Provable Data Plane Connectivity with Local Fast Failover

Introducing OpenFlow Graph Algorithms

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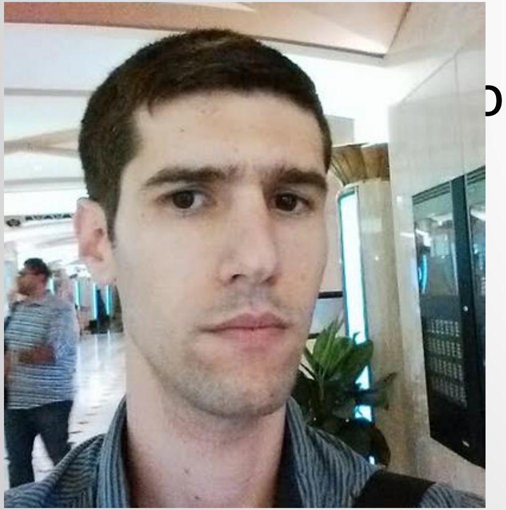

oduci w Graph Algorithms

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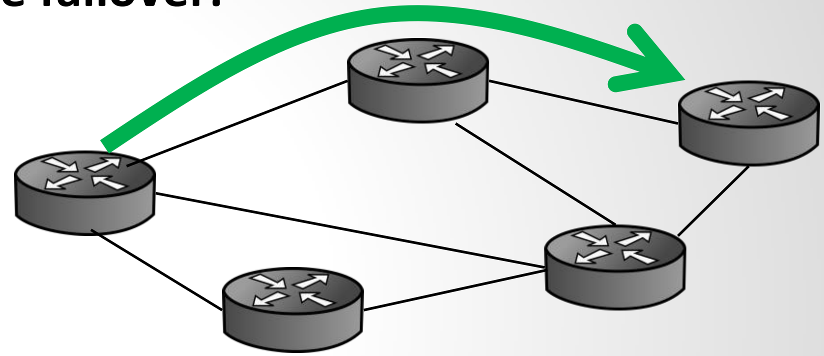
Robust Routing Mechanisms

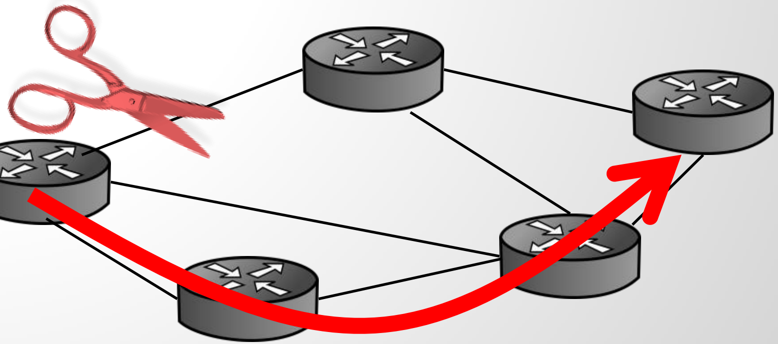
- **Link failures** today are not uncommon

- Modern networks provide **robust routing mechanisms**
  - i.e., routing which reacts to failures
  - example: MPLS local and global path protection

Before failover:

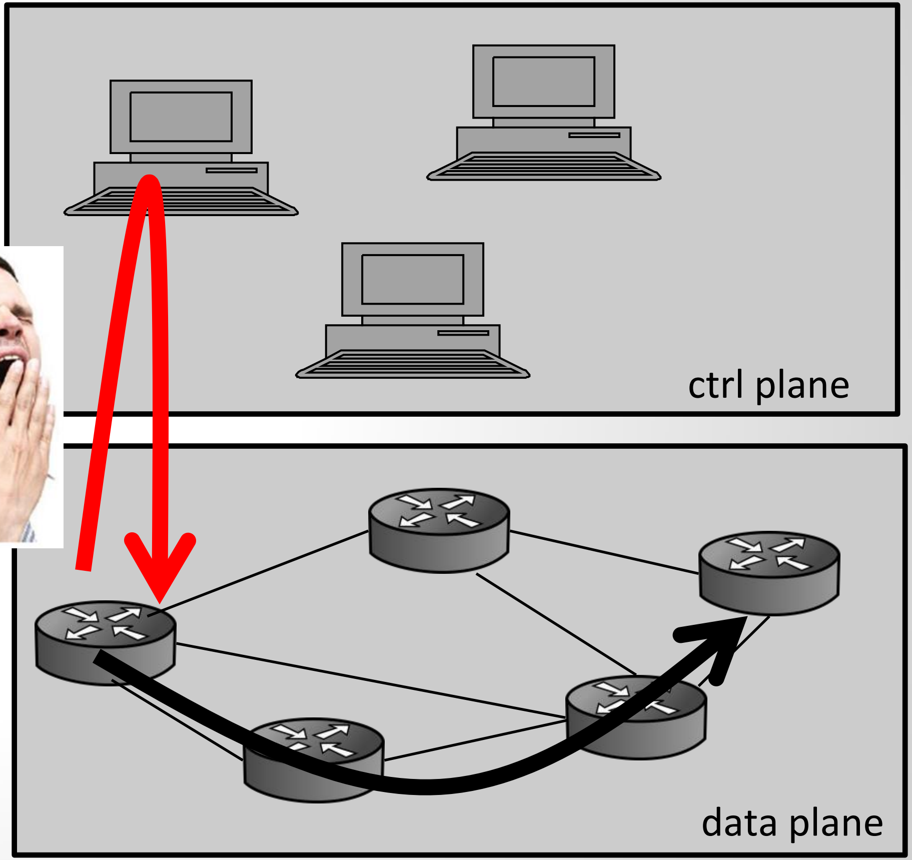


After failover:



Fast In-band Failover

- Important that failover happens **fast = in-band**
  - Reaction time in control plane can be orders of magnitude slower [1]
- For this reason: **OpenFlow Local Fast Failover Mechanism**
  - Supports conditional forwarding rules (depend on the local state of the link: live or not?)
- Gives fast but local and perhaps “**suboptimal**” forwarding sets
  - Controller improves globally later…



However, not much is known about how to ***use*** the OpenFlow fast failover mechanism.
E.g.: **How many failures** can be tolerated without losing connectivity?

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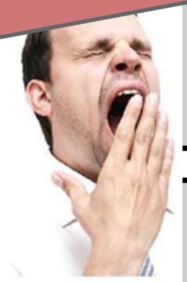

