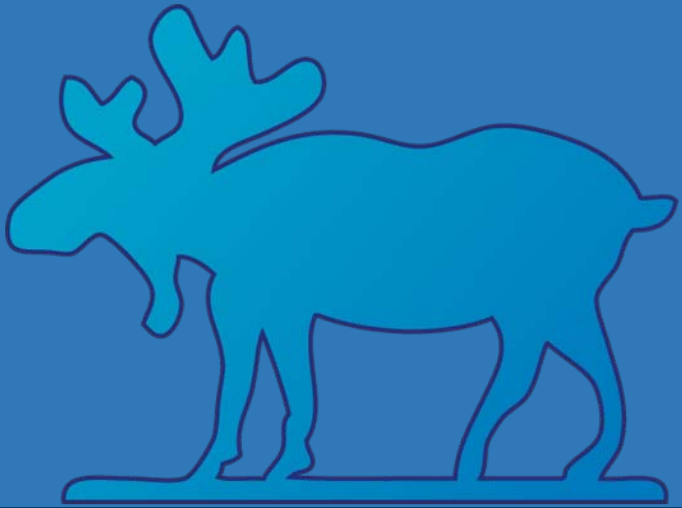
Addressing the Scalability of Ethernet with MOOSE



Malcolm Scott, Andrew Moore and Jon Crowcroft
University of Cambridge Computer Laboratory

Ethernet in the data centre

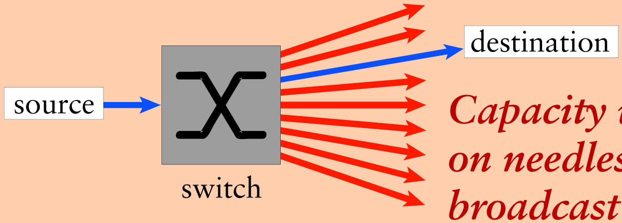
- **1970s protocol; still ubiquitous**
  - Usually used with IP, but not always (ATA-over-Ethernet)

- **Density of Ethernet addresses is increasing**
  - Larger data centres, more devices, more NICs
  - Virtualisation: each VM has a unique Ethernet address
    - (or more than one!)

Why not Ethernet?

Heavy use of broadcast

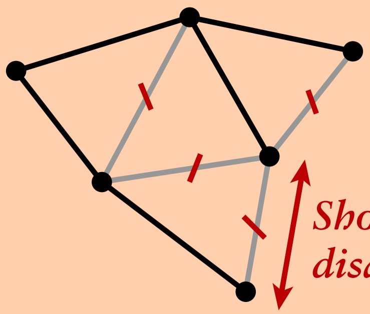
Broadcast ARP required for interaction with IP



Capacity wasted on needlessly broadcast frames!

On large networks, broadcast can overwhelm slower links e.g. wireless

Inefficient routing: Spanning Tree



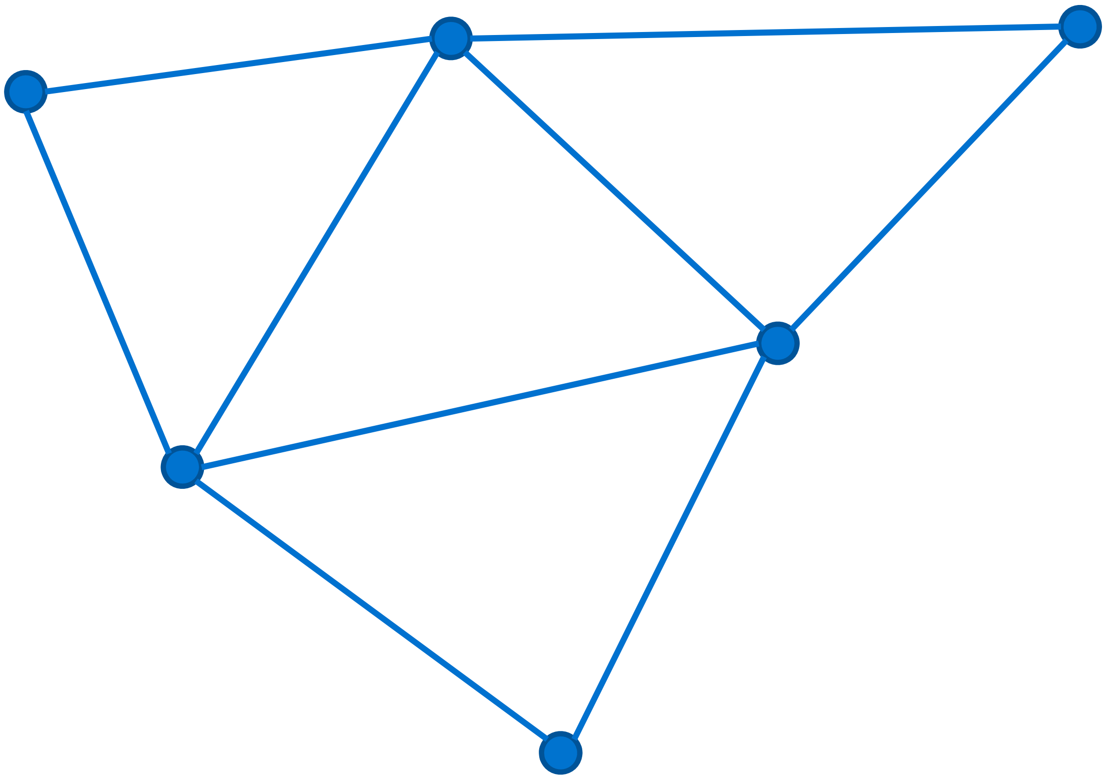
Shortest path disabled!

