Introduction to Intra-Domain Routing

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COMP0023

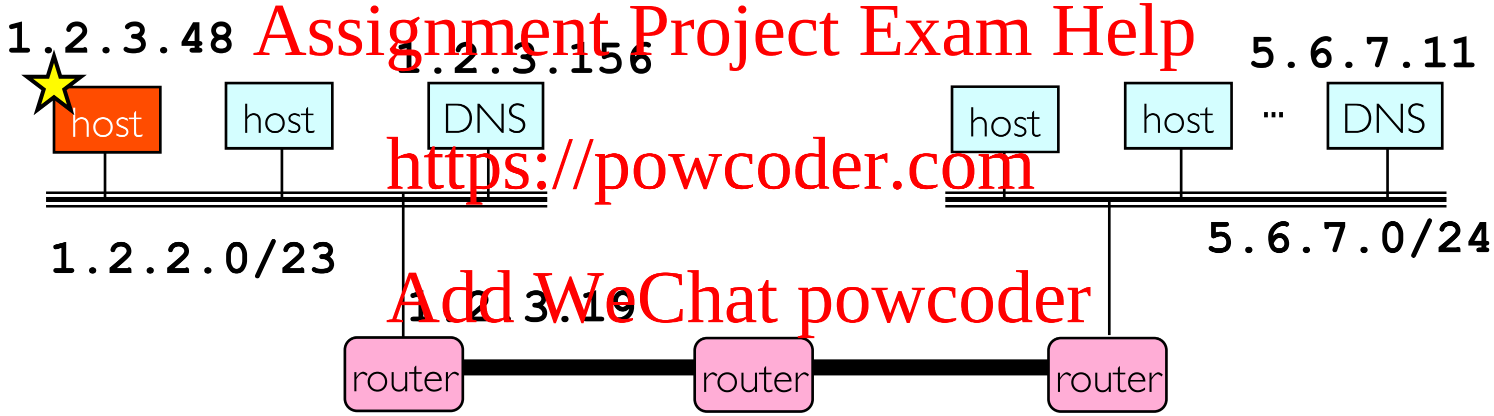
Agenda

- We delve into network layer's main functionality

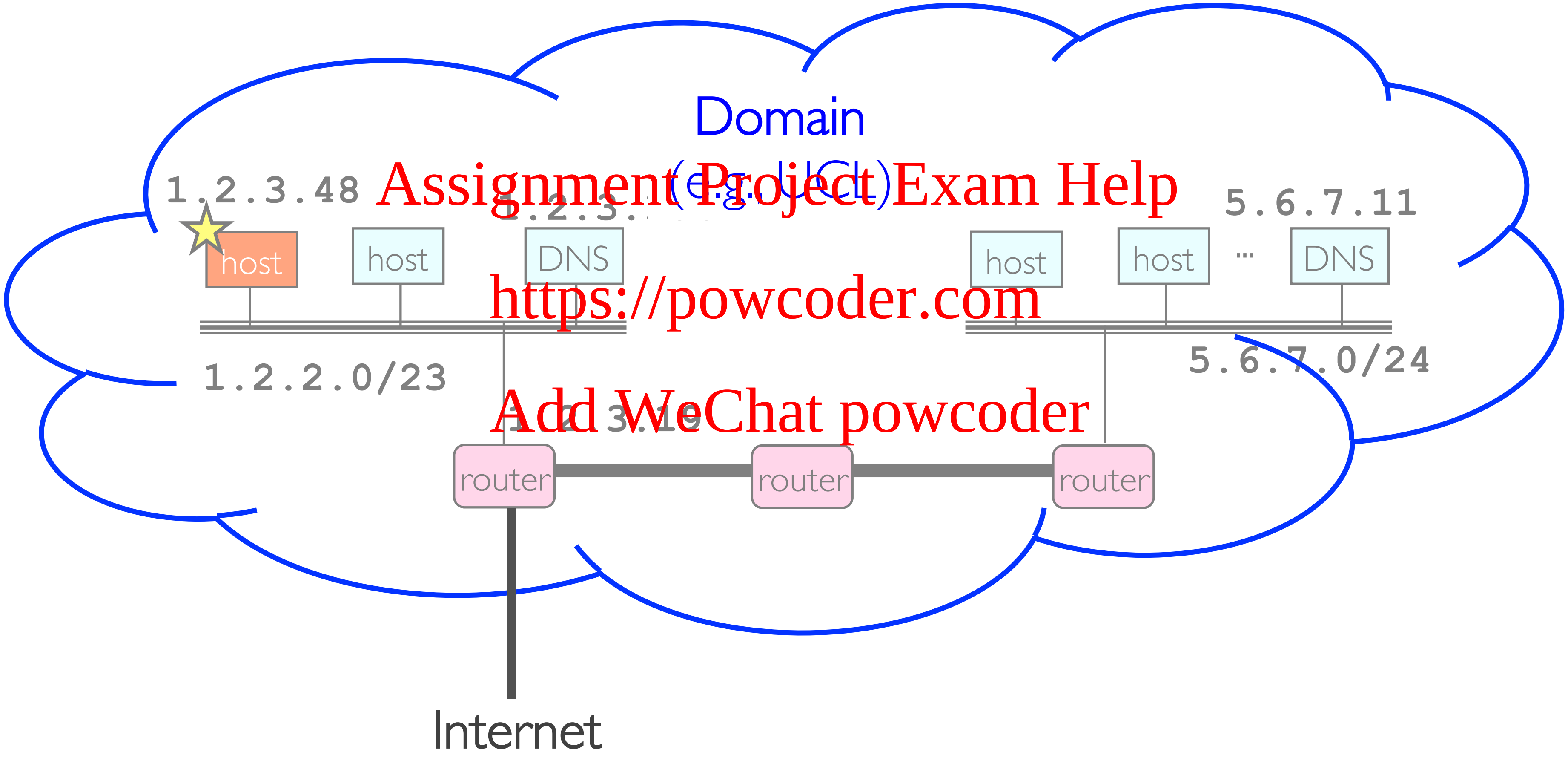
1. Setting
   - Context
   - Routing players

2. Intra-domain routing problem definition

Let's consider a network with several LANs



Several LANs can belong to a single organization



Collecting evidence from the real world

- Traceroute exposes real Internet paths
  – Unix: traceroute <destination>
  – Windows: tracert <destination>

- It displays all hops on the path between host where launched and <destination>
  – it sends a sequence of carefully constructed packets that "expire" after 1 hop, 2 hops, …
  – each of those packets elicits ICMP error from router that many hops from sender

A traceroute from UCL to Cambridge

```
traceroute to www.cl.cam.ac.uk (128.232.0.20), 64 hops max, 40 byte
   packets
 1  cisco (128.16.64.1)  0.370 ms  0.322 ms  0.361 ms
 2  128.40.255.29 (128.40.255.29)  0.483 ms  0.348 ms  0.487 ms
 3  128.40.20.1 (128.40.20.1)  0.486 ms  0.342 ms  0.362 ms
 4  128.40.20.62 (128.40.20.62)  0.486 ms  0.474 ms  0.363 ms
 5  ulcc-gsr.lmn.net.uk (194.83.101.5)  0.485 ms  0.346 ms  0.362 ms
 6  london-bar1.ja.net (146.97.40.33)  0.485 ms  0.470 ms  0.488 ms
 7  po10-0.lond-scr.ja.net (146.97.35.5)  0.735 ms  0.722 ms  0.610 ms
 8  po0-0.cambridge-bar.ja.net (146.97.35.10)  5.232 ms  4.964 ms  4.734
   ms
 9  route-enet-3.cam.ac.uk (146.97.40.50)  4.982 ms  4.841 ms  4.860 ms
10  route-cent-3.cam.ac.uk (192.153.213.194)  4.984 ms  4.964 ms
   4.861 ms
```

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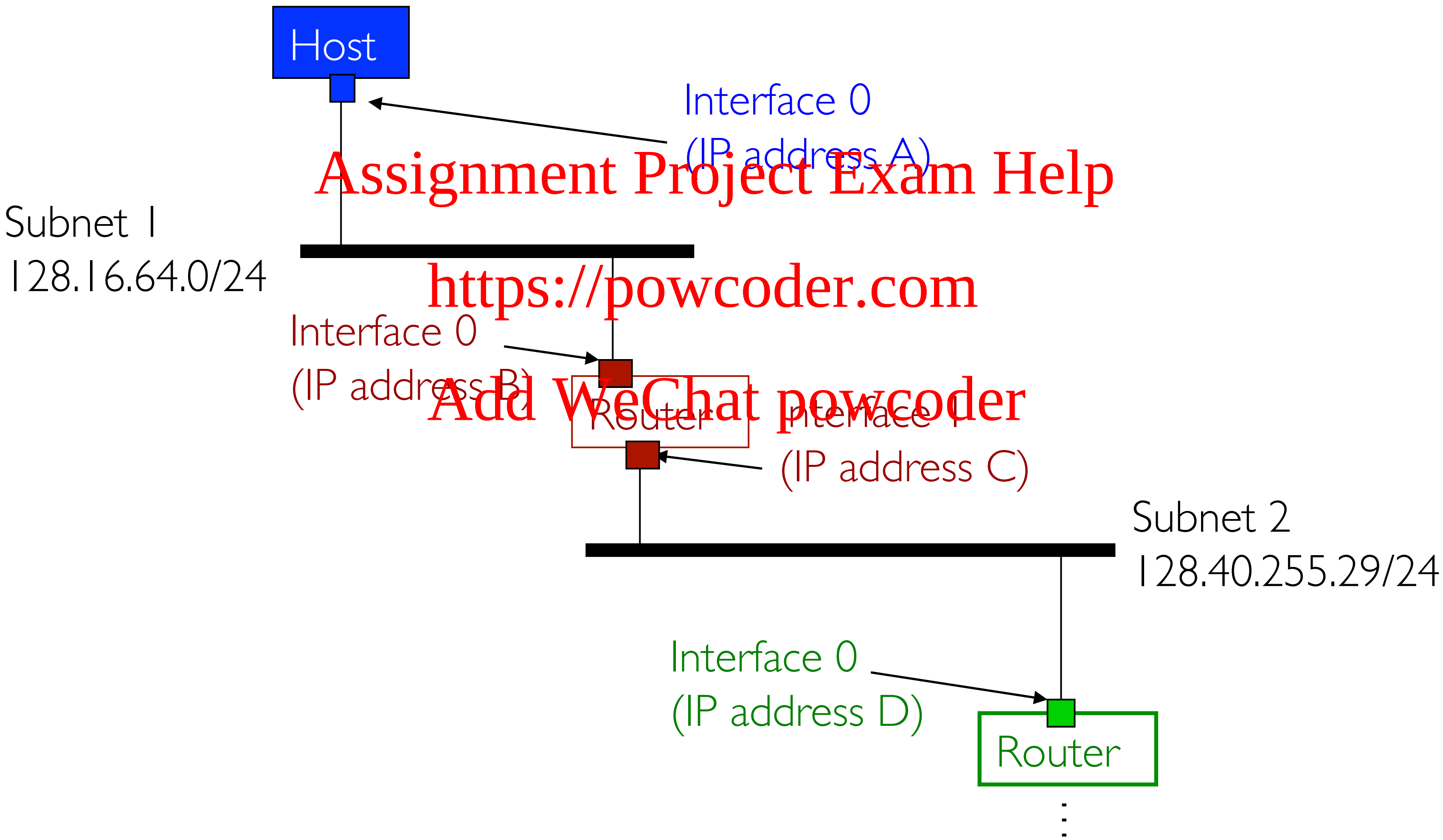
    4.861 ms
```

The big picture emerging from the traceroute



Routers keep routing tables

Three fields

- Destination: destination IP

- Outgoing interface: on which to forward packet for the given destination

- Metric: total cost to reach the destination

  – depends on interfaces' metrics (set by net admins)

Destination	Interface	Metric
A	0	0
B	1	0

Routers' destinations are IP prefixes

- Each host (interface) has unique 32-bit IP address
  – E.g., 128.16.64.1

- Must every router in entire Internet know about every other router and host?