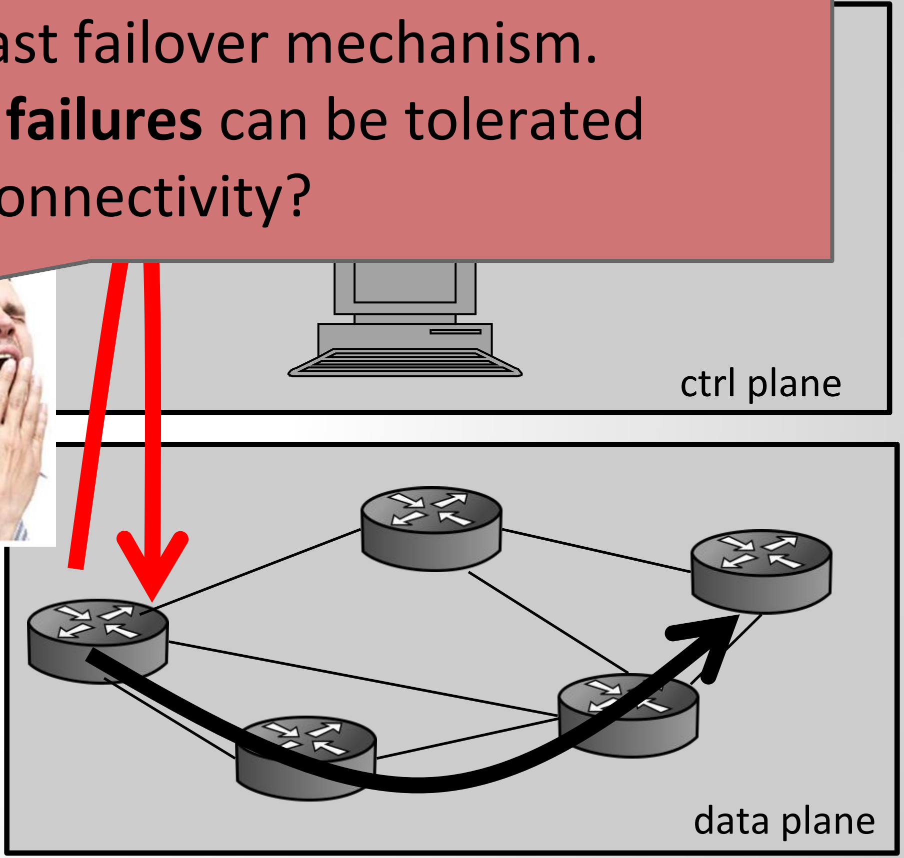

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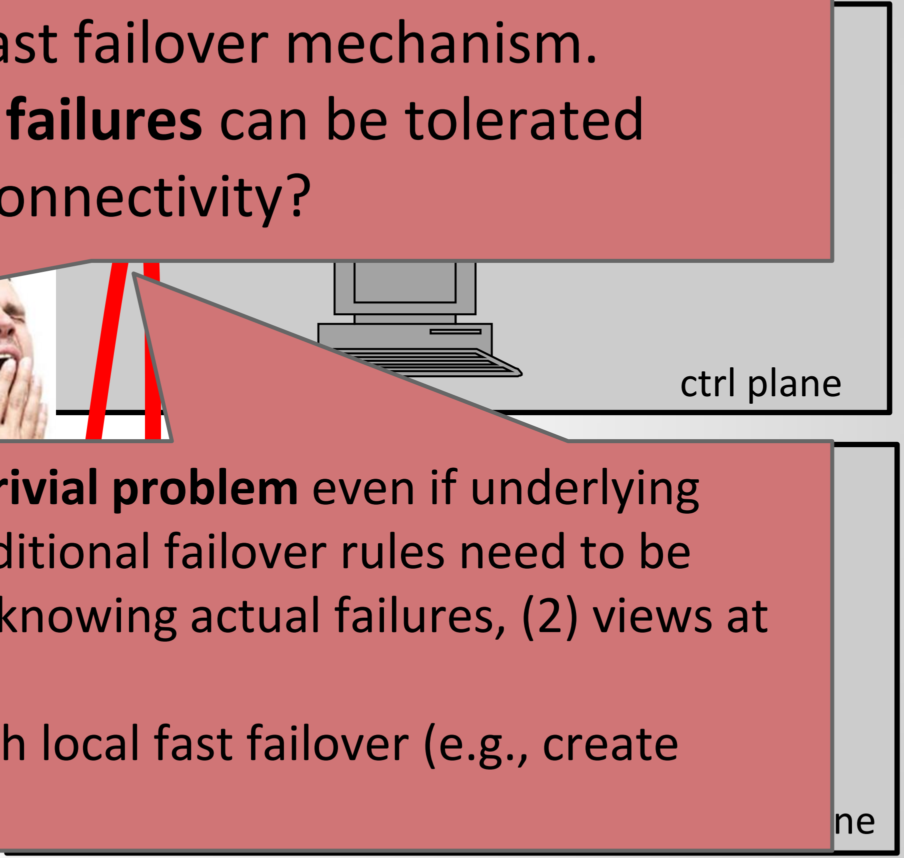

However, not much is known about how to ***use*** the OpenFlow fast failover mechanism.
E.g.: **How many failures** can be tolerated without losing connectivity?

