while (TRUE) {
                P(chopstick[min(j, (j + 1) % 5)]);
                P(chopstick[max(j, (j + 1) % 5)]);
                // eat
                V(chopstick[max(j, (j + 1) % 5)]);
                V(chopstick[min(j, (j + 1) % 5)]);
        }
}
```

Deadlock Prevention Techniques

4. Make everyone use the same ordering in accessing resource (All threads must call P(x) before P(y)

```
// chopstick[5] = {0, 0, 1 → 0, 1, 1};

person(int j) {
        while (TRUE) {
                P(chopstick[min(j, (j + 1) % 5)]);
                P(chopstick[max(j, (j + 1) % 5)]);
                // eat
                V(chopstick[max(j, (j + 1) % 5)]);
                V(chopstick[min(j, (j + 1) % 5)]);
        }
}
```



Deadlock Prevention Techniques

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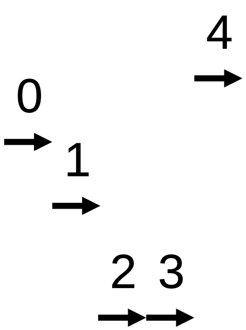
```
// chopstick[5] = {0, 0, 0, 1, 1};

person(int j) {
        while (TRUE) {
                P(chopstick[min(j, (j + 1) % 5)]);
                P(chopstick[max(j, (j + 1) % 5)]);
                // eat
                V(chopstick[max(j, (j + 1) % 5)]);
                V(chopstick[min(j, (j + 1) % 5)]);
        }
}
```



Deadlock Prevention Techniques

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```
// chopstick[5] = {0, 0, 0 → 1, 1, 1};

person(int j) {
        while (TRUE) {
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                // eat
                V(chopstick[max(j, (j + 1) % 5)]);
                V(chopstick[min(j, (j + 1) % 5)]);
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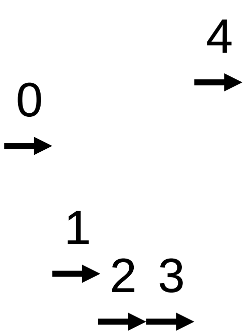
}
```



Deadlock Prevention Techniques

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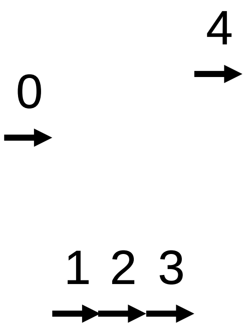
```
// chopstick[5] = {0, 0 → 1, 1, 1, 1};

person(int j) {
        while (TRUE) {
                P(chopstick[min(j, (j + 1) % 5)]);
                P(chopstick[max(j, (j + 1) % 5)]);
                // eat
                V(chopstick[max(j, (j + 1) % 5)]);
                V(chopstick[min(j, (j + 1) % 5)]);
        }
}
```

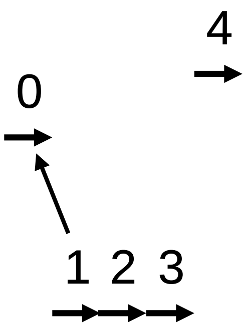


Deadlock Prevention Techniques

4. Make everyone use the same ordering in accessing resource (All threads must call P(x) before P(y)

```
// chopstick[5] = {0, 1 → 0, 1, 1, 1};

person(int j) {
        while (TRUE) {
                P(chopstick[min(j, (j + 1) % 5)]);
                P(chopstick[max(j, (j + 1) % 5)]);
                // eat
                V(chopstick[max(j, (j + 1) % 5)]);
                V(chopstick[min(j, (j + 1) % 5)]);
        }
}
```



