6.852: Distributed Algorithms
Fall, 2009

Class 24

Today's plan

- Self-stabilization
- Self-stabilizing algorithms:
  - Breadth-first spanning tree
  - Mutual exclusion
- Composing self-stabilizing algorithms
- Making non-self-stabilizing algorithms self-stabilizing
- Reading:
  - [Dolev, Chapter 2]
- Next time:
  - Partially synchronous distributed algorithms
  - Clock synchronization
  - Reading:
    - Chapters 23-25
    - [Attiya, Welch] Section 6.3, Chapter 13

Self-stabilization

- A useful fault-tolerance property for distributed algorithms.
- Algorithm can start in any state---arbitrarily corrupted.
- From there, if it runs normally (usually, without any further failures), it eventually gravitates back to correct behavior.
- [Dijkstra 73: Self-Stabilizing Systems in Spite of Distributed Control]
  - Dijkstra's most important contribution to distributed computing theory.
  - [Lamport talk, PODC 83] Reintroduced the paper, explained its importance, popularized it.
  - Became (still is) a major research direction.
  - Won PODC Influential Paper award, in 2002.
  - Award renamed the Dijkstra Prize.
- [Dolev book, 00] summarizes main ideas of the field.

Today…

- Basic ideas, from [Dolev, Chapter 2]
- Rest of the book describes:
  - Many more self-stabilizing algorithms.
  - General techniques for designing them.
  - Converting non-SS algorithms to SS algorithms.
  - Transformations between models, preserving SS.
  - SS in presence of ongoing failures.
  - Efficient SS.
  - Etc.

Self-Stabilization: Definitions

Self-stabilization

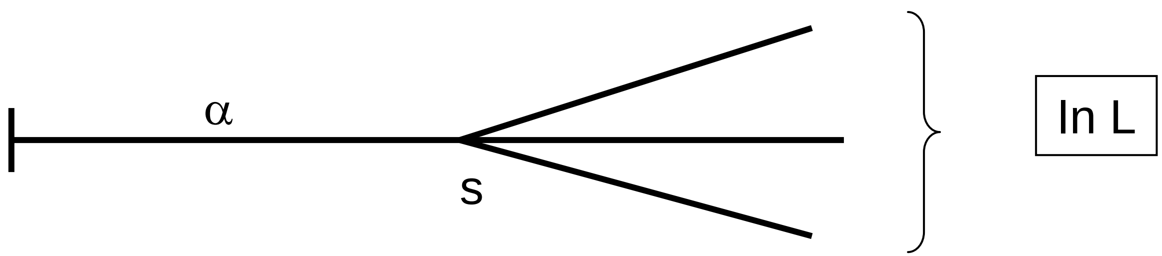
- [Dolev] considers:
  - Message-passing models, with FIFO reliable channels.
  - Shared-memory models, with read/write registers.
  - Asynchronous and synchronous models.
- To simplify, avoids internal process actions---combines these with sends, receives, or register access steps.
- Sometimes considers message losses (“loss” steps).
- Many models, must continually specify which is used.
- Defines executions:
  - Like ours, but needn’t start in initial state.
  - Same as our “execution fragments”.
- Fair executions:
  - Described informally.
  - Our task-based definition is fine.

Legal execution fragments

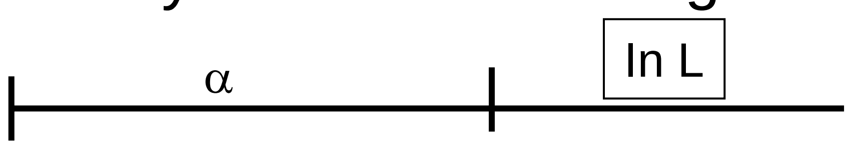
- Given a distributed algorithm A, define a set L of legal execution fragments of A.
- L can include both safety and liveness conditions.
- Example: Mutual exclusion problem
  - L might be the set of all fragments α satisfying:
    - Mutual exclusion:
      - No two processes are in the critical region, in any state in α.
    - Progress:
      - If in some state of α, someone is in T and no one is in C, then sometime thereafter, someone $\rightarrow$ C.
      - If in some state of α, someone is in E, then sometime thereafter, someone $\rightarrow$ R.

