CRITICAL SECTION PROBLEM

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Critical Section Problem

- Each of *N* processes is executing in an infinite loop, a sequence of statements that can be divided into two subsequences:
  - *critical section*
  - *non critical section*
- Three correctness specifications are required of any solution:
  - *Mutual Exclusion*
  - *Freedom from deadlock*
  - *Freedom from starvation*

Critical Section Problem

- Mutual Exclusion
  - Statements from the critical sections of two or more processes must not be interleaved
- Freedom from deadlock
  - If ***some*** processes are trying to enter their critical sections, then ***one*** of them must eventually succeed
- Freedom from starvation
  - If ***any*** process tries to enter its critical section, then ***that*** process must eventually succeed

Critical Section Problem

- A *synchronization* mechanism must be provided to ensure that the correctness requirements are met.
- Synchronization mechanism consists of additional statements that are placed before and after the critical section
- The statements placed before critical section are called *preprotocol* and those after it are called *postprotocol*

Critical Section Problem

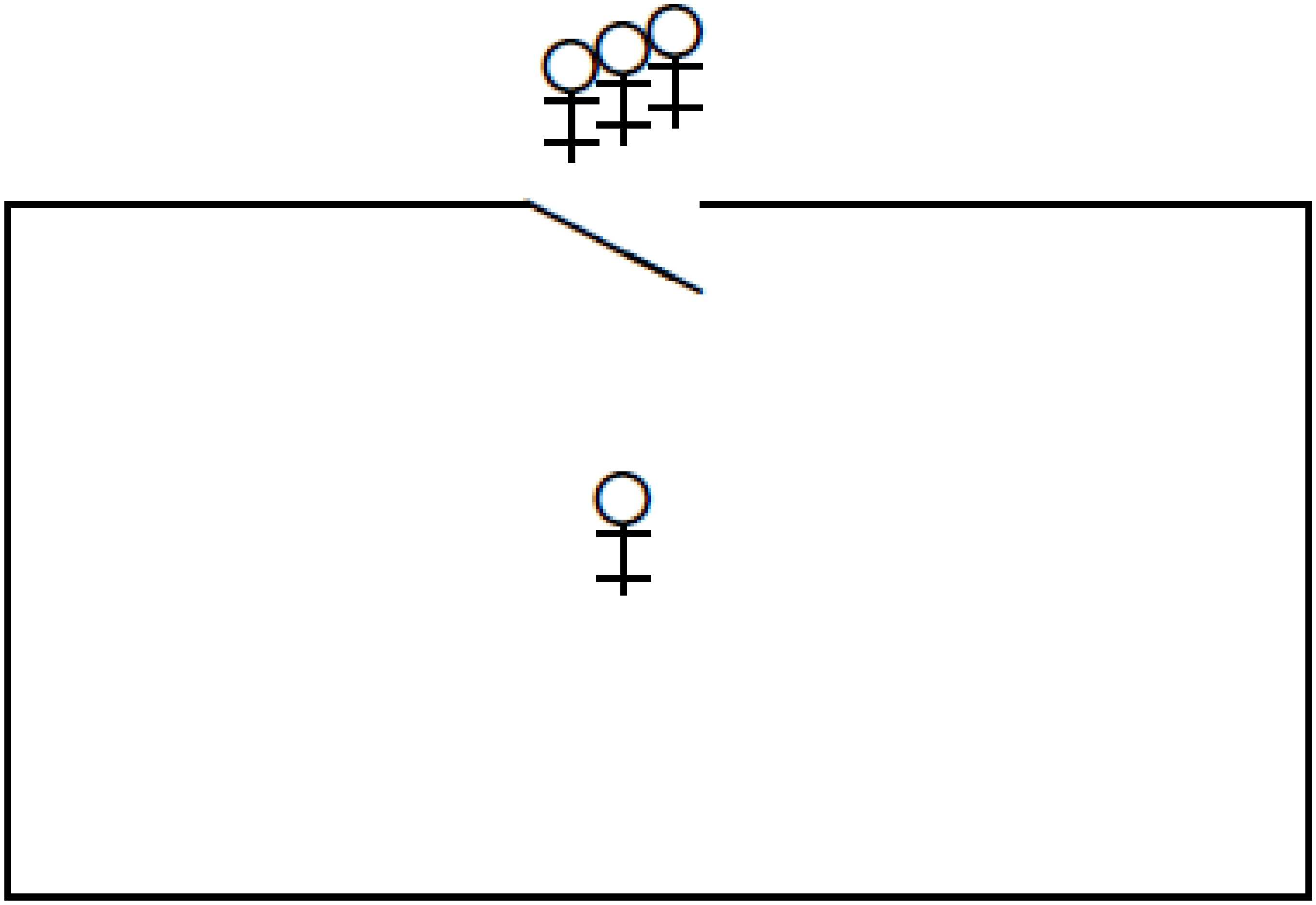
Algorithm 3.1: Critical section problem	
global variables	
p	**q**

local variables
loop forever
    non-critical section
    preprotocol
    critical section
    postprotocol
	local variables
	loop forever
	    non-critical section
	    preprotocol
	    critical section
	    postprotocol

Critical Section Problem

- The protocol may require local or global variables
- Critical section must progress
  - Once a process starts to execute the statements in a critical section, it must eventually finish execution of those statements
- The Non-Critical section need not progress
  - If the control pointer of a process is in its non-critical section, the process may terminate or enter an infinite loop

Critical Section Problem



Correctness

Algorithm 3.3: History in a sequential algorithm
integer a ← 1, b ← 2
p1: Millions of statements
p2: a ← (a+b)*5
p3: . . .

