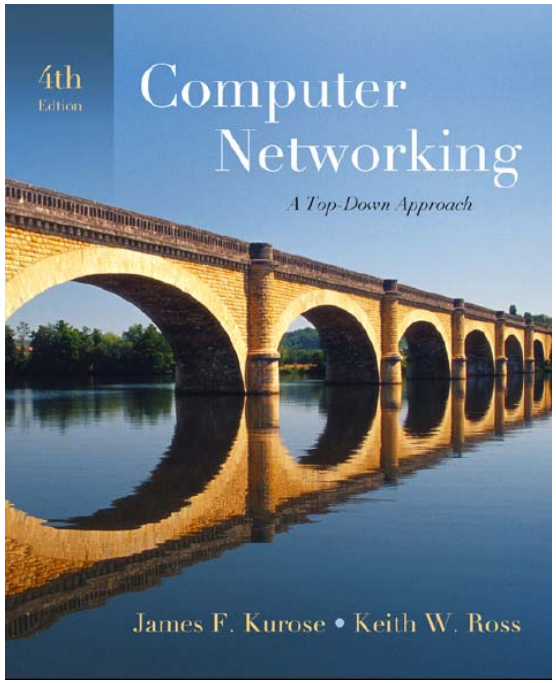
Chapter 4
Network Layer
網路層



Computer Networking: A Top Down Approach 4th edition.
Jim Kurose, Keith Ross
Addison-Wesley, July 2007.

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Chapter 4: Network Layer

網路層

Chapter goals:

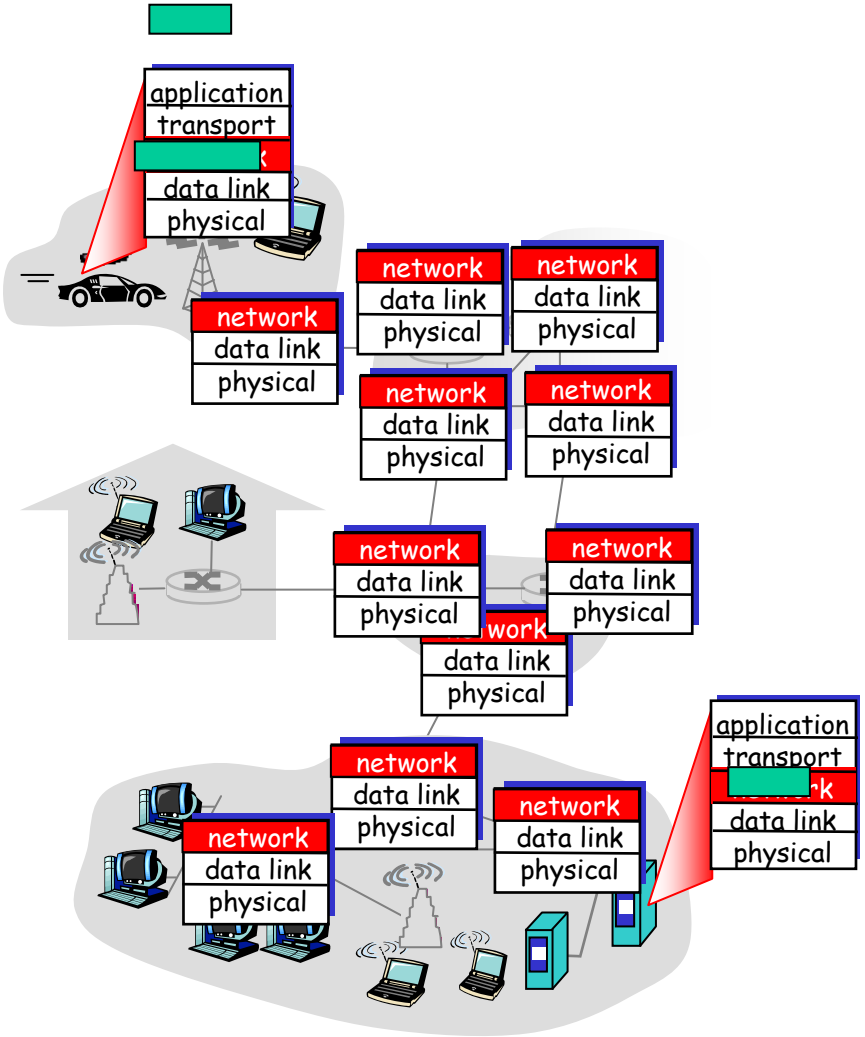
- understand principles behind network layer services:
  - network layer service models
  - forwarding versus routing 轉送與繞送
  - how a router works 路由器實作
  - routing (path selection) 選擇路徑
  - dealing with scale
  - advanced topics: IPv6, mobility
- instantiation, implementation in the Internet

Chapter 4: Network Layer

- 4. 1 Introduction
- 4.2 Virtual circuit and datagram networks
- 4.3 What's inside a router
- 4.4 IP: Internet Protocol
  - Datagram format
  - IPv4 addressing
  - ICMP
  - IPv6
- 4.5 Routing algorithms
  - Link state
  - Distance Vector
  - Hierarchical routing
- 4.6 Routing in the Internet
  - RIP
  - OSPF
  - BGP
- 4.7 Broadcast and multicast routing

