Computer Science 425
Distributed Systems

CS 425 / ECE 428

Fall 2014

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Lecture 26

Self-Stabilization

Reading: Relevant sections from Ghosh's textbook

Motivation

- As the number of computing elements increase in distributed systems failures become more common
- We desire that fault-tolerance should be automatic, without external intervention
- Two kinds of fault tolerance
  - masking: application layer does not see faults, e.g., redundancy and replication
  - non-masking: system deviates, deviation is detected and then corrected: e.g., roll back and recovery
- Self-stabilization is a general technique for non-masking distributed systems
- We deal only with transient failures which corrupt data, but not crash-stop failures

Self-stabilization

- **Technique for spontaneous healing**
- **Guarantees eventual safety following failures**

Feasibility demonstrated by Dijkstra (CACM `74)

E. Dijkstra

Self-stabilizing systems

- **Recover from any initial configuration to a legitimate configuration in a bounded number of steps, as long as the processes are not further corrupted**

- **Assumption:**

  Failures affect the state (and data) but not the program code

Self-stabilizing systems

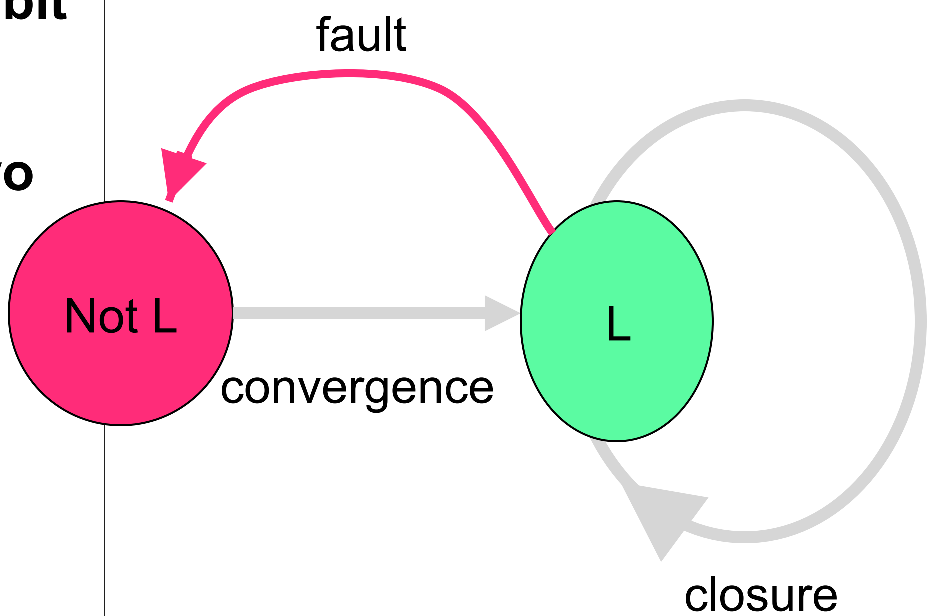
- The ability to spontaneously recover from any initial state implies that no initialization is ever required.

- Such systems can be deployed ad hoc, and are guaranteed to function properly within bounded number of steps

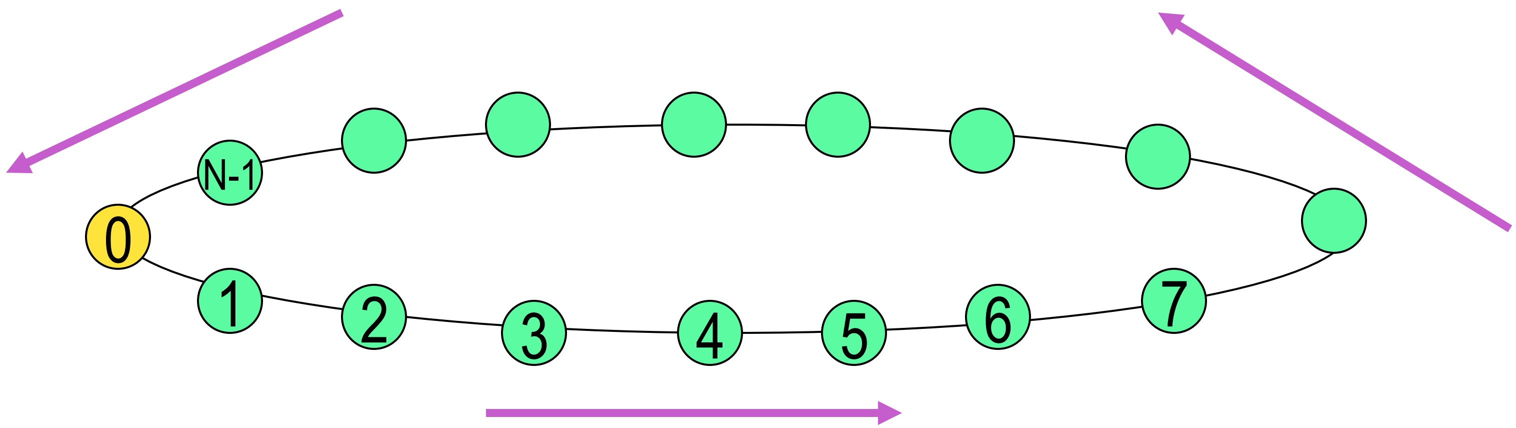
- Guarantees-fault tolerance when the mean time between failures (MTBF) >> mean time to recovery (MTTR)

