Distributed and Parallel Computing
Lecture 14

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Deadlocks

A *deadlock* is what the situation is called if a process is stuck in an infinite wait.

- A *communication deadlock* is where there is a cycle of processes each waiting for the next process in the cycle to send it a message
  - Process p will not send any message until it receives one from q, which will only send it after it receives a message from r, which will only send it after it receives a message from p.
- A *resource deadlock* is where there is a cycle of processes each waiting for a resource held by another process in the cycle
  - Process p wants to transfer money from account A to account B, has obtained a lock on A and is waiting to obtain a lock on B
  - Process q wants to transfer money from account B to account A, has obtained a lock on B and is waiting to obtain a lock on A

Dealing with Deadlocks

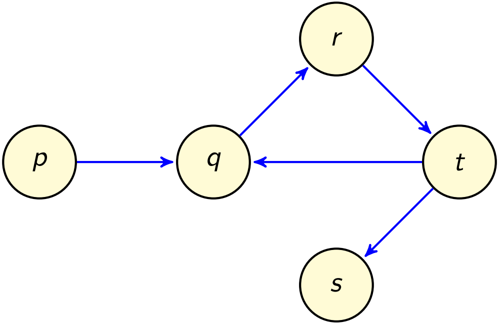
There are essentially 3 strategies for dealing with deadlocks:

- Make deadlocks impossible: Define protocols to ensure that a deadlock can never happen
  - e.g. require a process to obtain all necessary resources simultaneously before proceeding (if any cannot be obtained, release all held resources and try again)
  - Usually impractical and inefficient in distributed systems
- Avoid deadlocks
  - Only obtain resources if the global state ensures it is safe
  - Usually impractical in distributed systems
- Detect deadlocks
  - Detect deadlocks when they occur and break the chain by forcing one or more processes to fail, release their resources and recover

Waits-For Graph (WFG)

Model the deadlock state with a *Waits-For Graph (WFG)*

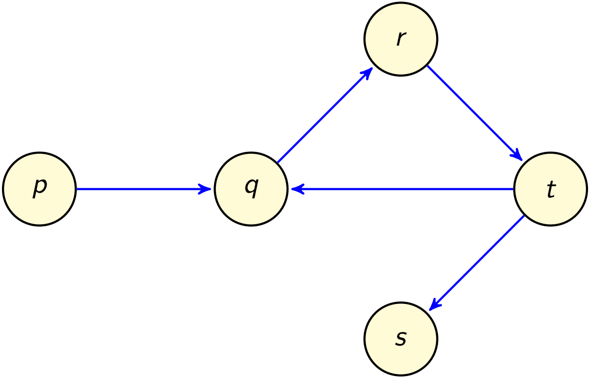
- Directed graph
- Nodes are processes
- Edge from p to q if p is blocked waiting for q to respond or release some resource
- In the simplest model, a cycle in the WFG $\Rightarrow$ deadlock



Deadlock Models

- *Single-resource* model:
  - A process can have at most one outstanding request for one (unit of a) resource
  - Cycle in WFG $\Rightarrow$ deadlock
  - Simplest model
- *AND* model
  - Each process can request multiple resources simultaneously and *all* requested resources must be supplied to unblock
  - Each node is called an *AND node*
  - Cycle in WFG $\Rightarrow$ deadlock
- *OR* model
  - Each process can request multiple resources simultaneously and *one* requested resource must be supplied to unblock
  - Each node is called an *OR node*
  - Cycle in WFG $\not\Rightarrow$ deadlock
  - *Knot* in WFG $\Rightarrow$ deadlock
  - a *knot* is a set of vertices such that every vertex u reachable from a knot vertex v can also reach v

OR Model Example



Cycle but no knot ⇒ no deadlock for OR-model

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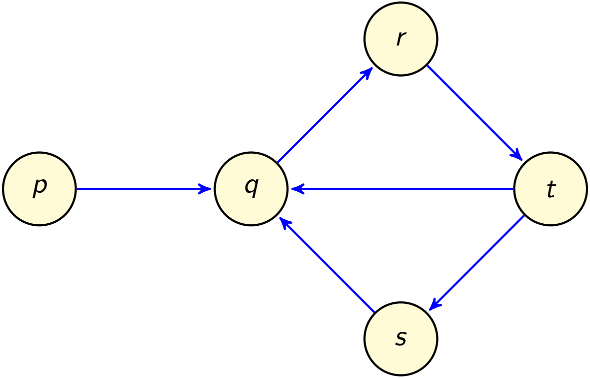


