Race Conditions: A Case Study

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What is a *Race Condition*?

- When ***two or more*** **processes/threads access a** ***shared*** **data item, the computed result depends on the order of execution.**
- **There are three elements here:**
  - ☐ **Multiple processes/threads**
  - ☐ **Shared data items**
  - ☐ **Results may be different if the execution order is altered**

A Very Simple Example

Current value of `Count` is 10

Process #1	Process #2
`Count++;`	`Count--;`

`LOAD  Count`
`ADD   #1`
`STORE Count`
	`LOAD  Count`
	`SUB   #1`
	`STORE Count`

We have no way to determine what the value `Count` may have.

Why is *Race Condition* so *Difficult* to Catch?

- *Statically* detecting race conditions in a program using multiple semaphores is NP-complete.
- Thus, no efficient algorithms are available. We have to use our debugging skills.
- It is virtually impossible to catch race conditions *dynamically* because the hardware must examine *every* memory access.

How about our students?

- **Normally, they do not realize/believe their programs do have race conditions.**
- **They claim their programs work, *because their programs respond to input data properly*.**
- **It takes time to convince them, because we have to trace their programs carefully.**
- **So, we developed a series of examples to teach students how to catch race conditions.**

Problem Statement

- **Two groups, A and B, of threads *exchange messages*.**
- **Each thread in A runs a function `T_A()`, and each thread in B runs a function `T_B()`.**
- **Both `T_A()` and `T_B()` have an infinite loop and never stop.**

Threads in group A

```
T_A()
{
  while (1) {
    // do something
    Ex. Message
    // do something
  }
}
```

Threads in group B

```
T_B()
{
  while (1) {
    // do something
    Ex. Message
    // do something
  }
}
```

What is *Exchange Message*?

- **When an instance A makes a message available, it can continue only if it receives a message from an instance of B who has successfully retrieves A’s message.**
- **Similarly, when an instance B makes a message available, it can continue only if it receives a message from an instance of A who has successfully retrieves B’s message.**
- ***How about exchanging business cards?***

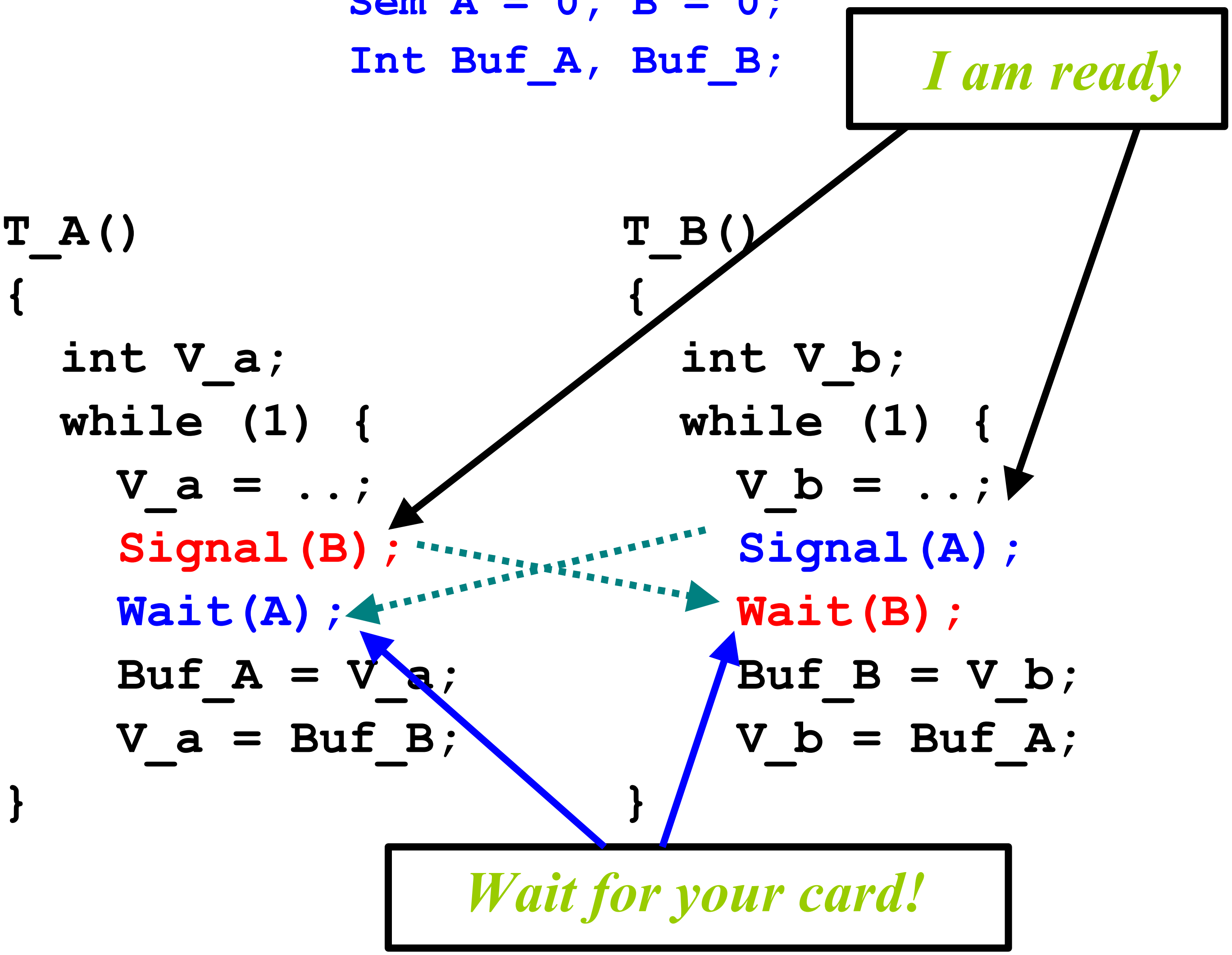
Watch for Race Conditions

- Suppose thread A_1 presents its message for B to retrieve. If A_2 comes for message exchange before B retrieves A_1's, will A_2's message overwrites A_1's?
- Suppose B has already retrieved A_1's message. Is it possible that when B presents its message, A_2 picks it up rather than A_1?
- Thus, the messages between A and B must be well-protected to avoid race conditions.

Students’ Work

- This problem and its variations were used as programming assignments, exam problems, and so on.
- A significant number of students successfully solve this problem.
- The next few slides show how students made mistakes .