Self-stabilization: Definition

- A global state s of algorithm A is safe with respect to legal set L, provided that every fair execution fragment of A that starts with s is in L.
- Algorithm A is self-stabilizing for legal set L if every fair execution fragment α of A contains a state s that is safe with respect to L.
  - Implies that the suffix of α starting with s is in L.
  - Also, any other fair execution fragment starting with s is in L.



- Weaker definition: Algorithm A is self-stabilizing for legal set L if every fair execution fragment α has a suffix in L.



Stronger vs. weaker definition of self-stabilization

- Stronger definition: Algorithm A is self-stabilizing for legal set L if every fair execution fragment of A contains a state s that is safe with respect to L.
- Weaker definition: Algorithm A is self-stabilizing for legal set L if every fair execution fragment has a suffix in L.

- [Dolev] generally uses the stronger definition; so will we.
- But occasionally, he appears to be using the weaker definition; we'll warn when this arises.

- Q: Equivalent definitions? Not in general. LTTR.

Non-termination

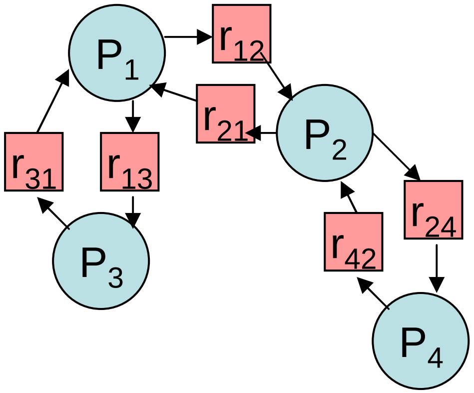
- Self-stabilizing algorithms for nontrivial problems don't terminate.

- E.g., consider message-passing algorithm A:
  - Suppose A is self-stabilizing for legal set L, and A has a terminating global state s.
    - All processes quiescent, all channels empty.
  - Consider a fair execution fragment α starting with s.
  - α contains no steps---just global state s.
  - Since A is self-stabilizing with respect to L, α must contain a safe state.
  - So s must be a safe state.
  - Then the suffix of α starting with s is in L; that is, just s itself is in L.
  - So L represents a trivial problem---doing nothing satisfies it.

- Similar argument for shared-memory algorithms.

Self-Stabilizing Algorithm 1: Self-Stabilizing Breadth-First Spanning Tree Construction

Breadth-first spanning tree



- Shared-memory model
- Connected, undirected graph G = (V,E).
- Processes $P_1,\ldots,P_n$, P_1 a designated root.
- Permanent knowledge (built into all states of the processes):
  - P_1 always knows it's the root.
  - Everyone always knows who their neighbors are.
- Neighboring processes in G share registers in both directions:
  - r_{ij} written by P_i, read by P_j.
- Output: A breadth-first spanning tree, recorded in the r_{ij} registers:
  - r_{ij}.parent = 1 if j is i's parent, 0 otherwise.
  - r_{ij}.dist = distance from root to i in the BFS tree = smallest number of hops on any path from 1 to i in G.
  - Values in registers should remain constant from some point onward.

In terms of legal sets…

- Define execution fragment α to be legal if:
  - The registers have correct BFS output values, in all states in α.
  - Registers never change.
- L = set of legal execution fragments.
- Safe state s:
  - Global state from which all extensions have registers with correct, unchanging BFS output values.
- SS definition says:
  - Any fair execution fragment α, starting from any state, contains some safe state s.
  - That is, one from which all extensions have registers with correct, unchanging BFS output values.
  - Implies that any fair execution fragment α has a suffix in which the register contents represent a fixed BFS tree.

BFS Algorithm strategy

- The system can start in any state, with
  - Any values (of the allowed types) in registers,
  - Any values in local process variables.
- Processes can’t assume that their own states and output registers are initially correct.

- Repeatedly recalculate states and outputs based on inputs from neighbors.
- In case of tie, use some default rule for selecting parent.

- Prove correctness, stabilization time, using induction on distance from root.

Root process P_1

do forever

    for every neighbor m do

        write r_{1m} := (0,0)

You're not my parent

My distance from root

- Keep writing (0,0) everywhere.
- Access registers in fixed, round-robin order.