Knot $\{q, r, s, t\} \Rightarrow$ deadlock for OR-model

More Deadlock Models

- *AND-OR* model
  - Generalisation of both *AND* and *OR* models
  - Each process can request any combination of *AND* and *OR* requests simultaneously and *a set satisfying the requested condition* of requested resources must be supplied to unblock
    e.g. x and (y or z)
  - No simple graph structure whose presence identifies deadlock
- $\binom{p}{q}$ or q-out-of-p model
  - Equivalent to *AND-OR* model
  - Each process can request from p resources simultaneously and q from these resources must be supplied to unblock
  - An *AND* node is equivalent to a p-out-of-p node and an *OR* node is equivalent ot a 1-out-of-p node.
- *Unrestricted* model
  - No assumptions other than stability of deadlock (once it occurs, it does not release without action to break the deadlock being taken)
  - Only of theoretical interest because of high overhead

Deadlock Detection

Two problems need to be solved to implement deadlock detection in a distributed system:

1. How to maintain the WFG?
2. How to find cycles or knots in the WFG?

To be correct, a deadlock detection algorithm must guarantee:

1. *Progress:* All existing deadlocks must be found in finite time
   - Once all wait-for edges of a deadlock have formed in the WFG, the algorithm should be able to detect the deadlock without having to wait further
2. *Safety:* The algorithm should not report deadlocks that do not exist (*phantom deadlocks*)
   - No global memory or shared clocks $\Rightarrow$ processes have only partial knowledge of global state
   - $\Rightarrow$ processes may detect cycles in the WFG that never truly existed but which are composed of different parts that did exist in the system at different times
   - Main source of errors in published papers on deadlock detection

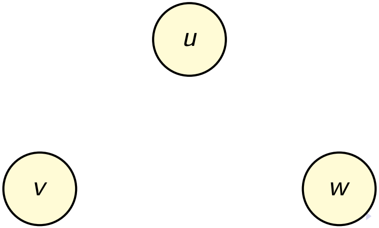
Conceptually, a WFG works as follows:

- There is one node v for each process v in the network
- A node v can be *active* or *blocked*
- An *active* node can make n-out-of-m requests of other nodes (and then becomes blocked) or grant requests to other nodes
- A *blocked* node can not make or grant requests but can become *active* if a sufficient number of its outstanding requests are granted
- When a *blocked* node with an outstanding n-out-of-m request has received n grants, it *purges* the remaining $m - n$ outstanding requests by informing the nodes involved that it no longer needs the resource requested

Mutually Exclusive Resources and the WFG

Mutually exclusive use of a resource requires a particular pattern on a WFG:

- u manages a mutually exclusive resource for v and w:



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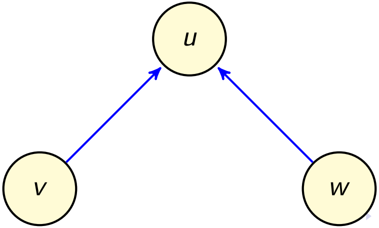

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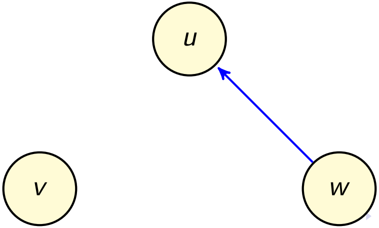
  - Problem: v holds the resource but nothing stops u granting w's request immediately



Mutually Exclusive Resources and the WFG

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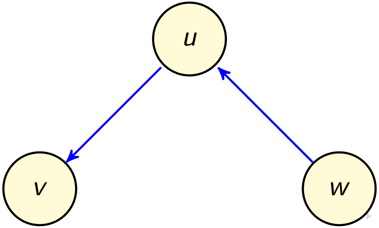
- Let u grants v's request first: then the edge $v \to u$ is removed
  - Problem: v holds the resource but nothing stops u granting w's request immediately
- Solution: granting v's request introduces a *new* dependency of u on v, which is modelled by adding an edge $u \to v$ for u to get back the resource from v



