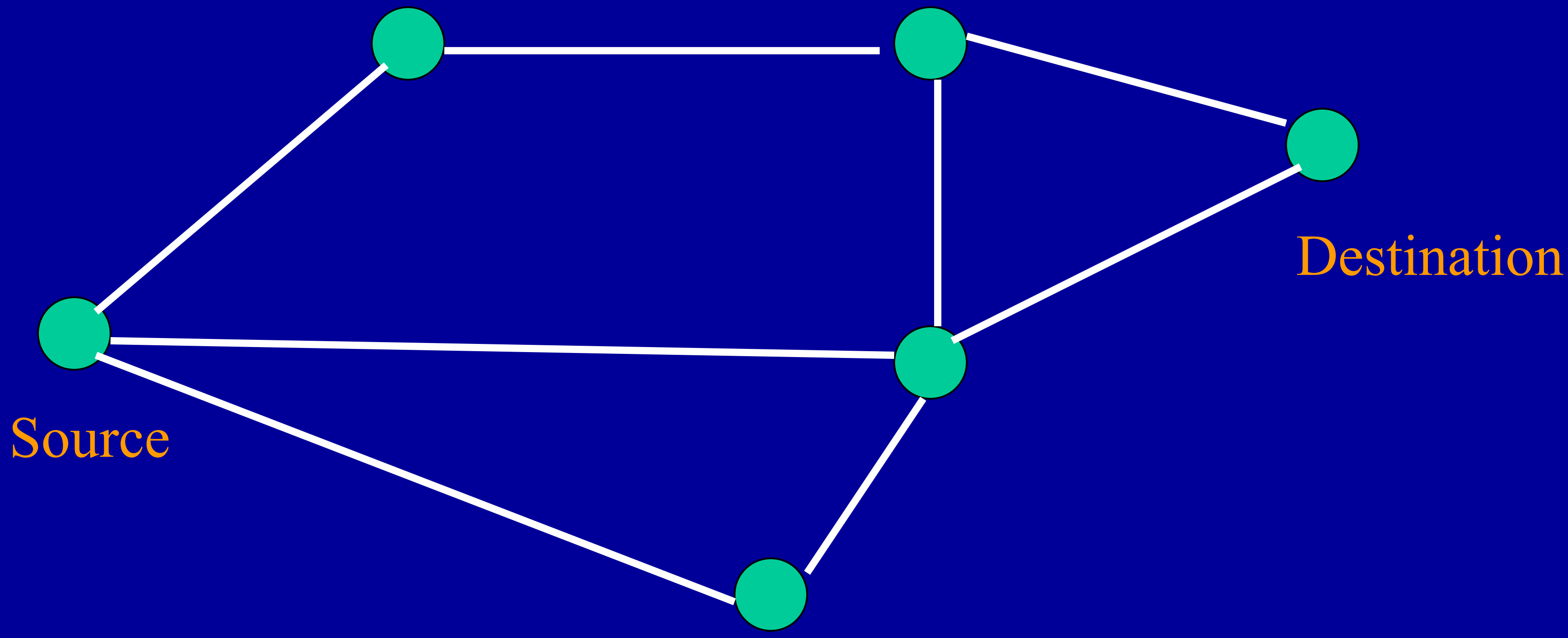
Formal verification of distance vector routing protocols

Routing in a network

(Find the cheapest route from Source to Destination)



L(***i, j***) = Cost of direct link ***i*** --- ***j***.

R(***a, b***) = Cost of route from ***a*** to ***b***.

R(***a, b***) = min{ L(***a, k***) + R(***k, b***) }

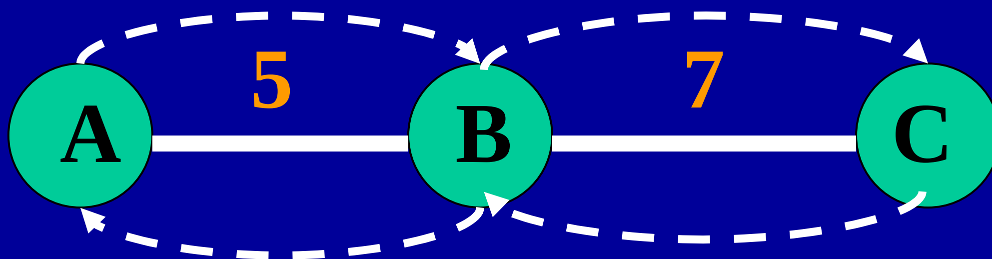
Outline

- RIP (Routing Information Protocol)
  - Internet routing protocol

- AODV (Ad-hoc On-demand Distance Vector routing)
  - Used for mobile ad-hoc networking.