Switches' address tables

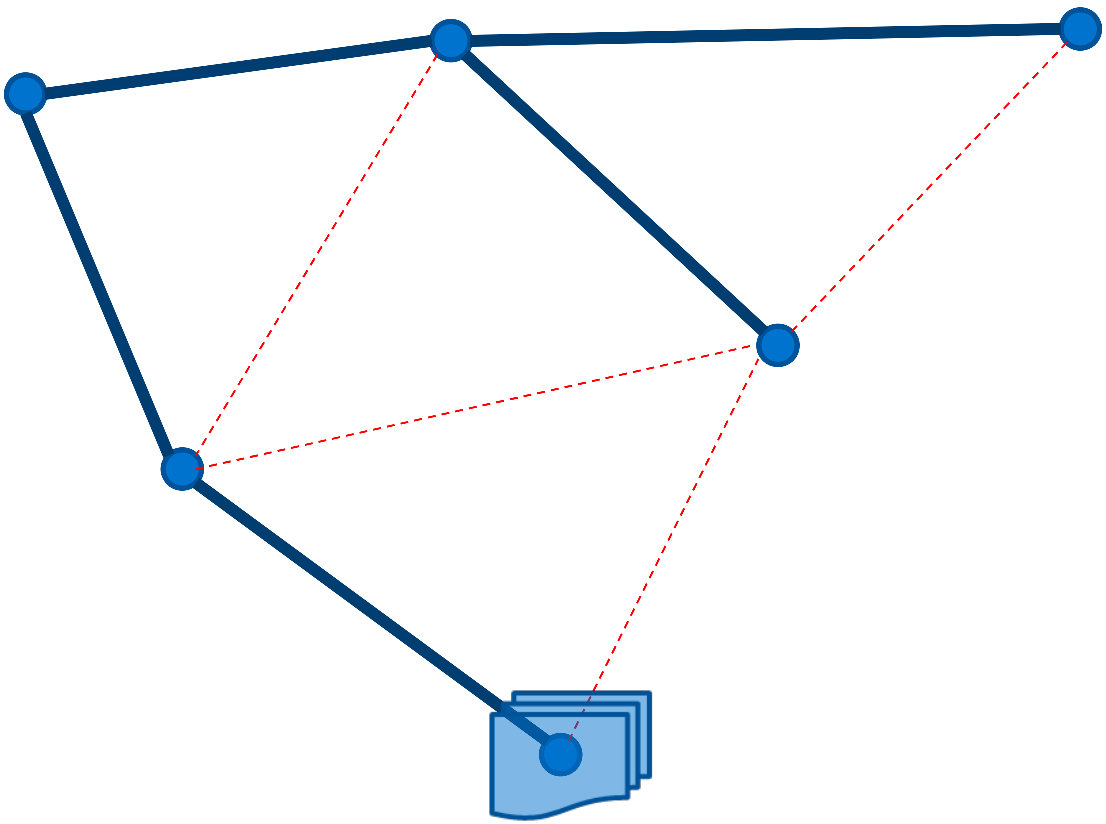
MAC address	Port
`01:23:45:67:89:ab`	12
`00:a1:b2:c3:d4:e5`	16
…	…

- Maintained by every switch
- Automatically learned
- Table capacity: ~16000 addresses
- *Full table results in unreliability, or at best heavy flooding*

Spanning tree switching illustrated

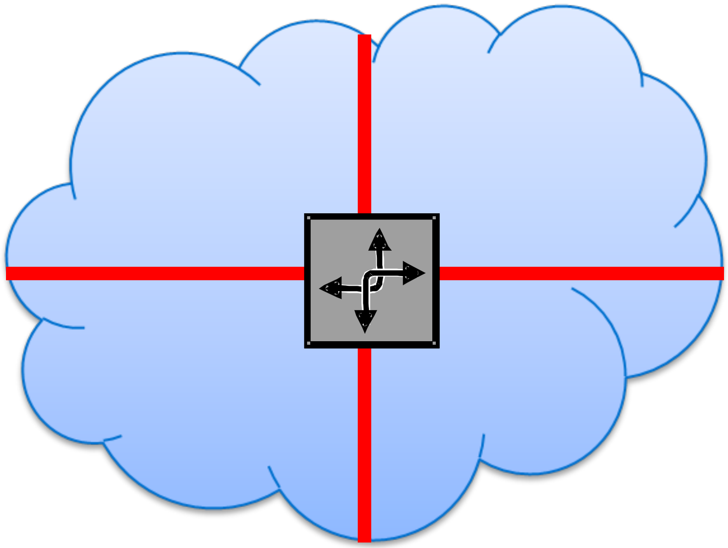


Spanning tree switching illustrated

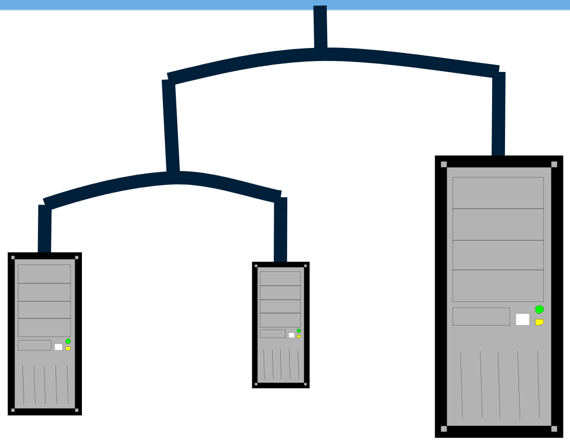


Ethernet in the data centre: divide and conquer?

- **Traditional solution: artificially subdivide network** at the IP layer: subnetting and routing
  - Administrative burden
  - More expensive equipment
  - Hampers mobility
    - IP Mobility has not (yet) taken off
  - Scalability problems remain within each subnet



Ethernet in the data centre: ...mobility?