First Attempt



```
Sem A = 0, B = 0;
Int Buf_A, Buf_B;
```

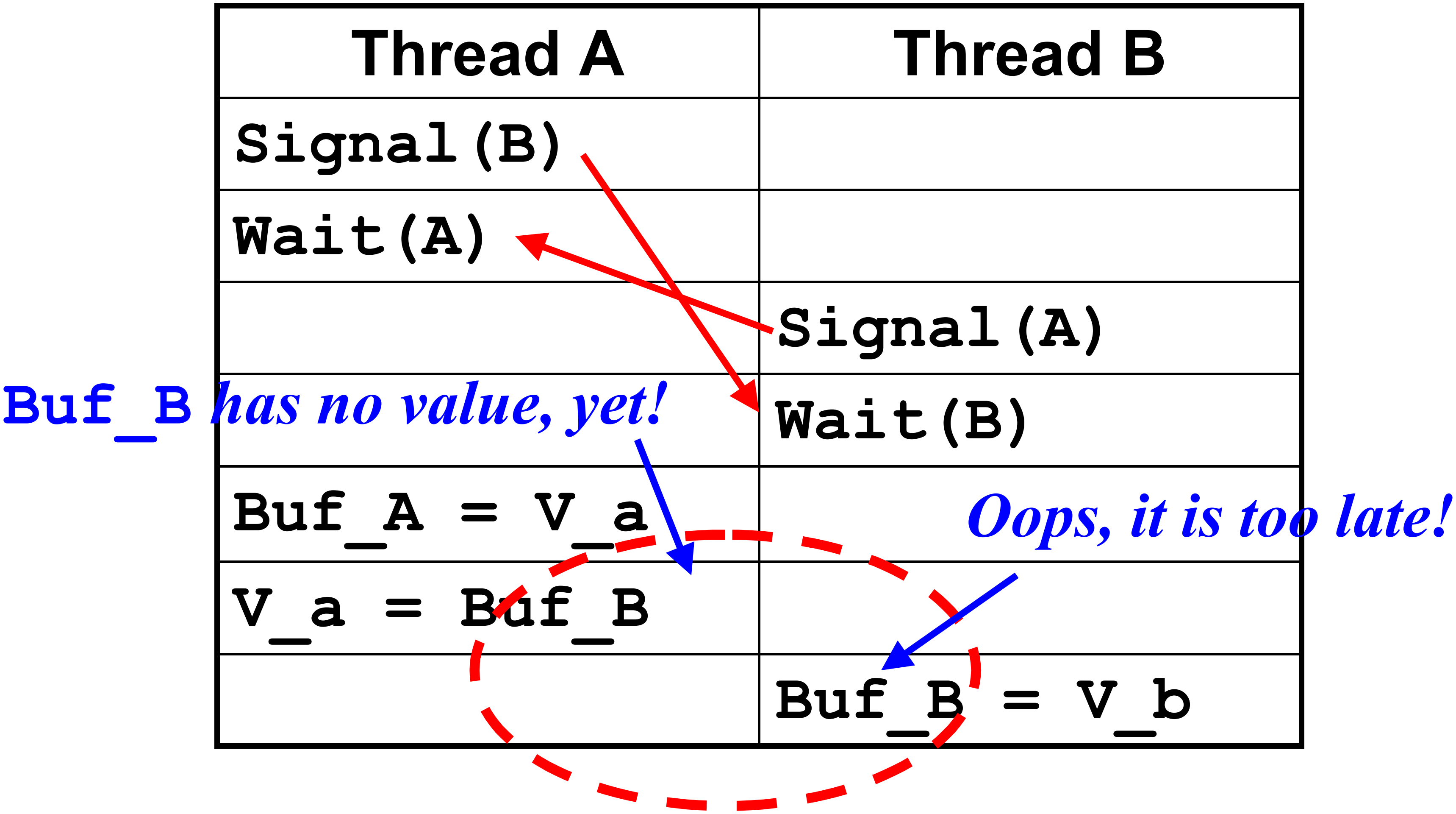
```
T_A()
{
  int V_a;
  while (1) {
    V_a = ..;
    Signal(B);
    Wait(A);
    Buf_A = V_a;
    V_a = Buf_B;
}
```

```
T_B()
{
  int V_b;
  while (1) {
    V_b = ..;
    Signal(A);
    Wait(B);
    Buf_B = V_b;
    V_b = Buf_A;
}
```

I am ready

Wait for your card!

First Attempt: Problem (a)

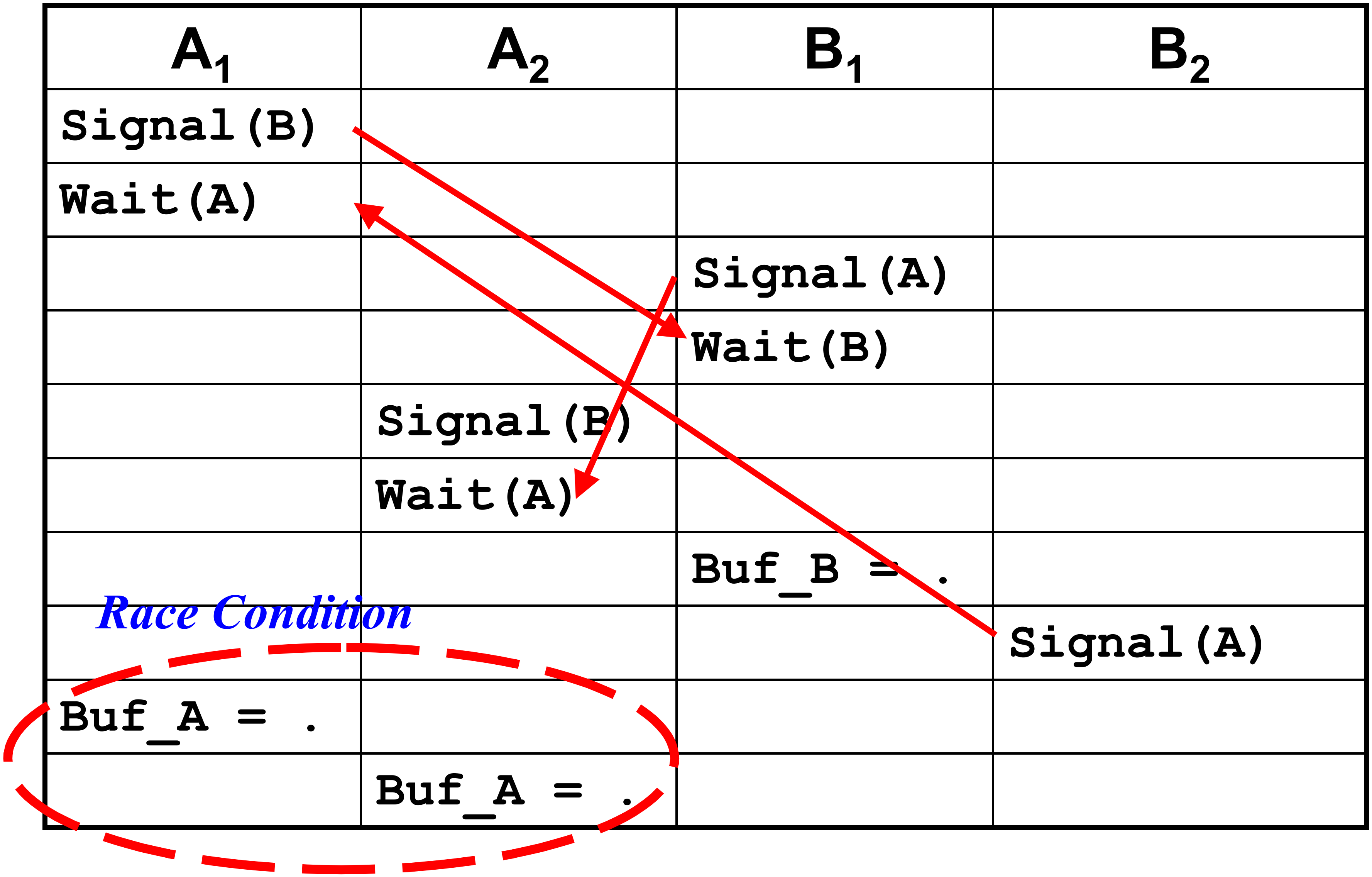


Thread A	Thread B
`Signal(B)`	
`Wait(A)`	
	`Signal(A)`
	`Wait(B)`
`Buf_A = V_a`	
`V_a = Buf_B`	
	`Buf_B = V_b`

`Buf_B` *has no value, yet!*

Oops, it is too late!