Network layer 網路層

- transport segment from sending to receiving host
- on sending side encapsulates segments into datagrams
  區段轉封包
- on rcving side, delivers segments to transport layer
- network layer protocols in *every* host, router
- router examines header fields in all IP datagrams passing through it



Two Key Network-Layer Functions

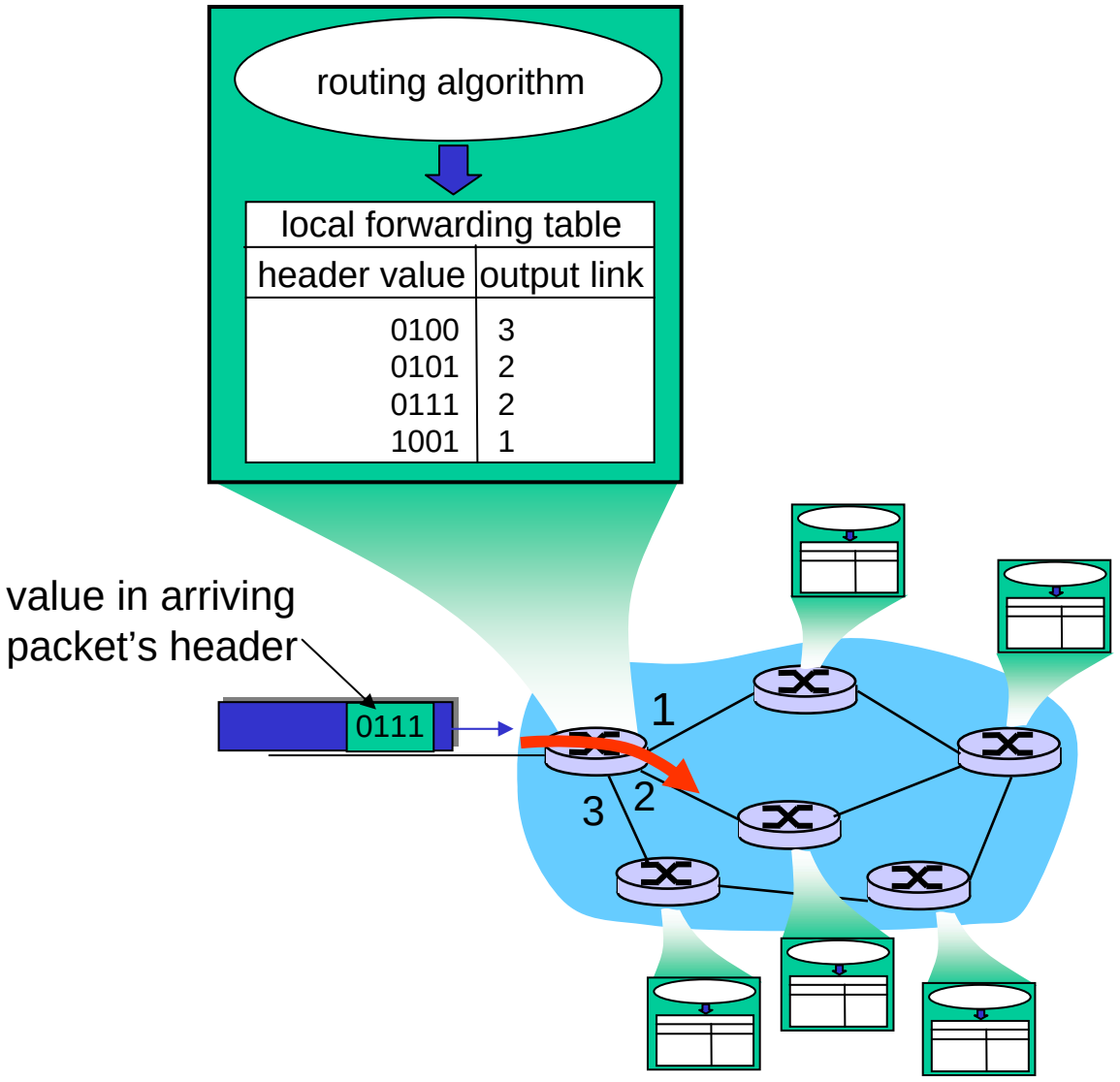
網路層主要工作：轉送、繞送

- *Forwarding轉送:* move packets from router's input to appropriate router output
  在router 內的工作
- *Routing 繞送:* determine route taken by packets from source to dest.
  決定路線
  - *routing algorithms*

analogy: 以搭飛機為例

- routing: process of planning trip from source to dest
- forwarding: process of getting through single interchange

Interplay between routing and forwarding



Connection setup
第三項網路層功能：連線建立

- 3rd important function in *some* network architectures:
  - ATM, frame relay, X.25 其它網路層通訊協定，非IP
- before datagrams flow, two end hosts *and* intervening routers establish virtual connection
  - routers get involved 中間的router也參與其中
- network vs transport layer connection service:
  - network: between two hosts (may also involve inervening routers in case of VCs)
    兩個hosts之間的連線
  - transport: between two processes
    兩個process之間的連線

Network service model 服務模型

Q: What *service model* for "channel" transporting datagrams from sender to receiver?