Deadlock Prevention Techniques

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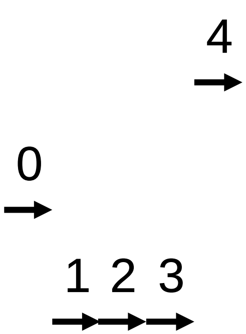



```
// chopstick[5] = {0, 0, 1, 1, 1};

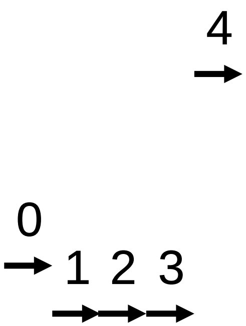
person(int j) {
        while (TRUE) {
                P(chopstick[min(j, (j + 1) % 5)]);
                P(chopstick[max(j, (j + 1) % 5)]);
                // eat
                V(chopstick[max(j, (j + 1) % 5)]);
                V(chopstick[min(j, (j + 1) % 5)]);
        }
}
```

Deadlock Prevention Techniques

4. Make everyone use the same ordering in accessing resource (All threads must call P(x) before P(y)

```
// chopstick[5] = {0, 0 → 1, 1, 1, 1};

person(int j) {
        while (TRUE) {
                P(chopstick[min(j, (j + 1) % 5)]);
                P(chopstick[max(j, (j + 1) % 5)]);
                // eat
                V(chopstick[max(j, (j + 1) % 5)]);
                V(chopstick[min(j, (j + 1) % 5)]);
        }
}
```



Deadlock Prevention Techniques

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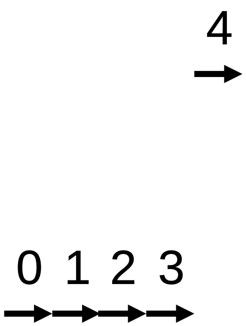



```
// chopstick[5] = {0 → 1, 1, 1, 1, 1};

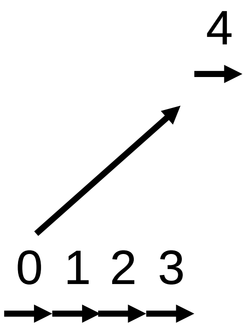
person(int j) {
        while (TRUE) {
                P(chopstick[min(j, (j + 1) % 5)]);
                P(chopstick[max(j, (j + 1) % 5)]);
                // eat
                V(chopstick[max(j, (j + 1) % 5)]);
                V(chopstick[min(j, (j + 1) % 5)]);
        }
}
```

Deadlock Prevention Techniques

4. Make everyone use the same ordering in accessing resource (All threads must call P(x) before P(y)

```
// chopstick[5] = {1 → 0, 1, 1, 1, 1};

person(int j) {
        while (TRUE) {
                P(chopstick[min(j, (j + 1) % 5)]);
                P(chopstick[max(j, (j + 1) % 5)]);
                // eat
                V(chopstick[max(j, (j + 1) % 5)]);
                V(chopstick[min(j, (j + 1) % 5)]);
        }
}
```

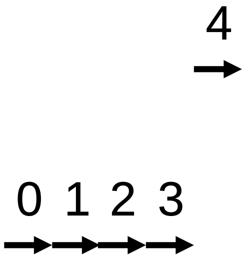


Deadlock Prevention Techniques

4. Make everyone use the same ordering in accessing resource (All threads must call P(x) before P(y)

```
// chopstick[5] = {0, 1, 1, 1, 1 → 0};

person(int j) {
        while (TRUE) {
                P(chopstick[min(j, (j + 1) % 5)]);
                P(chopstick[max(j, (j + 1) % 5)]);
                // eat
                V(chopstick[max(j, (j + 1) % 5)]);
                V(chopstick[min(j, (j + 1) % 5)]);
        }
}
```



More Deadlock Prevention Methods

5. Banker’s algorithm
6. A combination of techniques

Banker’s Algorithm

- The idea of Banker’s algorithm:
  - Allows the sum of requested resources > total resources
  - As long as, there is some way for all threads to finish without getting into any deadlocks