First Attempt: Problem (b)



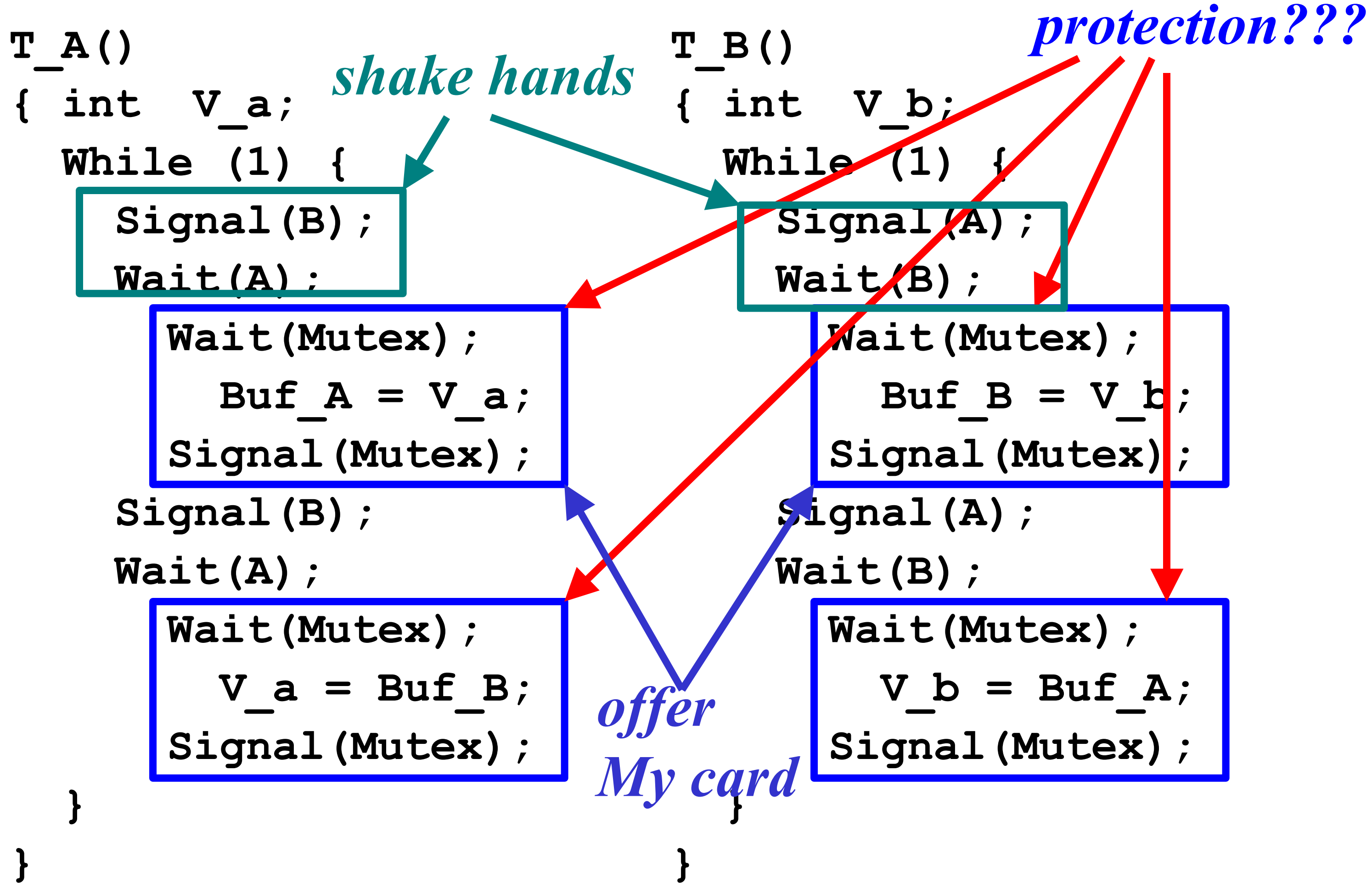
A_1	A_2	B_1	B_2
`Signal(B)`			
`Wait(A)`			
		`Signal(A)`	
		`Wait(B)`	
	`Signal(B)`		
	`Wait(A)`		
		`Buf_B = .`	
			`Signal(A)`
`Buf_A = .`			
	`Buf_A = .`		

What did we learn?

- **If there are shared data items, always protect them properly. Without a proper mutual exclusion, race conditions are likely to occur.**
- **In this first attempt, both global variables `Buf_A` and `Buf_B` are shared and should be protected.**

Second Attempt

```
Sem   A = B = 0;
Sem   Mutex = 1;
Int   Buf_A, Buf_B;
```



```
T_A()
{ int  V_a;
  While (1) {
    Signal(B);
    Wait(A);
     Wait(Mutex);
       Buf_A = V_a;
     Signal(Mutex);
    Signal(B);
    Wait(A);
     Wait(Mutex);
       V_a = Buf_B;
     Signal(Mutex);
  }
}
```

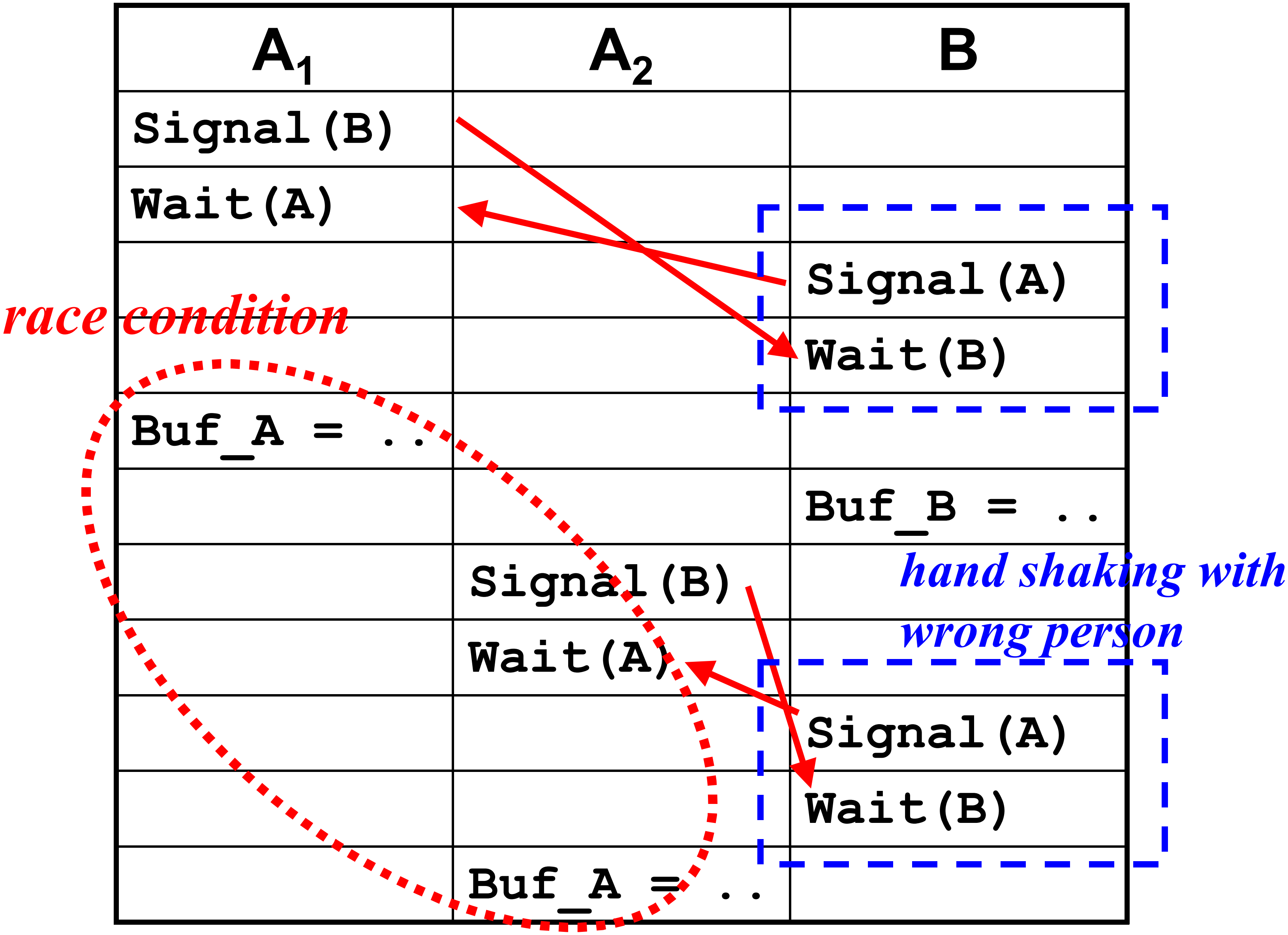
```
T_B()
{ int  V_b;
  While (1) {
    Signal(A);
    Wait(B);
     Wait(Mutex);
       Buf_B = V_b;
     Signal(Mutex);
    Signal(A);
    Wait(B);
     Wait(Mutex);
       V_b = Buf_A;
     Signal(Mutex);
  }
}
```