Example services for individual datagrams:

- guaranteed delivery
  傳送保證：一定會到
- guaranteed delivery with less than 40 msec delay
  一定在某個時間內到

Example services for a flow of datagrams:

- in-order datagram delivery
  依順序到
- guaranteed minimum bandwidth to flow
  保證頻寬
- restrictions on changes in inter-packet spacing
  封包間隔的限制（jitter）

Network layer service models:

Network Architecture	Service Model	Guarantees ?				Congestion feedback
		Bandwidth	Loss	Order	Timing	
Internet	best effort	none	no	no	no	no (inferred via loss)
ATM	CBR	constant rate	yes	yes	yes	no congestion
ATM	VBR	guaranteed rate	yes	yes	yes	no congestion
ATM	ABR	guaranteed minimum	no	yes	no	yes
ATM	UBR	none	no	yes	no	no

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  虛擬迴路及封包網路
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Network layer connection and connection-less service

- datagram network provides network-layer connectionless service 無連結服務
- VC network provides network-layer connection service 連結導向服務
- analogous to the transport-layer services, but:
  - service: host-to-host
  - no choice: network provides one or the other
    只能選擇一種，沒有兩種都提供的網路
  - implementation: in network core

Virtual circuits 虛擬迴路

"source-to-dest path behaves much like telephone circuit"

- performance-wise
- network actions along source-to-dest path

- call setup, teardown for each call *before* data can flow
- each packet carries VC identifier (not destination host address) 封包上帶著VC號碼
- *every* router on source-dest path maintains "state" for each passing connection
- link, router resources (bandwidth, buffers) may be *allocated* to VC (dedicated resources = predictable service) 資源指定

VC implementation

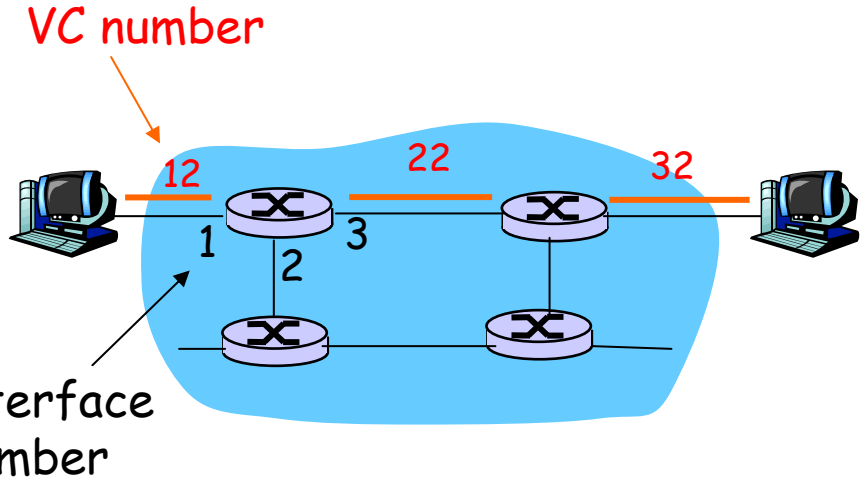
a VC consists of:

1. path from source to destination 一條從s到d的路徑
2. VC numbers, one number for each link along path
   多個VC號碼
3. entries in forwarding tables in routers along path
   轉送表上的紀錄

- packet belonging to VC carries VC number (rather than dest address) 不帶dest的位址
- VC number can be changed on each link.
  - New VC number comes from forwarding table

Forwarding table

轉送表範例



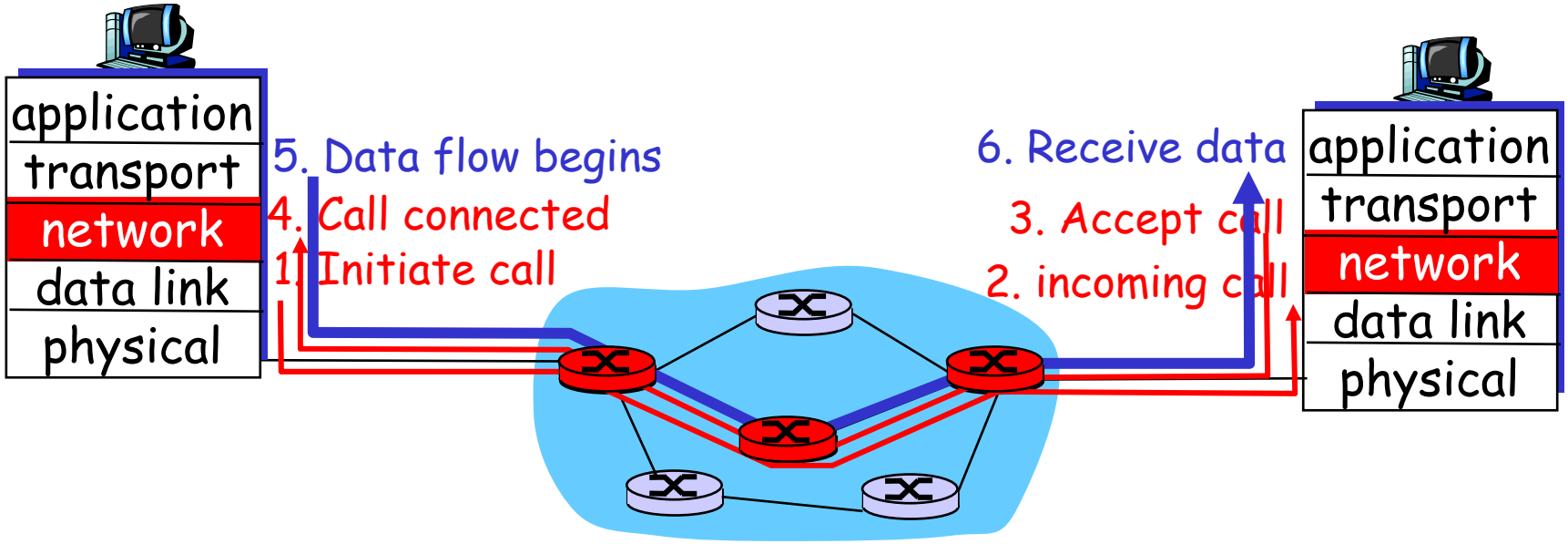
Forwarding table in northwest router:

Incoming interface	Incoming VC #	Outgoing interface	Outgoing VC #
1	12	3	22
2	63	1	18
3	7	2	17
1	97	3	87
…	…	…	…

Routers maintain connection state information!

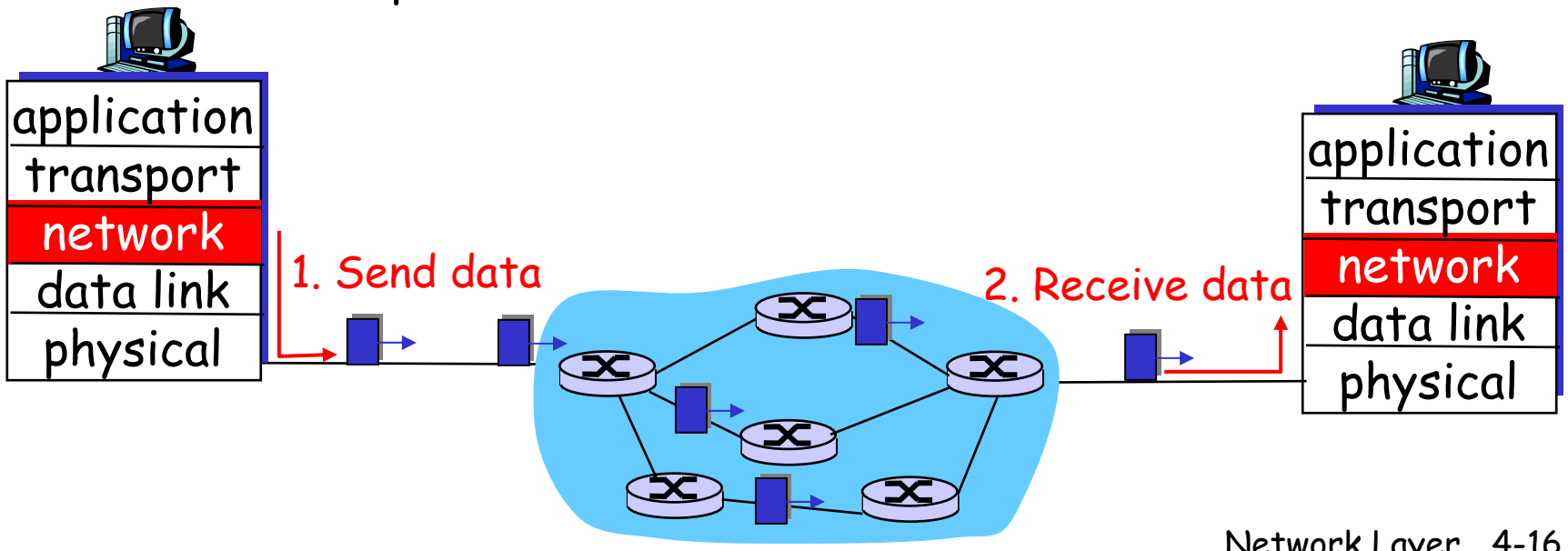
Virtual circuits: signaling protocols

- used to setup, maintain teardown VC
- used in ATM, frame-relay, X.25
- not used in today's Internet



Datagram networks 資料封包網路

- no call setup at network layer
- routers: no state about end-to-end connections
  路由器沒有connection的資訊及概念
  - no network-level concept of "connection"
- packets forwarded using destination host address
  - packets between same source-dest pair may take different paths



Forwarding table

4 billion
possible entries

Destination Address Range	Link Interface
11001000 00010111 00010000 00000000 through 11001000 00010111 00010111 11111111	0
11001000 00010111 00011000 00000000 through 11001000 00010111 00011000 11111111	1
11001000 00010111 00011000 00000000 through 11001000 00010111 00011111 11111111	2
otherwise	3

Longest prefix matching

Prefix Match	Link Interface
11001000 00010111 00010	0
11001000 00010111 00011000	1
11001000 00010111 00011	2
otherwise	3

Examples

DA: 11001000 00010111 00010110 10100001 Which interface?

DA: 11001000 00010111 00011000 10101010 Which interface?

Datagram or VC network: why?