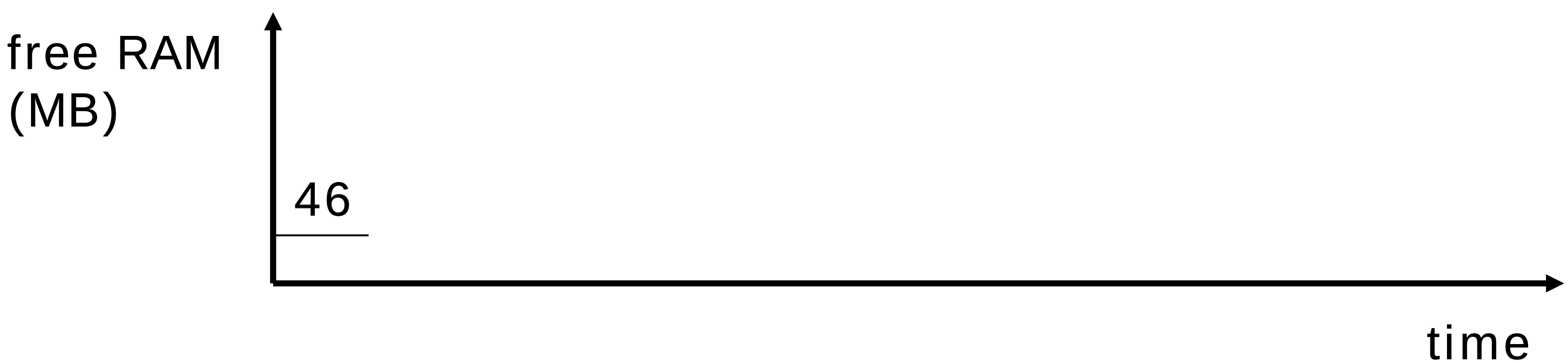
Banker's Algorithm

- ***Banker's algorithm***:
  - A thread states its maximum resource needs in advance
  - The OS allocates resource dynamically as needed. A thread waits if granting its request would lead to deadlocks
  - A request can be granted if some sequential ordering of threads is deadlock free

Example 1

- Total RAM 256 MB

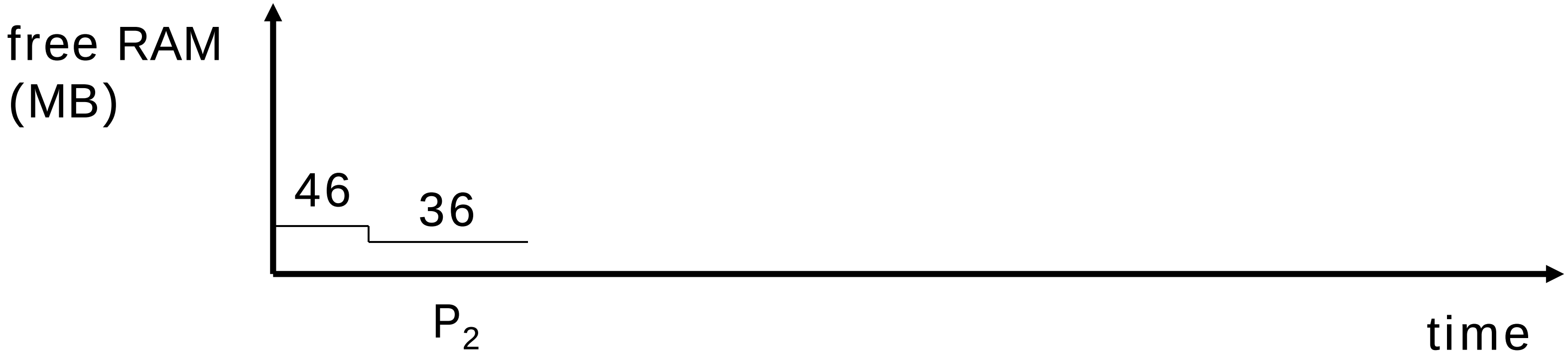
	Allocated	Still needed
P_1	80 MB	30 MB
P_2	10 MB	10 MB
P_3	120 MB	80 MB



