Lesson 10

Distributed Mutual Exclusion

Ch 10 [BenA 06]

Distributed System
Distributed Critical Section
Ricart-Agrawala
Token Passing Ricart-Agrawala
Token Passing Neilsen-Mizuno

17.3.2011 1

(Generic) Distributed System

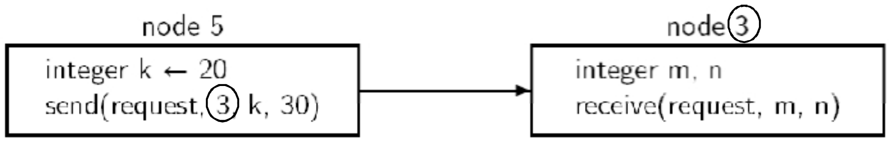
- Nodes have processes
- Communication channels between nodes
  - Each node connected to every other node
    - Two-way channel
  - Reliable communication channels
    - Provided by network layer below
    - Messages are not lost
    - Messages processed concurrently with other computations (e.g., critical sections)
  - Nodes do not fail
- Requirements reduced later on
  - courses on distributed systems topics

Unrealistic assumptions? Not really…

17.3.2011 2

(Generic) Distributed System

- Processes (nodes) communicate with (asymmetric) messages
  - Message arrival order is not specified
  - Transmission times are arbitrary, but finite
  - Message (header) does not include send/receiver id
  - Receiver does not know who sent the message
    - Unless sender id is in the message itself



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Distributed Processes

- Sender does not block
- Receiver blocks (suspended wait) until message of the proper type is received
- Atomicity problems in each node is not considered here
  - Solved with locking, semaphores, monitors, …
- Message receiving and subsequent actions are considered to be atomic actions
  - Atomicity within each system considered solved

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Distributed Critical Section Problem

- Processes within one node
  - Problem solved before
- Processes in different nodes
  - More complex
- State
  - Control pointer (CP, PC, program counter)
  - Local and shared variable values
  - Messages
    - Messages, that have been sent
    - Messages, that have been received
    - Messages, that are on the way
      - Arbitrary time, but finite!

Where are these?

Two Approaches for Crit. Section

- A) Ask everybody for permission to see, if it is my turn now
  - Lots of questions/answers
- B) I'll wait until I get the token, then it is my turn
  - Pass the token to next one (which one?), or keep it?
  - Wait until I get the token
  - Token (turn) goes around all the time
    - Moves only when needed?
- Both approaches have advantages/disadvantages
  - Who is "everybody"? How do I know them?
  - How do I know who has the token?
  - What if node/network breaks down?
  - What if token is lost?

Do not worry now about the token getting lost …

17.3.2011 7

Ricart-Agrawala for Distributed Mutex


G. Ricart


A. K. Agrawala

- Distributed Mutex, 1981 (Lamport, 1978)
- Modification of Bakery algorithm with ticket numbers
- Idea
  - Must know all other processes/nodes competing for CS
  - Choose own ticket number, "larger than previous"
  - Send it to everybody else
  - Wait until permission from everybody else
    - Exactly one will always get permission from everybody else?
    - All others will wait
  - Do your CS
  - Give CS permission to everybody who was waiting for you

mutex,
no deadlock,
no starvation?

17.3.2011 8

Algorithm 10.1: Ricart-Agrawala algorithm (outline)

```
            integer myNum ← 0
            set of node IDs deferred ← empty set
main
p1:  non-critical section
p2:  myNum ← chooseNumber
p3:  for all other nodes N
p4:     send(request, N, myID, myNum)
p5:  await reply's from all other nodes
p6:  critical section
p7:  for all nodes N in deferred
p8:     remove N from deferred
p9:     send(reply, N, myID)
receive
     integer source, reqNum
p10: receive(request, source, reqNum)
p11: if reqNum < myNum
p12:    send(reply,source,myID)
p13: else add source to deferred
```

main: application process, needs distr mutex

receive: server process, runs concurrently all the time

p2: not trivial!