Non-root process P_i

- Maintains local variables lr_{ji} to hold latest observed values of incoming registers r_{ji}.
- First loop:
  - Read all the r_{ji}, copy them into lr_{ji}.
- Use this local info to calculate new best distance dist, choose a parent that yields this distance.
  - Use default rule, e.g., smallest index, so always break ties the same way.
  - Needed to ensure stabilization to a fixed tree.
- Second loop:
  - Write dist to all outgoing registers.
  - Notify new parent.

Non-root process P_i

- do forever
  - for every neighbor m do
    - lr_{mi} := read(r_{mi})
  - dist := min({ lr_{mi}.dist }) + 1
  - found := false
  - for every neighbor m do
    - if not found and dist = lr_{mi}.dist + 1 then
      - write r_{im} := (1,dist)
      - found := true
    - else
      - write r_{im} := (0,dist)

- Note:
  - P_i doesn't take min of its own dist and neighbors' dists.
  - Unlike non-SS relaxation algorithms.
  - Ignores its own dist, recalculates solely from neighbors' dists.
  - Because its own value could be erroneous.

Correctness

- Prove this stabilizes to a particular "default" BFS tree.
- Define the default tree to be the unique BFS tree where ties in choosing parent are resolved using the rule:
  - Choose the smallest index yielding the shortest distance.
- Prove that, from any starting global state, the algorithm eventually reaches and retains the default BFS tree.
- More precisely, show it reaches a safe state, from which any execution fragment retains the default BFS tree.

- Show this happens within bounded time: $O(diam\ \Delta\ l)$, where
  - diam is diameter of G (max distance from P_1 to anyone is enough).
  - Δ is maximum node degree
  - l is upper bound on local step time
  - The constant in the big-O is about 4.

Correctness

- Uses a lemma marking progress through distances 0, 1, 2,..., diam, as for basic AsynchBFS.
- New complication: Erroneous, too-small distance estimates.
- Define a floating distance in a global state to be a value of some r_{ij}.dist that is strictly less than the actual distance from P_1 to P_i.
  - Can't be correct.

- Lemma: For every $k \geq 0$, within time $(4k+1)\Delta l$, we reach a configuration such that:
  1. For any i with dist(P_1,P_i) $\leq$ k, every r_{ij}.dist is correct.
  2. There is no floating distance < k.

- Moreover, these properties persist after this configuration.

Proof of lemma

- Lemma: For every $k \geq 0$, within time $(4k+1)\Delta l$, we reach a configuration such that:
  1. For any i with $dist(P_1,P_i) \leq k$, every $r_{ij}.dist$ is correct.
  2. There is no floating distance $< k$.

- Proof: Induction on k.
  - $k = 0$: P_1 writes (0,0) everywhere within time Δl.
  - Assume for k, prove for k+1:
    - Property 1:
      - Consider P_i at distance k+1 from P_1.
      - In one more interval of length $4\Delta l$, P_i has a chance to update its local dist and outgoing register values.
      - By inductive hypothesis, these updates are based entirely on:
        - » Correct distance values from nodes with distance $\leq k$ from P_1, and
        - » Possibly some floating values, but these must be $\geq k$.
      - So P_i will calculate a correct distance value.
    - Property 2:
      - For anyone to calculate a floating distance $< k+1$, it must see a floating distance $< k$.
      - Can't, by inductive hypothesis.