Algorithm 3.4: History in a concurrent algorithm	
integer a ← 1, b ← 2	
p	**q**
p1: Millions of statements	q1: Millions of statements
p2: a ← (a+b)*5	q2: b ← (a+b)*5
p3: . . .	q3: . . .

Correctness

- Sequential
  - $s_i = (p2, 10, 20)$ and $s_{i+1} = (p3, 150, 20)$

- Concurrent
  - $s_i = (p2, q2, 10, 20)$
  - $s^p_{i+1} = (p3, q2, 150, 20)$ or $s^q_{i+1} = (p2, q3, 10, 150)$

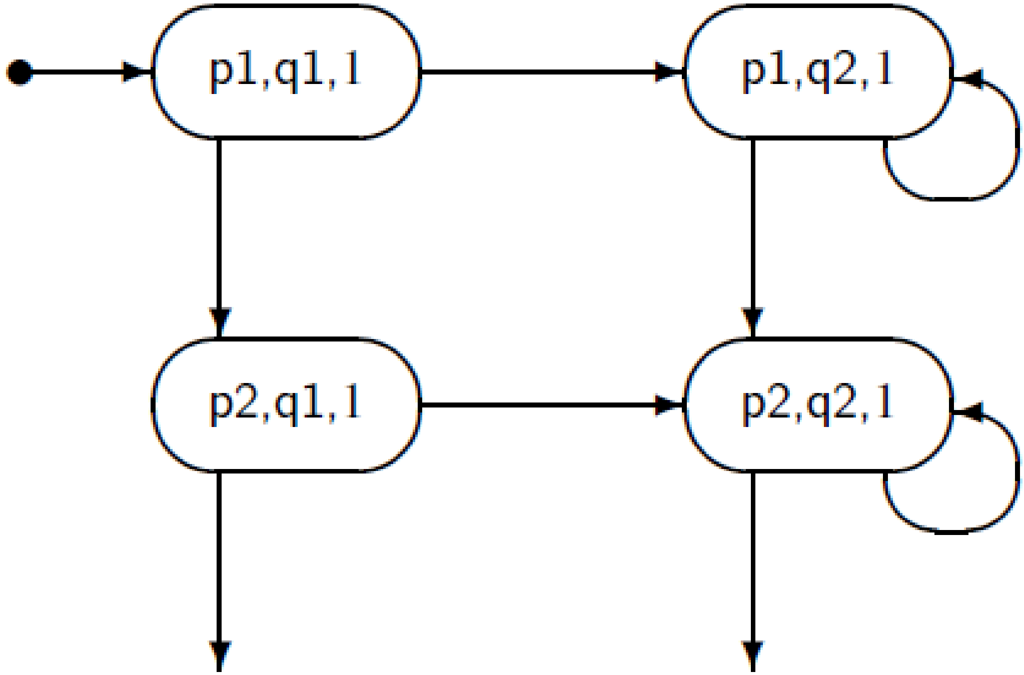
- The set of reachable states are the only states that can appear in any computation
- To check correctness, it is only necessary to examine the set of reachable states and the transitions among them

First Attempt

- await turn = 1 waits until the condition turn = 1 becomes true
- This can be implemented by a busy-wait loop

Algorithm 3.2: First attempt	
integer turn ← 1	
p	**q**
loop forever	loop forever
p1: non-critical section	q1: non-critical section
p2: await turn = 1	q2: await turn = 2
p3: critical section	q3: critical section
p4: turn ← 2	q4: turn ← 1