- **Mobility *is* relevant in the data centre**
  - Seamless virtual machine migration
  - Easy deployment:
    no location-dependent configuration
- **...and between data centres**
  - Large multi-data-centre WANs are becoming common
- **Ethernet is pretty good at mobility**

Large networks

- **Converged airport network**
  - Must support diverse commodity equipment
  - Roaming required throughout entire airport complex
  - Ideally, would use one large Ethernet-like network

- This work funded by “The INtelligent Airport” UK EPSRC project

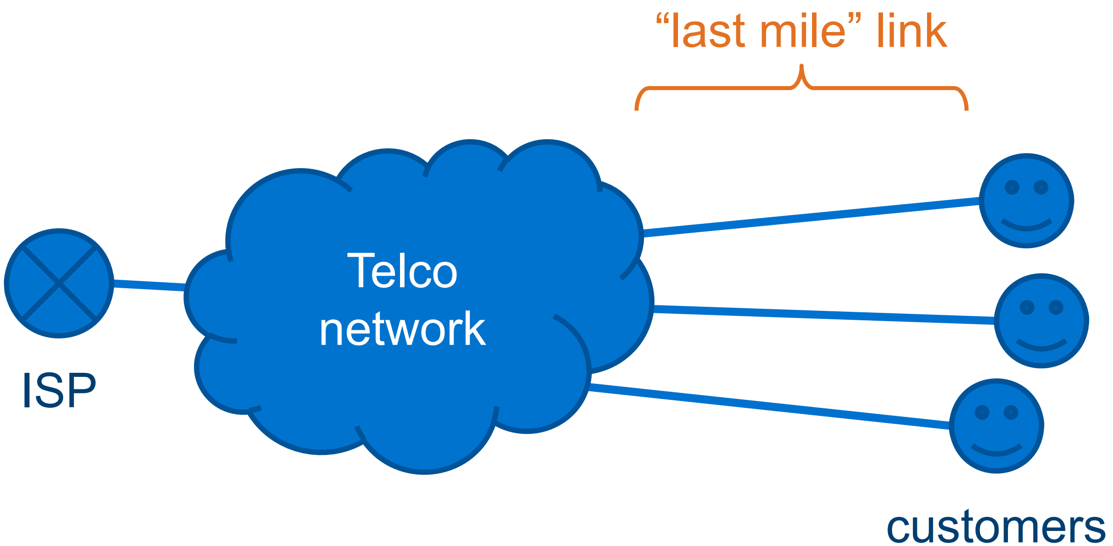
Large networks

- **Airports have surpassed the capabilities of Ethernet**
  - London Heathrow Airport: Terminal 5 alone is too big
  - MPLS-VPLS: similar problems to IP subnetting
    - VPLS adds more complexity:
      - LERs map every destination MAC address to a LSP: up to O(hosts)
      - LSRs map every LSP to a next hop: could be $O(\text{hosts}^2)$ in core!
    - Encapsulation does not help

Geographically-diverse networks

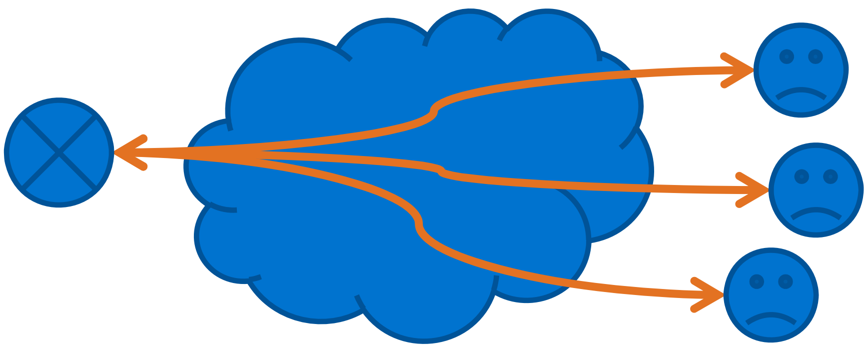
Fibre-to-the-Premises

- Currently, Ethernet is only used for small deployments



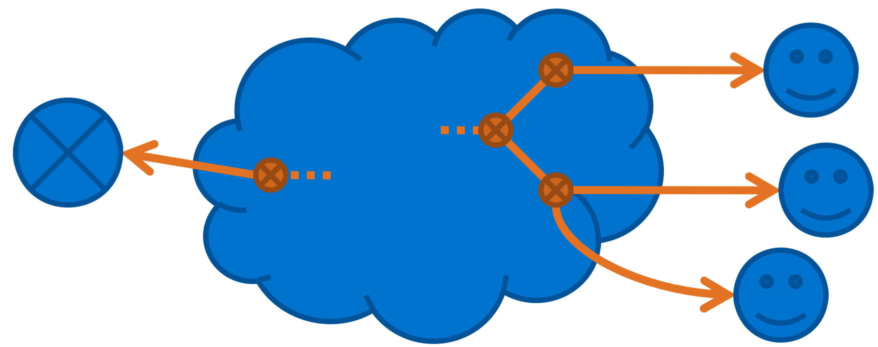
Geographically-diverse networks

Now:



- Everything goes via circuit to ISP
- Legacy reasons (dial-up, ATM)
- Nonsensical for peer-to-peer use
- Bottleneck becoming significant as number of customers and capacity of links increase

Future:



- In the UK: BT 21CN
- Take advantage of fully-switched infrastructure
- Peer-to-peer traffic travels directly between customers
- Data link layer protocol is crucial