  No; interfaces on same subnet share IP prefix
    - e.g., 128.16.64/24 for 128.16.64.1

- IP routing destination is subnet's prefix
  – Not single IP addresses

Routers use routing table to forward packets

- Packet for destination D arrives
- Router searches D in destination field of routing table
  - using longest-prefix match
    - If more than one route match D, choose the route with the longest prefix
- Possible outcomes:
  - if entry for D, forward on interface in the entry
  - if no entry, no route known → drop packet

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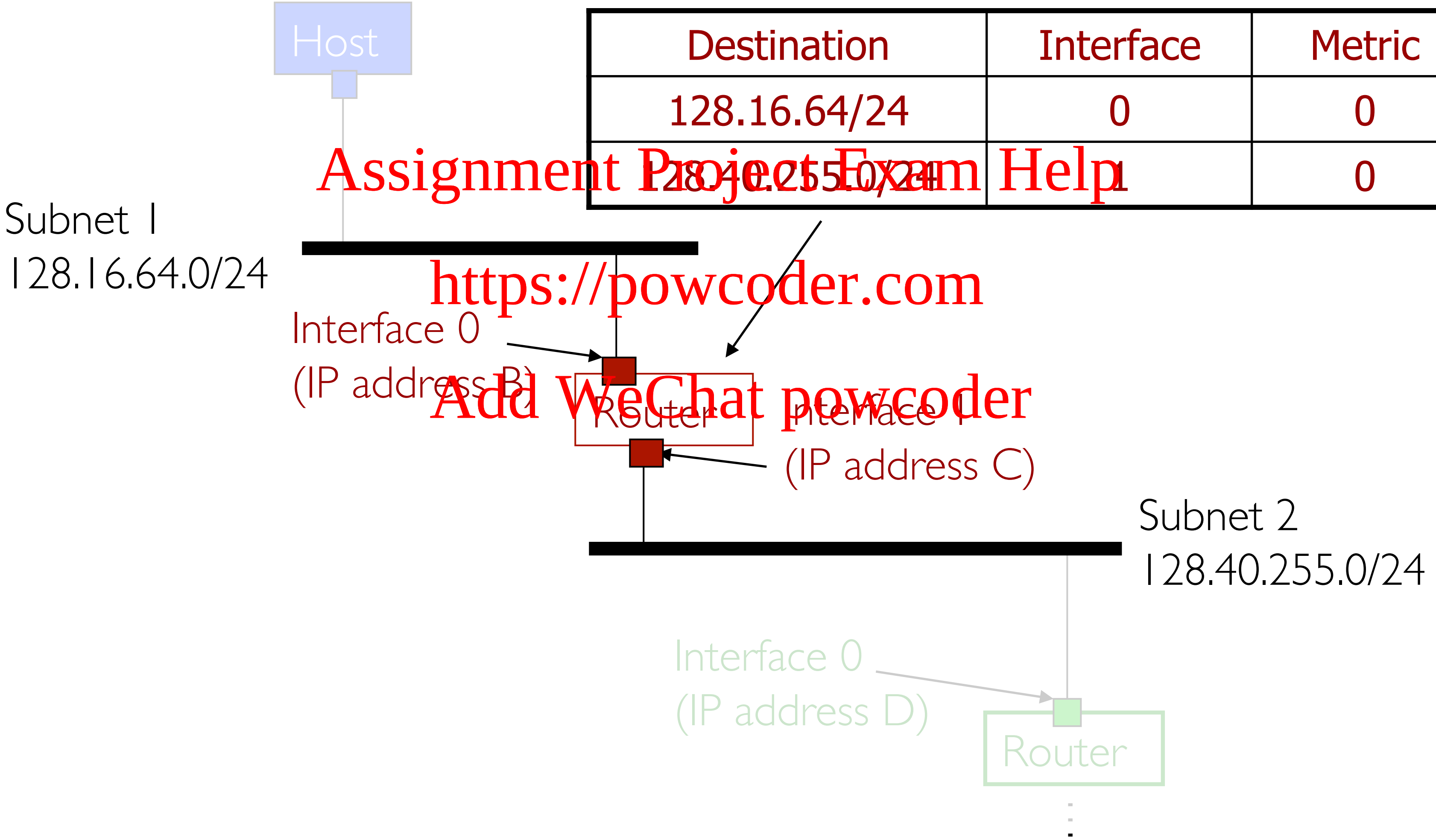
  - using longest-prefix match
    - If more th… …oose the route with the longest prefix
- Possible outcomes:
  - if entry for D, forward on interface in the entry
  - if no entry, no route known → drop packet

How to populate routing tables for any router in a domain?

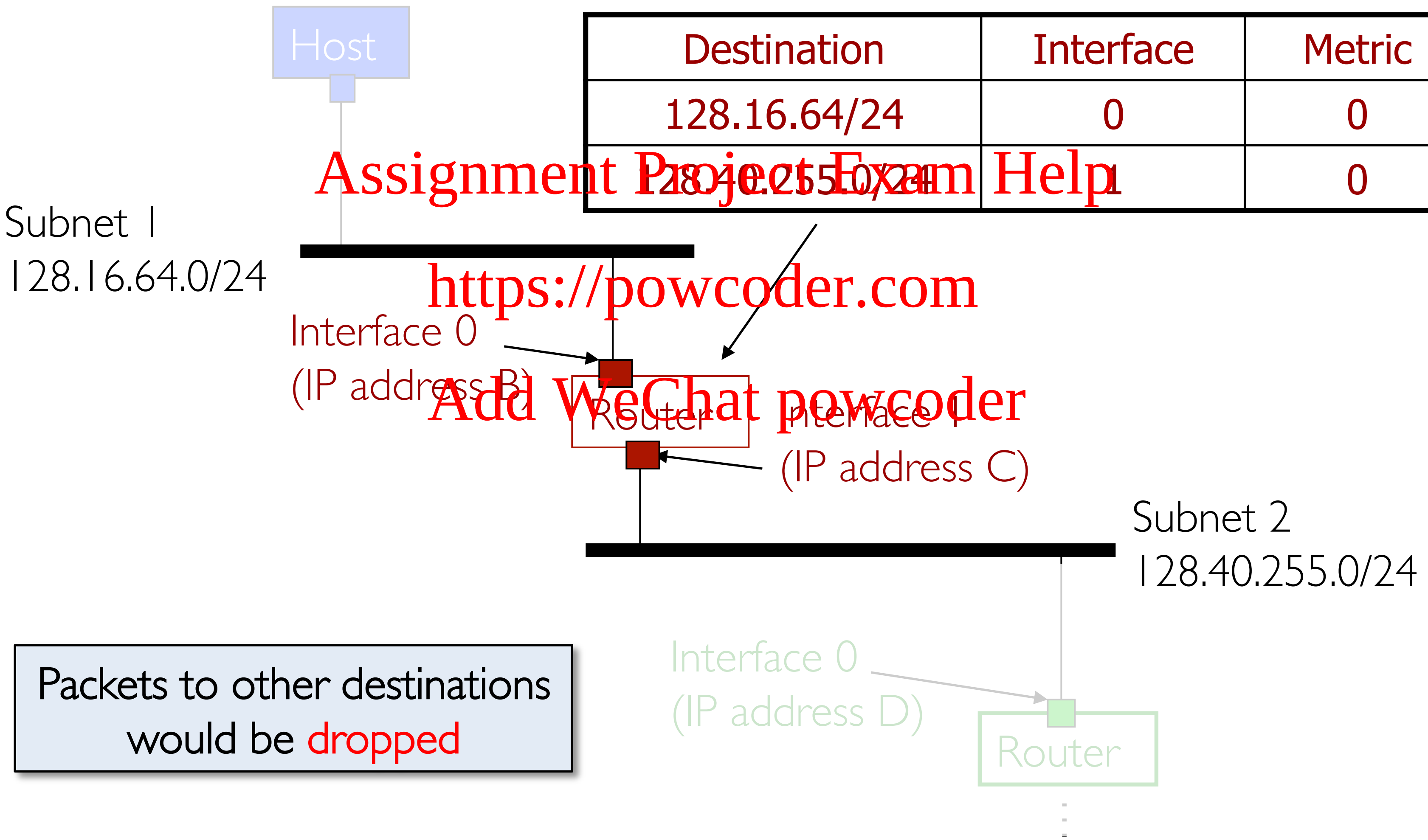
At startup, a router initializes its routing table for directly connected subnets

Destination	Interface	Metric
128.16.64/24	0	0
128.40.255.0/24	1	0



At startup, a router initializes its routing table for directly connected subnets

Destination	Interface	Metric
128.16.64/24	0	0
128.40.255.0/24	1	0

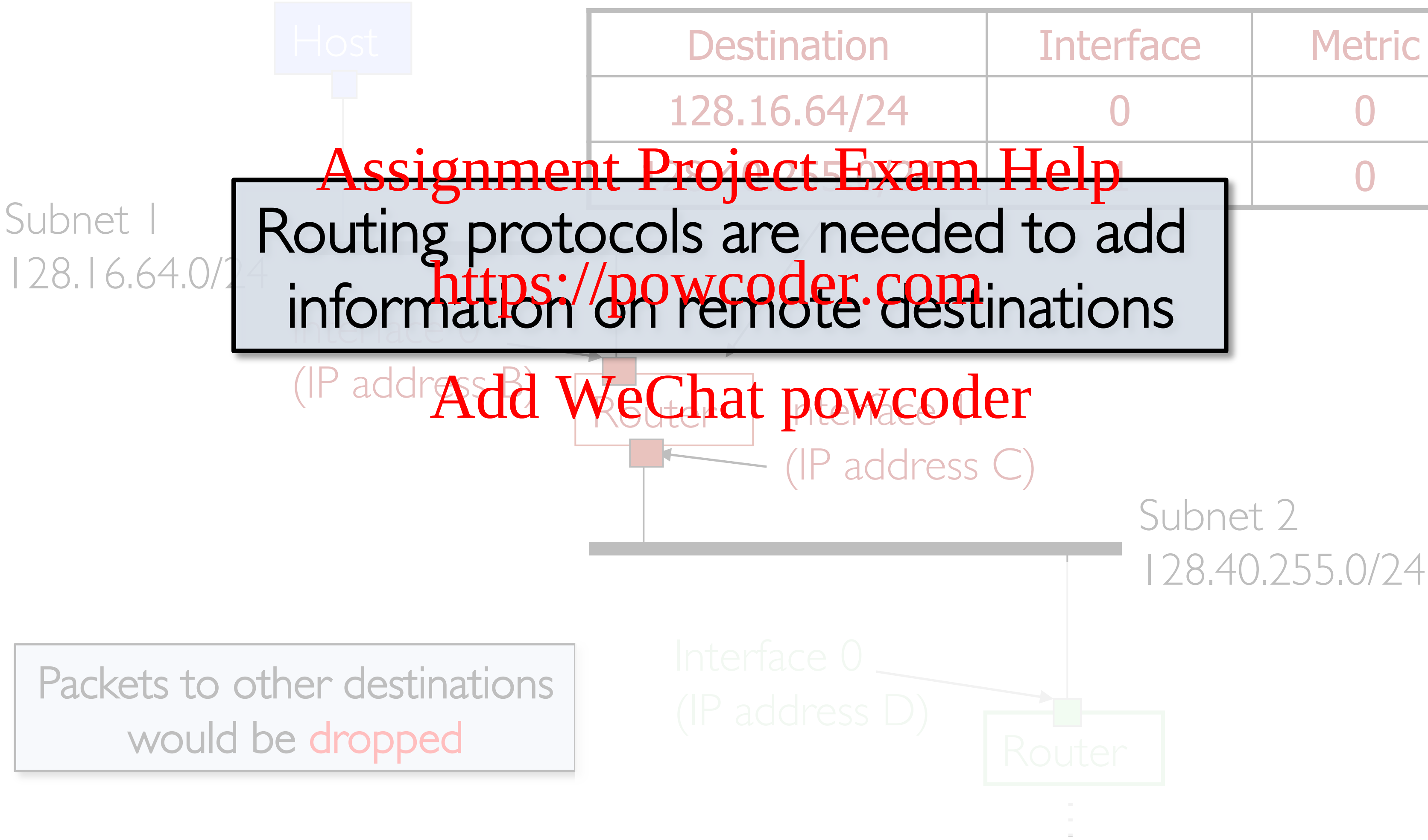


Packets to other destinations would be dropped

At startup, a router initializes its routing table for directly connected subnets

Destination	Interface	Metric
128.16.64/24	0	0
128.40.255.0/24	1	0

Routing protocols are needed to add information on remote destinations



Packets to other destinations would be dropped

Agenda

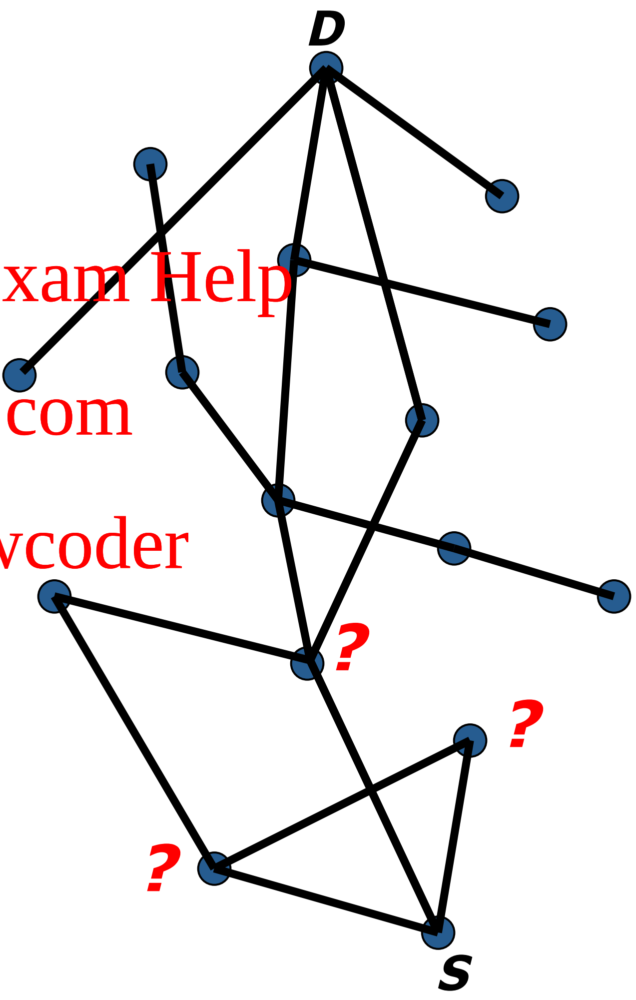
- We delve into network layer's main functionality

1. Setting
   - Context
   - Routing players

2. Intra-domain routing problem definition

Consider an arbitrary network

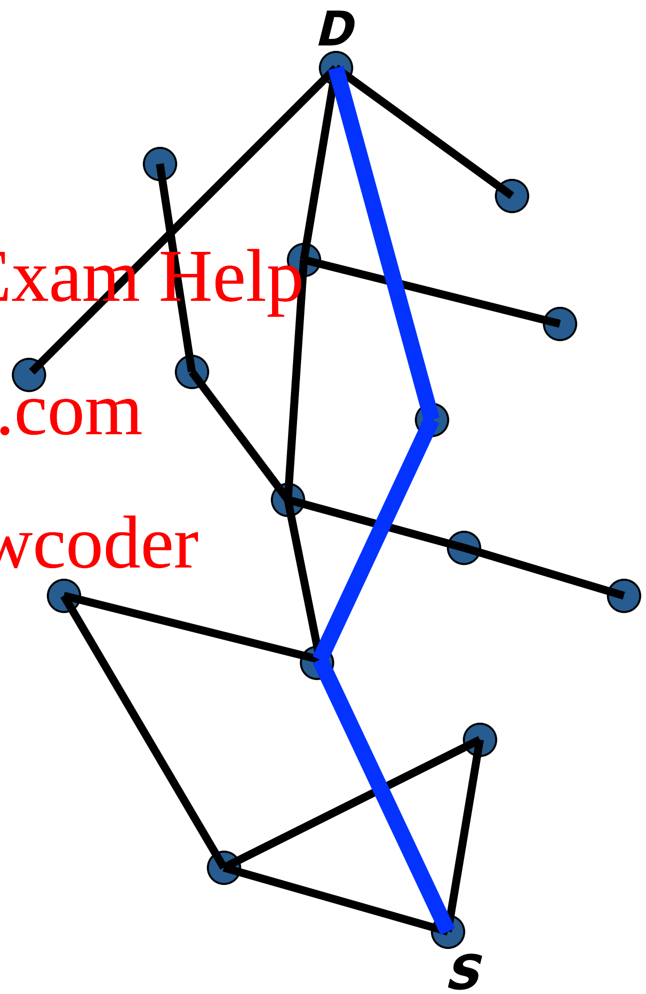
- Each router has an ID and several interfaces
  - Linked to many other routers and subnets
- Each router must choose the next-hop for received packets
  - Packets include info on destinations (IP addresses)
    - But not on intermediate hops



Routing protocols build routing tables

- Routing protocols define information and messages exchanged by routers
  - For routers to accumulate state (routing table entries) to forward packets

- Routing protocols also determine how to choose between alternative next-hops



Intra-domain routing goals

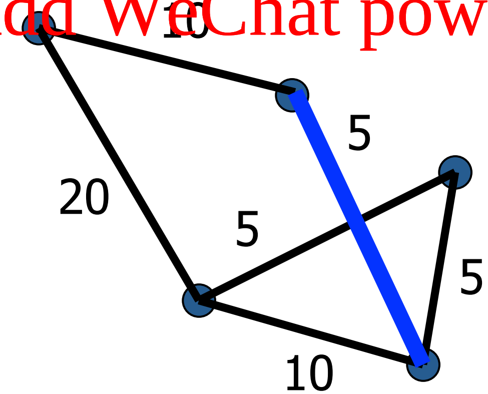
- Provide good performance
  - Typically, choose "good" paths for any pair of routers

- Automated path computation
  - Possibly, efficient in time and memory

- Deal with failures
  - Routes must be coherent with topology

Typical solution: shortest path routing

- View network as weighted graph
  - Routers are vertices, links are edges
  - Link metrics are edge weights



Typical solution: shortest path routing

Shortest paths problem:

– What path between two vertices offers minimal sum of edge weights?