shake hands

protection???

offer
My card

Second Attempt: Problem



A_1	A_2	B
`Signal(B)`		
`Wait(A)`		
		`Signal(A)`
		`Wait(B)`
`Buf_A = ..`		
		`Buf_B = ..`
	`Signal(B)`	
	`Wait(A)`	
		`Signal(A)`
		`Wait(B)`
	`Buf_A = ..`	

race condition

hand shaking with wrong person

What did we learn?

- **Improper protection is no better than no protection, because we have an *illusion* that data are well-protected.**
- **We frequently forgot that protection is done by a critical section, which *cannot be divided*.**
- **Thus, protecting "here is my card" followed by "may I have yours" separately is unwise.**

Third Attempt

```
Sem Aready = Bready = 1;
Sem Adone = Bdone = 0;
Int Buf_A, Buf_B;
```

ready to proceed

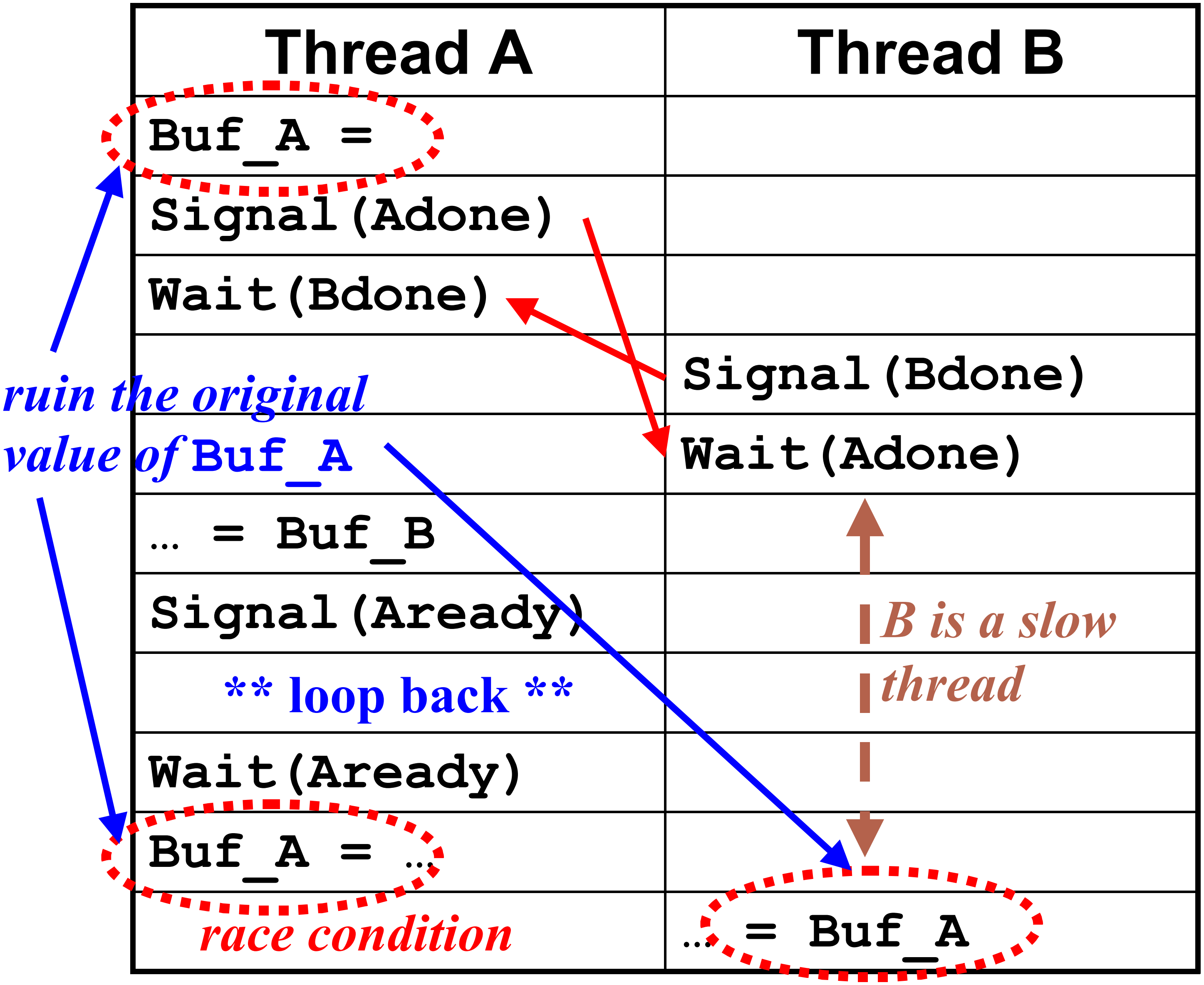
job done

```
T_A()
{ int V_a;
  while (1) {
    Wait(Aready);
      Buf_A = ..;
      Signal(Adone);
      Wait(Bdone);
      V_a = Buf_B;
    Signal(Aready);
  }
}
```

here is my card let me have yours

```
T_B()
{ int V_b;
  while (1) {
    Wait(Bready);
      Buf_B = ..;
      Signal(Bdone);
      Wait(Adone);
      V_b = Buf_A;
    Signal(Bready);
  }
}
```