該使用何種網路

Internet (datagram)

- data exchange among computers
  - "elastic" service, no strict timing req.
- "smart" end systems (computers)
  - can adapt, perform control, error recovery
  - simple inside network, complexity at "edge"
- many link types
  - different characteristics
  - uniform service difficult

ATM (VC)

- evolved from telephony
- human conversation:
  - strict timing, reliability requirements
  - need for guaranteed service
- "dumb" end systems
  - telephones
  - complexity inside network

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  路由器內部有什麼？
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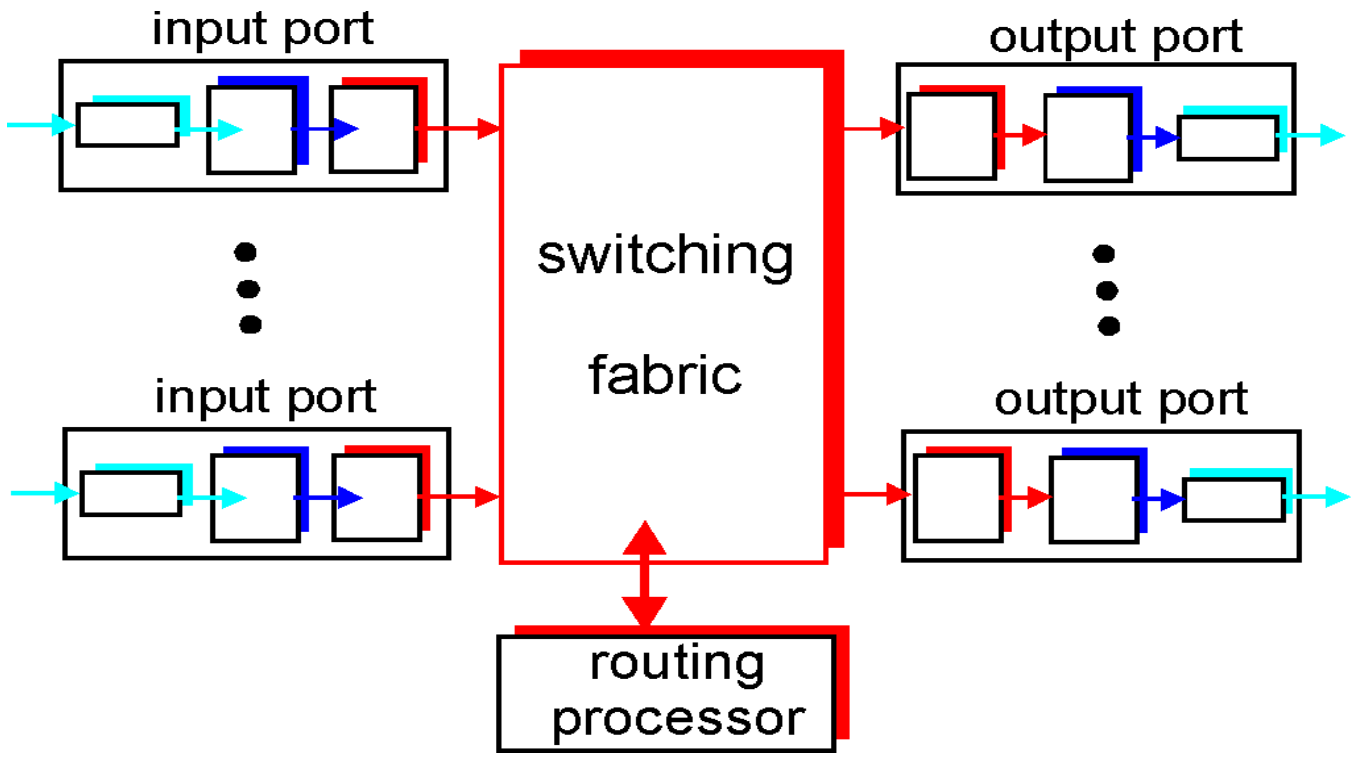
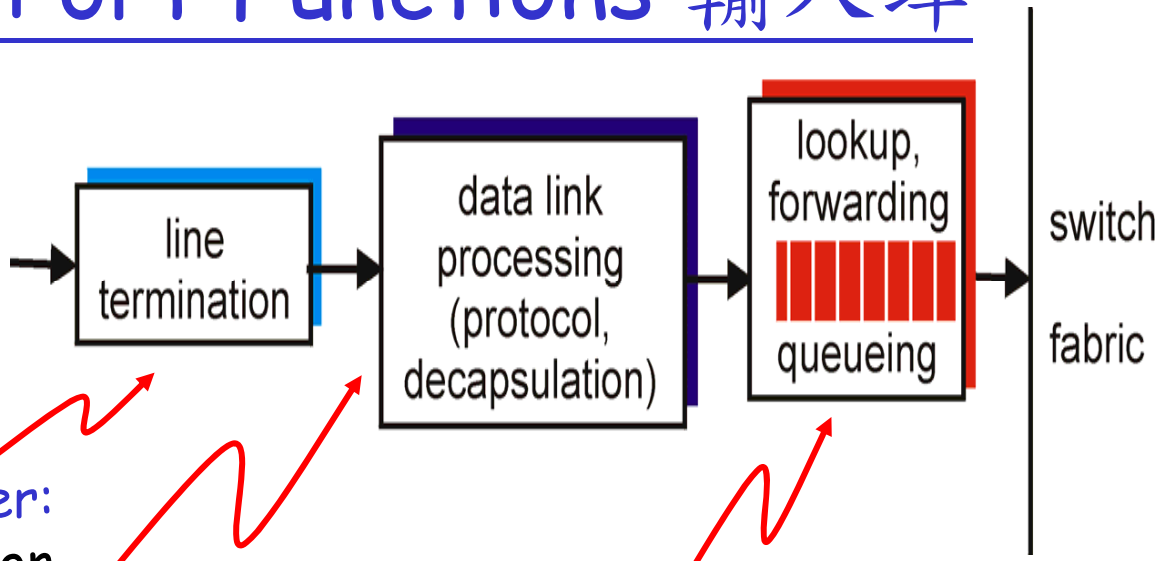
Router Architecture Overview

