Router Design

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CS 7260
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Today's Lecture

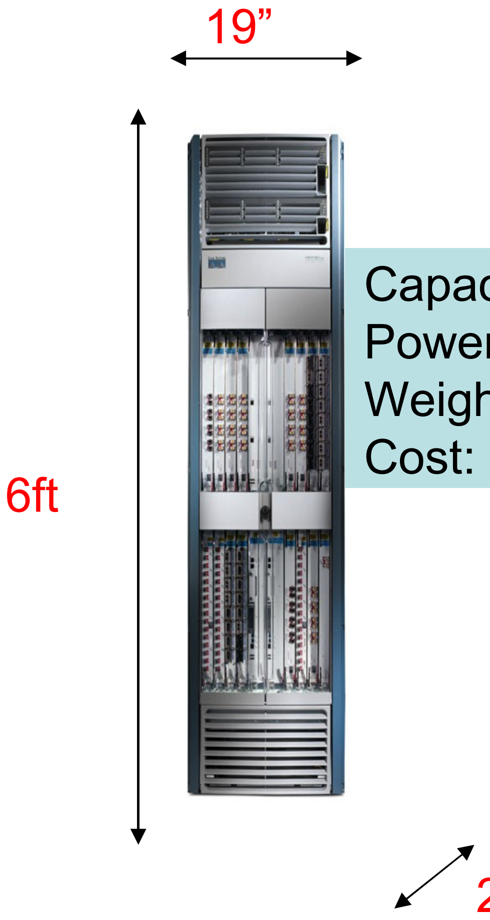
- The design of big, fast routers
- Partridge *et al.*, *A 50 Gb/s IP Router*
- Design constraints
  - Speed
  - Size
  - Power consumption
- Components
- Algorithms
  - Lookups and packet processing (classification, etc.)
  - Packet queueing
  - Switch arbitration

What’s In A Router

- Interfaces
  - Input/output of packets
- Switching fabric
  - Moving packets from input to output
- Software
  - Routing
  - Packet processing
  - Scheduling
  - Etc.

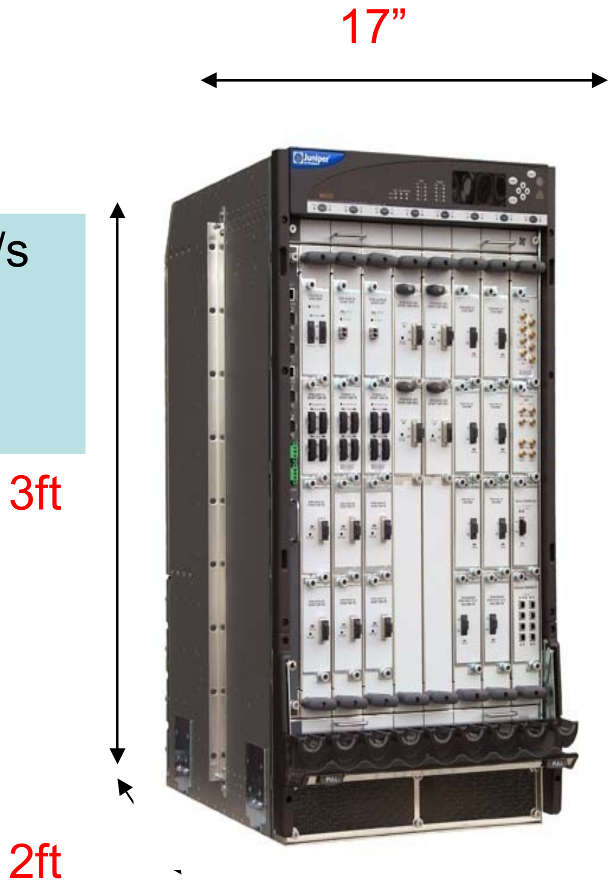
What a Router Chassis Looks Like

Cisco CRS-1



Capacity: 1.2Tb/s
Power: 10.4kW
Weight: 0.5 Ton
Cost: $500k

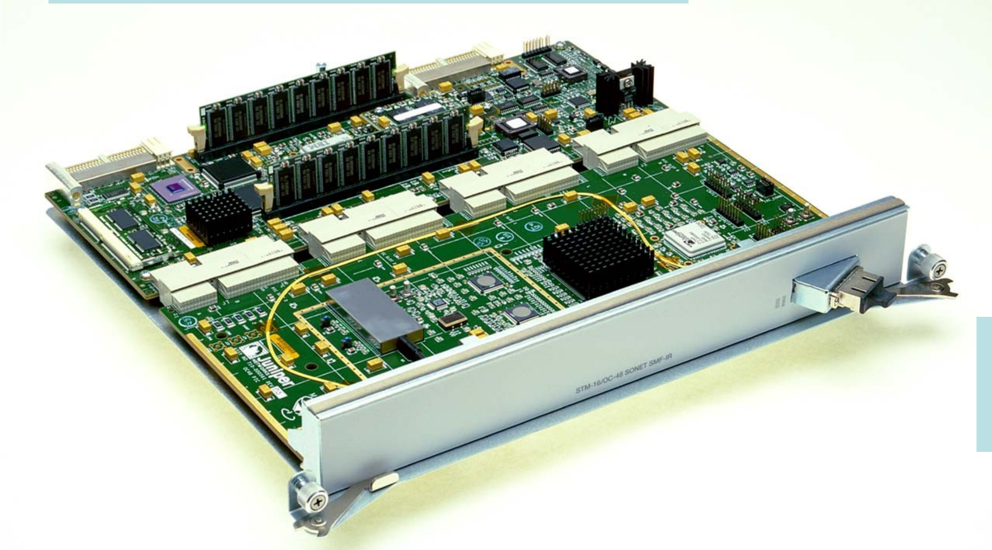
Juniper M320



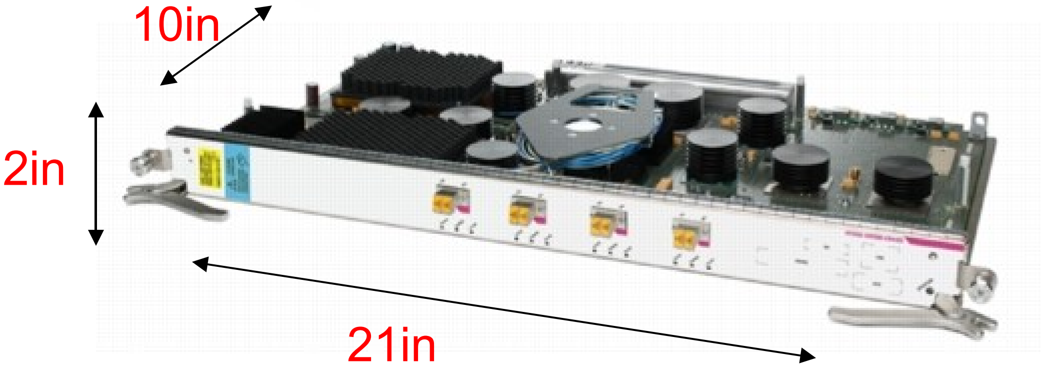
Capacity: 320 Gb/s
Power: 3.1kW

What a Router Line Card Looks Like

1-Port OC48 (2.5 Gb/s)
(for Juniper M40)



4-Port 10 GigE
(for Cisco CRS-1)



Power: about 150 Watts

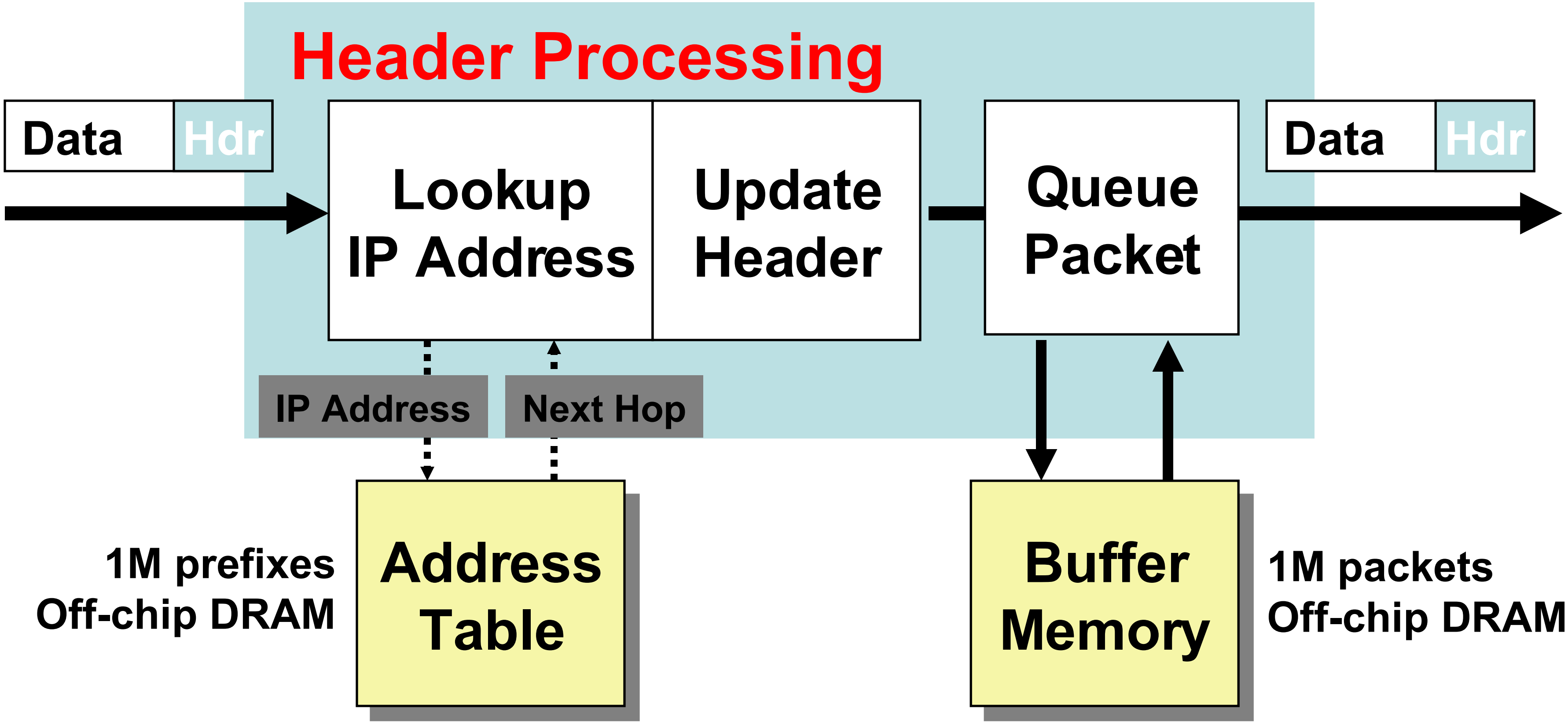
Big, Fast Routers: Why Bother?