Third Attempt: Problem



Thread A	Thread B
`Buf_A =`	
`Signal(Adone)`	
`Wait(Bdone)`	
	`Signal(Bdone)`
	`Wait(Adone)`
`… = Buf_B`	
`Signal(Aready)`	
** loop back **	
`Wait(Aready)`	
`Buf_A = …`	
race condition	`… = Buf_A`

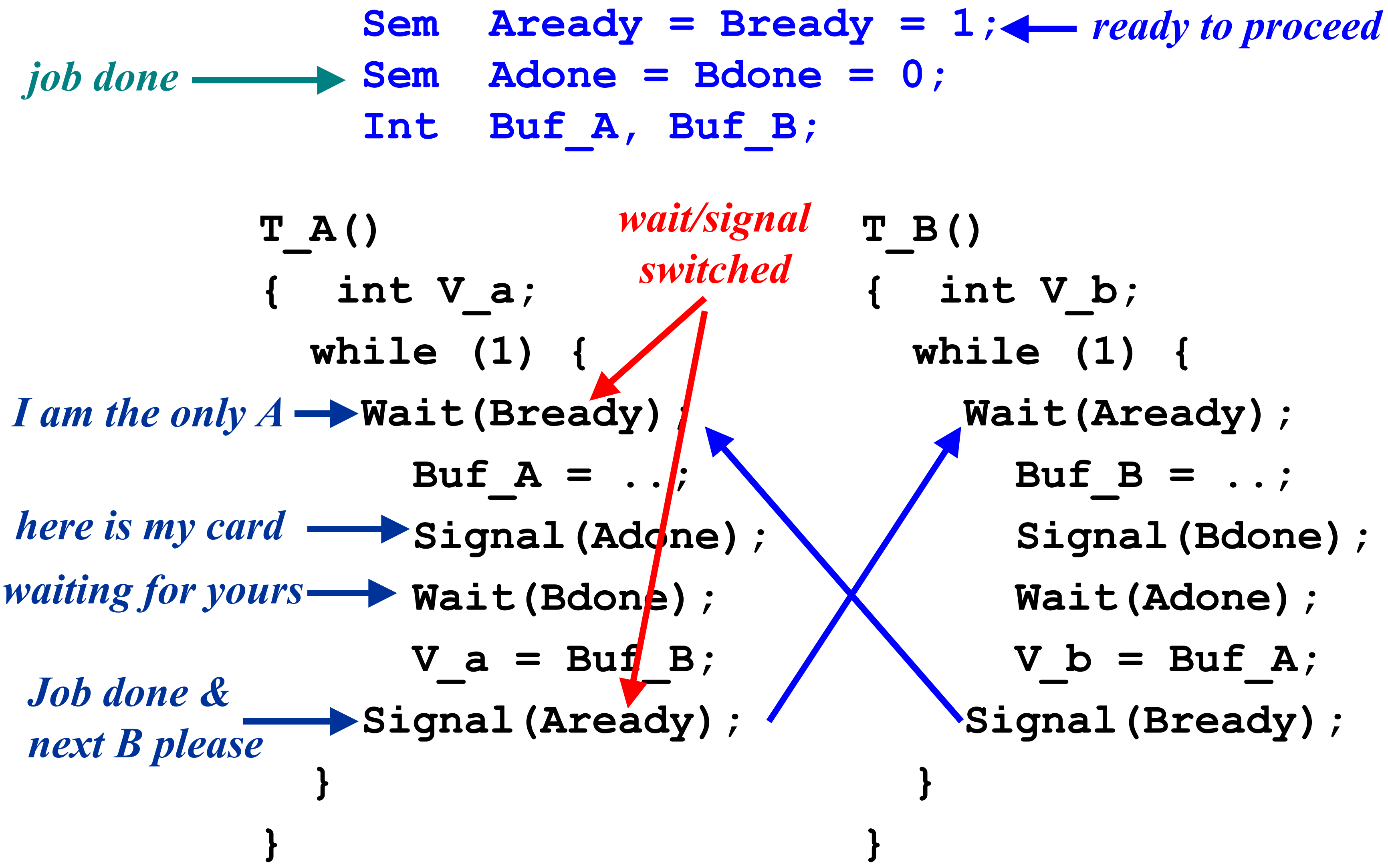
ruin the original value of `Buf_A`

B is a slow thread

What did we learn?

- **Mutual exclusion for one group may not prevent threads in other groups from interacting with a thread in the group.**
- **It is common that a student protects a shared item for one group and forgets other possible, unintended accesses.**
- **Protection must apply *uniformly* to all threads rather than within groups.**

Fourth Attempt



```
Sem  Aready = Bready = 1;
Sem  Adone = Bdone = 0;
Int  Buf_A, Buf_B;
```

ready to proceed

job done

wait/signal switched

```
T_A()
{  int V_a;
   while (1) {
     Wait(Bready);
       Buf_A = ..;
       Signal(Adone);
       Wait(Bdone);
       V_a = Buf_B;
     Signal(Aready);
   }
}
```

```
T_B()
{  int V_b;
   while (1) {
     Wait(Aready);
       Buf_B = ..;
       Signal(Bdone);
       Wait(Adone);
       V_b = Buf_A;
     Signal(Bready);
   }
}
```

