




# Operating Systems

# VII. Synchronization

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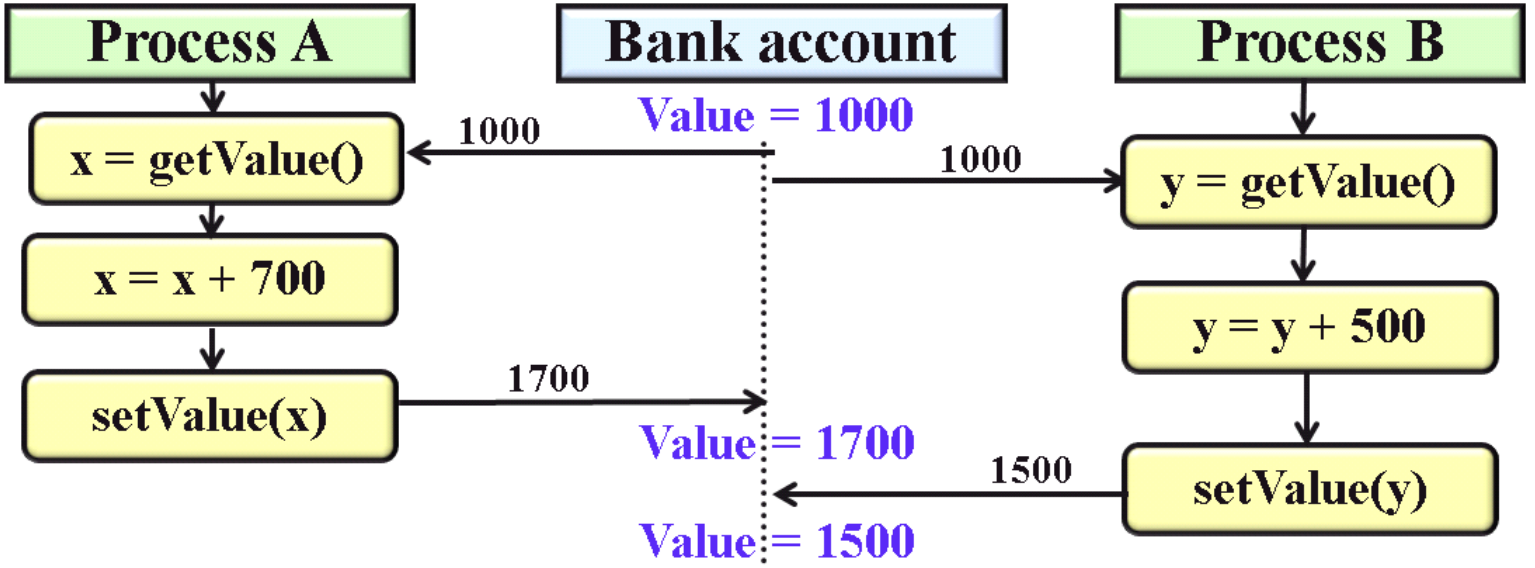
# Why is Synchronization Necessary?

- Know for a process / thread at which execution point is another process / thread
- Ensure shared data consistency

→ Where is my money?!