p5: Each one answers only when it is safe. Reply needs no content.

p7: all those waiting for my permission

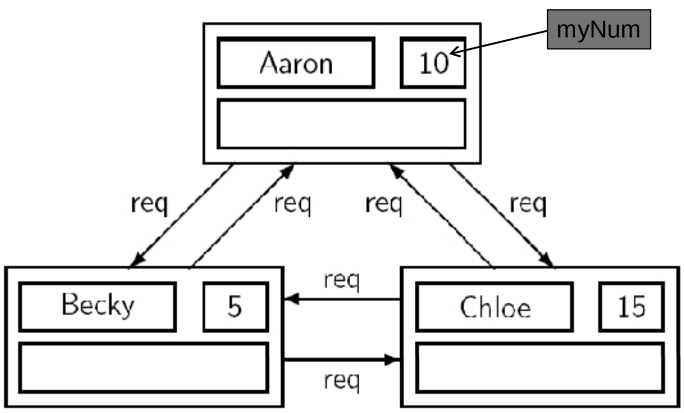
p11: most recent myNum

p13: make these wait by not sending reply

p2–p4, p7–p9, p11–p13: local mutex control?

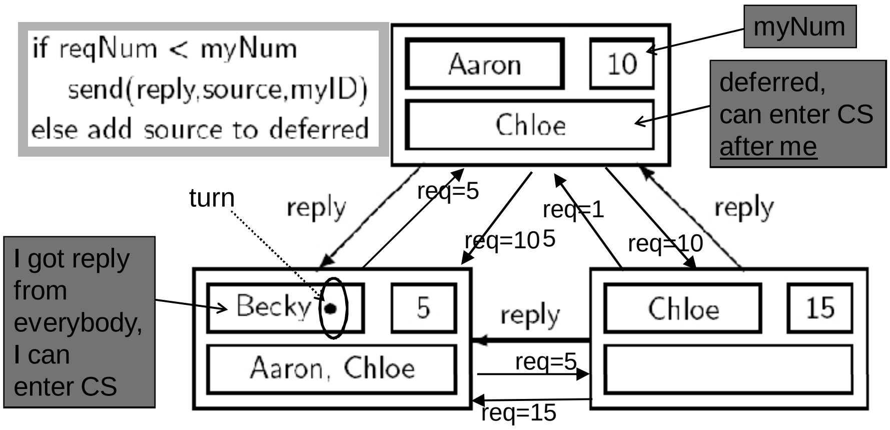
Ricart-Agrawala Example

- 3 processes, each trying to enter CS concurrently
  - No status information needed on who had CS last



Ricart-Agrawala Example (contd)

- Receive process runs at each node
  - What if Aaron's *receive* completes 1st? Last? Becky's? not yet?



- Distributed <u>virtual queue</u>:

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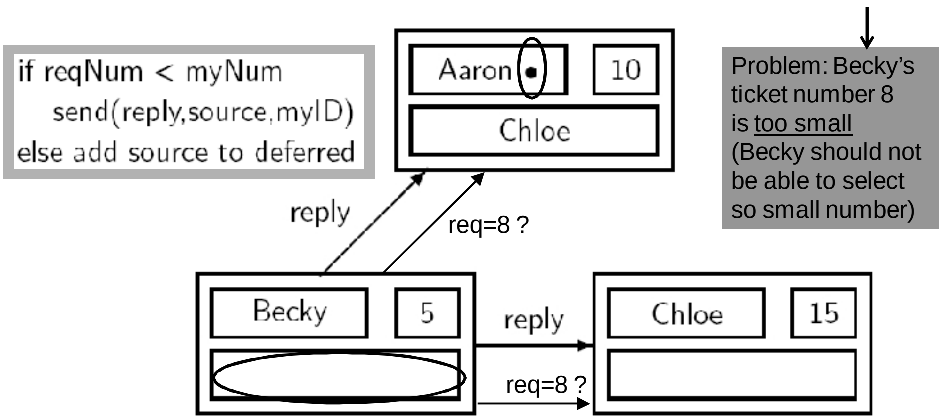
Ricart-Agrawala Example (contd)

- Becky executes CS, and then sends deferred replies to Aaron & Chloe
- Aaron has now replies from everybody, and it can enter CS
- What if Becky now selects ticket number 8, and requests CS?
  - Aaron's and Chloe's *receive* will both reply immediately? Ouch!