The underlying problem with Ethernet

MAC addresses provide
no location information

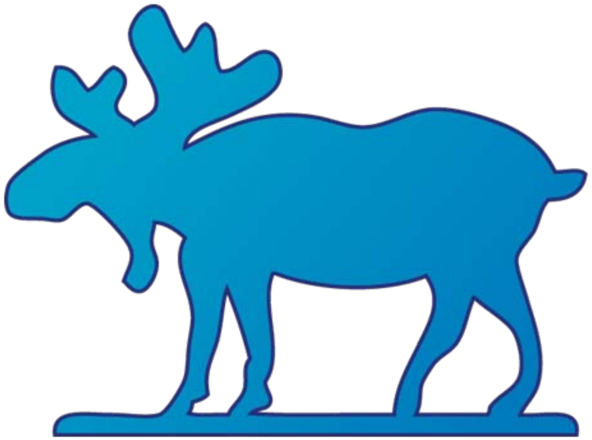
Flat vs. Hierarchical address spaces

- **Flat-addressed Ethernet:** manufacturer-assigned MAC address valid anywhere on any network
  - But every switch must discover and store the location of every host
- **Hierarchical addresses:** address depends on location
  - Route frames according to successive stages of hierarchy
  - No large forwarding databases needed
- **LAAs?** High administrative overhead if done manually

MOOSE: *Multi-level Origin-Organised Scalable Ethernet*

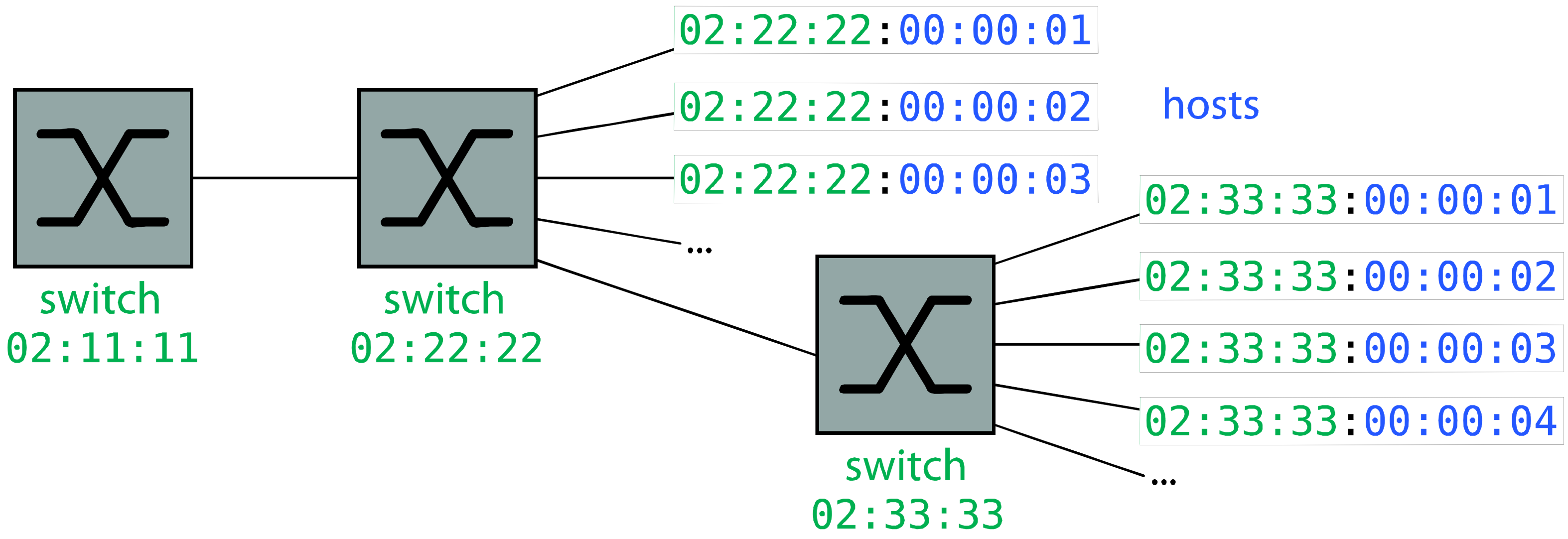
A new way to switch Ethernet

- Perform MAC address rewriting on ingress
- Enforce dynamic hierarchical addressing
- No host configuration required



- *Good platform for shortest-path routing*
- ***Appears to connected equipment as standard Ethernet***