- Faster link bandwidths
- Increasing demands
- Larger network size (hosts, routers, users)

Summary of Routing Functionality

- Router gets packet
- Looks at packet header for destination
- Looks up routing table for output interface
- Modifies header (ttl, IP header checksum)
- Passes packet to output interface

Generic Router Architecture



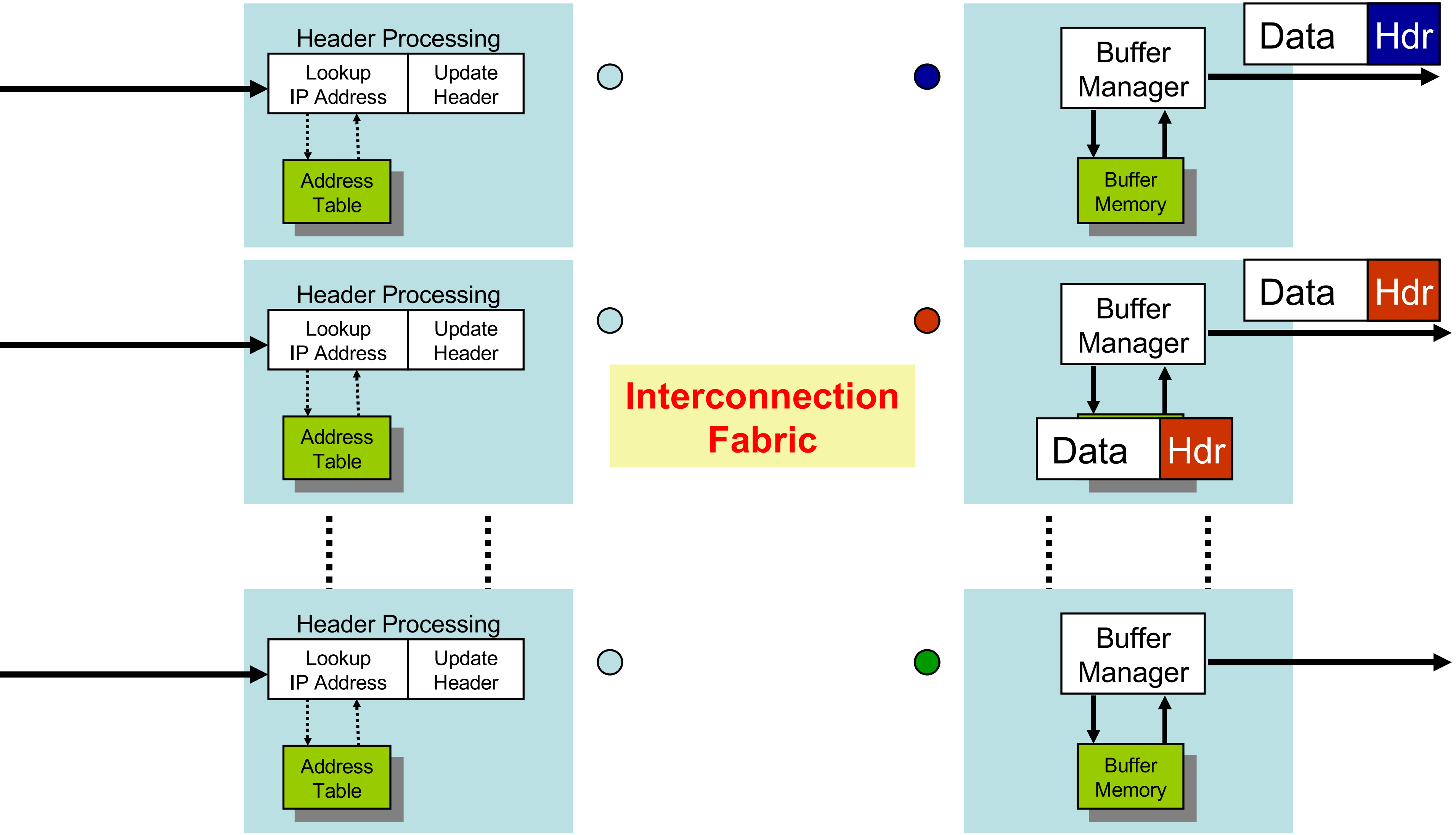
Question: What is the difference between this architecture and that in today's paper?

Innovation #1: Each Line Card Has the Routing Tables

- Prevents central table from becoming a bottleneck at high speeds

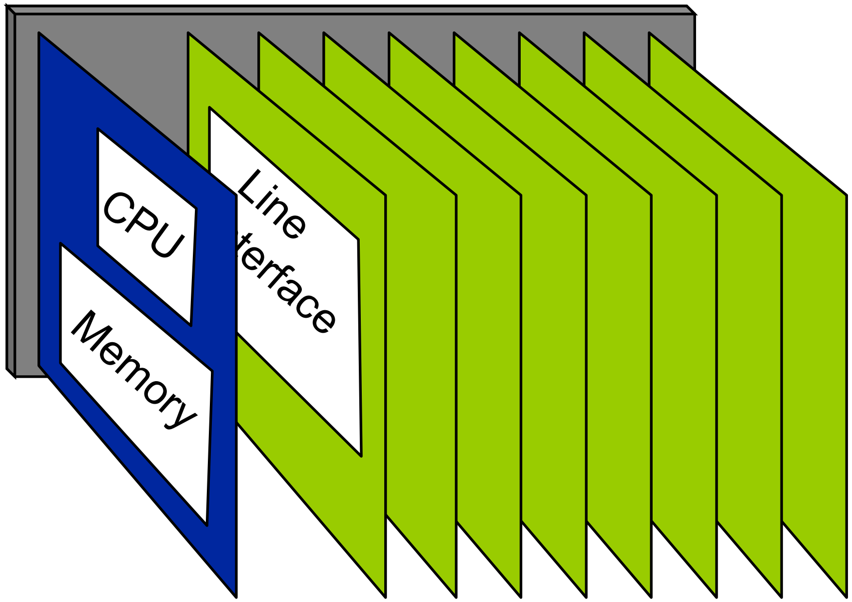
- **Complication:** Must update forwarding tables on the fly.
  - How does the BBN router update tables without slowing the forwarding engines?

