Outline for February 6, 2001

1. Greetings and felicitations!
   a. Friday times good, also Tuesday 3-4:30. Please send me your preferences!
2. Global state
   a. Show problem of slicing state when something is in transit
   b. Define local state; $send(m_{ij}) \in LS_i$ iff time of $send(m_{ij})$ < current time of LS_i; similar for receive
   c. transit(LS_i, LS_j); inconsistent(LS_i, LS_j); consistent state is one with inconsistent set empty for all pairs LS_i, LS_j
   d. Consistent global state: Chandry-Lamport
3. Termination detection
   a. Haung
4. Differences with non-distributed algorithms
   a. no shared memory, no common clock
   b. unpredictable message delays
5. Types of algorithms
   a. non-token algorithms: Lamport, Ricart and Agrawala, Maekawa
   b. token-based: Singhal, Raymond
   c. detection and recovery
6. System model
   a. states: *requesting* (entry section), *executing* (critical section), *idle* (remainder section), *idle token* (like idle, but you have the token)
   b. site: many others requesting entry, all are queued and served one at a time
7. Solution assumptions
   a. process names can be integers
   b. messages received in the order sent, in a finite amount of time, and correctly
   c. any process can communicate with any other process
8. Solution requirements
   a. mutual exclusion
   b. no deadlocks (progress)
   c. no starvation (bounded wait)
   d. fairness (requests executed in the order made, or in the order they arrive in system)
   e. fault tolerance (if a system fails, the algorithm can recover and continue to function)
9. Performance measures
   a. Performance under varying loads (low, high)
   b. Best, average, worst case performance
10. Terminology for non-token based protocols
   a. Request set R_i for a process p_i:set of nodes from which p_i must obtain permission to enter critical section
   b. Requests ordered bytimestamps: (*time*, *pid*); the pid is used to disambiguate equal timestamps
   c. Request sets satisfy the following conditions:
      i. *pairwise non-null intersection property*: for all $1 \le i, j \le n$ with $i \ne j$, $R_i \cap R_j \ne \varnothing$
      ii. *equal effort rule*: for all $1 \le i \le n$, $| R_i | = K$
      iii. *equal responsibility rule*: p_j is contained in D number of R_i.
      iv. for all $1 \le i \le n$, $p_i \in R_i$
11. Obvious solution: pick a single controlling site
   a. Advantages: 3 messages per request (site REQUEST, controller REPLY, site RELEASES)
   b. Disadvantages: single point of failure, congestion, controller does all the work
12. Lamport's
   a. Request set is all processes
   b. Performance: $3(n-1)$ messages
13. Ricart and Agrawala's

a. Request set is all processes
b. Performance: 2(*n*–1) messages

Chandy-Lamport Global State Recording Protocol

Introduction

The goal of this distributed algorithm is to capture a consistent global state. It assumes all communication channels are FIFO. It uses a distinguished message called a *marker* to start the algorithm.

Protocol

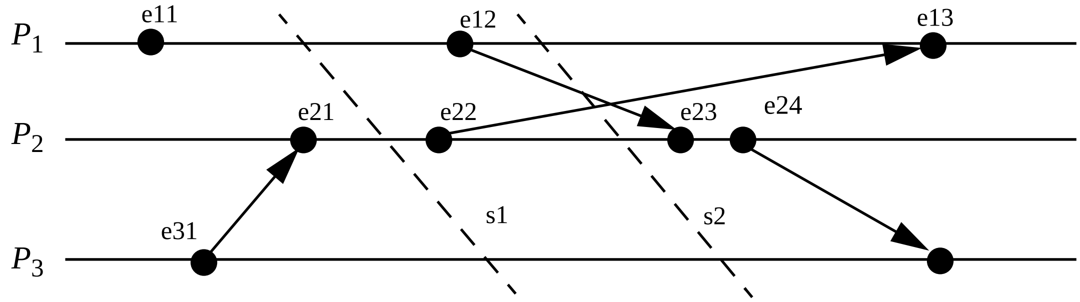
P_i sends marker

1. *Pi* records its local state LS_i
2. For each C_{ij} on which P_i has not already sent a marker, P_i sends a marker *before* sending other messages.

P_i receives marker from P_j

1. If P_i has *not* recorded its state:
   a. Record the state of C_{ji} as empty
   b. Send the marker as described above
2. If P_i has recorded its state LS_i
   a. Record the state of C_{ji} to be the sequence of messages received between the computation of LS_i and the marker from C_{ji}.

Example



Here, all processes are connected by communications channels C_{ij}. Messages being sent over the channels are represented by arrows between the processes.