Self-stabilizing systems

- Self-stabilizing systems exhibit non-masking fault-tolerance
- They satisfy the following two criteria
  - Convergence
  - Closure



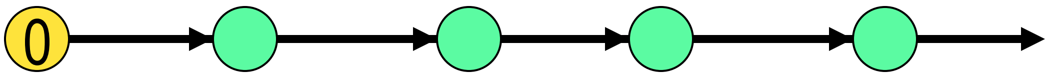
Example 1: Stabilizing mutual exclusion in unidirectional ring



Consider a unidirectional ring of processes.
Counter-clockwise ring.
One special process (yellow above) is process with id=0
Legal configuration = exactly one token in the ring (Safety)
Desired "normal" behavior: single token circulates in the ring

Dijkstra's stabilizing mutual exclusion

N processes: 0, 1, …, N-1
state of process j is x[j] ∈ {0, 1, 2, K-1}, where K > N



p_0 **if** x[0] = x[N-1] **then** x[0] := x[0] + 1

p_j j > 0 **if** x[j] ≠ x[j -1] **then** x[j] := x[j-1]

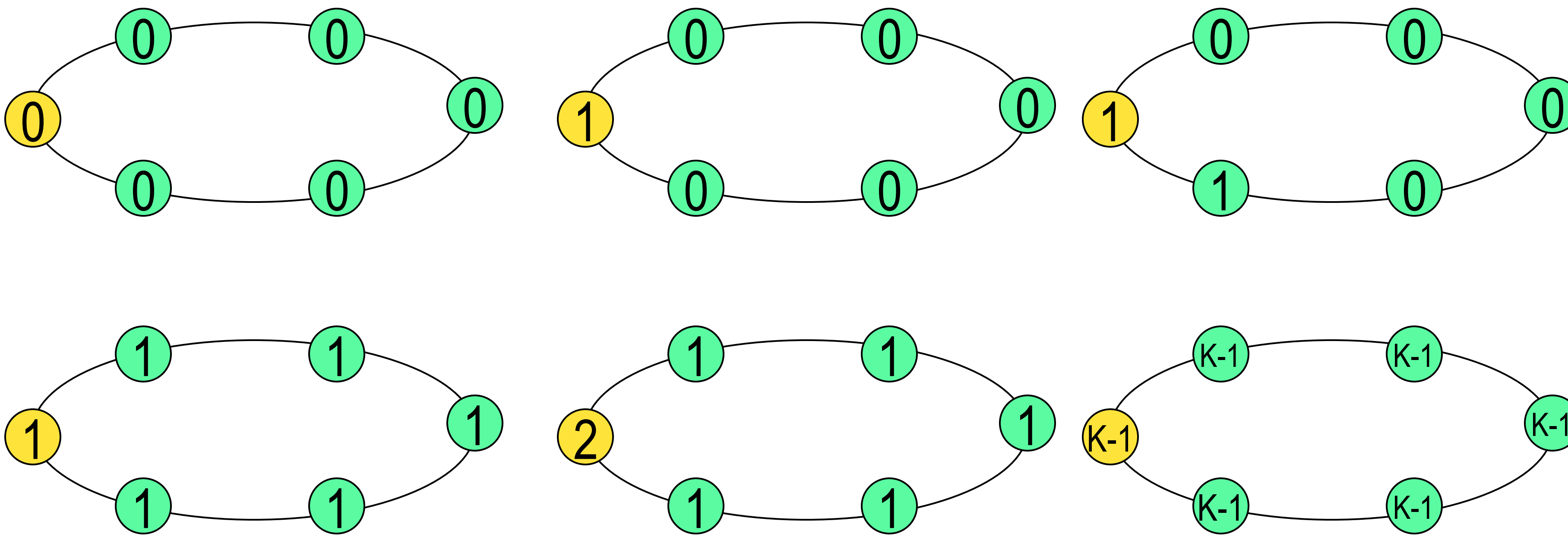
Wrap-around after K-1

TOKEN is @ a process p = "if" condition is true @ process p

Legal configuration: only one process has token

Can start the system from an arbitrary initial configuration

Example execution



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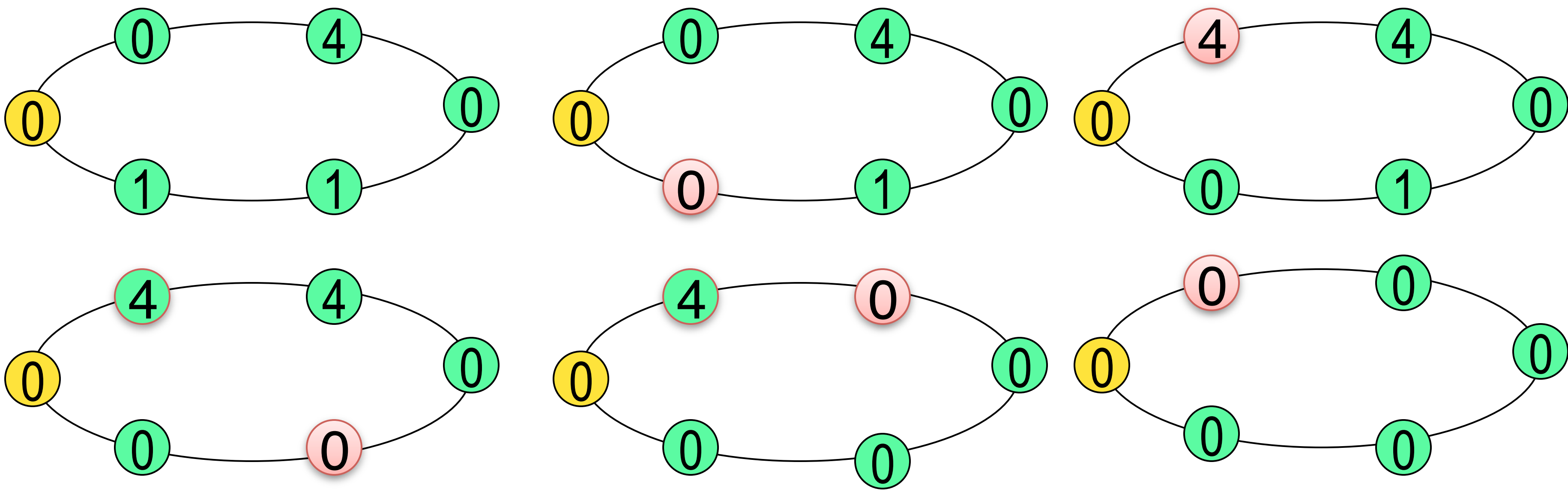
Stabilizing execution