MOOSE: *Multi-level Origin-Organised Scalable Ethernet*

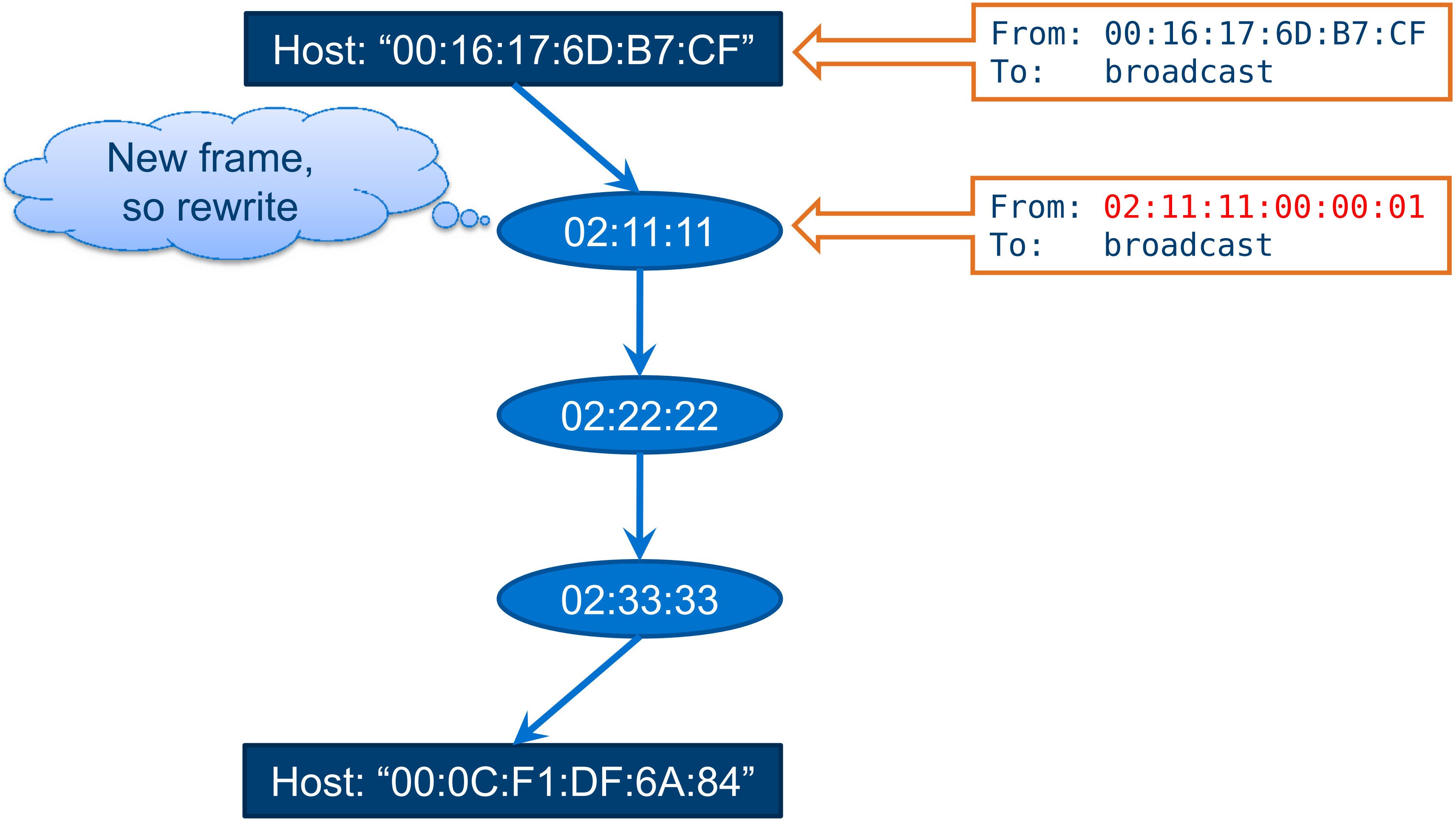


- **Switches assign each host a MOOSE address = switch ID . host ID**
  (MOOSE address must form a valid unicast LAA: two bits in switch ID fixed)
- Placed in source field in Ethernet header as each frame enters the network
  (no encapsulation, therefore no costly rewriting of destination address!)

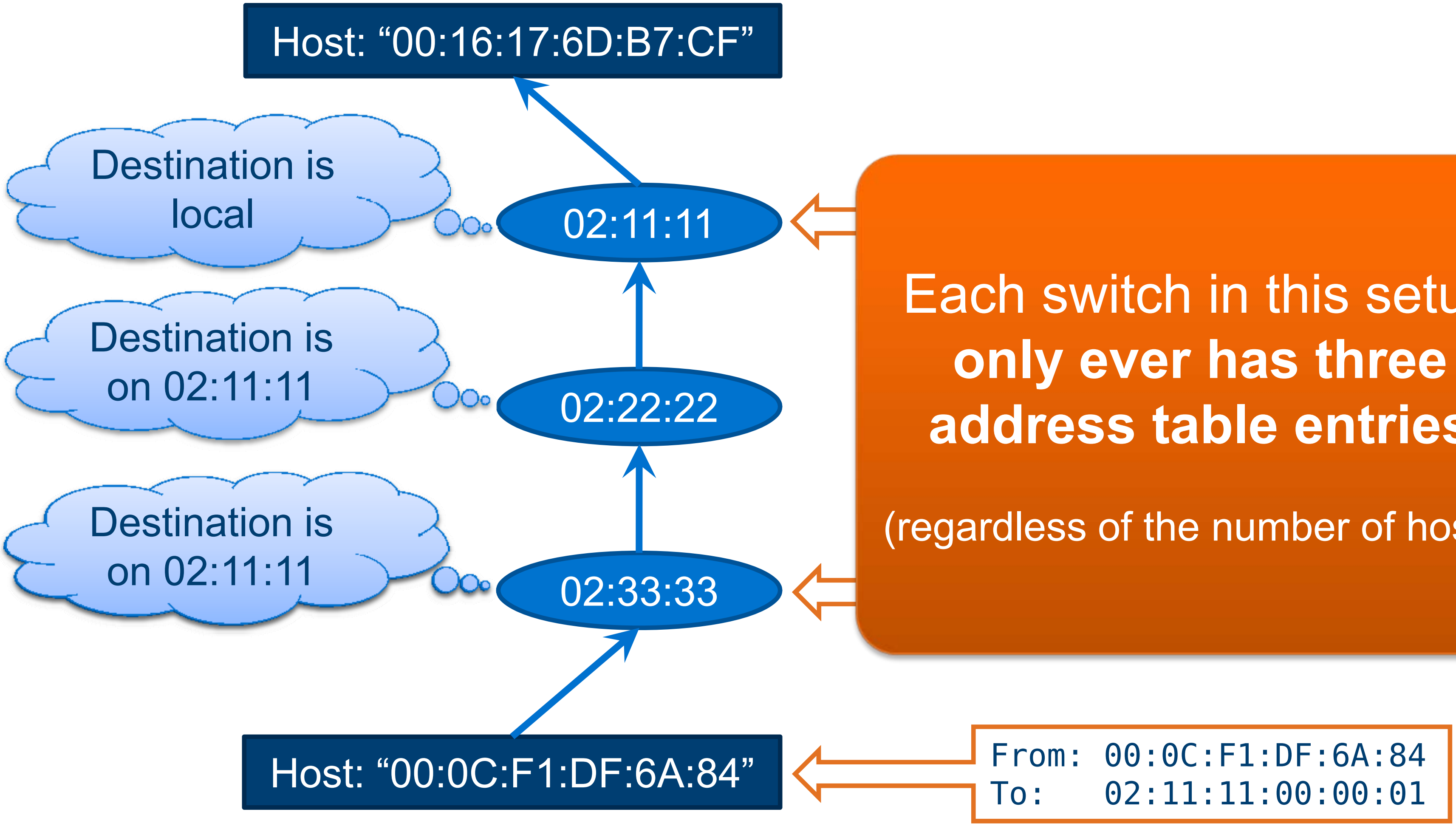
Allocation of host identifiers

- **Only the switch which allocates a host ID ever uses it for switching** (more distant switches just use the switch ID)
- Therefore the detail of how host IDs are allocated can vary between switches
  - Sequential assignment
  - Port number and sequential portion
    (isolates address exhaustion attacks)
  - Hash of manufacturer-assigned MAC address
    (deterministic: recoverable after crash)