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How to select ticket numbers

- Select always larger one than you have <u>seen</u> before
  - Larger than your previous *myNum*
  - Larger than any *requestedNum* that <u>you have seen</u>
    - They all came before you, and you should not try to get ahead of them
- What if equal ticket numbers?
  - Fixed priority, based on node/process id numbers
  - Used only with equal ticket numbers to avoid deadlock
    - Just like in Bakery algorithm

Discuss

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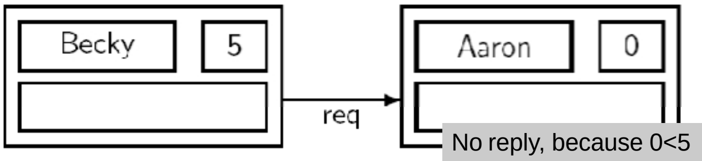
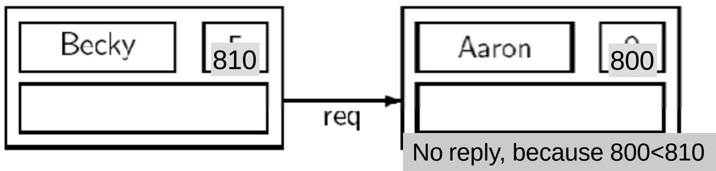
Quiescent Nodes (hiljaiset solmut)

- Nodes that do not try to enter CS (but they could)
  - They are still listed in "all other nodes"
  - Problem with <u>initial value</u> of *myNum*
  - Initial value zero?

```
if reqNum < myNum
   send(reply,source,myID)
else add source to deferred
```



  - Initial value N > 0 ; tickets numbers eventually will reach it



  - Cure: *receive* checks for tickets numbers only if *main* wants CS

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Algorithm 10.2: Ricart-Agrawala algorithm

```
        integer myNum ← 0                    requestCS ← false
        set of node IDs deferred ← empty set
  ⇨     integer highestNum ← 0
                        Main
        loop forever
p1:        non-critical section
p2:        requestCS ← true
p3:        myNum ← highestNum + 1
p4:        for all other nodes N
p5:           send(request, N, myID, myNum)
p6:        await reply's from all other nodes
p7:        critical section
p8:        requestCS ← false
p9:        for all nodes N in deferred
p10:          remove N from deferred
p11:          send(reply, N, myID)
```

Algorithm 10.2: Ricart-Agrawala algorithm (continued)

```
                        Receive
        integer source, requestedNum
        loop forever
p1:        receive(request, source, requestedNum)
p2:        highestNum ← max(highestNum, requestedNum)
p3:        if not requestCS or requestedNum ≪ myNum
p4:           send(reply, source, myID)
p5:        else add source to deferred
```

- Keep track of highest number seen
- What if one process asks for CS all the time?
- Same myNum OK?

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Algorithm 10.2: Ricart-Agrawala algorithm (continued)

```
                        Receive
        integer source, requestedNum
        loop forever
p1:        receive(request, source, requestedNum)
p2:        highestNum ← max(highestNum, requestedNum)
p3:        if not requestCS or requestedNum ≪ myNum
p4:           send(reply, source, myID)
p5:        else add source to deferred
```

original article

http://www.cc.gatech.edu/classes/AY2002/cs6210_fall/papers/MutualExForNetwork.pdf

- Mutex between main & receive?
  - Exact mutex boundaries?
- What to do when myNum overflows?
  - Restart everybody? When? How?
  - Fairness is not the problem, mutex is
- Correctness proofs
  - Mutex? No deadlock? No starvation?