How to use mechanism is a **non-trivial problem** even if underlying network stays connected: (1) conditional failover rules need to be allocated **ahead of time**, without knowing actual failures, (2) views at runtime are **inherently local**.
How not to **shoot in your foot** with local fast failover (e.g., create forwarding loops)?

Contribution: Very Robust Routing Possible with OpenFlow

Theorem: «Ideal» Forwarding Connectivity Possible

There exist algorithms which guarantee that packets always reach their destination, **independently of the number and locations** of failures, as long as the remaining network is connected.

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Three algorithms:

- **Modulo**
- **Depth-First**
- **Breadth-First**

Essentially classic **graph algorithms** (routing, graph search) implemented **in OpenFlow**. Make use of **tagging** to equip packets with meta-information to avoid forwarding loops.

Contribution: Very Robust Routing Possible with OpenFlow

Theorem: «Ideal» Forwarding Connectivity Possible

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Analysis of their **complexity**: maximum stretch (route length compared to ideal route), number of tags, number of OpenFlow rules.

Three algorithms:

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- **Depth-First**
- **Breadth-First**

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Overview of Contributions

High-Level Algorithms

Algorithm 2 Algorithm DFS

Input: current node: v_i, input port: in, packet dest: d, packet failover global params: $pkt.start$, packet tag array: $\{pkt.v_j\}_{j\in[n]}$

Output: output port

```
if pkt.start =
  out ← def
  if out faile
    pkt.start
    pkt.v_i.pa
    out ← 1
else
  if pkt.v_i.cu
    pkt.v_i.pa
  out ← pkt.
  if out = Δ
    out ← pk
    goto 19
while out fai
  out ← out ·
  if out = Δ_i + 1 then
    out ← pkt.v_i.par
    goto 19
pkt.v_i.cur ← out
return out
```

Algorithm 1 Algorithm MOD

Input: current node: v_i, packet dest: d, packet tag array: $\{pkt.v_j\}_{j\in[n]}$

Output: output port: out

```
if no tag then {same as pkt.v_i = 0}
  out ← default_route(i, d)
else
  out ← (pkt.v_i mod Δ_i) + 1
  pkt.v_i ← out
  while out failed do
    out ← (pkt.v_i mod Δ_i) + 1
    pkt.v_i ← out
return out
```

Algorithm 3 Algorithm BFS

Input: current node: v_i, input port: in, packet dest: d, packet failover global params: $pkt.start$, packet tag array: $\{pkt.v_j\}_{j\in[n]}$

Output: output port: out

```
if pkt.start = 0 then
i, d)
pkt.v_i.par = 0 then
d pkt.v_i.par ≠ in then
= pkt.v_i.par do
if out = 0 then
  out ← 1
  while out failed do
    out ← out + 1
    if out = Δ_i + 1 then
      Drop
  pkt.v_i.cur ← out
return out
```

Flow-Table Implementations

Flow Table $\Delta_i - 1$

Match sb	Instructions
0	Gr $\Delta_i - 1$, Table Δ_i
1	Drop

Flow Table Δ_i

Match sb	Instructions
0	Gr Δ_i,Table 0.2 (Send-Parent)
1	Drop

Table 5: DFS: Flow Tables of switch i.