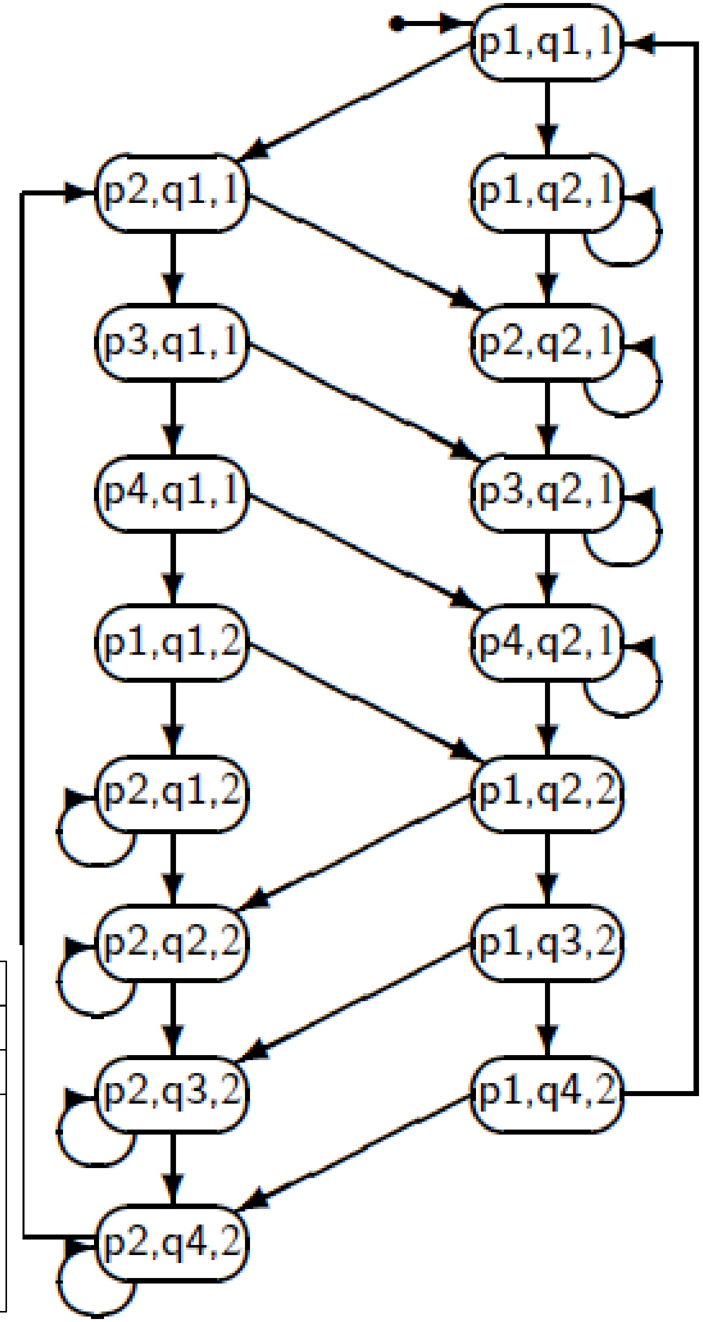
State Diagram – First steps



Algorithm 3.2: First attempt	
integer turn ← 1	
p	**q**
loop forever	loop forever
p1: non-critical section	q1: non-critical section
p2: await turn = 1	q2: await turn = 2
p3: critical section	q3: critical section
p4: turn ← 2	q4: turn ← 1

Sixteen steps

- (p3, q3,1) or (p3, q3,2) do not occur – mutual exclusion property holds



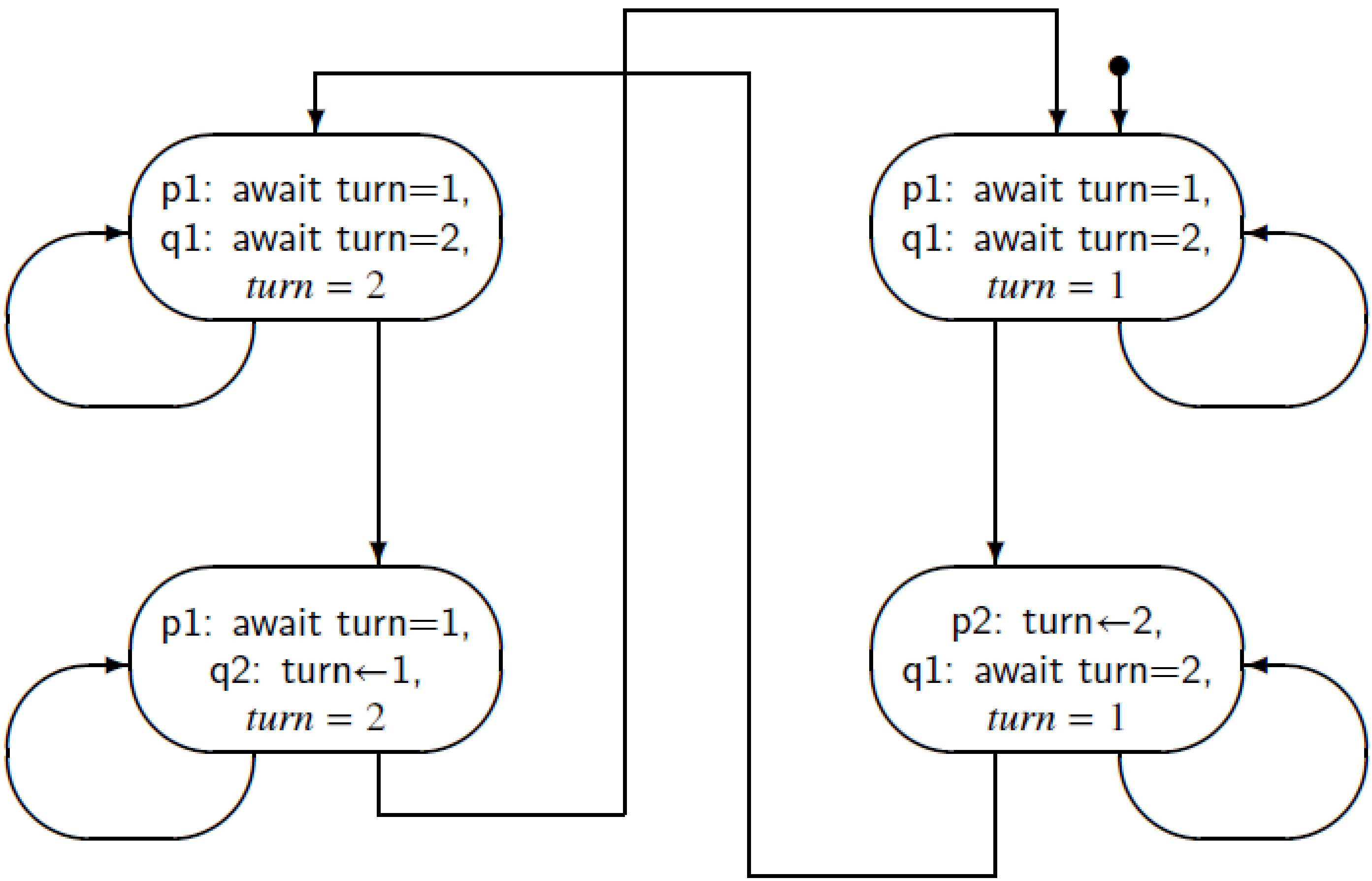
Algorithm 3.2: First attempt	
integer turn ← 1	
p	**q**
loop forever	loop forever
p1: non-critical section	q1: non-critical section
p2: await turn = 1	q2: await turn = 2
p3: critical section	q3: critical section
p4: turn ← 2	q4: turn ← 1