Example 1

- Total RAM 256 MB

	Allocated	Still needed
P_1	80 MB	30 MB
P_2	20 MB	0 MB
P_3	120 MB	80 MB



Example 1

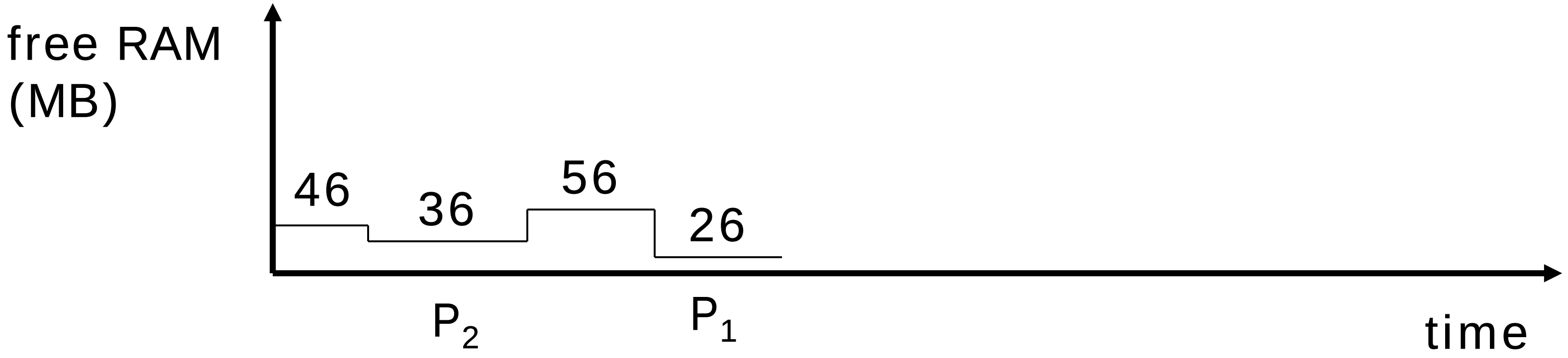
- Total RAM 256 MB

	Allocated	Still needed
P_1	80 MB	30 MB
P_2	0 MB	0 MB
P_3	120 MB	80 MB

Example 1

- Total RAM 256 MB

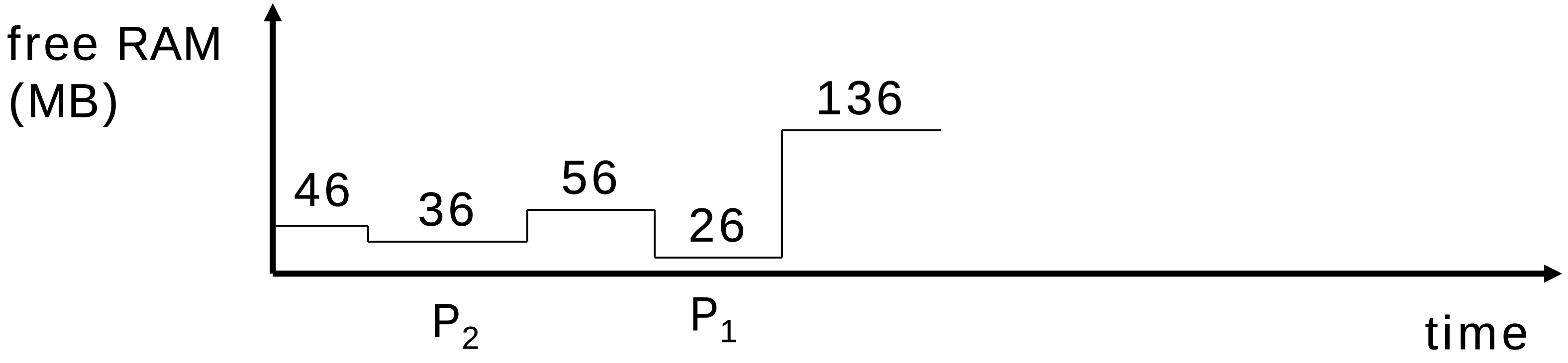
	Allocated	Still needed
P_1	110 MB	0 MB
P_2	0 MB	0 MB
P_3	120 MB	80 MB