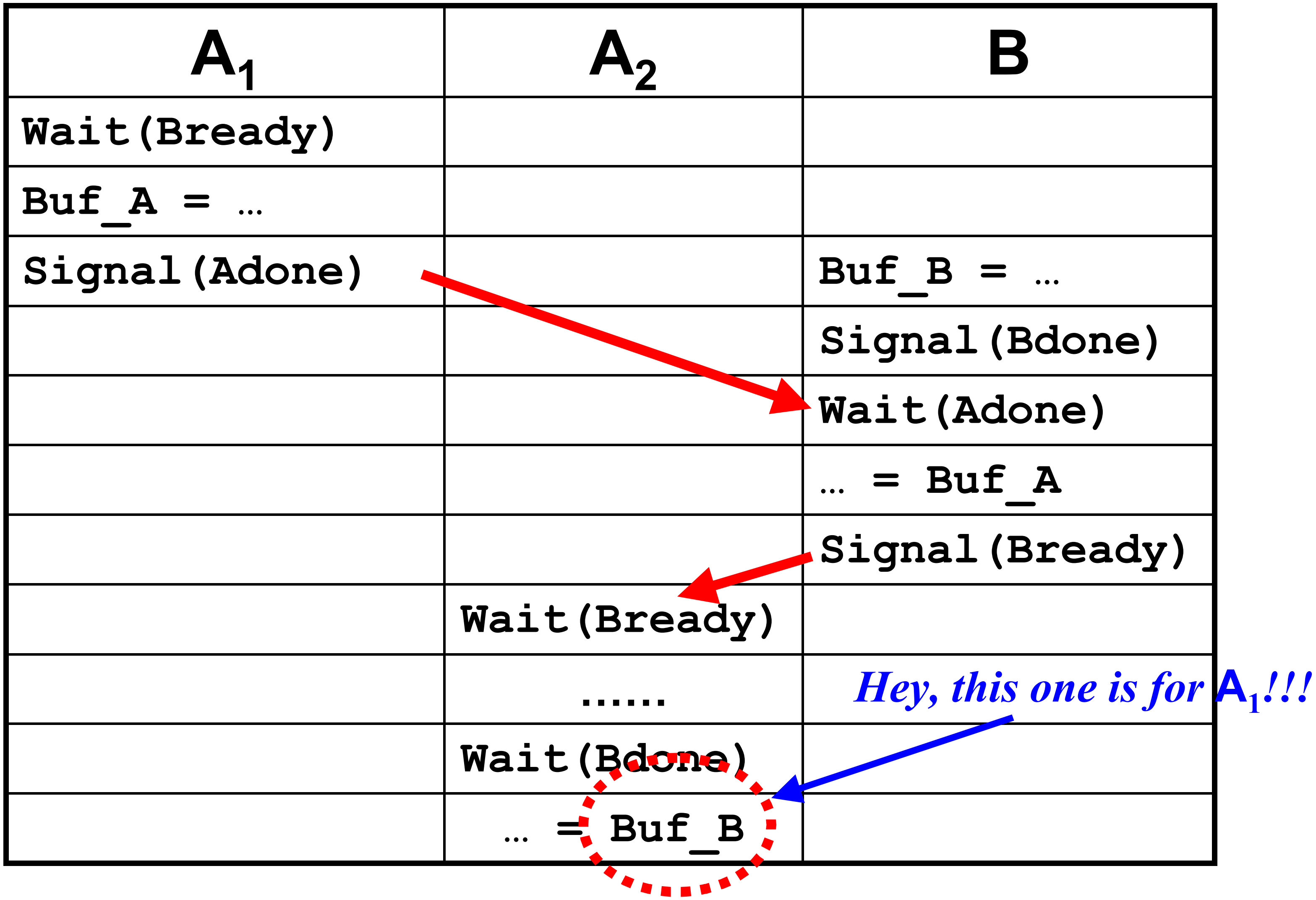
I am the only A

here is my card

waiting for yours

Job done & next B please

Fourth Attempt: Problem



A_1	A_2	B
`Wait(Bready)`		
`Buf_A = …`		
`Signal(Adone)`		`Buf_B = …`
		`Signal(Bdone)`
		`Wait(Adone)`
		`… = Buf_A`
		`Signal(Bready)`
	`Wait(Bready)`	
	`……`	
	`Wait(Bdone)`	
	`… = Buf_B`	

Hey, this one is for **A_1***!!!*

What did we learn?

- **We use locks for mutual exclusion.**
- **The owner, the one who locked the lock, should unlock the lock.**
- **In the above "solution," `Aready` is acquired by a thread A but released by a thread B. This is risky!**
- **In this case, a pure lock is more natural than a binary semaphore.**

A Good Attempt

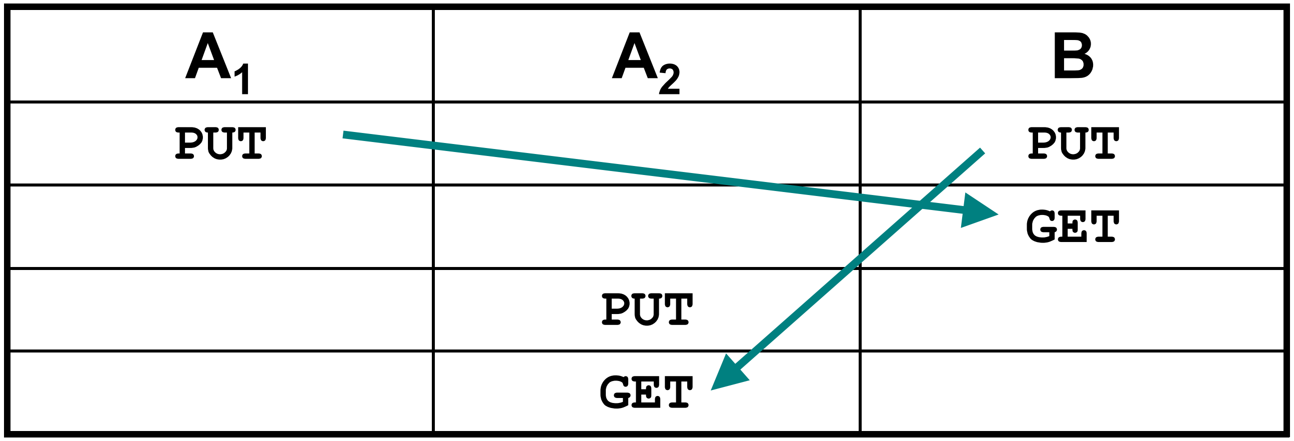
How about the use of a bounded buffer?

```
int Buf_A, Buf_B;
```

Buffer variables

```
T_A()
{  int  V_a;
    while (1) {
    PUT(V_a, Buf_A);
    GET(V_a, Buf_B);
  }
}
```

```
T_B()
{  int  V_b;
    while (1) {
    PUT(V_b, Buf_B);
    GET(V_b, Buf_A);
  }
}
```



A_1	A_2	B
PUT		PUT
		GET
	PUT	
	GET	

A Good Attempt

Protection still makes sense

```
Sem Mutex = 1;
int Buf_A, Buf_B;
```

```
T_A()
{  int  V_a;
   while (1) {
      Wait(Mutex);
        PUT(V_a, Buf_A);
        GET(V_a, Buf_B);
      Signal(Mutex);
   }
}
```

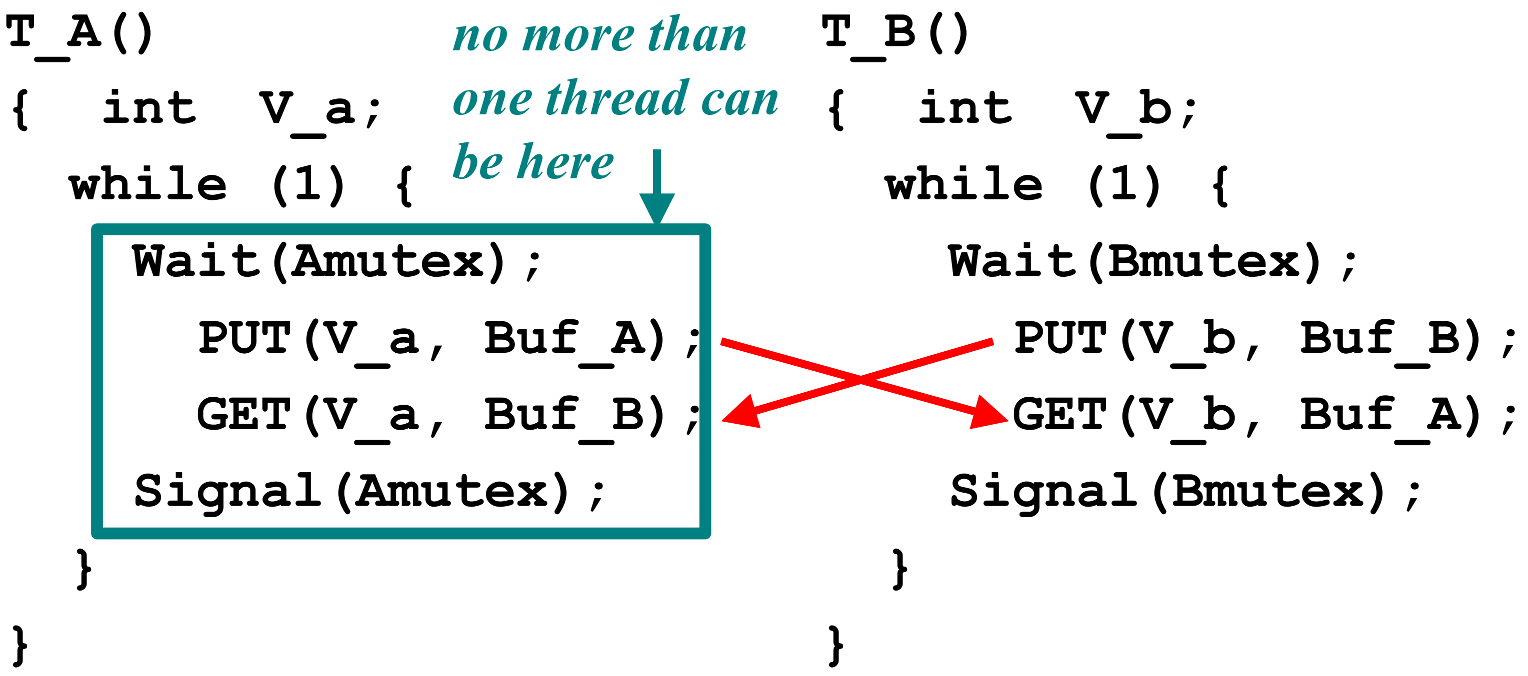
```
T_B()
{  int  V_b;
   while (1) {
      Wait(Mutex);
        PUT(V_b, Buf_B);
        GET(V_b, Buf_A);
      Signal(Mutex);
   }
}
```

