University of Rome Tor Vergata
ICT and Internet Engineering

Network and System Defense

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Lecture 9: BGP/MPLS VPNs

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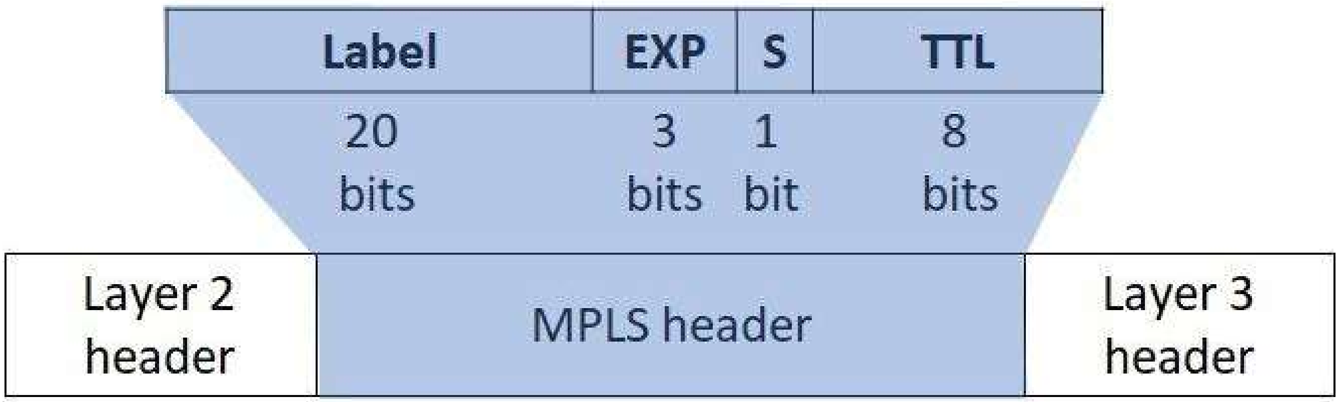
MultiProtocol Label Switching (MPLS)

BGP permette di costruire VPN e scambiare pacchetti tra VPN

simile a vpn ma questa è indipendente dalla rete sottostante e dal protocollo utilizzato

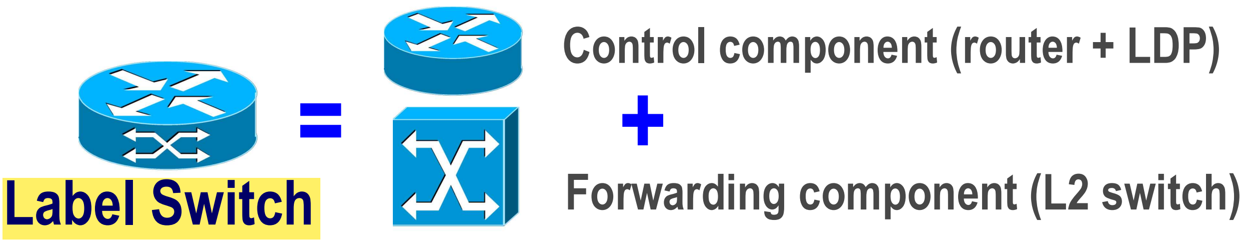
MPLS: architecture

- The key idea of the MPLS architecture is to associate a brief identifier, namely Label, to every packet.
- Internetworking nodes can then apply fast forwarding mechanisms based on label switching / label swapping
- MPLS is independent both from the transport subnet (Frame Relay, ATM, etc.) both from adopted network protocols



MPLS ha un header di 4 bytes, 20 bits di label VLAN tag, TTL ha la stessa funzione che in IP è il Time To Live

MPLS Network Node

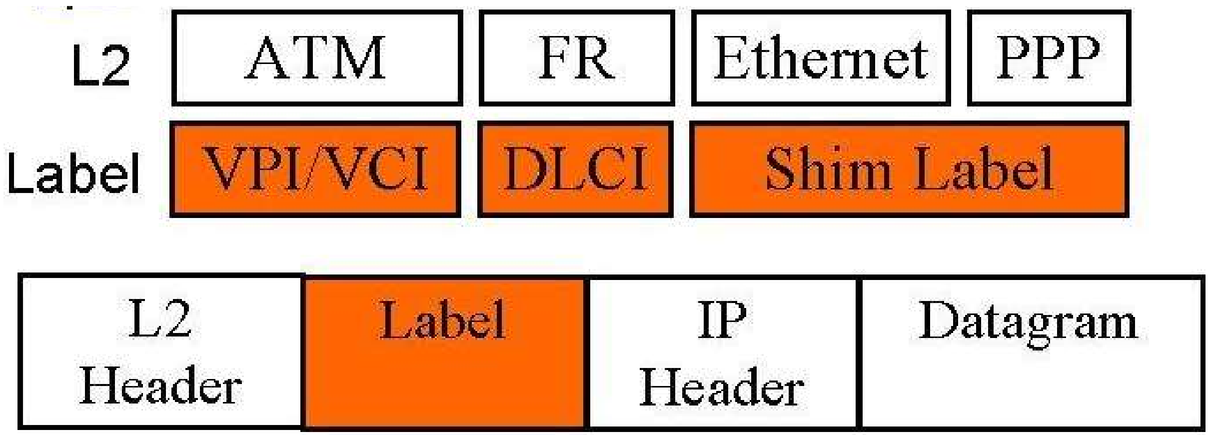


- ***Control Component***
  - A set of modules dealing with Label allocation and binding Labels between adjacent nodes
  - Layer 3 «intelligence» (IP addressing, IP routing)
- ***Forwarding Component***

  si può pensare come un semplice level 2 switch, basato su un exact match delle label
  - Forwarding based on the label swapping paradigm
- The two components must be independent: they can employ different protocols within every medium
- The Control Component is sometimes realized as a part (SW or HW) of the network node, other times as external controller

Label Encoding

- If data-link layer natively supports a field for the label (ATM does it with VPI/VCI, Frame Relay with DLCI), this can be used to insert the MPLS label
- If data-link layer doesn't support that field, the MPLS label is embedded in an MPLS header, inserted between layer 2 and layer 3 headers (e.g. Ethernet/MPLS/IP)



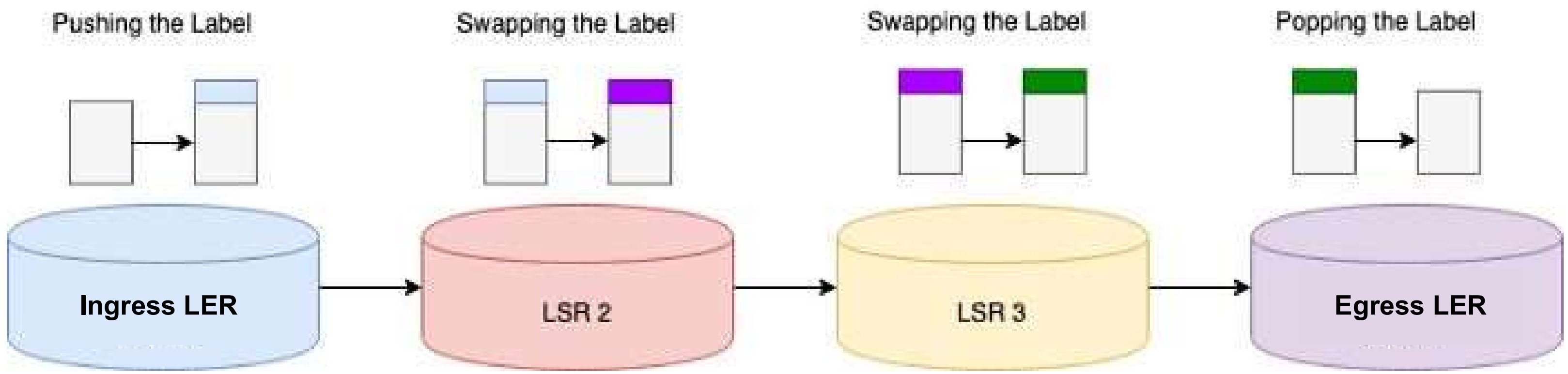
Terminology

- ***Label Edge Router (LER):*** edge routers for an MPLS network: they have forwarding functionalities from and to the outer networks, applying and removing the labels to ingress and egress packets
- ***Label Switching Router (LSR):*** switches operating label swapping inside the MPLS network and supporting forwarding functionalities parla solo MLPS
- ***Label Distribution Protocol (LDP):*** in conjunction with traditional routing protocols, LDP is used for distributing labels between network devices
- ***Forwarding Equivalence Class (FEC):*** a set of IP packets that are forwarded in the same way (for instance along the same path, with the same treatment) seguono lo stesso path
- ***Label Switched Path (LSP):*** the path through one or more LSRs followed by a packet belonging to a certain FEC

Label Switching Operation: Push, Forwarding and Pop

- ❑ The ingress LER of the MPLS backbone analyzes the packet's IP header, classifies the packet, adds the label and forwards it to the next hop LSR
- ❑ In the LSRs cloud the packet is forwarded along the LSP according to the label. At each hop labels are swapped (local label: remote label)
- ❑ The egress LER removes the label and the packet is forwarded based on IP destination address

tutto forma il label switched path



label di ingresso prende il pacchetto IP e inserisce una Label (PUSH)

può fare lo swap della Label

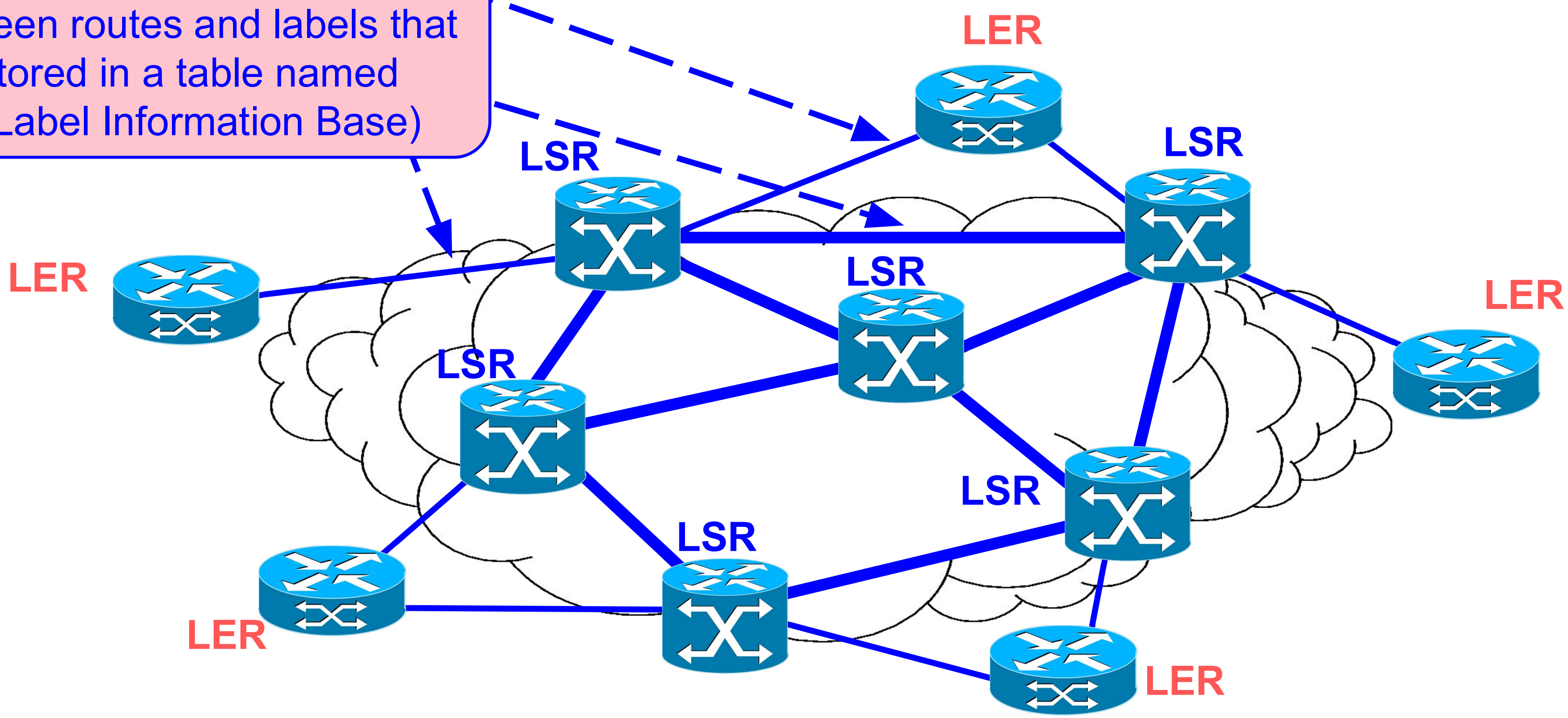
stessa cosa

rimuove (POP) la Label e forwarda il pacchetto secondo standard IP forwarding. Nei passaggi intermedi le IP routing tables non vengono utilizzate

Label Switching Operation: Control

LDP is used for distributing the <label, prefix> associations between MPLS nodes

LDP creates the associations between routes and labels that are stored in a table named LIB (Label Information Base)



LDP è il protocollo per la distribuzione basata su Label, le informazioni riguardo i percorsi da seguire sono inserite nelle tabelle LIB.