- Classic graph algorithms find single-source shortest paths when the entire graph is known centrally

  – Dijkstra's Algorithm, Bellman-Ford Algorithm

- Typically, no central knowledge of entire graph
  – Each router only knows its own interfaces' addresses

Challenge: deal with changing networks

- Network components are not reliable
  - Links may be cut, router or their interfaces may fail

- Changing networks induce hazards

  - Need for (fast) re-convergence to new, correct paths after a failure

  - Potential for forwarding loops
    - Amplify traffic → congest links
      - TTL will eventually expire, but typically too late
  - Possibility of temporary disconnections (i.e., blackholes)

Distance Vector Routing

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Agenda

- We are now ready to study Distance Vector routing

1. Algorithm
2. Pathologies
3. Optimizations

Basic Distance Vector Algorithm

- Distributed Bellman-Ford (DBF)

- Principle: "tell everything you know to your neighbours"

  – Periodically, send all your routing table entries (destination and metric fields) to all your neighbouring routers

Basic Distance Vector Algorithm: DBF

(Failures Not Yet Considered)

Upon receipt of routing table entry for destination D with metric m on interface i:

m += *configured metric for interface i*

rt = lookup(D) *in routing table*

if (rt = “not found”) then

rt_new = *new routing table entry*

$rt\_new.dst$ = D; $rt\_new.metric$ = m; $rt\_new.iface$ = i

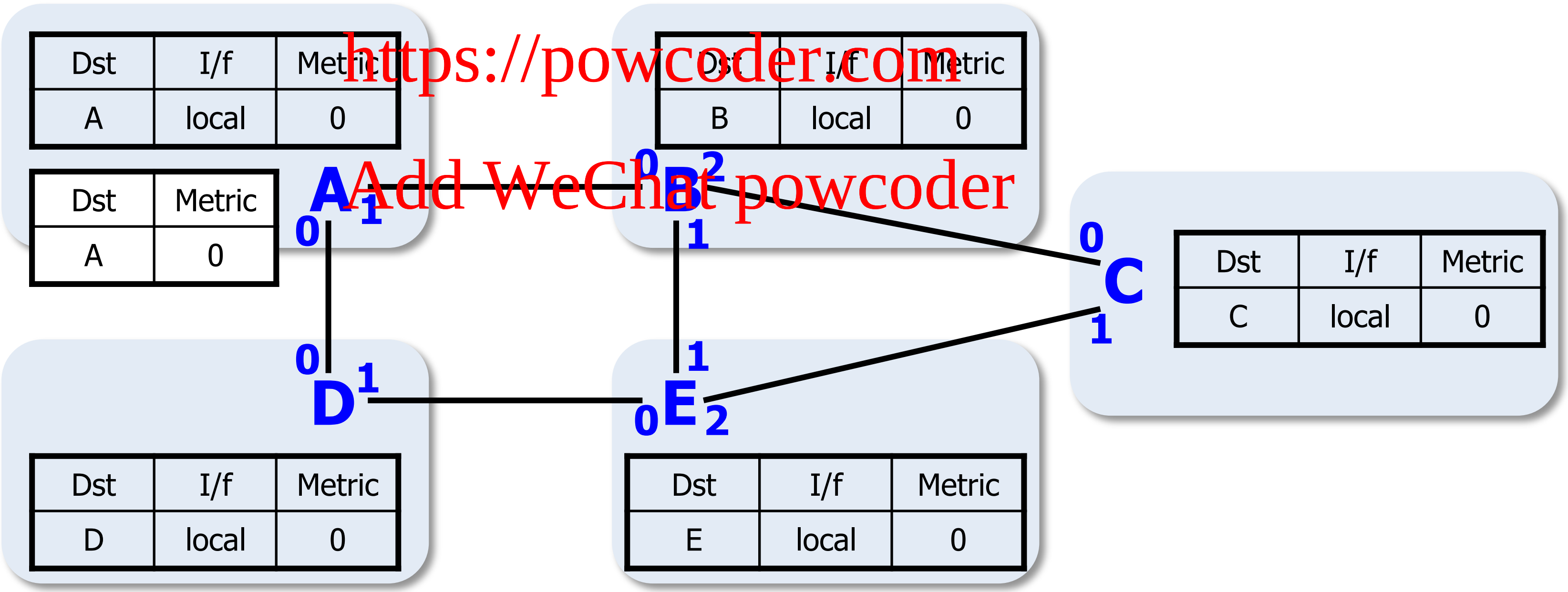
add rt_new *to routing table*

else if (m < $rt.metric$) then

$rt.metric$ = m; $rt.iface$ = i

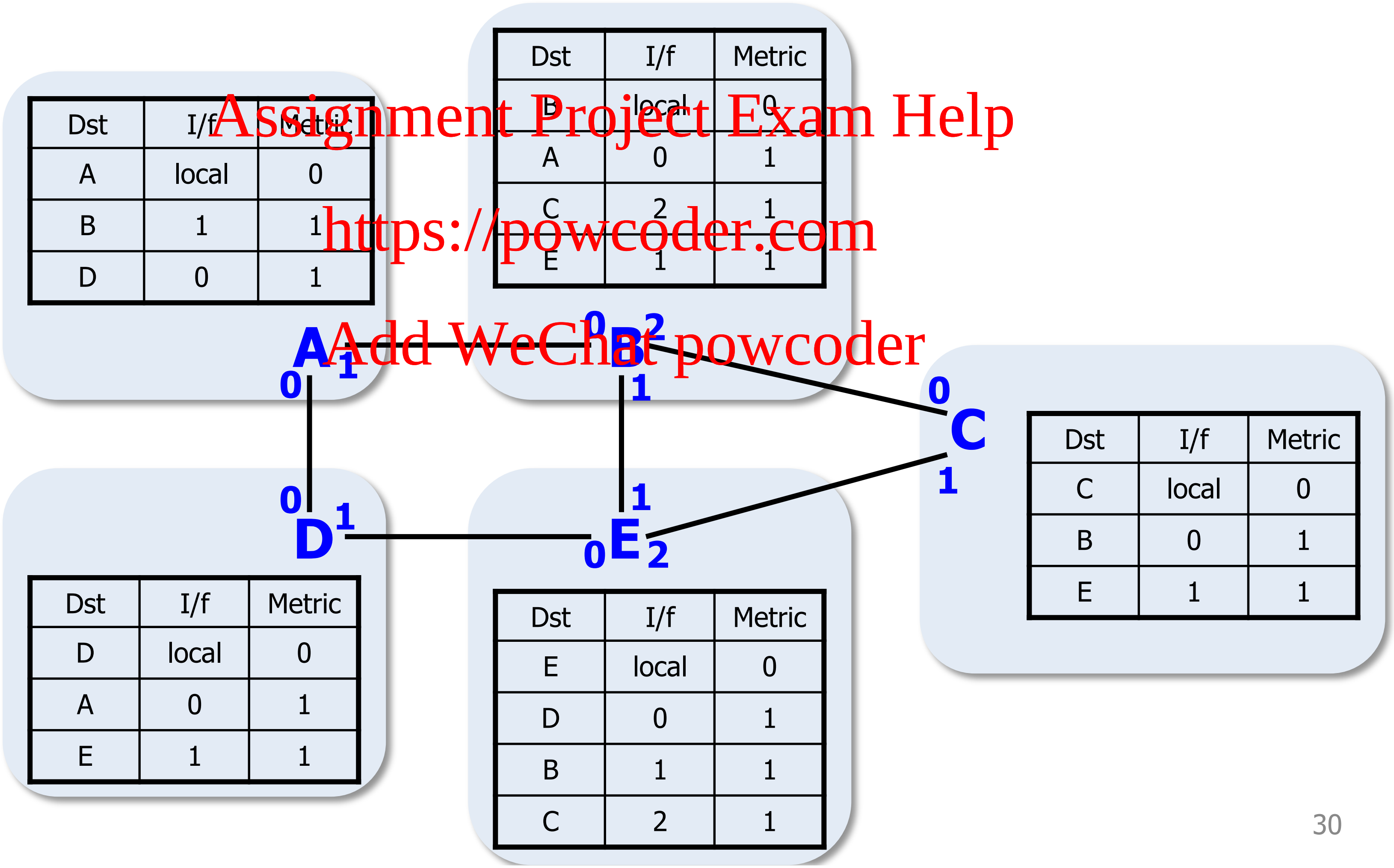
Distance Vector: Example

- Consider simple network where all nodes are routers, addresses are simply single letters
- Initial routing tables when routers first start:



Distance Vector: Iteration 1

- Routers incorporate received announcements:



Dst	I/f	Metric
A	local	0
B	1	1
D	0	1

Dst	I/f	Metric
B	local	0