Snapshot s_1:

P_1 records LS_1, sends markers on C_{12} and C_{13}

P_2 receives marker from P_1 on C_{12}; it records its state LS_2, records state of C_{12} as empty, and sends marker on C_{21} and C_{23}

P_3 receives marker from P_1 on C_{13}; it records its state LS_3, records state of C_{13} as empty, and sends markers on C_{31} and C_{32}.

P_1 receives marker from P_2 on C_{21}; as LS_1 is recorded, it records the state of C_{21} as empty.

P_1 receives marker from P_3 on C_{31}; as LS_1 is recorded, it records the state of C_{31} as empty.

P_2 receives marker from P_3 on C_{32}; as LS_2 is recorded, it records the state of C_{32} as empty.

P_3 receives marker from P_2 on C_{23}; as LS_3 is recorded, it records the state of C_{23} as empty.

Snapshot s_2: now messages are in transit on C_{12} and C_{21}.

P_1 records LS_1, sends markers on C_{12} and C_{13}

P_2 receives marker from P_1 on C_{12} after the message from P_1 arrives; it records its state LS_2, records state of C_{12} as empty, and sends marker on C_{21} and C_{23}

P_3 receives marker from P_1 on C_{13}; it records its state LS_3, records state of C_{13} as empty, and sends markers on C_{31} and C_{32}.

P_1 receives marker from P_2 on C_{21}; as LS_1 is recorded, and a message has arrived since LS_1 was recorded, it records the state of C_{21} as containing that message.

P_1 receives marker from P_3 on C_{31}; as LS_1 is recorded, it records the state of C_{31} as empty.

P_2 receives marker from P_3 on C_{32}; as LS_2 is recorded, it records the state of C_{32} as empty.

P_3 receives marker from P_2 on C_{23}; as LS_3 is recorded, it records the state of C_{23} as empty.

Huang's Termination Detection Protocol

Introduction

The goal of this protocol is to detect when a distributed computation terminates.

Notation

- *n* processes
- P_i process; without loss of generality, let P_0 be the *controlling agent*
- W_i. weight of process P_i; initially, $W_0 = 1$ and for all other i, $W_i = 0$.
- $B(W)$ computation message with assigned weight W
- $C(W)$ control message sent from process to controlling agent with assigned weight W

Protocol

P_i sends a computation message to P_j

1. Set W_i' and W_j to values such that $W_i' + W_j = W_i$, $W_i > 0$, $W_j > 0$. (W_i' is the new weight of P_i.)
2. Send $B(W_j)$ to P_j

P_j receives a computation message $B(W)$ from P_i

1. $W_j = W_j + W$
2. If P_j is idle, P_j becomes active

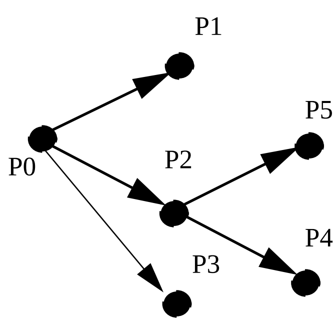
P_i becomes idle:

1. Send $C(W_i)$ to P_0
2. $W_i = 0$
3. P_i becomes idle

P_i receives a control message $C(W)$:

1. $W_i = W_i + W$
2. If $W_i = 1$, the computation has completed.

Example



The picture shows a process P_0, designated the *controlling agent*, with $W_0 = 1$. It asks P_1, P_2, and P_3 to do some computation. It sets W_1 to 0.3, W_2 to 0.2, and W_3 to 0.5. P_2 in turn asks P_4 and P_5 to do some computations. It sets W_4 to 0.1 and W_5 to 0.1.

When P_5 terminates, it sends $C(W_3) = C(0.1)$ to P_0, which changes W_0 to $0 + 0.1 = 0.1$.

When P_3 terminates, it sends $C(W_3) = C(0.5)$ to P_0, which changes W_0 to $0.1 + 0.5 = 0.6$.

When P_4 terminates, it sends $C(W_4) = C(0.1)$ to P_0, which changes W_0 to $0.6 + 0.1 = 0.7$.

When P_1 terminates, it sends $C(W_1) = C(0.3)$ to P_0, which changes W_0 to $0.7 + 0.3 = 1$.

P_0 thereupon concludes that the computation is finished.

Total number of messages passed: 9 (one to start each computation, one to return the weight to the controlling node).

Lamport's Distributed Mutual Exclusion Protocol

Introduction

Lamport's scheme uses distributed clocks. Every process notifies all others when it wants to enter the region of mutual exclusion. The process desiring to go in, enters when all others trying to get in made their request later.