The journey of a frame



The return journey of a frame

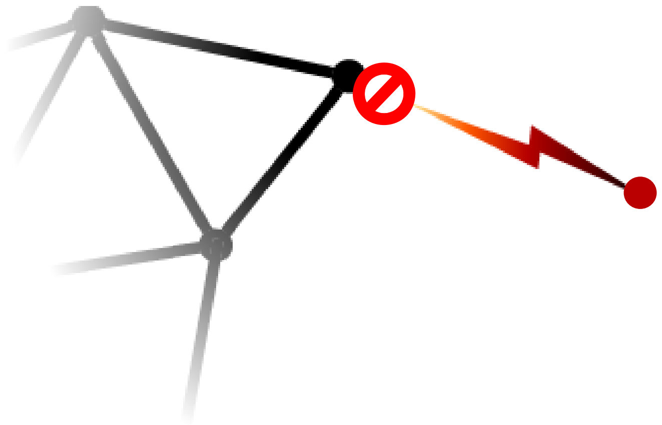


Each switch in this setup **only ever has three address table entries**

(regardless of the number of hosts)

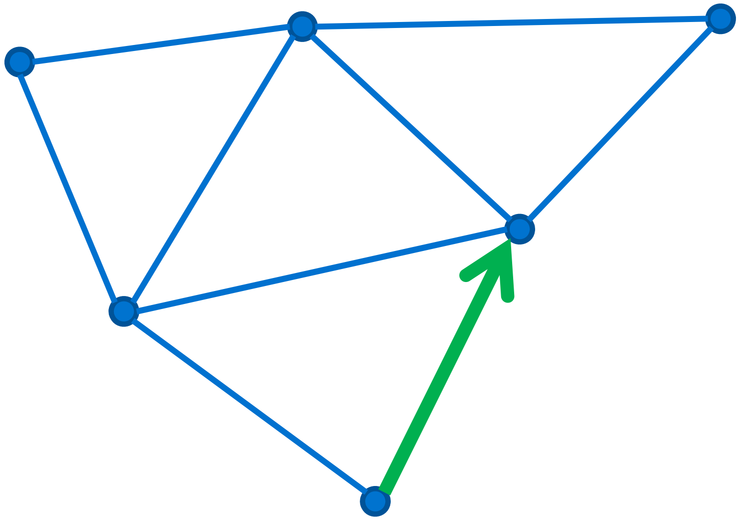
Security and isolation benefits

- **The number of switch IDs is predictable, unlike the number of MAC addresses**
  - Address flooding attacks are ineffective
  - Resilience of dynamic networks (e.g. wireless) is increased
- **Host-specified MAC address is not used for switching**
  - Spoofing is ineffective



Shortest path routing

- **MOOSE switch ≈ layer 3 router**
  - One “subnet” per switch
    - `02:11:11:00:00:00/24`
    - Don’t advertise individual MAC addresses!
  - Run a routing protocol between switches, e.g. OSPF variant
    - OSPF-OMP may be particularly desirable: optimised multipath routing for increased performance



Beyond unicast

- **Broadcast: unfortunate legacy**
  - DHCP, ARP, NBNS, NTP, plethora of discovery protocols...
  - Deduce spanning tree using reverse path forwarding (PIM): no explicit spanning tree protocol
  - Can optimise away most common sources, however
- **Multicast and anycast for free**
  - SEATTLE suggested generalised VLANs (“groups”) to emulate multicast
  - Multicast-aware routing protocol can provide a true L2 multicast feature

ELK: Enhanced Lookup

- **General-purpose directory service**
  - Master database: held on one or more servers in core of network
  - Slaves can be held near edge of network to reduce load on masters
    - Read: anycast to nearest slave
    - Write: multicast to all masters
    - Entire herd of ELK kept in sync by masters via multicast + unicast

ELK: Enhanced Lookup

- **Primary aim: handle ARP & DHCP without broadcast**
  - ELK stores (MAC address, IP address) tuples
    - Learned from sources of ARP queries
    - Acts as DHCP server, populating directory as it grants leases
  - Edge switch intercepts broadcast ARP / DHCP query and converts into anycast ELK query
  - ELK is not guaranteed to know the answer, but it usually will
    - (ARP request for long-idle host that isn’t using DHCP)