Two key router functions: 兩大功能

- run routing algorithms/protocol (RIP, OSPF, BGP)
- *forwarding* datagrams from incoming to outgoing link



Input Port Functions 輸入埠



Physical layer:
bit-level reception

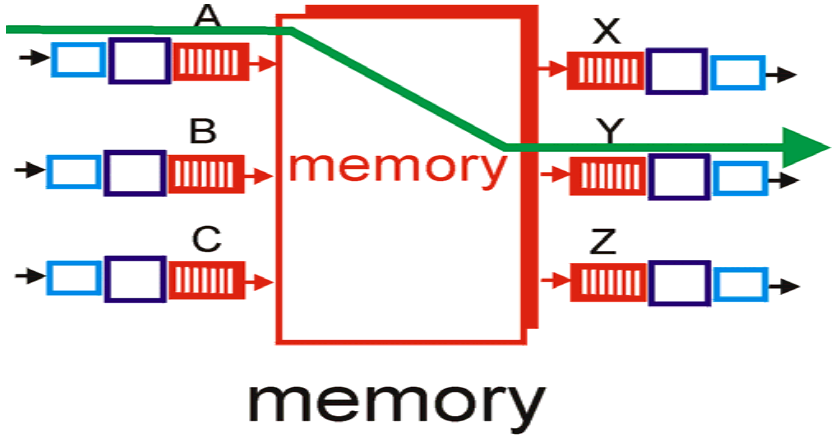
Data link layer:
e.g., Ethernet
see chapter 5

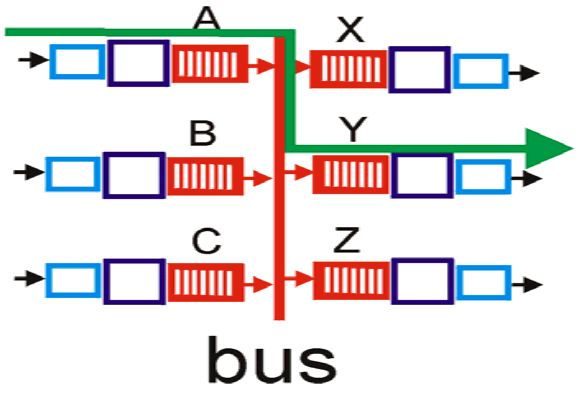
Decentralized switching: 分散式處理

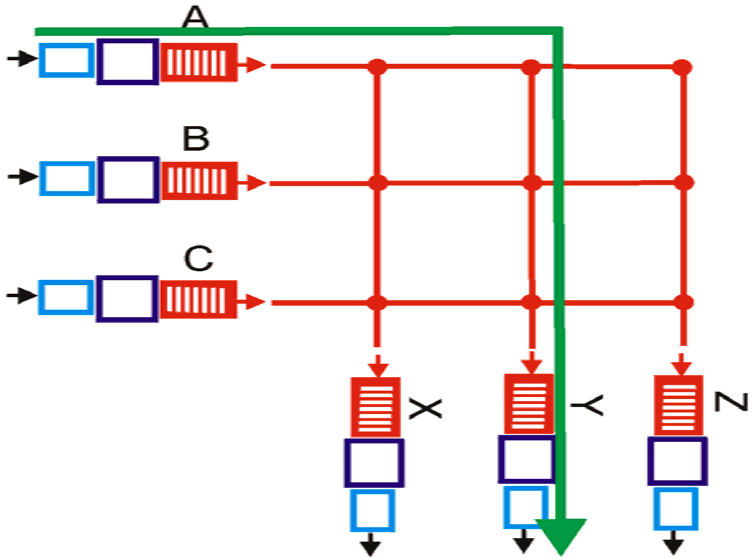
- given datagram dest., lookup output port using forwarding table in input port memory
- goal: complete input port processing at 'line speed'
- queuing: if datagrams arrive faster than forwarding rate into switch fabric