Representation of a Distributed WFG

We do not wish to centralise deadlock detection by getting the full global WFG onto a single node. Instead:

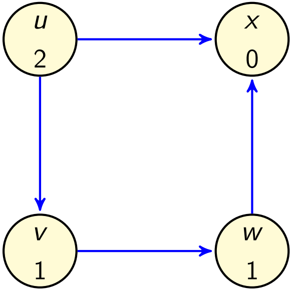
- Each node retains information about its local part of the WFG
- Distributed deadlock detection algorithm invoked by initiator:
  - Detects whether this node is deadlocked
  - Triggered after timeout when this node suspects it might be deadlocked

At each node u, have a number of variables:

- $\texttt{OUT}_u$: The set of nodes u has sent a request to that are not yet granted or purged
- $\texttt{IN}_u$: The set of nodes u has received a request from that are not yet granted or purged
- n_u: The number of grants that u currently needs to receive until it becomes unblocked. Note that $0 \leq n_u \leq |\texttt{OUT}_u|$ and $n_u = 0 \Leftrightarrow \texttt{OUT}_u = \{\}$

Rather than searching for cycles or knots in the WFG (NP-hard), we simulate granting of grantable requests in the WFG until no more requests can be granted and see if the initiator node is unblocked

- Initiator is u



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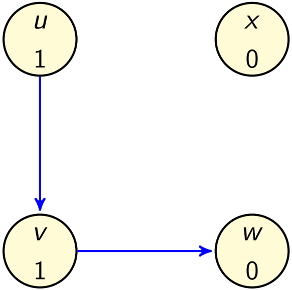

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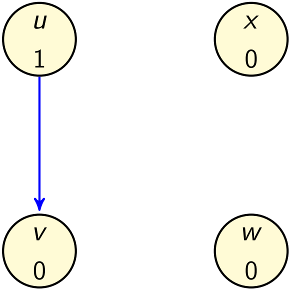

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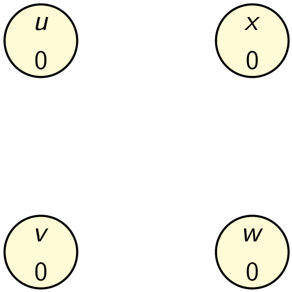

Bracha-Toueg Deadlock Detection Algorithm

Bracha-Toueg [1984] presented 3 variants of an algorithm for distributed deadlock detection:

1. On a network with instant messages where the base algorithm is static during deadlock detection
   - i.e. no requests, grants or purges occuring in parallel with deadlock detection
2. On a network with time delays in message delivery where the base algorithm is static
3. On a network with time delays in message delivery and the base algorithm is dynamic

Bracha-Toueg Deadlock Detection Algorithm

- Variation 1 requires that the $\mathtt{IN}_u$, $\mathtt{OUT}_u$ and n_u on each node u be pre-calculated from the local state and channel states of a globally consistent snapshot
- Variation 2 relaxes the need for the channel states to be used
- Variation 3 relaxes the need for a global snapshot to be pre-calculated
  - i.e. it integrates taking the snapshot with the deadlock detection

We will consider only the first variation, where we first apply a global snapshot algorithm which calculates $\mathtt{IN}_u$, $\mathtt{OUT}_u$ and n_u on each node u from the local and channel states.

Bracha-Toueg idea

Starting with the globally consistent $\texttt{IN}_u$, $\texttt{OUT}_u$ and n_u on each node u, execute 2 nested *Echo* algorithms to (virtually) construct a spanning tree of spanning trees.