Discuss

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Token Based Algorithms

- Problems with permission based algorithms
  - Need permission from everybody (very many?)
    - At least everybody active
  - Inactive participants (those not wanting in CS) slow you down
    - Need reply from all of them!
    - Lots of synchronization even if only one tries to get into CS
    - →→→ Lots of communication (many messages)
- Token based algorithms
  - Have token, that is enough
    - No synchronization with everybody else needed
  - Get token, send token is simple
    - Communicate only with a few (fewer) nodes
    - Scalable?
  - Mutex is trivial, how about deadlock and starvation?

Ricart-Agrawala Token-Pass Ideas

- Send token to next one only when I know that someone wants it
  - o/w keep token until needed
- Keep local *requested* array for best knowledge for the most recent CS request times
  - Update this based on received CS request messages
- Keep local *granted* array, that has precise knowledge when each node actually was last granted CS
  - Update it only when CS granted
  - Pass it with token to next node
    - Only this *granted* array (with token) is exactly correct!
    - Other nodes have (slightly) old *granted* array

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Algorithm 10.3: Ricart-Agrawala token-passing algorithm

```
boolean haveToken ← true in node 0, false in others
integer array[NODES] requested ← [0,...,0]
integer array[NODES] granted ← [0,...,0]
integer myNum ← 0
boolean inCS ← false

sendToken
  if exists N such that requested[N] > granted[N]
    for some such N
      send(token, N, granted)
      haveToken ← false

Receive
integer source, reqNum
loop forever
  receive(request, source, reqNum)
  requested[source] ← max(requested[source], reqNum)
  if haveToken and not inCS
    sendToken
```

Annotations:
- requested: local data in node
- granted: distributed global data
- If no one else wants token, I will keep it
- Receive: server process, runs all the time
- requested[N]: Ticket number for newest request for CS (that I know of)
- granted[N]: Ticket number last time in CS
- sendToken: Give also most recent *granted[]*

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Algorithm 10.3: Ricart-Agrawala token-passing algorithm (continued)

Main — application process, needs distr mutex

```
loop forever
   non-critical section
   if not haveToken
      myNum ← myNum + 1
      for all other nodes N
         send(request, N, myID, myNum)
      receive(token, granted)
      haveToken ← true
   inCS ← true
   critical section
   granted[myID] ← myNum
   inCS ← false
   sendToken
```

- If I have token, no delays.
- Request token from everybody. Very many messages?
- Just one very large message?
- Wait until token received
- Update one field
- Only if someone wants it! Send *granted* also.

- Mutex?
- No deadlock?
- No starvation?
  - "some" in sendToken?
- Scalable?
- Overflows?

Discuss

Algorithm 10.3: Ricart-…

Main — application proc…

Chloe's view

	Aaron	Becky	Chloe	Danielle	Evan
requested	4	3	0	5	1
granted	4	2	2	4	1

```
loop forever
   non-critical section
   if not haveToken
      myNum ← myNum + 1
      for all other nodes N
         send(request, N, myID, myNum)
      receive(token, granted)
      haveToken ← true
   inCS ← true
   critical section
   granted[myID] ← myNum
   inCS ← false
   sendToken
```

- Request token from everybody. Very many messages?
- Wait until token received
- Update one field
- Only if someone wants it! Send *granted* also.

- Can Chloe be 3rd time in CS?
- Who wants CS now?
- If Chloe has token, and is in non-CS, what happens next?
- If Chloe has token and is in CS, what happens next?
- Why is Chloe's own requested[i] zero?
- Could Becky have kept the token since last use?

