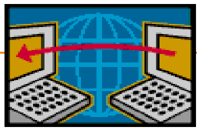

Advanced Topics in Routing

EE122 Fall 2012

Scott Shenker

http://inst.eecs.berkeley.edu/~ee122/

Materials with thanks to Jennifer Rexford, Ion Stoica, Vern Paxson
and other colleagues at Princeton and UC Berkeley

Announcements

Holy Trinity of Routing: LS, DV, PV

- Normally presented as the complete story
- But we know how to do much better
- That is what we will talk about today…..

Major Routing Challenges:

- Policy Oscillations
- Resilience
- Traffic Engineering

Another Purpose for Today

- EE122 (CS version) is algorithmically vacuous
  - AIMD is the high point of intellectual depth (ugh)
- The algorithms described today are nontrivial
  - Algorithms simple, but their properties are nonobvious
- **You** will prove two results as a class exercise
  - 5 minutes, in groups, try to come up with reasoning
  - I'll help shape it into a proof

Policy Dispute Resolution

Policy Oscillations

- Last time we discussed how BGP might never converge due to "policy oscillations"
- We now discuss how we might solve this problem

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Policy Oscillations (cont'd)

- Policy autonomy vs network stability
  - Oscillations possible with small degree of autonomy
  - Focus of much recent research
- Not an easy problem
  - PSPACE-complete to decide whether given policies will eventually converge!
- However, if policies follow normal business practices, stability is guaranteed
  - "Gao-Rexford conditions"
  - Essentially the provider/peer/customer policy categories

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Theoretical Results (in more detail)

- If preferences obey Gao-Rexford, BGP is safe
  - Safe = guaranteed to converge
- If there is no "dispute wheel", BGP is safe
  - But converse is not true
- If there are two "stable states", BGP is unsafe
  - But converse is not true
- If domains can't lie about routes, and there is no dispute wheel, BGP is incentive compatible

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Objectives for New Policy Approach

- Do not reveal any ISP policies
- Distributed, online dispute detection and resolution
- Pick "normal" path (according to policies) if no oscillation exists
  - *Get something reasonable if oscillation would exist*
- Account for transient oscillations, don't permanently blacklist routes

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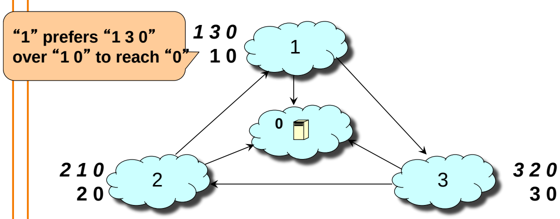
Example of Policy Oscillation



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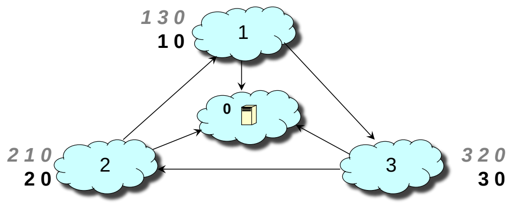
Step-by-Step of Policy Oscillation

Initially: nodes 1, 2, 3 know only shortest path to 0



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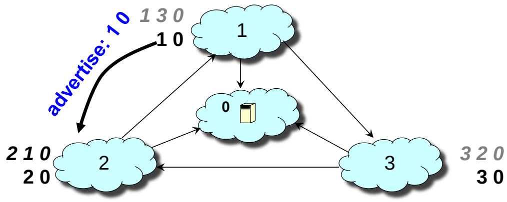
Step-by-Step of Policy Oscillation

1 **advertises** its path 1 0 to 2



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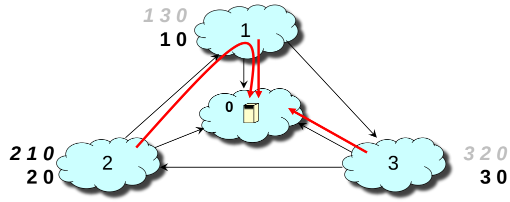
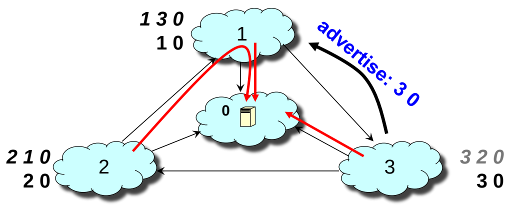


