Distributed Algorithms in Networks

EECS 122: Lecture 17

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The Internet is a HUGE Distributed System

- Nodes are local processors
- Messages are exchanged over various kinds of links
- Nodes contain sensors which sense local changes
- Nodes control the network jointly
  - Method for doing this is a distributed algorithm
  - Example: Routing
- Time taken to solve the problem has two components:
  - Computation time taken for local processing
  - Communication time for messages to be received over the links

Solving Global Problems in a Distributed Setting

- Examples:
  - Minimum Spanning Tree
  - Shortest Path
  - Leader Election
  - Topology Broadcast
- Much easier to think in terms of centralized algorithms
  - Creativity needed to convert to the distributed case

Network Protocols often have unintended effects

- TCP
  - Example 1
    - TCP connections detect congestion after it has happened
    - May cause packet drops from uncongested “well behaved flows”
      - Non congested flows back off
  - Example 2
    - Two TCP flows sharing the same router get uneven bandwidths because one has a much smaller RTT than the other
- Routing
  - Oscillation and countless other pathologies
- It is very difficult to avoid these unintended effects

Today

- Focus on protocol design issues
- How to move from Centralized to Distributed Alg.
- Synchronous and Asynchronous computation
  - Why does the Asynchronous Bellman Ford converge?
- Selfish behavior distributed systems

The Network is Heterogeneous

- Speed
  - Dialup to terabit fiber
- Reliability
  - Hosts: Distributed Server farms to 486 PC
  - Links: Noisy wireless to virtually error free fiber
- Congestion
- Trustworthiness
- What is a general enough model to cover all of this?

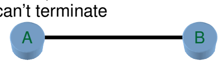
Consensus over an Unreliable Link

- A and B in a connection over an unreliable link
- They both want to terminate the connection only if they are certain that no more packets will arrive from the other user

- A won't terminate unless it knows that B knows it is about to terminate.
- B won't terminate unless it knows that A knows it is about to terminate

Consensus Problem

- Suppose B tells A it can terminate and A receives this message, say M
- A can terminate, but B will never know if A actually received M and so it can't terminate

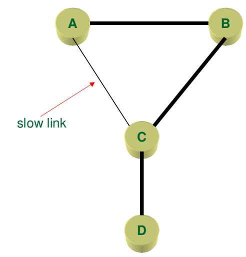


- A sends ACK(M) to B, but then A needs to makes sure that B received this message, so it must wait for ACK(ACK(M))…
- A never terminates.
- In fact, NO protocol exists to solve this problem!
- Worth convincing yourself of this fact.

Link model

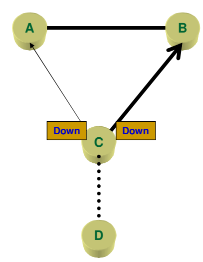
- Error correction
  - Assume that errors can "eventually" corrected
- Propagation Delay
  - Fixed
  - Variable but no more than d
  - Variable with no upper bound
- Other components of delay
  - Queueing Delay
  - Transmission Delay
- Packet order
  - FIFO
  - Can be delivered in arbitrary order

Maintaining accurate topology information



Whenever a link goes down/up, its end points send messages to all their neighbors who then flood.

Maintaining accurate topology information



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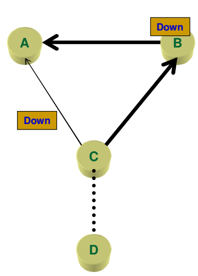
1. CD fails

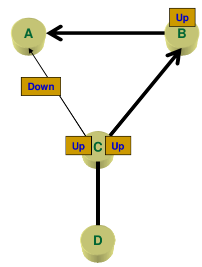
Maintaining accurate topology information



Whenever a link goes down/up, its end points send messages to all their neighbors who then flood.

1. CD fails
   - A marks the link down

Maintaining accurate topology information



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2. CD comes back up

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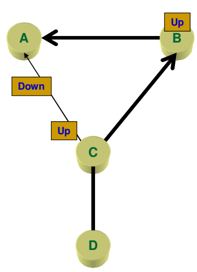

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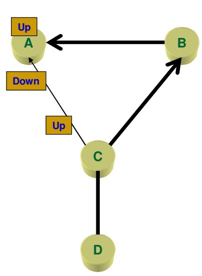

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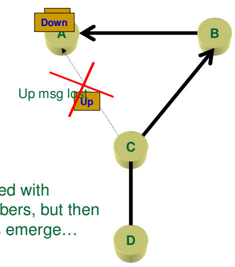


This can be fixed with sequence numbers, but then other problems emerge…

Whenever a link goes down/up, its end points send messages to all their neighbors who then flood.

1. CD fails
   - A marks the link down
2. CD comes back up
   - A marks the link up
3. A marks the link down
4. CA fails
   - Up message lost

A thinks CD is down when it is actually up!