Distance-vector routing in RIP

	A	B	C
Initially	A: 0 B: 5 C: ∞	A: 5 B: 0 C: 7	A: ∞ B: 5 C: 0



	A	B	C
After exchange	A: 0 B: 5 ***C: 12***	A: 5 B: 0 C: 7	A: 12 B: 5 ***C: 0***

RIP

Routing table: Each node maintains the cost of route to every other node

Initially: All nodes know cost to neighbors

Desired Final Goal: All nodes know cost to all other nodes

while(1)

{

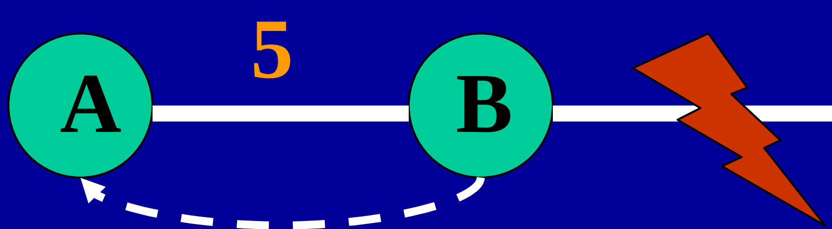
  Nodes periodically send their routing table to every neighbor;

  R(*a*, *b*) = min{ L(*a*, *k*) + R(*k*, *b*) };

}

Count to Infinity

After exchange	A: 0 B: 5 ***C: 12***	A: 5 B: 0 C: 7	A: 12 B: 5 ***C: 0***



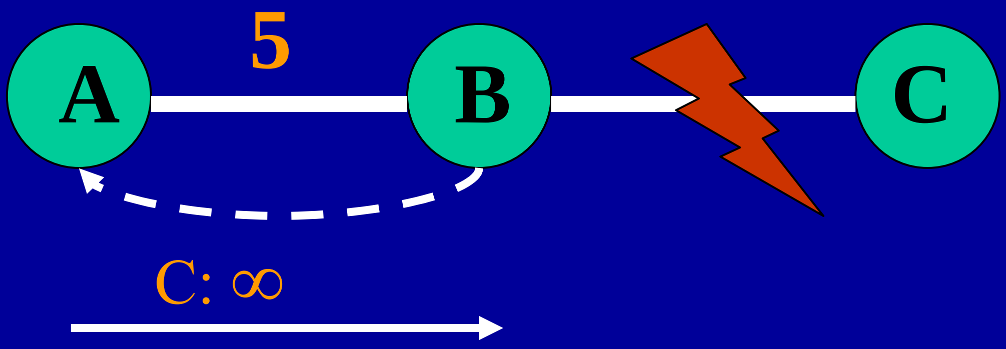
C: 12 →

C: 12+5=17 ←

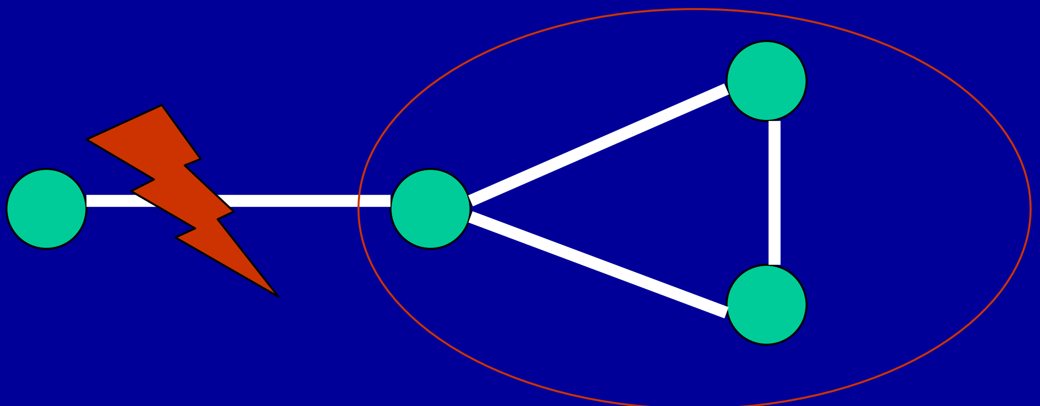
C: 17+5=22 →

Poisoned reverse

Works for loops of two routers (adds more cases for Verification)



RIP limitation: Doesn’t work for loops of three or more routers



Infinity = 16

- Since we can’t solve the loop problem
  - Set Infinity to 16
- RIP is not to be used in a network that has more than 15 hops.