Step-by-Step of Policy Oscillation

3 **advertises** its path 3 0 to 1



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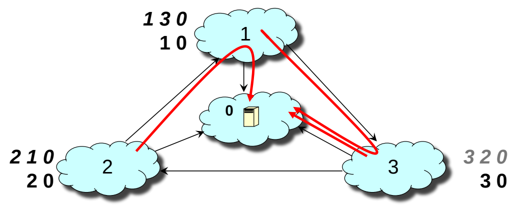

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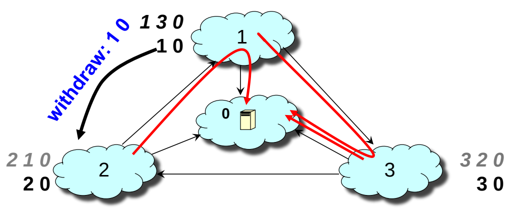
1 **withdraws** its path 1 0 from 2



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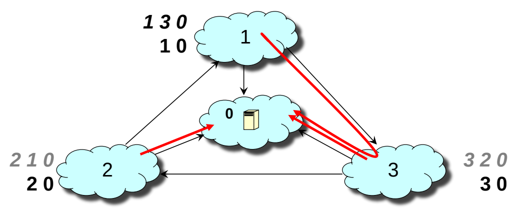
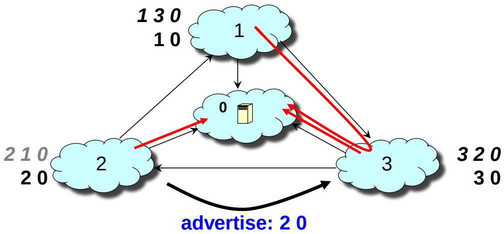


Step-by-Step of Policy Oscillation

2 **advertises** its path 2 0 to 3



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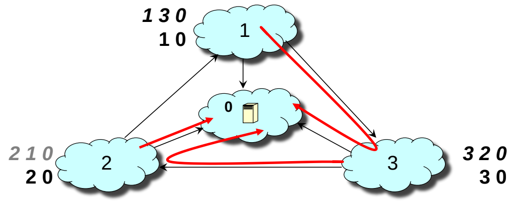

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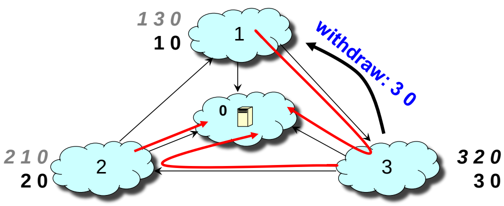

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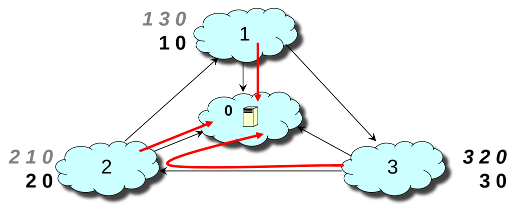

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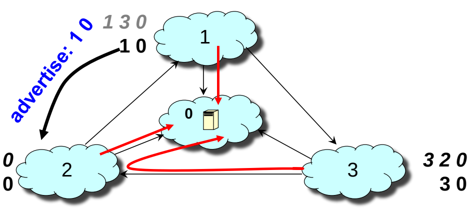

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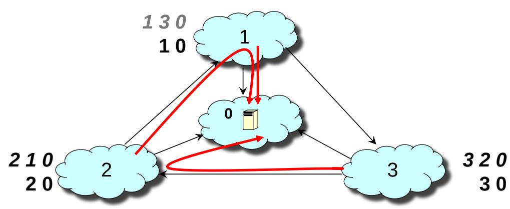

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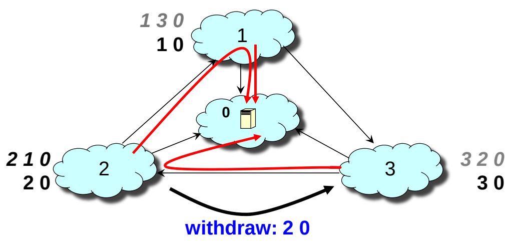

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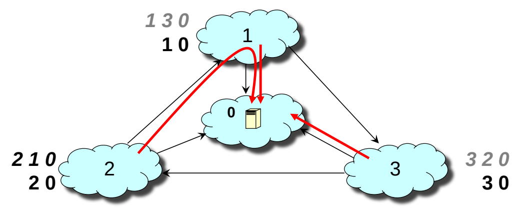
Step-by-Step of Policy Oscillation



We are back to where we started!