Three types of switching fabrics

三類switching fabrics





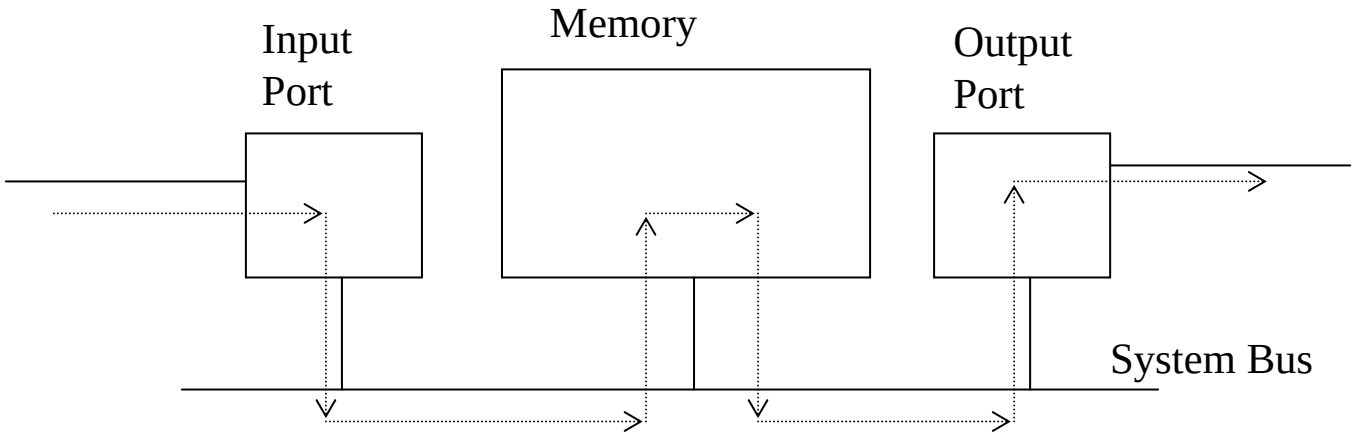


Interconnection network

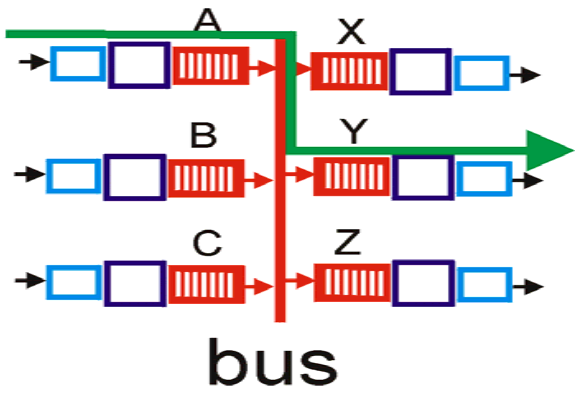
Switching Via Memory

First generation routers: 第一代路由器

- traditional computers with switching under direct control of CPU
- packet copied to system's memory
- speed limited by memory bandwidth (2 bus crossings per datagram)



Switching Via a Bus

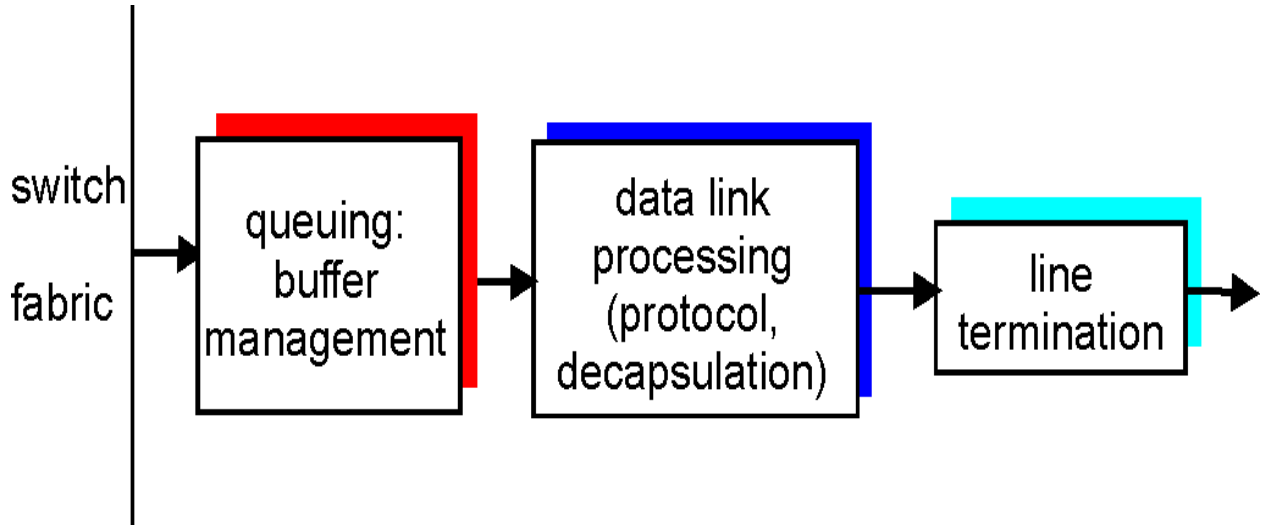


- datagram from input port memory to output port memory via a shared bus 共用匯流排
- bus contention: switching speed limited by bus bandwidth 競爭資源
- 32 Gbps bus, Cisco 5600: sufficient speed for access and enterprise routers

Switching Via An Interconnection Network (cross connect)