Example 1

- Total RAM 256 MB

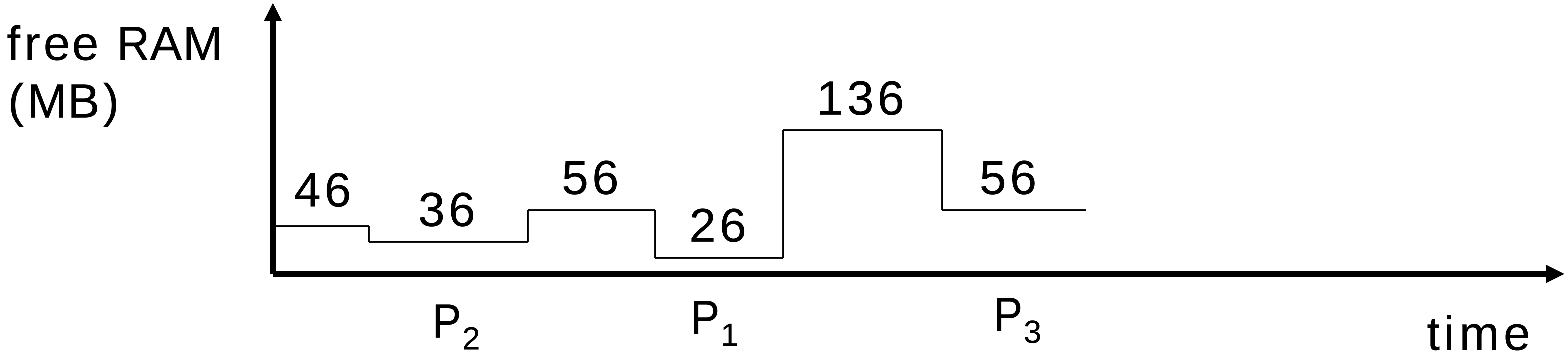
	Allocated	Still needed
P_1	0 MB	0 MB
P_2	0 MB	0 MB
P_3	120 MB	80 MB



Example 1

- Total RAM 256 MB

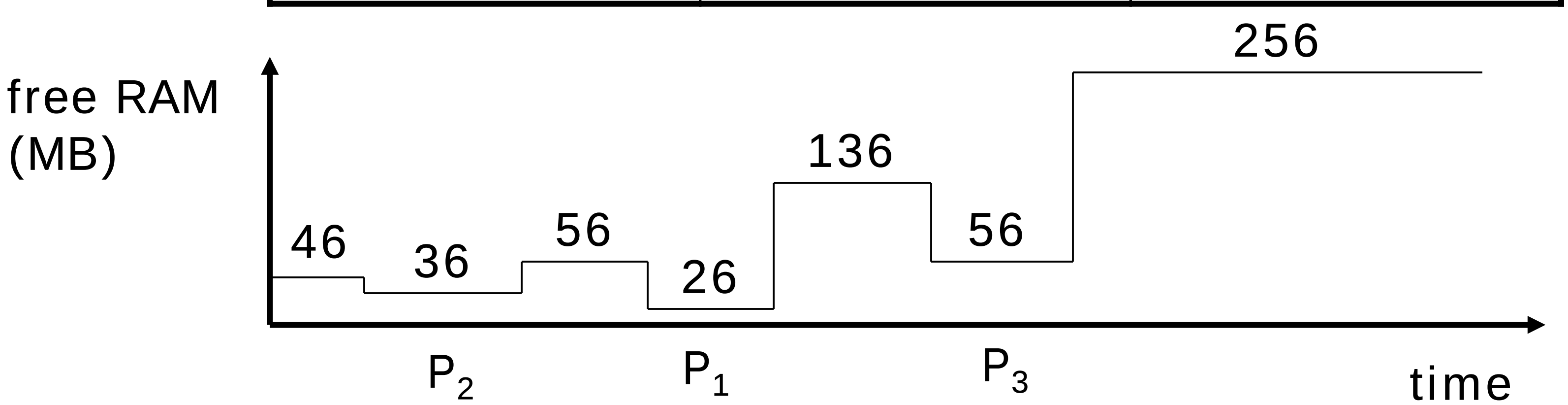
	Allocated	Still needed
P_1	0 MB	0 MB
P_2	0 MB	0 MB
P_3	200 MB	0 MB