First Attempt (Abbreviated)

Algorithm 3.5: First attempt (abbreviated)	
integer turn ← 1	
p	**q**
loop forever	loop forever
p1: await turn = 1	q1: await turn = 2
p2: turn ← 2	q2: turn ← 1

Algorithm 3.2: First attempt	
integer turn ← 1	
p	**q**
loop forever	loop forever
p1: non-critical section	q1: non-critical section
p2: await turn = 1	q2: await turn = 2
p3: critical section	q3: critical section
p4: turn ← 2	q4: turn ← 1

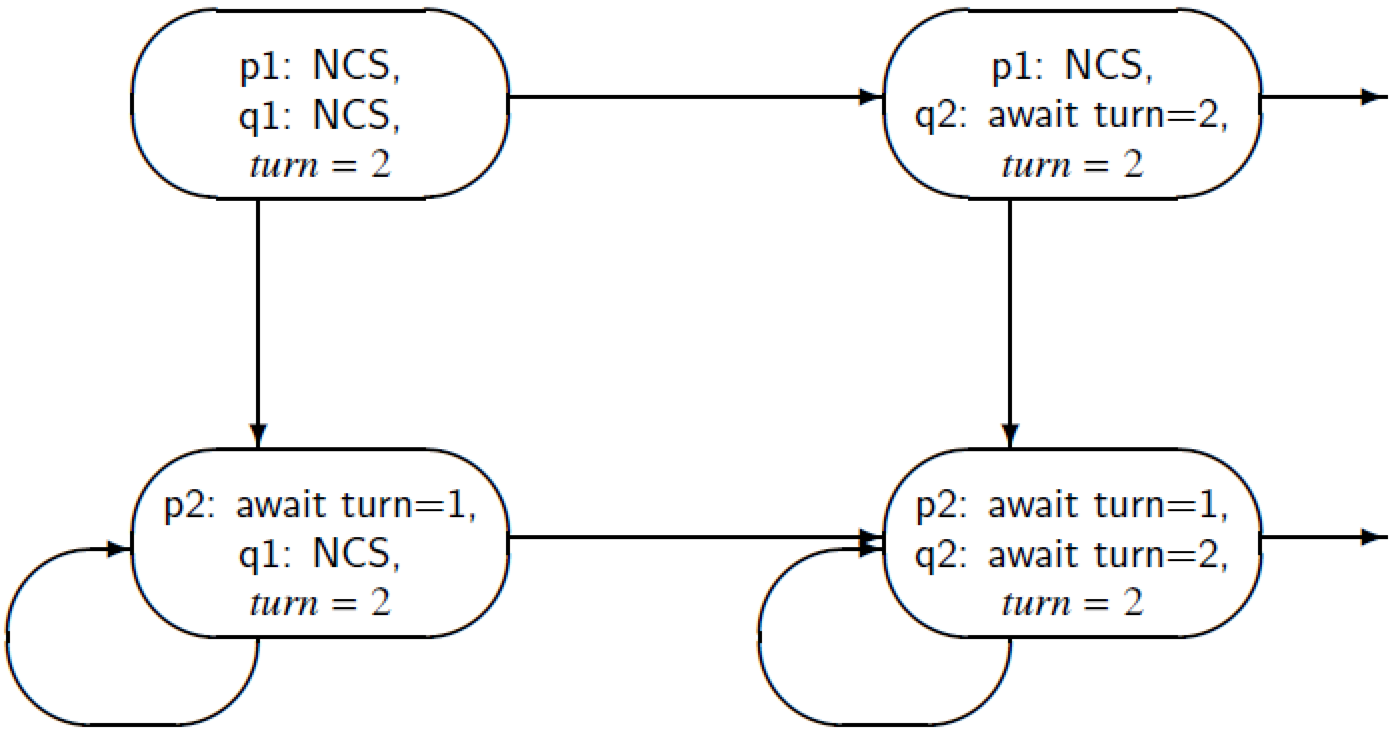
State Diagram – First Attempt (Abbv)