critical sections

System will lock up when A or B enters its critical section.

A Good Attempt: Make It Right

```
Sem Amutex = Bmutex = 1;
int Buf_A, Buf_B;
```



no more than one thread can be here

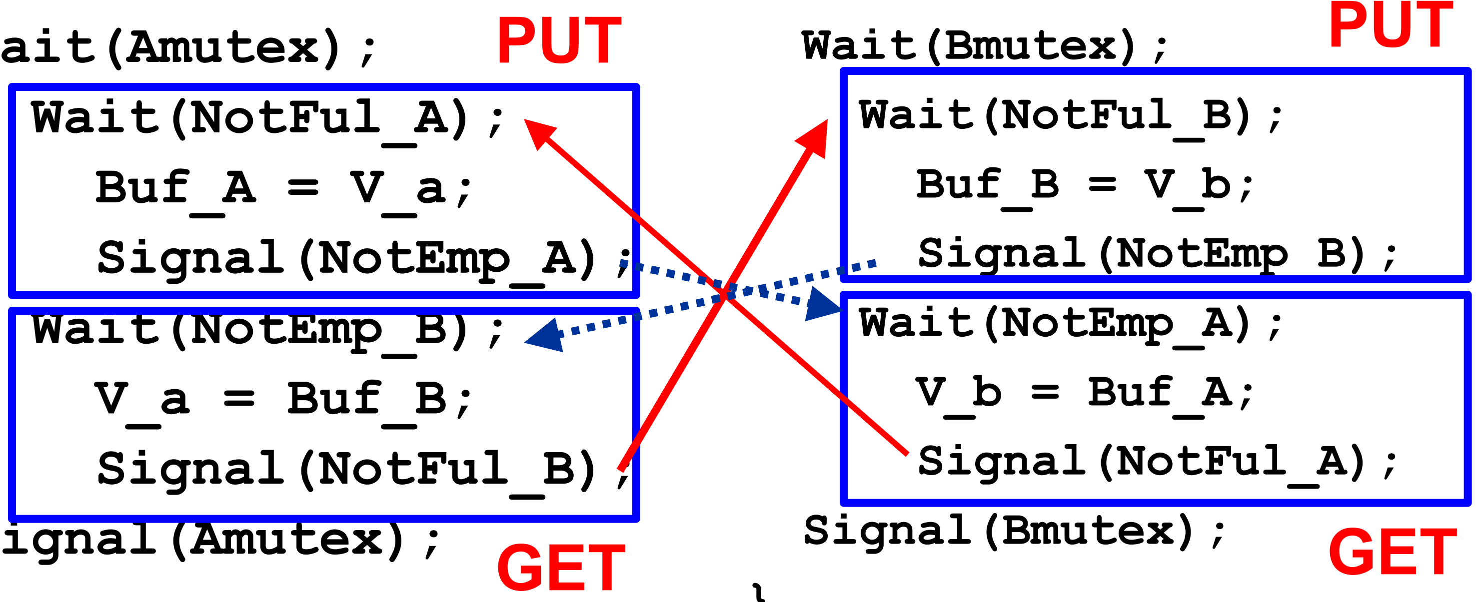
```
T_A()
{  int  V_a;
   while (1) {
     Wait(Amutex);
       PUT(V_a, Buf_A);
       GET(V_a, Buf_B);
     Signal(Amutex);
   }
}
```

```
T_B()
{  int  V_b;
   while (1) {
     Wait(Bmutex);
       PUT(V_b, Buf_B);
       GET(V_b, Buf_A);
     Signal(Bmutex);
   }
}
```

This solution works, even though each group has Its own *protection*. The PUT and GET make a difference.

A Good Attempt: Symmetric

```
Sem Amutex = Bmutex = 1;
Sem NotFul_A=NotFul_B=1; Sem NotEmp_A=NotEmp_B=0;
int Buf_A, Buf_B;
```

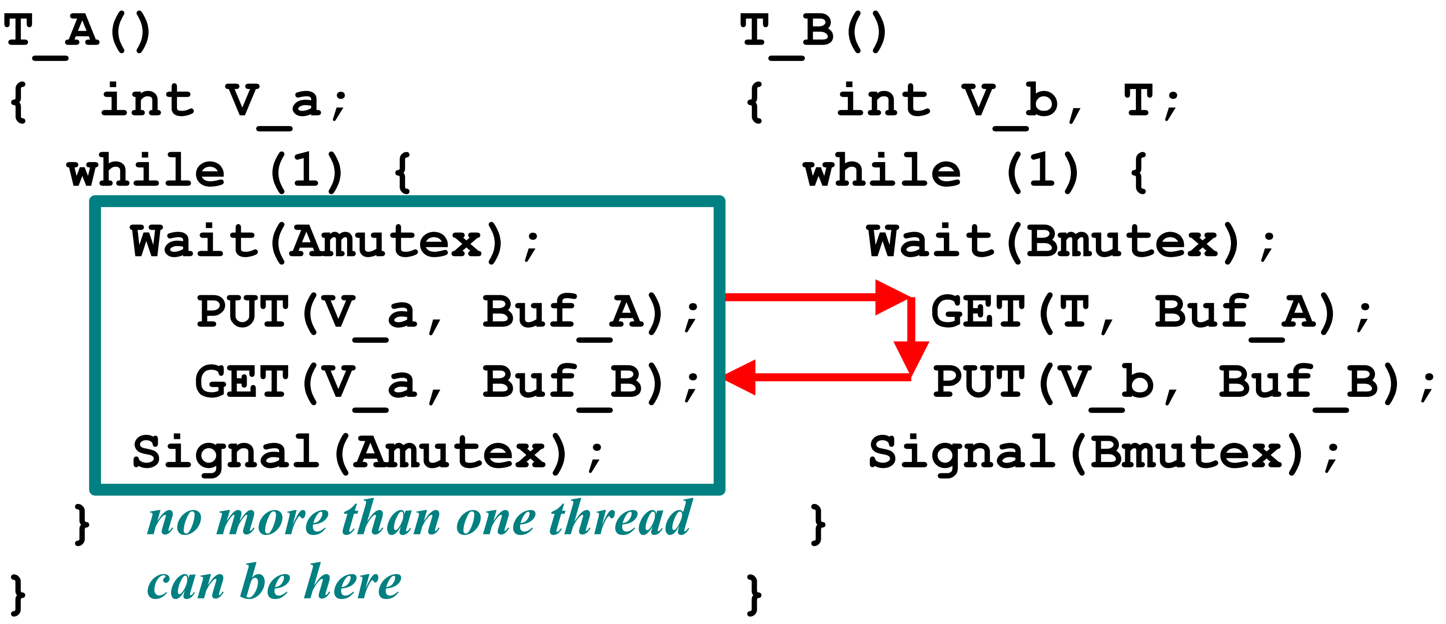


```
T_A()
{  int V_a;
   while (1) {
     Wait(Amutex);
       Wait(NotFul_A);
         Buf_A = V_a;
         Signal(NotEmp_A);
       Wait(NotEmp_B);
         V_a = Buf_B;
         Signal(NotFul_B);
     Signal(Amutex);
   }
}
```

```
T_B()
{  int V_b;
   while (1) {
     Wait(Bmutex);
       Wait(NotFul_B);
         Buf_B = V_b;
         Signal(NotEmp_B);
       Wait(NotEmp_A);
         V_b = Buf_A;
         Signal(NotFul_A);
     Signal(Bmutex);
   }
}
```