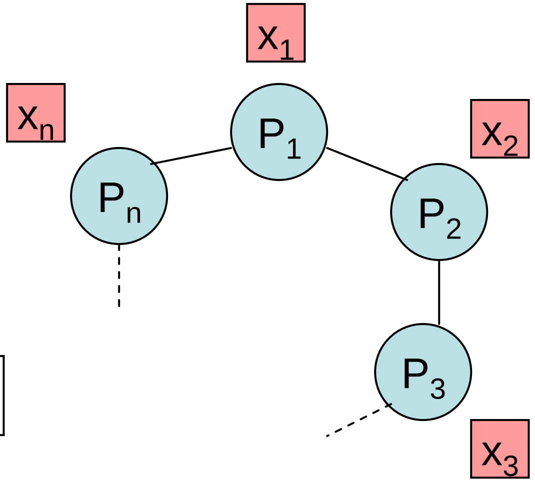
Proof, cont'd

- We have proved:
  - Lemma: For every $k \geq 0$, within time $(4k+1)\Delta l$, we reach a configuration such that:
    1. For any i with $dist(P_1,P_i) \leq k$, every $r_{ij}.dist$ is correct.
    2. There is no floating distance < k.
- So within time (4 diam +1) Δl, all the $r_{ij}.dist$ values become correct.
- Persistence is easy to show.
- Once all the $r_{ij}.dist$ values are correct, everyone will use the default rule and always obtain the default BFS tree.
- Ongoing failures:
  - If arbitrary failures occur from time to time, not too frequently, the algorithm gravitates back to correct behavior in between failures.
  - Recovery time depends on size (diameter) of the network.

Self-Stabilizing Algorithm 2: Self-Stabilizing Mutual Exclusion

Self-stabilizing mutual exclusion

- [Dijkstra 73]
- Ring of processes, each with output variable x_i.
- Large granularity: In one atomic step, process P_i can read both neighbors' variables, compute its next value, and write it to variable x_i.



P_1:

do forever:

if $x_1 = x_n$ then $x_1 := x_1 + 1 \bmod (n+1)$

That's (n+1), not n.

P_i, $i \neq 1$:

do forever:

if $x_i \neq x_{i-1}$ then $x_i := x_{i-1}$

- P_1 tries to make its variable one more than its predecessor's (mod n+1).
- Each other process tries to make its variable equal to its predecessor's

Mutual exclusion

- In what sense does this "solve mutual exclusion"?
- Definition: "P_i is enabled" (or "P_i can change its state") in a configuration, if the variables are set so P_i can take a step and change the value of its variable x_i.
- Legal execution fragment α:
  - In any state in α, exactly one process is enabled.
  - For each i, α contains infinitely many states in which P_i is enabled.
- Use this to solve mutual exclusion:
  - Say P_i interacts with requesting user U_i.
  - P_i grants U_i the critical section when:
    - U_i has requested it, and
    - P_i is enabled.
  - When U_i returns the resource, P_i actually does its step, changing x_i.
  - Guarantees mutual exclusion, progress.
  - Also lockout-freedom.

Lemma 1

- Legal α:
  - In any state in α, exactly one process is enabled.
  - For each i, α contains infinitely many states in which P_i is enabled.

- Lemma 1: A configuration in which all the x variables have the same value is safe.
- This means that, from such a configuration, any fair execution fragment is legal.
- Proof: Only P_1 can change its state, then P_2, then P_3, …, and so on around the ring (forever).

- Remains to show: Starting from any state, the algorithm eventually reaches a configuration in which all the x values are the same.
- This uses some more lemmas.

Lemma 2

- Lemma 2: In every configuration, at least one of the potential x values, {0,…,n}, does not appear in any x_i.
- Proof: Obviously. There are n+1 values and only n variables.

Lemma 3

- Lemma 3: In any fair execution fragment (from any configuration c), P_1 changes x_1 at least once every nl time.
- Proof:
  - Assume not---P_1 goes longer than nl without changing x_1 from some value v.
  - Then by time l, P_2 sets x_2 to v,
  - By time 2l, P_3 sets x_3 to v,
  - …
  - By (n-1)l, P_n sets x_n to v.
  - All these values remain = v, as long as x_1 doesn't change.
  - But then by time nl, P_1 sees $x_n = x_1 = v$, and increments x_1.

Lemma 4

- Lemma 4: In any fair execution fragment α, a configuration in which all the x values are the same (and so, a safe configuration) occurs within time $(n^2 + n)l$.
- Proof:
  - Let c = initial configuration of α.
  - Let v = some value that doesn't appear in any x_i, in c.
  - Then v doesn't appear anywhere, in α, unless/until P_1 sets $x_1 := v$.
  - Within time nl, P_1 changes x_1, incrementing it by 1, mod (n+1).
  - Within another nl, P_1 increments x_1 again.
  - …
  - Within n^2l, P_1 increments x_1 to v.
  - At that point, there are still no other v's anywhere else.
  - Then this v propagates all the way around the ring.
  - P_1 doesn't change x_1 until v reaches x_n.
  - Yields all $x_i = v$, within time $(n^2 + n)l$.