Flow Table A (Start)

Match		Instructions
$pkt.start$	dst	
0	1	Gr 0.1, Table 1
0	2	Gr 0.2, Table 1
...	...	...
0	n	Gr 0.n, Table 1
*	*	Table B

Flow Table B

Match			Instructions
in	$pkt.v_i.cur$	$pkt.v_i.par$	
1	0	*	$pkt.v_i.par \leftarrow in$, Table 2
1	1	2	Table 3
2	2	3	Table 4
3	3	4	Table 5
...	...	...	...
$\Delta_i - 2$	$\Delta_i - 2$	$\Delta_i - 1$	Table Δ_i
$\Delta_i - 1$	$\Delta_i - 1$	Δ_i	Table C
*	0	*	$pkt.v_i.par \leftarrow in$, Table 1
1	1	*	Table 2
2	2	*	Table 3
3	3	*	Table 4
...	...	...	...
$\Delta_i - 1$	$\Delta_i - 1$	*	Table Δ_i
Δ_i	Δ_i	*	Table C
1	*	*	Fwd 1
2	*	*	Fwd 2

Complexity Analysis

THEOREM 1. MOD *ensures data plane connectivity when-*

Algorithm	Packet Memory	Message count	Rules space
Module	nlogd	Exp(n)	O(n*d)
DFS	nlogd	2|E|	O(n*d)
BFS	nlogd	2kn	O(n*d)
BFS*	k(logd+logn)	2kn	O(n*(d+k))

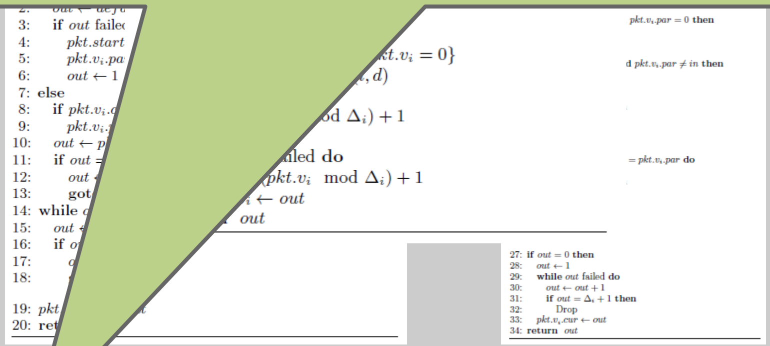
Related Work

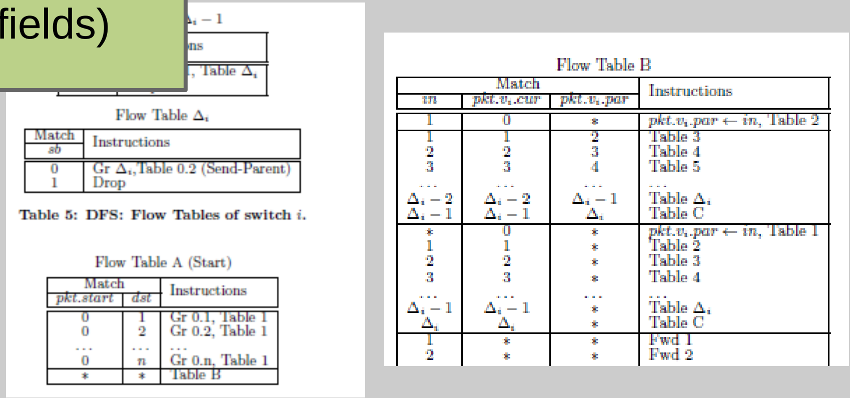
- Borokhovich, OPODIS’13
- [1] Liu et al. NSDI’13
- Graph-search literature

Overview of Contributions

We expect that our algorithms scale up to 500-node networks (ignoring link capacities)
(e.g., using our NoviKit 250 switches, with 32MB flow table space and full support for extended match fields)

v-Table Implementations





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Overview of Contributions

We expect that our algorithms scale up to **500-node networks** (ignoring link capacities)
(e.g., using our NoviKit 250 switches, with 32MB flow table space and full support for extended match fields)

…-Table Implementations

Inherent tradeoffs between **robustness and network load** of failover **without tagging**.

Same objective: ideal connectivity. But their **link-reversal algorithms** not applicable to OpenFlow: require dynamic state at router.

Complexity Analysis

Lower bounds with **implications on optimality** of our algorithms.