# Critical Sections

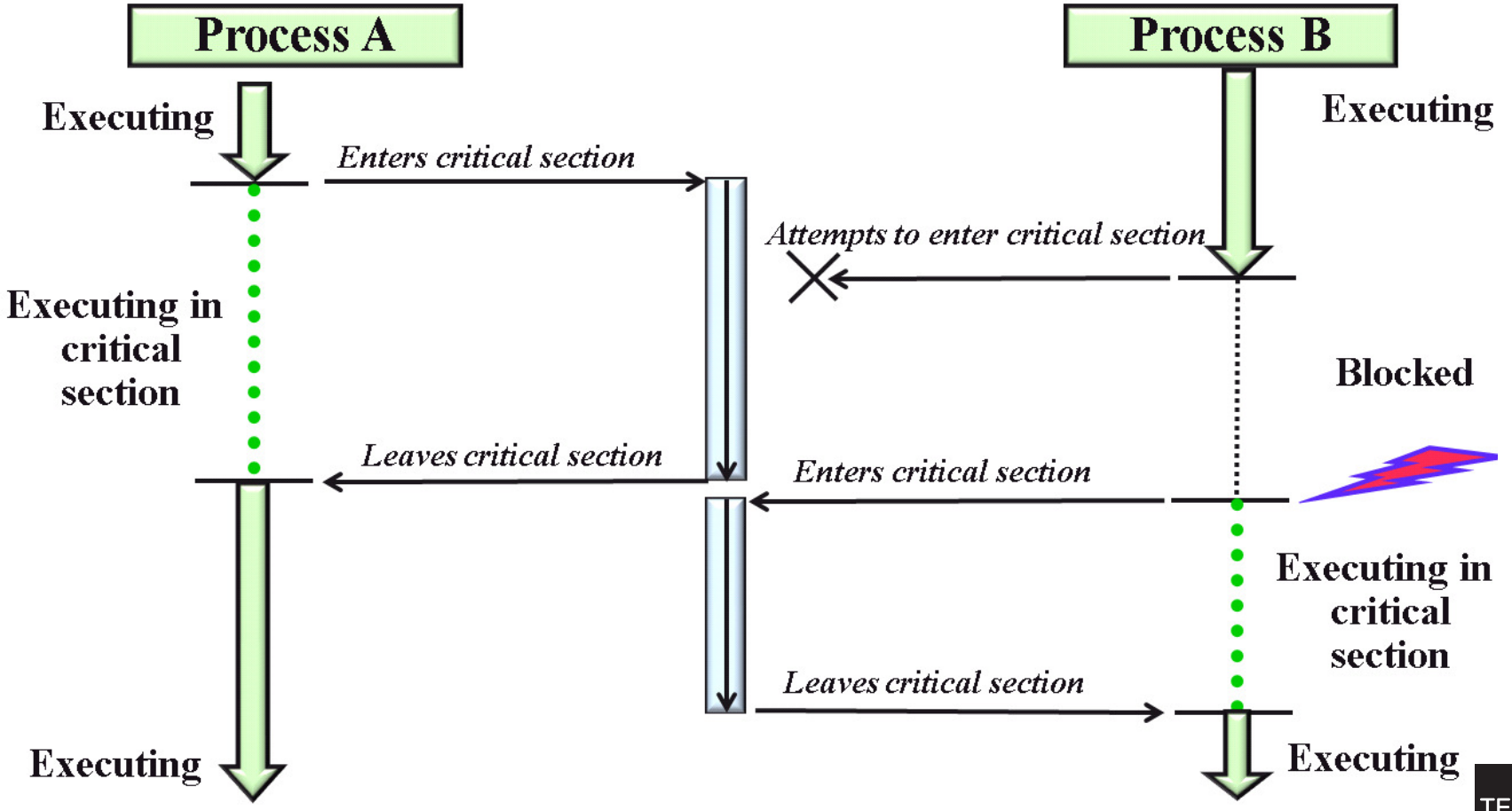
## Critical sections must satisfy the following requirements:

1. **Mutual exclusion (or safety condition)**: At most one process at a time is allowed to execute code inside a critical section of code
2. **Machine independence**: No assumptions should be made about speeds or the number of CPUs
3. **Progress**: Process running outside a critical section may not block other processes
4. **Bounded waiting (or liveness)**: Process should be guaranteed to enter a critical section within a finite time

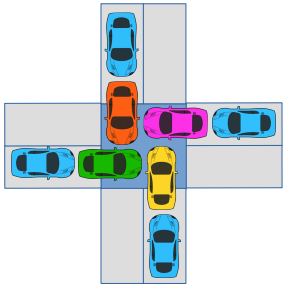
## Used for resources shared between processes / threads