Putting the pieces together

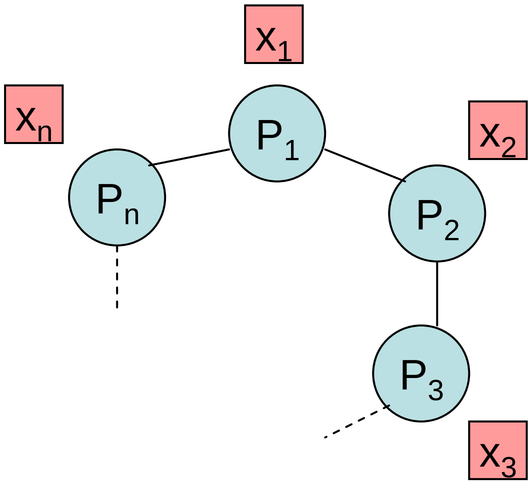
- Legal execution fragment α:
  - In any state in α, exactly one process is enabled.
  - For each i, α contains infinitely many states in which P_i is enabled.
- L = set of legal fragments.

- Theorem: Dijkstra's algorithm is self-stabilizing with respect to legal set L.
- In the sense of reaching a safe state.

- Remark:
  - This uses n+1 values for the x_i variables.
  - A curiosity:
    - This also works with n values, or even n-1.
    - But not with n-2 [Dolev, p. 20].

Reducing the atomicity

- Dijkstra's algorithm reads x_{i-1}, computes, and writes x_i, all atomically.
- Now adapt this for usual model, in which only individual read/write steps are atomic.



- Consider Dijkstra's algorithm on a 2n-process ring, with processes Q_j, variables y_j. j = 1, 2, …, 2n.
  - Needs 2n+1 values for the variables.

- Emulate this in the usual n-process ring, with processes P_i, variables x_i:
  - P_i emulates both Q_{2i-1} and $Q_{2i.}$
  - y_{2i-1} is a local variable of P_i.
  - y_{2i} corresponds to x_i.

Reducing the atomicity

- Consider Dijkstra's algorithm on a 2n-process ring, with processes Q_j, variables y_j. j = 1, 2, …, 2n.
- Emulate this in an n-process ring, with processes P_i, variables x_i.
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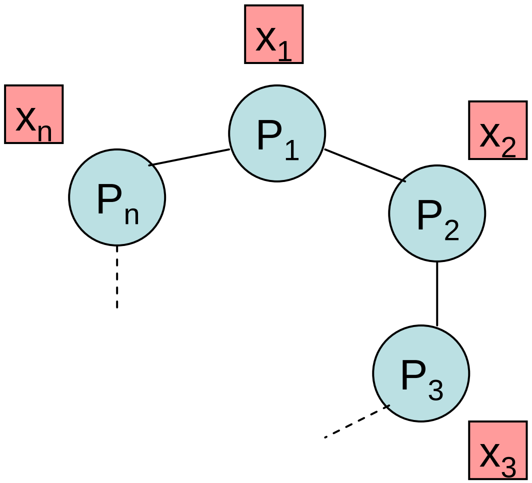


- To emulate a step of Q_{2i-1}, P_i reads from x_{i-1}, writes to its local variable y_{2i-1}.
- To emulate a step of Q_{2i}, P_i reads from its local variable y_{2i-1}, writes to x_i.
- Since in each case one variable is internal, can emulate each step with just one ordinary read or write to shared memory.

Composing Self-Stabilizing Algorithms

Composing self-stabilizing algorithms

- Consider several algorithms, where
  - A_1 is self-stabilizing for legal set L_1,
  - A_2 is SS for legal set L_2, "assuming A_1 stabilizes for L_1"
  - A_3 is SS for legal set L_3, "assuming A_1 stabilizes for L_1 and A_2 stabilizes for L_2"
  - etc.
- Then we should be able to run all the algorithms together, and the combination should be self-stabilizing for $L1 \cap L2 \cap L3 \cap \ldots$
- Need composition theorems.
- Details depend on which model we consider.
- E.g., consider two shared memory algorithms, A_1 and A_2.