Algorithm	Rules space
Module	O(n*d)
DFS	O(n*d)
BFS	
BFS*	O(n*(d+k))

Related Work

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Conclusion

- Fast failover: example of a function that should be kept in the data plane
- Our result shows that non-trivial functions can be computed in the OpenFlow data plane!
- Our algorithms: may serve in compilers for higher-level languages, e.g., FatTire

Backup Slides

Complexity

- Today switches allow to match a few hundreds bits which can support a network of few dozens elements

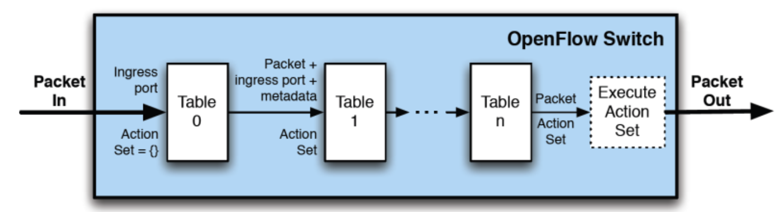
- Some advanced experimental switches allow to match any offset in the packet thereby supporting huge networks of a few hundreds elements

- The ability to match every offset is expected to be supported by future versions of OpenFlow standard

OpenFlow Failover in a Nutshell

OpenFlow 101

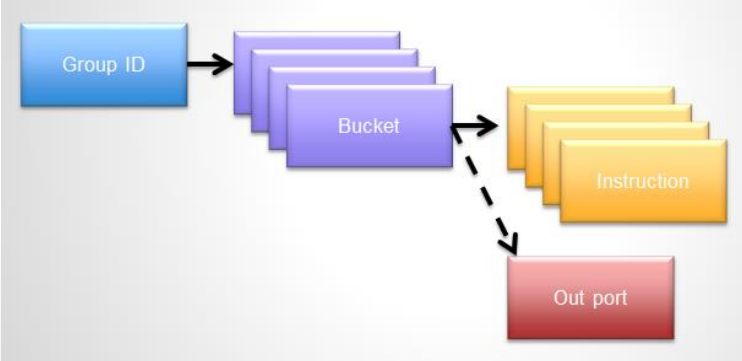
- **OpenFlow** based on a pipeline of forwarding tables: each switch has multiple flow tables and a group table
- Each **flow table** in the switch contains a set of flow entries; each flow entry consists of match fields, counters, and an ordered list of action buckets
- **Groups** can be applied on a packet while processed
- Each **action bucket** contains a set of actions to execute, and provides the ability to define multiple forwarding behaviors
- The group table consists of multiple groups, where different groups can have different types, e.g., fast failover



Each packet carries an Action set: empty at the start, updated while packet is processed, executed at the end.

Without controller, an OpenFlow switch forwards according to:

- Static configuration
- Links status
- Packet header
- Input port



Related Theory Literature

- Automata and Labyrinths [Budach 1978]
  - No finite automaton can explore all graphs
- Graph exploration by a finite automaton [Fraigniaud, Ilcinkas, Peerb, Pelcc, Peleg 2005]
  - $\Omega(\log n)$ memory for n nodes graph
  - $\Theta(D \log d)$ for a graph with diameter D and maximum degree d (DFS is optimal).
- An Agent Exploration in Unknown Undirected Graphs with Whiteboards [Sudo, Baba, Nakamura, Ooshita, Kakugawa, Masuzawa 2010]
  - $O(\log d)$ memory in each node.