Generic Router Architecture

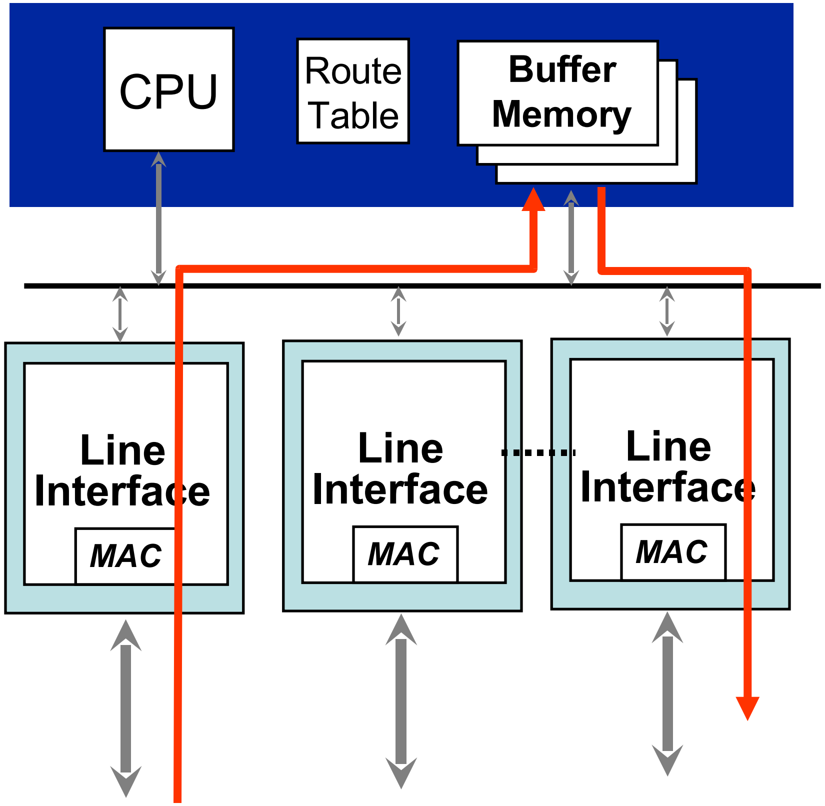


First Generation Routers

Shared Bus

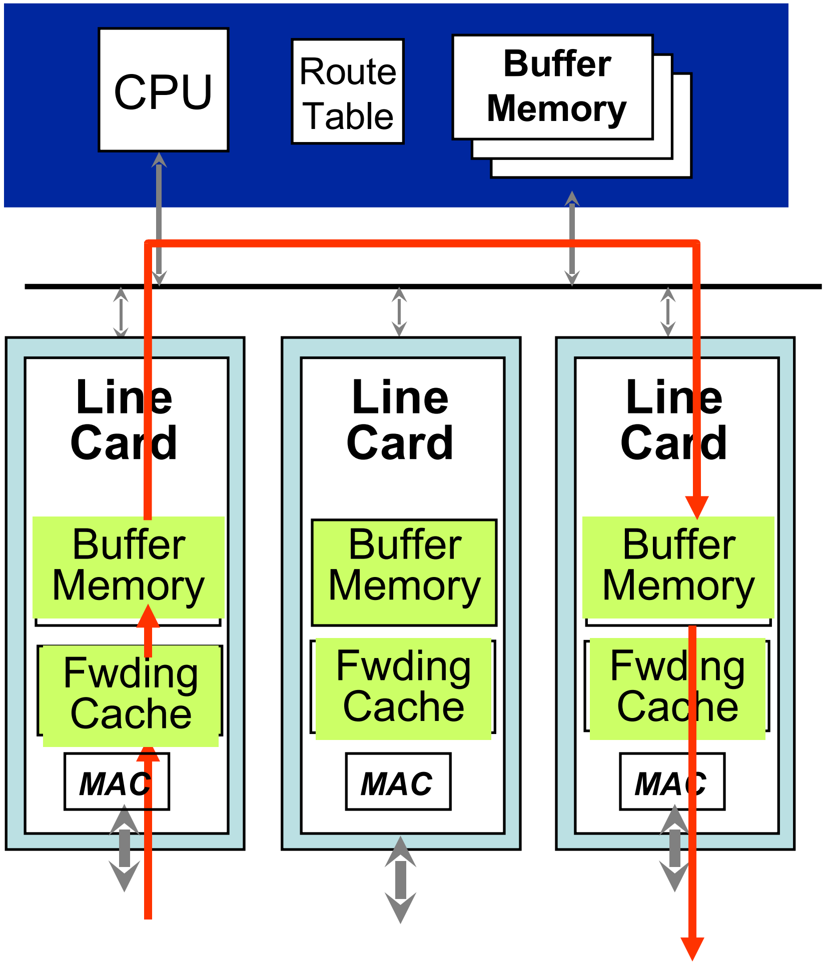


Off-chip Buffer



Typically <0.5Gb/s aggregate capacity

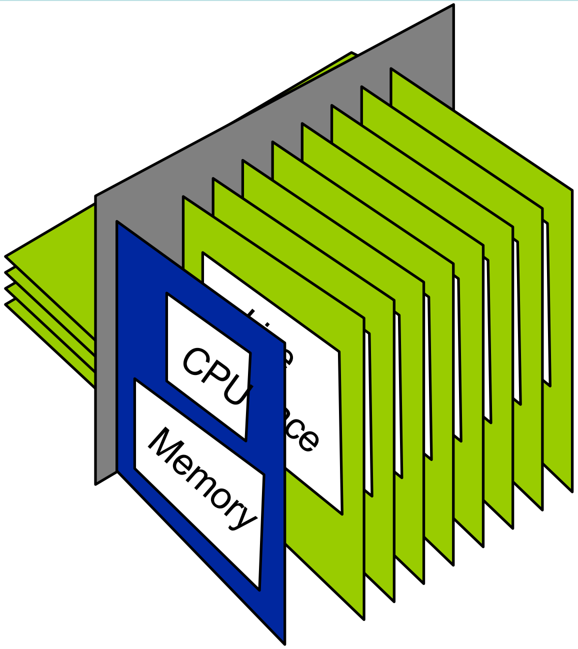
Second Generation Routers

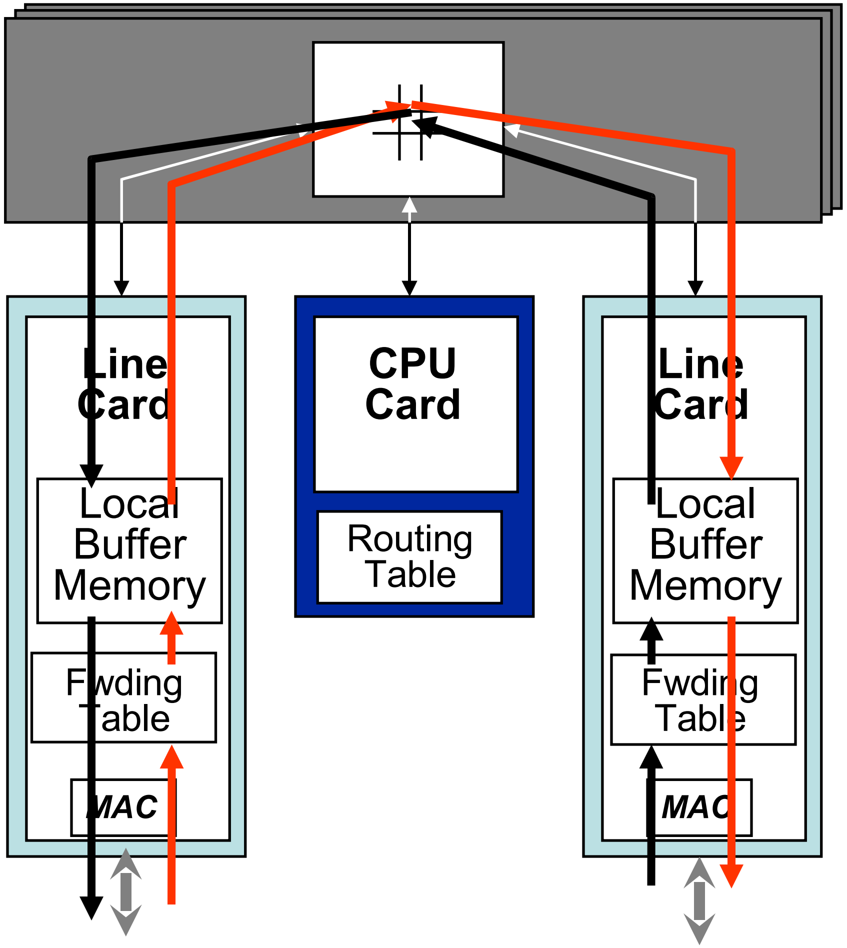


Typically <5Gb/s aggregate capacity

Third Generation Routers

“Crossbar”: Switched Backplane





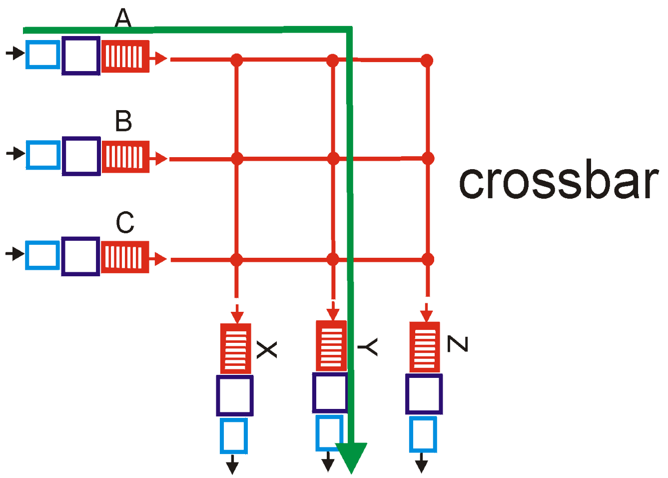
Typically <50Gb/s aggregate capacity

Innovation #2: Switched Backplane

- Every input port has a connection to every output port

- During each timeslot, each input connected to zero or one outputs

- **Advantage:** Exploits parallelism
- **Disadvantage:** Need scheduling algorithm

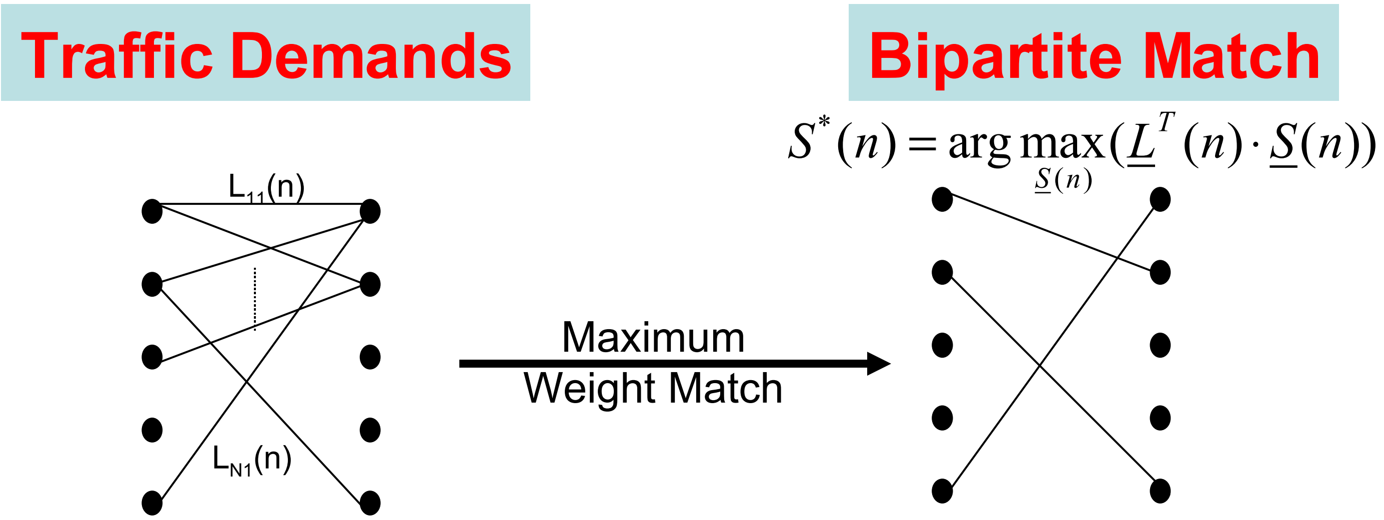


Router Components and Functions

- Route processor
  - Routing
  - Installing forwarding tables
  - Management
- Line cards
  - **Packet processing and classification**
  - Packet forwarding
- Switched bus (“Crossbar”)
  - Scheduling