Example 1

- Total RAM 256 MB

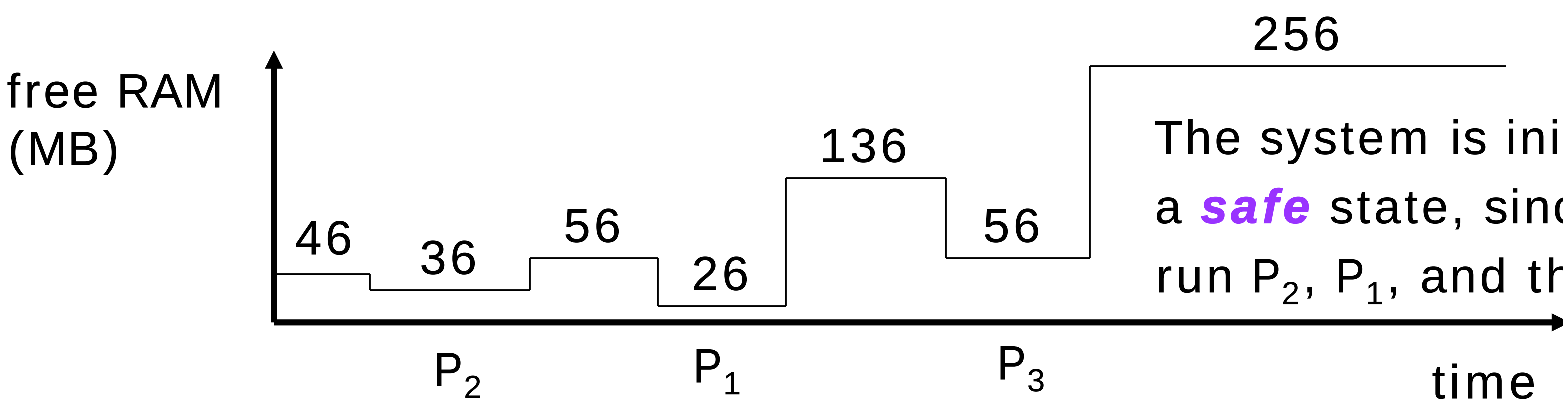
	Allocated	Still needed
P_1	0 MB	0 MB
P_2	0 MB	0 MB
P_3	0 MB	0 MB



Example 1

- Total RAM 256 MB

	Allocated	Still needed
P_1	80 MB	30 MB
P_2	10 MB	10 MB
P_3	120 MB	80 MB



The system is initially in a ***safe*** state, since we can run P_2, P_1, and then P_3