Module Algorithm

Algorithm 1 Algorithm Mod

Input: current node: v_i, packet dest: d, tags array: $\{pkt.v_j\}_{j \in [n]}$

Output: new next hop: $next$

```
if no tag then {same as pkt.v_i = 0}
    next ← default_route(i, d)
else
    next ← (pkt.v_i mod Δ_i) + 1
    pkt.v_i ← next
    while (v_i, v_next) is failed do
        next ← (pkt.v_i mod Δ_i) + 1
        pkt.v_i ← next
return next
```

DFS Algorithm

Algorithm 2 Algorithm DFS

Input: current node: v_i, packet dest: d, tags array: T
Output: new next hop: $next$

if $pkt.start = 0$ **then**
  $next \leftarrow default\_route(i, d)$
  if $(v_i, next)$ failed **then**
    $pkt.start \leftarrow 1$
    $pkt.v_i.par \leftarrow in$
    $next \leftarrow 1$
else
  $next \leftarrow pkt.v_i.cur + 1$
  if $next = \Delta_i + 1$ **then**
    $next \leftarrow pkt.v_i.par$
    goto 17
while $(v_i, next)$ failed or $next = pkt.v_i.par$ **do**
  $next \leftarrow next + 1$
  if $next = \Delta_i + 1$ **then**
    $next \leftarrow pkt.v_i.par$
    goto 17

$pkt.v_i.cur \leftarrow next$
return $next$

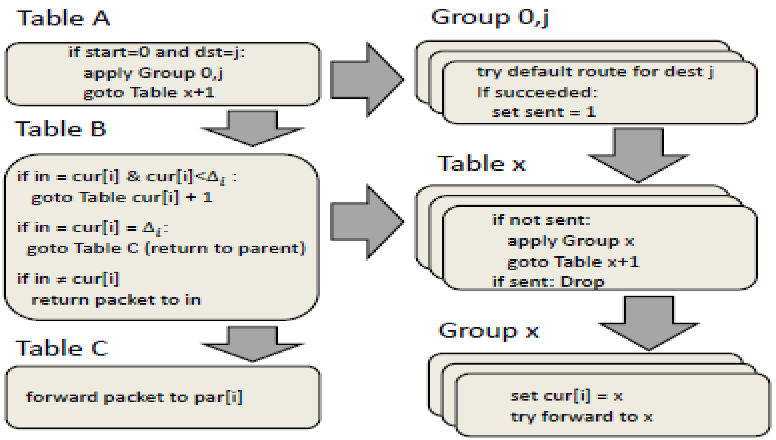


Figure 1: DFS Tables illustration for node i.

BFS Algorithm

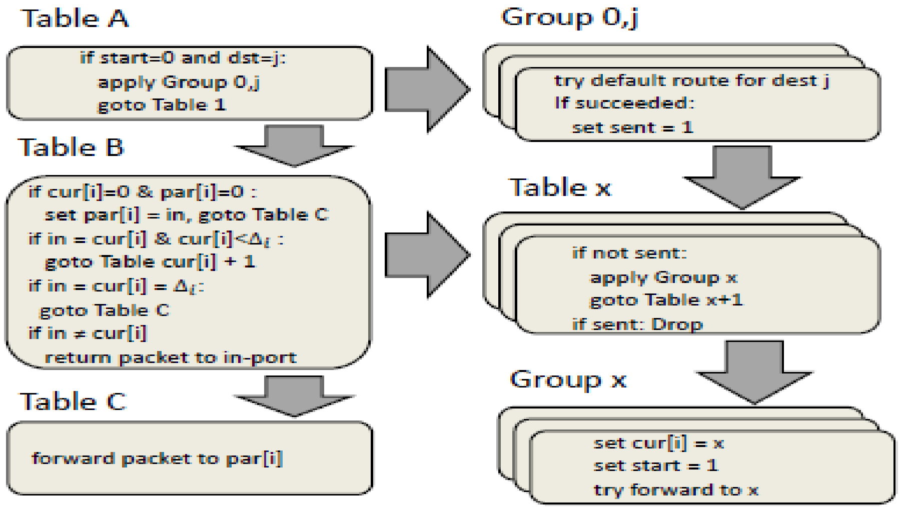


Figure 2: BFS Tables illustration for node i.

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