2 tipi di working mode

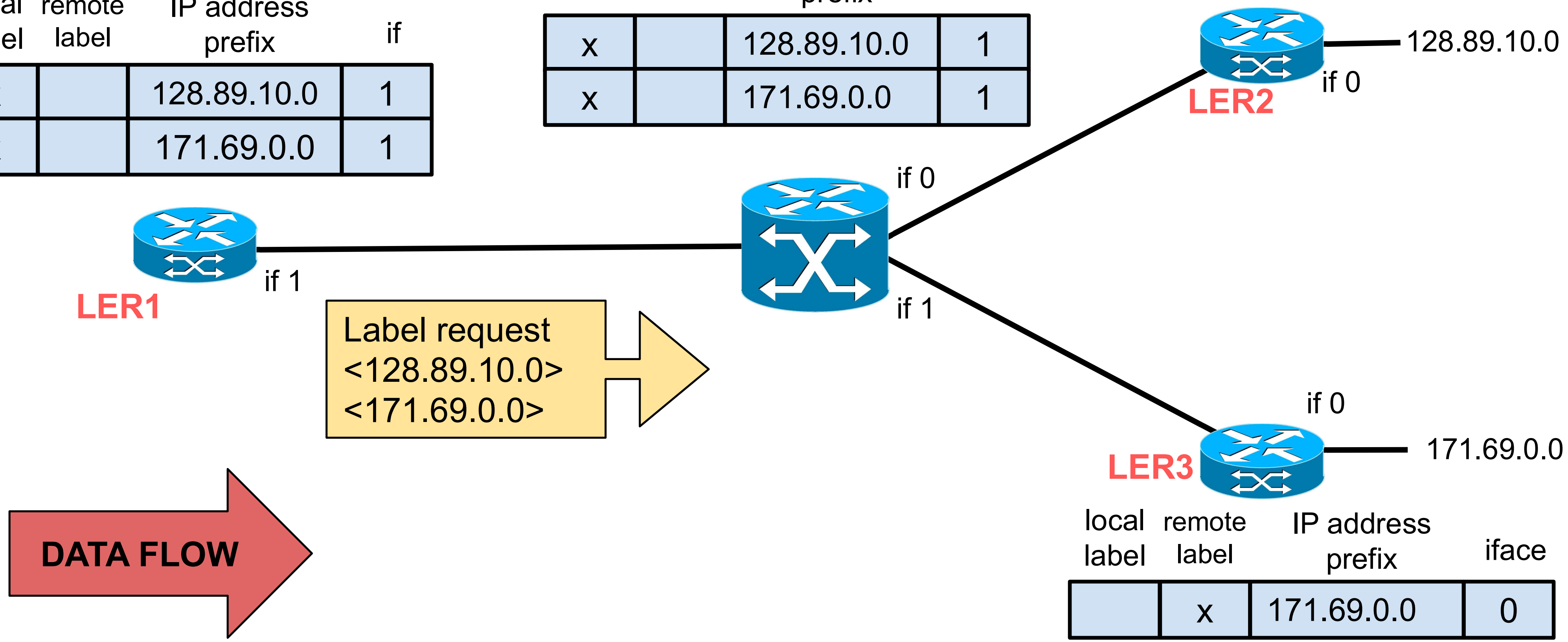
LDP: Downstream on Demand

local label	remote label	IP address prefix	if
x		128.89.10.0	1
x		171.69.0.0	1

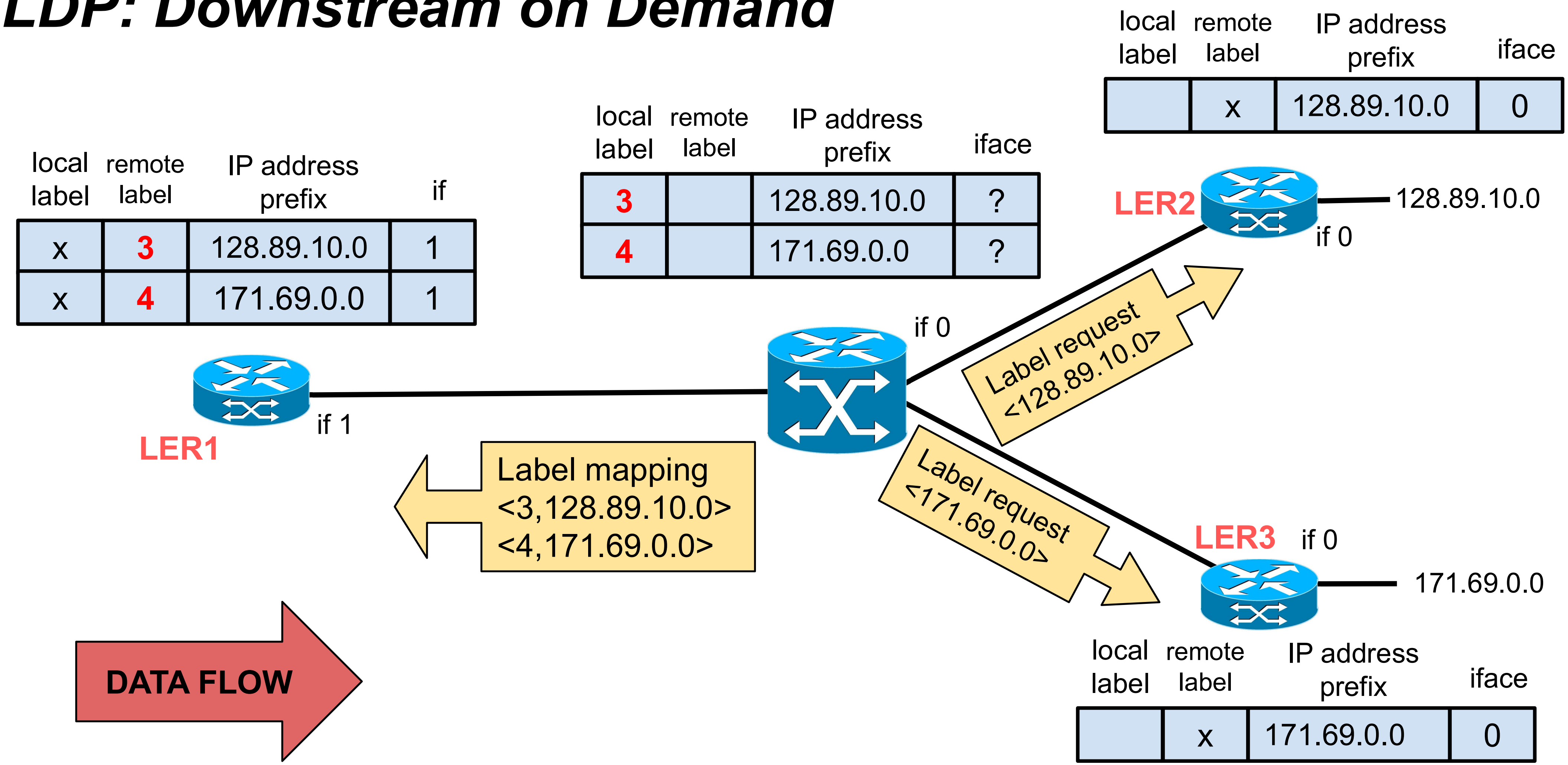
local label	remote label	IP address prefix	iface
x		128.89.10.0	1
x		171.69.0.0	1

local label	remote label	IP address prefix	iface
	x	128.89.10.0	0

local label	remote label	IP address prefix	iface
	x	171.69.0.0	0



LDP: Downstream on Demand



local label	remote label	IP address prefix	if
x	3	128.89.10.0	1
x	4	171.69.0.0	1

local label	remote label	IP address prefix	iface
3		128.89.10.0	?
4		171.69.0.0	?

local label	remote label	IP address prefix	iface
	x	128.89.10.0	0

local label	remote label	IP address prefix	iface
	x	171.69.0.0	0

ogni richiesta viene risposta con un label mapping, in base all'indirizzo che si vuole raggiungere bisogna applicare una Label diversa

local label è quello che ci aspettiamo in ingresso per quel router
remote è cosa applicare per permettere il router a quella destinazione

IP routing è utilizzato come setup

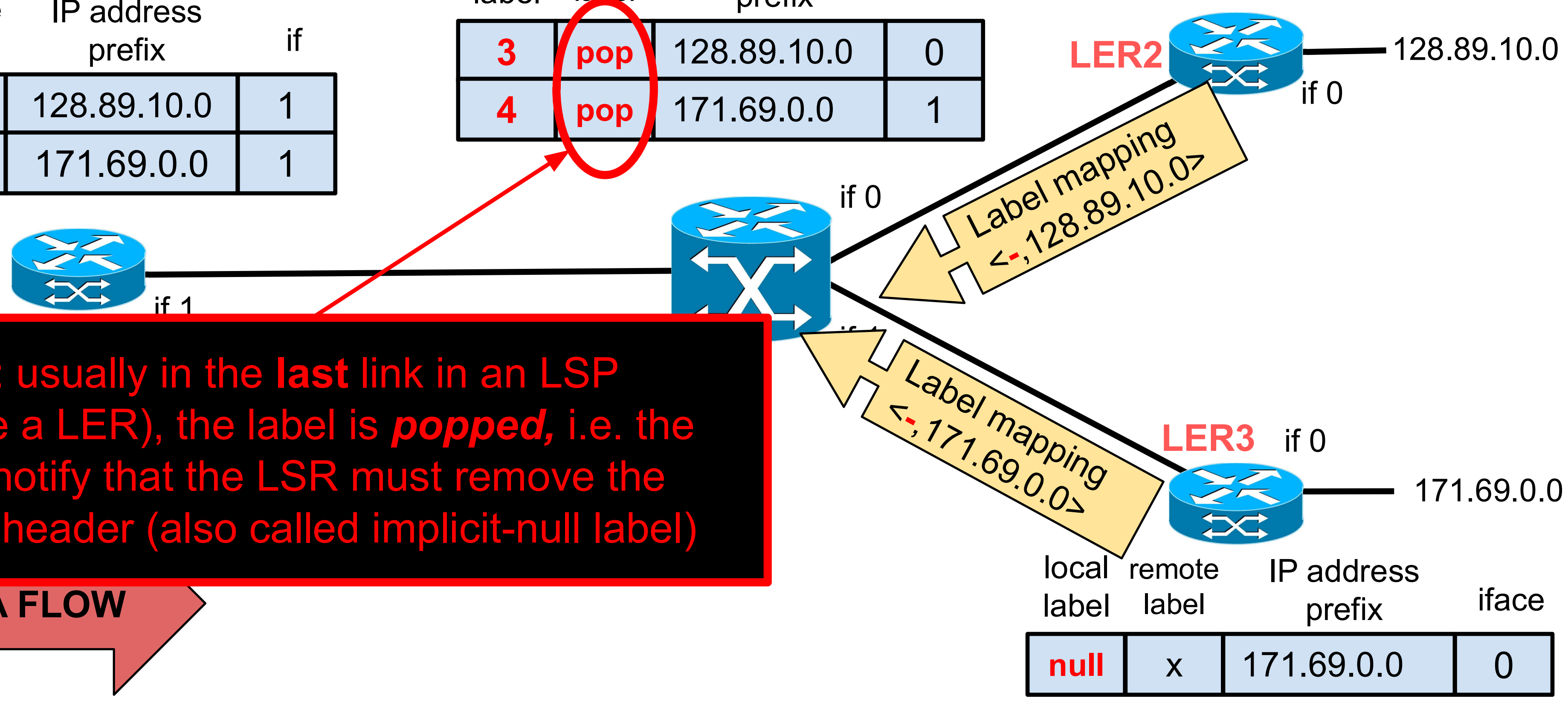
LDP: Downstream on Demand

local label	remote label	IP address prefix	if
x	**3**	128.89.10.0	1
x	**4**	171.69.0.0	1

local label	remote label	IP address prefix	iface
3	**pop**	128.89.10.0	0
4	**pop**	171.69.0.0	1

local label	remote label	IP address prefix	iface
null	x	128.89.10.0	0

local label	remote label	IP address prefix	iface
null	x	171.69.0.0	0



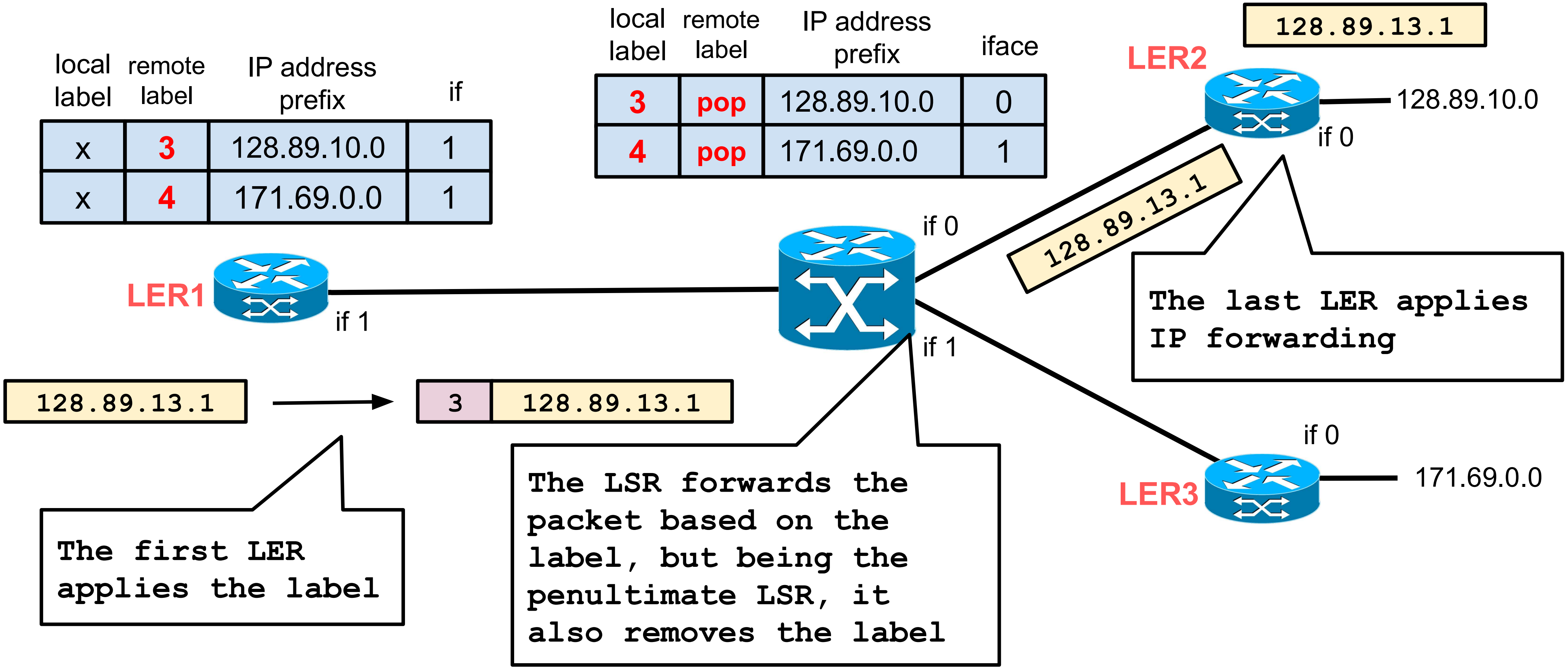
NOTE: usually in the **last** link in an LSP (before a LER), the label is ***popped,*** i.e. the LERs notify that the LSR must remove the MPLS header (also called implicit-null label)

i router inviano i pacchetti per avvertire del pop dei prefissi il penultimo nodo

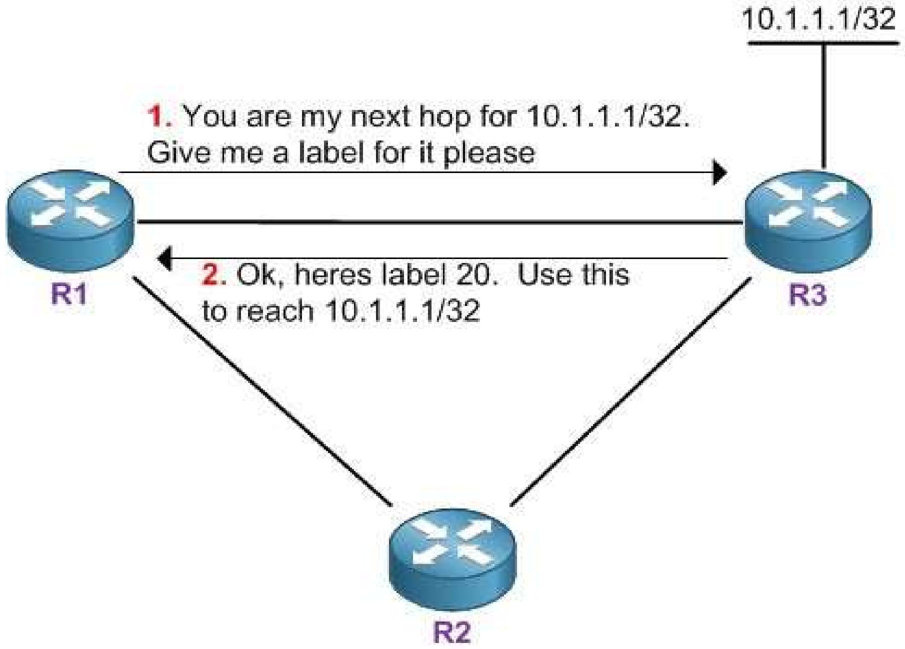
Label Switching Operation: Forwarding

local label	remote label	IP address prefix	if
x	3	128.89.10.0	1
x	4	171.69.0.0	1

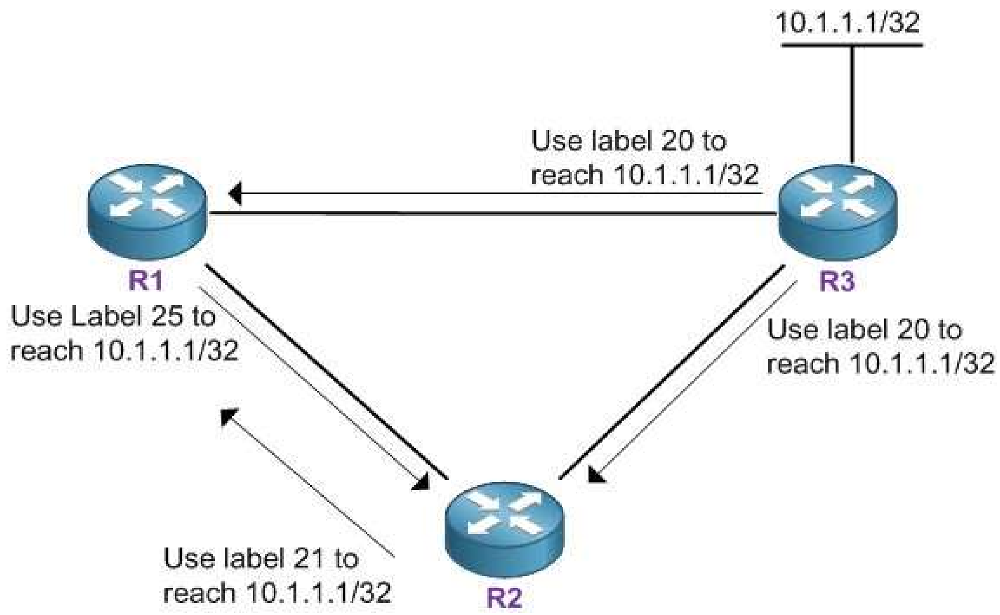
local label	remote label	IP address prefix	iface
3	pop	128.89.10.0	0
4	pop	171.69.0.0	1



LDP: Downstream OnDemand vs Unsolicited



OnDemand

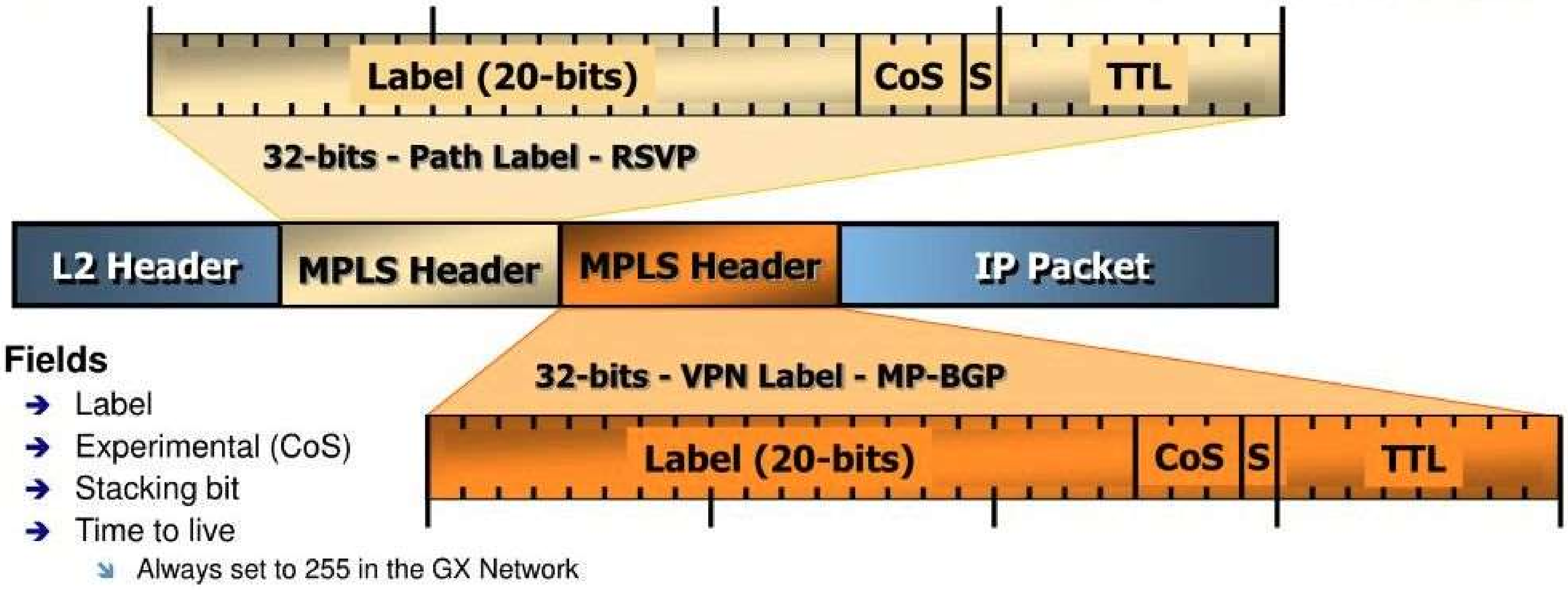


Unsolicited
(Cisco default)

si possono avere più MPLS header, label switching guardano al più esterno MPLS header.
Il bit S posto a 1 indica che quella è l'ultima label

Label Stacking

MPLS label can be stacked to aggregate, in a network section, two or more LSP in a single LSP with higher pecking order (e.g. MPLS VPNs, details in a few slides...)