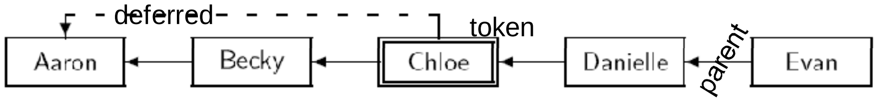
Neilsen-Mizuno Token Based Algorithm

- Rigart-Agrawala: token carries queue of waiting processes
  - Token can be very large, which may be problematic
- Neilsen-Mizuno: virtual tree structure within the nodes implements the queue

virtuaalinen virittävä (viritys-) puu

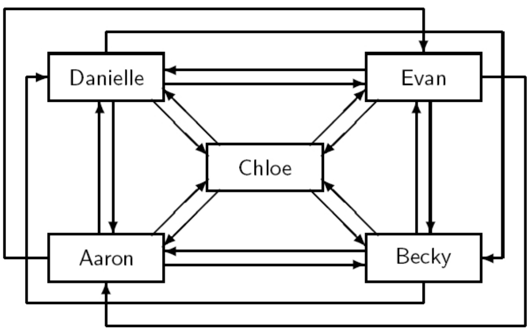
  - Algorithm utilizes *virtual spanning tree* of nodes
    - *Spanning tree:* all nodes linked as a tree, no cycles
  - Simple *token* indicates "turn" for critical section
  - *Parent* link points to the direction of last in line for CS
    - Parent == 0: node may have token and is last in line for CS
  - *Deferred* link points to next in line for CS

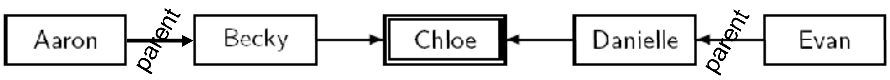
Chloe has token, Aaron is waiting for it



Neilsen-Mizuno Example

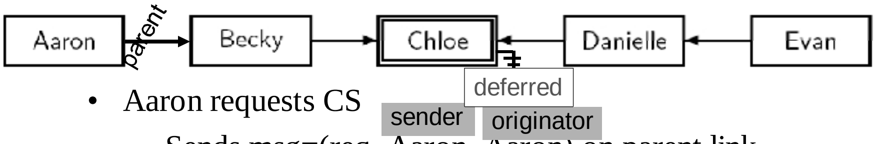
- Fully connected nodes
- Chloe is in CS
- No one waits for CS





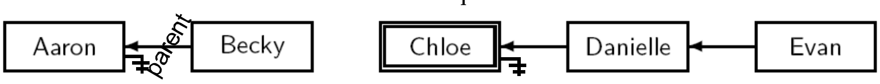
Neilsen-Mizuno Example (contd)

- Chloe has token, nobody waits for it



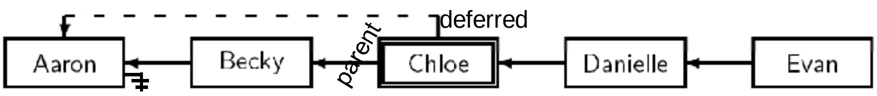
- Aaron requests CS
  - Sends msg=(req, Aaron, Aaron) on parent link
  - Removes himself from parent spanning tree

- Becky receives msg, and forwards the request “upward”
  - Sends msg=(req, Becky, Aaron) to Chloe
  - Moves to new parent spanning tree, points to Aaron
    - Aaron is now last to request CS



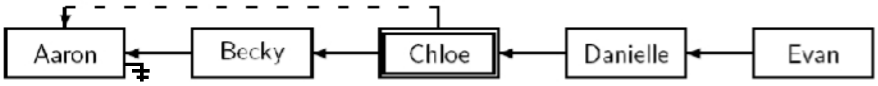
Neilsen-Mizuno Example (contd)

- Chloe receives msg (req, Becky, Aaron)
  - Chloe in CS, sets deferred field to Aaron and sets parent field to Becky
    - Chloe was (also) last in line for CS

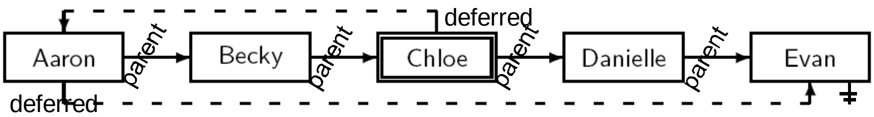


  - When Chloe completes CS, she will pass token to Aaron
    - Token transferred directly to the next process in line for critical section (if any)
      - Just token is passed, no big array with it

Neilsen-Mizuno Example (contd)