Convergence

- Convergence:
  - All nodes eventually agree upon routes
- Divergence:
  - Nodes exchange routing messages indefinitely.
- Ignore topology changes
  - We are concerned only with the period between topology changes.

Some definitions

- Universe is modeled as a bipartite graph
  - Nodes are partitioned into routers and networks
  - Interfaces are edges.
  - Each routers connects to at least two networks.
  - Routers are neighbors if they connect to same network
- Actually, we can do away with bipartite graph by assuming that router = network (i.e. each network has one router) .
- An entry for destination ***d*** at a router ***r*** has:
  - hops(r): Current distance estimate
  - nextR(r): next router on the route to ***d.***
  - nextN(r): next network on route to ***d.***

More definitions

- **D(*r*)** = 1 if ***r*** is connected to ***d***

  = 1 + min{ D(***s***)| ***s*** is a neighbor of ***r*** }
- ***k*-circle** around ***d*** is the set of routers:

  $C_k = \{ r \mid D(r) \leq k \}$

- **Stability:** For $1 \leq k \leq 15$, universe is ***k*-stable** if:

(S1): Every router ***r*** in C_k has hops(***r***) = D(***r***)

Also, D(nextR(***r***)) = D(***r***) – 1.

(S2): For every router ***r*** outside C_k, hops(***r***) > ***k***.

Convergence

- Aim of routing protocol is to expand ***k***-circle to include all routers
- A router ***r*** at distance ***k***+1 from ***d*** is (***k***+1)-stable if it has an optimal route:
  - Hops(***r***)=***k***+1 and nextR(***r***) is in C_k.
- Convergence theorem (Correctness of RIP)
  - For any ***k*** < 16, starting from an arbitrary state of the universe, for any fair sequence of messages, there is a time t_k, such that the universe is ***k***-stable at all times $t \geq t_k$.

Tools

- HOL (higher order logic)
  - Theorem prover (more expressive, more effort)
- SPIN
  - Model checker (less expressive, easier modeling)
- Number of routers is infinite
  - SPIN would have too many states
  - States reduced by using abstraction

