Lesson 3

Critical Section Problem

Ch 3 [BenA 06]

Critical Section Problem
Solutions without HW Support
State Diagrams for Algorithms
Busy-Wait Solutions with HW Support

Mutual Exclusion Real World Example

Fig. Pesutuvan varaus

- How to reserve a laundry room?
  - Housing corporation with many tenants
- Reliable — mutual exclusion, i.e., mutex
  - No one else can reserve, once one reservation for given time slot is done — non-preemptive
  - One can not remove other's reservations — keskeytettämätön
- Reservation method — distributed/centralized
  - One can make decision independently (without discussing with others) on whether laundry room is available or not
  - One can have reservation for at most one time slot at a time — no simultaneous resource possession
- People not needing the laundry room are not bothered
- One should not leave reservation on when moving out
- One should not lose reservation tokens/keys — recovery?

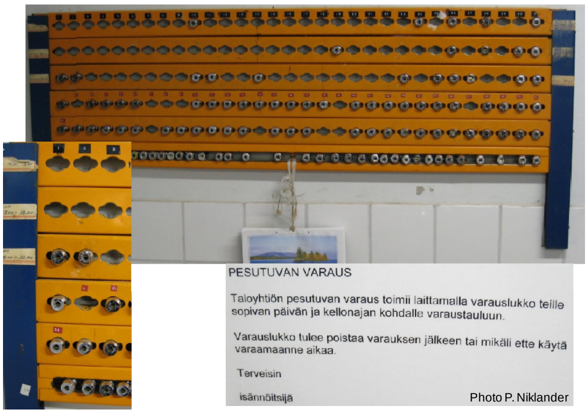

Photo P. Niklander

Concurrent Indivisible Operations

- Echo

```
char out, in; // globals
procedure echo {
  input (in, keyboard);
  out = in;
  output (out, display);
}
```

Process P1	Process P2
…	…
input (in,..);	…
	input(in,..);
out = in;	out = in;
…	output (out,..);
output(out,..);	

  - What if *out* and/or *in* local variables?
- Data base update
  - Name, id, address, salary, annual salary, …
- How/when/by whom to define granularity for indivisible operations?

Executing Many Processes Concurrently

- One CPU
  - Execute one process until
    - It requests a service that takes time to do
    - Some interrupt occurs and operating system gives execution turn to somebody else
      - E.g., time slice interrupt — aikaviipalekeskeytys
  - Another process may still run concurrently in GPU or some other I/O controller
- Many CPU's
  - Execute many processes always concurrently
  - Execution turn for one process may end any time (request service, or interrupt occurs)

Critical Section Problem

- Critical section (CS)
  - Code segment that only one process may be executing at a time
  - May also be set of code segments, and only one process may be executing at a time any code segment in that set
  - Not necessarily an atomic operation
    - Other processes may be scheduled, but they can not execute in (this) critical section
- Critical Section Problem (Mutex Problem)
  - How to guarantee that only one process at a time is executing critical section?

Discuss

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Critical Section (CS) Solution

- Mutex (mutually exclusive code) solved — poissulkemisong. ratk.
- No deadlock: someone will succeed — ei lukkiutumista
- No starvation (and no unnecessary delay) — ei nälkiintymistä
  - Everyone succeeds eventually
- *Protocol* does not use common variables with CS actual work
  - Can use it's own local or shared variables

Algorithm 3.1: Critical section problem

global variables	
p	**q**
local variables	local variables
loop forever	loop forever
non-critical section	non-critical section
preprotocol	preprotocol
critical section	critical section
postprotocol	postprotocol

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Critical Section Assumptions

Algorithm 3.1: Critical section problem

global variables	
p	**q**
local variables	local variables
loop forever	loop forever
non-critical section	non-critical section
preprotocol	preprotocol
critical section	critical section
postprotocol	postprotocol

"unsafe zone" (non-critical sections); "safe zone" (preprotocol, critical section, postprotocol)