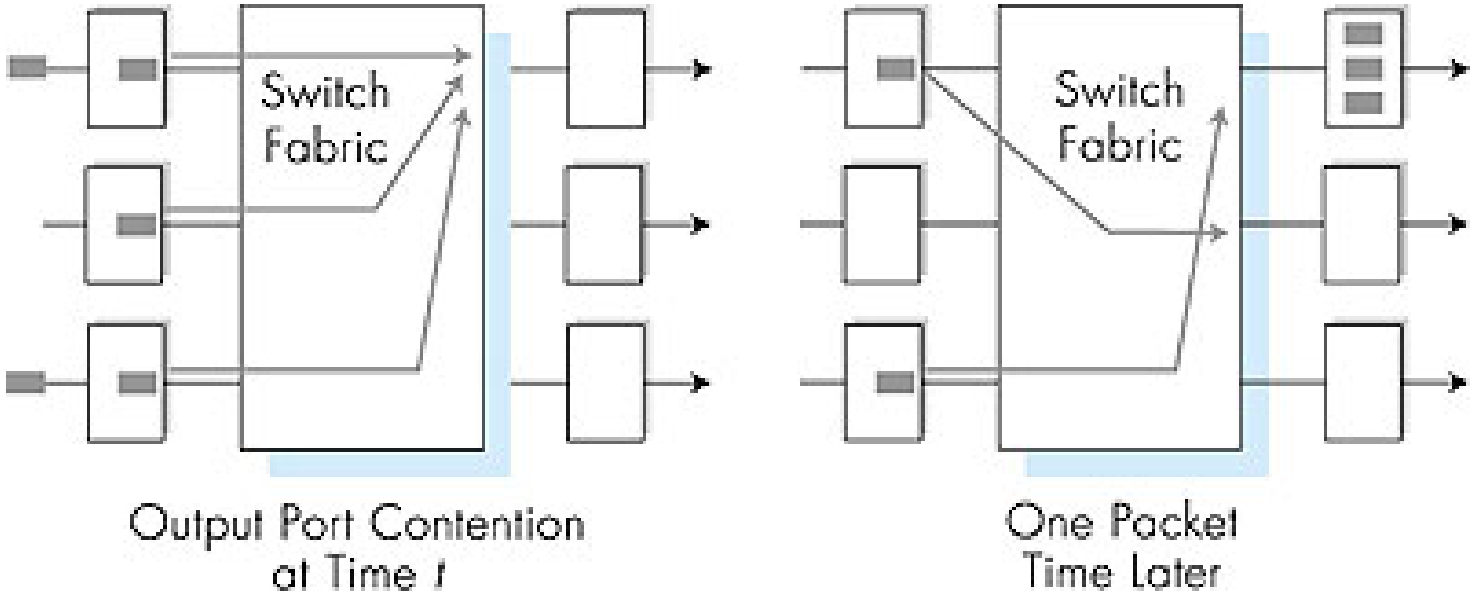
- overcome bus bandwidth limitations
  解決bus的頻寬問題
- Banyan networks, other interconnection nets initially developed to connect processors in multiprocessor
- advanced design: fragmenting datagram into fixed length cells, switch cells through the fabric.
- Cisco 12000: switches 60 Gbps through the interconnection network

Output Ports 輸出埠



- *Buffering* required when datagrams arrive from fabric faster than the transmission rate
- *Scheduling discipline* chooses among queued datagrams for transmission

Output port queueing 輸出埠排隊



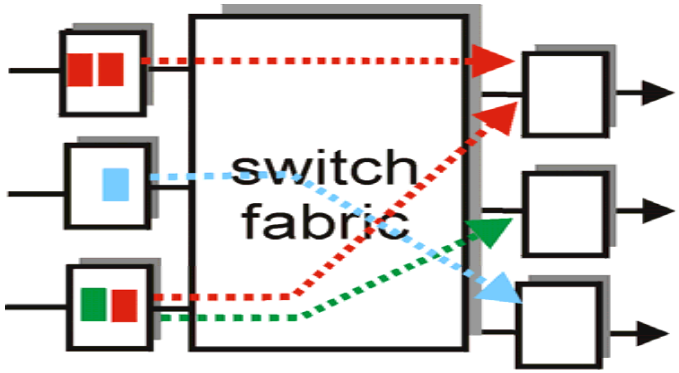
- buffering when arrival rate via switch exceeds output line speed
- *queueing (delay) and loss due to output port buffer overflow!*

How much buffering?

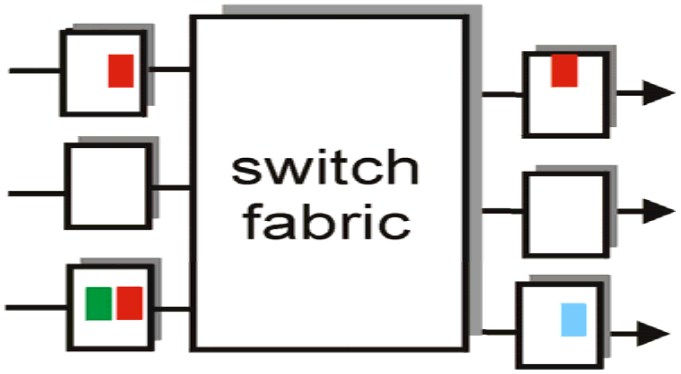
- RFC 3439 rule of thumb: average buffering equal to "typical" RTT (say 250 msec) times link capacity C
  - e.g., C = 10 Gps link: 2.5 Gbit buffer
- Recent recommendation: with N flows, buffering equal to $\frac{RTT \cdot C}{\sqrt{N}}$

Input Port Queuing 輸入埠排隊

- Fabric slower than input ports combined -> queueing may occur at input queues
- Head-of-the-Line (HOL) blocking: queued datagram at front of queue prevents others in queue from moving forward
- *queueing delay and loss due to input buffer overflow!*



output port contention
at time t - only one red
packet can be transferred



green packet
experiences HOL blocking