MPLS and BGP

Problem: how can internal routers (e.g. R2) forward transit packets, i.e. intended to one of the 800k external routes?

1. Replicate BGP tables also in core routers (costly)
2. Full mesh LSPs between border routers through which only transit traffic is forwarded
   - ❏ Internal routers only matters about routing tables to reach internal network nodes

Replicare le tabelle BGP anche nei router nel core è costoso, quello che si fa è utilizzare MPLS internamente e BGP ai bordi della rete.

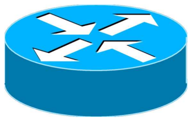
Intra-AS Virtual Private Networks with MPLS/BGP

Intra-AS VPNs

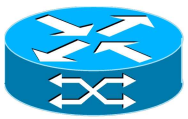
IPS=internet service provider

- Routing Information exchange between Company and ISP routers
  - Routing happens on a layer composed both by company entities and by ISP entities
- De facto based on BGP/MPLS solution
  - Enterprise's gateway transfers data to the ISP which handles the forwarding through other Enterprise's sites
  - Routing (connections topology) is actually in the hands of the ISP
  - Plug & Play, adding a site is a matter of ISP configuration only, the company has to do almost nothing

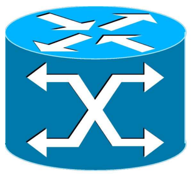
Elements of a VPN BGP/MPLS network



Customer Edge: is the Company side router facing with the ISP which provides the VPN BGP/MPLS service. It has standard routing functionalities; its only peer is the Provider edge with which exchanges info through BGP messages



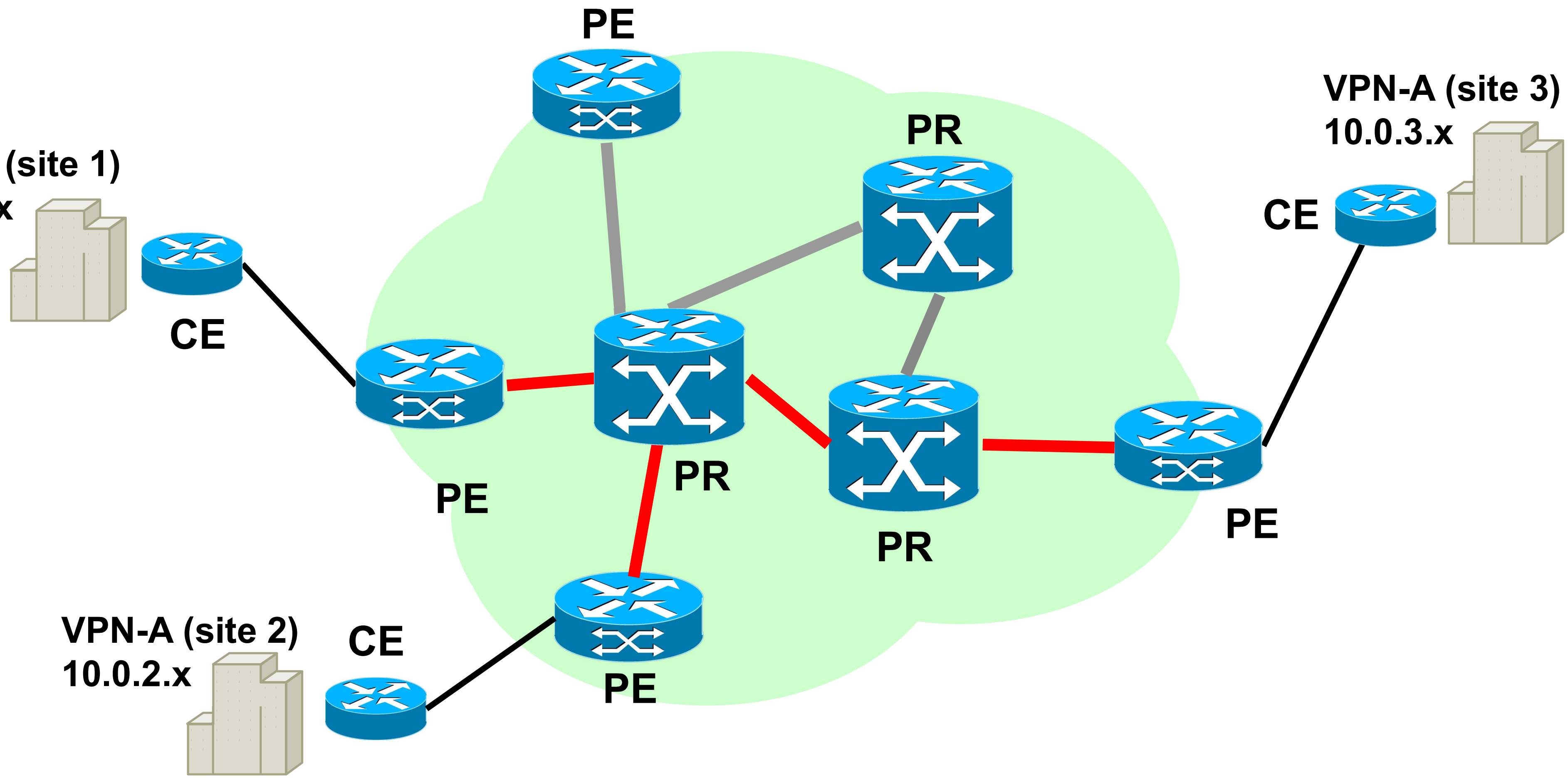
Provider Edge: is the access router on the ISP side in which one or more Customer Edges are connected. Besides IP functionalities, it also handles the MPLS LER role.



Provider Router: Label Switched Router (LSR) composing the MPLS backbone of the ISP

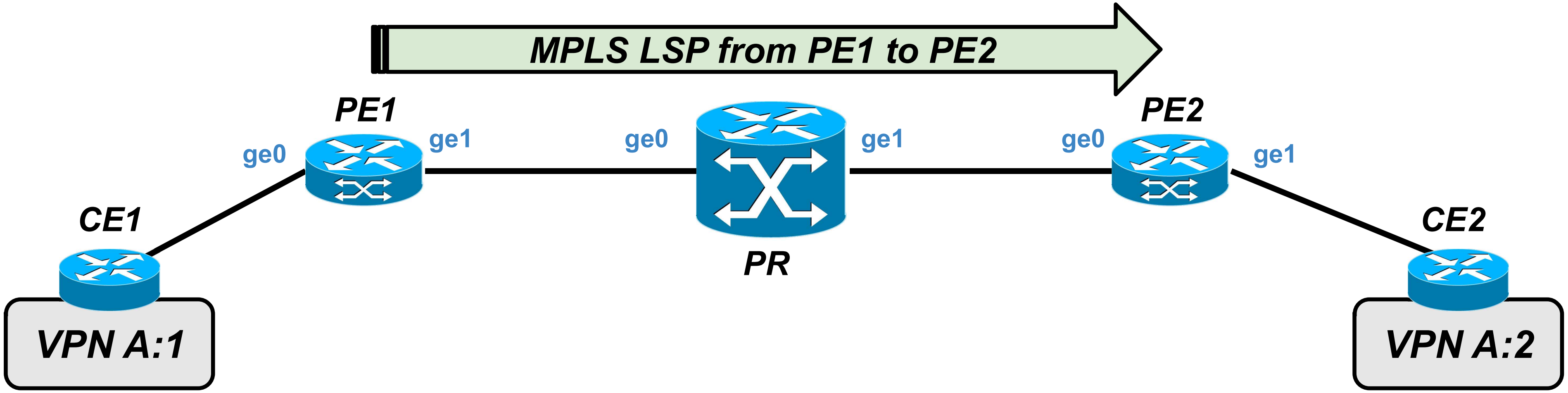
MPLS/VPN Backbone: MPLS network with properly configures LSPs to interconnect all the Provider Edges.

VPN MPLS service architecture



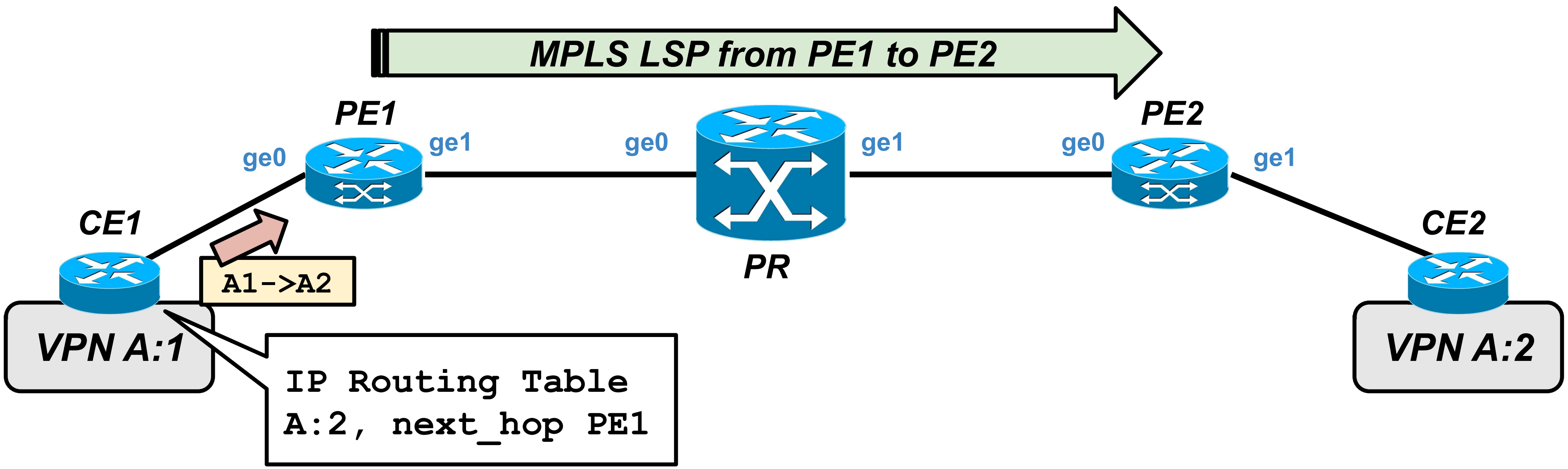
abbiamo diversi siti legati all'azienda

Forwarding mechanism (trivial solution)

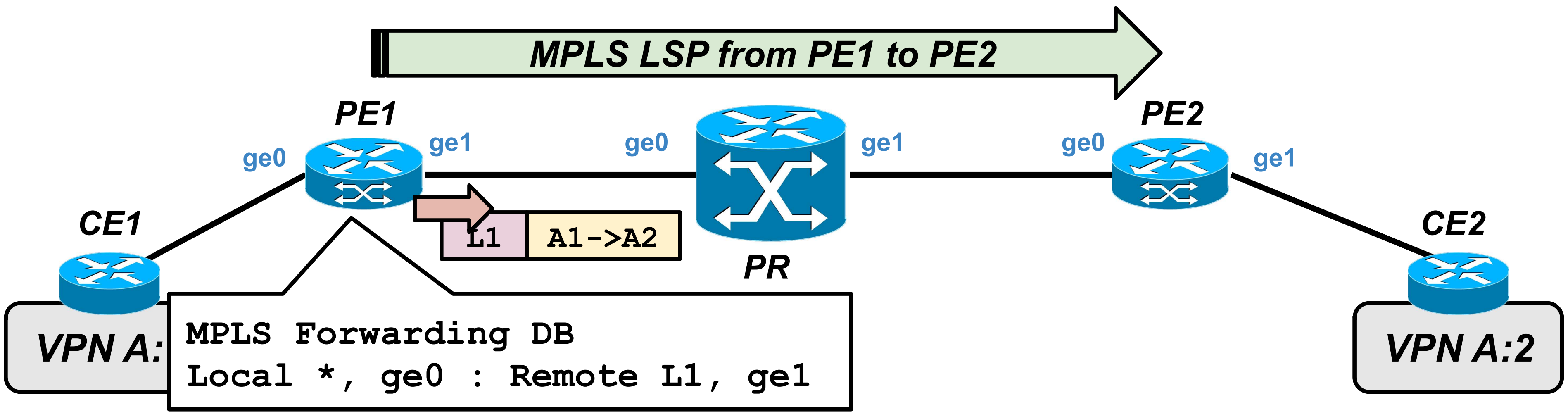


forwarding: customer edge1 si vuole connettere al 2, ognuno connessi ai provider edge 1 e 2, c'è un solo router che cambia label.
provider edge 1 applica la label L1, PR cambia la label a L2 e fa il forwarding, PE2 toglie la label e lo manda a CE2.

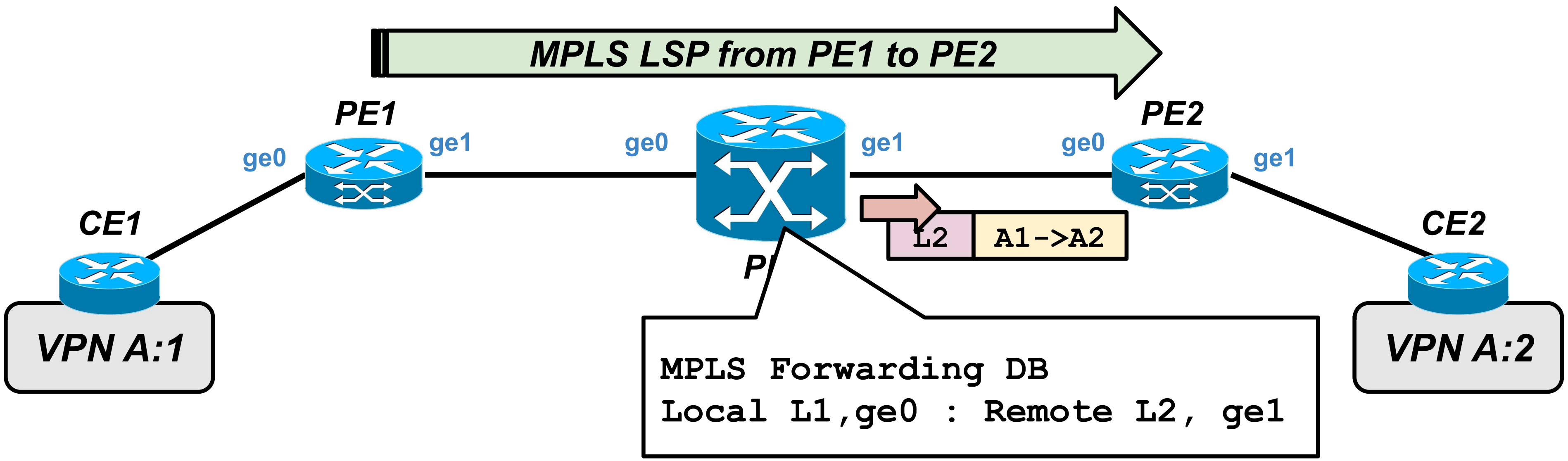
Forwarding mechanism (trivial solution)



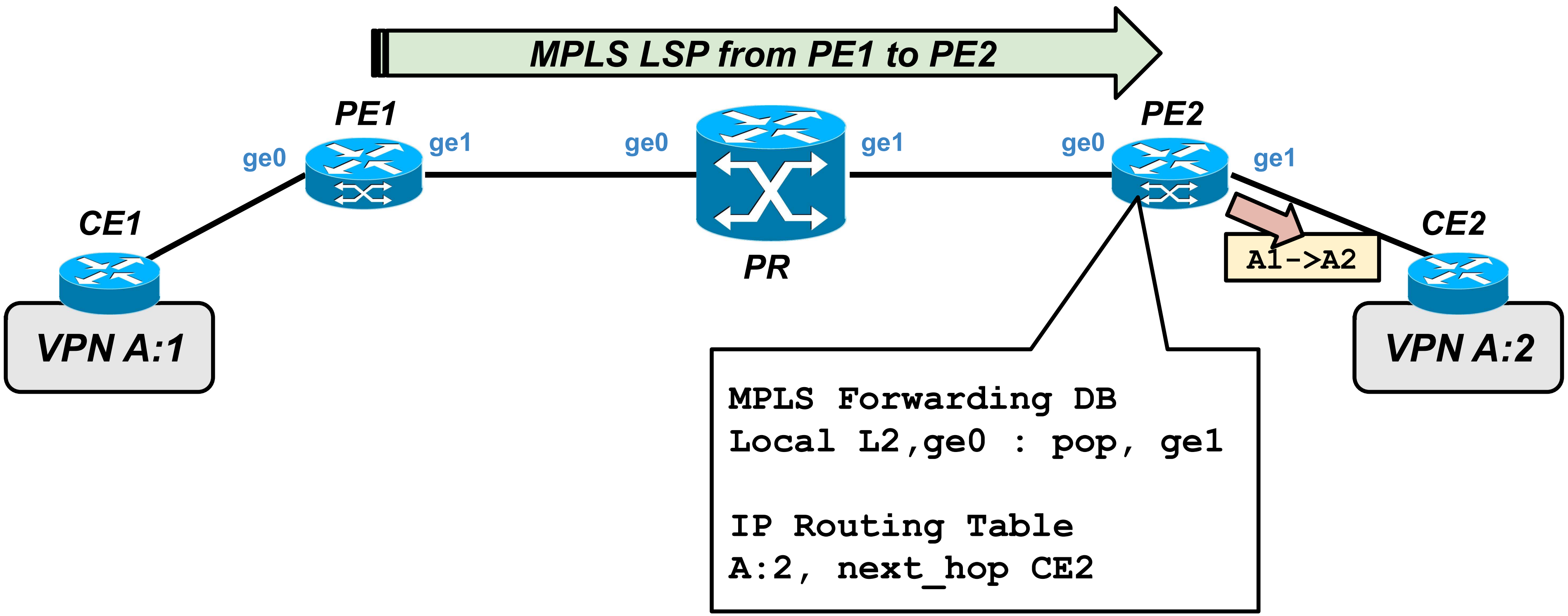
Forwarding mechanism (trivial solution)