Correctness of First Attempt

- Proof of Mutual exclusion is immediate from the state diagram
- Proof of freedom from deadlock
  - If ***some*** processes are trying to enter their critical sections, then ***one*** of them must eventually succeed
- Proof of freedom from starvation
  - There is always some process holding the permission resource, so some process can always enter the CS ensuring there is no deadlock
  - If the process holding the permission resource remains indefinitely in its NCS, other process will never receive the resource and will never enter CS

State Diagram – Fragment



Second Attempt

- First attempt – both processes set and tested a single variable.
- If one process dies, other is blocked
- Each process is now given its own variable
- `want`***i*** is true from step where process **i** wants to enter its critical section until it leaves
- `await` statements ensure that a process does not enter its CS while another process has its flag set

Second Attempt

Algorithm 3.6: Second attempt	
boolean wantp ← false, wantq ← false	
p	**q**
loop forever	loop forever
p1: non-critical section	q1: non-critical section
p2: await wantq = false	q2: await wantp = false
p3: wantp ← true	q3: wantq ← true
p4: critical section	q4: critical section
p5: wantp ← false	q5: wantq ← false

Second Attempt

- If a process halts in its critical section, the value of its variable `want` will remain false and the other process will always succeed in immediately entering the critical section
- Solves the problem of *starvation*
- But as we move ahead, we see that *mutual exclusion* property is not satisfied.

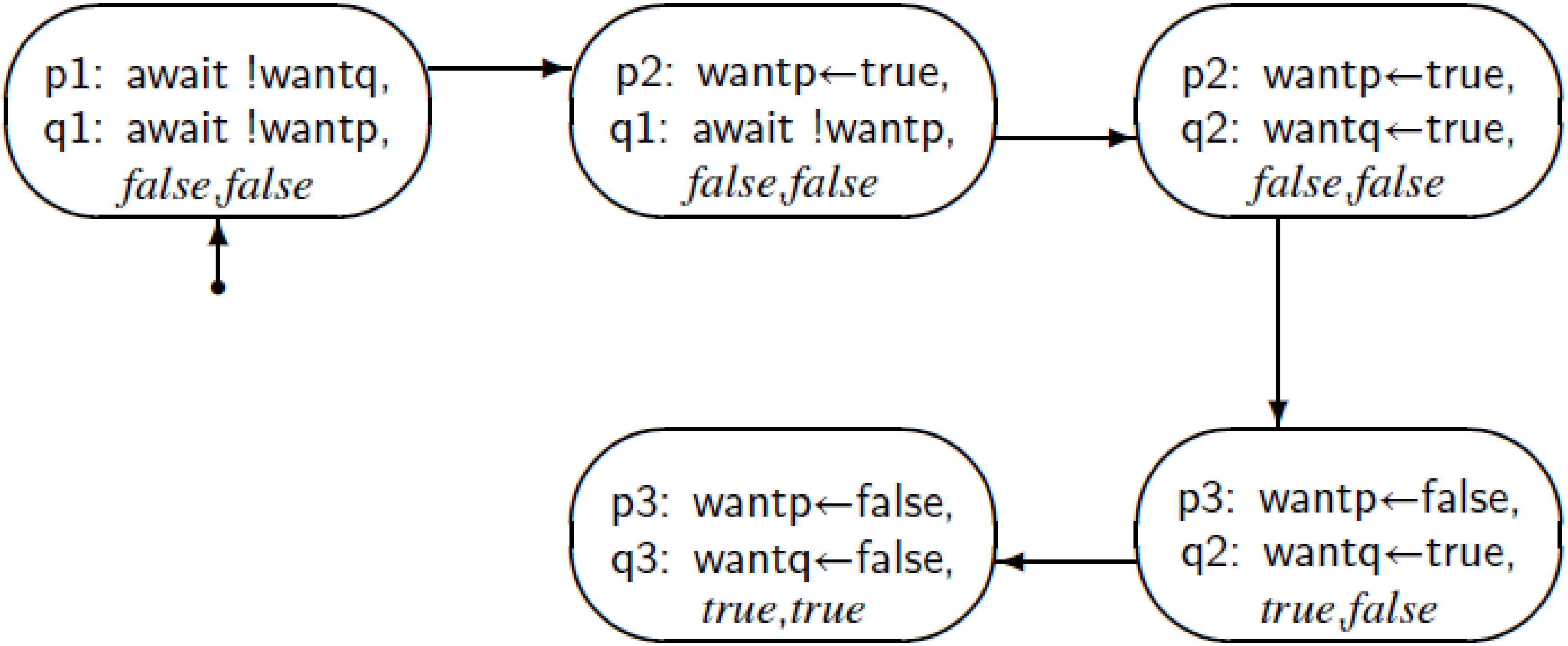
Second Attempt (Abbreviated)

Algorithm 3.7: Second attempt (abbreviated)	
boolean wantp ← false, wantq ← false	
p	**q**
loop forever	loop forever
p1: await wantq = false	q1: await wantp = false
p2: wantp ← true	q2: wantq ← true
p3: wantp ← false	q3: wantq ← false