Supported by many programming mechanisms

# Mutual Exclusion Using Critical Sections



# Handling Deadlocks



## Definition

- Use of shared resources: *request*, *use*, *release*
- Deadlock = situation in which a process waits for a resource that will never be available

## (i) Prevent the system to enter a deadlock state

- **Deadlock prevention**: Restraining how requests can be made
- **Deadlock avoidance**: More information from user on the use of resources

# Handling Deadlocks

(ii) Allow the system to enter a deadlock state and then recover

- **Process termination**
- **Resource preemption**

(iii) Ignore the problem (i.e., assume deadlocks never occur in the system)

- **Most OS**, including Linux

# Software Approaches

## Disabling Interrupts / Enabling interrupts

- Unwise to empower user processes to turn off interrupts!

## Lock variables

- Procedure
  - Reads the value of a shared variable
  - If 0, sets it to 1 and enters the critical section
  - If 1, waits until the variable equals to 0
- There is a major flaw related to scheduling
  - Can you guess why?

# Software Approaches (Cont.)

## Strict alternation

- Busy waiting (waste of CPU)
- Violates the progress requirement of critical-sections
  - Can you guess why?

### Process 0

```
While(TRUE){
   while(turn != 0);
   /*begin critical section */
   ...
   turn = 1;
   /* end critical section */
}
```

### Process 1

```
While(TRUE){
   while(turn != 1);
   /*begin critical section */
   ...
   turn = 0;
   /* end critical section */
}
```

# Software Approaches (Cont.)

## Dekker's and Peterson's solution

- 1965, 1981
- Alternation + lock variables

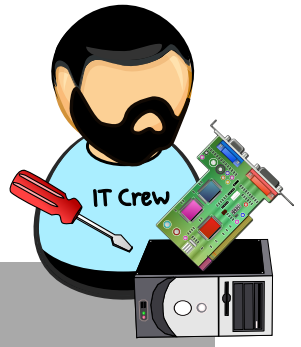
### Process 0

```
while(true) {
 flag[0] = true;
 turn = 0;
 while(flag[1] && (turn==0)) {
        // busy wait
}

 /* Critical section */
 ...
 flag[0] = false;
 /* End critical section */
}
```

### Process 1

```
while(true) {
 flag[1] = true;
 turn = 1;
 while(flag[0] && (turn==1)){
        // busy wait
}

 /* Critical section */
 ...
 flag[1] = false;
 /* End critical section */
}
```

# Hardware Approaches




## The Test and Set Lock (TSL) Instruction

- Special assembly instruction which is **atomic**
- TSL Rx, LOCK
  - Reads the content of the memory at address *lock*, stores it in register *Rx*, and sets the value at address *lock* to 1

## Assembly code to enter / leave critical sections

```
Enter_critical_section:
  TSL register, LOCK          | Copies lock to register and set lock to 1
  CMP register, #0            | Was lock equal to 0?
  JNE Enter_critical_section  | If != 0 -> lock was set -> loop
  RET                         | Enters critical section

Leave_critical_section:
  MOVE LOCK, #0               | Stores 0 in lock
  RET                         | Quits critical section
```

# Limits of Peterson's and TSL solutions

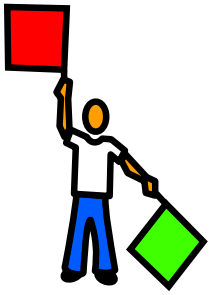
## Busy waiting & Priority inversion problem

- If a lower priority process is in critical section and a higher priority process busy waits to enter this critical section, the lower priority process never gains CPU $\rightarrow$ **Higher priority processes can never enter critical section**

## Solution: sleep/wake-up

- *Sleep()*: Caller is blocked on a given address until another process wakes it up
- *Wakeup()*: Caller wakes up all processes waiting on a given address

# Semaphores



## Definition

- A semaphore is a **counter** shared by multiple processes
- Processes can **increment** or **decrement** this counter in an atomic way
- Mainly used to protect access to shared resources
- Different APIs to use semaphores
  - IPC System V
    - *semget*(), *semclt*(), *semop*()
  - POSIX
    - *semopen*(), *sempost*(), *semwait*(), ...