Composing SS algorithms

- Consider read/write shared memory algorithms, A_1 and A_2, where:
  - All of A_1's shared registers are written only by A_1 processes.
    - No inputs arrive in A_1's registers.
  - All of A_2's shared registers are written only by A_1 and A_2 processes.
    - No other inputs arrive in A_2's registers.
  - Registers shared between A_1 and A_2 are written only by A_1 processes, not by A_2 processes.
  - One-way information flow, from A_1 and A_2.
  - A_1 makes sense in isolation, but A_2 depends on A_1 for some inputs.

- Definition: A_2 is self-stabilizing for L_2 with respect to A_1 and L_1 provided that: If α is any fair execution fragment of the combination of A_1 and A_2 whose projection on A_1 is in L_1, then α has a suffix in L_2.
- Theorem: If A_1 is SS for L_1 and A_2 is SS for L_2 with respect to A_1 and L_1, then the combination of A_1 and A_2 is SS for L_2.

Weaker definition of SS

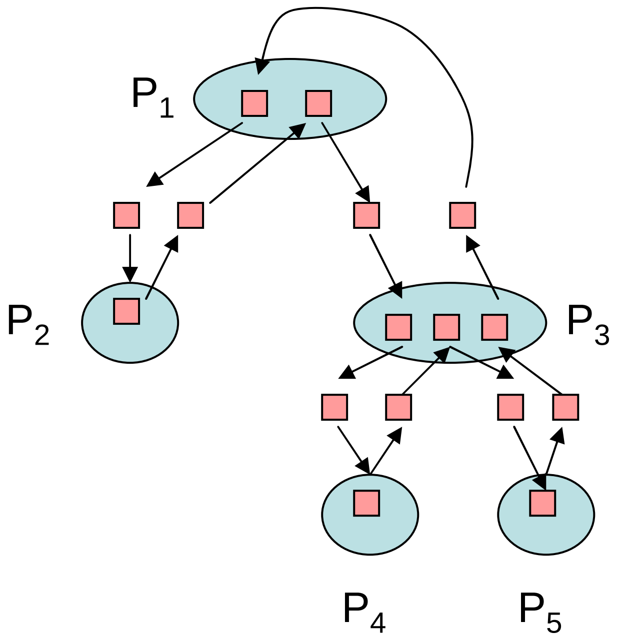
- At this point, [Dolev] seems to be using the weaker definition for self-stabilization:
- Instead of:
  - Algorithm A is self-stabilizing for legal set L if every fair execution fragment α of A contains a state s that is safe with respect to L.
- Now using:
  - Algorithm A is self-stabilizing for legal set L if every fair execution fragment α has a suffix in L.
- So we'll switch here.

Composing SS algorithms

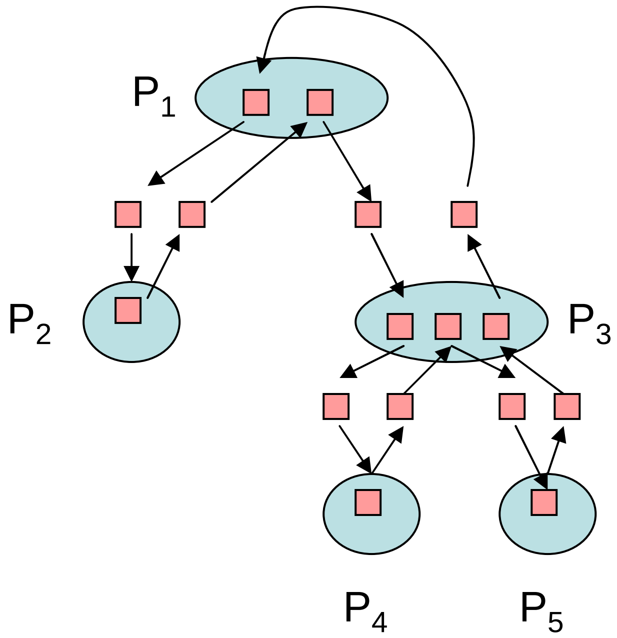
- Def: A_2 is self-stabilizing for L_2 with respect to A_1 and L_1 provided that any fair execution fragment of the combination of A_1 and A_2 whose projection on A_1 is in L_1, has a suffix in L_2.
- Theorem: If A_1 is SS for L_1 and A_2 is SS for L_2 with respect to A_1 and L_1, then the combination of A_1 and A_2 is SS for L_2.
- Proof:
  - Let α be any fair exec fragment of the combination of A_1 and A_2.
  - We must show that α has a suffix in L_2 (weaker definition of SS).
  - Projection of α on A_1 is a fair execution fragment of A_1.
  - Since A_1 is SS for L_1, this projection has a suffix in L_1.
  - Therefore, α has a suffix α' whose projection on A_1 is in L_1.
  - Since A_2 is self-stabilizing with respect to A_1, α' has a suffix α'' in L_2.
  - So α has a suffix in L_2, as needed.
- Total stabilization time is the sum of the stabilization times of A_1 and A_2.