Tabular Form

Process p	Process q	wantp	wantq
p1: await wantq=false	q1: await wantp=false	*false*	*false*
p2: wantp←true	**q1: await wantp=false**	*false*	*false*
p2: wantp←true	q2: wantq←true	*false*	*false*
p3: wantp←false	**q3: wantq←true**	*true*	*false*
p3: wantp←false	q3: wantq←false	*true*	*true*

State Diagram – Fragment



Second Attempt

- To prove that mutual exclusion holds, it must be checked that no forbidden state appears in any scenario
- If mutual exclusion does in fact hold, we need to construct the full state diagram for the algorithm, because every path in the diagram is a scenario
- Every state must be examined to make sure it is not a forbidden state
- We can stop construction if a forbidden state is encountered.

Third Attempt

- Second attempt – variables `want` are intended to indicate when a process is in its critical section
- Once a process has completed its `await`, it cannot be prevented from entering its CS
- The state reached after `await` but before assignment to `want` is effectively part of CS, but value of `want` does not indicate this

Third Attempt

- Recognizes that the `await` statement should be part of the critical section by moving the assignment to `want` before the `await`
- The construction of the state diagram shows that mutual exclusion is not violated
- However, the algorithm can *deadlock* as shown

Third Attempt

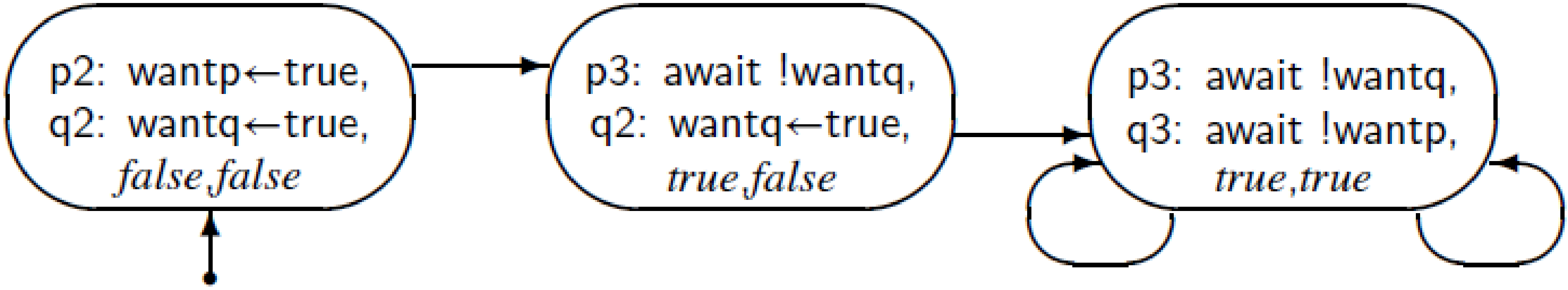
Algorithm 3.8: Third attempt			
boolean wantp ← false, wantq ← false			
p		**q**	
	loop forever		loop forever
p1:	non-critical section	q1:	non-critical section
p2:	wantp ← true	q2:	wantq ← true
p3:	await wantq = false	q3:	await wantp = false
p4:	critical section	q4:	critical section
p5:	wantp ← false	q5:	wantq ← false

Algorithm 3.6: Second attempt			
boolean wantp ← false, wantq ← false			
p		**q**	
	loop forever		loop forever
p1:	non-critical section	q1:	non-critical section
p2:	await wantq = false	q2:	await wantp = false
p3:	wantp ← true	q3:	wantq ← true
p4:	critical section	q4:	critical section
p5:	wantp ← false	q5:	wantq ← false

Tabular Form

Process p	Process q	wantp	wantq
p1: non-critical section	q1: non-critical section	*false*	*false*
p2: wantp←true	**q1: non-critical section**	*false*	*false*
p2: wantp←true	q2: wantq←true	*false*	*false*
p3: await wantq=false	**q2: wantq←true**	*true*	*false*
p3: await wantq=false	q3: await wantp=false	*true*	*true*

State Diagram – Fragment



Deadlock and Livelock

- Term deadlock is usually used with a frozen computation where nothing whatsoever is being computed
- A scenario where several processes are actively executing statements, but nothing useful gets done is called livelock

Livelock

- Attempting to use resource preemption approaches to preventing deadlock may cause livelock: Processes don’t deadlock, but fail to make progress either
- A thread often acts in response to the action of another thread. If the other thread's action is also a response to the action of another thread, then *livelock* may result.
- As with deadlock, livelocked threads are unable to make further progress. However, the threads are not blocked — they are simply too busy responding to each other to resume work.
- *Deadlock:* "Me first, Me first” *Livelock:* "You first, You first"

Livelock

- Wayne and Larry want to listen to a CD on CD player
- Larry has the CD but wants the CD player
- Wayne has the CD player but wants the CD
- Wayne steals (i.e. preempts) the CD from Larry, meanwhile Larry steals the CD player from Wayne
- Now, Wayne has the CD and Larry has the CD player
- Wayne steals the CD player from Larry, meanwhile Larry steals the CD from Wayne
- Now, Wayne has the CD player and Larry has the CD
- . . .
- **Livelock**

Deadlock vs Livelock

- Deadlock
  - It happens when a process waits for another one who is using some needed resource to finish with it, while the other process also wait for the first process to release some other resource.
- Livelock
  - A Livelock looks like a deadlock in the sense that two (or more) processes are blocking each others. But with the livelock, each process is waiting “actively”, trying to resolve the problem on its own (like reverting back its work and retry).