# Mutex

## Definition

- Mutual Exclusion
- A *mutex* has two states: **locked**, **unlocked**
- Only one thread / process at a time can lock a mutex
- When a mutex is locked, other processes / threads block when they try to lock the same mutex:
  - Locking stops when the mutex is unlocked
  - One of the waiting process / thread succeeds in locking the mutex

# Mutex: Main Functions (*pthread* Library )

## Initialize a mutex

```
pthread_mutex_t myMutex;
pthread_mutex_init(&myMutex, NULL);
```

## Lock the mutex

- Waits for the lock

```
pthread_mutex_lock(&mymutex);
```

- Returns immediately if mutex is locked

```
pthread_mutex_trylock(&mymutex);
```

## Unlock the mutex

```
pthread_mutex_unlock(&mymutex);
```

# Condition Variables

- Used to signal a condition has changed

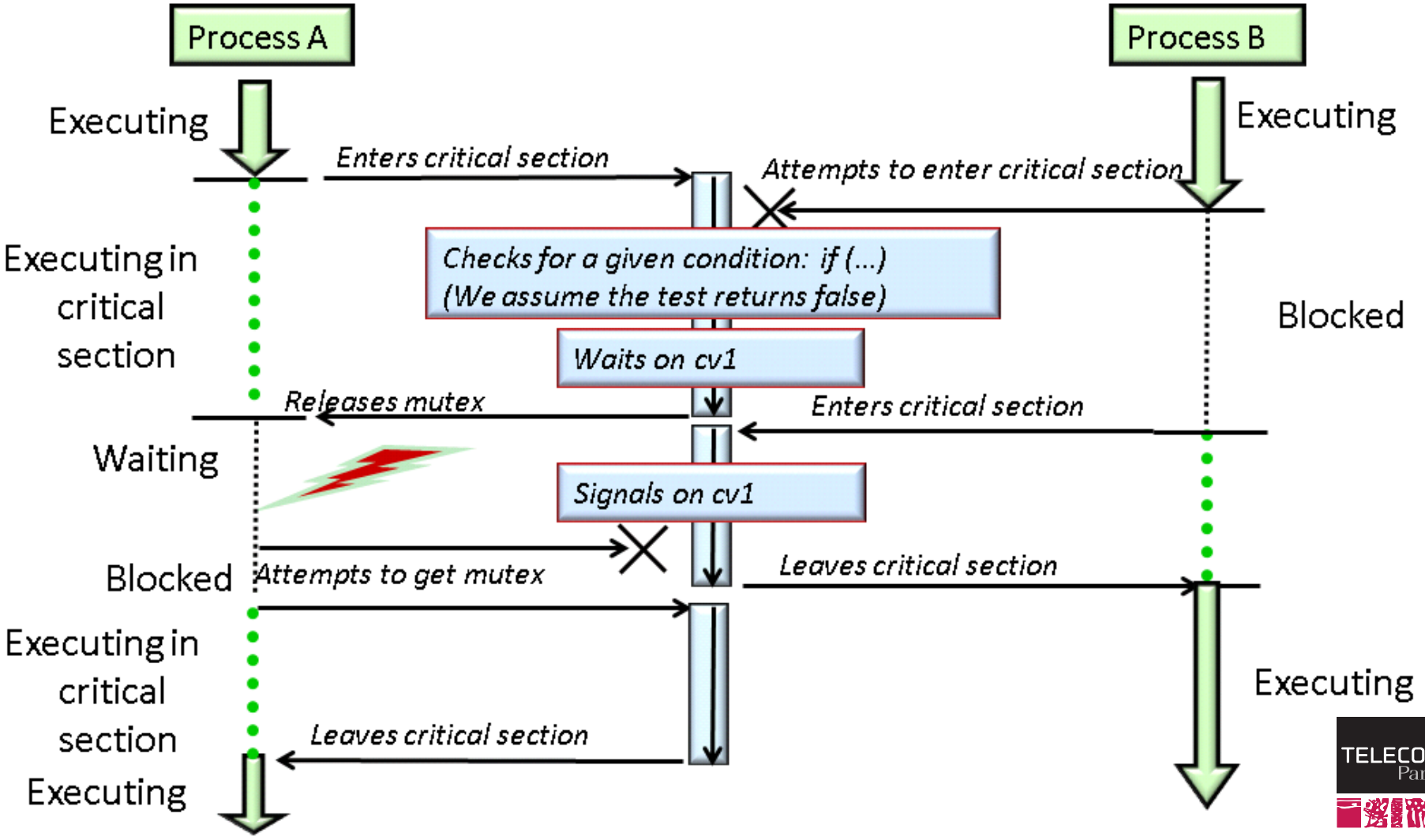
## To wait on a condition

- Put lock on mutex
- Wait on that condition → Automatic release of the lock

## To signal a change on a condition

- Put lock on mutex
- Signal that condition

# Use of Condition Variables



# Producer/Consumer Example (*pthread* lib.)

```c
#include <stdlib.h>
#include <pthread.h>

#define N_THREADS_PROD 3
#define N_THREADS_CONS 4

void *produce(void *); void produceData(int id);
void *consume(void *) ;void consumeData(int id);

int data = 0; int maxData = 5;
pthread_mutex_t myMutex;
pthread_cond_t full, empty;

int main(void) {
  int i;