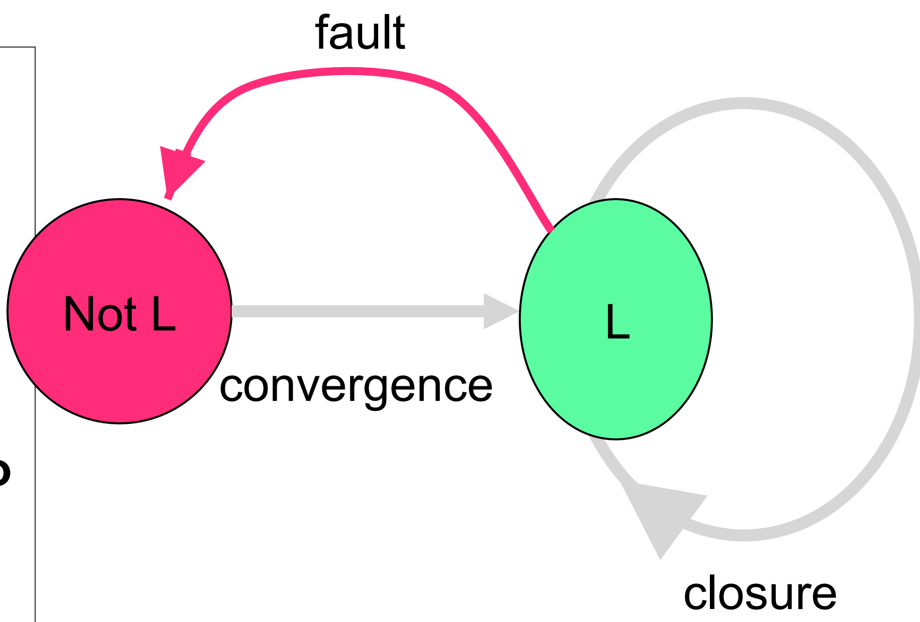


p_0 **if** $x[0] = x[N-1]$ **then** $x[0] := x[0] + 1$

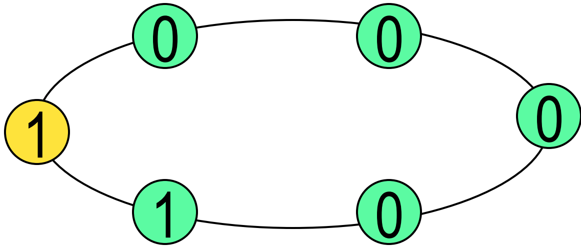
p_j $j > 0$ **if** $x[j] \neq x[j-1]$ **then** $x[j] := x[j-1]$

What Happens

- **Legal configuration = a configuration with a single token**
- **Perturbations or failures take the system to configurations with multiple tokens**
  - **e.g. mutual exclusion property may be violated**
- **Within finite number of steps, if no further failures occur, then the system returns to a legal configuration**

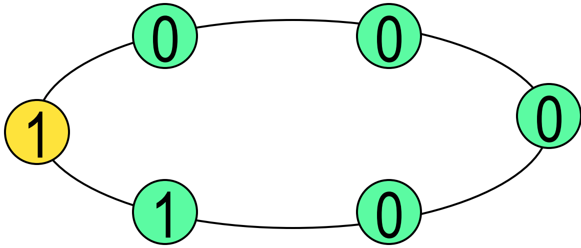


Why does it work ?



1. At any configuration, at least one process can make a move (has token)
2. Set of legal configurations is closed under all moves
3. Total number of possible moves from (successive configurations) never increases
4. Any illegal configuration C converges to a legal configuration in a finite number of moves

Why does it work ?

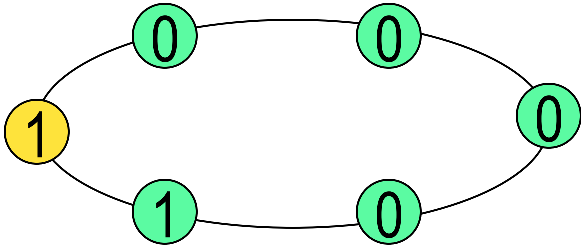


1. At any configuration, at least one process can make a move (has token), i.e., if condition is false at all processes
   - Proof by contradiction: suppose no one can make a move
   - Then $p_1,\ldots,p_{N-1}$ cannot make a move
   - Then x[N-1] = x[N-2] = … x[0]
   - But this means that p_0 can make a move => contradiction

p_0 **if** x[0] = x[N-1] **then** x[0] := x[0] + 1

p_j j > 0 **if** x[j] ≠ x[j -1] **then** x[j] := x[j-1]

Why does it work ?