Crossbar Switching

- **Conceptually:** *N* inputs, *N outputs*
  - Actually, inputs are also outputs
- In each timeslot, one-to-one mapping between inputs and outputs.
- **Goal:** Maximal matching



Traffic Demands

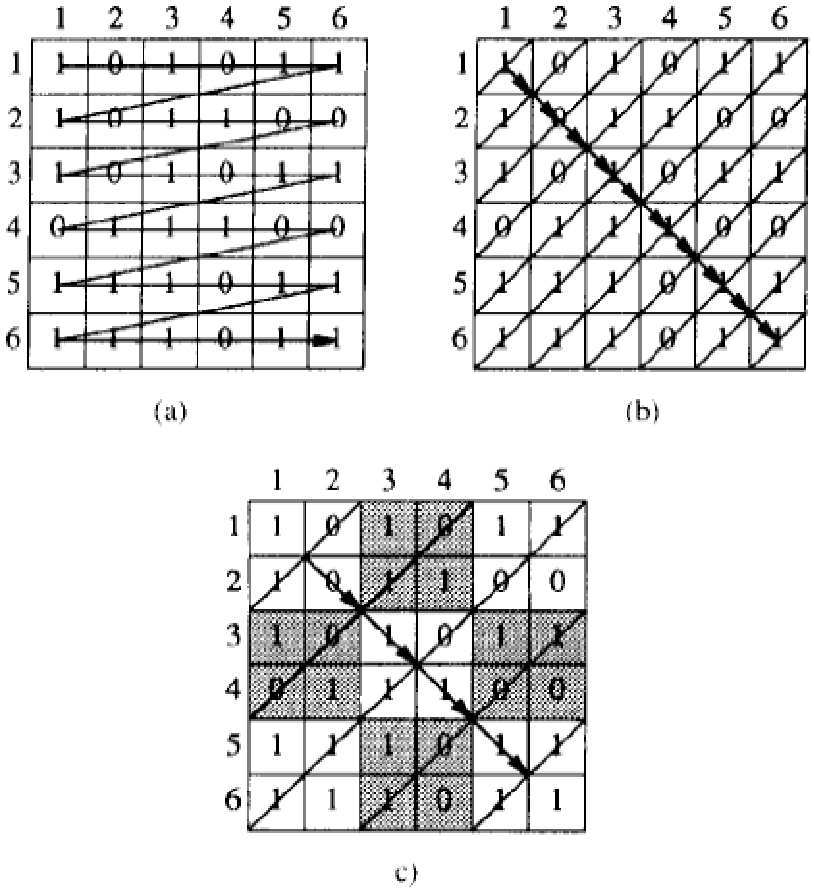
Bipartite Match

$$S^*(n) = \arg\max_{\underline{S}(n)} (\underline{L}^T(n) \cdot \underline{S}(n))$$

Maximum Weight Match

Early Crossbar Scheduling Algorithm

- Wavefront algorithm



(a)

(b)

c)

Problems: Fairness, speed, …

Alternatives to the Wavefront Scheduler

- PIM: Parallel Iterative Matching
  - **Request:** Each input sends requests to all outputs for which it has packets
  - **Grant:** Output selects an input at random and grants
  - **Accept:** Input selects from its received grants

- **Problem:** Matching may not be maximal
- **Solution:** Run several times

- **Problem:** Matching may not be “fair”
- **Solution:** Grant/accept in round robin instead of random

Scheduling and Fairness

- What is an appropriate definition of fairness?
  - One notion: Max-min fairness
  - Disadvantage: Compromises throughput

- Max-min fairness gives priority to low data rates/small values

- Is it guaranteed to exist?
- Is it unique?

Max-Min Fairness

- A flow rate x is **max-min fair** if any rate x cannot be increased without decreasing some y which is smaller than or equal to x.

- How to share equally with different resource demands
  - small users will get all they want
  - large users will evenly split the rest
- More formally, perform this procedure:
  - resource allocated to customers in order of increasing demand
  - no customer receives more than requested
  - customers with unsatisfied demands split the remaining resource

Example

- Demands: 2, 2.6, 4, 5; capacity: 10
  - 10/4 = 2.5
  - **Problem:** 1st user needs only 2; excess of 0.5,
- Distribute among 3, so 0.5/3=0.167
  - now we have allocs of [2, 2.67, 2.67, 2.67],
  - leaving an excess of 0.07 for cust #2
  - divide that in two, gets [2, 2.6, 2.7, 2.7]
- Maximizes the minimum share to each customer whose demand is not fully serviced

How to Achieve Max-Min Fairness

- **Take 1:** Round-Robin
  - Problem: Packets may have different sizes
- **Take 2:** Bit-by-Bit Round Robin
  - Problem: Feasibility
- **Take 3:** Fair Queuing
  - Service packets according to soonest "finishing time"

Adding QoS: Add weights to the queues…

Why QoS?

- Internet currently provides one single class of **“best-effort” service**
  - No assurances about delivery
- Existing applications are ***elastic***
  - Tolerate delays and losses
  - Can adapt to congestion
- Future “real-time” applications may be ***inelastic***

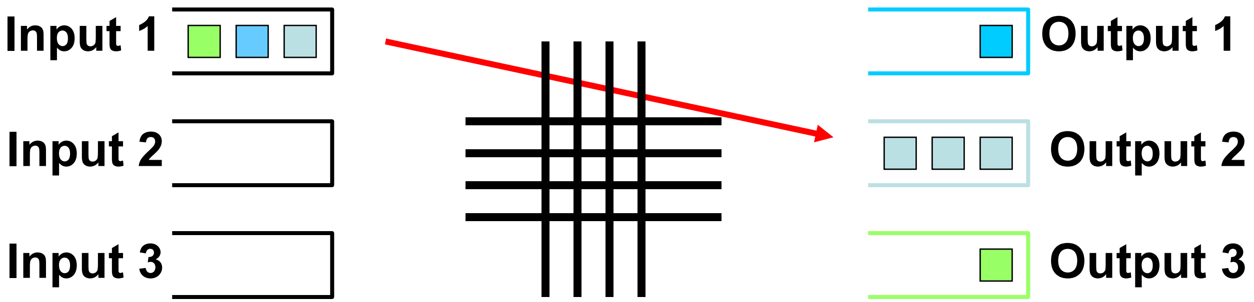
Other Goal: Utilization

- **"100% Throughput":** no packets experience head-of-line blocking
- Does the previous scheme achieve 100% throughput?
- What if the crossbar could have a "speedup"?

Key result: Given a crossbar with 2x speedup, any maximal matching can achieve 100% throughput.

Head-of-Line Blocking

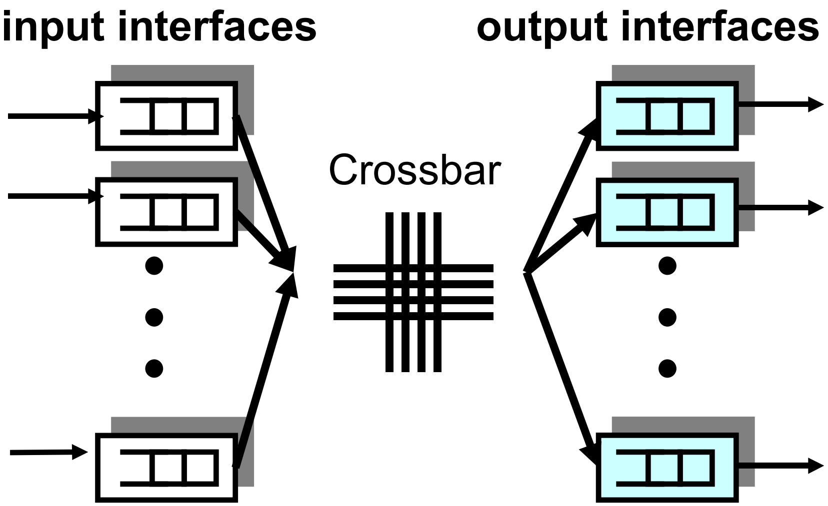
Problem: The packet at the front of the queue experiences contention for the output queue, blocking all packets behind it.