  pthread_t tid_p[N_THREADS_PROD];
  pthread_t tid_c[N_THREADS_CONS];

 pthread_mutex_init(&myMutex, NULL);

  for(i=0; i<N_THREADS_PROD; i++) {pthread_create(&tid_p[i], NULL, produce, (void *)i);
  for(i=0; i<N_THREADS_CONS; i++) {pthread_create(&tid_c[i], NULL, consume, (void *)i);

  for ( i = 0; i < N_THREADS_PROD; i++) {pthread_join(tid_p[i], NULL); }
  for ( i = 0; i < N_THREADS_CONS; i++) {pthread_join(tid_c[i], NULL); }

 return (0);
}
```

# Producer/Consumer Example (Cont.)

```
void *produce(void *arg) {
  int myId = (int)arg;
  while(1) {
    produceData(myId);
    sleep(random() % 5);
  }
}

void *consume(void *arg) {
  int myId = (int)arg;
  while(1) {
    consumeData(myId);
    sleep(random() % 5);
  }
}
```

# Producer/Consumer Example (Cont.)

```
void produceData(int id) {
  pthread_mutex_lock(&myMutex);
  if (data == maxData) {
    printf("#%d is waiting for less data; data = %d\n", id, data);
    pthread_cond_wait(&full, &myMutex);
  }
  data ++;
  printf("#%d is producing data; data = %d\n", id, data);
  pthread_cond_signal(&empty);
  pthread_mutex_unlock(&myMutex);
}

void consumeData(int id){
  pthread_mutex_lock(&myMutex);
  if (data == 0) {
    printf("#%d is waiting for more data; data = %d\n", id, data);
    pthread_cond_wait(&empty, &myMutex);
  }
  data--;
  printf("#%d is consuming data; data = %d\n", id, data);
  pthread_cond_signal(&full);
  pthread_mutex_unlock(&myMutex);
}
```