1. At any configuration, at least one process can make a move (has token)
2. Set of legal configurations is <u>closed</u> under all moves
   - If only p_0 can make a move, then for all i,j: x[i] = x[j]. After p_0's move, only p_1 can make a move
   - If only pi (i≠0) can make a move
     » for all j < i, x[j] = x[i-1]
     » for all k ≥ i, x[k] = x[i], and
     » x[i-1] ≠ x[i]
     » x[0] ≠ x[N-1]

   in this case, after p_i's move only p_{i+1} can move

p_0 **if** x[0] = x[N-1] **then** x[0] := x[0] + 1

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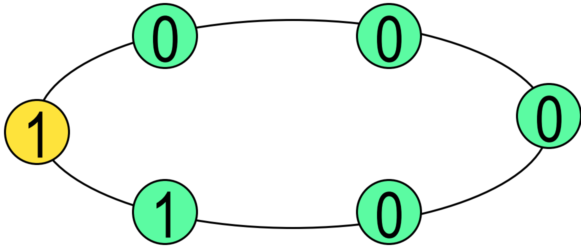

1. **At any configuration, at least one process can make a move (has token)**
2. **Set of legal configurations is closed under all moves**
3. **Total number of possible moves from (successive configurations) never increases**
   - **any move by p_i either enables a move for p_{i+1} or none at all**

p_0 **if** x[0] = x[N-1] **then** x[0] := x[0] + 1

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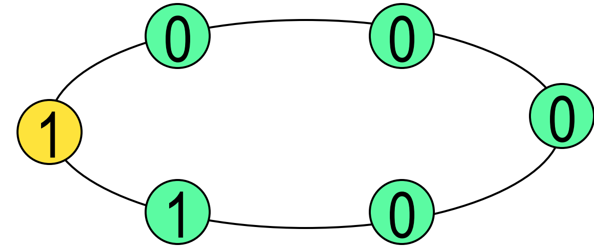

1. At any configuration, at least one process can make a move (has token)
2. Set of legal configurations is closed under all moves
3. Total number of possible moves from (successive configurations) never increases
4. Any illegal configuration C converges to a legal configuration in a finite number of moves
   - There must be a value, say v, that does not appear in C (since K > N)
   - Except for p_0, none of the processes create new values (since they only copy values)
   - Thus p_0 takes infinitely many steps, and since it only self-increments, it eventually sets x[0] = v (within K steps)
   - Soon after, all other processes copy value v and a legal configuration is reached in N-1 steps

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Putting it All Together

- **Legal configuration = a configuration with a single token**
- **Perturbations or failures take the system to configurations with multiple tokens**
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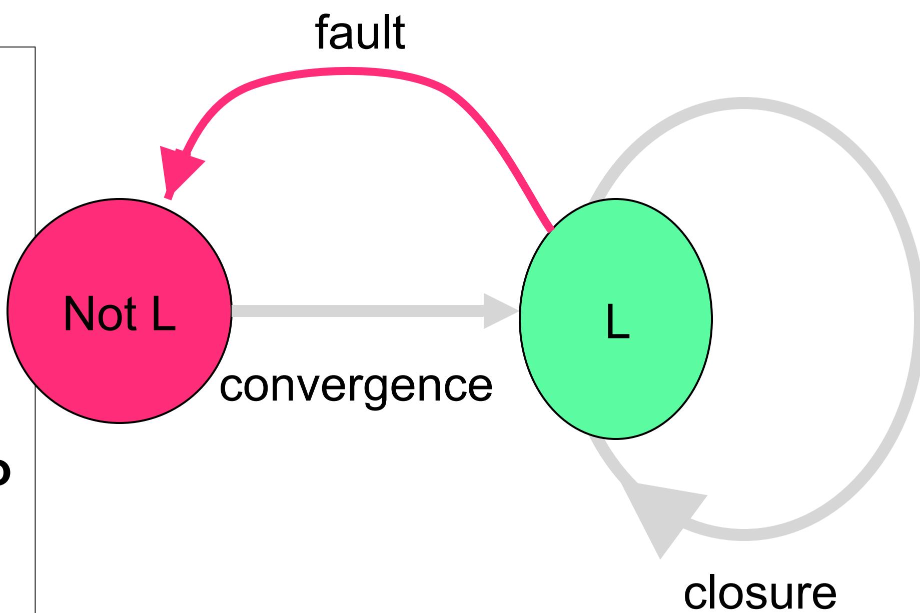

Summary

- Many more self-stabilizing algorithms
  - Self-stabilizing distributed spanning tree
  - Self-stabilizing distributed graph coloring
  - Not covered in the course – look them up on the web!

Reminders

- MP2, HW4 due soon after break
  - I hope you've already started. If not, start now! Don't start after break; it's too late then.

- Only 3 lectures left!

- Have a good Thanksgiving break!

- (No lectures or office hours next week)