- Preprotocol and postprotocol have no common local/global variables with critical/non-critical sections
  - They do not disturb/affect each other
- Non-critical section may stall or terminate
  - Can not assume it to complete
- Critical section will complete (will not terminate or die)
  - Postprotocol eventually executed once critical section is entered
- Process will not terminate in preprotocol or postprotocol (!!!)
  - Process may terminate (die) only in non-critical section

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Critical Section Solution

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

- How to prove correct or incorrect?
  - Mutex? (functional correct, one at a time in CS)
  - No deadlock? (eventually someone from many will get in)
  - No starvation? (eventually any specific one will get in)

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"await condition" statement

- Pseudo language construct [redacted]
- Implement somehow *waiting until given condition becomes true*
  - Use clever algorithms
    - Dekker, Peterson, …
  - Use hardware (HW) help – special instructions & data?
    - Interrupts, lock variables with busy wait loops, …
  - Use operating system (OS) – suspend process?
    - Semaphores, barrier operations, busy waits loops, …
    - Implemented using HW (or those clever algorithms)
  - Use programming language utilities?
    - Semaphores, monitor condition variables, barrier operations, protected object *when* statements, …
    - Implemented using OS
- Specifics discussed more later on

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Correctness Proofs

- Prove incorrect
  - Come up with one scenario that does not work
    - Two processes execute in sync?
    - Some other unlikely scenario?

    often non-trivial
- Prove correct
  - Heuristics: "I did not come up with any proofs (counterexample) for incorrectness and I am smart"
    - ⇨ I can not prove incorrectness
    - ⇨ It must be correct…

    "easy", unreliable
  - State diagrams — difficult, reliable
    - Describe algorithm with states:

      { relevant control pointer (cp) values, relevant local/global variable values }
    - Analyze state diagrams to prove correctness

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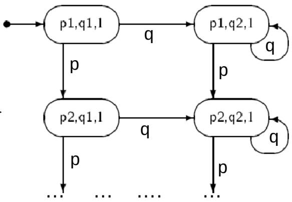
State Diagram for Alg. 3.2

Algorithm 3.2

- State {p_i, q_i, turn}
  - Control pointer p_i
  - Control pointer q_i
  - Global variable turn
  - 1st four states →
- Mutex ok
  - State {p3, q3, turn} not accessible in state diagram?
- No deadlock?
  - When many processes try concurrently, one will succeed
- No starvation?
  - Whenever any (one) process tries, it will eventually succeed

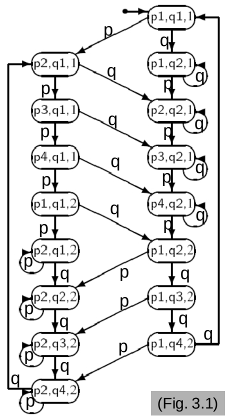
How to prove it?



State Diagram for Algorithm 3.2

Algorithm 3.2

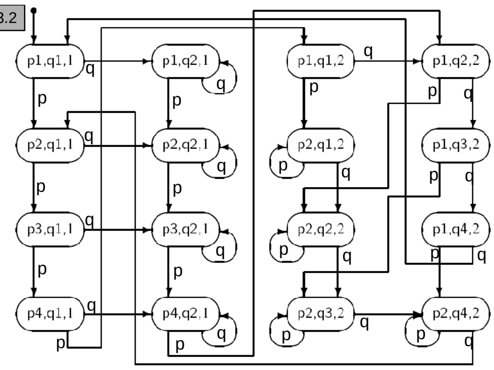
- Create complete diagram with all accessible states
- No states
  - {p3, q3, 1}
  - {p3, p3, 2}
- I.e., mutex secured proof!
- Problem:
  - Too many states?
  - Difficult to create
  - Difficult to analyze



(Fig. 3.1)

Alternate Layout for Full State Diagram

Alg. 3.2

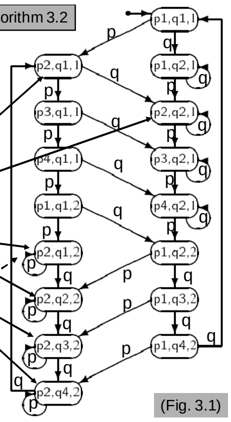


Correctness (3)