Applying the composition theorem

- Theorem supports modular construction of SS algorithms.
- Example: SS mutual exclusion in an arbitrary rooted undirected graph
  - A_1:
    - Constructs rooted spanning tree, using the SS BFS algorithm.
    - The r_{ij} registers contain all the tree info (parent and distance).
  - A_2:
    - Takes A_1's r_{ij} registers as input.
    - Solves mutual exclusion using a Dijkstra-like algorithm, which runs on the stable tree in the r_{ij} registers.
  - Q: But Dijkstra's algorithm uses a ring---how can we run it on a tree?
  - A: Thread the ring through the nodes of the tree, e.g.:



Mutual exclusion in a rooted tree



- Use the read/write version of the Dijkstra ring algorithm, with local and shared variables.
- Each process P_i emulates several processes of Dijkstra algorithm.
- Bookkeeping needed, see [Dolev, p. 24-27].

- Initially, both the tree and the mutex algorithm behave badly.
- After a while (O(diam Δ l) time), the tree stabilizes (since the BFS algorithm is SS), but the mutex algorithm continues to behave badly.
- After another while (O(n^2 l) time), the mutex algorithm also stabilizes (since it's SS given that the tree is stable).
- Total time is the sum of the stabilization times of the two algorithms: O(diam Δ l) + O(n^2 l) = O(n^2 l).

Self-Stabilizing Emulations

Self-stabilizing emulations
[Dolev, Chapter 4]

- Design a SS algorithm A_2 to solve a problem L_2, using a model that is more powerful then the “real” one.
- Design an algorithm A_1 using the real model, that “stabilizes to emulate” the powerful model
- Combine A_1 and A_2 to get a SS algorithm for L_2 using the real model.

Self-stabilizing emulations

- Example 1 [Dolev, Section 4.1]: Centralized scheduler
  - Rooted undirected graph of processes.
  - Powerful model: Process can read several variables, change state, write several variables, all atomically.
  - Basic model: Just read/write steps.
  - Emulation algorithm A_1:
    - Uses Dijkstra-style mutex algorithm over BFS spanning tree algorithm
    - Process performs steps of A_2 only when it has the critical section (global lock).
    - Performs all steps that are performed atomically in the powerful model, before exiting the critical section.
  - Stabilizes to emulate the more powerful model.
  - Initially, both emulation A_1 and algorithm A_2 behave badly.
  - After a while, emulation begins behaving correctly, yielding mutual exclusion.
  - After another while, A_2 stabilizes for L_2.

Self-stabilizing emulations

- Example 2 [Nolte]: Virtual Node layer for mobile networks
  - Mobile ad hoc network: Collection of processes running on mobile nodes, communicating via local broadcast.
  - Powerful model: Also includes stationary Virtual Nodes at fixed geographical locations (e.g., grid points).
  - Basic model: Just the mobile nodes.
  - Emulation algorithm A_1:
    - Mobile nodes in the vicinity of a Virtual Node's location cooperate to emulate the VN.
    - Uses Replicated State Machine strategy, coordinated by a leader.
  - Application algorithm A_2 running over the VN layer:
    - Geocast, or point-to-point routing, or motion coordination,…
  - Initially, both the emulation A_1 and the application algorithm A_2 behave badly.
  - Then the emulation begins behaving correctly, yielding a VN Layer.
  - Then the application stabilizes.