Deadlock vs Livelock

- A livelock is similar to a deadlock, except that the states of the processes involved in the livelock constantly change with regard to one another, none progressing.

Fourth Attempt

- Third attempt – when a process sets a variable want to be true, not only does it indicate its intention to enter its critical section, but also insists on its right to do so
- Deadlock occurs when both processes simultaneously insist on entering their CS
- Requires a process to give up its intention to enter the CS if it discovers that it is contending with the other process

Fourth Attempt

Algorithm 3.9: Fourth attempt			
boolean wantp ← false, wantq ← false			
	p		**q**
	loop forever		loop forever
p1:	non-critical section	q1:	non-critical section
p2:	wantp ← true	q2:	wantq ← true
p3:	while wantq	q3:	while wantp
p4:	wantp ← false	q4:	wantq ← false
p5:	wantp ← true	q5:	wantq ← true
p6:	critical section	q6:	critical section
p7:	wantp ← false	q7:	wantq ← false

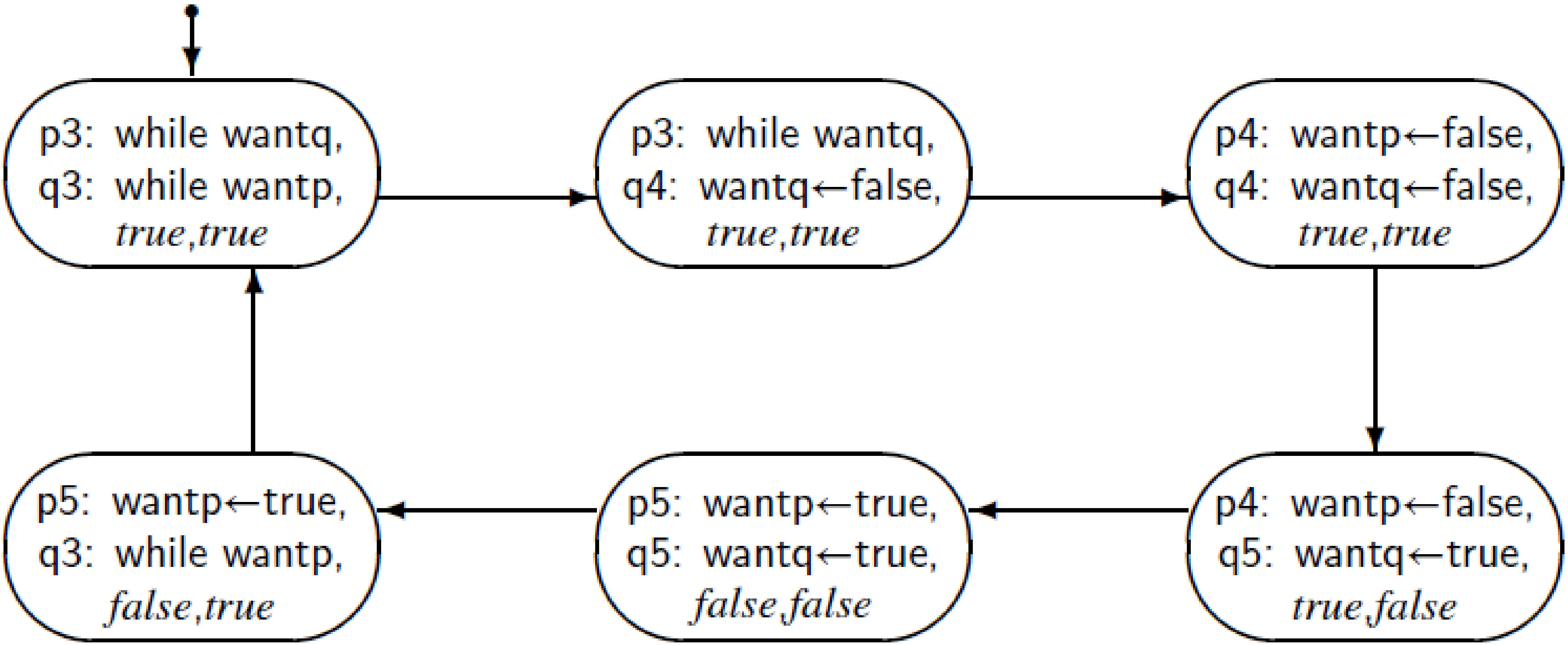
Fourth Attempt

- Statements p4 and p5 will be meaningless in a sequential algorithm, but useful in concurrent algorithm
- Arbitrary interleaving from and between the two processes, second process may execute an arbitrary number of statements between the two assignment statements to wantp
- When process p relinquishes the attempt to enter the critical section by resetting wantp to false, process q may now execute the wait statement and succeed in entering the CS