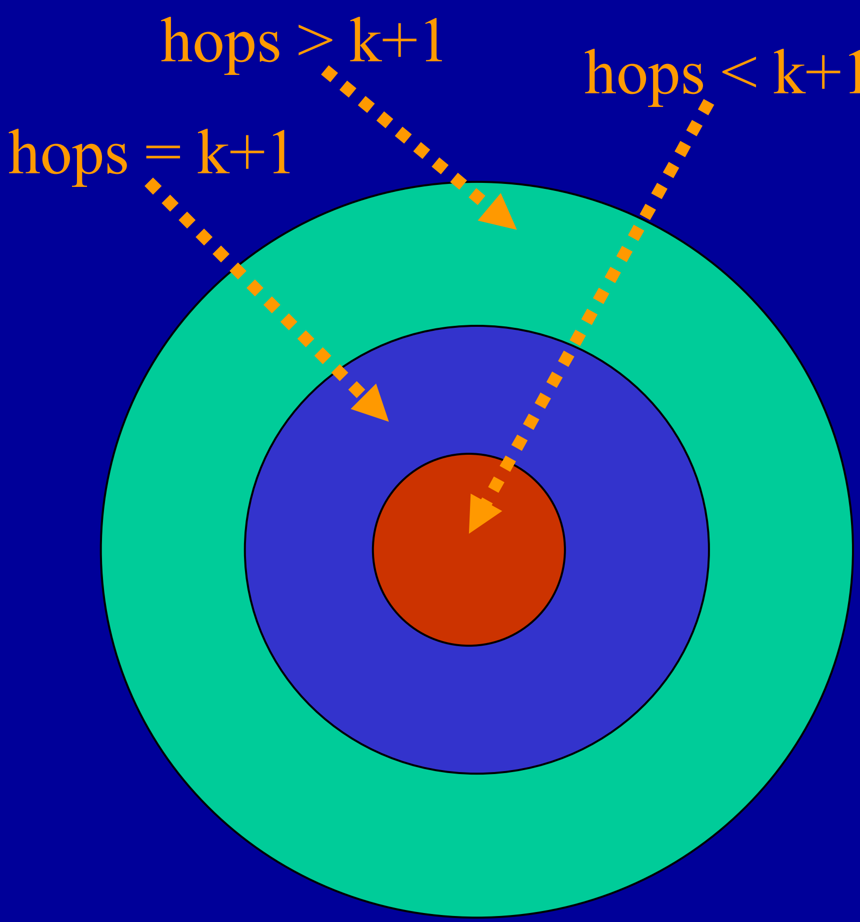
Lemmas in convergence proof

- Proved by induction on ***k***.
  - Lemma 1: Universe is initially 1-stable. (Proved in HOL).
  - Lemma 2: Preservation of Stability. For any $k < 16$, if the universe is ***k***-stable at some time ***t***, then it is ***k***-stable at any time $t' \geq t$. (Proved in HOL).
  - Lemma 3: For any $k < 15$ and router r such that $D(r)=k+1$, if the universe is ***k***-stable at some time t_k, then there is a time $t_{r,k} \geq t_k$ such that ***r*** is ***(k+1)***-stable at all times $t \geq t_{r,k}$. (Proved in SPIN)
  - Lemma 4: Progress. For any $k < 15$, if the universe is ***k***-stable at some time t_k, then there is a time $t_{k+1} \geq t_k$ such that the universe is (k+1)-stable at all times $t \geq t_k+1$. (Proved in HOL).

Abstraction

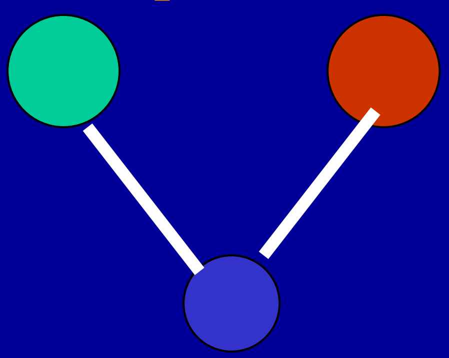
- To reduce state-space for SPIN
- Abstraction examples:
  - If property P holds for two routers, then it will hold for arbitrarily many routers.
  - Advertisements of distances can be assumed to be ***k*** or ***k***+1.
- Abstraction should be:
  - ***Finitary***: should reduce system to finite number of states
  - ***Property-preserving***: Whenever abstract system satisfies the property, concrete system also satisfies the property

Abstraction of universe



Concrete system with many routers

Advertiser send updates



Router processes Updates

Hop-count is {LT, EQ, GR}

Abstract system with 3 routers

Bound on convergence time

- Theorem: A universe of radius ***R*** becomes 15-stable within time = min{15, ***R***}* Δ. (Assuming there were no topology changes).

After Δ	weakly 2-stable
After 2Δ	weakly 3-stable
After 3Δ	weakly 4-stable
After 4Δ	weakly 5-stable
…	…
After (***R***-1)Δ	weakly ***R***-stable
After ***R***Δ	***R***-stable

Weak stability

- Universe is weakly ***k***-stable if:
  - Universe is ***k***-1 stable
  - For all routers on ***k***-circle: either ***r*** is ***k***-stable or hops(***r***) > ***k***.
  - For all routers ***r*** outside C_k (D(***r***) > ***k***), hops(***r***) > ***k***.
- By using weak stability, we can prove a sharp bound