A	0	1
C	2	1
E	1	1

Dst	I/f	Metric
C	local	0
B	0	1
E	1	1

Dst	I/f	Metric
D	local	0
A	0	1
E	1	1

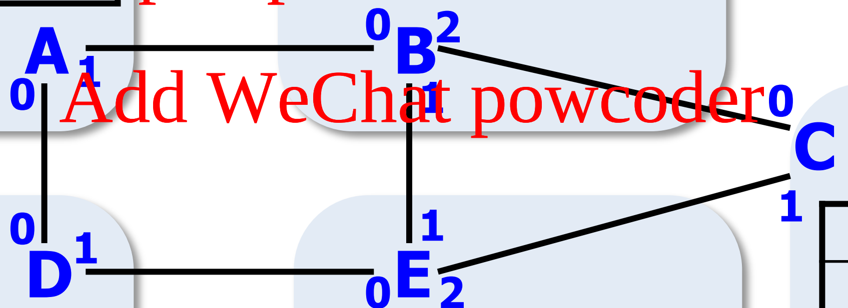
Dst	I/f	Metric
E	local	0
D	0	1
B	1	1
C	2	1

Distance Vector: Iteration 2

- Routers incorporate received announcements:

Dst	I/f	Metric
A	local	0
B	1	1
D	0	1
E	0	2
C	1	2

Dst	I/f	Metric
B	local	0
A	0	1
C	2	1
E	1	1
D	1	2



Dst	I/f	Metric
D	local	0
A	0	1
E	1	1
B	0	2
C	1	2

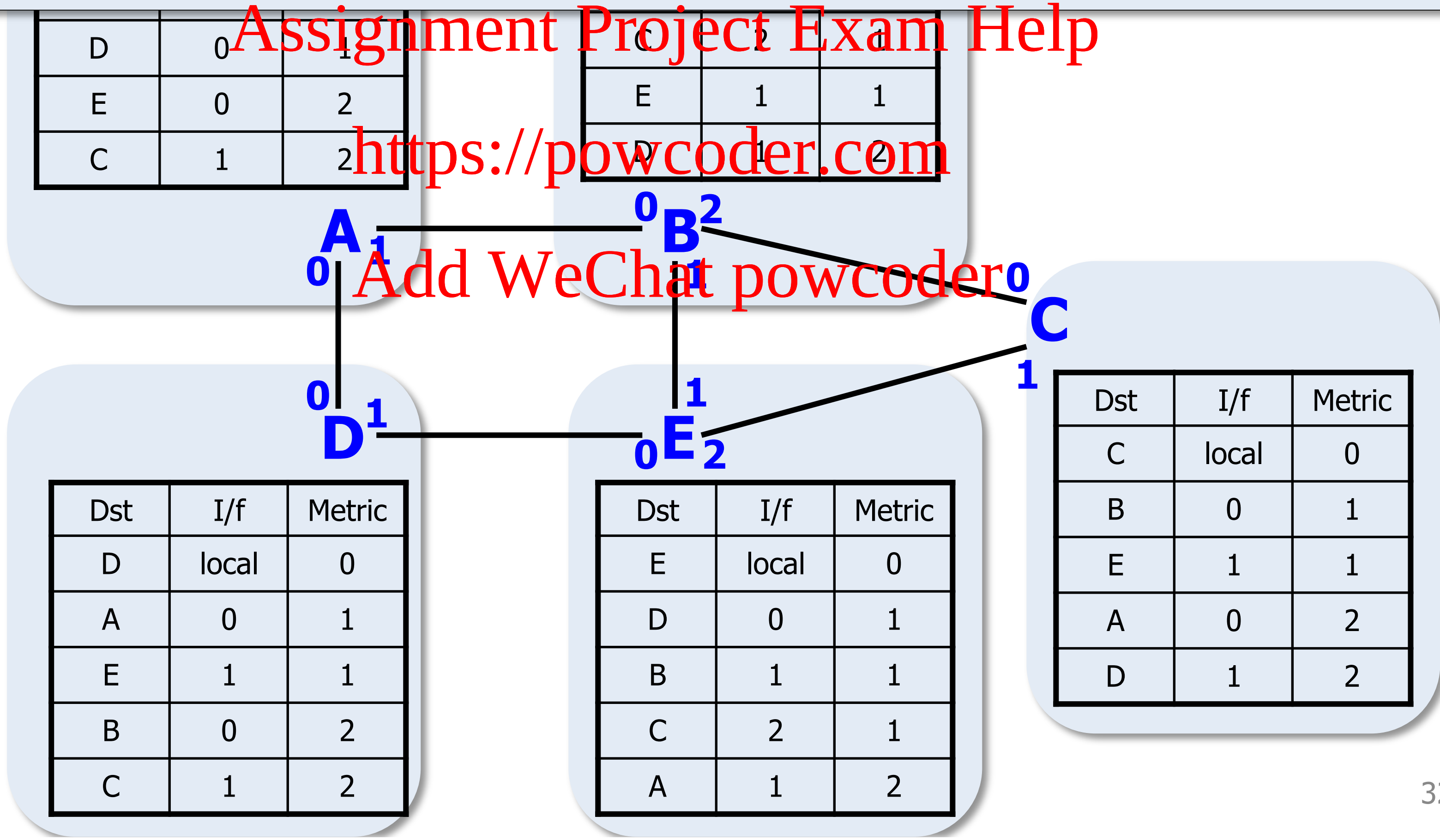
Dst	I/f	Metric
E	local	0
D	0	1
B	1	1
C	2	1
A	1	2

Dst	I/f	Metric
C	local	0
B	0	1
E	1	1
A	0	2
D	1	2

Distance Vector: Iteration 2

Convergence:

routing tables no longer changing;
routes reflect up-to-date knowledge of topology



Dst	I/f	Metric
D	local	0
A	0	1
E	1	1
B	0	2
C	1	2

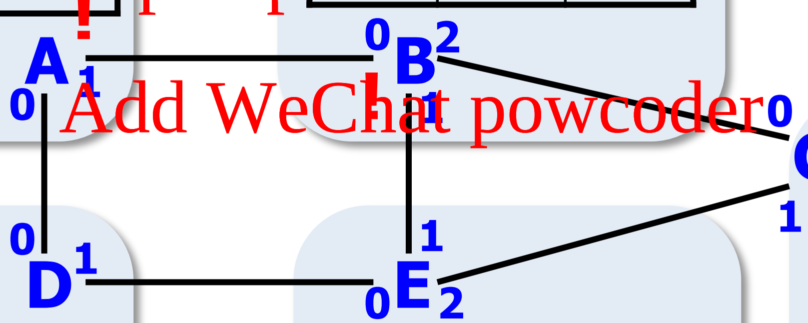
Dst	I/f	Metric
E	local	0
D	0	1
B	1	1
C	2	1
A	1	2

Dst	I/f	Metric
C	local	0
B	0	1
E	1	1
A	0	2
D	1	2

Link Failure (1)

Dst	I/f	Metric
A	local	0
B	1	1
D	0	1
E	0	2
C	1	2

Dst	I/f	Metric
B	local	0
A	0	1
C	2	1
E	1	1
D	1	2

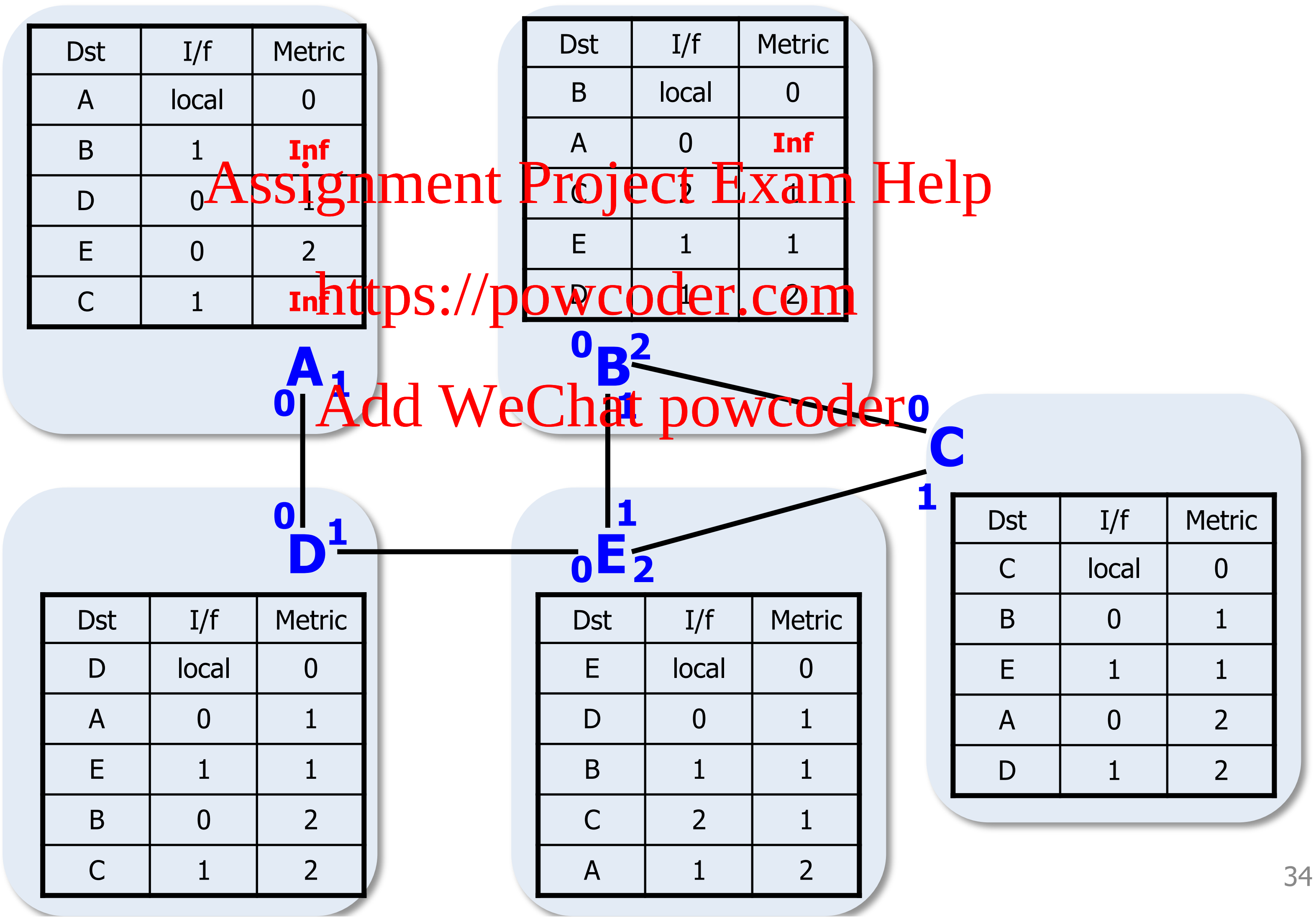


Dst	I/f	Metric
D	local	0
A	0	1
E	1	1
B	0	2
C	1	2

Dst	I/f	Metric
E	local	0
D	0	1
B	1	1
C	2	1
A	1	2

Dst	I/f	Metric
C	local	0
B	0	1
E	1	1
A	0	2
D	1	2

Link Failure (I)



Dst	I/f	Metric
A	local	0
B	1	Inf
D	0	1
E	0	2
C	1	Inf

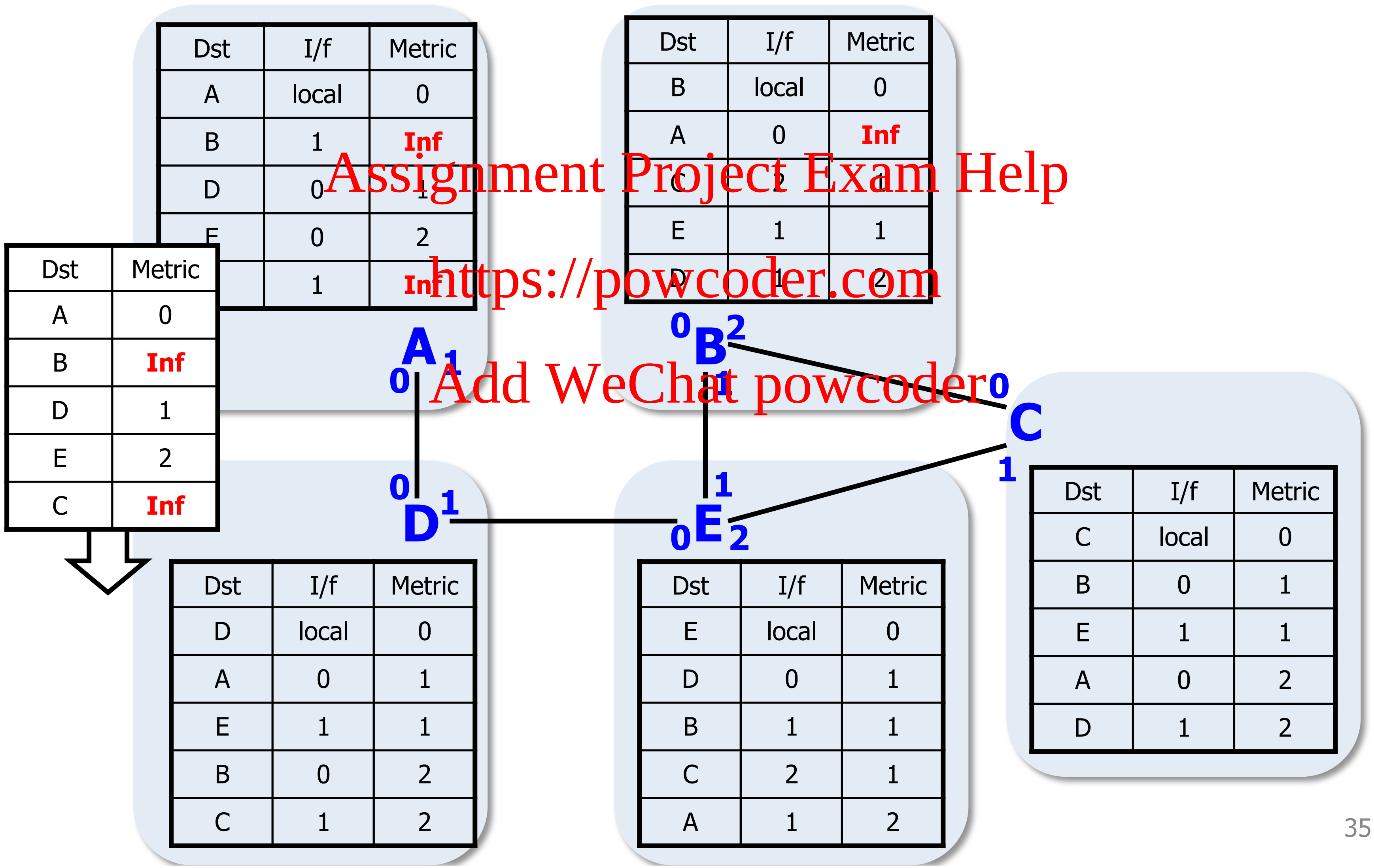
Dst	I/f	Metric
B	local	0
A	0	Inf
C	2	1
E	1	1
D	1	2

Dst	I/f	Metric
D	local	0
A	0	1
E	1	1
B	0	2
C	1	2

Dst	I/f	Metric
E	local	0
D	0	1
B	1	1
C	2	1
A	1	2

Dst	I/f	Metric
C	local	0
B	0	1
E	1	1
A	0	2
D	1	2

Link Failure (2)



Dst	I/f	Metric
A	local	0
B	1	Inf
D	0	1
E	0	2
C	1	Inf

Dst	I/f	Metric
B	local	0
A	0	Inf
C	2	1
E	1	1
D	1	2

Dst	Metric
A	0
B	Inf
D	1
E	2
C	Inf

Dst	I/f	Metric
D	local	0
A	0	1
E	1	1
B	0	2
C	1	2

Dst	I/f	Metric
E	local	0
D	0	1
B	1	1
C	2	1
A	1	2

Dst	I/f	Metric
C	local	0
B	0	1
E	1	1
A	0	2
D	1	2

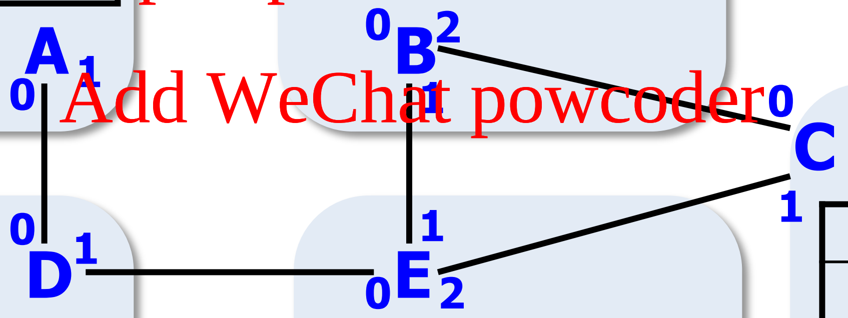
Link Failure (2)

Problem:
D ignores the update for the route to B because the metric is worse than the one it already has.