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Nodes See Signs of Trouble

- Route choices oscillation
  - Node 1:
    - 1 0 , **1 3 0** , 1 0 , **1 3 0** , ...
  - Node 2:
    - 2 0 , **2 1 0** , 2 0 , **2 1 0** , ...
  - Node 3:
    - 3 0 , **3 2 0** , 3 0 , **3 2 0** , ...
- Choices alternate between **more preferred** and less preferred routes

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Basic Idea

- If node notices that it is constantly selectng routes that are more / less preferred than previous route
  - Node thinks it may be involved in oscillation
- Computes local "precedence" figure
  - Higher precedence value for less preferred routes
  - In example, 1 0 gets higher value than 1 3 0
- Route advertisements carry this precedence
  - Two precedence values:
    - Incoming (carried by packet)
    - Local (determined by own past history)

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Precedence Calculation

- Routes are first ranked by "incoming precedence"
  - Pick most preferred route among those with lowest incoming precedence value
- Outgoing precedence is sum of incoming and local precedence

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Use of Precedence Values

- Maintain *history* of routes encountered during oscillations
  - In table below, prefer P0 to P1 to P2

AS Path	Incoming Precedence	Local Precedence (Computed)
P0	1	0
P1	1	1
P2	0	1

- Pick path P2, mark with precedence 1

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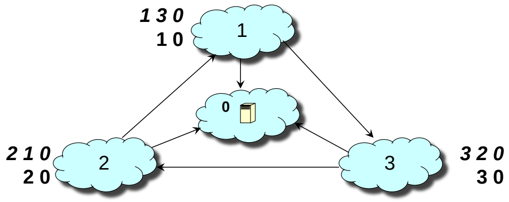
Example of Policy Oscillation



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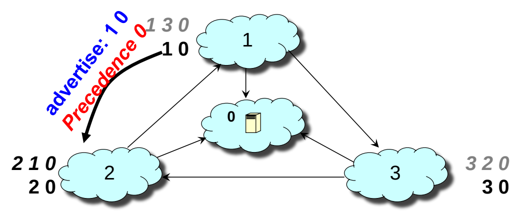
1 **advertises** its path 1 0 to 2



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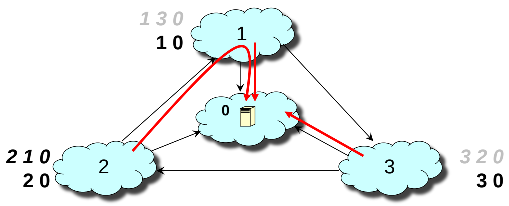

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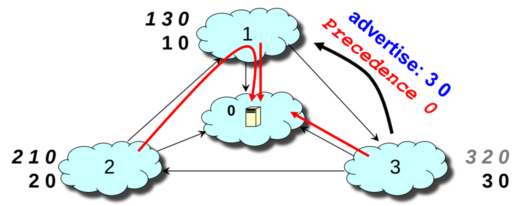

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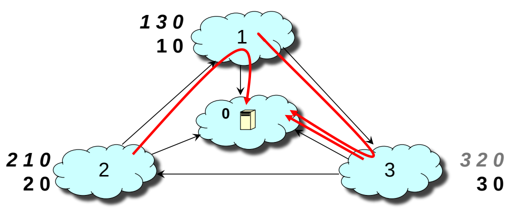

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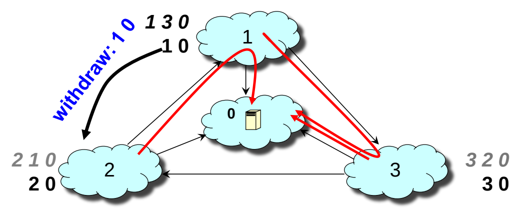