Synchronous v/s Asynchronous Algorithms

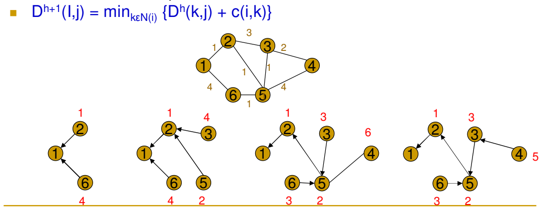
- Synchronous algorithms can be described in terms of global iterations. The time taken for a given iteration is the time taken for the slowest processor to complete that iteration: *time driven*
  - E.g. TDM or SONET
- Asynchronous algorithms execute at a processor based on received messages and internal state: *event driven*
  - *E.g.* IP protocols which must run over heterogeneous systems

Slotted Time

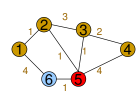
- Slotted system 1,2,…,3…
  - All nodes agree on slot boundaries
    - “Have access to a global clock”
- Helps to co-ordinate the nodes
  - Every node can run the same algorithm
    - Proving correctness is generally tractable if the centralized algorithm is analyzable
    - Easier to understand the sequence of communication between nodes

Synchronous Bellman-Ford (SBF)

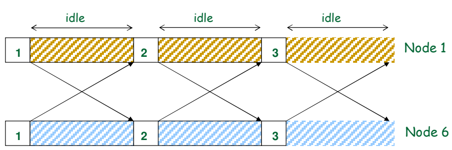
- Every node runs the same algorithm
- Time is slotted and in every tick each node sends its distance vector.
- At time h, node i has as an estimate of the shortest path to node 1 that has <= h+1 hops
- $D^{h+1}(I,j) = \min_{k \in N(i)} \{D^h(k,j) + c(i,k)\}$



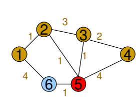
Synchronous Timing



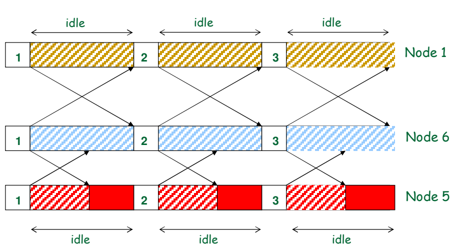
Great when links are reliable and similar…



Synchronous Timing

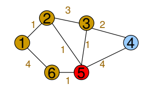


But what when some links are much faster?

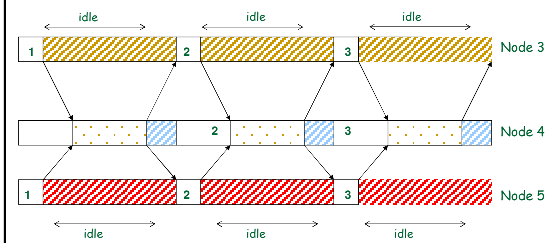


Node 5 suffers synchronization penalty

Synchronization Penalty



Slow nodes can create a penalty as well



Penalty can be huge!

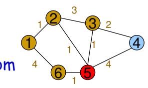
Implementing a Synchronous Algorithm

- Suppose the slowest process can complete an iteration in time T_p
- Link delay is always less than T_l
- Then a slot size of T_p+T_l or more is sufficient
  - But most processors may be idle most of the time
- What if T_p and or T_l are not known?

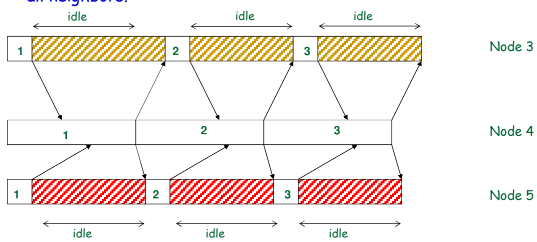
Locally Synchronous Computation

- Forget about fixed slots
- When a node has received all round k-1 messages from its neighbors, it computes and sends out its round k message
- Worst-case: As slow as synchronous computation
- Generally much faster
- Any synchronous algorithm that isn't using time as a part of the computation will also work when run in a locally synchronous manner.

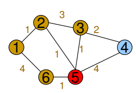
Local Synchronization



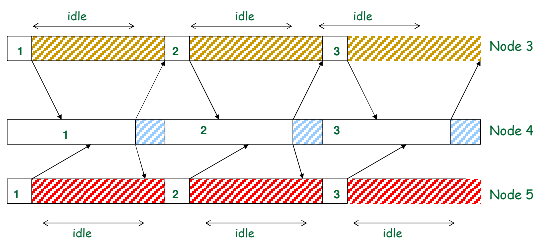
Send update k after you've heard update k-1 from all neighbors.



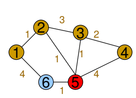
Compare with Synchronous



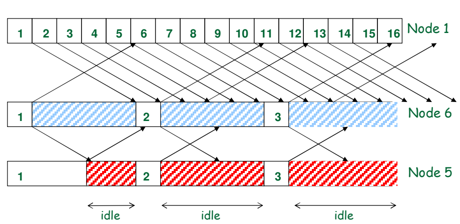
Slot size is affected by the slow node 4



Asynchronous computation



No notion of "slot size" at all!