Dst	I/f	Metric
A	local	0
B	1	Inf
D	0	1
E	0	2
[illegible]	1	Inf

Dst	Metric
A	0
B	Inf
D	1
E	2
C	Inf

A	0	Inf
C	2	1
E	1	1
D	1	2



Dst	I/f	Metric
D	local	0
A	0	1
E	1	1
B	0	2
C	1	2

Dst	I/f	Metric
E	local	0
D	0	1
B	1	1
C	2	1
A	1	2

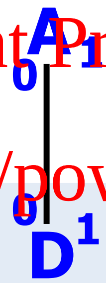
Dst	I/f	Metric
C	local	0
B	0	1
E	1	1
A	0	2
D	1	2

DV Algorithm, Revised

- Upon receipt of routing table entry for destination D with metric m on interface i:


```
m += metric for interface i
rt = lookup(D) in routing table
if (rt = "not found") then
    r_new = new routing table entry
    r_new.D = D;   r_new.metric = m;   r_new.iface = i
    add r_new to table
else if (i == rt.iface) then
    rt.metric = m
else if (m < rt.metric) then
    rt.metric = m;   r.iface = i
```

Link Failure (3)



Dst	Metric
A	1
B	**Inf**
D	2
E	3
C	**Inf**

+

Dst	I/f	Metric
D	local	0
A	0	1
E	1	1
B	0	2
C	1	2

→

Dst	I/f	Metric
D	local	0
A	0	1
E	1	1
B	0	Inf
C	1	2

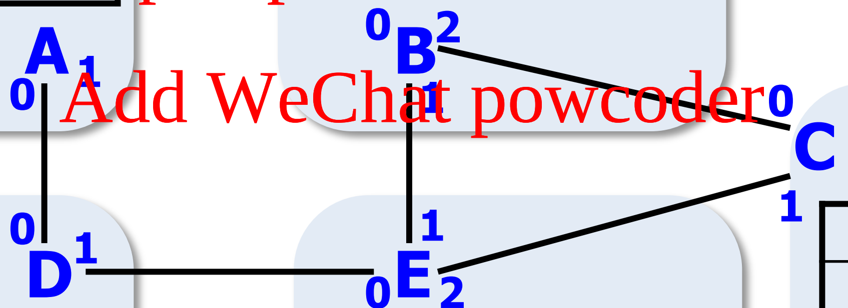
Link Failure (3)

A

Dst	I/f	Metric
A	local	0
B	1	Inf
D	0	1
E	0	2
C	1	Inf

B

Dst	I/f	Metric
B	local	0
A	0	Inf
C	2	1
E	1	1
D	1	2



D

Dst	I/f	Metric
D	local	0
A	0	1
E	1	1
B	0	Inf
C	1	2

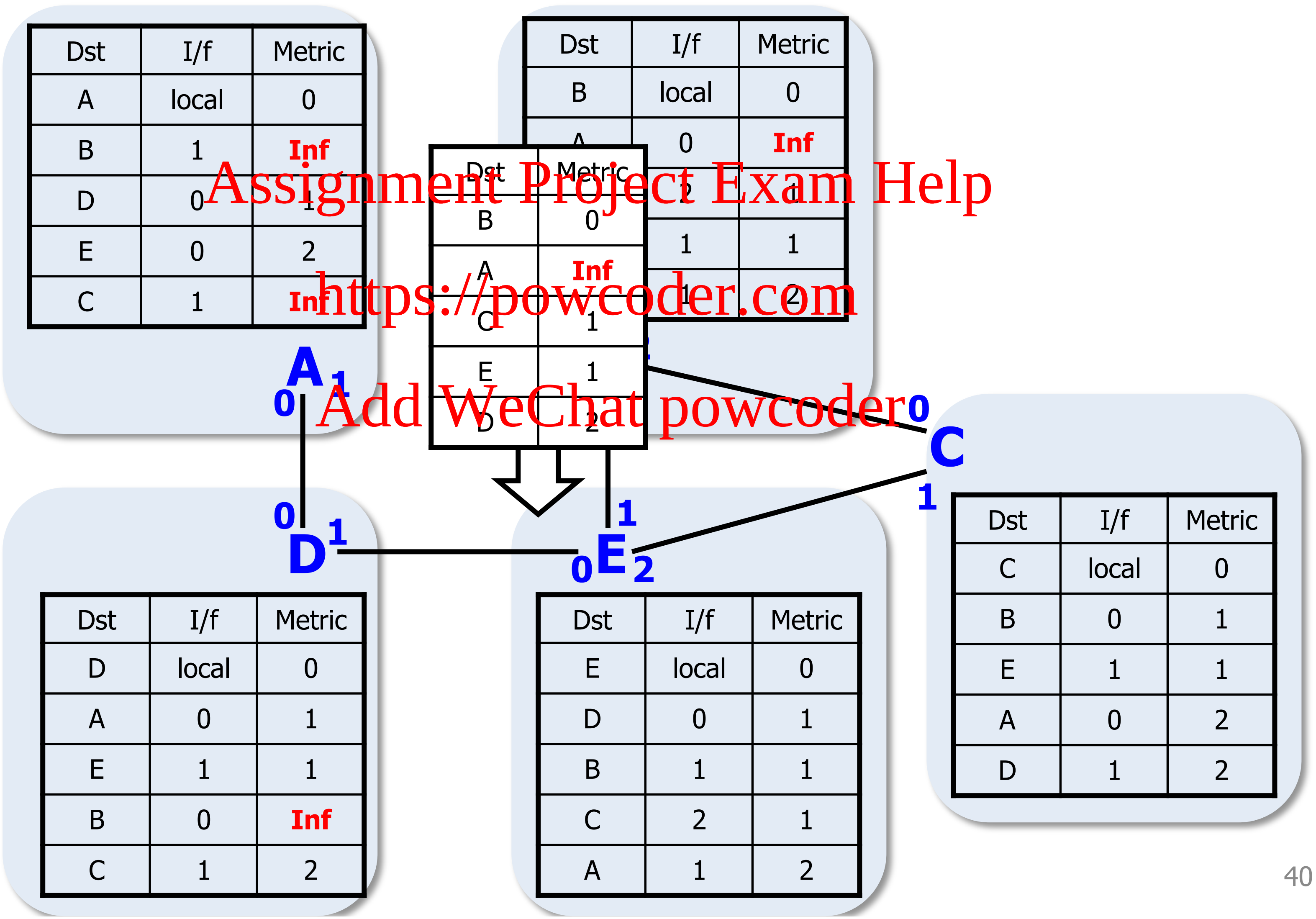
E

Dst	I/f	Metric
E	local	0
D	0	1
B	1	1
C	2	1
A	1	2

C

Dst	I/f	Metric
C	local	0
B	0	1
E	1	1
A	0	2
D	1	2

Link Failure (4)



Dst	I/f	Metric
A	local	0
B	1	Inf
D	0	1
E	0	2
C	1	Inf

Dst	I/f	Metric
B	local	0
A	0	Inf
[illegible]	2	[illegible]
[illegible]	1	1
[illegible]	1	2

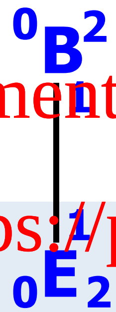
Dst	Metric
B	0
A	Inf
C	1
E	1
D	2

Dst	I/f	Metric
D	local	0
A	0	1
E	1	1
B	0	Inf
C	1	2

Dst	I/f	Metric
E	local	0
D	0	1
B	1	1
C	2	1
A	1	2

Dst	I/f	Metric
C	local	0
B	0	1
E	1	1
A	0	2
D	1	2

Link Failure (5)



Dst	Metric
B	1
A	**Inf**
C	2
E	2
D	3

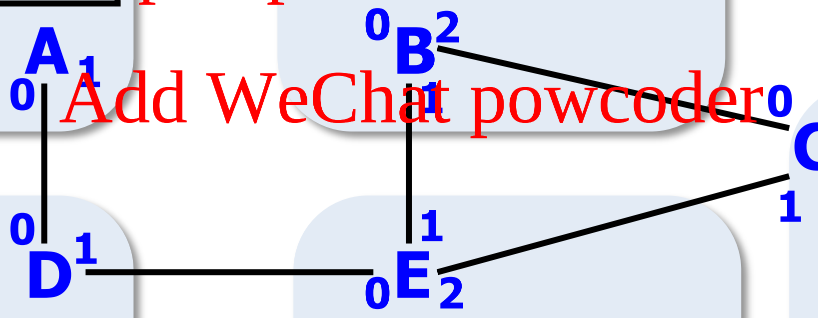
+

Dst	I/f	Metric
E	local	0
D	0	1
B	1	1
C	2	1
A	1	2

→

Dst	I/f	Metric
E	local	0
D	0	1
B	1	1
C	2	1
A	1	**Inf**

Link Failure (5)



A:

Dst	I/f	Metric
A	local	0
B	1	**Inf**
D	0	1
E	0	2
C	1	**Inf**

B:

Dst	I/f	Metric
B	local	0
A	0	**Inf**
C	2	1
E	1	1
D	1	2

C:

Dst	I/f	Metric
C	local	0
B	0	1
E	1	1
A	0	2
D	1	2

D:

Dst	I/f	Metric
D	local	0
A	0	1
E	1	1
B	0	**Inf**
C	1	2

E:

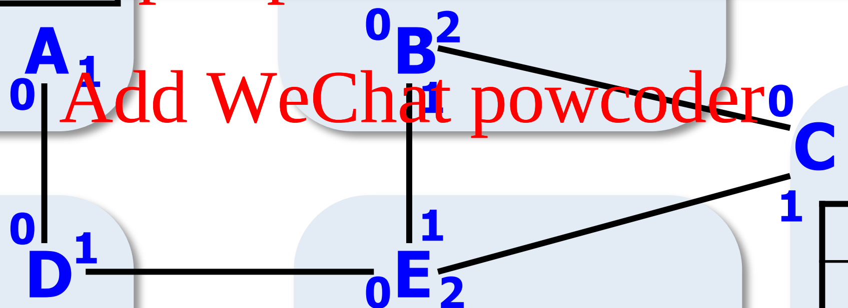
Dst	I/f	Metric
E	local	0
D	0	1
B	1	1
C	2	1
A	1	**Inf**

Link Failure (6)

Next round: all routers broadcast their tables to neighbours…

Dst	I/f	Metric

Dst	I/f	Metric



Dst	I/f	Metric
D	local	0
A	0	1
E	1	1
B	0	**Inf**