Notation

- n processes $p_1, \ldots, p_n$
- t_j timestamp

Protocol

1. To enter the critical section, p_i sends REQUEST(t_i, i) to all sites and puts the request on its queue.
2. When p_i receives a REQUEST(t_j, j) message, it returns a REPLY(t'_j, j) to p_j and puts the request on its queue.
3. When p_i receives a RELEASE(t_j, j) message, it deletes p_j's request from the queue.
4. p_i enters the critical section when both of the following conditions hold:
   a. p_i has received a message with timestamp larger than (t_i, i) from each of the other sites
   b. p_i's request is at the front of its request queue
5. When p_i leaves the critical section, it removes its request from the top of the queue and sends RELEASE(t_i, i) to all sites and puts the request on its queue.

Example

There are three processes, p_1, p_2, and p_3. p_1 and p_3 seek mutually exclusive access to a shared resource.

who	*action*	*what*	*whom*	*C1*	*C2*	*C3*	*Q1*	*Q2*	*Q3*
				10	4	4			
p1	sends	Q(10,1)	all	11			Q(10,1)		
p3	sends	Q(4,3)	all			5			Q(4,3)
p2	receives	Q(10,1)	p1		10			Q(10,1)	
p2	sends	P(10,2)	p1		11				
p2	receives	Q(4,3)	p3		11			Q(4,3)Q(10,1)	
p2	sends	P(11,2)	p3		12				
p1	receives	Q(4,3)	p3	11			Q(4,3)Q(10,1)		
p1	sends	P(11,1)	p3	12					
p3	receives	Q(10,1)	p1			10			Q(4,3)Q(10,1)
p3	sends	P(10,3)	p1			11			
p1	receives	P(10,3)	p3	12			Q(4,3)Q(10,1)P(10,3)		
p3	receives	P(11,1)	p1			12			Q(4,3)Q(10,1)P(11,1)
p3	receives	P(11,2)	p3			13			Q(4,3)Q(10,1)P(11,1)P(11,2)
p3	**enters**								Q(4,3)Q(10,1)
p1	receives	P(10,2)	p2		12		Q(4,3)Q(10,1)P(10,2)P(10,3)		
p3	**leaves**								Q(10,1)
p3	sends	R(13,3)	p1,p2			14			
p2	receives	R(13,3)	p3		13			Q(10,1)	
p1	receives	R(13,3)	p3	13			Q(10,1)P(10,2)P(10,3)		
p1	**enters**						Q(10,1)		
p1	**leaves**						–		
p1	sends	R(13,1)	p1,p2	14					
p2	receives	R(13,1)	p1		14			–	
p3	receives	R(13,1)	p1			15			–

Ricart and Agrawala's Distributed Mutual Exclusion Protocol

Introduction

Ricart and Agrawala's protocol is an optimization of Lamport's. They piggyback the release message onto the reply.

Notation

- n processes $p_1, \ldots, p_n$
- t_j timestamp

Protocol

1. To enter the critical section, p_i sends REQUEST(t_i, i) to all sites.
2. When p_i receives a REQUEST(t_j, j) message:
   a. if it is not trying to enter the region of mutual exclusion, it returns REPLY(t'_j, j) to p_j.
   b. if it is trying to enter the region of mutual exclusion, and if (t_i, i) $\Rightarrow$ (t_j, j), it retains the REQUEST.
   c. otherwise it returns a REPLY(t'_j, j) to p_j..
3. When p_i has received a REPLY message from every other process, it enters the region of mutual exclusion.
4. When p_i leaves the region of mutual exclusion, it sends REPLY(t_i, i) to all processes with deferred requests.

Example

There are three processes, p_1, p_2, and p_3. p_1 and p_3 seek mutually exclusive access to a shared resource.

who	***action***	***what***	***whom***	***C1***	***C2***	***C3***	***Q1***	***Q2***	***Q3***
				10	4	4			
p1	sends	Q(10,1)	all	11			Q(10,1)		
p3	sends	Q(4,3)	all			5			Q(4,3)
p2	receives	Q(10,1)	p1		10				
p2	sends	P(10,2)	p1		11				
p2	receives	Q(4,3)	p3						
p2	sends	P(11,2)	p3		12				
p1	receives	Q(4,3)	p3				Q(10,1)		
p1	sends	P(11,1)	p3	12					
p3	receives	Q(10,1)	p1			10			Q(4,3)Q(10,1)
p3	receives	P(11,1)	p1			11			Q(4,3)Q(10,1)P(11,1)
p3	receives	P(11,2)	p2			12			Q(4,3)Q(10,1)P(11,1)P(11,2)
p3	**enters**								Q(4,3)Q(10,1)
p1	receives	P(10,2)	p2				Q(10,1)P(10,2)		
p3	**leaves**								Q(10,1)
p3	sends	P(12,3)	p1			13			–
p1	receives	P(12,3)	p3	13			Q(10,1)P(10,2)P(12,3)		
p1	**enters**						Q(10,1)		
p1	**leaves**						–		