# Producer/Consumer Example: Execution

```
$ gcc -lpthread -o prod prodcons.c
$ ./prod
#1 is producing data; data = 1
#2 is consuming data; data = 0
#0 is waiting for more data; data = 0
#0 is producing data; data = 1
#0 is consuming data; data = 0
#3 is waiting for more data; data = 0
#2 is producing data; data = 1
#3 is consuming data; data = 0
#1 is waiting for more data; data = 0
#0 is waiting for more data; data = 0
#3 is waiting for more data; data = 0
#2 is waiting for more data; data = 0
#0 is producing data; data = 1
#1 is consuming data; data = 0
#1 is producing data; data = 1
#0 is consuming data; data = 0
#2 is producing data; data = 1
#3 is consuming data; data = 0
#0 is producing data; data = 1
#2 is consuming data; data = 0
#0 is producing data; data = 1
#0 is consuming data; data = 0
#1 is waiting for more data; data = 0
#3 is waiting for more data; data = 0
#2 is producing data; data = 1
#0 is consuming data; data = 0
#1 is consuming data; data = -1
#2 is producing data; data = 0
#3 is consuming data; data = -1
#0 is producing data; data = 0
#0 is waiting for more data; data = 0
...
```

So, the code is wrong! Where???

# Producer/Consumer Example (Updated)

```
void produceData(int id) {
  pthread_mutex_lock(&myMutex);
  while (data == maxData) {
    printf("#%d is waiting for less data; data = %d\n", id, data);
    pthread_cond_wait(&full, &myMutex);
  }
  data ++;
  printf("#%d is producing data; data = %d\n", id, data);
  pthread_cond_signal(&empty);
  pthread_mutex_unlock(&myMutex);
}

void consumeData(int id){
  pthread_mutex_lock(&myMutex);
  while (data == 0) {
    printf("#%d is waiting for more data; data = %d\n", id, data);
    pthread_cond_wait(&empty, &myMutex);
  }
  data--;
  printf("#%d is consuming data; data = %d\n", id, data);
  pthread_cond_signal(&full);
  pthread_mutex_unlock(&myMutex);
}
```

# Producer/Consumer Example: Execution (Updated)

```
$gcc -lpthread -o prod prodcons.c
$prod
#3 is waiting for more data; data = 0
#1 is waiting for more data; data = 0
#2 is producing data; data = 1
#2 is producing data; data = 2
#0 is consuming data; data = 1
#2 is consuming data; data = 0
#2 is waiting for more data; data = 0
#3 is waiting for more data; data = 0
#0 is producing data; data = 1
#1 is consuming data; data = 0
#2 is producing data; data = 1
#2 is consuming data; data = 0
#1 is producing data; data = 1
#3 is consuming data; data = 0
#0 is waiting for more data; data = 0
#2 is waiting for more data; data = 0
#0 is producing data; data = 1
#0 is consuming data; data = 0
#0 is waiting for more data; data = 0
#3 is waiting for more data; data = 0
#1 is waiting for more data; data = 0
#2 is producing data; data = 1
#2 is producing data; data = 2
#2 is consuming data; data = 1
#0 is consuming data; data = 0
#1 is producing data; data = 1
#3 is consuming data; data = 0
#2 is producing data; data = 1
#2 is producing data; data = 2
#1 is consuming data; data = 1
#0 is producing data; data = 2
#0 is producing data; data = 3
#2 is consuming data; data = 2
#2 is producing data; data = 3
#2 is producing data; data = 4
#1 is producing data; data = 5
#0 is consuming data; data = 4
#1 is consuming data; data = 3
#3 is consuming data; data = 2
#1 is producing data; data = 3
#1 is producing data; data = 4
#0 is producing data; data = 5
#0 is waiting for less data; data = 5
#2 is consuming data; data = 4
#0 is producing data; data = 5
#1 is consuming data; data = 4
#2 is producing data; data = 5
#0 is consuming data; data = 4
#1 is producing data; data = 5
#0 is waiting for less data; data = 5
#2 is waiting for less data; data = 5
#3 is consuming data; data = 4
...
```