C	1	2

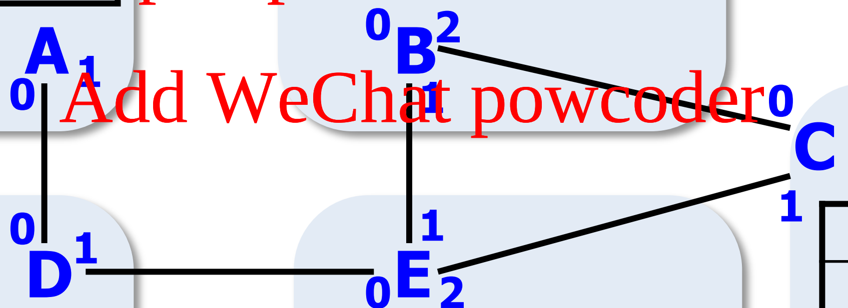
Dst	I/f	Metric
E	local	0
D	0	1
B	1	1
C	2	1
A	1	**Inf**

Dst	I/f	Metric
C	local	0
B	0	1
E	1	1
A	0	2
D	1	2

Link Failure (7)

Dst	I/f	Metric
A	local	0
B	1	Inf
D	0	1
E	0	2
C	0	3

Dst	I/f	Metric
B	local	0
A	0	Inf
C	2	1
E	1	1
D	1	2



Dst	I/f	Metric
D	local	0
A	0	1
E	1	1
B	1	2
C	1	2

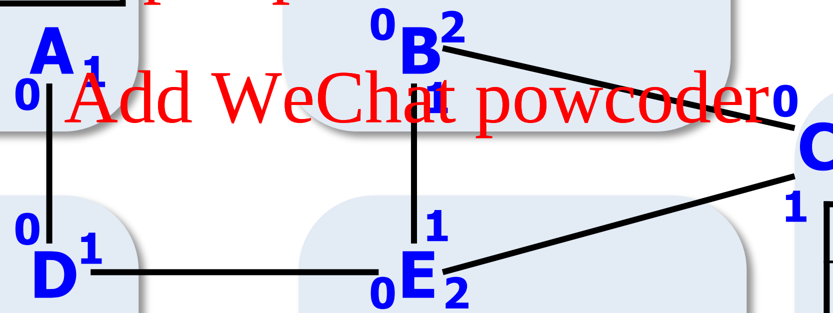
Dst	I/f	Metric
E	local	0
D	0	1
B	1	1
C	2	1
A	0	2

Dst	I/f	Metric
C	local	0
B	0	1
E	1	1
A	0	Inf
D	1	2

Link Failure (8)

Dst	I/f	Metric
A	local	0
B	**0**	**3**
D	0	1
E	0	2
C	**0**	**3**

Dst	I/f	Metric
B	local	0
A	**1**	**3**
C	2	1
E	1	1
D	1	2



Dst	I/f	Metric
D	local	0
A	0	1
E	1	1
B	**1**	**2**
C	1	2

Dst	I/f	Metric
E	local	0
D	0	1
B	1	1
C	2	1
A	**0**	**2**

Dst	I/f	Metric
C	local	0
B	0	1
E	1	1
A	**1**	**3**
D	1	2

Agenda

- We are now ready to study Distance Vector routing

1. Algorithm

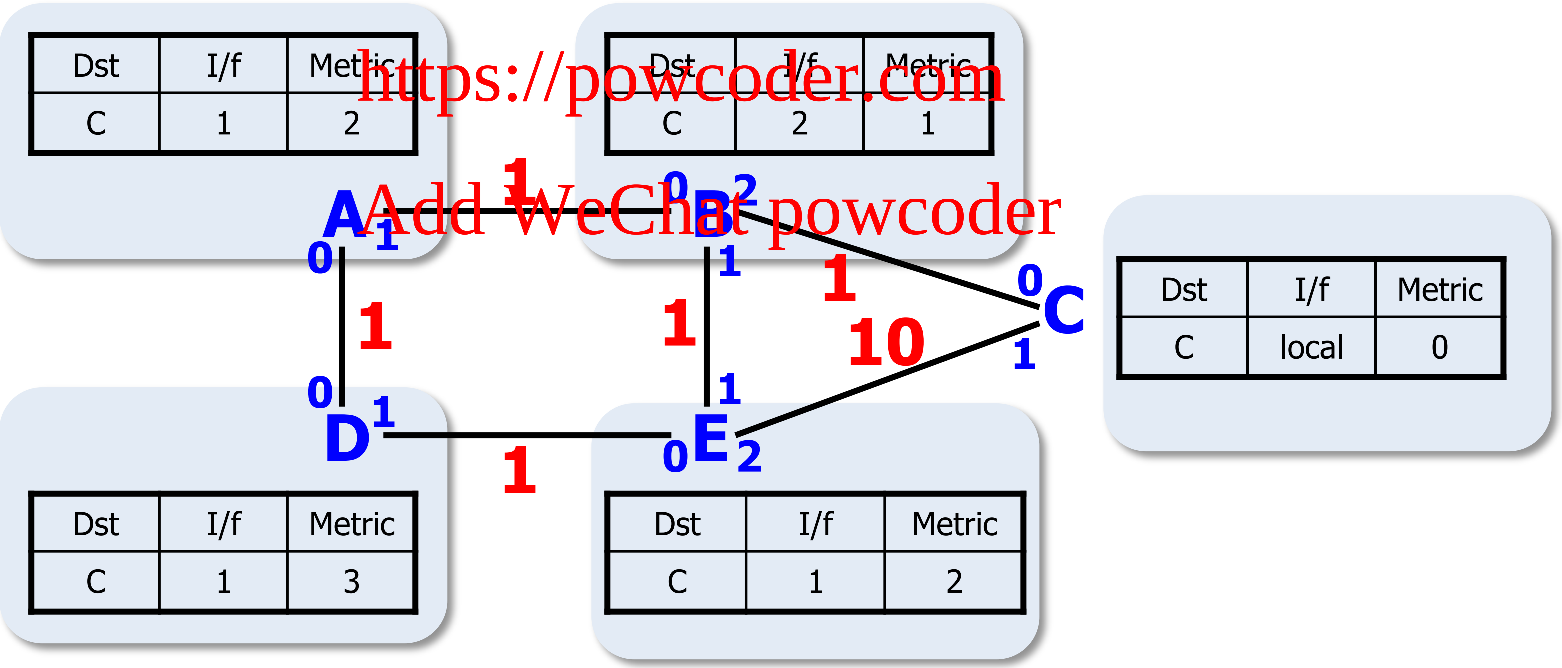
2. Pathologies

   - Bouncing

   - Counting to Infinity
3. Optimizations

Bouncing (I)

- Consider same network, where link (C, E) has metric 10; all others have metric 1
- Consider all nodes' routes to C after convergence
- Now suppose link (B, C) breaks



Bouncing (II)

- Suppose A advertises its table first…

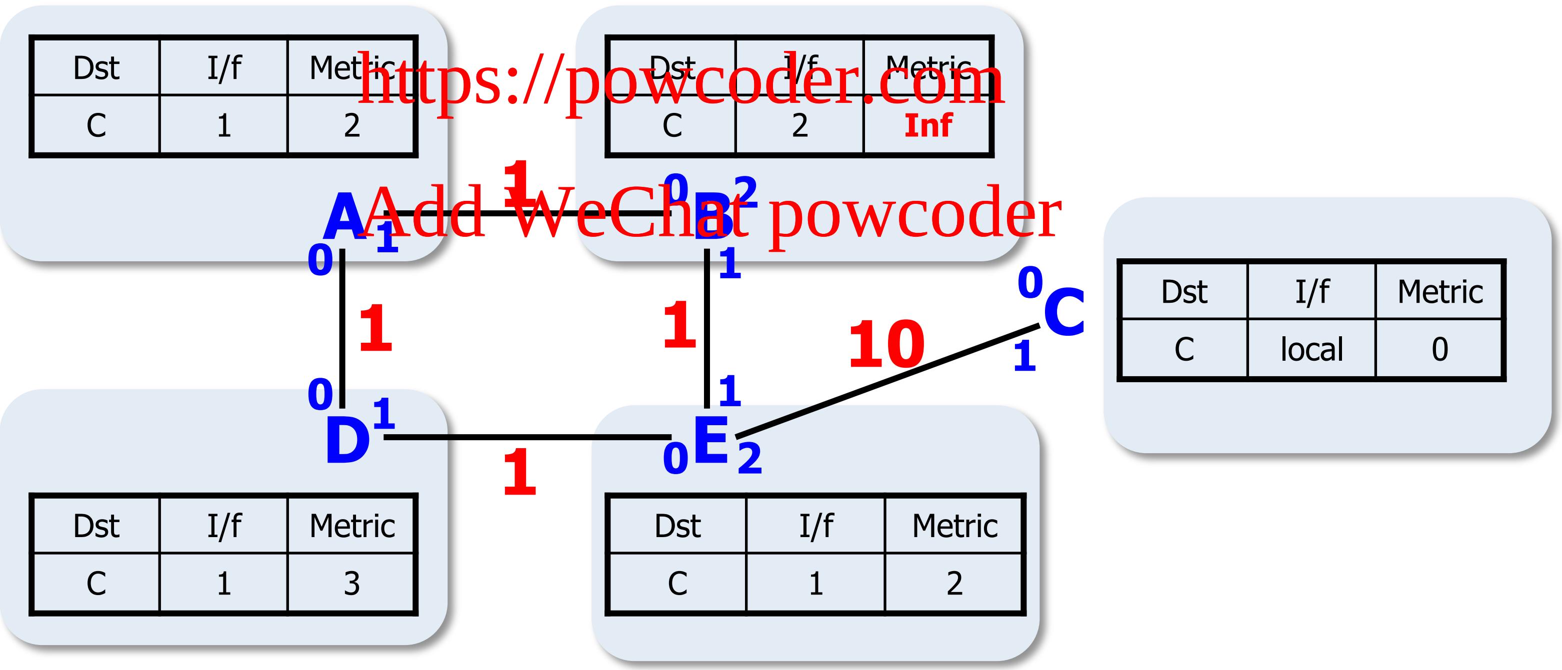


Table at A:

Dst	I/f	Metric
C	1	2

Table at B:

Dst	I/f	Metric
C	2	**Inf**

Table at C:

Dst	I/f	Metric
C	local	0

Table at D:

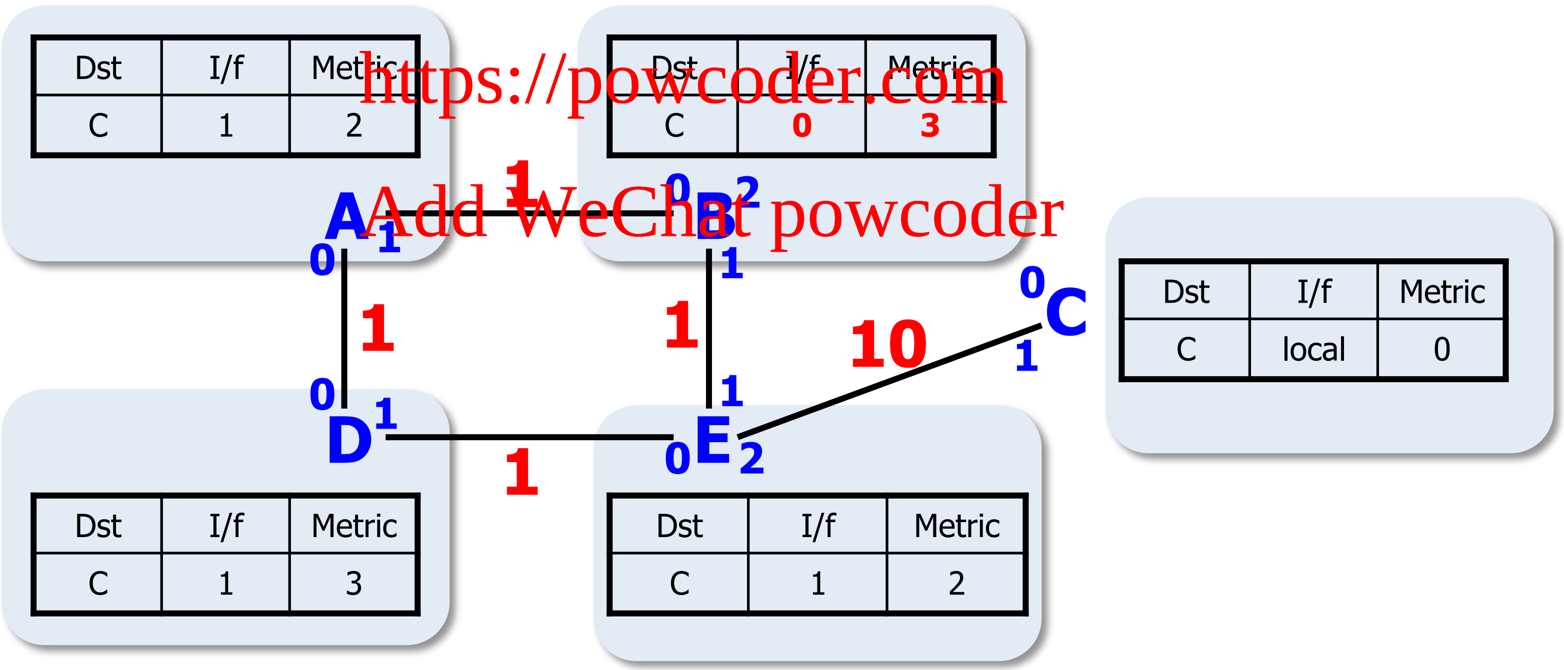
Dst	I/f	Metric
C	1	3

Table at E:

Dst	I/f	Metric
C	1	2

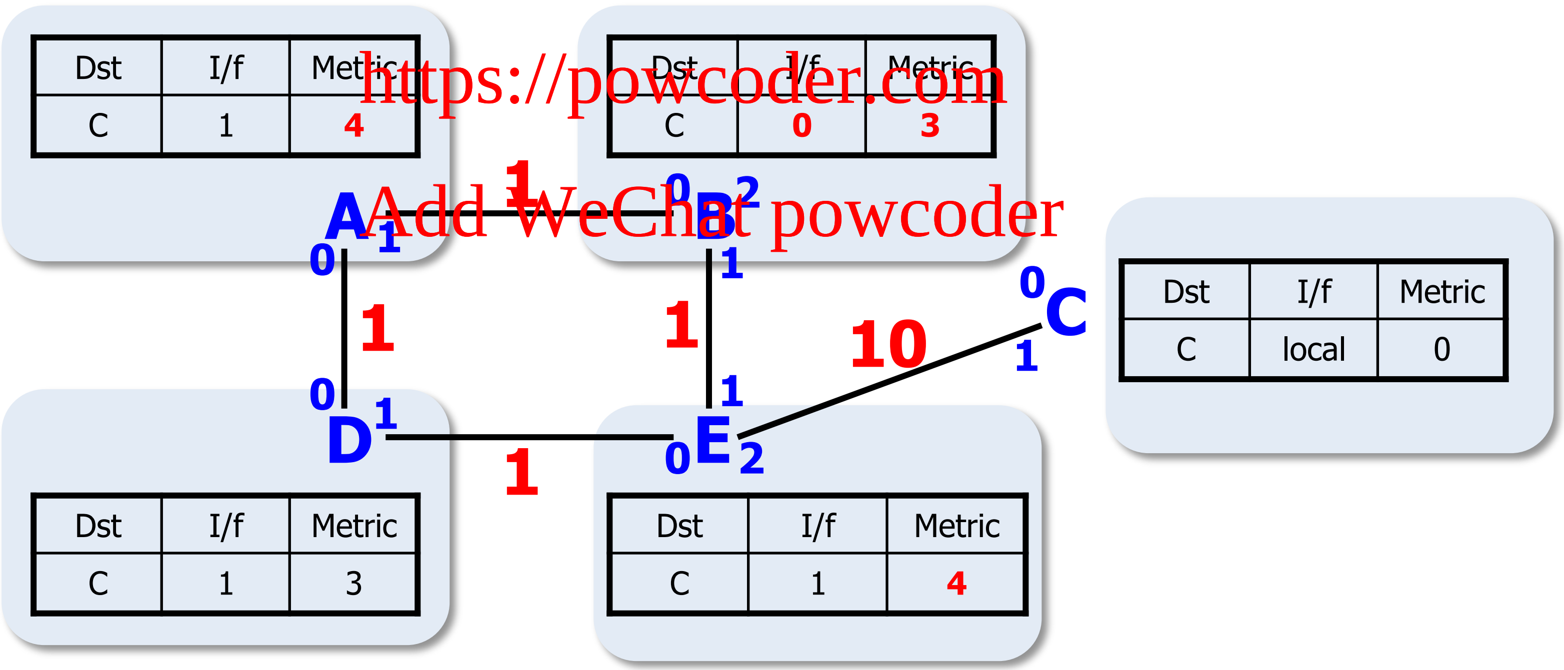
Bouncing (III)

- Suppose A advertises its table first…
- …and B advertises its table next…



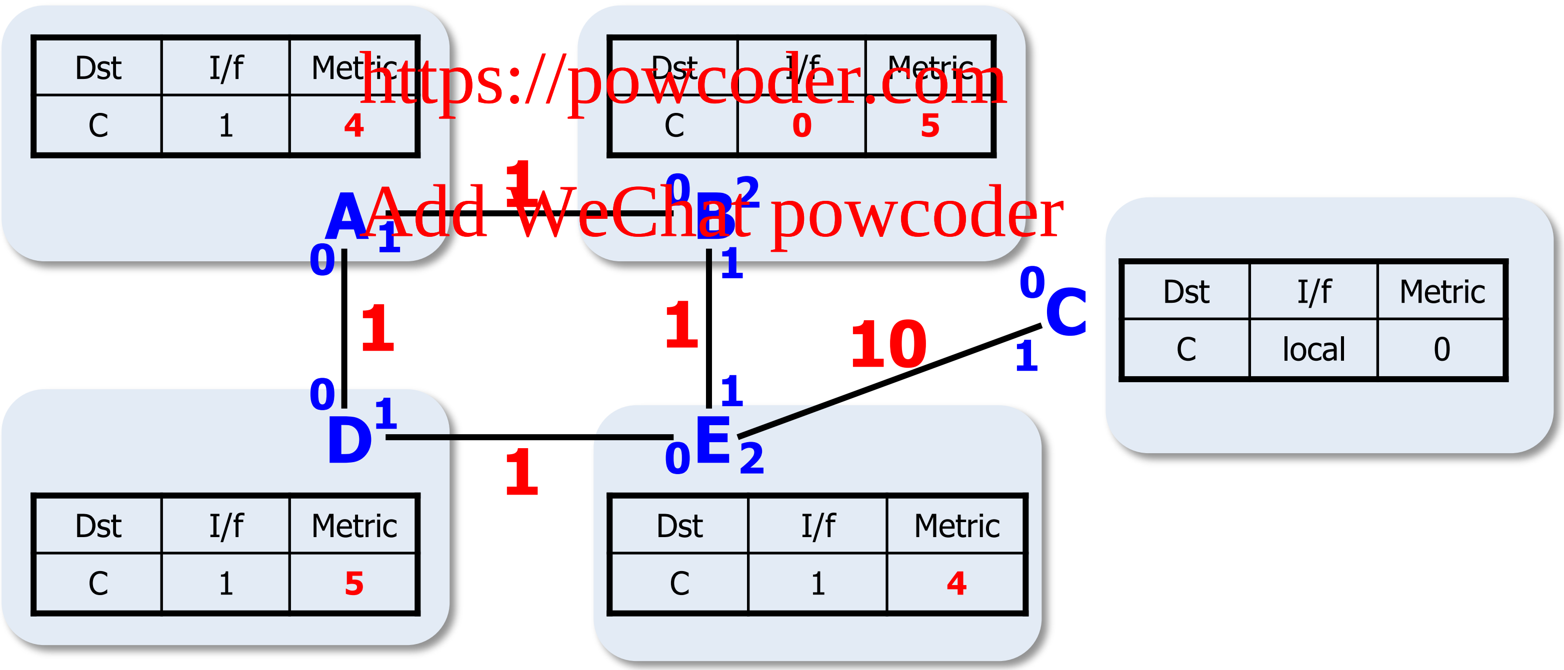
Bouncing (IV)

- Suppose A advertises its table first…
- …and B advertises its table next…
- Loop between A and B for destination C!
- If C now advertises its table, E will ignore cost 10 route!



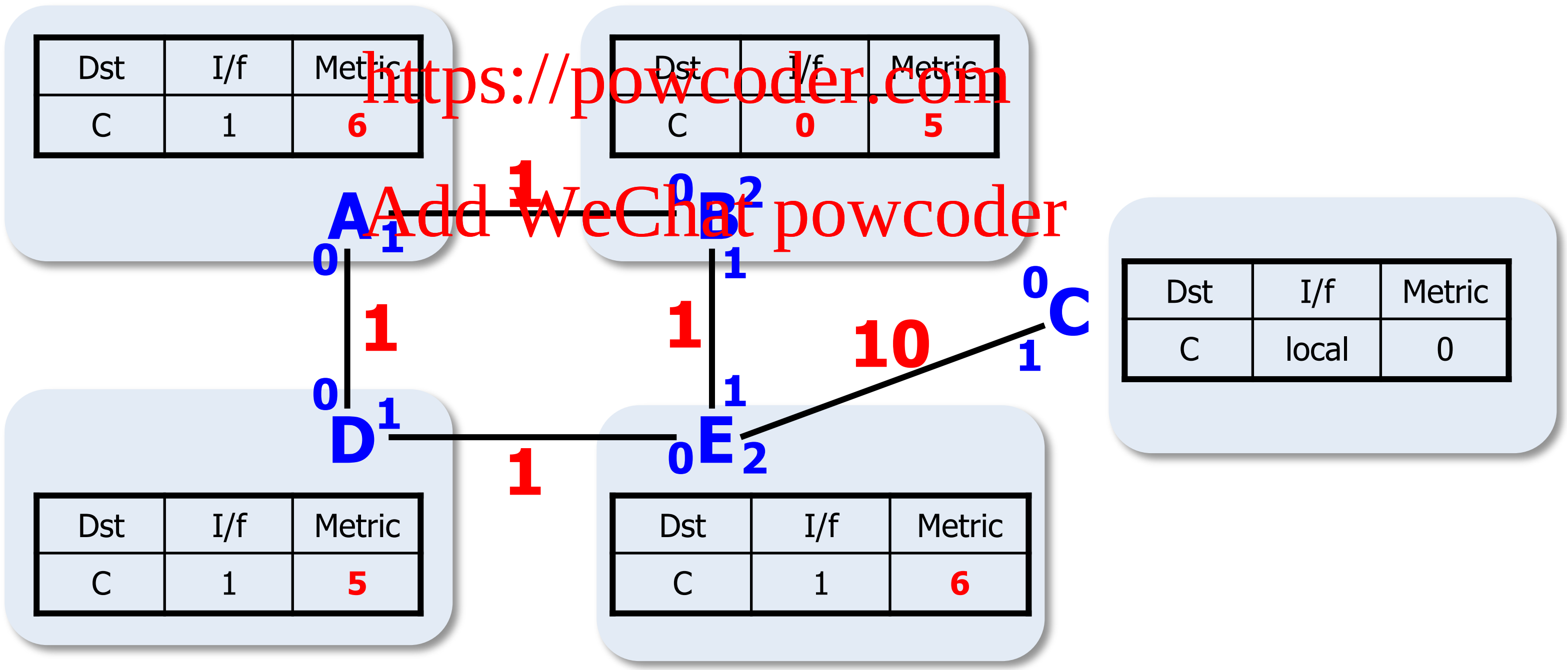
Bouncing (V)

- Suppose A and E advertise next… (B,D update metrics)



Bouncing (VI)

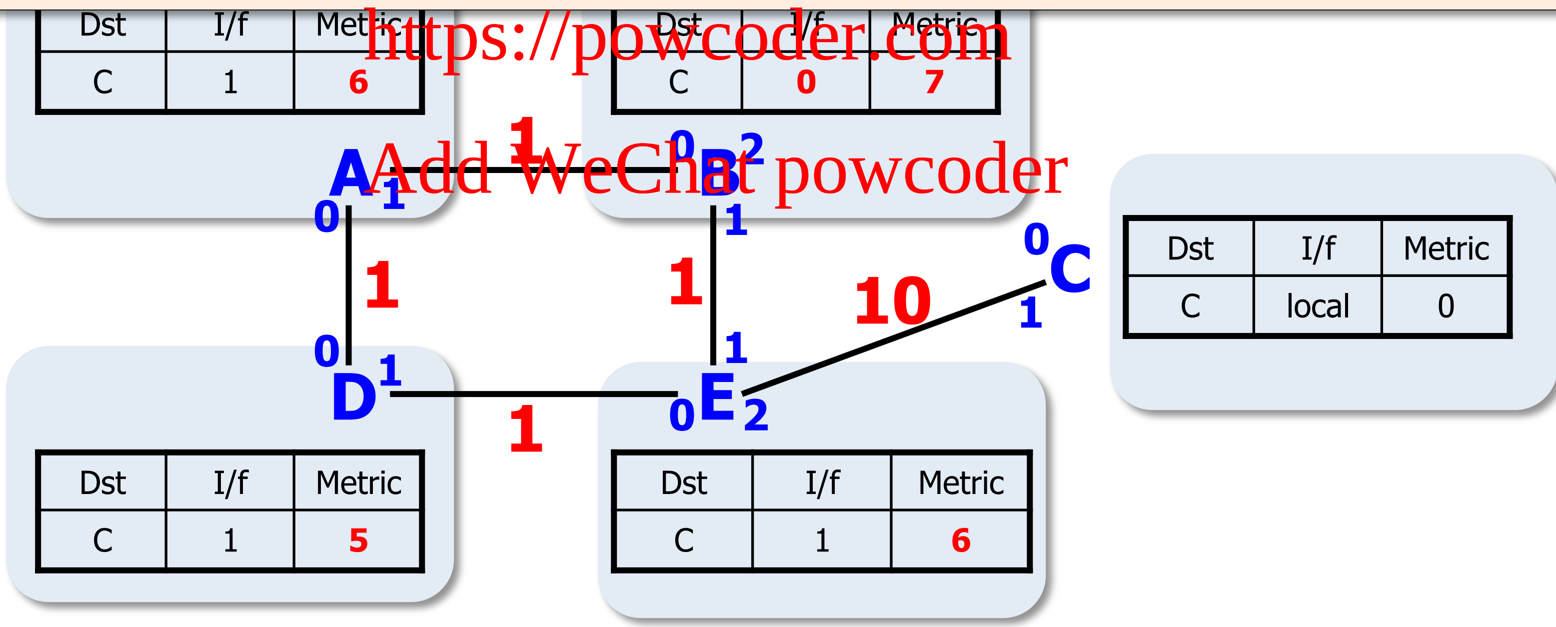
- Suppose A and E advertise next… (B,D update metrics)
- …and B advertises next (A and E update metrics)



Bouncing (VII)

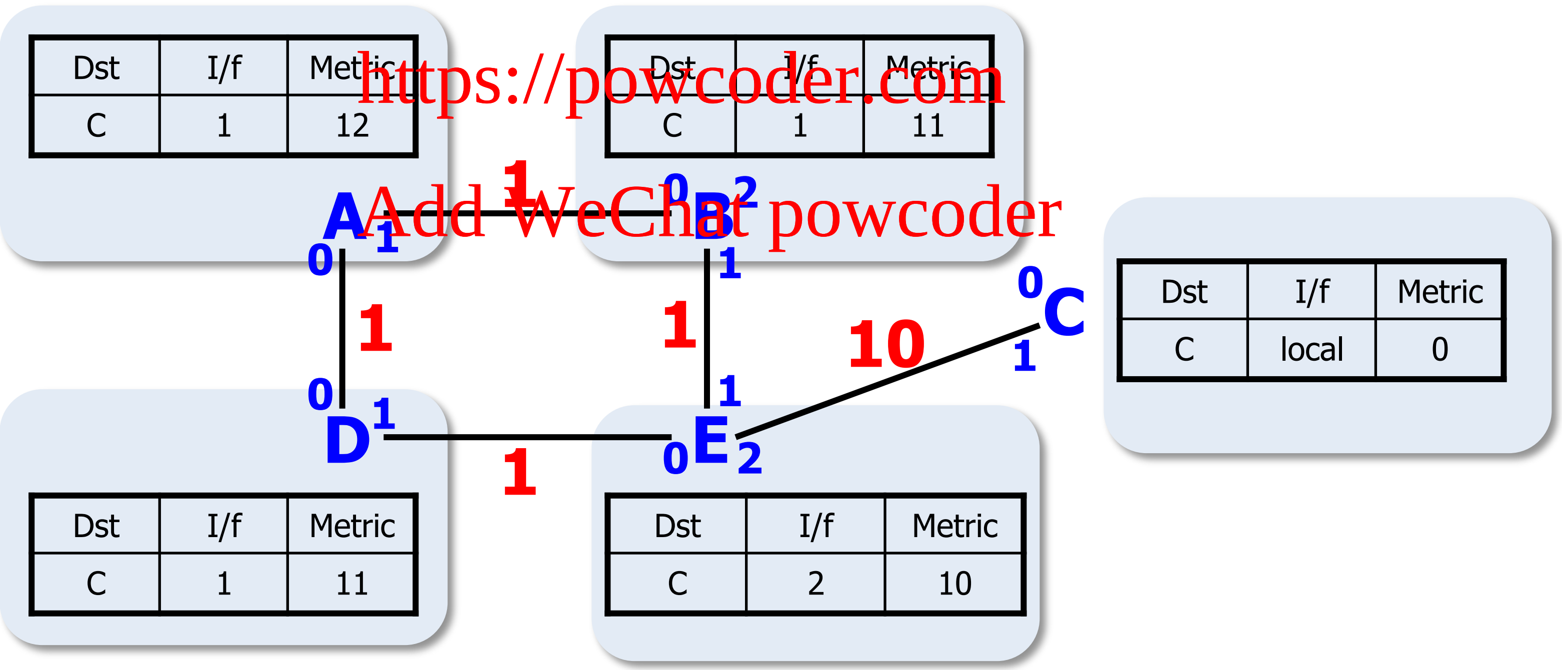
- Suppose A and E advertise next… (B,D update metrics)

And so on…



Bouncing (VIII)

- Long, painful convergence process, details dependent on message ordering
- Transient loops
- Eventually, converged state:



Dst	I/f	Metric
C	1	12

Dst	I/f	Metric
C	1	11

Dst	I/f	Metric
C	local	0

Dst	I/f	Metric
C	1	11

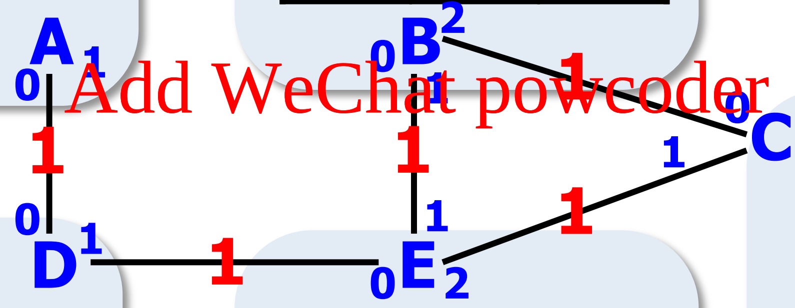
Dst	I/f	Metric
C	2	10

Counting to Infinity (I)

- Converged after link (A, B) breaks
- Suppose (D, E) now breaks

Dst	I/f	Metric
A	local	0
B	0	3
D	0	1
E	0	2
C	0	3

Dst	I/f	Metric
B	local	0
A	1	3
C	2	1
E	1	1
D	1	2



Dst	I/f	Metric
C	local	0
B	0	1
E	1	1
A	1	3
D	1	2

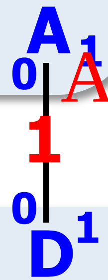
Dst	I/f	Metric
D	local	0
A	0	1
E	1	1
B	1	2
C	1	2

Dst	I/f	Metric
E	local	0
D	0	1
B	1	1
C	2	1
A	0	2

Counting to Infinity (II)

Dst	I/f	Metric
A	local	0
B	0	3
D	0	1
E	0	2
C	0	3

- Network partitioned
- Focus on {A, D} partition
- Suppose sequence of events:
  - D notices link failure
  - A advertises its routing table
- Loop for {B, C, E} between A and D!
- How long will loop persist?



Dst	Metric
A	1
B	4
D	2
E	3
C	4

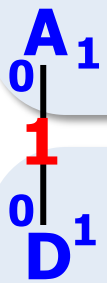
+

Dst	I/f	Metric
D	local	0
A	0	1
E	1	Inf
B	1	Inf
C	1	Inf

→

Dst	I/f	Metric
D	local	0
A	0	1
E	0	3
B	0	4
C	0	4

Counting to Infinity (III)



Dst	I/f	Metric
A	local	0
B	0	5
D	0	1
E	0	4
C	0	5

Dst	I/f	Metric
A	local	0
B	0	**7**
D	0	1
E	0	**6**
C	0	**7**

…

Dst	I/f	Metric
A	local	0
B	0	**Inf**
D	0	1
E	0	**Inf**
C	0	**Inf**

Dst	I/f	Metric
D	local	0
A	0	1
E	0	3
B	0	4
C	0	4

Dst	I/f	Metric
D	local	0
A	0	1
E	0	**5**
B	0	**6**
C	0	**6**

…

Dst	I/f	Metric
D	local	0
A	0	1
E	0	**Inf**
B	0	**Inf**
C	0	**Inf**

- Each advertisement increments metrics for partitioned destinations by one
- Loop persists until count reaches infinity!

Agenda

- We are now ready to study Distance Vector routing

1. Algorithms

2. Pathologies

3. Optimizations
   - Split Horizon
   - Poison Reverse

Avoiding direct loops

- Bouncing and counting to infinity cause slow convergence, create loops
- Consider any link (X,Y) and destination Z
  - with X's next hop toward Z being Y

Split Horizon:

clearly, Y should never choose X as next hop toward Z

- Intuition: X should never announce to Y a path with short distance to Z if it's forwarding to Z via Y!

Split Horizon with Poison Reverse

- Again, consider link (X,Y), destination Z
  - with X's next hop toward Z being Y

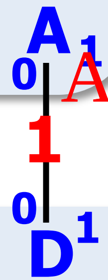
- More generally: routers should announce different routing tables to different neighbors

- Split horizon: don't announce route for destination Z on interface used as next hop toward Z!