Forwarding mechanism (trivial solution)

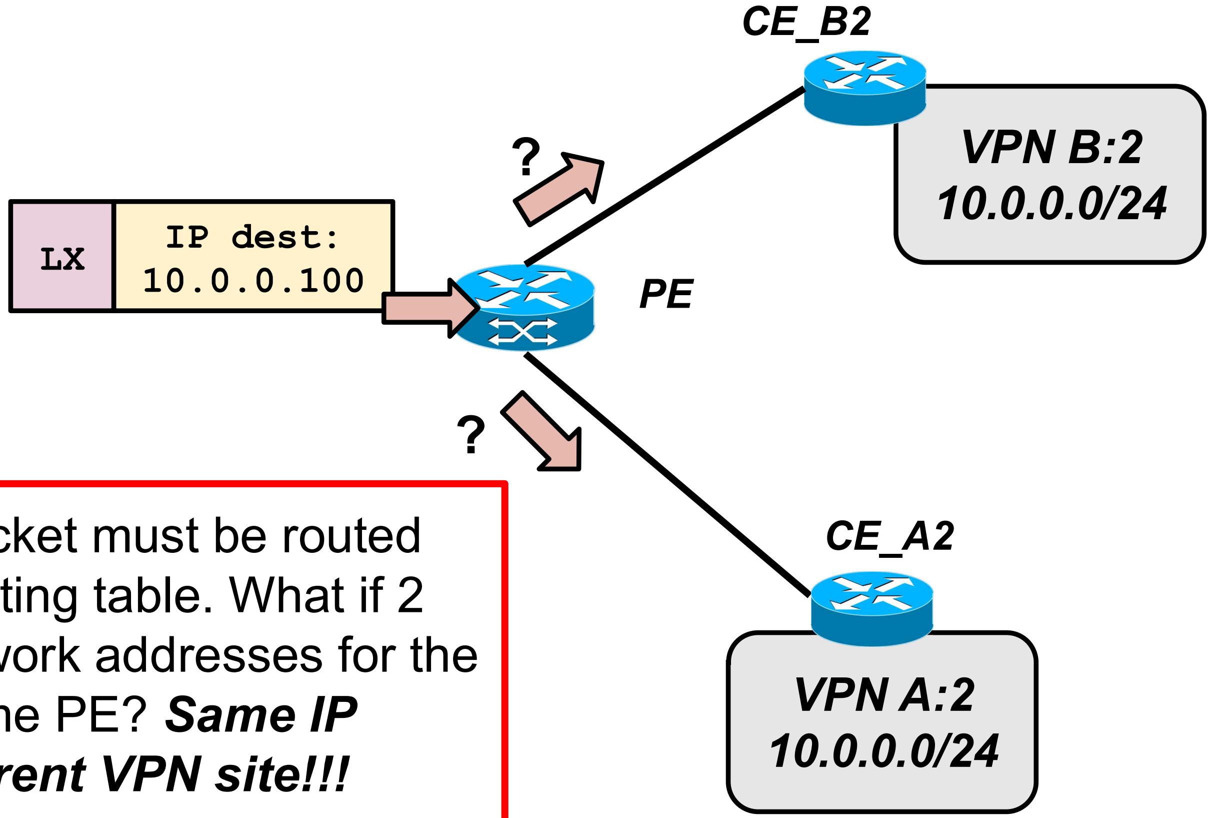


Forwarding mechanism (trivial solution)



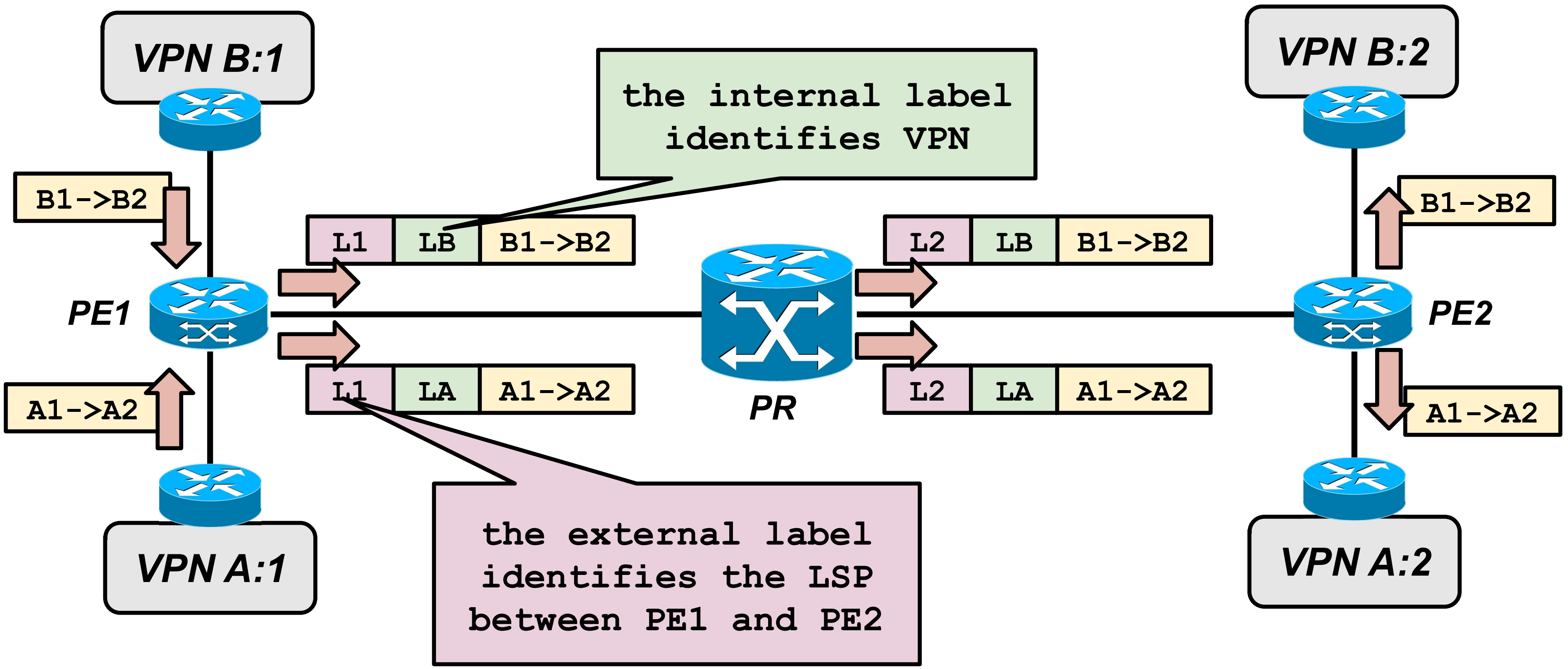
but customer VPN addressing is un-coordinated...

PROBLEMA: potrei avere lo stesso indirizzo di rete in due VPN diverse



After the MPLS pop(), the packet must be routed according to PE's local IP routing table. What if 2 customers chose the same network addresses for the sites connected to the same PE? ***Same IP destination for two different VPN site!!!***

Solution: double MPLS encapsulation

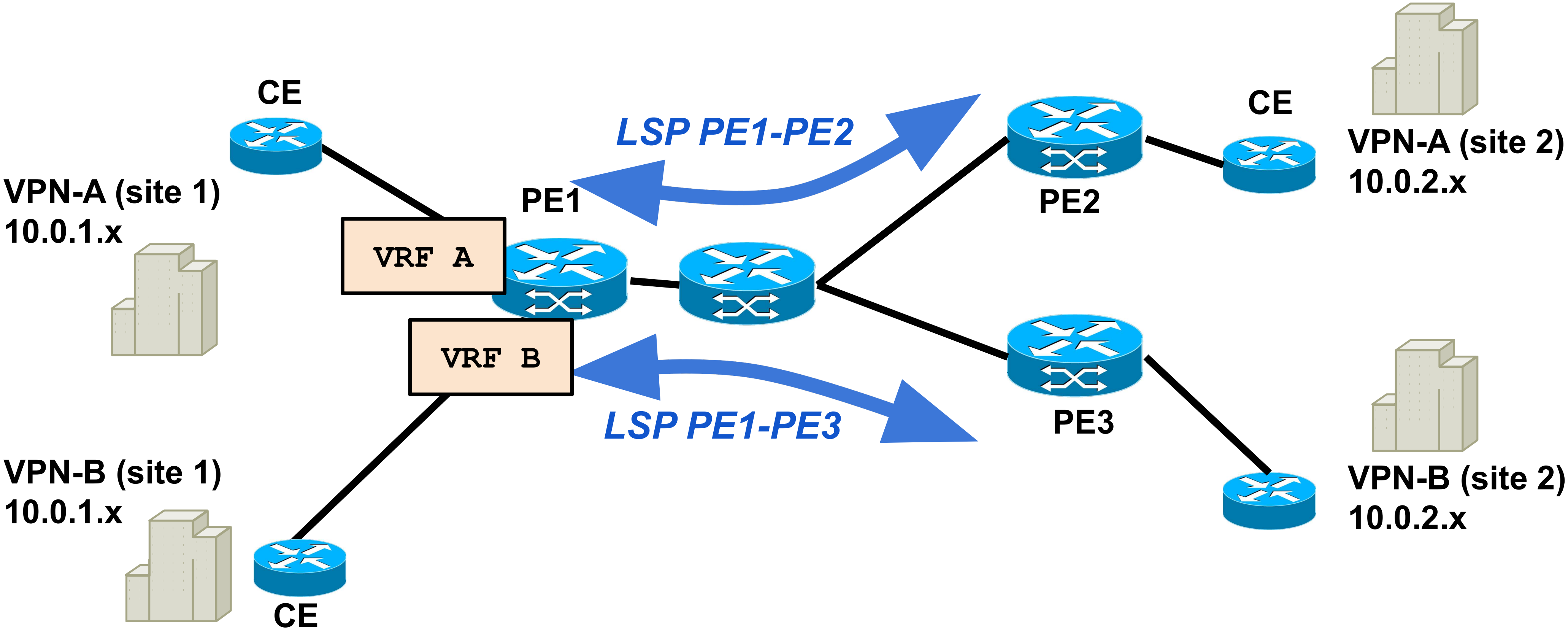


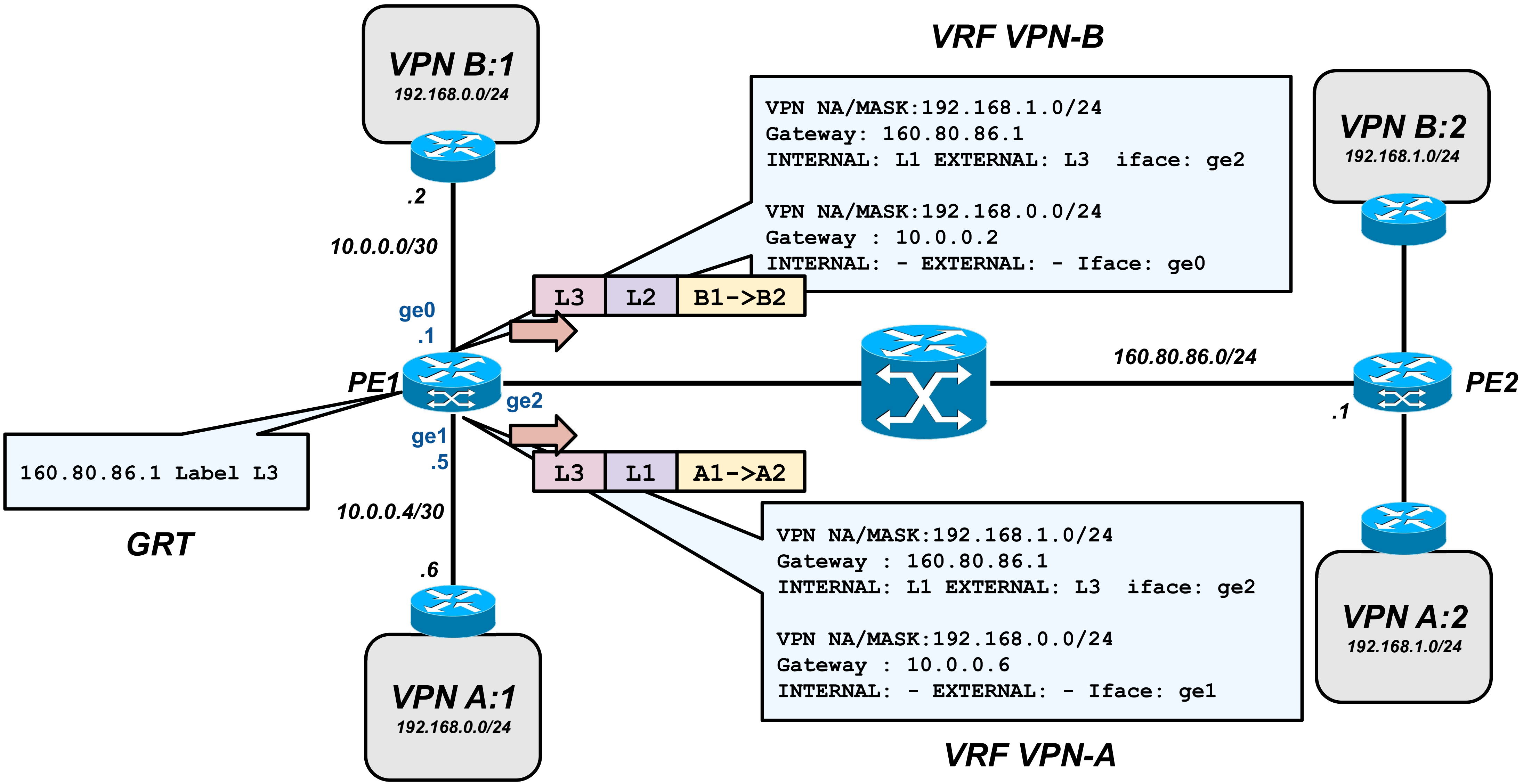
LABEL STACKING, aggiungiamo informazioni al pacchetto con extra label per mantenere queste informazioni. L'internal label identifica la VPN (il customer), l'external label identifica il label switch path

Managing multiple forwarding tables at the PE

- The PE associates the incoming packet to the customer VPN by simply ***matching the ingress interface***
- The MPLS forwarding table changes according to the specific VPN the customers belong to
- The PE must support ***as many forwarding tables as the customers VPNs connected to it***
- Such forwarding tables are called ***VPN Routing and Forwarding (VRF)*** tables
  - A VRF entry contains (logically) the following tuple: <VPN network address, VPN mask, Next PE IP Address, Internal label, Output Interface>
- In addition to the VRF, a PE stores a single ***Global Forwarding Table (GRT)*** which permits to reach a PE from another PE
  - a GRT entry contains the tuple: <PE IP address, external label, Output Interface>

High Level Architecture




VRF VPN-B
VPN B:1
192.168.0.0/24
.2
10.0.0.0/30
VPN NA/MASK:192.168.1.0/24
Gateway: 160.80.86.1
INTERNAL: L1 EXTERNAL: L3 iface: ge2
VPN NA/MASK:192.168.0.0/24
Gateway : 10.0.0.2
INTERNAL: - EXTERNAL: - Iface: ge0
VPN B:2
192.168.1.0/24
L3
L2
B1->B2
ge0
.1
PE1
ge2
160.80.86.0/24
PE2
.1
160.80.86.1 Label L3
ge1
.5
L3
L1
A1->A2
10.0.0.4/30
GRT
.6
VPN NA/MASK:192.168.1.0/24
Gateway : 160.80.86.1
INTERNAL: L1 EXTERNAL: L3 iface: ge2
VPN NA/MASK:192.168.0.0/24
Gateway : 10.0.0.6
INTERNAL: - EXTERNAL: - Iface: ge1
VPN A:1
192.168.0.0/24
VPN A:2
192.168.1.0/24
VRF VPN-A

è un problema gestire staticamente queste tabelle perciò ci vengono incontro alcuni protocolli

Populating the GFT and the VRFs

- The Global Forwarding Table is configured by the provider during the set-up or the MPLS/VPN backbone (i.e. LSPs between PEs)
- The GFT can be populated manually (in the case of manual LSPs), or automatically in the case of a set-up with signalling protocols like LDP, RSVP-TE or CR-LDP
- VRFs contain two forwarding categories:
  - Forwarding to LOCAL sites
  - Forwarding to REMOTE sites
- Forwarding to local sites can be:
  - Manually configured
  - Obtained through specific routing protocols (OSPF, RIP, etc.), running the CE-PE link
- Remote routes are obtained through an extension of the BGP-4 protocol, namely Multi-Protocol interior BGP (***MP-iBGP***)