Example 2

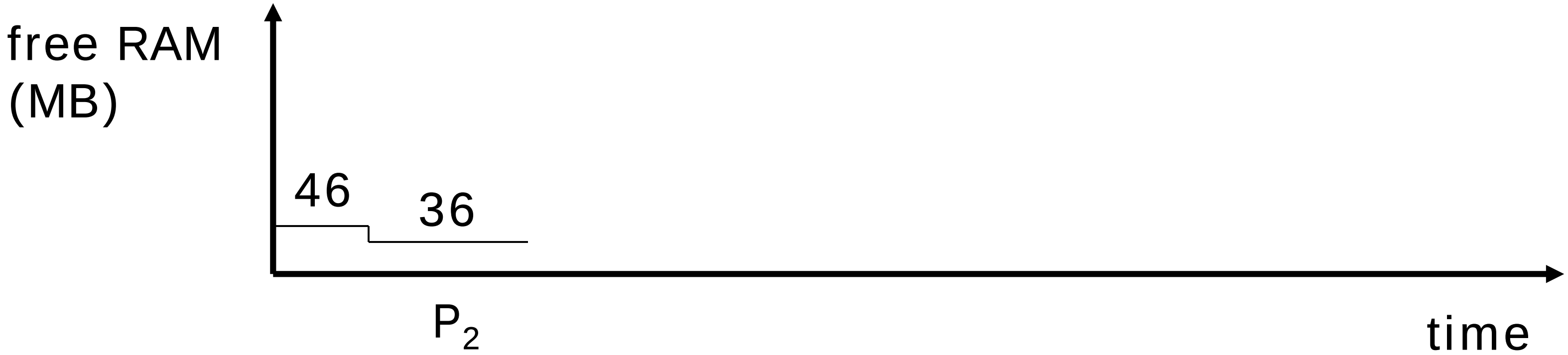
- Total RAM 256 MB

	Allocated	Still needed
P_1	80 MB	60 MB
P_2	10 MB	10 MB
P_3	120 MB	80 MB

Example 2

- Total RAM 256 MB

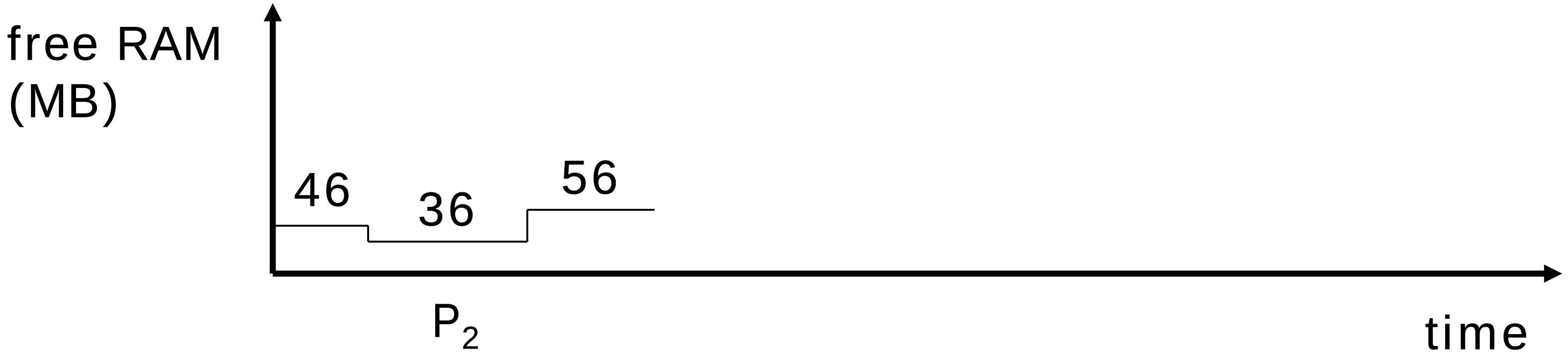
	Allocated	Still needed
P_1	80 MB	60 MB
P_2	20 MB	0 MB
P_3	120 MB	80 MB