- Chloe still has CS, Evan wants CS
  - Sends (req, Evan, Evan) to Danielle
  - Danielle sends (req, Danielle, Evan) to Chloe
  - Chloe sends (req, Chloe, Evan) to Becky
  - Becky sends (req, Becky, Evan) to Aaron
  - Aaron makes a *deferred* link to Evan



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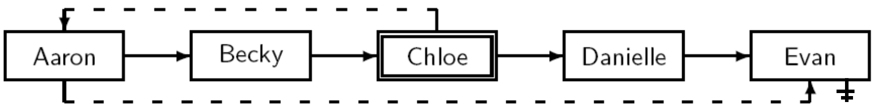
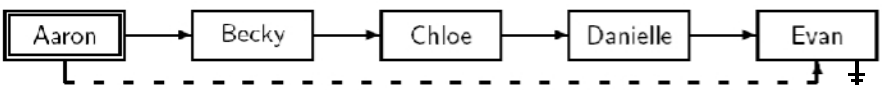
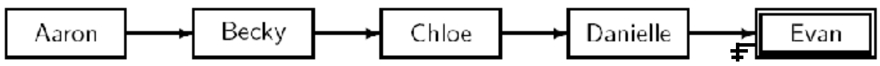
Neilsen-Mizuno Example (contd)



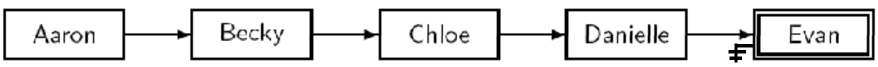
- Chloe completes CS, passes token to Aaron



- Aaron completes CS, passes token to Evan



- Evan completes CS, keeps token



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Algorithm 10.4: Neilsen-Mizuno token-passing algorithm

```
          integer parent ← (initialized to form a tree)
          integer deferred ← 0
          boolean holding ← true in the root, false in others
     Main
     loop forever
p1:    non-critical section
p2:    if not holding
p3:       send(request, parent, myID, myID)
p4:       parent ← 0
p5:       receive(token)
p6:    holding ← false
p7:    critical section
p8:    if deferred ≠ 0
p9:       send(token, deferred)
p10:      deferred ← 0
p11:   else holding ← true
```

Target node, not part of message

holding = have token, <u>not</u> in CS

mark latest request for CS

wait here until permission for CS obtained

someone wants the CS next

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Algorithm 10.4: Neilsen-Mizuno token-passing algorithm

Receive (runs concurrently with main, mutex problems solved…)

```
     integer source, originator
     loop forever
p12:   receive(request, source, originator)
p13:   if parent = 0                          last in queue
p14:      if holding                          have token, not in CS
p15:         send(token, originator)
p16:         holding ← false
p17:      else deferred ← originator          place new req last in queue
p18:   else send(request, parent, myID, originator)   forward request
p19:   parent ← source                        update direction for last request
```

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Ricart-Agrawala vs. Neilsen-Mizuno

- Number of messages needed?
- Size of messages?
- Size of data structures in each node?
- Behaviour with heavy load?
  - Many need CS at the same time
- Behaviour with light load?
  - Requests for CS do not come often
  - Usually only one process requests CS at a time

17.3.2011 31

Other Distributed Mutex Algorithms

- Other token-based algorithms
  - Token ring: token moves all the time
  - Lots of token traffic even when no CS requests
- Centralized server
  - Simple, not very many messages
  - Not scalable, may become bottleneck
- Give up unrealistic assumptions
  - Nodes may fail
  - Messages may get lost, token may get lost
- See other courses → Courses on distributed systems topics (hajautetut järjestelmät)

17.3.2011 32

Summary

- Distributed critical section is hard, avoid it
  - Use centralized solutions if possible?
- Permission based solutions
  - Ricart-Agrawala – ask everyone
- Token based solutions
  - Ricart-Agrawala – centralized state in granted[]
  - Neilsen-Mizuno – queue kept in spanning tree
- There are other algorithms
- How do they scale up?

17.3.2011 33