Making Non-Self-Stabilizing Algorithms Self-Stabilizing

Making non-self-stabilizing algorithms self-stabilizing

- [Dolev, Section 2.8]: Recomputation of floating outputs.
  - Method of converting some non-SS distributed algorithms to SS algorithms.
- What kinds of algorithms?
  - Algorithm A, computes a distributed function based on distributed inputs.
  - Assumes processes' inputs are in special, individual input variables, I_i, whose values never change (e.g., contain fixed information about local network topology).
  - Outputs placed in special, individual output variables O_i.
- Main idea: Execute A repeatedly, from its initial state, with the fixed inputs, with two kinds of output variables:
  - Temporary output variables o_i.
  - Floating output variables FO_i.
- Use the temporary variables o_i the same way A uses O_i.
- Write to the floating variables FO_i only at the end of function computation.
- When restarting A, reset all variables except the floating outputs FO_i.
- Eventually, the floating outputs should stop changing.

Example: Consensus

- Start with a simple synchronous, non-fault-tolerant, non-self-stabilizing network consensus algorithm A, and make it self-stabilizing.
- Undirected graph G = (V,E), known upper bound D on diameter.
- Non-SS consensus algorithm A:
  - Everyone starts with Boolean input in I_i.
  - After D rounds, everyone agrees, and decision value = 1 iff someone's input = 1.
  - At intermediate rounds, process i keeps current consensus proposal in O_i.
  - At each round, send O_i to neighbors, resets O_i to "or" of its current value and received values.
  - Stop after D rounds.
- A works fine, in synchronous model, if it executes once, from initial states.

Example: Consensus

- To make this self-stabilizing:
  - Run algorithm A repeatedly, with the FO_i as floating outputs.
  - While running A, use o_i instead of O_i.
  - Copy o_i to FO_i at the end of each execution of A.

- This is not quite right…
  - Assumes round numbers are synchronized.
  - Algorithm begins in an arbitrary global state, so round numbers can be off.

Example: Consensus

- Run algorithm A repeatedly, with the FO_i as floating outputs.
- While running A, use o_i instead of O_i.
- Copy o_i to FO_i at the end of each execution of A.

- Must also synchronize round numbers 1,2,…,D.
  - Needs a little subprotocol.
  - Each process, at each round, sets its round number to max of its own and all those of its neighbors.
  - When reach D, start over at 1.
- Eventually, rounds become synchronized throughout the network.
- Thereafter, the next full execution of A succeeds, produces correct outputs in the FO_i variables.
- Thereafter, the FO_i will never change.

Extensions

- Can make this into a fairly general transformation, for synchronous algorithms.
- Using synchronizers, can extend to some asynchronous algorithms.

Making non-SS algorithms SS: Monitoring and Resetting [Section 5.2]

- AKA Checking and Correction.
- Assumes message-passing model.
- Basic idea:
  - Continually monitor the consistency of the underlying algorithm.
  - Repair the algorithm when inconsistency is detected.
- For example:
  - Use SS leader election service to choose a leader (if there isn't already a distinguished process).
  - Leader, repeatedly:
    - Conducts global snapshots,
    - Checks consistency,
    - Sends out corrections if necessary.
- Local monitoring and resetting [Varghese thesis, 92]
  - For some algorithms, can check and restore local consistency predicates.
  - E.g., BFS: Can check that local distance is one more than parent's distance, recalculate dist and parent if not.

Other stuff in the book

- Discussion of practical motivations.
- Proof methods for showing SS.
- Stabilizing to an abstract specification.
- Model conversions, for SS algorithms:
  - Shared memory $\rightarrow$ message-passing
  - Synchronous $\rightarrow$ asynchronous
- SS in presence of ongoing failures.
  - Stopping, Byzantine, message loss.
- Efficient “local” SS algorithms.
- More examples.

Next time…

- Partially synchronous distributed algorithms
- Reading:
  - Chapters 23-25
  - [Attiya, Welch], Section 6.3, Chapter 13

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