Algorithm 3.2

- Mutex?
  - Ok, no state {p3, q3, ??}
- No deadlock?
  - many try, one can always get in? (into a state with p3 or q3)
  - {**p2**, q1, 1}: P can get in
  - {**p2**, q2, 1}: P can get in
  - {**p2**, q1 tai q2, 2}:
    - Q can get in
  - {**p2**, q3 tai q4, 2}:
    - P can get in eventually
  - {pi, q2, ?} similarly. *q.e.d.*
- No starvation?
  - One tries, it will eventually get in?
  - {p2, q1, 2}
    - Q dies (ok to die in q1), P will starve! **Not good!**

All states with p2



(Fig. 3.1)

Reduced Algorithm for Easier Analysis

[redacted]

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

- Reduce algorithm to reduce number of states of state diagrams: leave irrelevant code out
  - Nothing relevant (for mutex) left out?

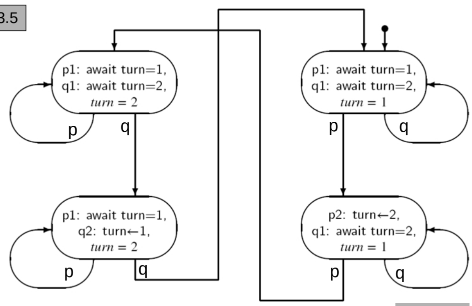
Algorithm 3.5: First attempt (abbreviated)

integer turn ← 1

p		q	
	loop forever		loop forever
p1:	await turn = 1	q1:	await turn = 2
p2:	turn ← 2	q2:	turn ← 1

State Diagram for Reduced Algorithm

Alg. 3.5

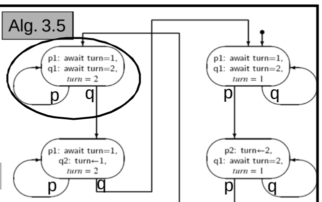


(Fig. 3.2)

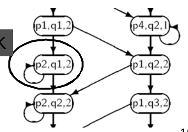
- Much fewer states!

Correctness of Reduced Algorithm (2)

Alg. 3.5



- Mutex? OK
  - No state {p2, q2, turn}
- No deadlock: Some are trying, one may get in?
  - Top left (p & q trying): q will get in OK
  - Bottom left (p trying): q will eventually execute (assumption!)
  - Top & bottom right: mirror situation
- No starvation?
  - Tricky, reduced too much!
    - NCS combined with await
  - Look at original diagram Not OK
    - Problem if Q dies in NCS



should be OK to die in NCS, but not OK to die in protocol

Critical Section Solution #2

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

- Each have their own global variable *wantp* and *wantq*
  - True when process is in critical section
- Process dies in NCS?
  - Starvation problem ok, because it's *want*-variable is false
- Mutex? Deadlock?

Attempt #2 Reduced

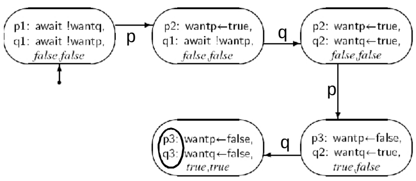
Algorithm 3.7: Second attempt (abbreviated)

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

pro-to-col (p1, p2, p3); NCS; CS

- No mutex! {p3, q3, ?} reachable
  - Problem: p2 should be part of critical section (but is not!)



Critical Section Solution #3

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

- Avoid previous problem, <u>mutex ok</u>
- <u>Deadlock possible</u>: {p3, q3, wantp=true, wantq=true}
- Problem: <u>cyclic wait</u> possible, both <u>insist</u> their turn next
  - No preemption