Populating the GFT and the VRFs

- VRFs are synchronized by exchanging the reachability info inside MP-iBGP announces
- An MP-iBGP announce is sent by a PE to all other PEs; an overlay full mesh between PEs must exist

bisogna pensare i LRS come un unico grande switch, per questo full mesh. IP level è come un unico hop

- ***Assumption***: the cost of the direct hop between two PEs is 1, being this an IP level hop (not MPLS hop)
- A same MP-iBGP announce carries reachability information relative to prefixes of more VRFs

Route Distinguisher

- Thanks to MP-iBGP announces, the BGP engine inside the PE calculates the next-hop (and internal label) towards every announced prefix
- VRFs belonging to different VPNs can notify a same private prefix since the addressing spaces can be overlapped.
- To differentiate overlapped prefixes (i.e. make them different to the BGP engine), ***a VRF is identified by an ID named Route Distinguisher (64 bit)***
- Usually, all the VRFs of the same VPN use the same Route Distinguisher, since the prefixes inside a VPN cannot overlap.
- In this way, the Route Distinguisher can be reused

Route Distinguisher

- The RD is placed before the net_id in the MP-iBGP entries
- The routes computed by BGP are inserted inside the enabled VRFs (see Route Target next…)

MP-iBGP announcements examples:

`100:5:192.168.1.0/24 next-hop 160.80.86.1 int label 56 RT 100:1`

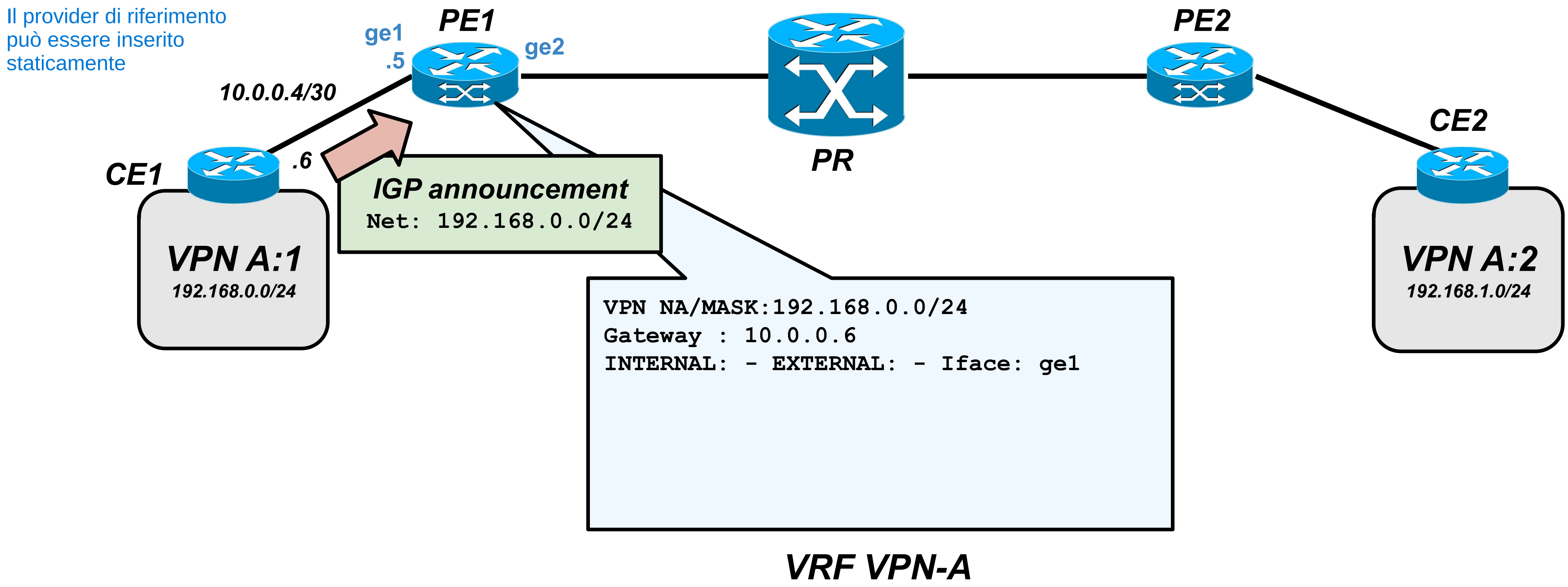
`100:9:192.168.1.0/24 next-hop 160.80.86.15 int label 32 RT 200:1`

To accept the MP-iBGP announcements:

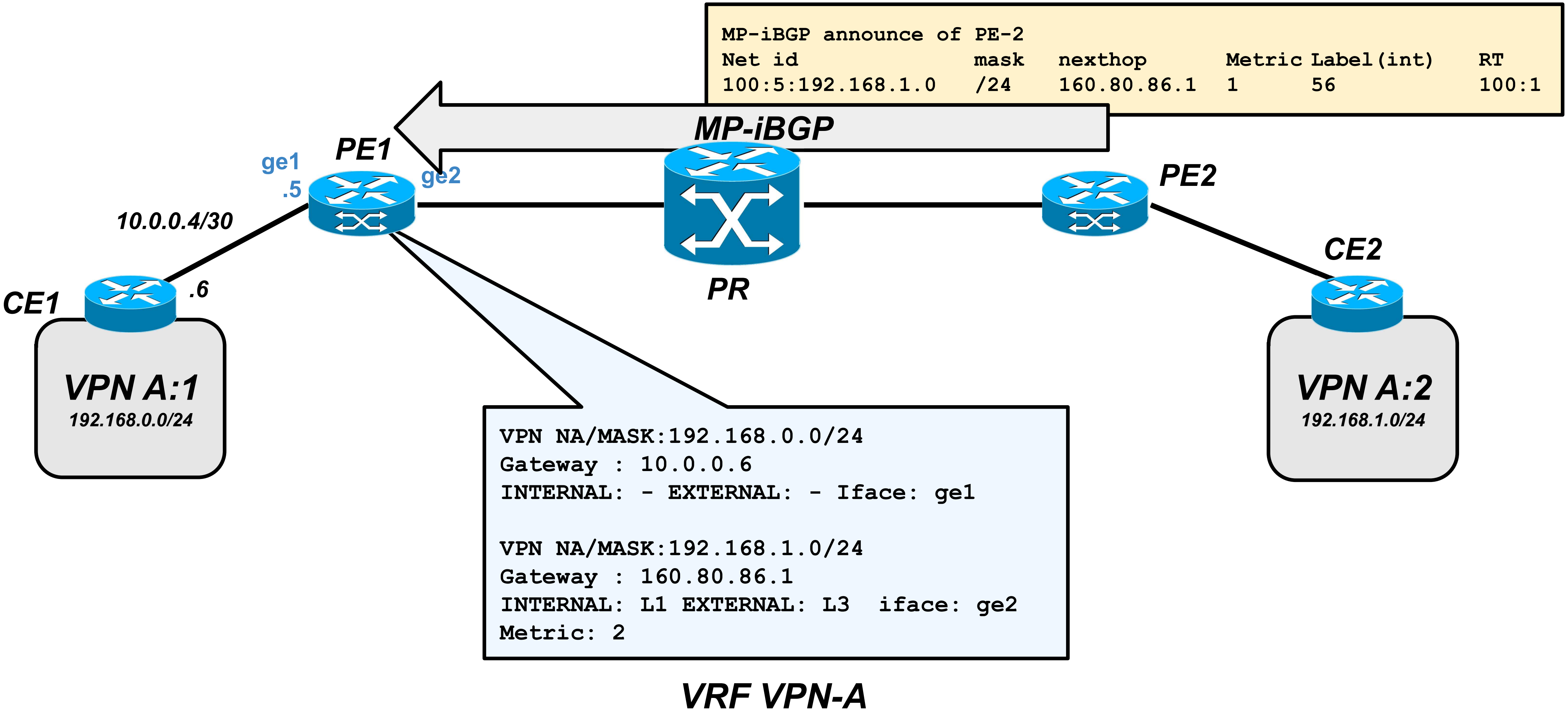
`VRF RT import 100:1`

`VRF RT import 200:1`

Populating VRFs: example



Populating VRFs: example



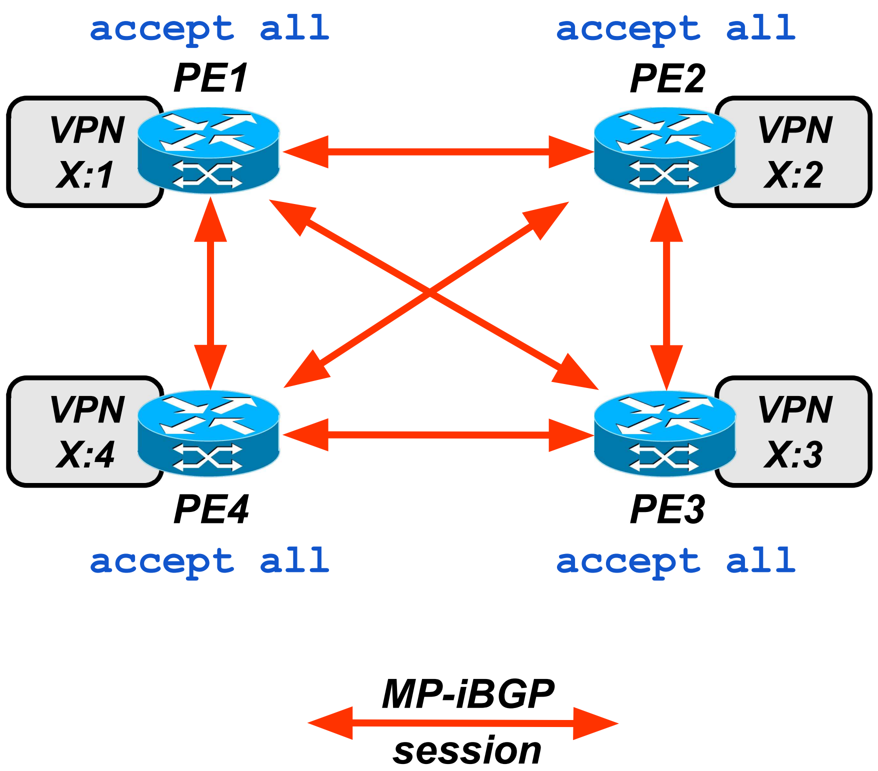
What about the VPN topology?

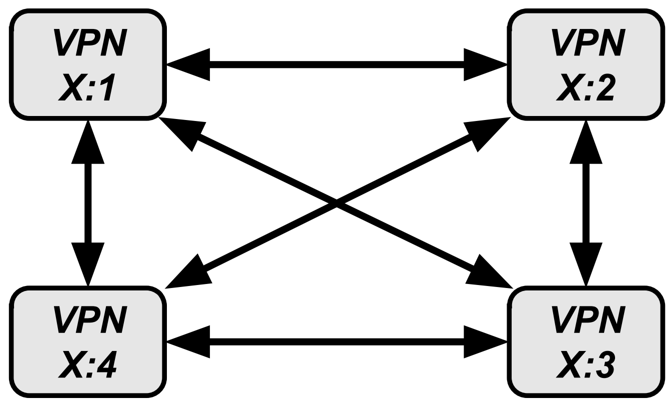
- If MP-iBGP messages are diffused among all PEs, all the VPNs have a full-mesh topology
- PROBLEM: what if I want different topologies for different VPNs?
- BGP principles say that if I have an overlay topology in which MP-iBGP messages are diffused, the (forwarding) topology of VPN-x is the set of the overlay shortest-paths between any couple of nodes
- Since direct connections between two PEs have metric 1, the VPN-x topology matches the overlay topology in which MP-iBGP messages are notified
- Therefore, if the overlay network in which MP-iBGP messages are forwarded is full-mesh, the VPN topology is full-mesh, too

What about the VPN topology?

- To change the logical topology of VPN-x it is necessary to change the MP-iBGP overlay network of VPN-x
- Solution 1: create a different MP-iBGP overlay forwarding topology for each VPN
  - High management effort, cannot aggregate inside the same MP-iBGP message the routing information relative to more VPNs, etc…
- ***Solution 2: keep the MP-iBGP full mesh and filter incoming announcements***
  - Having an overlay full-mesh for MP-iBGP common between PEs
  - Define the specific overlay needed for a given VPN
  - Flood MP-iBGP messages on the common MP-iBGP overlay
  - Receivers elaborate only announces coming from links of the specific overlay

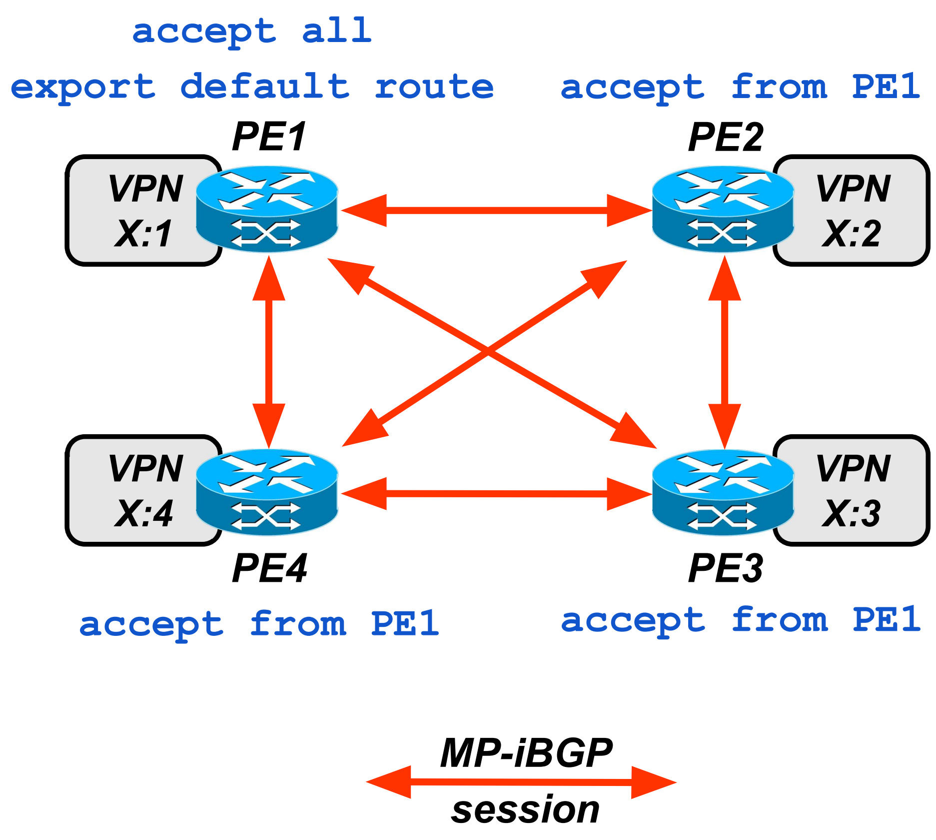
Populating VRFs - VPN Full Mesh

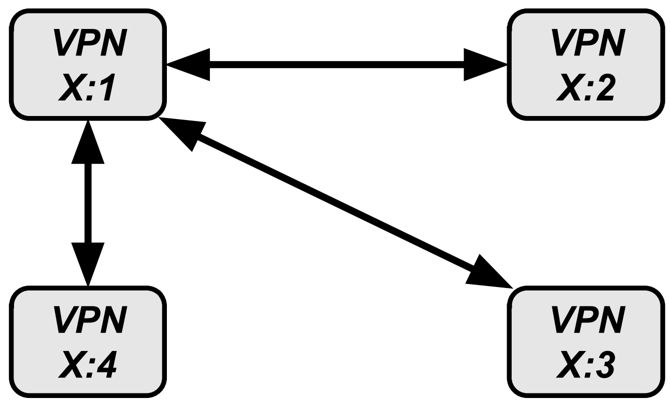




VPN Topology

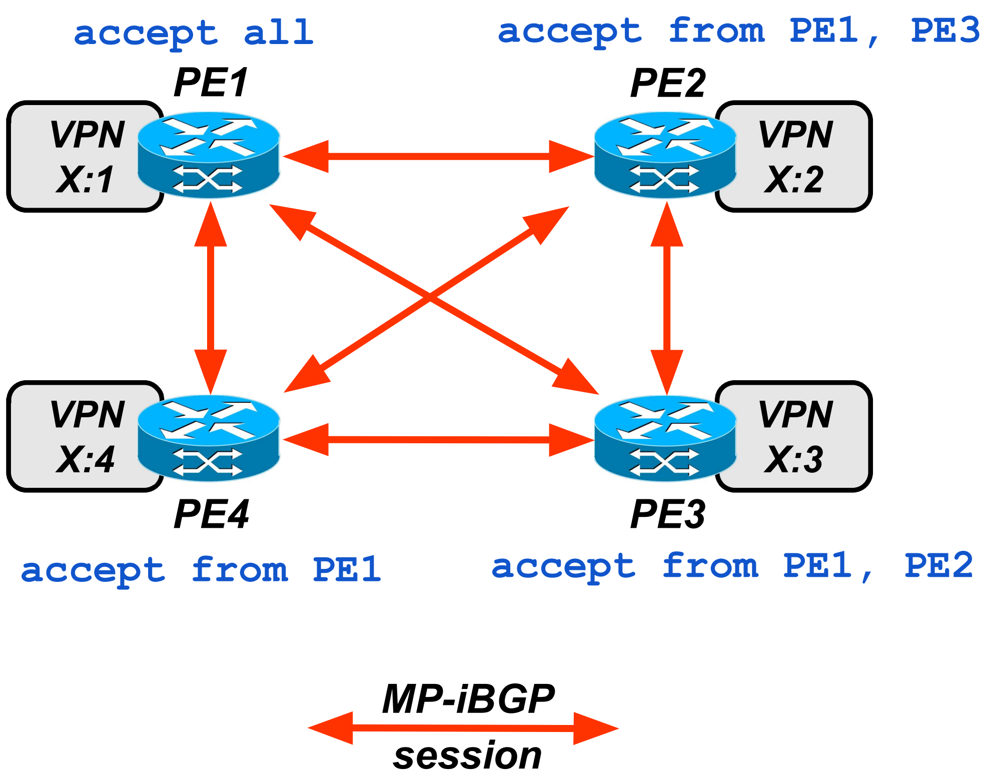
Populating VRFs - VPN Hub (X:1) and Spoke (X:2,3,4)