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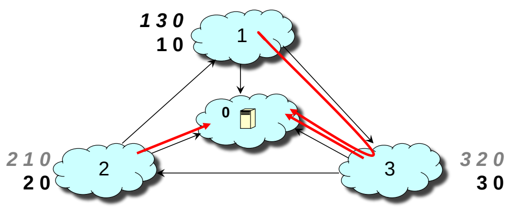
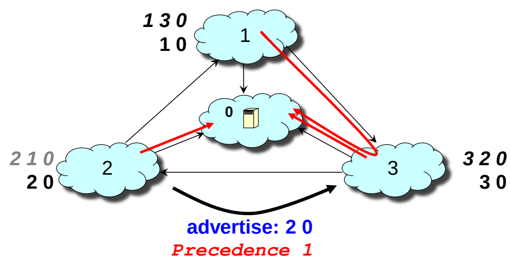


Step-by-Step of Policy Oscillation

2 advertises its path 2 0 to 3

Routes stabilize at this point

3 cannot choose 2 0 route from 2, because of higher precedence value



"Proof" of why it works

- Assume that policy oscillation exists within scheme
- Some router A must prefer a path offered by a router B that does *not* prefer that path
  - If everyone is getting first choice, no oscillation!
  - So A's first choice is B's second choice for some A,B
- But router A cannot choose that path because it will have a lower precedence

Properties of Solution

- If no policy oscillation exists, get usual routes
- If policy oscillation would have existed, approach short-circuits oscillation
- If, after convergence, non-zero global precedence values exist, $\Rightarrow$ dispute(s) exist
- Only precedence values advertised, no other routes or policies revealed
- **Why isn't this deployed?**

Routing Resilience

Resilience

- Basic routing algorithms rely on timely consistency or global convergence to achieve ensure delivery
  - LS: routers need to have same picture of network
  - DV: if algorithm hasn't converged, might loop
- As nets grow, this gets harder and takes longer
  - ***Need both consistency/convergence and timeliness!***
- Creates lag between failure detection and recovery
  - Lag is biggest barrier to achieving 99.999% reliability

Hacks Used Today

- Preconfigured backup paths
  - When link fails, router has a backup route to use
  - Very helpful against single failures
  - Only limited protection against multiple failures
  - No systematic paradigm
- ECMP: Equal-Cost Multipath
  - Similar to backups, but narrower applicability
  - Choose among several "shortest-paths"

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Solutions Presented Today

- Multipath (one slide)
- Failure-carrying packets
- Routing-along-DAGs

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Multipath Routing

- Multipath:
  - Providing more than one path for each S-D pair
  - Allow ***endpoints*** to choose among them
    - o This can be implemented by having a "path" field in packet
- Good: if one path goes down, can use another
- Bad: Delay while endpoints detect failure (RTT)
- Absolutely necessary because of E2E arguments
  - ***But not a fundamental paradigm shift***
- *Part of solution, but still need more reliable routing*

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Fundamental Question

Can we completely eliminate the need to "reconverge" after link failures?

i.e., can we tolerate failures without losses?

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Failure-Carrying Packets (FCP)

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FCP Approach: Step 1

- Ensure all routers have consistent view of network
  - But this view can be out-of-date
  - ***Consistency is easy if timeliness not required***
- Use reliable flooding
  - Each map has sequence number
- Routers write this number in packet headers, so packets are routing according to the same "map"
  - Routers can decrement this counter, not increment it
  - Eventually all routers use the same graph to route packet
- This achieves consistency, but not timeliness….

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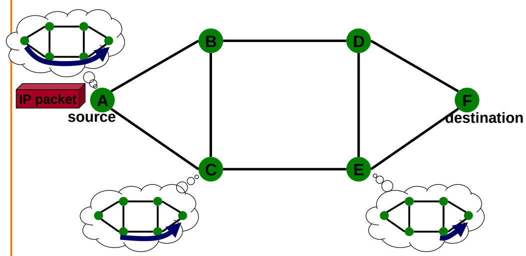
FCP Approach: Step 2

- Carry failure information in the packets!
  - Use this information to “fix” the local maps
- When a packet arrives and the next-hop link for the path computed with the consistent state is down, *insert failure information into packet header*
  - Then compute new paths assuming that link is down
- If failure persists, it will be included in next consistent picture of network
  - Then not needed in packet header