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

- Avoid deadlock by <u>giving away your turn</u> if needed
- Mutex ok: P in p6 only if !wantq (⇨ Q is not in q6)
- Deadlock (livelock) possible:
  {p3, q3, …}→{p4, q4, …}→{p5, q5, …}
  - Unlikely but possible!
  - **Livelock**: both <u>executing</u> all the time, not waiting suspended
    - Neither one advances

elolukko

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

- Combine 1st and 4th attempt
- 3 global (mutex ctr) variables: shared *turn*, <u>semi-private</u> *want*'s
  - only one process <u>writes</u> to *wantp* or *wantq* (= semi-private)
- *turn* gives you the <u>right to insist</u>, i.e., <u>priority</u>
  - Used only when both want CS at the same time

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
```

Proof

- Mutex ok: P in p8 only if !wantq (⇨ Q can not be in q8)
- No deadlock, because P or Q can continue to CS from {p3, q3, ..}
- No starvation, because
  - If in {p6, …}, then eventually {p6, q9, …} and {..., q10, ...}
  - Next time {p3, …} or {p4, …} will lead to {p8, …}

[redacted]

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
```

- mutex with **no HW-support needed, need only shared memory**
- Bad: complex, many instructions
  - Must execute each instruction at a time, in this order
    - Will not work, if compiler optimizes code too much!
  - In simple systems, can do better with HW support
    - Special machine instructions to help with this problem

Discuss

Mutex with HW Support

- Specific machine instructions for this purpose
  - Suitable for many situations
  - Not suitable for all situations
- Interrupt disable/enable instructions
- Test-and-set instructions
  - Other similar instructions
- Specific memory areas
  - Reserved for concurrency control solutions
  - Lock variables (for test-and-set) in their own cache?
    - Different cache protocol for lock variables?
    - Busy-wait without memory bus use?

```
Disable
-- Critical Section --
Enable
```

```
Lock (L)
-- Critical Section --
Unlock (L)
```


Disable Interrupts

- Environment
  - All (competing) processes on run on the same processor (core?)
  - Not for multiprocessor systems
    - Disabling interrupts does it only for the processor executing that instruction
- Disable/enable interrupts
  - Prevent process switching during critical sections
    - Good for only very short time
    - Prevents also (other) operating system work (in that processor) while in CS

Disable
Enable

[redacted]

```
Disable
-- CS --
Enable
```

```
Disable
-- CS --
Enable
```


Test-and-set Lock Variables

Lukkomuuttujat

- Environment
  - All processes with shared memory
  - Should have multiple processors
  - Not very good for uniprocessor systems (or synchronizing processes running on the same processor)
    - Wait (**busy-wait**) while holding the processor!
- Test-and-set *machine instruction*
  - Indivisibly read old value and write new value (complex mem-op)

```
Test-and-set (common, local)
        local ← common   ; read old state
        common ← 1       ; mark reserved
```

shared local

```
Test-and-set (shLock, locked);
while (locked)
    Test-and-set (shLock, locked);
-- CS --
shLock = 0;
```

```
Test-and-set (shLock, locked);
while (locked)
    Test-and-set (shLock, locked);
-- CS --
shLock = 0;
```


Other Machine Instructions for Synchronization Problem Busy-Wait Solutions

- Test-and-set

```
Test-and-set (common, local)
        local ← common   ; read state
        common ← 1       ; mark reserved
```

- Exchange

```
Exchange (common, local)
        local ↔ common   ; swap values
```

- Fetch-and-add

```
Fetch-and-add (common, local, x)
        local ← common          ; read state
        common ← common+x  ; add x
```

- Compare-and-swap

```
int Compare-and-swap (common, old, new)
        return_val ← common
        if (common == old)
                common ← new
```

Use all in busy-wait loops

"read-modify-write" memory bus transaction (local in HW register)

"read-after-write" memory bus transaction may also be used

Lock variables and busy wait

- Need shared memory
- Use processor while waiting
  - Waste of a processor?
  - Not so smart with just one processor
    - Busy waits suspended when *time slice* ends (i.e., when OS time slice interrupt occurs)
  - Should wait only a very short time
    - Unless plenty of processors
  - Real fast resume when wait ends
    - Good property in some environments

Summary

- Critical section (CS)
- Critical Section Problem
- Solutions without HW Support
- State Diagrams for Algorithms
- Busy-Wait Solutions with HW Support