- Poison Reverse (optional): X announces to Y its distance to Z is infinity!

Example: Split Horizon and Poison Reverse

- Same example as counting to infinity: {A, D} partitioned
- D detects link break, A announces first
- No loop, immediate convergence after one advertisement!

Dst	I/f	Metric
A	local	0
B	0	3
D	0	1
E	0	2
C	0	3



Dst	Metric
A	1
B	**Inf**
D	**Inf**
E	**Inf**
C	**Inf**

+

Dst	I/f	Metric
D	local	0
A	0	1
E	1	Inf
B	1	Inf
C	1	Inf

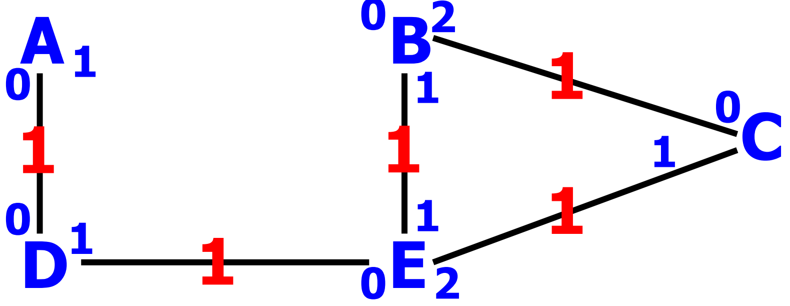
→

Dst	I/f	Metric
D	local	0
A	0	1
E	1	**Inf**
B	1	**Inf**
C	1	**Inf**

Limitations: Split Horizon and Poison Reverse

- Consider same example, but {B, C, E} partition
- Link (A, B) already failed, routing has converged
- Now link (D, E) fails
- Consider only destination D

Dst	I/f	Metric
D	1	2



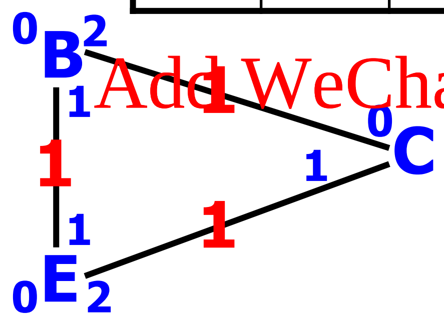
Dst	I/f	Metric
D	1	2

Dst	I/f	Metric
D	0	1

Limitations (II): Split Horizon and Poison Reverse

- E notices failed link, updates local table

Dst	I/f	Metric
D	1	2



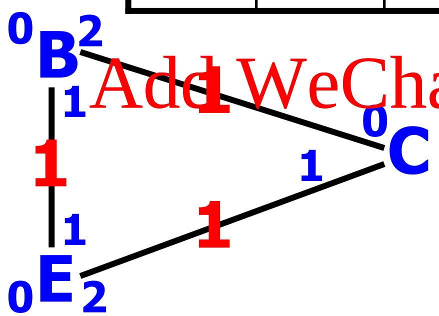
Dst	I/f	Metric
D	1	2

Dst	I/f	Metric
D	0	**Inf**

Limitations (III): Split Horizon and Poison Reverse

- E advertises its new table
  - Suppose advertisement reaches B, but not yet C

Dst	I/f	Metric
D	1	**Inf**



Dst	I/f	Metric
D	1	2

Dst	I/f	Metric
D	0	**Inf**

Limitations (IV): Split Horizon and Poison Reverse

- C advertises its table, with split horizon and poison reverse

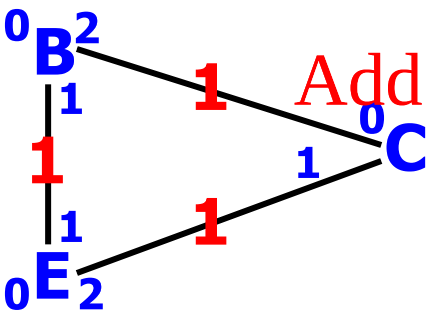
Dst	I/f	Metric
D	1	Inf

+

Dst	Metric
D	3

→

Dst	I/f	Metric
D	**2**	**3**



Dst	I/f	Metric
D	1	2

Dst	I/f	Metric
D	0	Inf

+

Dst	Metric
D	Inf

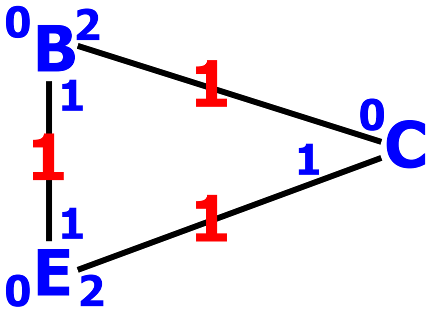
→

Dst	I/f	Metric
D	0	**Inf**

Limitations (V): Split Horizon and Poison Reverse

- B advertises its routing table, with split horizon and poison reverse
- For destination D, loop {C → E → B → C}!
  - resolved only by counting to infinity

Dst	I/f	Metric
D	2	3



Dst	I/f	Metric
D	1	2

+

Dst	Metric
D	Inf

→

Dst	I/f	Metric
D	1	2

Dst	I/f	Metric
D	0	Inf

+

Dst	Metric
D	4

→

Dst	I/f	Metric
D	**1**	**4**

Summary: Distance Vector routing

- DV algorithm: periodically dump routing table contents to neighbors
- Convergence: after topology change, point when routing tables stop changing
- Pros:
  - simple
  - finds correct routes after topology changes
- Cons:
  - bouncing, counting to infinity cause loops
  - slow to converge after some topology changes
  - split horizon, poison reverse only partial solutions