Maximum throughput in such a switch: 2 – sqrt(2)

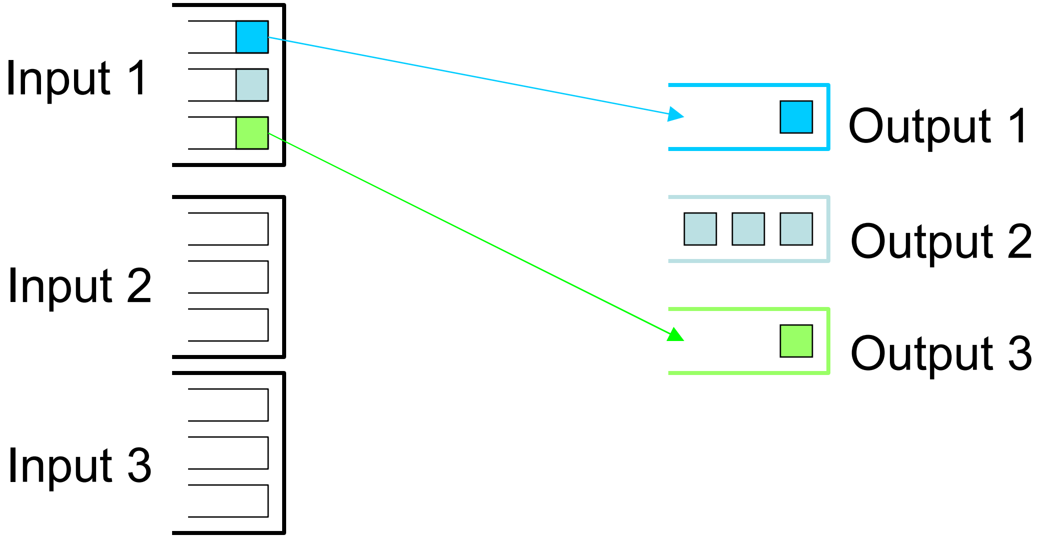
Combined Input-Output Queueing

- **Advantages**
  - Easy to build
    - 100% can be achieved with limited speedup
- **Disadvantages**
  - Harder to design algorithms
    - Two congestion points
    - Flow control at destination



Solution: Virtual Output Queues

- Maintain N virtual queues at each input
  - one per output

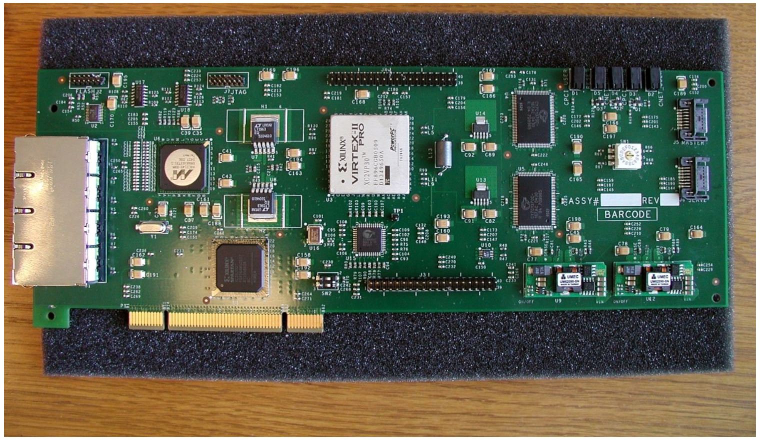


Processing: Fast Path vs. Slow Path

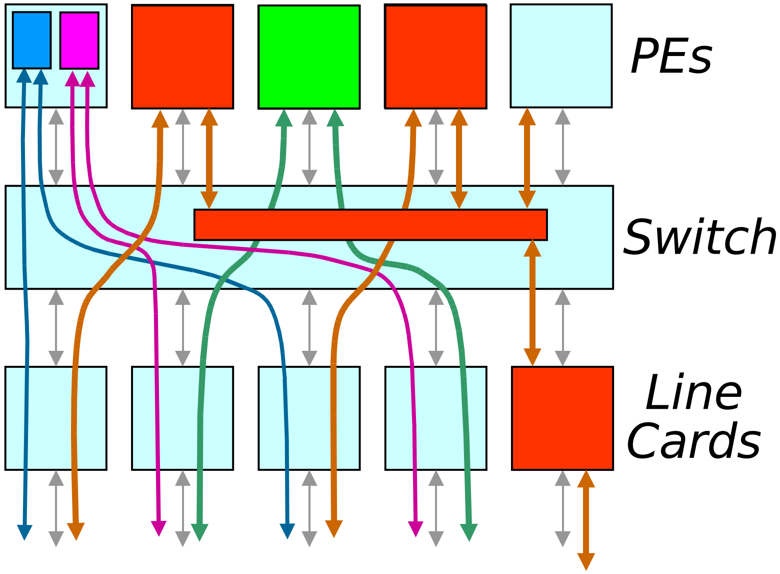
- **Optimize for common case**
  - BBN router: 85 instructions for fast-path code
  - Fits entirely in L1 cache
- Non-common cases handled on slow path
  - Route cache misses
  - Errors (*e.g.*, ICMP time exceeded)
  - IP options
  - Fragmented packets
  - Mullticast packets

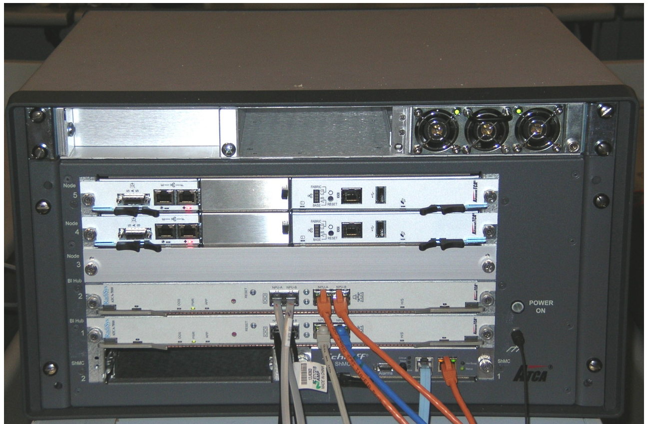
Recent Trends: Programmability

- NetFPGA: 4-port interface card, plugs into PCI bus (Stanford)
  - Customizable forwarding
  - Appearance of many virtual interfaces (with VLAN tags)



- Programmability with Network processors (Washington U.)



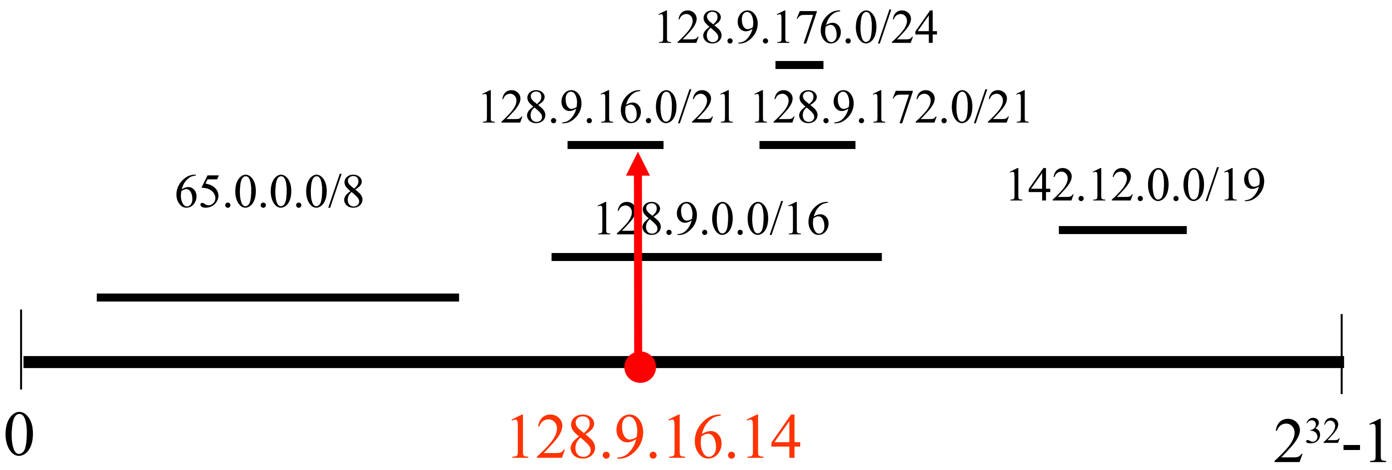


IP Address Lookup

Challenges:

1. **Longest-prefix match (not exact).**
2. Tables are large and growing.
3. Lookups must be fast.

IP Lookups find Longest Prefixes



Routing lookup: Find the longest matching prefix (aka the most specific route) among all prefixes that match the destination address.