Example: FCP routing



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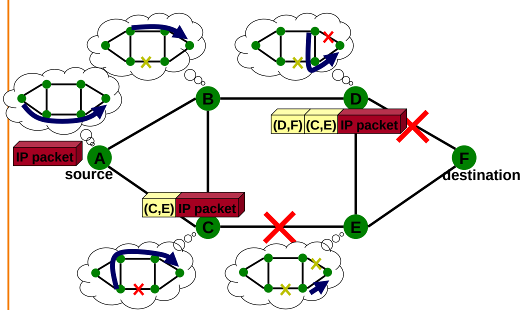

Class Exercise: Prove This Works

- Develop line of argument about why this guarantees connectivity
- Under what circumstances does guarantee hold?

Keys to Proof

- Deadend: as long as map plus failures has connectivity, no dead ends
- Loops: Assume loop. The nodes on the loop all share the same “consistent” map plus a set of failures in the packet header. Therefore, they compute the same path. Contradiction.

Condition for Correctness

- Consider a set of changes to network from the last consistent map before packet is sent until TTL of packet would expire.
- If intersection of all network states during change process is connected, then FCP will deliver packet

Properties of FCP

- Guarantees packet delivery
  - As long as a path exists during failure process
- Major conceptual change
  - Don't rely solely on protocols to keep state consistent
  - Information carried in packets ensures eventual consistency of route computation
  - This theme will recur in next design….
  - **Ion's Stoica's thesis!**

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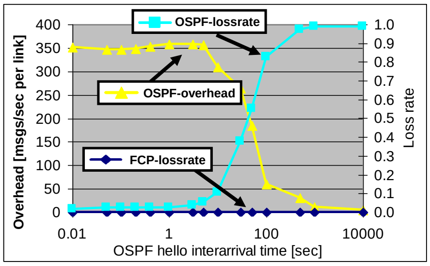
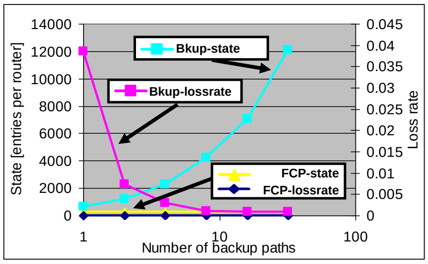
Results: OSPF vs. FCP



- Unlike FCP, OSPF cannot simultaneously provide low churn and high availability

Results: Backup-paths vs. FCP



- Unlike FCP, Backup-paths cannot simultaneously provide low state and lossrate

Problems with FCP

- Requires changes to packet header
  - And packet headers could get long
- Requires fast recomputation of routes
  - Can precompute common cases, but worst case is bad
- Does not address traffic engineering
  - What is that?

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Traffic Engineering (TE)

- Connectivity is necessary but not sufficient
- Need to also provide decent service
- Requires that links on the path not be overloaded
  - Congestion control lowers drop rate, but need to provide reasonable bandwidth to connections by spreading load
- TE is a way of distributing load on the network
  - i.e., not all packets travel the "shortest path"

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Routing Along DAGs (RAD)

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Avoiding Recomputation: Take II

- Recover from failures without global recomputation
- Support locally adaptive traffic engineering
- Without any change in packet headers, etc.
- Or requiring major on-the-fly route recomputation

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Background

- Focus only on routing table for single destination
  - Could be a prefix, or a single address
  - Routing to each destination is independent, so this is fine
- Today we compute ***paths*** to particular destination
  - From each source to this destination there is a path
- When path breaks, need to recompute path
  - The source of all our troubles!

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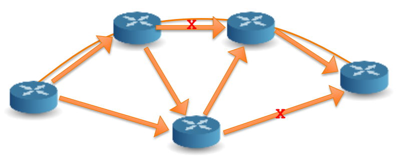
Our Approach: Shift the Paradigm

Routing compute paths from source to destination
Move from *path* to *DAG* (Directed Acyclic Graph)
If a link fails, all affected paths must be recomputed

Path
DAG



Packets can be sent on <u>any</u> of the DAG's outgoing links
No need for global recomputation after each failure

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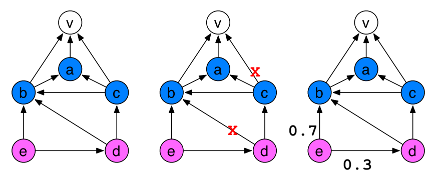
DAG Properties