- The first spanning tree is rooted at the initiator and traversed using Notify/Done messages
- The nested spanning trees are rooted at each active node, traversed using Grant/Ack messages and propagate all grants through the WFG

The Bracha-Toueg Algorithm

Initially: $\forall u, \texttt{notified}_u = \texttt{free}_u = \texttt{False}$. Initiator calls Notify()

$\texttt{Notify}_u()$:
- $\texttt{notified}_u \leftarrow \texttt{True}$
- for all $w \in \texttt{OUT}_u$, send $\langle\texttt{NOTIFY}\rangle$ to w
- if $n_u = 0$, then $\texttt{Grant}_u()$
- for all $w \in \texttt{OUT}_u$, await $\langle\texttt{DONE}\rangle$ from w

$\texttt{Grant}_u()$:
- $\texttt{free}_u \leftarrow \texttt{True}$
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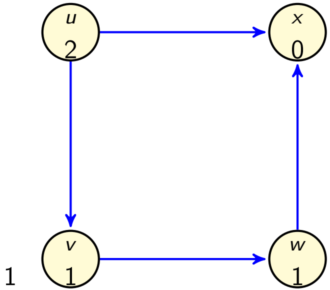
On receive $\langle\texttt{NOTIFY}\rangle$:
- If not $\texttt{notified}_u$, then $\texttt{Notify}_u()$
- u sends back $\langle\texttt{DONE}\rangle$

On receive $\langle\texttt{GRANT}\rangle$:
- If $n_u > 0$, then
  - $n_u \leftarrow n_u - 1$
  - if $n_u = 0$, then $\texttt{Grant}_u()$
- u sends back $\langle\texttt{ACK}\rangle$

Initiator u is not deadlocked if $\texttt{free}_u$ is True at the end

A node awaiting $\langle\texttt{DONE}\rangle$ or $\langle\texttt{ACK}\rangle$ can process incoming $\langle\texttt{NOTIFY}\rangle$ and $\langle\texttt{GRANT}\rangle$ messages.



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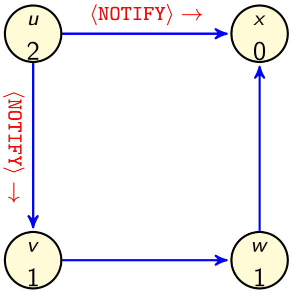

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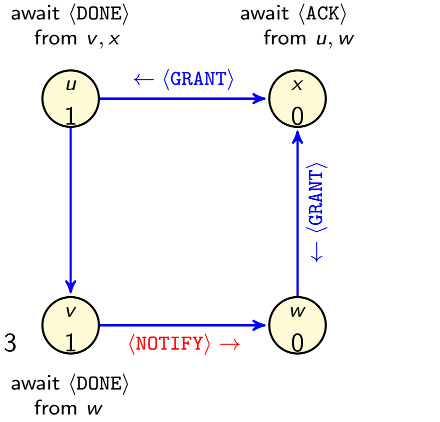

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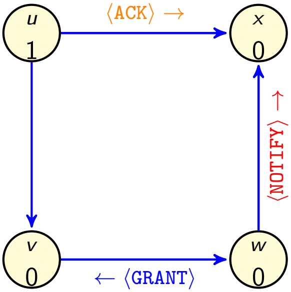

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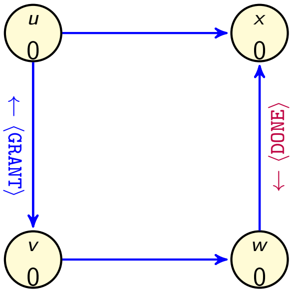

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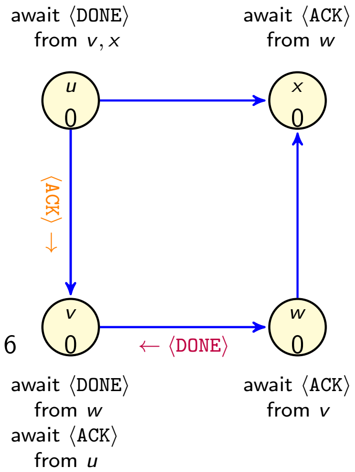

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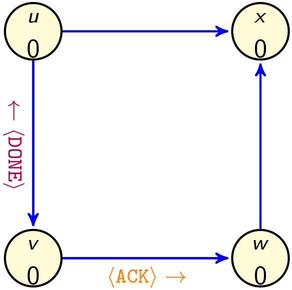