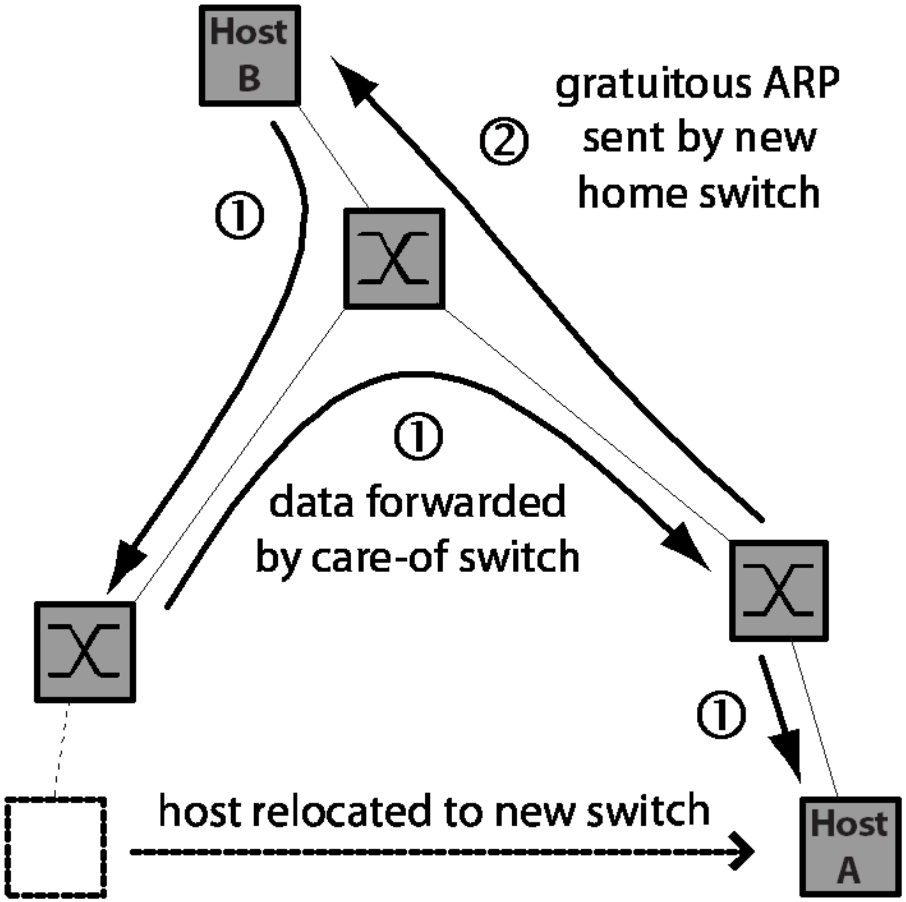
Mobility

If a host moves, it is allocated a new MOOSE address by its new switch

- Other hosts may have the old address in ARP caches

1) **Forward frames**, IP Mobility style
   (new switch discovers host's old location by querying other switches for its real MAC address)

2) **Gratuitous ARP**,
   Xen VM migration style

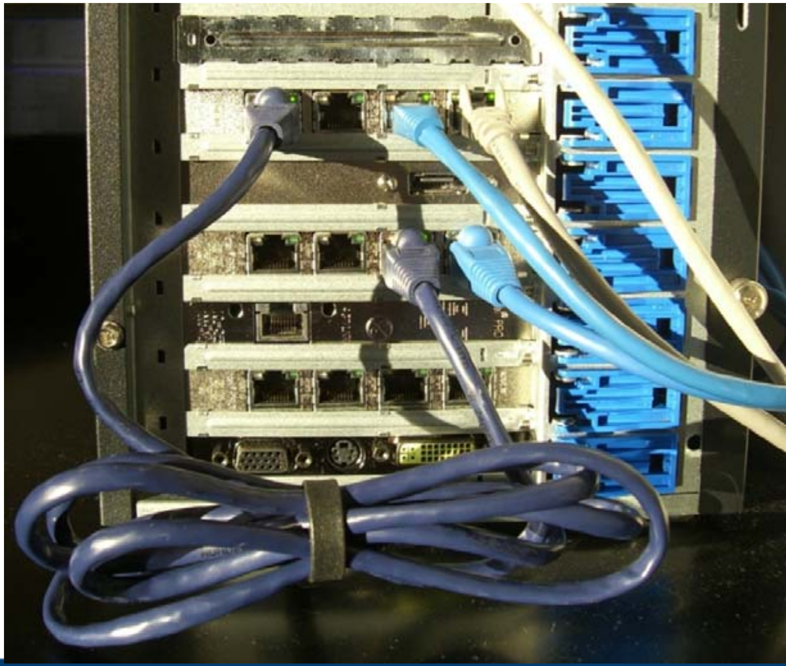


Related work

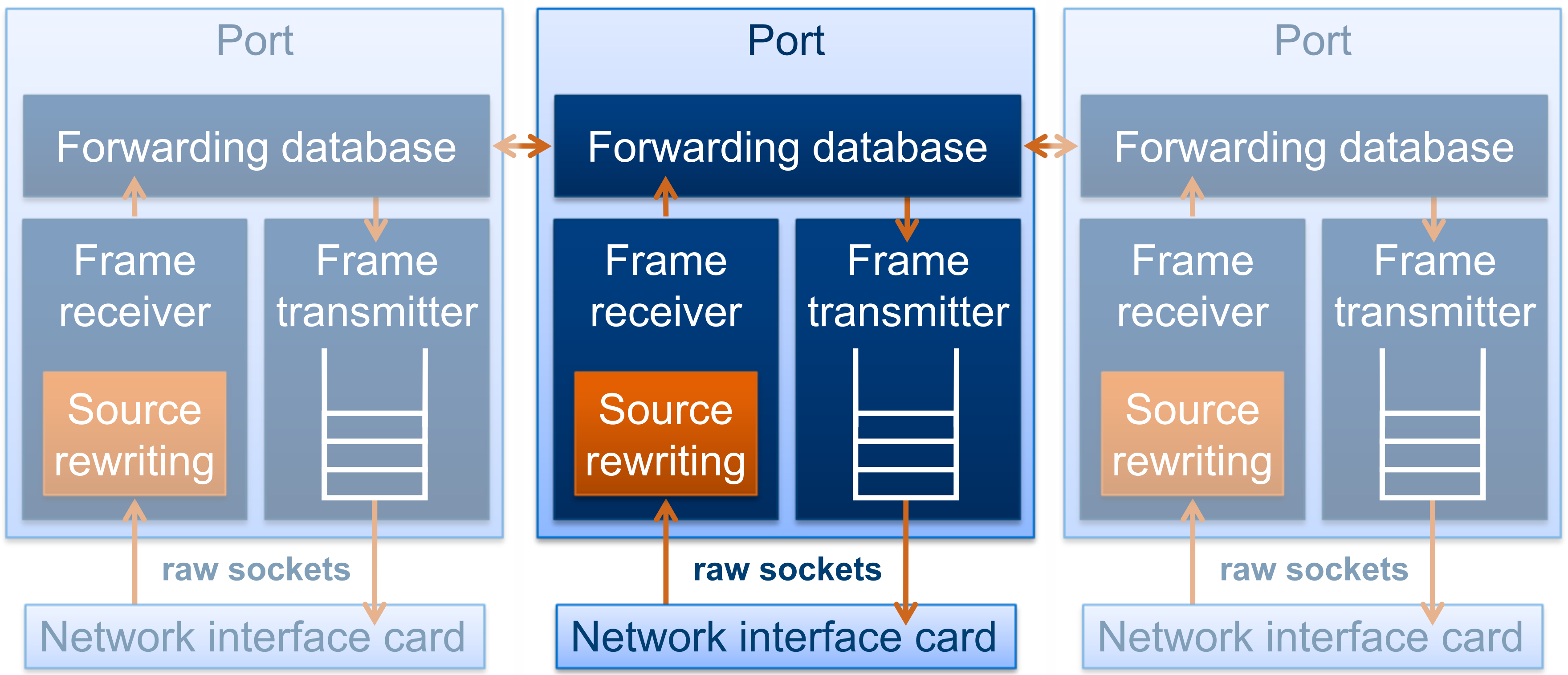
- **Encapsulation**
  (MPLS-VPLS, IEEE TRILL, ...)
  - Destination address lookup: Big lookup tables
- **Domain-narrowing**
  (PortLand – Mysore *et al.*, UCSD)
  - Is everything *really* a strict tree topology?
- **Complete redesign**
  (Myers *et al.*)
  - To be accepted, must be Ethernet-compatible
- **DHT for host location**
  (SEATTLE – Kim *et al.*, Princeton)
  - Unpredictable performance; topology changes are costly