IP Address Lookup

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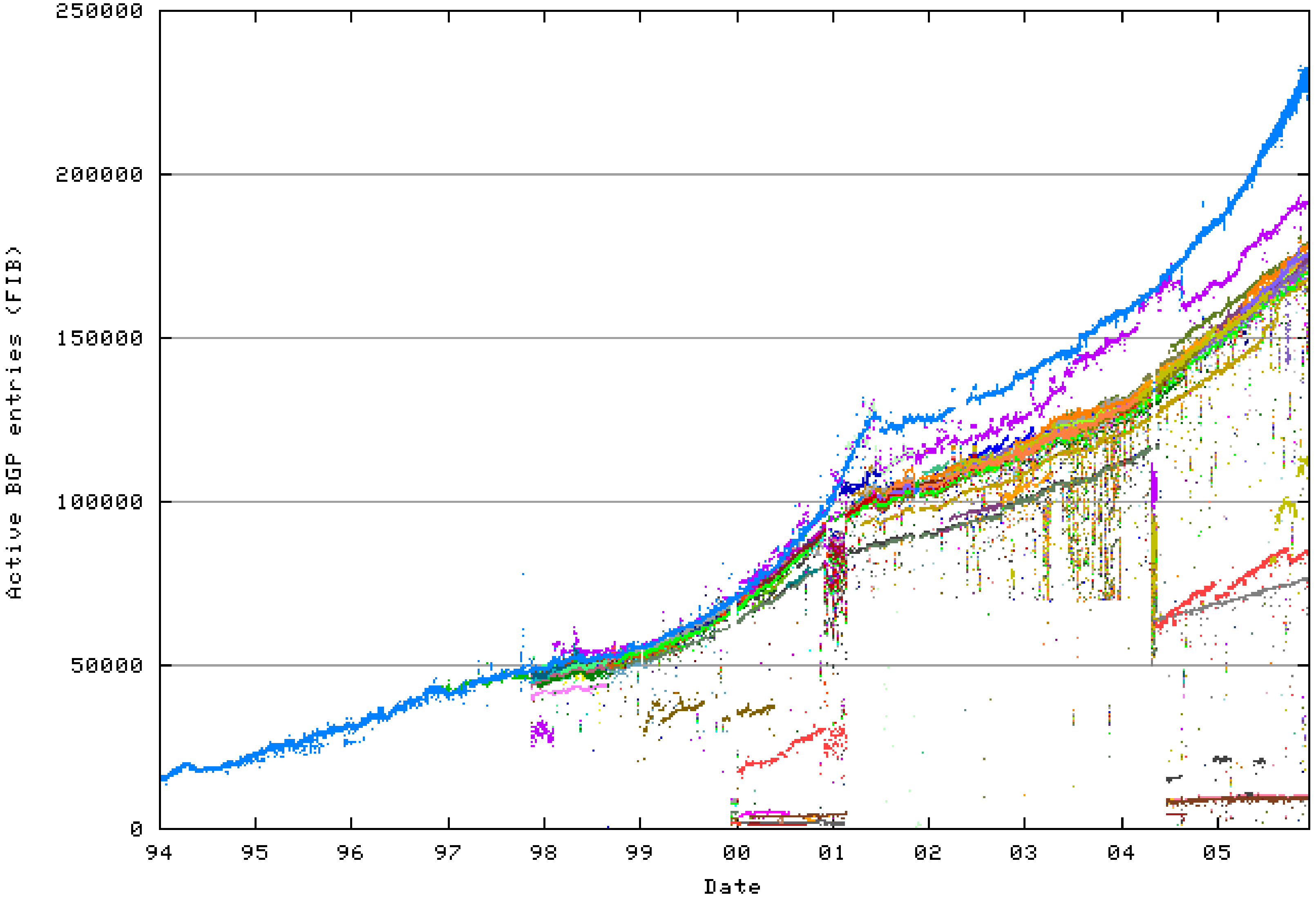
Address Tables are Large



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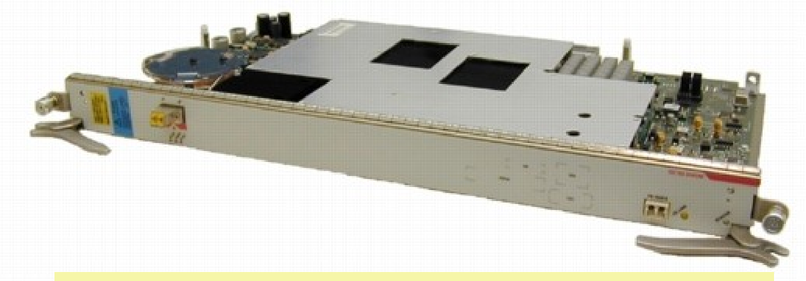
Lookups Must be Fast



Cisco CRS-1 1-Port OC-768C (Line rate: 42.1 Gb/s)

Year	Line	40B packets (Mpkt/s)
1997	622Mb/s	1.94
1999	2.5Gb/s	7.81
2001	10Gb/s	31.25
2003	40Gb/s	125

OC-12

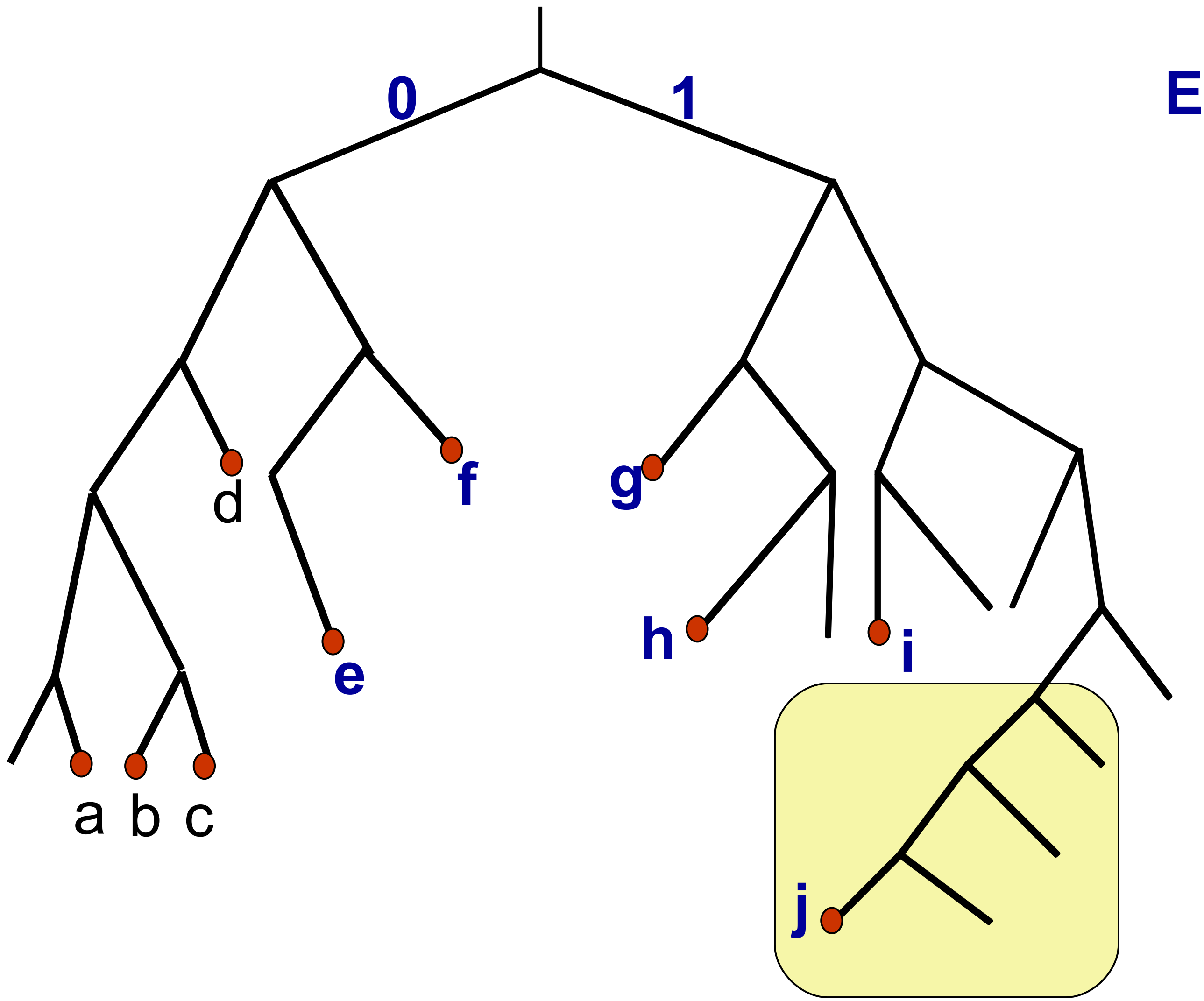
OC-48

OC-192

OC-768

Still pretty rare outside of research networks

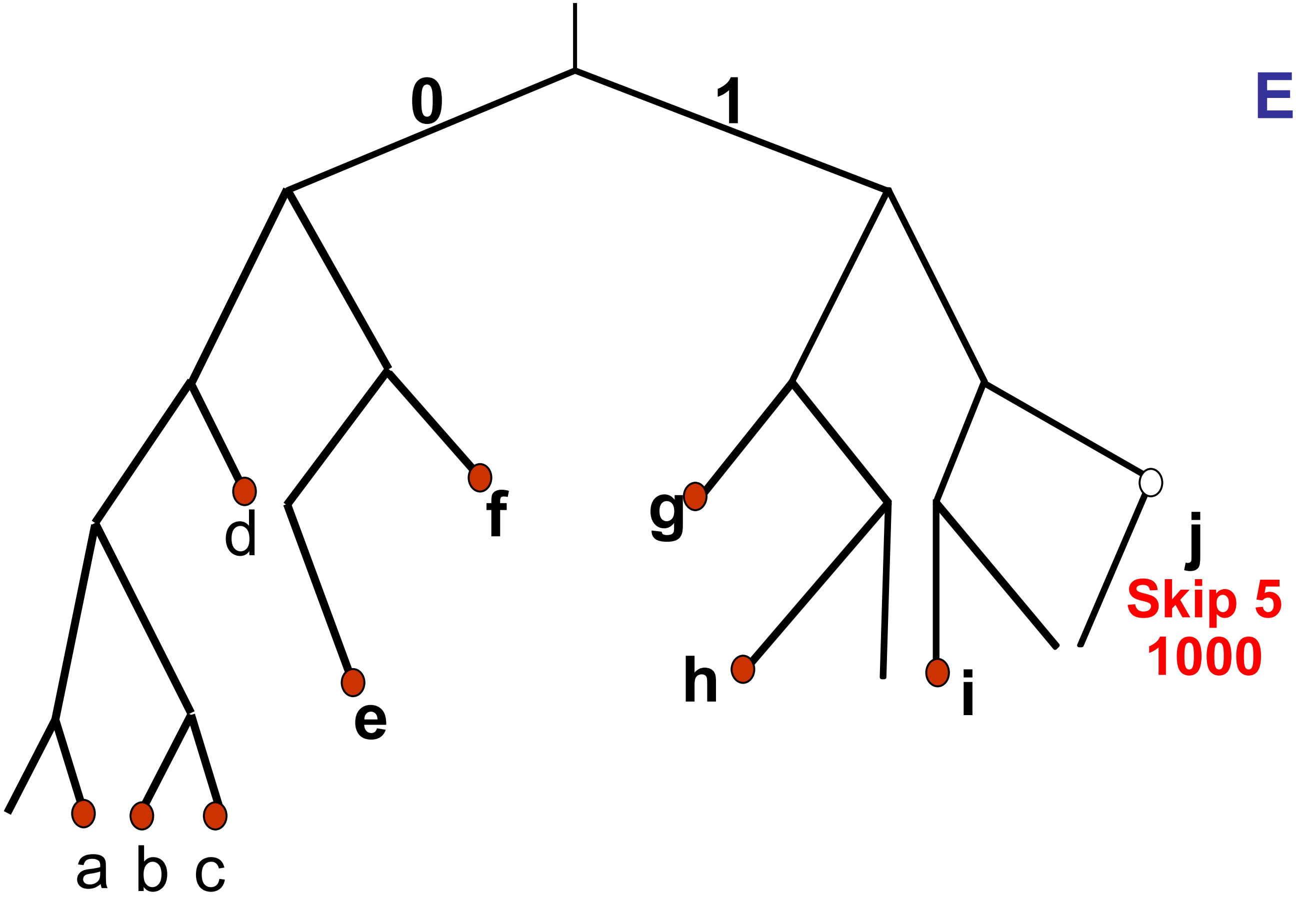
IP Address Lookup: Binary Tries



Example Prefixes:

- a) 00001
- b) 00010
- c) 00011
- d) 001
- e) 0101
- f) 011
- g) 100
- h) 1010
- i) 1100
- j) 11110000

IP Address Lookup: Patricia Trie



Example Prefixes

a) 00001
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f) 011
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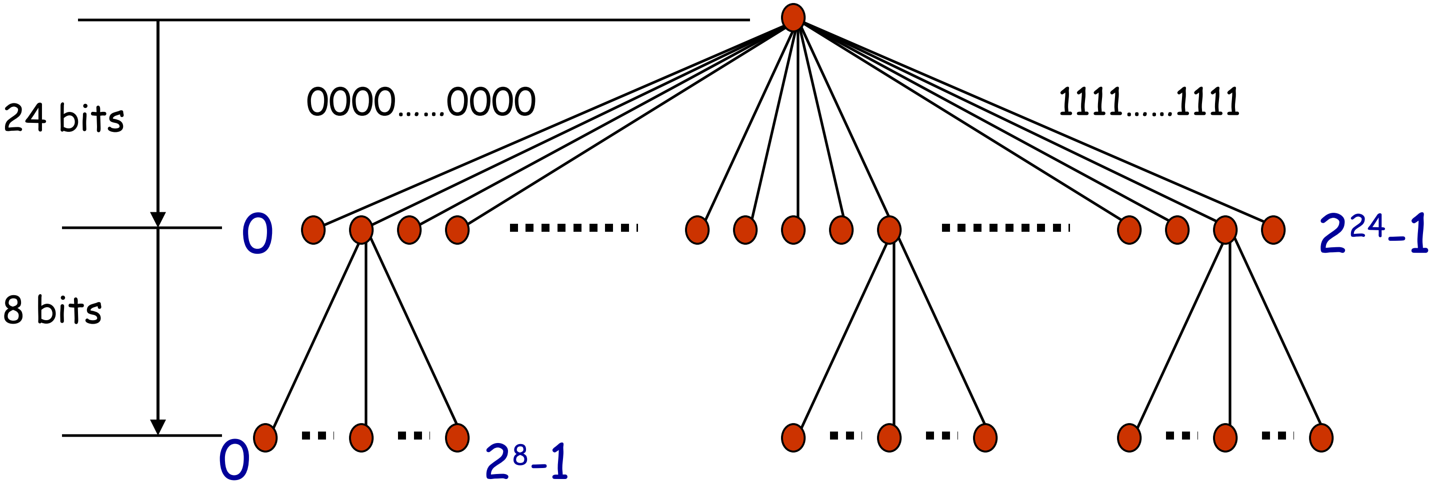
h) 1010
i) 1100
j) 11110000

Problem: Lots of (slow) memory lookups

Address Lookup: Direct Trie



- When pipelined, one lookup per memory access
- **Inefficient use of memory**

Faster LPM: Alternatives

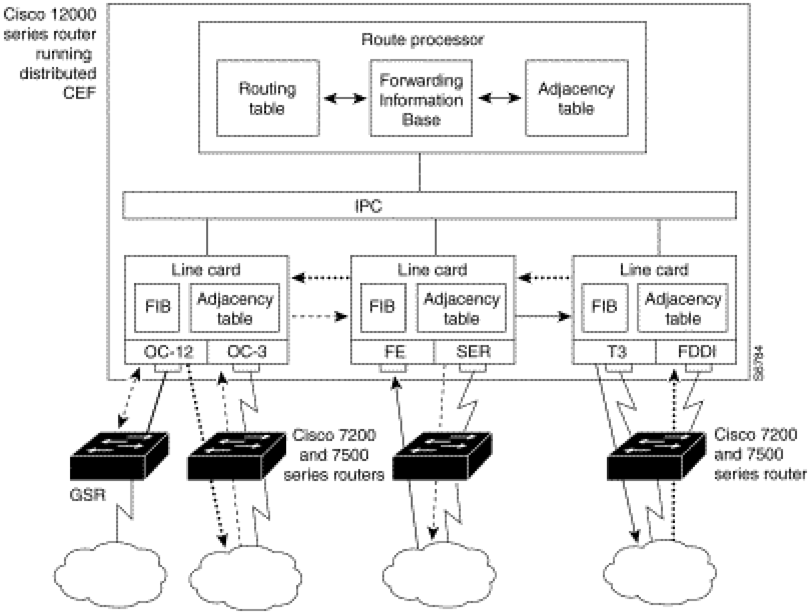
- Content addressable memory (CAM)
  - **Hardware-based** route lookup
  - Input = tag, output = value

  - Requires exact match with tag
    - Multiple cycles (1 per prefix) with single CAM
    - Multiple CAMs (1 per prefix) searched in parallel
  - Ternary CAM
    - (0,1,don’t care) values in tag match
    - Priority (*i.e.*, longest prefix) by order of entries

Historically, this approach has not been very economical.

Faster Lookup: Alternatives

- Caching
  - Packet trains exhibit temporal locality
  - Many packets to same destination
- Cisco Express Forwarding



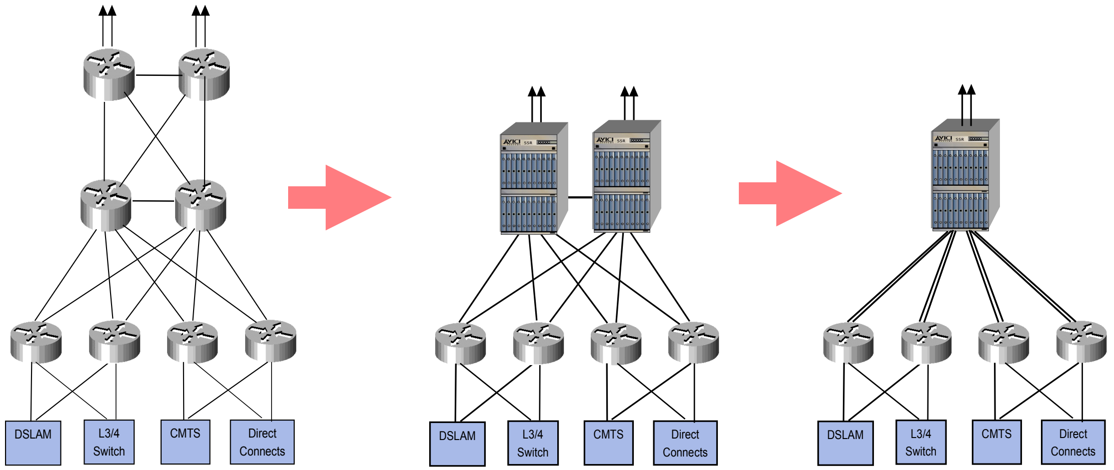
IP Address Lookup: Summary

- Lookup limited by memory bandwidth.
- Lookup uses high-degree trie.

- State of the art: 10Gb/s line rate.
- Scales to: 40Gb/s line rate.