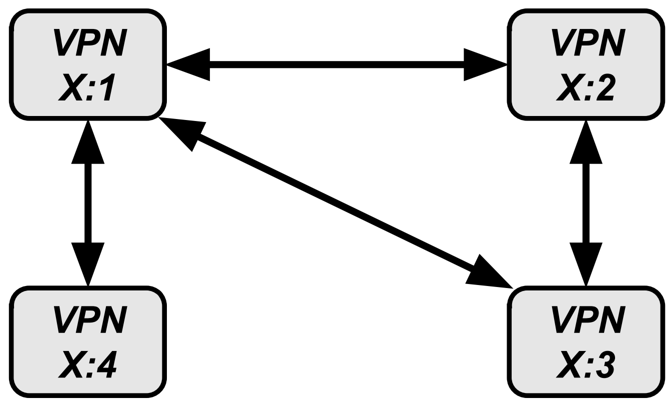




VPN Topology

Populating VRFs - VPN partial mesh



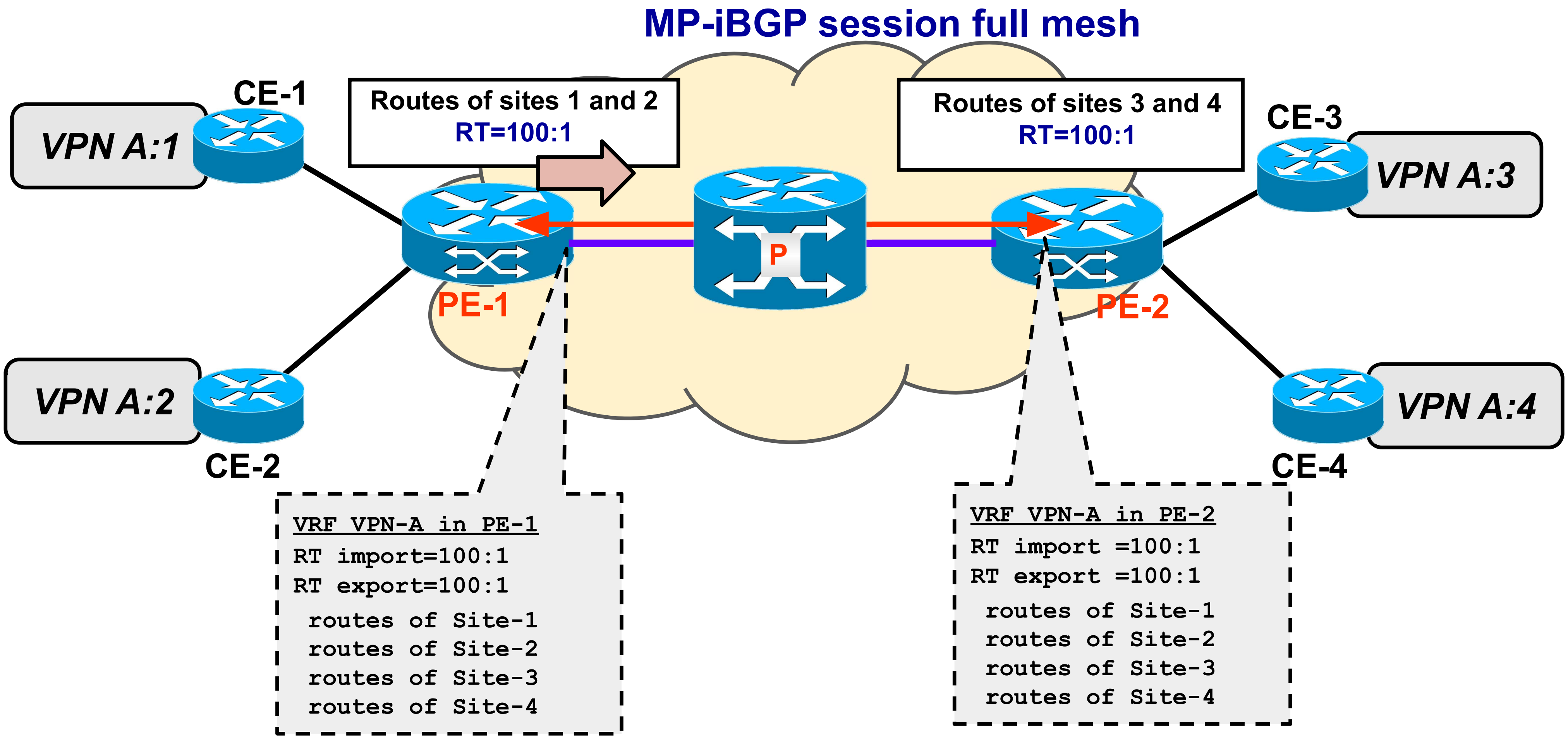


VPN Topology

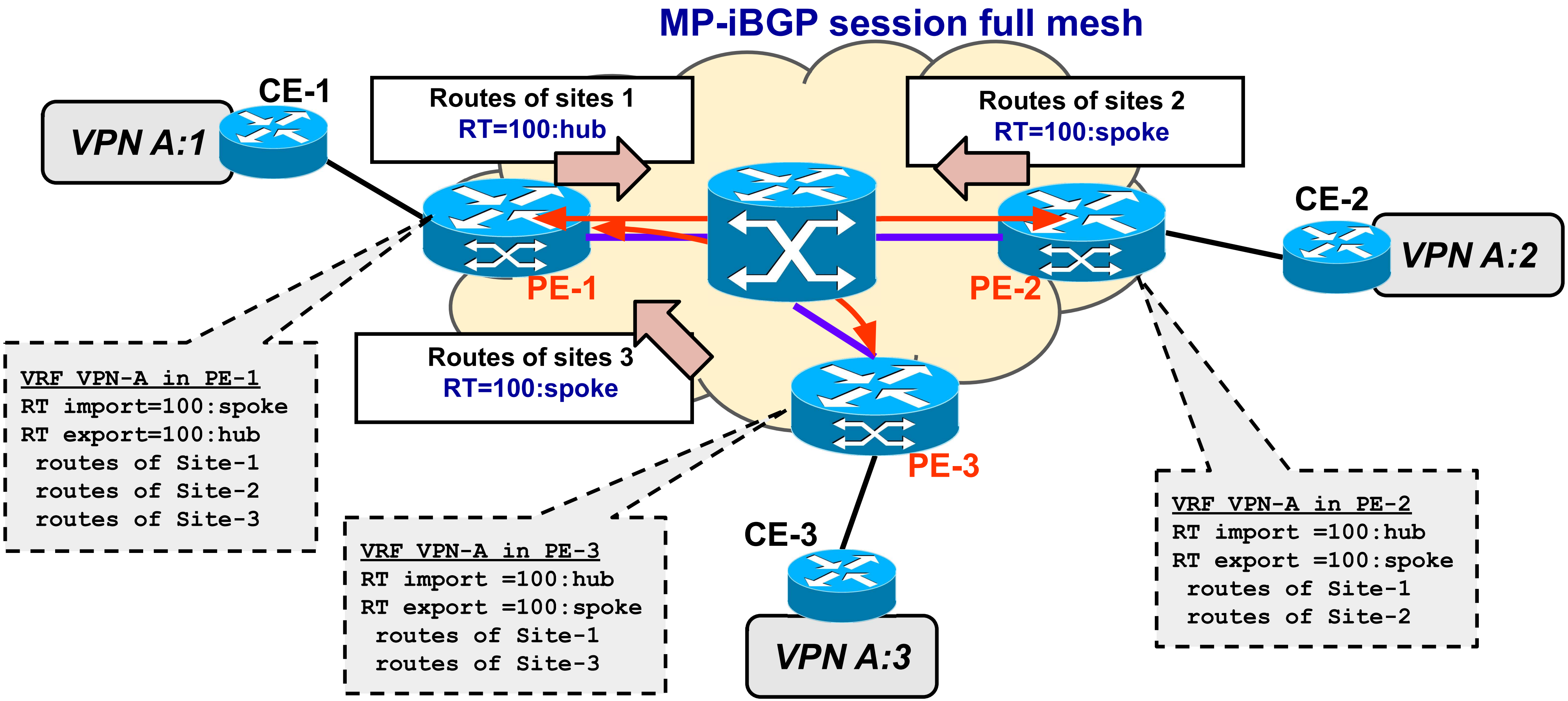
Route Target

- The Route Target concept permits to realize a specific overlay for the VPN-x discussed before. Therefore, permits to define VPN-x topology.
- It's the VPN/MPLS "way" to tell to a VRF-x to "accept only a subset of MP-iBGP announces"
- How:
  - Each VRF transmitting announces, labels (exports) these announces with a configurable ID (Route target) of 64 bit size
  - Each VRF can receive (import) only announces with a configurable subset of Route Targets

Using the "Route Target": Example 1



Using the "Route Target": Example 2

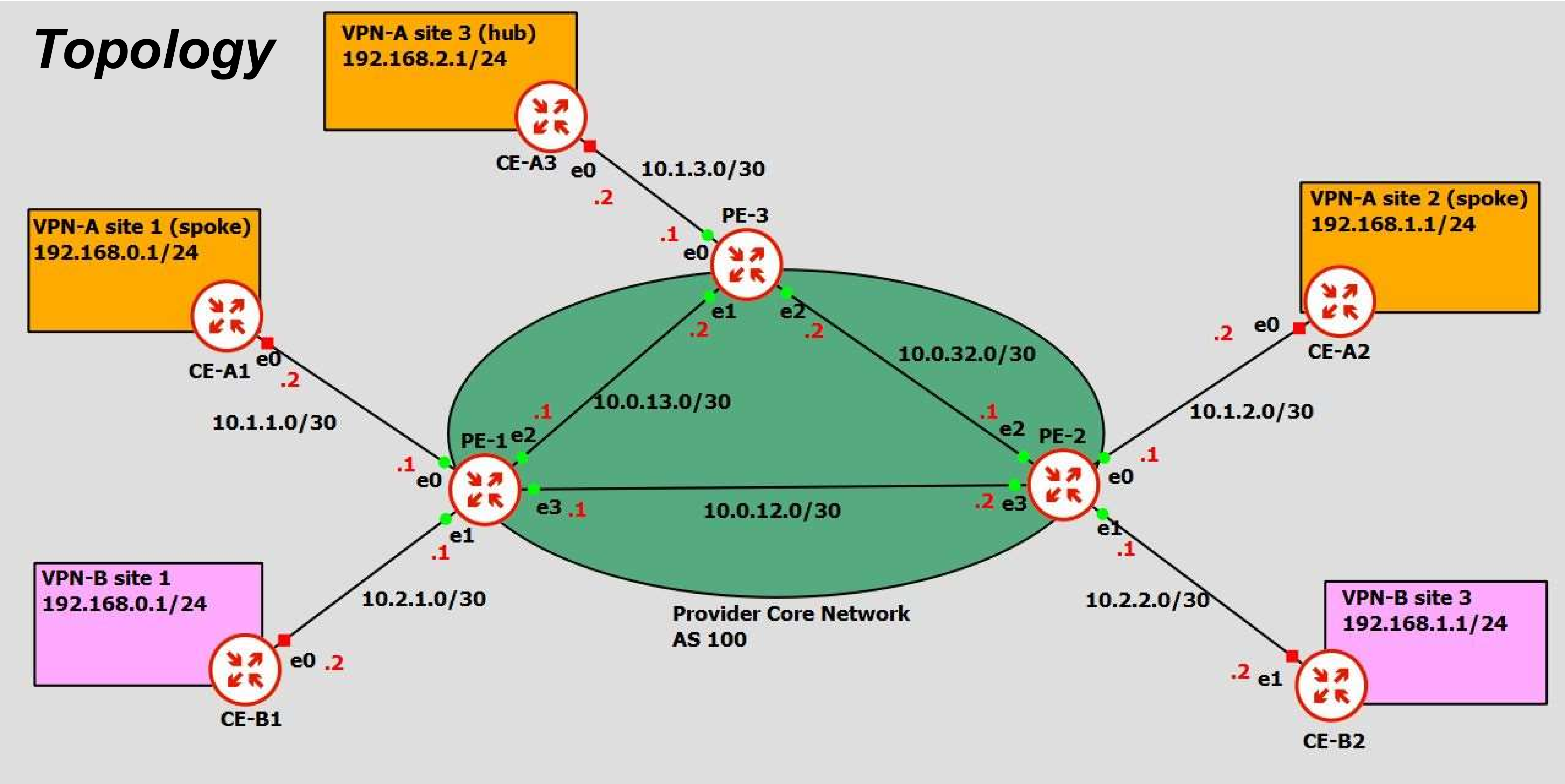


VPN/MPLS configuration

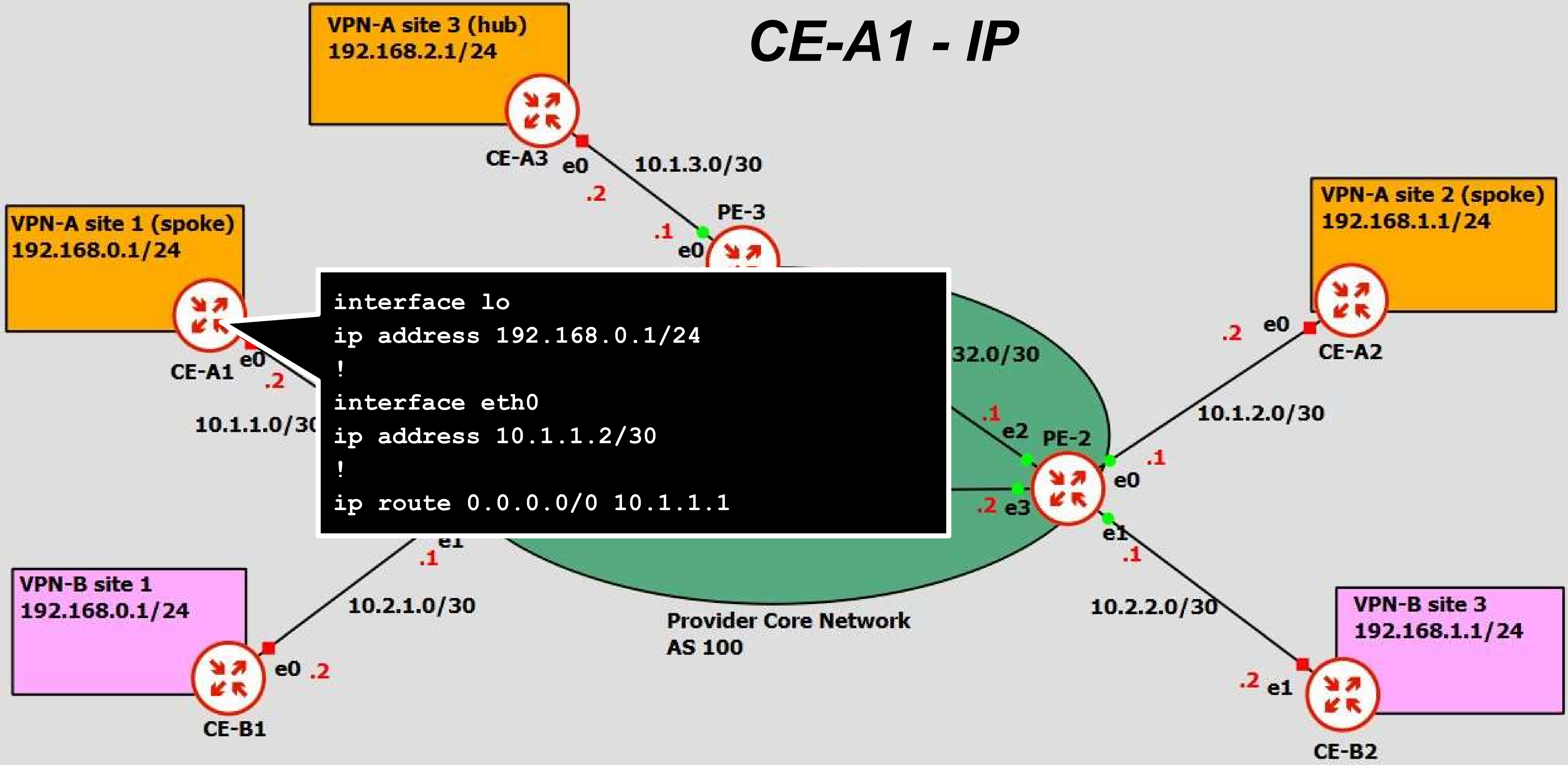
- Initialization
  - Configure LSP MPLS (e.g. with LDP) between all PEs
  - Enable BGP peering for prefixes of type VPNv4 (RD+net_id) between all PEs
- For each new VPN site
  - @ client
    - Notify to ISP the need of another VPN site and the relative topology
    - Install a CE as enterprise gateway
    - Configure the default gateway of the CE with the IP address of the access PE
    - Optional: enable on CE a routing protocol on the CE-PE path (e.g. OSPF)
  - @ provider
    - Initialize a new VRF on access PE
    - Define/Configure the Route Distinguisher
    - Define/Configure Route Import and Route Export and eventually update the import/export RTs on the other PEs, coherently with the requested topology
    - Associate the ingress PE interface with the VRF
    - Enable MP-iBGP on such VRF