Lemmas in Proof of timing bound

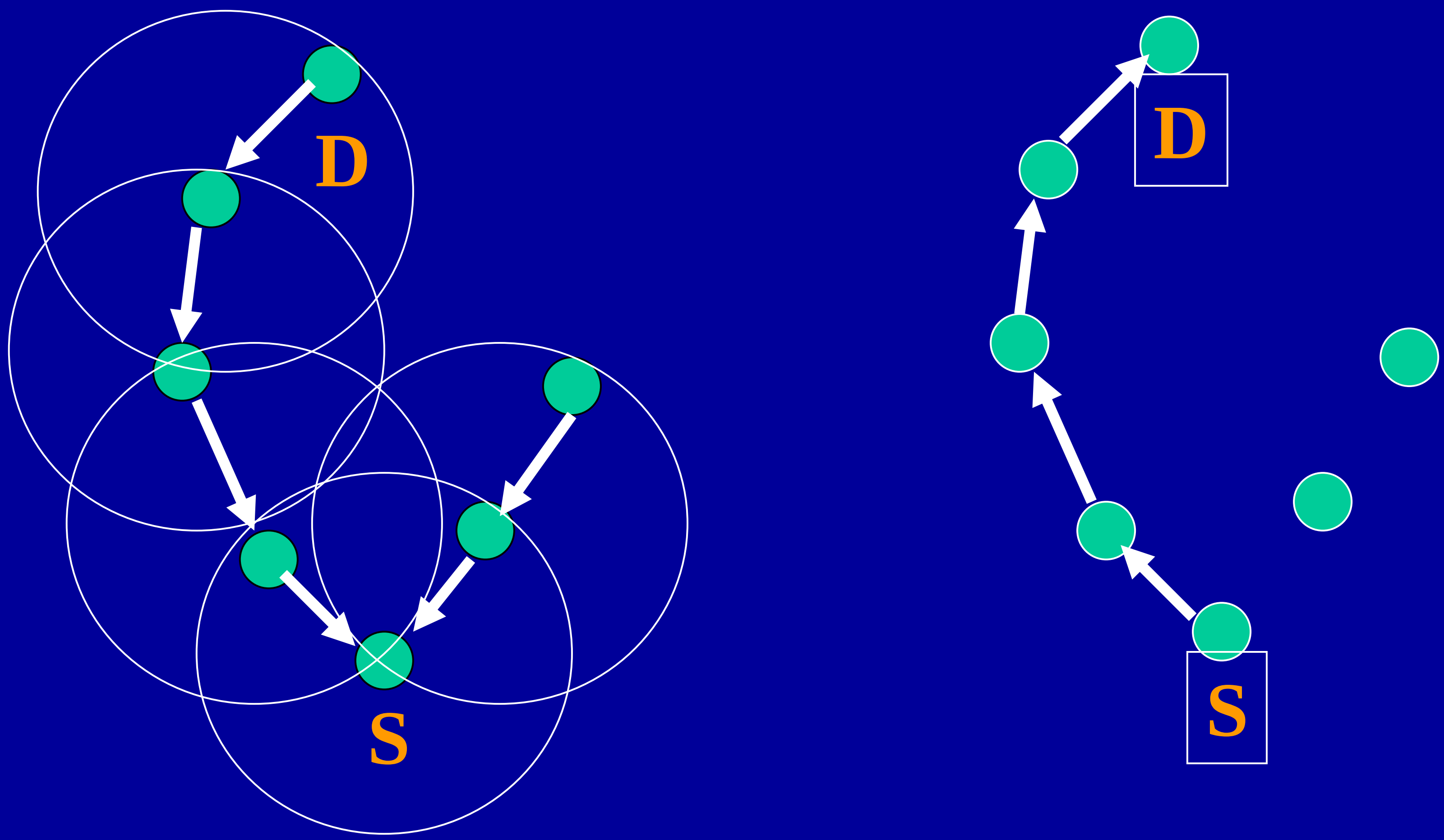
- Lemma 5: Preservation of weak stability. For any $2 \leq \boldsymbol{k} \leq 15$, if the universe is weakly $\boldsymbol{k}$-stable at some time $\boldsymbol{t}$, then it is weakly $\boldsymbol{k}$-stable at any time $\boldsymbol{t'} \geq \boldsymbol{t}$.
- Lemma 6: Initial Progress. If the topology does not change, the universe becomes weakly 2-stable after Δ time.
- Lemma 7: For any $2 \leq \boldsymbol{k} \leq 15$, if the universe is weakly $\boldsymbol{k}$-stable at some time $\boldsymbol{t}$, then it is $\boldsymbol{k}$-stable at time $\boldsymbol{t} + \Delta$.

Proof continued

- Lemma 8: Progress. For any $2 \leq \boldsymbol{k} \leq 15$, if the universe is weakly ***k***-stable at some time ***t***, then it is weakly (***k***+1)-stable at time $\boldsymbol{t} + \Delta$.

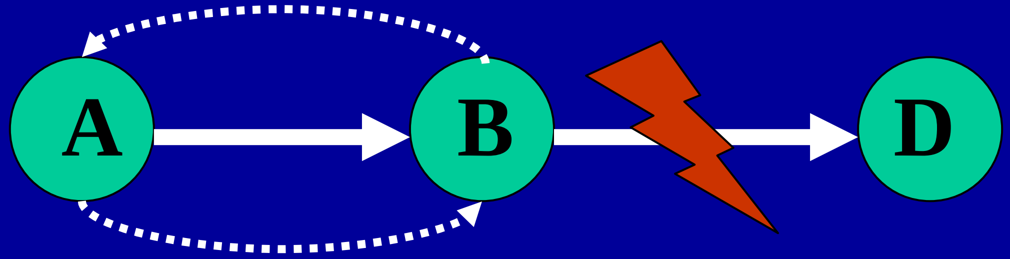
AODV

Routes are computed on-demand to save bandwidth.