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Initiator u is not deadlocked if $\texttt{free}_u$ is True at the end

A node awaiting $\langle\texttt{DONE}\rangle$ or $\langle\texttt{ACK}\rangle$ can process incoming $\langle\texttt{NOTIFY}\rangle$ and $\langle\texttt{GRANT}\rangle$ messages.

await $\langle\texttt{DONE}\rangle$
from x

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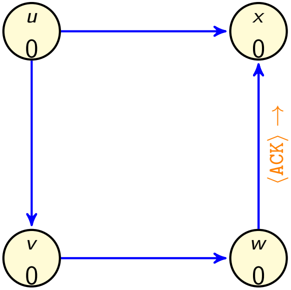


The Bracha-Toueg Algorithm

Initially: $\forall u, \texttt{notified}_u = \texttt{free}_u = \texttt{False}$. Initiator calls $\texttt{Notify}()$

$\texttt{Notify}_u()$:
- $\texttt{notified}_u \leftarrow \texttt{True}$
- for all $w \in \texttt{OUT}_u$, send $\langle\texttt{NOTIFY}\rangle$ to w
- if $n_u = 0$, then $\texttt{Grant}_u()$
- for all $w \in \texttt{OUT}_u$, await $\langle\texttt{DONE}\rangle$ from w

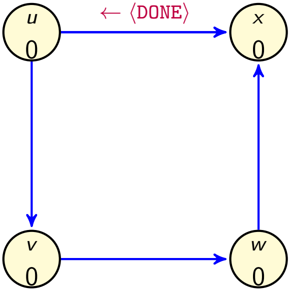
$\texttt{Grant}_u()$:
- $\texttt{free}_u \leftarrow \texttt{True}$
- for all $w \in \texttt{IN}_u$ send $\langle\texttt{GRANT}\rangle$ to w
- for all $w \in \texttt{IN}_u$ await $\langle\texttt{ACK}\rangle$ from w

On receive $\langle\texttt{NOTIFY}\rangle$:
- If not $\texttt{notified}_u$, then $\texttt{Notify}_u()$
- u sends back $\langle\texttt{DONE}\rangle$

On receive $\langle\texttt{GRANT}\rangle$:
- If $n_u > 0$, then
  - $n_u \leftarrow n_u - 1$
  - if $n_u = 0$, then $\texttt{Grant}_u()$
- u sends back $\langle\texttt{ACK}\rangle$

Initiator u is not deadlocked if $\texttt{free}_u$ is $\texttt{True}$ at the end

A node awaiting $\langle\texttt{DONE}\rangle$ or $\langle\texttt{ACK}\rangle$ can process incoming $\langle\texttt{NOTIFY}\rangle$ and $\langle\texttt{GRANT}\rangle$ messages.



9

The Bracha-Toueg Algorithm

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$\texttt{Grant}_u()$:

$\texttt{free}_u \leftarrow \texttt{True}$
for all $w \in \texttt{IN}_u$ send $\langle\texttt{GRANT}\rangle$ to w
for all $w \in \texttt{IN}_u$ await $\langle\texttt{ACK}\rangle$ from w

On receive $\langle\texttt{NOTIFY}\rangle$:

If not $\texttt{notified}_u$, then $\texttt{Notify}_u()$
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On receive $\langle\texttt{GRANT}\rangle$:

If $n_u > 0$, then
$n_u \leftarrow n_u - 1$
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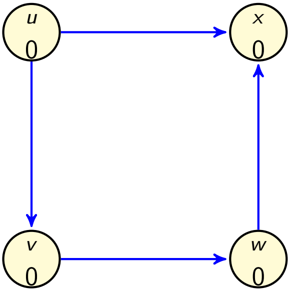

Bracha-Toueg doesn't guarantee that a deadlock won't occur in the future: only whether the initiator is deadlocked or not.

- The global snapshot will capture the state either before the resource is handed off to the first requestor, or after.
- The WFG will be different in the two cases
- Bracha-Toueg will give the correct answer for the particular case of the WFG that appears in the global state, even if the next operation would necessarily put the node into deadlock