Laboratory: BGP/MPLS VPN

Topology

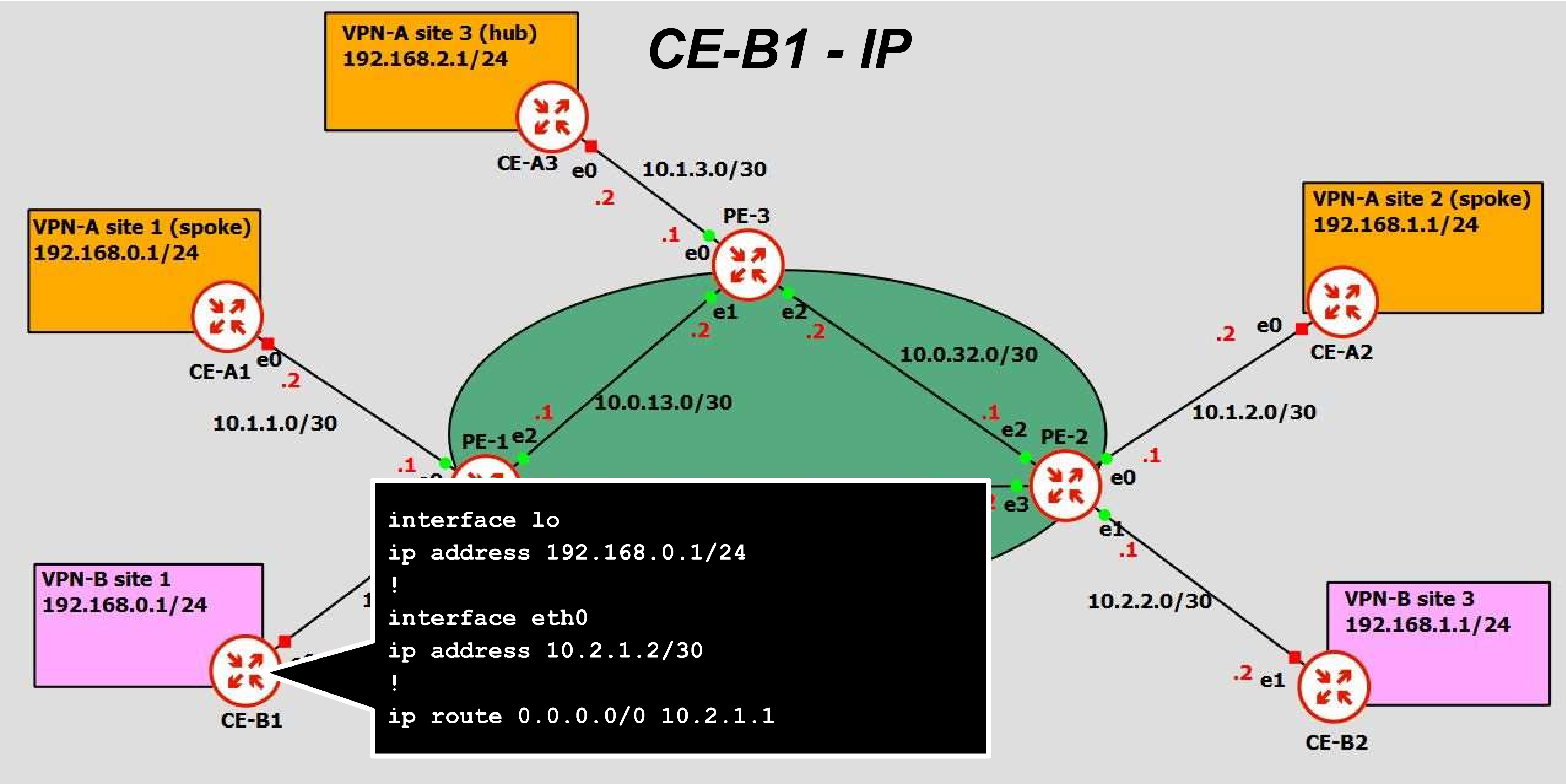

VPN-A site 3 (hub)
192.168.2.1/24
CE-A3
e0
.2
10.1.3.0/30
.1
e0
PE-3
e1
e2
.2
.2
10.0.32.0/30
VPN-A site 1 (spoke)
192.168.0.1/24
CE-A1
e0
.2
10.1.1.0/30
.1
e0
PE-1
e2
.1
10.0.13.0/30
e3
.1
e1
.1
10.0.12.0/30
VPN-A site 2 (spoke)
192.168.1.1/24
CE-A2
e0
.2
10.1.2.0/30
.1
e0
PE-2
e2
.1
.2
e3
e1
.1
VPN-B site 1
192.168.0.1/24
CE-B1
e0
.2
10.2.1.0/30
Provider Core Network
AS 100
10.2.2.0/30
VPN-B site 3
192.168.1.1/24
.2
e1
CE-B2

CE-A1 - IP



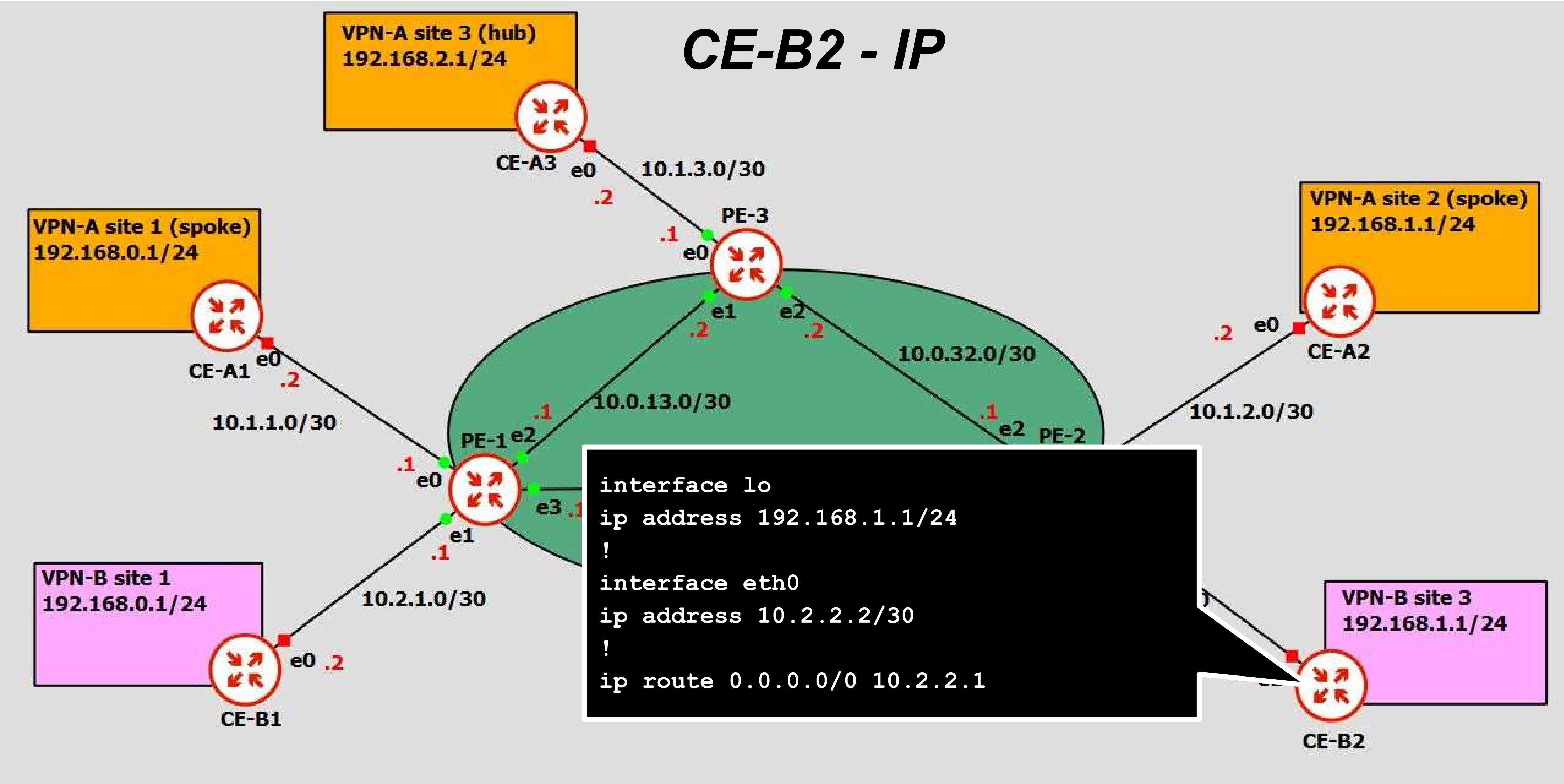

```
interface lo
ip address 192.168.0.1/24
!
interface eth0
ip address 10.1.1.2/30
!
ip route 0.0.0.0/0 10.1.1.1
```

CE-B1 - IP



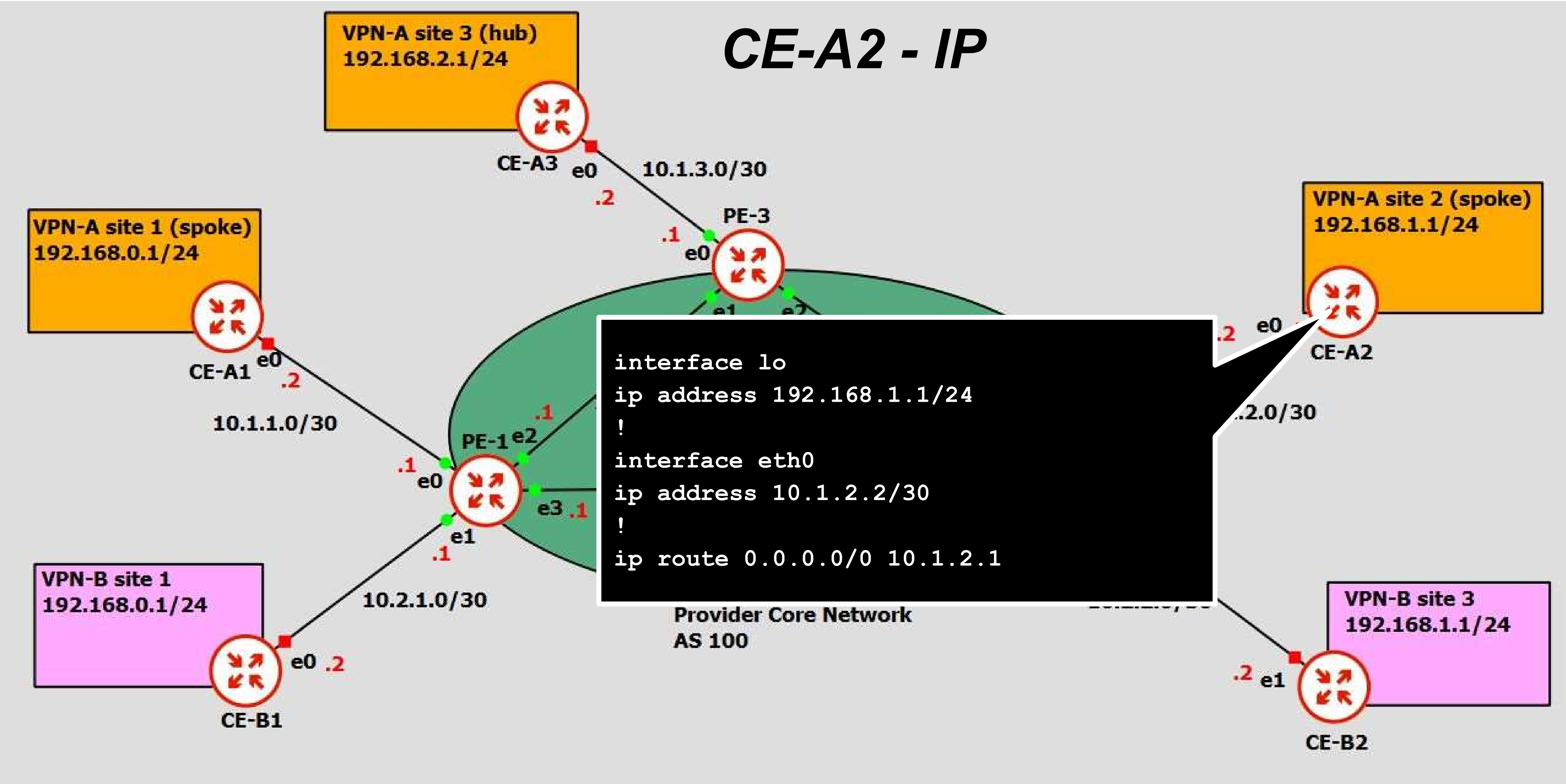

```
interface lo
ip address 192.168.0.1/24
!
interface eth0
ip address 10.2.1.2/30
!
ip route 0.0.0.0/0 10.2.1.1
```

CE-B2 - IP



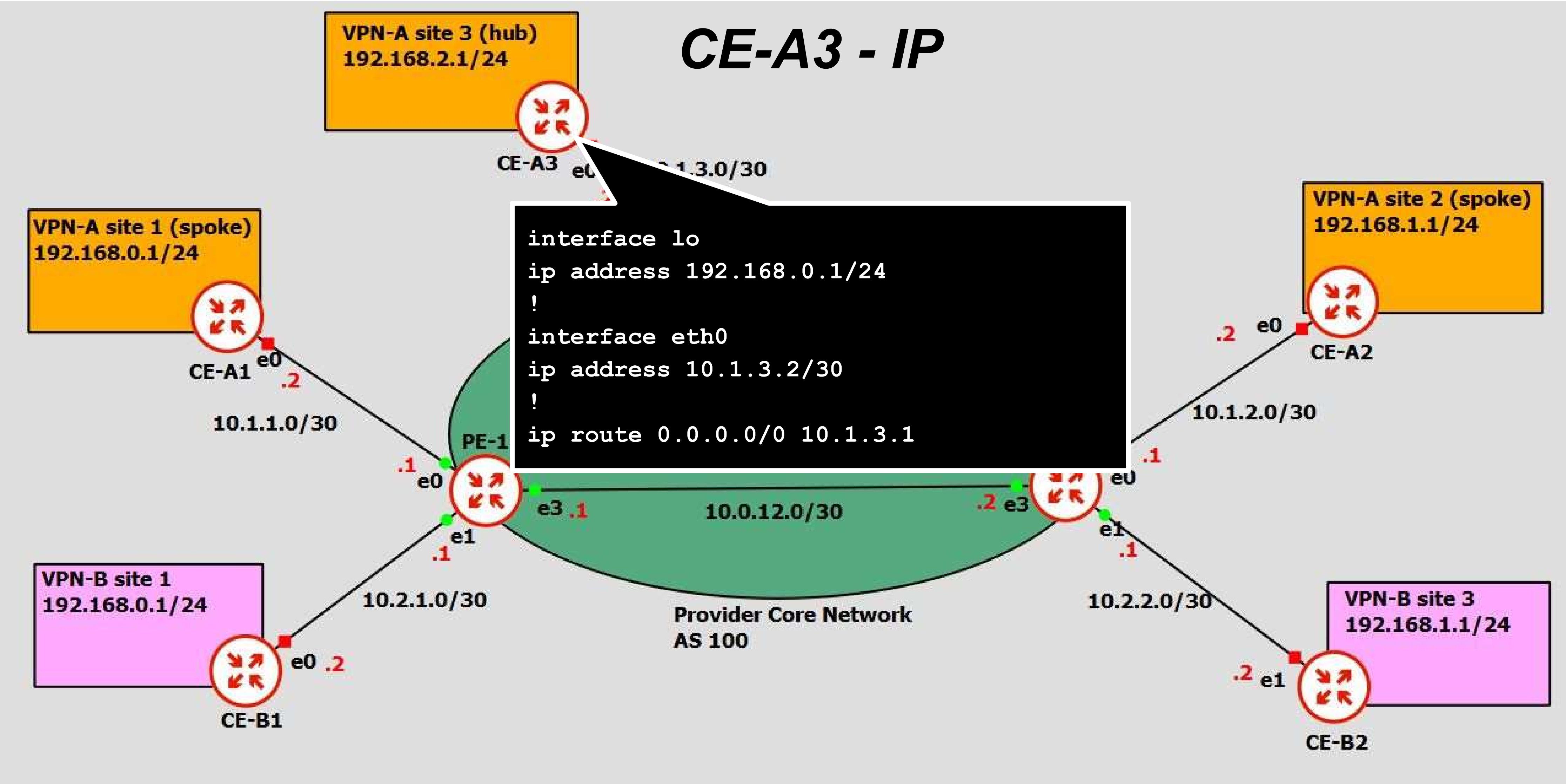

```
interface lo
ip address 192.168.1.1/24
!
interface eth0
ip address 10.2.2.2/30
!
ip route 0.0.0.0/0 10.2.2.1
```