Prototype implementation

- **Proof-of-concept in threaded, object-oriented Python**
  - Designed for clarity and to mimic a potential hardware design
    - Modularity
    - Separation of control and data planes
  - Capable of up to 100 Mbps switching on a modern PC
  - Could theoretically handle very large number of nodes



Prototype implementation: Data plane



Prototype implementation: Data plane

- **Two forwarding databases:**
  - Locally-connected hosts (MAC address, host ID, Port)
  - Remote switches (switch ID, Port)
- **Inside the Frame Receiver:**
  1) Received frame from raw socket packaged in Frame object
  2) DHCP or ARP? Send to control plane ("software")
  3) Rewrite source if not already MOOSE
     - Allocate host ID if necessary: port number, sequential ID
  4) Update locally-connected-host forwarding database
  5) Consult relevant forwarding database for output Port; enqueue frame with that Port's Frame Transmitter

Prototype implementation: Control plane

- **Separate thread**
- **Routing protocol: PWOSPF**
  - Only for proof-of-concept: real implementation would likely need OSPF's authentication features etc.
  - Map switch IDs onto PWOSPF's 4-byte address fields by padding RHS with null bytes
    - `02.11.11.00/24`
  - Maintain Ports' remote-switches forwarding databases
    (routing tables, really)

Prototype evaluation

Unmodified PC's ARP cache:

Address	HWtype	HWaddress	Iface
10.100.11.1	ether	02:00:0c:01:00:01	eth1
10.100.11.3	ether	02:00:0a:01:00:01	eth1
10.100.11.4	ether	02:00:0a:03:00:01	eth1
10.100.11.8	ether	02:00:0b:02:00:01	eth1

- **Virtual network (Xen)**
  - Six virtual switches, 10 VMs each: MOOSE vs. Linux bridging
    - Linux bridge FDBs: 60 entries on each switch: ***O*(hosts)**
    - MOOSE FDBs: 5 switch entries + 10 host entries on each switch: the latter will remain constant in larger deployments, so ***O*(switches)**

Future work

- **NetFPGA implementation**
  - (Dan Wagner-Hall)
- **Enterprise Ethernet features**
  - Quality-of-Service
  - 802.1Q-compatible VLANs: opportunities to explore

Final thoughts

- **Ethernet: another 35 years?**
  - Not an ideal starting point, but it's what we've got
  - If it is to last, it needs to scale yet remain compatible
  - MOOSE is a simple, novel and easily-implementable approach
    - *Address the cause, not the symptom*

"we choose to achieve reliability through simplicity"

– Robert M. Metcalfe and David R. Boggs

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Thank you

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Related work

- **Encapsulation-based solutions:**
  (MPLS-VPLS, Hadžić, SmartBridge, Rbridges / IEEE TRILL, ...)
  - Effective shortest-path routing, but...
  - Big lookup tables everywhere
  - Replace one scalability problem with another
- **Complete redesigns:** (Myers et al.)
  - The only “perfect” solution
  - But to be accepted, must be Ethernet-compatible

Related work: domain-narrowing

- **PortLand:** (Mysore *et al.*, UCSD)
  - Observe that data centres are usually “fat trees”
  - Optimise for strict hierarchical network
  - *No provision for other topologies*
    - Real deployments may come unstuck
  - Consider entire network to be a single fabric

Related work: SEATTLE (Kim *et al.*, Princeton)

- **Forward frames through a Distributed Hash Table (DHT)**
  - Elegant idea; effectively solves most of the problems
- **But, likely to cause unpredictable performance**
  - DHTs are variable-latency
  - May forward some hosts' frames through distant, slow switches
  - Cache mitigates this to an extent, but could be flooded

Related work: SEATTLE (Kim *et al.*, Princeton)

- **Topology changes are very expensive**
  (when the set of reachable switches changes)
  - *Any* such change leads to DHT reorganisation
  - ...Which involves switches throughout the network

- **Data plane complexity:**
  - SEATTLE switch must do much more for each frame than Ethernet
    - (MOOSE's data plane is quite simple)