Why should this work?

Why bother with Asynchronous Algorithms

- To reduce the synchronization penalty
- Difficult to get the synchronous algorithm to start
- The network is dynamic
  - Flows
  - Topology
    - Think of the algorithm having to "restart" with a new set of initial conditions, every time there is a failure
- Changes create "events" which may or may not have global impact
  - Event-driven algorithms better suited

Asynchronous Bellman Ford (ABF)

- Don't even wait to hear from all neighbors!
  - Use most recent information to compute new distance vectors
    - i.e. use last received values of D() and d
  - Whenever ready, each node i computes
    - $D(i) = \min_{k \in N(i)} [D(k) + c(i,k)]$
    - Sends the result to each of its neighbors
  - No notion of global iterations
- In general, nodes are using different and possibly inconsistent estimates

Asynchronous Bellman Ford

- Regardless of how asynchronous the nodes are, the algorithm will eventually converge to the shortest path
- Links can go down and come up – but as long as the topology is fixed after some time t, the algorithm will eventually converge to the shortest path
- Why?
  - There's some hope because the D(j) can only go up if one of j's neighbors estimates has gone up.

Idea

- There are too many different “runs” of ABF, so lets try to bound the range of distance estimates of D(j) over time
- Do this by two different runs of Synchronous BF
  - Set different initial estimates
    - One run U, uses the familiar ones, i.e. estimate is infinity if no edge
    - The other, L, uses -1if no edge!
  - One bounds the estimates from above, one from below and both find the correct the shortest paths eventually
- For every iteration k of the two SBF runs
  - $L^k(j) \leq L^{k+1}(j) \leq D^*(j) \leq U^{k+1}(j) \leq U^k(j)$
- For any asynchronous run, A, it is possible to show that for any k, there is a time t such that
  - $L^k(j) \leq L^{k+1}(j) \leq A_t(j) \leq U^{k+1}(j) \leq U^k(j)$
- Since both lower and upper runs converge to the optimal, so will ABF eventually

Soft State

- State with Time-Out
- Example: A host joins a group by sending a “join” message to a “host manager”. The manager adds the host to the group for the next T seconds. If the host wants to stay in the group it must send a refresh message within T seconds to the manager. Otherwise it is dropped.
- Advantage: Manager robust to host failure
- Disadvantage: Too many messages
- Most internet protocols use this way of communicating
- Trades of simplicity of correctness with complexity of communication

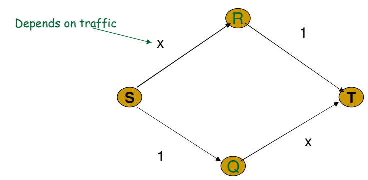
The nature of asynchronous distributed protocols

- Generally non-intuitive
- Limited theory to work with
  - Correctness extremely hard to prove
  - Robustness hard to analyze
- Networking gurus have a vast knowledge of special cases that can lead to strange behaviors
  - Misconfiguration is a big cause of errors
- Soft state helps a lot, but wastes many messages!
- What about just broadcasting topology information accurately so that these problems go away…

Trustworthiness

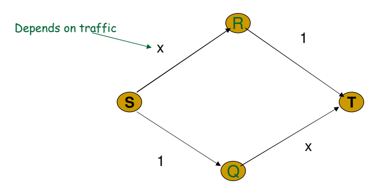
- Three levels
  - Honest: Always in conformance of the protocol
  - Selfish: May lie to get better performance out of the protocol (BGP)
  - Malicious: Unpredictable
- Internet Protocols (for the most part) assume Honest protocol agents
  - Unreliable infrastructure
- Infrastructure has gotten more reliable, and agents have gotten less honest…
- Braess’s Paradox: Example of how Greediness and distributed algorithms can lead to suboptimality

Congestion Sensitive Routing



Weights are delays/bit
1 unit of traffic from s to t
u bits on the upper path
1-u bits on the lower path

Each Node is Greedy



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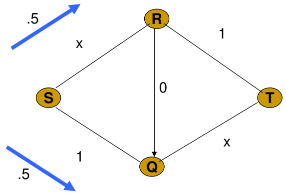
- Node S minimizes
  - Total delay = u(u+1) + (1-u)(2-u) = 2(u^2 – u +1)
- Delay minimized at u=.5
- So Total Delay = 1.5 s

Greediness leads to suboptimality

S still sends .5 on each path



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BRAESS'S PARADOX

R is greedy
R diverts all .5 units
on to the new link

*Now total delay is **2**!*

Conclusions

- Distributed Algorithms are not intuitive
- There is no systematic way to design them
  - Active research area is making some progress
  - Until then use
    - Hacking Abilities
    - Simulation
    - Control Theory
    - Optimization
    - Graph Theory
    - Game Theory
    - ….
- Greedy and malicious users complicate the protocol design problem even more
  - Another active research area making progress
- This is why it is hard to build networks…