Fourth Attempt

- A state diagram will show that the mutual exclusion property holds and that there is no deadlock
- Scenario for starvation exists as shown in figure in next slide
- If interleaving is perfect, where the execution of a statement of process q is always followed by the execution of an equivalently numbered statement of process p, both the processes are starved

State Diagram – Fragment



Dekker’s Algorithm

- Combination of first and fourth attempts
- First Attempt – explicitly passed the right to enter the Critical Section
- This caused processes to be closely coupled and prevented correct behavior in absence of contention
- Fourth Attempt – each process had its own variable which prevented problems in absence of contention
- Both processes however insist on entering CS in the presence of contention

Dekker's Algorithm

Algorithm 3.10: Dekker's algorithm			
boolean wantp ← false, wantq ← false			
integer turn ← 1			
p		**q**	
	loop forever		loop forever
p1:	non-critical section	q1:	non-critical section
p2:	wantp ← true	q2:	wantq ← true
p3:	while wantq	q3:	while wantp
p4:	if turn = 2	q4:	if turn = 1
p5:	wantp ← false	q5:	wantq ← false
p6:	await turn = 1	q6:	await turn = 2
p7:	wantp ← true	q7:	wantq ← true
p8:	critical section	q8:	critical section
p9:	turn ← 2	q9:	turn ← 1
p10:	wantp ← false	q10:	wantq ← false

Dekker’s Algorithm

- Similar to fourth attempt
- *Right to insist on entering* rather than *Right to enter* is explicitly passed between the processes
- The individual variables ensure mutual exclusion

- Dekker’s algorithm is correct: it satisfies the mutual exclusion property
- Its free from starvation and deadlock

Advanced Algorithm

- Two reasons
  - They work for arbitrary number of processes
  - They raise additional issues concerning concurrency abstraction and the specification of the CS problem
  - Developed by Leslie Lamport
- Bakery Algorithm

Bakery Algorithm

- A process wishing to enter its critical section is required to take a numbered ticket, whose value is greater than the values of all outstanding tickets
- The process waits until its ticket has the lowest value of all outstanding tickets and enters its critical section
- Name is taken from the ticket dispensers used in bakeries
- Customers are served first come first served basis

Bakery Algorithm

Algorithm 5.1: Bakery algorithm (two processes)	
integer np $\leftarrow$ 0, nq $\leftarrow$ 0	
p	**q**
loop forever	loop forever
p1: non-critical section	q1: non-critical section
p2: np $\leftarrow$ nq + 1	q2: nq $\leftarrow$ np + 1
p3: await nq = 0 or np $\leq$ nq	q3: await np = 0 or nq < np
p4: critical section	q4: critical section
p5: np $\leftarrow$ 0	q5: nq $\leftarrow$ 0

Bakery Algorithm

- np and nq hold the ticket numbers of the two processes
- A value of 0 indicates that the process does not want to enter the CS
- A positive value represents an implicit queue of the processes that want to enter
- Lower numbers denoting closeness to the head of the queue
- If ticket numbers are equal we arbitrarily assign precedence to one process

Bakery Algorithm

- The following formulas are invariant
  - $np = 0 \leftrightarrow p1 \vee p2$
  - $nq = 0 \leftrightarrow q1 \vee q2$
  - $p4 \rightarrow (nq = 0) \vee (np \leq nq)$
  - $q4 \rightarrow (np = 0) \vee (nq < np)$
- Bakery Algorithm for two processes satisfies mutual exclusion property
  - $(p4 \wedge q4) \rightarrow (np \leq nq) \wedge (nq < np)$
- The two process bakery algorithm is free from starvation

Bakery Algorithm (N Processes)

Algorithm 5.2: Bakery algorithm (N processes)	
integer array[1..n] number ← [0,. . . ,0]	
	loop forever
p1:	non-critical section
p2:	number[i] ← 1 + max(number)
p3:	for all *other* processes j
p4:	await (number[j] = 0) or (number[i] ≪ number[j])
p5:	critical section
p6:	number[i] ← 0

Bakery Algorithm (N Processes)

- Each of the n processes executes the same algorithm
- i is set to a different constant in the range 1 to N called the ID number of the processes
- The statement for all other processes j is an abbreviation for

```
for j from 1 to N
  if j ≠ i
```

Bakery Algorithm (N Processes)

- The notation `(number [i] << number [j])` is an abbreviation for

```
(number [i] < number [j])or
((number [i] = number [j]) and
                  (i < j))
```

- Either the first ticket is less than the second or they are equal and first process ID number is lower than the second

Bakery Algorithm (N Processes)

- Each process chooses a number that is greater than the maximum of all outstanding ticket numbers
- A process is allowed to enter its critical section when it has lower ticket number than all other processes
- In case of tie in comparing the ticket numbers, the lower numbered process is arbitrarily given precedence.

Bakery Algorithm (N Processes)

- Algorithm is elegant because it has the property that no variable is both read and written by more than one process (unlike *turn* variable in Dekker's algorithm).
- However it is impractical because each process must query every other process for the value of its ticket number and the entire loop must be extended even if no other process wants to enter the critical section.