Fourth-Generation: Collapse the POP

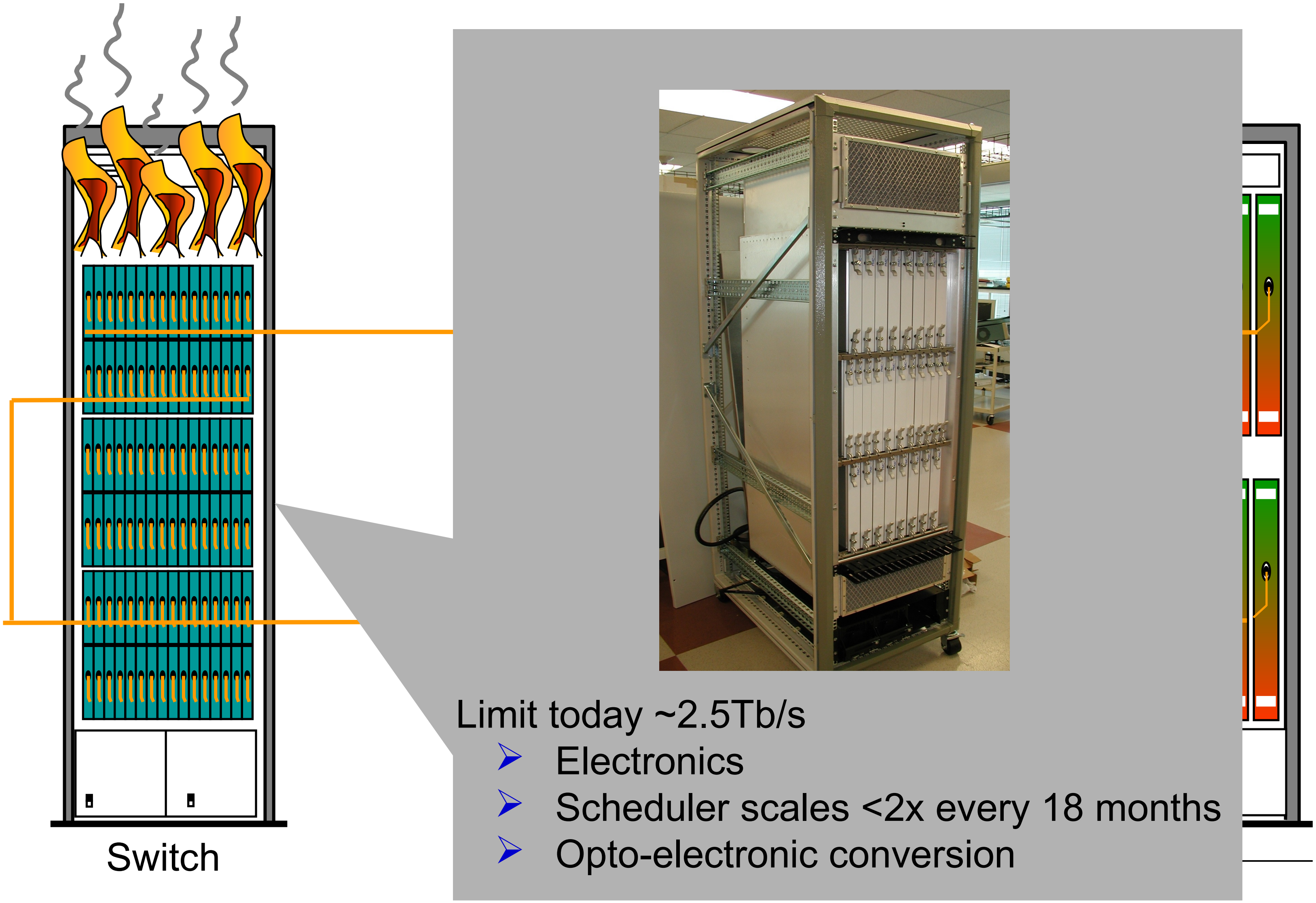
High Reliability and Scalability enable “vertical” POP simplification



Reduces CapEx, Operational cost

Increases network stability

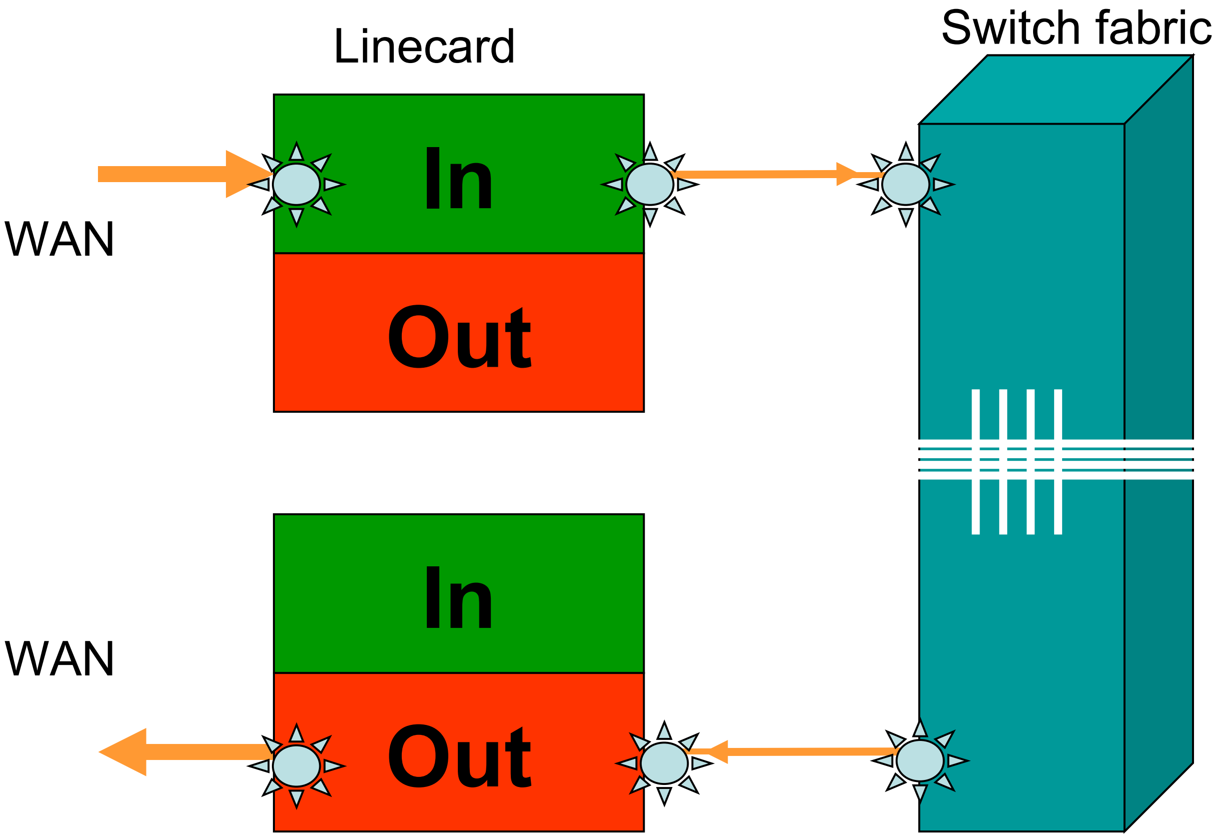
Fourth-Generation Routers



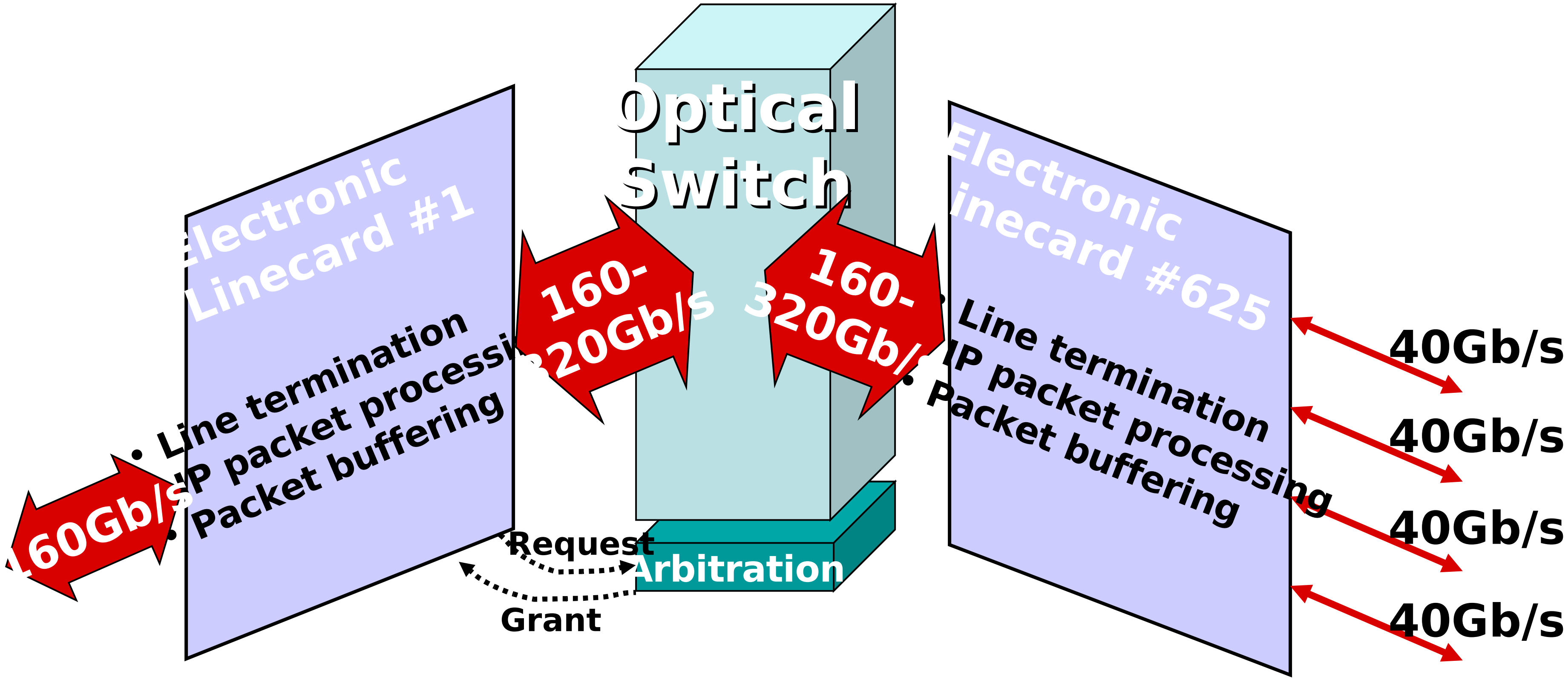
Limit today ~2.5Tb/s

- Electronics
- Scheduler scales <2x every 18 months
- Opto-electronic conversion

Multi-rack routers



Future: 100Tb/s Optical Router



(100Tb/s = 625 * 160Gb/s)

McKeown *et al.*, *Scaling Internet Routers Using Optics, ACM SIGCOMM 2003*

Challenges with Optical Switching

- Missequenced packets
- Pathological traffic patterns
- Rapidly configuring switch fabric
- Failing components