AODV

- Each route request has a sequence number for freshness.
- Among two routes of equal freshness, smaller hop-count is preferred.
- Property formally verified is **loop freedom**
  - Above conditions mean a lot of cases need to be checked



Searching for loop formation

- The 3-node network shown previously, is run in SPIN.
  - `Ω(!((next$_D$(A)==B) /\ (next$_D$(B)==A)))
- Four ways of loop formation are found.
- Standard does not cover these cases.
- Formal verification can aid protocol design.

Ways of loop formation

- To get an idea of case-analysis required, loops can be formed by:
  - Route reply from B to A getting dropped.
  - B deleting route on expiry.
  - B keeping route but marks it as expired.
  - A not detecting a crash of B.
- Loop was avoided by:
  - B keeping route as expired, incrementing the sequence number and never deleting it.
  - Is a good indicator of a loop-free solution.

Guaranteeing AODV loop freedom

- Based on the avoidance of loops for 3 nodes, we assume:
  - Nodes never delete routes, incrment sequence number of expired routes, detect crashes immediately.
- Based on these assumptions, loop freedom is proved.
- Theorem: Consider an arbitrary network of nodes running AODV*v2*. If all nodes conform to above assumption, there will be no routing loops.

Abstraction

- Abstract sequence number is ***{GR, EQ, LT }***
- Abstract hop count is ***{GR, EQ, LT }***
- Abstract next pointer is ***{EQ, NE}***
- Lemma 9: If $\boldsymbol{t_1} \leq \boldsymbol{t_2}$ and for all $\boldsymbol{t}$: $\boldsymbol{t_1} < \boldsymbol{t} \leq \boldsymbol{t_2}$. ¬ restart($\boldsymbol{n}$)($\boldsymbol{t}$), then:

  $$\text{seqno}_d(\boldsymbol{n})(\boldsymbol{t_1}) \leq \text{seqno}_d(\boldsymbol{n})(\boldsymbol{t_2})$$

- Lemma 10: If $\boldsymbol{t_1} \leq \boldsymbol{t_2}$ and $\text{seqno}_d(\boldsymbol{n})(\boldsymbol{t_1})=\text{seqno}_d(\boldsymbol{n})(\boldsymbol{t_2})$, and for all $\boldsymbol{t}$: $\boldsymbol{t_1}< \boldsymbol{t} \leq \boldsymbol{t_2}$. ¬ restart($\boldsymbol{n}$)($\boldsymbol{t}$), then $\text{hops}_d(\boldsymbol{n})(\boldsymbol{t_1}) \geq \text{hops}_d(\boldsymbol{n})(\boldsymbol{t_2})$

Adding to abstraction

- The following lemma involves two nodes.
- Abstract sequence number is ***{GR, EQ, LT}*** x ***{EQ, NE}***
- Abstract hop count is ***{GR, EQ, LT }*** x ***{EQ, NE}***
- Abstract next pointer is ***{EQ, NE}*** x ***{EQ, NE}***
- Lemma 11: If $\text{next}_d(\underline{\boldsymbol{n}})(\boldsymbol{t})=\boldsymbol{n'}$, then there exists a time $\boldsymbol{lut} \le \boldsymbol{t}$, such that:
  - $\text{seqno}_d(\boldsymbol{n})(\boldsymbol{t}) = \text{seqno}_d(\boldsymbol{n})(\boldsymbol{lut})$
  - $1 + \text{hops}_d(\boldsymbol{n})(\boldsymbol{t}) = \text{hops}_d(\boldsymbol{n'})(\boldsymbol{lut})$
  - For all $\boldsymbol{t'}$: $\boldsymbol{lut} < \boldsymbol{t'} \le \boldsymbol{t}$. $\neg\, \text{restart}(\boldsymbol{n'})(\boldsymbol{t'})$.

Conclusion

- Specific technical contributions
  - First proof of correctness of the RIP standard.
  - Statement and automated proof of a sharp real-time bound on RIP convergence
  - Automated proof of loop-freedom for AODV.