CE-A2 - IP



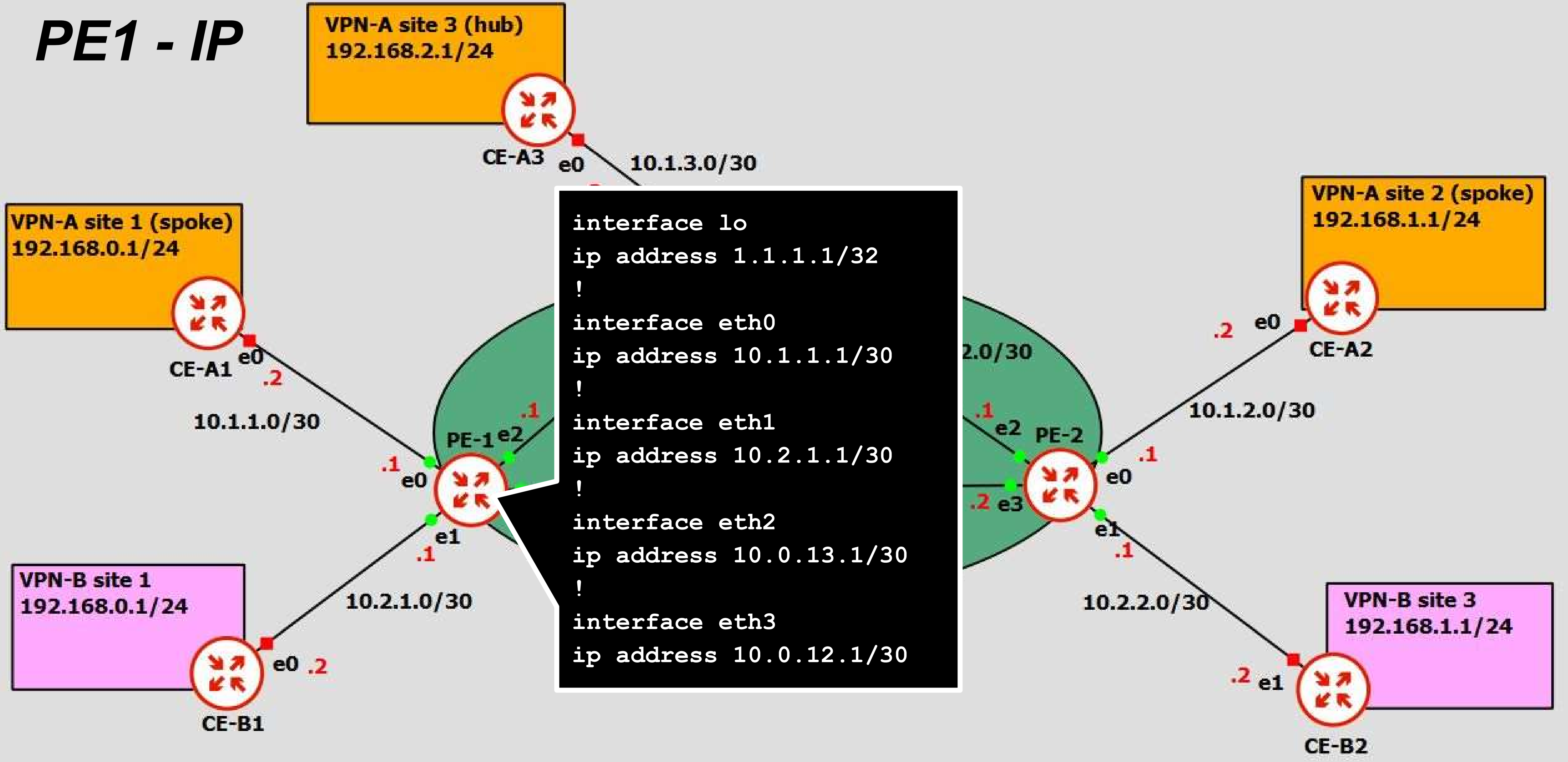

```
interface lo
ip address 192.168.1.1/24
!
interface eth0
ip address 10.1.2.2/30
!
ip route 0.0.0.0/0 10.1.2.1
```

CE-A3 - IP



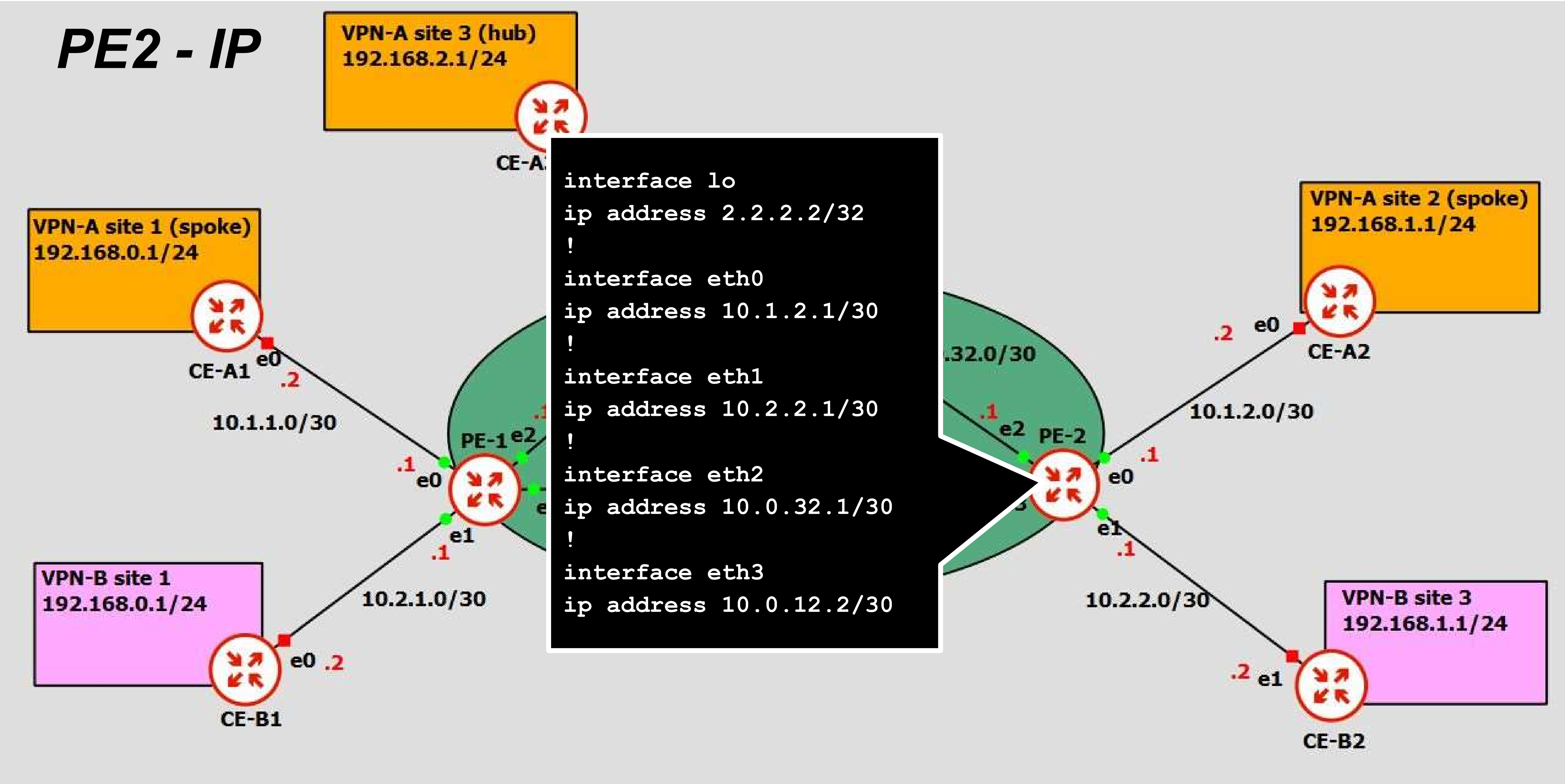

```
interface lo
ip address 192.168.0.1/24
!
interface eth0
ip address 10.1.3.2/30
!
ip route 0.0.0.0/0 10.1.3.1
```

PE1 - IP



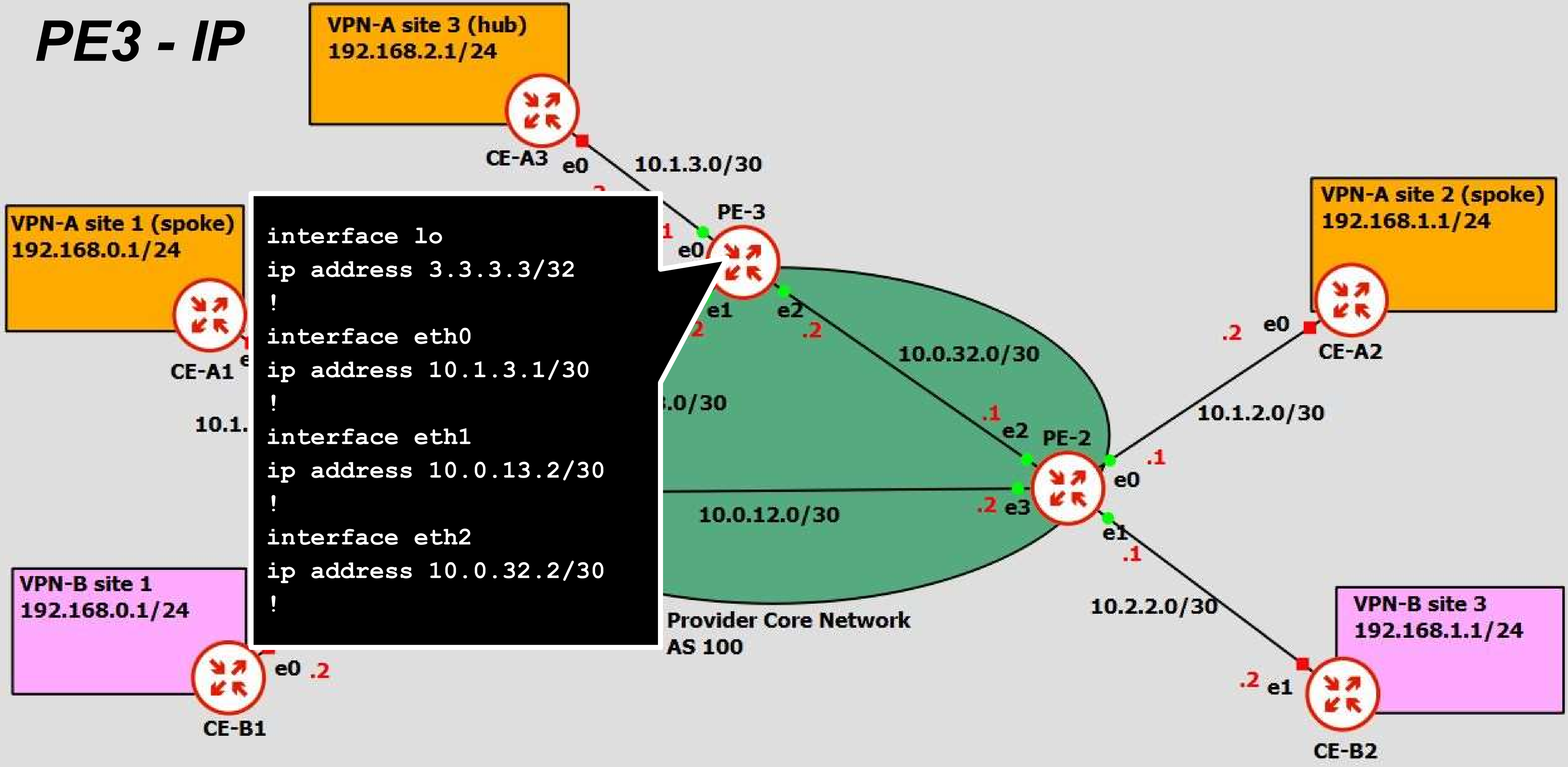

```
interface lo
ip address 1.1.1.1/32
!
interface eth0
ip address 10.1.1.1/30
!
interface eth1
ip address 10.2.1.1/30
!
interface eth2
ip address 10.0.13.1/30
!
interface eth3
ip address 10.0.12.1/30
```

PE2 - IP



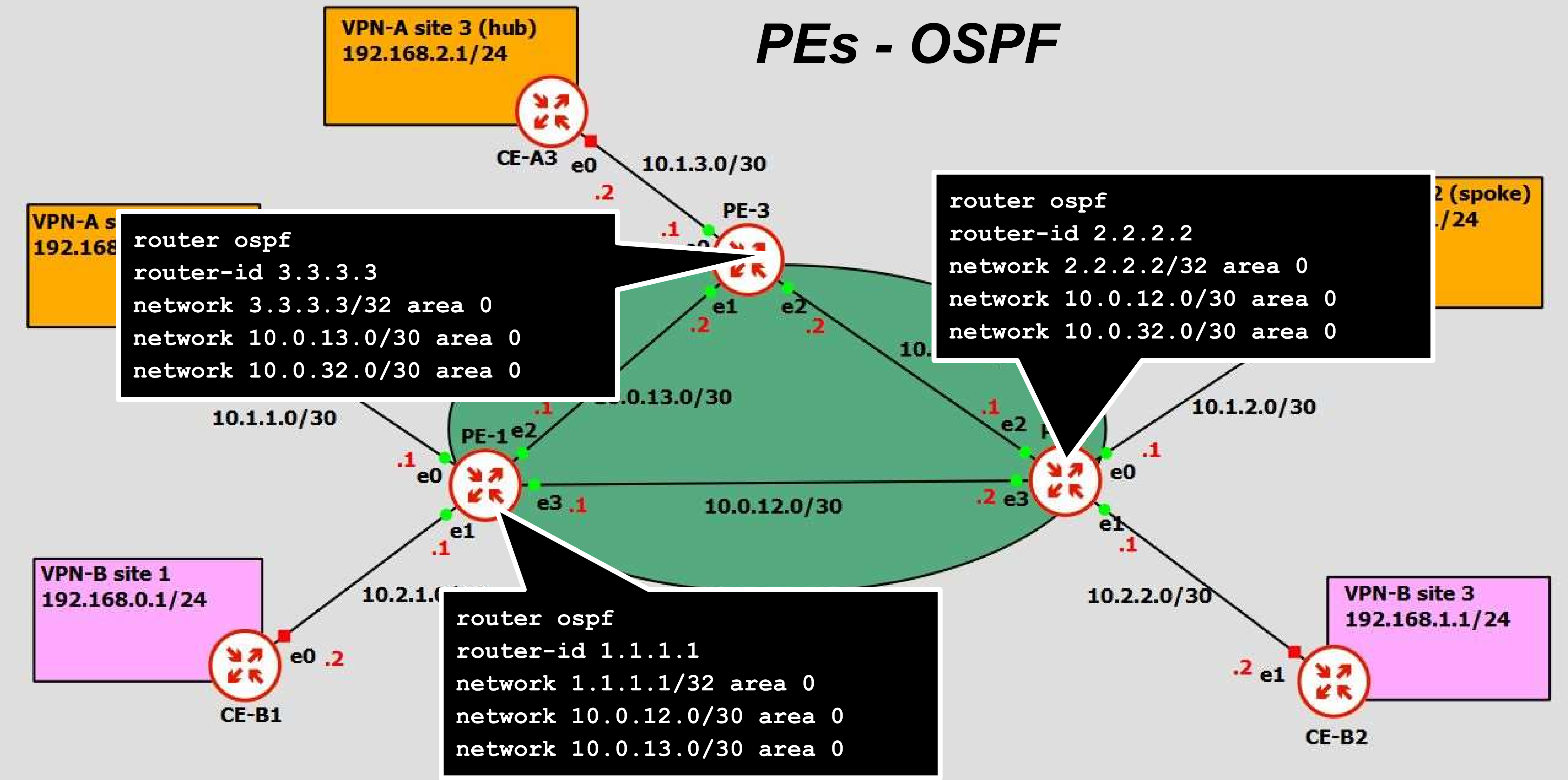

```
interface lo
ip address 2.2.2.2/32
!
interface eth0
ip address 10.1.2.1/30
!
interface eth1
ip address 10.2.2.1/30
!
interface eth2
ip address 10.0.32.1/30
!
interface eth3
ip address 10.0.12.2/30
```

PE3 - IP



VPN-A site 3 (hub)
192.168.2.1/24
CE-A3
e0
10.1.3.0/30
PE-3
e0
e1
e2
.2
VPN-A site 1 (spoke)
192.168.0.1/24
CE-A1
10.1.
interface lo
ip address 3.3.3.3/32
!
interface eth0
ip address 10.1.3.1/30
!
interface eth1
ip address 10.0.13.2/30
!
interface eth2
ip address 10.0.32.2/30
!
10.0.32.0/30
.0/30
10.0.12.0/30
.1
e2
PE-2
e0
.1
.2
e3
e1
.1
VPN-A site 2 (spoke)
192.168.1.1/24
.2
e0
CE-A2
10.1.2.0/30
10.2.2.0/30
Provider Core Network
AS 100
VPN-B site 1
192.168.0.1/24
e0
.2
CE-B1
VPN-B site 3
192.168.1.1/24
.2
e1
CE-B2

PEs - OSPF


VPN-A site 3 (hub)
192.168.2.1/24
CE-A3
e0
10.1.3.0/30
.2
.1
PE-3
e1
e2
.2
.2
router ospf
router-id 3.3.3.3
network 3.3.3.3/32 area 0
network 10.0.13.0/30 area 0
network 10.0.32.0/30 area 0
router ospf
router-id 2.2.2.2
network 2.2.2.2/32 area 0
network 10.0.12.0/30 area 0
network 10.0.32.0/30 area 0
10.1.1.0/30
.1
e0
PE-1
e2
e3
.1
e1
.1
10.0.12.0/30
.2
e3
e2
.1
e0
.1
e1
.1
10.1.2.0/30
10.2.2.0/30
VPN-B site 1
192.168.0.1/24
CE-B1
e0
.2
VPN-B site 3
192.168.1.1/24
.2
e1
CE-B2
router ospf
router-id 1.1.1.1
network 1.1.1.1/32 area 0
network 10.0.12.0/30 area 0
network 10.0.13.0/30 area 0