A Good Attempt: Another Version

```
Sem  Amutex = Bmutex = 1;
int  Buf_A, Buf_B;
```



```
T_A()
{  int V_a;
   while (1) {
     Wait(Amutex);
       PUT(V_a, Buf_A);
       GET(V_a, Buf_B);
     Signal(Amutex);
   }
}
```

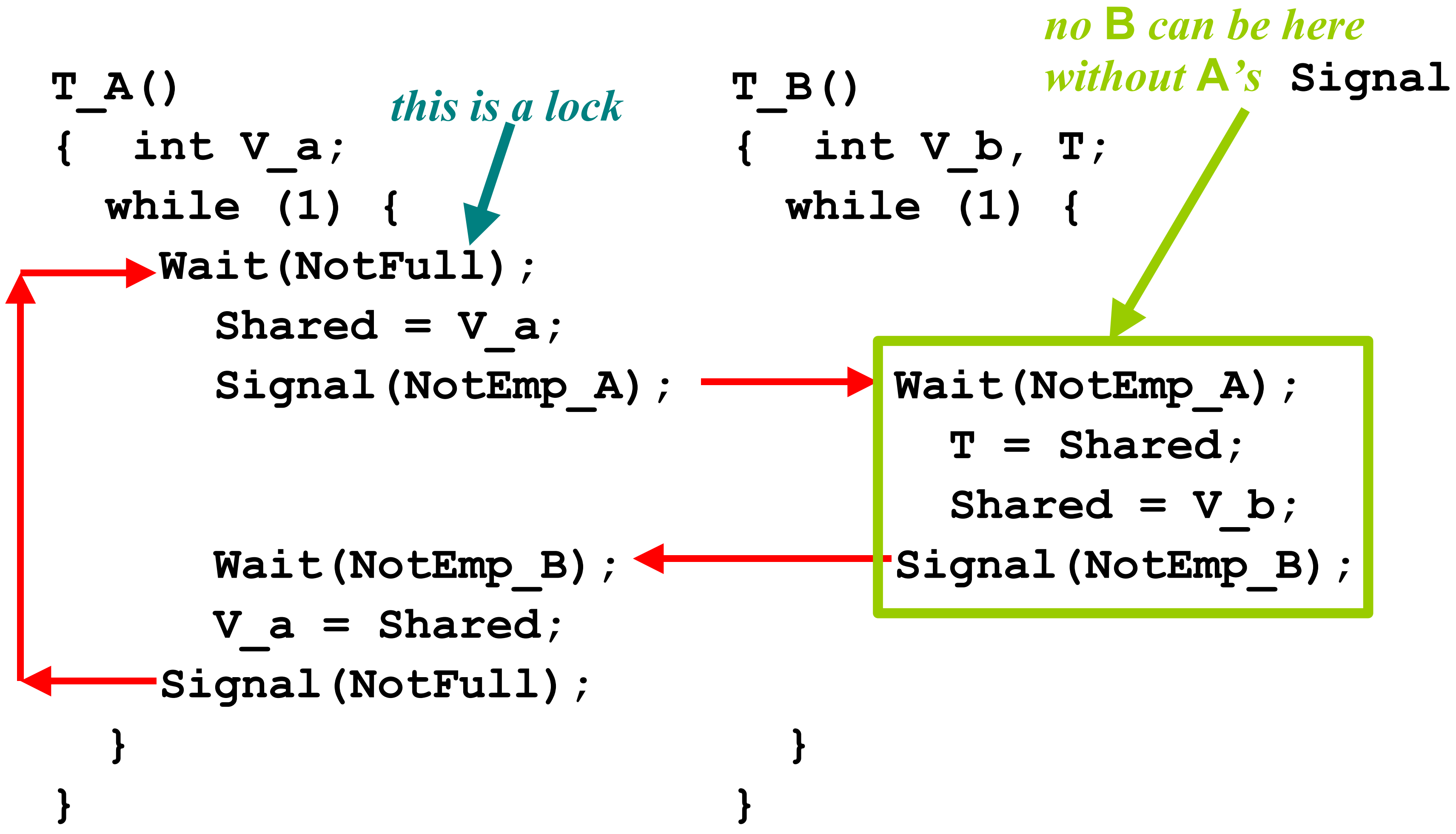
no more than one thread can be here

```
T_B()
{  int V_b, T;
   while (1) {
     Wait(Bmutex);
       GET(T, Buf_A);
       PUT(V_b, Buf_B);
     Signal(Bmutex);
   }
}
```

Note that the **`PUT`*****s and*** **`GET`*****s also provide mutual exclusion.***

A Good Attempt: Non-Symmetric

```
Sem NotFull = 1, NotEmp_A = NotEmp_B = 0;
int Shared;
```



```
T_A()
{  int V_a;
 while (1) {
  Wait(NotFull);
   Shared = V_a;
   Signal(NotEmp_A);


   Wait(NotEmp_B);
   V_a = Shared;
  Signal(NotFull);
 }
}
```

```
T_B()
{  int V_b, T;
 while (1) {
   Wait(NotEmp_A);
    T = Shared;
    Shared = V_b;
   Signal(NotEmp_B);
 }
}
```

this is a lock

no **B** *can be here without* **A***’s* `Signal`

What did we learn?

- **Understand the solutions to the classical synchronization problems, because they are *useful*.**
- **The problem in hand could be a variation of some classical problems.**
- **Combine, apply and/or simplify the classical solutions.**
- **Thus, classical problems are not toy problems! They have their meaning.**

Conclusions

- **Detecting race conditions is difficult as it is an NP-hard problem.**
- **Detecting race conditions is also difficult to teach as there is no theory. It is heuristic.**
- **Incorrect mutual exclusion is no better than no mutual exclusion.**
- **Use solutions to classical problems as models.**
- **The examples have been classroom tested, and are useful, helpful and well-received.**