- Guaranteed loop-free
- Local decision for failure recovery
- Adaptive load balancing



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Load Balancing

- Use local decisions:
  - Choose which outgoing links to use
  - Decide how to spead the load across these links
  - Push back when all outgoing links are congested
    - Send congestion signal on incoming links to upstream nodes
- Theorem:
  - When all traffic goes to a single destination, local load balancing leads to optimal throughput
- Simulations:
  - In general settings, local load balancing close to optimal

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DAG-based Routing

- Essentially a principled paradigm for backup paths
  - Can tolerate many failures
  - Scalable
  - Easy to understand and manage

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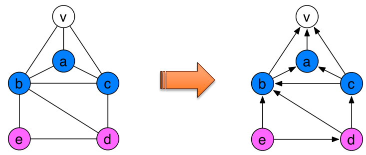
Computing DAG

- Use each link in a single direction
- DAG iff link directions follow global order
- Computing a DAG for destination v is simple:
  - Essentially a shortest-path computation
  - With consistent method of breaking ties

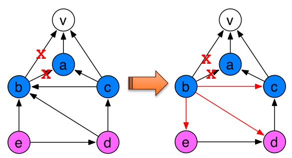


What about Connectivity?

- Multiple outgoing links improve connectivity
  - But can RAD give “perfect” connectivity?
- If all outbound links fail that node is disconnected
  - Even if underlying graph is still connected
- How can we fix this?

Link Reversal

- If all outgoing links fail, reverse incoming links to outgoing



RAD Algorithm

- When packet arrives, send out ***any*** outgoing link
- When an outgoing link fails (or is reversed)
  - If other outgoing links exist, do nothing
  - If no other outgoing links exist, reverse all incoming links
    - o i.e., change them to outgoing

Link Reversal Properties

- Connectivity guaranteed!
  - If graph is connected, link reversal process will restore connectivity in DAG
- This has been known in wireless literature
  - Now being applied to wired networks
- If you don’t think this is neat, then you are asleep.
  - Local rule to produce ideal connectivity!

Class Exercise: Prove This Works

- Develop line of argument about why this guarantees connectivity

Keys to Proof

- Deadend: algorithm never results in dead-ends
  - At least one link will be outbound, if you have a link
- Loops:
  - Assume network does not have loop at beginning
    - (i.e., we have a DAG)
  - Link reversal cannot create a loop
    - Because reversed node cannot be part of a loop
  - Therefore, topology never in a state where a loop exists
- Are we done with proof?

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No, link reversals might not terminate

- Must prove topology reaches fixed point
  - If underlying graph is connected
- Not reaching a fixed point means process of node reversals continues forever
- Since network is of finite size, this process must repeat in a cycle of node reversals
- How can we prove this is impossible?

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Fact #1

- If a node has a path to the destination, then it will never reverse itself.
- Conclusion: the set of nodes with a path to the destination is nondecreasing

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Fact #2

- For a node to do a second link reversal, all of its neighbors must have also reversed its links.
- Therefore, the set of nodes doing a link reversal is an expanding set
- Can only re-reverse all reversing nodes if the process reaches the “edge” of network
- But once this process touches a node which is connected to the source, it stops. **QED.**

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Summary of RAD

- Local responses lead to:
  - Guaranteed connectivity
  - Close-to-optimal load balancing
- Can be used for L2 and/or L3
  - No change in packet headers

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Why Isn’t RAD Enough?

- The link reversals are on the “control plane”
- They take time to compute
- Packets can be lost in the meantime…
- Exactly the problem with FCP route recomputation
  - Works on control-plane speeds, not data speeds
- Any suggestions?

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Data-Driven Connectivity (DDC)

- Define link reversal properties in terms of actions that can occur at data speeds
- Events: packet arriving in “reverse” direction
- Action: remove that link from outgoing set
- Goal: define simple algorithms that can be supported in HW
  - Ask Panda for more details

Review

- Major Routing Challenges:
  - Resilience
  - Traffic Engineering
  - Policy Oscillations
- We have solutions for all of them!
  - FCP, RAD, and Policy Dispute Resolution
- Are they deployed? No…..
  - Will they be deployed? Maybe…..
- ..