Example 2

- Total RAM 256 MB

	Allocated	Still needed
P_1	80 MB	60 MB
P_2	0 MB	0 MB
P_3	120 MB	80 MB



Example 2

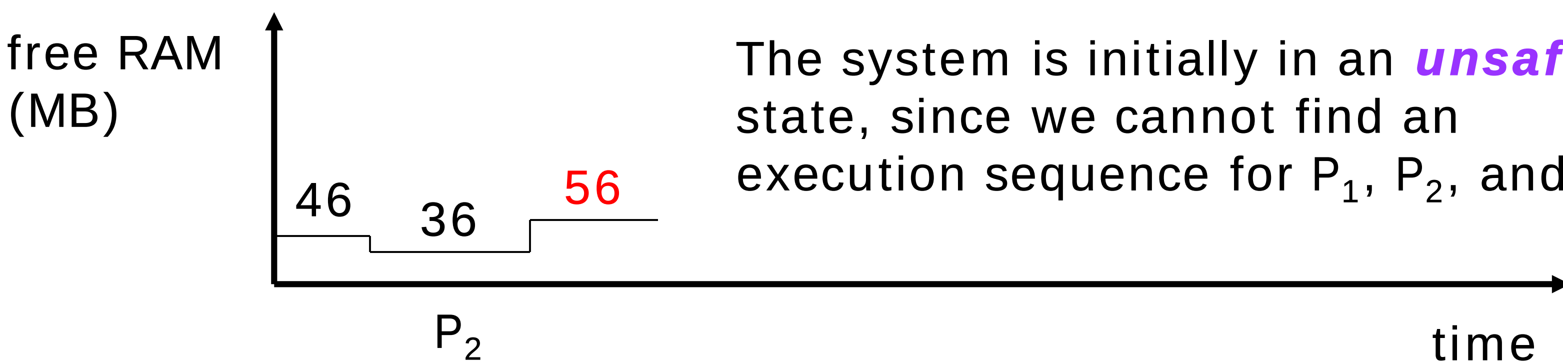
- Total RAM 256 MB

	Allocated	Still needed
P_1	80 MB	60 MB
P_2	0 MB	0 MB
P_3	120 MB	80 MB

Example 2

- Total RAM 256 MB

	Allocated	Still needed
P_1	80 MB	60 MB
P_2	10 MB	10 MB
P_3	120 MB	80 MB

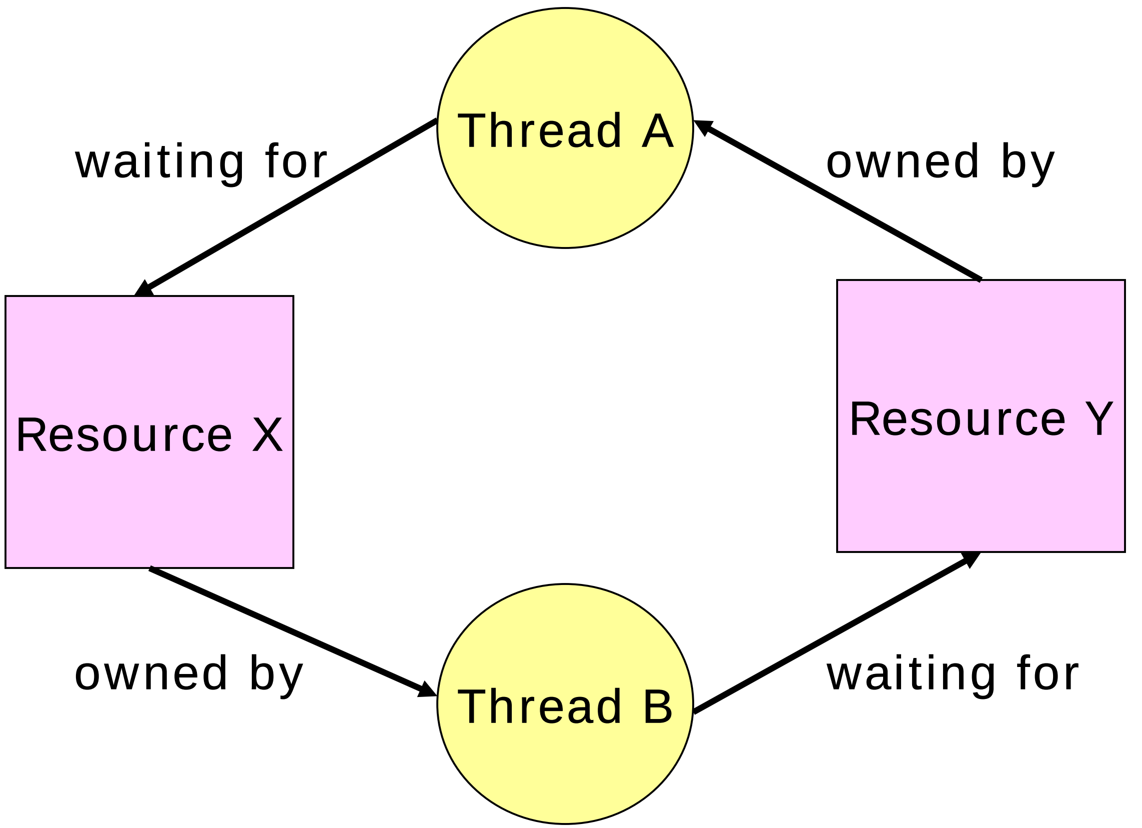


The system is initially in an ***unsafe*** state, since we cannot find an execution sequence for P_1, P_2, and P_3

Deadlock Detection and Recovery

- Scan the resource allocation graph
- Detect circular chains of requests
- Recover from the deadlock

Resource Allocation Graph



Once A Cycle is Detected…

- Some possible actions
  - Kill a thread and force it to give up resources
    - Remaining system may be in an inconsistent state
  - Rollback actions of a deadlocked thread
    - Not always possible (a file maybe half-way through modifications)
    - Need ***checkpointing***, or taking snapshots of system states from time to time